Science and Technology Facilities Council

University of Southampton

Collider Phenomenology

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with thanks to Eleni Vryonidou & Jonathan Gaunt

Plan for the lectures

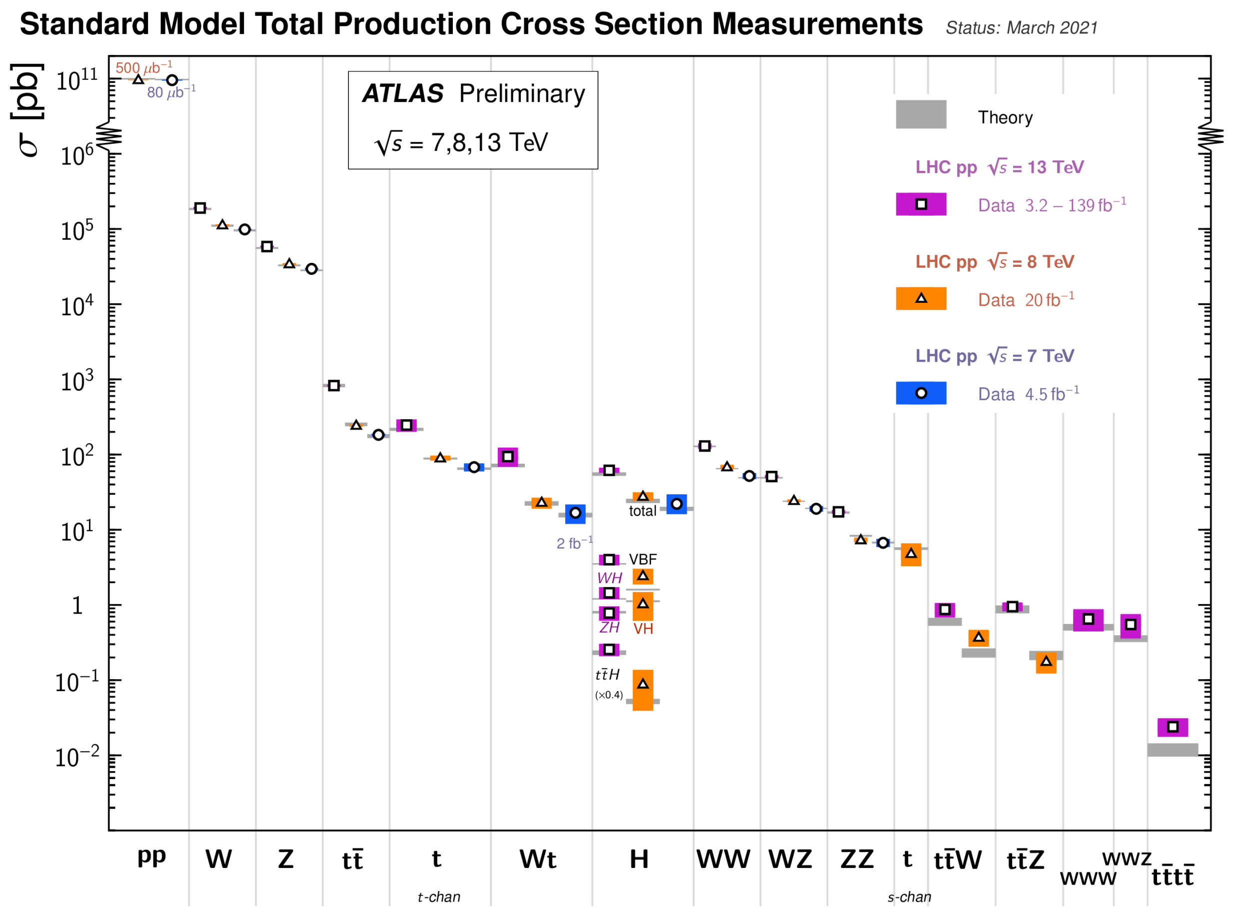
- Basics of collider physics
- Basics of QCD
    - DIS and the Parton Model
    - Higher order corrections
    - Asymptotic freedom
    - QCD improved parton model
- State-of-the-art computations for the LHC
- Monte Carlo generators
- Higgs phenomenology
- Top phenomenology
- Searching for New Physics: EFT

Basics of collider physics

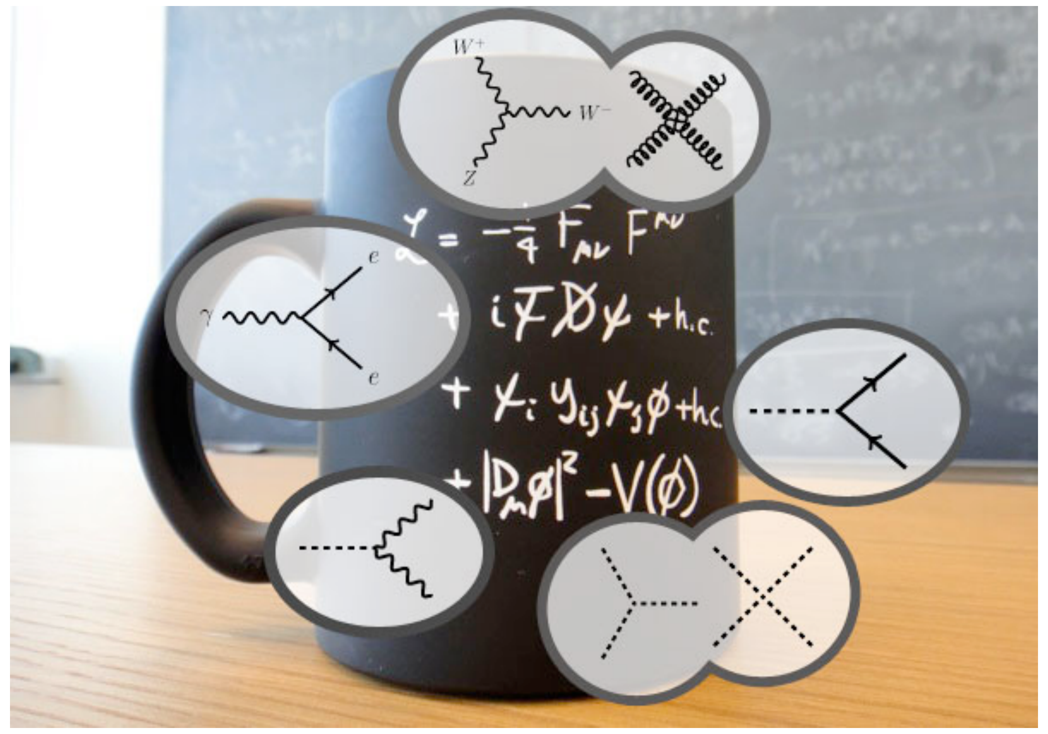
Goals of collider physics:

- Test theoretical predictions: Standard Model and New Physics
- Hopefully find the unexpected!

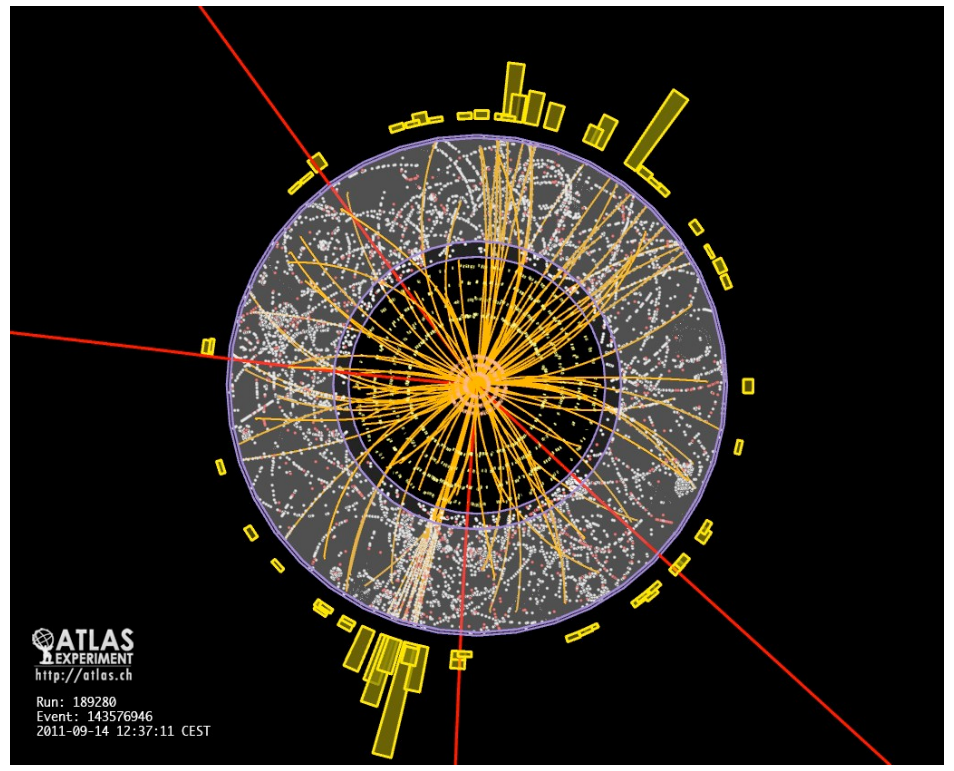
Collider physics



Interpretation



Theory



Experiment

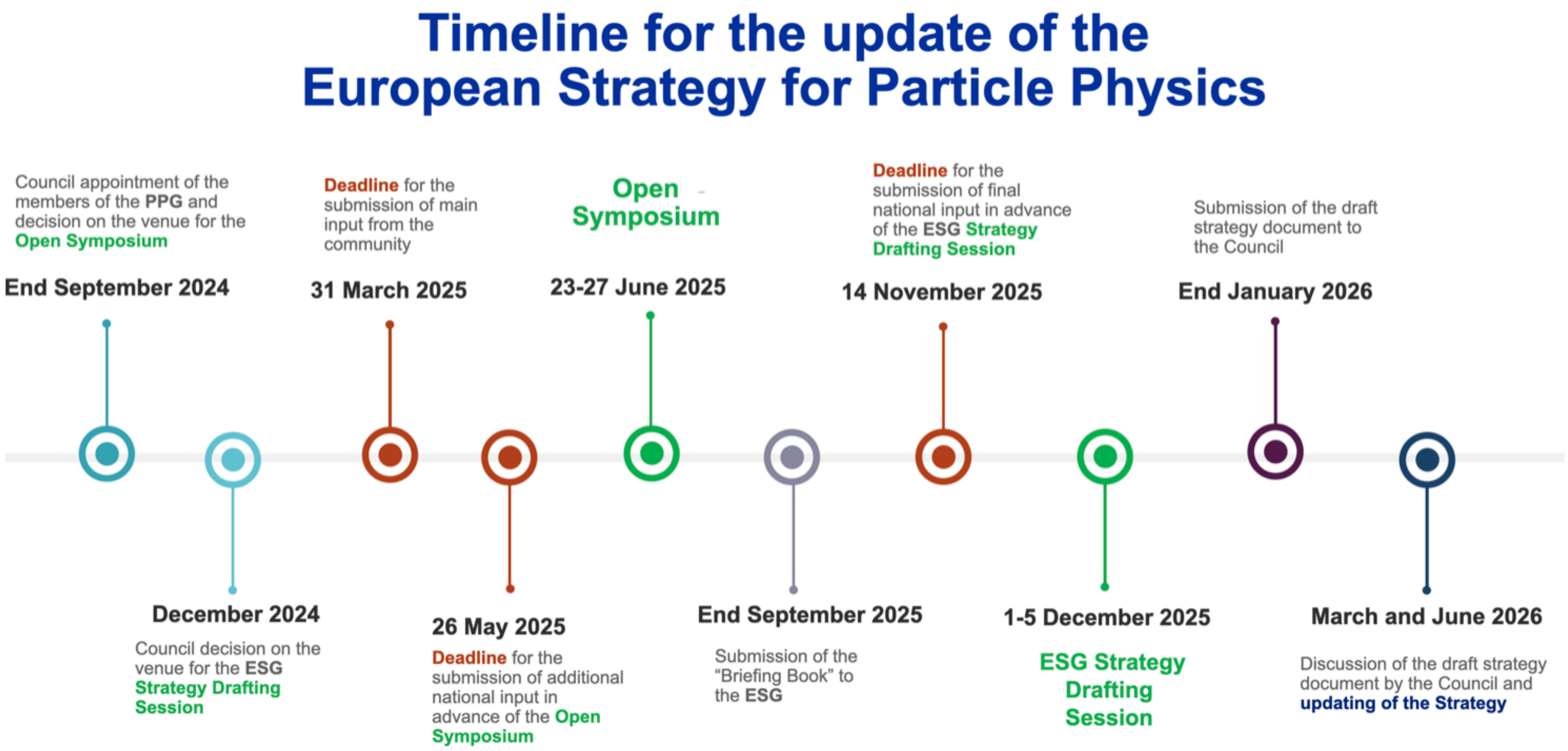
Need good control of every step

Historical perspective

Why bother? Because it works!

Collider	When	Collisions	Energy	Main Impact
SPS-CERN	1981-1984	pp	600 GeV	W/Z bosons
Tevatron	1983-2011	p-anti p	2 TeV	Top quark
LEP-CERN	1989-2000	e+e-	210 GeV	Precision EW
HERA-DESY	1992-2007	ep	320 GeV	QCD/PDFs
BELLE	1999-2010	e+e-	10 GeV	Flavour physics
LHC	2009-Today	pp	7/8/13/13.6 TeV	Higgs…

Future of collider physics?



Collider reach

$$A + B \to X \qquad M_X^2 = (p_1 + p_2)^2$$

Fixed target experiment:

$$p_1 \simeq (E,0,0,E)$$
$$p_2 = (m,0,0,0)$$

$$M_X \simeq \sqrt{2mE}$$

Collider experiment:

$$p_1 \simeq (E,0,0,E)$$
$$p_2 \simeq (E,0,0,-E)$$

$$M_X \simeq 2E$$

Better energy scaling for collider experiment

Note: fixed target can benefit from dense target

Collider aspects

Luminosity: rate of particles in colliding bunches

$$\mathscr{L} = \frac{N_1 N_2 f}{A}$$

N_i number of particles in bunches

f bunch collision rate

A transverse bunch area

Integrated Luminosity: $L = \int \mathscr{L} dt$

Number of events for process with cross-section σ: $L\sigma$

LHC luminosity Run II $L = 300$ fb^{-1}

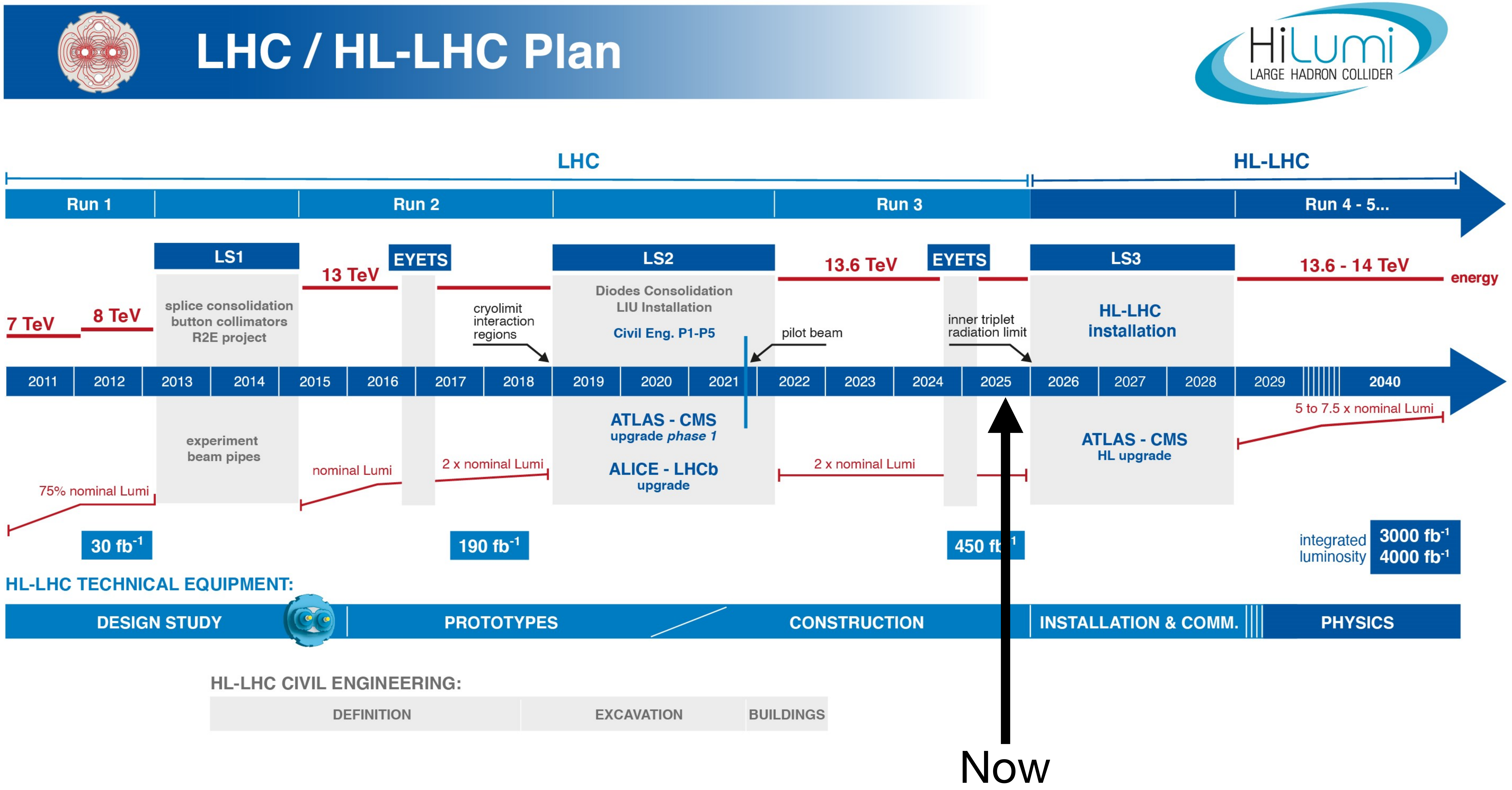
HL-LHC luminosity $L = 3000$ fb^{-1}

Circular vs linear: circular colliders are compact, but suffer from synchrotron radiation

Lepton vs Hadron: Lepton colliders, all energy available in the collision

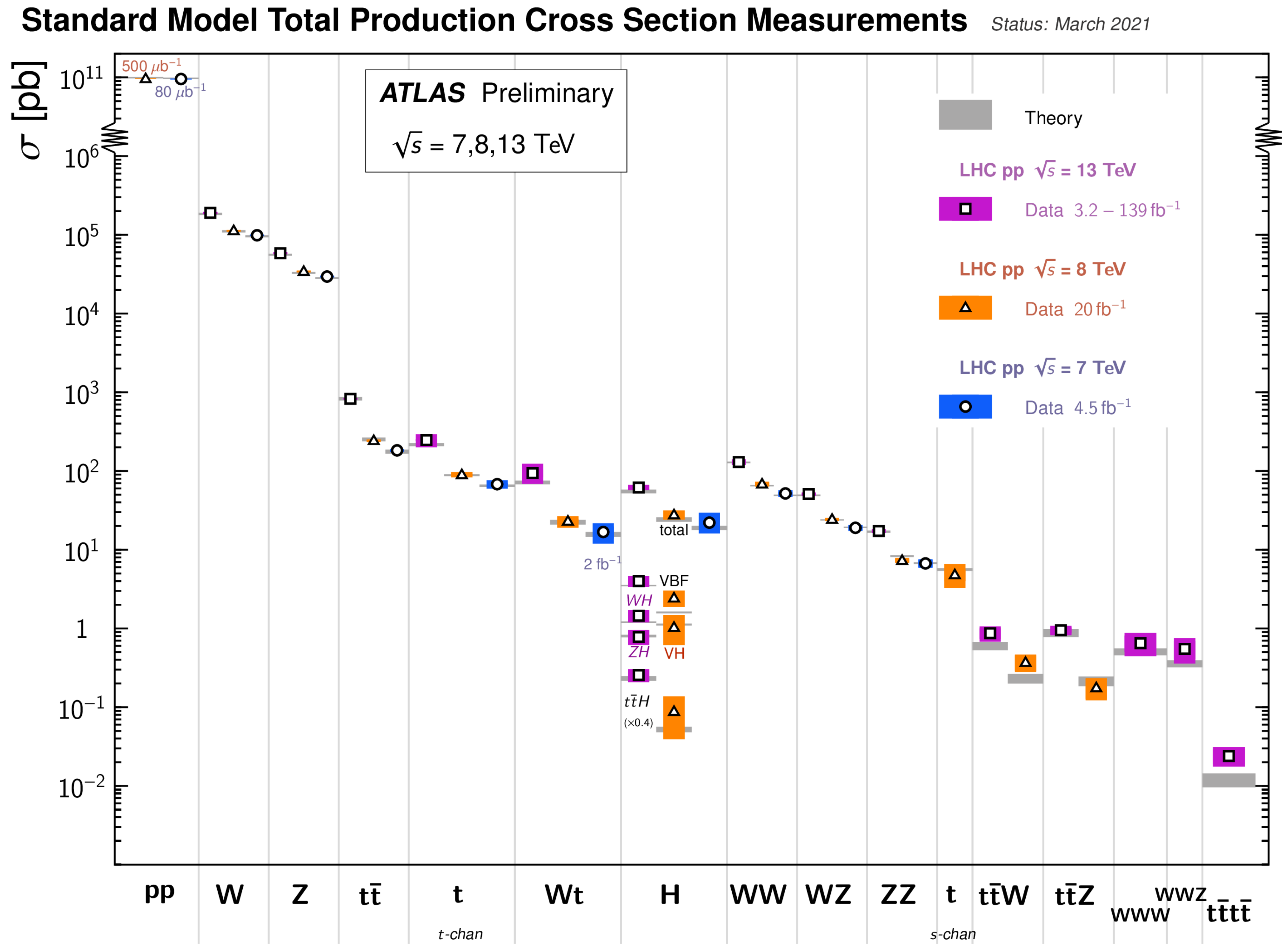
Hadron colliders, energy available determined by PDFs but can generally reach higher energies

LHC: a hadron collider

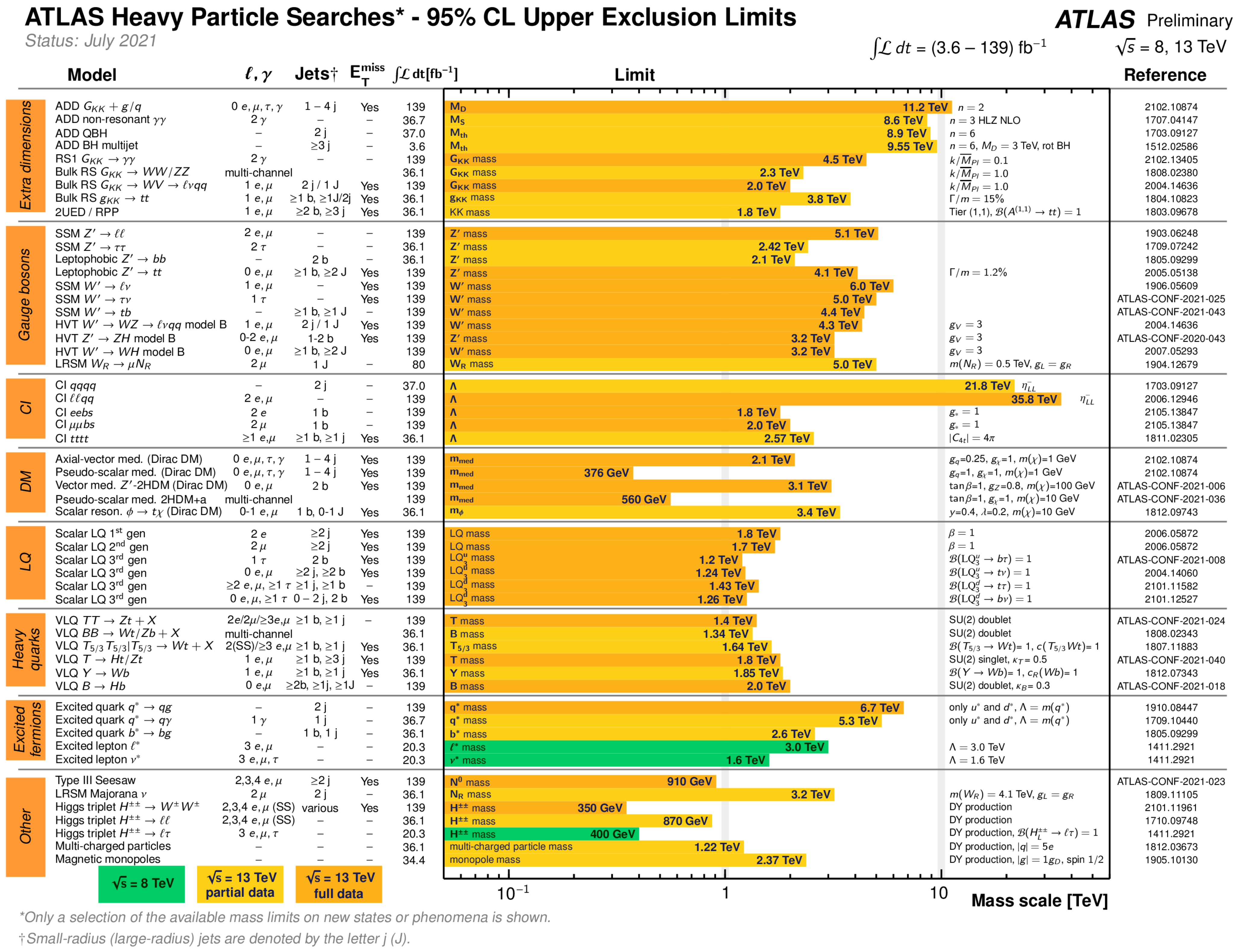


LHC status

Rediscovering the SM



Searching for the unknown



Good agreement with the SM

LHC physics

No sign of new physics! Searches for deviations continue

New Physics can be:
Weakly coupled: Small rates means that more Luminosity can help

Exotic: Need new ways to search for it, going beyond standard searches or even beyond high-energy colliders

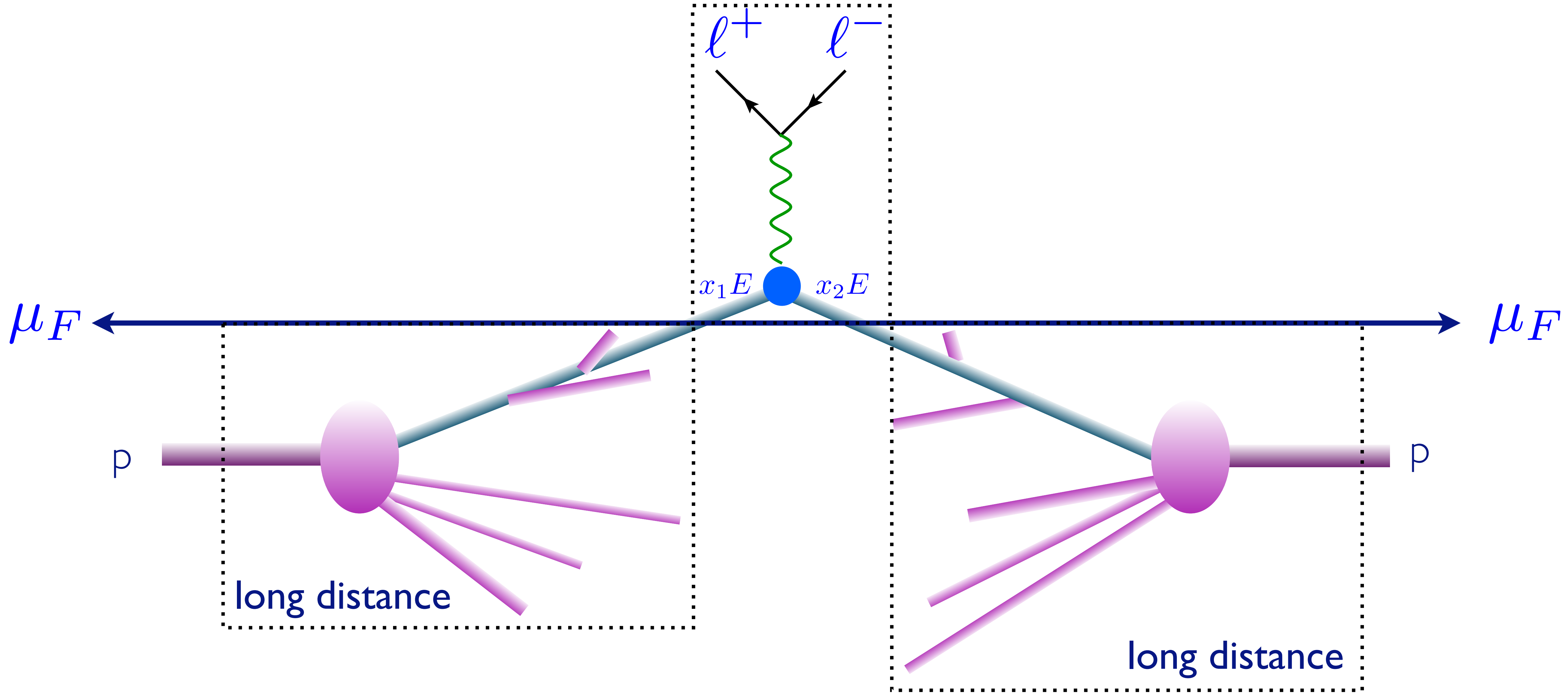
Heavy: Not enough energy to produce it
Need indirect searches: SMEFT

What is next for LHC physics

- New Physics is hiding well!
- Need to probe small deviations from the Standard Model using very precise predictions.
- Precise predictions are needed for both the SM and BSM.

In this course we will study the ingredients which enter in theoretical predictions and interpretations of LHC data!

How to compute cross-sections for the LHC?



$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral — Parton density functions — Parton-level cross section

Master formula for LHC physics

$$\sum_{a,b}\int dx_1 dx_2 d\Phi_{\rm FS}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral

Important aspect of a Monte Carlo generator

Parton density functions

Universal:

~Probabilities of finding given parton with given momentum in proton

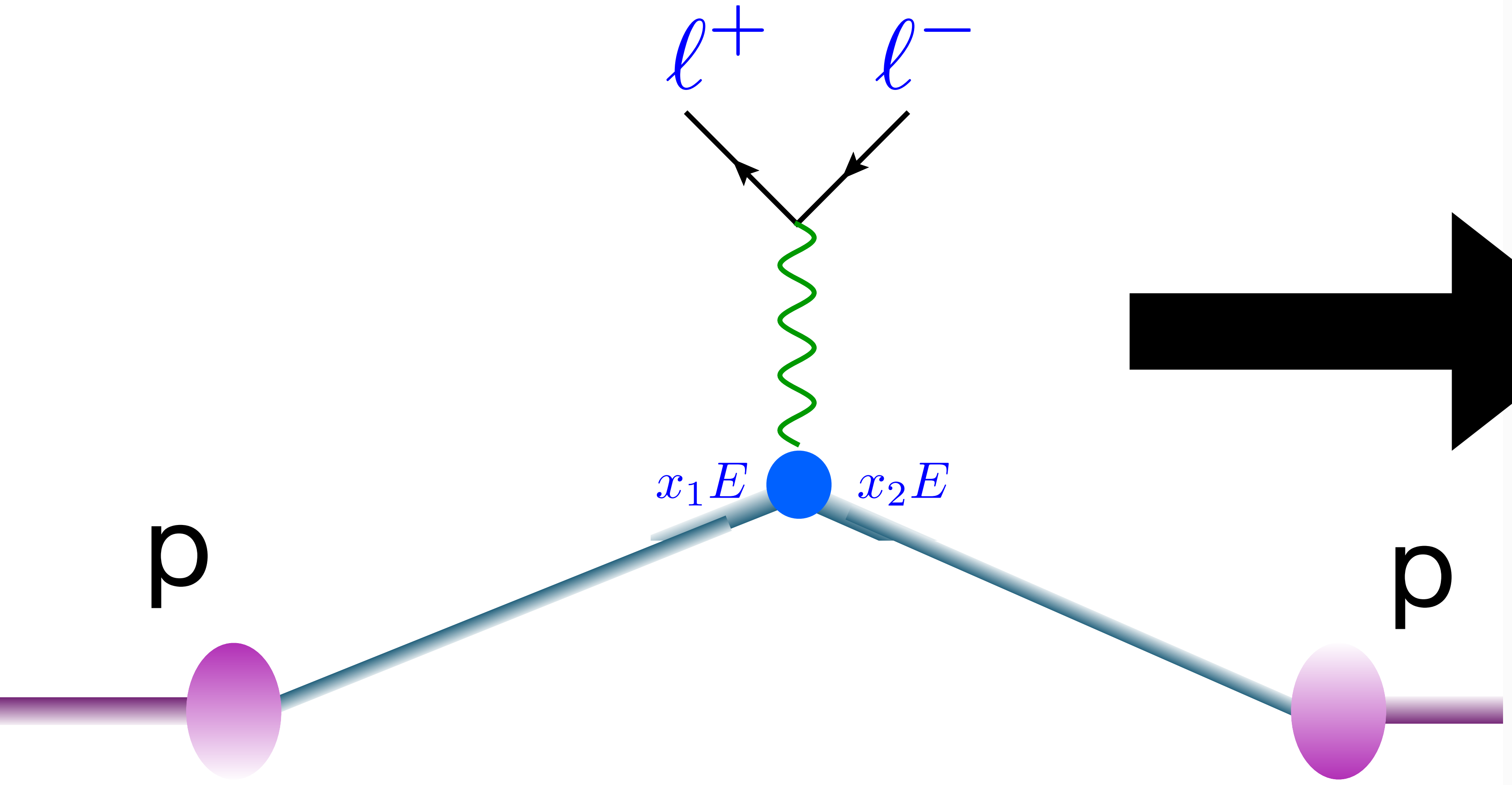
Extracted from data

Parton-level cross section

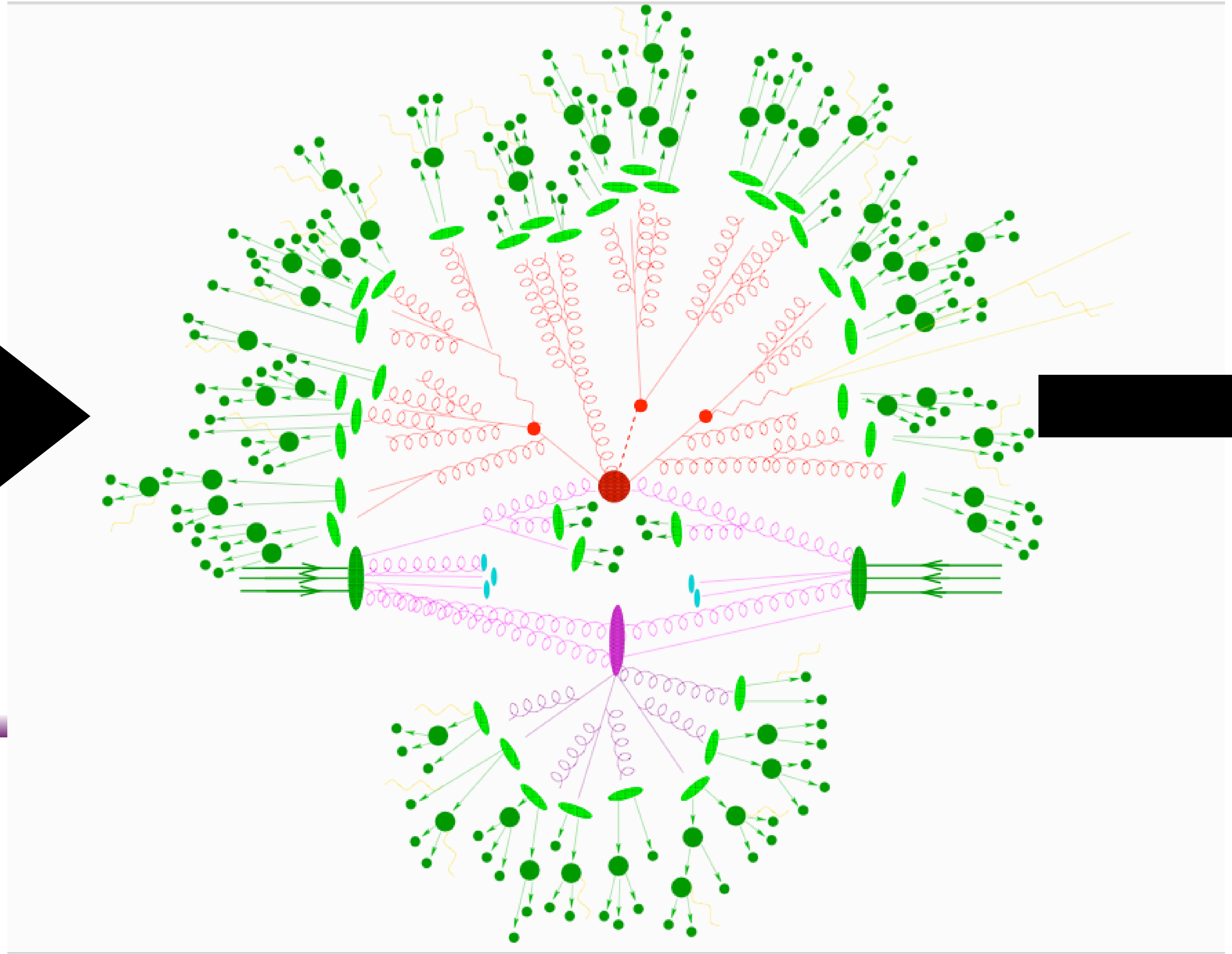
Subject of huge efforts in the LHC theory community to systematically improve this

We will study this formula in detail this week

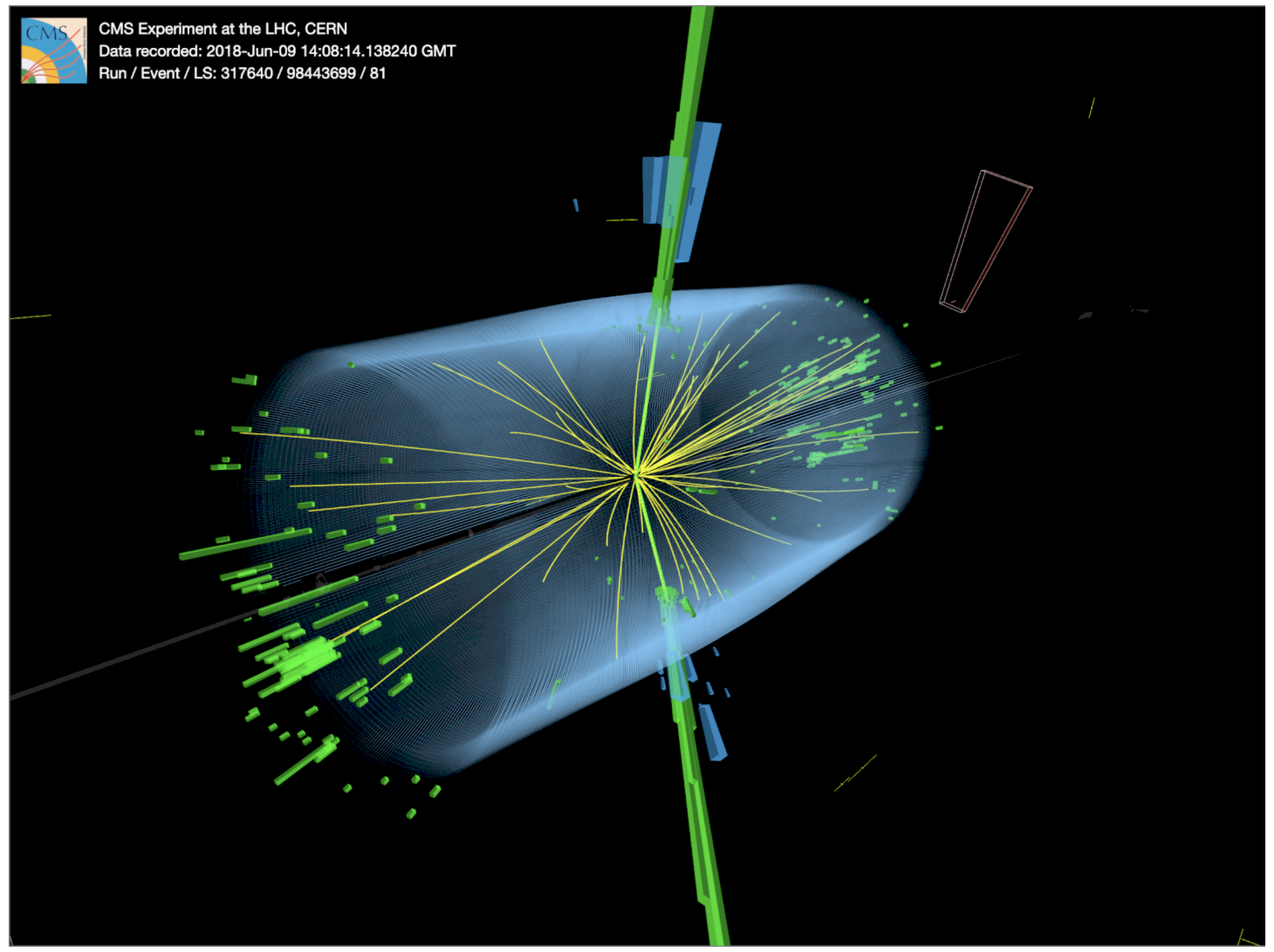
From the hard scattering to events



Ideally

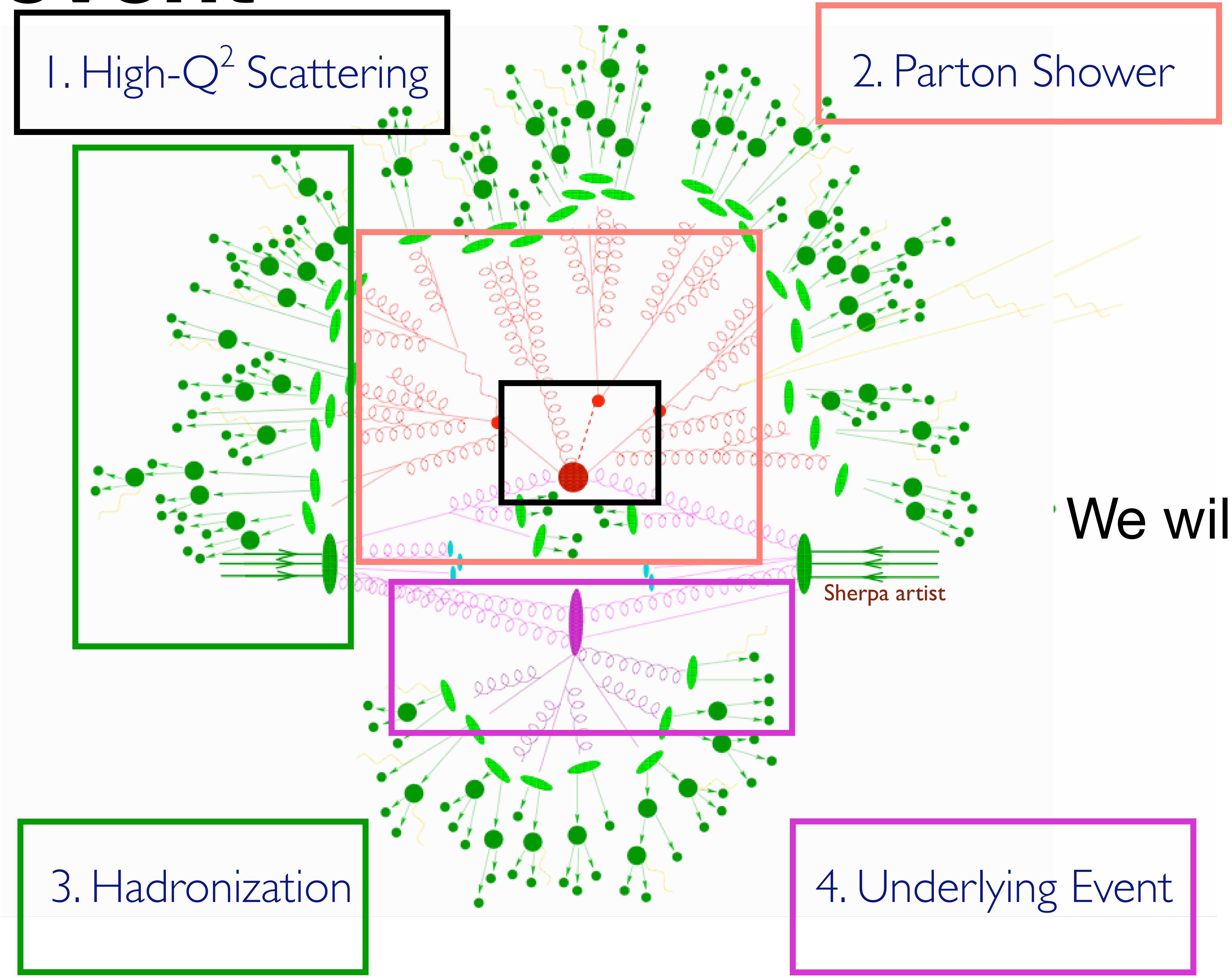


Artist's impression of reality



Reality

An LHC event



We will discuss all of these!

QCD…

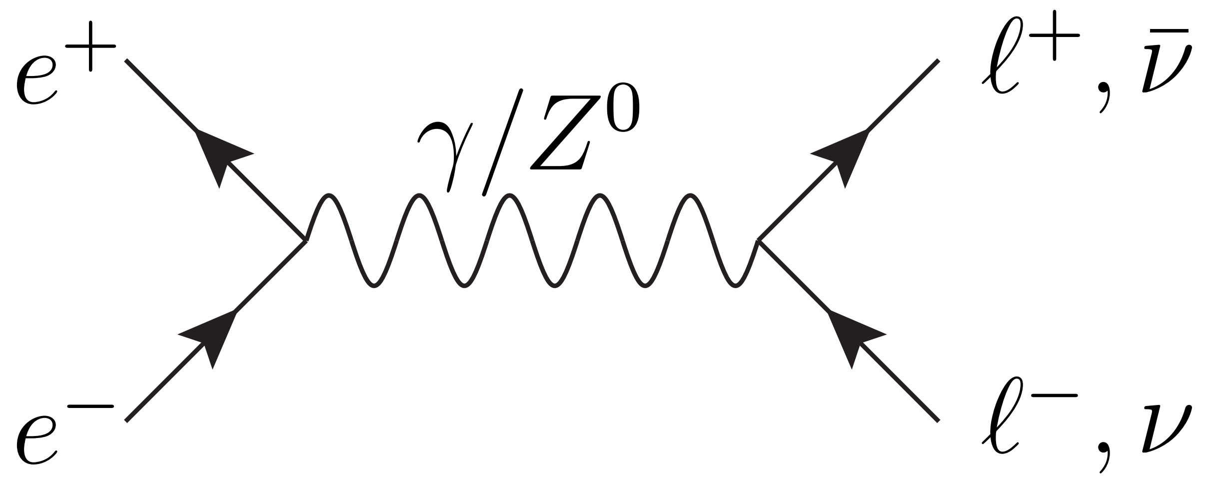
LHC is a proton-proton collider:

- colliding particles are proton constituents which are coloured particles

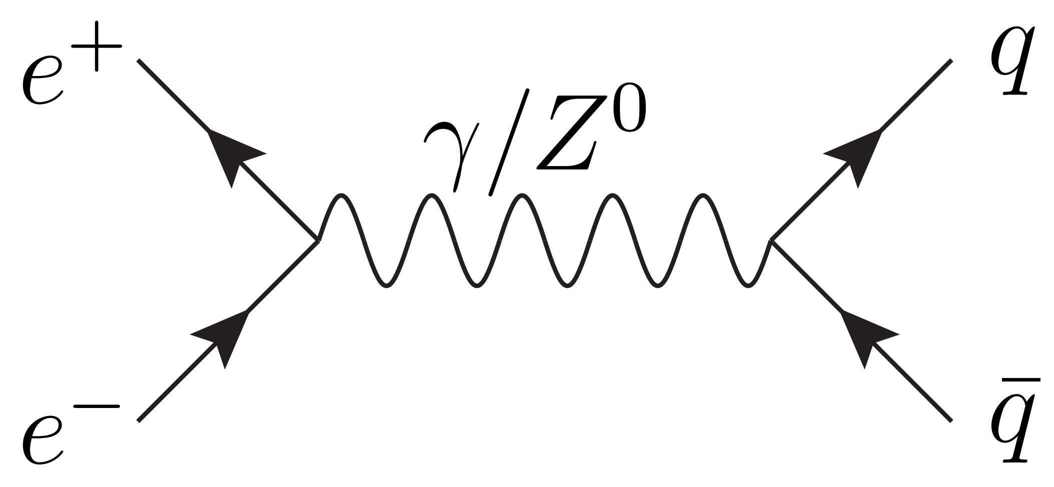
QCD plays a crucial role in what we eventually observe in the detectors

Why is QCD “special”? Let’s compare it to what we know best: QED

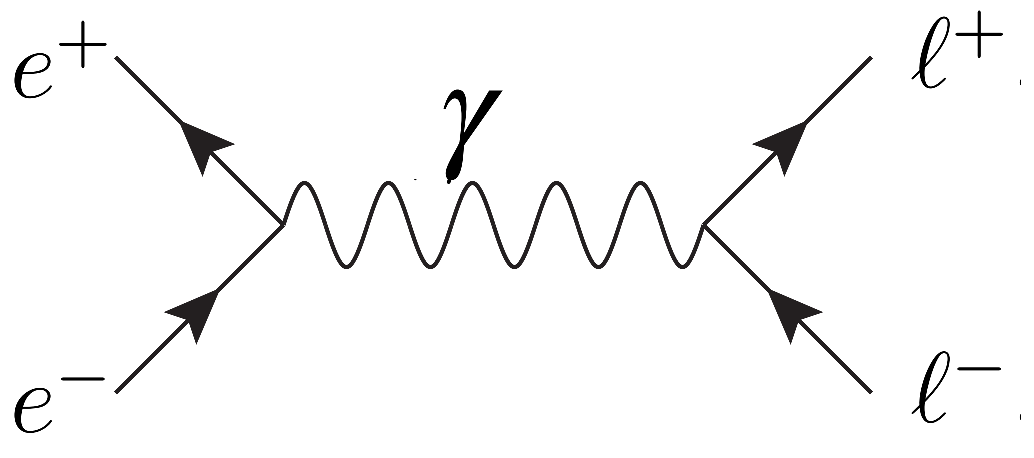
From QED to QCD

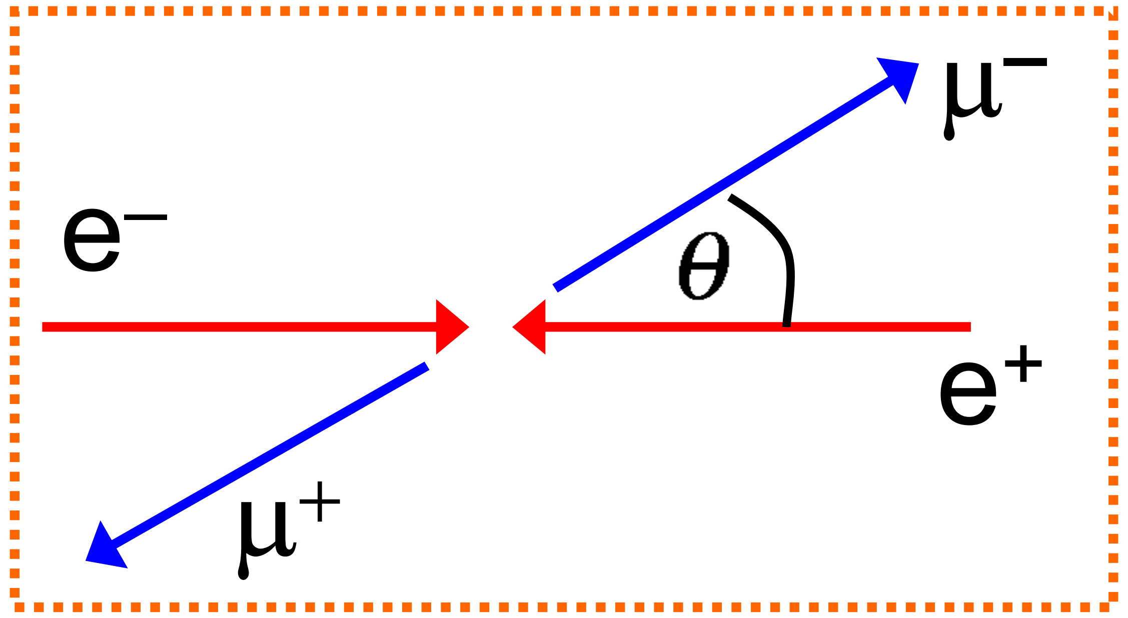


vs



Let's compute the matrix element for:





Summing and averaging:

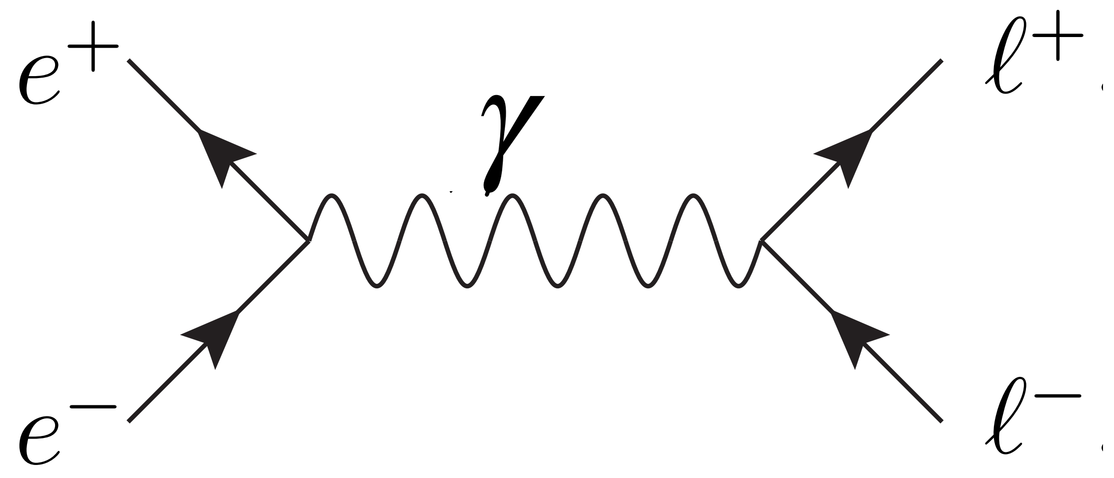
$$\bar{\sum} |M|^2 = \frac{2e^4}{s^2}[t^2 + u^2]$$

Try this out!

Mandelstam variables: $s = (p_{e+} + p_{e-})^2$ $\quad t = (p_{e+} - p_{\mu+})^2 = -\frac{s}{2}(1 - \cos\theta)$

Why? $s + t + u = 0$ $\quad u = (p_{e+} - p_{\mu-})^2 = -\frac{s}{2}(1 + \cos\theta)$

From QED to QCD



$$\bar{\sum} |M|^2 = \frac{2e^4}{s^2}[t^2 + u^2]$$

$$\bar{\sum} |M|^2 \propto (1 + \cos^2\theta)$$

Cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \bar{\sum} |M|^2$$

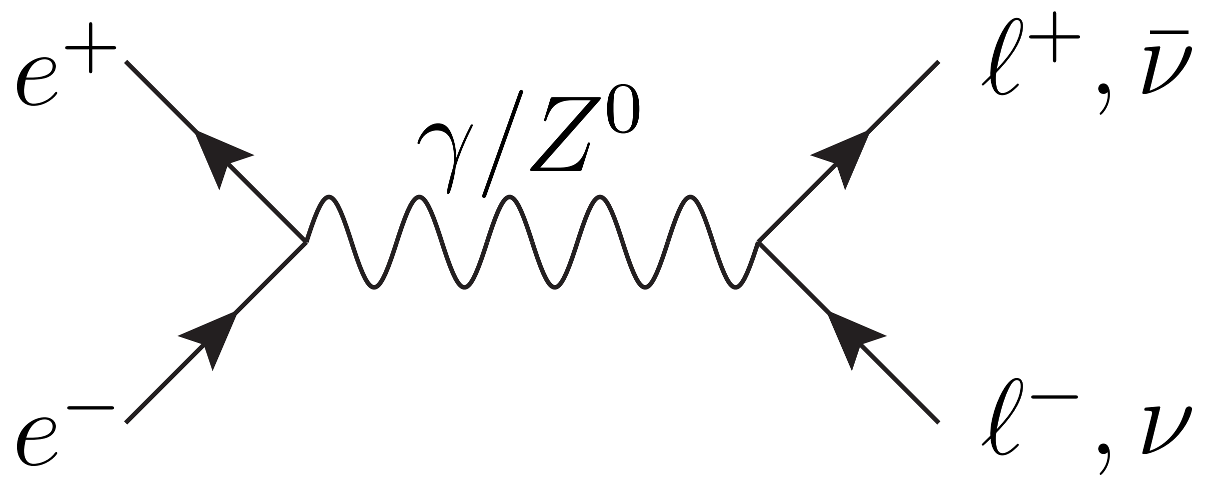
2-body phase-space+Momentum conservation

$$d\Omega = d\phi\, d\cos\theta$$

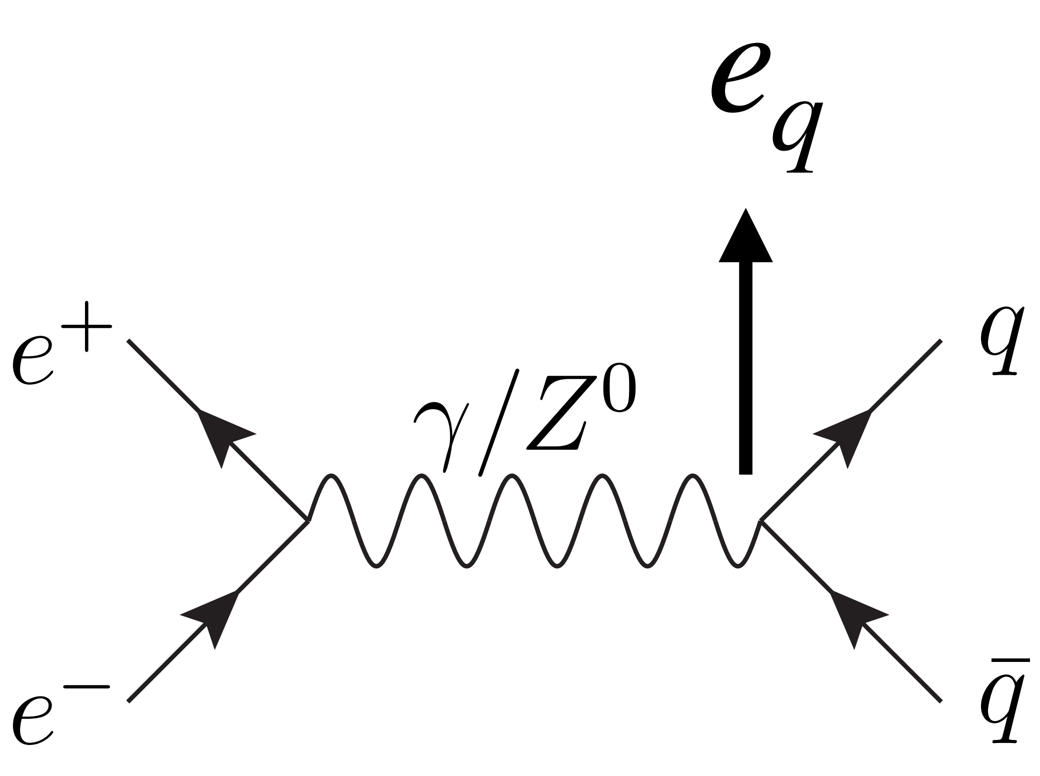
$$\sigma_{e^+e^- \to \mu^+\mu^-} = \frac{4\pi\alpha^2}{3s}$$

Try this out!

From QED to QCD



vs



$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \sim N_c \sum_q e_q^2$$

$$= 2(N_c/3) \quad q = u, d, s$$

$$= 3.7(N_c/3) \quad q = u, d, s, c, b$$

Difference due to colour!!!

Quark—anti-pair can be one of $r\bar{r}, g\bar{g}, b\bar{b}$

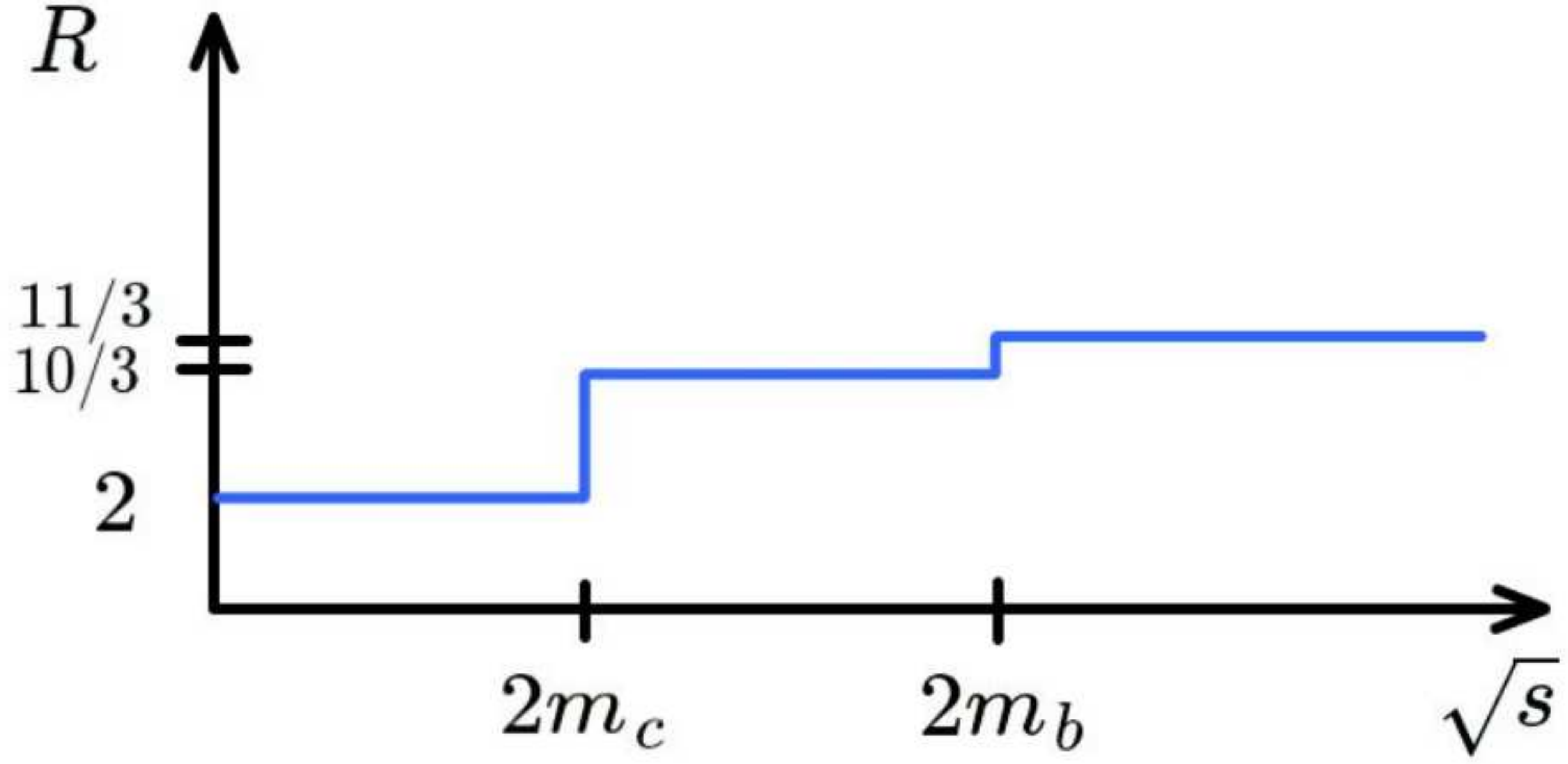
Why did we pick $\mu^+\mu^-$?

Experimental evidence for colour!

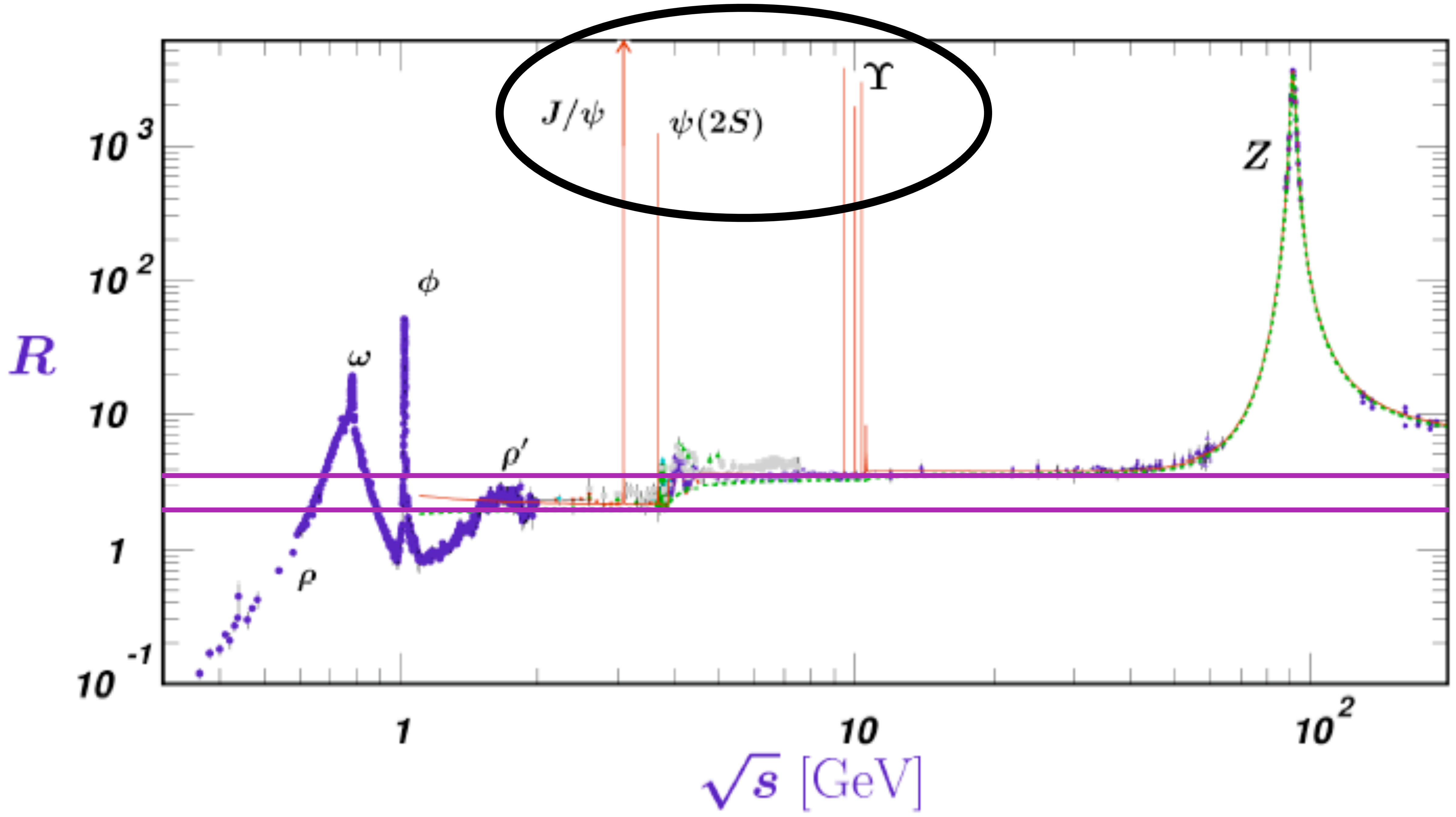
From QED to QCD

Alternative, W decays @ LEP

R-ratio computation



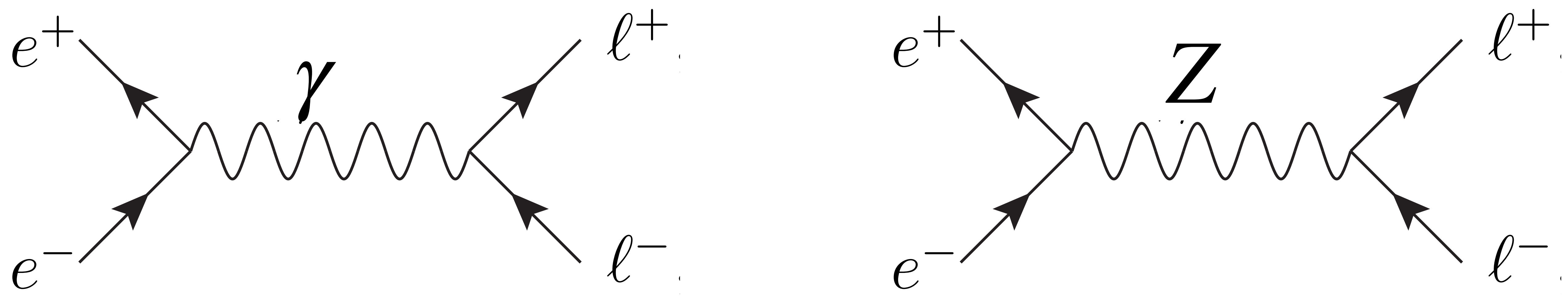
Expected



Measured

Quarkonium states: very small width, very long lived states

A few words about the Z-resonance



Z contribution becomes relevant when $\sqrt{s} \sim M_Z$

We then need both diagrams and their interference

See exercise!

Z-resonance

Feynman rules

Z is an unstable particle, we can't simply use $\frac{1}{s - M_Z^2}$

Breit-Wigner propagator: $\frac{1}{s - M_Z^2 + i\Gamma M}$

Schematic amplitude

Narrow width approximation:

Show limit def'n

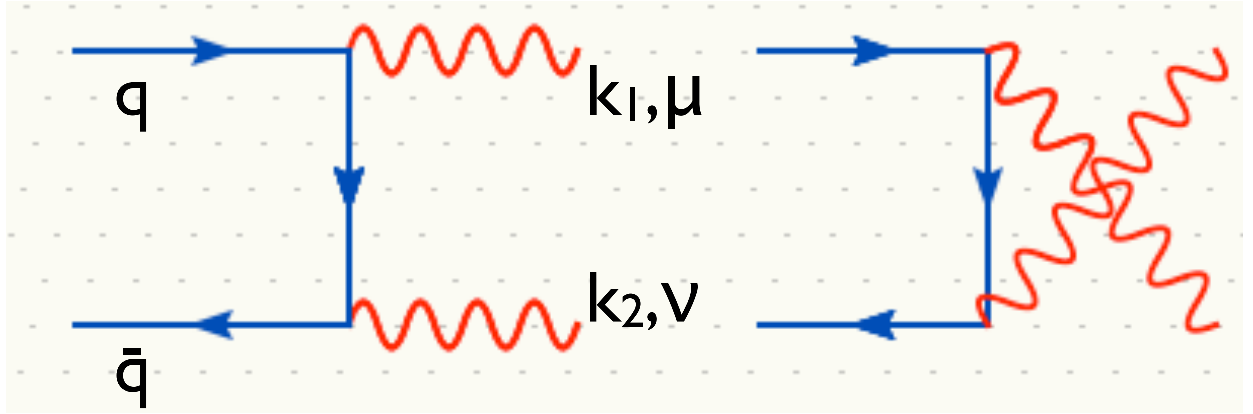
$$\frac{1}{(\hat{s} - M_Z^2)^2 + M_Z^2\Gamma_Z^2} \approx \frac{\pi}{M_Z\Gamma_Z}\delta(\hat{s} - M_Z^2) \quad \text{if } \Gamma_Z/M_Z \ll 1$$

$$\sigma_{e^+e^-\to Z\to\mu^+\mu^-} \simeq \sigma_{e^+e^-\to Z} \times Br(Z \to \mu^+\mu^-) \text{ with } Br(Z \to \mu^+\mu^-) = \Gamma_{Z\to\mu^+\mu^-}/\Gamma_Z$$

Simplifies computations for particles with narrow width (e.g. Higgs)

From QED to QCD

Let's compute the amplitude for $q\bar{q} \to \gamma\gamma$



$$i\mathcal{M} = \mathcal{M}_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} = D_1 + D_2 = e^2\left(\bar{v}(\bar{q})\not{\epsilon}_2\frac{1}{\not{q}-\not{k}_1}\not{\epsilon}_1 u(q) + \bar{v}(\bar{q})\not{\epsilon}_1\frac{1}{\not{q}-\not{k}_2}\not{\epsilon}_2 u(q)\right)$$

Gauge invariance requires: $\epsilon_1^{*\mu}k_2^{\nu}\mathcal{M}_{\mu\nu} = \epsilon_2^{*\nu}k_1^{\mu}\mathcal{M}_{\mu\nu} = 0$

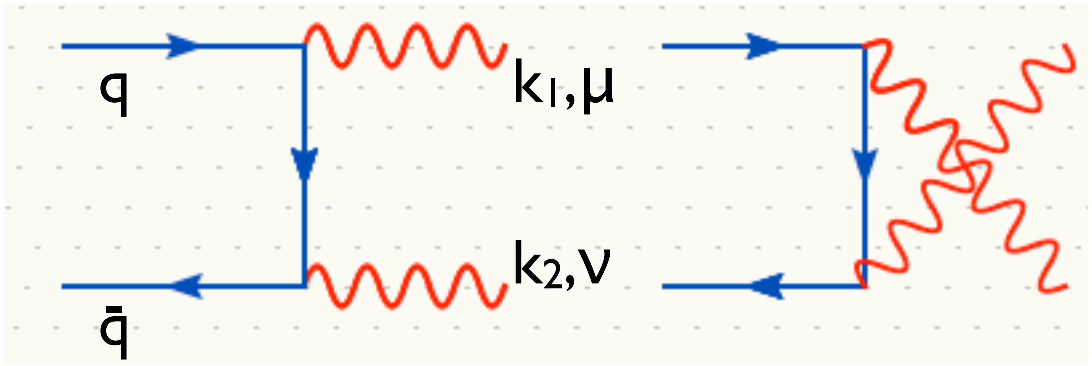
$$\mathcal{M}_{\mu\nu}k_1^{*\mu}\epsilon_2^{*\nu} = e^2\left(\bar{v}(\bar{q})\not{\epsilon}_2\frac{1}{\not{q}-\not{k}_1}\not{k}_1 u(q) + \bar{v}(\bar{q})\not{k}_1\frac{1}{\not{q}-\not{k}_2}\not{\epsilon}_2 u(q)\right)$$

$$= -\bar{v}(\bar{q})\not{\epsilon}_2 u(q) + \bar{v}(\bar{q})\not{\epsilon}_2 u(q) = 0$$

More steps

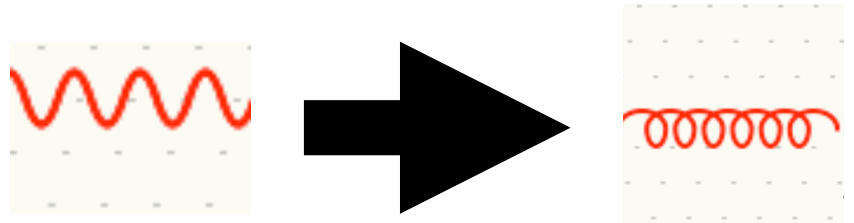
Works fine!

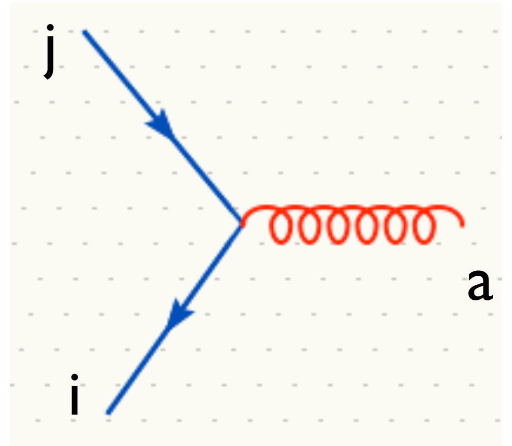
From QED to QCD



$$i\mathcal{M} = \mathcal{M}_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} = D_1 + D_2 = e^2\left(\bar{v}(\bar{q})\not{\epsilon}_2\frac{1}{\not{q}-\not{k}_1}\not{\epsilon}_1 u(q) + \bar{v}(\bar{q})\not{\epsilon}_1\frac{1}{\not{q}-\not{k}_2}\not{\epsilon}_2 u(q)\right)$$

Let's do the same for $q\bar{q} \to gg$





$$-ig_s t^a_{ij}\gamma^\mu$$

$$\frac{i}{g_s^2}M_g \equiv (t^b t^a)_{ij}D_1 + (t^a t^b)_{ij}D_2$$

$$M_g = (t^a t^b)_{ij}M_\gamma - g^2 f^{abc}t^c_{ij}D_1$$

$$[t^a, t^b] = if^{abc}t^c$$

Is this gauge invariant?

$$k_{1\mu}M_g^\mu = -g_s^2 f^{abc}t^c_{ij}\bar{v}_i(\bar{q})\not{\epsilon}_2 u_i(q)$$

We don't get zero anymore!

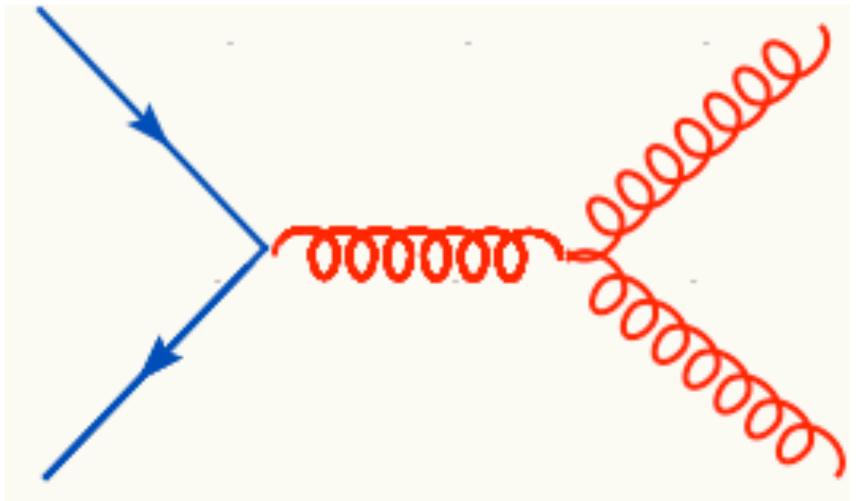
$$k_{1\mu}M_g^\mu = i(-g_s f^{abc}\epsilon_2^\mu)(-ig_s t^c_{ij}\bar{v}_i(\bar{q})\gamma_\mu u_i(q))$$

Looks like QCD vertex

From QED to QCD

Example 2: QCD and gauge invariance

What are we missing?



$$-ig_s^2 D_3 = \left(-ig_s t^a_{ij} \bar{v}_i(\bar{q})\gamma^\mu u_j(q)\right) \times \left(\frac{-i}{p^2}\right) \times \left(-g f^{abc} V_{\mu\nu\rho}(-p, k_1, k_2)\epsilon_1^\nu(k_1)\epsilon_2^\rho(k_2)\right)$$

- Lorentz invariant
- Anti-symmetry
- Dimensional analysis

$$V_{\mu_1\mu_2\mu_3}(p_1, p_2, p_3) = V_0\left[(p_1 - p_2)_{\mu_3} g_{\mu_1\mu_2} + (p_2 - p_3)_{\mu_1} g_{\mu_2\mu_3} + (p_3 - p_1)_{\mu_2} g_{\mu_3\mu_1}\right]$$

$$k_1 \cdot D_3 = g^2 f^{abc} t^c V_0 \left[\bar{v}(\bar{q})\not{\epsilon}_2 u(q) - \frac{k_2 \cdot \epsilon_2}{2k_1 \cdot k_2}\bar{v}(\bar{q})\not{k}_1 u(q)\right]$$

Gauge invariant IFF the other gluon is physical!

An empirical way to write down the triple gluon vertex!

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \sum_f \bar{\psi}_i^{(f)}(i\not{\partial} - m_f)\psi_i^{(f)} - \bar{\psi}_i^{(f)}(g_s t^a_{ij}\not{A}_a)\psi_j^{(f)}$$

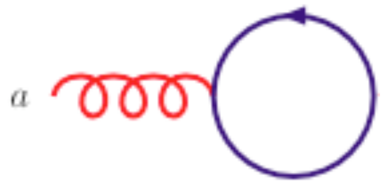
Gauge Fields | Matter | Interaction

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

See QCD-QED course!

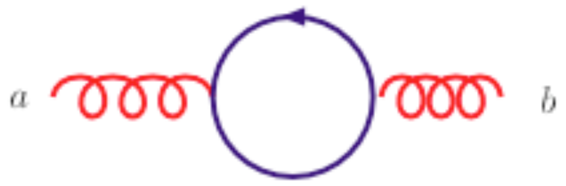
Colour algebra

$\mathrm{Tr}(t^a) = 0$



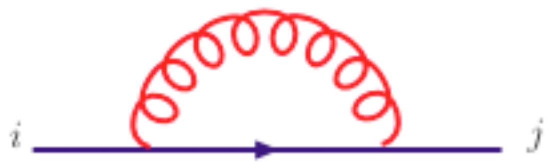
= 0

$\mathrm{Tr}(t^a t^b) = T_R \delta^{ab}$



= T_R *

$(t^a t^a)_{ij} = C_F \delta_{ij}$



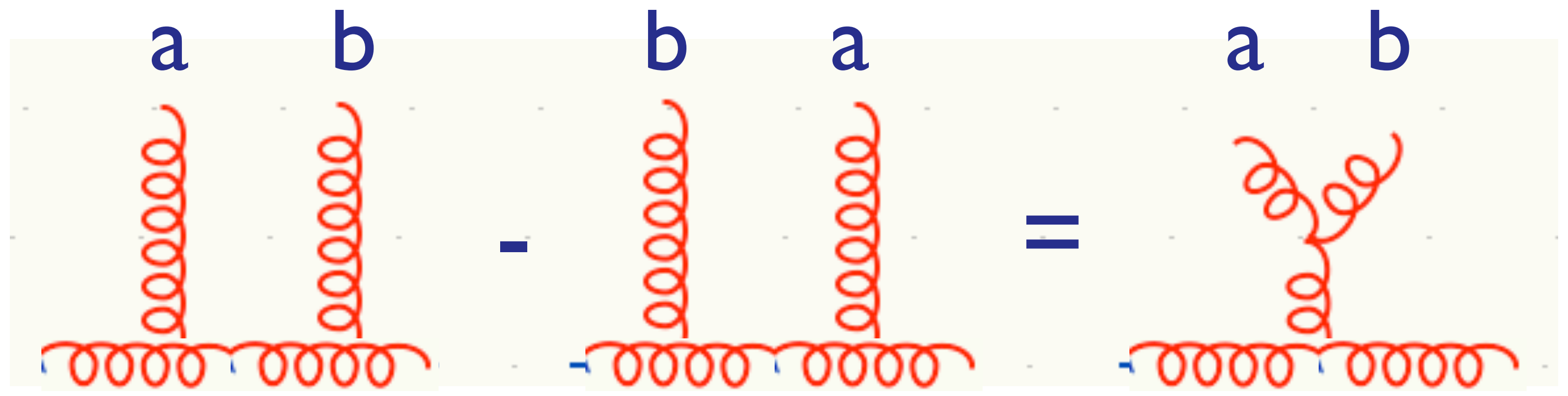
= C_F *

$$\sum_{cd} f^{acd} f^{bcd}$$
$$= (F^c F^c)_{ab} = C_A \delta_{ab}$$

= C_A*

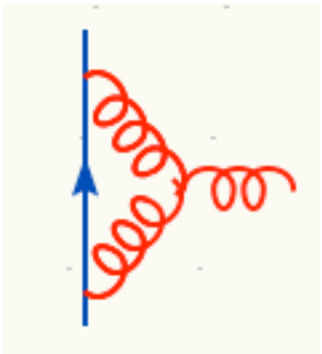
$[t^a, t^b] = i f^{abc} t^c$

$[F^a, F^b] = i f^{abc} F^c$

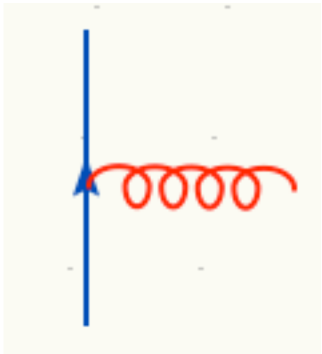


1-loop vertices

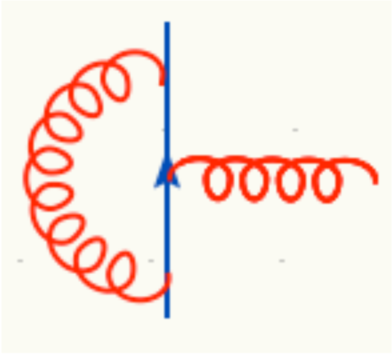
$if^{abc}(t^b t^c)_{ij} = \frac{C_A}{2} t^a_{ij}$



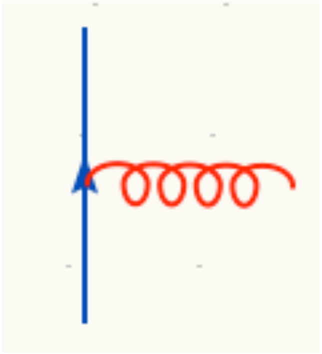
= C_A/2 *



$(t^b t^a t^b)_{ij} = (C_F - \frac{C_A}{2}) t^a_{ij}$



= -1/2/Nc *



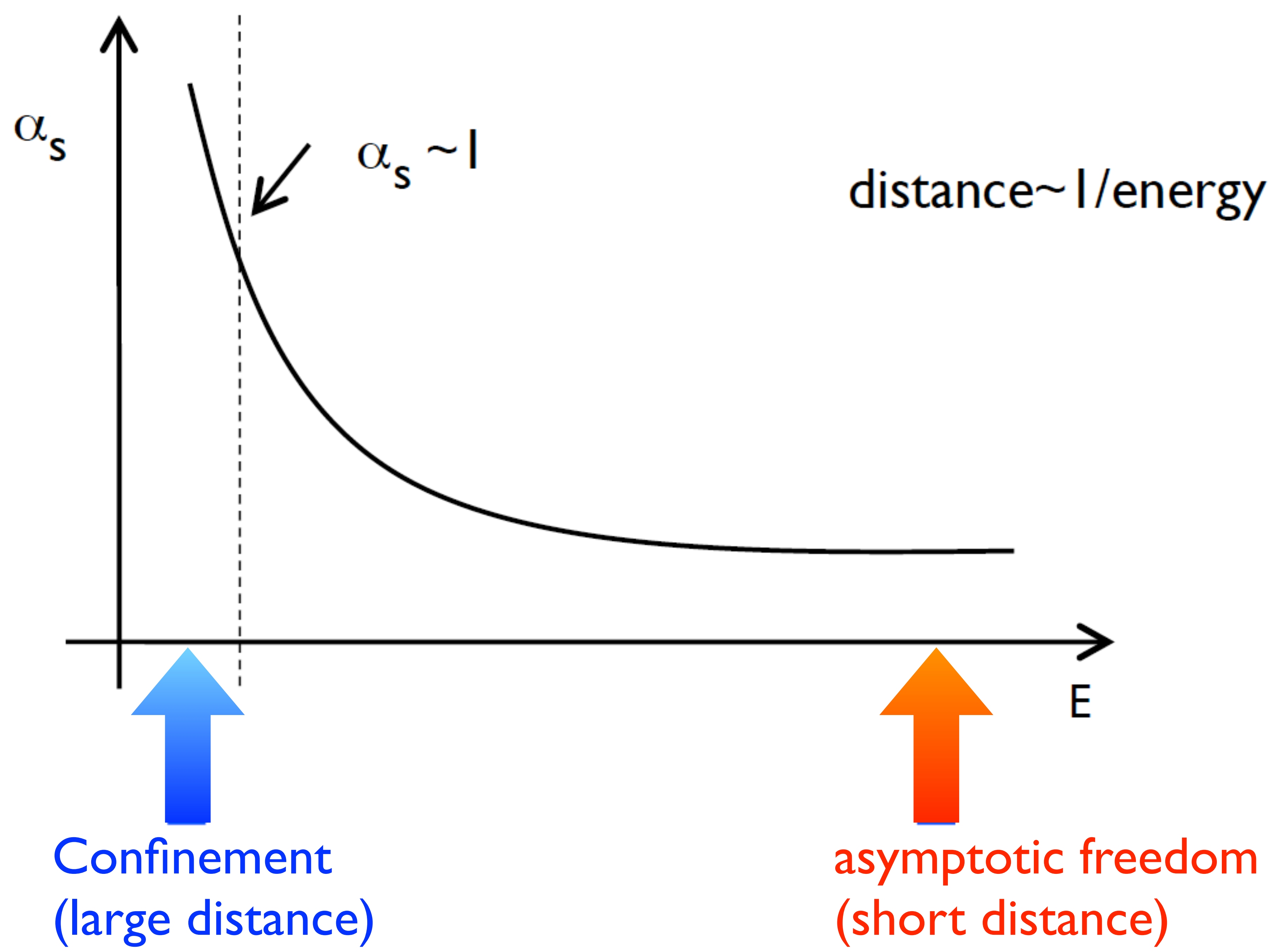
Can be a bottleneck for higher order computations! People always on the lookout for simplifications! Quite a few computations are done in the large N_c limit.

Properties of QCD

Slide on running coupling QED

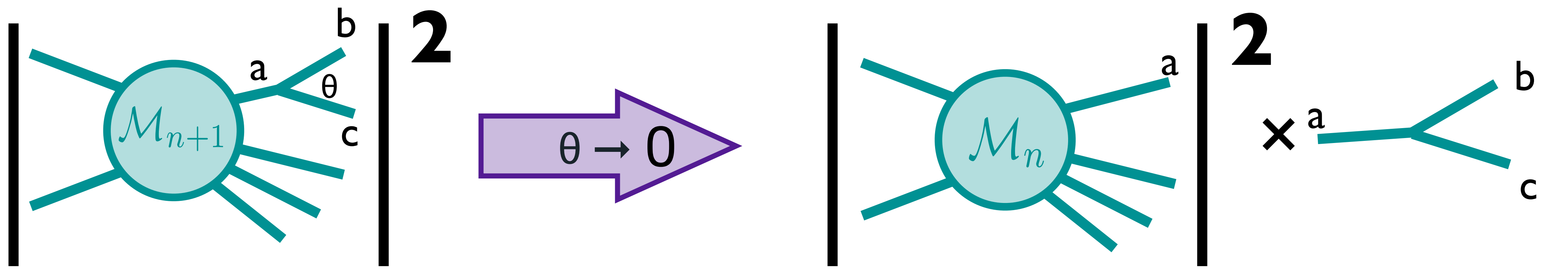
UV: Asymptotic freedom

- Perturbative computations
- Parton model



IR: Universality

- Collinear Factorisation
- Parton showers



Plan for the lectures

- Basics of collider physics
- Basics of QCD
    - DIS and the Parton Model
    - Higher order corrections
    - Asymptotic freedom
    - QCD improved parton model
- State-of-the-art computations for the LHC
- Monte Carlo generators
- Higgs phenomenology
- Top phenomenology
- Searching for New Physics: EFT

Master formula for LHC physics

$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\rm FS}\, f_a(x_1, \mu_F) f_b(x_2, \mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$

Phase-space integral

Important aspect of a Monte Carlo generator

Parton density functions

Universal:

~Probabilities of finding given parton with given momentum in proton

Extracted from data

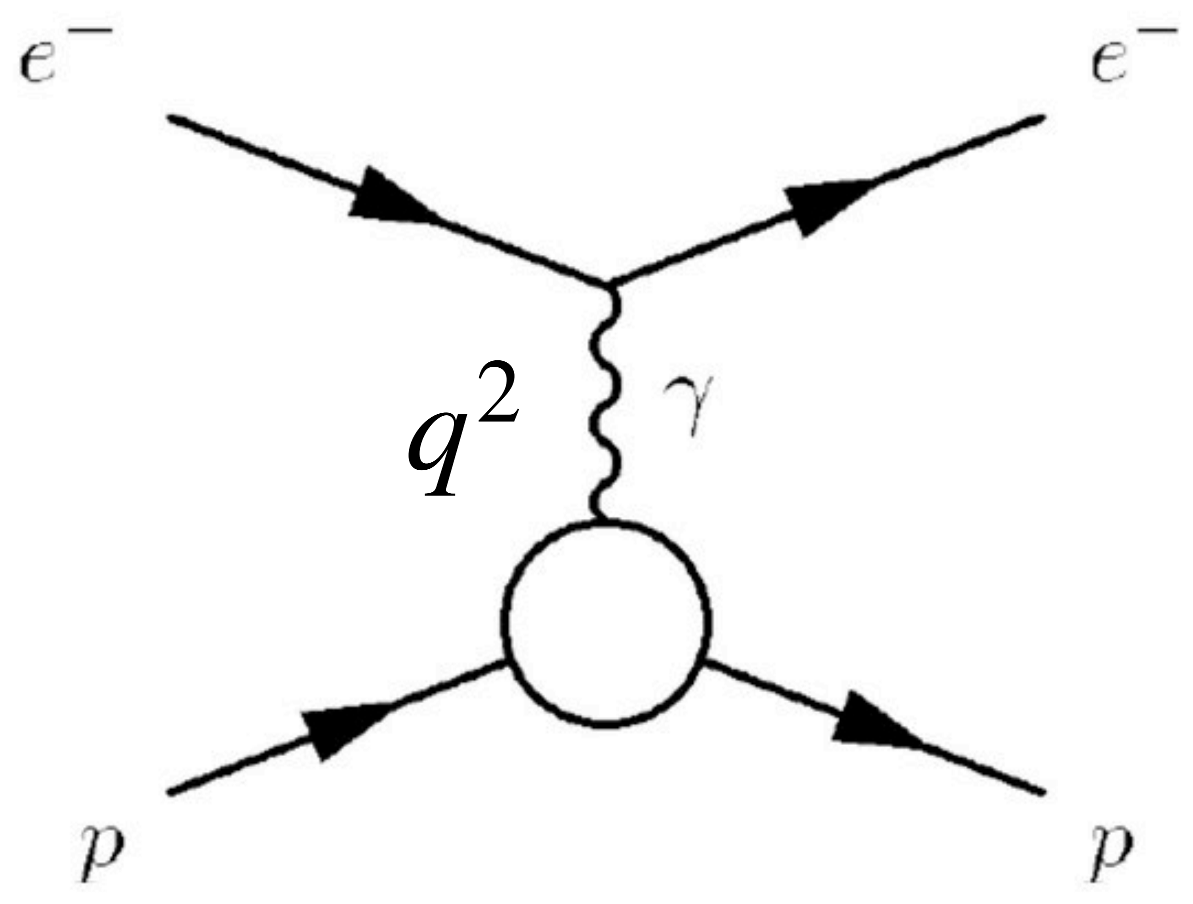
Parton-level cross section

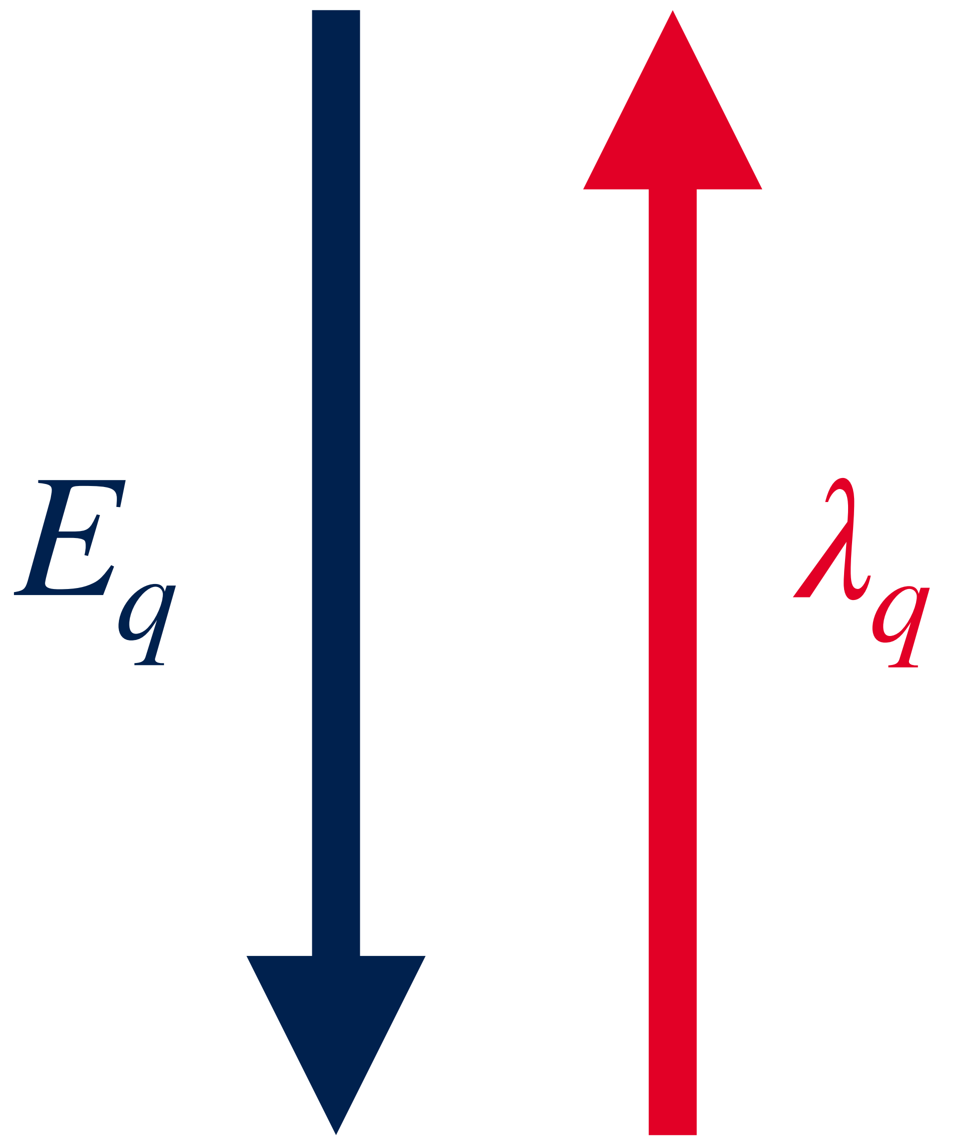
Subject of huge efforts in the LHC theory community to systematically improve this

Structure of the proton

Best tool: electron proton scattering: $e^- p \to e^- p$

- Probe proton structure via virtual photon (Z-boson)
- Different regimes for different photon energies (wavelengths)





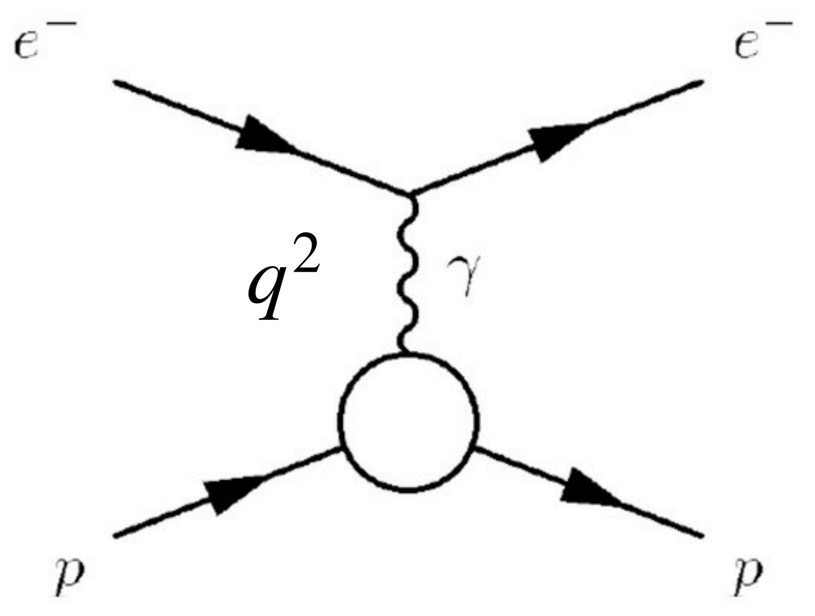
Point-like

Finite size

Constituent quarks

Sea of strongly interacting quarks/gluons

Low energy



Long wavelength photons see proton as point-like

Spin 1/2 scattering in QED

$$\mathcal{M}_{fi} = i\frac{e^2}{q^2}[\bar{u}(k')\,\gamma^\mu\, u(k)]\,[\bar{u}(p')\,\gamma_\nu\, u(p)] \qquad q^2 = (k-k')^2$$

Non relativistic limit: $q^2 \ll m_e^2$

$\Rightarrow$ Rutherford scattering

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Ruth.}} = \frac{\alpha^2}{16\,E_k^2\,\sin^4(\theta/2)}$$

$$E_k = |\vec{k}|^2/2m_e$$

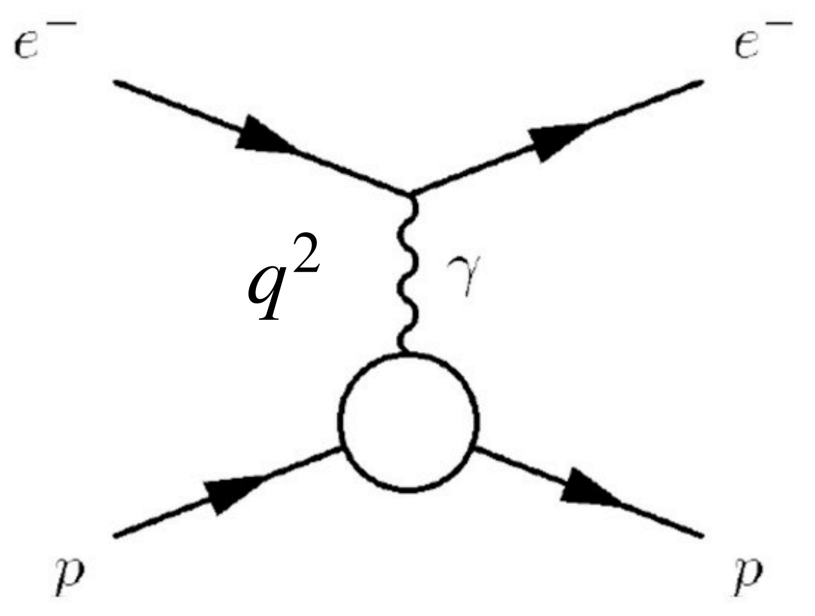
Relativistic electron: $m_e^2 \ll q^2 \ll m_p^2$

$\Rightarrow$ Mott scattering

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Mott}} = \frac{\alpha^2}{4\,E^2\,\sin^4(\theta/2)}\cos^2\left(\frac{\theta}{2}\right)$$

$$E \simeq |\vec{k}|$$

Intermediate energy



Form factor

Photon experiences finite extent of the proton

- Resolves charge distribution of the proton

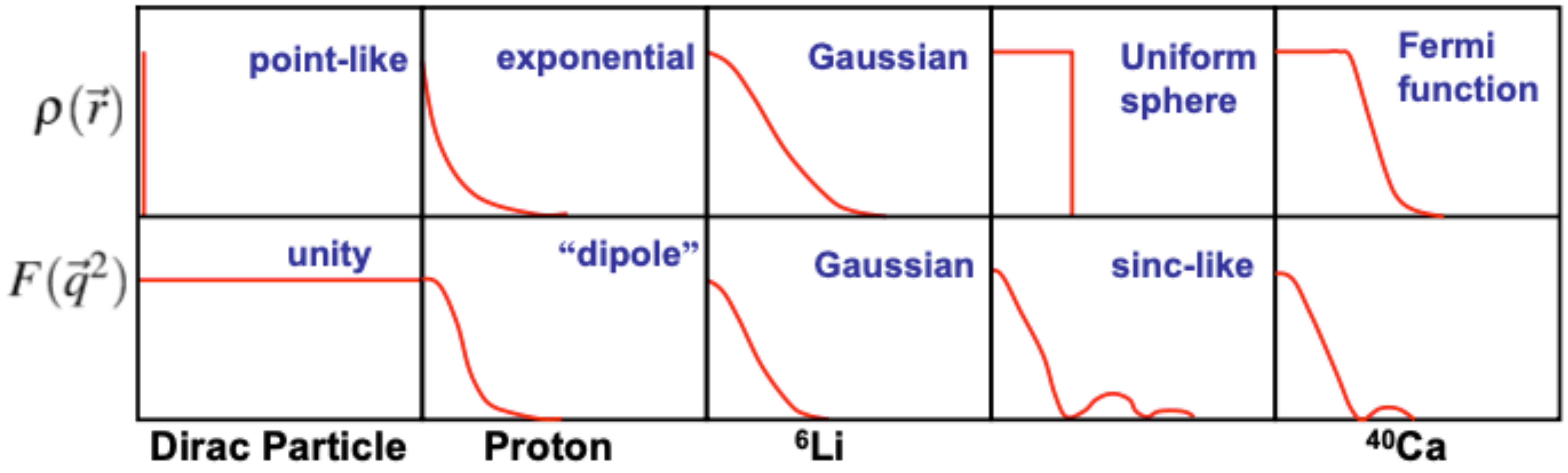
$$\Rightarrow \quad \mathcal{M}_{fi} = \mathcal{M}_{fi}^{\text{point}} F(\mathbf{q}^2)$$

$$F(\mathbf{q}^2) = \int d^3\mathbf{r}\, \rho(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$

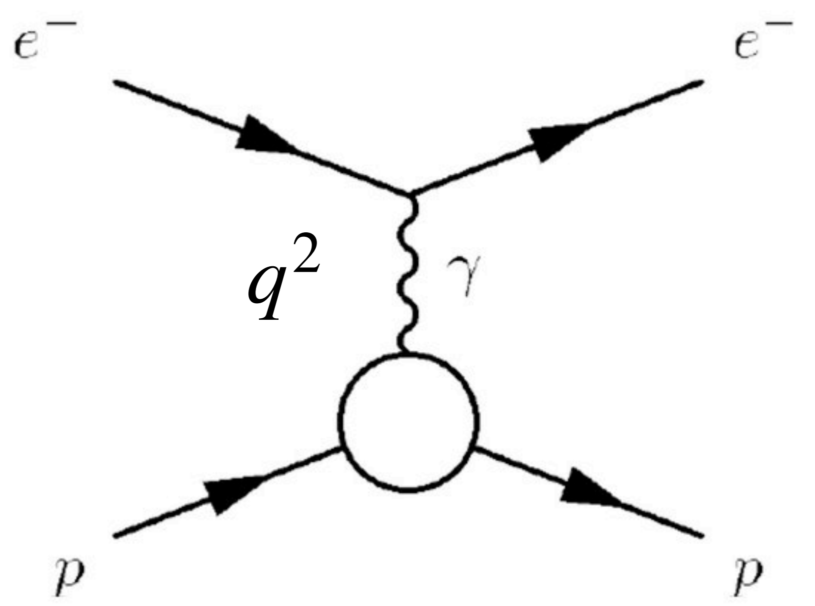
Form factor correction: $\lambda_q \sim r_p$

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Mott}} \to \frac{\alpha^2}{4E^2 \sin^4(\theta/2)} \cos^2\left(\frac{\theta}{2}\right) \left| F\left(\mathbf{q}^2\right)\right|^2$$

[M. Thompson; Modern Particle Physics]



Intermediate energy



Relativistic corrections: $q^2 > m_p^2$ $\quad Q^2 \equiv -q^2 = 4\,E\,E'\sin^2\left(\frac{\theta}{2}\right)$

- Proton recoil becomes important
- New angular dependence from magnetic (spin-spin) interactions

⇒ Rosenbluth formula

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Ros.}} = \frac{\alpha^2}{4\,E^2\sin^4(\theta/2)}\frac{E'}{E}\left[\cos^2\left(\frac{\theta}{2}\right) + \frac{Q^2}{2m_p^2}\sin^2\left(\frac{\theta}{2}\right)\right]$$

recoil — dominates at high Q^2

c.f. Gordon decomposition

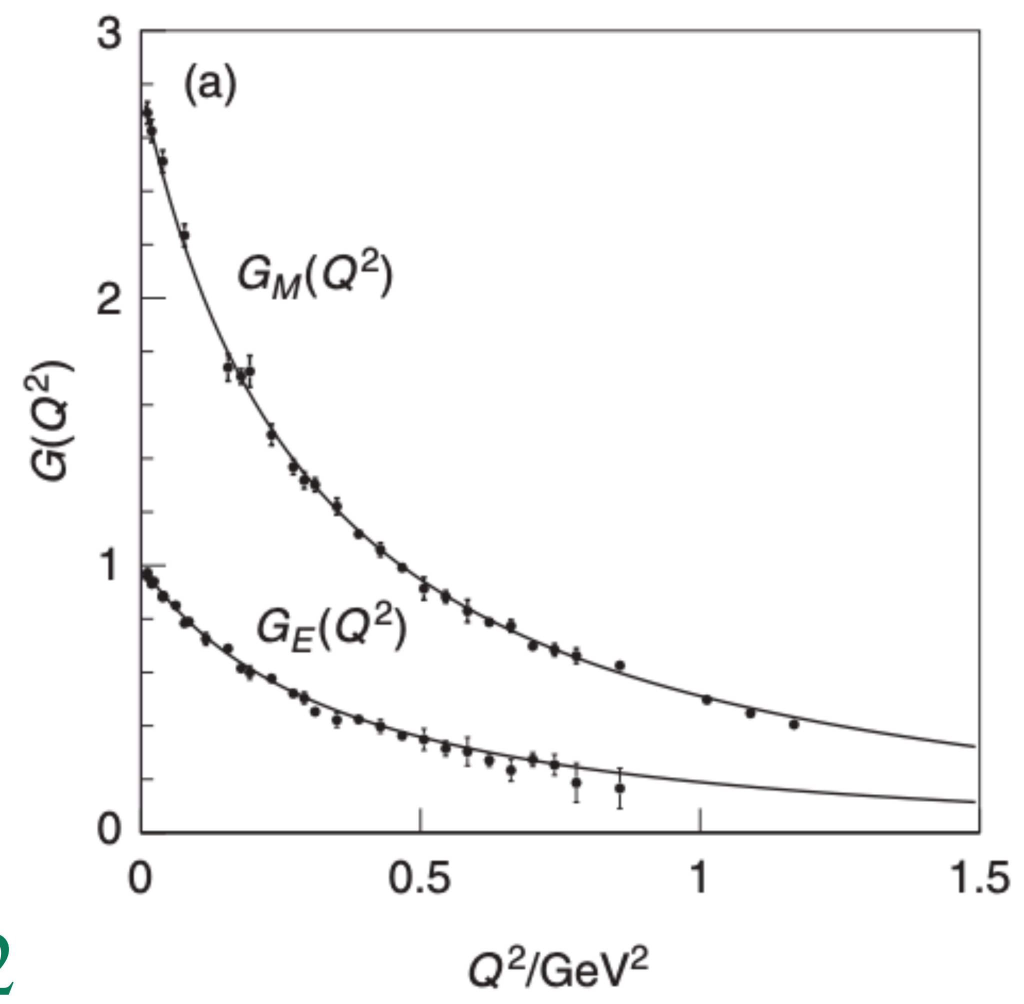
'electric' — 'magnetic'

$$\bar{u}_F\gamma^\mu u_I = \frac{1}{2m}\bar{u}_F\left[(p_F + p_I)^\mu + i\sigma^{\mu\nu}(p_F - p_I)_\nu\right]u_I$$

Magnetic term $\sim q_\nu$ gives rise to magnetic moment of spin 1/2 particles

$$H = -\vec{\mu}\,.\,\vec{B}, \quad \vec{\mu} = -\frac{ge}{2m}\vec{S}, \quad g \sim 2$$

[M. Thompson; Modern Particle Physics]



Intermediate energy

Finite size + relativistic: requires two form factors

- Electric & magnetic, $G_E(Q^2)$ & $G_M(Q^2)$
- Lorentz invariance: $\mathbf{q}^2 \to Q^2$

$$Q^2 = \mathbf{q}^2 + O(\tau) \qquad \tau \equiv \frac{Q^2}{4m_p^2}$$

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Ros.}} = \frac{\alpha^2}{4\,E^2 \sin^4(\theta/2)} \frac{E'}{E} \left[\frac{|G_E|^2 + \tau |G_M|^2}{1+\tau} \cos^2\left(\frac{\theta}{2}\right) + 2\tau |G_M|^2 \sin^2\left(\frac{\theta}{2}\right) \right]$$

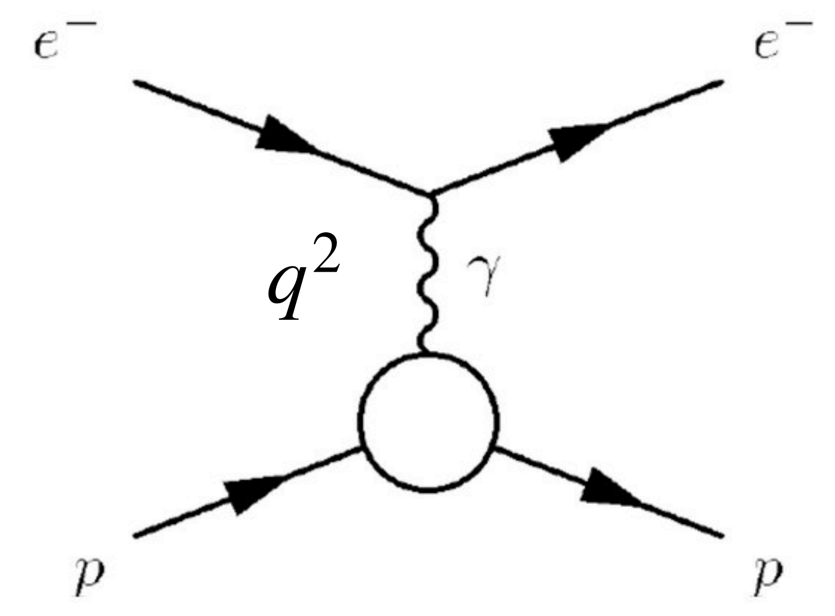
$$G_E(Q^2) \sim F\left(\mathbf{q}^2\right) = \int d^3\mathbf{r}\,\rho(\mathbf{r})\,e^{i\mathbf{q}\cdot\mathbf{r}} \qquad G_M(Q^2) \sim \int d^3\mathbf{r}\,\mu(\mathbf{r})\,e^{i\mathbf{q}\cdot\mathbf{r}}$$

Measure FFs experimentally by studying angular distributions in $e^- p$ scattering

$$g_p = G_M(0) = \int d^3\mathbf{r}\,\mu(\mathbf{r}) = 2.79\,g_e$$

$g_p \neq g_e$ suggests the the proton is not a point-like particle

High energy



Magnetic form factor dominates: $Q^2 \gg m_p$

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Ros.}} \sim \frac{\alpha^2}{4\,E^2\sin^4(\theta/2)}\frac{E'}{E}\left[\frac{Q^2}{2m_P^2}|G_M|^2\sin^2\left(\frac{\theta}{2}\right)\right]$$

$$G_M(Q^2) \sim \frac{2.79}{(1+Q^2/0.71\text{GeV}^2)^2} \propto Q^{-4}$$

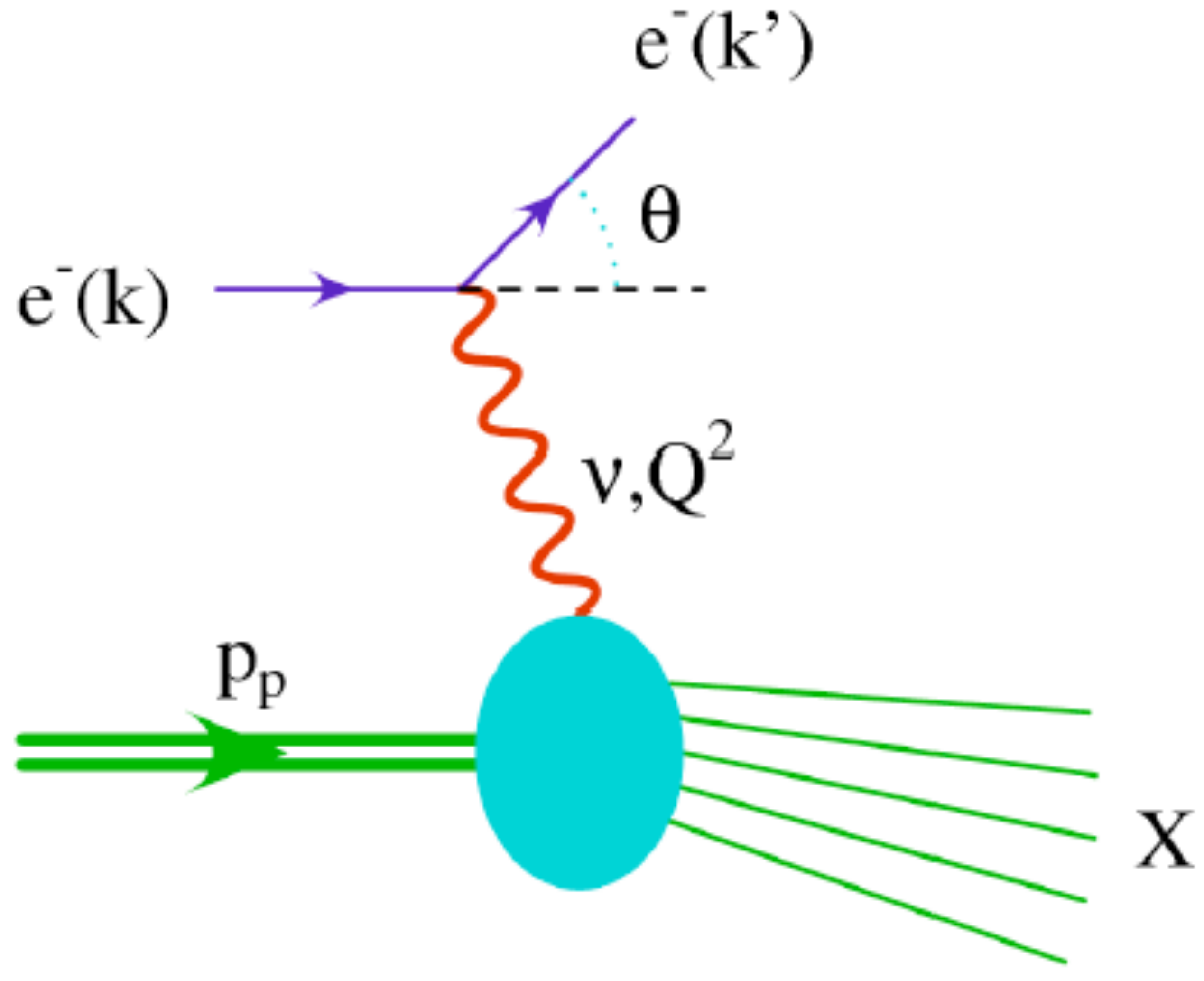
$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{Ros.}} \sim Q^{-6}$$

Elastic scattering cross section falls off rapidly

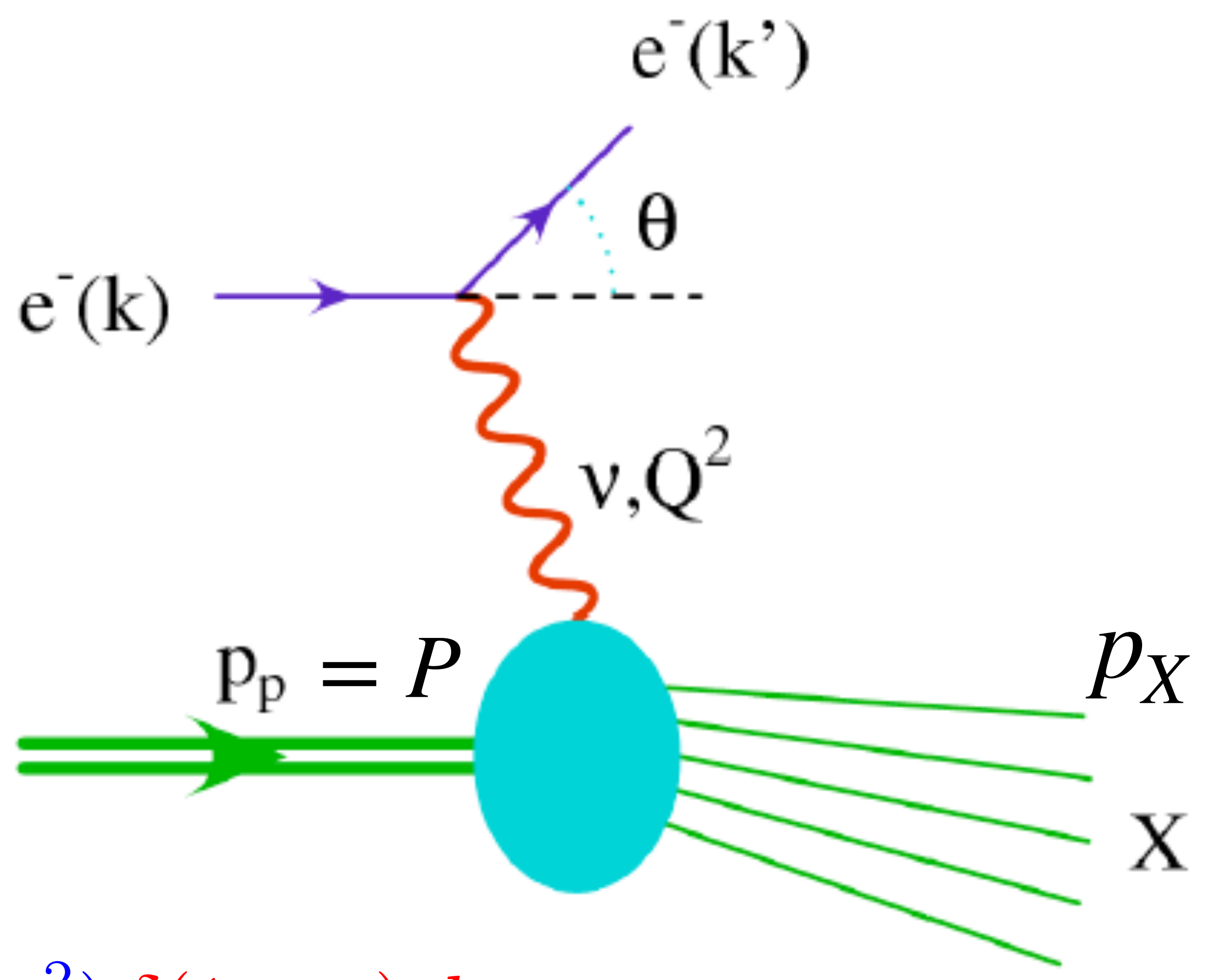
'elastic': $AB \to AB$ (proton remains intact)

Also 'inelastic' process: $e^-p \to e^-X$

- Proton breaks up and can lead to a multitude of hadron final states (X)
- In general both contributions exist: $d\sigma_{\text{el.}} + d\sigma_{\text{inel.}}$



Inelastic kinematics



For $2 \to 2$ elastic scattering at a fixed CM energy, $\sqrt{s}$

- Kinematics fixed by one variable, e.g. θ

Inelastic scattering, $W^2 \equiv p_X^2 \neq m_p^2$

- Now need 2 variables to fully describe

$$\frac{d\sigma_{\text{elastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\text{point}} \cdot F^2_{\text{elastic}}(q^2)\,\delta(1-x)\,dx$$

$$\frac{d\sigma_{\text{inelastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\text{point}} \cdot F^2_{\text{inelastic}}(q^2, x)\,dx$$

Useful variables:

Bjorken x

$$x \equiv \frac{Q^2}{2P\cdot q} = \frac{Q^2}{Q^2 + W^2 - m_p^2}$$

$$W^2 \geq m_p^2 \Rightarrow 0 \leq x \leq 1$$

Inelasticity, y

$$y \equiv \frac{P\cdot q}{P\cdot k} = 1 - \frac{E'}{E}$$

Fractional electron energy loss

Energy loss, $\nu \equiv \dfrac{P\cdot q}{m_p} = E - E' > 0$

$$Q^2 = -q^2 = -(k-k')^2$$

$$s = (P+k)^2$$

$$W^2 \equiv (P+q)^2 = M^2 + \frac{1-x}{x}Q^2$$

Deep Inelastic scattering

What can $F^2(q^2)$ look like?

1. Proton charge is smoothly distributed (probe penetrates proton like a knife through butter)

$$F^2_{elastic}(q^2) \sim F^2_{inelastic}(q^2, x) \ll 1$$

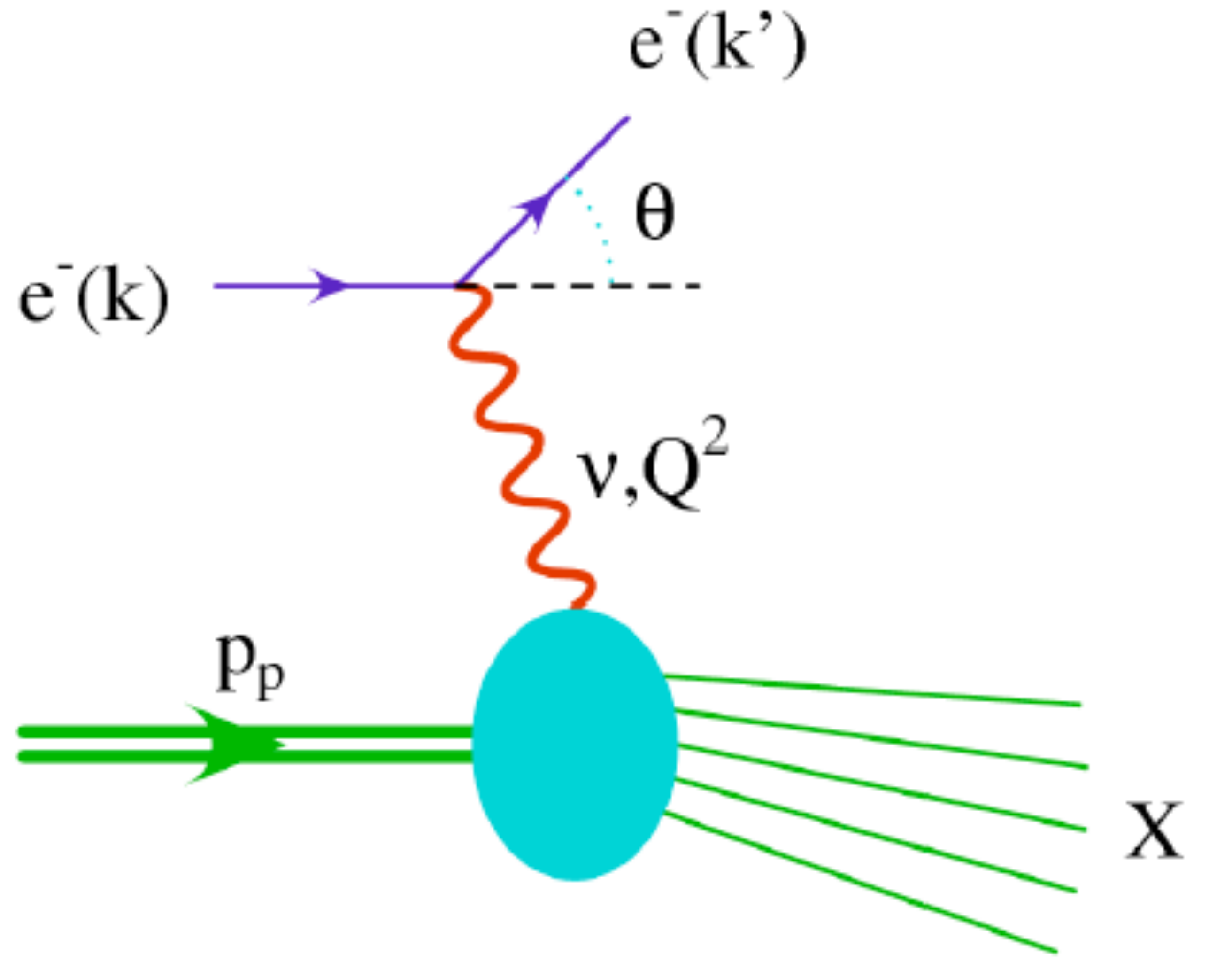
2. Proton consists of tightly bound charges (quarks hit as single particles, but cannot fly away because tightly bound)

$$F^2_{elastic}(q^2) \sim 1 \qquad F^2_{inelastic}(q^2, x) \ll 1$$

!!!3. $F^2_{elastic}(q^2) \ll 1 \qquad F^2_{inelastic}(q^2, x) \sim 1$

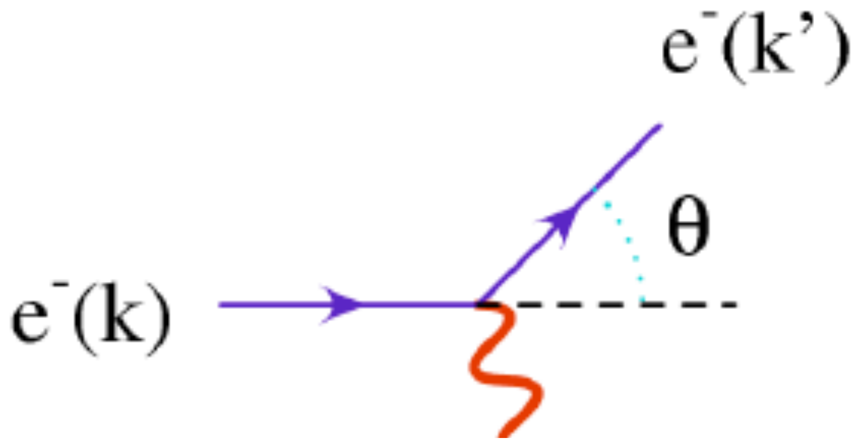
Quarks are free particles which fly away without caring about confinement!

DIS cross section



Final state phase space: $d\Phi = \frac{d^3\mathbf{k}'}{(2\pi)^3\, 2E'} d\Phi_X = \frac{m_p E}{8\pi^2} y\, dx\, dy\, d\Phi_X$

Spin-averaged ME: $|\overline{\mathscr{M}}|^2 = \frac{1}{4}\sum_\lambda |\mathscr{M}|^2 = \frac{e^2}{Q^4} L^{\mu\nu} H^X_{\mu\nu}$



$$L_{\mu\nu} = \frac{1}{4}\sum_{\lambda_e} [\bar{u}(k')\gamma_\mu u(k)]\,[\bar{u}(k)\gamma_\nu u(k')]$$

$$= \mathrm{Tr}[\not{k}'\gamma_\mu \not{k}\gamma_\nu] = k'_\mu k_\nu + k'_\nu k_\mu + k\cdot k' g_{\mu\nu}$$

|QED leptonic current|²

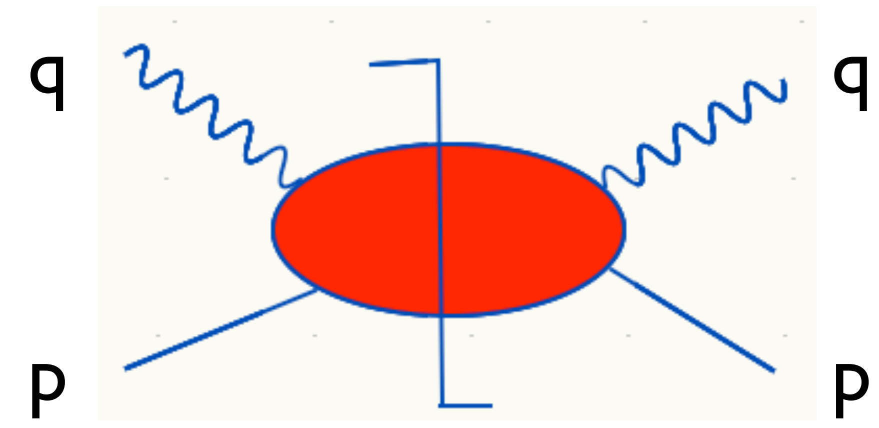
What is $H^X_{\mu\nu}$? Hadronic current is non perturbative, depends on X state

$$\sigma^{ep\to eX} = \sum_X \frac{1}{4m_p E}\int d\Phi\, |\overline{\mathscr{M}}|^2 = \frac{1}{4m_p E}\int d\Phi_k \frac{e^2}{Q^4} L^{\mu\nu} W_{\mu\nu}$$

For inclusive DIS $\left(\sum_X\right)$

$$W_{\mu\nu} \equiv \sum_X \int d\Phi_X H^X_{\mu\nu}$$

Hadronic tensor & structure functions



Most general form obeying Lorentz & gauge invariance

- Must be a covariant function of P^μ, q^μ $[p_X = (p+q)]$
- Gauge invariance: Ward identity (current conservation) for real photon amplitude

$$q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0$$

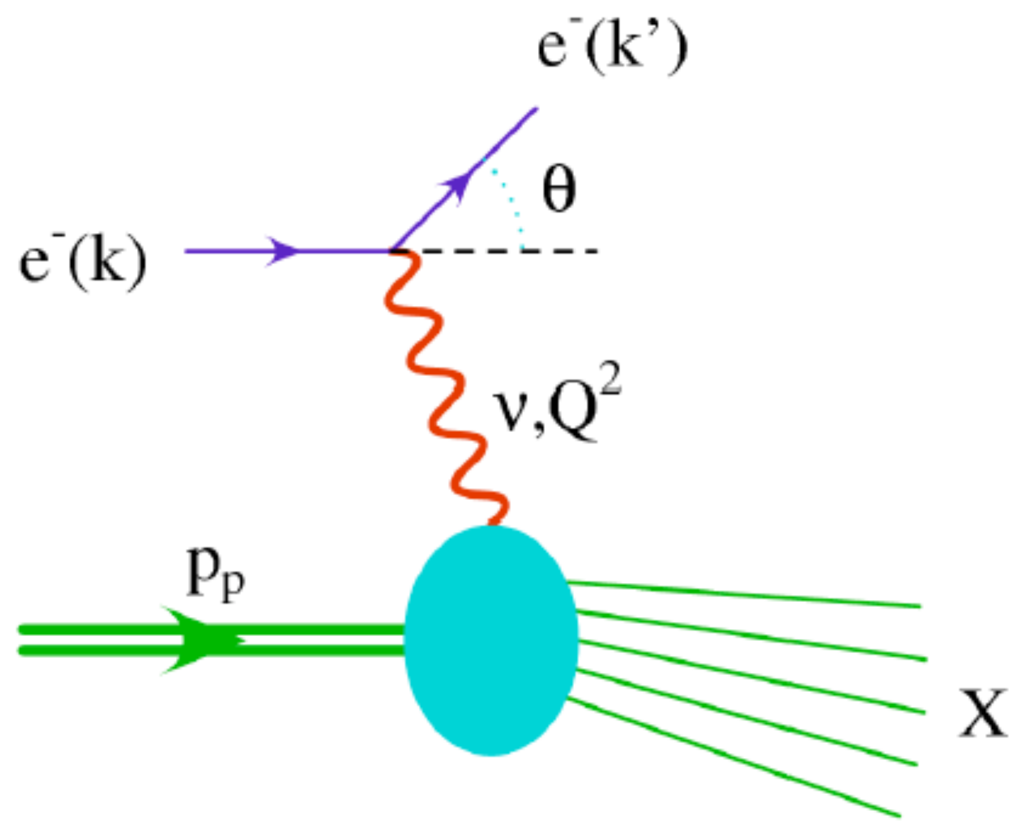
- P, T symmetries imply $W_{\mu\nu} = W_{\nu\mu}$, $[L_{\mu\nu}$ is $(\mu \leftrightarrow \nu)$ symmetric anyway]

$$W_{\mu\nu} = \left(-g_\mu\nu + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \left(P_\mu - q_\mu \frac{P \cdot q}{q^2}\right)\left(P_\nu - q_\nu \frac{P \cdot q}{q^2}\right) \frac{1}{P \cdot q} F_2(x, Q^2)$$

Need 2 independent structure functions $F_{1,2}(x, Q^2)$

- Depend on two independent, Lorentz invariant kinematic variables of DIS
- Must be determined from data

DIS cross section



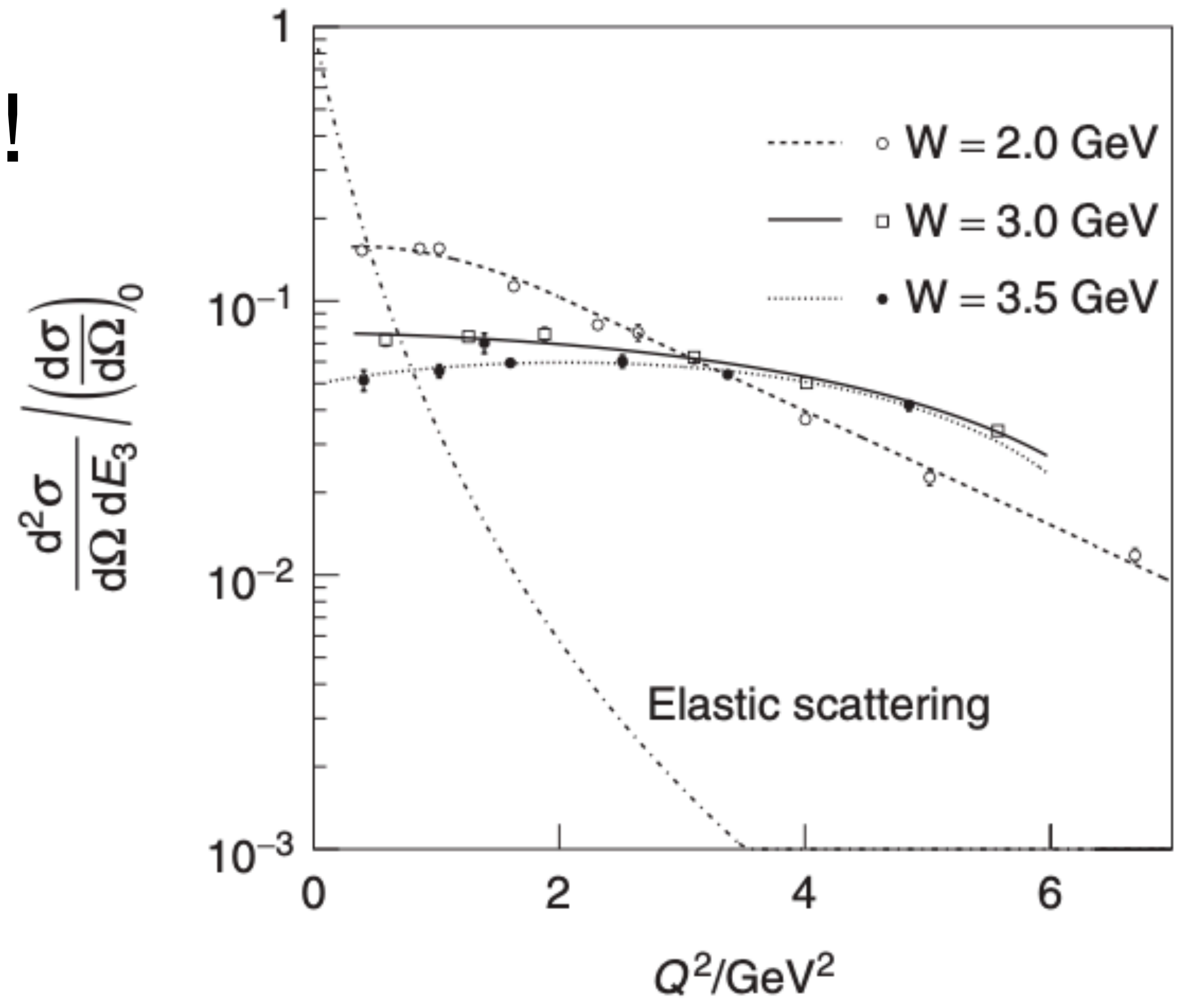
Finally $\sigma^{ep\to eX} = \frac{1}{4m_p E}\int d\Phi_k \frac{e^2}{Q^4} L^{\mu\nu} W_{\mu\nu}$

$$\Rightarrow \quad \frac{d^2\sigma}{dQ^2 dx} = \frac{4\pi\alpha^2}{Q^4}\left(\left[1+(1-y)^2\right]F_1(x,Q^2) + \frac{1-y}{x}\left[F_2(x,Q^2) - 2xF_1(x,Q^2)\right]\right)$$

Observed σ_{DIS} approximately independent of Q^2!

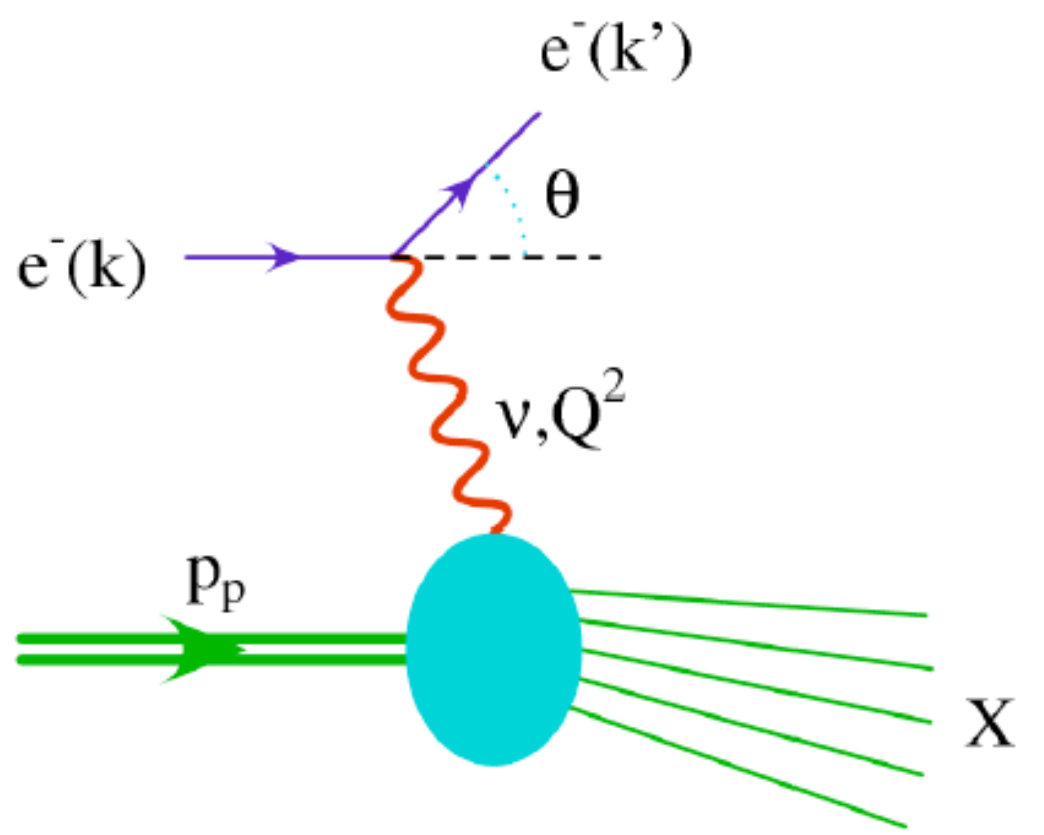
- AKA "Bjorken scaling"

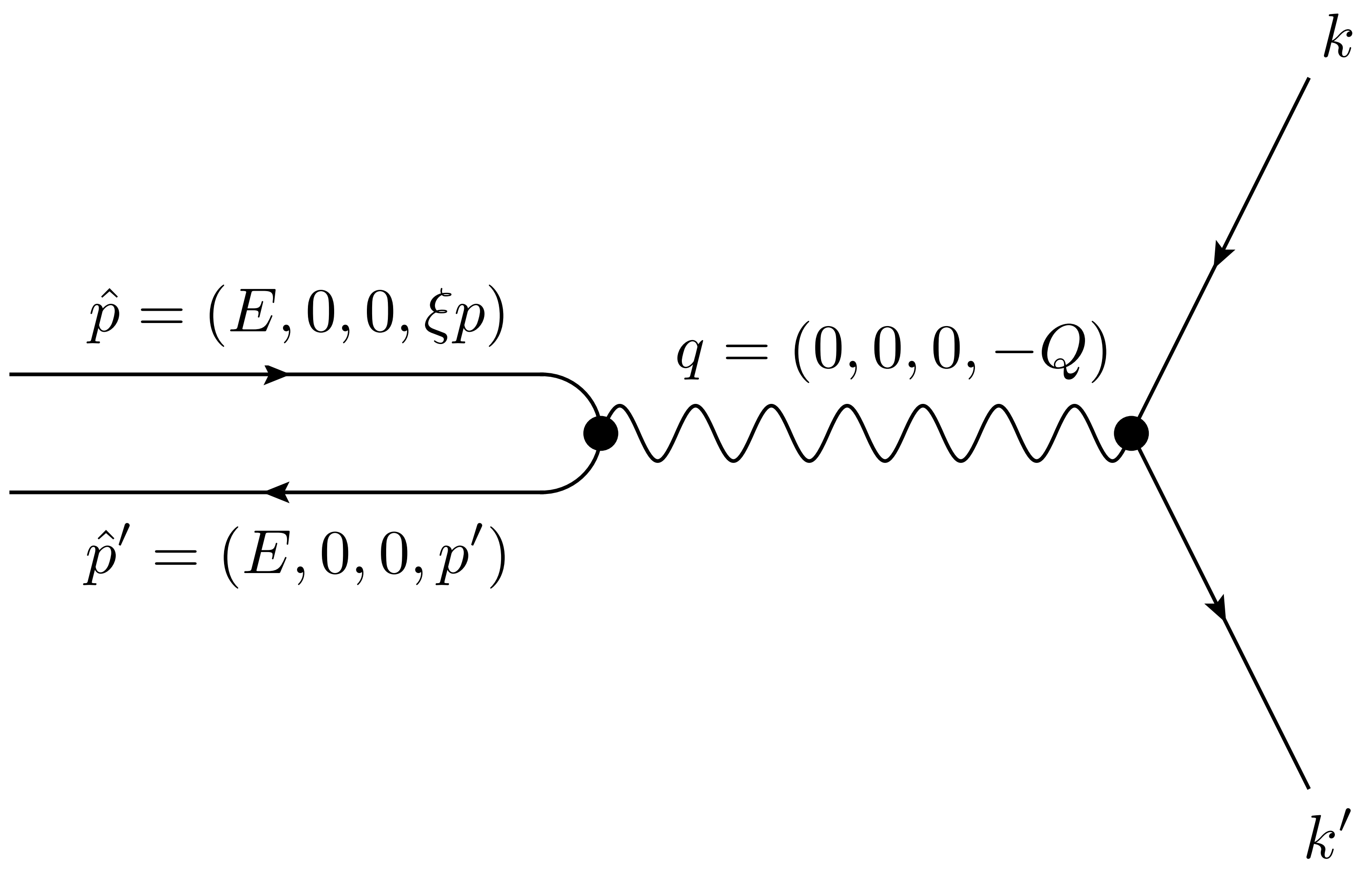
Independence on photon resolution scale suggests scattering with a point-like, fundamental constituent: parton = quarks!



Parton Model

Breit frame: proton moves fast $(p \gg m_p)$ & photon has zero energy





$$p \equiv \left(\sqrt{\frac{Q^2}{4x^2} + m^2}, \frac{Q}{2x}, \vec{0}_\perp\right) \approx \left(\frac{Q}{2x} + \frac{xm^2}{Q}, \frac{Q}{2x}, \vec{0}_\perp\right)$$

$$q \equiv \left(0, -Q, \vec{0}_\perp\right).$$

Proton extent

Rest frame $\Delta t \sim \Delta x \sim \dfrac{1}{m_p}$

Breit frame

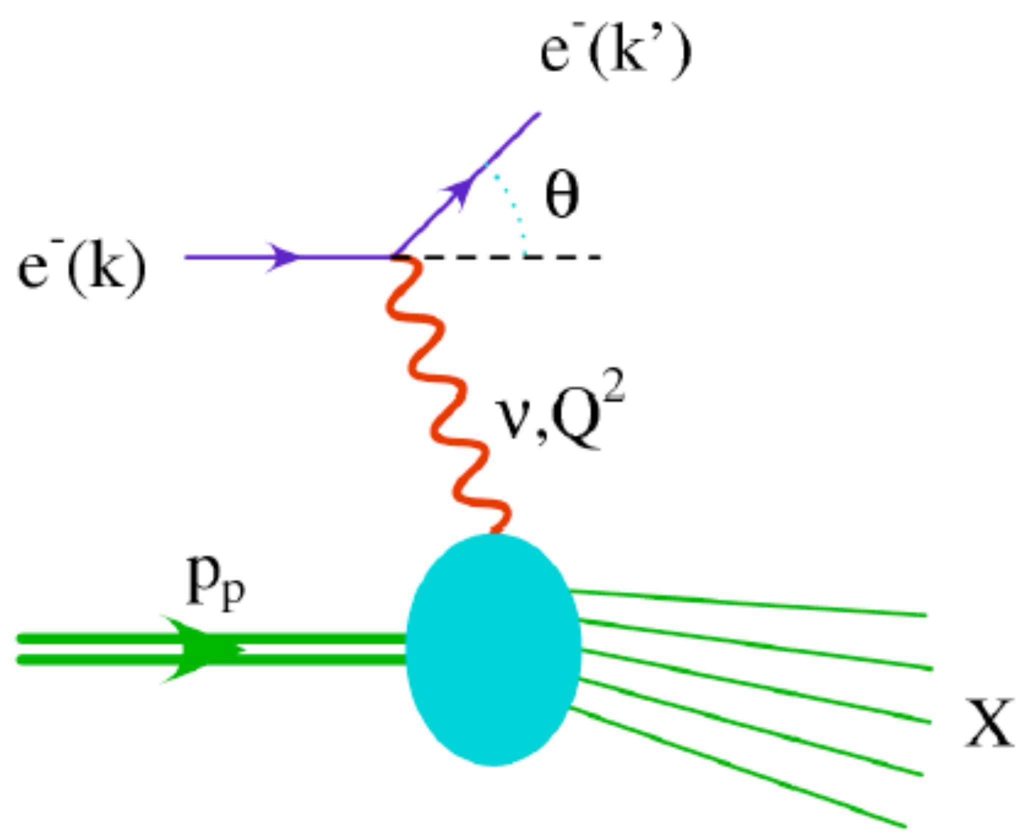
$$\gamma_p \sim \frac{Q}{m_p} \qquad \Delta x' = \frac{\Delta x}{\gamma_p} \sim \frac{1}{Q} \qquad \Delta t' = \gamma_p \Delta t \sim \frac{Q}{m_p^2}$$

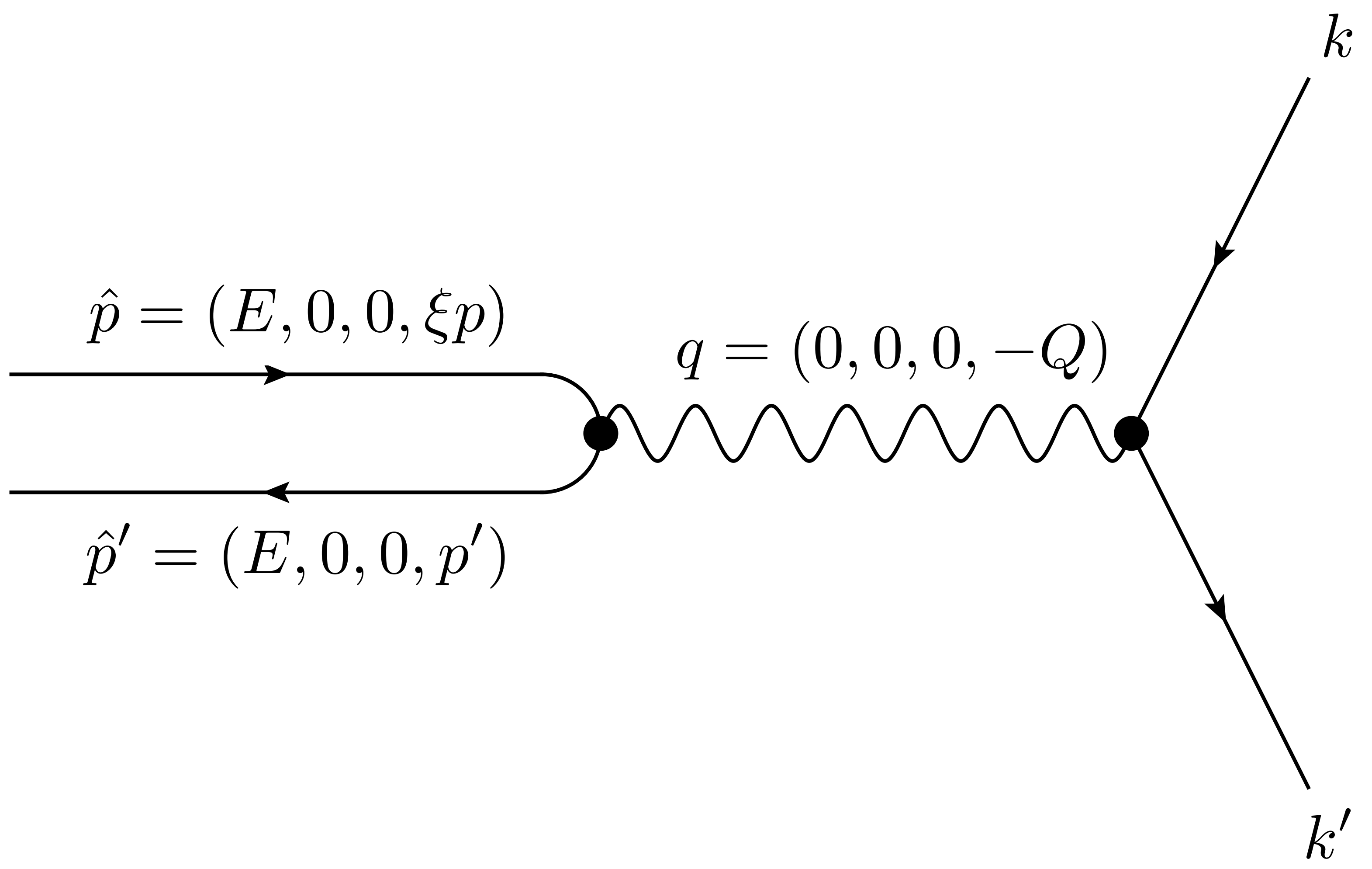
Photon extent: $\Delta t_\gamma = \sim \dfrac{1}{Q} \ll \Delta t'$

The time scale of a typical parton-parton interaction is much larger than the hard interaction time.

Parton Model

Breit frame: proton moves fast $(p \gg m_p)$ & photon has zero energy





$$p \equiv \left(\sqrt{\frac{Q^2}{4x^2} + m^2}, \frac{Q}{2x}, \vec{0}_\perp\right) \approx \left(\frac{Q}{2x} + \frac{xm^2}{Q}, \frac{Q}{2x}, \vec{0}_\perp\right)$$

$$q \equiv \left(0, -Q, \vec{0}_\perp\right).$$

- The time scale of a typical parton-parton interaction is much larger than the hard interaction time.
- Schematically: in the Breit frame the proton is therefore Lorentz contracted to a kind of pancake.
- The photon interaction then takes place on the very short time scale as it passes through.
- Partons experience time dilation: interact with each other on much longer timescales
- During the short photon interaction time, the quark does not interact with spectator partons

- It can be treated as a free quark!

Parton Model

In Breit frame, suppose parton q carries a fraction ξ of proton momentum

- Before scattering $(\xi P)^2 \simeq m_q^2$
- After scattering it has a momentum $p'_q = \xi P + q$

$$m_q^2 \equiv p_q'^2 \simeq (\xi P)^2 + 2\xi P \cdot q + q^2 \quad \Rightarrow \quad \xi = \frac{-q^2}{2P \cdot q} = \frac{Q^2}{2P \cdot q} \equiv x$$

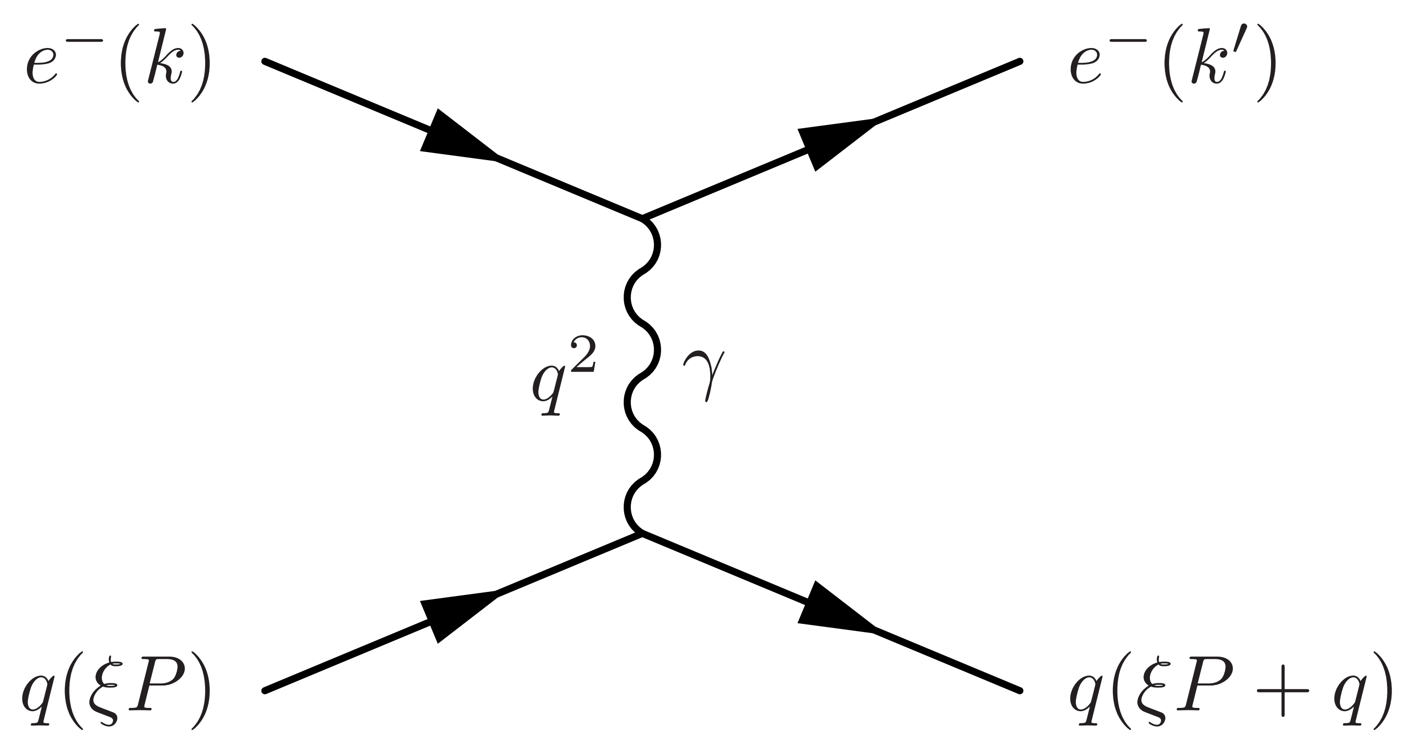
Identify Bjorken x with the proton momentum fraction carried by the Parton

Photon 'sees' partons are quasi-free inside the proton

- Write DIS cross section in terms of the 'partonic' $e^- q \to e^- q$ cross sections

$$\frac{d\hat{\sigma}}{dQ^2} = \frac{4\pi\alpha^2 Q_q^2}{Q^4} \frac{1}{2} \left[1 + (1 - \hat{y})^2\right]$$

Factorisation

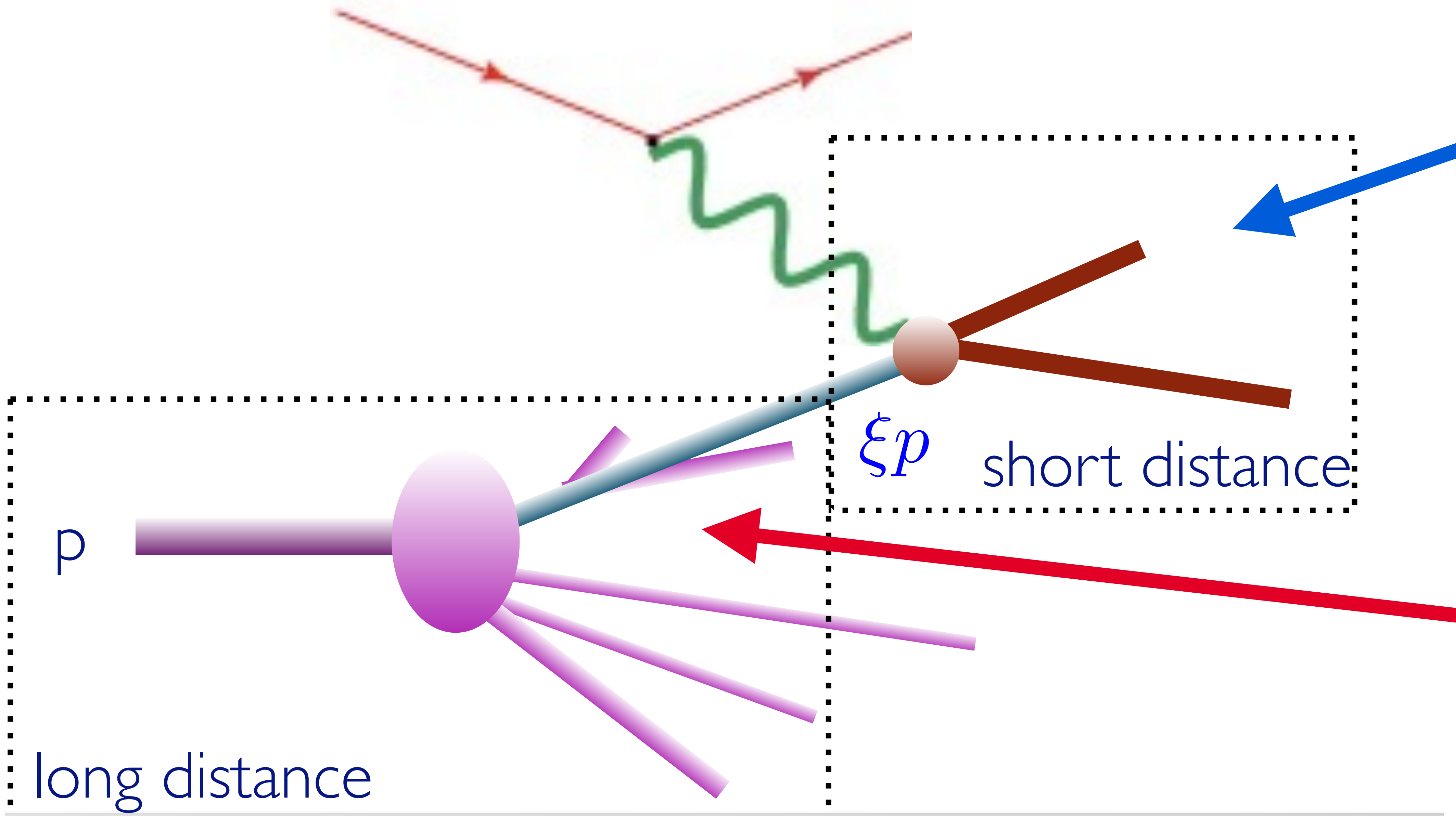


Defining analogous $\hat{x}$ & $\hat{y}$ variables for eq scattering

$$\hat{x} = \frac{Q^2}{2\xi P \cdot q} = \frac{x}{\xi}$$

$$\hat{y} = \frac{\xi P \cdot q}{\xi P \cdot k} = y$$

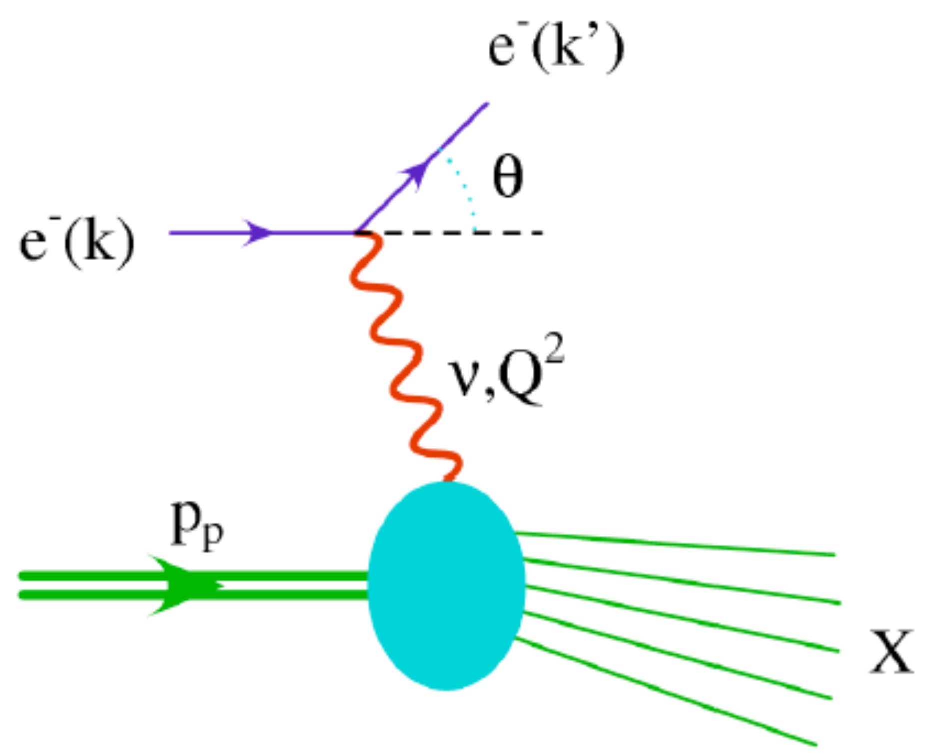
$$\Rightarrow \quad \frac{d\sigma^{\text{DIS}}}{dx dQ^2} = \int_0^1 \frac{d\xi}{\xi} \sum_i f_i(\xi) \frac{d\hat{\sigma}_i}{d\hat{x} dQ^2}\left(\hat{x}, Q^2\right)$$



$\frac{d\hat{\sigma}}{d\hat{x} dQ^2}$ Parton-photon double differential scattering cross section

$f_i(\xi)$ Probability for finding parton i in the proton with momentum fraction ξ

Factorised DIS cross section



Compare our two expressions for $d\sigma^{\mathrm{DIS}}$

$= 0!$

$$a) \quad \frac{d^2\sigma}{dQ^2 dx} = \frac{4\pi\alpha^2}{Q^4}\left(\left[1+(1-y)^2\right]F_1\left(x,Q^2\right) + \frac{1-y}{x}\left[F_2\left(x,Q^2\right) - 2xF_1\left(x,Q^2\right)\right]\right)$$

$$b) \quad \frac{d\sigma}{dx dQ^2} = \int_0^1 \frac{d\xi}{\xi}\sum_i f_i(\xi)\frac{d\hat{\sigma}_i}{d\hat{x}dQ^2}\left(\hat{x},Q^2\right) \Leftarrow \frac{d\hat{\sigma}_i}{d\hat{x}dQ^2} = \frac{4\pi\alpha^2 Q_i^2}{Q^4}\frac{1}{2}\left[1+(1-y)^2\right]\delta(\hat{x}-1)$$

$\xi = x$

Get structure functions in terms of parton distribution functions $f_i(x)$

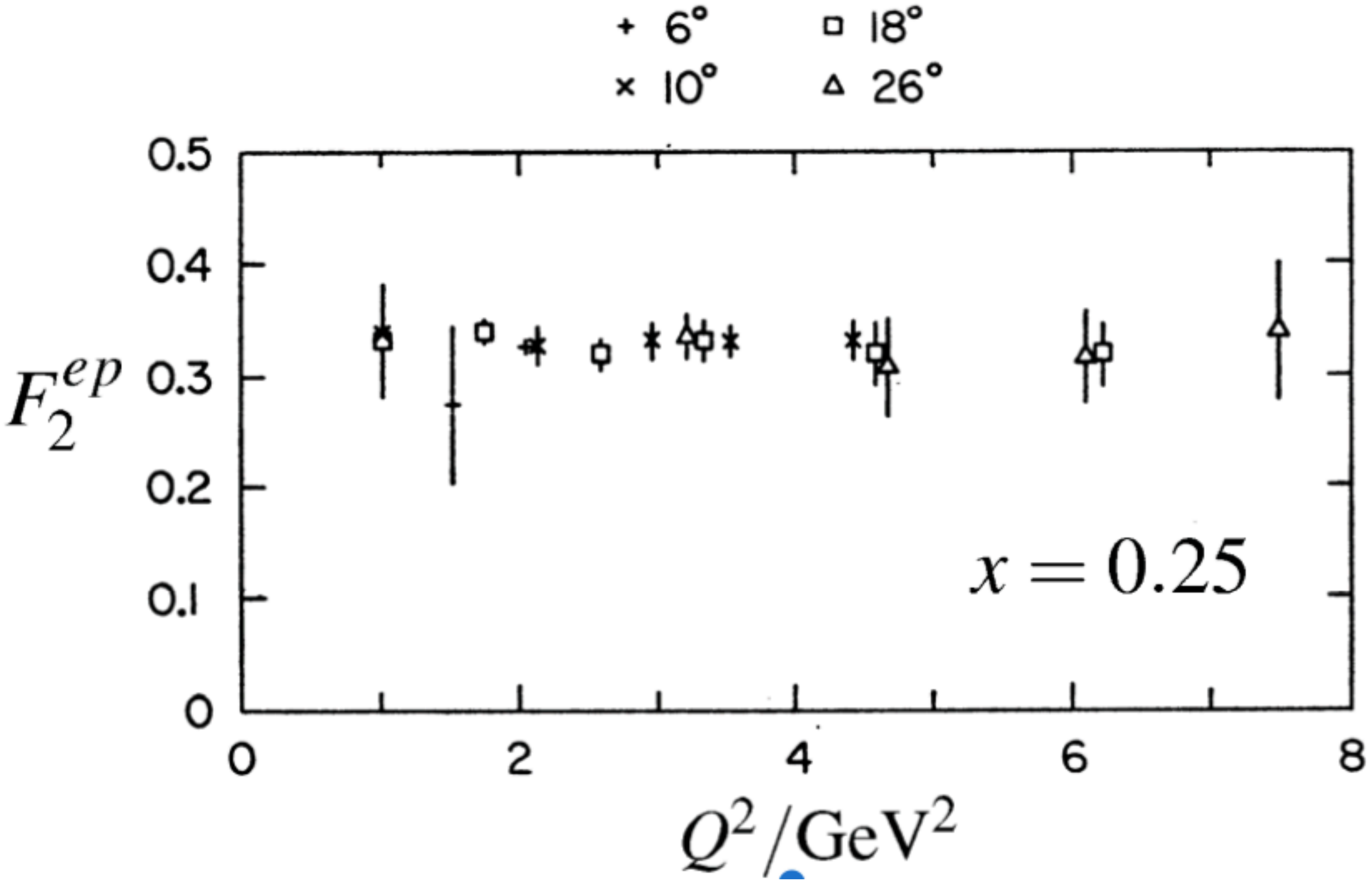
$$F_1\left(x,Q^2\right) = \frac{1}{2}\sum_{i=q,\bar{q}} Q_i^2 f_i(x) \qquad F_2\left(x,Q^2\right) = 2xF_1\left(x,Q^2\right)$$

Callan-Gross relation: consequence of partons being spin-1/2 quarks

- Probability to find (anti-)quark in the proton with momentum fraction x
- Independent of Q^2 (Bjorken scaling)

Scaling and Callan-Gross relation

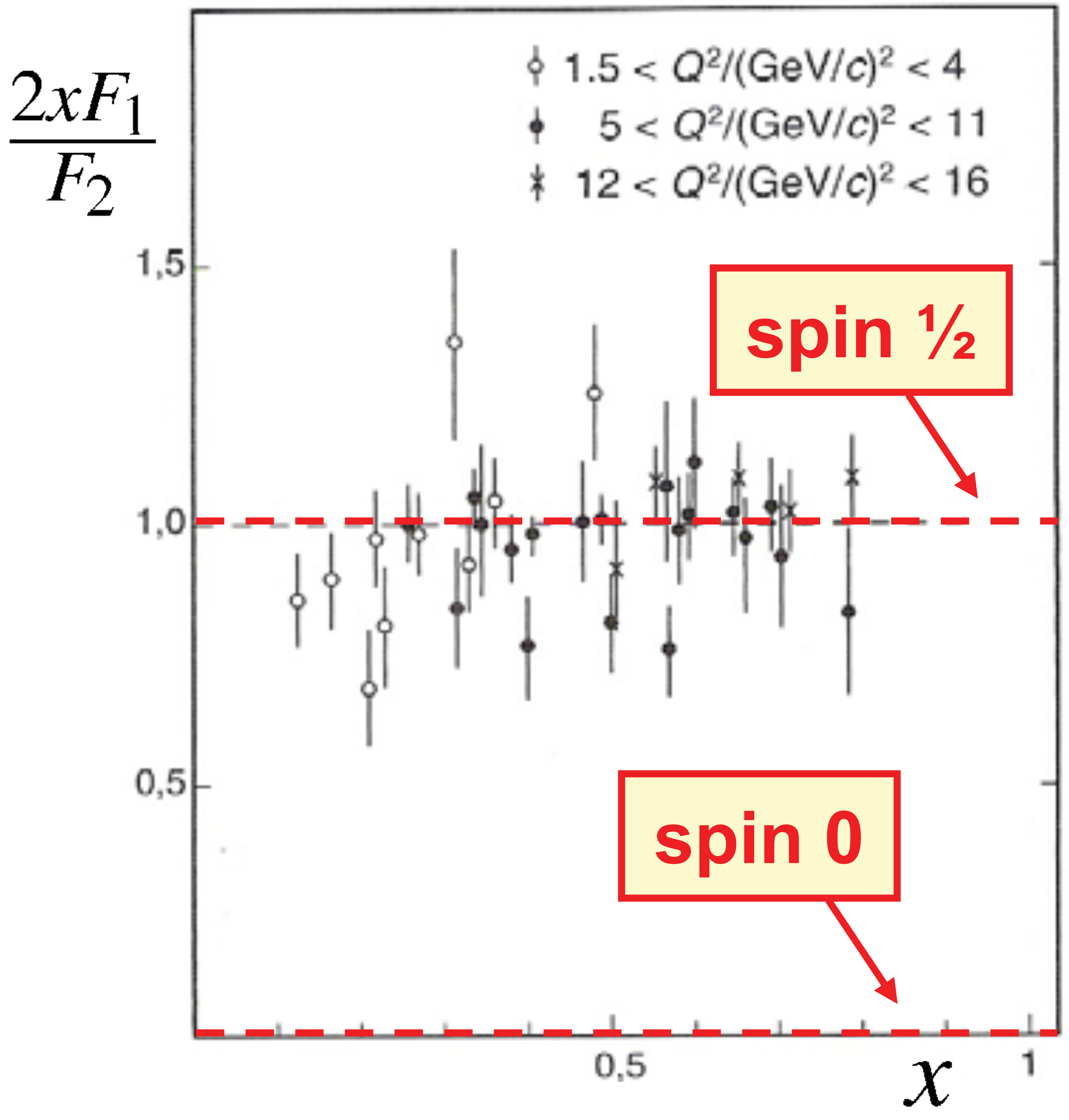
Scaling: Q^2-independence of structure functions



J.T.Friedman + H.W.Kendall, Ann. Rev. Nucl. Sci. 22 (1972) 203

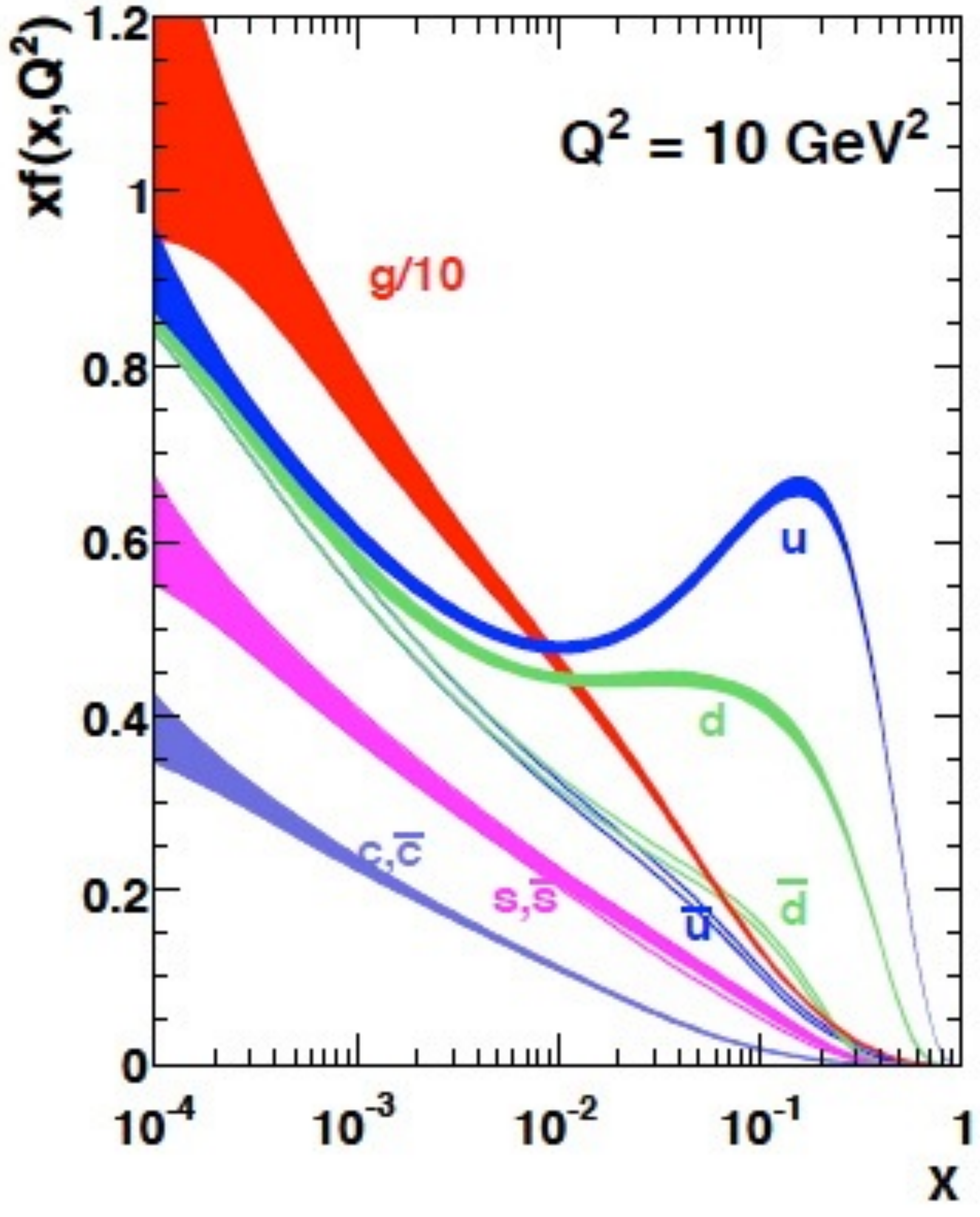
Evidence that quarks are point-like proton constituents

Callan-Gross relation



Evidence that quarks are spin-1/2 particles!

Parton distribution functions



$$
\begin{aligned}
u(x) &= u_V(x) + \bar{u}(x) \\
d(x) &= d_V(x) + \bar{d}(x) \\
s(x) &= \bar{s}(x)
\end{aligned}
$$

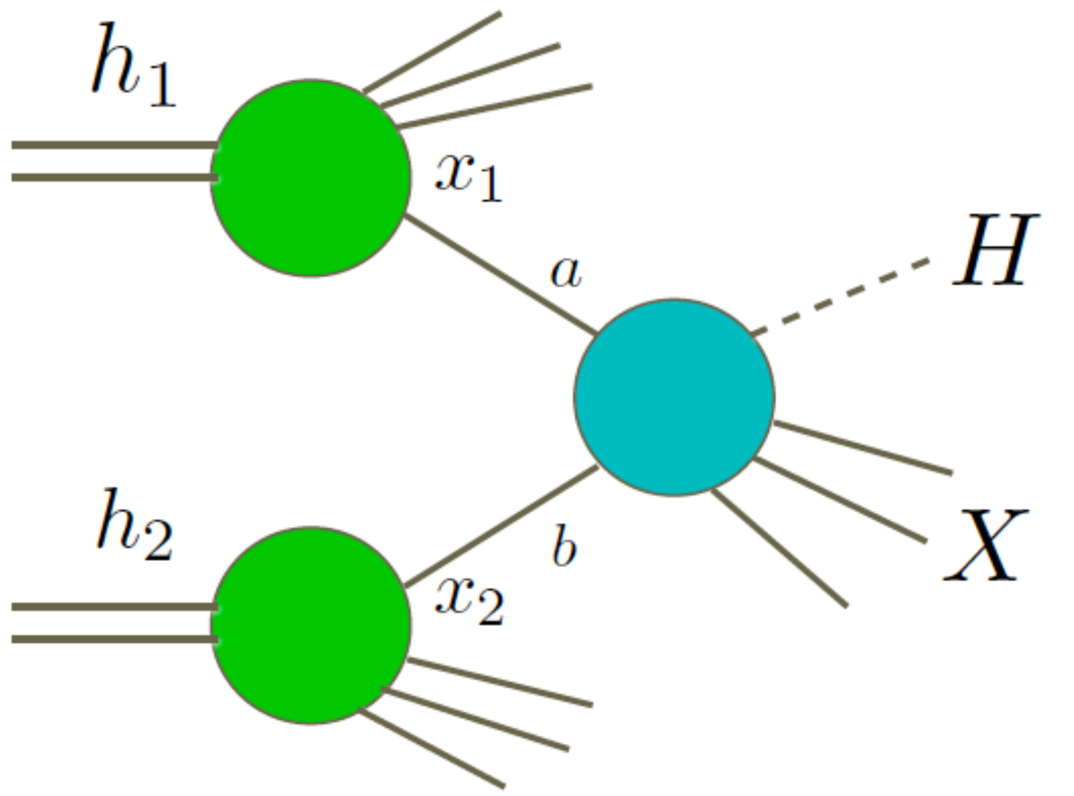
$$\int_0^1 dx\, u_V(x) = 2\,, \quad \int_0^1 dx\, d_V(x) = 1$$

$$\sum_q \int_0^1 dx\, x[q(x) + \bar{q}(x)] \simeq 0.5$$

Quarks carry only 50% of the proton momentum

Evidence for gluons!

LHC cross sections



pp collision at a CM energy $\sqrt{S}$

- Partonic collision $ab \to X$, $\hat{s} = (p_a + p_b)^2$

$$d\sigma_{pp\to X} = \sum_{ab} dx_1\, dx_2 \left(f_a(x_1) f_b(x_2) + a \leftrightarrow b\right) d\Phi_X \frac{\left|\mathcal{M}_{ab\to X}\right|^2}{F} (2\pi)^2 \delta^{(4)}(p_a + p_b - p_X)$$

$= d\hat{\sigma}_{ab}(\hat{s}, p_X)$

$F = 2\hat{s}$ (massless)

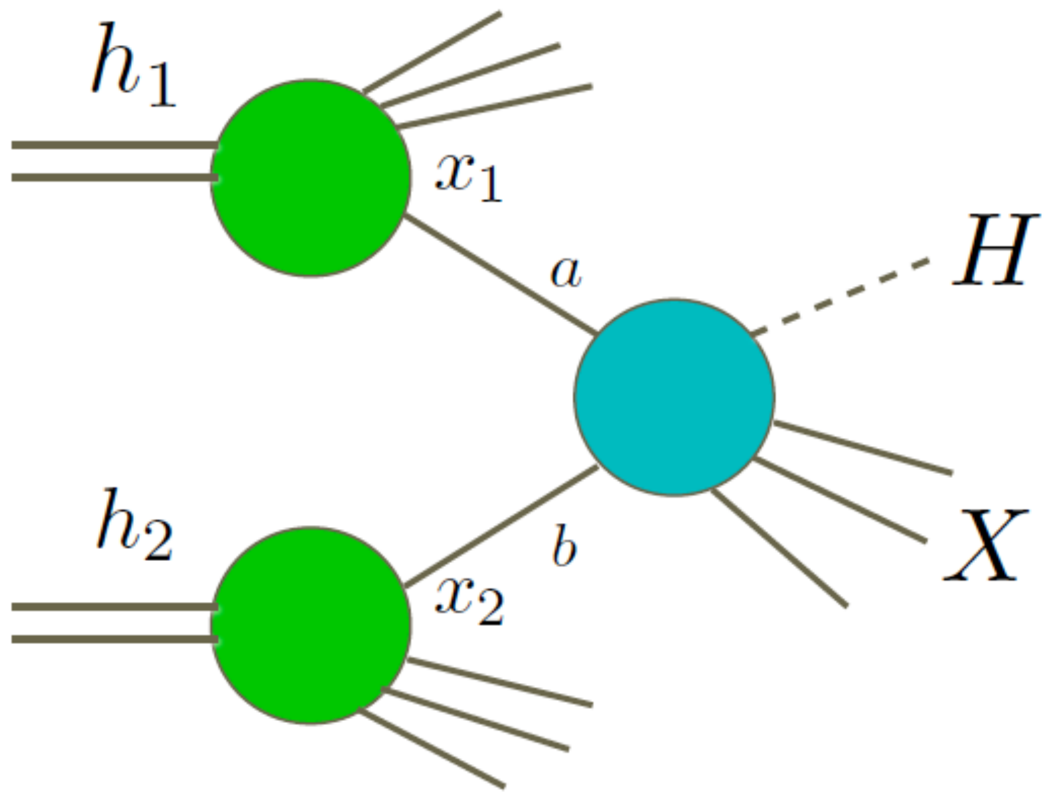
Colliding partons carry momentum fractions x_1 and x_2, respectively

- Partonic centre of mass energy $\hat{s} = s x_1 x_2 \Rightarrow \tau \equiv \hat{s}/s$
- Momentum imbalance in lab frame $\Rightarrow$ net longitudinal momentum $y = \frac{1}{2}\log\frac{x_1}{x_2}$

$$x_1 = \sqrt{\tau}e^{y} \quad x_2 = \sqrt{\tau}e^{-y} \quad \Rightarrow \quad dx_1\, dx_2 = dy\, d\tau$$

see exercises

Parton luminosity



$$d\sigma_{pp\to X} = \sum_{ab} dx_1\, dx_2 \left(f_a(x_1)f_b(x_2) + a \leftrightarrow b\right) d\hat{\sigma}_{ab}(sx_1x_2, p_X)$$

$dx_1dx_2 \to d\tau dx_1$

$$\sigma_{pp\to X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \frac{\tau}{\hat{s}} \int_\tau^1 \frac{dx}{x} \left(f_a(x)f_b(\tau/x) + a \leftrightarrow b\right) (\hat{s}\hat{\sigma}_{ab})$$

Define parton luminosity: $\mathscr{L}_{ab} = \frac{1}{s}\frac{dL_{ab}}{d\tau} \equiv \frac{\tau}{\hat{s}} \frac{1}{1+\delta_{ab}} \int_\tau^1 \frac{dx}{x} \left(f_a(x)f_b(\tau/x) + f_a(\tau/x)f_b(x)\right)$

- Dimensions of a cross section

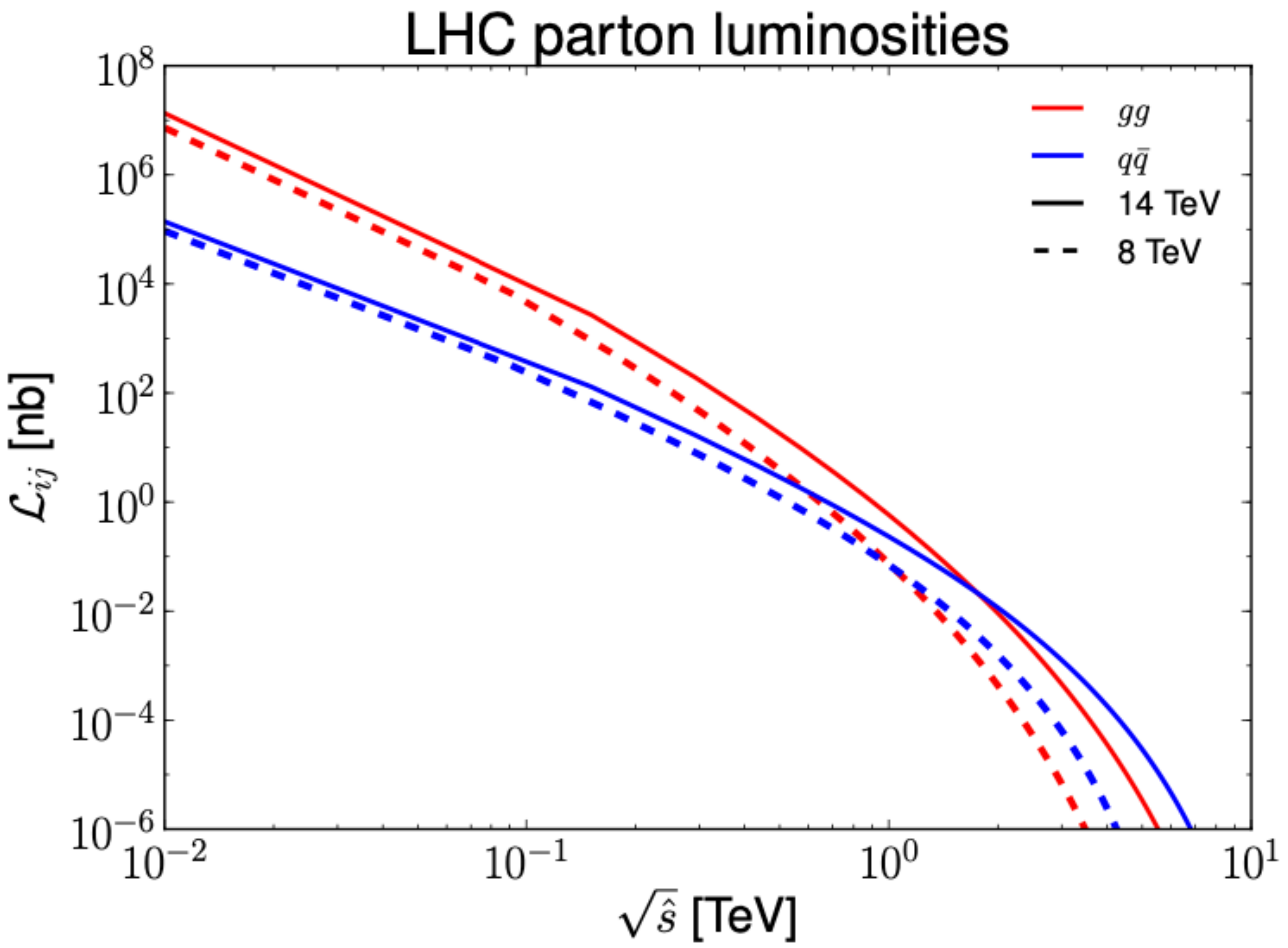
$$\sigma_{pp\to X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \cdot \mathscr{L}_{ab}(s,\tau) \cdot \left[\hat{s}\hat{\sigma}_{ab}\right]$$

$\mathscr{L}_{ab}$: 'luminosity' of partonic initial state as function of τ, for a given s

$[\hat{s}\hat{\sigma}_{ab}]$: Dimensionless factor, approximately determined by couplings

Parton luminosity

$$\sigma_{pp\to X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \cdot \mathscr{L}_{ab}(s,\tau) \cdot \left[\hat{s}\hat{\sigma}_{ab}\right]$$



Gluon-gluon luminosity dominates at lower $\sqrt{\hat{s}}$ (low x)

$\mathscr{L}_{q\bar{q}}$ and $\mathscr{L}_{gg}$ cross over around $\sqrt{\hat{s}} \sim 1\,\mathrm{TeV}$

Single production of a particle with mass, M_X

$$\hat{\sigma}_{ab\to X}(\hat{s}) \to \hat{\sigma}_{ab\to X}\left(M_X^2\right)\delta\left(\hat{s} - M_X^2\right)$$

e.g. Higgs boson

Parton model summary

DIS experiments show that virtual photon scatters off massless, free, point like, spin-1/2 quarks

One can **factorise** the short- and long-distance physics entering this process. Long-distance physics absorbed in PDFs. Short distance physics described by the hard scattering of the parton with the virtual photon.

$$\sum_{a,b} \int dx_1 dx_2 \, d\Phi_{PS} \, f_a(x_1) f_b(x) \, \hat{\sigma}(\hat{s})$$

Phase-space integral Parton density functions Parton-level cross section

Master formula for LHC physics

$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral

Important aspect of a Monte Carlo generator

Parton density functions

Universal:

~Probabilities of finding given parton with given momentum in proton

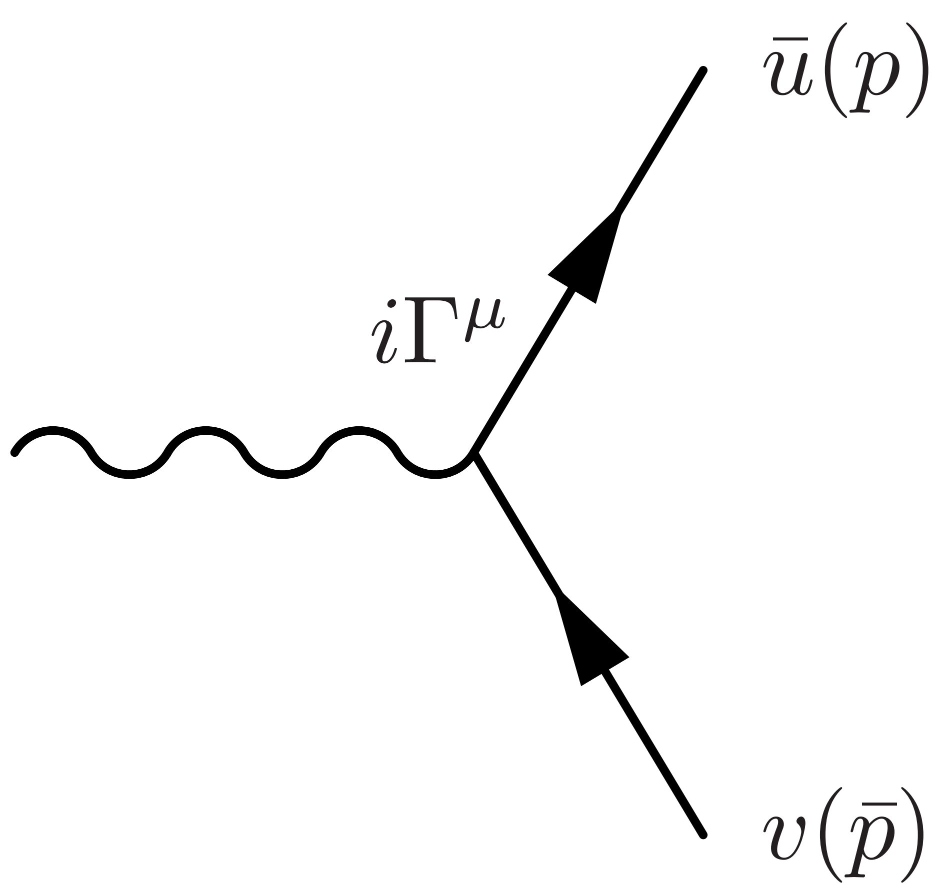
Extracted from data

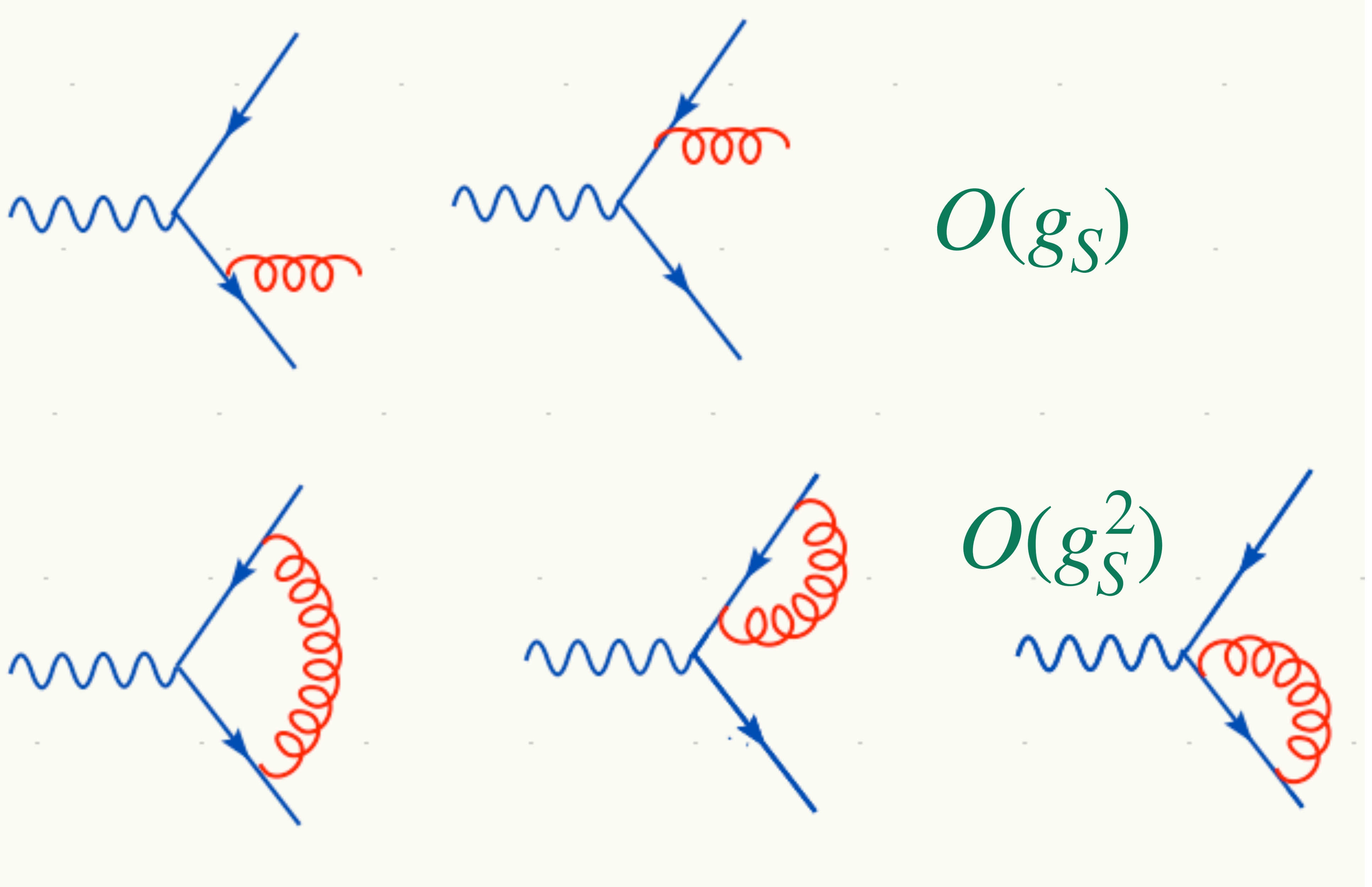
Parton-level cross section

Subject of huge efforts in the LHC theory community to systematically improve this

Higher order corrections

Born





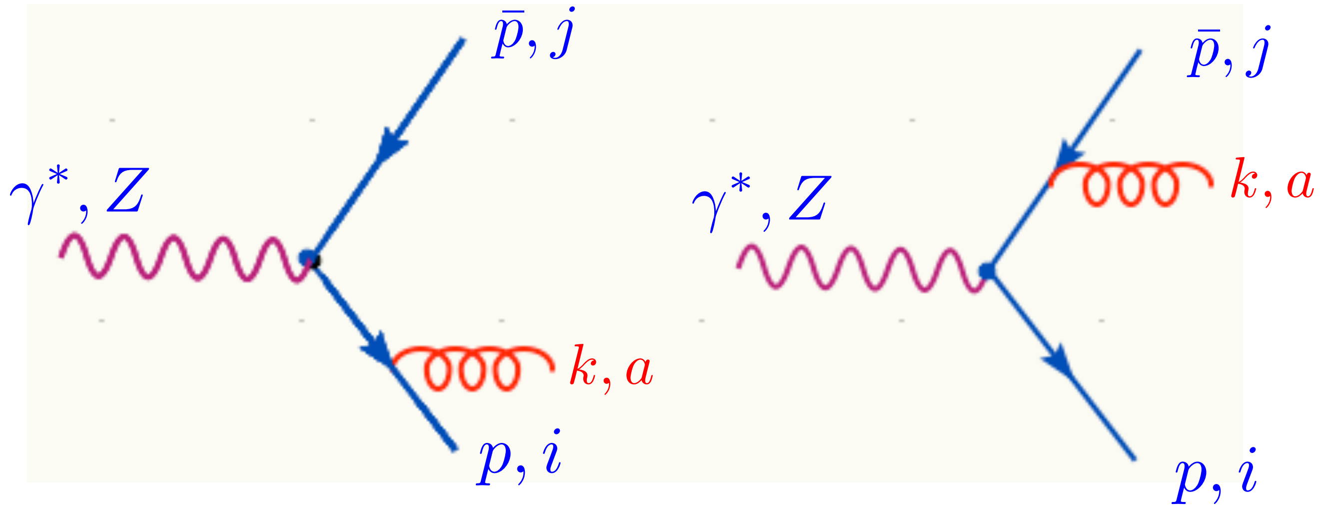
Real emission

Virtual (loop) correction

$$\sigma_{NLO} = \sigma_{LO} + \underbrace{\int_R |A_{\text{real}}|^2 d\Phi_3}_{O(g_S^2)} + \underbrace{\int_V 2\text{Re}\left[A_{\text{Born}} A^*_{\text{vir}}\right] d\Phi_2}_{O(g_S^2)}$$

QCD in the final state

Real corrections:



$$A = \bar{u}(p)\not{\epsilon}(-ig_s)\frac{-i}{\not{p}+\not{k}}\Gamma^\mu v(\bar{p})t^a + \bar{u}(p)\Gamma^\mu \frac{i}{\not{\bar{p}}+\not{k}}(-ig_s)\not{\epsilon}v(\bar{p})t^a$$

$$= -g_s\left[\frac{\bar{u}(p)\not{\epsilon}(\not{p}+\not{k})\Gamma^\mu v(\bar{p})}{2p\cdot k} - \frac{\bar{u}(p)\Gamma^\mu(\not{\bar{p}}+\not{k})\not{\epsilon}v(\bar{p})}{2\bar{p}\cdot k}\right]t^a$$

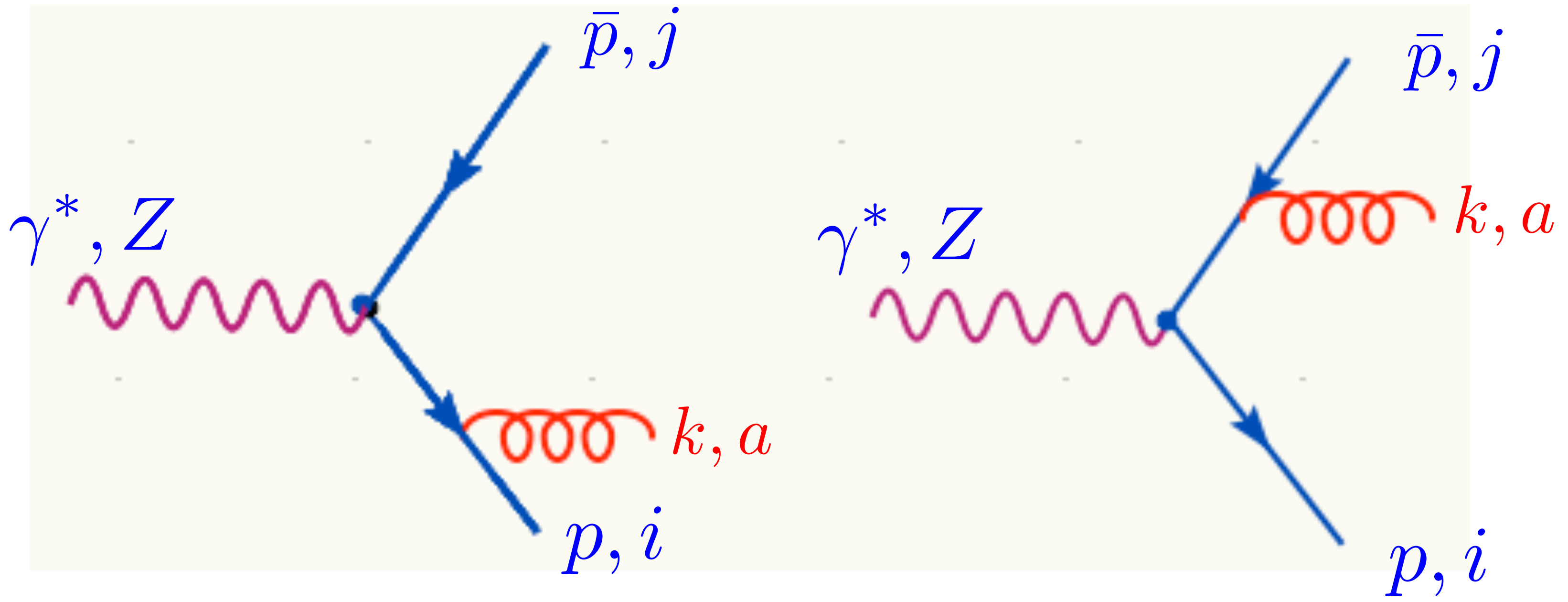
What are those denominators?

$$p \cdot k = p_0 k_0 (1 - \cos\theta)$$

What happens when the gluon is soft ($k_0 \to 0$) or collinear ($\theta \to 0$) to the quark?

QCD in the final state

What happens when the gluon is soft ($k_0 \to 0$) or collinear ($\theta \to 0$) to the quark?



$k \ll p$

$$A_{\text{soft}} = -g_s\,[t_a]^{ij}\left(\frac{p\cdot\epsilon}{p\cdot k} - \frac{\bar{p}\cdot\epsilon}{\bar{p}\cdot k}\right)A^{ij}_{\text{Born}}$$

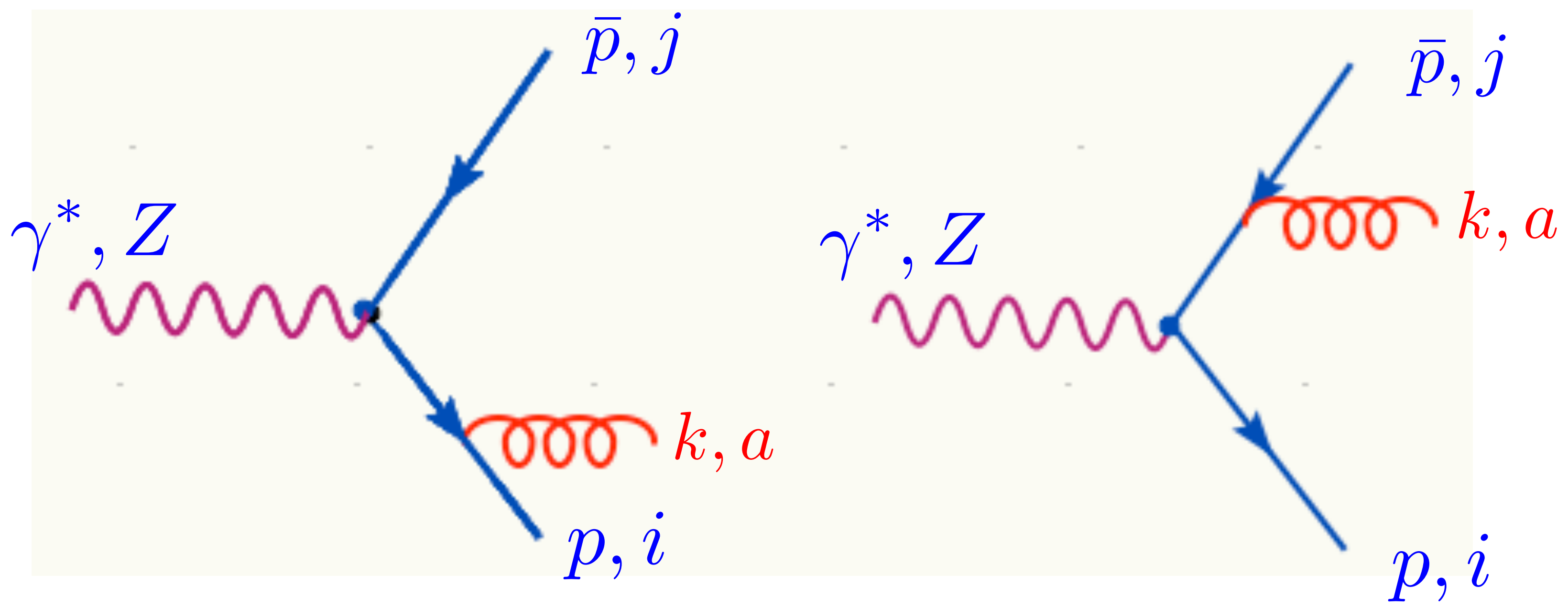
Very important property of QCD & QED

Factorisation of long-wavelength (soft) emission from the short-distance (hard) scattering!

Soft emission factor is universal!

QCD in the final state

How does it contribute to the NLO cross-section?



$$\sigma_{NLO} = \sigma_{LO} + \int_R |A_{\text{real}}|^2 \, d\Phi_3 + \int_V 2\text{Re}\left[A_{\text{Born}} A^*_{\text{vir}}\right] \, d\Phi_2$$

$$A_{\text{real}} \simeq -g_s \, [t_a]^{ij} \left(\frac{p \cdot \epsilon}{p \cdot k} - \frac{\bar{p} \cdot \epsilon}{\bar{p} \cdot k} \right) A^{ij}_{\text{Born}}$$

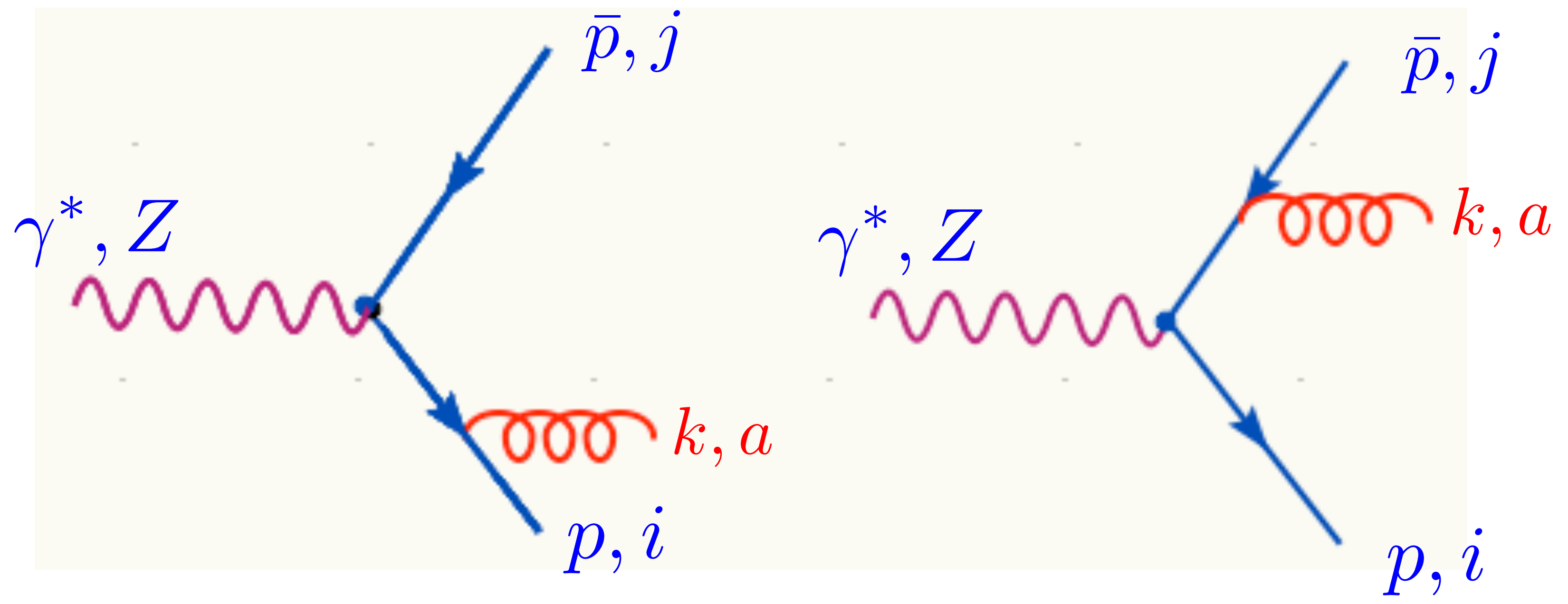
$$\sum_{\lambda_g, \lambda_q} |A_{\text{real}}|^2 = \sum_{\lambda_g} g_s^2 \, 3C_F \left(\frac{p \cdot \epsilon p \cdot \epsilon^*}{(p \cdot k)^2} - \frac{\bar{p} \cdot \epsilon p \cdot \epsilon^* + (p \leftrightarrow \bar{p})}{(\bar{p} \cdot k)(p \cdot k)} + \frac{\bar{p} \cdot \epsilon \bar{p} \cdot \epsilon^*}{(\bar{p} \cdot k)^2} \right) |\bar{A}_{\text{Born}}|^2$$

$$\sum_{\lambda_g} \epsilon_\mu \epsilon^*_\nu = -g_{\mu\nu}$$

$$\sigma^{q\bar{q}g}_{\text{real}} = C_F \, g_s^2 \, \sigma^{q\bar{q}}_{\text{Born}} \int \frac{d^3\vec{k}}{2k_0(2\pi)^3} \frac{2p \cdot \bar{p}}{(p \cdot k)(\bar{p} \cdot k)}$$

$$= C_F \frac{\alpha_S}{2\pi} \sigma^{q\bar{q}}_{\text{Born}} \int d\cos\theta \, \frac{dk_0}{k_0} \frac{4}{(1 - \cos\theta)(1 + \cos\theta)}$$

QCD in the final state



$$\sigma_{\text{real}}^{q\bar{q}g} = C_F\, g_s^2\, \sigma_{\text{Born}}^{q\bar{q}} \int \frac{d^3\vec{k}}{2k_0(2\pi)^3} \frac{2p\cdot\bar{p}}{(p\cdot k)(\bar{p}\cdot k)}$$

$$= C_F \frac{\alpha_S}{2\pi} \sigma_{\text{Born}}^{q\bar{q}} \int d\cos\theta\, \frac{dk_0}{k_0} \frac{4}{(1-\cos\theta)(1+\cos\theta)}$$

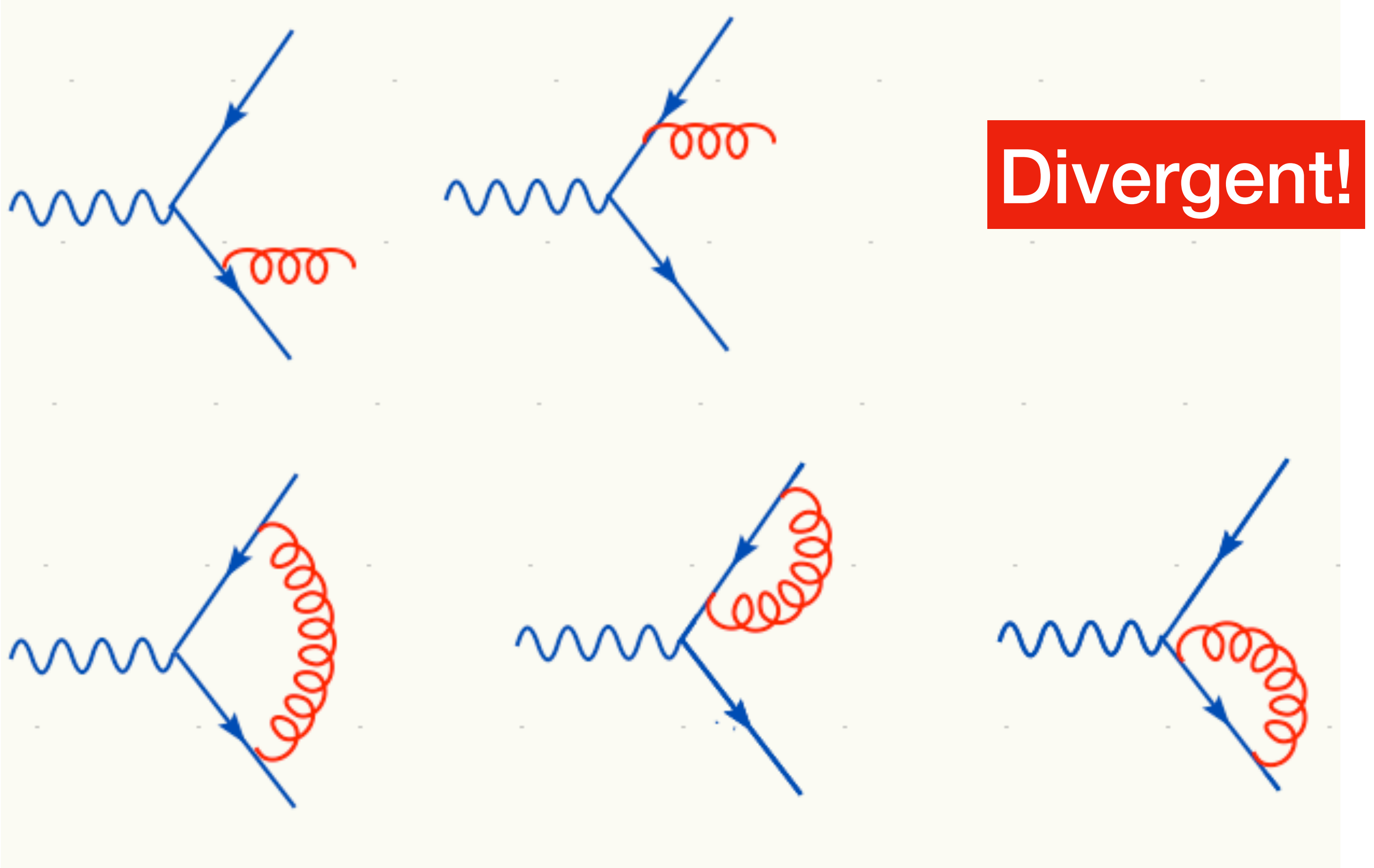
Real emission diagrams: IR singularities

Soft divergence Collinear divergence

- Infrared divergences arise from interactions that happen a long time after the creation of the quark/antiquark pair.
- When distances become comparable to the hadron size of ~1 Fermi, quasi-free partons of the perturbative calculation are confined/hadronized non-perturbatively.

How do we proceed with our calculation?

Cancellation of divergences



Divergent!

Real

Virtual

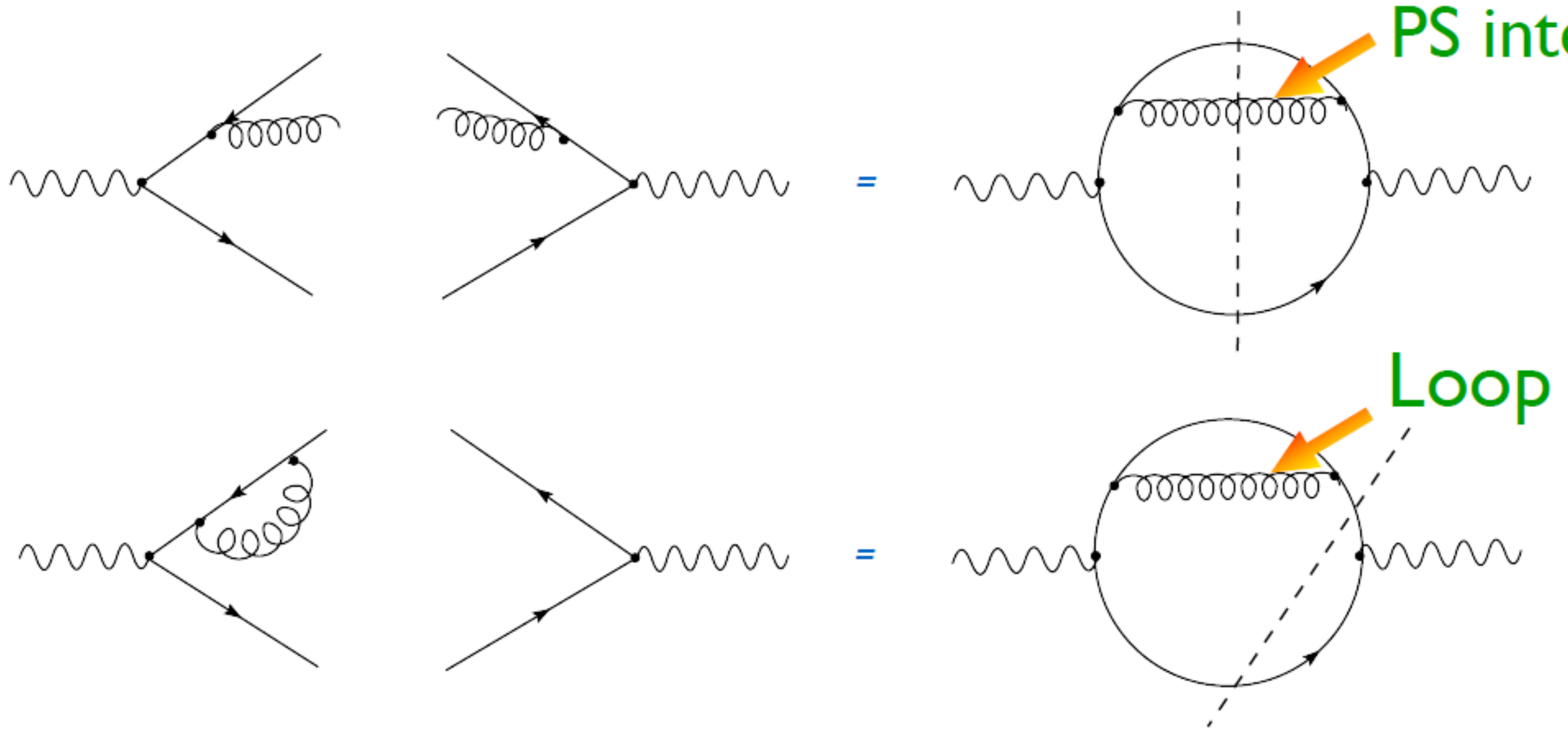
Also divergent!

In practice: regularise both divergences (with either dimensional regularisation or mass regulator)

Mass regulator (λ): $(p+k)^2 \to 2p\cdot k + \lambda^2$

send $\lambda^2 \to 0$ at the end

Dimensional regularisation ($\epsilon = d-4$)



$$\sigma^{\mathrm{REAL}} = \sigma^{\mathrm{Born}} C_F \frac{\alpha_S}{2\pi}\left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} - \pi^2\right)$$

$$\sigma^{\mathrm{VIRT}} = \sigma^{\mathrm{Born}} C_F \frac{\alpha_S}{2\pi}\left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \pi^2\right)$$

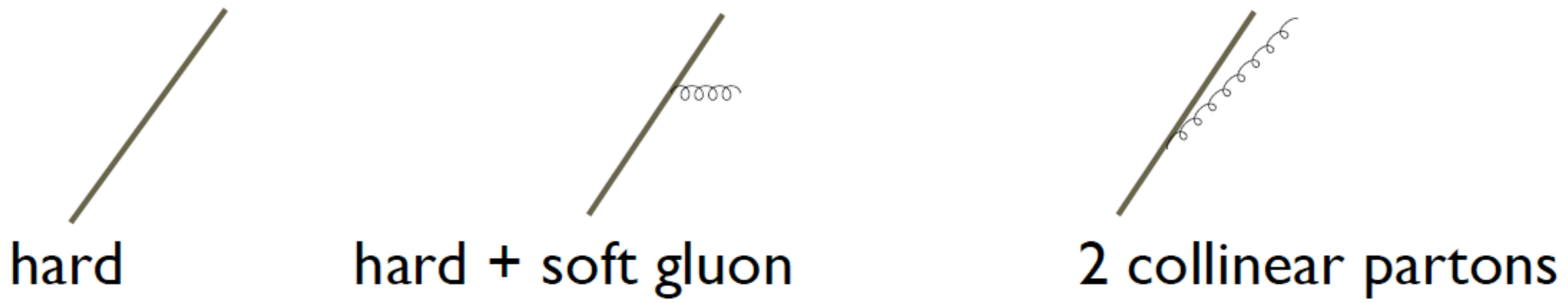
$$\lim_{\epsilon\to 0}(\sigma^{\mathrm{REAL}} + \sigma^{\mathrm{VIRT}}) = C_F \frac{3}{4}\frac{\alpha_S}{\pi}\sigma^{\mathrm{Born}}$$

$$R_1 = R_0\left(1 + \frac{\alpha_S}{\pi}\right)$$

Finite!

KLN Theorem

Kinoshita-Lee-Nauenberg theorem: Infrared singularities in a massless theory cancel out after summing over degenerate (initial and final) states



Physically…

- hard parton can't be distinguished from a hard parton plus a soft gluon
- …or from two collinear partons with the same energy.
- final state with a soft gluon is nearly degenerate with a final state with no gluon at all (virtual)

Hence, one needs to add all degenerate states to get a physically sound observable

Infrared safety

Consequently…

We need to pick observables which are insensitive to soft/collinear radiation.

- These observables are determined by hard, short-distance physics
- Long distance effects suppressed by an inverse power of a large momentum scale.

Schematically for an IR safe observable

$$\mathcal{O}_{n+1}(k_1, k_2, \ldots, k_i, k_j, \ldots k_n) \to \mathcal{O}_n(k_1, k_2, \ldots k_i + k_j, \ldots k_n)$$

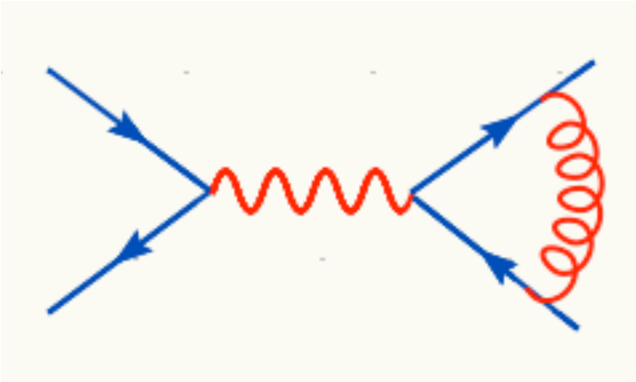
whenever one of the k_i/k_j becomes soft or k_i and k_j are collinear

Which observables are infrared safe?

‣ energy of the hardest particle in the event	NO
‣ multiplicity of gluons	NO
‣ momentum flow into a cone in rapidity and angle	YES
‣ jet cross-sections	DEPENDS

See exercises!

Asymptotic freedom

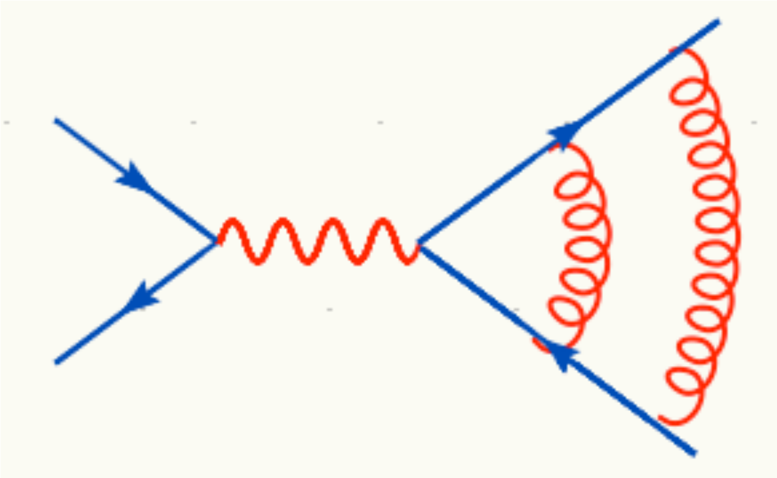


$$R_1 = R_0\left(1+\frac{\alpha_S}{\pi}\right)$$

No divergences!

What happens at higher orders?

$M_{UV} \to \infty$ (cutoff regulator)



$$R^{(2)} = R^{(0)}\left(1+\frac{\alpha_S}{\pi}+\left(\frac{\alpha_S}{\pi}\right)^2\left(c+\pi b_0\log\left(\frac{M_{\rm UV}^2}{Q^2}\right)\right)\right) \qquad b_0=\frac{11N_c-4n_fT_R}{12\pi}$$

UV divergences don't cancel! We need renormalisation!

Renormalising the bare coupling we have:

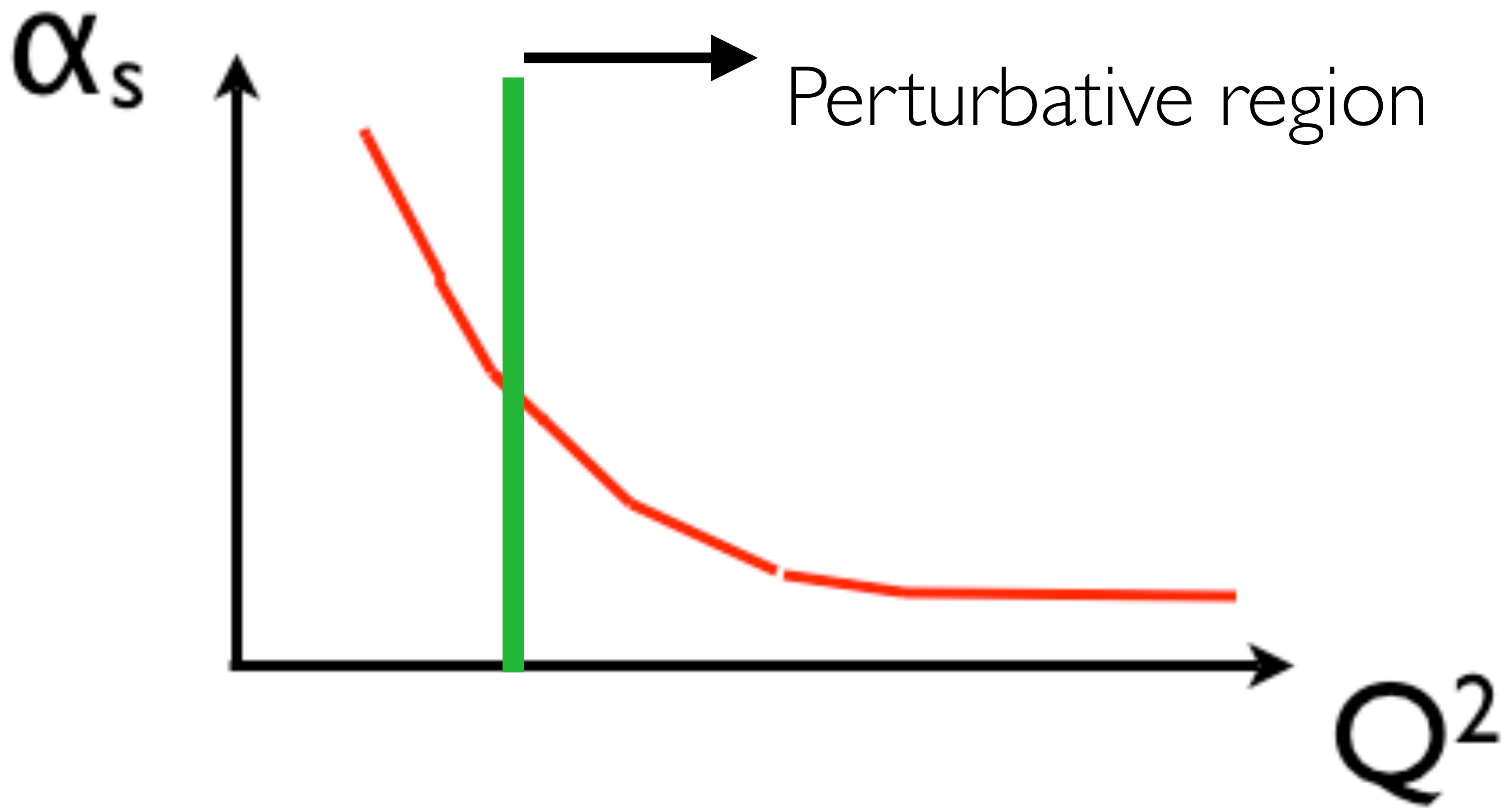
$$\alpha_S(\mu)=\alpha_S^{\rm bare}+b_0\log\left(\frac{M_{\rm UV}^2}{\mu^2}\right)(\alpha_S^{\rm bare})^2$$

$\mu =$ renormalisation scale

$$R_2^{\rm ren}(\alpha_S(\mu),\frac{\mu^2}{Q^2})=R_0\left(1+\frac{\alpha_S(\mu)}{\pi}+\left[c+\pi b_0\log\frac{\mu^2}{Q^2}\right]\left(\frac{\alpha_S(\mu)}{\pi}\right)^2\right)$$

Finite but scale dependent!

Asymptotic freedom



QCD $b_0 = \frac{11N_c - 2n_f}{12\pi} \Rightarrow \beta(\alpha_S) < 0$

QED $b_0 = -\frac{n_f}{3\pi} \Rightarrow \beta(\alpha_{EM}) > 0$

$$\mu^2 \frac{d\alpha}{d\mu^2} = \beta(\alpha) = -(b_0\alpha^2 + b_1\alpha^3 + b_2\alpha^4 + \cdots)$$

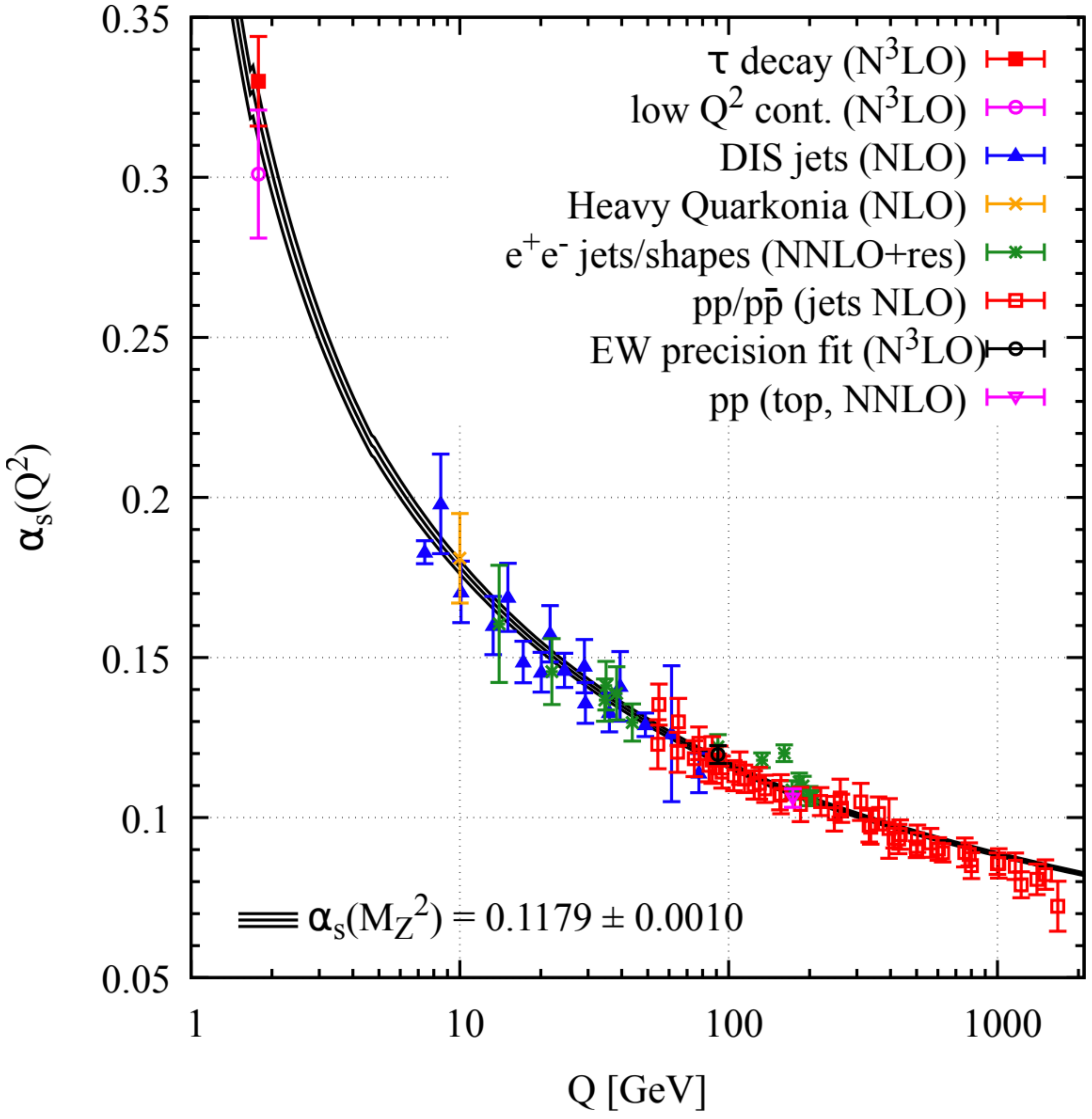
1-loop

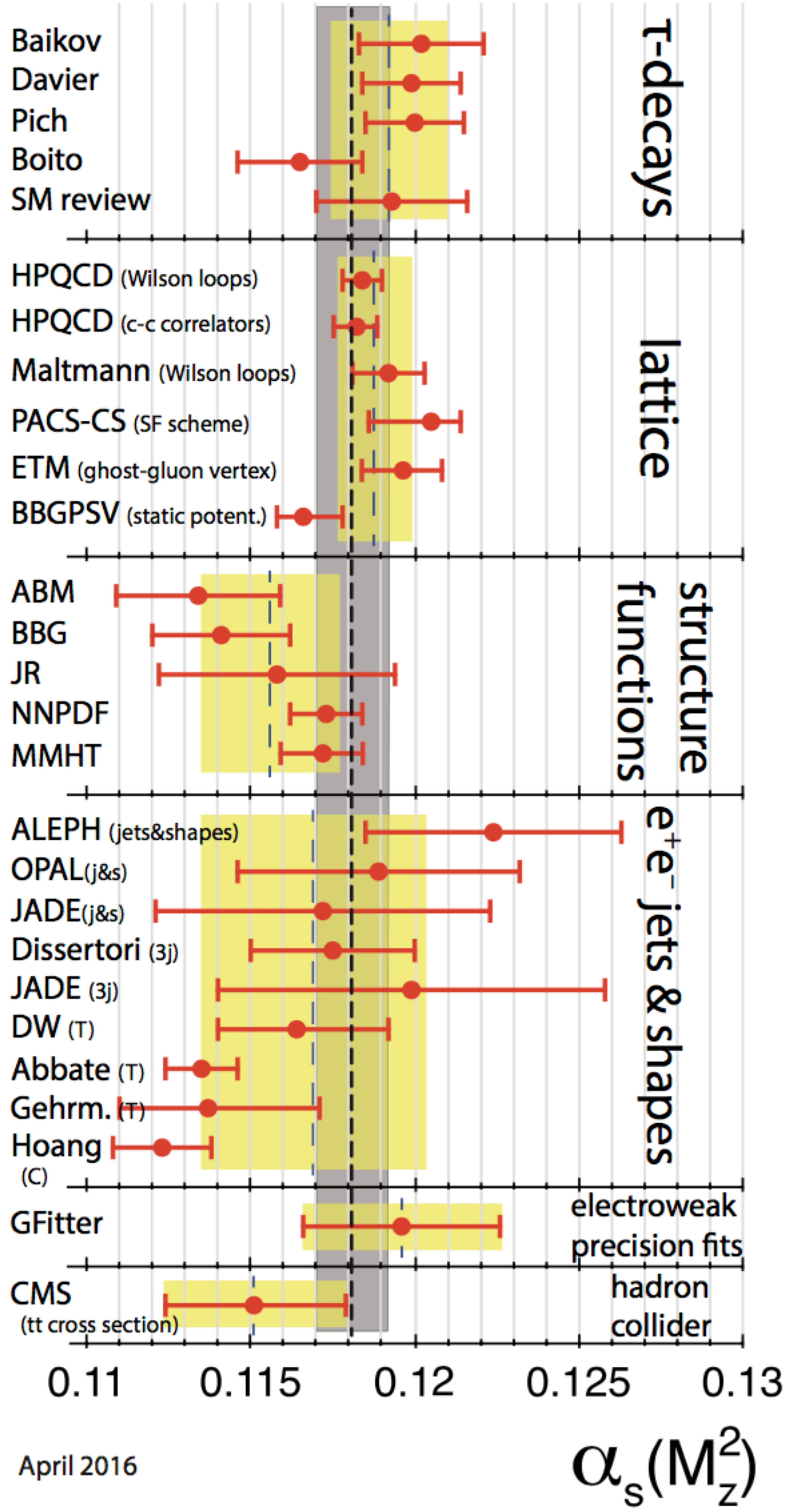
$$\beta(\alpha_S) \equiv \mu^2 \frac{\partial \alpha_S}{\partial \mu^2} = -b_0\alpha_S^2 \quad \Rightarrow \quad \alpha_S(\mu) = \frac{1}{b_0 \log \frac{\mu^2}{\Lambda^2}}$$

2-loop

$$\alpha_S(\mu) = \frac{1}{b_0 \log \frac{\mu^2}{\Lambda^2}} \left[1 - \frac{b_1}{b_0^2} \frac{\log\log \mu^2/\Lambda^2}{\log \mu^2/\Lambda^2}\right]$$

Running of α_s





Many measurements at different scales all leading to very consistent results once evolved to the same reference scale, M_Z.

Going back to the Master formula

$$\sum_{a,b} \int dx_1 dx_2 \, d\Phi_{PS} \, f_a(x_1) f_b(x) \, \hat{\sigma}(\hat{s})$$

$$\downarrow$$

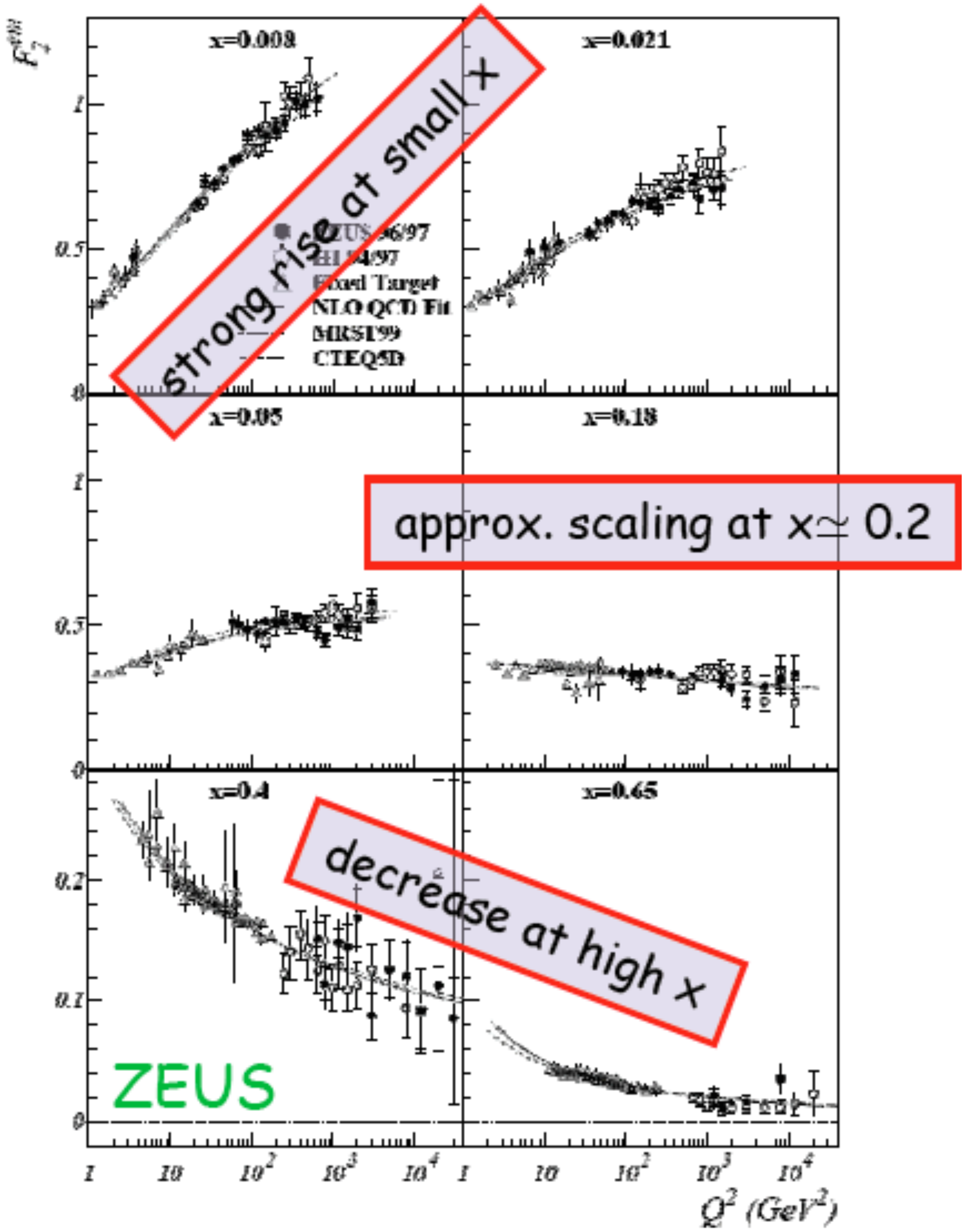
$$\sum_{a,b} \int dx_1 dx_2 \, d\Phi_{PS} \, f_a(x_1) f_b(x) \, \hat{\sigma}(\hat{s}, \mu_R)$$

$$\downarrow$$???

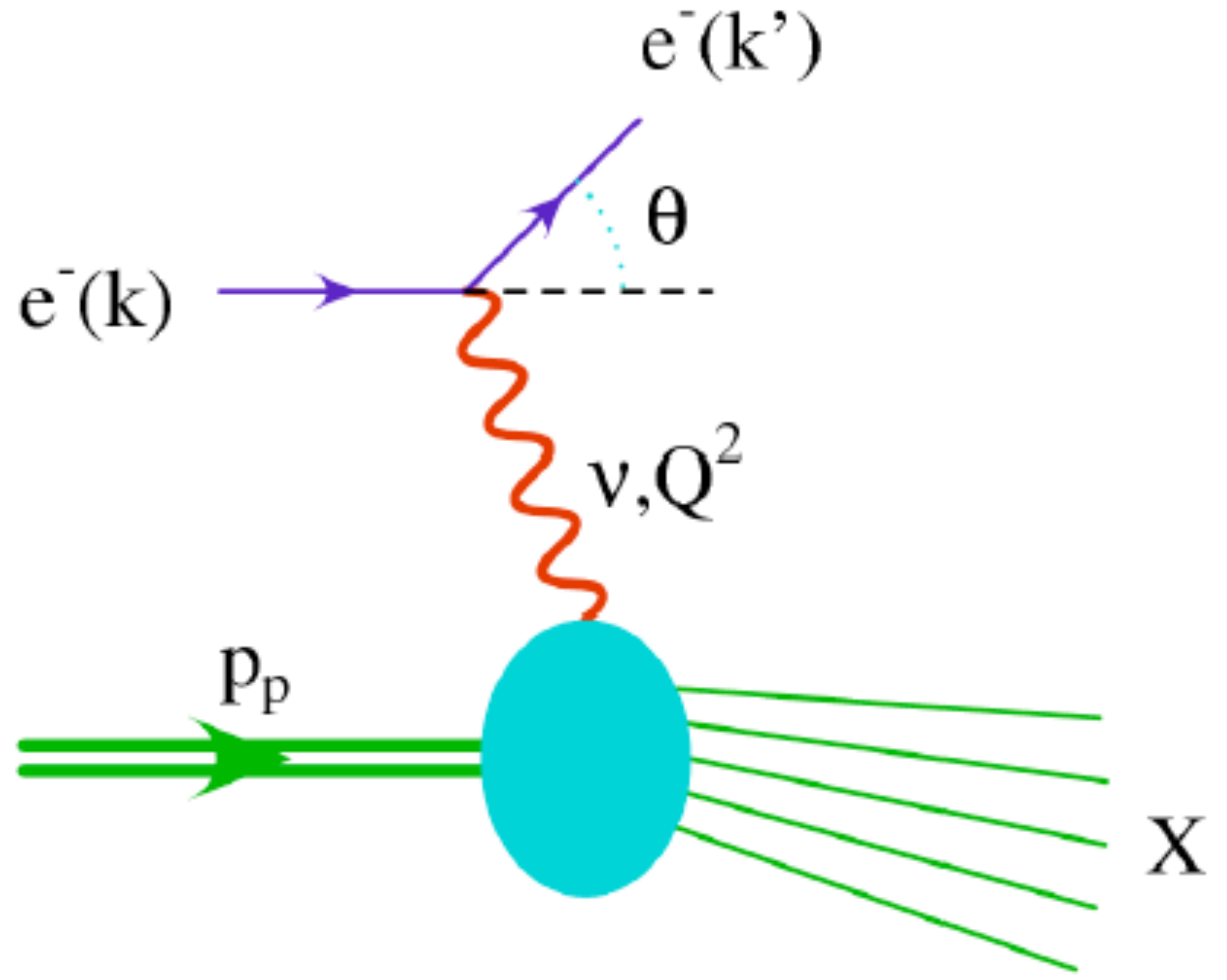
$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}} \, f_a(x_1, \mu_F) f_b(x_2, \mu_F) \, \hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$

QCD improved parton model

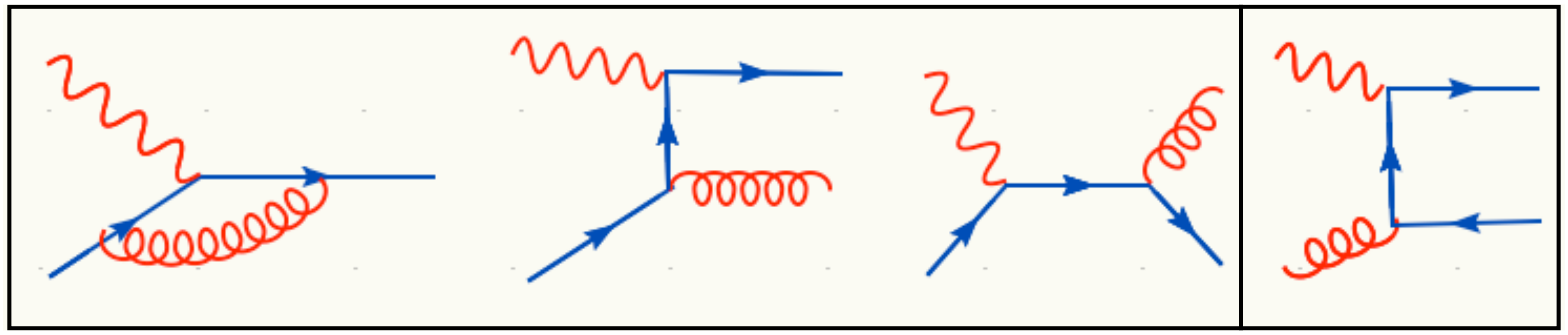
The parton model predicts scaling. Experiment shows:



Scaling violation



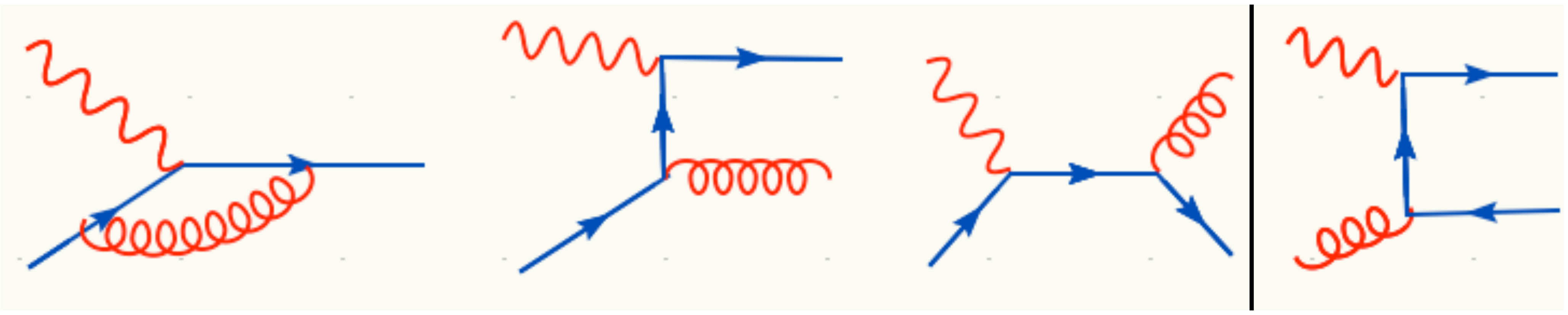
What are we missing?



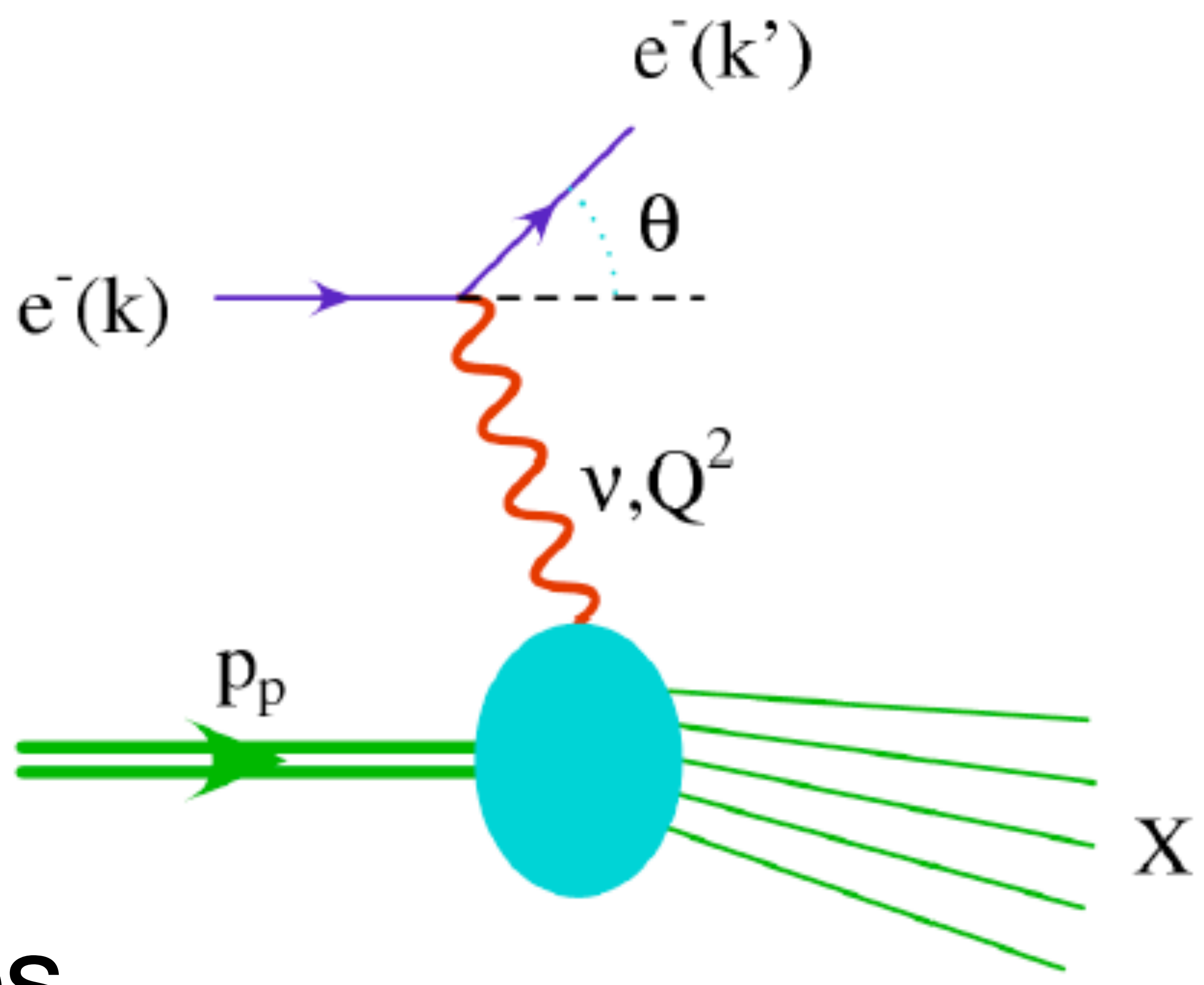
α_S corrections to the LO process

photon-gluon fusion

QCD improved parton model



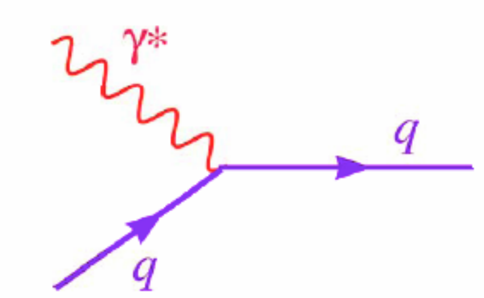
What do we expect?

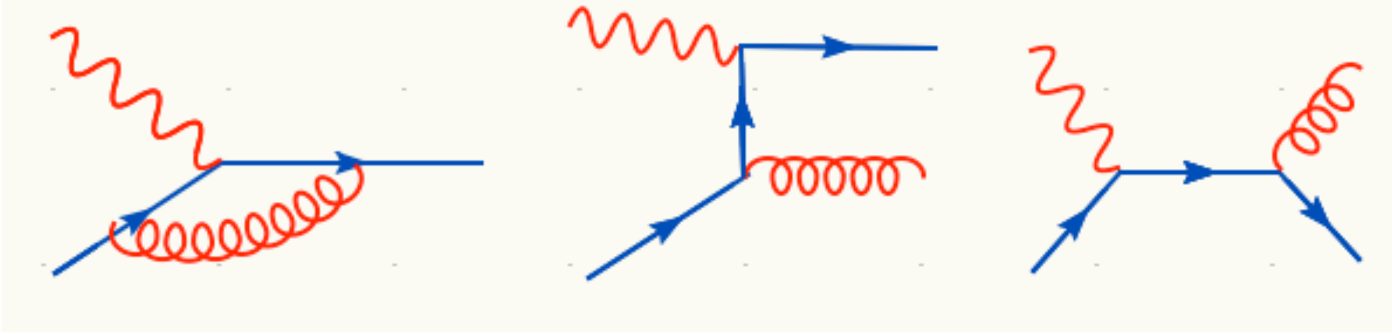


Given the computation of R at NLO, we expect IR divergences

We need to regulate these, and hope that they cancel!

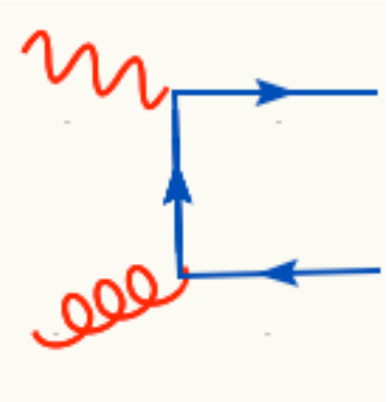
$$\frac{d^2\hat{\sigma}}{dx dQ^2}\Big|_{F_2} \equiv \hat{F}_2^q$$



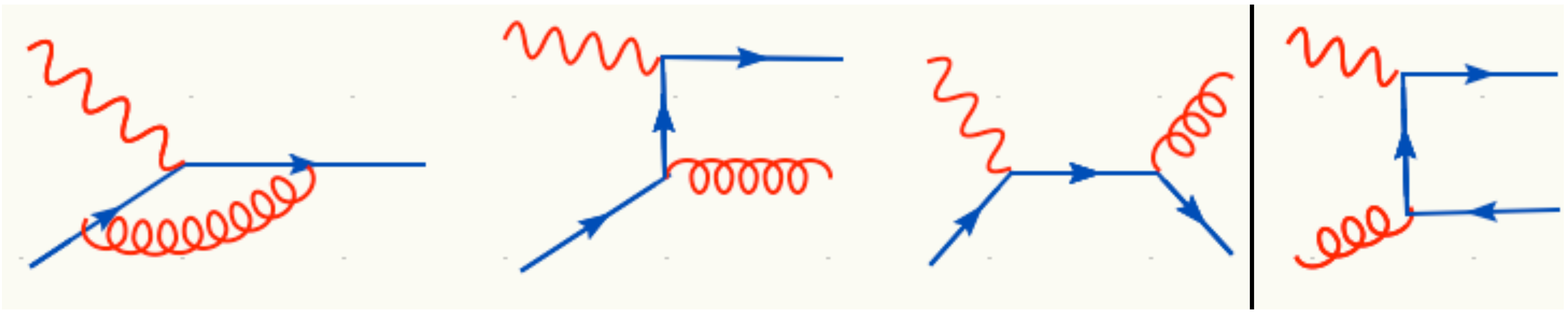


Soft and UV divergences cancel but a collinear divergence arises:

$$\hat{F}_2^q = e_q^2 x[\delta(1-x) + \frac{\alpha_s}{4\pi} P_{qq} \log \frac{Q^2}{m_g^2} + C_2^q(x)] \qquad \hat{F}_2^g = e_q^2 x[0 + \frac{\alpha_s}{4\pi} P_{qg} \log \frac{Q^2}{m_g^2} + C_2^g(x)]$$



QCD improved parton model



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IR cut-off

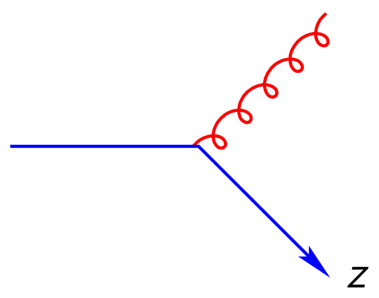
What are functions P_{qq} and P_{qg}?

Splitting functions $P_{ij}(x)$: they give the probability of parton j splitting into parton i which carries momentum fraction x of the original parton

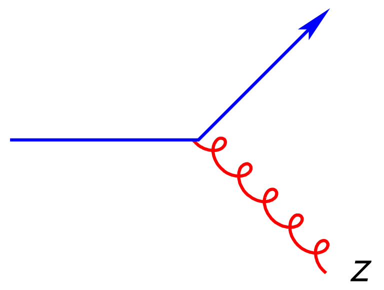
Altarelli-Parisi Splitting functions

Branching has a universal form given by the Altarelli-Parisi splitting functions

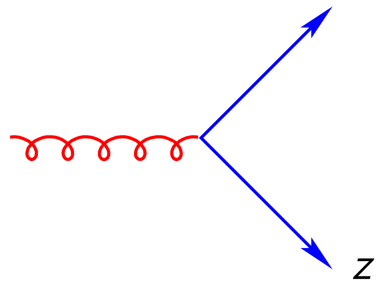
$$P_{q\to qg}(z) = C_F\left[\frac{1+z^2}{1-z}\right],$$



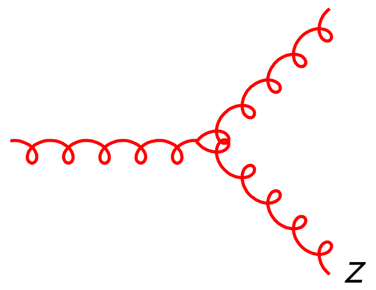
$$P_{q\to gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right].$$



$$P_{g\to qq}(z) = T_R\left[z^2+(1-z)^2\right],$$



$$P_{g\to gg}(z) = C_A\left[z(1-z)+\frac{z}{1-z}+\frac{1-z}{z}\right]$$



These functions are universal for each type of splitting

What does this collinear divergence mean?

Residual long-distance physics, not disappearing once real and virtual corrections are added. These appear along with the universal splitting functions.

Can a physical observable be divergent?

No, as the physical observable is the hadronic structure function:

$$F_2^q(x,Q^2) = x\sum_{i=q,\bar{q}} e_q^2 \left[f_{i,0}(x) + \frac{\alpha_S}{2\pi}\int_x^1 \frac{d\xi}{\xi} f_{i,0}(\xi)\left[P_{qq}(\frac{x}{\xi})\log\frac{Q^2}{m_g^2} + C_2^q(\frac{x}{\xi})\right]\right]$$

We can absorb the dependence on the IR cutoff into the PDF:

$$f_q(x,\mu_f) \equiv f_{q,0}(x) + \frac{\alpha_S}{2\pi}\int_x^1 \frac{d\xi}{\xi} f_{q,0}(\xi) P_{qq}(\frac{x}{\xi})\log\frac{\mu_f^2}{m_g^2} + z_{qq}$$

Renormalised PDFs!

Factorisation

Structure function is a measurable object and cannot depend on scale at all orders (renormalisation group invariance)

$$F_2^q(x,Q^2) = x\sum_{i=q,\bar{q}} e_q^2 \int_x^1 \frac{d\xi}{\xi} f_i(\xi,\mu_f^2)\left[\delta(1-\frac{x}{\xi}) + \frac{\alpha_S(\mu_r)}{2\pi}\left[P_{qq}(\frac{x}{\xi})\log\frac{Q^2}{\mu_f^2} + (C_2^q - z_{qq})(\frac{x}{\xi})\right]\right]$$

Long distance physics is universally factorised into the PDFs, which now depend on μ_f. PDFs are not calculable in perturbation theory. PDFs are universal, they don't depend on the process.

Factorisation scale μ_f acts as a cut-off, emissions below μ_f are included in the PDFs.

LHC Master Formula

$$\sum_{a,b} \int dx_1 dx_2 \, d\Phi_{PS} \, f_a(x_1) f_b(x) \, \hat{\sigma}(\hat{s})$$

Parton model

↓ Renormalisation

$$\sum_{a,b} \int dx_1 dx_2 \, d\Phi_{PS} \, f_a(x_1) f_b(x) \, \hat{\sigma}(\hat{s}, \mu_R)$$

↓ QCD improved parton model

$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}} \, f_a(x_1, \mu_F) f_b(x_2, \mu_F) \, \hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$ ✔

DGLAP

We can't compute PDFs in perturbation theory but we can predict their evolution in scale:

$$\mu^2 \frac{\partial f(x,\mu^2)}{\partial \mu^2} = \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P(z) f\left(\frac{x}{z},\mu^2\right)$$

Altarelli, Parisi; Gribov-Lipatov; Dokshitzer '77

Universality of splitting functions: we can measure pdfs in one process and use them as an input for another process

$$P_{ab}(\alpha_S, z) = \frac{\alpha_S}{2\pi} P_{ab}^{(0)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ab}^{(2)}(z) + \ldots..$$

LO (1974) NLO (1980) NNLO (2004)

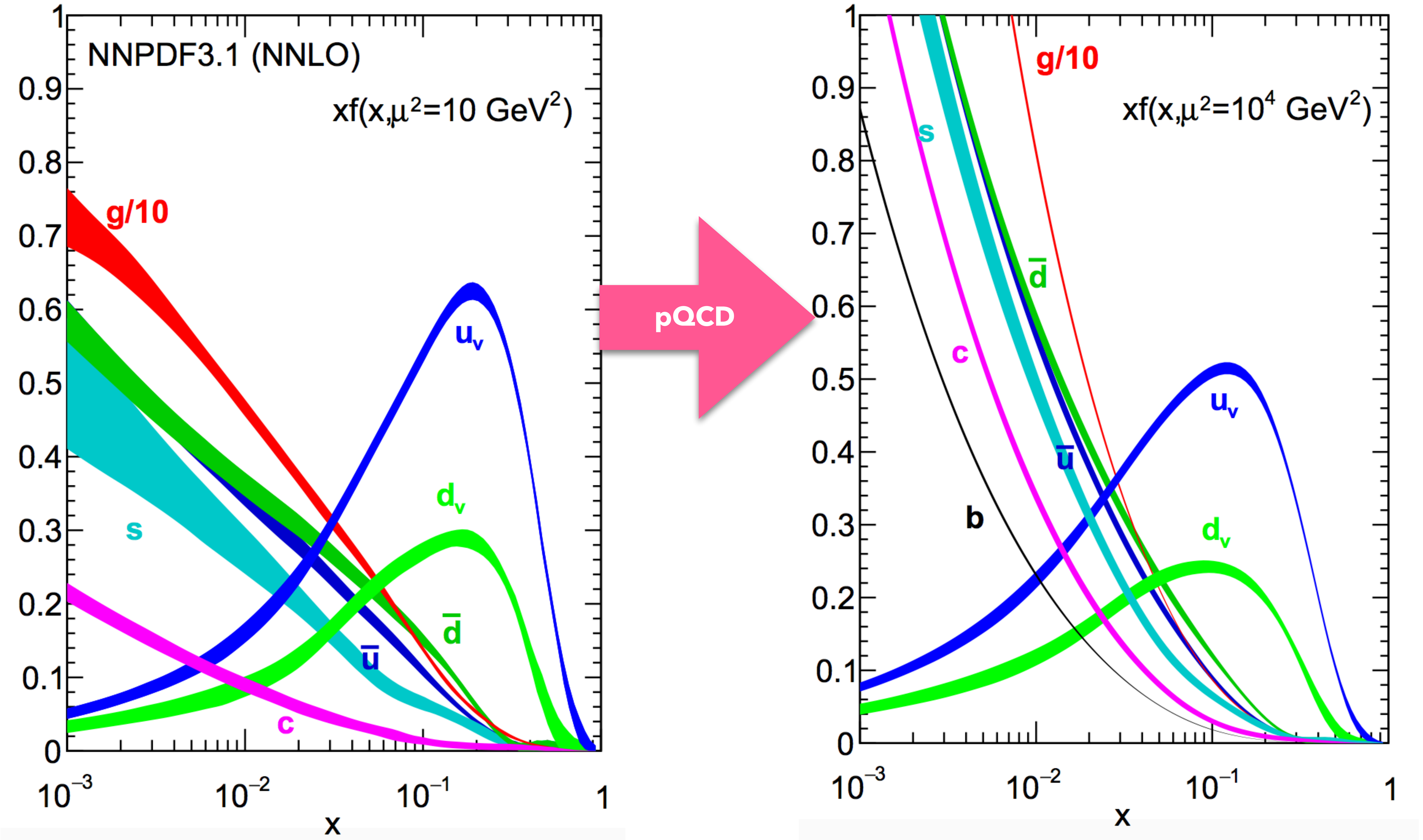
Splitting functions improved in perturbation theory!

LO Dokshitzer; Gribov, Lipatov; Altarelli, Parisi (1977)

NLO Floratos,Ross,Sachrajda; Floratos, Lacaze, Kounnas Gonzalez-Arroyo,Lopez,Yndurain; Curci,Furmanski Petronzio, (1981)

NNLO - Moch, Vermaseren, Vogt, 2004

PDF evolution



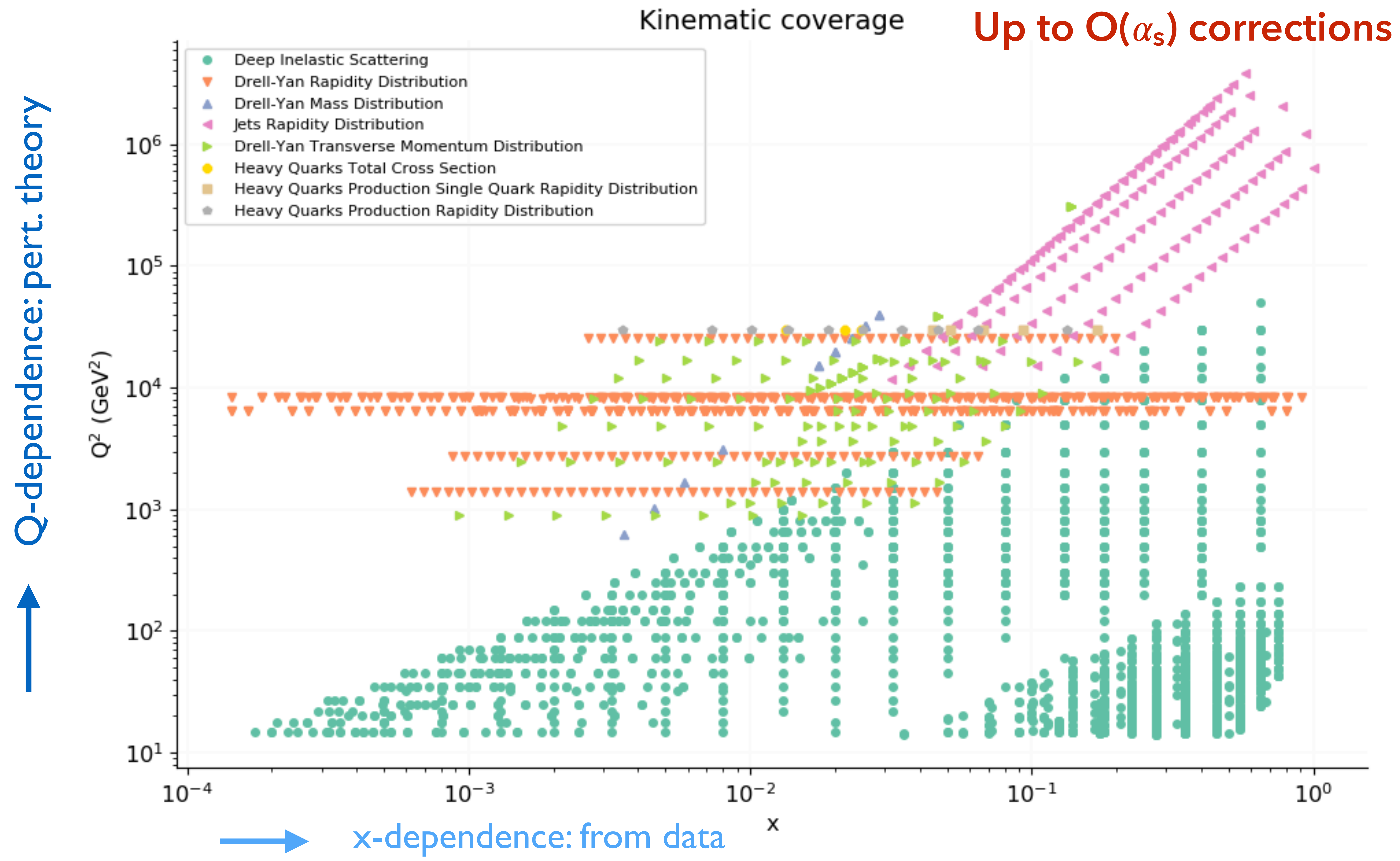
PDF extraction

We can't compute PDFs in perturbation theory but we can extract them from data, and use DGLAP equations to evolve them to different scales.

- Choose **experimental data** to fit and include all info on correlations

  Theory settings: perturbative order, EW corrections, intrinsic heavy quarks, α_s, quark masses value and scheme
- Choose a starting scale Q_0 where pQCD applies
- **Parametrise** independent quarks and gluon distributions at the starting scale
- Solve **DGLAP equations** from initial scale to scales of experimental data and build up observables
- **Fit** PDFs to data
- Provide PDF **error sets** to compute PDF uncertainties

Data for PDF determination



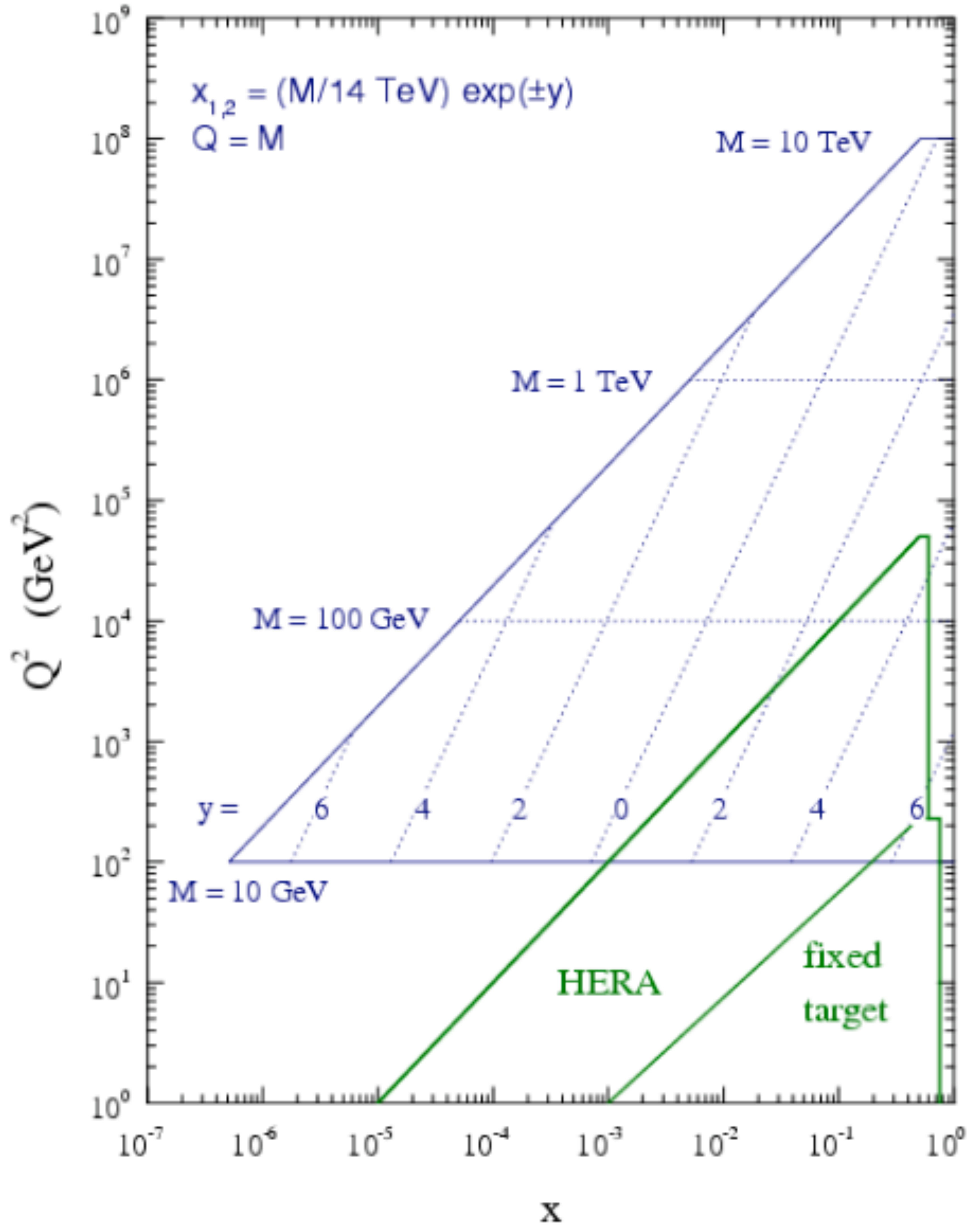
LHC kinematics

For the production of a particle of mass M:

$$M^2 = x_1 x_2 S = x_1 x_2 4E_{\text{beam}}^2$$

$$y = \frac{1}{2}\log\frac{x_1}{x_2}$$

$$x_1 = \frac{M}{\sqrt{S}}e^{y} \quad x_2 = \frac{M}{\sqrt{S}}e^{-y}$$



See exercises!

Data complementarity

GLUON

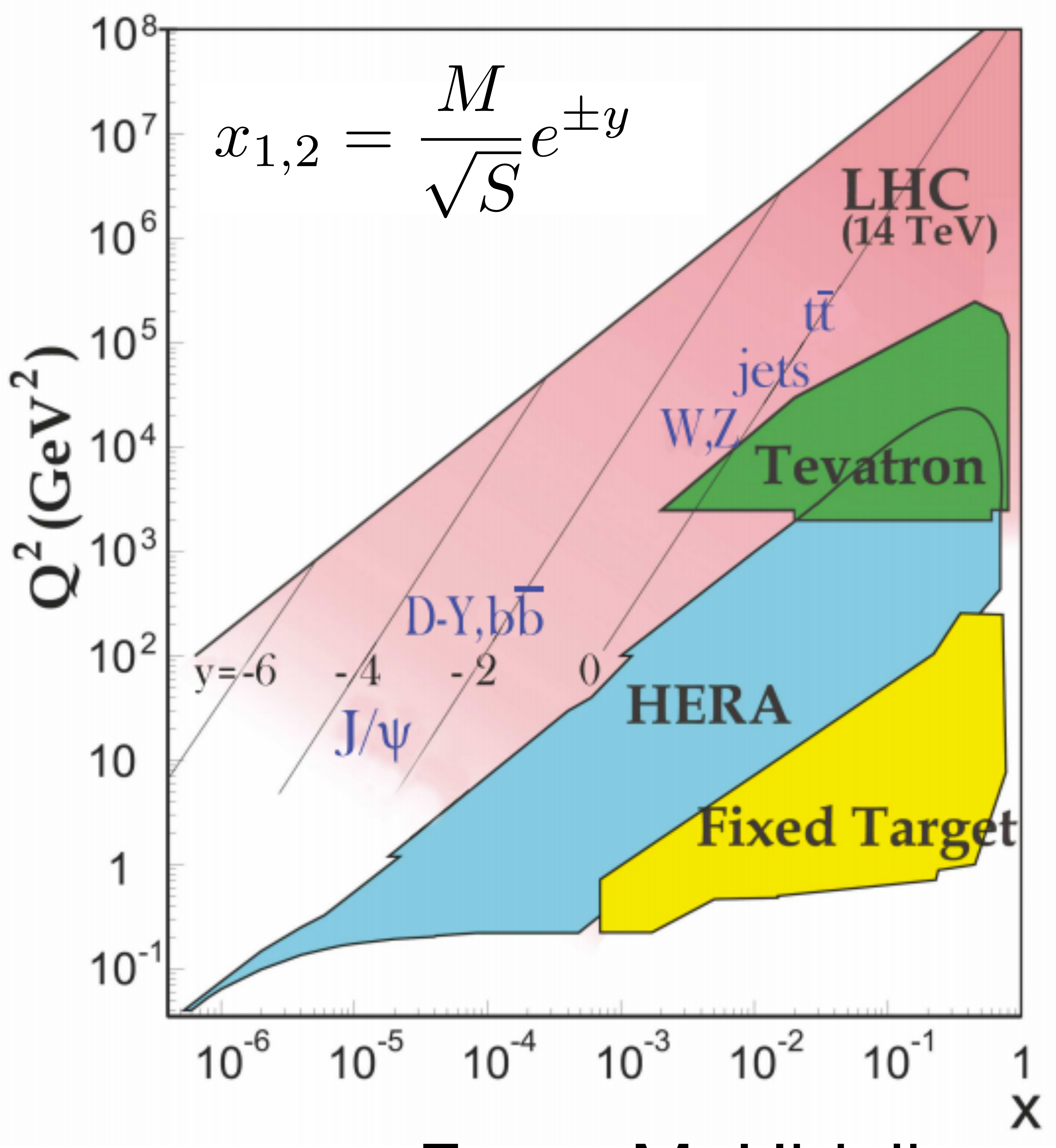
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T V(+jets) distribution **(small/medium x)**

QUARKS

- High p_T W(+jets) ratios **(medium/large x)**
- W and Z production **(medium x)**
- Low and high mass Drell-Yan **(small and large x)**
- Wc **(strangeness at medium x)**

PHOTON

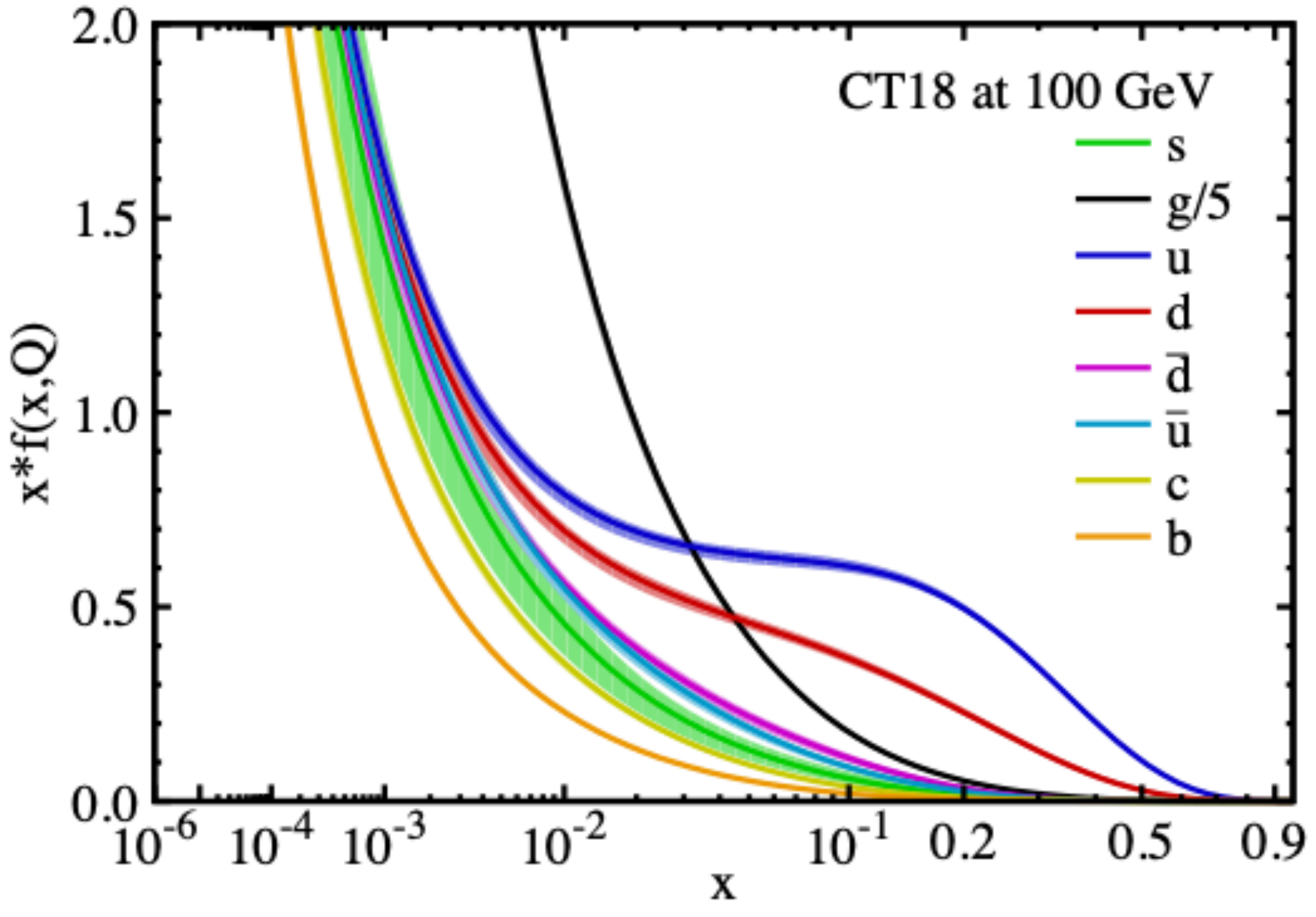
- Low and high mass Drell-Yan
- WW production



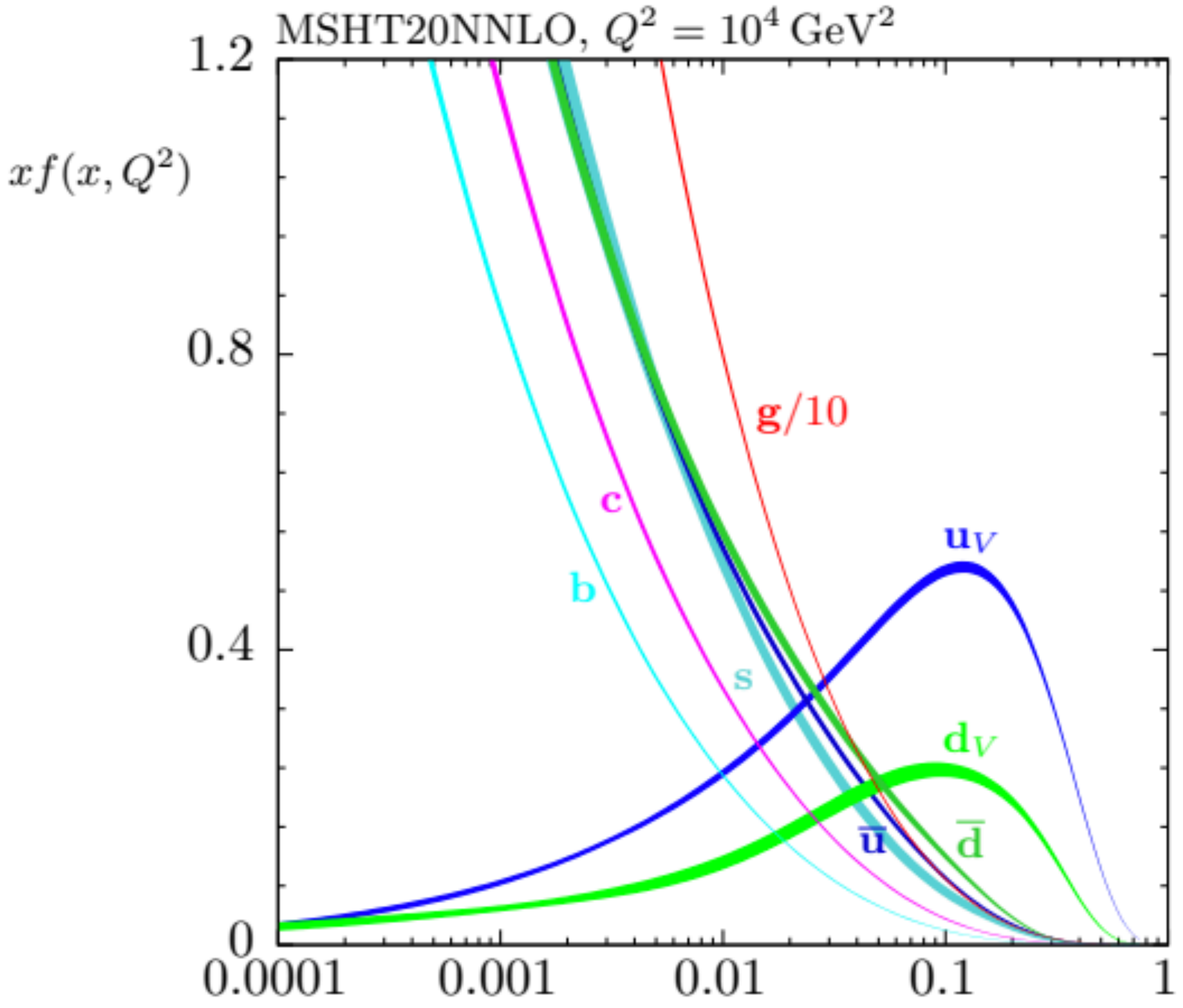
From. M. Ubiali

Modern PDFs

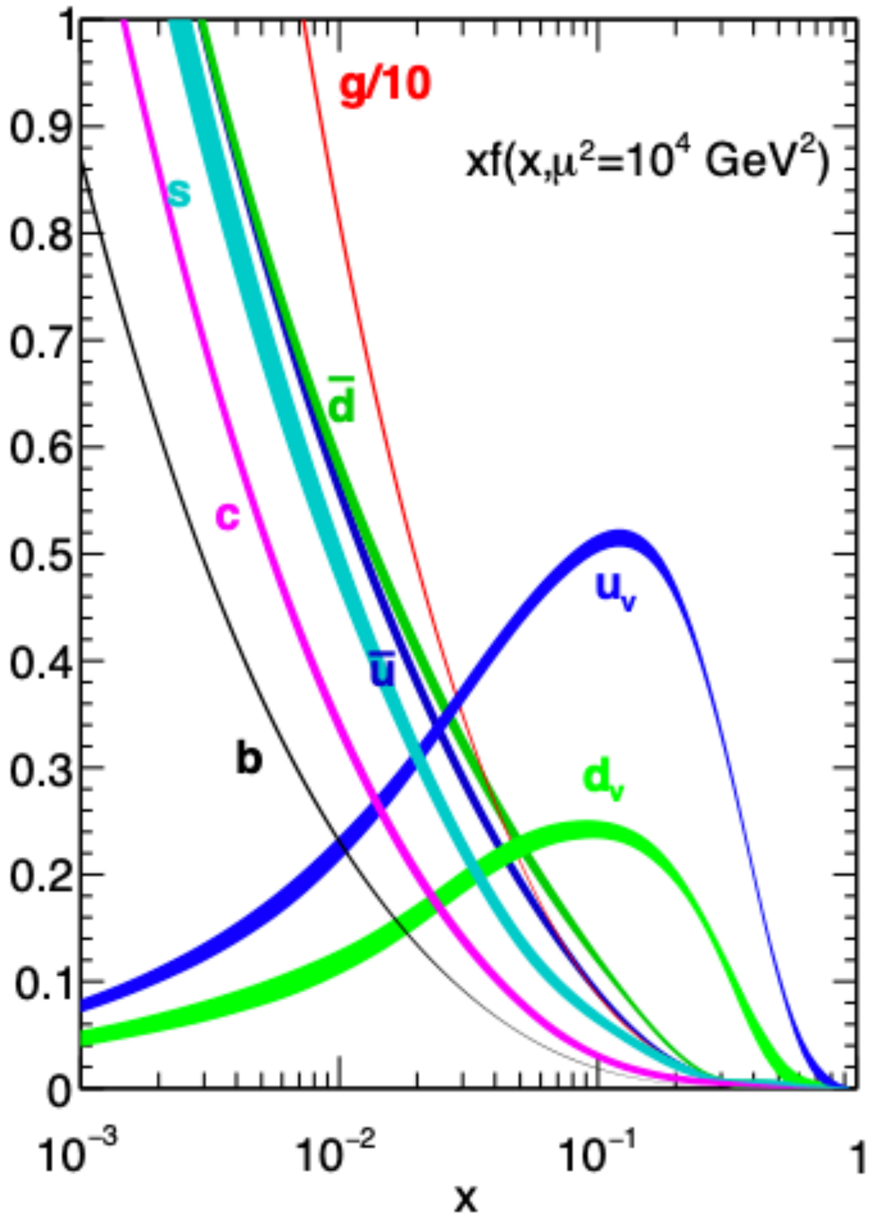
CT18



MSTH20

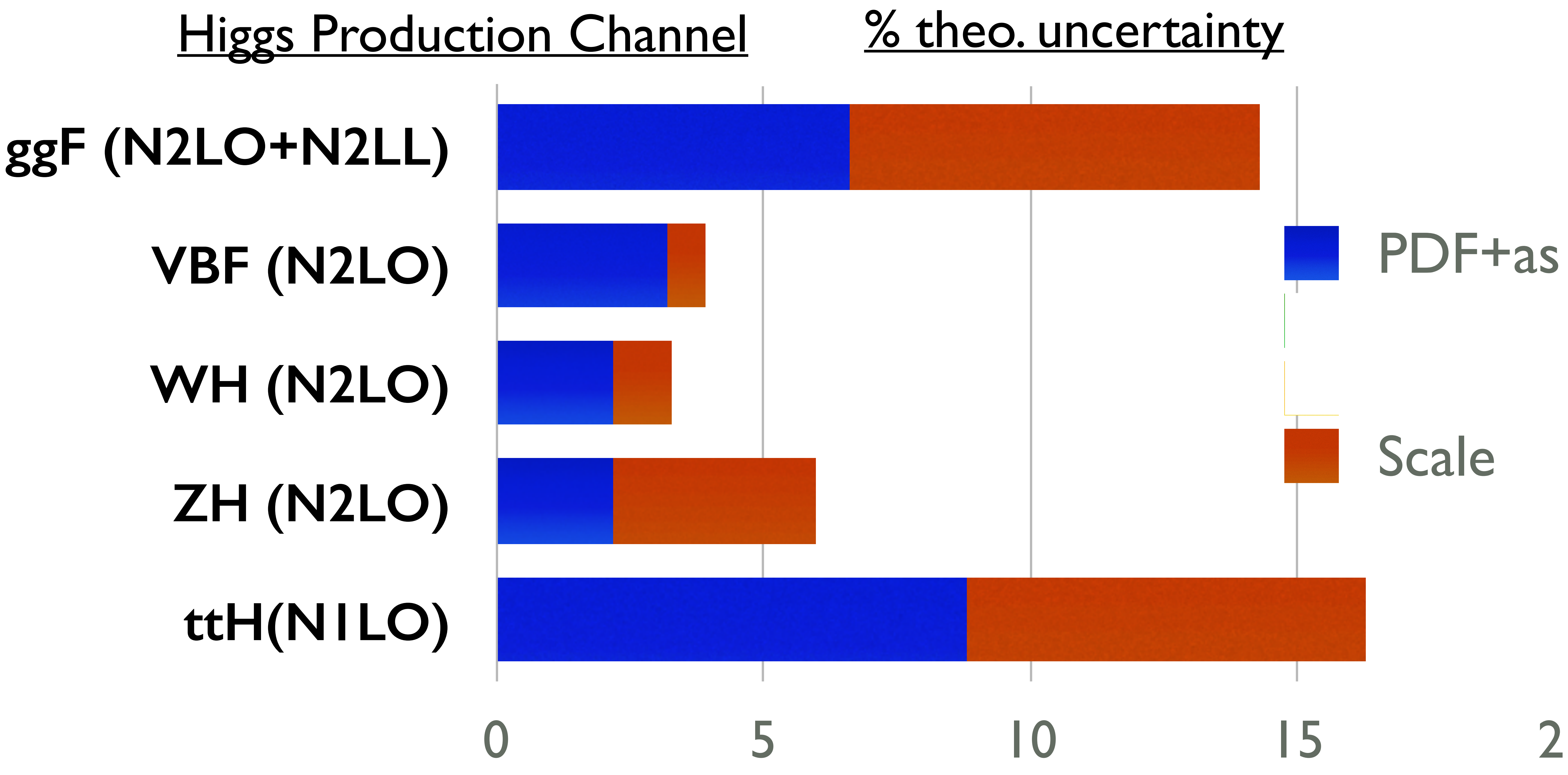


NNPDF3.1

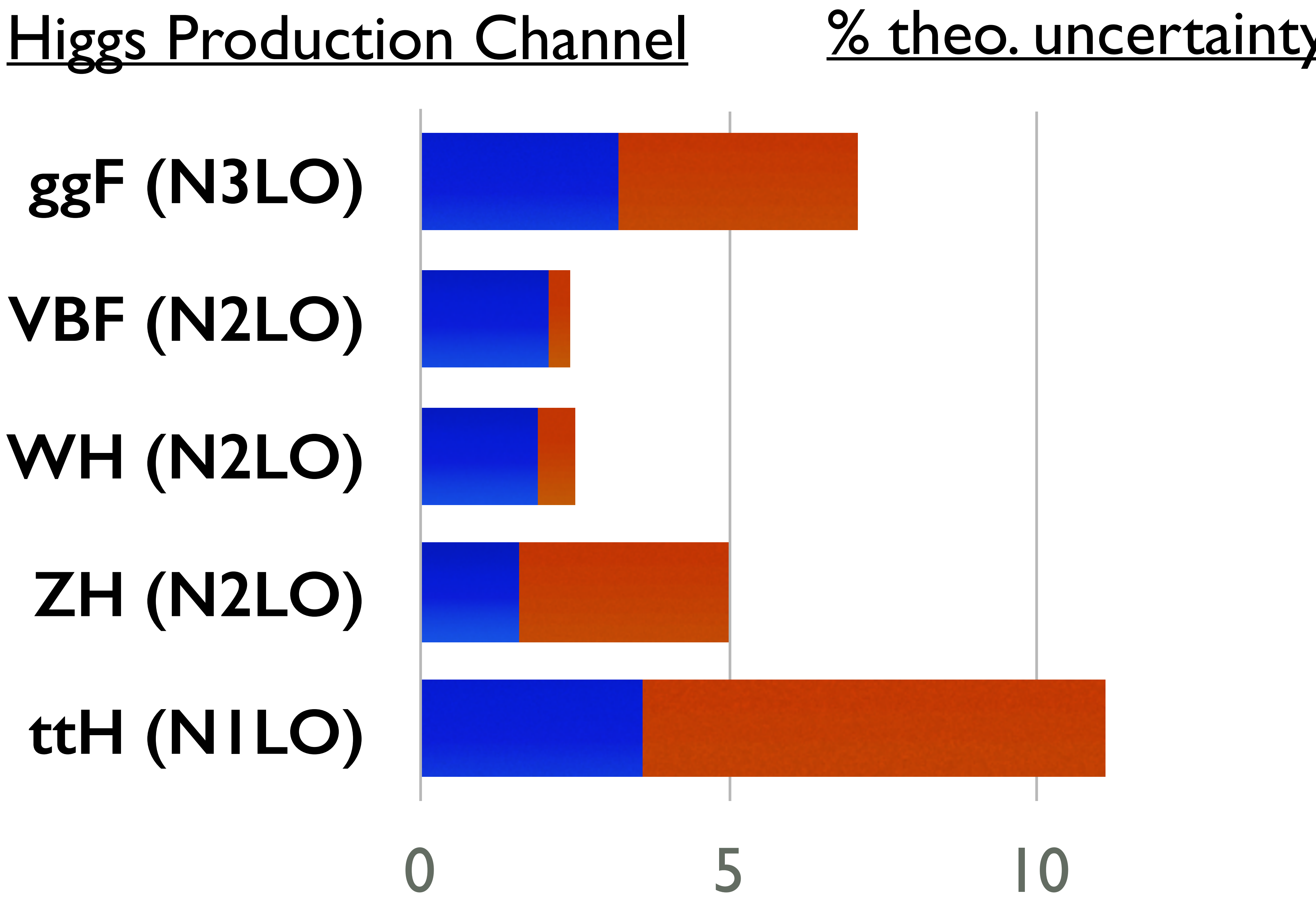


Different collaborations, predictions usually computed with different PDFs to extract an uncertainty envelope.

Impact of PDF uncertainties



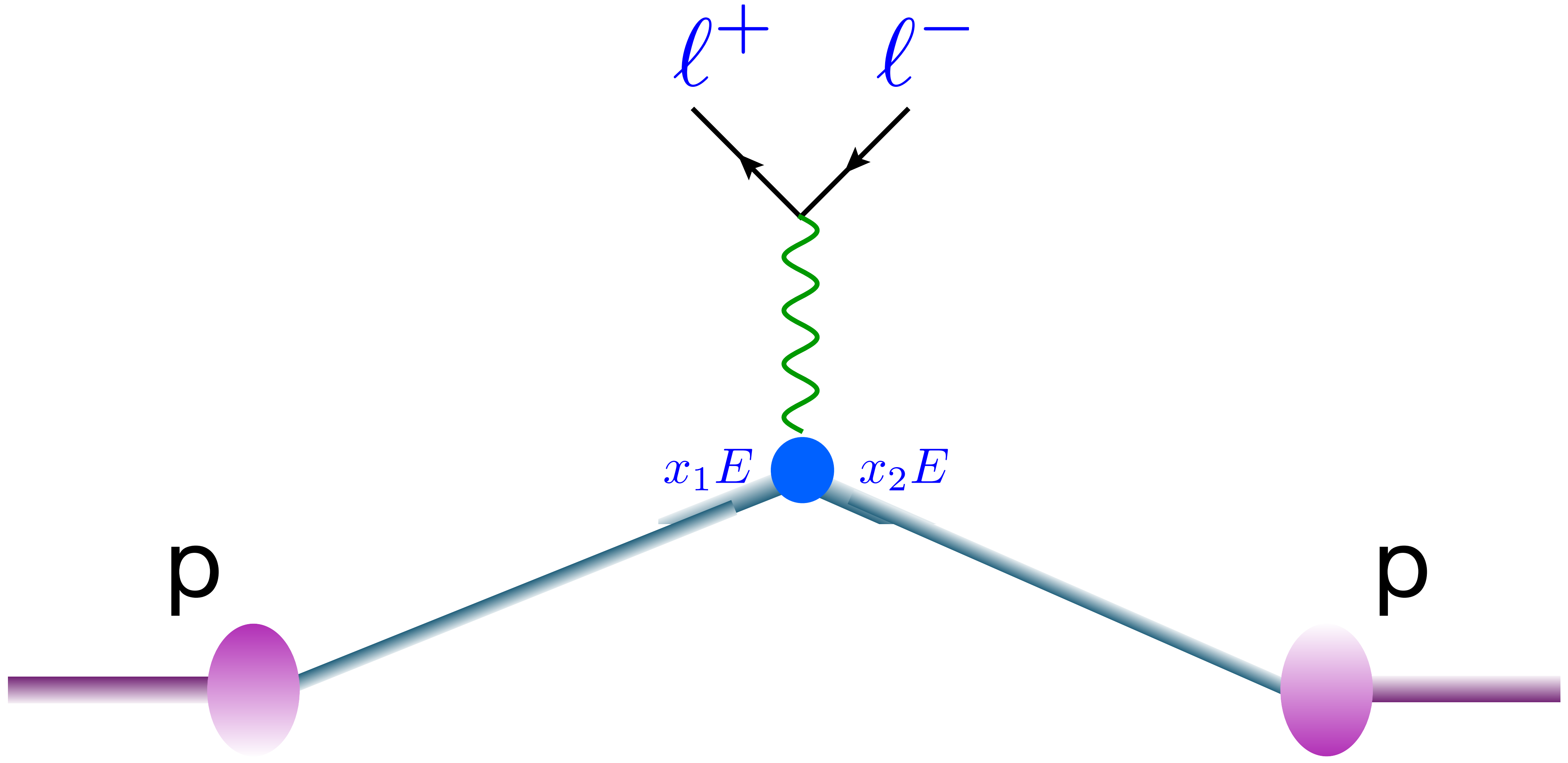
Yellow Report 3 (2013)

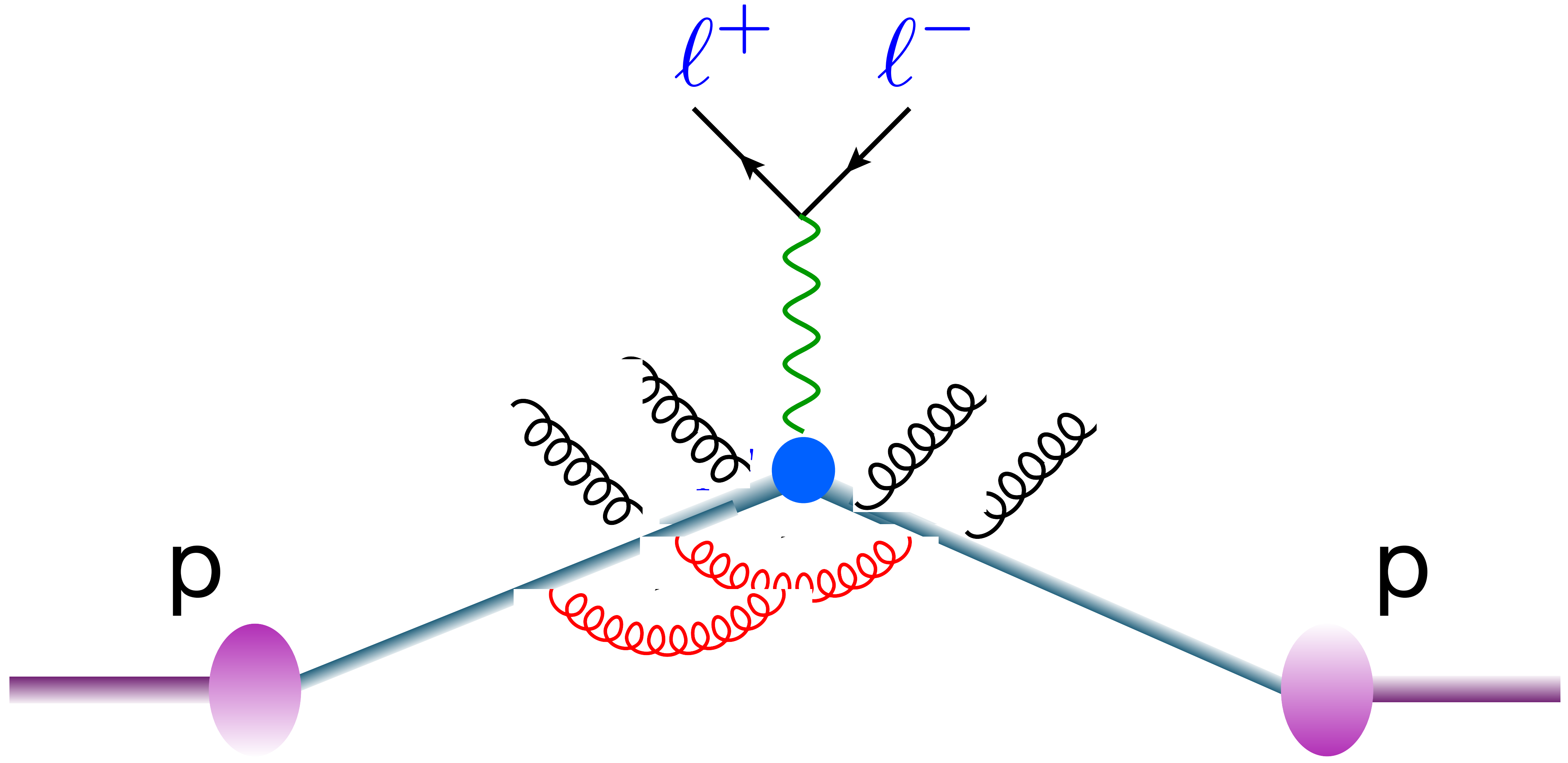


Yellow Report 4 (2016)

Progress in PDFs!

Fixed order computations



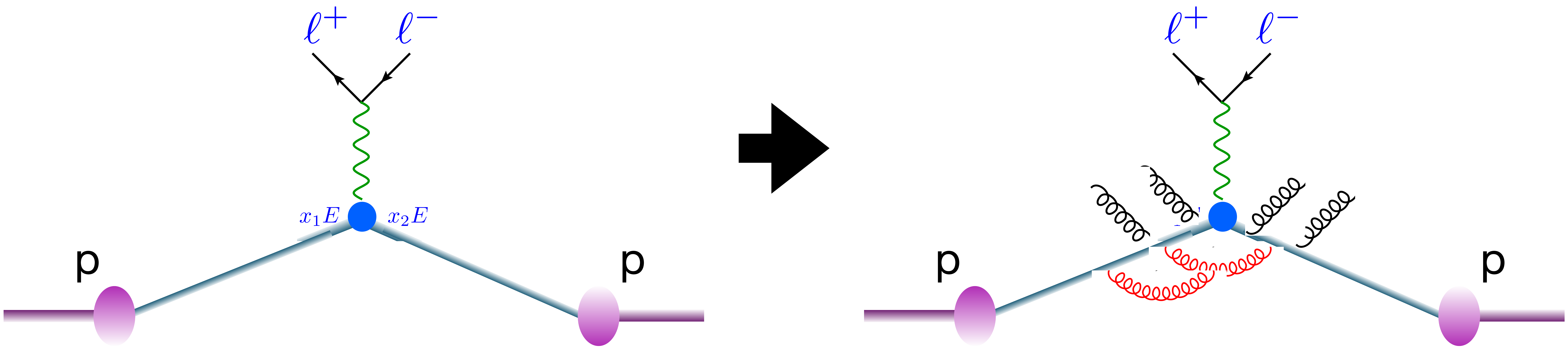


$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\text{FS}}\, f_a(x_1, \mu_F) f_b(x_2, \mu_F)\, \hat{\sigma}_{ab \to X}(\hat{s}, \mu_F, \mu_R)$$

$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \ldots \right)$$

LO NLO NNLO N3LO

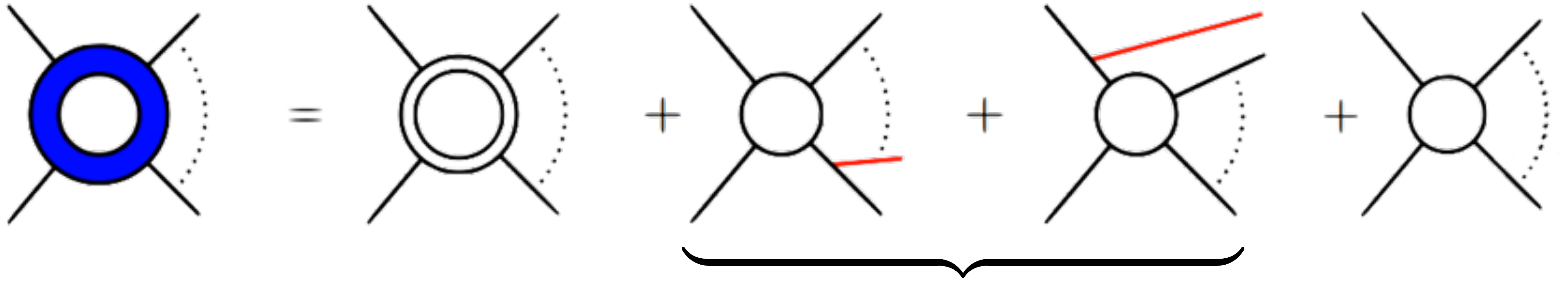
Fixed order computations



We need to add real and virtual corrections to the hard scattering dealing with singularities

Relatively straightforward at NLO (automated), complicated at NNLO (tens of processes), extremely hard at NNNLO (handful of processes known)

Structure of an NLO calculation



$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Virtual part — Real emission part — Born

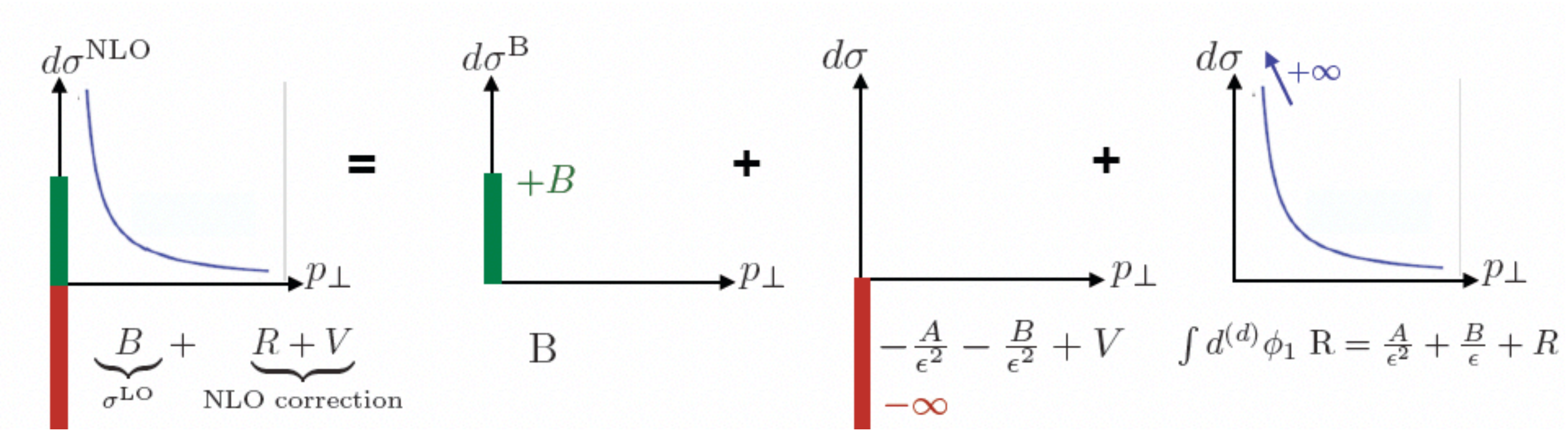
Difficulties:

- Loop calculations: tough and time consuming
- Divergences: Both real and virtual corrections are divergent
- More channels, more phase space integrations

Difficulty

How to deal with NLO in practice?

NLO corrections involve divergences: Divergences are bad for numerical computations



$$\sigma_{\text{NLO}} = \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\mathcal{V} + \int d\Phi^{(n+1)}\mathcal{R}$$

Subtraction:

$$= \int d\Phi^{(n)}\mathcal{B} + \int d\Phi^{(n)}\left[\mathcal{V} + \int d\Phi^{(1)} S\right] + \int d\Phi^{(n+1)}\left[\mathcal{R} - S\right]$$

finite finite

Subtraction techniques at NLO

Dipole subtraction

- Catani, Seymour hep-ph/9602277
- Automated in MadDipole, Sherpa, HELAC-NLO

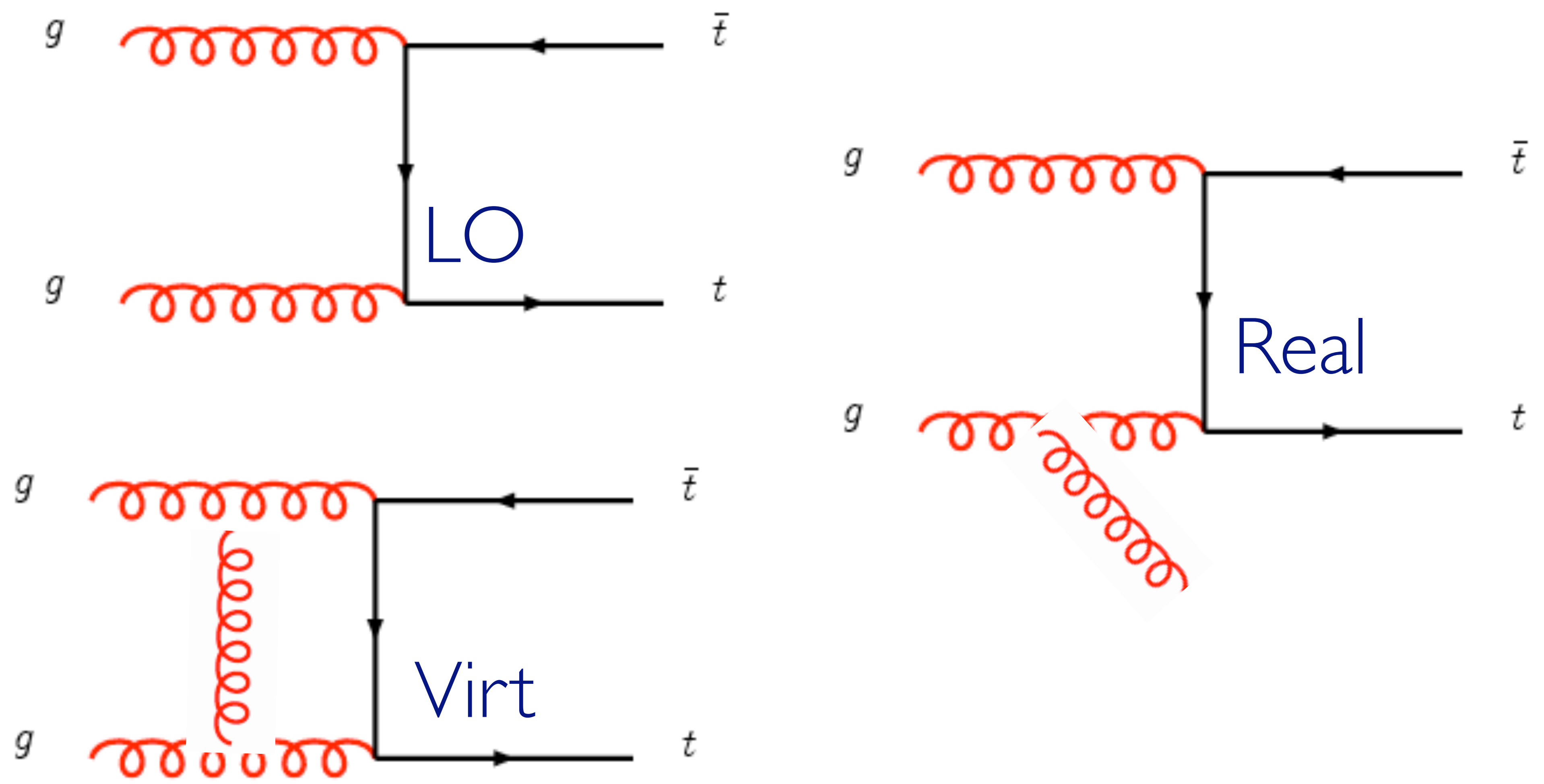
FKS subtraction

- Frixione, Kunszt, Signer hep-ph/9512328
- Automated in MadGraph5_aMC@NLO and Powheg/Powhel

Detailed discussion of these could be another lecture course!

A note about NLO

Example: top pair production



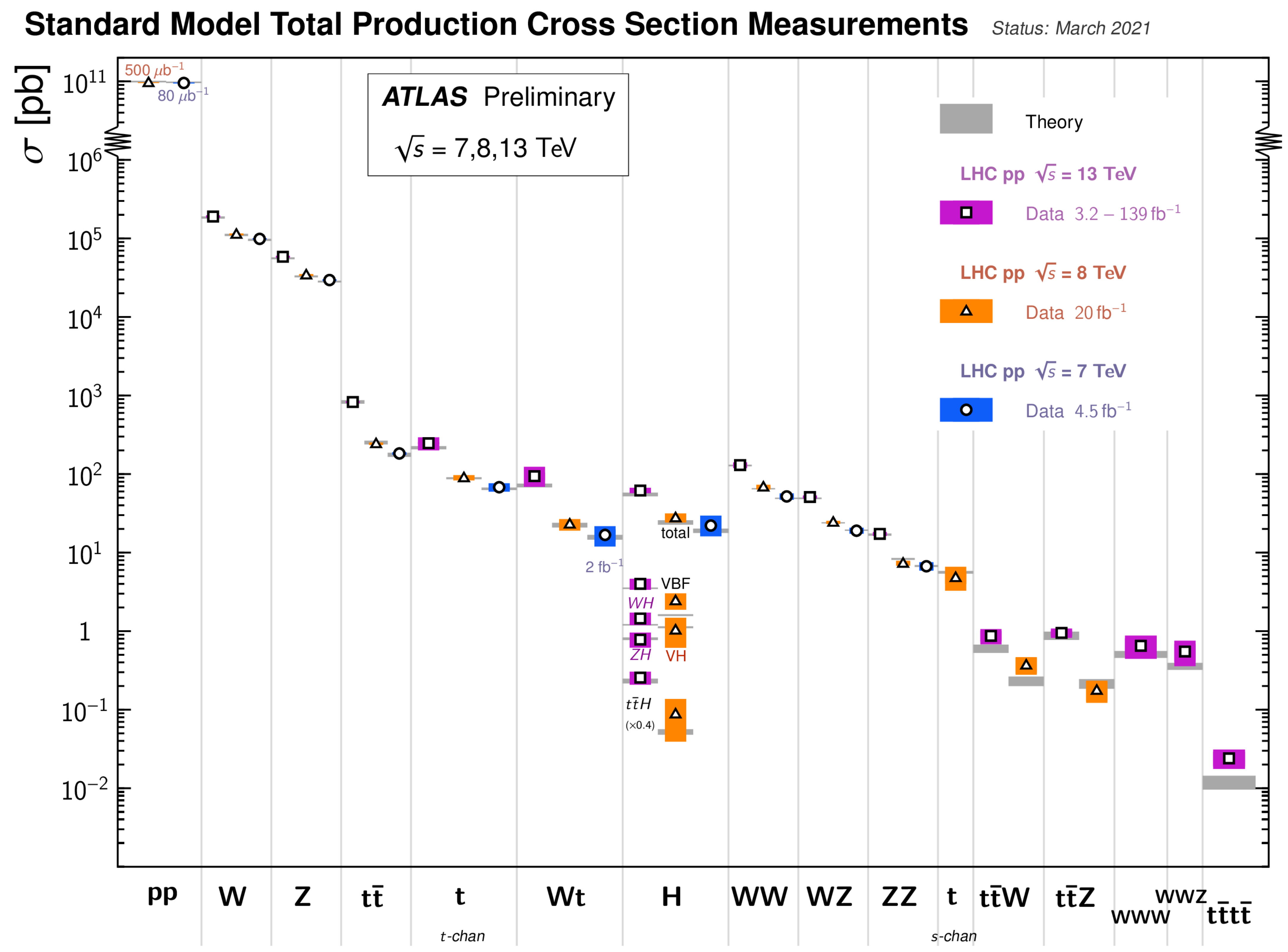
NLO

Which observables do we compute at NLO?

- Total cross-section ✓
- pT of a top quark ✓
- pT of top pair ✗
- pT of hardest jet ✗
- tt invariant mass ✓

It is certain observables which are computed at NLO

Need for higher-orders

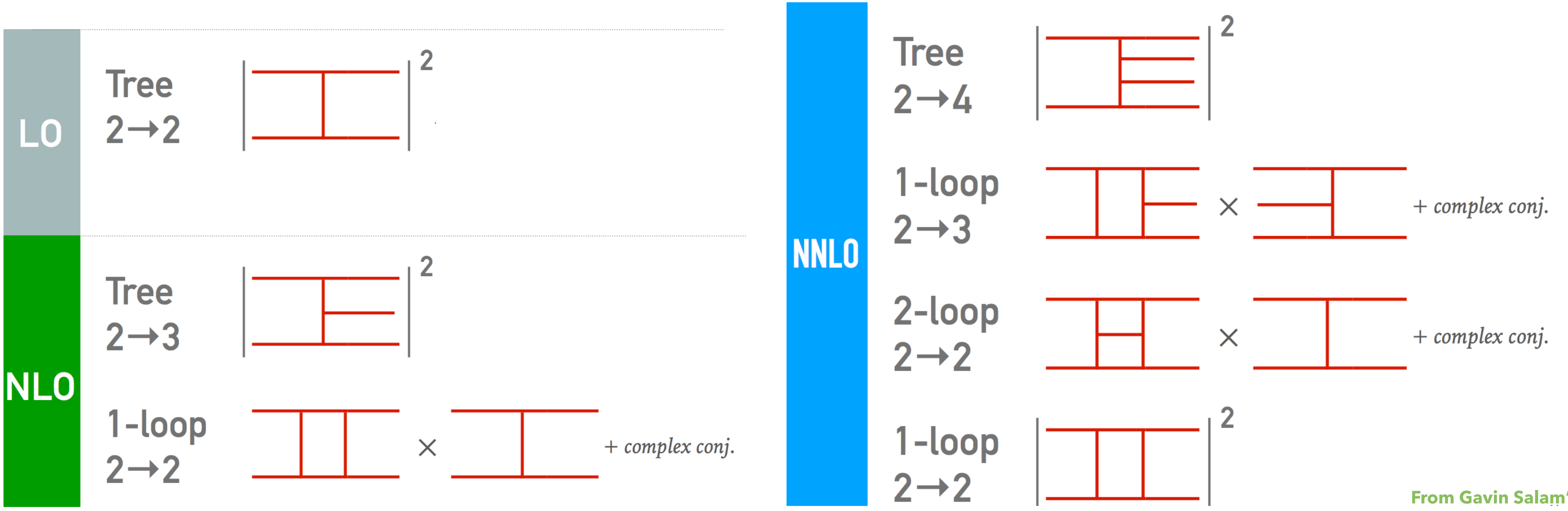


Reminder:

Level of experimental precision demands precise theoretical predictions

Theorists are not simply having fun!!!

Higher order computations



From Gavin Salam's lectures
Quy Nhon Vietnam 2018

Complexity rises a lot with each N!

Status of hard scattering cross-sections

LO automated

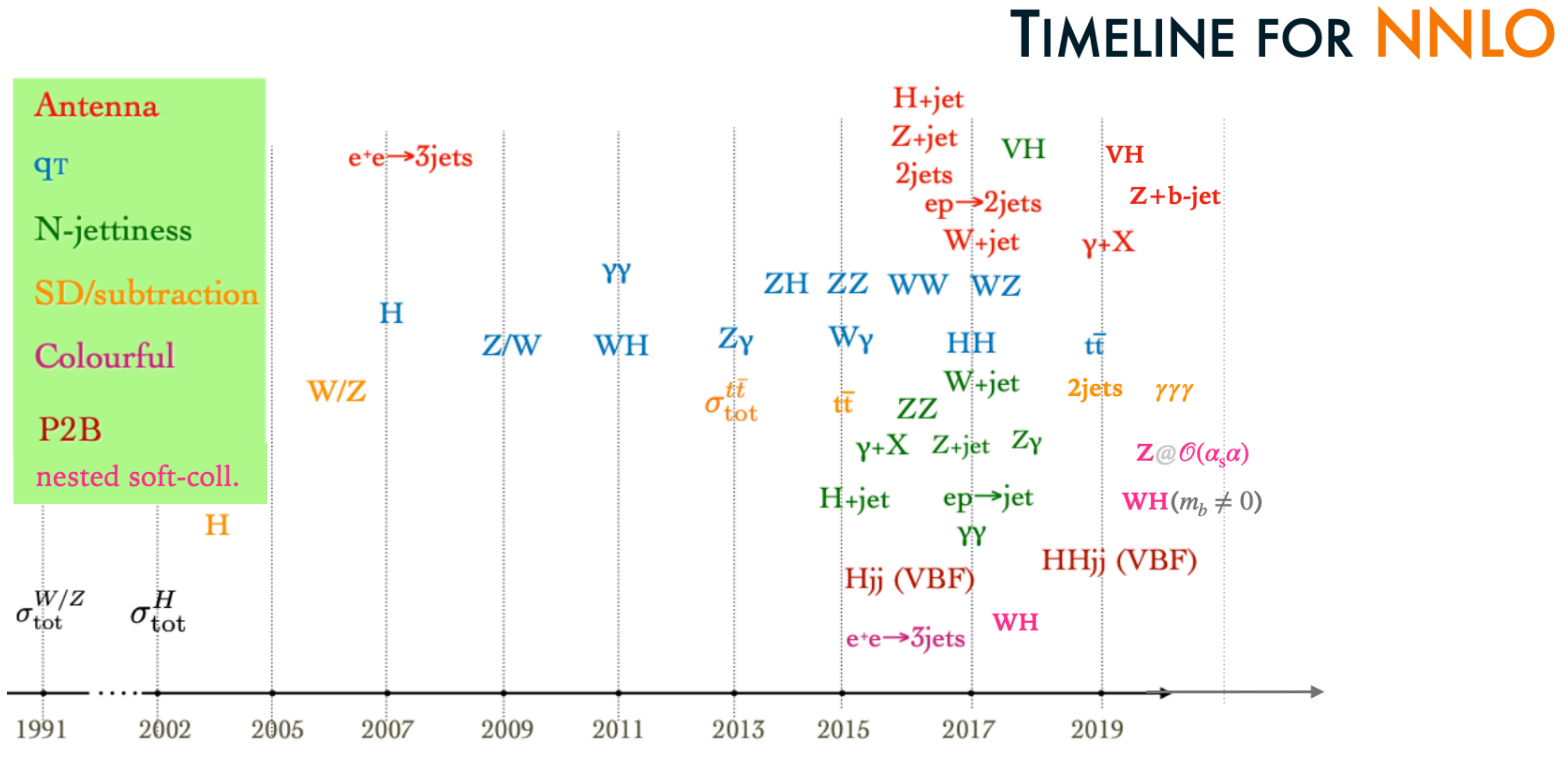
NLO automated

NNLO: Several processes known (VV production, top pair production, all $2 \to 1$ processes)

NNNLO: only a handful of processes!

- Higgs in gluon fusion (Anastasiou et al, arXiv:1602.00695)
- Higgs in VBF (Dreyer et al, arXiv:1811.07906)
- Higgs in bottom annihilation (Duhr et al, arXiv:1904.09990)
- Drell-Yan (Duhr et al, arXiv:2001.07717, 2007.13313)

Progress in higher-order computations

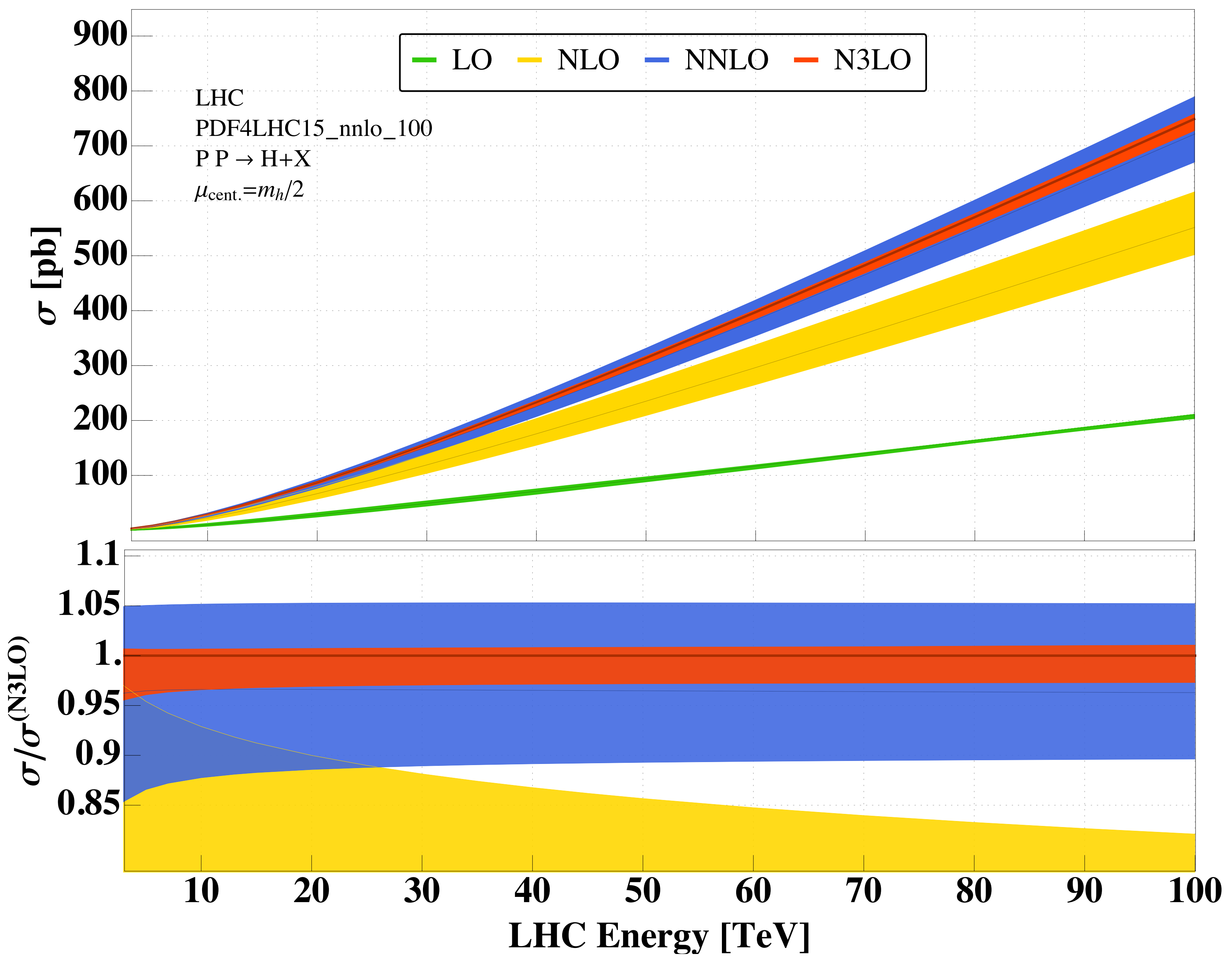


A. Huss, QCD@LHC-X 2020

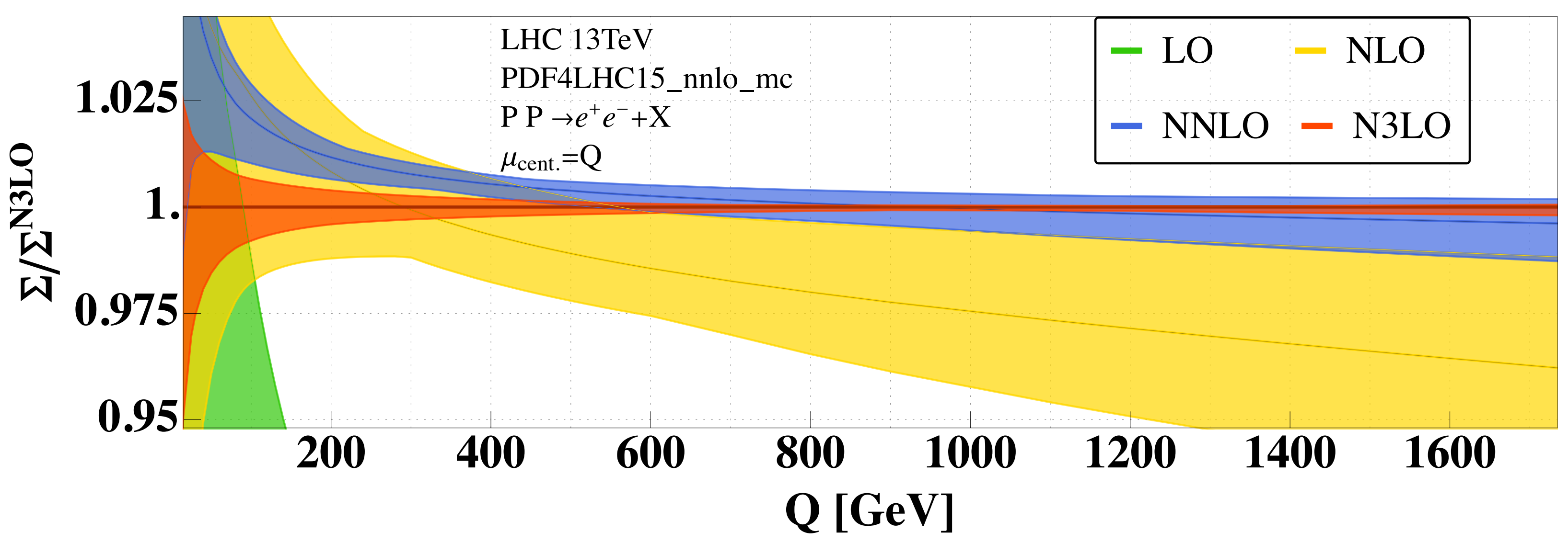
Hard scattering cross-section

$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \dots \right)$$

LO NLO NNLO N3LO



Improved accuracy and precision



Dilepton production

Higgs production arXiv:2203.06730

Uncertainties in theory predictions

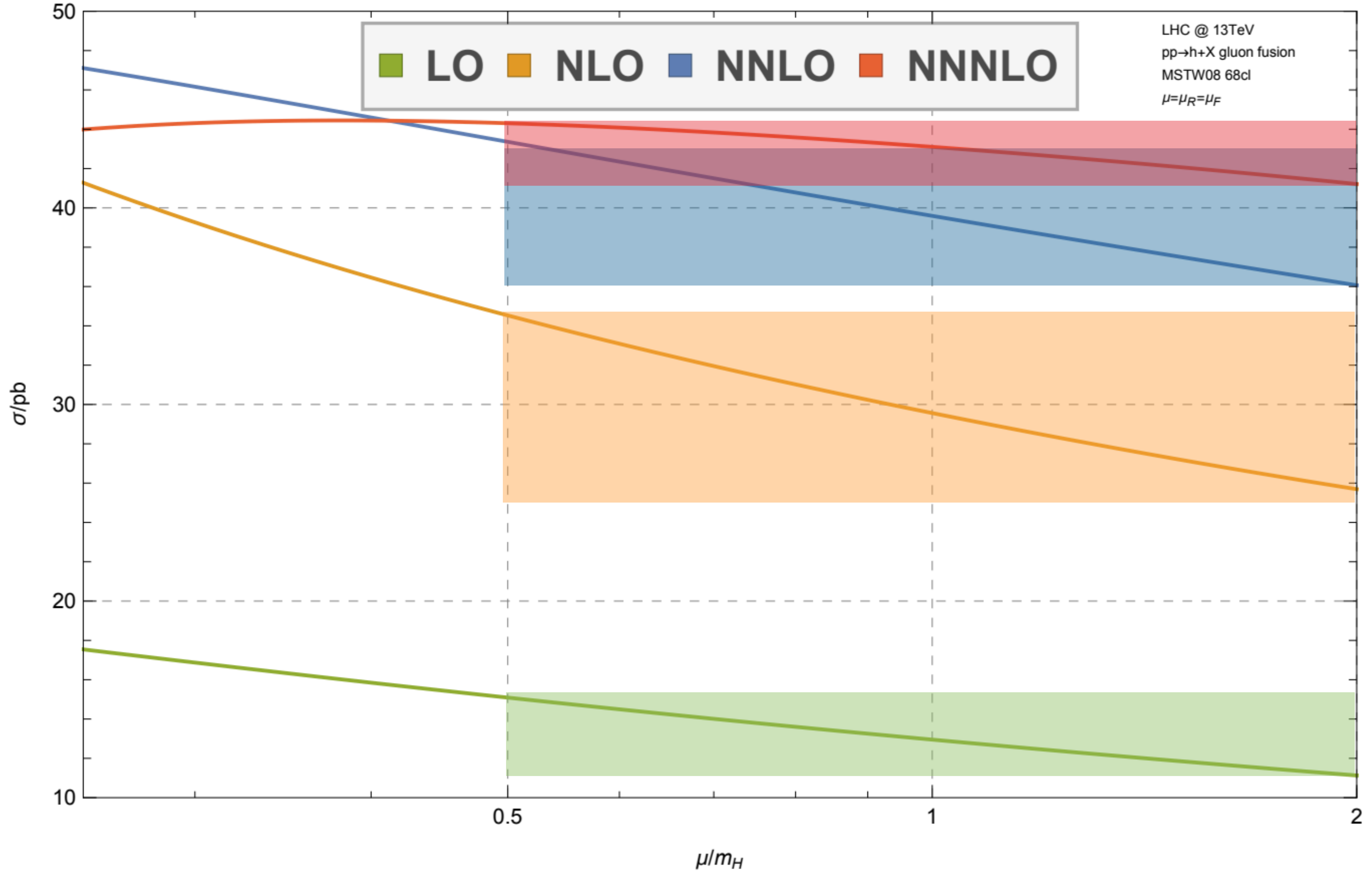
All order result should be μ independent

How do we estimate uncertainties?

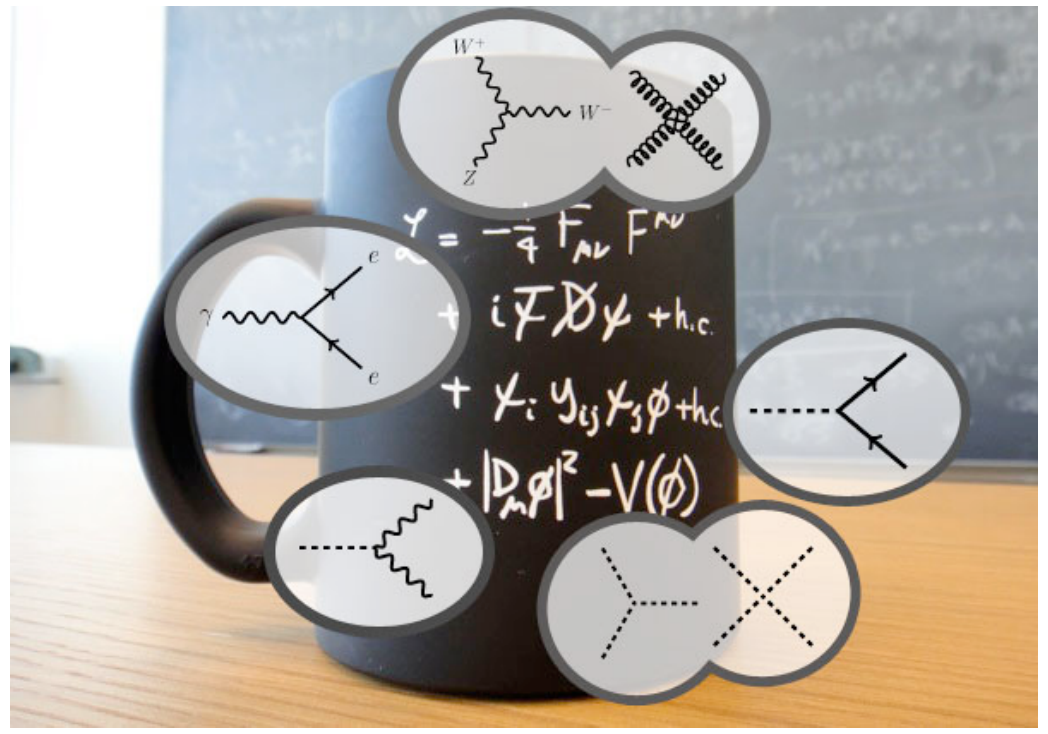
Vary the renormalisation and factorisation scale

Typically pick some central scale μ_0 and vary the scale up and down by a factor of 2

Aim to capture unknown higher order corrections, not exact science!



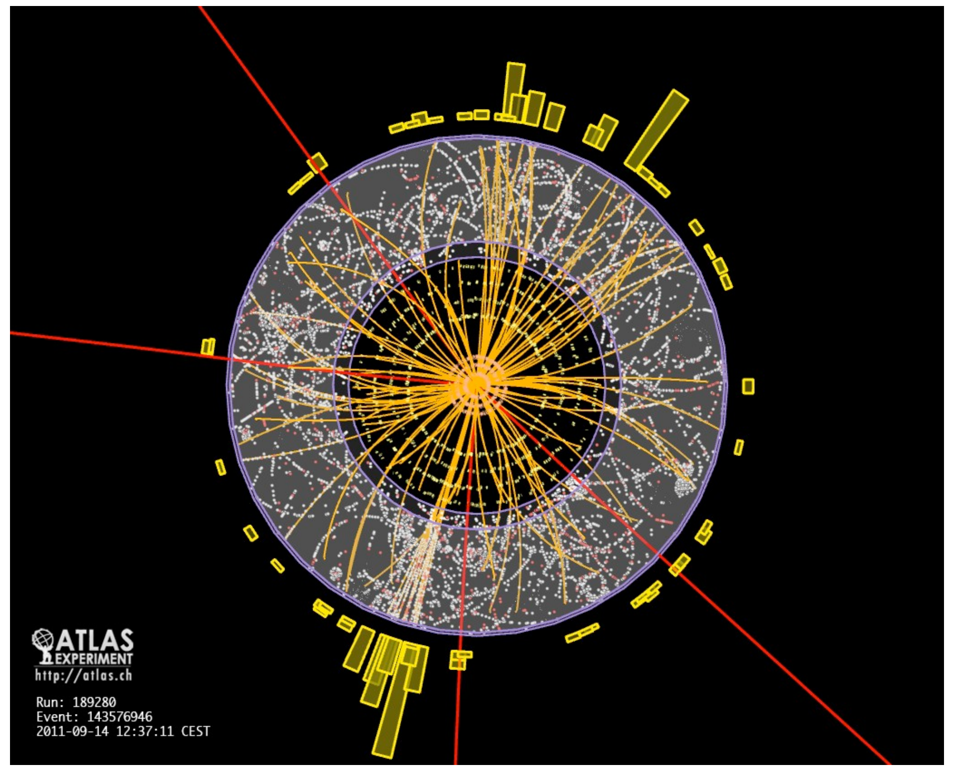
How do we actually compute all of these?



Theory

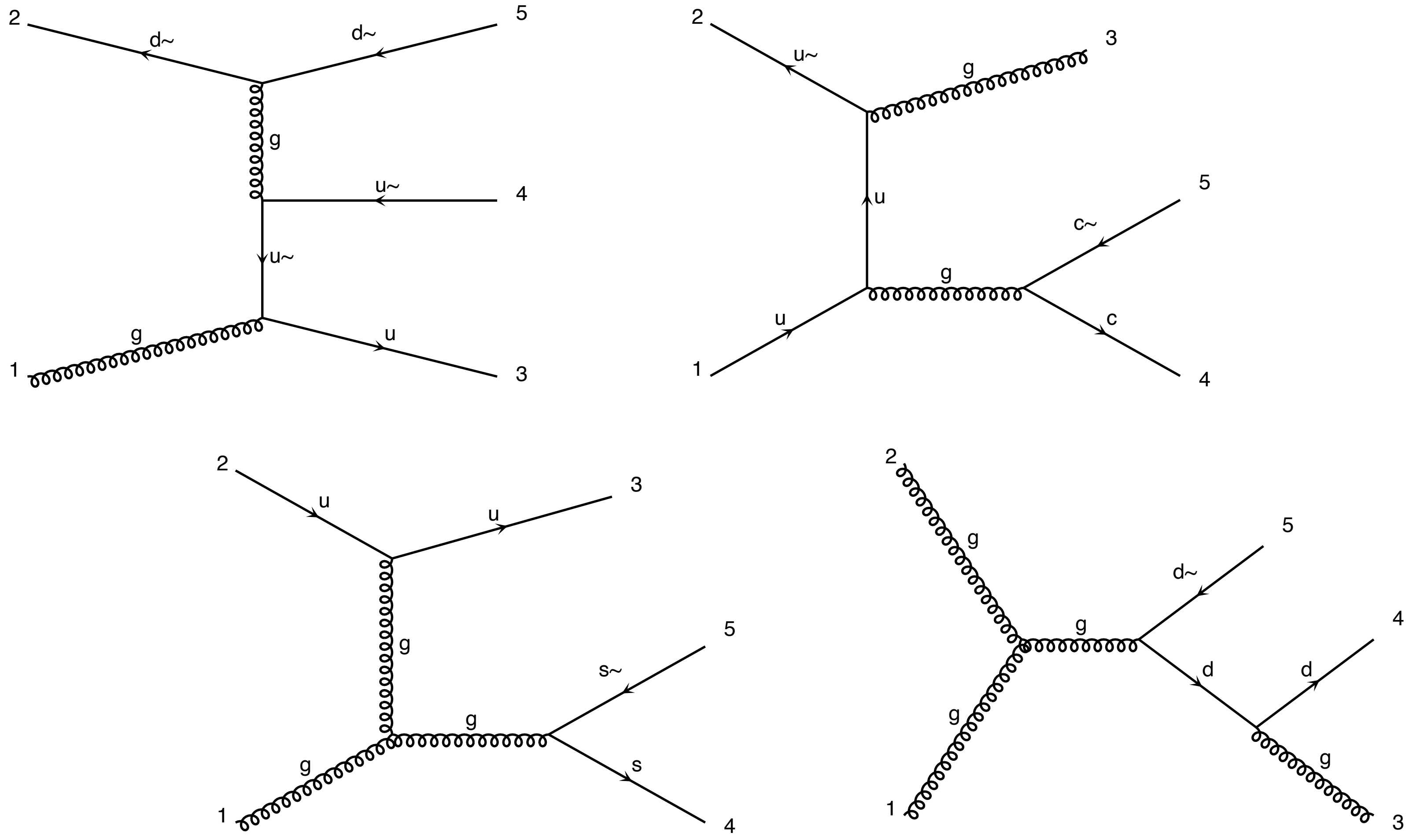
Monte Carlo

Experiment



Focusing on LO

Example: 3 jet production in pp collisions



1. Know the Feynman rules (SM or BSM)
2. Find all possible Subprocesses

97 processes with 781 diagrams generated in 2.994 s

Total: 97 processes with 781 diagrams

3. Compute the amplitude
4. Compute $|M|^2$ for each subprocess, sum over spin and colour
5. Integrate over the phase space

$$\sigma = \frac{1}{2s}\int |\mathcal{M}|^2 d\Phi(n)$$

LO calculation of a cross-section

How many subprocesses?

Amplitude computation (Feynman diagrams)

Square the amplitude, sum over spin and colour

Integrate over the phase space

Difficulty

Complexity increases with

- number of particles in the final state
- number of Feynman diagrams for the process (typically organise these in terms of leading couplings: see tutorial)

Structure of an automated MC generator

I. Input Feynman rules
II. Define initial and final state
III. Automatically find all subprocesses
IV. Compute matrix element (including tricks like helicity amplitudes)
V. Integrate over the phase space by optimising the PS parametrisation and sampling
VI. Unweight and write events in the Les Houches format

Next: Shower+Hadronisation
Detector simulation and reconstruction

Output of LO MC generators

Example: gg>ZZ

LHE event format

```
<event>
 4      0 +1.1211000e+00 1.89058500e+02 7.81859000e-03 1.15931300e-01
       21 -1    0    0  502  501 +0.0000000000e+00 +0.0000000000e+00 +4.6570159241e+01 4.6570159241e+01 0.0000000000e+00 0.0000e+00 1.0000e+00
       21 -1    0    0  501  502 -0.0000000000e+00 -0.0000000000e+00 -1.9187776299e+02 1.9187776299e+02 0.0000000000e+00 0.0000e+00 1.0000e+00
       23  1    1    2    0    0 +1.3441082214e+01 +1.3065682927e+01 -5.1959303141e+01 1.0661295577e+02 9.1187600000e+01 0.0000e+00 1.0000e+00
       23  1    1    2    0    0 -1.3441082214e+01 -1.3065682927e+01 -9.3348300610e+01 1.3183496646e+02 9.1187600000e+01 0.0000e+00 1.0000e+00
</event>
```

PDG Momenta Mass

All Information needed to pass to parton shower is included in the event

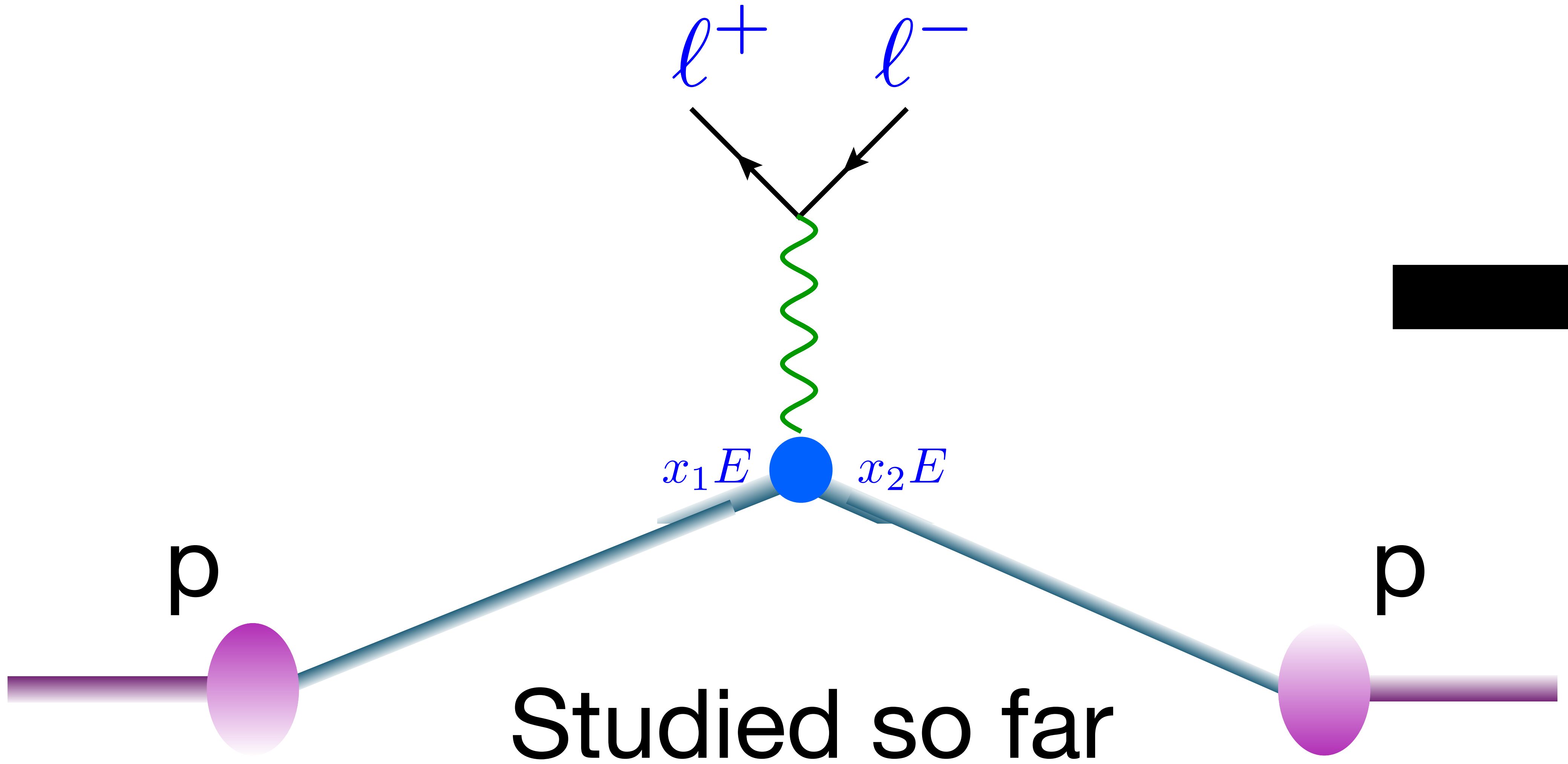
Available public MC generators

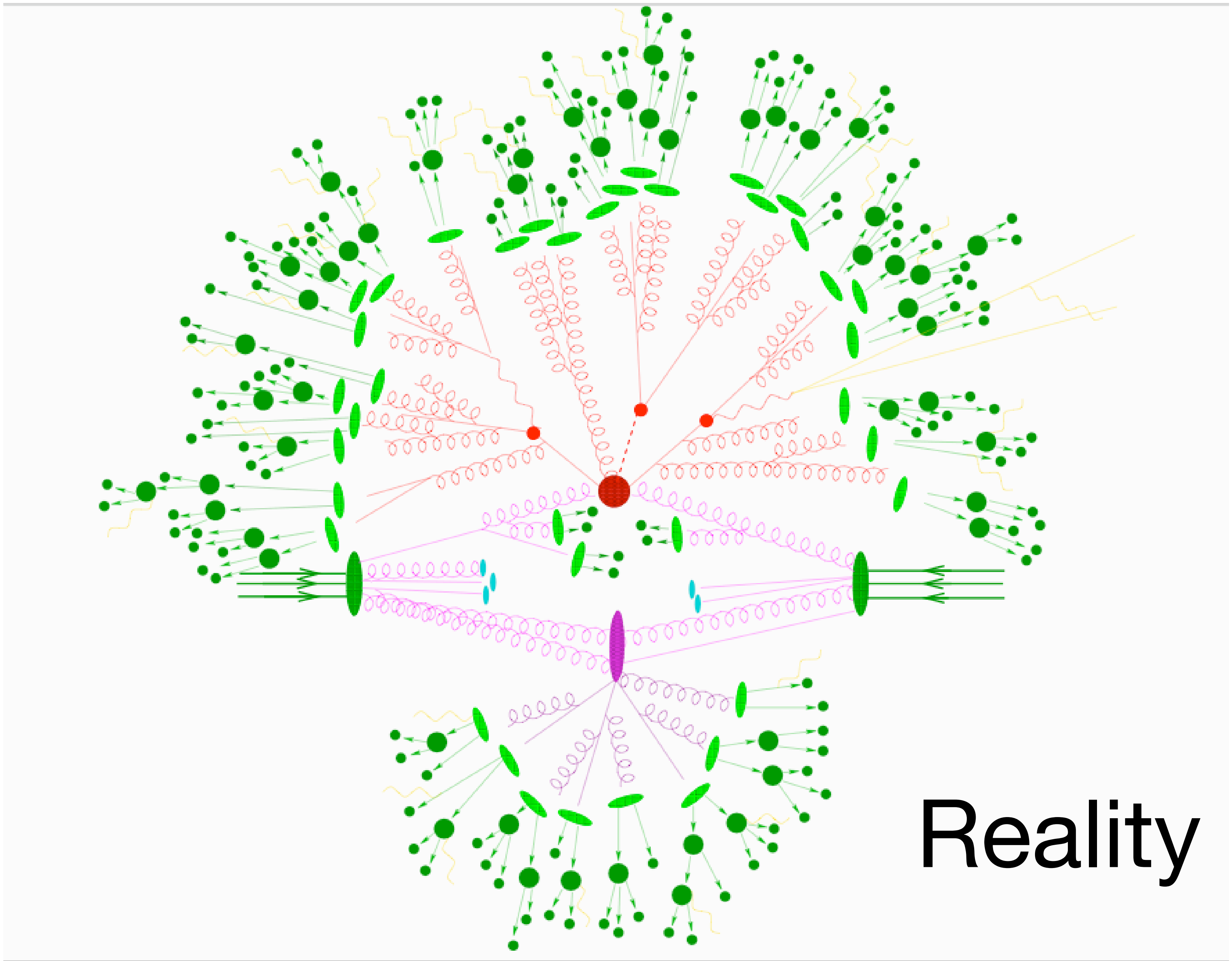
Matrix element generators (and integrators):

- MadGraph/MadEvent
- Comix/AMEGIC (part of Sherpa)
- HELAC/PHEGAS
- Whizard
- CalcHEP/CompHEP

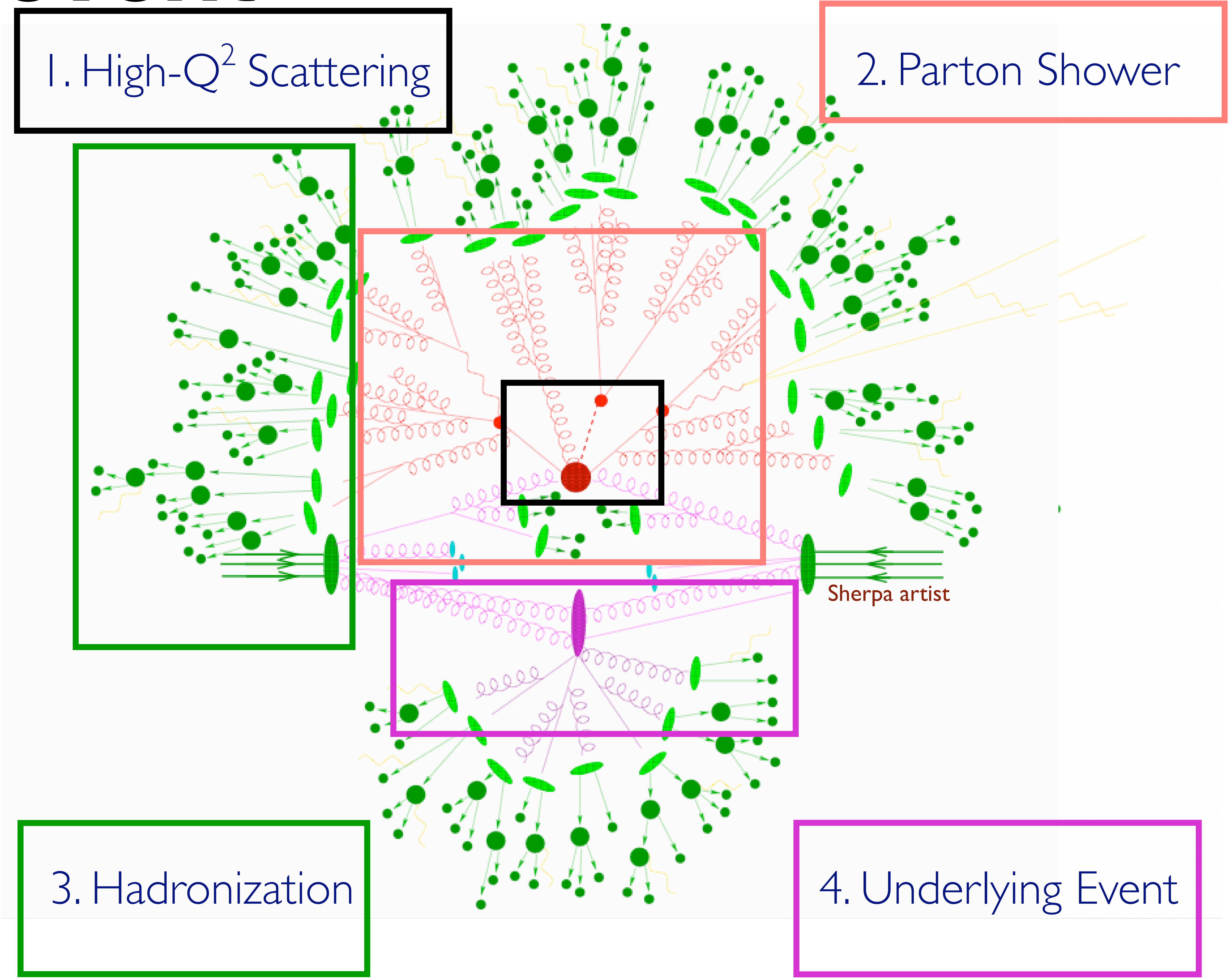
Is Fixed Order enough?

Fixed order computations can't give us the full picture of what we see at the LHC



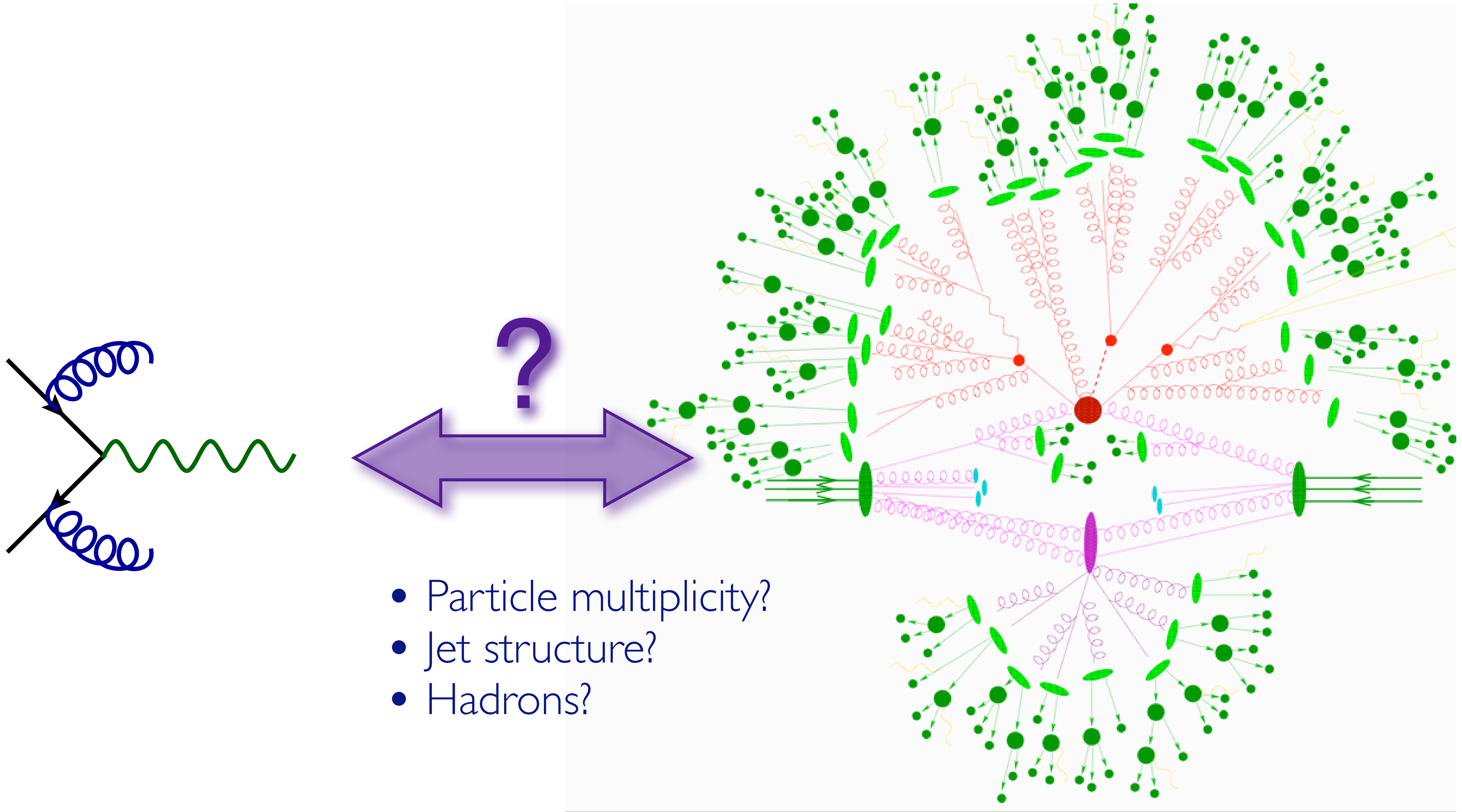


An LHC event



1. High-Q^2 Scattering
2. Parton Shower
3. Hadronization
4. Underlying Event
Sherpa artist

Is fixed order enough?



- Fixed order calculations involve only a few partons
- Not what we see in detectors
- Need Shower and Hadronisation

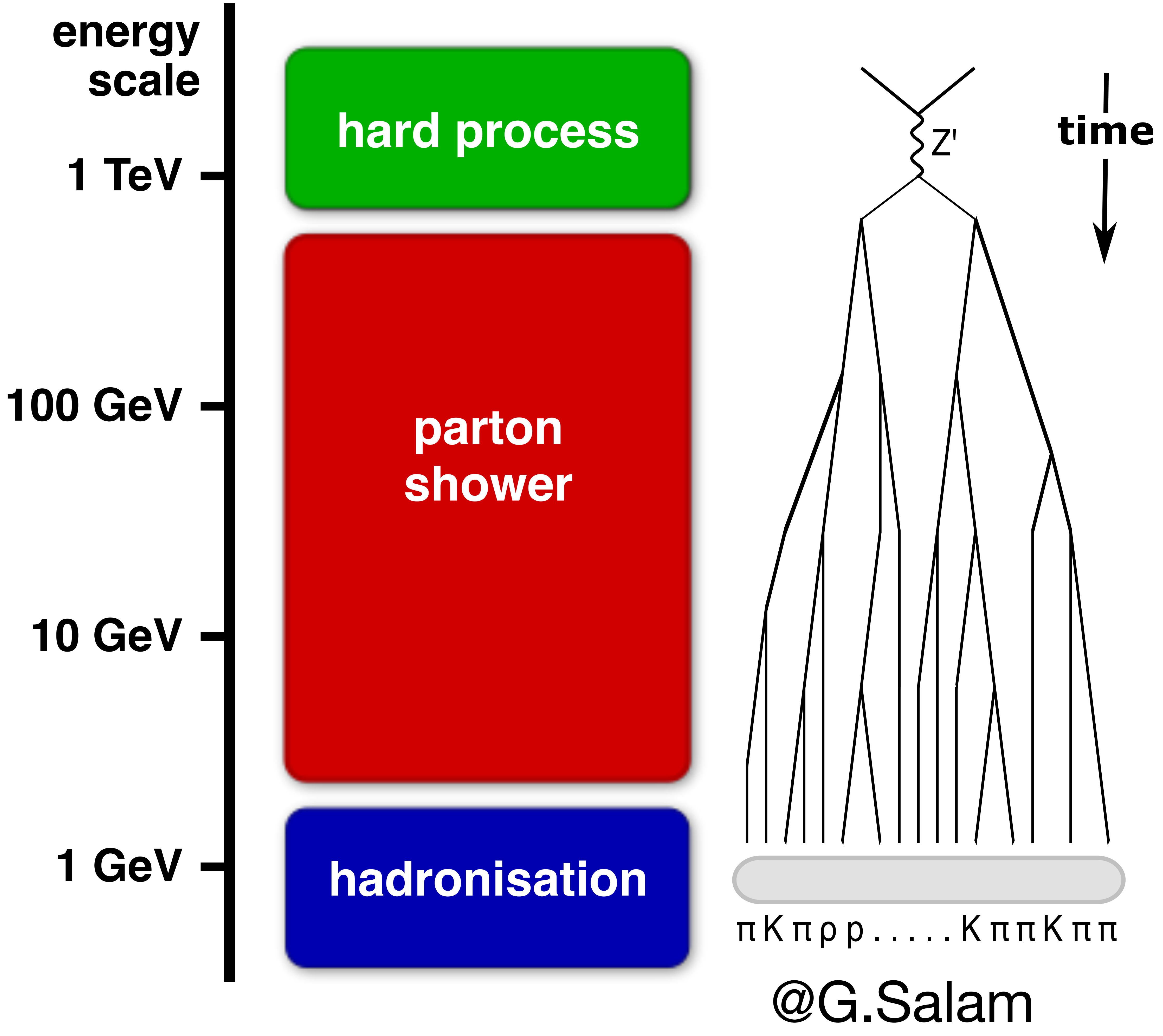
A multiscale story

High-Q^2 scattering: process dependent, systematically improvable with higher order corrections, where we expect new physics

Parton Shower: QCD, universal, soft and collinear physics

Hadronisation: low Q^2, universal, based on different models

Underlying event: low Q^2, involves multiple interactions



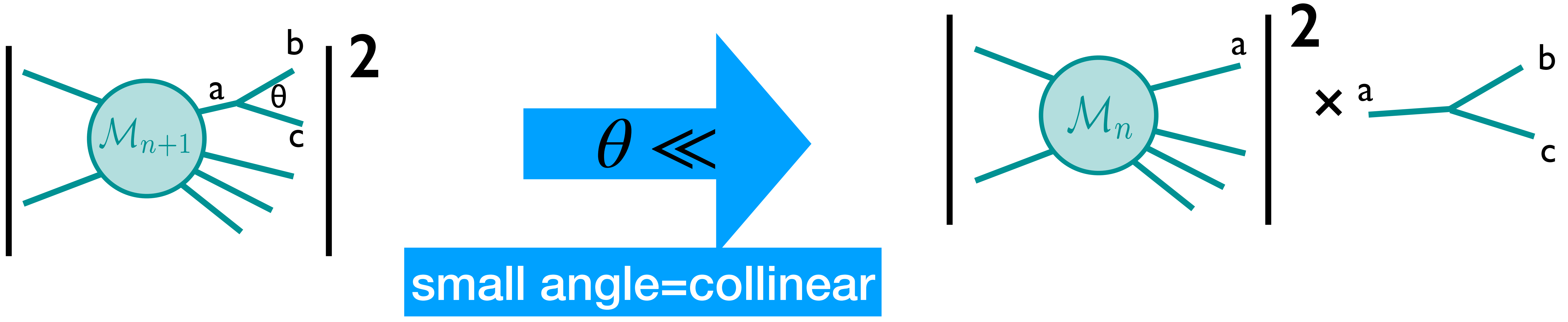
Parton Shower

- Dress partons with radiation with an arbitrary number of branchings
- Preserve the inclusive cross-section: unitary
- Needs to evolve in scale from Q~1TeV (hard scattering) down to ~GeV
- ..at which point hadronisation takes place

Basics of parton shower

Factorisation!

Starting with one splitting



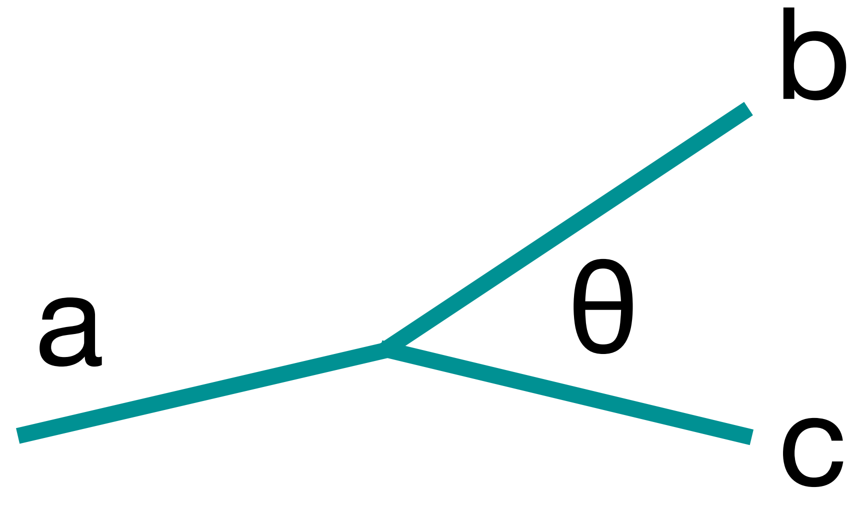
- Time scale associated with splitting much longer than the one of the hard scattering
- This kind of splitting should be described by a branching probability
- The parton shower will quantify the probability of emission

Collinear factorisation:

$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \;\simeq\; |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

Collinear factorisation and splitting functions

$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \simeq |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$



- t is the evolution variable
  - t tends to zero in the collinear limit (this factor is singular)
- z energy fraction transferred from parton a to parton b in splitting ($z \to 1$ in the soft limit)
- ϕ azimuthal angle

The branching probability has the same form for all quantities $\propto \theta^2$

- transverse momentum $k_\perp \sim z^2(1-z)^2\theta^2E^2$
- invariant mass $Q^2 \sim z(1-z)\theta^2E^2$

$$\frac{d\theta^2}{\theta^2} = \frac{dk_\perp^2}{k_\perp^2} = \frac{dQ^2}{Q^2}$$

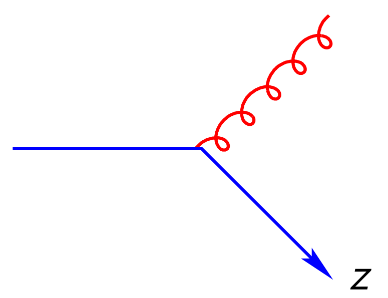
$$t \in \{\theta^2, k_\perp^2, Q^2\}$$

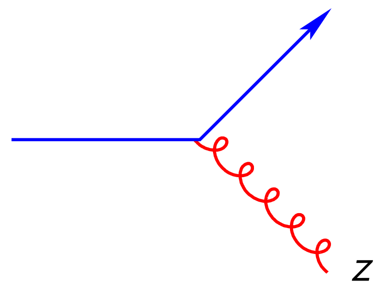
Altarelli-Parisi Splitting functions

Branching has a universal form given by the Altarelli-Parisi splitting functions (as we saw in DIS)

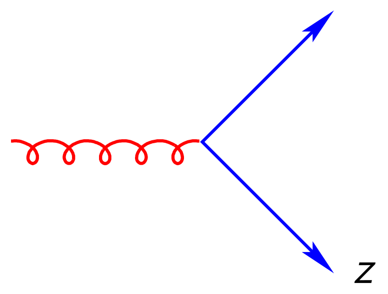
$$\frac{dt}{t}dz\frac{d\phi}{2\pi}\frac{\alpha_S}{2\pi}P_{a\to bc}(z)$$

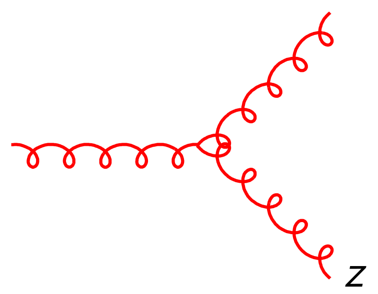
$$P_{q\to qg}(z) = C_F\left[\frac{1+z^2}{1-z}\right], \qquad P_{q\to gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right].$$





$$P_{g\to qq}(z) = T_R\left[z^2+(1-z)^2\right], \qquad P_{g\to gg}(z) = C_A\left[z(1-z)+\frac{z}{1-z}+\frac{1-z}{z}\right]$$



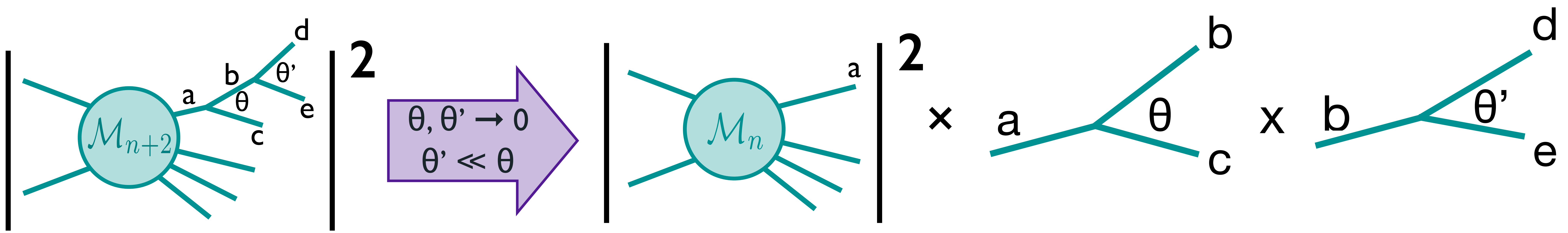


These functions are universal for each type of splitting

Plan for the lectures

- Basics of collider physics
- Basics of QCD
    - DIS and the Parton Model
    - Higher order corrections
    - Asymptotic freedom
    - QCD improved parton model
- State-of-the-art computations for the LHC
- Monte Carlo generators
    - Parton Shower
    - Hadronisation
- Jet algorithms
- Aspects of LHC phenomenology
    - Higgs phenomenology
    - Top phenomenology
    - Searching for New Physics: EFT

Multiple emissions



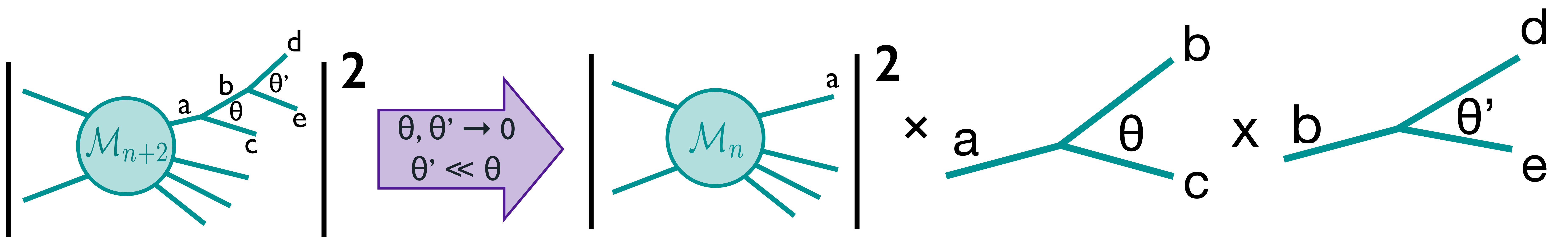
$$|\mathcal{M}_{n+2}|^2 d\Phi_{n+2} \;\simeq\; |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z) \;\times \frac{dt'}{t'} dz' \frac{d\phi'}{2\pi} \frac{\alpha_S}{2\pi} P_{b\to de}(z')$$

We can generalise this for an arbitrary number of emissions

Iterative sequence of emissions which does not depend on the history (Markov Chain)

➡ **No interference: Classical**

Multiple emissions



Dominant contribution comes from subsequent emissions which satisfy strong ordering $\theta \gg \theta' \gg \theta''$

For k emissions the rate takes the form:

$$\sigma_{n+k} \propto \alpha_S^k \int_{Q_0^2}^{Q^2} \frac{dt}{t} \int_{Q_0^2}^{t} \frac{dt'}{t'} \ldots \int_{Q_0^2}^{t^{(k-2)}} \frac{dt^{(k-1)}}{t^{(k-1)}} \propto \sigma_n \left(\frac{\alpha_S}{2\pi}\right)^k \log^k(Q^2/Q_0^2)$$

- Q is the hard scale and Q_0 is an infrared cut off (separating non-perturbative regime)
- Each power of α_s comes with a logarithm (breakdown of perturbation theory when large)

Basics of PS

- Collinear factorisation allows subsequent branchings from the hard process scale down to the non-perturbative regime
- Different legs and subsequent emissions are uncorrelated
- No interference effects
- Captures leading contributions
  - Resummed calculation
  - Bridge between fixed order and hadronisation

Sudakov form factor

We need to take the survival probability into account, i.e. a parton can split at scale t if it has not branched at $t' > t$

The probability of branching between scale t and $t + dt$ (with no emission before) is:

$$dp(t) = \sum_{bc} \frac{dt}{t} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

The no-splitting probability between scale t and $t + dt$ is $1 - dp(t)$

The probability of no emission between Q^2 and t is:

$$\Delta(Q^2, t) = \prod_k \left[1 - \sum_{bc} \frac{dt_k}{t_k} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] =$$

$$\exp\left[-\sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] = \exp\left[-\int_t^{Q^2} dp(t')\right]$$

Sudakov form factor

$$\text{Sudakov form factor} = \text{No emission probability}$$

Sudakovs

The Sudakov is used to create the branching tree of a parton

The probability of k ordered splittings from a leg at given scale is

$$\begin{aligned}
dP_1(t_1) &= \Delta(Q^2, t_1)\; dp(t_1)\Delta(t_1, Q_0^2), \\
dP_2(t_1, t_2) &= \Delta(Q^2, t_1)\; dp(t_1)\; \Delta(t_1, t_2)\; dp(t_2)\; \Delta(t_2, Q_0^2)\Theta(t_1 - t_2) \\
\ldots &= \ldots \\
dP_k(t_1, \ldots, t_k) &= \Delta(Q^2, Q_0^2) \prod_{l=1}^{k} dp(t_l)\Theta(t_{l-1} - t_l)
\end{aligned}$$

The shower selects the t_i scales for the splitting randomly but weighted with no emission probability (before or after)

Unitarity

The parton shower is unitary. Sum of all possibilities should be 1.

Probability of k ordered splittings:

$$dP_k(t_1, ..., t_k) \quad = \quad \Delta(Q^2, Q_0^2) \prod_{l=1}^{k} dp(t_l)\Theta(t_{l-1} - t_l)$$

Integrating this gives us:

$$P_k \equiv \int dP_k(t_1, ..., t_k) = \Delta(Q^2, Q_0^2) \frac{1}{k!} \left[\int_{Q_0^2}^{Q^2} dp(t) \right]^k , \quad \forall k = 0, 1, ...$$

Summing over all possible numbers of emissions (0 to ∞):

$$\sum_{k=0}^{\infty} P_k = \Delta(Q^2, Q_0^2) \sum_{k=0}^{\infty} \frac{1}{k!} \left[\int_{Q_0^2}^{Q^2} dp(t) \right]^k = \Delta(Q^2, Q_0^2) \exp \left[\int_{Q_0^2}^{Q^2} dp(t) \right] = 1$$

Probability is conserved ✓

Evolution parameter in parton shower

A parton shower is constructed:

- Within the simplest collinear approximation, the splitting functions are universal, and fully factorised from the "hard" cross section
- Within the simplest approximation, decays are independent (apart from being ordered in a decreasing sequence of scales)

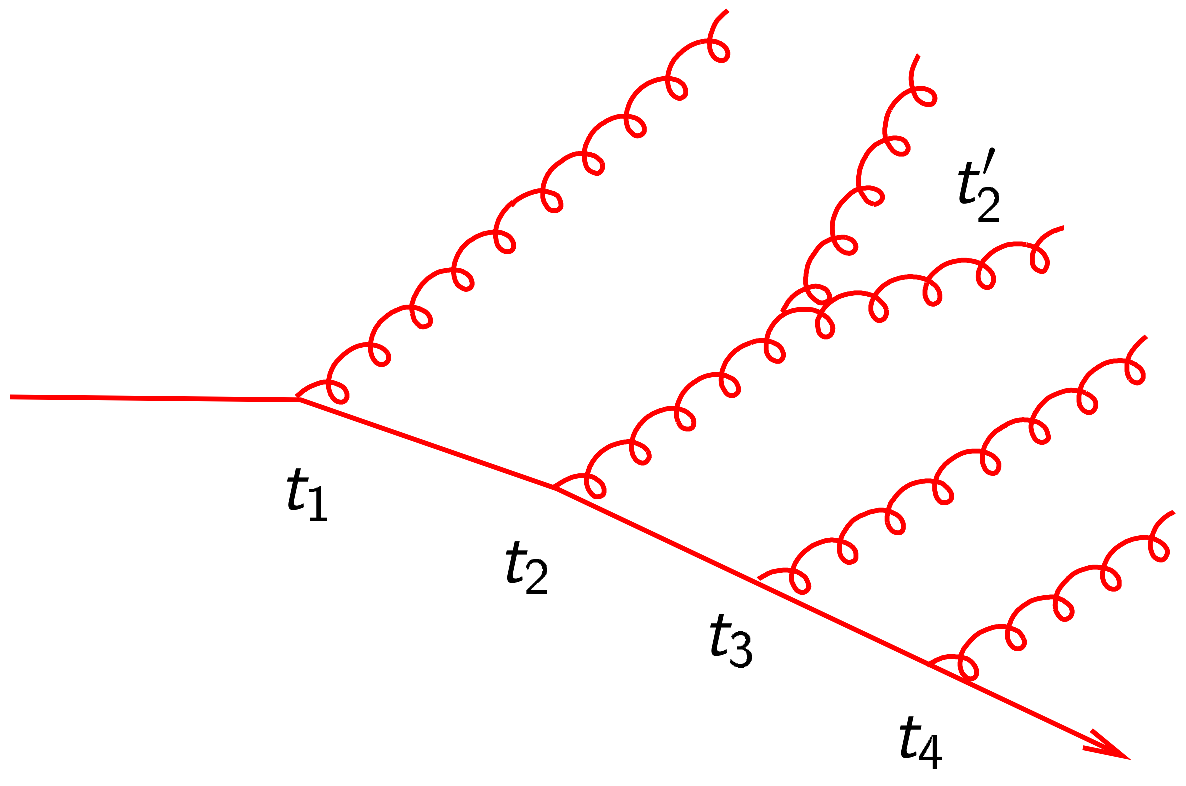
Other variables can be used as evolution parameter:

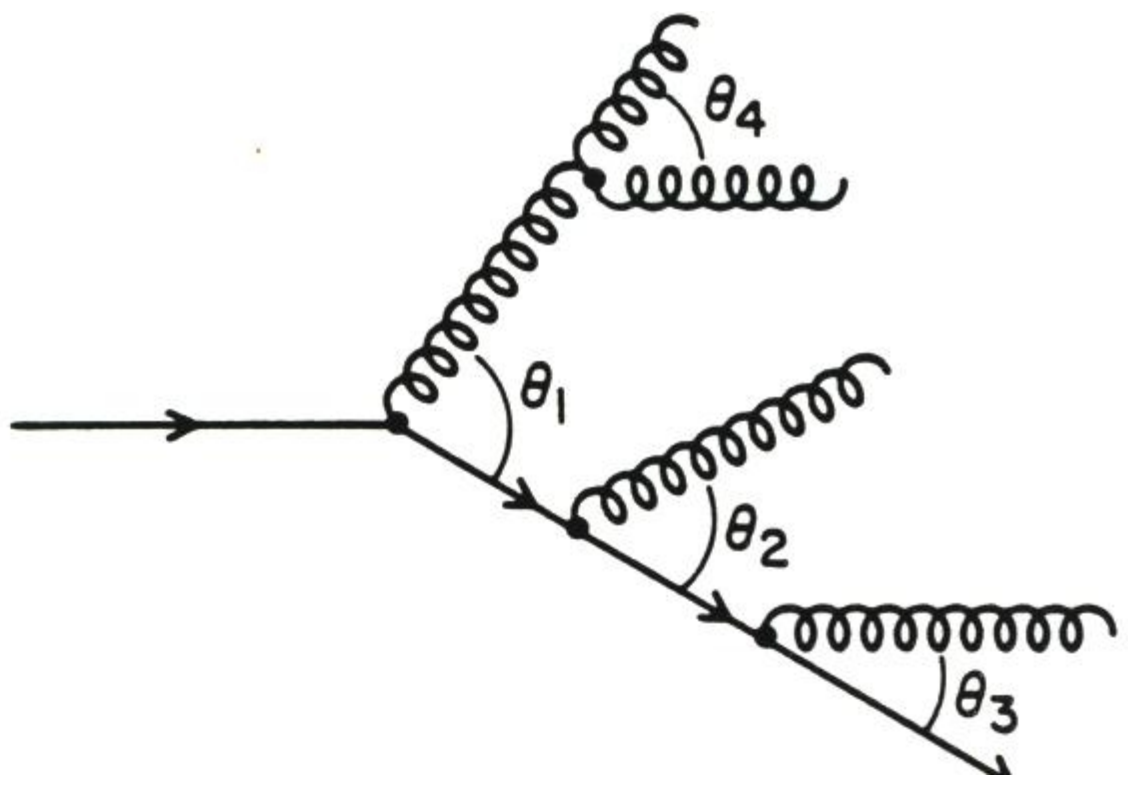
$$\frac{d\theta^2}{\theta^2} \sim \frac{dQ^2}{Q^2} \sim \frac{dp_\perp^2}{p_\perp^2} \sim \frac{d\tilde{q}^2}{\tilde{q}^2} \sim \frac{dt}{t}$$

- θ: HERWIG
- Q^2: PYTHIA ≤ 6.3, SHERPA.
- $p_\perp$: PYTHIA ≥ 6.4, ARIADNE, Catani–Seymour showers.
- $\tilde{q}$: Herwig++.

Same collinear behaviour, differences in the soft limit

Ordered branchings





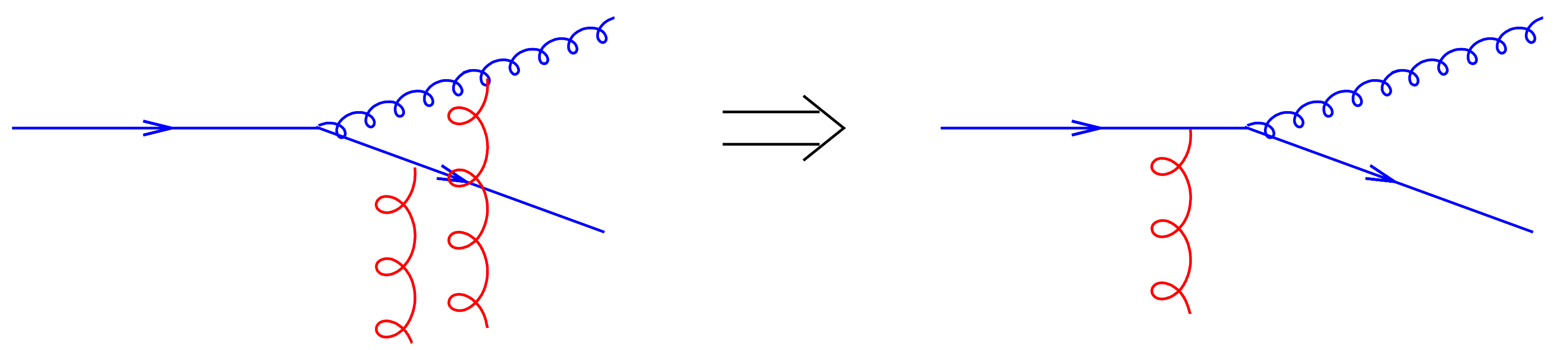
Shower is based on ordered splittings

$$t_1 \gg t_2 \gg t_3 \gg t_4 \text{ and } t_2 \gg t_2'$$

Emission with smaller and smaller angles

$$\theta_1 > \theta_2 > \theta_3 \qquad \theta > \theta_4$$

Note:



Inside the cones partons emit as independent charges, outside radiation is **coherent** as if coming directly from the initial colour charge

Hadronisation

- Colourless hadrons observed in detectors, not partons.
- Hadronisation describes creation of hadrons in QCD at low scales where $\alpha_s \sim \mathcal{O}(1)$
- Requires non perturbative input
- Two models: cluster and string

Color-singlet parton pairs end up “close” in phase space. This is called preconfinement.

Involves collecting $q\bar{q}$ pairs into color-singlet clusters.

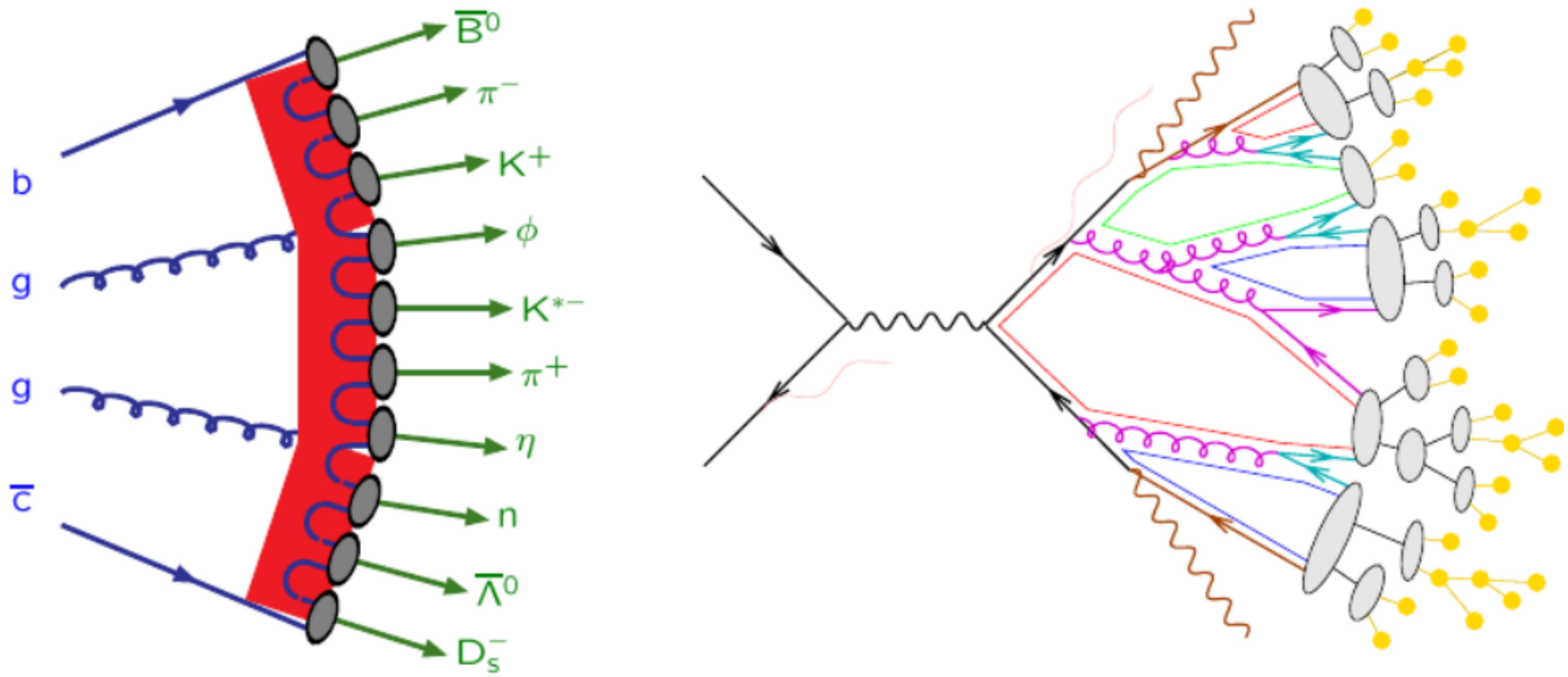
Cluster hadronisation

Create strings from color string, with gluons “stretching the string” locally. It uses non-perturbative insights

String hadronisation

Hadronisation

Sjöstrand, Durham '09



program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Summary: Parton shower

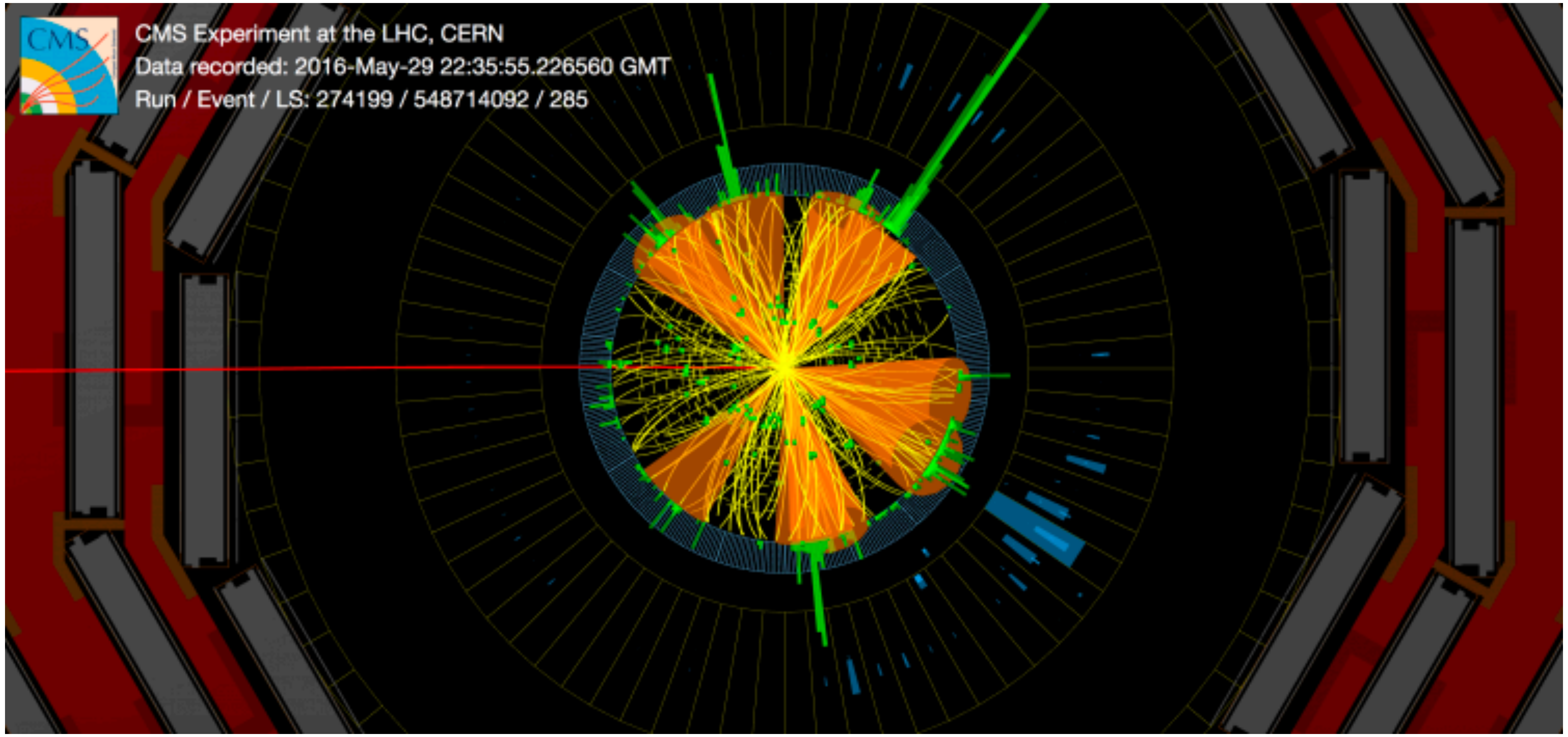
- A parton shower dresses partons with radiation such that the sum of probabilities is one.
  - Predictions become exclusive.
  - General-purpose, process-independent tools
  - Based on collinear factorisation and build around the Sudakov form factors provide a resummed prediction
  - Similar ideas can be used for the initial state shower (need to account for PDFs-deconstruction of the DGLAP evolution, **backwards evolution**)
- Full description starting from hard scattering, shower and hadronisation (also underlying event)
- Move to hadronisation at a cut off at which perturbative QCD can't be trusted
  - Hadronisation is also universal and independent of the collider energy

Parton shower programs

	Current release series	Hard matrix elements	Shower algorithms	MPI	Hadronization
H7	Herwig 7	Internal, libraries, event files	QTilde, Dipoles	Eikonal	Clusters, (Strings)
	Pythia 8	Internal, event files	Pt ordered, DIRE, VINCIA	Interleaved	Strings
	Sherpa 2	Internal, libraries	CSShower, DIRE	Eikonal	Clusters, Strings

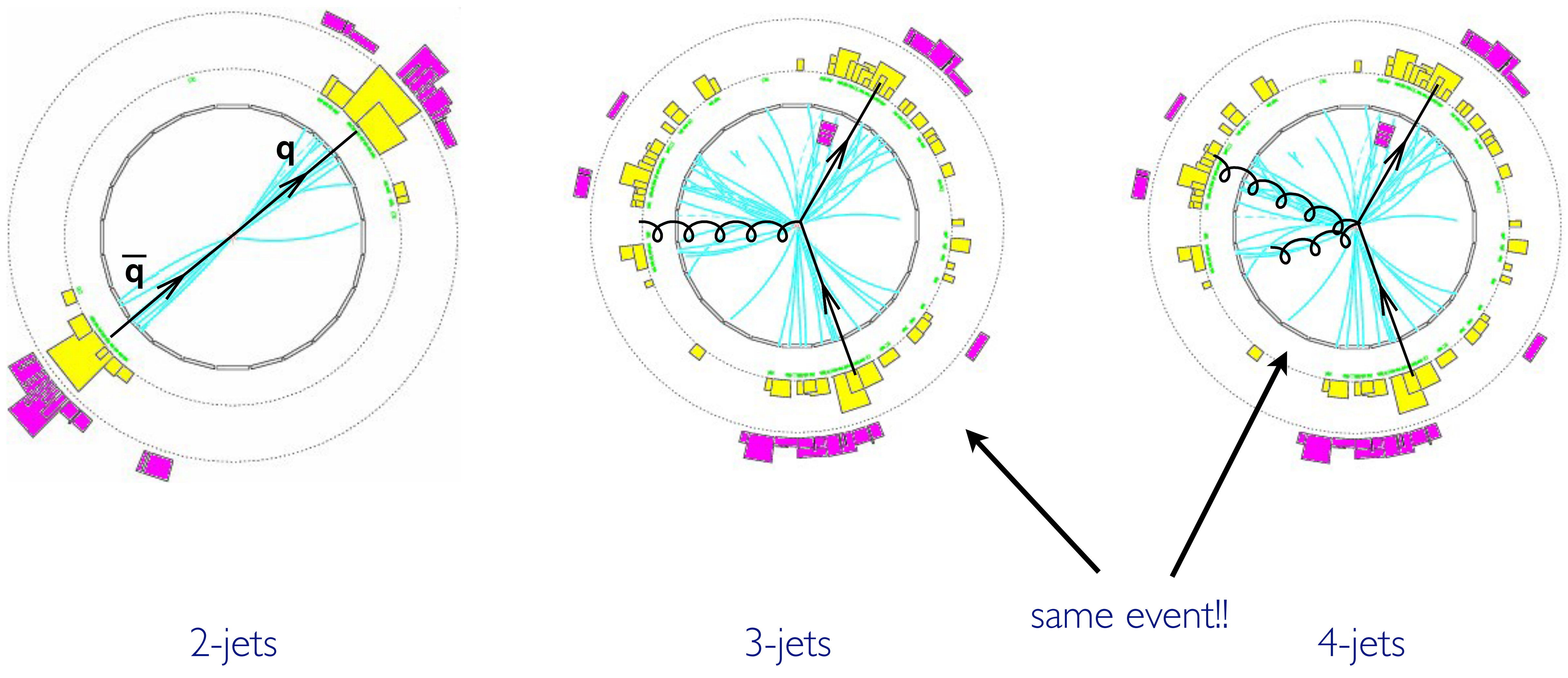
Herwig and Pythia use LHE files e.g. produced in MG5_aMC

What do we see in the detectors?



Collimated sprays of particles: Jets!

Jets

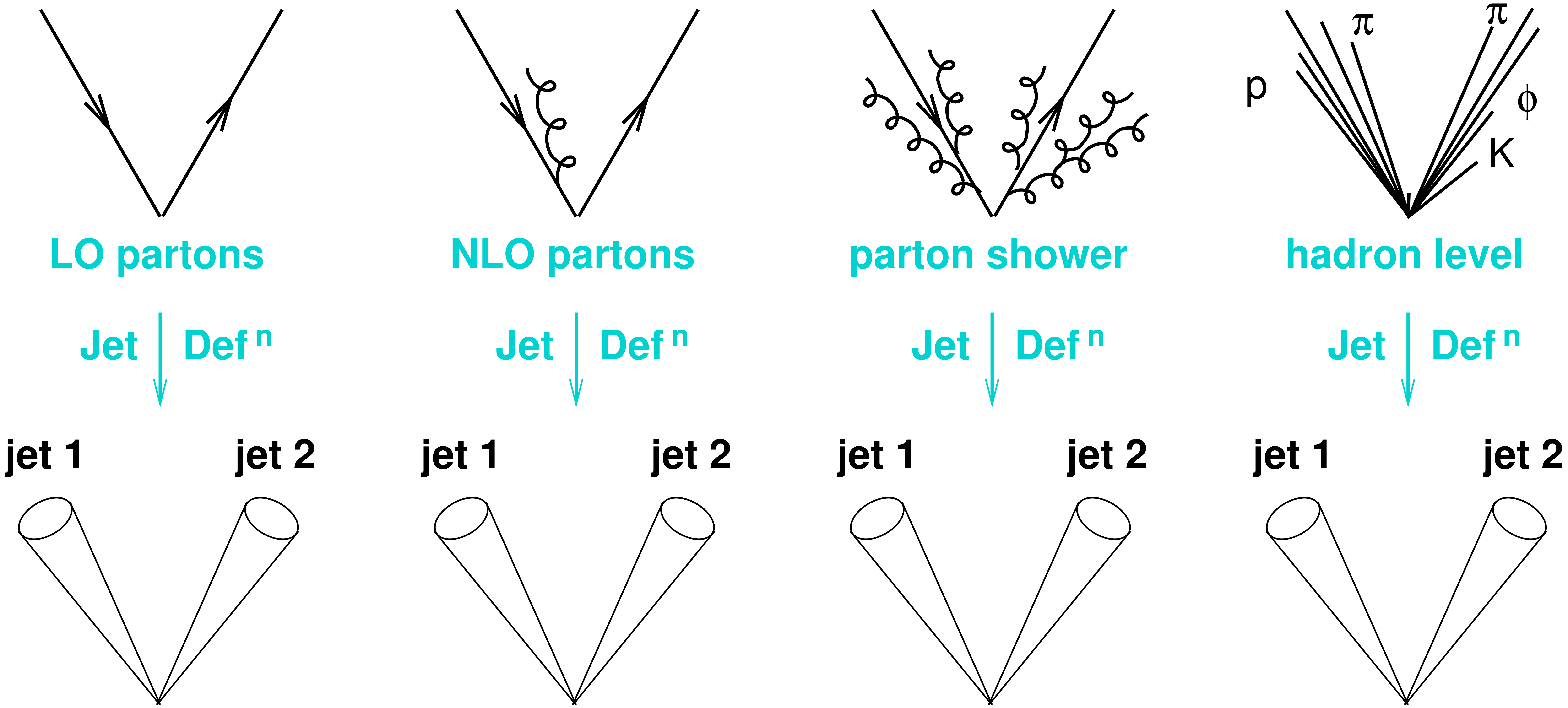


How do we decide?

Jet algorithms:

A set of rules to project information from the hadrons we see in the detectors onto a small number of parton-like objects

Jet algorithms



Procedure needs to be IRC safe!

Example of jet algorithms

Sequential recombination algorithm

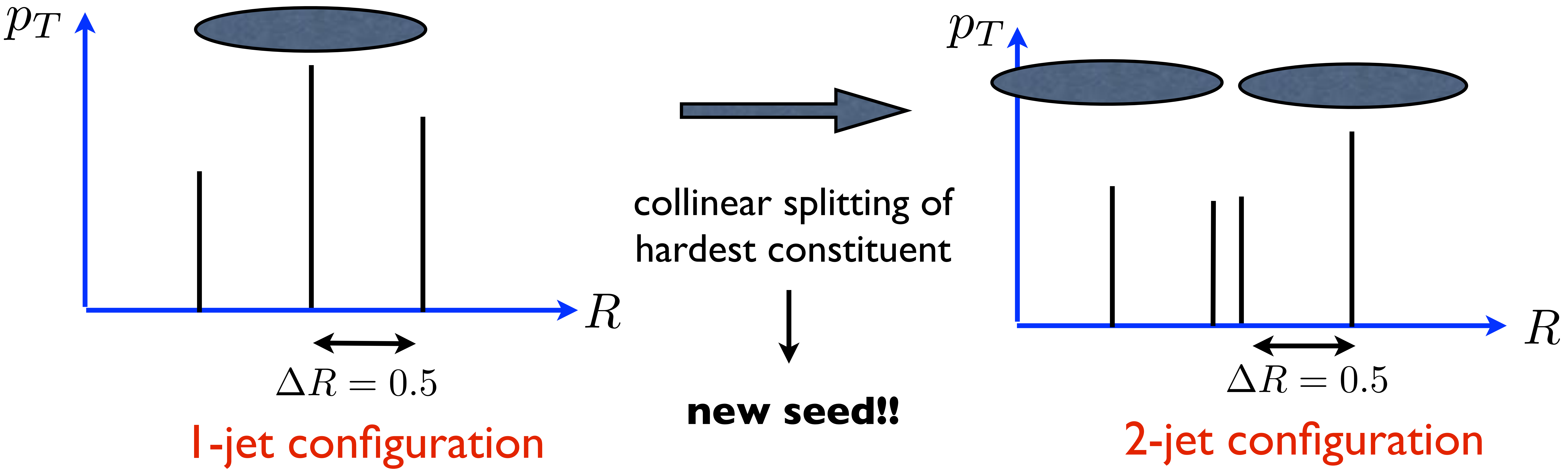
- Bottom-up: combine particles starting from closest ones
- How? Choose a distance measure, iterate recombination until few objects left, call them jets
- Usually trivially made IRC safe, but their algorithmically complex
- Examples: Jade, k_t, Cambridge/ Aachen, anti-k_t ...

Cone:

- Top-down approach: find coarse regions of energy flow.
- How? Find stable cones (i.e. their axis coincides with sum of momenta of particles in it)
- Can be programmed to be fairly fast, at the price of being complex
- Examples: JetClu, MidPoint, ATLAS cone, CMS cone, SISCone

IR safety and cone algorithms

Example: Take the hardest constituent of event as seed for jet cone



Sensitive to collinear emission! Not IRC!

Example of jet algorithm

Distance measure	$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = p_{Ti}^2$

Steps:

1. Find the smallest of d_{ij}, d_{iB}
2. If ij recombine them
3. If iB call i a jet and remove from particles
4. Repeat from I until no particles left

Minimum distance between jets is R

Number of jets above p_{Tj} is IR safe

Example of jet algorithm

4-jets found!

Example of jet algorithms

KT algorithm

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{ti}^2$$

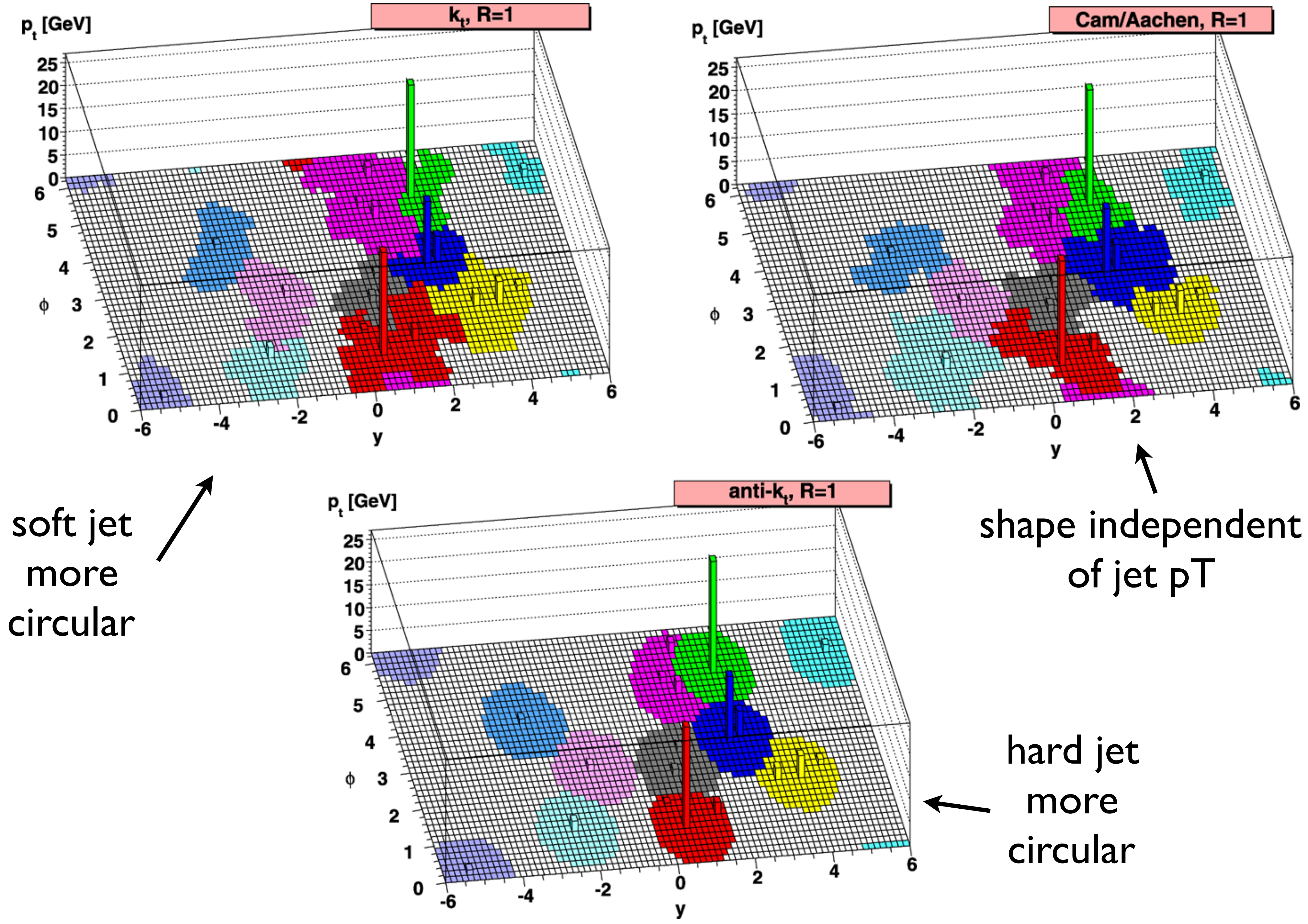
Anti-KT algorithm

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)}\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = \frac{1}{p_{ti}^2}$$

Cambridge/Aachen $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = 1$

See exercises!



G. Salam

Summary so far

- We try to improve cross-section computations by going to higher orders: LO, NLO, NNLO etc ✓
- We try to describe collinear radiation with the parton shower ✓
- We identify jets using IRC jet algorithms ✓

Any room for improvement?

Fixed order vs parton shower

Parton shower describes soft and collinear radiation: not appropriate for hard emissions

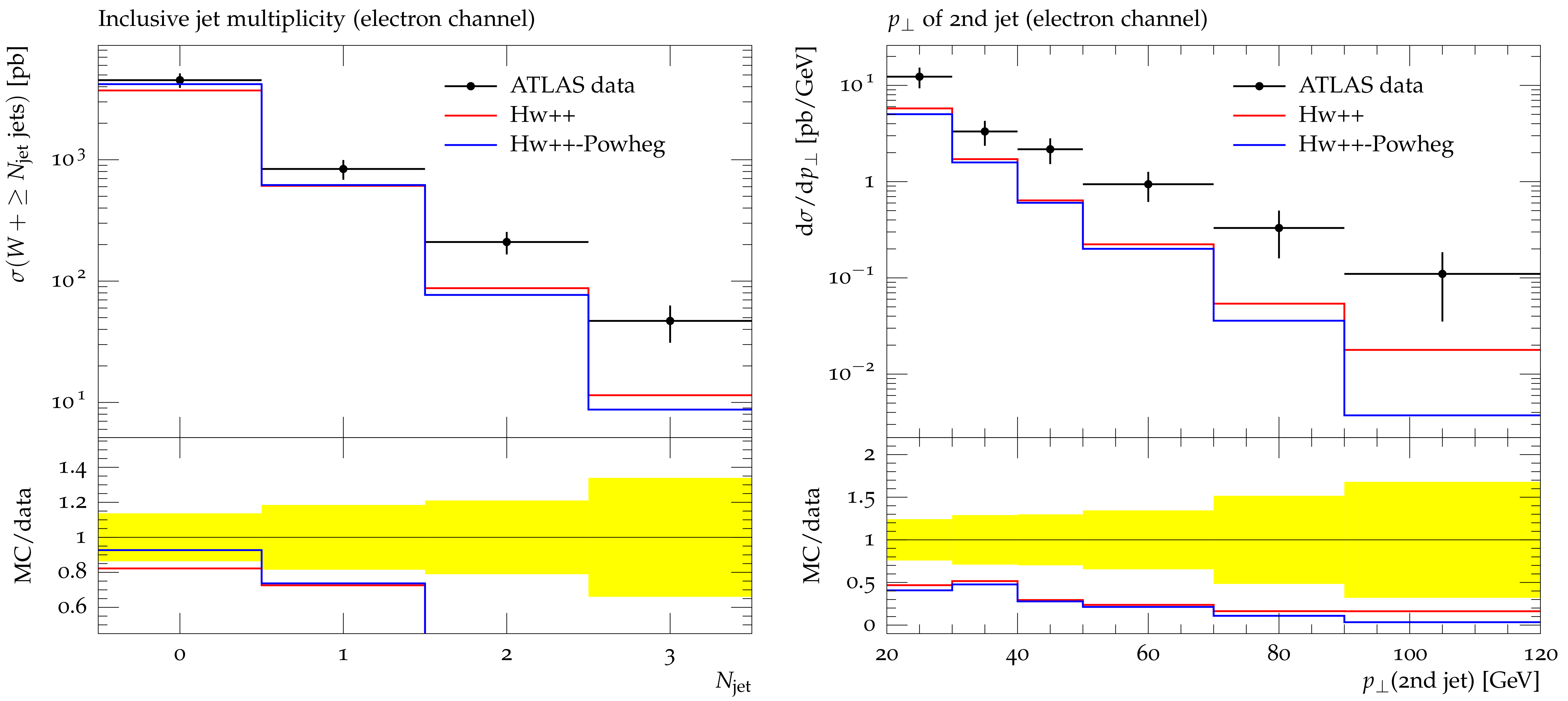
For hard radiation we need input from the matrix element

Two directions of improving parton shower Monte Carlo

- ME+PS merging: include higher multiplicity (but leading order) matrix elements
- NLO+PS matching: include NLO corrections to the matrix elements to reduce theoretical uncertainties and then match to the parton shower

Parton shower results

$W + $jets, LHC 7 TeV.



Parton shower can't describe high multiplicity hard jet events

➡ Need input from the matrix element

Towards LO merging

ME + Shower MC

ME

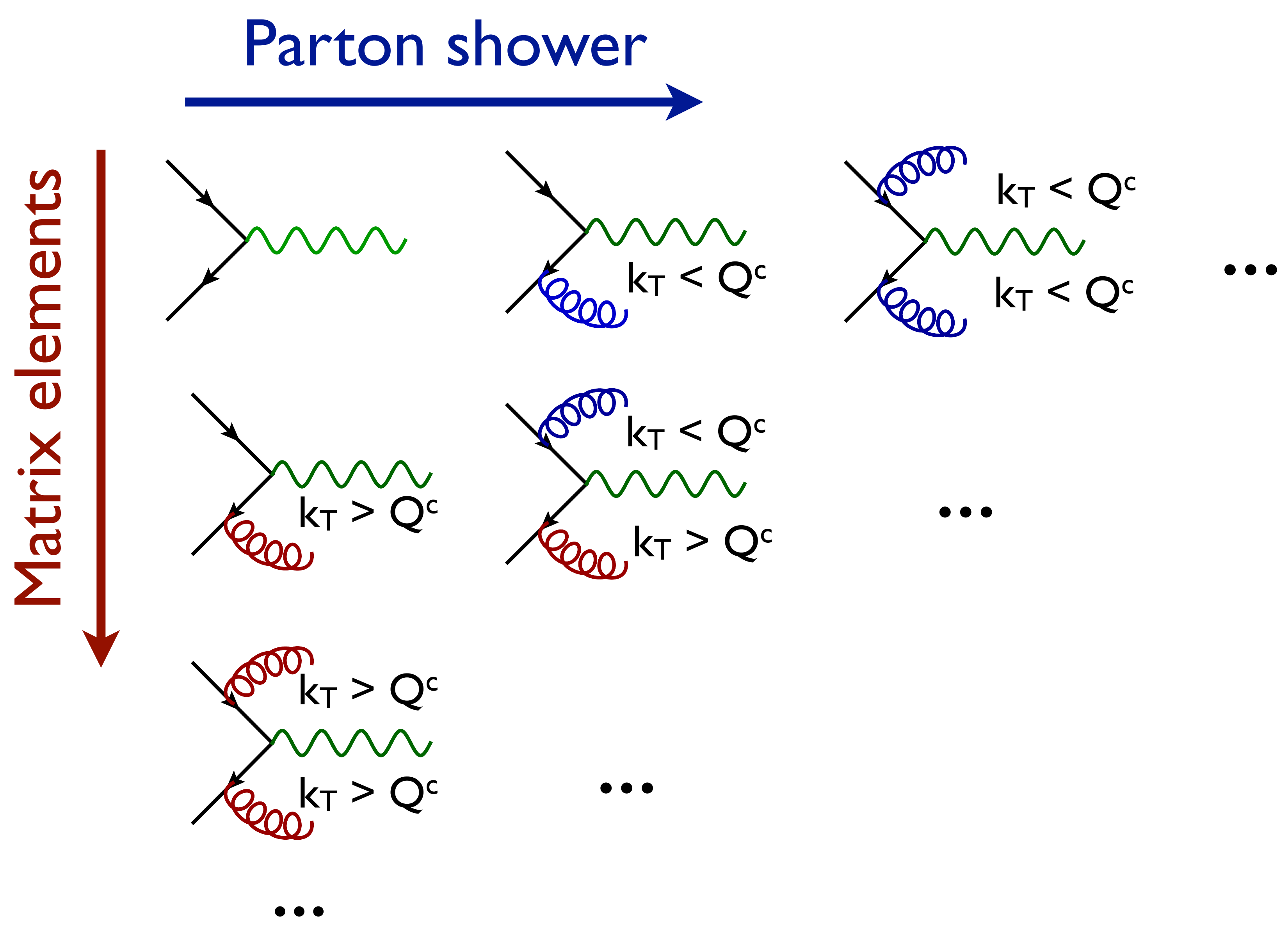
1. Fixed order calculation
2. Computationally expensive
3. Limited number of particles
4. Valid when partons are hard and well separated
5. Quantum interference correct
6. Needed for multi-jet description

Shower MC

1. Resums logs to all orders
2. Computationally cheap
3. No limit on particle multiplicity
4. Valid when partons are collinear and/or soft
5. Partial interference through angular ordering
6. Needed for hadronization

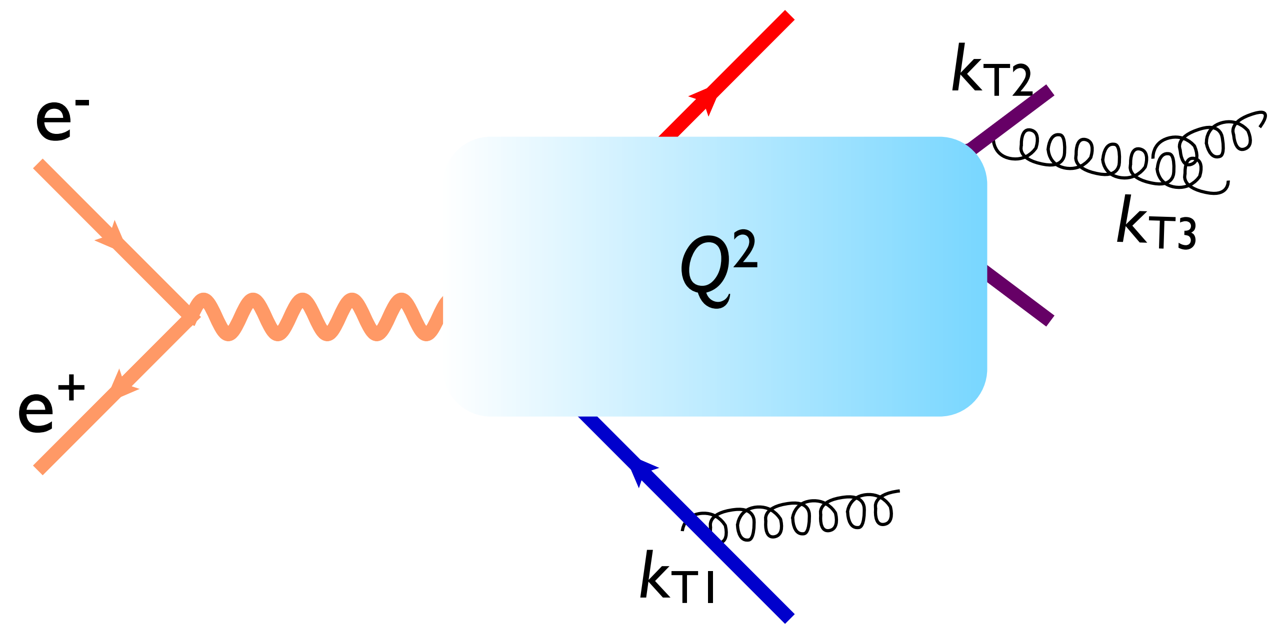
MERGE

Double counting



- Overlap between ME and PS: double counting
- Apply a cut in phase space: a merging scale Q^c to divide the shower and matrix element regions
- Ensure the transition is smooth between them
- The matrix element should look like the parton shower at the cutoff

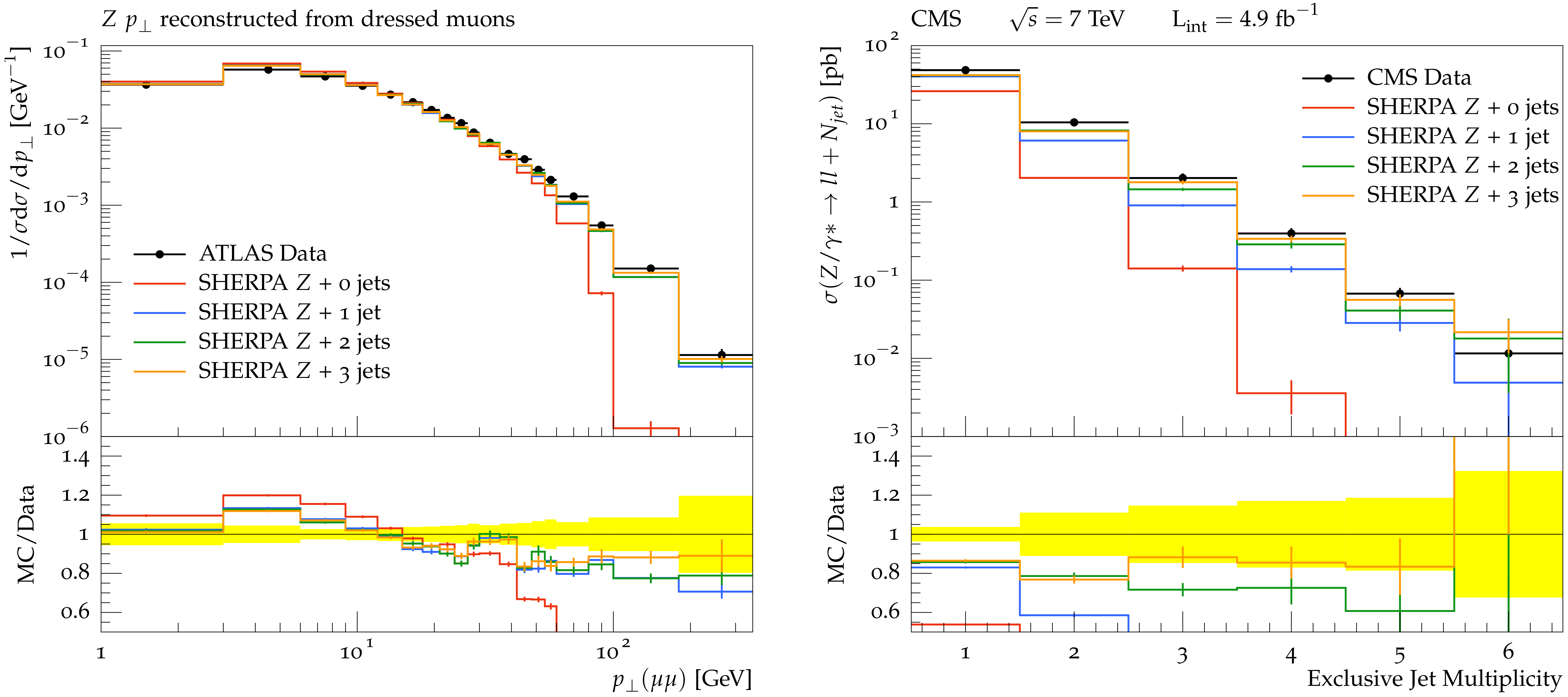
Example: MLM merging



[M.L. Mangano, 2002, 2006]
[J. Alwall et al 2007, 2008]

1. Generate parton configuration from matrix element
2. Shower the event without any restriction (shower from Q_0)
3. Cluster jets with a clustering algorithm
4. Match partons and jets
5. Reject if not all partons and jets match or if additional jets have been produced

Exp vs Theory



ATLAS, Phys. Lett. B **705** (2011) 415; CMS, Phys. Rev. D **91** (2015) no.5, 052008

Much better agreement with experiment!

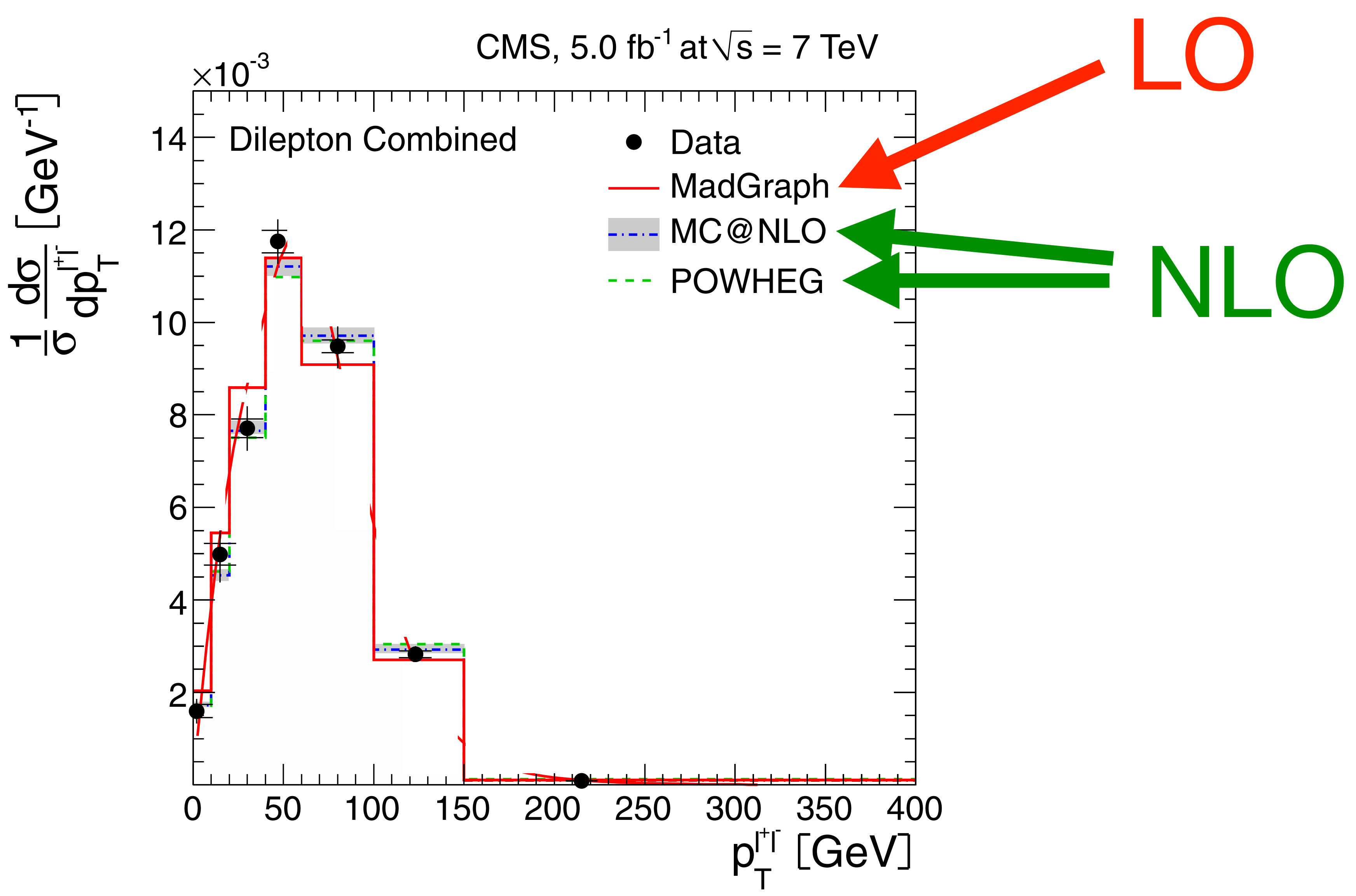
Summary: LO merging

- Good description of both hard and soft/collinear regimes
- Double counting problem is solved by throwing away events where the matrix element partons are too soft or the radiation from the parton shower is too hard.
- Better agreement with data in high-multiplicity regions ✔

Is LO merging enough?

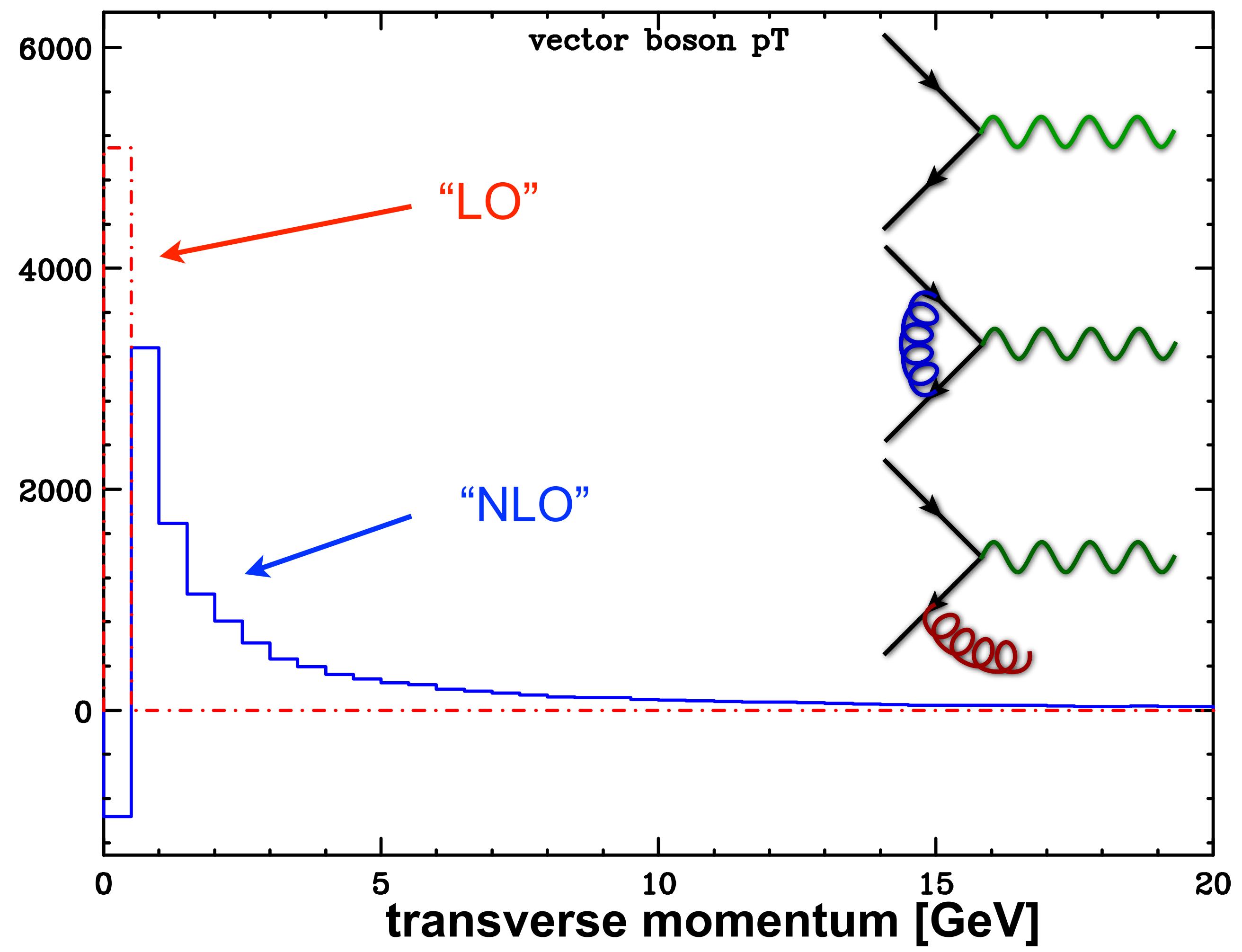
We have seen the importance of higher-order corrections to predict rates and distributions and reduce uncertainties

Need at least NLO to describe the data!



Let's match NLO predictions to the parton shower

Higher orders and PS matching



Note: Fixed order calculation makes no sense in the small p_T region

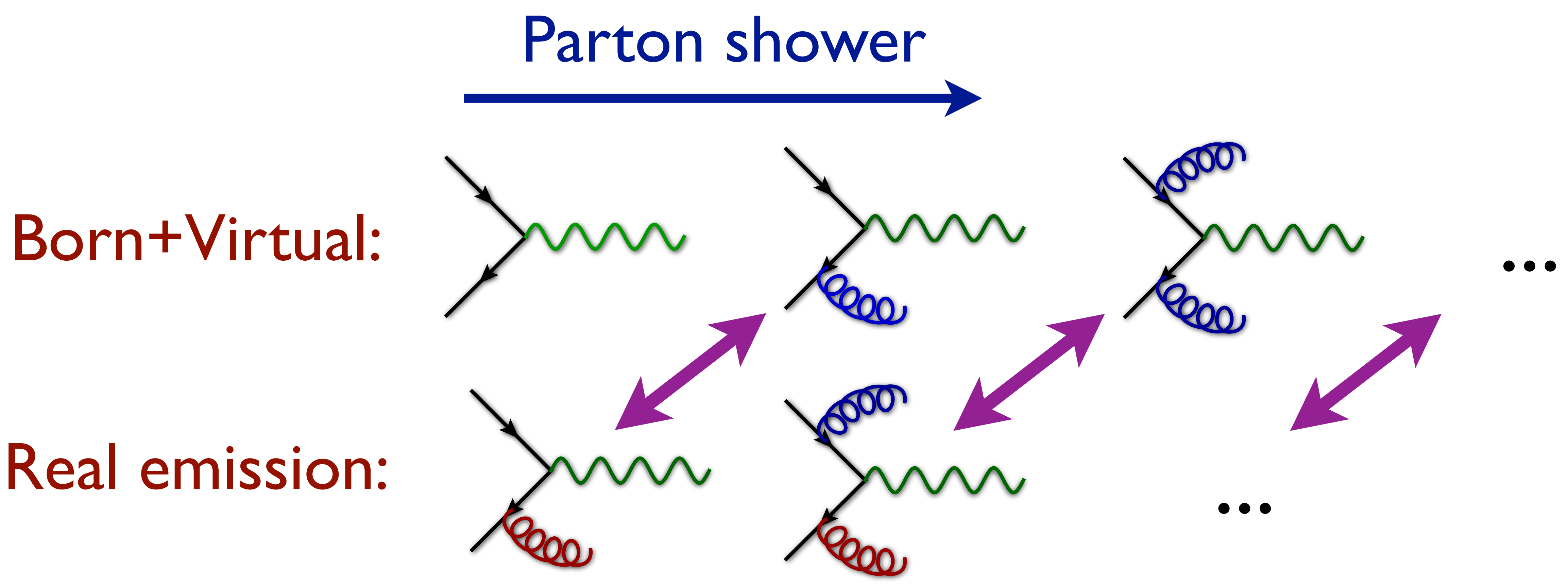
NLO has divergences in virtual and real corrections

The real emission has to be integrated over the full phase-space to cancel the IR poles against the virtual corrections

Our trick of introducing a cut (merging scale) like we did for LO merging cannot work

We need a new procedure to match NLO matrix elements with parton showers

Double counting @NLO



Double counting between the shower and the real emission matrix element

Overlap between virtual corrections and the Sudakov suppression in the zero emission probability

The Sudakov form factor is the no-emission probability, defined as $\Delta = 1 - P$ where P is the probability of branching

That means Δ contains contributions from the virtual corrections

→ Double counting

NLO+PS

Two main methods:

MC@NLO: Frixione, Webber 2002

POWHEG: Nason 2004

also

KRKNLO, Vincia, Geneva

MC@NLO matching

To remove the double counting add and subtract the same term to m and m+1 configurations

$$\frac{d\sigma_{\mathrm{MC@NLO}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC\right) \right] I_{\mathrm{MC}}^{(m)}(O)$$
$$+ \left[d\Phi_{m+1}(R - MC) \right]) I_{\mathrm{MC}}^{(m+1)}(O)$$

MC are the contributions of the PS to go from m body Born final state to the m+1 real emission final state: Shower subtraction terms

MC@NLO features

Good features of including the subtraction counter terms

- Double counting avoided: The rate expanded at NLO coincides with the total NLO cross section
- Smooth matching: MC@NLO coincides (in shape) with the parton shower in the soft/collinear region and it agrees with the NLO in the hard region
- Stability: weights associated to different multiplicities are separately finite. The MC term has the same infrared behaviour as the real emission.

Not so nice feature:

- Parton shower dependence: the form of the MC terms depends on what the parton shower does exactly. Need special subtraction terms for each parton shower to which we want to match: updates in showers might not be compatible with MC terms

Summary: NLO+PS

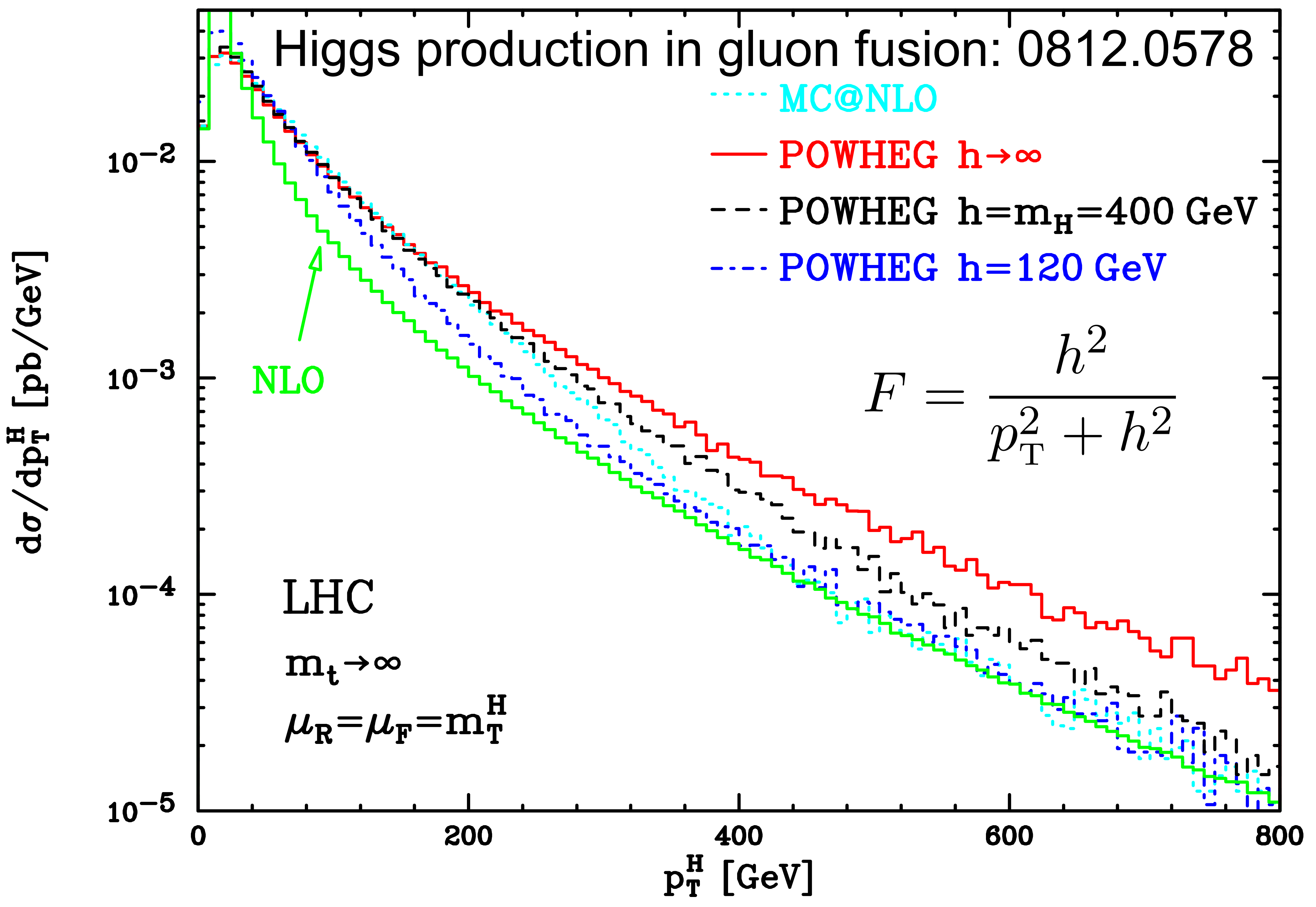
Higher order computations matched to parton showers allow us to have useful features from both!

MC@NLO: subtraction term avoids double counting between NLO and parton shower

Other NLO+PS method:

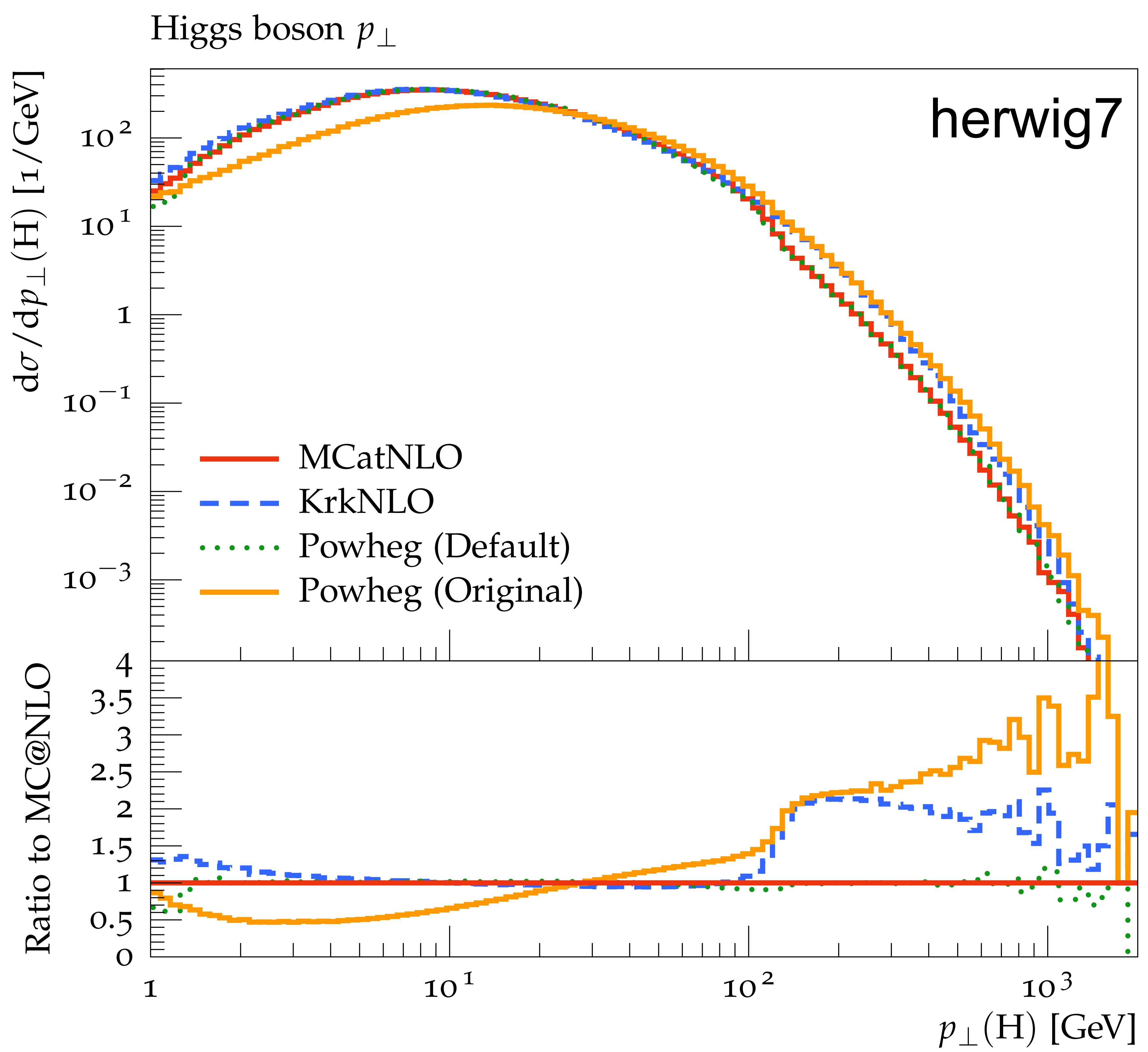
POWHEG: overall k-factor and modification of first emission to fill hard region of phase-space based on the real emission matrix elements

Showered results



$$F = \frac{h^2}{p_T^2 + h^2}$$

$$\mathcal{R} = \mathcal{R}\left(\frac{h^2}{p_\perp^2 + h^2} + \frac{p_\perp^2}{p_\perp^2 + h^2}\right) = \mathcal{R}^{(S)} + \mathcal{R}^{(F)}$$



Original Powheg was giving too hard tails

Improved Powheg very close to MC@NLO

Merging@NLO

To improve both high multiplicity regions and rates

Two main methods of merging@NLO

- FxFx
- MEPS@NLO

Make MC@NLO calculation exclusive in more jets by vetoing additional radiation and resumming the dependence on the merging scale

- CKKW-L approach (i.e. Sudakov rejection based on shower kernels)

Used in Sherpa's "MEPS@NLO"

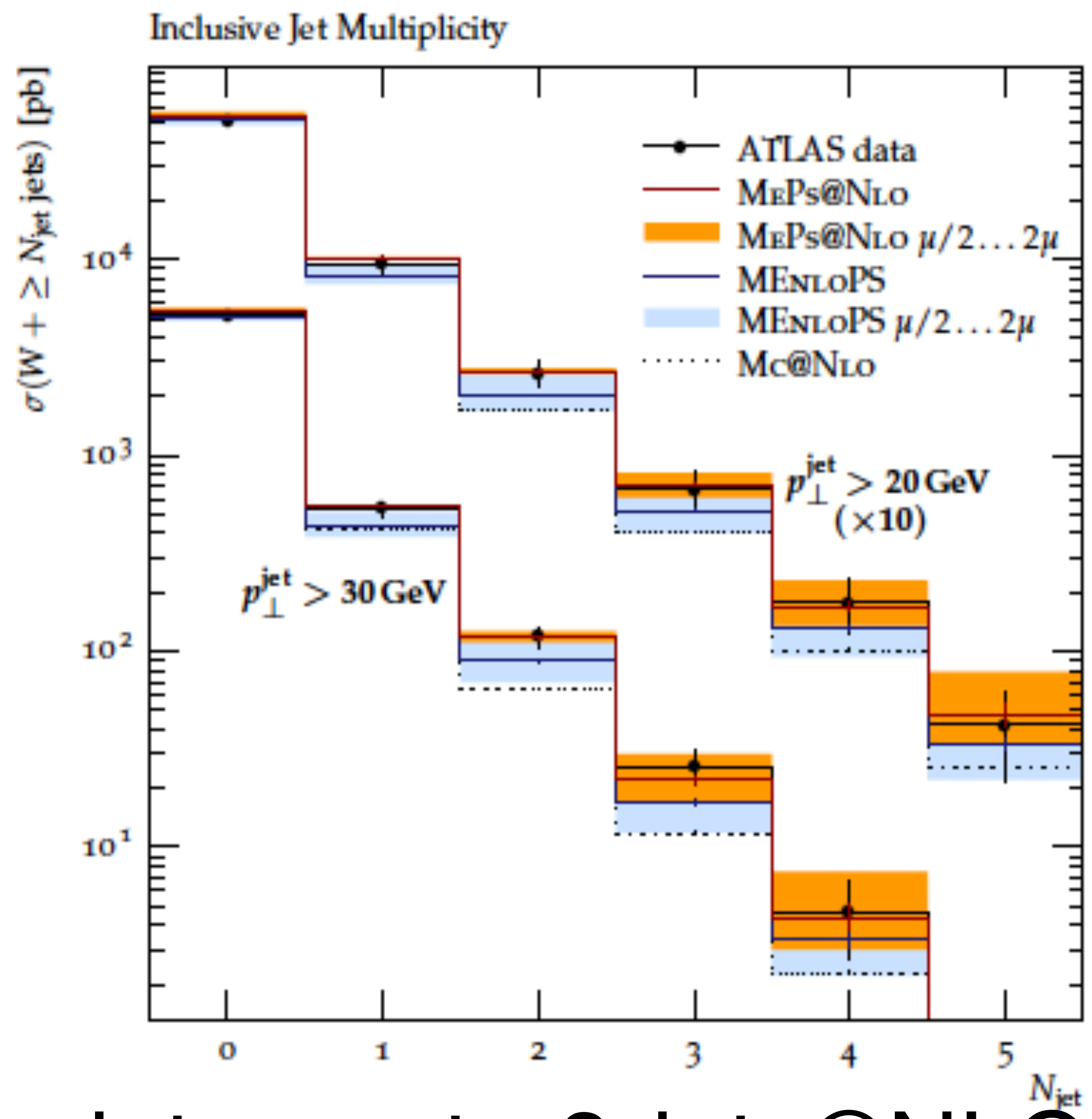
CKKW from hard scale down to the scale of the softest jet not affected by veto;

- MLM-type rejection from there down to merging scale

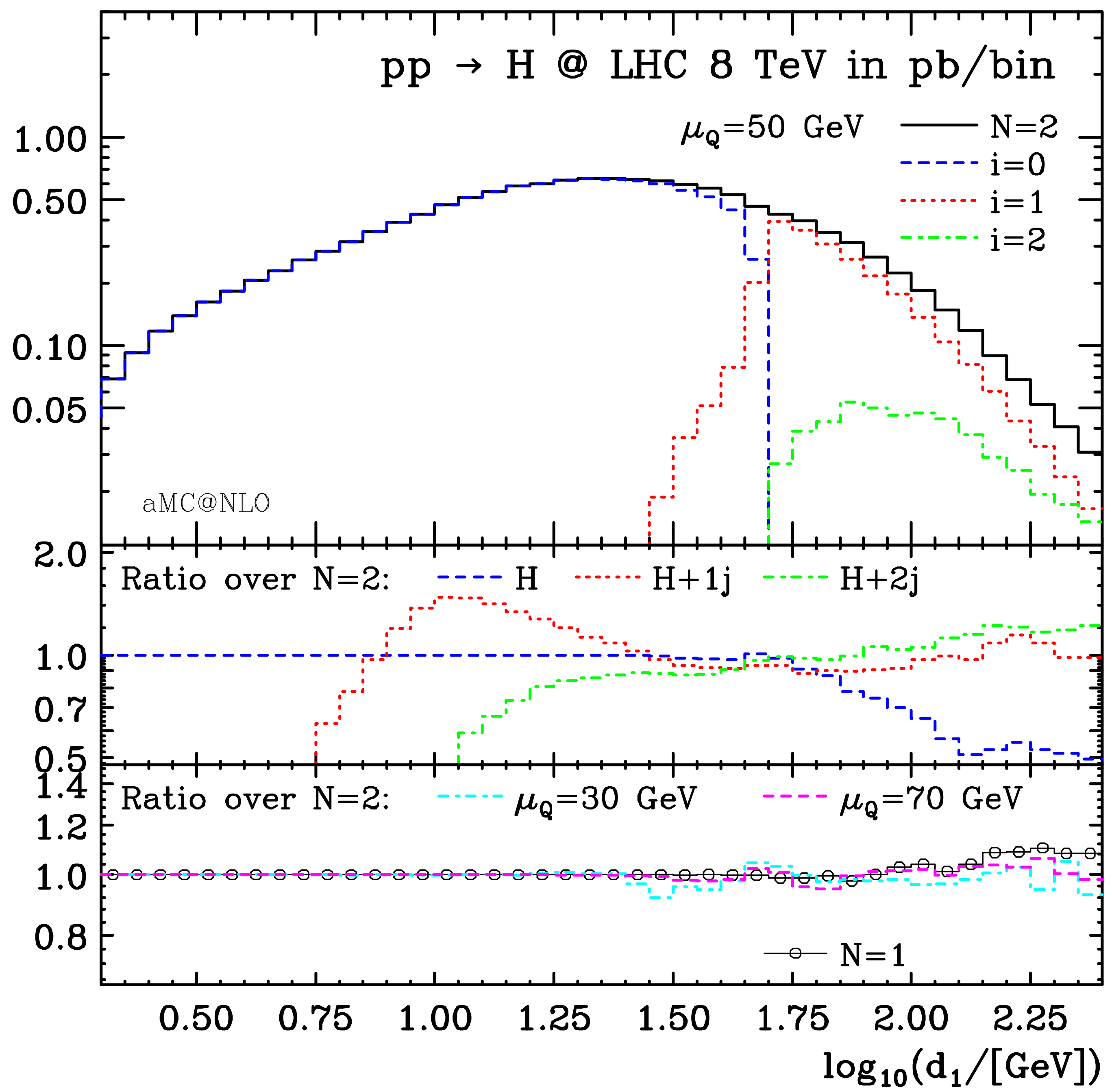
Used in MadGraph5_aMC@NLO with Pythia or Herwig: "FxFx merging"

Merging@NLO

[Hoeche et al. , 1207.5030]



[Frederix, Frixione, 1209.6215]



W + jets: up to 3-jets@NLO

Jet multiplicity

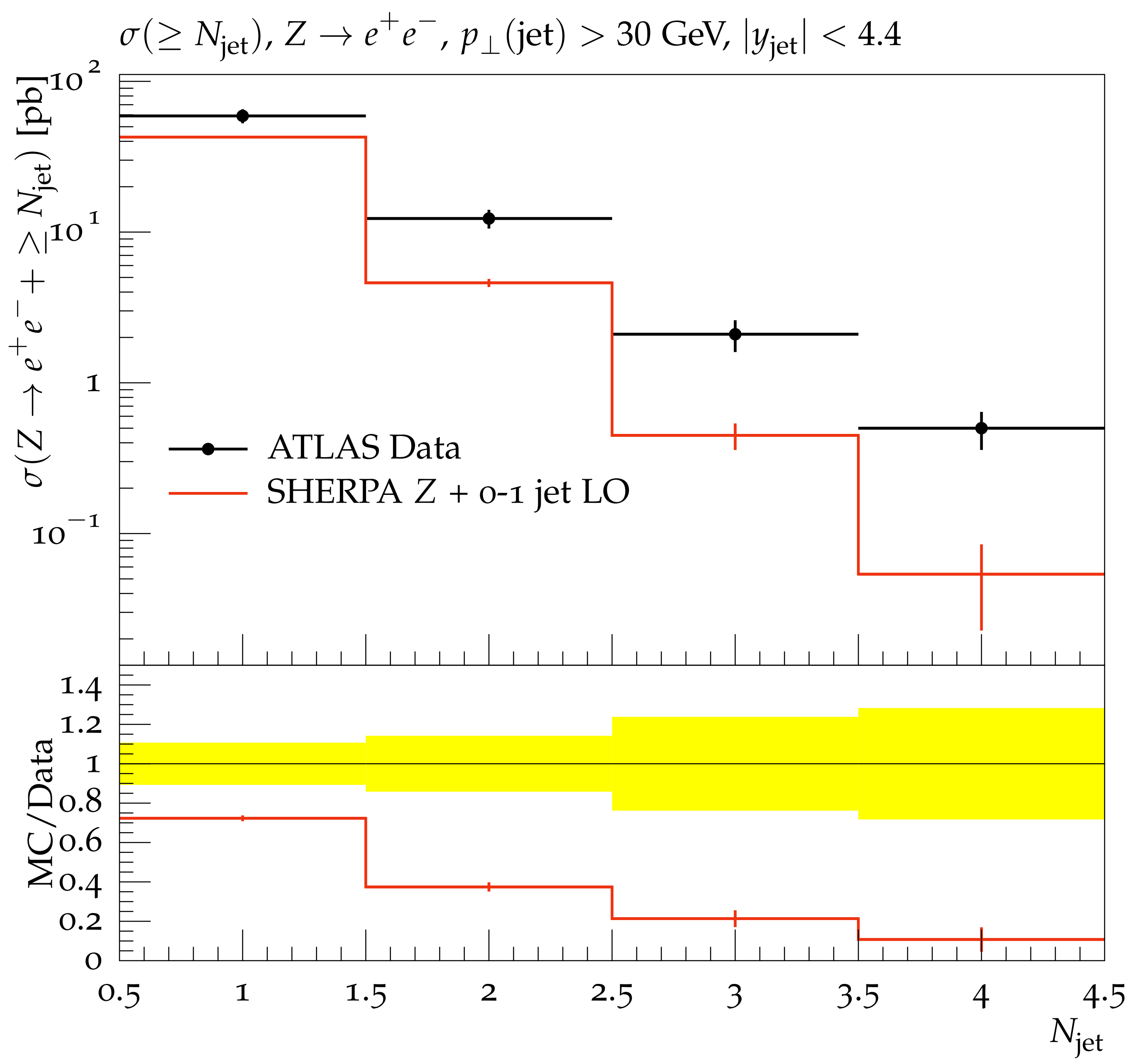
Good agreement with LHC data

H + jets: up to 2-jets@NLO

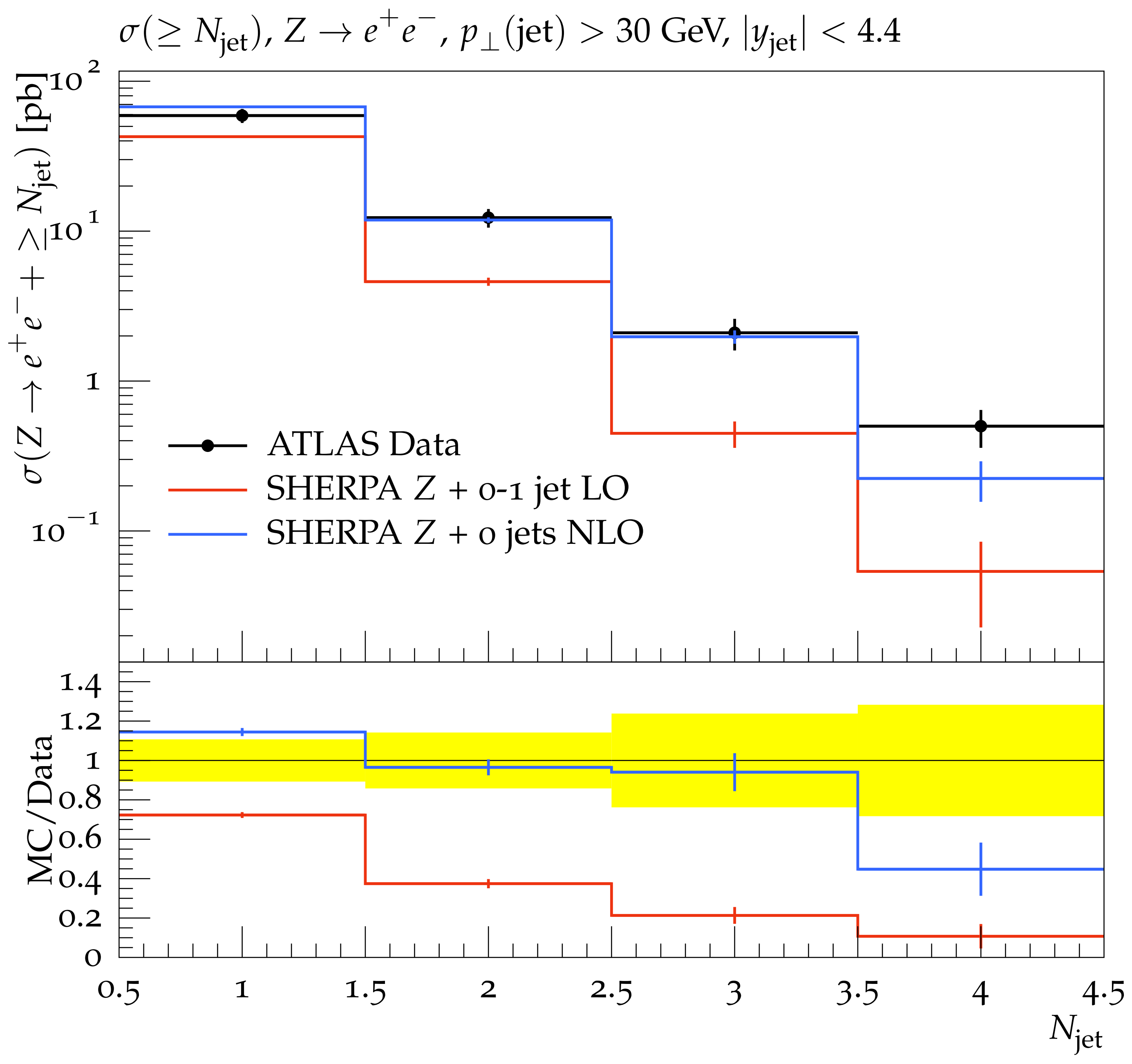
Differential jet rate

Very mild merging scale dependence

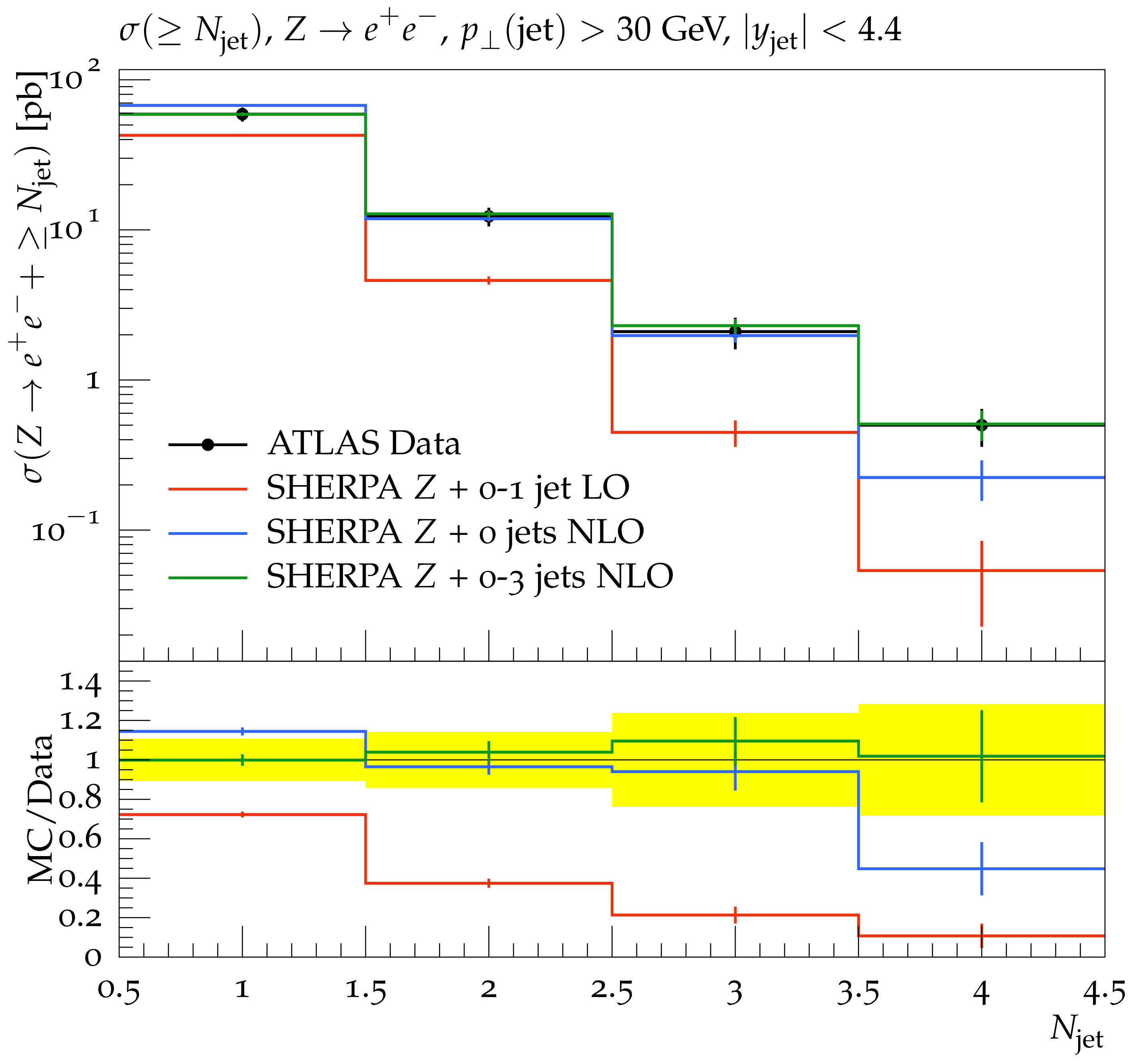
Is this progress relevant?



Merging at LO



NLO+PS

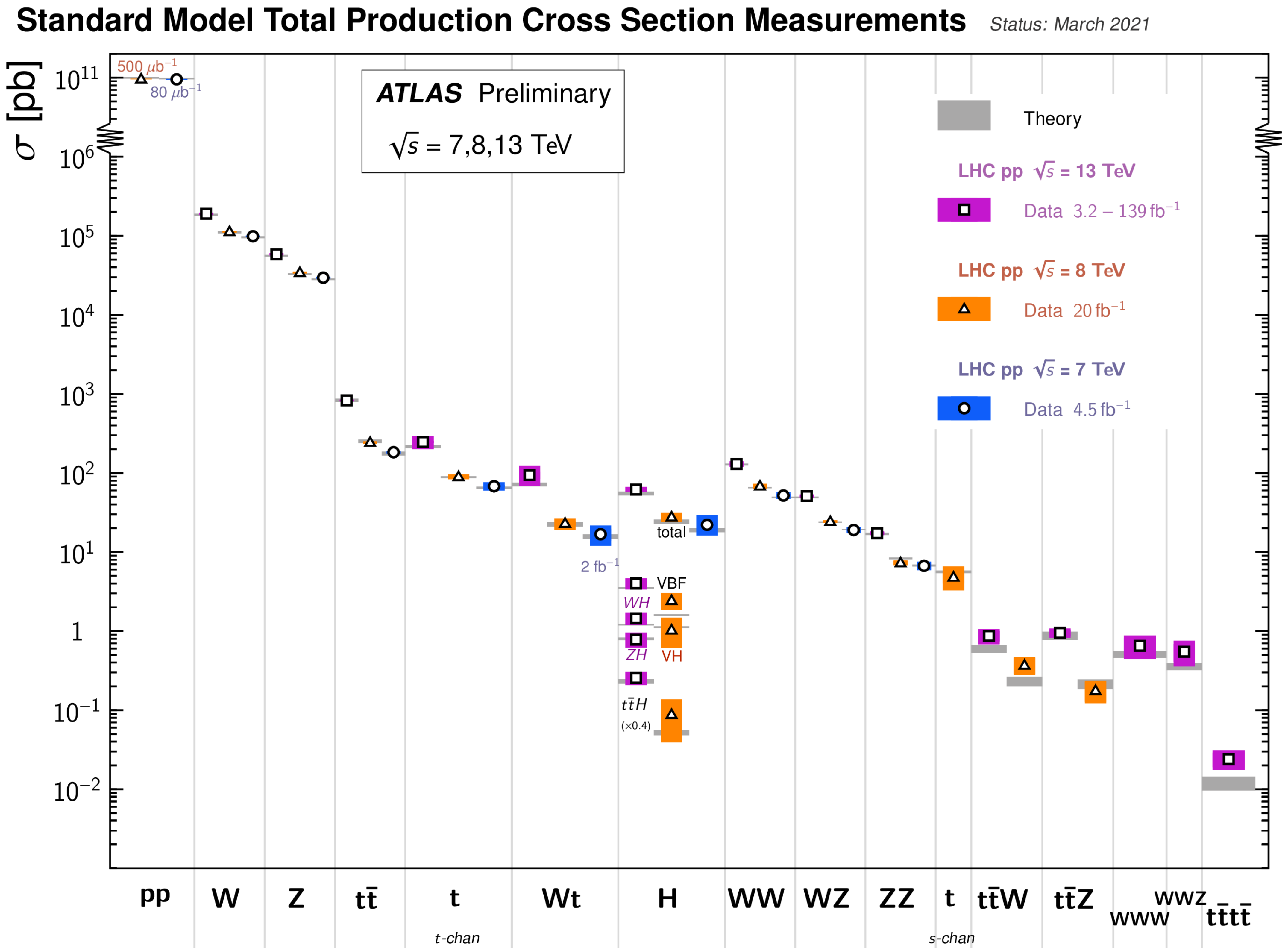


NLO+PS merging

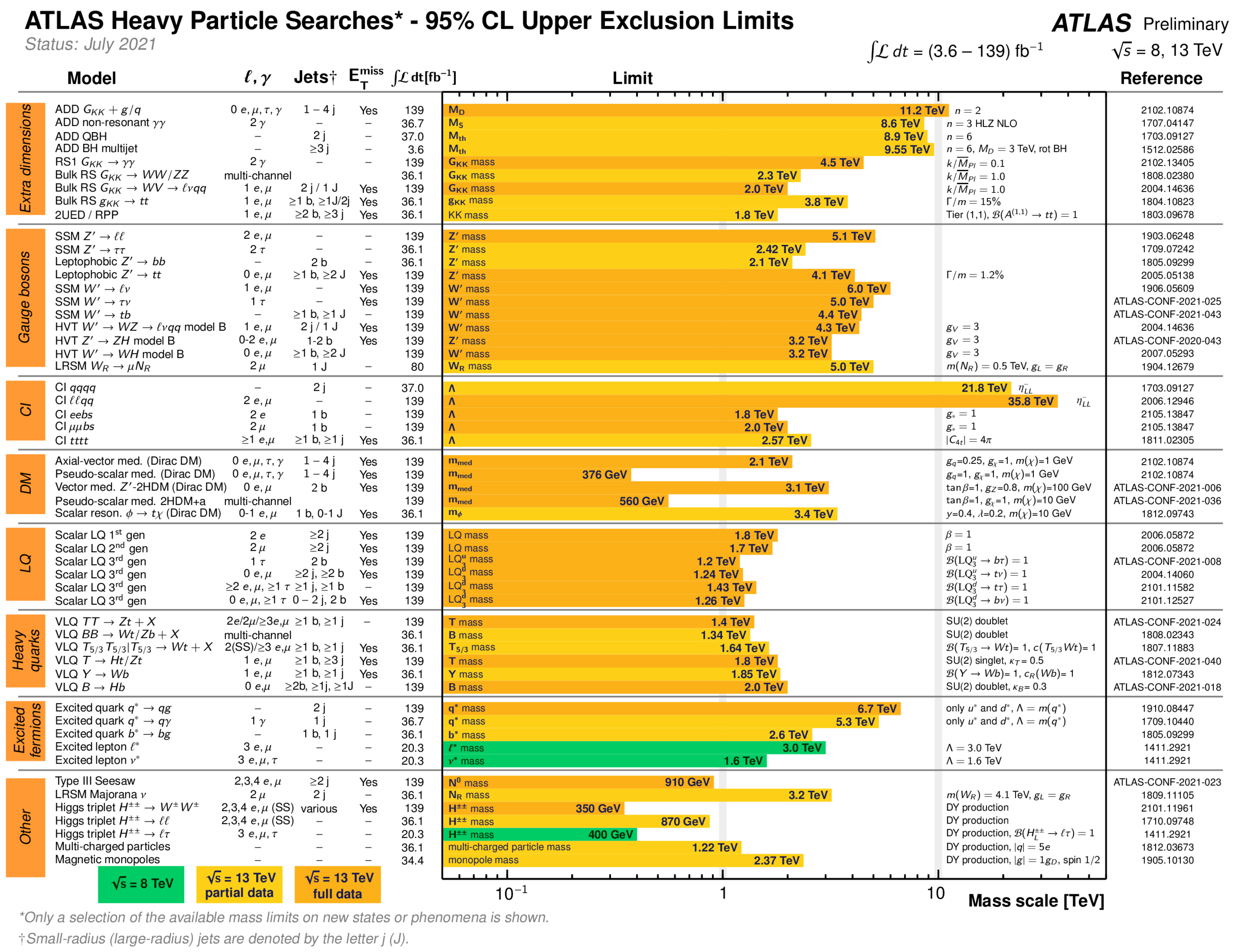
Impressive improvement in description of data!

LHC status

Exploring & refining the SM

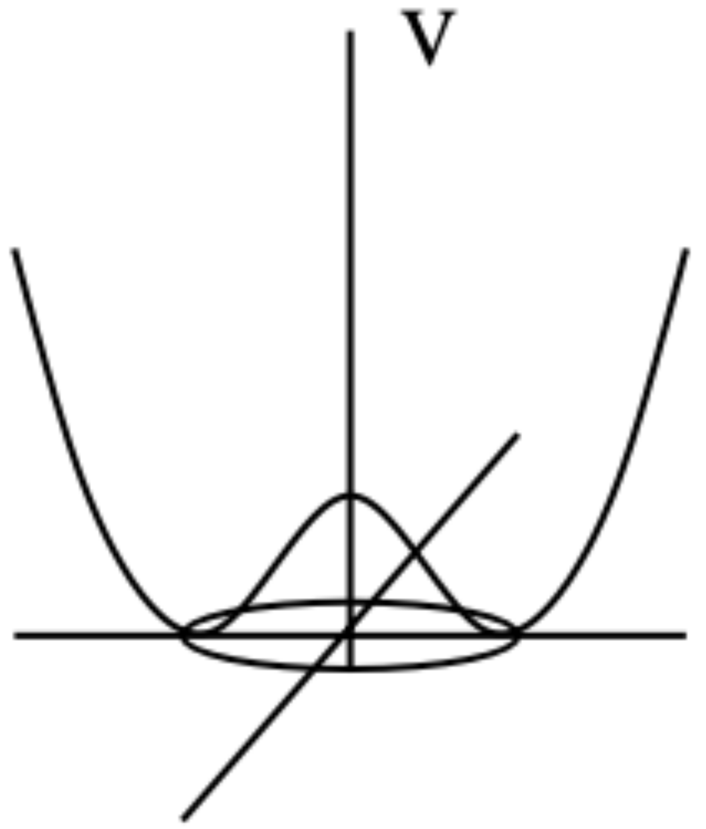


Searching for the unknown



Good agreement with the SM

Higgs phenomenology



In the SM, the Higgs field plays the role of EWSB

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \quad \Rightarrow \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad v^2 = \frac{\mu^2}{\lambda}$$

Generates mass for all fundamental particles

- Higgs boson (h) couplings are proportional to mass

Gauge $$(D^\mu H)^\dagger (D_\mu H) \supset \underbrace{(gv)^2 V^\mu V_\mu}_{\sim m_V^2},\ \underbrace{g^2 v h\, V^\mu V_\mu}_{\sim m_V^2/v},\ \underbrace{g^2 hh\, V^\mu V_\mu}_{\sim m_V^2/v^2}$$

Yukawa $$y_f \bar{F}_L H f_R \supset \underbrace{y_f v \bar{f} f}_{\sim m_f},\ \underbrace{y_f h \bar{f} f}_{\sim m_f/v}$$

Potential $$V(H) \supset \underbrace{\lambda v^2 h^2}_{\sim m_h^2},\ \underbrace{\lambda v h^3}_{\sim m_h^2/v},\ \underbrace{\lambda h^4}_{\sim m_h^2/v^2}$$

Not necessarily the case in BSM theories, important to test!

Custodial symmetry

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$V(H^\dagger H)$ as a consequence of $SU(2)_L$ gauge symmetry

$$H = \begin{pmatrix} \phi_0 + i\phi_1 \\ \phi_2 + i\phi_3 \end{pmatrix} \Rightarrow H^\dagger H = \sum_{i=0\dots3} \phi_i^2 = |(\phi_0, \phi_1, \phi_2, \phi_3)|^2$$

$O(4) \simeq SU(2) \times SU(2)$ symmetry

$O(4)$ symmetry broken by $\langle \phi_0 \rangle = v$,

- EW vacuum has residual $O(3) \simeq SU(2)$ symmetry

$$\vec{v} = \begin{pmatrix} \phi_0 = v \\ \phi_1 = 0 \\ \phi_2 = 0 \\ \phi_3 = 0 \end{pmatrix} \times R_{O(3)} = \vec{v}$$

Make $SU(2) \times SU(2)$ manifest by using bi-doublet notation for Higgs field

$$\mathscr{H} \equiv (i\sigma_2 H^*, H) = \begin{pmatrix} H_0^* & H_+ \\ -H_+^* & H_0 \end{pmatrix} \Rightarrow$$

$$\mathrm{Tr}[\mathscr{H}^\dagger \mathscr{H}] = 2H^\dagger H$$

$$V(H) = -\frac{\mu^2}{2}\mathrm{Tr}[\mathscr{H}^\dagger \mathscr{H}] + \frac{\lambda}{4}\mathrm{Tr}[\mathscr{H}^\dagger \mathscr{H}]^2$$

Custodial symmetry

$$V(\mathscr{H}) = -\frac{\mu^2}{2}\mathrm{Tr}[\mathscr{H}^\dagger\mathscr{H}] + \frac{\lambda}{4}\mathrm{Tr}[\mathscr{H}^\dagger\mathscr{H}]^2$$

$\mathscr{H}$ transformation under $SU(2)_L \times SU(2)_R$: $\mathscr{H} \to U_L \mathscr{H} U_R^\dagger$ $\langle \mathscr{H}^\dagger \mathscr{H} \rangle = v^2 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

- $V(\mathscr{H})$ invariant under this **global** transformation
- Vacuum preserves $SU(2)_V$ subgroup where $U_L = U_R$ $U\langle \mathscr{H}^\dagger \mathscr{H} \rangle U^\dagger = \langle \mathscr{H}^\dagger \mathscr{H} \rangle$

SM: global → gauge symmetries

- Completely gauge $SU(2)_L$ but only gauge T_R^3: $D^\mu \mathscr{H} = \partial_\mu \mathscr{H} - igW_\mu^I \sigma_I \mathscr{H} - i\frac{g'}{2}B_\mu \mathscr{H}\sigma_3$
- If $g' = 0$, $SU(2)_V \Rightarrow W_\mu^i$ all have the same masses
- Form a triplet of $SU(2)_V$ custodial symmetry
- $U(1)_Y$ modifies the picture in a particular way

$$\begin{pmatrix} W_1 \\ W_2 \\ W_3 \\ B \end{pmatrix} : \quad M_V = \begin{pmatrix} m_W^2 & 0 & 0 & 0 \\ 0 & m_W^2 & 0 & 0 \\ 0 & 0 & m_W^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Custodial symmetry

$$V(H) = -\frac{\mu^2}{2}\mathrm{Tr}[\mathscr{H}^\dagger\mathscr{H}] + \frac{\lambda}{4}\mathrm{Tr}[\mathscr{H}^\dagger\mathscr{H}]^2$$

Suppose we completely gauged $SU(2)_R$

$$\tilde{D}^\mu\mathscr{H} = \partial_\mu\mathscr{H} - igW^I_\mu\sigma_I\mathscr{H} - ig'B^I_\mu\mathscr{H}\sigma_I$$

- 3 identical mass + 3 massless gauge bosons
- $SU(2)_V$ manifest

$$\begin{pmatrix} W_i \\ B_i \end{pmatrix} : \quad M_V = \frac{v^2}{2}\begin{pmatrix} g^2 & gg' \\ gg' & g'^2 \end{pmatrix}, \lambda_i = \frac{v^2}{2}\left(g^2 + g'^2, 0\right)$$

In the SM we partly gauge T^3_R of $SU(2)_R$

- H_0 & H_+ have opposite charge
- $SU(2)_V$ imposes $m_W^2 = m_Z^2 c_W^2$

$$SU(2)_V \simeq O(3)$$

$$\begin{pmatrix} W_1 \\ W_2 \\ W_3 \\ B \end{pmatrix} : \quad M_V = \frac{v^2}{2}\begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} = \begin{pmatrix} m_W^2 & 0 & 0 & 0 \\ 0 & m_W^2 & 0 & 0 \\ 0 & 0 & m_Z^2 c_W^2 & m_Z^2 c_W s_w \\ 0 & 0 & m_Z^2 c_W s_w & m_Z^2 s_W^2 \end{pmatrix}$$

$$\rho_{\text{tree}} = \frac{m_W^2}{m_Z^2 c_W} \simeq 1$$

Very strong prediction that we can use to test for BSM!

Custodial symmetry

$$\rho_{\text{tree}} = \frac{m_W^2}{m_Z^2 c_W} \simeq 1$$

Yukawa sector of the SM explicitly breaks custodial symmetry

- Right handed fermions do not form a doublet

$$F_L = \begin{pmatrix} f_L^u \\ f_L^d \end{pmatrix}, F_R = \begin{pmatrix} f_R^u \\ f_R^d \end{pmatrix}$$

$y_{f^u} \neq y_{f^d}$

$$\mathscr{L}_f \sim y_F \bar{F}_L \mathscr{H} F_R \neq y_{f^d} \bar{F}_L H f_R^d + y_{f^u} \bar{F}_L \tilde{H} f_R^u$$

$y_{f^u} = y_{f^d}$

- Loops of SM fermions modify $\rho = 1 + \Delta\rho_{\text{SM}} \approx 1.0004 \pm 0.0002$ (LEP)
- Higgs boson loops proportional to g' also contribute to $\Delta\rho_{\text{SM}}$

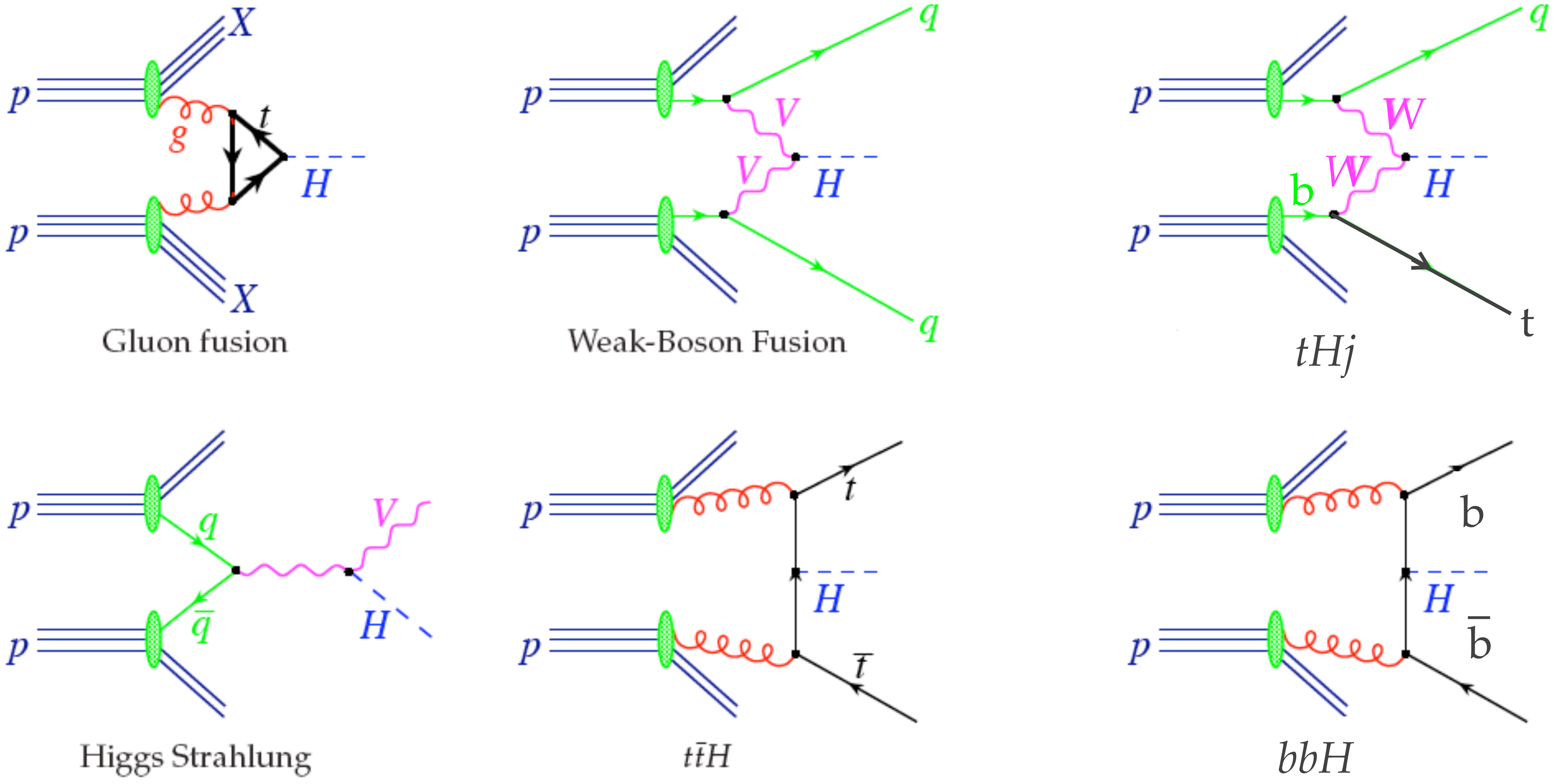
We can test the SM by searching for deviations $\Delta\rho_{\text{BSM}}$

- *e.g.* new EW scalar multiplets that get a vev
- Doublets always give $\rho_{\text{tree}} = 1$

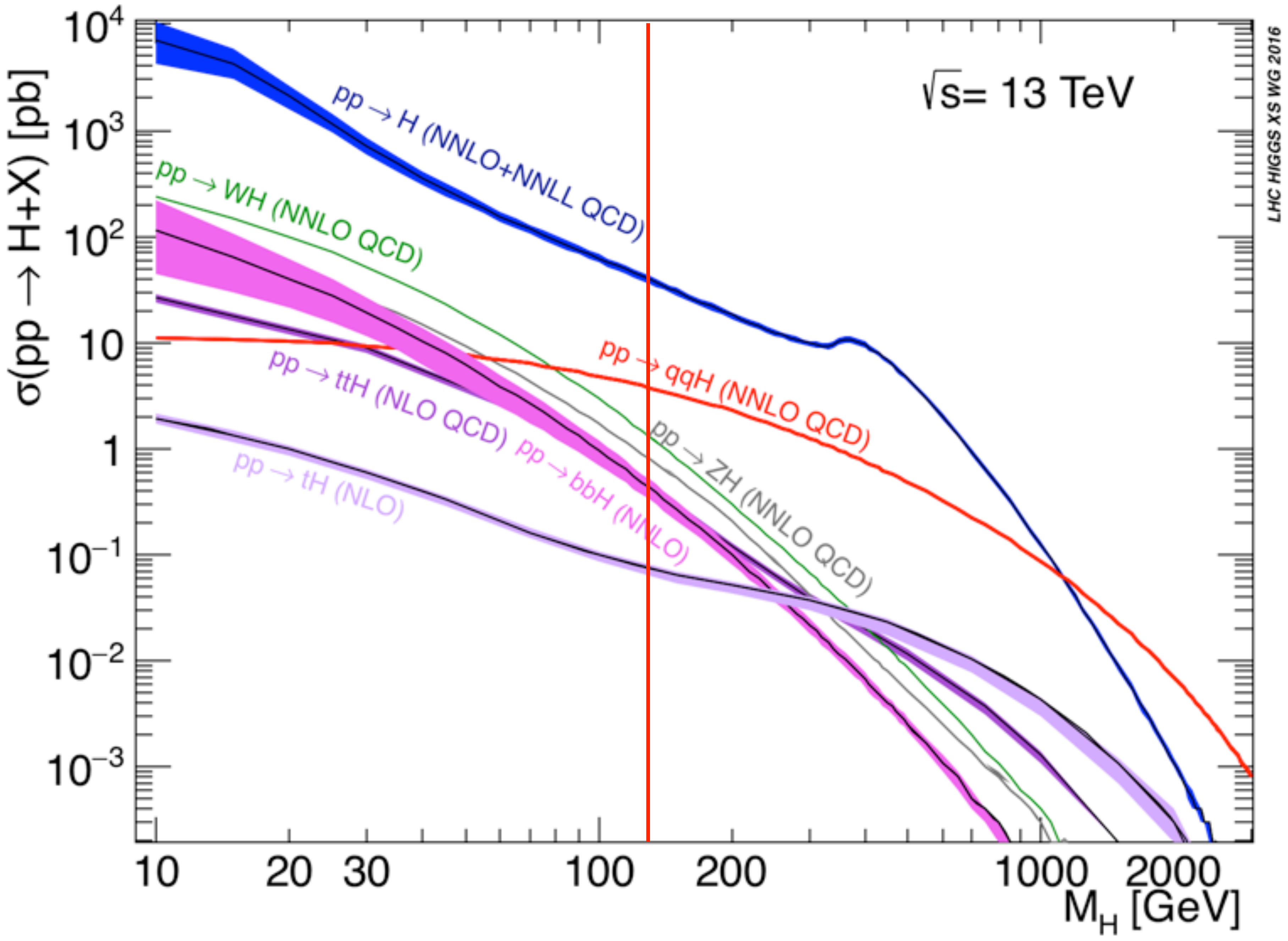
$$\rho_{\text{tree}} = \frac{\sum_j |v_j|^2 \left[T_j(T_j+1) - Y_j^2\right]}{2\sum_j |v_j|^2 Y_j^2}$$

$v_i \ll v_{\text{SM}}$ or only specific representations allowed

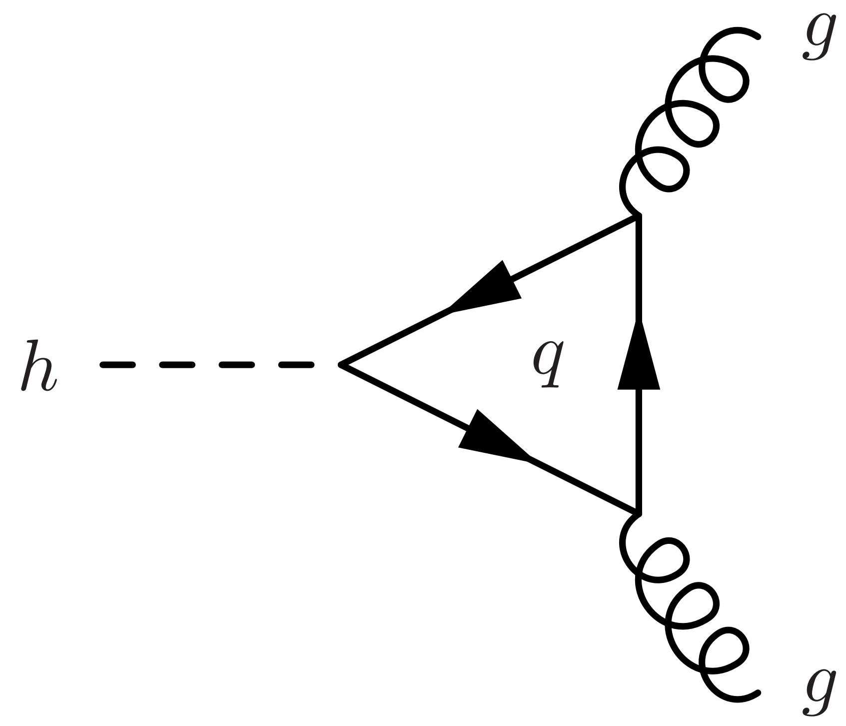
Higgs production @ hadron colliders



$m_h = 125\,\mathrm{GeV}$



Gluon fusion



Higgs boson coupling to gluons induced by quark loops

- $gg \to h$ amplitude is finite at LO (one-loop)

$$\hat{\sigma}_{gg\to h} = \frac{G_F\,\alpha_s^2}{288\sqrt{2}\pi}\left|\sum_q A_q(\tau_q)\right|^2 \qquad \tau_q = \frac{4m_q^2}{m_h^2} \qquad A_q(\tau) = \frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right] \qquad f(\tau) = \begin{cases} \arcsin^2 1/\sqrt{\tau} & \tau \geq 1 \\ \frac{1}{2}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

- No tree-level ggh interaction $\Rightarrow$ no local counter term to absorb divergence, must be finite!

Small m_q limit: $\tau \to 0, A(\tau) \to 0$

- Dominated by heavy quark loops e.g. top (bottom)

Large m_q limit: $\tau \to \infty, A(\tau) \to 1$

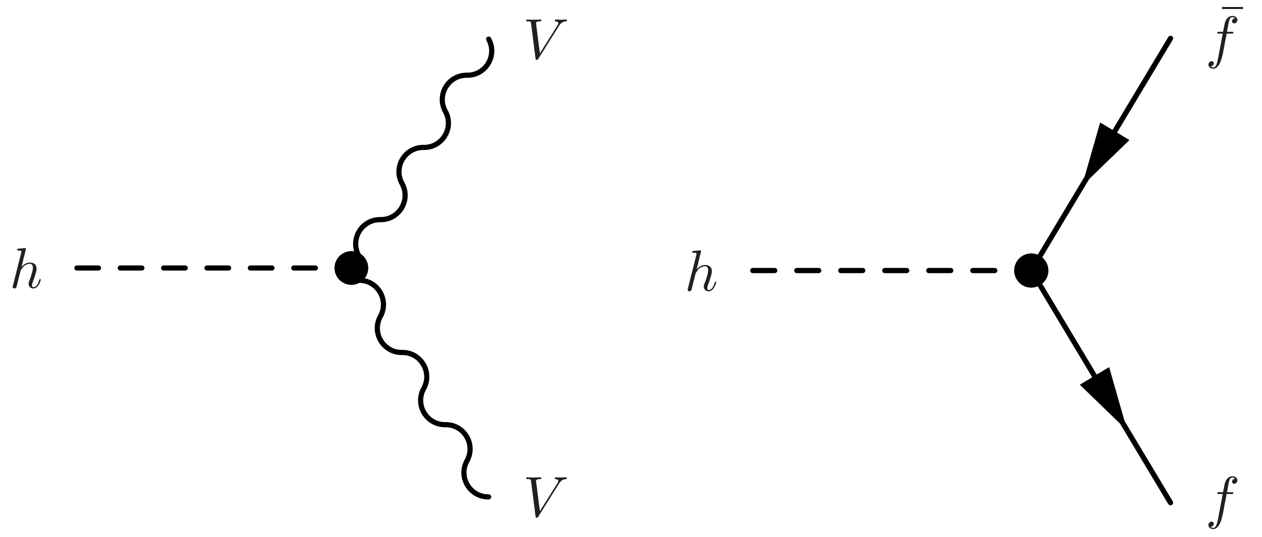
- Non-decoupling behaviour!

Coupling ∝ mass

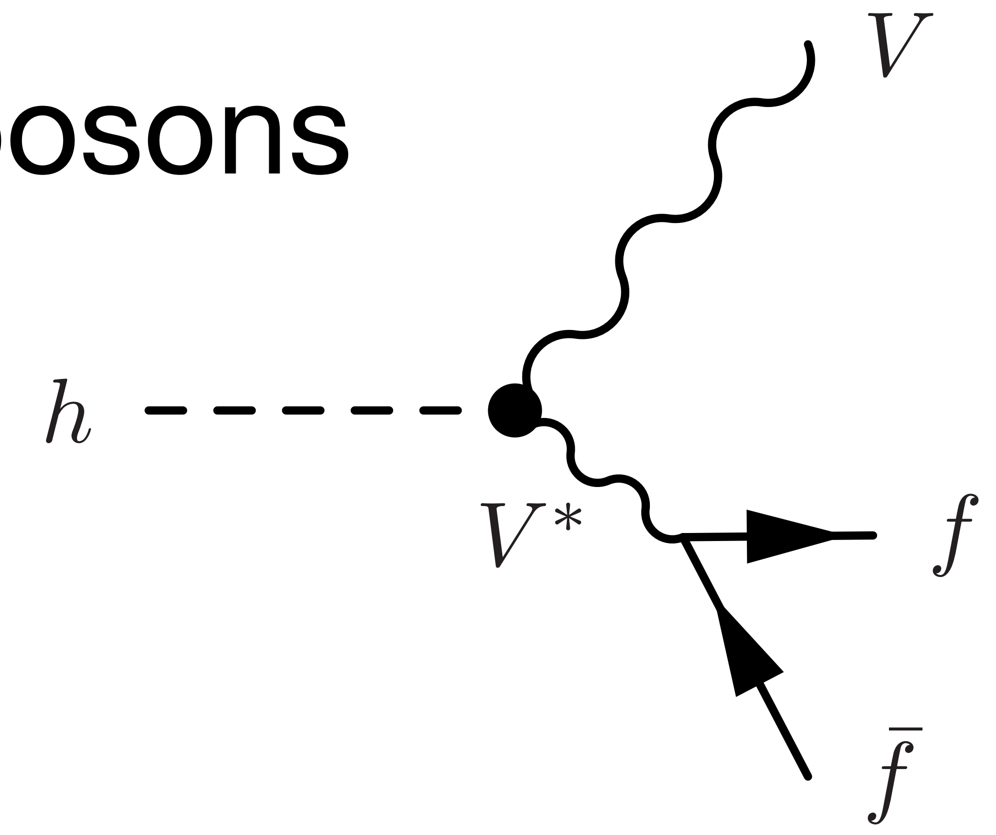
$m_q \to \infty \Leftrightarrow y_q \to \infty$

Precise $gg \to h$ measurement used to rule out 4th generation of quarks that gets mass from EWSB!

Higgs decay



Tree level: Higgs decays into pairs of SM fermions & W/Z bosons

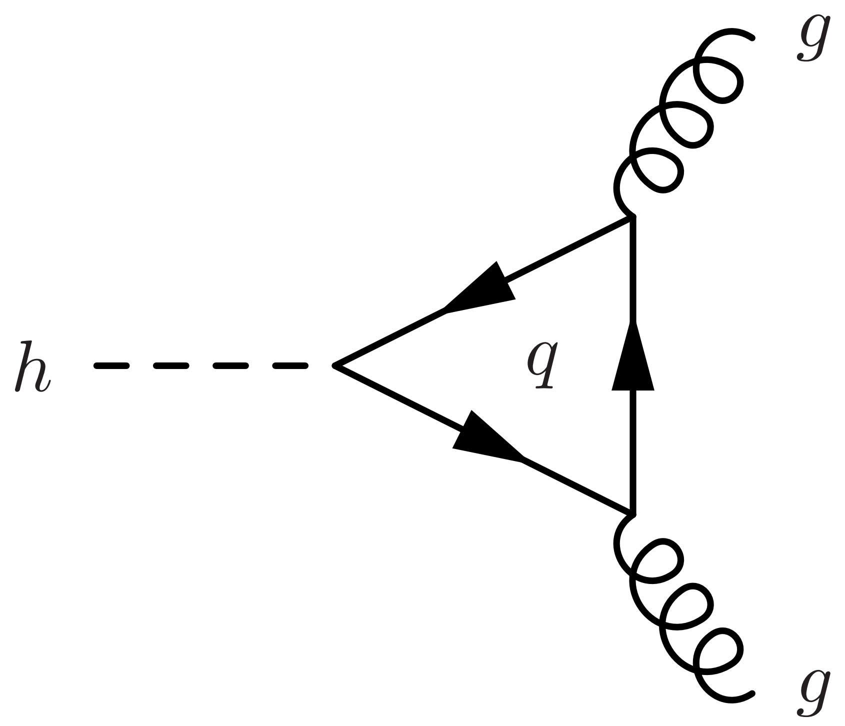


- For $m_h < 2m_V$, off shell contributions can be relevant

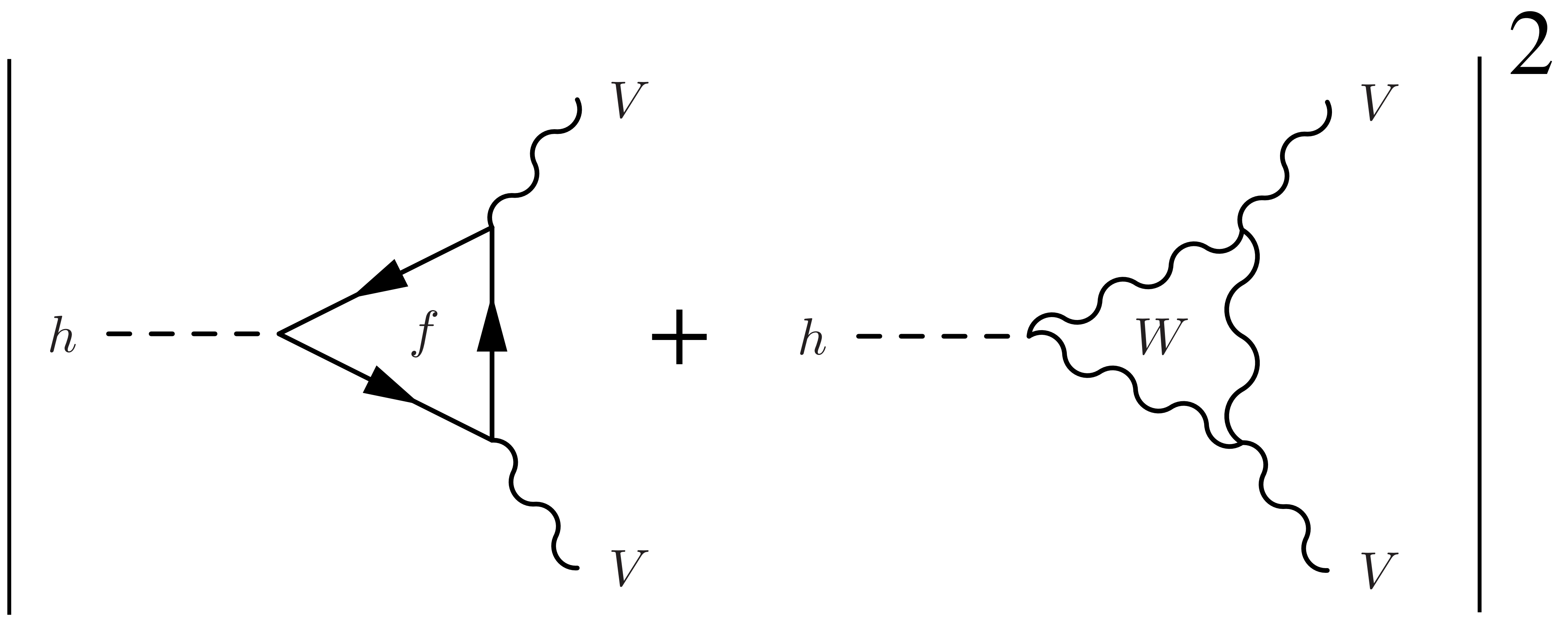
Loop level: decays to massless gauge bosons

- $gg, \gamma\gamma$ & $Z\gamma$
- c.f. gluon fusion & non-decoupling behavior

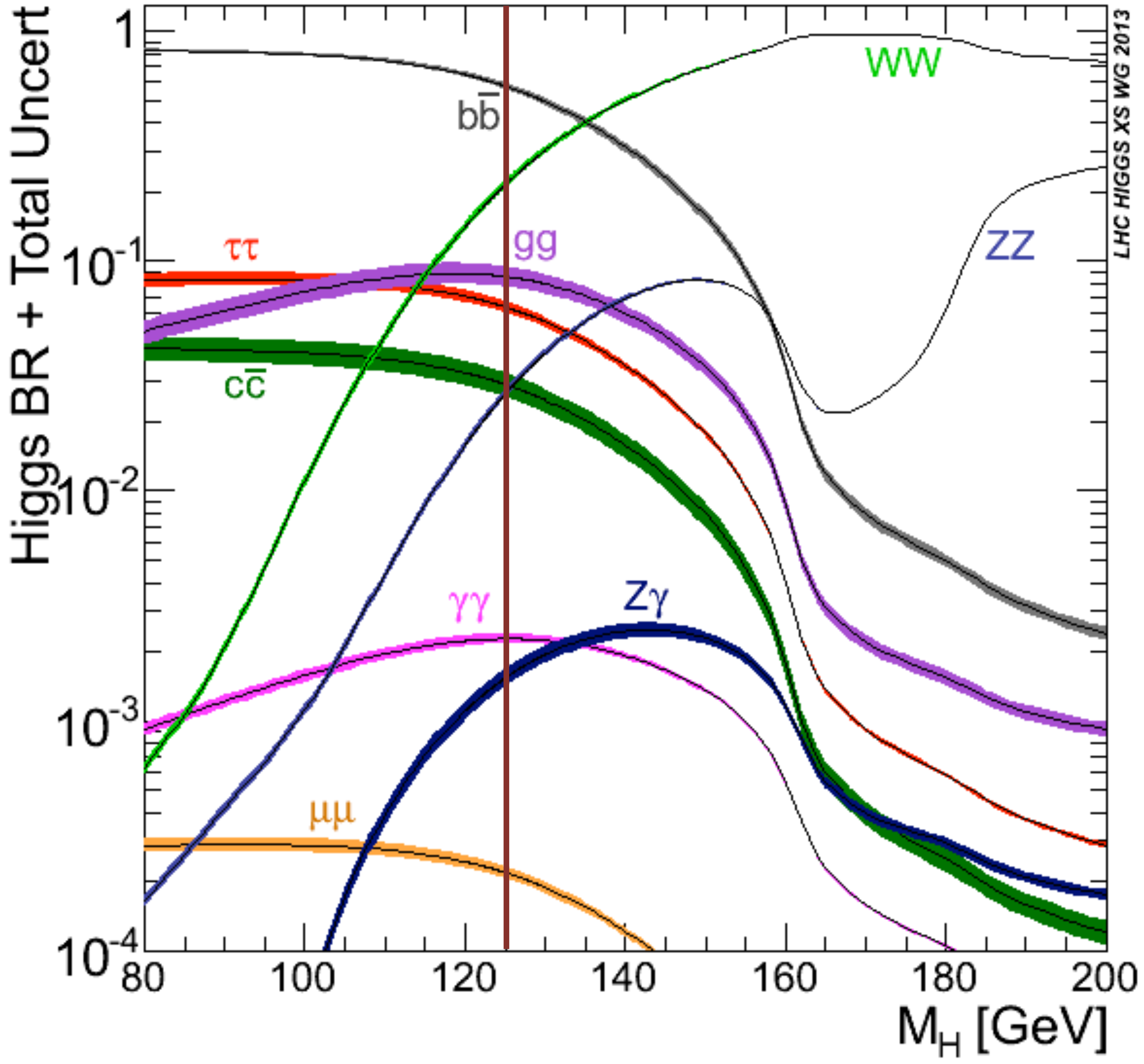
$h \to gg$



$h \to \gamma\gamma / Z\gamma$



Higgs branching fractions

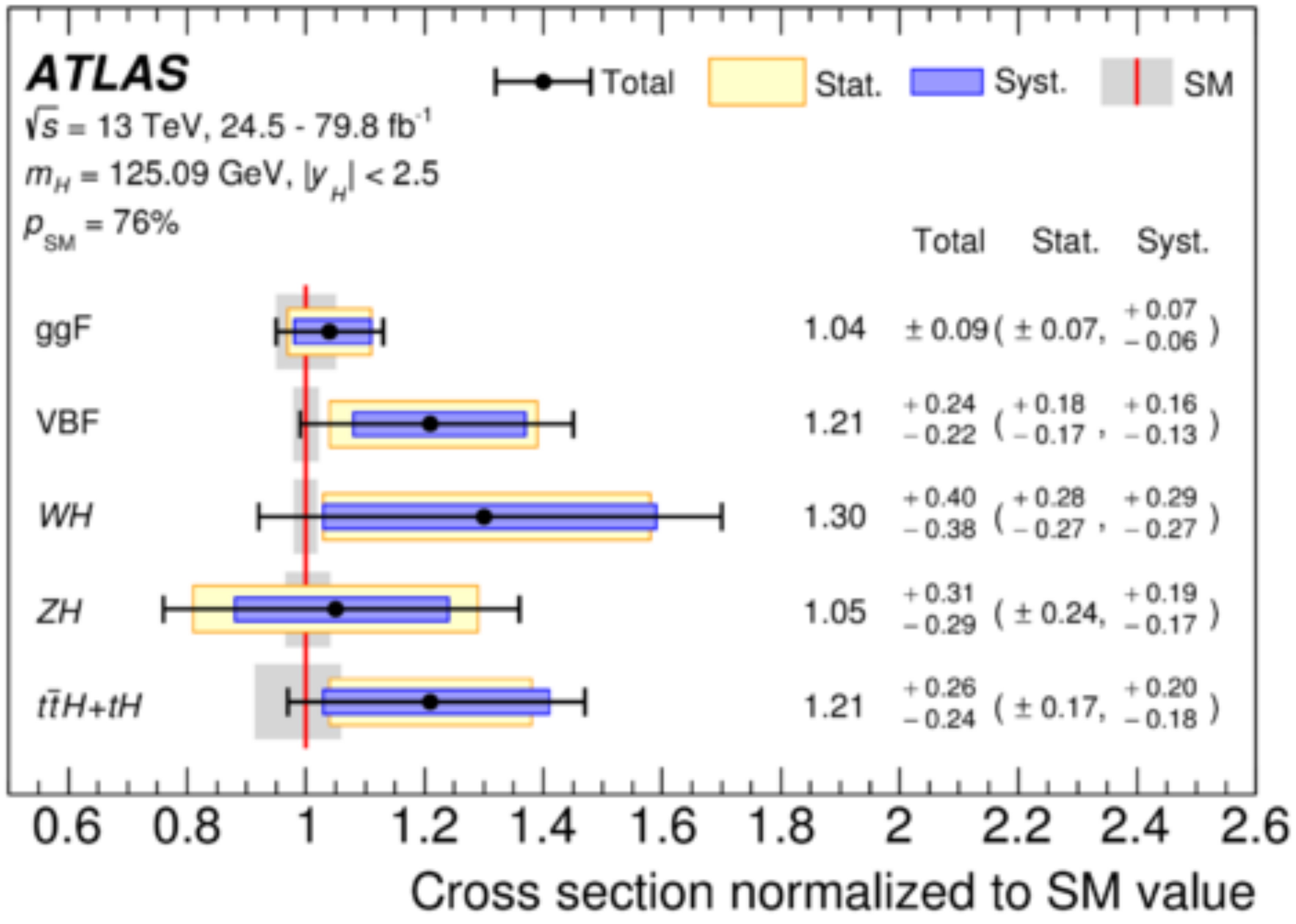


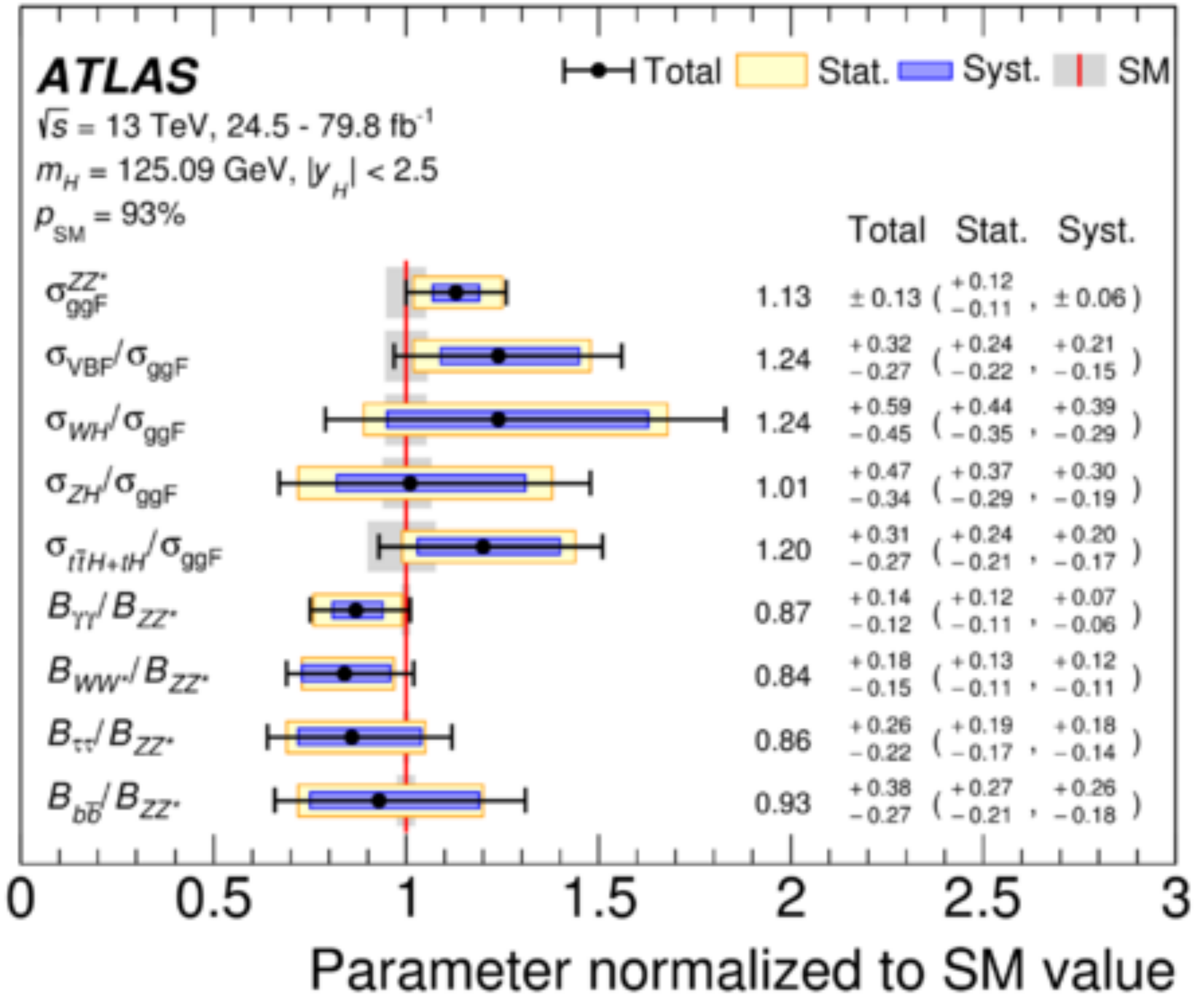
- Wealth of decay channels for 125 GeV, rich phenomenology
- Very narrow! $\Gamma \sim 4\,\mathrm{MeV}$
- Diphoton and $ZZ^* \to 4\ell$ final state are the cleanest signatures
- Hadronic channels are hard at the LHC because of the backgrounds, but accessible through boosted techniques!

Higgs measurements

'Signal strengths' $\mu_i = \sigma^{\text{exp.}}/\sigma^{\text{th.}}_{\text{SM}}$

$\mu^{\text{prod}}_{\text{tot}} = 1.002 \pm 0.057$





Characterising the Higgs boson

We measure combinations of Higgs production modes & decay channels

- Use narrow width approximation (c.f. Z boson discussion)

$$\sigma_{pp}(ii \to h \to ff) \simeq \sigma_{pp}(ii \to h) \times BR(h \to ff) + O\left(\Gamma_h^2/m_h^2\right)$$
$$= \sigma_{pp}(ii \to h) \times \Gamma(h \to ff)/\Gamma_h$$

- Define 'modifiers' for SM Higgs couplings, $\kappa_i = y_i/y_i^{\mathrm{SM}}$:

$$\sigma_{ii\to h} = \kappa_i^2\,\sigma_{ii}^{\mathrm{SM}}, \qquad \Gamma_{ff} = \kappa_f^2\,\Gamma_{h\to ff}^{\mathrm{SM}}, \qquad \Gamma_h = \kappa_h^2\,\Gamma_h^{\mathrm{SM}}$$

$$\Rightarrow \quad \sigma_{pp}(ii \to h \to ff) = \sigma_{pp}^{\mathrm{SM}}(ii \to h \to ff) \cdot \boxed{\frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_h^2}} \qquad \mu_{ii\to ff} = \frac{\sigma_{ii\to ff}}{\sigma_{ii\to ff}^{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_h^2}$$

Characterising the Higgs boson

Effective $gg/\gamma\gamma/Z\gamma$ coupling modifiers

$$\kappa_g^2(\kappa_t,\kappa_b) = \frac{\Gamma_{h\to gg}}{\Gamma^{SM}_{h\to gg}} = \frac{\hat{\sigma}_{gg\to h}}{\hat{\sigma}^{SM}_{gg\to h}} \qquad \kappa^2_{\gamma/Z\gamma}(\kappa_t,\kappa_b,\kappa_Z,\kappa_W) = \frac{\Gamma_{h\to\gamma\gamma/Z\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma/Z\gamma}}$$

- Can be considered independent or determined by tree level κ_i's

BSM interpretations: Higgs-scalar mixing

- Scalar singlet with Higgs portal coupling

$$\mu_S\, S_0\,(H^\dagger H) \to \mu_S\, v\, S_0\, h_0$$

$$\begin{pmatrix} h \\ S \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_0 \\ S_0 \end{pmatrix}$$

$$\Rightarrow \quad \kappa_i = \cos\alpha < 1$$

- two-Higgs-Doublet Model (2HDM)

$$\kappa_V = \sin(\beta-\alpha) \qquad \text{‘Type I’}$$

$$\kappa_u = \kappa_d = \kappa_l = \cos(\beta-\alpha)/\tan\beta + \sin(\beta-\alpha)$$

$$\kappa_V = \sin(\beta-\alpha) \qquad \text{‘Type II’}$$

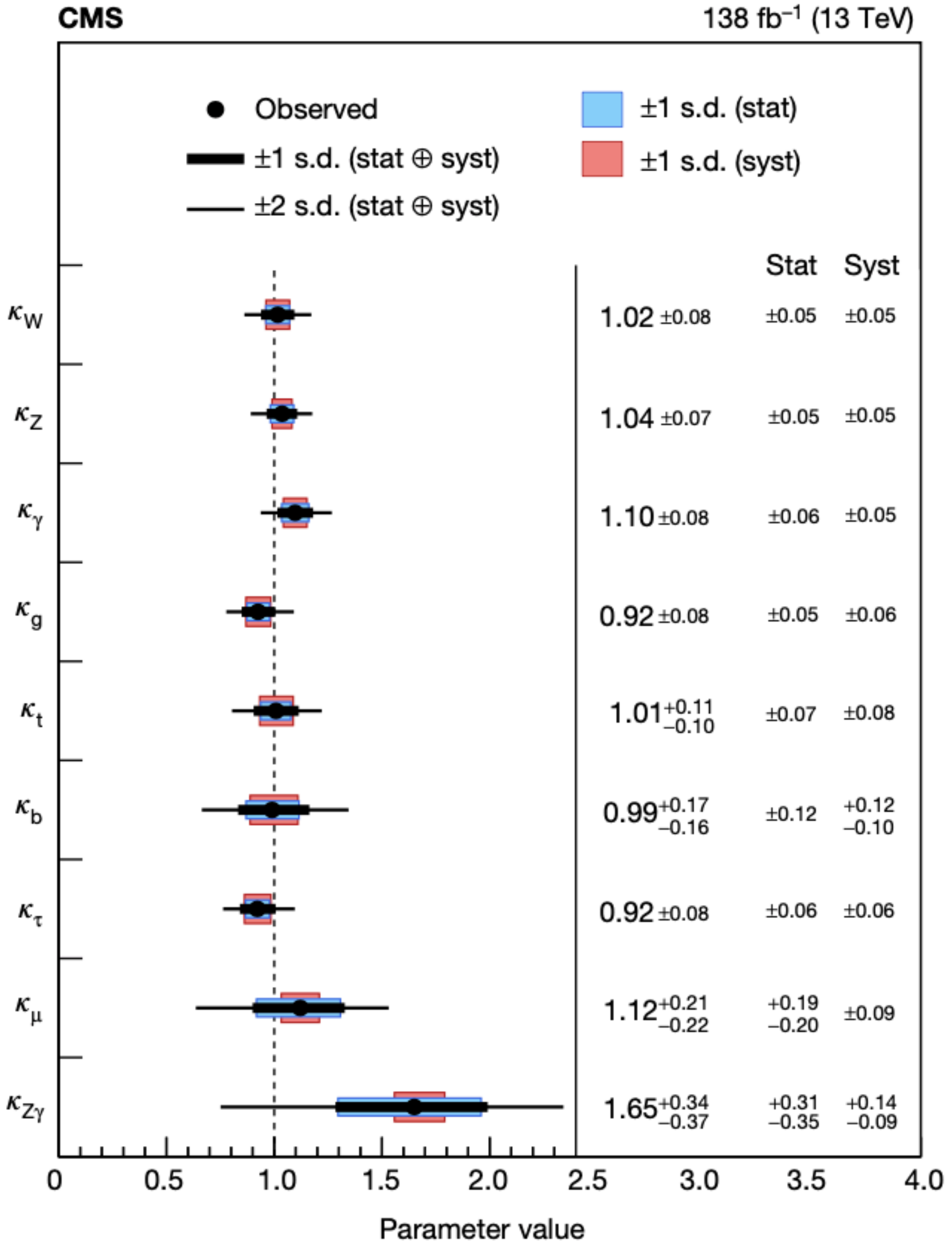
$$\kappa_u = \cos(\beta-\alpha)/\tan\beta + \sin(\beta-\alpha)$$

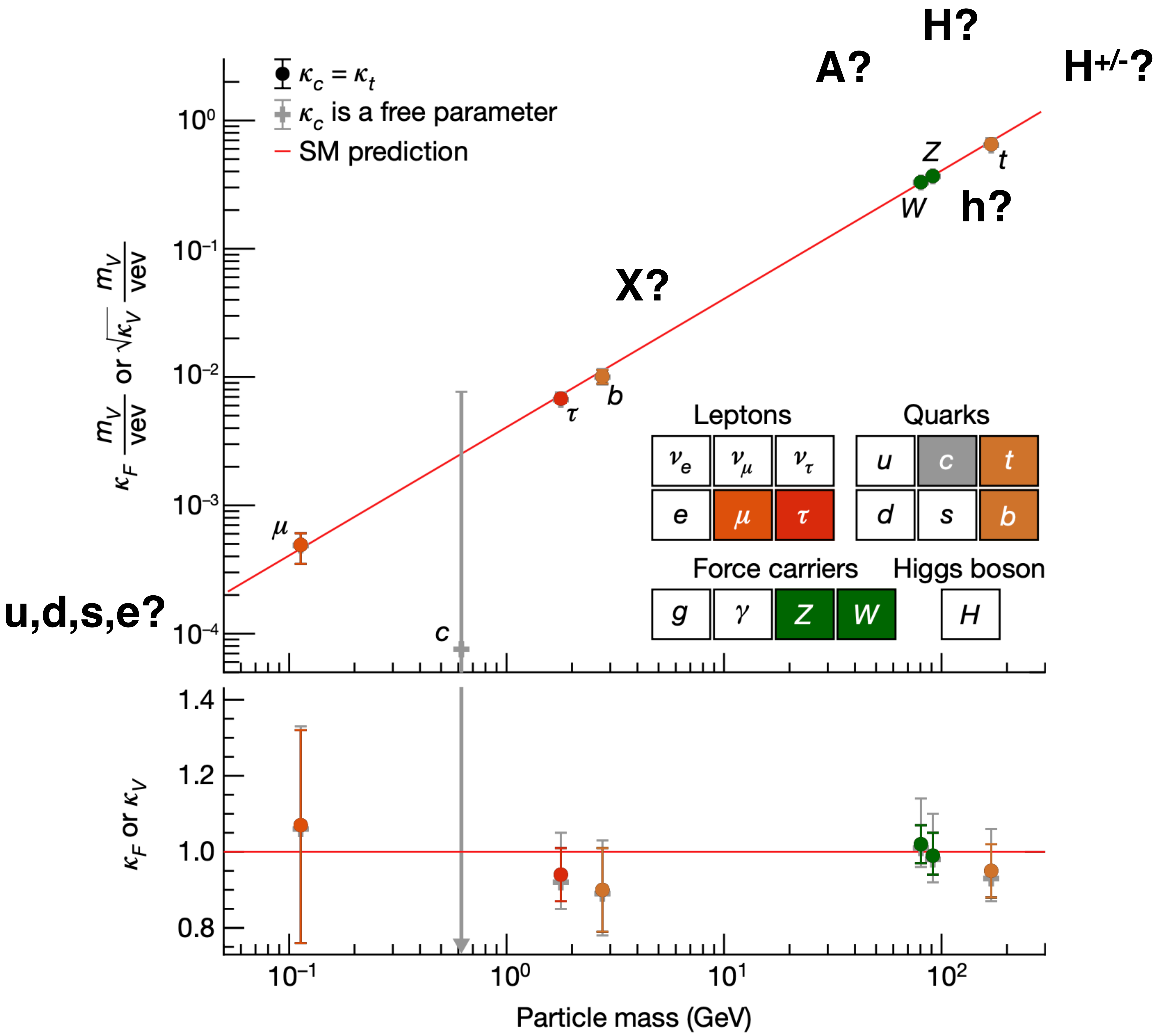
$$\kappa_d = \kappa_l = \sin(\beta-\alpha) - \cos(\beta-\alpha)\,\tan\beta$$

Knowns and Unknowns

[ATLAS; 2207.00092]

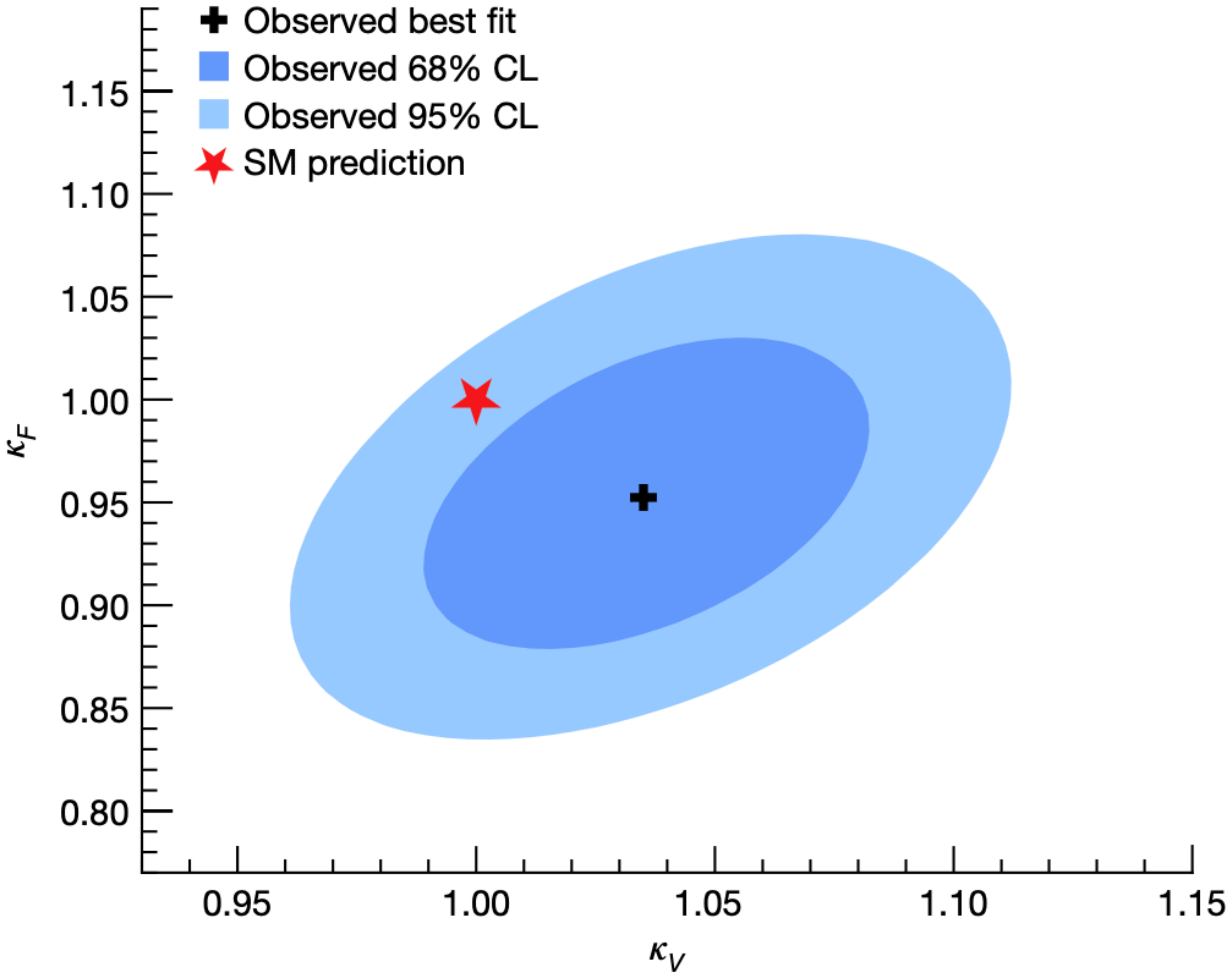
[CMS; 2207.00043]





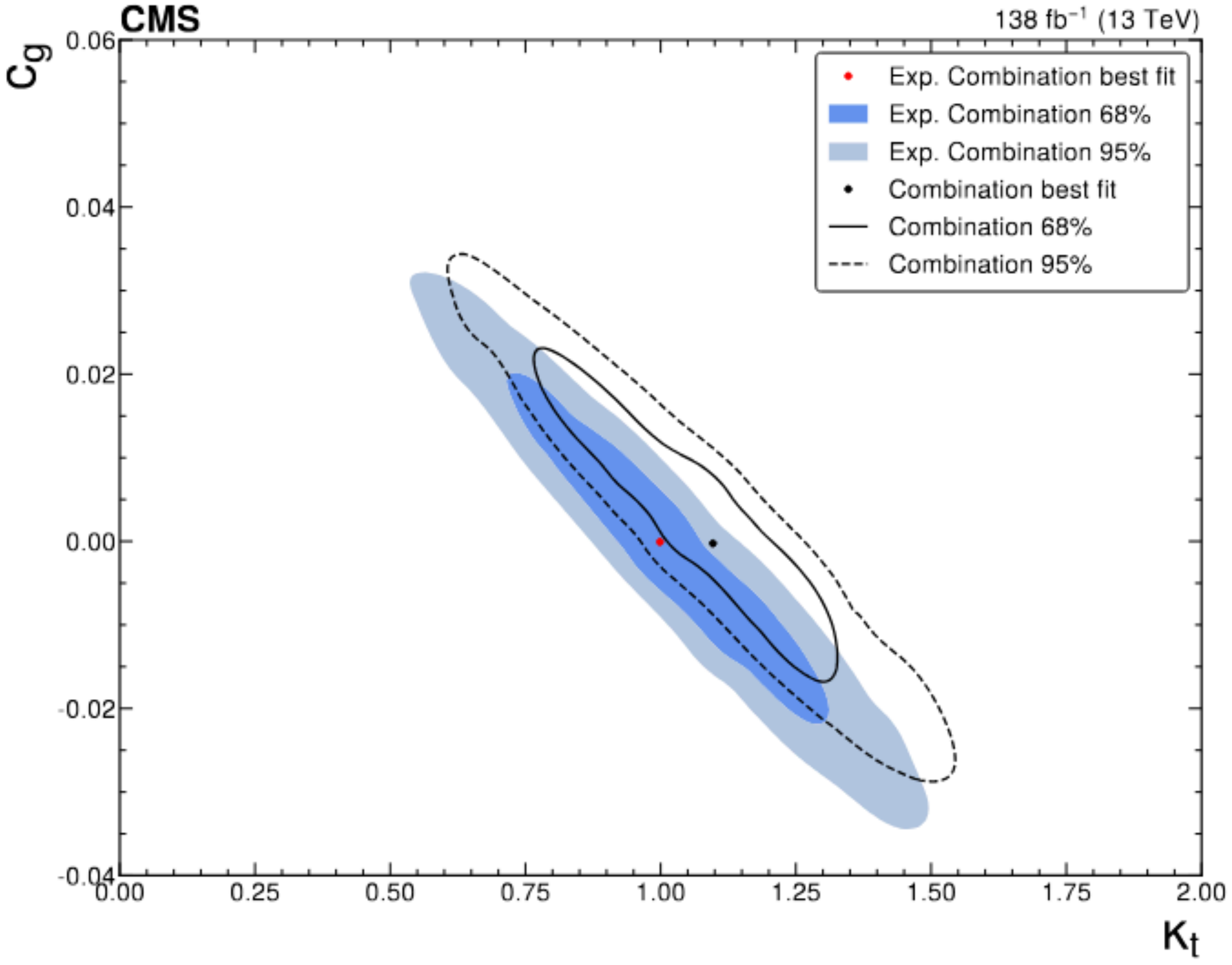
Correlations

[ATLAS; 2207.00092]



$$\kappa_{t,b,c,\ldots} = \kappa_F \qquad \kappa_{Z,W} = \kappa_V$$

[CMS; 2504.13081]



Bound on new scalars

Singlet

$$\kappa_i = \cos\alpha$$

$$\mu_i = \cos^2\alpha$$

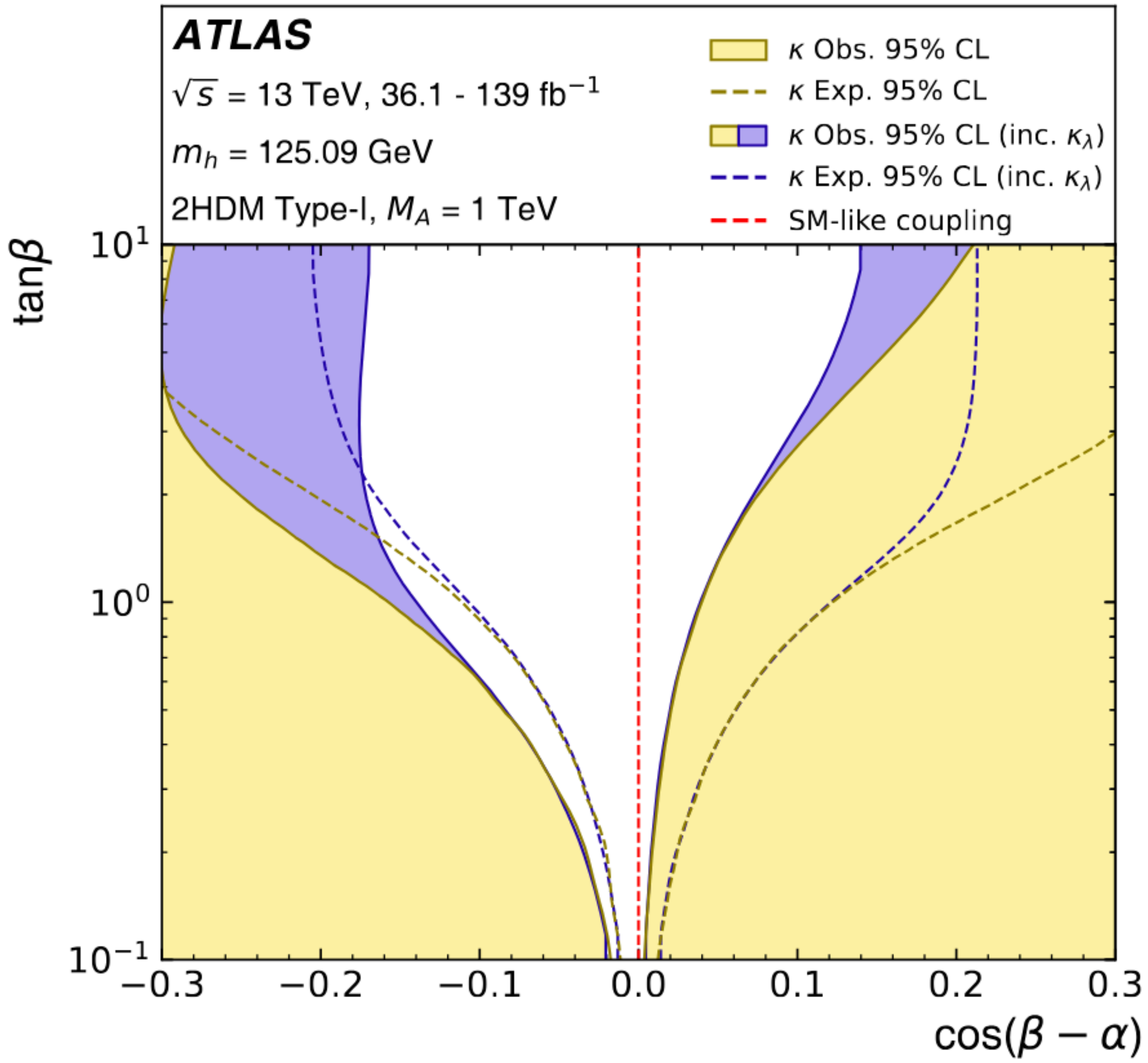
(BRs unchanged)

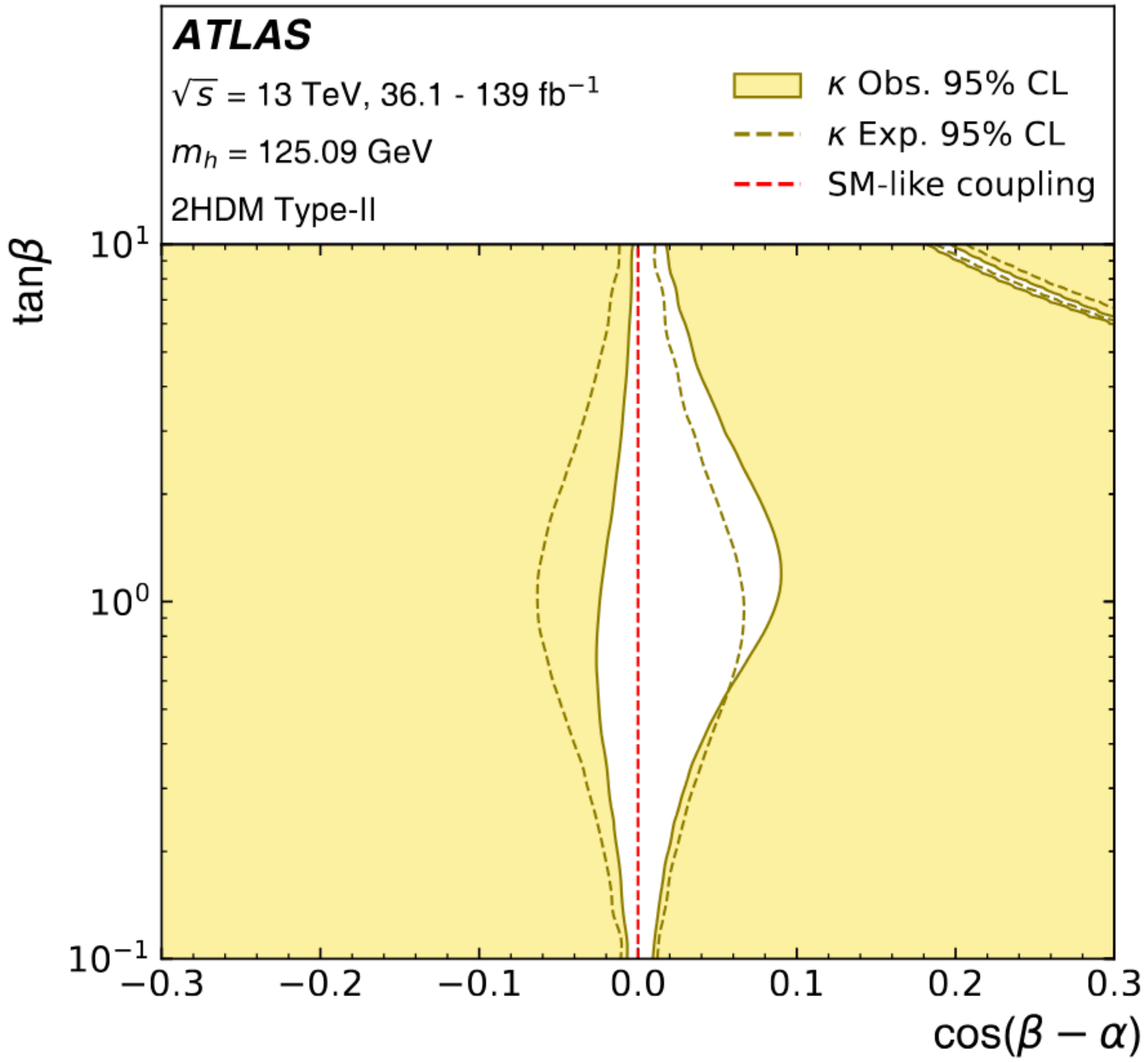
$$\mu_{\text{tot}}^{\text{prod}} = 1.002 \pm 0.057$$

$$\Rightarrow \quad \sin\alpha \lesssim 0.2$$

2HDM

[ATLAS; 2402.05742]





Independent of mass of new states

Beyond kappa-framework?

Pros
- Simple
- Intuitive

Cons
- Incomplete
- Theoretically ill-defined

Can we do better?
- More model-independent
- Can be mapped to wide class of BSM

Incompleteness

- Restricted to SM couplings only
- No exotic Higgs production or decays into BSM states
- Defined in terms of on-shell Higgs production & decay
- Only predicts modified total rates: LHC has much more differential information to offer

BSM coupling structures

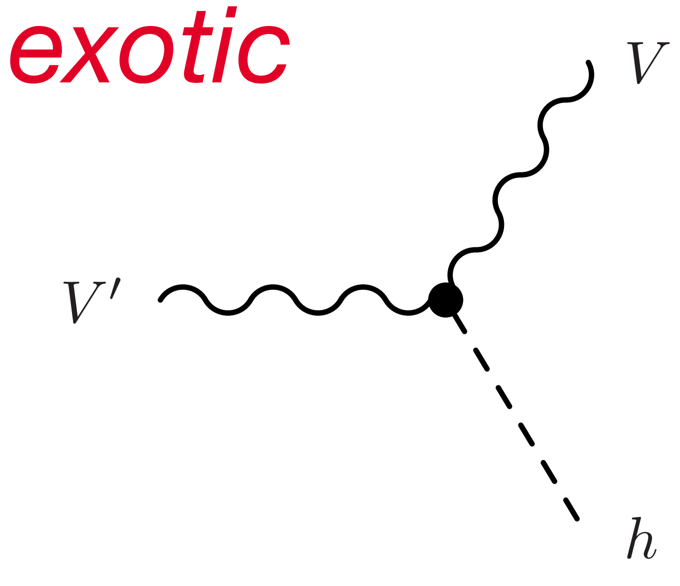
SM: $hV_\mu V^\mu$

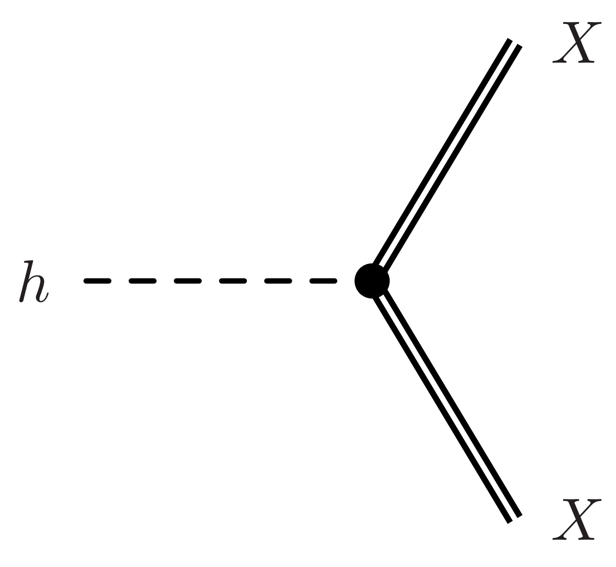
BSM: $hV_{\mu\nu}V^{\mu\nu}$?

CPV: $hV_{\mu\nu}\tilde{V}^{\mu\nu}$?

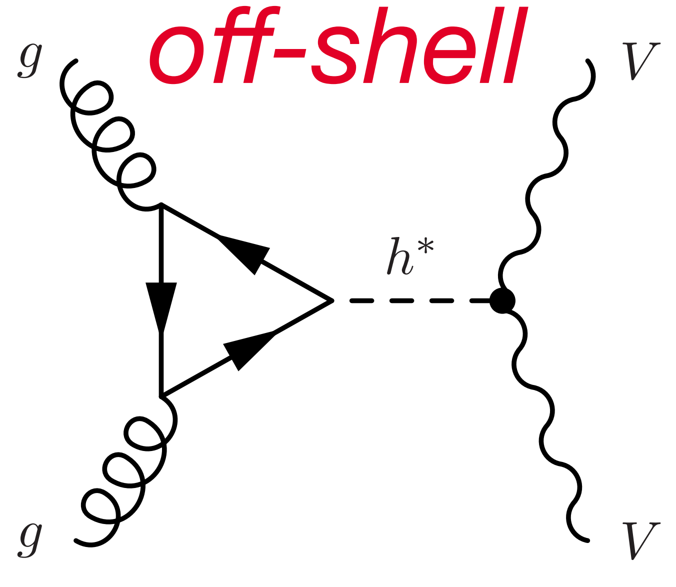
e.g. heavy quark loop

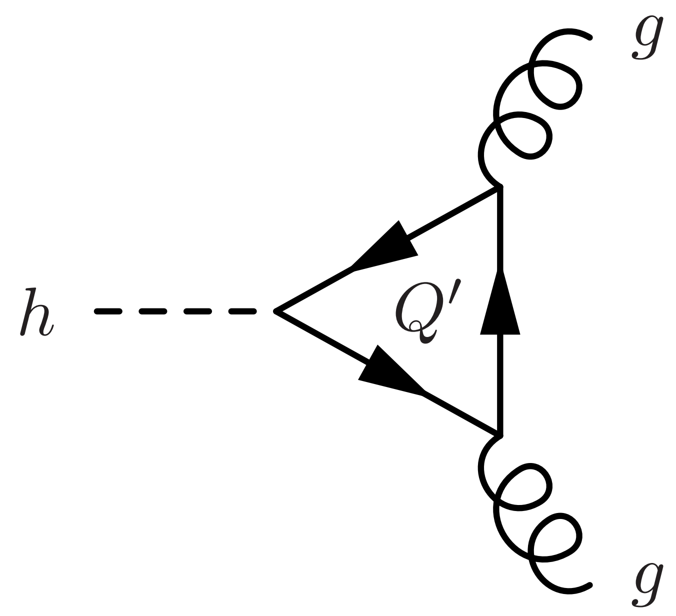
exotic





off-shell





$\Rightarrow \quad f(q^2, M_Q^2)\cdot h\, G^A_{\mu\nu}G^{\mu\nu}_A$

Beyond kappa-framework?

Theoretical consistency

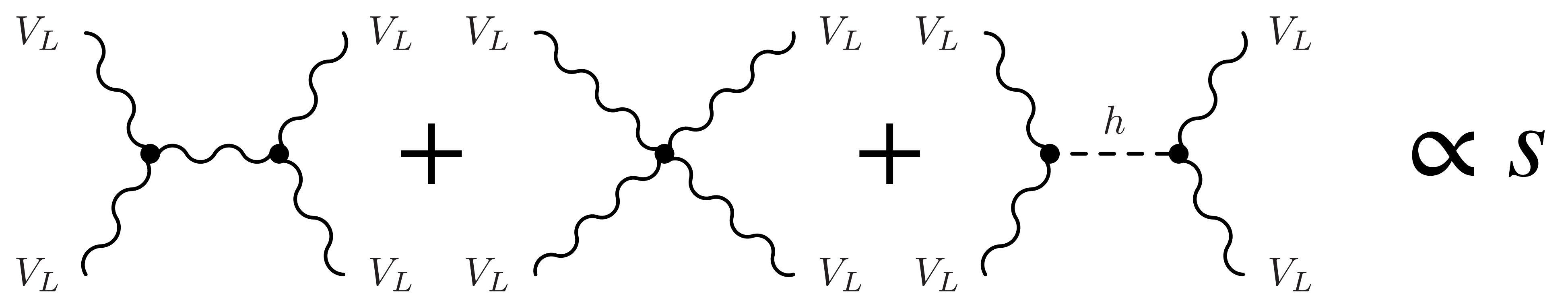
- Its not a theory! no Lagrangian, Feynman rules

Lets try…

$$\mathscr{L}_\kappa = \sum_f \kappa_f \frac{m_f}{v} h \bar{f}_L f_R + \sum_{V=W,Z} \kappa_V \frac{m_V^2}{v} h V^\mu V_\mu + \sum_{X=g,\gamma,Z\gamma} \frac{\kappa_X}{v} h X^{\mu\nu} X_{\mu\nu}$$

Modifies couplings that exist after EWSB: not $SU(2)$ gauge invariant

- EW loop corrections not possible
- Breaking relations between masses & couplings
  $\Rightarrow$ unitarity violation
- κ_X have enhanced momentum dependence
  $\Rightarrow$ beyond total rates



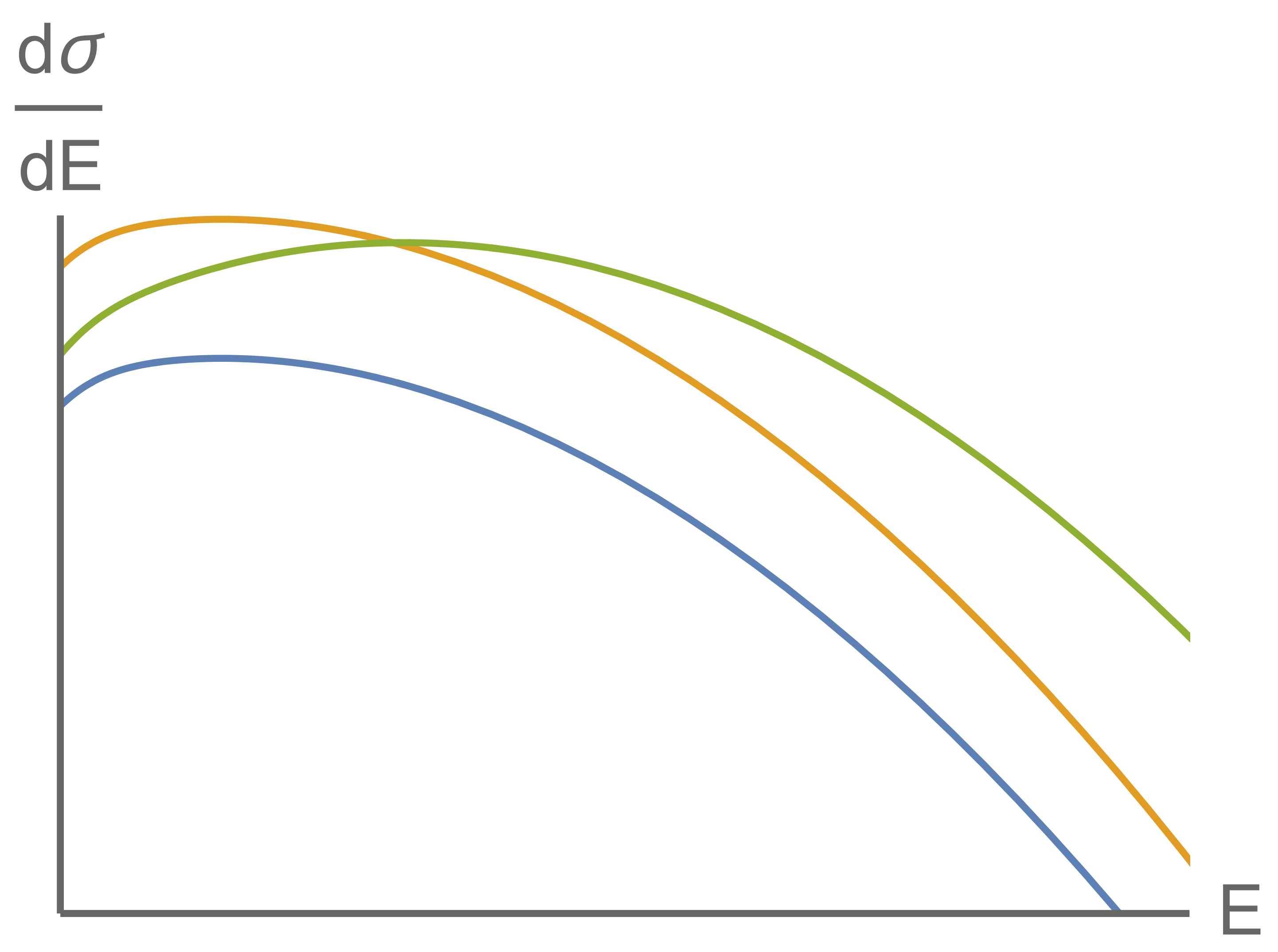
Need EFT framework, see later

Differential measurements

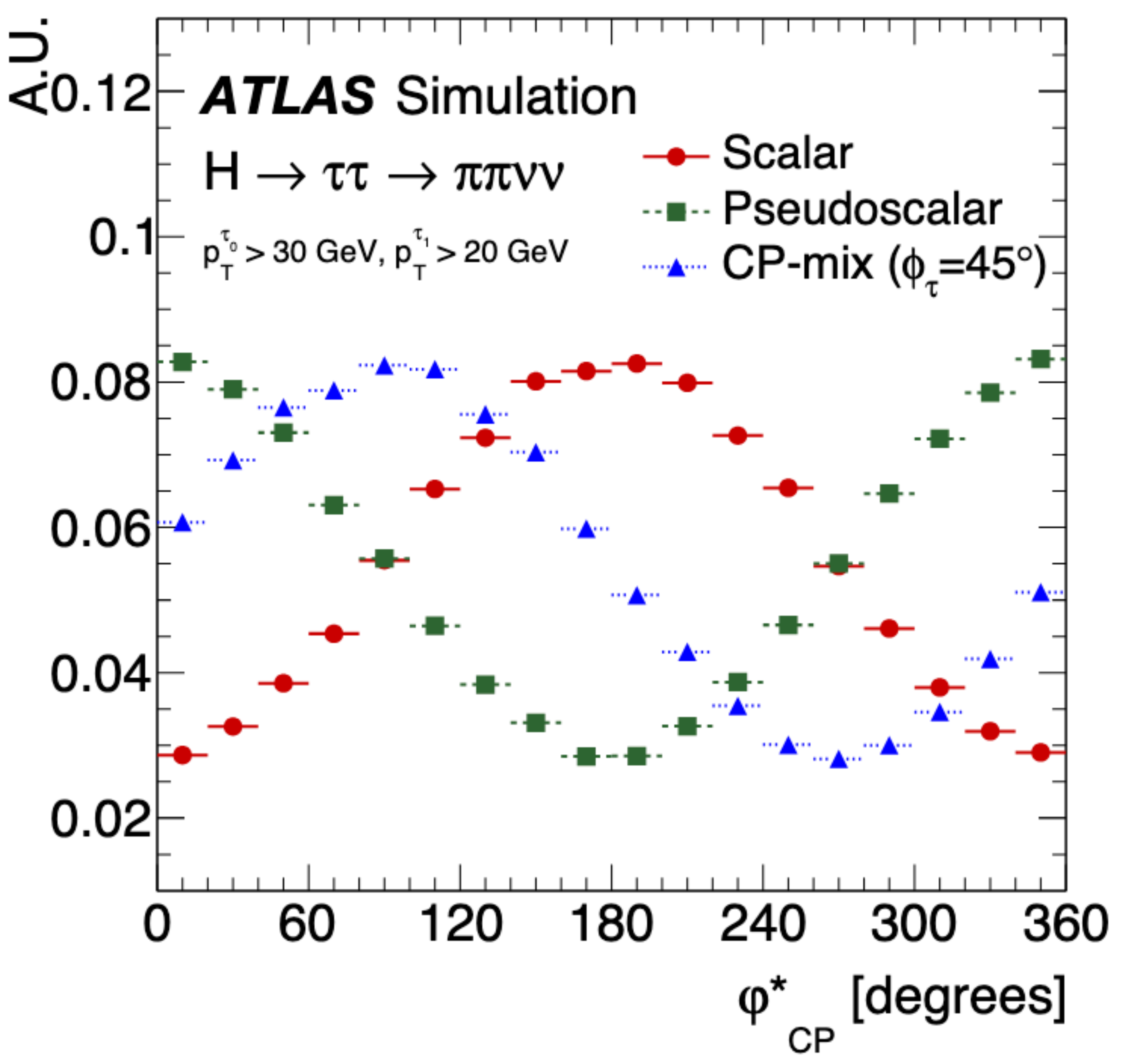
$$\sigma_{pp\to X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \cdot \mathscr{L}_{ab}(s,\tau) \cdot \left[\hat{s}\hat{\sigma}_{ab}(\hat{s}, p_X)\right]$$

Hadron colliders scan partonic invariant mass: $0 \leq \sqrt{\hat{s}} \leq \sqrt{s}$

- Measure energy dependence of scattering
- Angular dependence ⇒ spin information



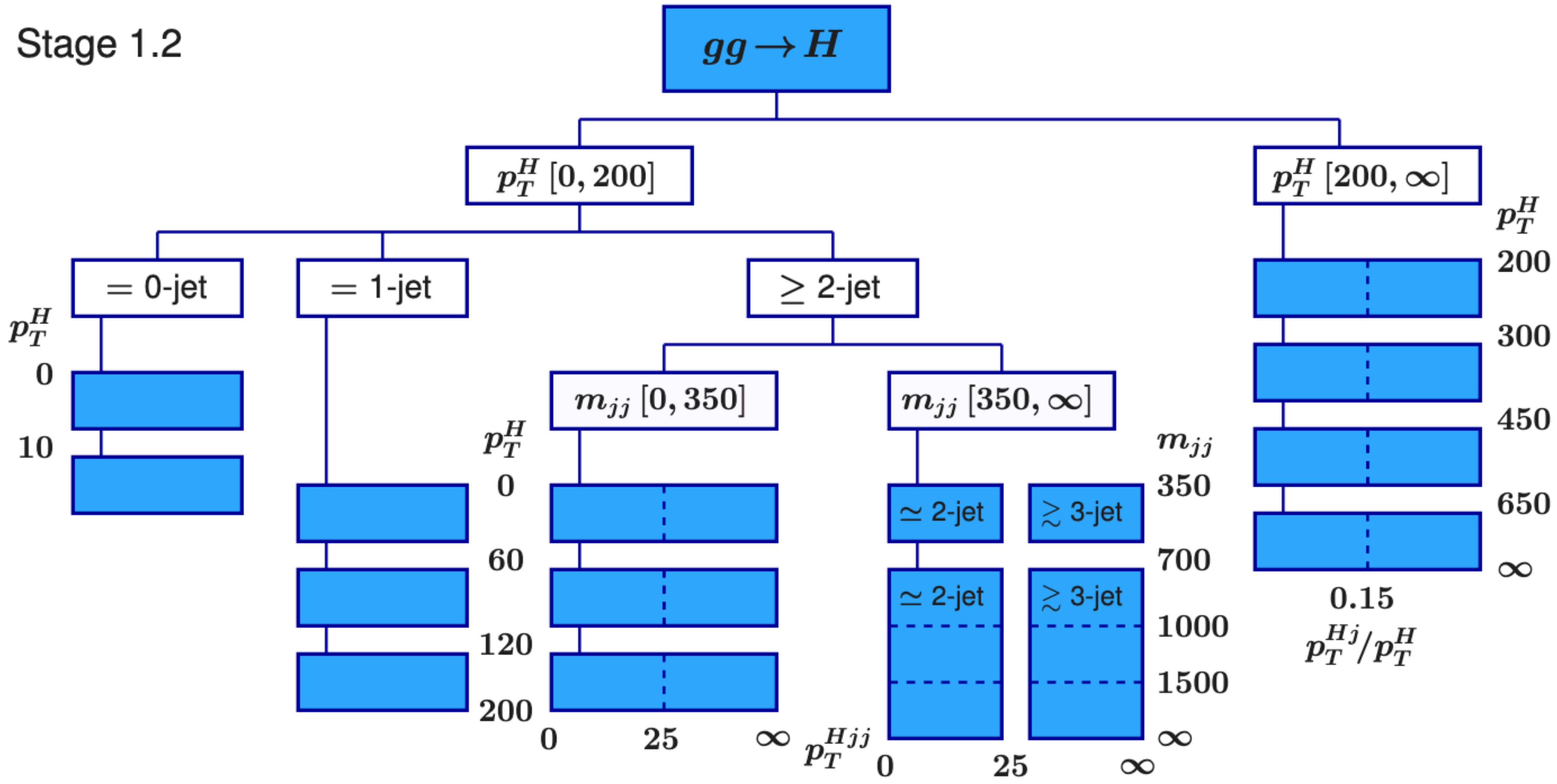
[ATLAS; 2212.05833]

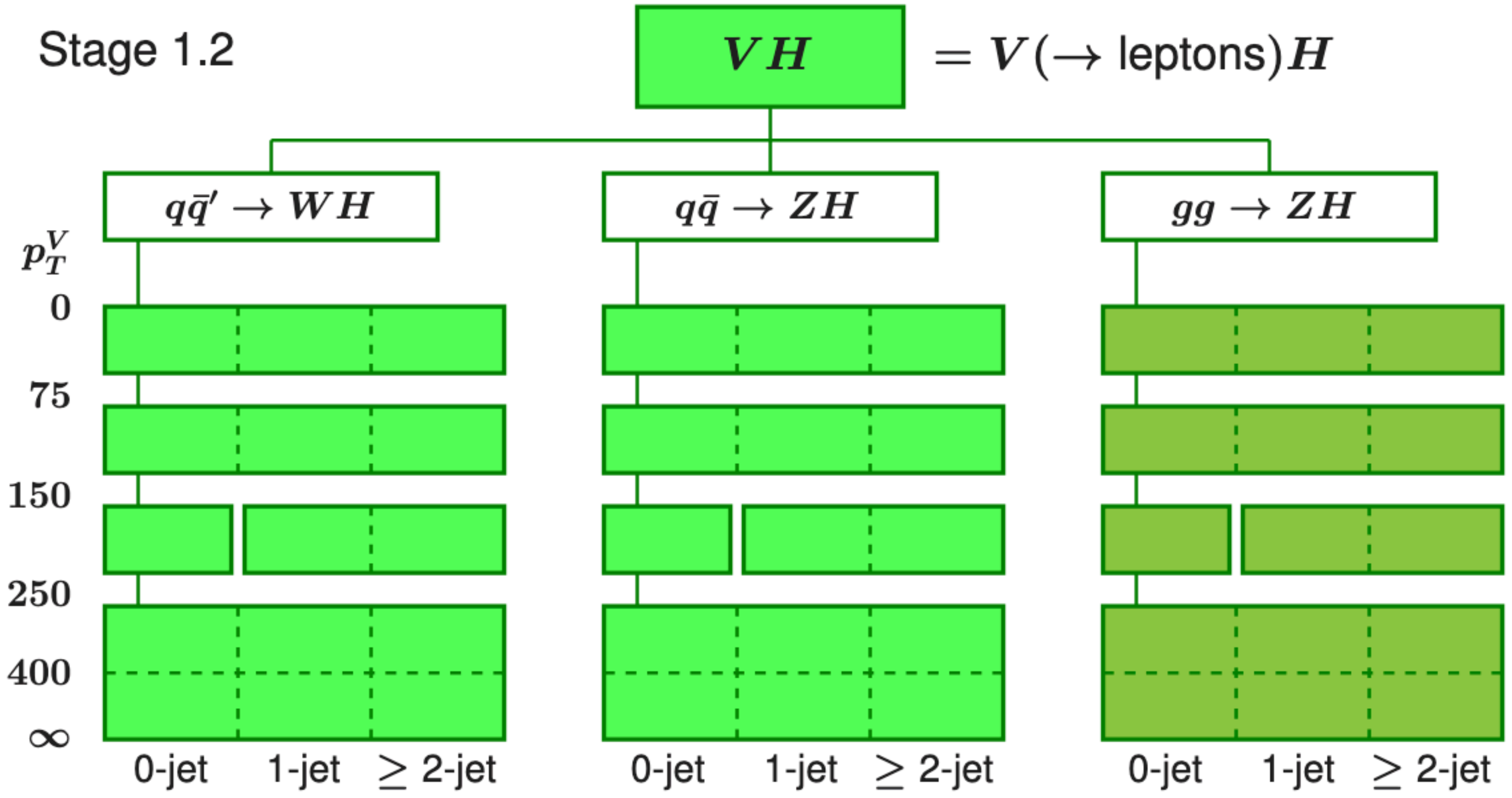


Simplified Template Cross Sections (STXS)

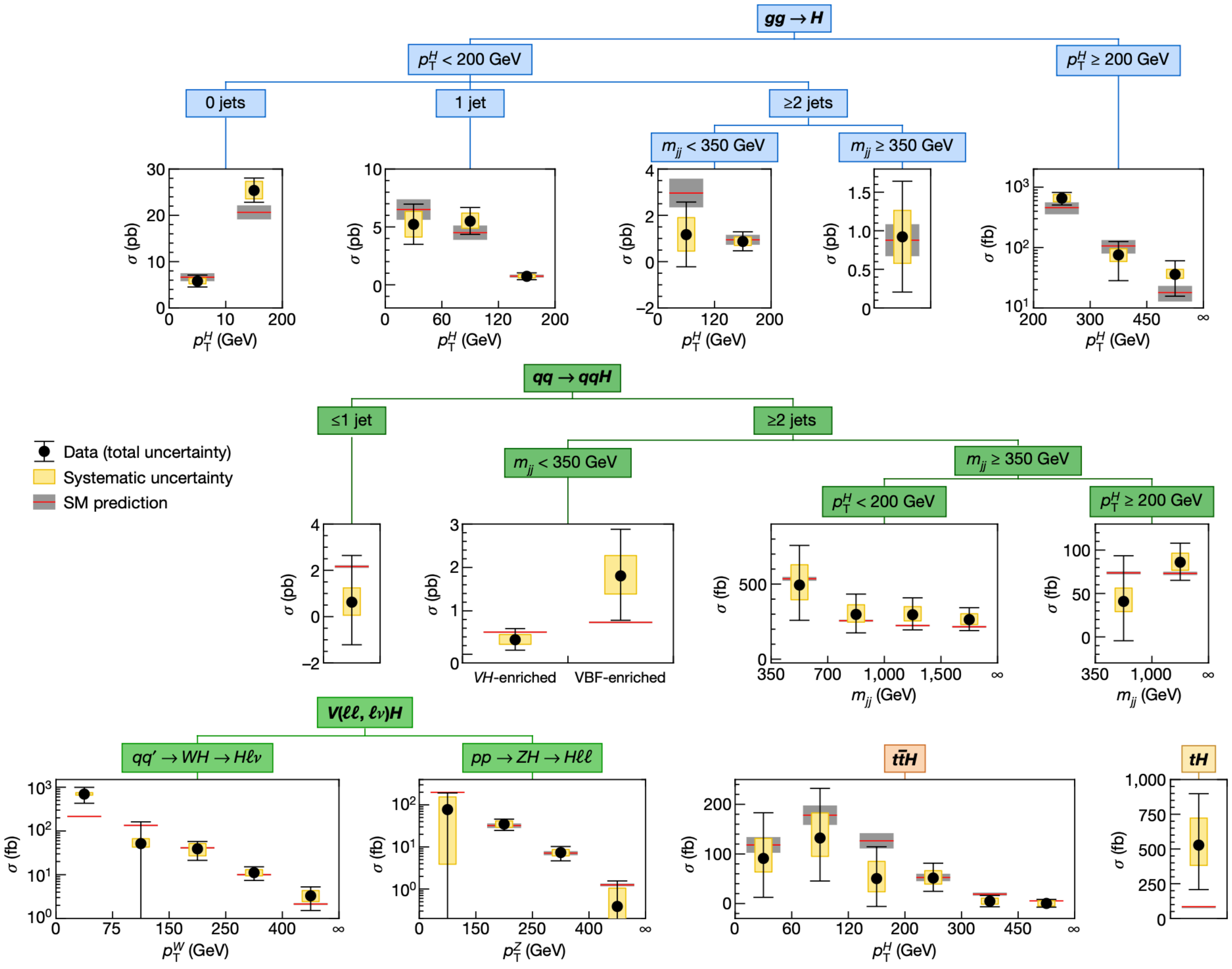
Intermediate stage between κ-framework & fully differential measurements

- Probe differential rates: p_T^h, p_T^V, jet multiplicity & kinematics
- Unified theoretical definitions $\Rightarrow$ global combination across production & decay modes





STXS

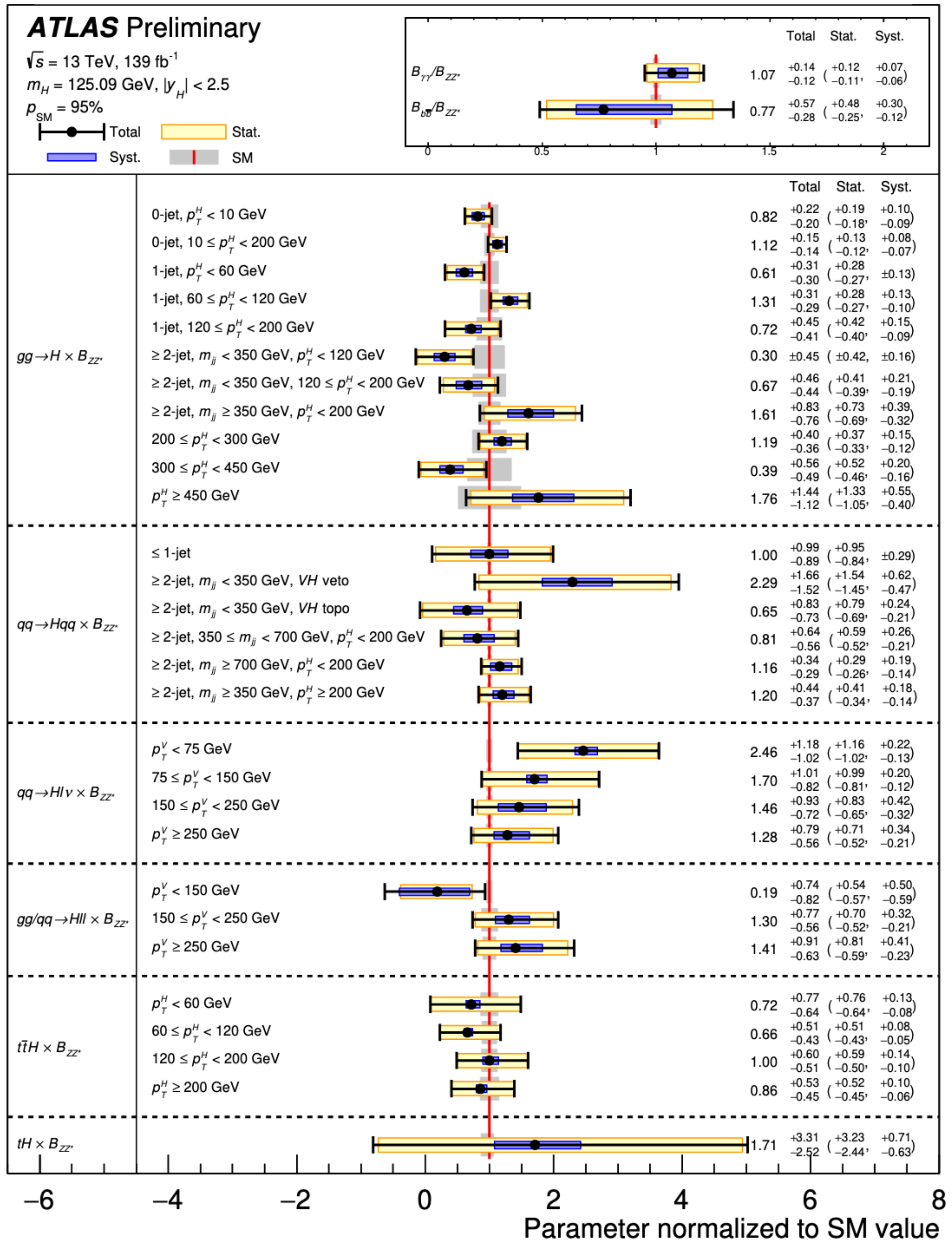


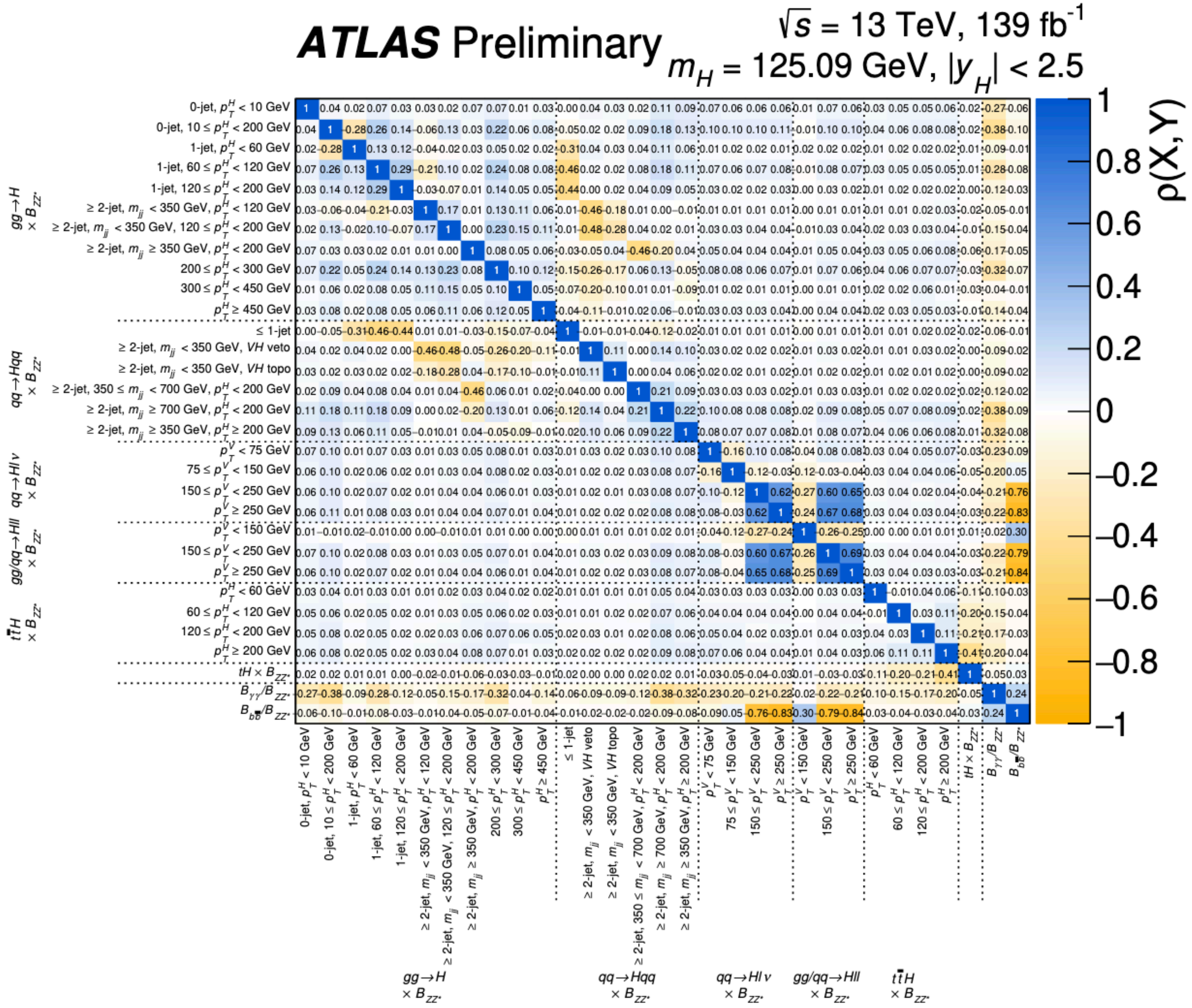
gg → H
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
0 jets
1 jet
≥2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
qq → qqH
≤1 jet
≥2 jets
m_{jj} < 350 GeV
m_{jj} ≥ 350 GeV
p_T^H < 200 GeV
p_T^H ≥ 200 GeV
Data (total uncertainty)
Systematic uncertainty
SM prediction
VH-enriched
VBF-enriched
V(ℓℓ, ℓν)H
qq′ → WH → Hℓν
pp → ZH → Hℓℓ
$t\bar{t}H$
tH
σ (pb)
σ (fb)
p_T^H (GeV)
m_{jj} (GeV)
p_T^W (GeV)
p_T^Z (GeV)

STXS *[ATLAS-CONF-2020-027]*

Correlation information crucial!

Interpret beyond κ's e.g. EFT





Higgs self-couplings

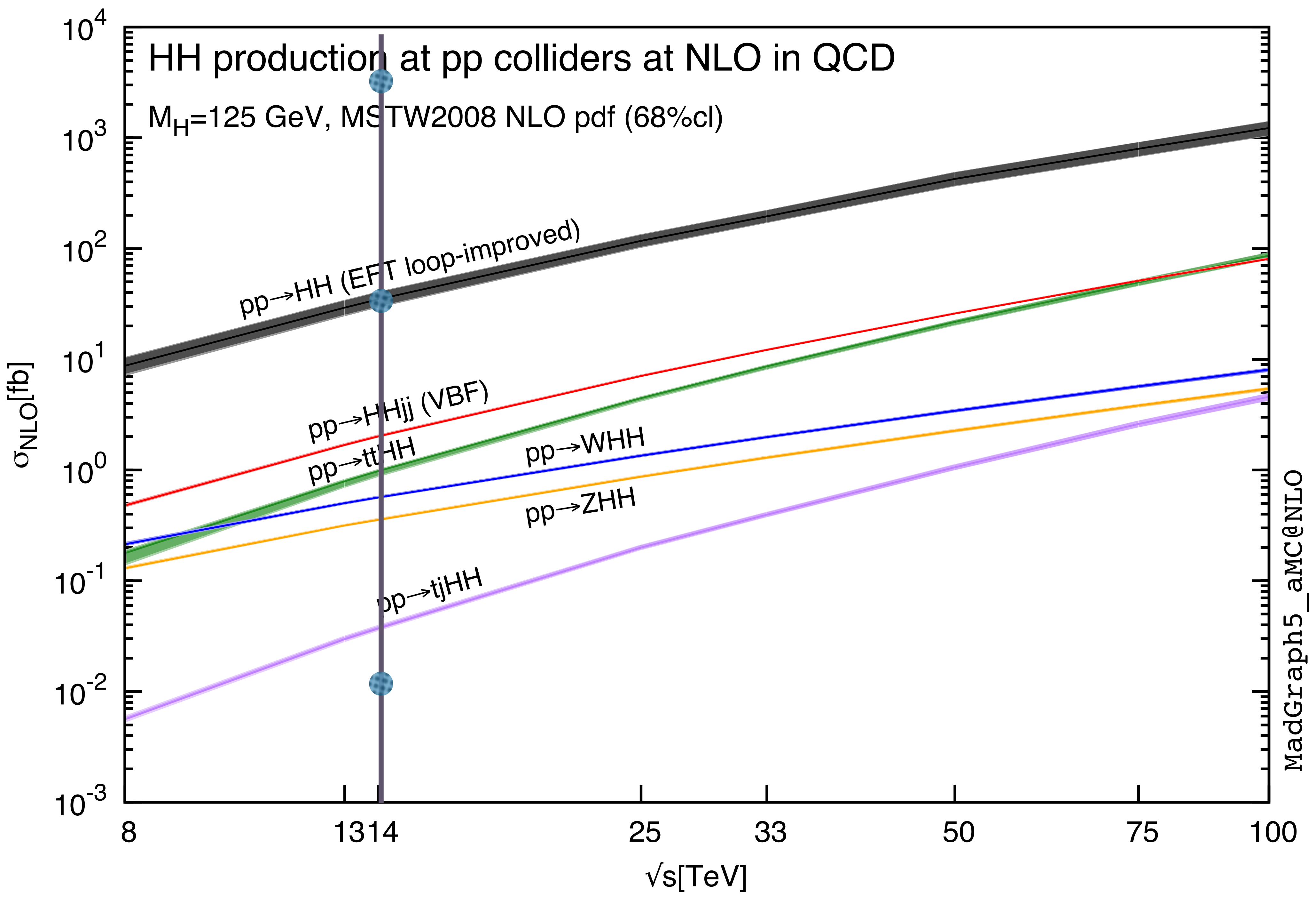
Fixed values in the SM

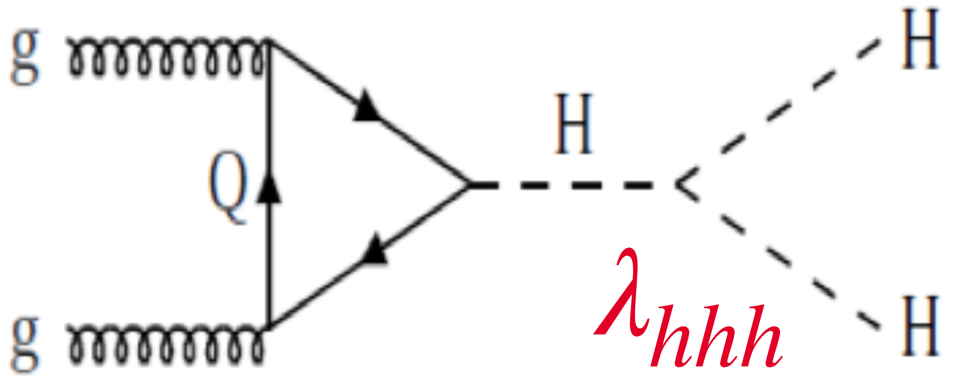
$$\lambda_{hhh} = \lambda_{hhhh} = \frac{m_h^2}{2v^2}$$

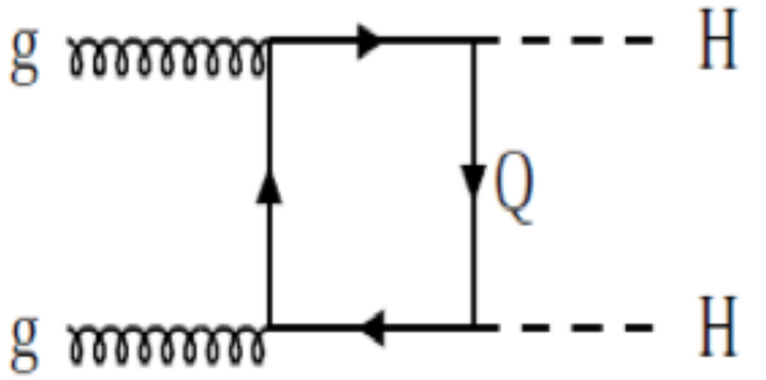
Higgs potential: $V(H) = \frac{1}{2}m_h^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4}\lambda_{hhhh} h^4$

- Measuring $\lambda_{hhh}, \lambda_{hhhh}$ tests the SM: How?

Multi-Higgs production







At 14 TeV from gg fusion:

$$\sigma_H = 55 \text{ pb}$$

$\times 10^{-3}$

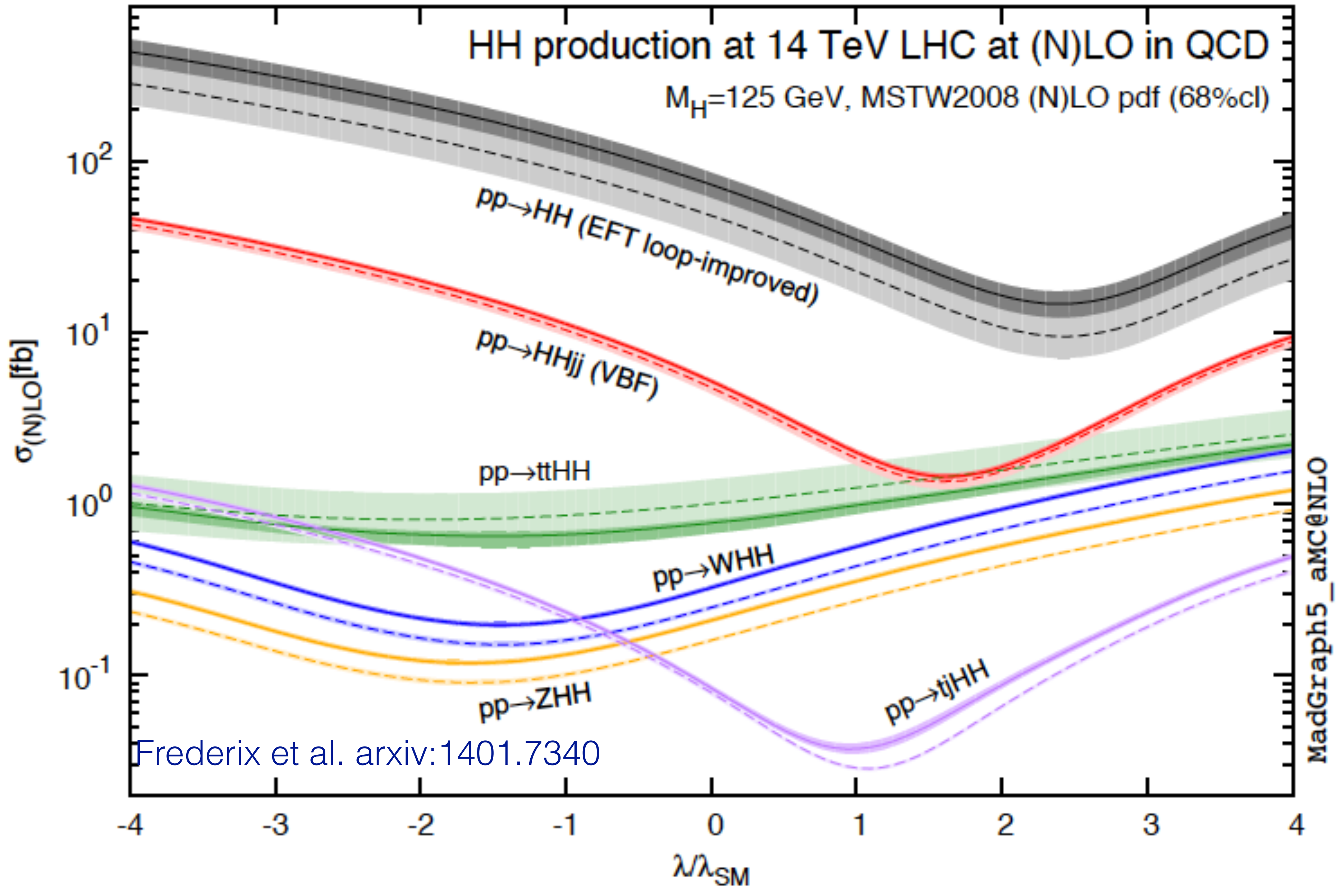
$$\sigma_{HH} = 44 \text{ fb}$$

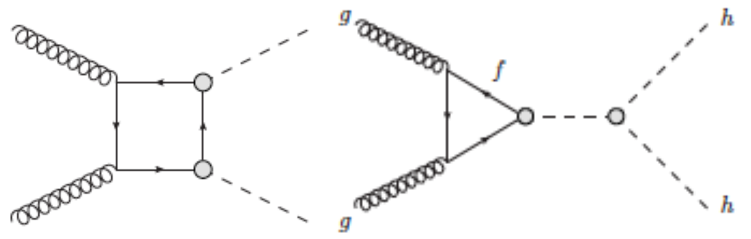
$\times 10^{-3}$

$$\sigma_{HHH} = 110 \text{ ab}$$

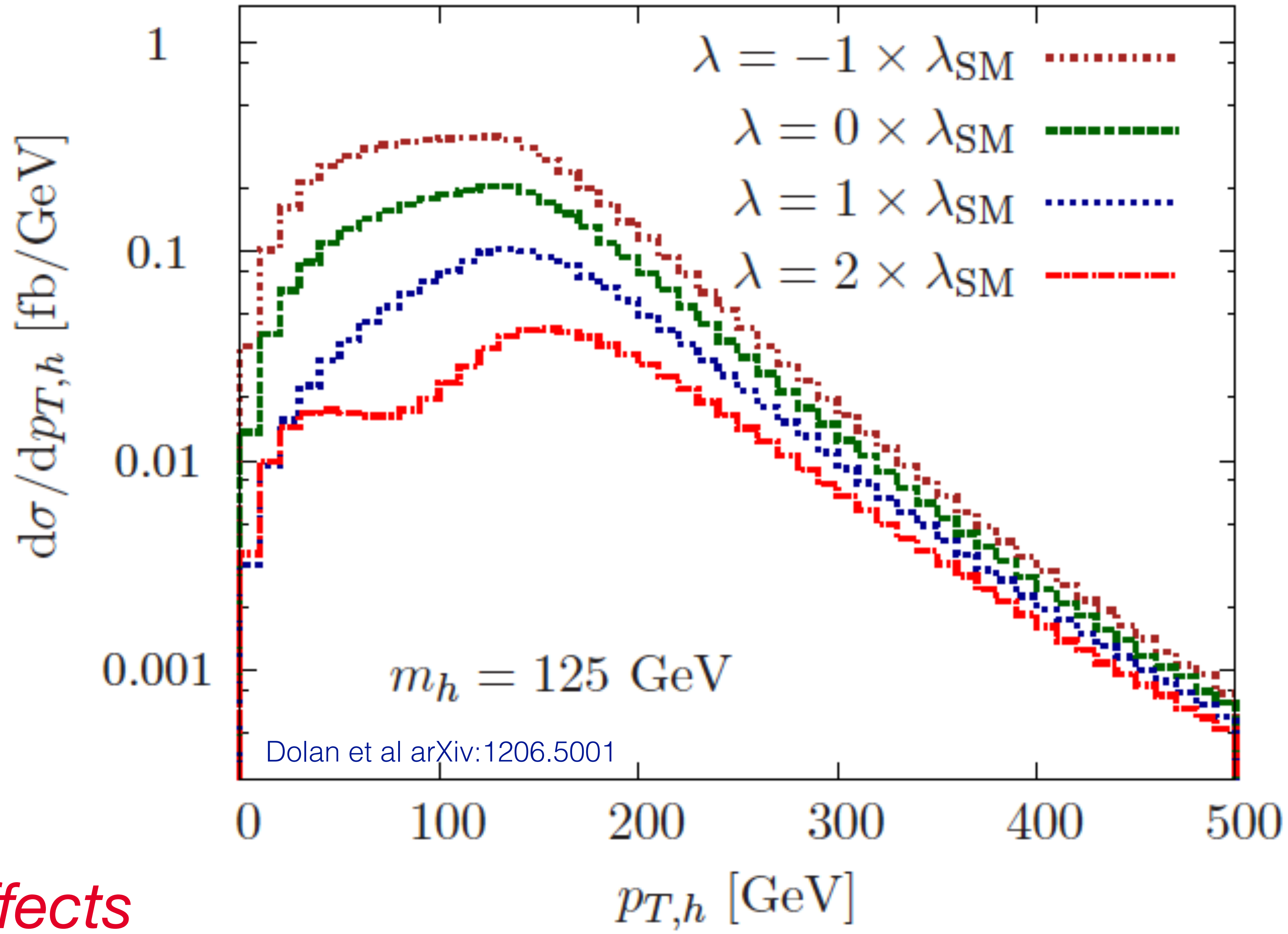
SM: not enough hhh events for HL-LHC ($3ab^{-1}$)

How to extract the Higgs self-coupling





$\sigma_{HH}(\kappa_\lambda, \kappa_t, \kappa_g)$



SM cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma(HH)$[fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$

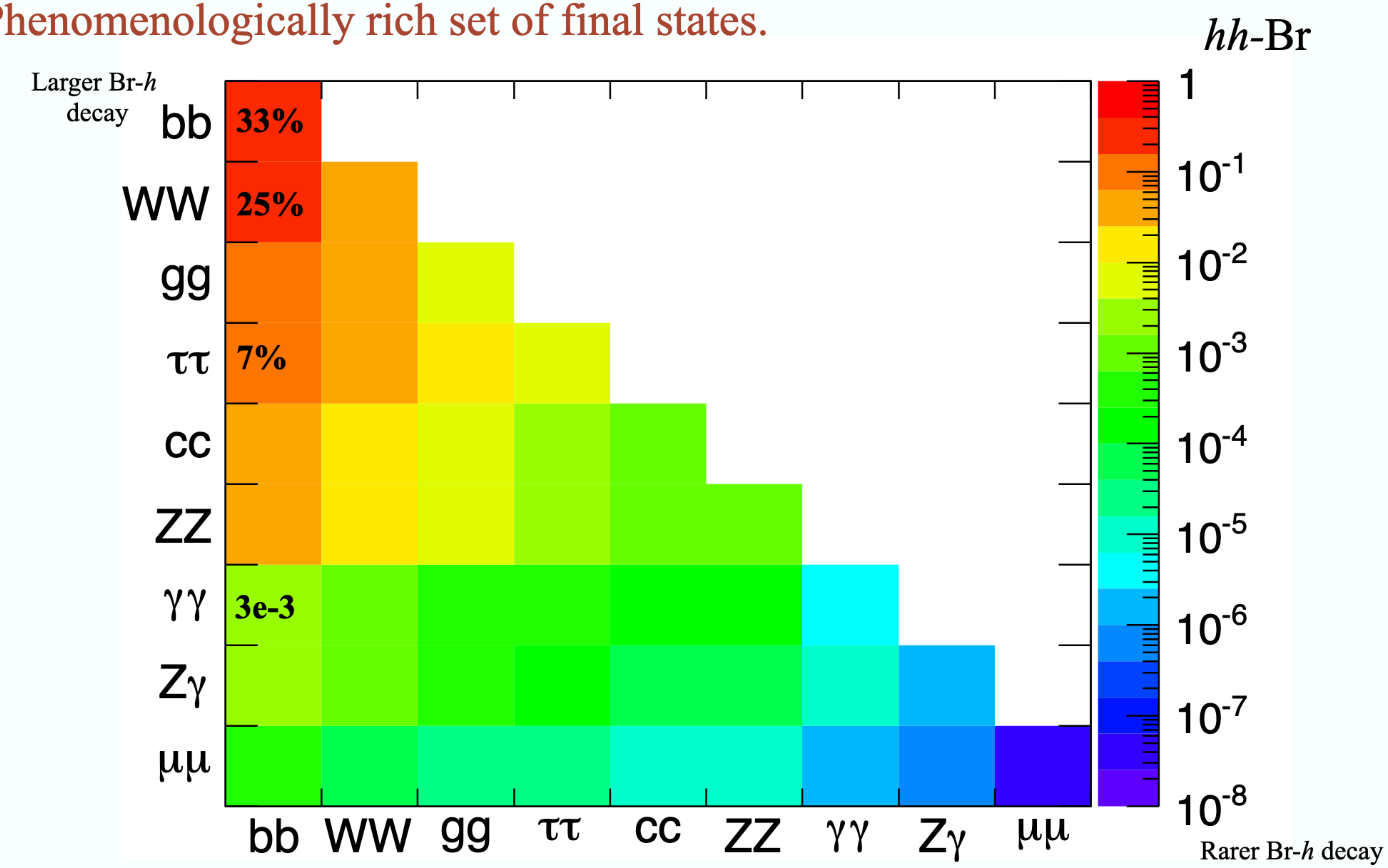
Grazzini et al arXiv:1803.02463

Interference effects between triangle & box diagrams

Need for differential information

Measuring di-higgs production

Phenomenologically rich set of final states.



$b\bar{b}$: large QCD backgrounds

- Boosted (jet substructure) techniques at high p_T^h

$\gamma\gamma$: clean but very small BR

WW: clean leptonic W decay

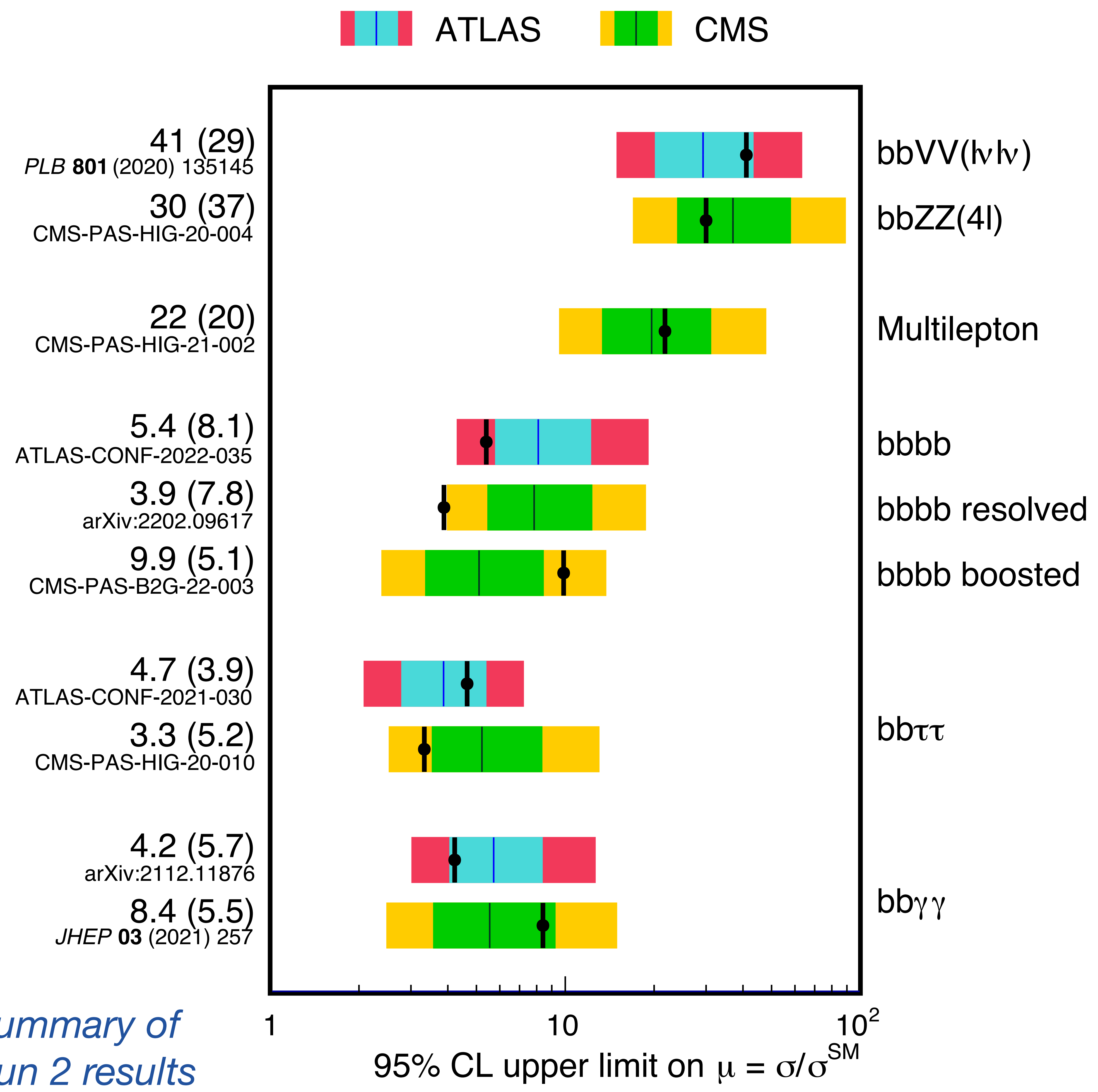
- Missing energy from neutrinos

$\tau\tau$: complicated decays

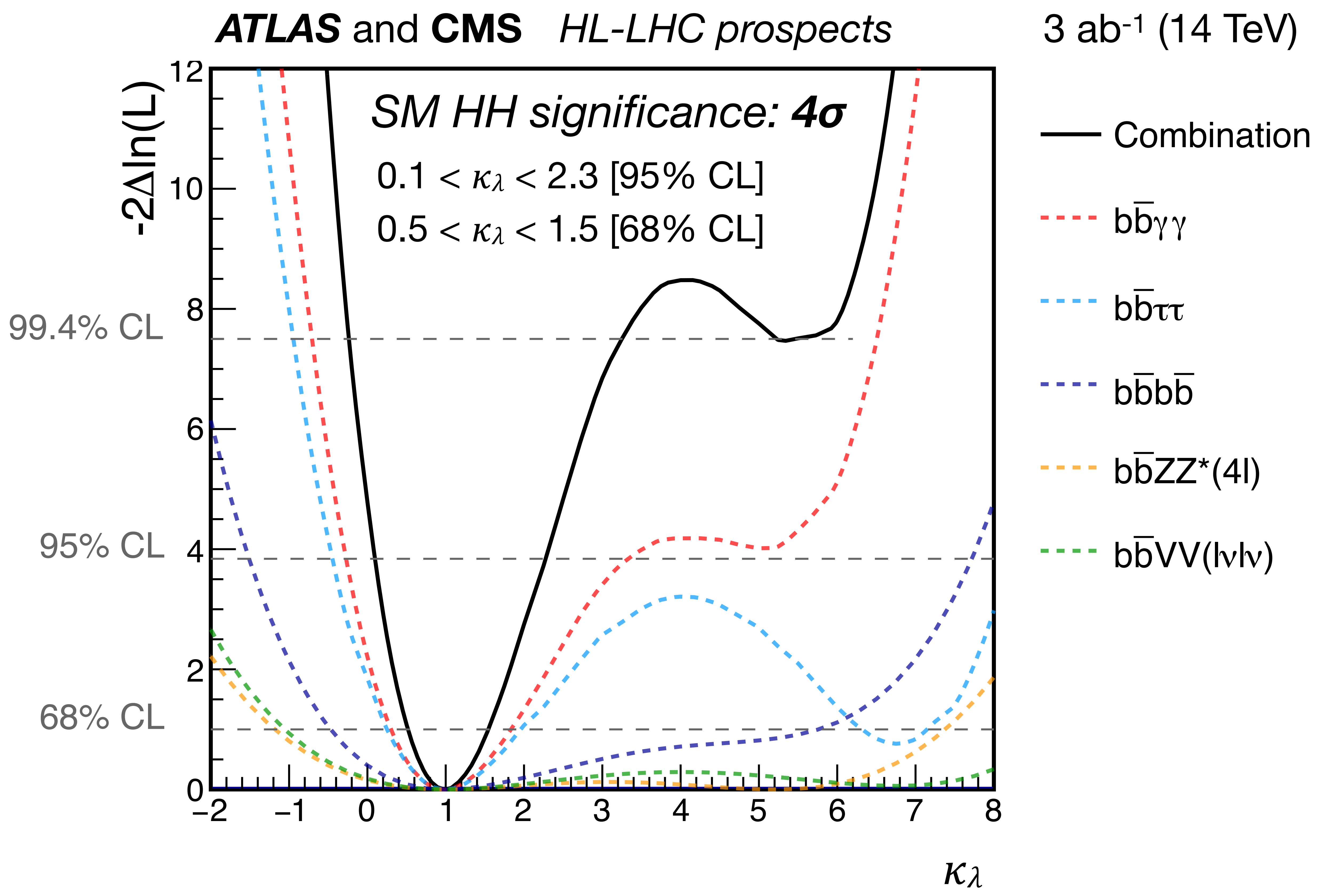
- Leptonic (neutrinos) or hadronic

Best: $b\bar{b}\gamma\gamma/b\bar{b}\tau\tau/b\bar{b}WW/b\bar{b}b\bar{b}$

How to extract the Higgs self-coupling



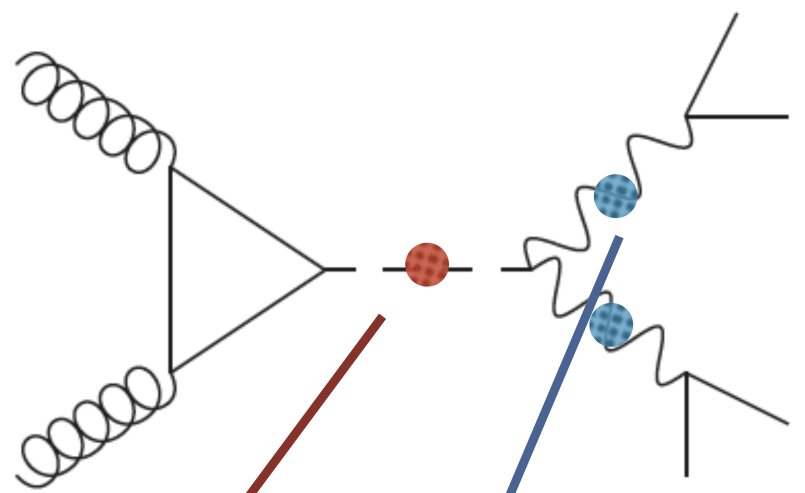
Summary of Run 2 results



A challenge even for the HL-LHC

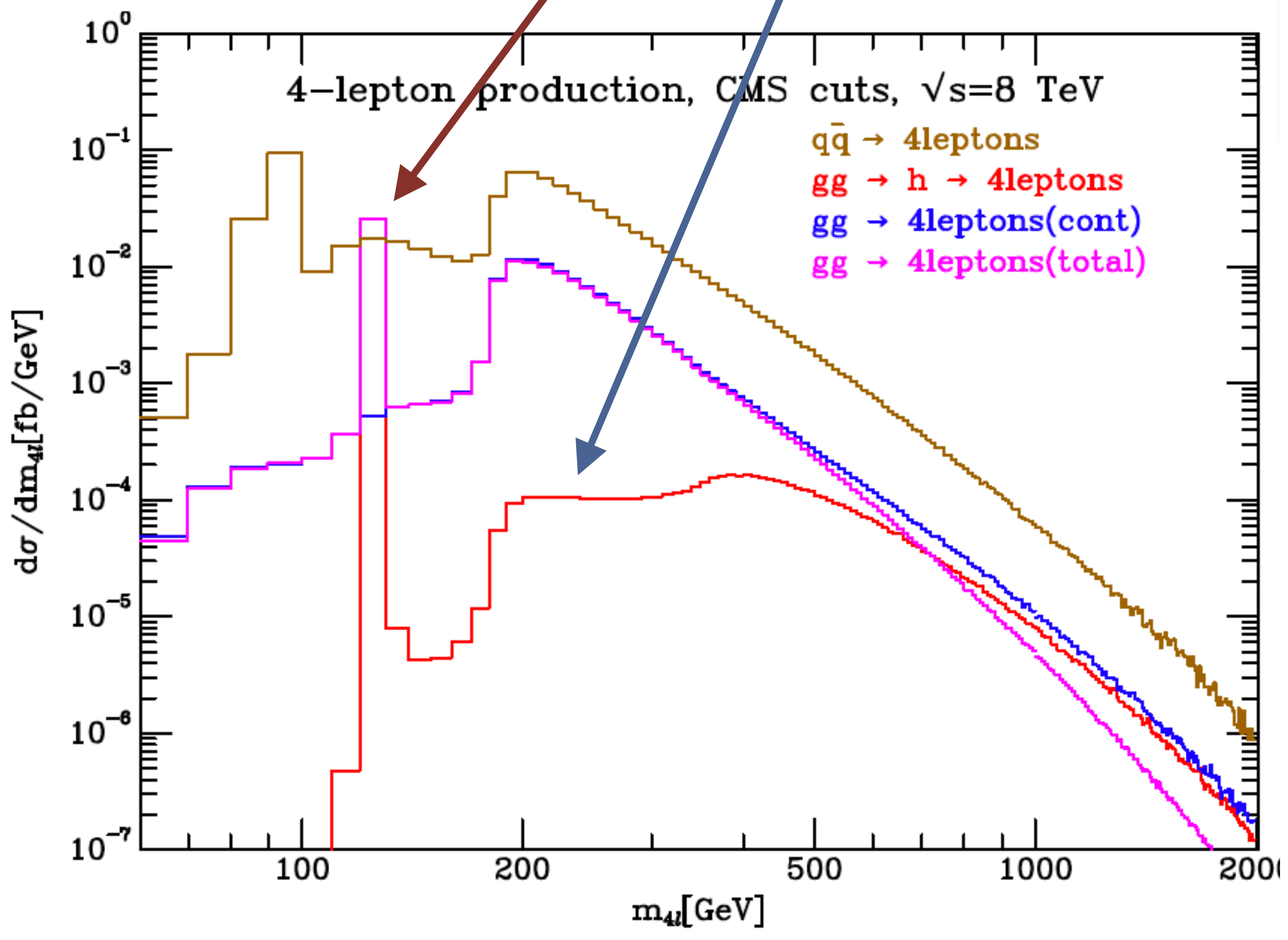
Higgs width

The SM Higgs width is 4MeV. How can we measure it?



On-shell/Off-shell : gg→ZZ→4leptons

$$\hat{\sigma}(gg \to h \to ZZ) \sim \int ds \frac{| A(gg \to h) |^2 | A(h \to ZZ) |^2}{(s - m_h^2)^2 + \Gamma_h^2 m_h^2}$$



- On-shell: $\hat{\sigma}(gg \to h \to ZZ)^{on} \sim \frac{\kappa_g^2(m_h^2)\kappa_Z^2(m_h^2)}{m_h \Gamma_h}$
- Above: $\hat{\sigma}(gg \to h \to Z_L Z_L)^{above} \sim \int ds \frac{\kappa_g^2(s)\kappa_Z^2(s)}{M_Z^4}$

beware: model dependent

$$\sigma^{\text{above}} / \sigma^{\text{on-peak}} \sim \Gamma_H$$

CMS: $\Gamma_{\rm H} = 3.2^{+2.4}_{-1.7}\,\text{MeV}$

BSM Higgs decays

What if the Higgs couples to other particles that are lighter than m_h?

- e.g. Higgs portal $2m_S < m_h$ or dark matter $h \to \chi\chi$
- Light scalar or vector $m_X < m_H - m_Z$: $h \to ZX$

$$|H|^2$$ gauge invariant mass-dimension 2

Higgs is a natural portal to new physics:

- No symmetries to prevent BSM coupling via portal $|H|^2 \mathcal{O}_{\rm BSM} \;\; (= \chi\bar{\chi}, SS, \ldots)$
- If light new physics exists, there is a good chance that the Higgs might decay into it

For $h \to XY$ we have a nice kinematic constraint: $m_{XY}^2 = m_H^2$

- Dark sector or long lived particles $\Rightarrow$ missing energy
- Rich programme of searches under way

See e.g. overview in *[ATLAS; 2405.04914]*

Invisible/unobserved Higgs decays

What if we cant observe the decay channel directly?

- Completely invisible Higgs decay into e.g. DM
- Some yet unobserved final state: too high background or simply not yet searched for

Partial width contributions will still modify the Higgs width $\Gamma_h = \Gamma_h^{\mathrm{SM}} + \Gamma_{\mathrm{unobs.}}$

- If nothing else about the Higgs couplings is modified

$\Rightarrow$ Global reduction of $\mu_i \propto \frac{\Gamma_h^{\mathrm{SM}}}{\Gamma_h} = 1 - \mathrm{BR}_{\mathrm{unobs.}}$

$$\mu_{\mathrm{tot}}^{\mathrm{prod}} = 1.002 \pm 0.057$$

$$\mathrm{BR}_{\mathrm{unobs.}} \lesssim 0.08$$

Strong assumption!

- $\mathrm{BR}_{\mathrm{unobs.}}$ is degenerate with a universal coupling modifier $\kappa_{\mathrm{univ.}}$ $\quad \mu_i = \kappa_{\mathrm{univ.}}^4 \cdot (1 - \mathrm{BR}_{\mathrm{unobs.}})$

Indirect constraints

μ_i combination

Fix $B_{i,u} = 0$

Float $B_{i,u} \neq 0$ with theoretical assumption:

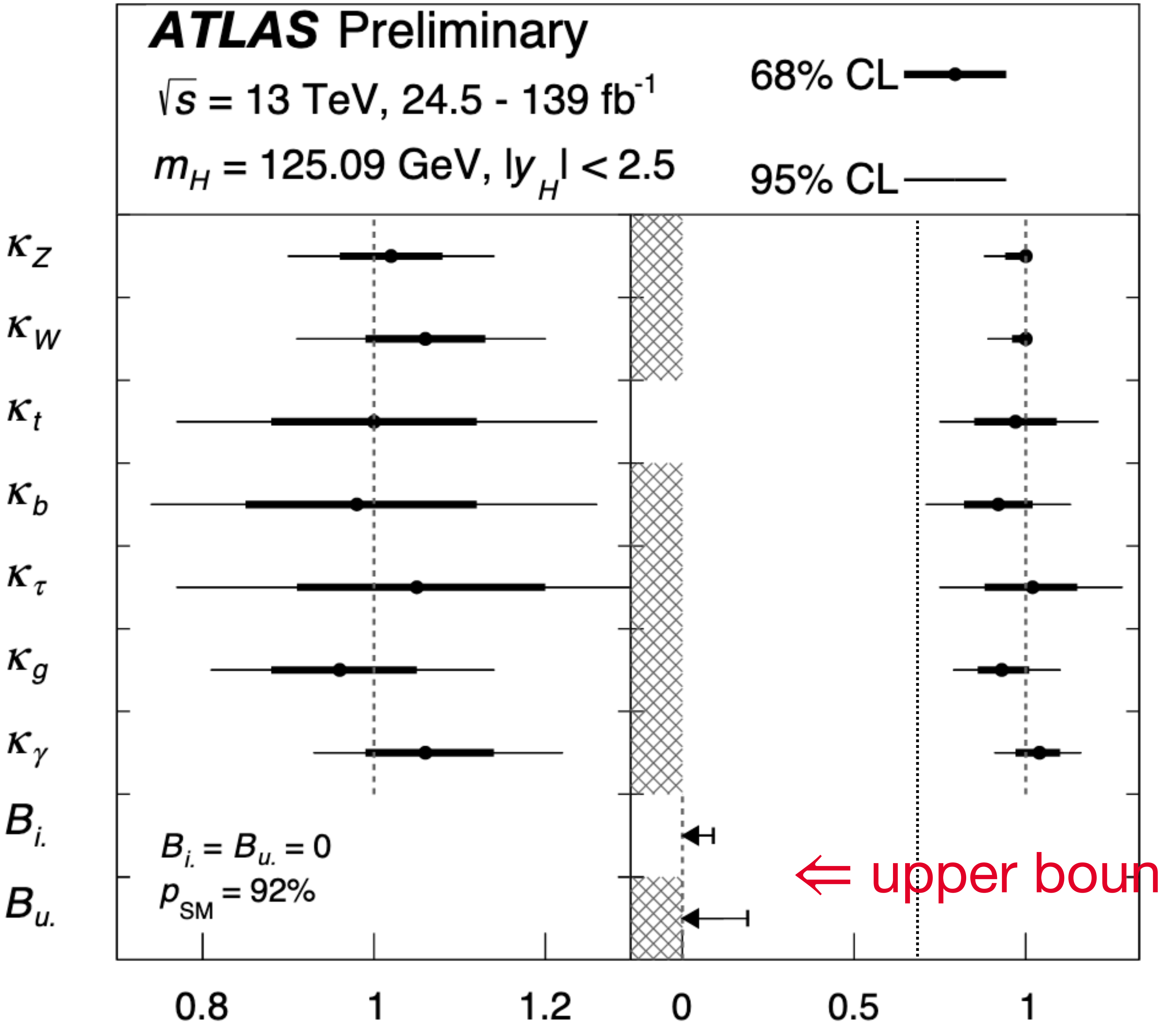
$\kappa_{Z,W} < 0$

Not possible otherwise

Moderate impact on other κ_i

$h \to$ invisible

$h \to$ unobserved



$\Leftarrow$ upper bounds

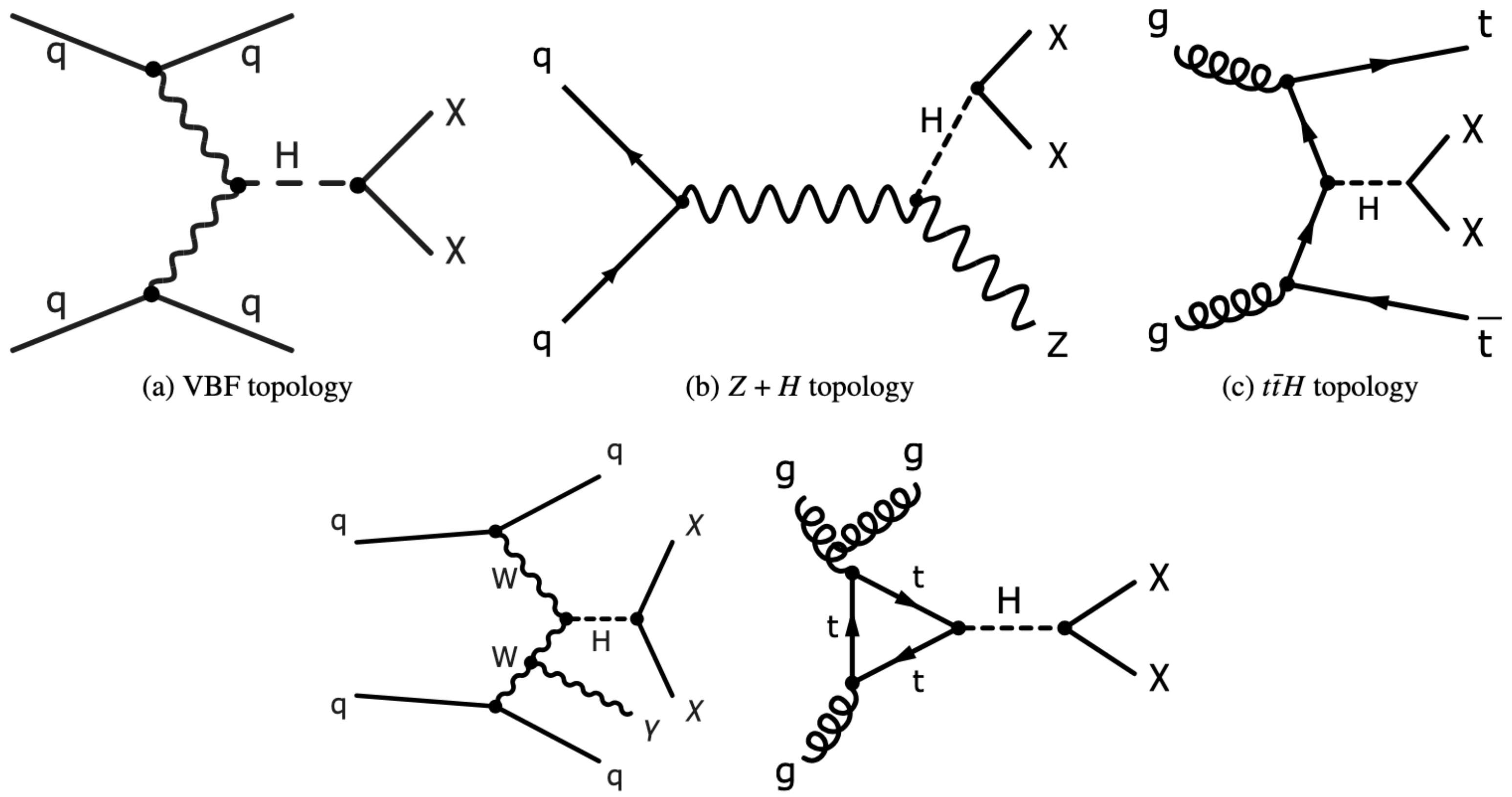
Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	1.02 ± 0.06	> 0.88 at 95% CL
κ_W	1.06 ± 0.07	> 0.89 at 95% CL
κ_b	$0.98\,^{+0.14}_{-0.13}$	0.92 ± 0.10
κ_t	1.00 ± 0.12	0.97 ± 0.12
κ_τ	$1.05\,^{+0.15}_{-0.14}$	$1.02\,^{+0.13}_{-0.14}$
κ_γ	$1.06\,^{+0.08}_{-0.07}$	$1.04\,^{+0.06}_{-0.07}$
κ_g	$0.96\,^{+0.09}_{-0.08}$	$0.93\,^{+0.08}_{-0.07}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.19 at 95% CL

Invisible Higgs decays

$pp \to X + (h \to \text{MET})$

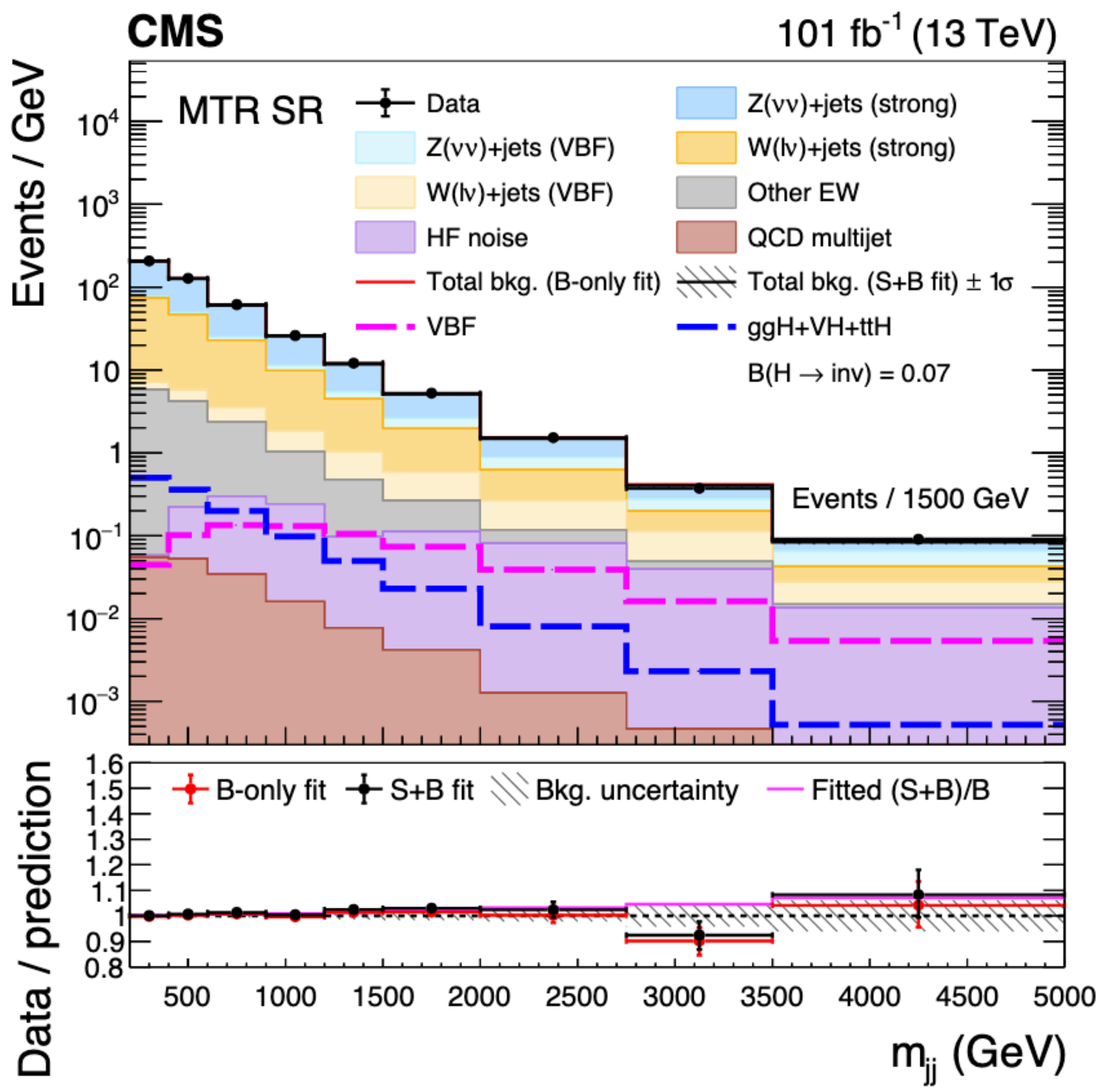
Purely invisible Higgs decay is a distinct phenomenological signature

- Requires something (X) for the Higgs to recoil against
- Tag X and measure missing transverse energy (MET)



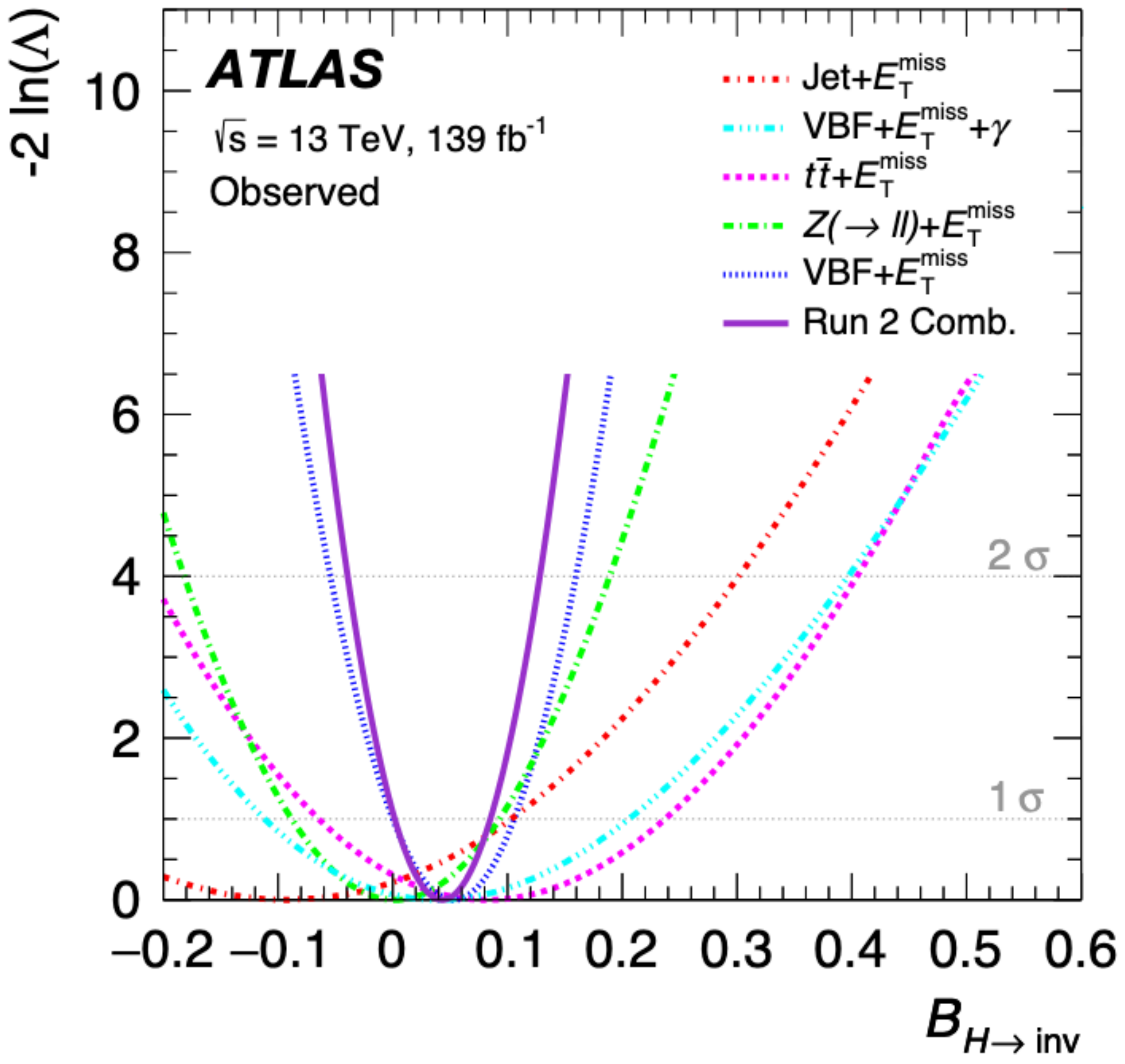
(a) VBF topology (b) $Z+H$ topology (c) $t\bar{t}H$ topology (d) VBF + photon topology (e) H+jet topology

VBF: [CMS; 2201.11585]

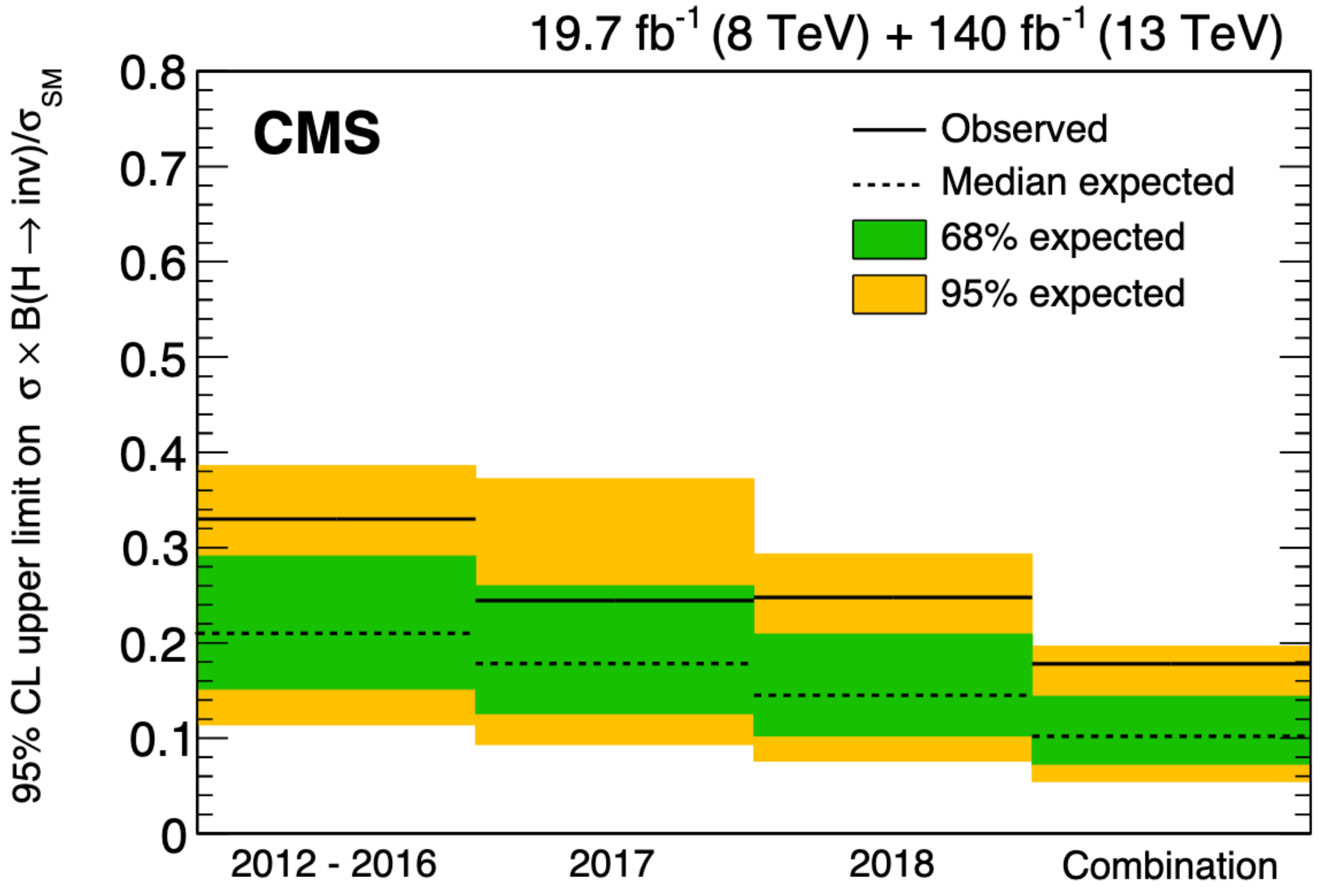


[ATLAS; 2301.10731]

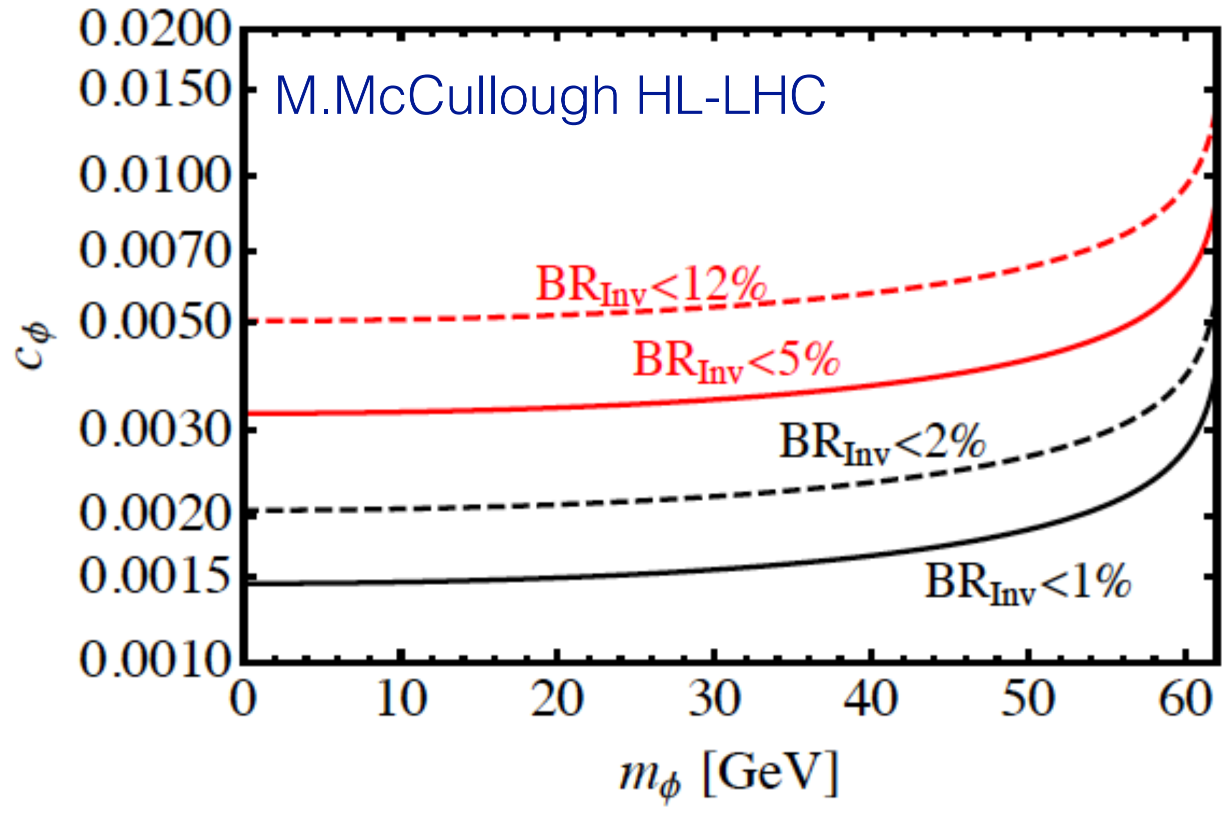
$\text{BR}_{\text{inv.}} < 0.113$ @ 95% C.L.



Searching for the invisible

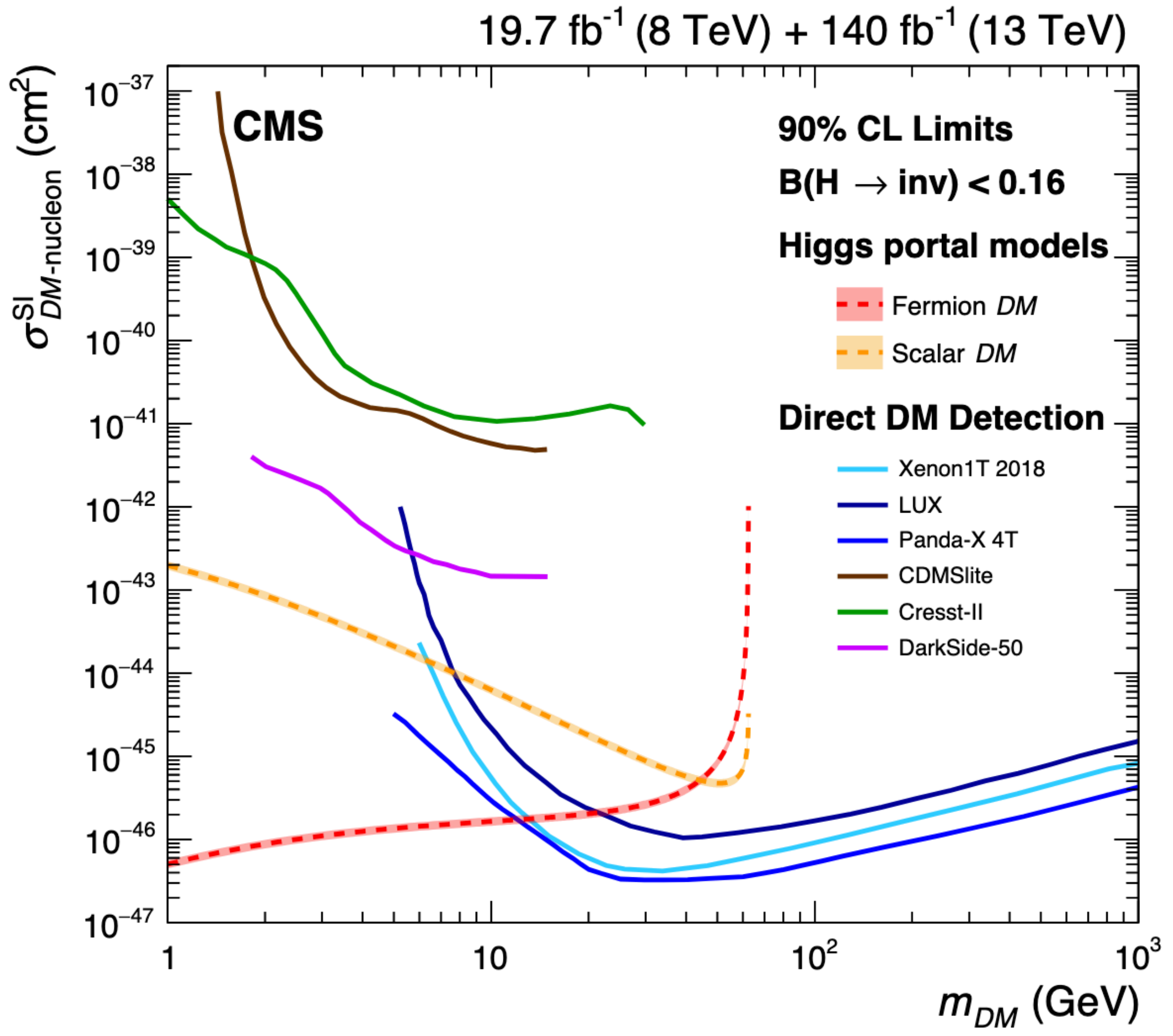


Immediate implications for any model with particles of mass m<m$_H$/2

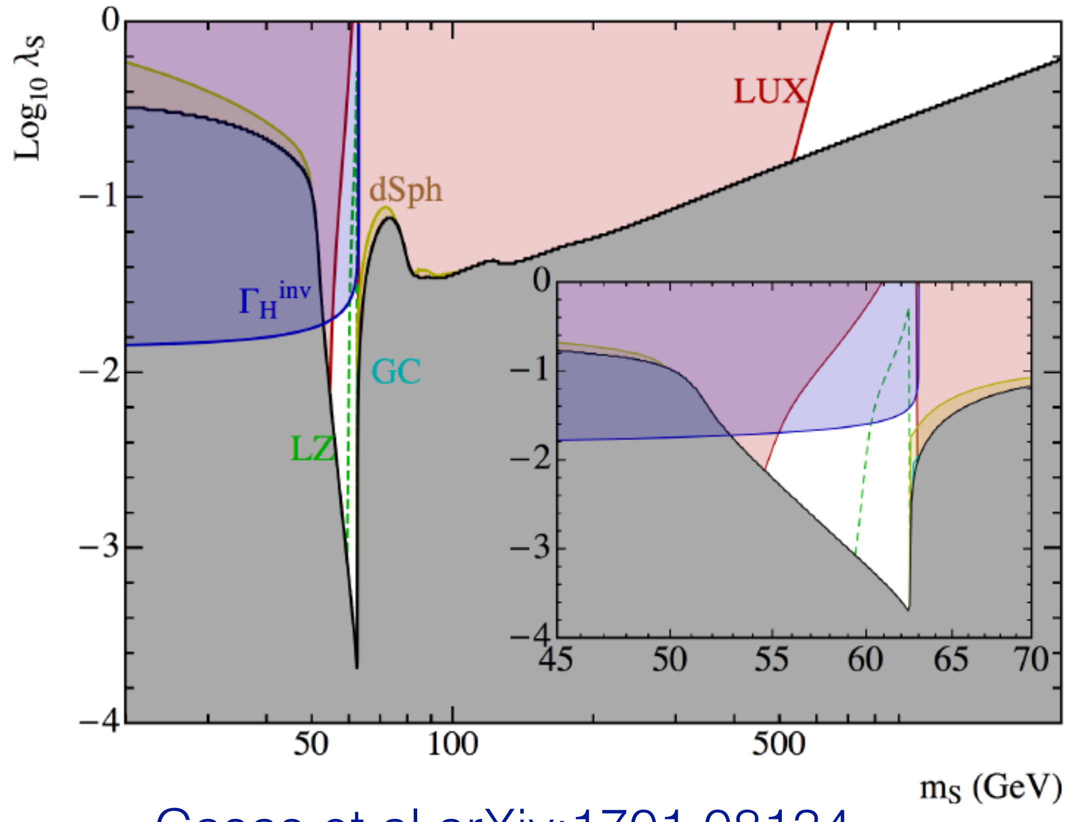


$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

Simplest extension of the SM:
The Higgs portal
A window to the Dark Sector



Important Dark Matter implications

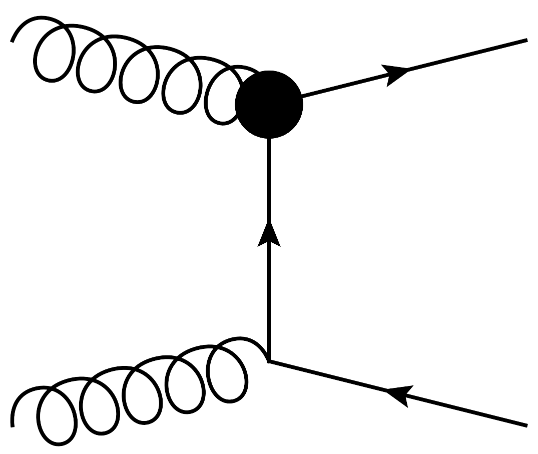


Casas et al arXiv:1701.08134

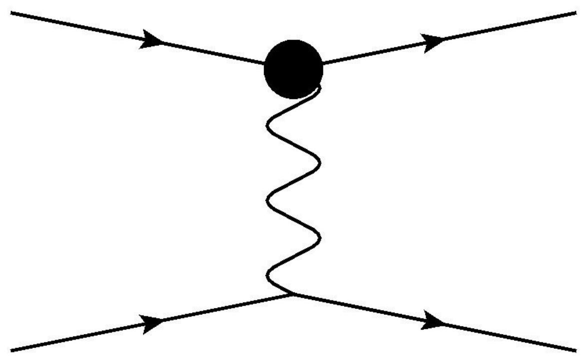
LHC is a top factory

Rich phenomenology:

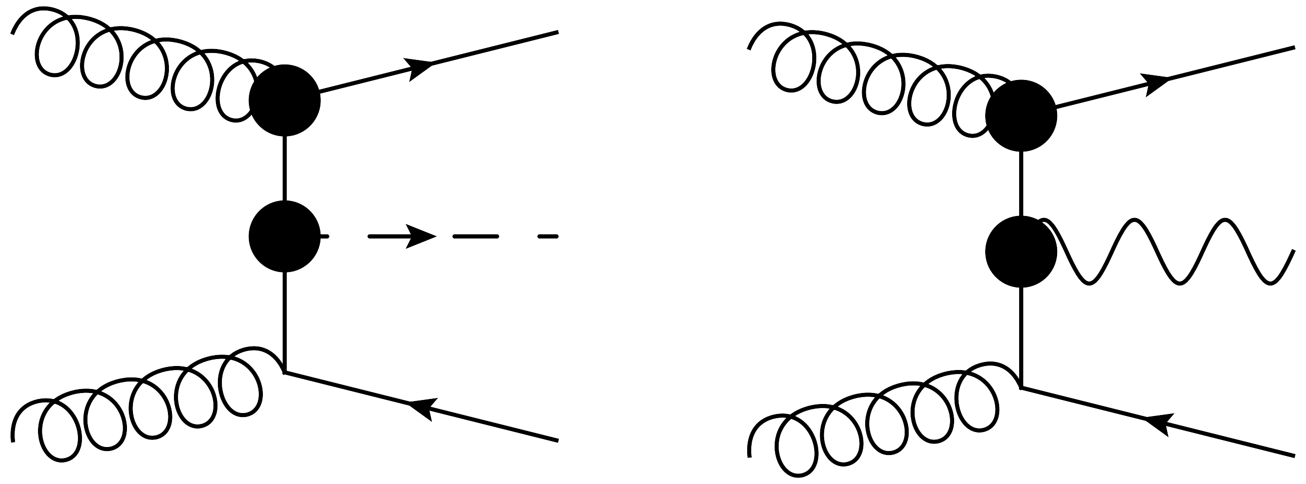
pair production



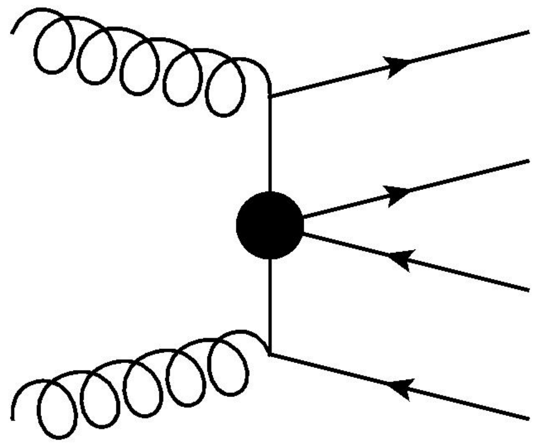
single



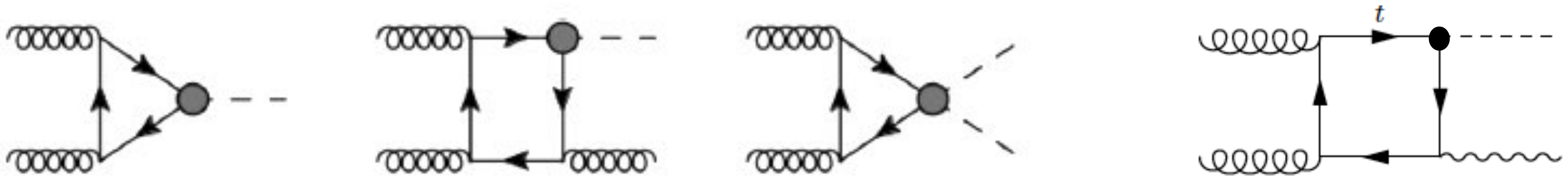
associated production



4 tops



top loops



connection to Higgs physics

Top physics

Why study the top quark ?

1. Heaviest known particle: Strong coupling to the Higgs

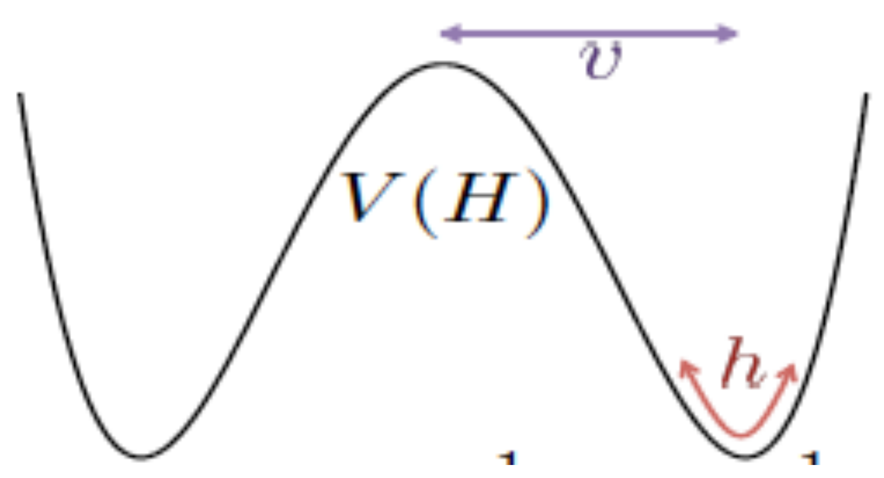
2. Portal to new physics: e.g. EWSB, composite Higgs

3. LHC is a top factory: precise access to top properties through a lot of production channels

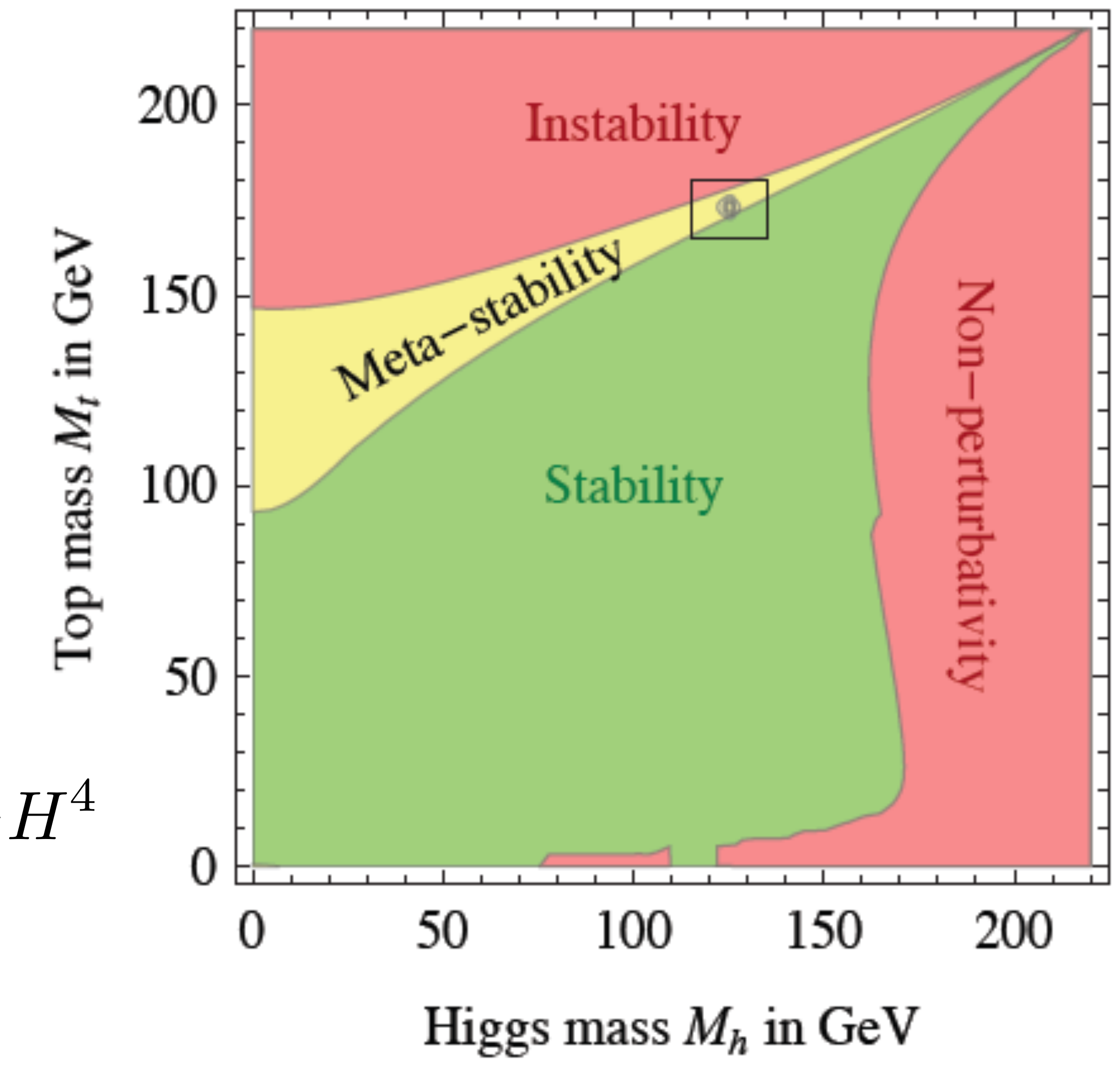
Top has a special place in the Universe

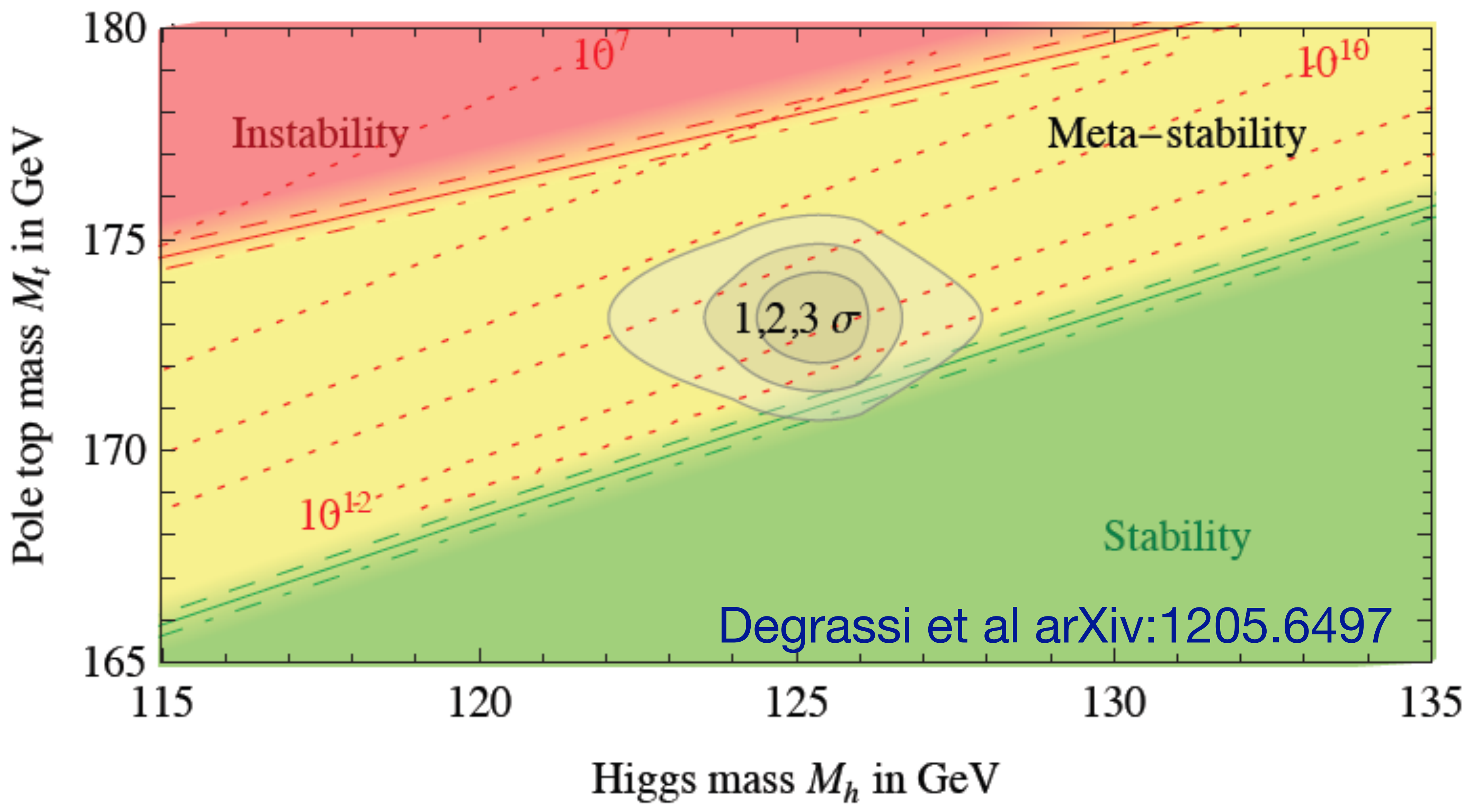
Stability of the vacuum

Higgs potential:



$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$





Need λ to be positive (and remain positive)!

$$\frac{d\lambda(\mu)}{d\log\mu^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + \frac{3}{8}g^4 + \frac{3}{16}\left(g^2+g'^2\right)^2 - 3h_t^4 - 3\lambda g^2 - \frac{3}{2}\lambda\left(g^2+g'^2\right) + 6\lambda h_t^2\right] \qquad m_t = \frac{h_t v}{\sqrt{2}} \qquad m_H^2 = 2\lambda v^2$$

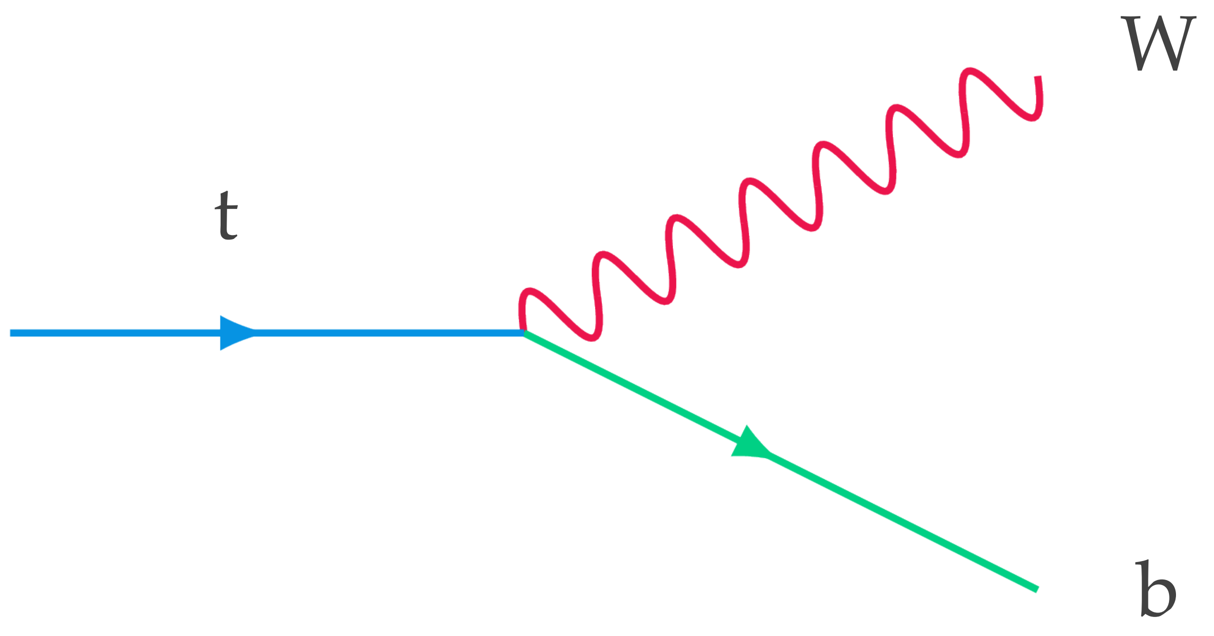
$$h_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\text{GeV}} - 173.15\right)\ldots \pm 0.00200_{\text{th}}$$

Top Yukawa!

Top quark is a special quark

Spin Correlations

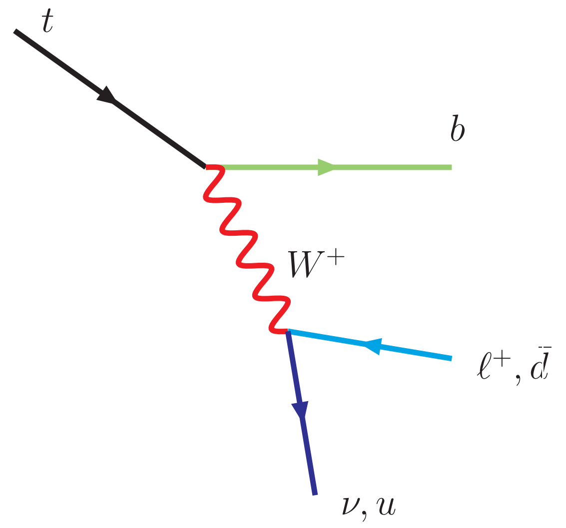
The top decays before hadronising



$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}$ s
$\tau_{top} \approx h/\ \Gamma_{top} = 1/(G_F\, m_t^3\, |V_{tb}|2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}$ s
(with h=6.6 10^{-25} GeV s)

Spin information is preserved!

Top Spin effects



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1 + p\, k_i \cos\theta}{2}$$

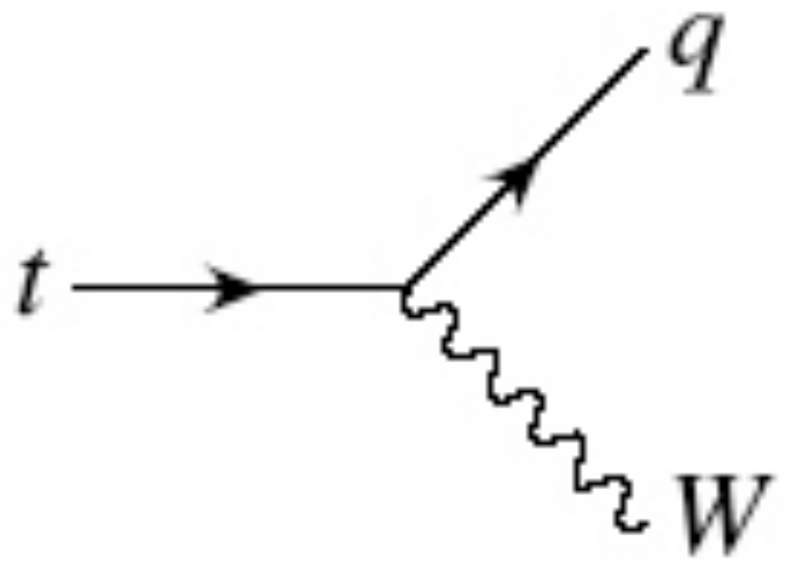
k_i	ℓ^+	$\bar{d}$	u	b
LO:	1	1	-0.32	-0.39
NLO:	0.999	0.97	-0.31	-0.37

Lepton+ or d emitted in the top spin direction

Spin analysing power

We can check how the top is produced!

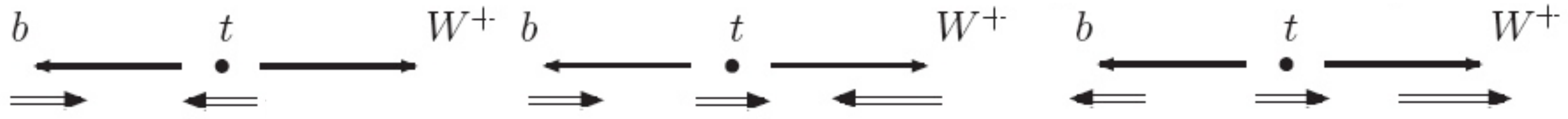
Weak interaction and W polarisation



$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)$$

Only left-handed tops in the decay!

Helicities of W bosons

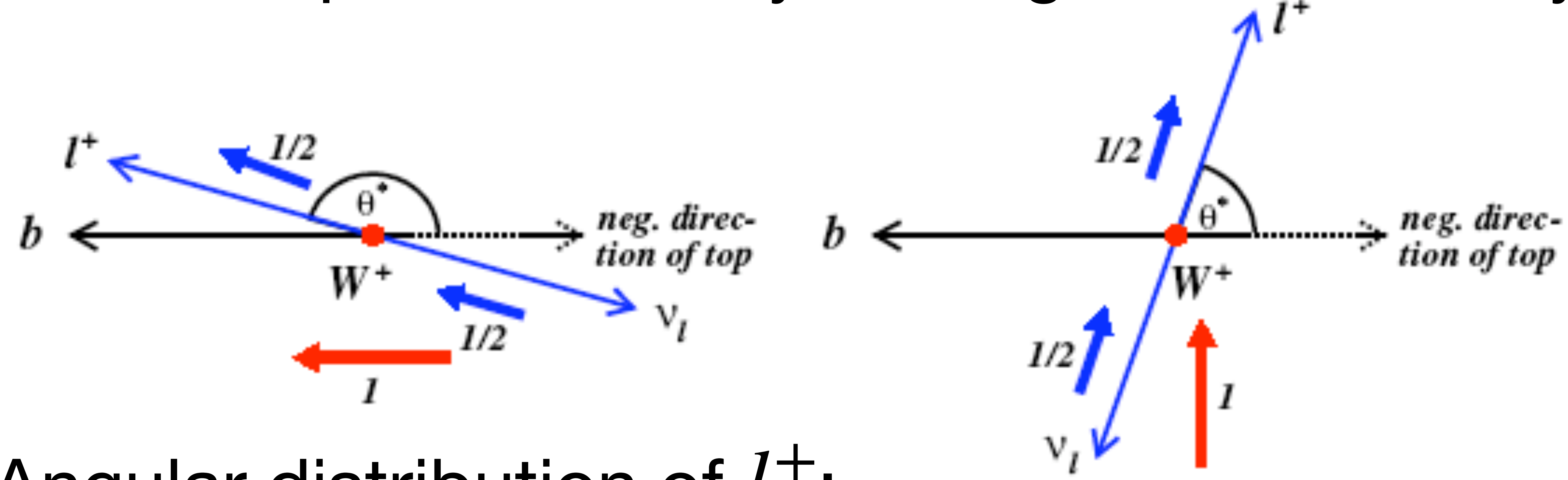


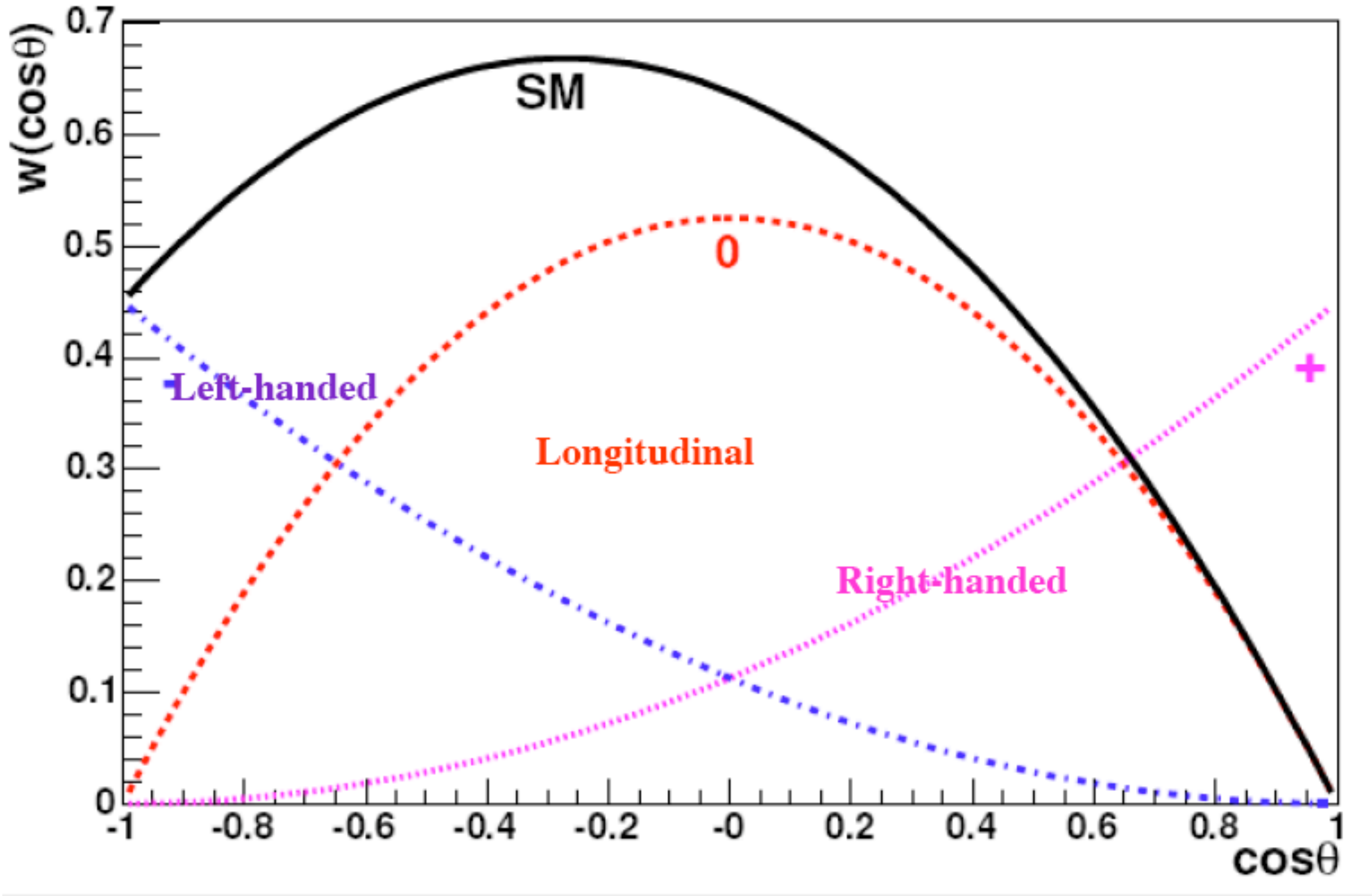
longitudinal left-handed right-handed

? ? ?

Weak interaction and W polarisation

Extract W polarisation by looking at the W decay products:





Angular distribution of l^+:

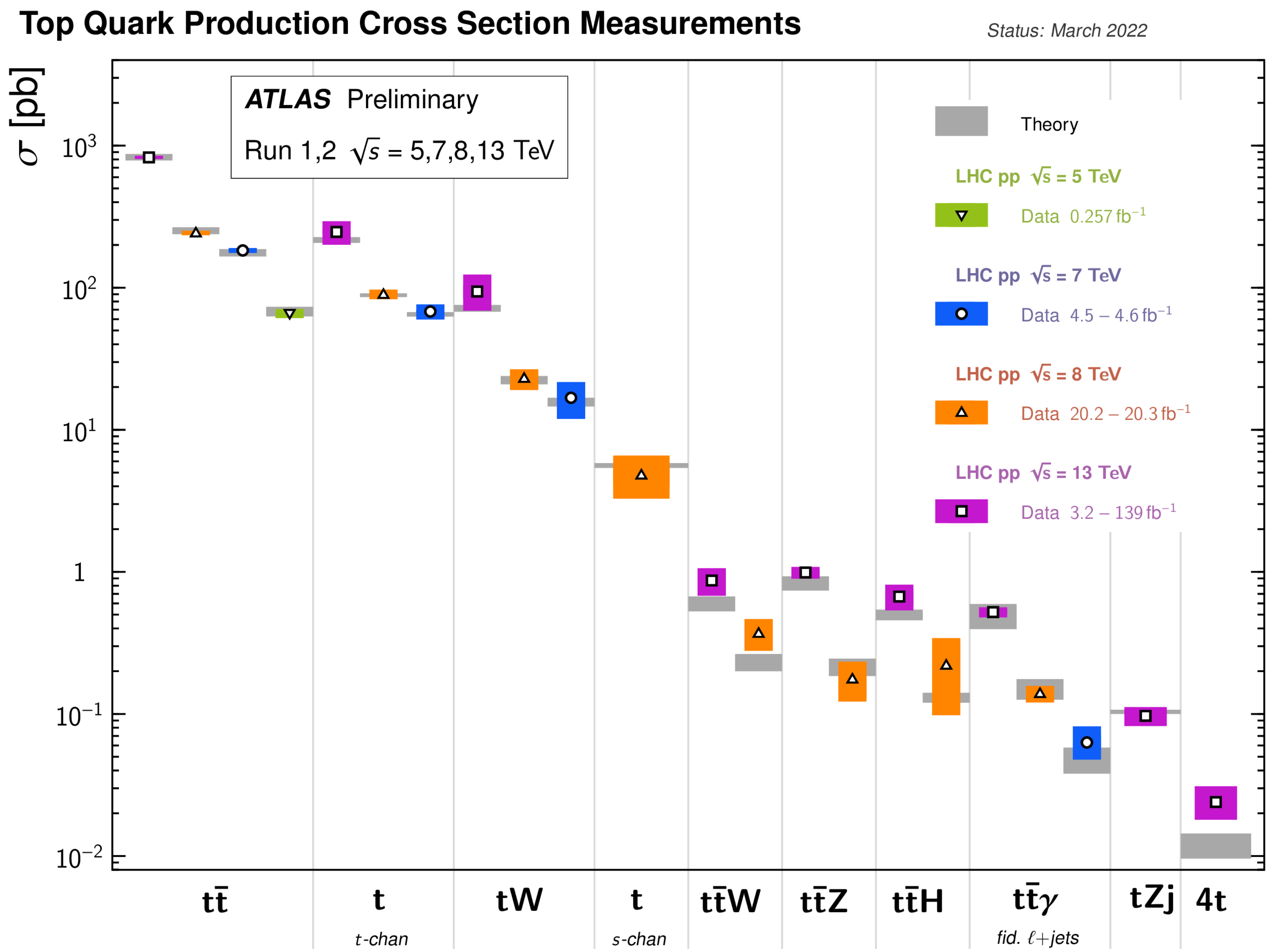
$$\frac{1}{N}\frac{dN(W \to l\nu)}{dcos\theta} = K\left[f_0 \sin^2\theta + f_L(1-\cos\theta)^2 + f_R(1+\cos\theta)^2\right]$$

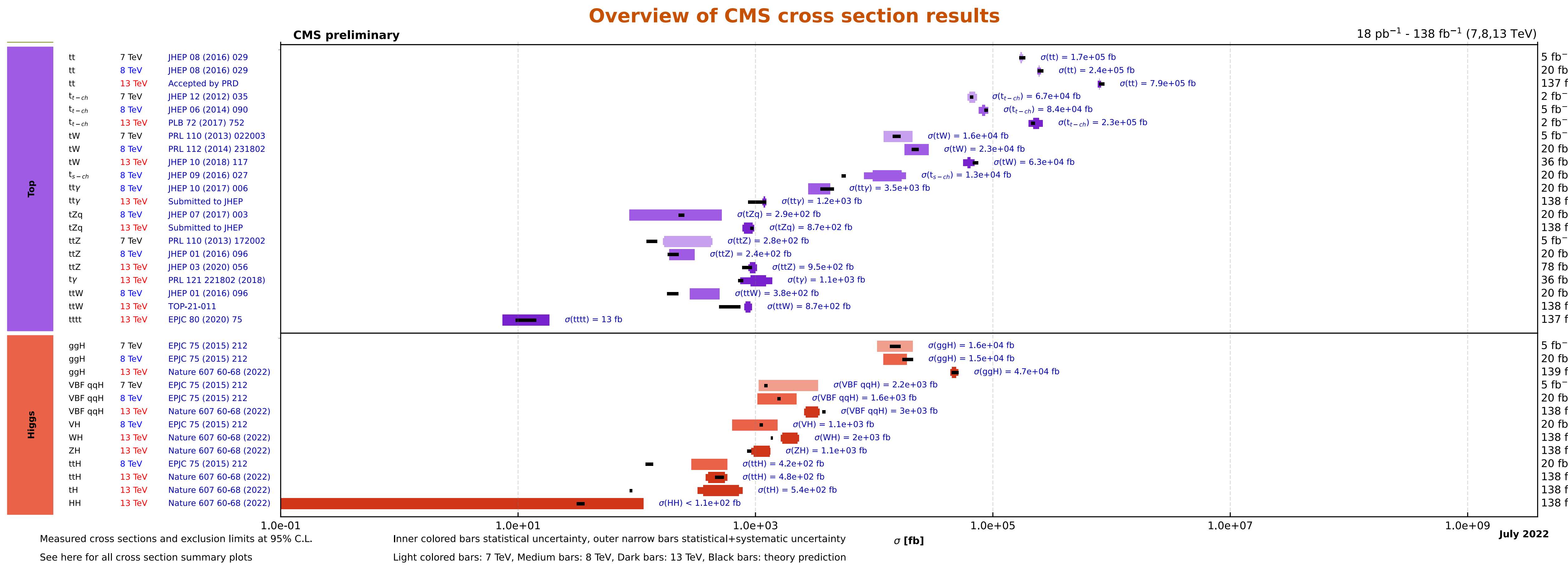
$$f_0 = \frac{m_t^2}{2m_W^2 + m_t^2} \sim 70\,\% \qquad f_L = \frac{2m_W^2}{2m_W^2 + m_t^2} \sim 30\,\% \qquad f_R \sim 0\,\%$$

for $m_b = 0$

Check of Wtb interaction!

Status of top measurements





Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt[fb^{-1}]$	Measurement	Theory
$t\bar{t}$	13	36.1 fb^{-1}	$\sigma = 826.4 \pm 3.6 \pm 19.6$ pb	$\sigma = 832 + 40 - 45$ pb (top++ NNLO+NNLL)
t_{t-chan}	13	3.2 fb^{-1}	$\sigma = 247 \pm 6 \pm 46$ pb	$\sigma = 217 \pm 10$ pb (NLO+NLL)
$t\bar{t}W$	13	36.1 fb^{-1}	$\sigma = 870 \pm 130 \pm 140$ fb	$\sigma = 600 \pm 72$ fb (Madgraph5 + aMCNLO)
$t\bar{t}Z$	13	139 fb^{-1}	$\sigma = 990 \pm 50 \pm 80$ fb	$\sigma = 840 + 90 - 100$ fb (NLO QCD + EW)
$t\bar{t}H$	13	80 fb^{-1}	$\sigma = 670 \pm 90 + 110 - 100$ fb	$\sigma = 507 + 35 - 50$ fb (LHCHXSWG NLO QCD + NLO EW)
$t\bar{t}\gamma$	13	36.1 fb^{-1}	$\sigma = 521 \pm 9 \pm 41$ fb	$\sigma = 495 \pm 99$ fb (PRD 83 (2011) 074013)
tZj	13	139 fb^{-1}	$\sigma = 97 \pm 13 \pm 7$ fb	$\sigma = 102 + 5 - 2$ fb (Madgraph5 + aMCNLO (NLO))
4t	13	139 fb^{-1}	$\sigma = 24 + 7 - 6$ fb	$\sigma = 12.0 \pm 2.4$ fb (JHEP 02 (2018) 031)

Very precise measurements!

In some cases:

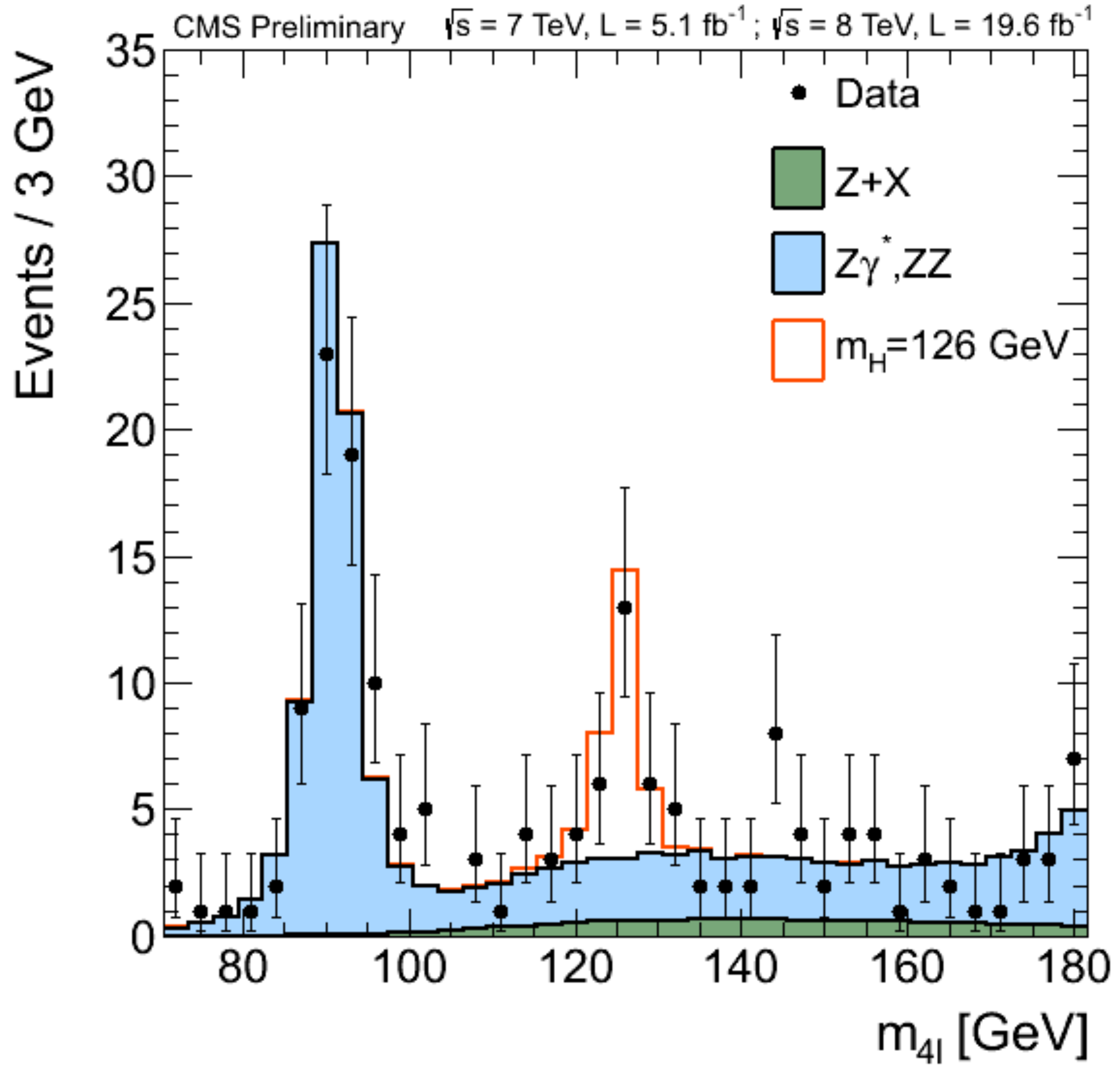
$$\Delta_{EXP} < \Delta_{TH}$$

New Physics searches at the LHC

Model-dependent

SUSY, 2HDM…

New particles

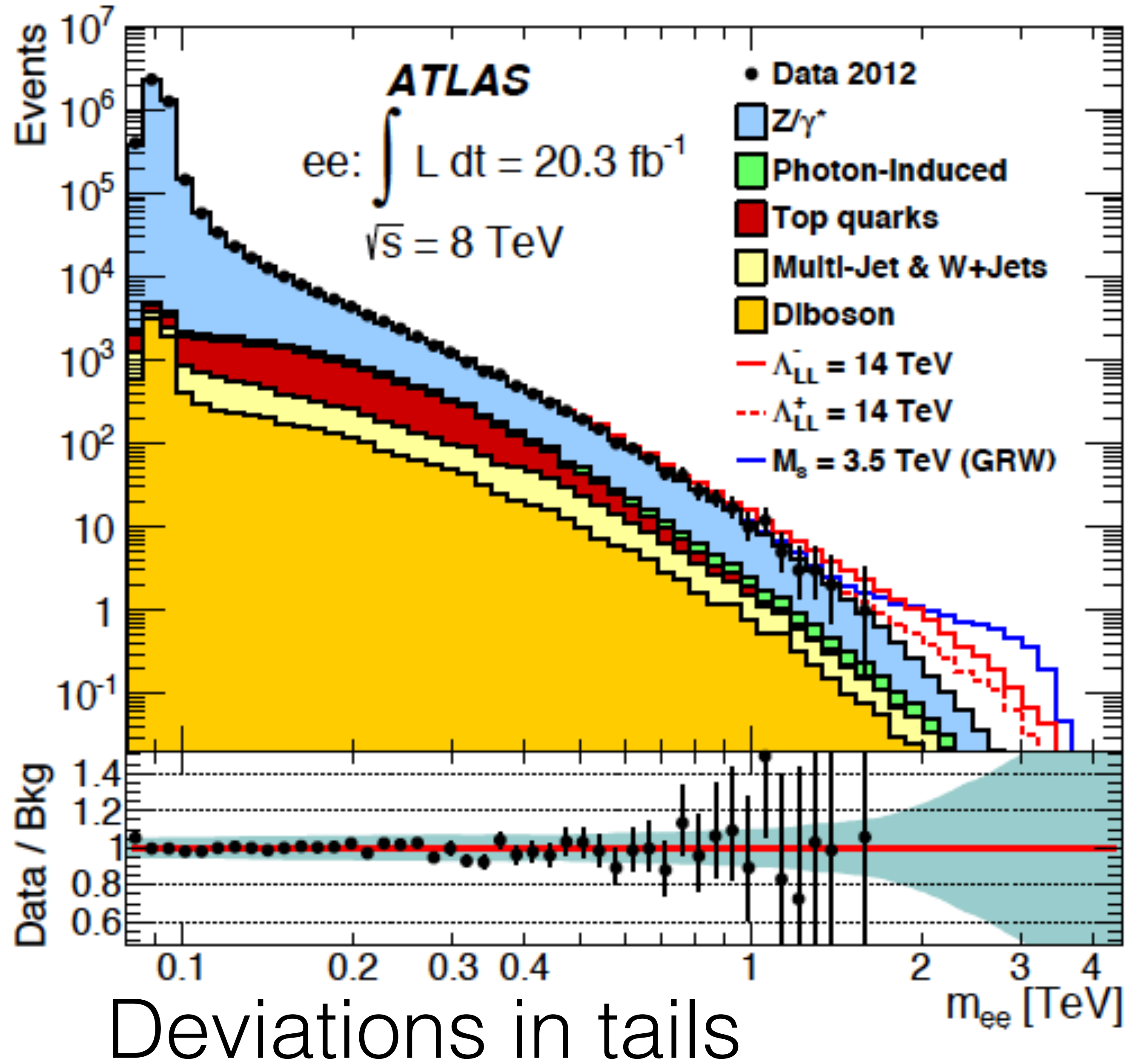


Model-Independent

simplified models,EFT

New Interactions of SM particles

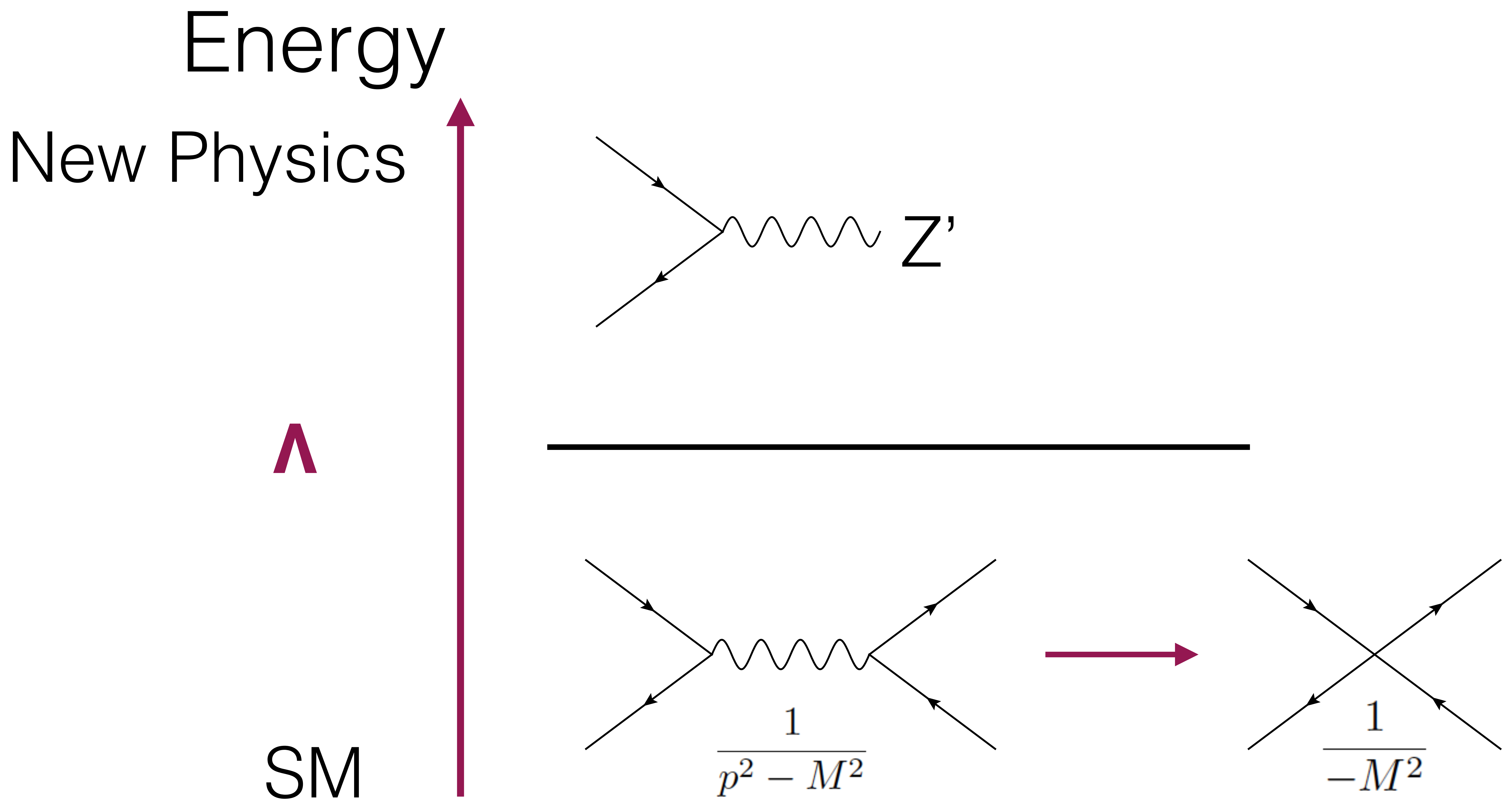
anomalous couplings, EFT



Deviations in tails

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

EFT: What is it all about?



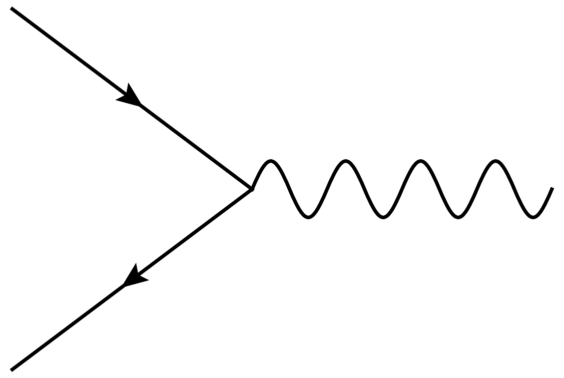
$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$ A Taylor expansion

We have integrated out the Z’

EFT: What is it all about?

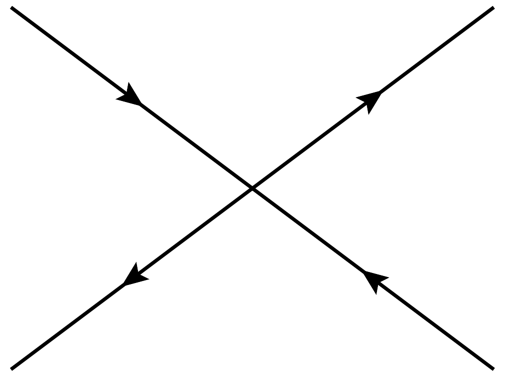
Energy

New Physics



$$\mathcal{L}_{NP}(\varphi, Z')$$

Λ=M



$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

SM

$$\frac{1}{-M^2}$$

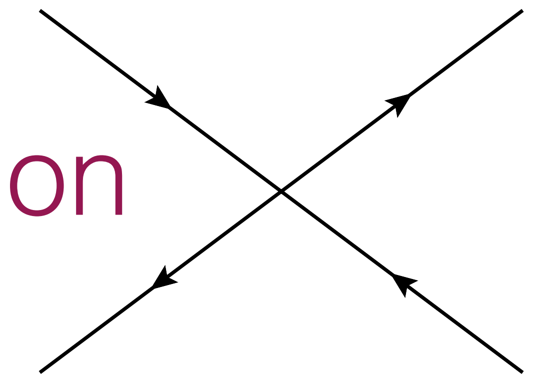
$$\mathcal{L}_{Dim6}(\varphi) = \boxed{\frac{C}{\Lambda^2}}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

c/Λ^2 can be linked to High Scale physics: Matching and Running

EFT for New Physics

Low Energy Effective Theory without the Z'

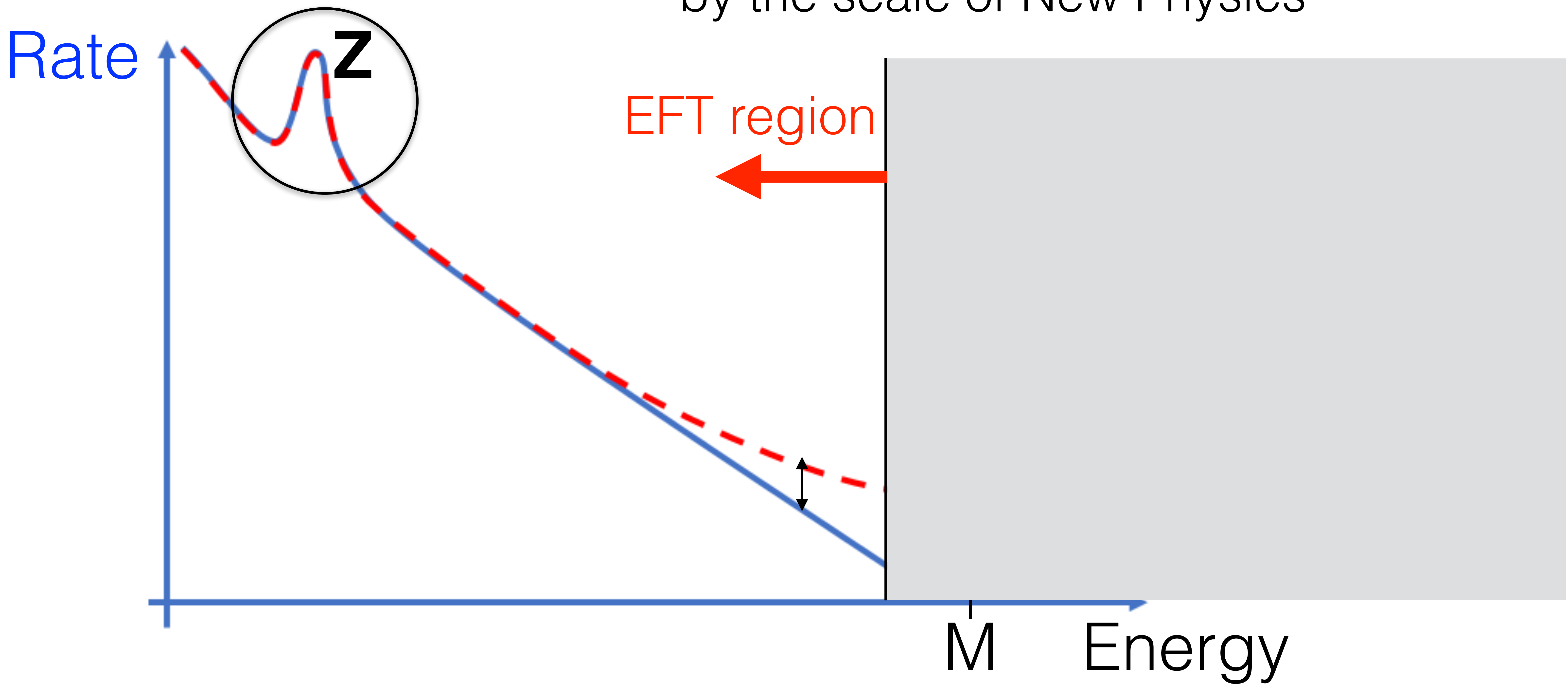
New Interaction



$$\frac{1}{-M^2}$$

$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

Modified interactions suppressed by the scale of New Physics

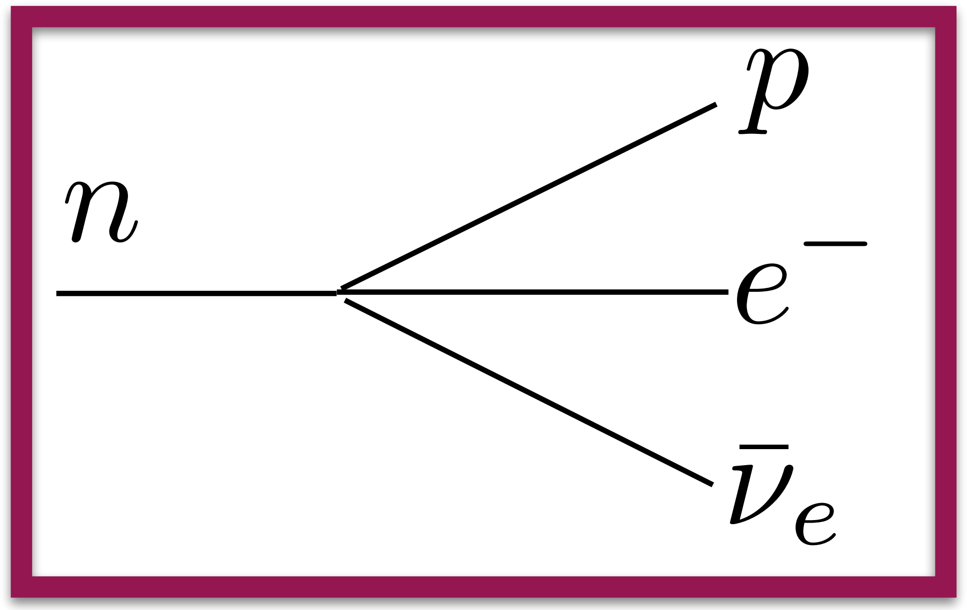


The way to probe New Physics in the absence of light states

Does the effective theory work?

An example of a successful EFT:

$$n \to p + e^- + \bar{\nu}_e$$

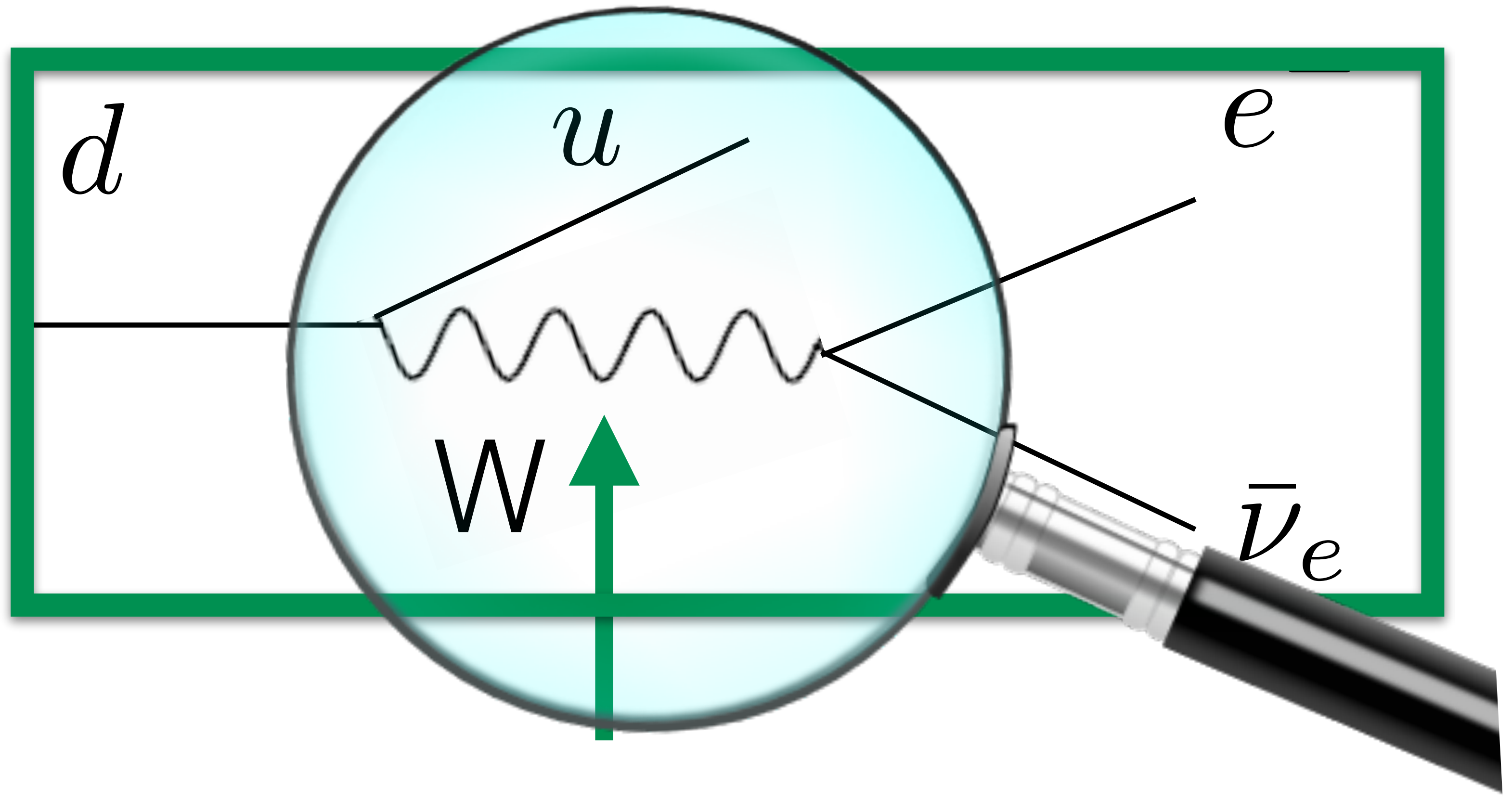


Fermi formulated his theory in the 1930's

It described β-decay data very well

Energy of β-decay: ~MeV

But this is not the full theory: cross-section rising with energy, violating unitarity

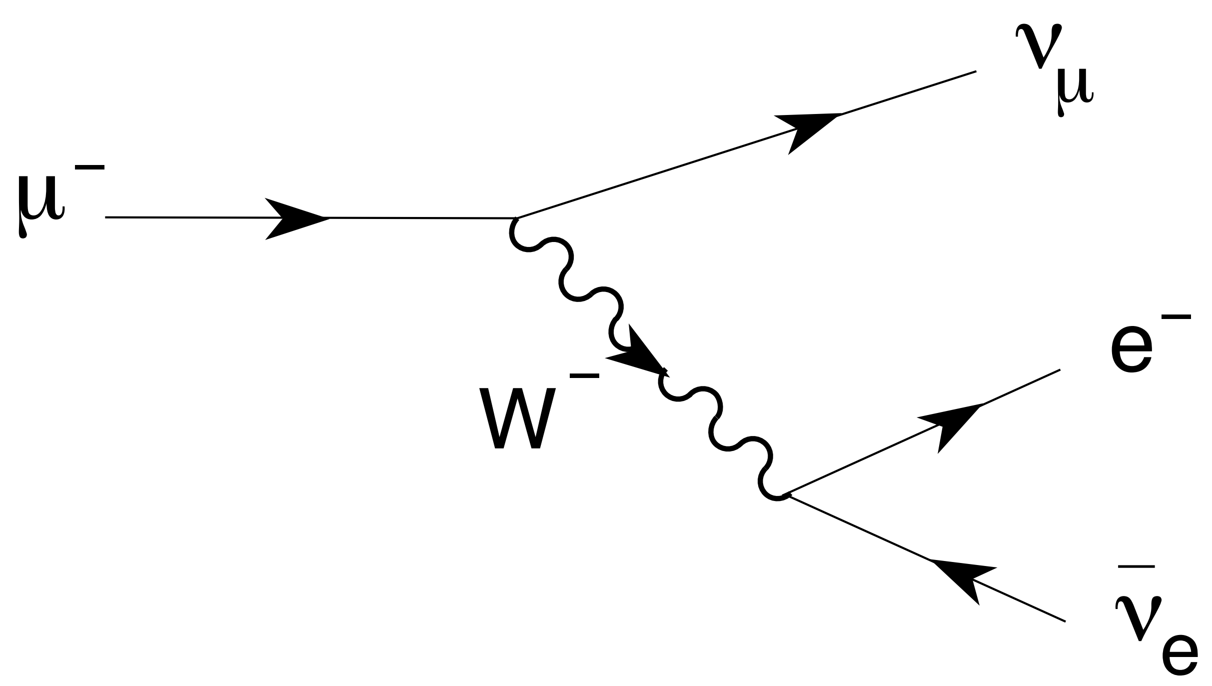


1983 Discovery of W-boson at CERN UA1 and UA2
M_W=80 GeV >> Q_β

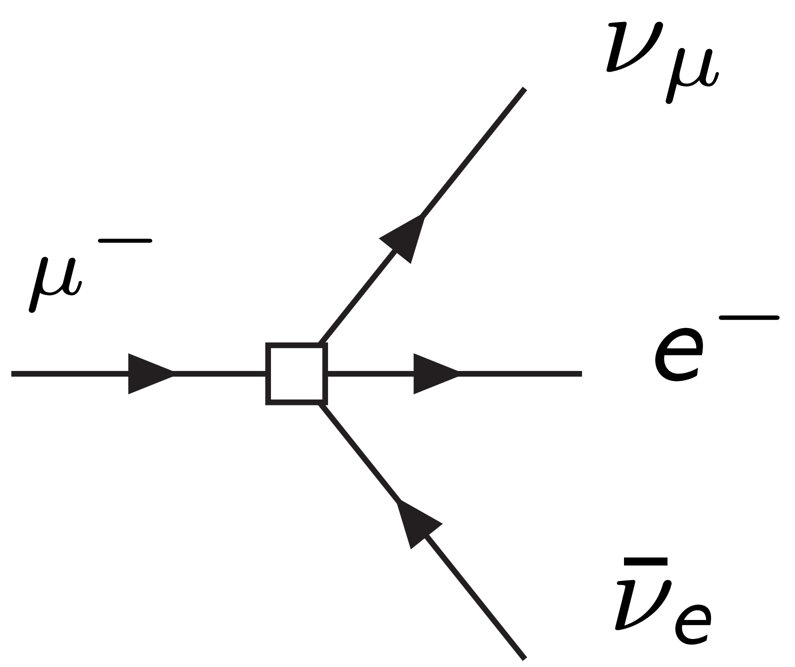
Energy borrowed from the vacuum
A virtual W-boson exchange

Low energy weak interactions

Muon Decay



$$\frac{-g_{\mu\nu} + \frac{q^\mu q^\nu}{M_W^2}}{q^2 - M_W^2} \quad \xrightarrow{q^2 \ll M_W^2} \quad \frac{g_{\mu\nu}}{M_W^2}$$



$$\mathcal{L}_I = -\frac{g}{2\sqrt{2}} \left\{ W_\mu^\dagger \mathcal{J}^\mu + \text{h.c.} \right\}$$

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \mathcal{J}_\mu^\dagger \mathcal{J}^\mu \qquad \frac{G_F}{\sqrt{2}} = \frac{g^2}{8\, M_W^2}$$

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e^2}{m_\mu^2}\right) \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

Full dependence on low energy parameters: agreement with full theory up to 10^{-6} ✔

General EFT considerations

- EFT is a field theory, the low-energy limit of a full theory
- Same IR behaviour as the full theory (but different UV behaviour)
- It can make quantitative predictions (without knowing the full theory)
- Predictions can be improved in a systematic way (higher order corrections to matching, running and mixing)
- Eventually need full theory to go beyond the low energy region (unitarity violation)

Power counting: Systematic expansion in a small parameter p/M

Locality: Factorise quantities into short distance parameters (Wilson coefficients) and long distance operator matrix elements

(We are integrating out heavy fields: in practice done with the path integral see for example arXiv:1804.05863)

Why use an effective theory?

Top-bottom: We know the full theory but it's too complicated

EFT simplifies the calculation by only including the relevant interactions

It focuses on the relevant scale

Examples: SCET, HQEFT

Bottom-up: We don't know the full theory, we are trying to describe measurements and guess the full theory

Efficient to characterise new physics

Examples: **SMEFT**, Fermi Theory (when formulated in the 1930's)

SMEFT for New Physics

- Focus on SMEFT:
  - only SM fields
  - respecting SM symmetries ✔
  - valid below scale Λ

- Gauge invariant ✔
- Higher-order corrections: renormalisable order by order in 1/Λ ✔

$$\mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \cdots$$

- Complete description ✔
- Model Independent (apart from symmetries and no new light states) ✔

Let's take a tour of SMEFT

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4}\sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}}\mathcal{O}_i^{(D)}$$ → Processes and observables

→ Sensitivity → Measurements → Constraints

→ UV

Huge effort to improve each one of these steps!

SMEFT dimension-5

One lepton number violating operator at dim-5 Weinberg (1979)

$$\mathcal{L} = \frac{c}{\Lambda}(L^T \epsilon \phi) C (\phi^T \epsilon L) + h.c.$$

$m_\nu = c\frac{v^2}{\Lambda}$ Majorana neutrino mass

Neutrino masses of 0.01-0.1eV imply $\Lambda \sim 10^{15}$ TeV!!!

Possible UV completion: see-saw model

$$\mathcal{L} = -y_D \bar{L} \epsilon \phi^* \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R + \text{H.c.}$$

➡

$\nu \sim \nu_L$ $\quad m_\nu \sim m_D^2 / M_R$

$N \sim \nu_R$ $\quad M_R$

Not relevant for LHC physics

SMEFT@dim-6

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

59(2499) operators at dim-6:

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arxiv:1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Warsaw basis of dimension-6 operators

SMEFT@dim6

59 operators in flavour universal scenario

2499 if fully general

Is there any hope?

- Not all operators enter in all observables
- Many observables available
- We can make “reasonable” assumptions →
  - no B,L violation
  - Flavour (universality, MFV…)
  - CP conservation

<100 operators for the LHC

Examples of operators

Dimension-6 operators of the SMEFT:

Class	Warsaw Example	Interaction	Impact
$\psi^2 H^3$	$(\varphi^\dagger\varphi)\ (\bar{q}_i\, u_j\, \tilde{\varphi})$	Higgs-fermion (Yukawa)	ttH
$\psi^2 H^2 D$	$(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$	gauge-fermion (Z,W)	ttZ production, Wtb, single top
$\psi^2 X H$	$(\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$	dipole	ttZ, ttA, WtB (ttVH)
ψ^4	$(\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$	four fermion	top pair production, single top, ttH, ttV, tttt

Assuming $i = j = 3$

From Operators to Observables

Operators have different impact on particle interactions

1) Modification of SM vertices

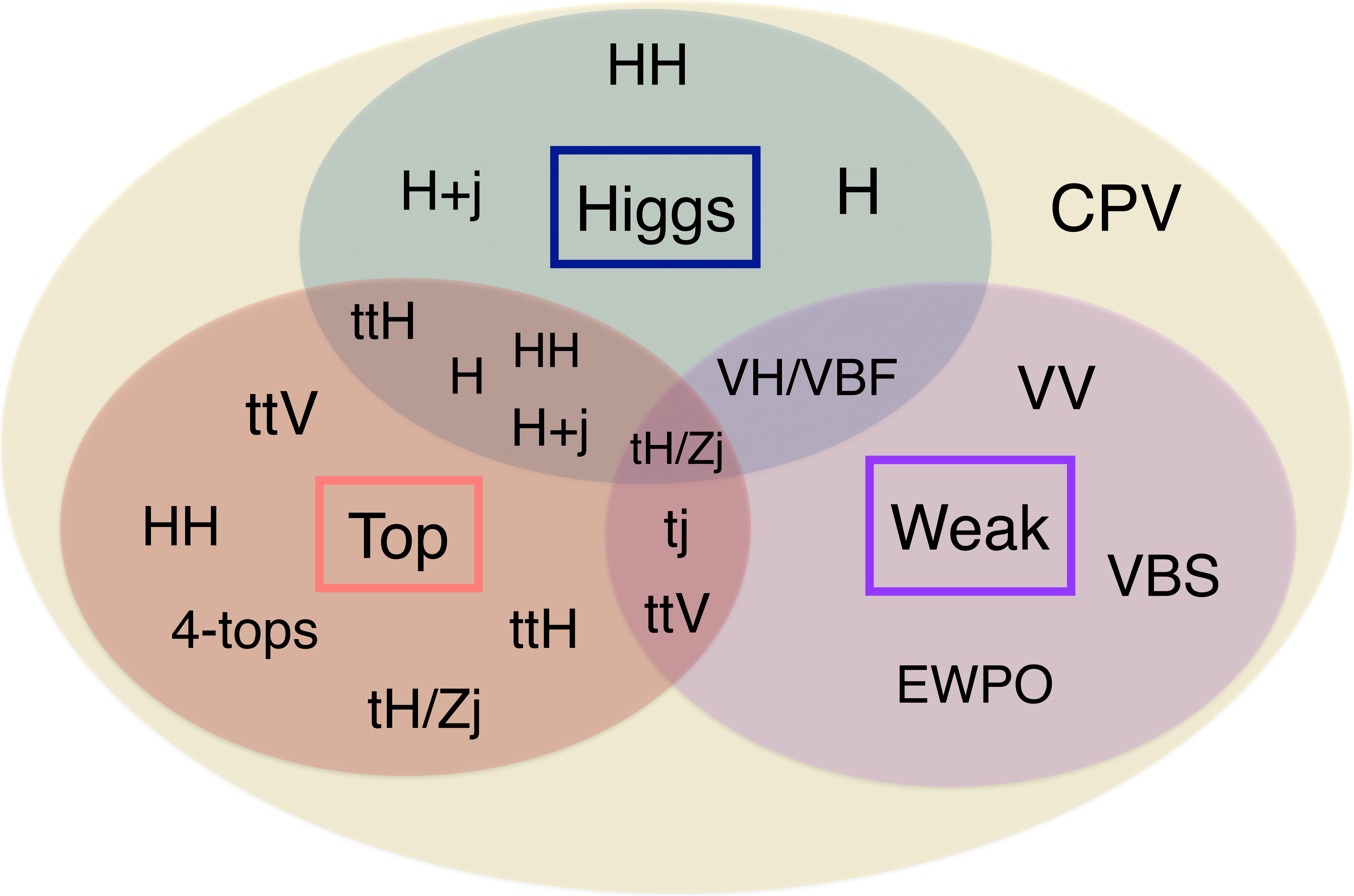
2) New Lorentz structures

(3) Indirect effect due to impact on input parameters and canonical normalisation of fields

What is next? Study particular processes and observables to maximise sensitivity on different operators

Fit data to extract EFT coefficients

SMEFT in practice



EFT has a global character

EFT pathway to New Physics

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

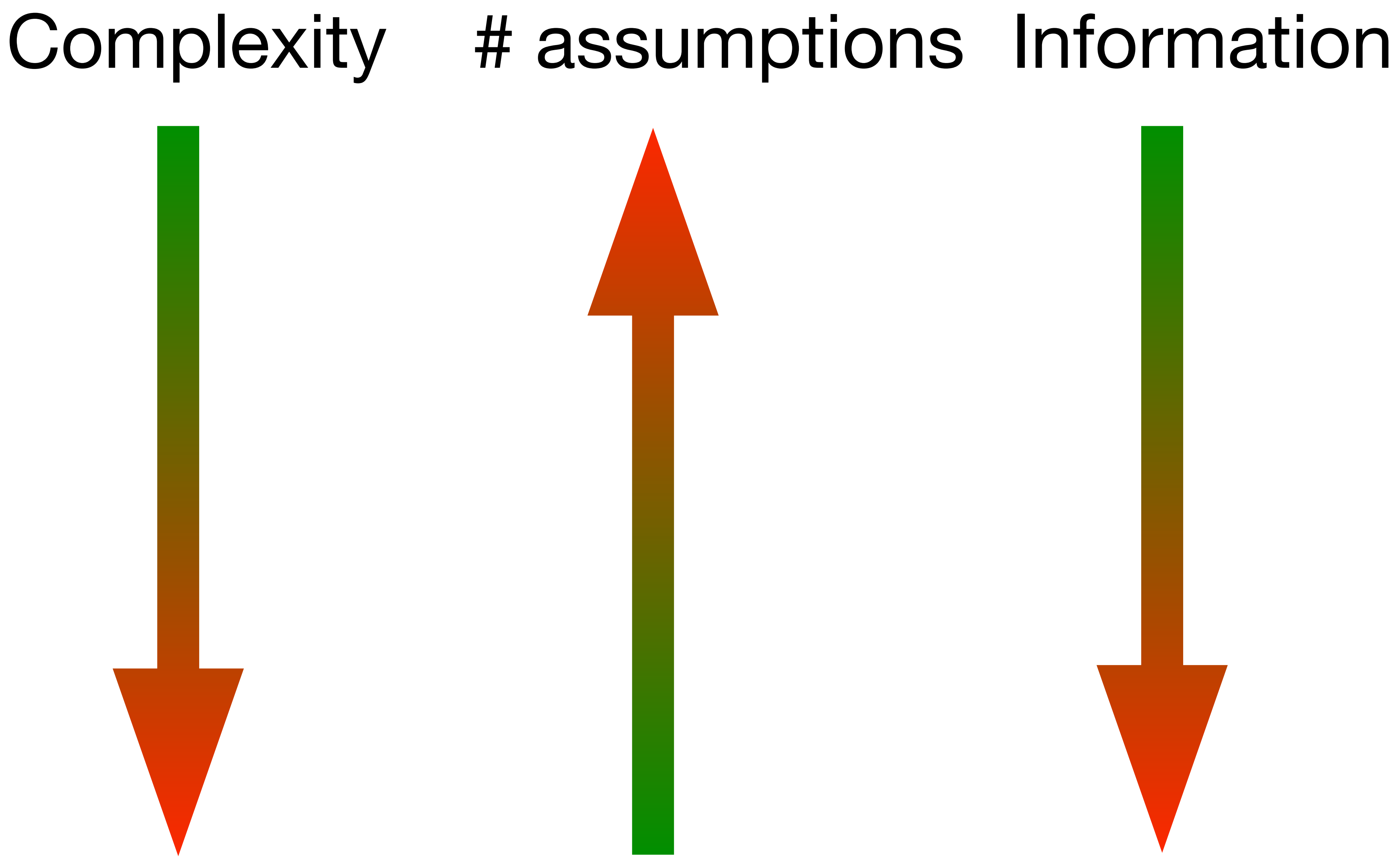
Precise EFT predictions

Precise SM predictions

Precise experimental measurements

$$\frac{c_i^6(\mu)}{\Lambda^2}$$

EFT interpretations

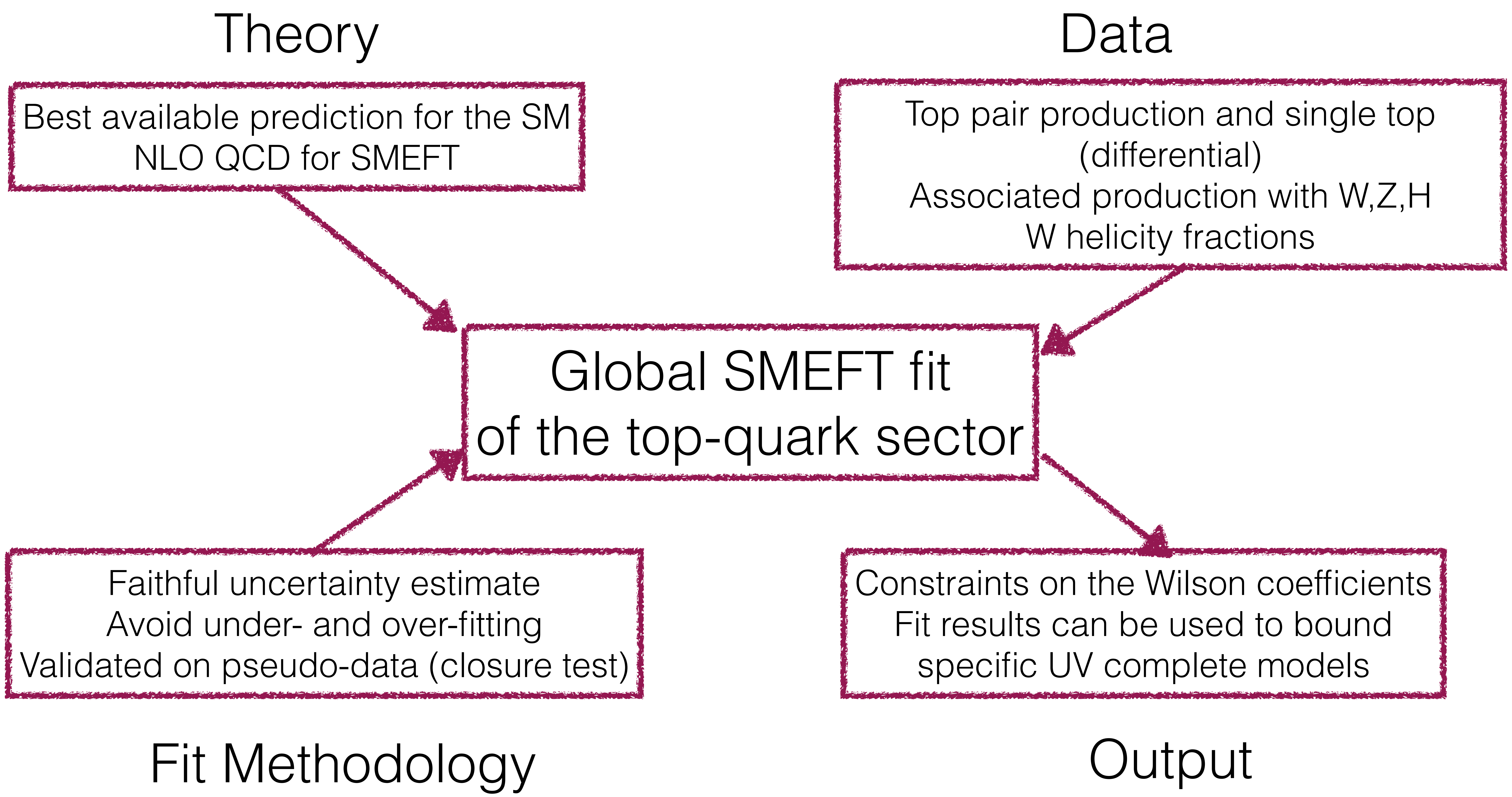


- Inclusive (fiducial) cross-section
- Differential parton level
- Differential particle level
- Detector level

LHC EFT WG effort:

https://indico.cern.ch/category/12671/

Global fit Setup



Observables

Data

Top-pair production
W-helicities,
asymmetry

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	8 TeV, 20.3 fb^{-1}	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_ljets	8 TeV, 20.3 fb^{-1}	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	8 TeV, 20.3 fb^{-1}	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	8 TeV, 20.3 fb^{-1}	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_ljets_2015	13 TeV, 2.3 fb^{-1}	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	13 TeV, 2.1 fb^{-1}	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_ljets_2016	13 TeV, 35.8 fb^{-1}	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	13 TeV, 35.8 fb^{-1}	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_ljets_2016 (*)	13 TeV, 35.8 fb^{-1}	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WhelF_8TeV	8 TeV, 20.3 fb^{-1}	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WhelF_8TeV	8 TeV, 20.3 fb^{-1}	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	8 TeV, 20.3 fb^{-1}	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	8 TeV, 20.3 fb^{-1}	charge asymmetry	A_C	5	[58]

4 tops, ttbb, top-pair associated production

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	13 TeV, 2.3 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[70]
CMS_ttbb_13TeV_2016 (*)	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[78]
CMS_tttt_13TeV	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	13 TeV, 137 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	13 TeV, 137 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	8 TeV, 19.5 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	13 TeV, 77.5 fb^{-1}	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	8 TeV, 20.3 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	13 TeV, 3.2 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	13 TeV, 36 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	8 TeV, 19.5 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	8 TeV, 20.3 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	13 TeV, 3.2 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	13 TeV, 36 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[80]

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	8 TeV, 19.7 fb^{-1}	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	8 TeV, 20.2 fb^{-1}	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	8 TeV, 19.7 fb^{-1}	t-channel	$d\sigma/d\|y^{(t+\bar{t})}\|$	6	[84]
CMS_t_sch_8TeV	8 TeV, 19.7 fb^{-1}	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	8 TeV, 20.3 fb^{-1}	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	13 TeV, 3.2 fb^{-1}	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	13 TeV, 2.2 fb^{-1}	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	13 TeV, 2.3 fb^{-1}	t-channel	$d\sigma/d\|y^{(t+\bar{t})}\|$	4	[89]
CMS_t_tch_13TeV_2016 (*)	13 TeV, 35.9 fb^{-1}	t-channel	$d\sigma/d\|y^{(t)}\|$	5	[91]

Single top t-, s-channel

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tW_8TeV_inc	8 TeV, 20.2 fb^{-1}	inclusive (dilepton)	$\sigma_{\rm tot}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	8 TeV, 20.2 fb^{-1}	inclusive (single lepton)	$\sigma_{\rm tot}(tW)$	1	[101]
CMS_tW_8TeV_inc	8 TeV, 19.7 fb^{-1}	inclusive	$\sigma_{\rm tot}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	13 TeV, 3.2 fb^{-1}	inclusive	$\sigma_{\rm tot}(tW)$	1	[97]
CMS_tW_13TeV_inc	13 TeV, 35.9 fb^{-1}	inclusive	$\sigma_{\rm tot}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	13 TeV, 36.1 fb^{-1}	inclusive	$\sigma_{\rm tot}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	13 TeV, 139.1 fb^{-1}	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^- q)$	1	[102]
CMS_tZ_13TeV_inc	13 TeV, 35.9 fb^{-1}	inclusive	$\sigma_{\rm fid}(Wb\ell^+\ell^- q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	13 TeV, 77.4 fb^{-1}	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^- q)$	1	[103]

tW, tZ

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
LEP2_WW_diff (*)	[182, 296] GeV	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_W$	40	[128]
ATLAS_WZ_13TeV_2016 (*)	13 TeV, 36.1 fb^{-1}	fully leptonic	$d\sigma^{\rm (fid)}/dm_T^{WZ}$	6	[129]
ATLAS_WW_13TeV_2016 (*)	13 TeV, 36.1 fb^{-1}	fully leptonic	$d\sigma^{\rm (fid)}/dm_{e\mu}$	13	[130]
CMS_WZ_13TeV_2016 (*)	13 TeV, 35.9 fb^{-1}	fully leptonic	$d\sigma^{\rm (fid)}/dp_T^Z$	11	[131]

Diboson

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_CMS_SSinc_RunI (*)	7+8 TeV, 20 fb^{-1}	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[114]
ATLAS_SSinc_RunI (*)	8 TeV, 20 fb^{-1}	Incl. μ_i^f	$h \to Z\gamma, \mu\mu$	2	[115]
ATLAS_SSinc_RunII (*)	13 TeV, 80 fb^{-1}	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[116]
CMS_SSinc_RunII (*)	13 TeV, 36.9 fb^{-1}	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[117]

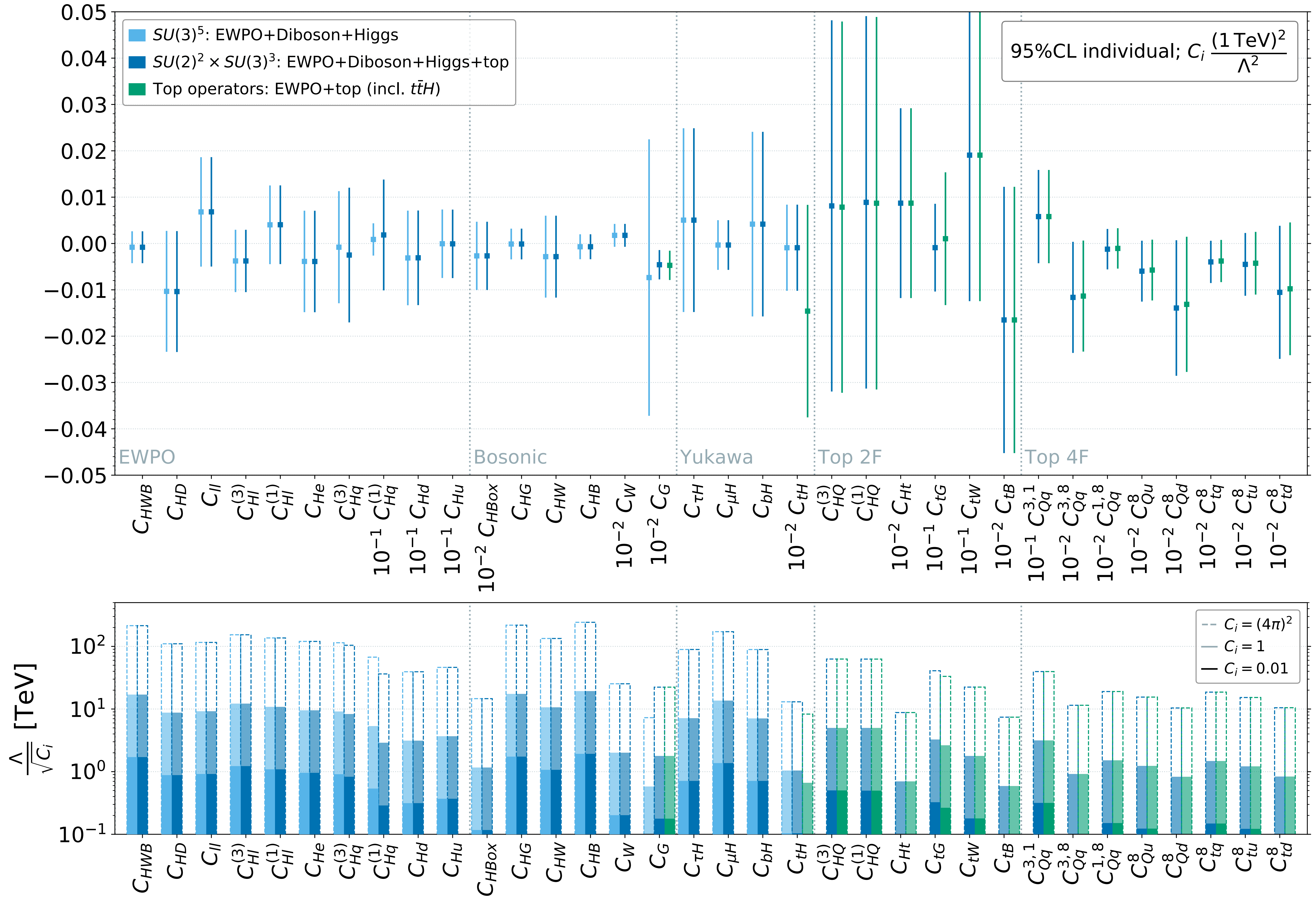
Higgs signal strengths

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_H_13TeV_2015 (*)	13 TeV, 35.9 fb^{-1}	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	[121]
ATLAS_ggF_13TeV_2015 (*)	13 TeV, 36.1 fb^{-1}	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ(\to 4l)$	$d\sigma/dp_T^h$	9	[122]
ATLAS_Vh_hbb_13TeV (*)	13 TeV, 79.8 fb^{-1}	Wh, Zh	$d\sigma^{\rm (fid)}/dp_T^W$ $d\sigma^{\rm (fid)}/dp_T^Z$	2 3	[123]
ATLAS_ggF_ZZ_13TeV (*)	13 TeV, 79.8 fb^{-1}	ggF, $h \to ZZ$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[116]
CMS_ggF_aa_13TeV (*)	13 TeV, 77.4 fb^{-1}	ggF, $h \to \gamma\gamma$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[124]

Higgs differential

Category	Processes	$n_{\rm dat}$
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

Full fit: individual



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Individual: only one non-zero c_i

(optimistic, unrealistic)

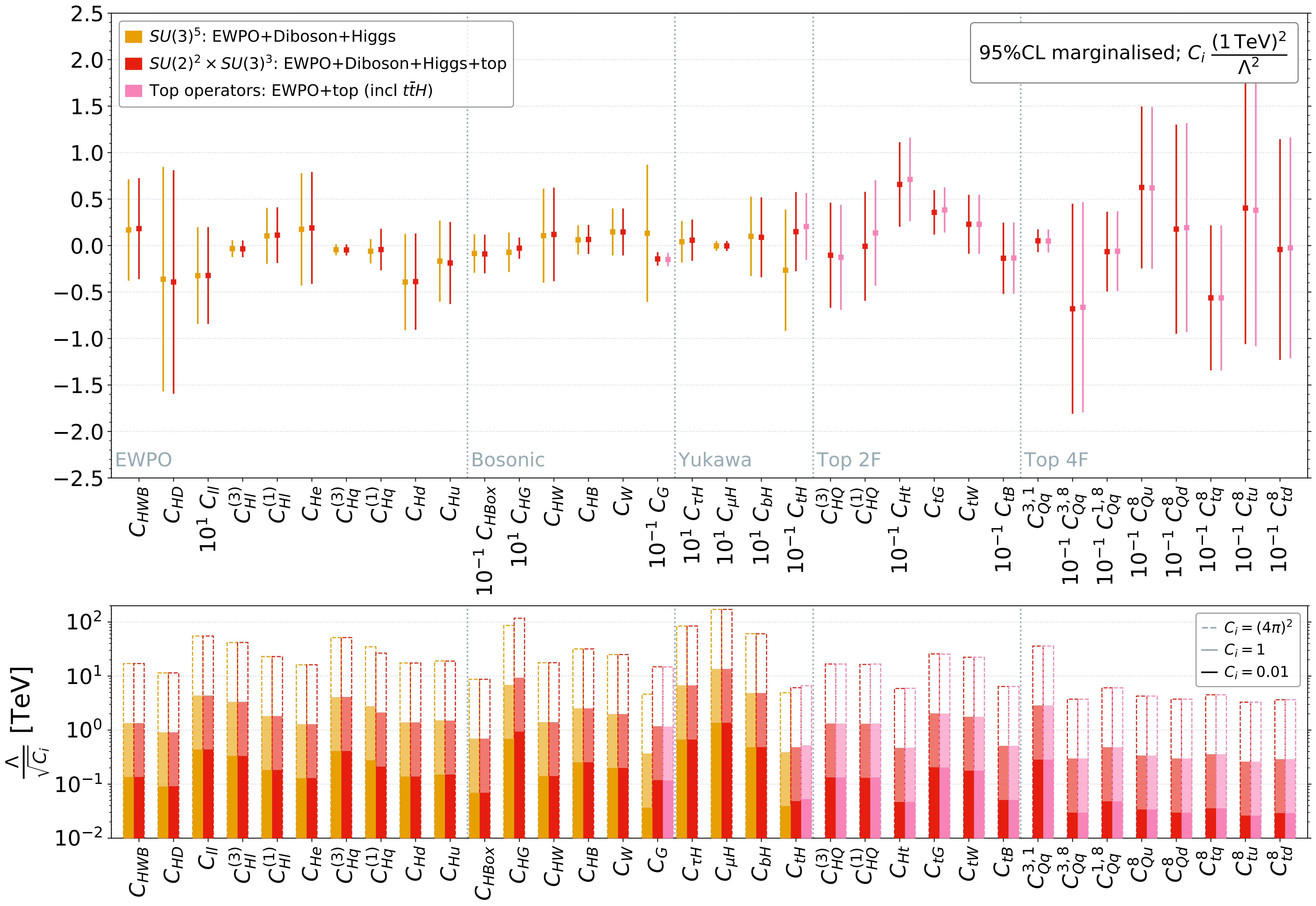
What does that mean for the UV scale?

Strongly coupled

Weakly coupled

$$\frac{c_i^6(\mu)}{\Lambda^2}$$

Full fit: marginalised



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

All coefficients allowed to be non-zero

Bounds significantly worse in a marginalised fit

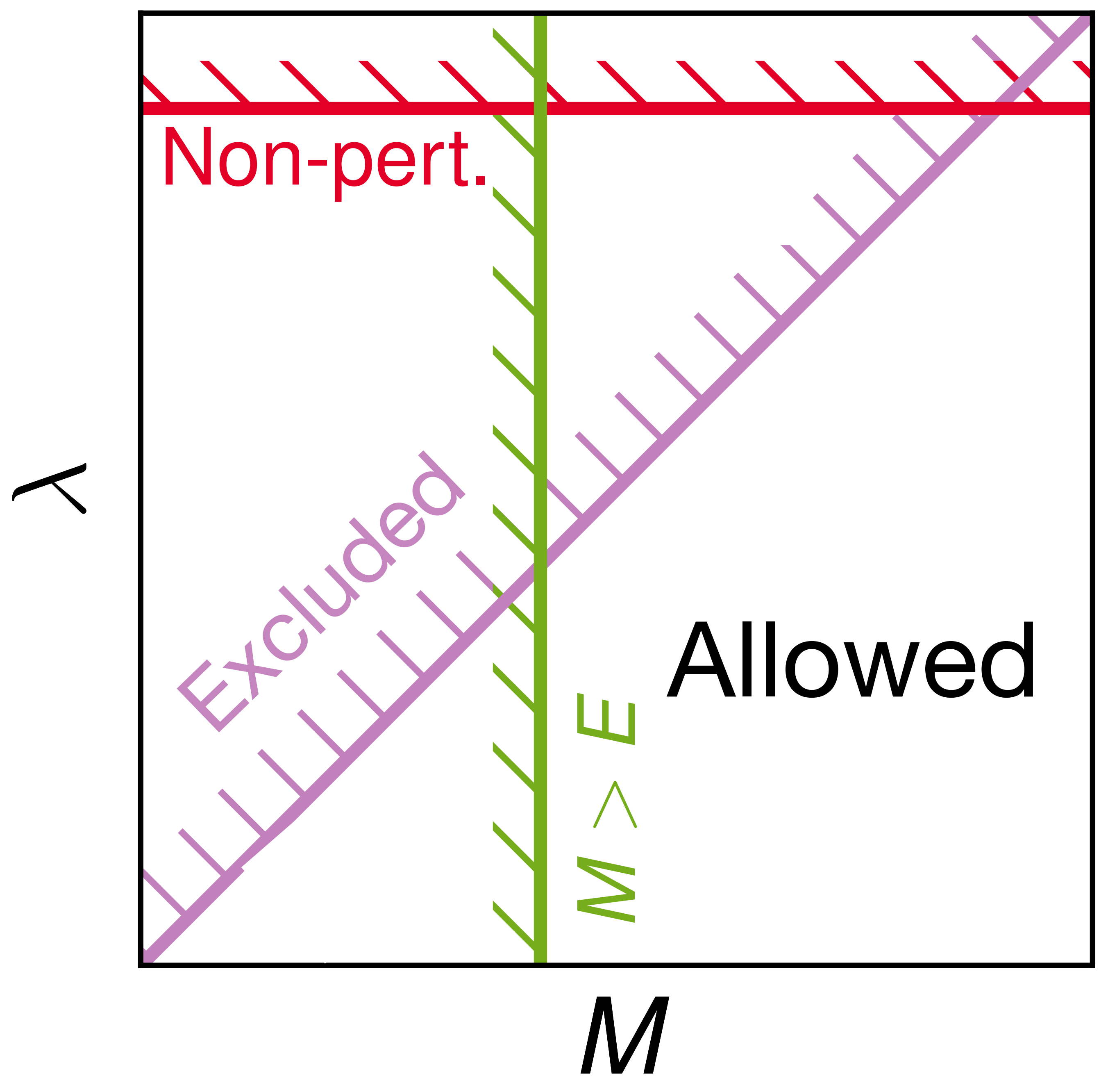
For weakly coupled theories Λ bound below the TeV scale: **EFT Validity???**

What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV. Bounds depend on

- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

constraint: $\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$



From EFT to the UV

	Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.	
	S	0	1	1	0	$(M_S,\, \kappa_S)$	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1},\lambda_{\Delta_1})$	
	S_1	0	1	1	1	(M_{S_1},y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$	
Scalars	φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6 \cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$	VLL
	Ξ	0	1	3	0	(M_Ξ,κ_Ξ)	Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1},\lambda_{\Sigma_1})$	
	Ξ_1	0	1	3	1	$(M_{\Xi_1},\kappa_{\Xi_1})$	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_U,λ_U)	
Z’	B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)	
W’	B_1	1	1	1	1	(M_{B_1},g_{B_1})	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$	(M_{Q_1},λ_{Q_1})	
	W	1	1	3	0	$(M_W,\hat{g}_H^W)$	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$	(M_{Q_5},λ_{Q_5})	
	W_1	1	1	3	1	$(M_{W_1},\hat{g}_{W_1}^\varphi)$	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$	(M_{Q_7},λ_{Q_7})	VLQ
VLL	N	$\frac{1}{2}$	1	1	0	(M_N,λ_N)	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$	(M_{T_1},λ_{T_1})	
	E	$\frac{1}{2}$	1	1	-1	(M_E,λ_E)	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$	(M_{T_2},λ_{T_2})	
VLQ	T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T,s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB},s_L^{t,b})$	

Matching

Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						$-\frac{3}{2}$	$-\, y_\tau$	$-\, y_t$	$-\, y_b$
$\{Q_1, Q_7\}$								y_t	

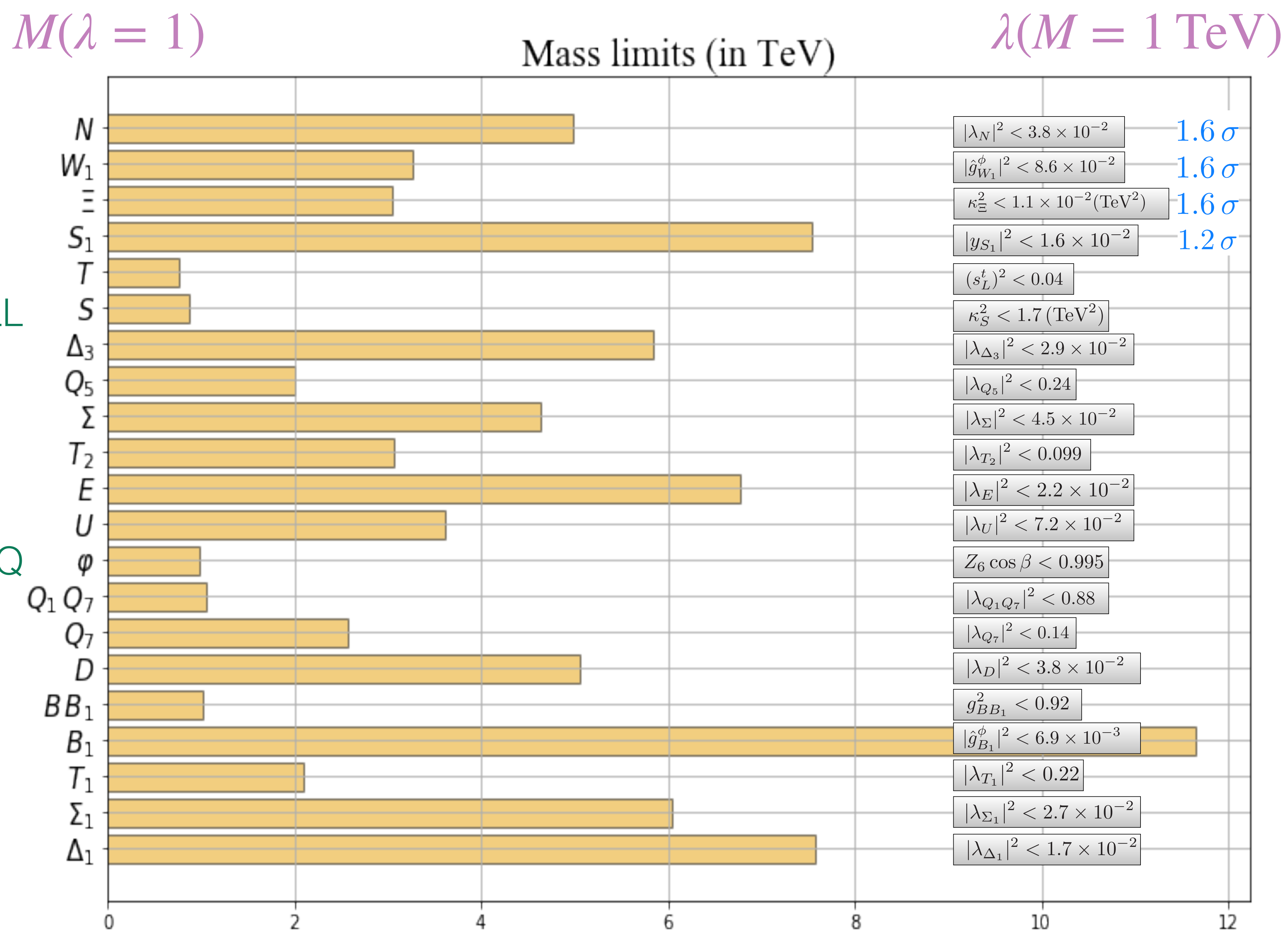
Model	C_{Hq}^3	C_{Hq}^1	$(C_{Hq}^3)_{33}$	$(C_{Hq}^1)_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}	
U	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
D	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$	
Q_5						$-\frac{1}{2}$		$\frac{y_b}{2}$	
Q_7					$\frac{1}{2}$		$\frac{y_t}{2}$		
T_1	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$		

Tree-level matching dictionary
de Blas et al. JHEP 03 (2018) 109

- EFT bounds translate to constraints on parameters of UV models
- Simplest case: single-field extensions of the SM

From EFT to UV

	Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.
Scalars	S	0	1	1	0	(M_S, κ_S)	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1},\lambda_{\Delta_1})$
	S_1	0	1	1	1	(M_{S_1},y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$
	φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6 \cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$
	Ξ	0	1	3	0	(M_Ξ,κ_Ξ)	Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1},\lambda_{\Sigma_1})$
	Ξ_1	0	1	3	1	$(M_{\Xi_1},\kappa_{\Xi_1})$	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_U,λ_U)
Z'	B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)
W'	B_1	1	1	1	1	(M_{B_1},g_{B_1})	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$	(M_{Q_1},λ_{Q_1})
	W	1	1	3	0	$(M_W,\hat{g}_H^W)$	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$	(M_{Q_5},λ_{Q_5})
	W_1	1	1	3	1	$(M_{W_1},\hat{g}_{W_1}^\varphi)$	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$	(M_{Q_7},λ_{Q_7})
VLL	N	$\frac{1}{2}$	1	1	0	(M_N,λ_N)	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$	(M_{T_1},λ_{T_1})
	E	$\frac{1}{2}$	1	1	-1	(M_E,λ_E)	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$	(M_{T_2},λ_{T_2})
VLQ	T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T,s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB},s_L^{t,b})$



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

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Fix coupling and set bound on mass or the other way round

THANK YOU