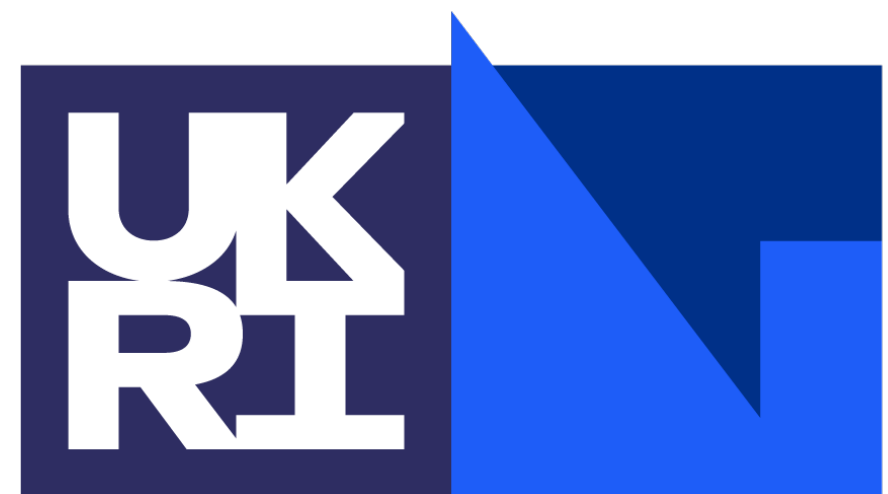




Science and
Technology
Facilities Council



University of
Southampton

Collider Phenomenology

Ken Mimasu

STFC HEP school, Durham
14-18/9/26

with thanks to Eleni Vryonidou & Jonathan Gaunt

Plan for the lectures

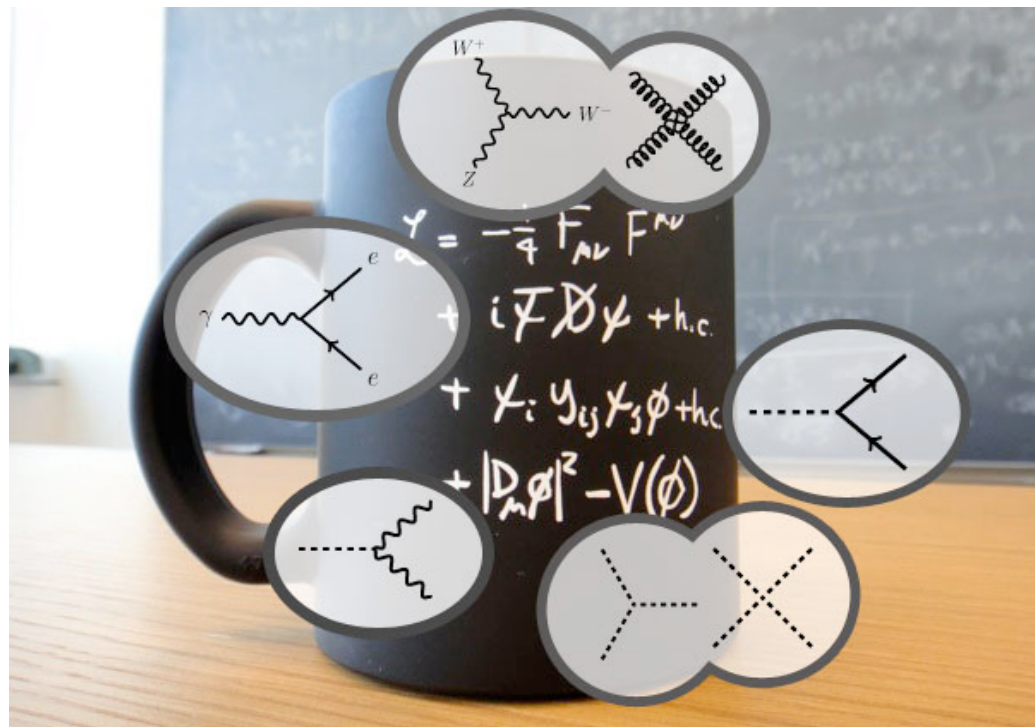
- Basics of collider physics
- Basics of QCD
 - DIS and the Parton Model
 - Higher order corrections
 - Asymptotic freedom
 - QCD improved parton model
- State-of-the-art computations for the LHC
- Monte Carlo generators
- Higgs phenomenology
- Top phenomenology
- Searching for New Physics: EFT

Basics of collider physics

Goals of collider physics:

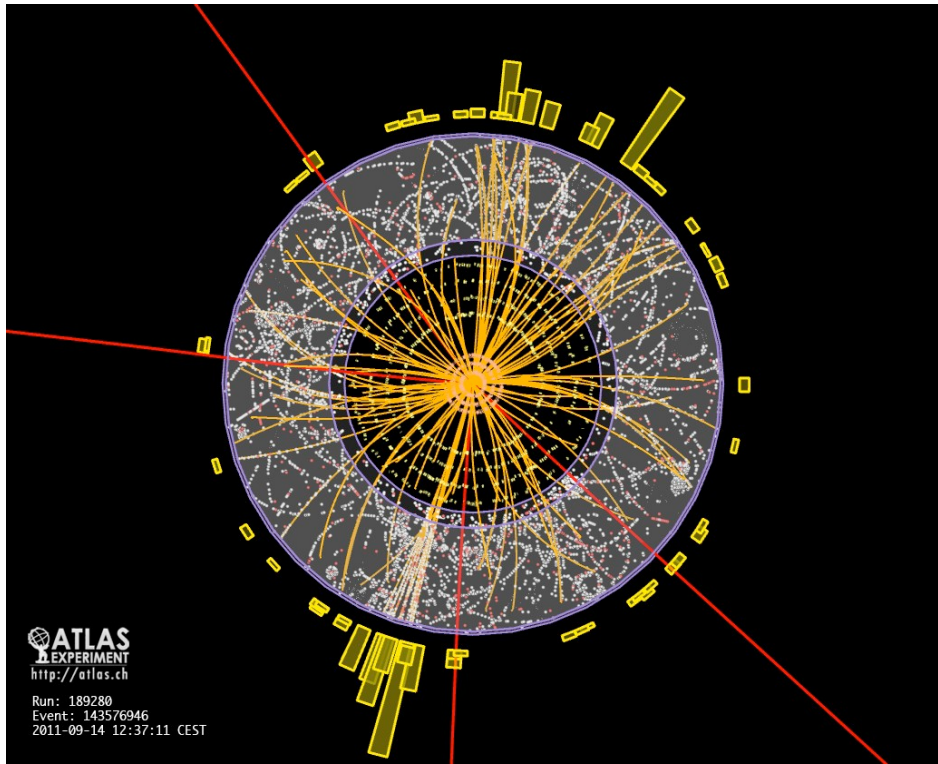
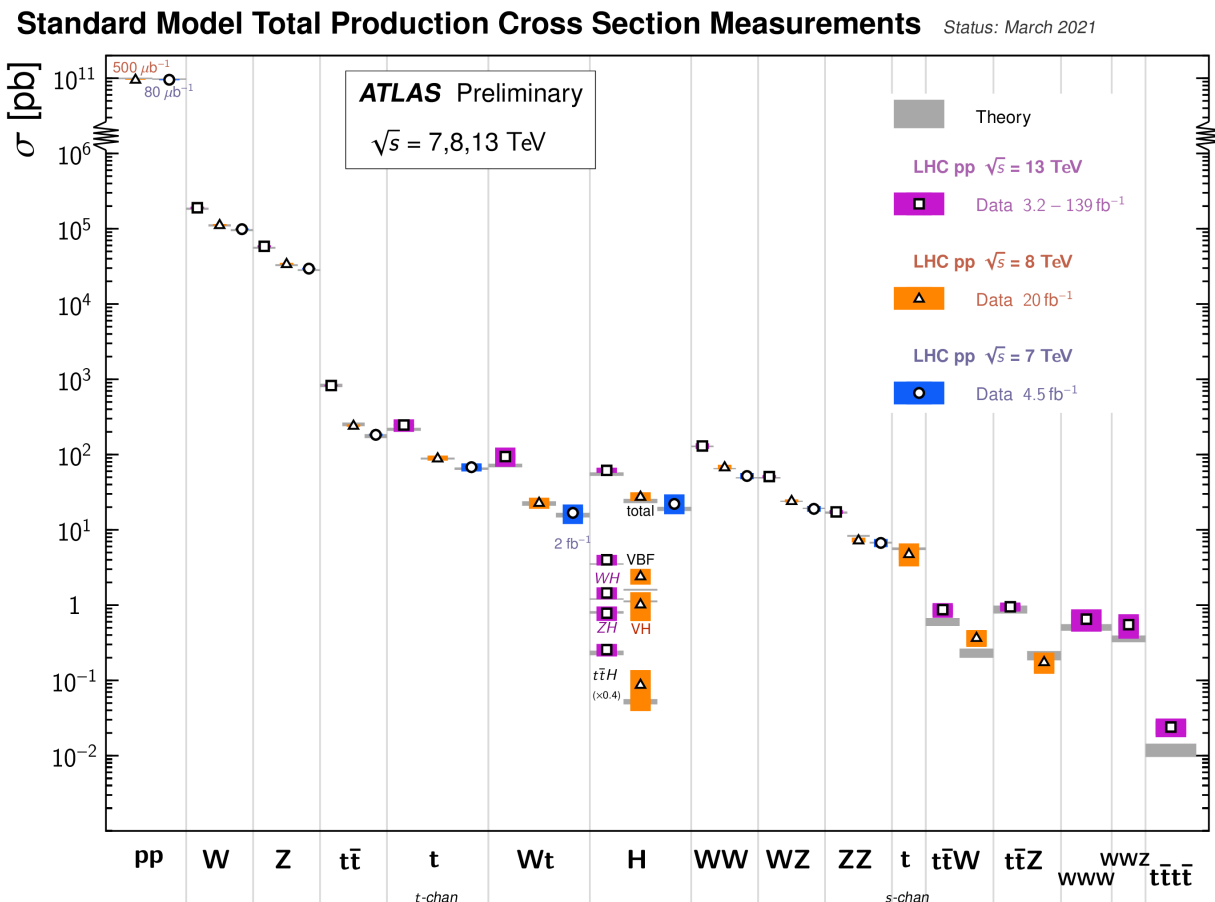
-  Test theoretical predictions: Standard Model and New Physics
-  Hopefully find the unexpected!

Collider physics



Theory

Interpretation



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?

Timeline for the update of the European Strategy for Particle Physics



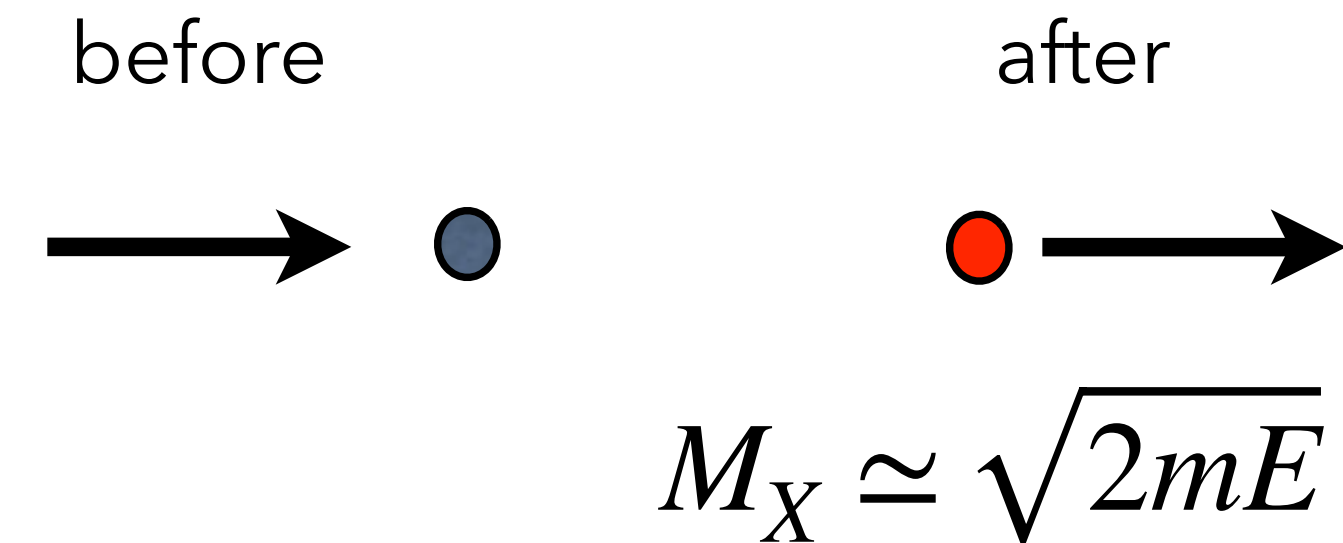
Future of collider physics?



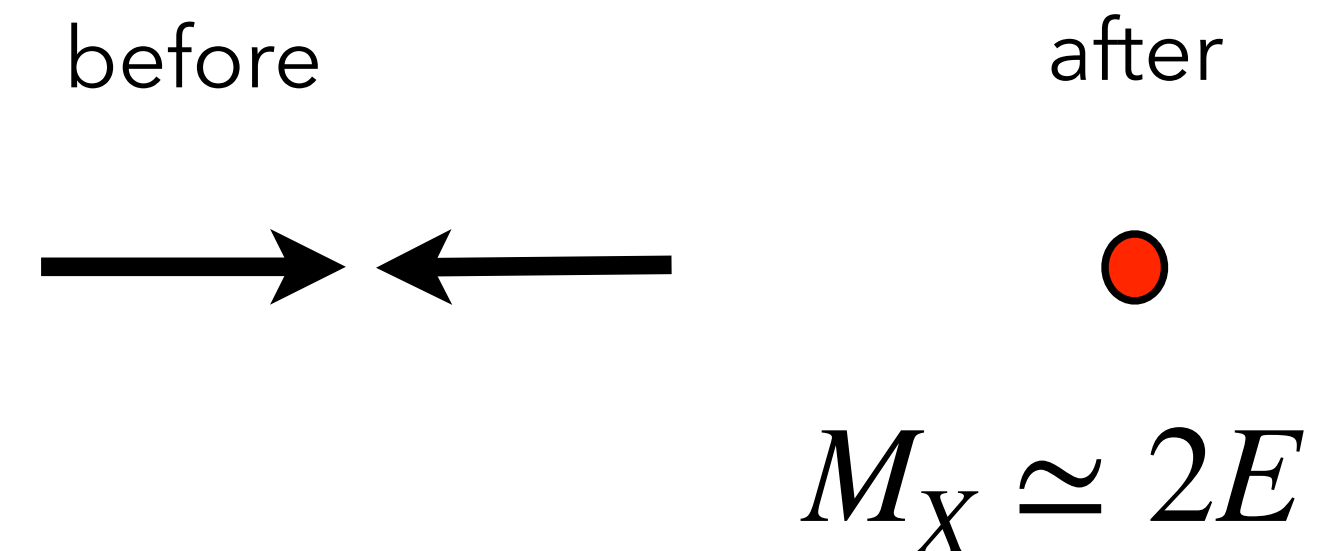
Collider reach

$$A + B \rightarrow X \quad M_X^2 = (p_1 + p_2)^2$$

Fixed target experiment: $p_1 \simeq (E, 0, 0, E)$
 $p_2 = (m, 0, 0, 0)$



Collider experiment: $p_1 \simeq (E, 0, 0, E)$
 $p_2 \simeq (E, 0, 0, -E)$



Better energy scaling for collider experiment

Note: fixed target can benefit from dense target

Collider aspects

Luminosity: rate of particles in colliding bunches

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

N_i number of particles in bunches
 f bunch collision rate
 A transverse bunch area

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

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

LHC luminosity Run II $L = 300 \text{ fb}^{-1}$
HL-LHC luminosity $L = 3000 \text{ fb}^{-1}$

Circular vs linear:

circular colliders are compact, but suffer from synchrotron radiation

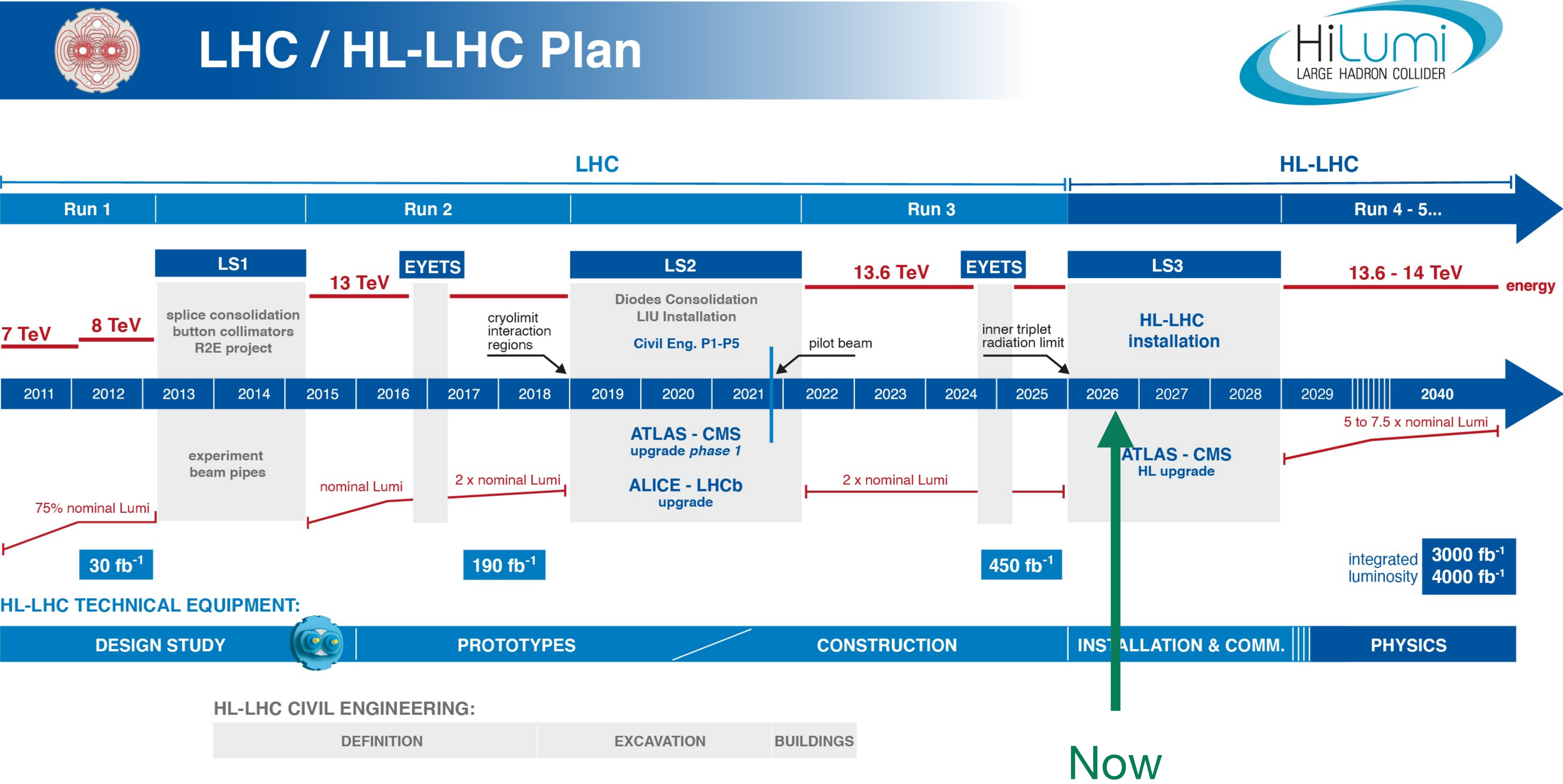
$$P \propto \frac{1}{R} \left(\frac{E}{M} \right)^4$$

Lepton vs Hadron:

Lepton colliders, all energy available in the collision

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

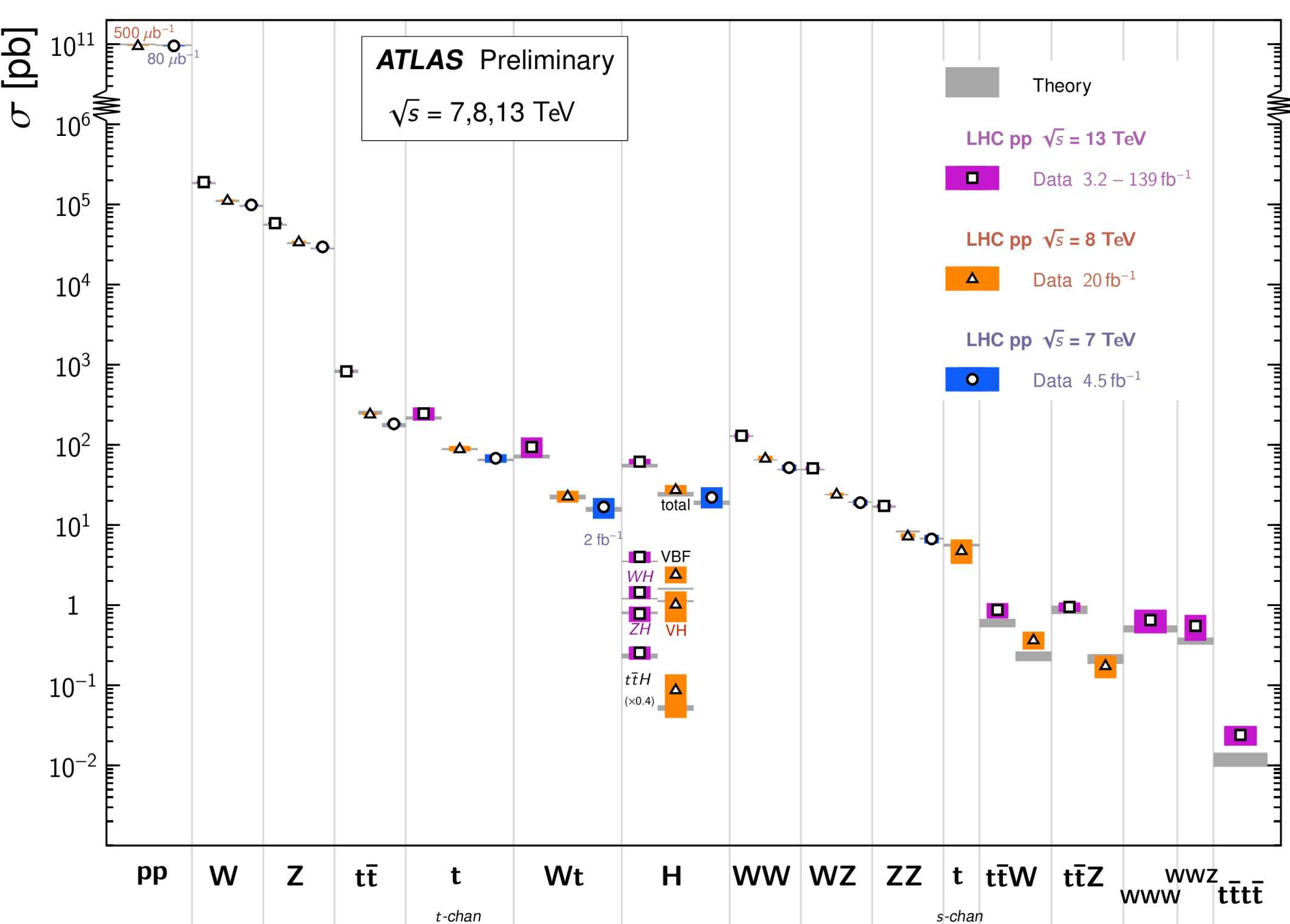
LHC: a hadron collider



LHC status

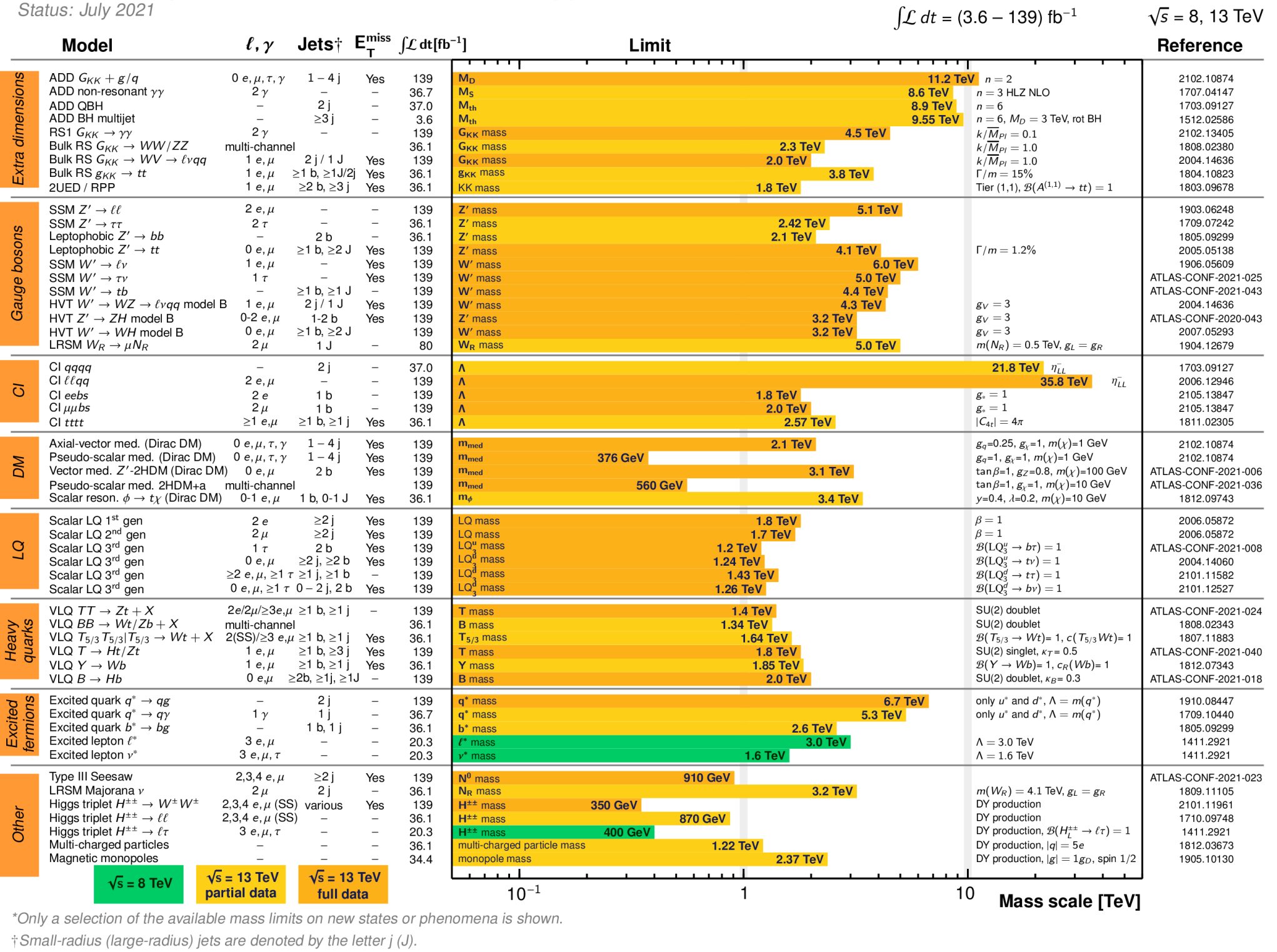
Exploring & refining the SM

Standard Model Total Production Cross Section Measurements Status: March 2021



Searching for the unknown

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits Status: July 2021



Good agreement with the SM

LHC physics

No sign of new physics so far! 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

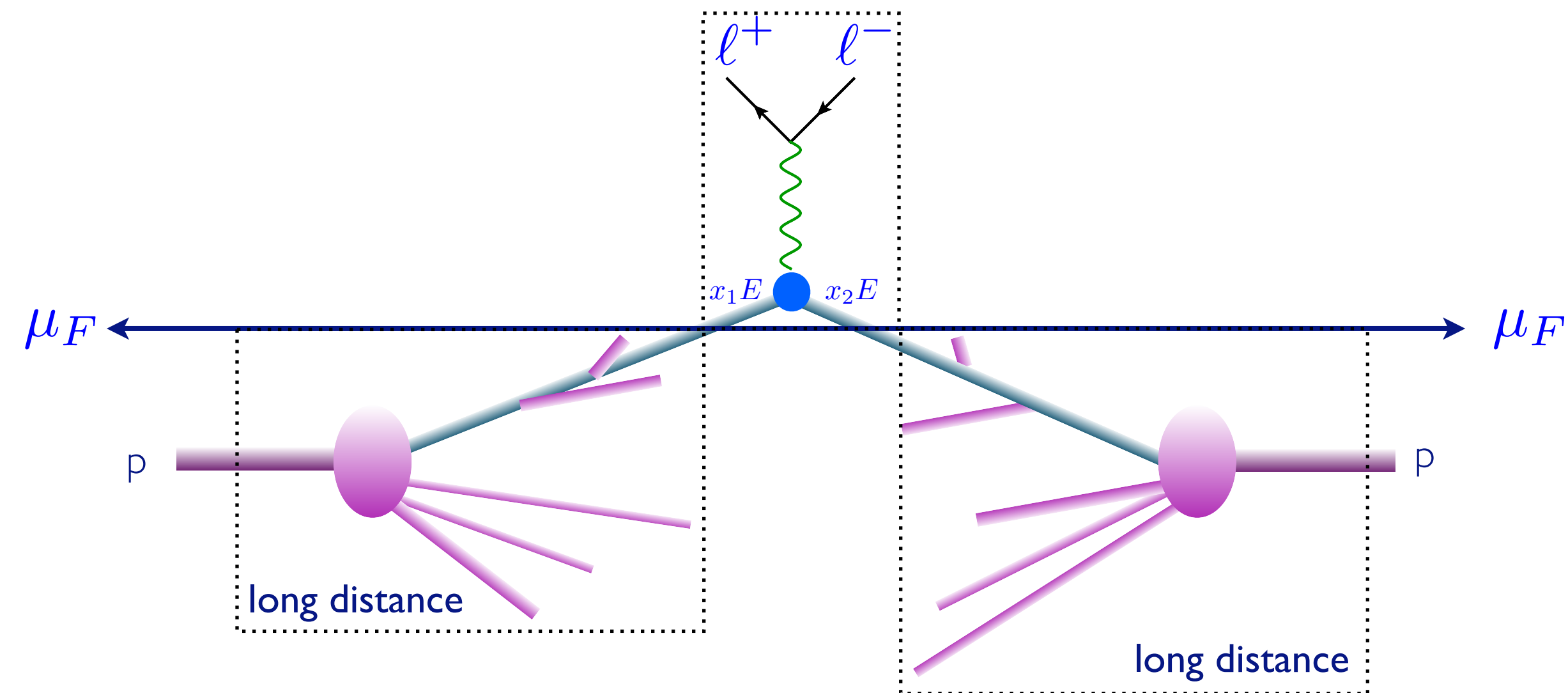
Need indirect searches via precision measurements: EFT

What is next for LHC physics

- New Physics is hiding well!
- Need to probe small deviations from the Standard Model.
- 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?



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

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

Master formula for LHC physics

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

Phase-space integral

Important
aspect of a
Monte Carlo
generator

Parton density functions

Universal:

~Probabilities of finding
given parton with given
momentum in proton

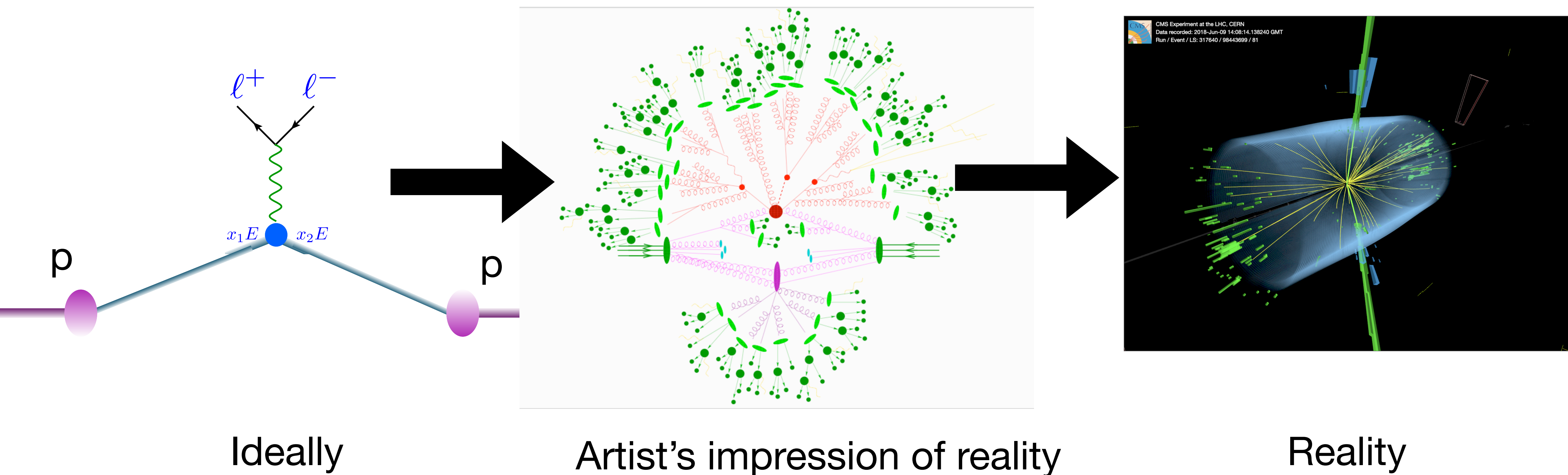
Extracted from data

Parton-level cross section

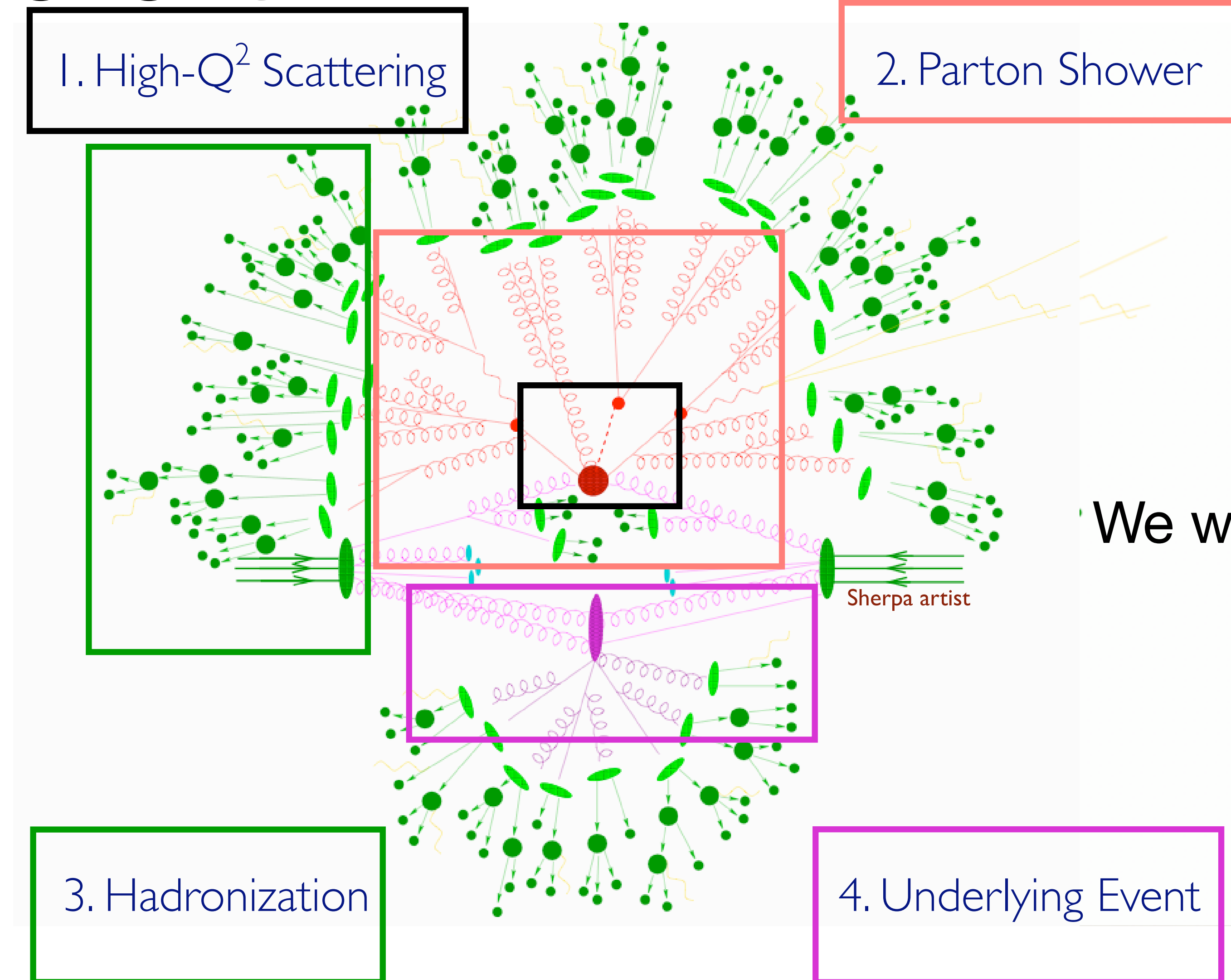
Subject of huge efforts in
the LHC theory community
to systematically improve
this

We will study this formula in detail this week

From the hard scattering to events



An LHC event



We will discuss all of these!

QCD...

LHC is a proton-proton collider:

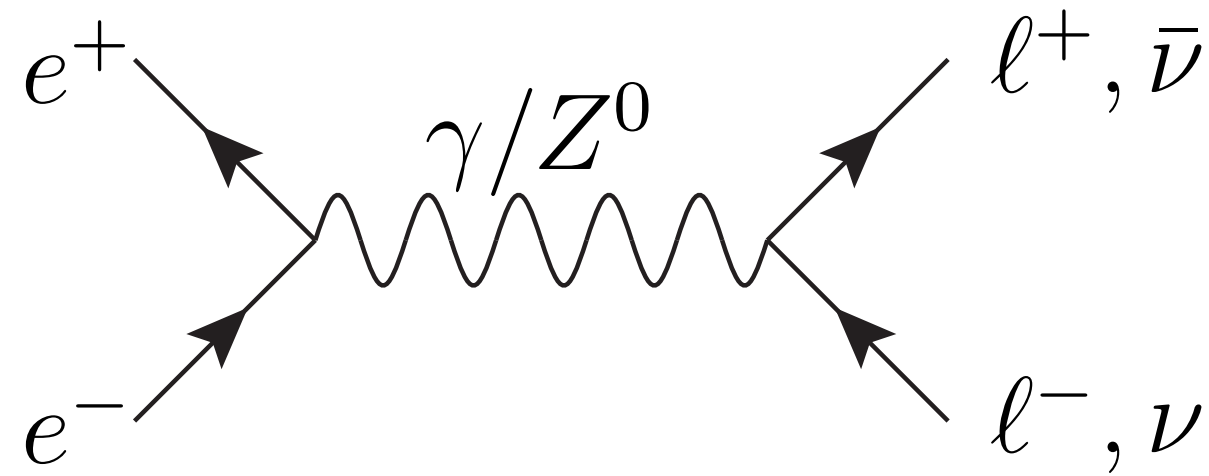
- Colliding particles are proton constituents which are **coloured** particles

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

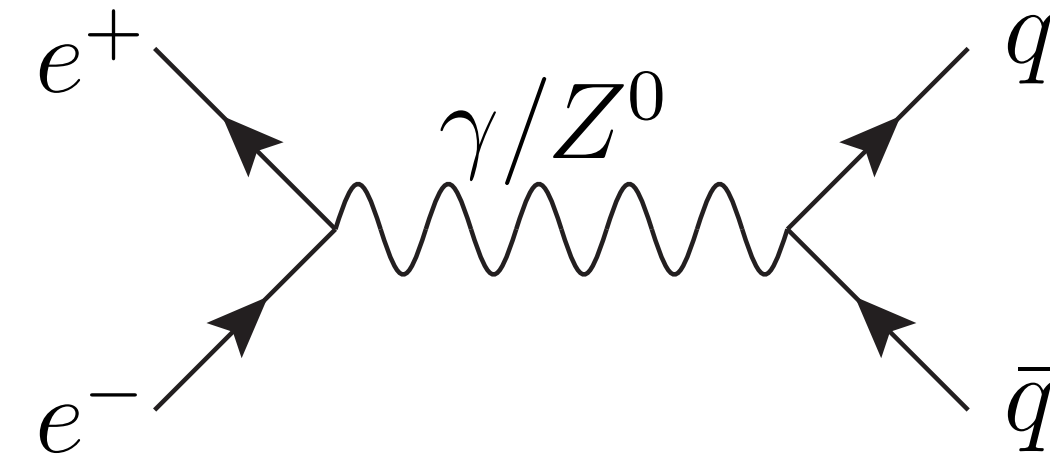
Why is QCD “special”?

Let's compare it to what we know best: QED

From QED to QCD

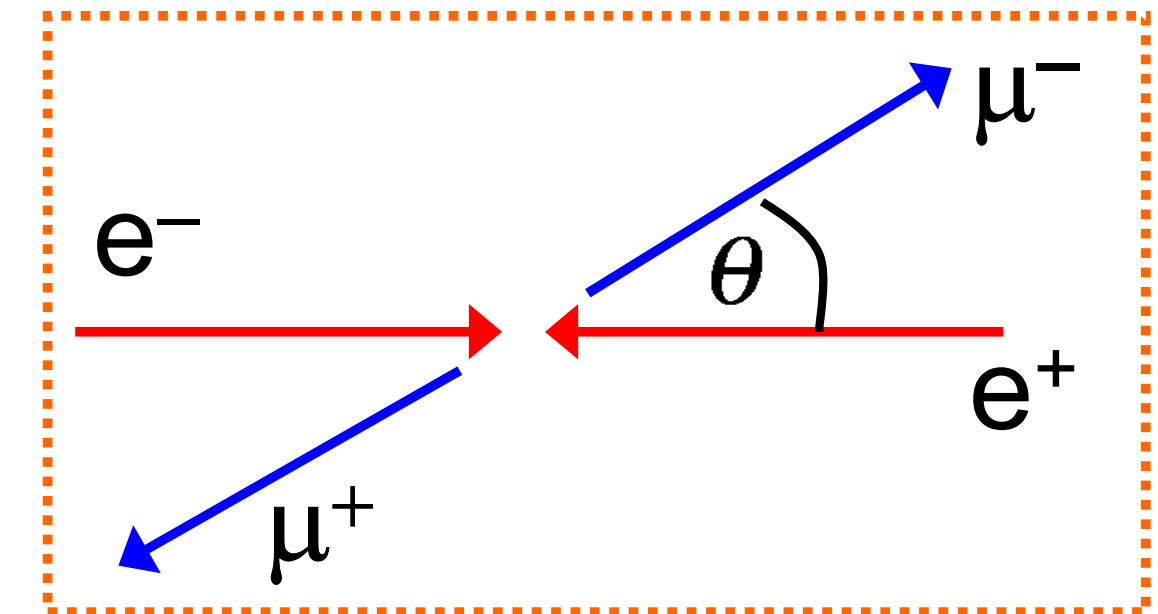
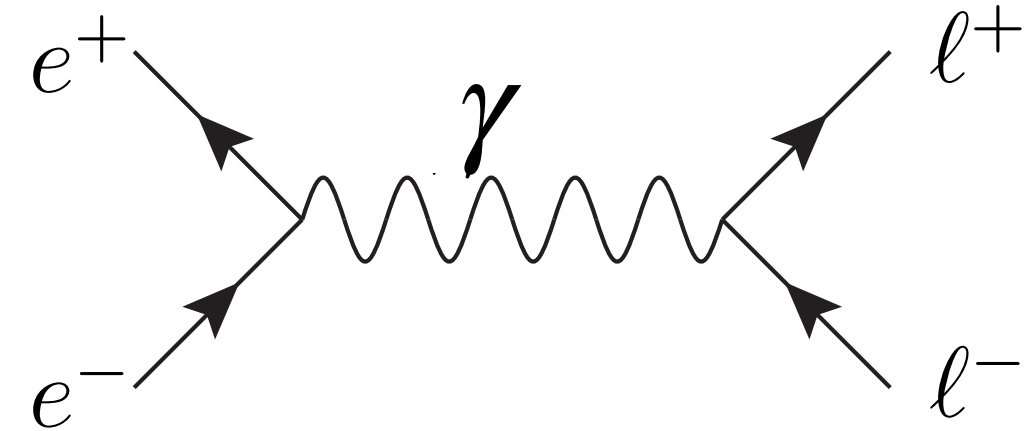


VS



Let's compute the matrix element for:
Summing and averaging spins:

$$\bar{\sum} |M|^2 = \frac{2e^4}{s^2} [t^2 + u^2] \quad \text{Try this out!}$$



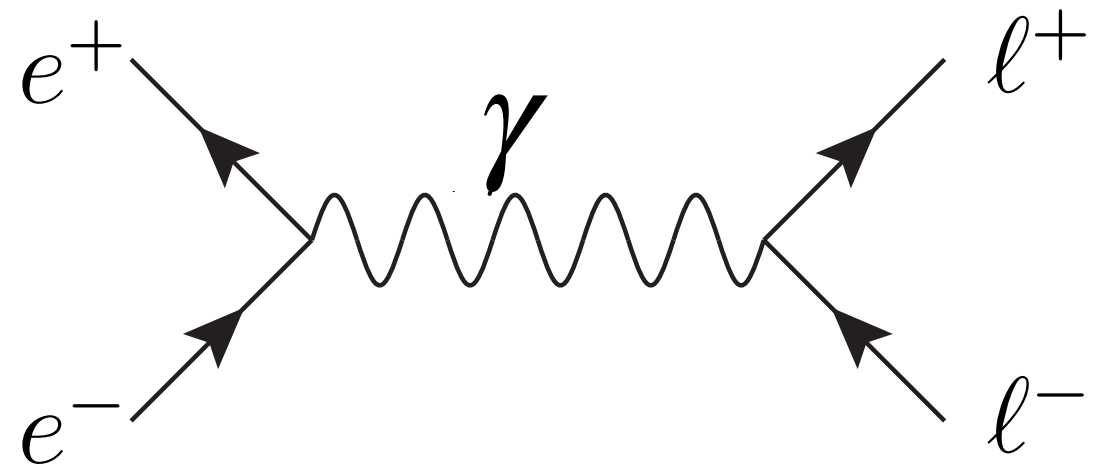
Mandelstam variables:

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

Why? $s + t + u = \sum_{i \in \text{ext.}} m_i^2 \sim 0$

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

From QED to QCD



$$\bar{\sum} |M|^2 = \frac{2e^4}{s^2} [t^2 + u^2] \quad \bar{\sum} |M|^2 \propto (1 + \cos^2\theta)$$

Cross-section:

2-body phase-space + momentum conservation

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

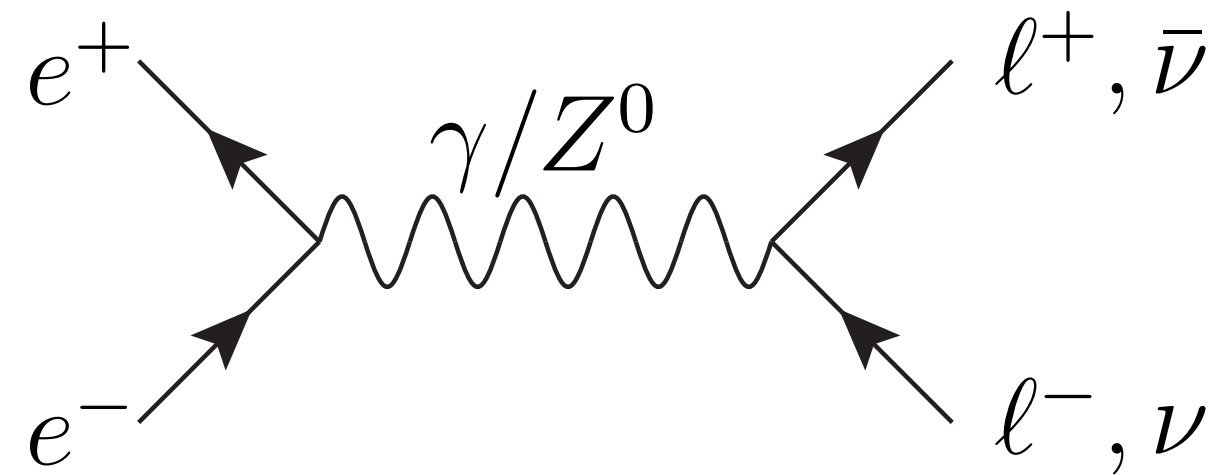
$$d\Omega = d\phi d\cos\theta$$

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

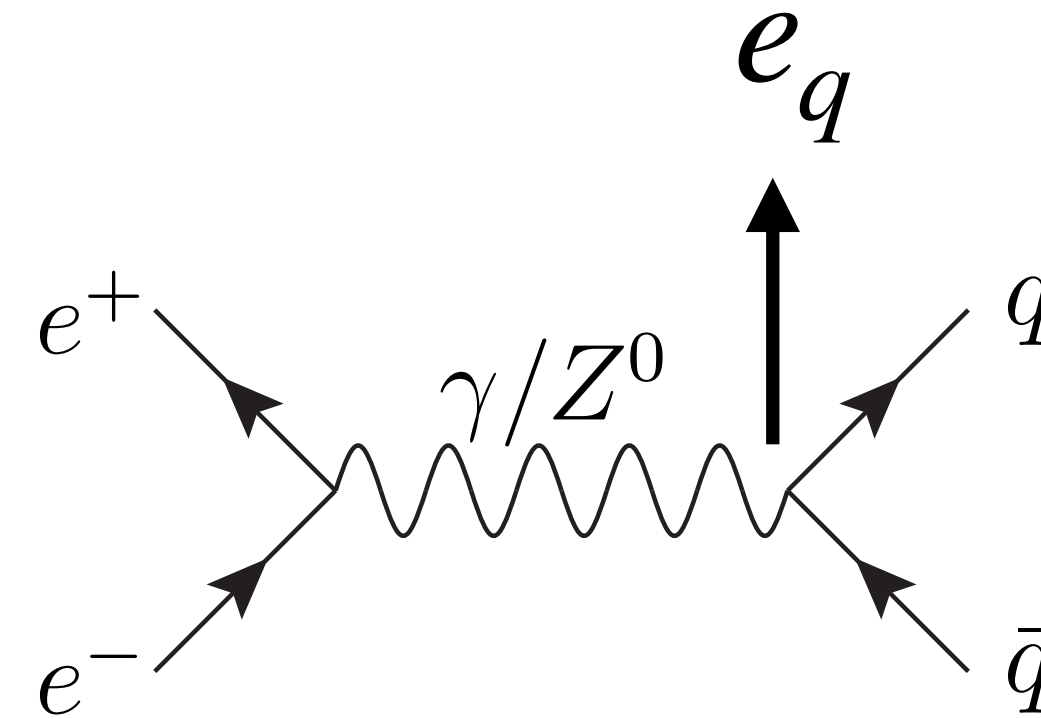
$$\alpha = \frac{e^2}{4\pi}$$

Try this out!

From QED to QCD



vs



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

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

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

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

Difference due to colour d.o.f

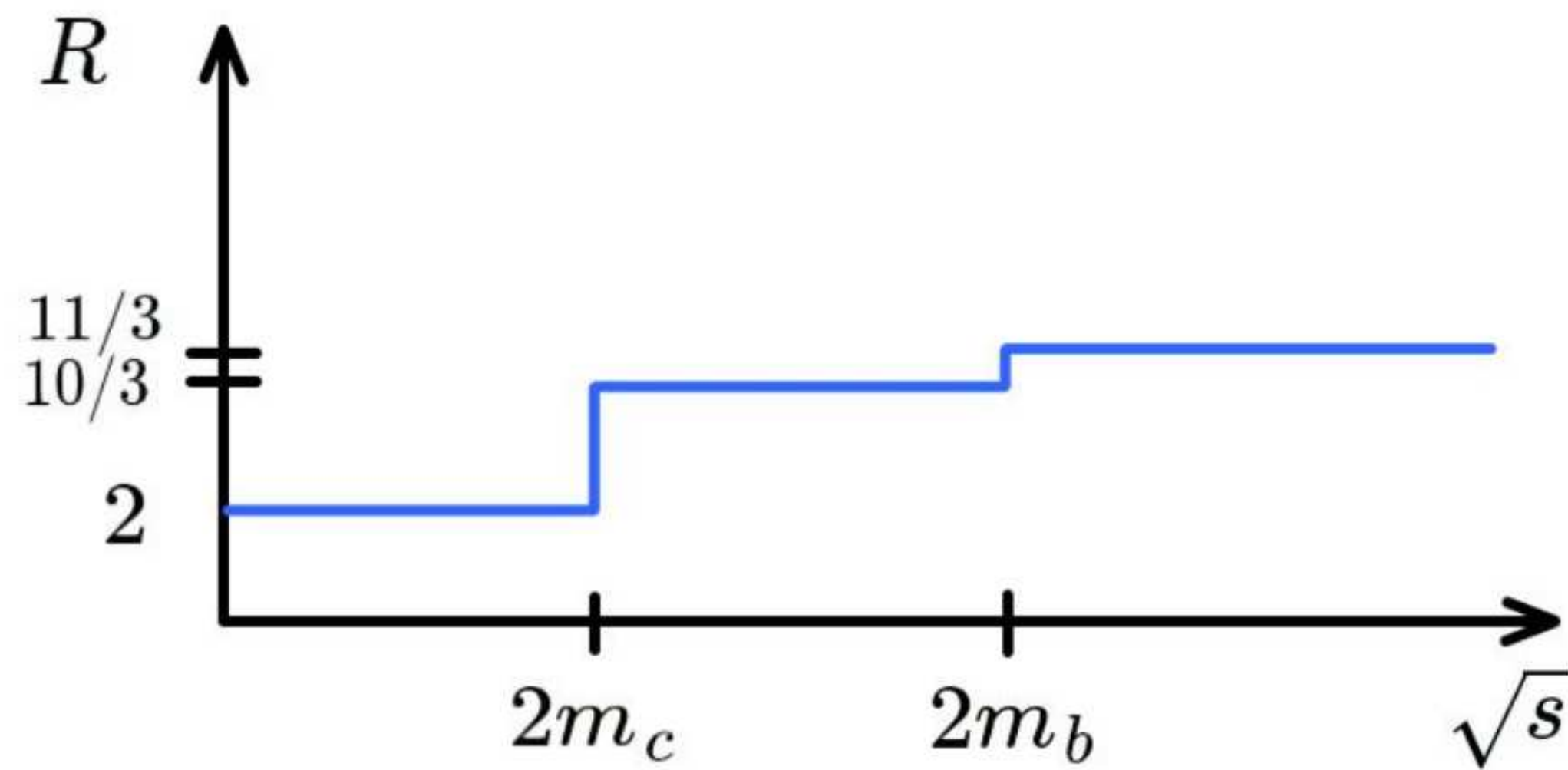
Quark—anti-pair can be one of $r\bar{r}$, $g\bar{g}$, $b\bar{b}$

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

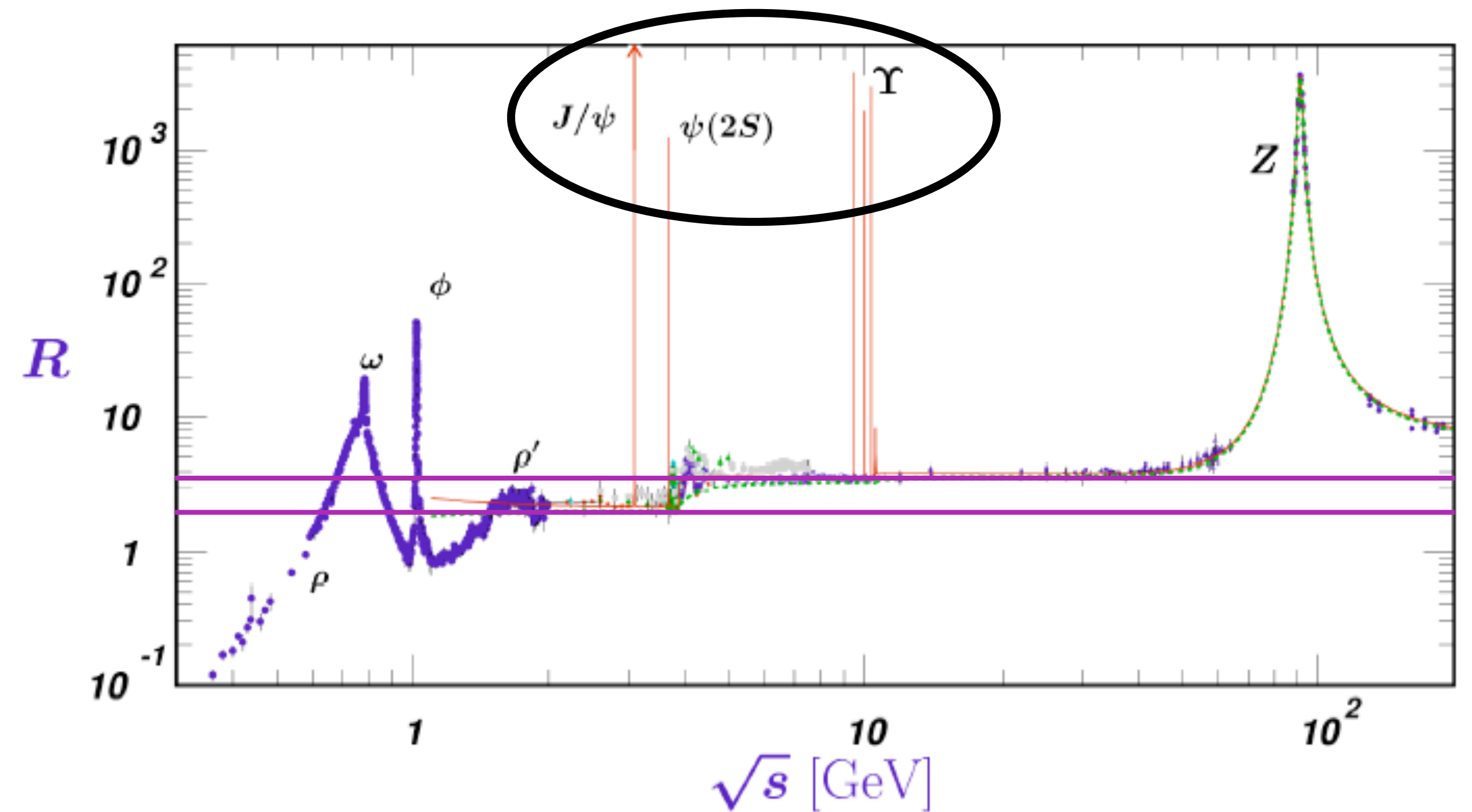
Experimental evidence for colour!

From QED to QCD

R-ratio computation



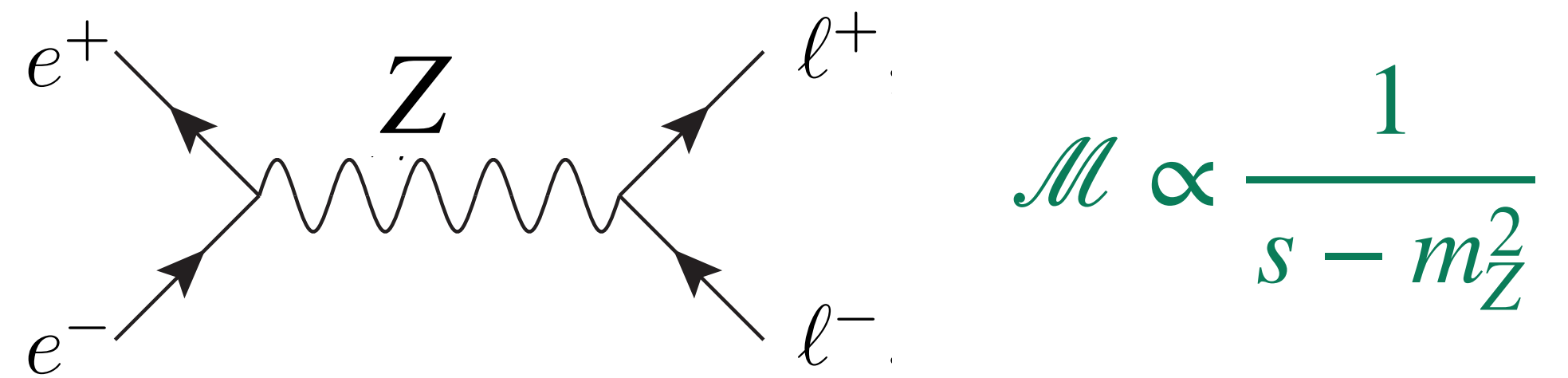
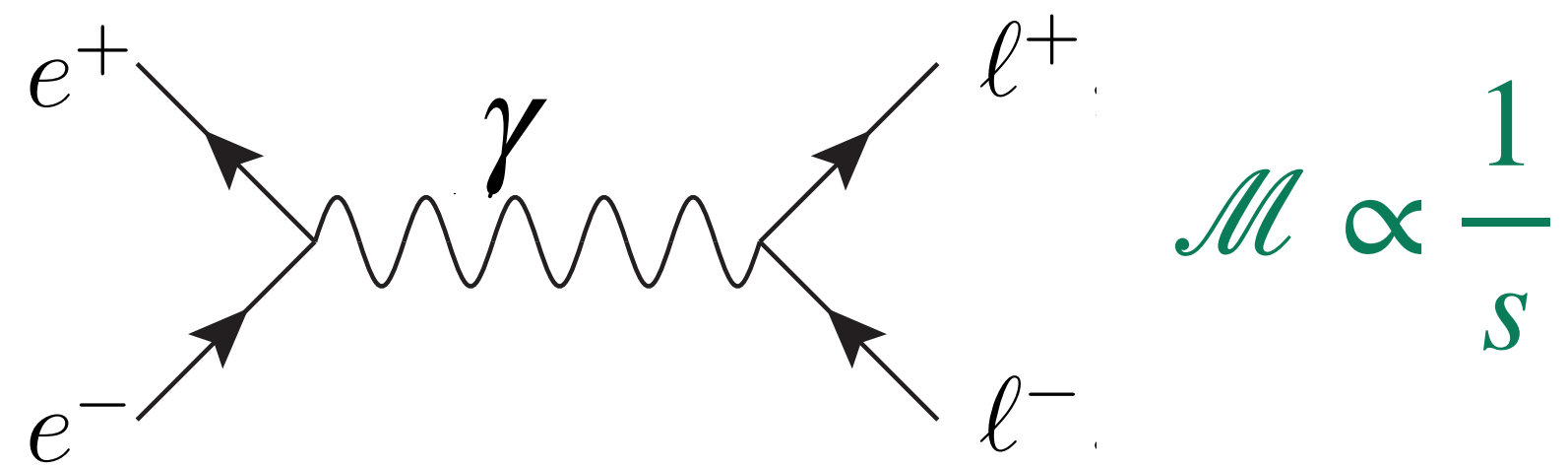
Expected



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

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

Breit-Wigner propagator: $\frac{1}{s - M_Z^2 + i\Gamma_Z M_Z}$ Resonant peak regulated by width

Narrow width approximation:

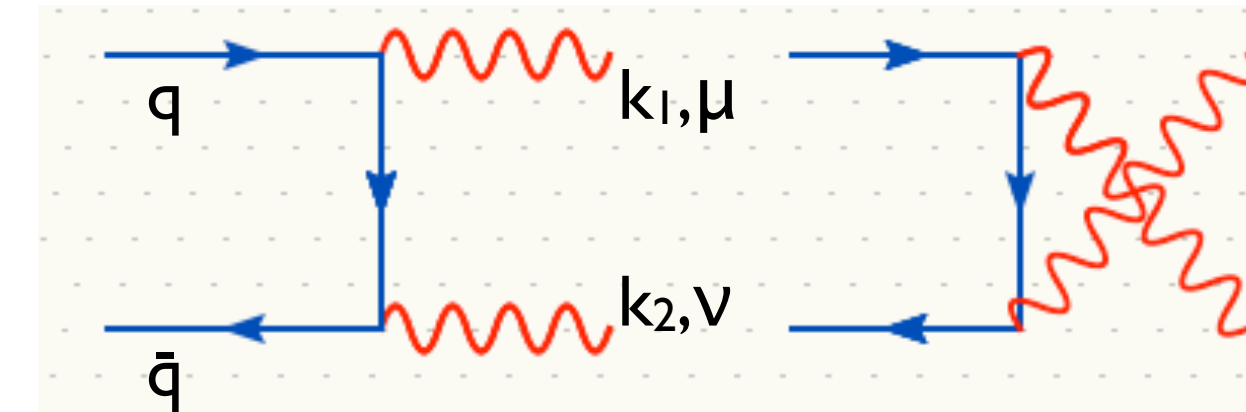
$$\frac{1}{(\hat{s} - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \approx \frac{\pi}{M_Z \Gamma_Z} \delta(\hat{s} - M_Z^2) \quad \text{if } \Gamma_Z/M_Z \ll 1 \quad m_Z \sim 90 \text{ GeV}, \Gamma_Z \sim 2.5 \text{ GeV}$$

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

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

From QED to QCD

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



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

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

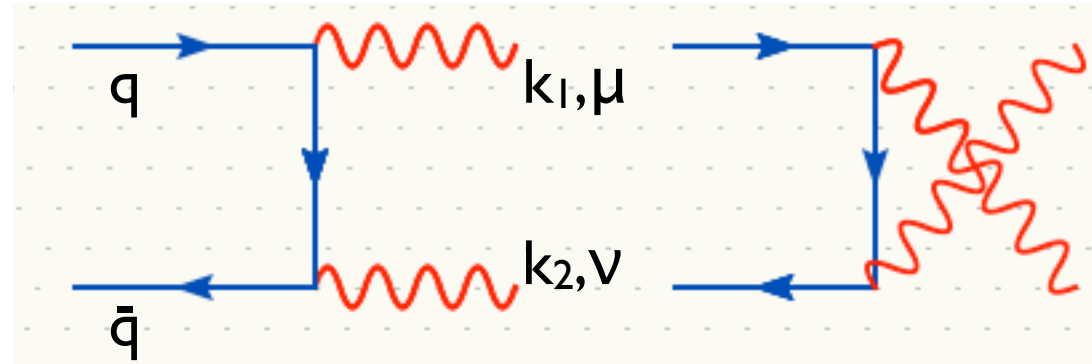
“Ward identity”

$$\begin{aligned} \mathcal{M}_{\mu\nu} k_1^{*\mu} \epsilon_2^{*\nu} &= e^2 \left(\bar{v}(\bar{q}) \not{\epsilon}_2 \frac{1}{\not{q} - \not{k}_1} \not{k}_1 u(q) + \bar{v}(\bar{q}) \not{k}_1 \frac{1}{\not{q} - \not{k}_2} \not{\epsilon}_2 u(q) \right) \\ &= -\bar{v}(\bar{q}) \not{\epsilon}_2 u(q) + \bar{v}(\bar{q}) \not{\epsilon}_2 u(q) = 0 \end{aligned}$$

Try it out!

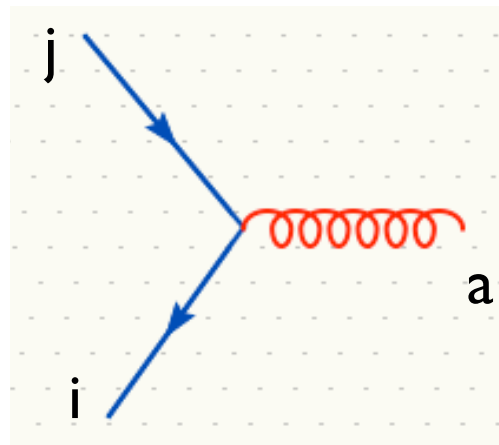
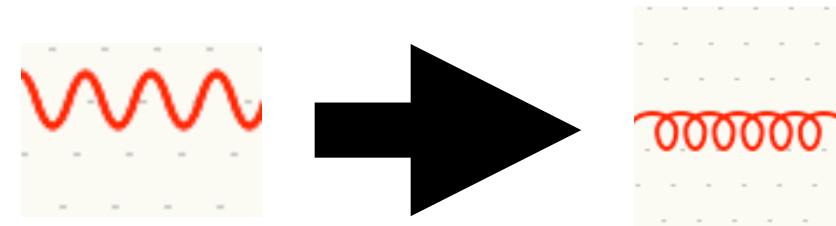
Works fine!

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 $q\bar{q} \rightarrow gg$



$$-ig_s t_{ij}^a \gamma^\mu$$

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

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

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

Is this gauge invariant?

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

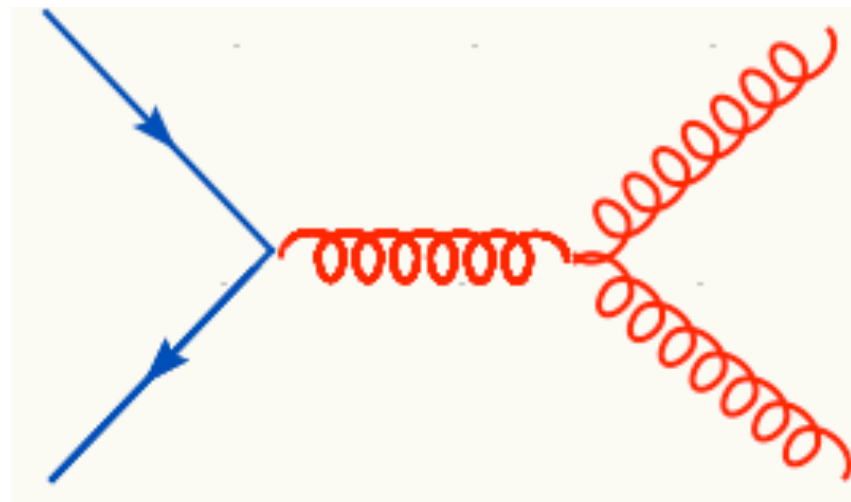
We don't get zero anymore!

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

...looks like QCD vertex

From QED to QCD

What are we missing?



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

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

- Lorentz covariant

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

- Anti-symmetry

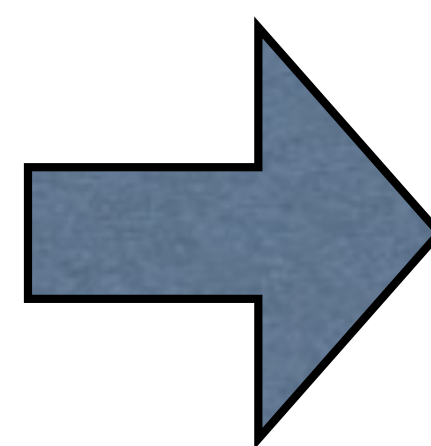
- Dimensional analysis

Gauge invariant IFF the other gluon is physical!

An empirical way to write down the triple gluon vertex!

QCD Lagrangian

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu}}_{\text{Gauge Fields}} + \sum_f \underbrace{\bar{\psi}_i^{(f)} (i\not{\partial} - m_f) \psi_i^{(f)}}_{\text{Matter}} - \underbrace{\bar{\psi}_i^{(f)} (g_s t_{ij}^a A_a) \psi_j^{(f)}}_{\text{Interaction}}$$


 $F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f^{abc} A_\mu^b A_\nu^c \Leftarrow \text{Self-interactions}$

See QCD-QED course!

$$[t^a]_{ij}$$

A Feynman diagram consisting of a red wavy line on the left, labeled with a red italic 'a'. This line enters a purple circular loop. Inside the loop, there is a small arrow pointing clockwise. To the right of the loop, the text '= 0' is written in a large, bold, blue font.

The diagram shows a red wavy line on the left labeled a , followed by a blue circle with a counter-clockwise arrow, then another red wavy line on the right labeled b . This is followed by an equals sign, then the text Tr , then an asterisk, and finally a single red wavy line.

$$\text{Feynman diagram: fermion line with self-energy loop} = C_F * \text{Feynman diagram: fermion line with self-energy loop}$$

$$if^{abc}(t^bt^c)_{ij} = \frac{C_A}{2}t_{ij}^a$$

$$= (F^c F^c)_{ab} = C_A \delta_{ab}$$

$$a \text{---} \text{loop} \text{---} b = C_A * \text{gluon line}$$

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

$$= C_A/2 *$$

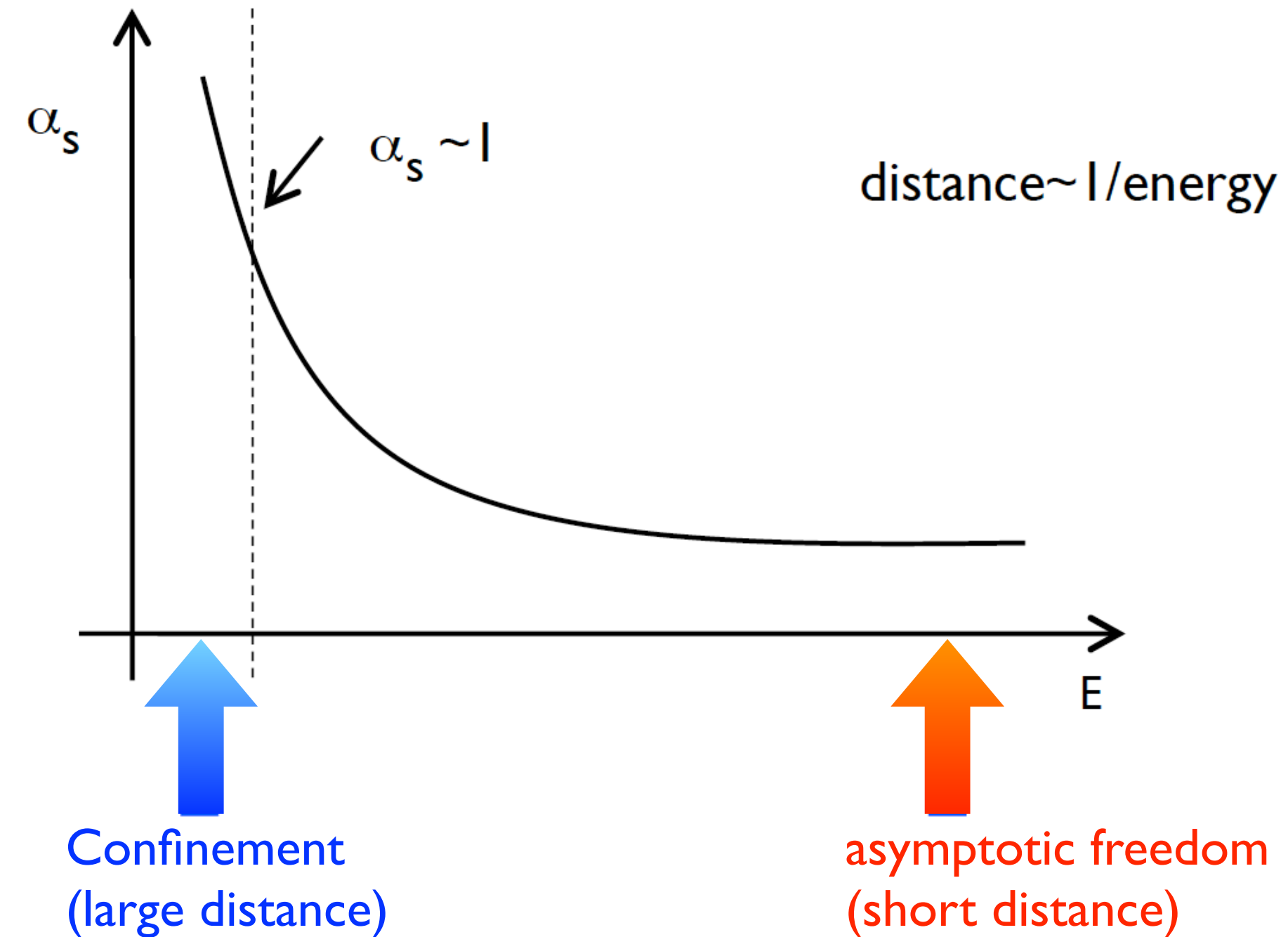
$$= -1/2/N_c *$$

29

Properties of QCD

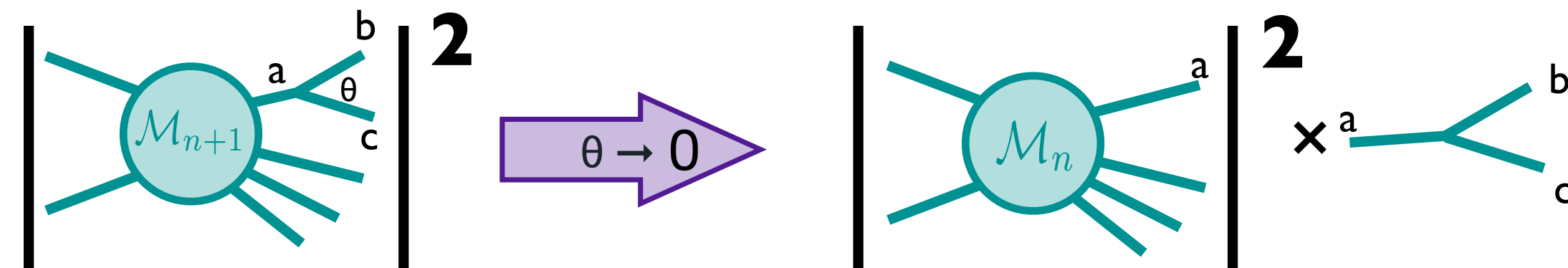
UV: Asymptotic freedom

- Perturbative computations
- Parton model



IR: Universality

- Collinear Factorisation
- Parton showers



Master formula for LHC physics

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

Phase-space integral
Important aspect of a Monte Carlo generator

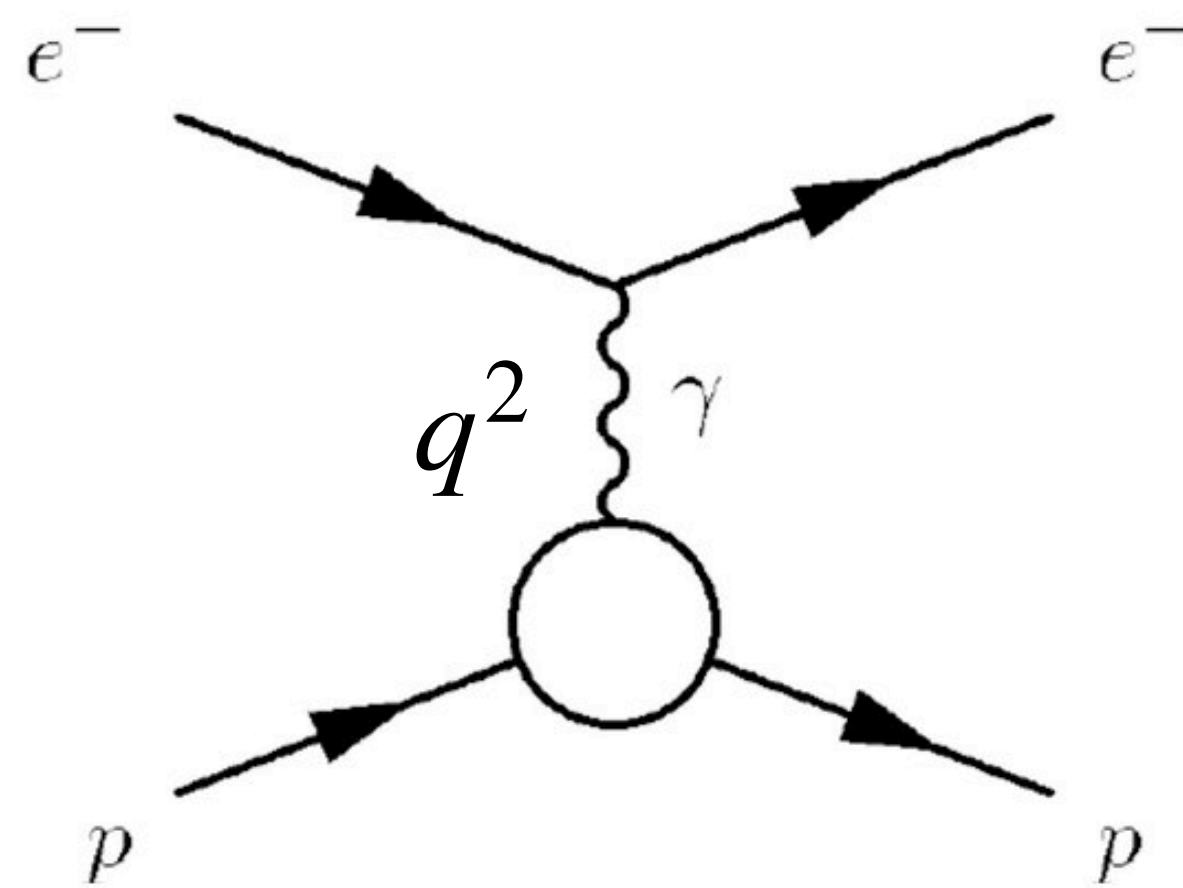
Parton density functions
Universal:
~Probabilities of finding given parton with given momentum in proton
Extracted from data

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: $e^- p \rightarrow e^- p$

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



Point-like

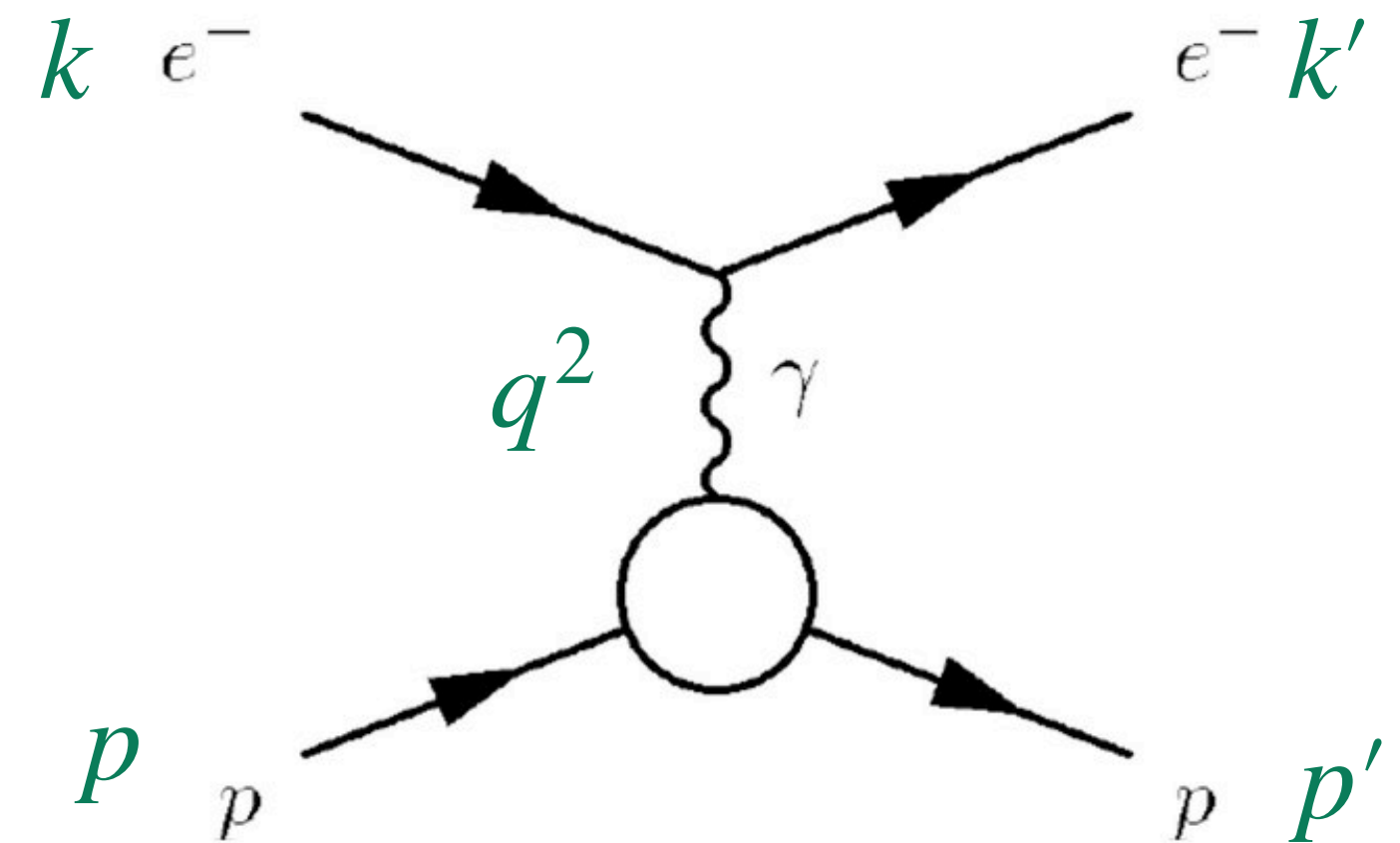
Finite size

Constituent quarks

*Sea of strongly
interacting
quarks/gluons*

Low energy

Long wavelength photons see proton as point-like



Spin 1/2
scattering
in QED

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

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

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

⇒ Rutherford scattering

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

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

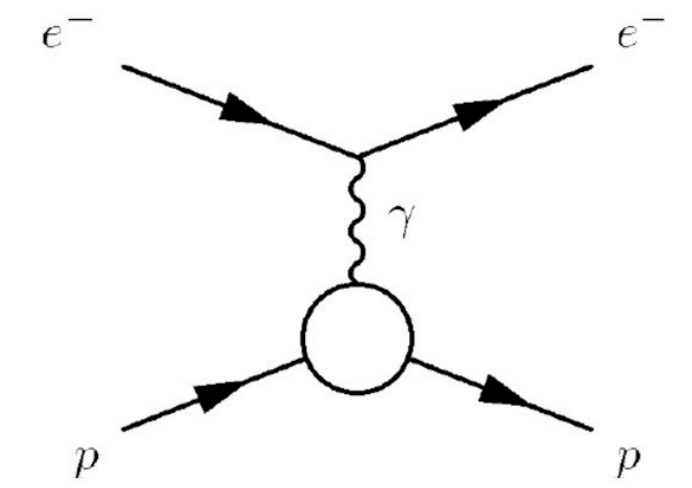
Relativistic electron: $m_e^2 \ll q^2 \ll m_p^2$

⇒ 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

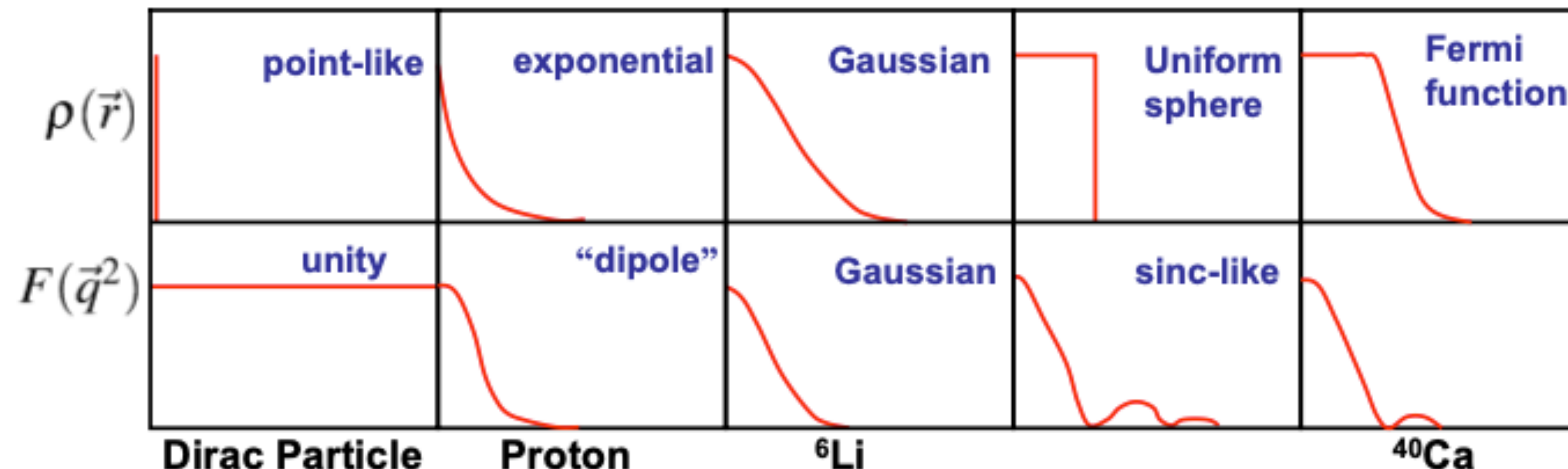
$$\Rightarrow \mathcal{M}_{fi} = \mathcal{M}_{fi}^{\text{point}} F(\mathbf{q}^2)$$

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

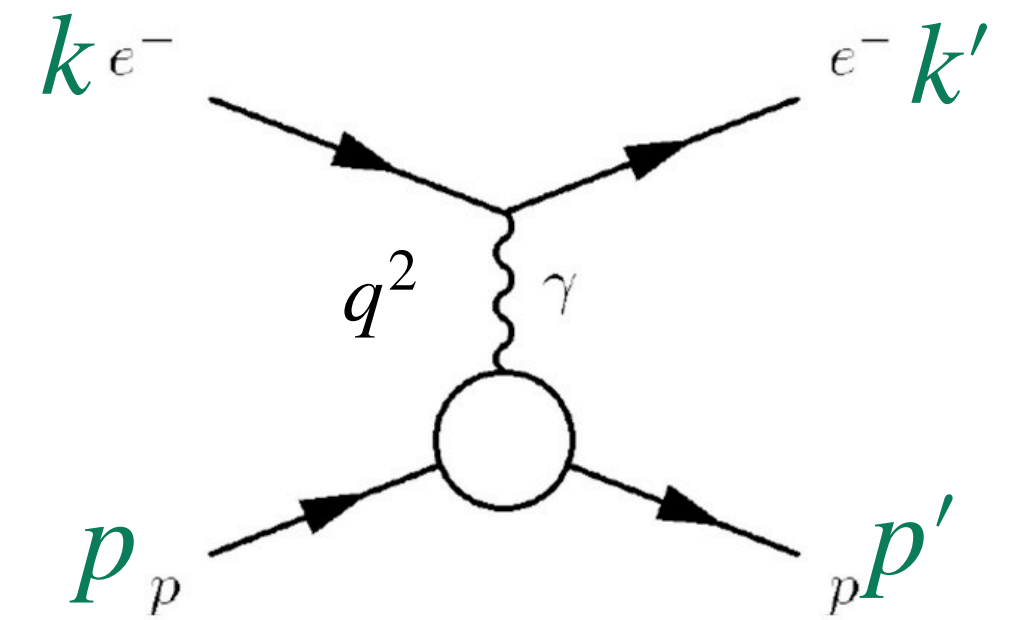
Form factor correction: $\lambda_q \sim r_p$

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

[M. Thompson; Modern Particle Physics]



Intermediate energy



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

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

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

recoil dominates at high Q^2

c.f. Gordon decomposition

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

‘electric’ ‘magnetic’

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

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

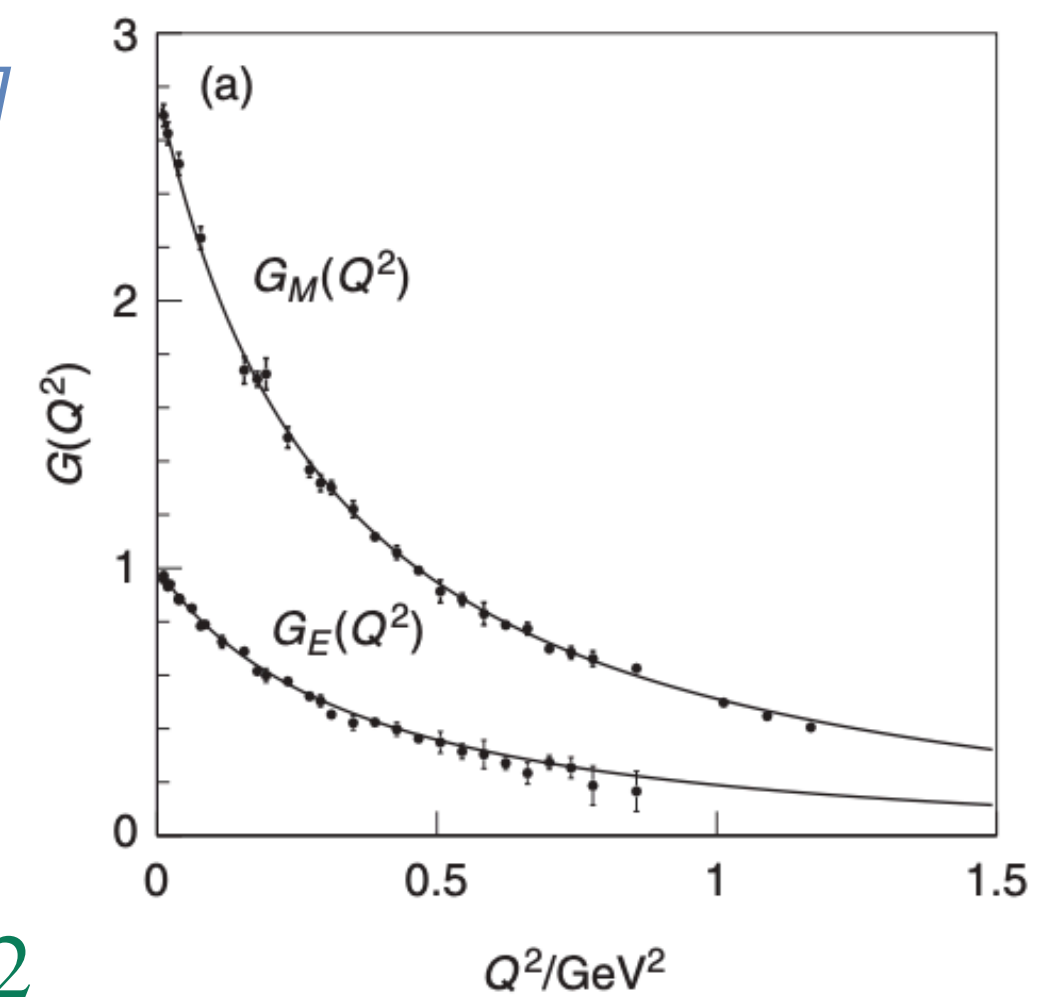
Elastic scattering formula

Finite size + relativistic: requires two form factors

- Electric & magnetic, $G_E(Q^2)$ & $G_M(Q^2)$

- Lorentz invariance: $\mathbf{q}^2 \rightarrow Q^2$

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



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

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

$$G_M(Q^2) \sim \int d^3\mathbf{r} \mu(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}}$$

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

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

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

High energy

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

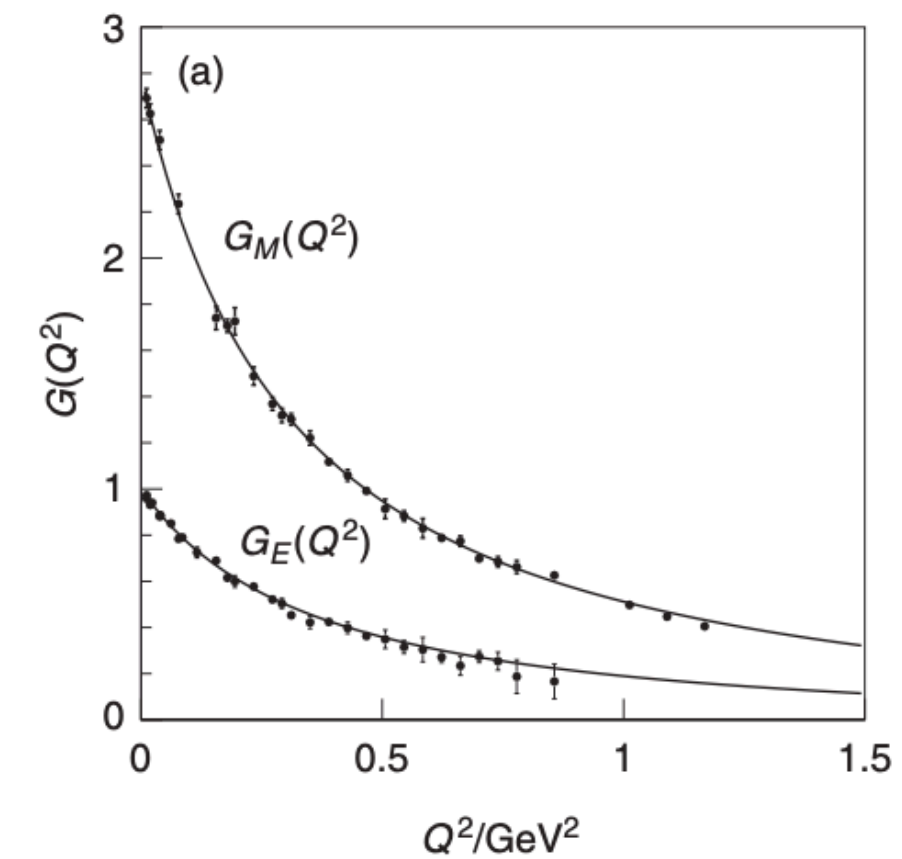
$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{Ros.}} \sim \frac{\alpha^2}{4 E^2 \sin^4(\theta/2)} \frac{E'}{E} \left[\frac{Q^2}{2m_p^2} |G_M|^2 \sin^2 \left(\frac{\theta}{2} \right) \right]$$

Elastic scattering cross section falls off rapidly

‘elastic’: $AB \rightarrow AB$ (proton remains intact)

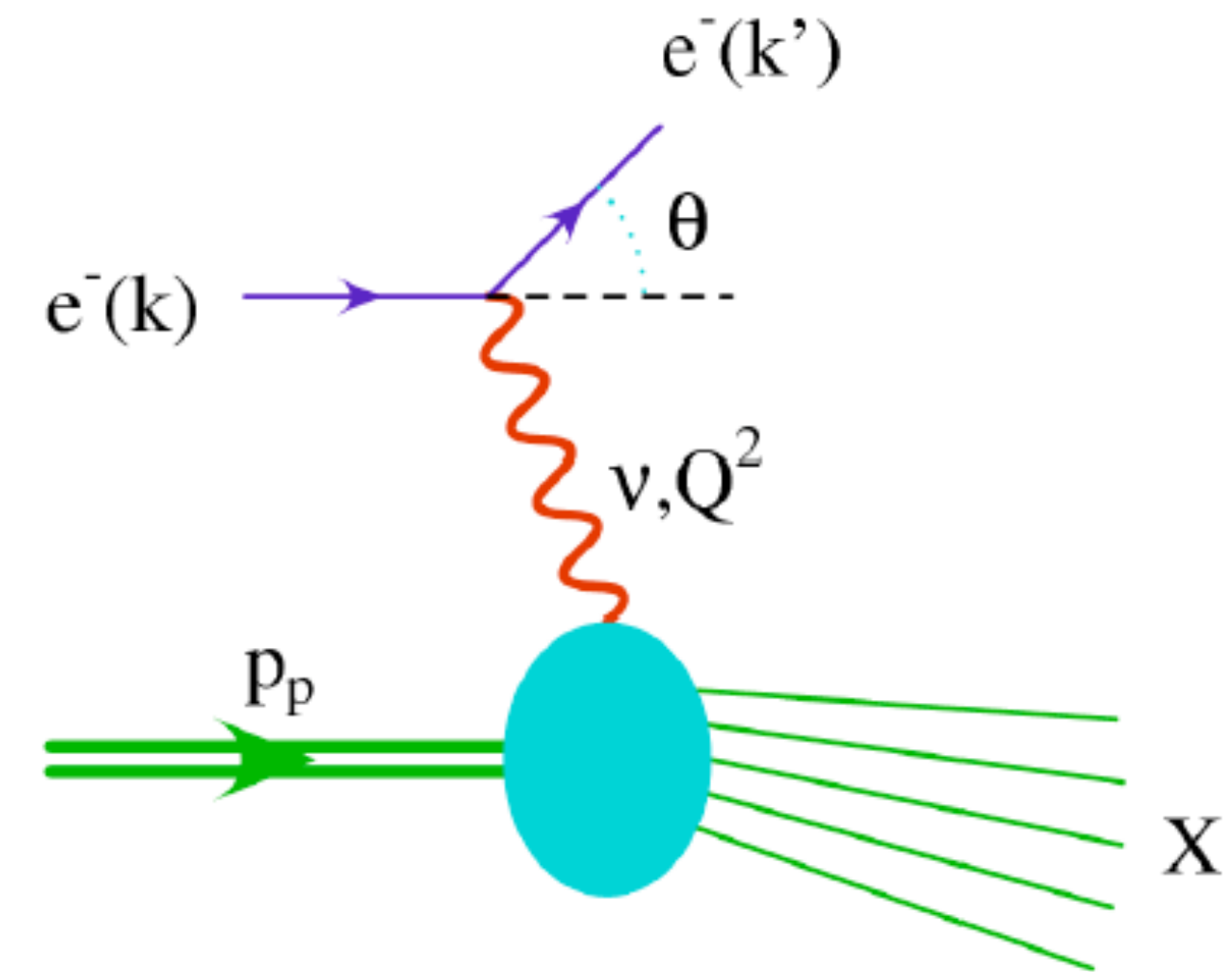
Also ‘inelastic’ process: $e^- p \rightarrow e^- X$

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



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

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



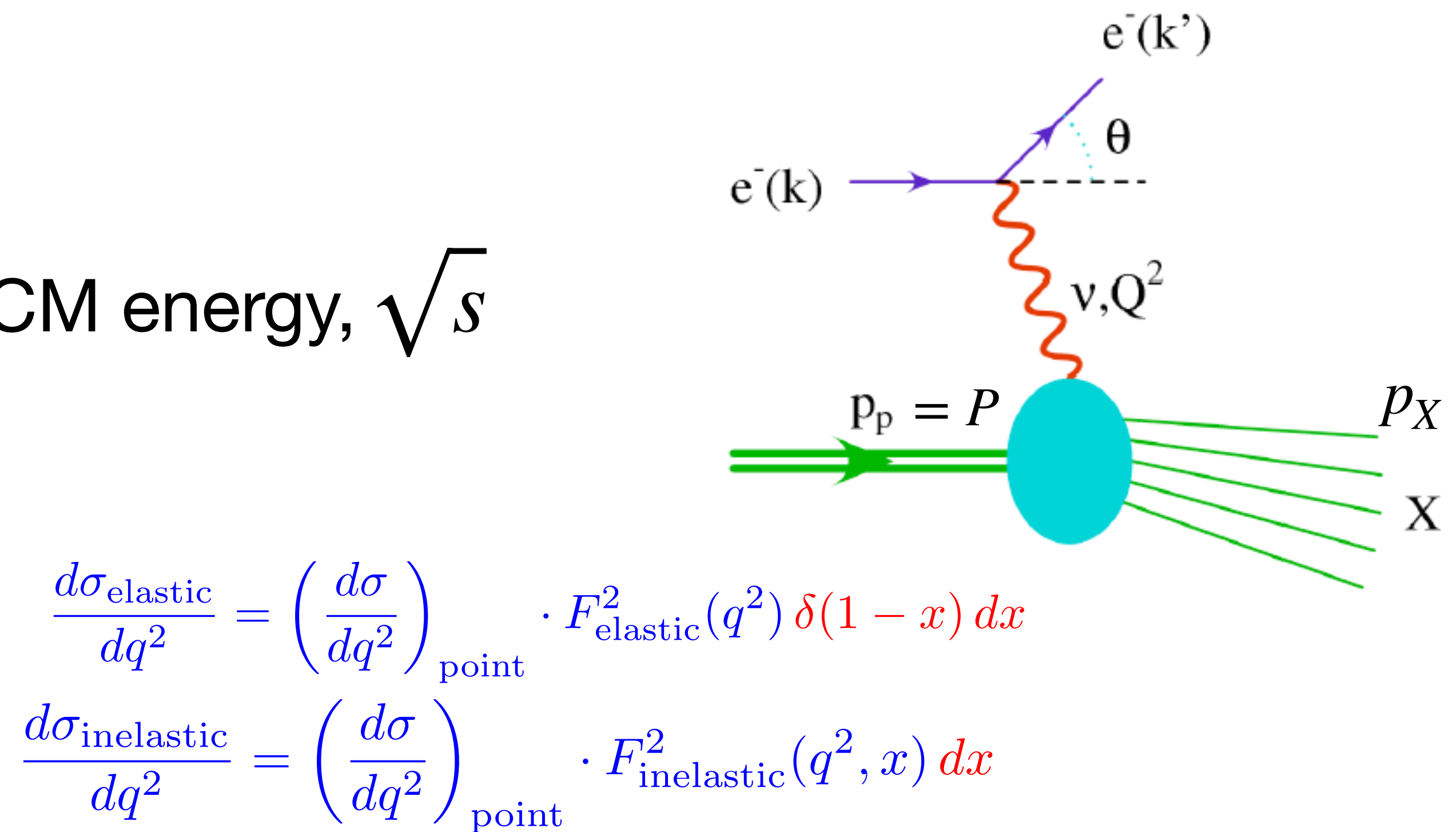
Inelastic kinematics

For $2 \rightarrow 2$ 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



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

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

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

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

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

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

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

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)

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

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

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

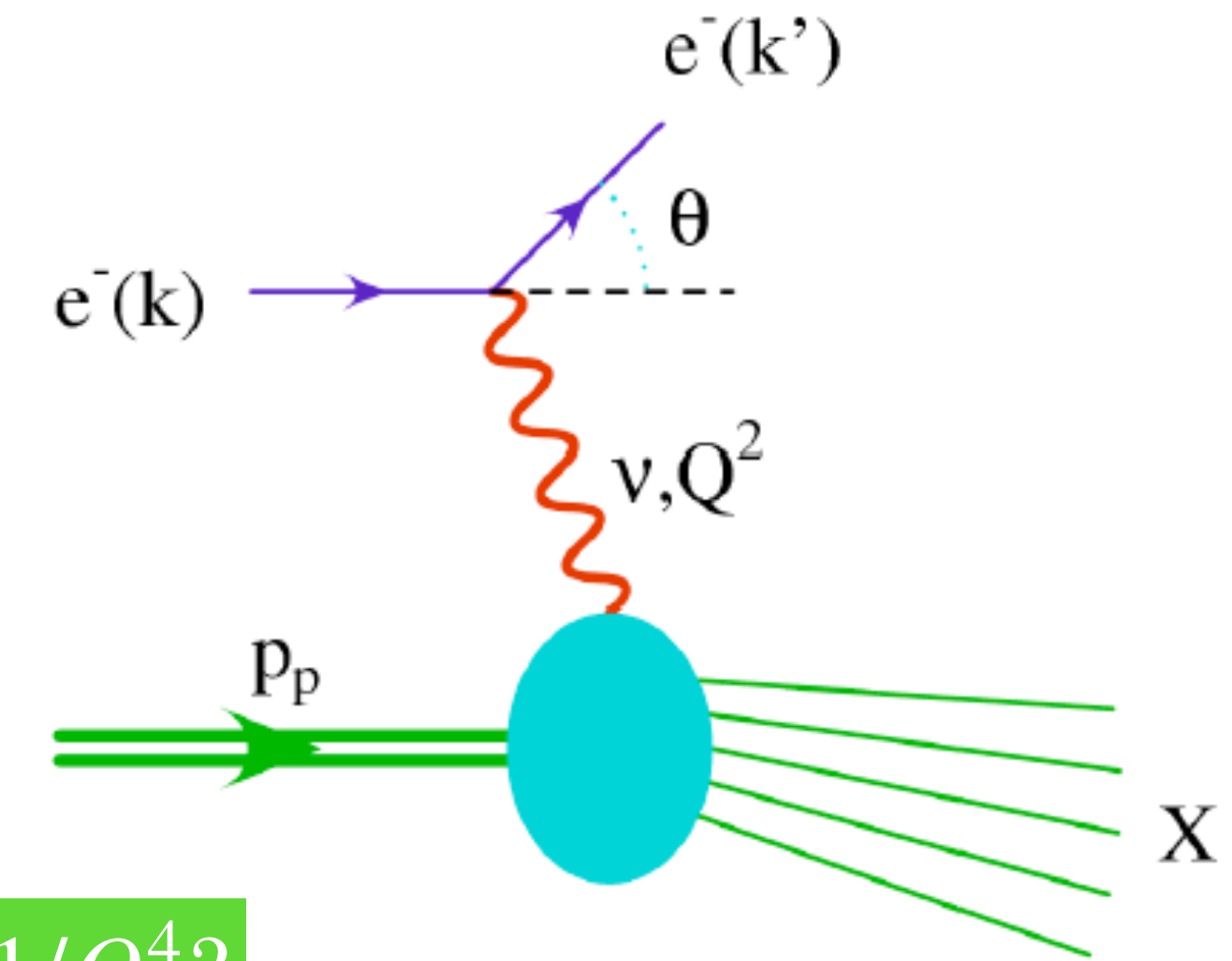
$$!!!3. F_{elastic}^2(q^2) \ll 1 \quad F_{inelastic}^2(q^2, x) \sim 1$$

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

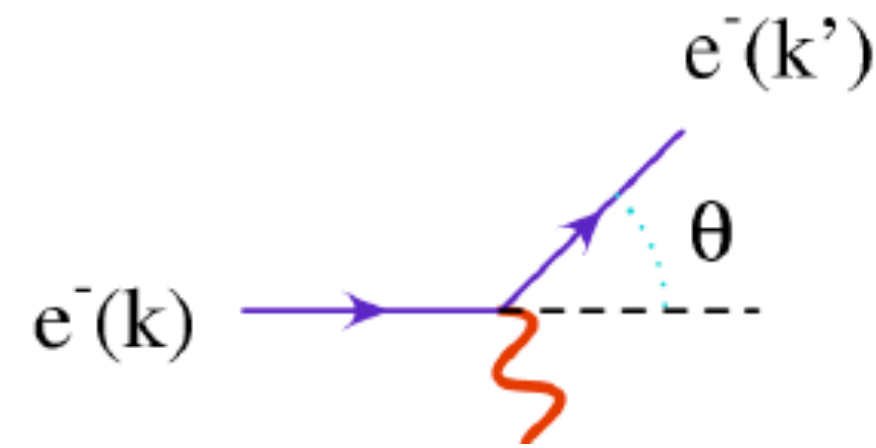
DIS cross section

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

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



Why $1/Q^4$?



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

$|\text{QED leptonic current}|^2$

$$= \text{Tr}[k' \gamma_{\mu} k \gamma_{\nu}] = k'_{\mu} k_{\nu} + k'_{\nu} k_{\mu} + k \cdot k' g_{\mu\nu}$$

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

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

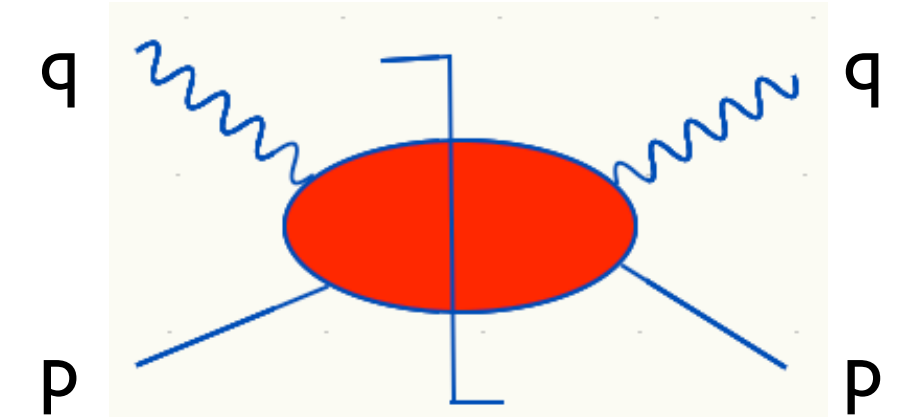
For inclusive DIS ($\sum_X$)

$$W_{\mu\nu} \equiv \sum_X \int d\Phi_X H_{\mu\nu}^X$$

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

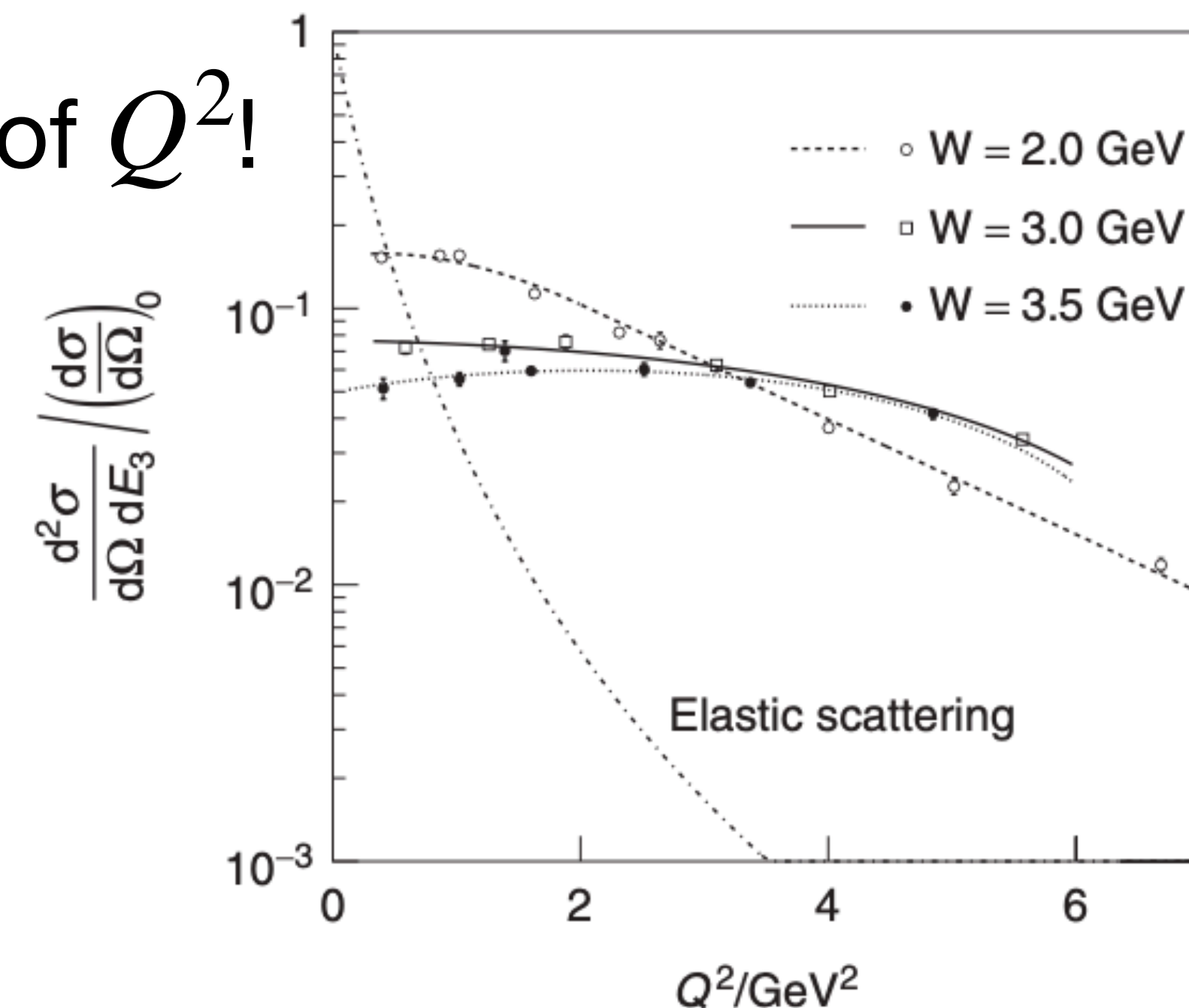
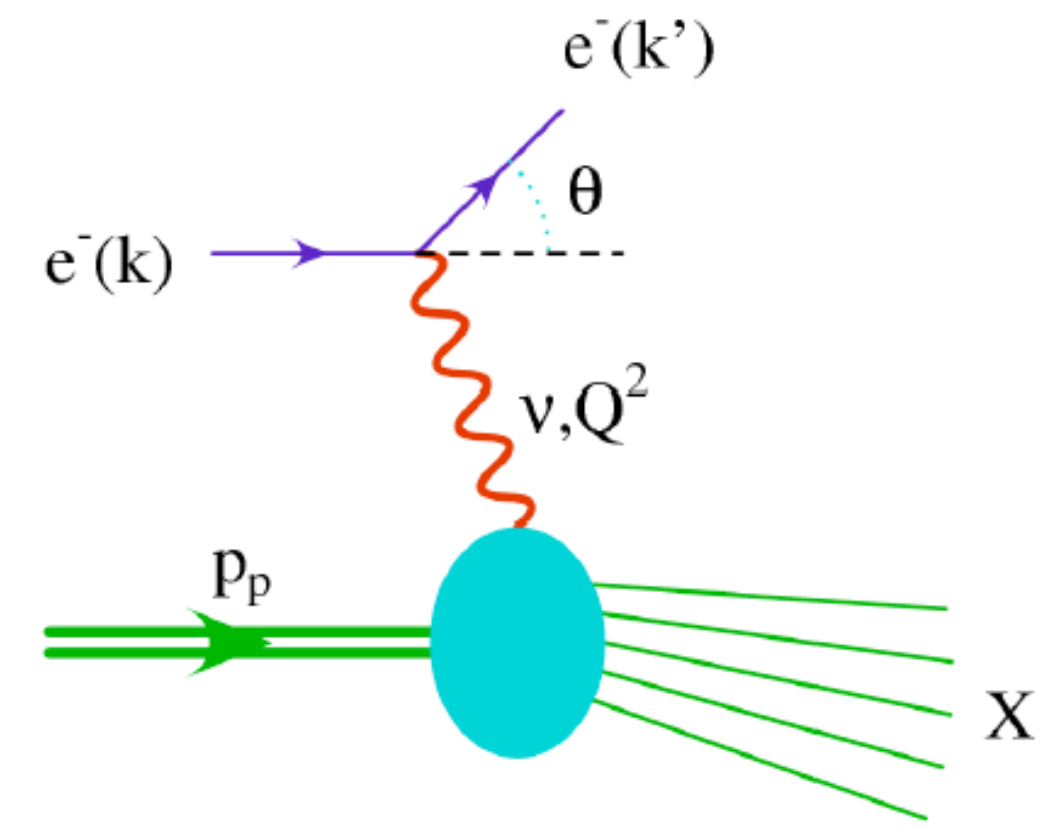
Finally
$$\sigma^{ep \rightarrow eX} = \frac{1}{4m_p E} \int d\Phi_{k'} \frac{e^2}{Q^4} L^{\mu\nu} W_{\mu\nu}$$

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

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

- AKA “Bjorken scaling”

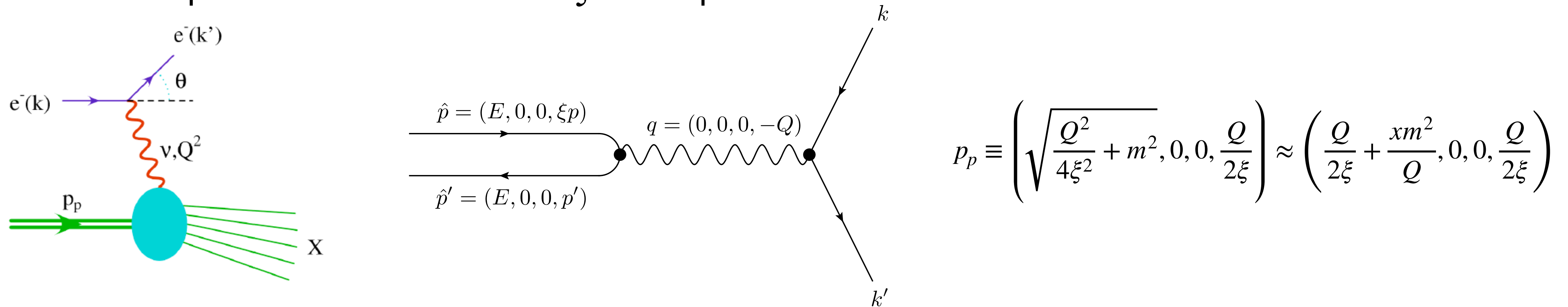
Independence on photon resolution scale suggests scattering with a **point-like, fundamental constituent: parton = quarks!**



Parton Model

Breit frame: proton moves fast ($p \gg m_p$) in $\hat{z}$ direction & photon has zero energy

- Struck parton carries a fraction ξ of the proton momentum



- Energies of $\hat{p}$ and $\hat{p}'$ are equal $\Rightarrow$ magnitudes of momenta are equal

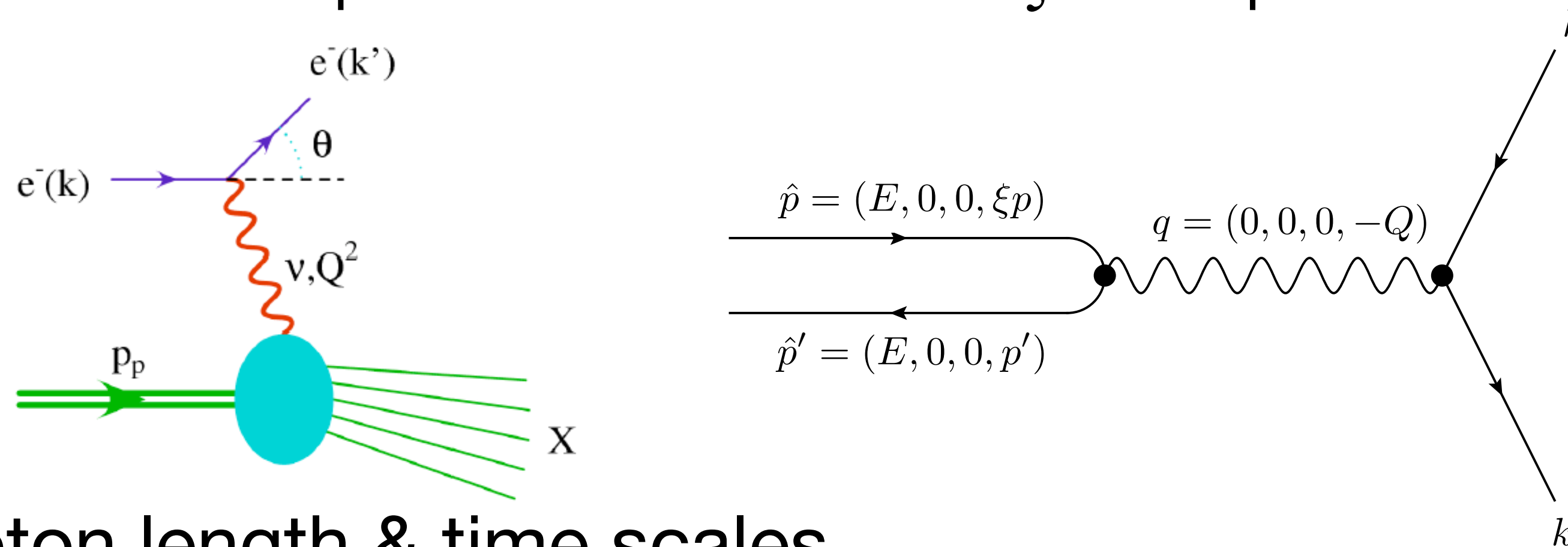
$$\hat{p} = (E, 0, 0, \xi p) \quad \& \quad \hat{p}' = (E, 0, 0, -\xi p) \quad \Rightarrow \quad \xi p - Q = -\xi p \quad \Rightarrow \quad |\mathbf{p}| = \frac{Q}{2\xi}$$

- Proton 4-momentum: $p = \left(E_p, 0, 0, \frac{Q}{2\xi} \right)$

Parton Model

Breit frame: proton moves fast ($p \gg m_p$) in $\hat{z}$ direction & photon has zero energy

- Struck parton carries a fraction ξ of the proton momentum



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

Proton length & time scales

Rest frame $p = (m_p, 0, 0, 0)$ $\Delta t \sim \Delta x \sim \frac{1}{m_p}$

Breit frame

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

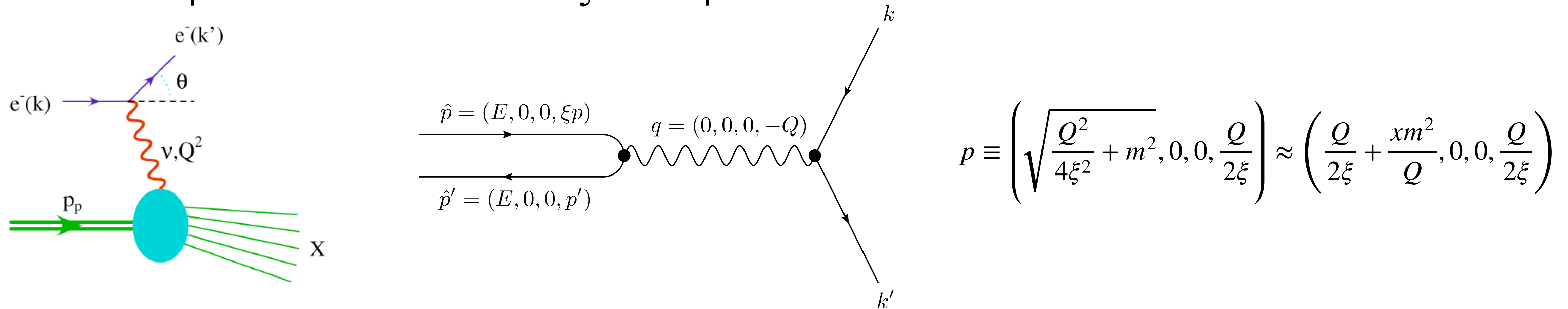
Photon timescale: $\Delta t_\gamma = \sim \frac{1}{Q} \ll \Delta t'$

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

Parton Model

Breit frame: proton moves fast ($p \gg m_p$) in $\hat{z}$ direction & photon has zero energy

- Struck parton carries a fraction ξ of the proton momentum



- 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, the parton i carries a fraction ξ of proton momentum

- Before scattering $(\xi P)^2 \simeq 0$
- After scattering it has a momentum $p'_i = \xi P + q$

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

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' $e^- q \rightarrow e^- q$ cross sections

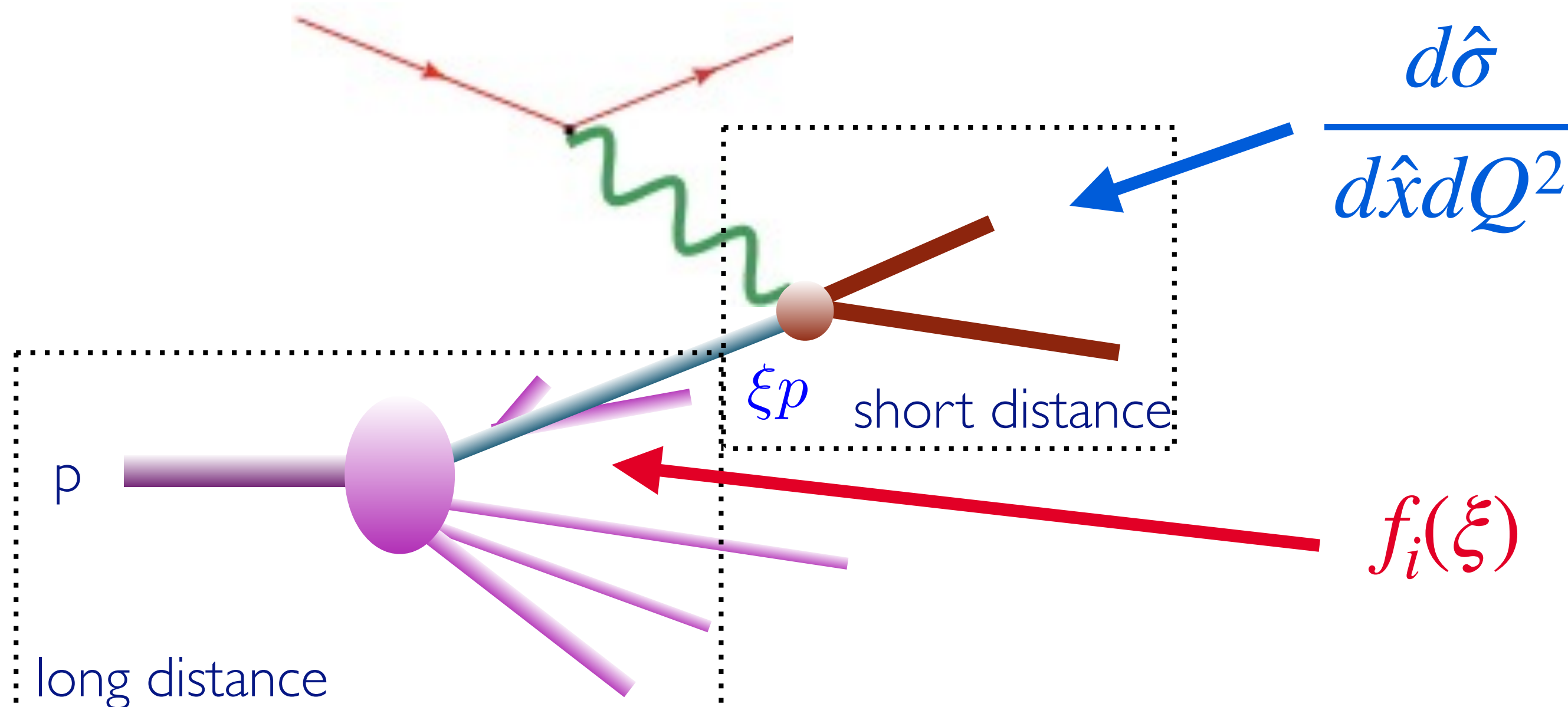
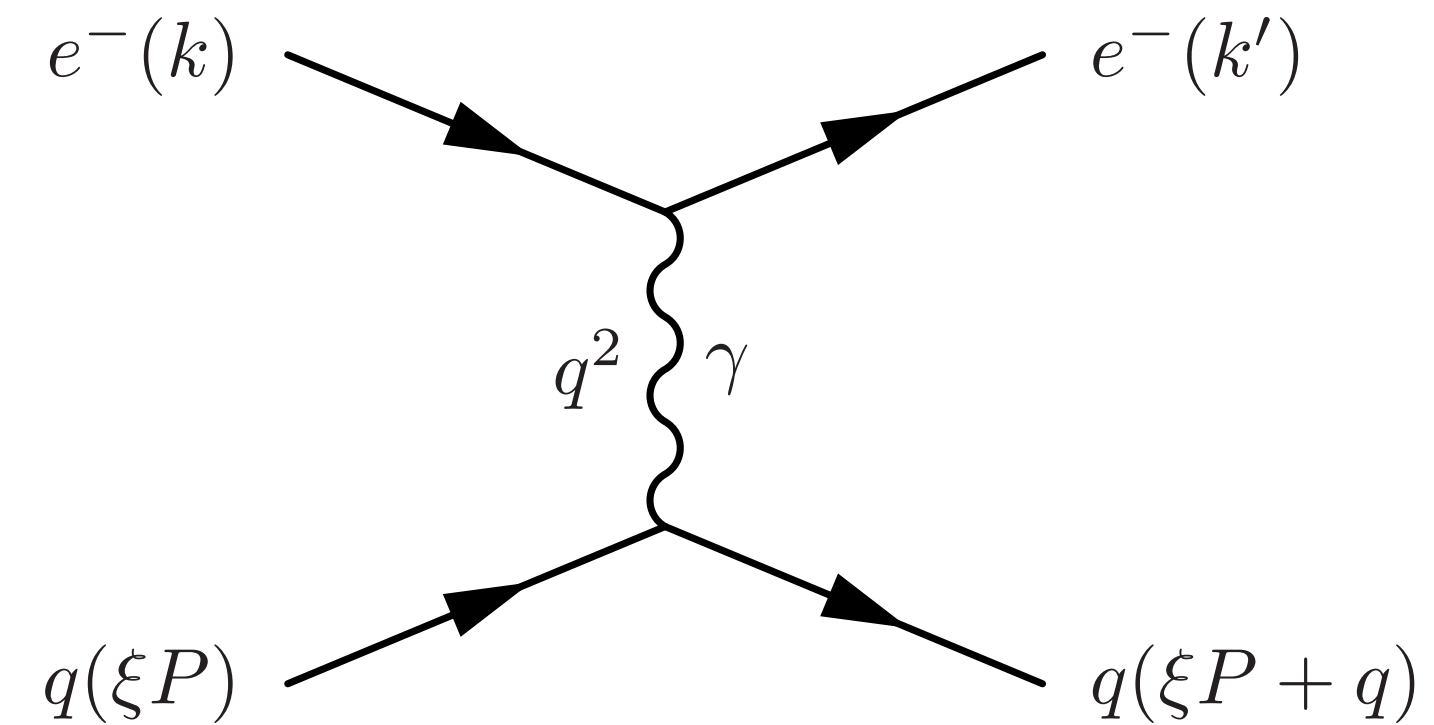
$$\frac{d\hat{\sigma}}{dQ^2} = \frac{4\pi\alpha^2 Q_q^2}{Q^4} \frac{1}{2} \left[1 + (1 - \hat{y})^2 \right]$$

Factorisation

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

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

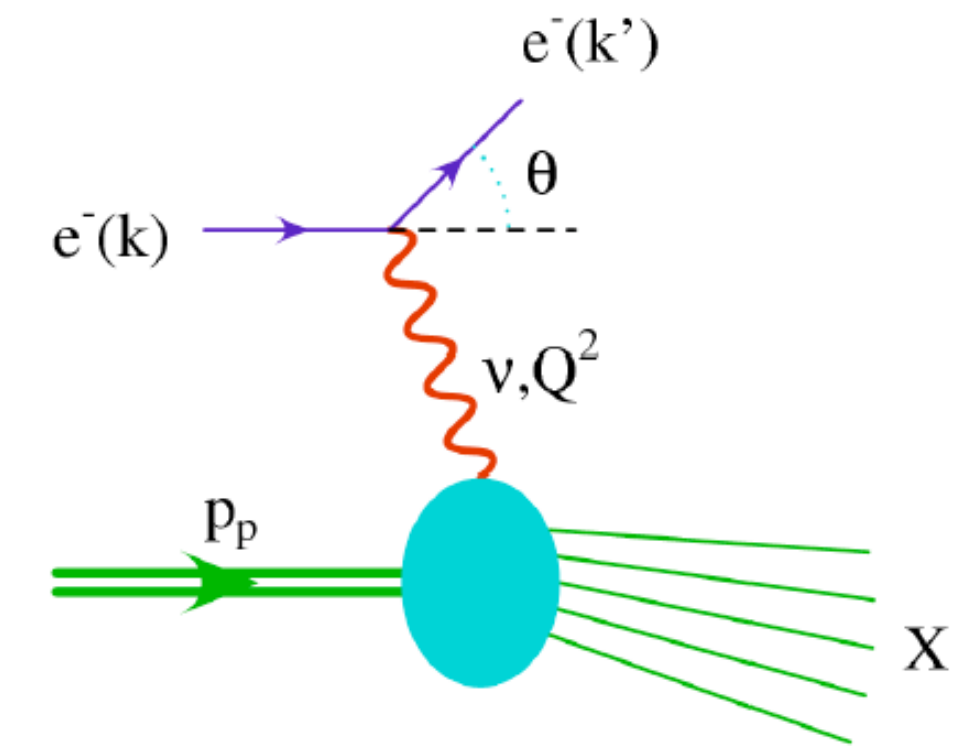
$$\hat{y} = \frac{\xi P \cdot q}{\xi P \cdot k} = y$$



$\frac{d\hat{\sigma}}{d\hat{x}dQ^2}$ 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 $d\sigma^{\text{DIS}}$

= 0!

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

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

$\xi = x$

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

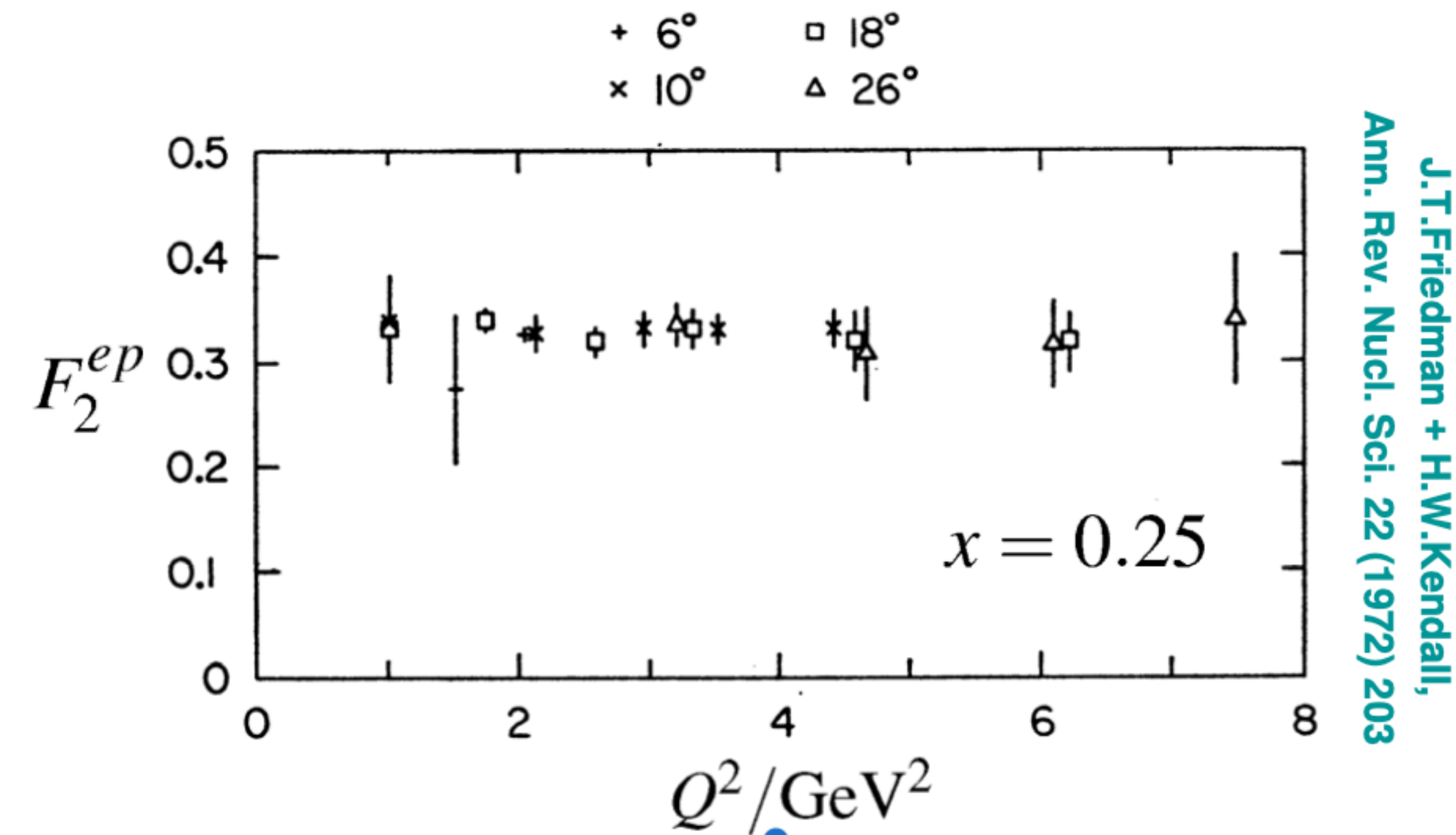
$$F_1(x, Q^2) = \frac{1}{2} \sum_{i=q, \bar{q}} Q_i^2 f_i(x) \quad F_2(x, Q^2) = 2xF_1(x, Q^2)$$

*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)

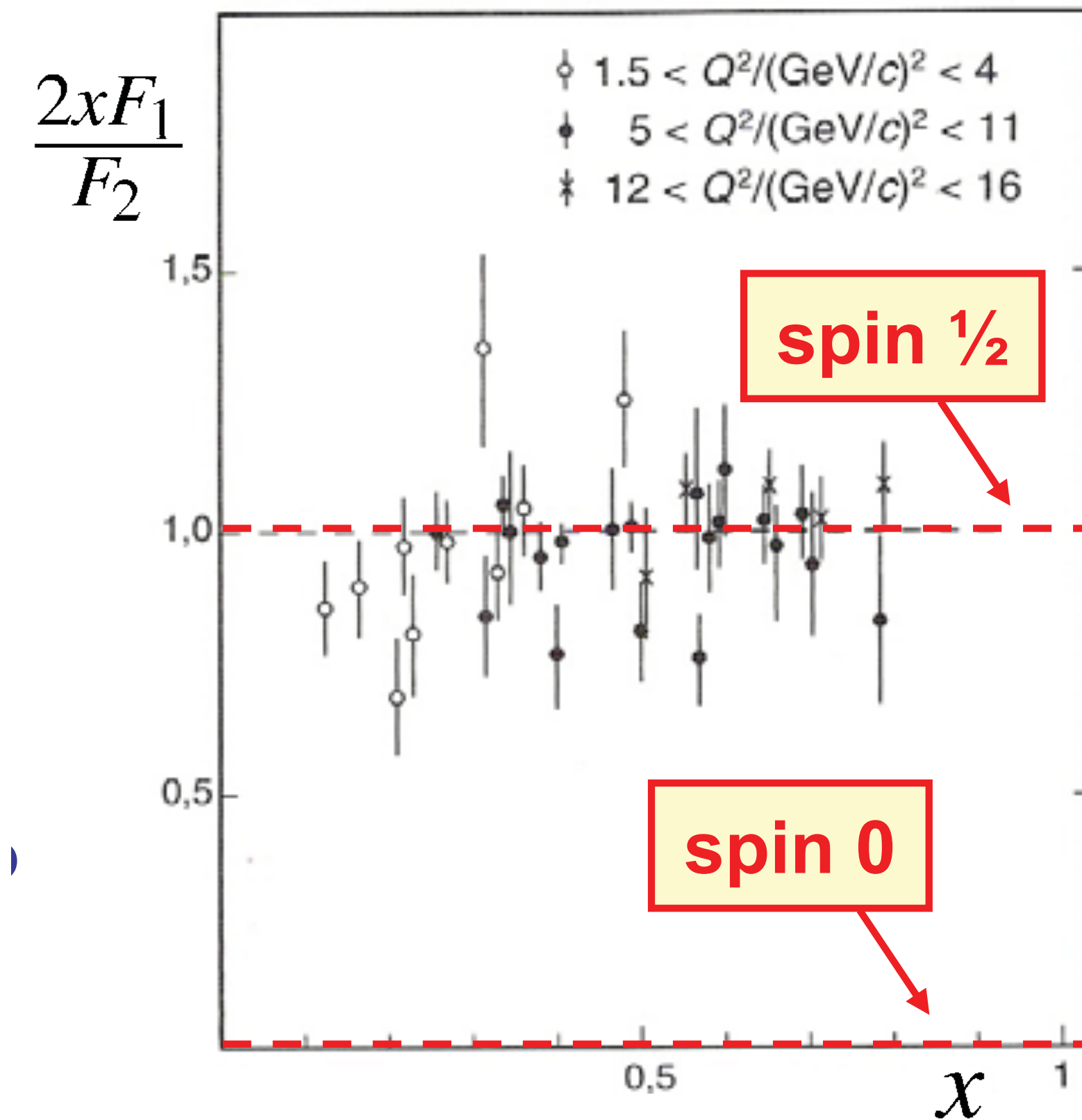
Scaling and Callan-Gross relation

Scaling: Q^2 -independence of structure functions



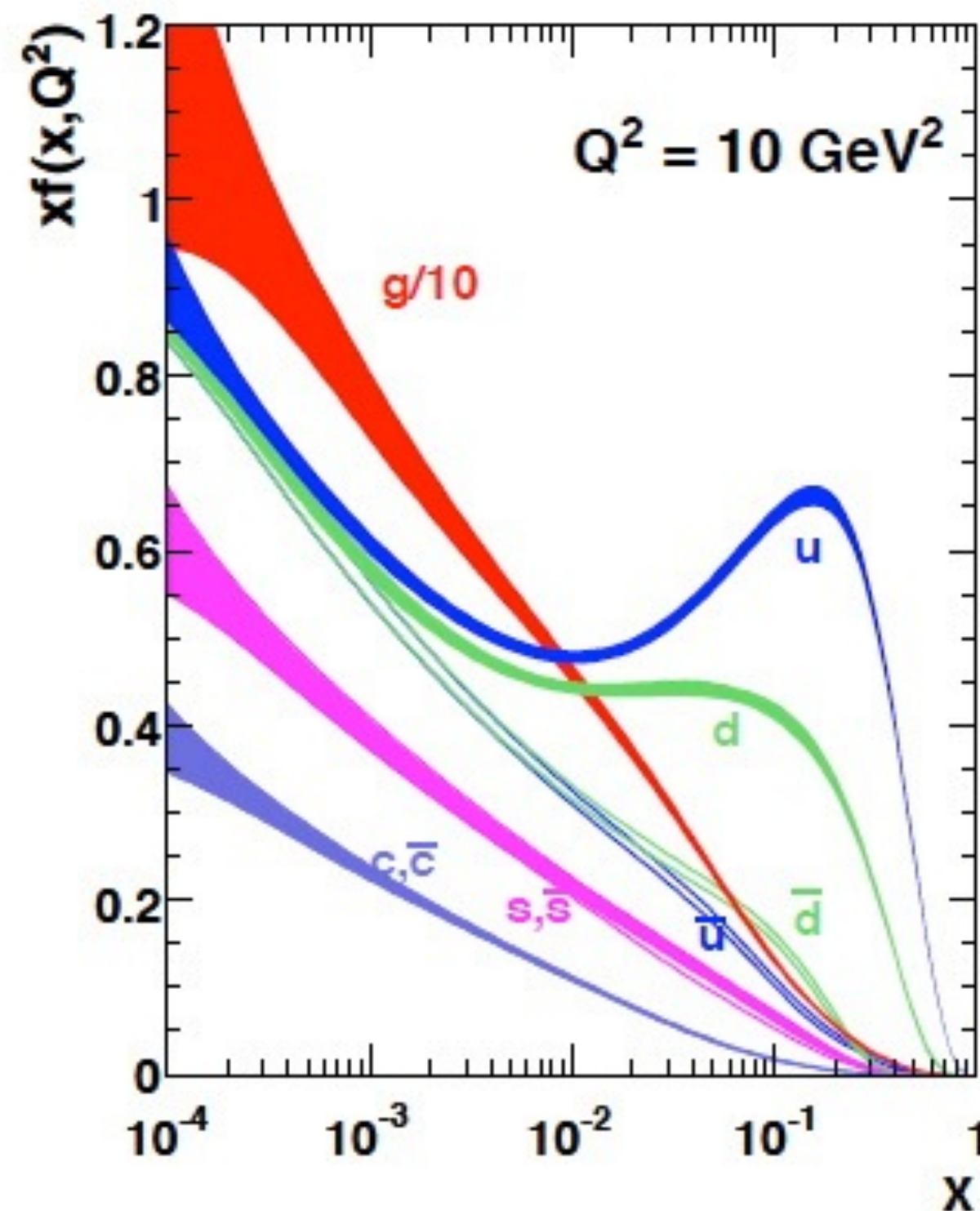
Evidence that quarks are point-like proton constituents

Callan-Gross relation



Evidence that quarks are spin-1/2 particles!

Parton distribution functions



$$u(x) = u_V(x) + \bar{u}(x)$$

$$d(x) = d_V(x) + \bar{d}(x)$$

$$s(x) = \bar{s}(x)$$

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

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

Quarks carry only 50% of the proton momentum

Evidence for gluons!

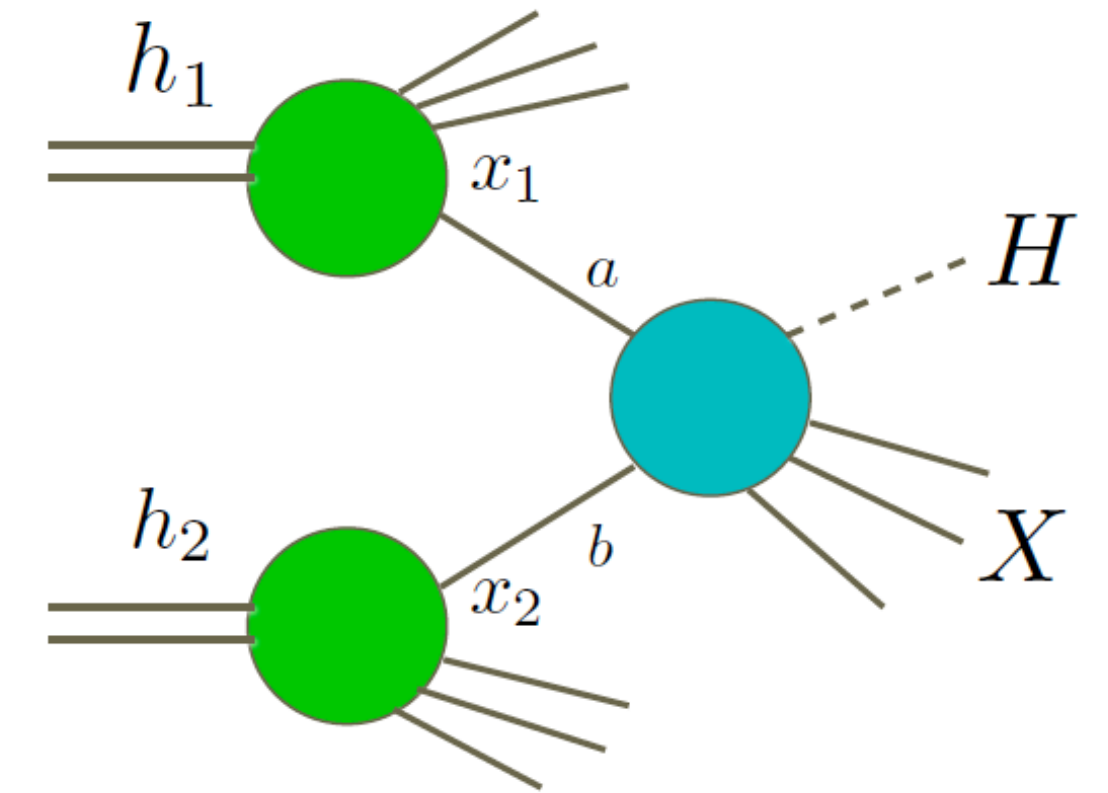
Proton is a sea of strongly interaction quarks & gluons

PDFs are universal: don't depend on hard scattering

LHC cross sections

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

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



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

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

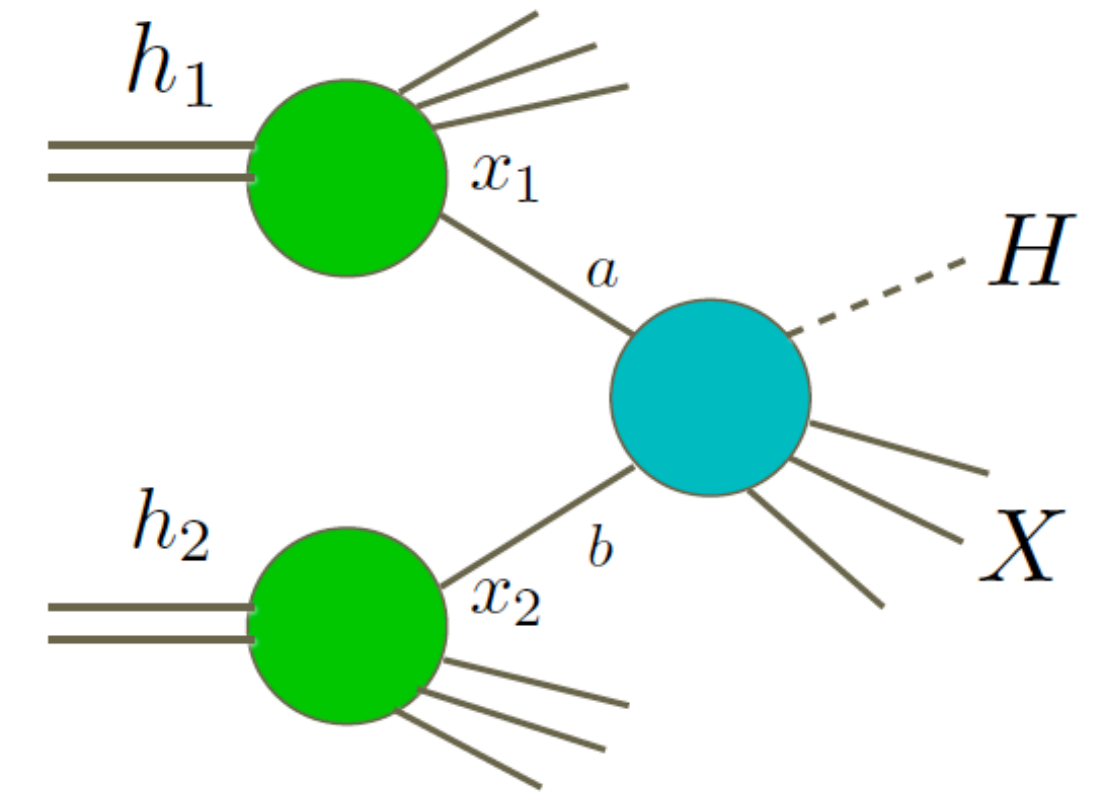
$F = 2\hat{s}$ (massless)

Colliding partons carry momentum fractions x_1 and x_2 , respectively

- Partonic centre of mass energy $\hat{s} = sx_1x_2 \Rightarrow \tau \equiv \hat{s}/s = x_1x_2$
- Momentum imbalance in lab frame $\Rightarrow$ net longitudinal momentum $y = \frac{1}{2} \log \frac{x_1}{x_2}$

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

Parton luminosity



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

$$dx_1 dx_2 \rightarrow d\tau dx_1 \quad \sigma_{pp \rightarrow X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \frac{\tau}{\hat{s}} \int_{\tau}^1 \frac{dx}{x} (f_a(x)f_b(\tau/x) + a \leftrightarrow b) (\hat{s}\hat{\sigma}_{ab})$$

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

- Dimensions of a cross section

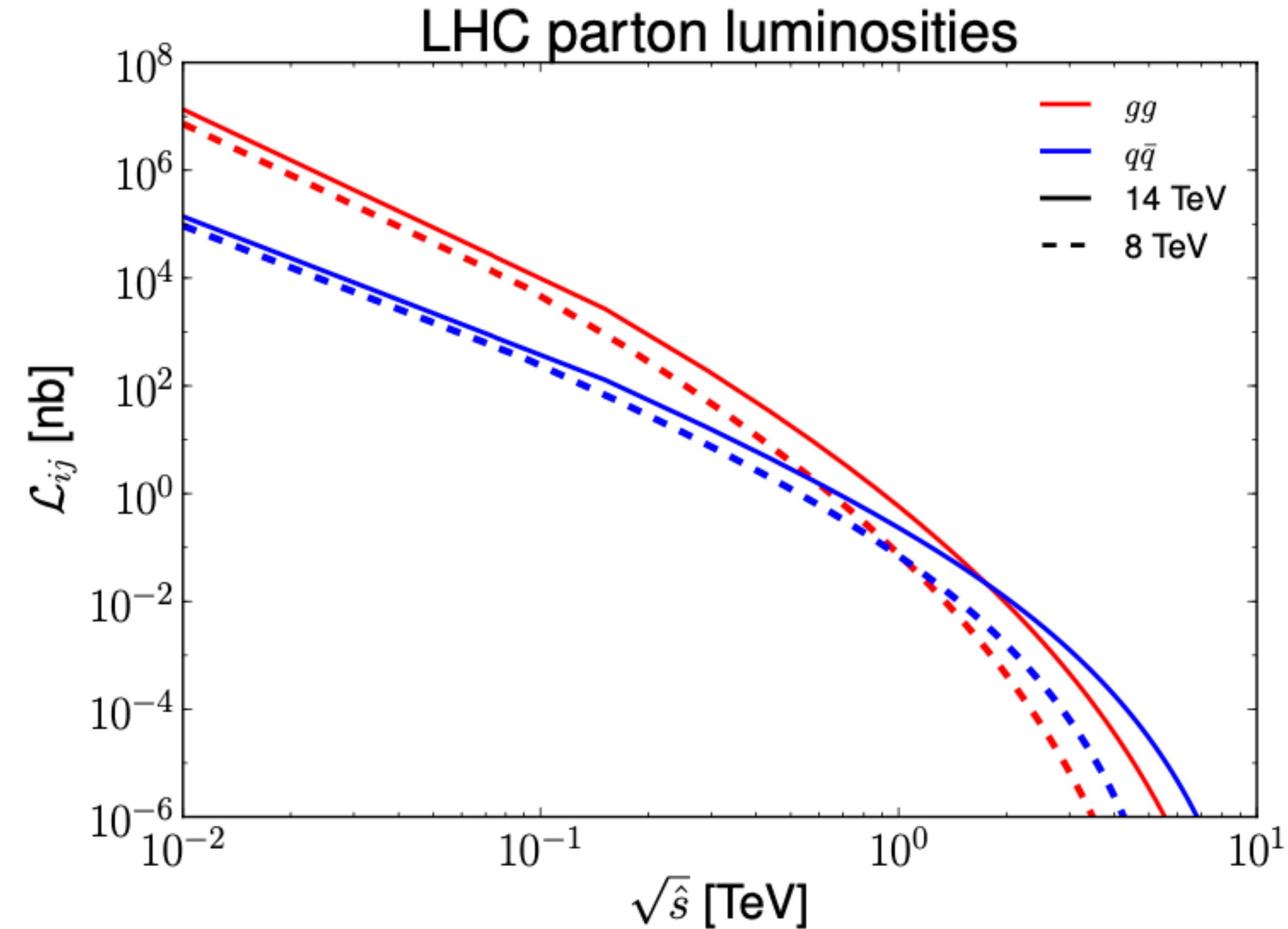
$$\sigma_{pp \rightarrow X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \cdot \mathcal{L}_{ab}(s, \tau) \cdot [\hat{s}\hat{\sigma}_{ab}]$$

$\mathcal{L}_{ab}$: '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

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



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

$\mathcal{L}_{q\bar{q}}$ and $\mathcal{L}_{gg}$ cross over around $\sqrt{\hat{s}} \sim 1 \text{ TeV}$

Single production of a particle with mass, M_X

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

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

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

Phase-space integral

Important
aspect of a
Monte Carlo
generator

Parton density functions

Universal:

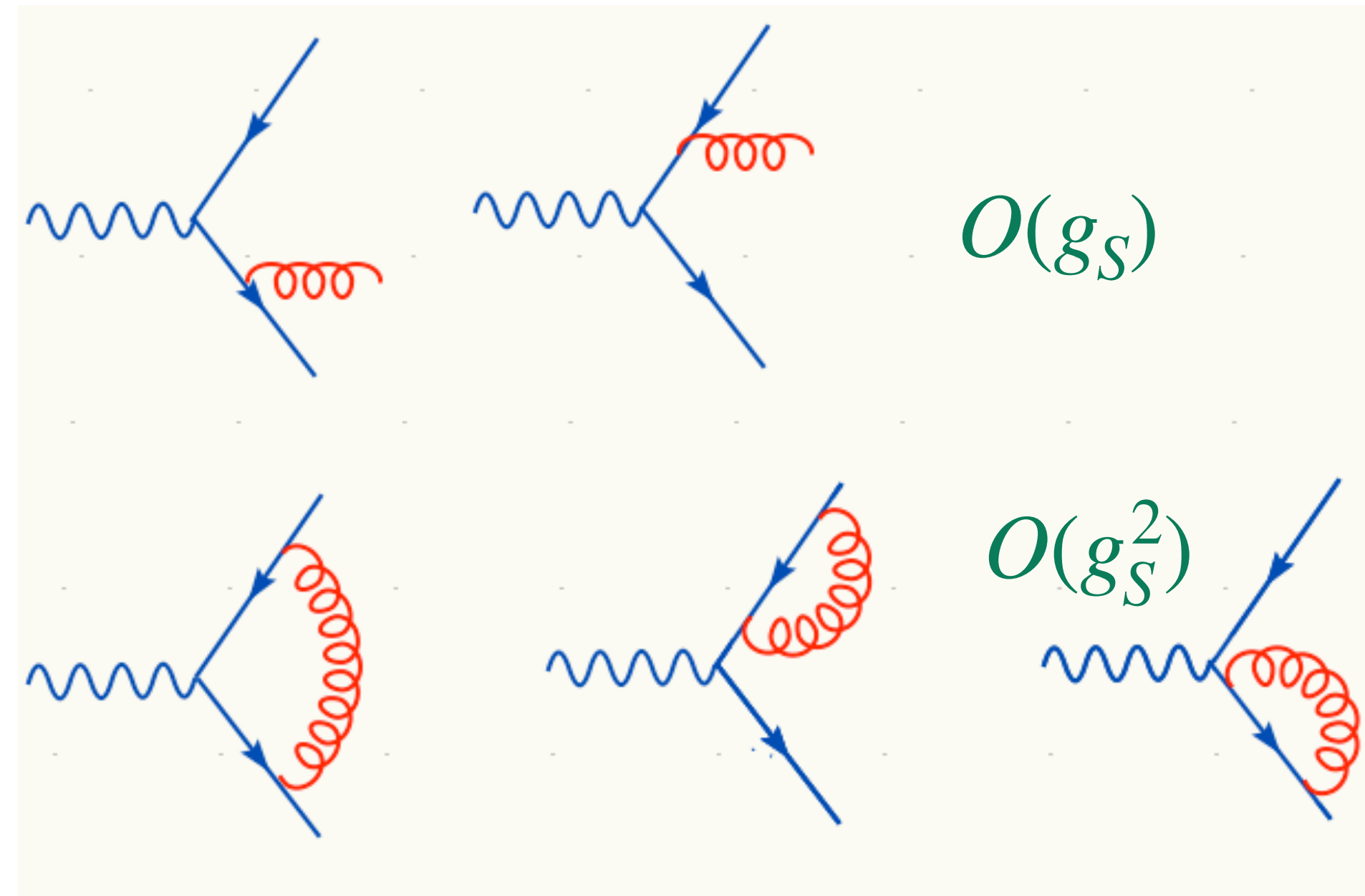
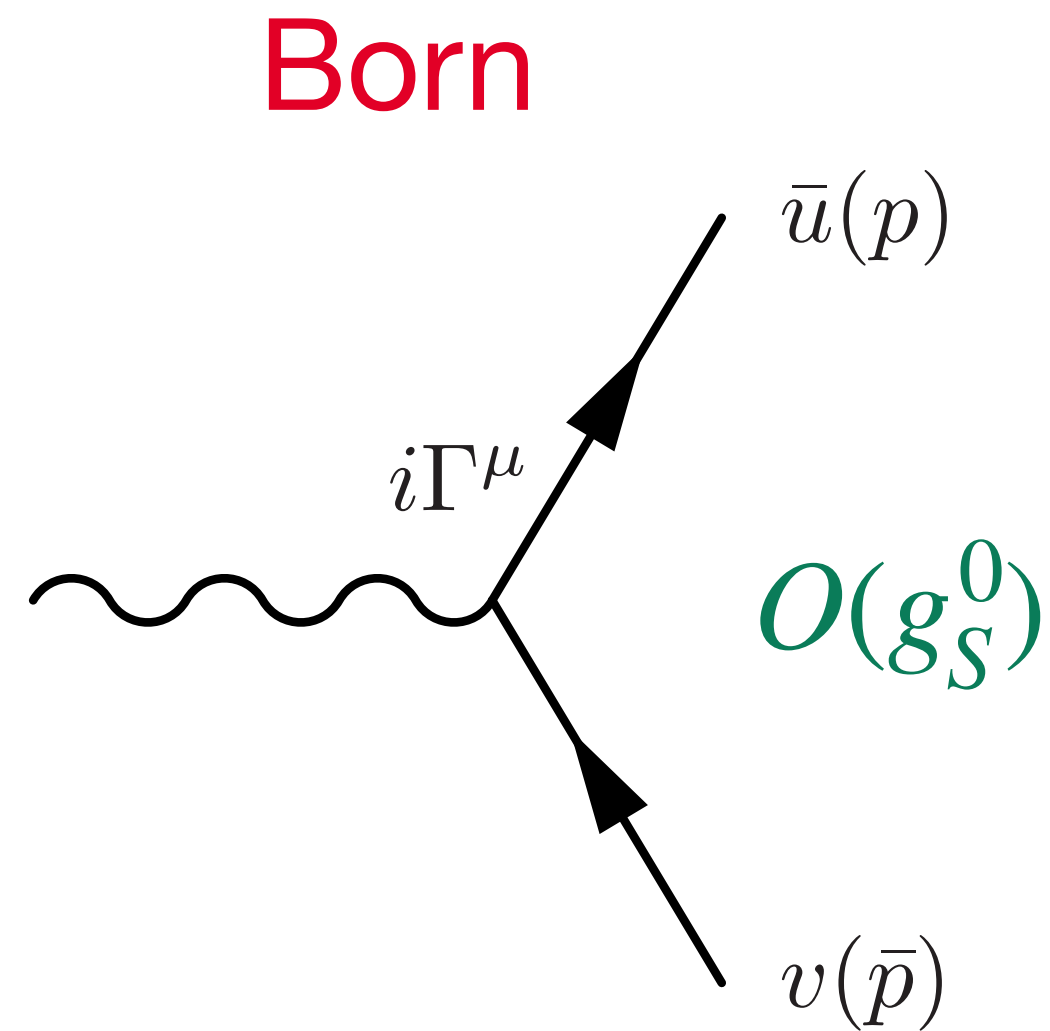
~Probabilities of finding
given parton with given
momentum in proton

Extracted from data

Parton-level cross section

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

Higher order corrections



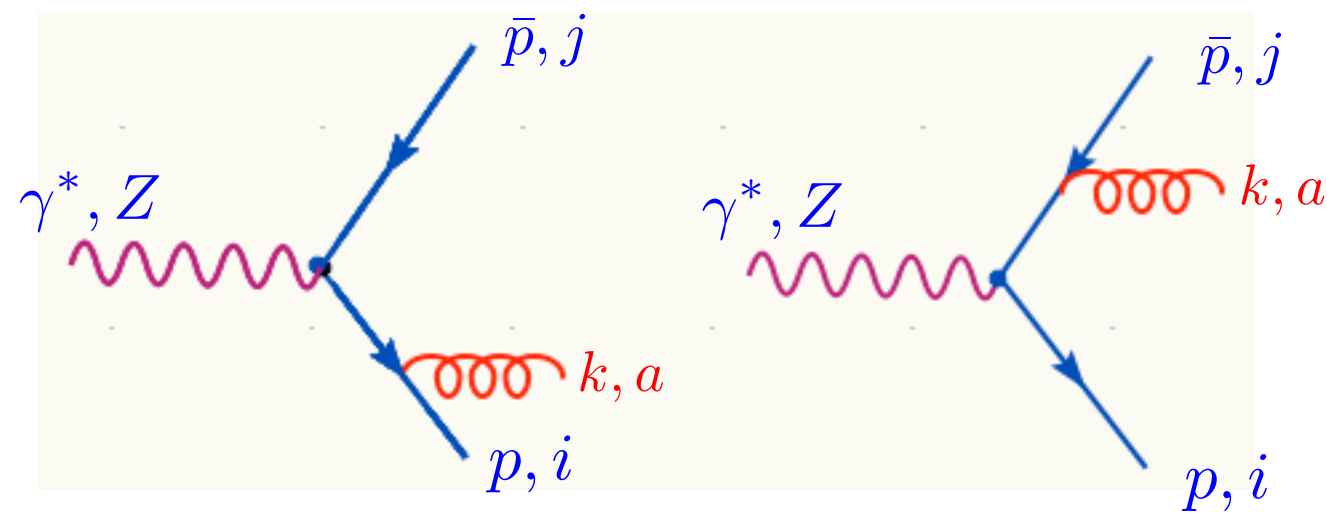
Real emission

Virtual (loop)
correction

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

QCD in the final state

Real corrections:



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

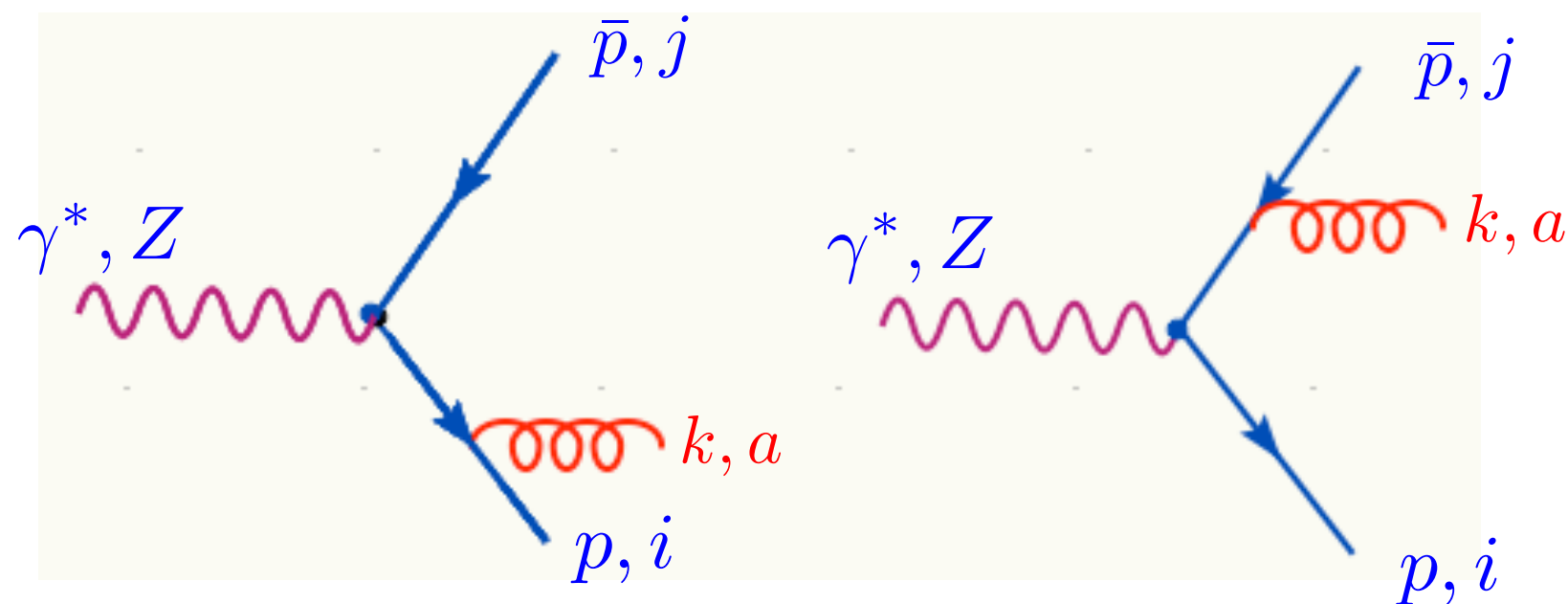
What are those denominators?

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

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

QCD in the final state

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



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

Try it out!

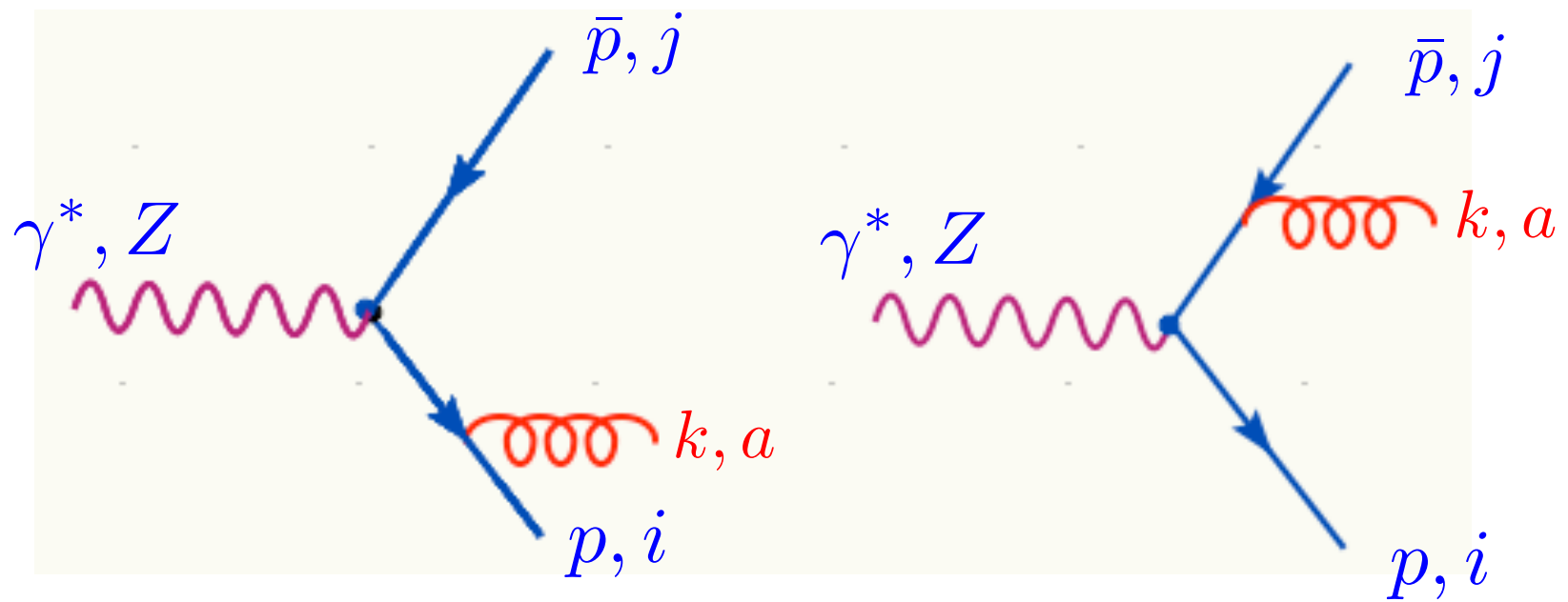
Very important property of QCD & QED

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?



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

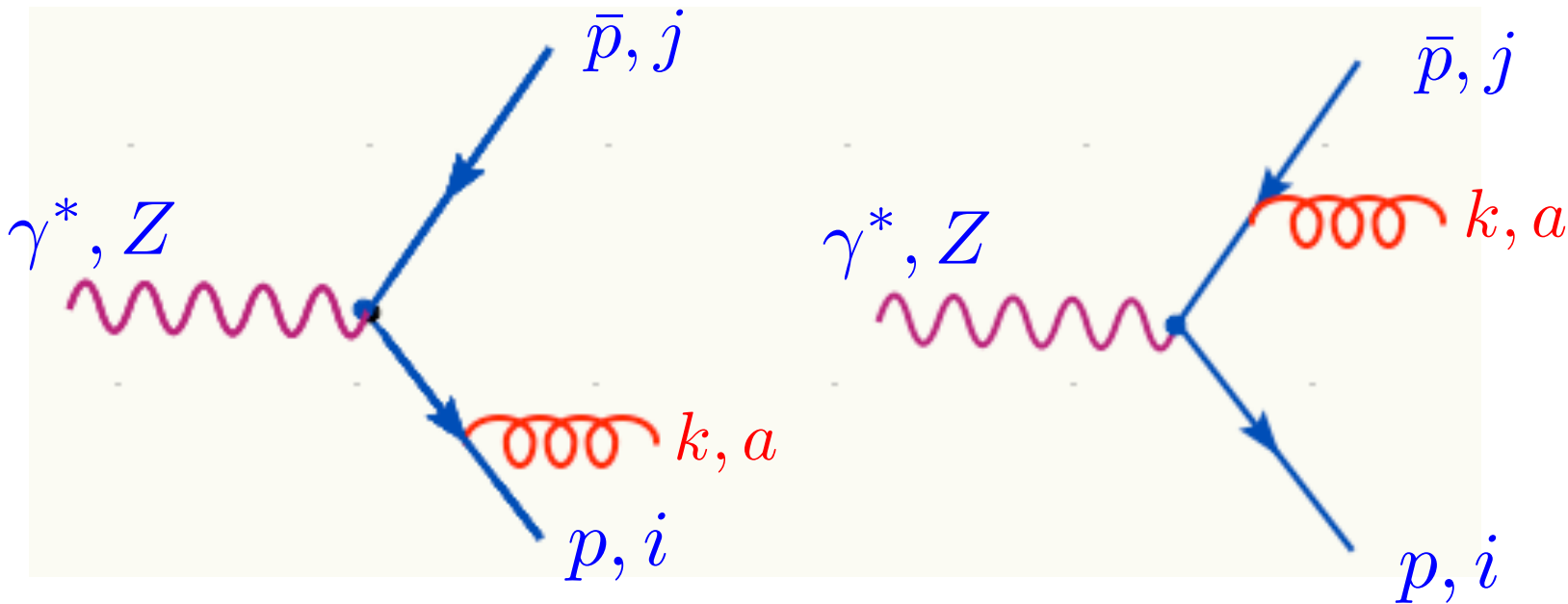
$$A_{\text{real}} \simeq -g_s [t_a]^{ij} \left(\frac{p \cdot \epsilon}{p \cdot k} - \frac{\bar{p} \cdot \epsilon}{\bar{p} \cdot k} \right) A_{\text{Born}}^{ij}$$

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

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

$$\begin{aligned} \sigma_{\text{real}}^{q\bar{q}g} &= C_F g_s^2 \sigma_{\text{Born}}^{q\bar{q}} \int \frac{d^3 \vec{k}}{2k_0 (2\pi)^3} \frac{2p \cdot \bar{p}}{(p \cdot k)(\bar{p} \cdot k)} \\ &= C_F \frac{\alpha_S}{2\pi} \sigma_{\text{Born}}^{q\bar{q}} \int d\cos \theta \frac{dk_0}{k_0} \frac{4}{(1 - \cos \theta)(1 + \cos \theta)} \end{aligned}$$

QCD in the final state



$$\begin{aligned}\sigma_{\text{real}}^{q\bar{q}g} &= C_F g_s^2 \sigma_{\text{Born}}^{q\bar{q}} \int \frac{d^3\vec{k}}{2k_0(2\pi)^3} \frac{2p \cdot \bar{p}}{(p \cdot k)(\bar{p} \cdot k)} \\ &= C_F \frac{\alpha_S}{2\pi} \sigma_{\text{Born}}^{q\bar{q}} \int d\cos\theta \frac{dk_0}{k_0} \frac{4}{(1 - \cos\theta)(1 + \cos\theta)}\end{aligned}$$

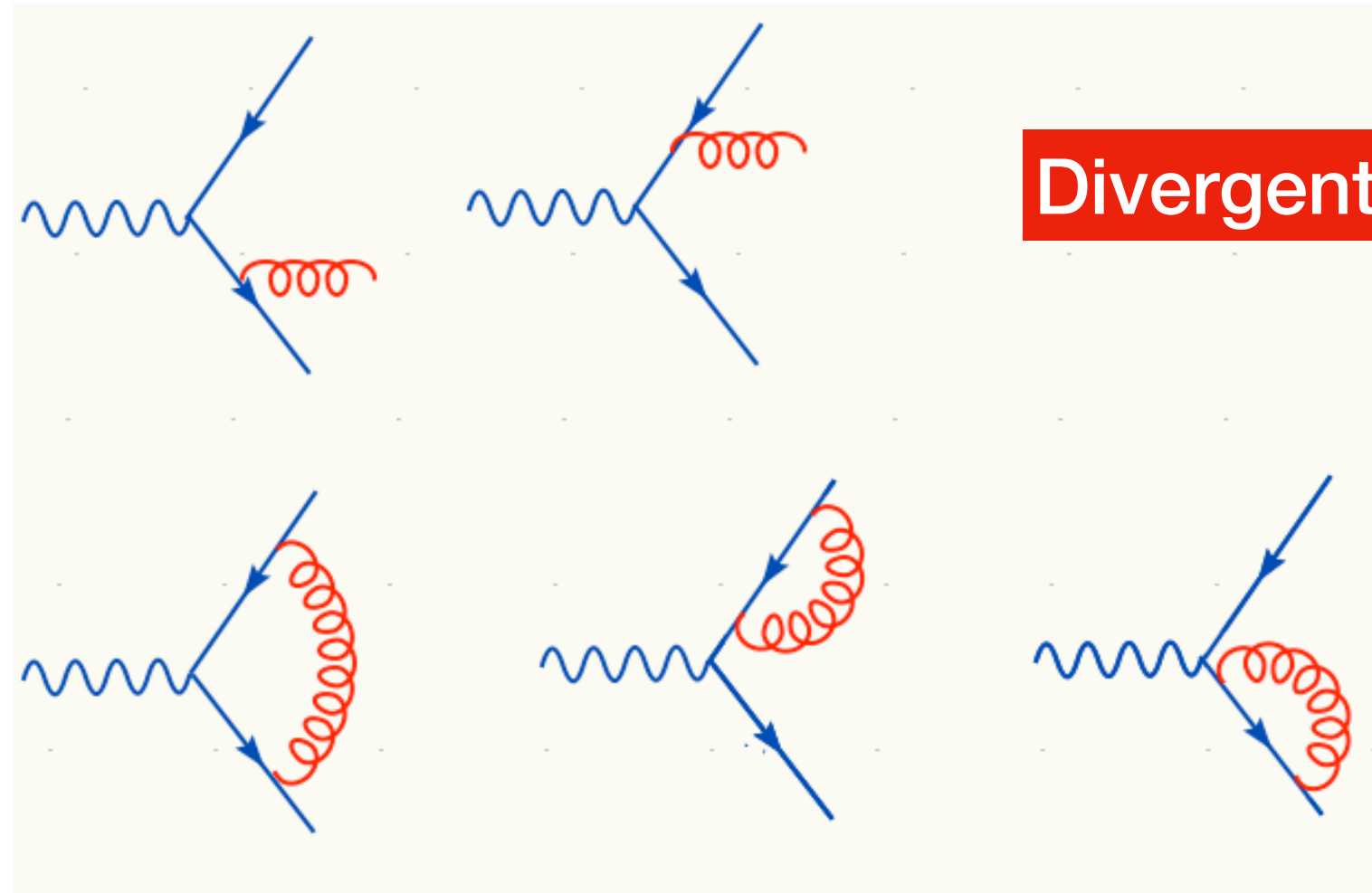
Real emission diagrams: IR singularities

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



Real

Virtual

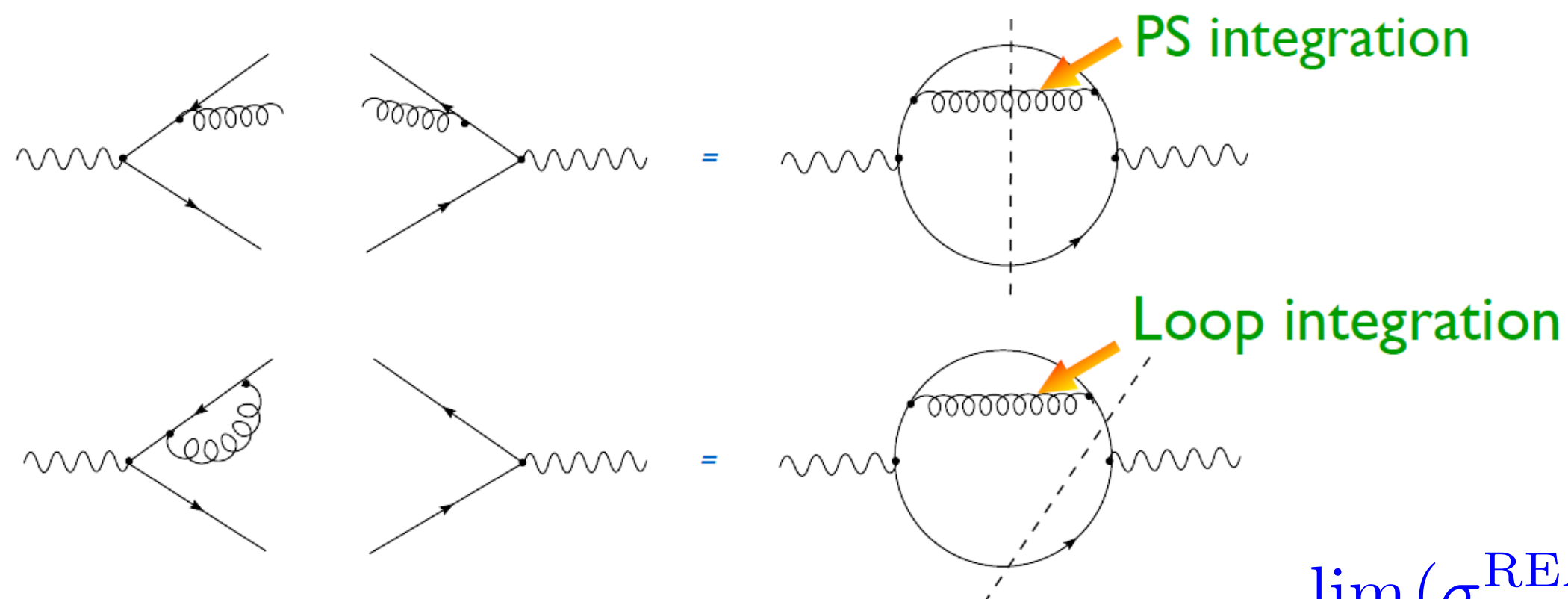
Also divergent!

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

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

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

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



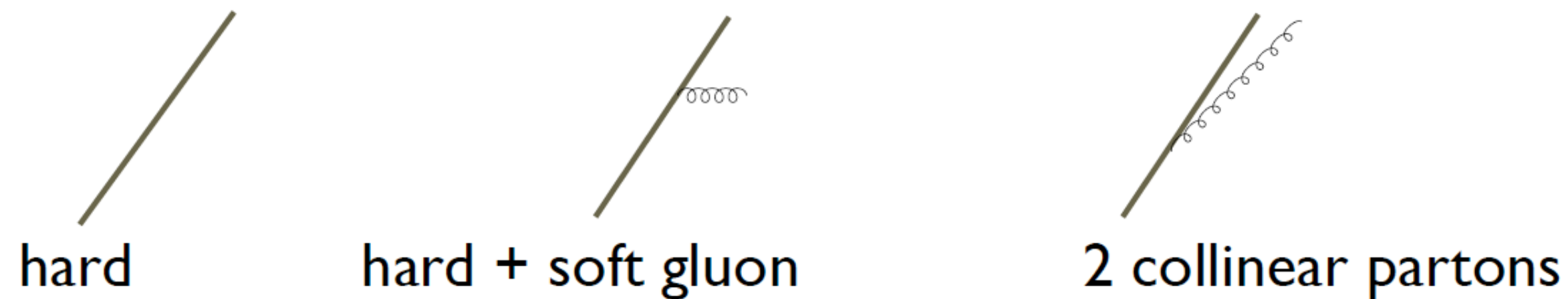
$$\sigma^{\text{REAL}} = \sigma^{\text{Born}} C_F \frac{\alpha_S}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} - \pi^2 \right)$$

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

$$\lim_{\epsilon \rightarrow 0} (\sigma^{\text{REAL}} + \sigma^{\text{VIRT}}) = C_F \frac{3}{4} \frac{\alpha_S}{\pi} \sigma^{\text{Born}} \quad R_1 = R_0 \left(1 + \frac{\alpha_S}{\pi} \right) \quad \textbf{Finite!}$$

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

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

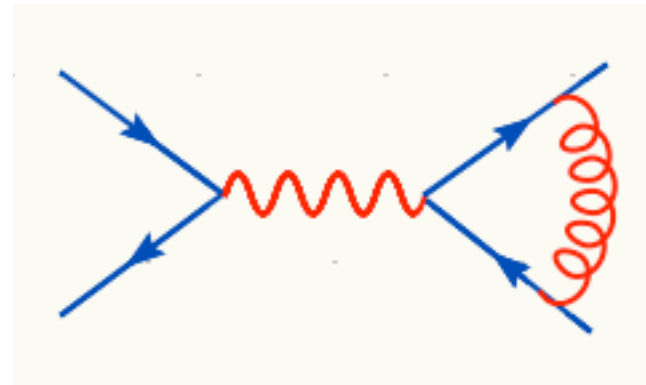
whenever one of the k_i/k_j becomes soft or k_i and k_j are collinear

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!

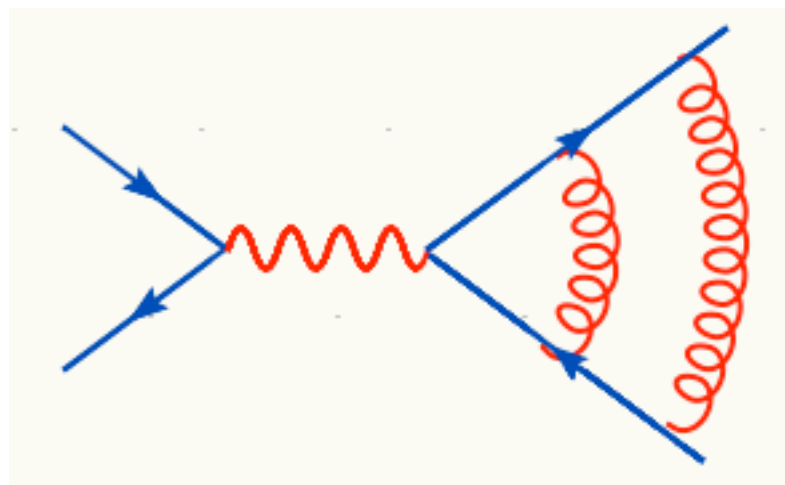
Asymptotic freedom



$$R_1 = R_0 \left(1 + \frac{\alpha_S}{\pi} \right) \quad \text{No divergences!}$$

What happens at higher orders?

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



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

UV divergences don't cancel! We need renormalisation!

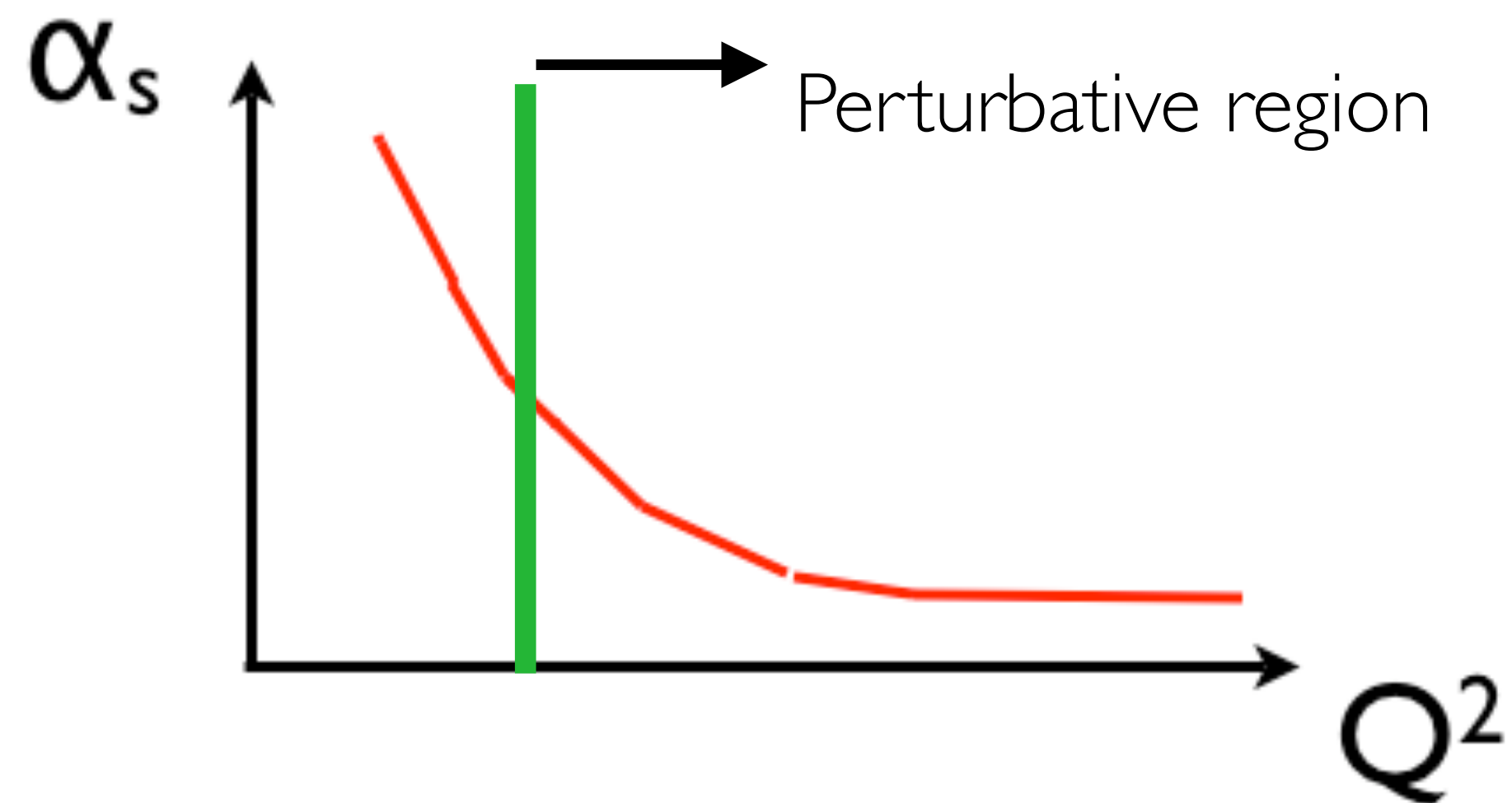
Renormalising the bare coupling we have:

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

μ = renormalisation scale

Finite but scale dependent!

Asymptotic freedom



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



1-loop

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

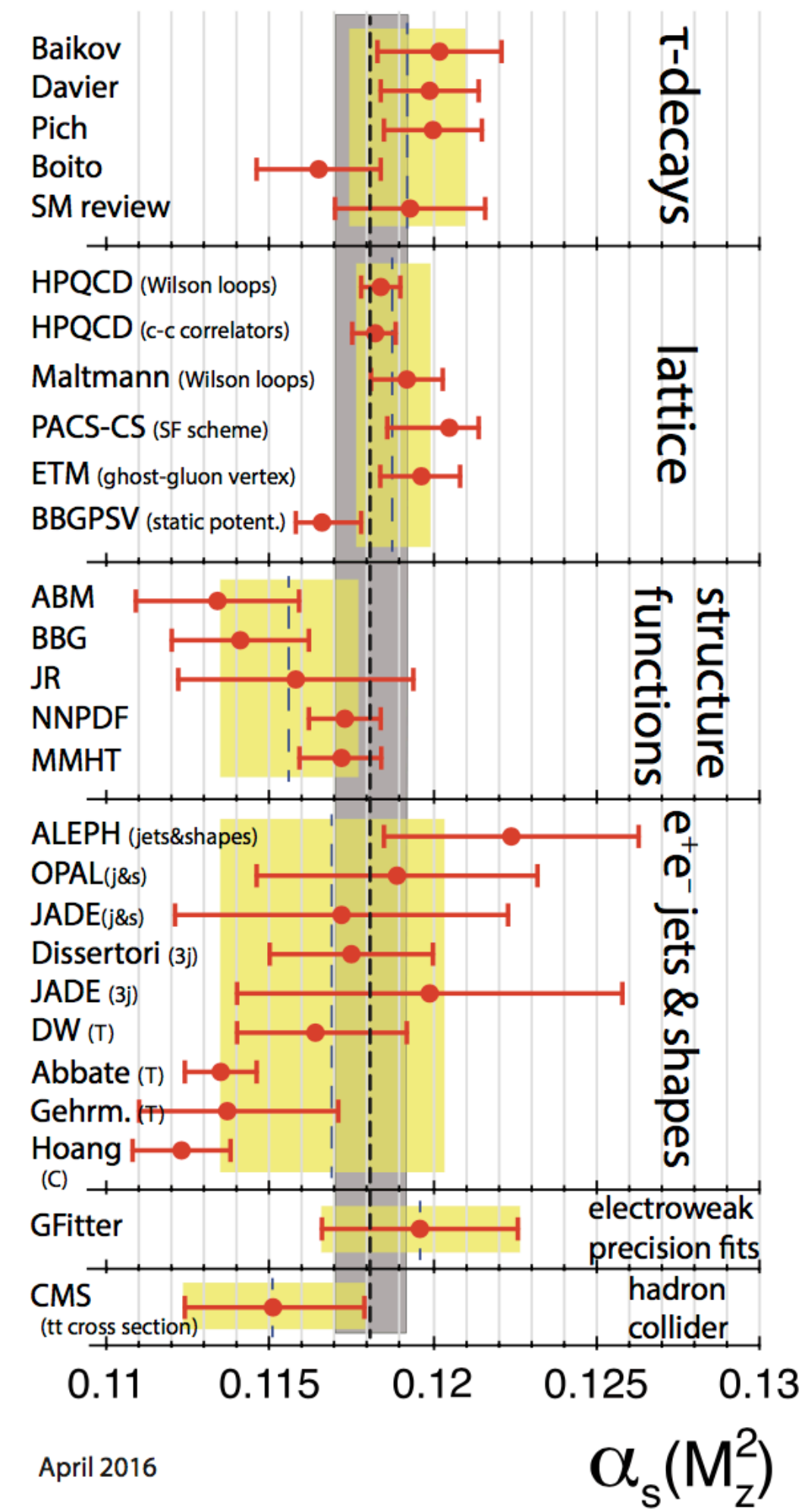
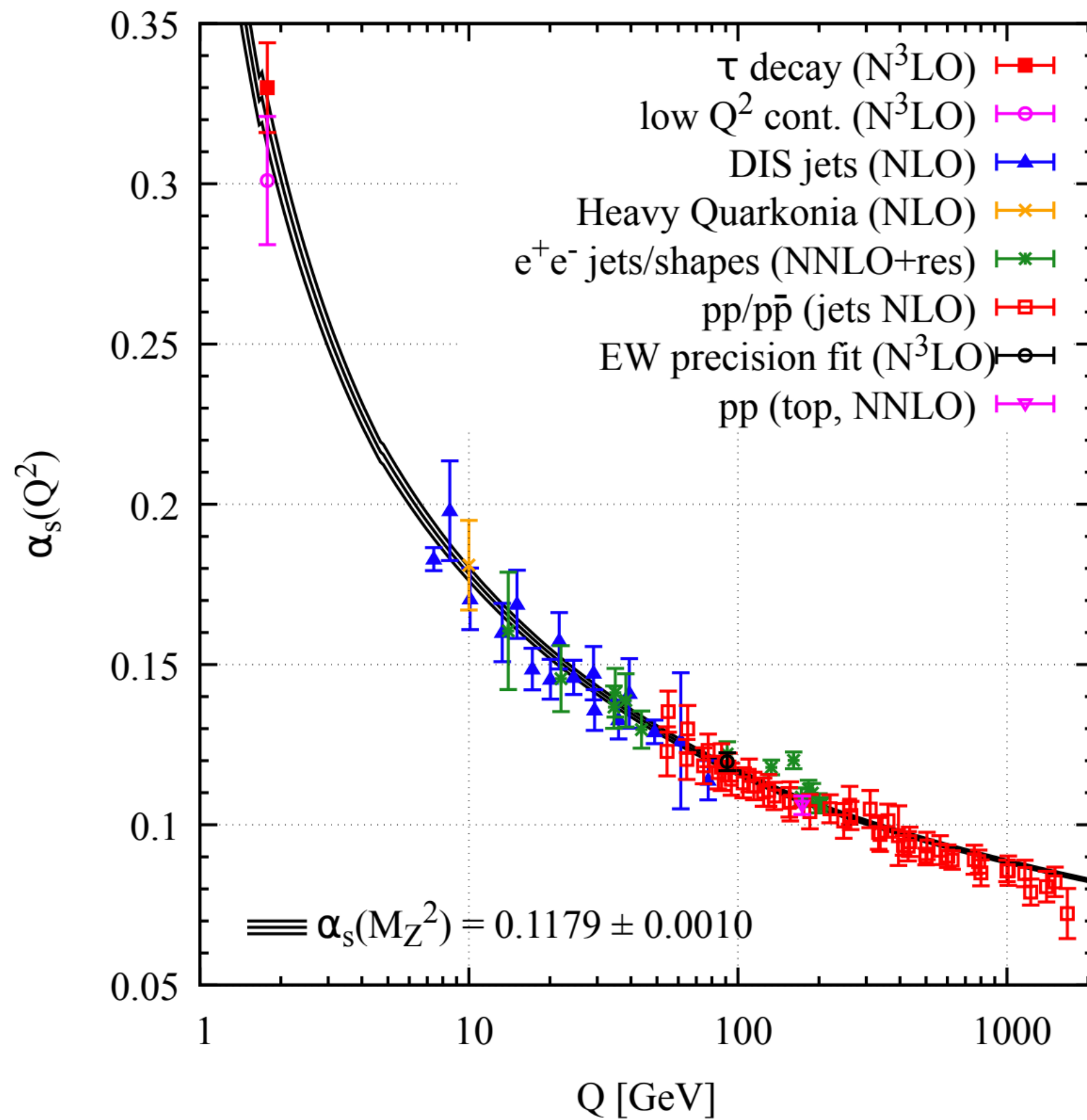
2-loop

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

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

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

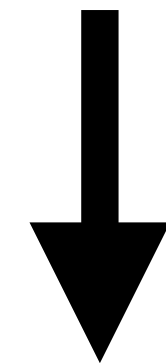
Running of α_s



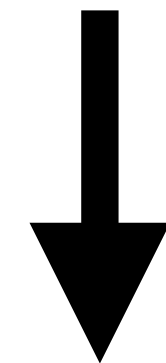
Many measurements at different scales all leading to very consistent results once evolved to the same reference scale, M_Z .

Going back to the Master formula

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



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

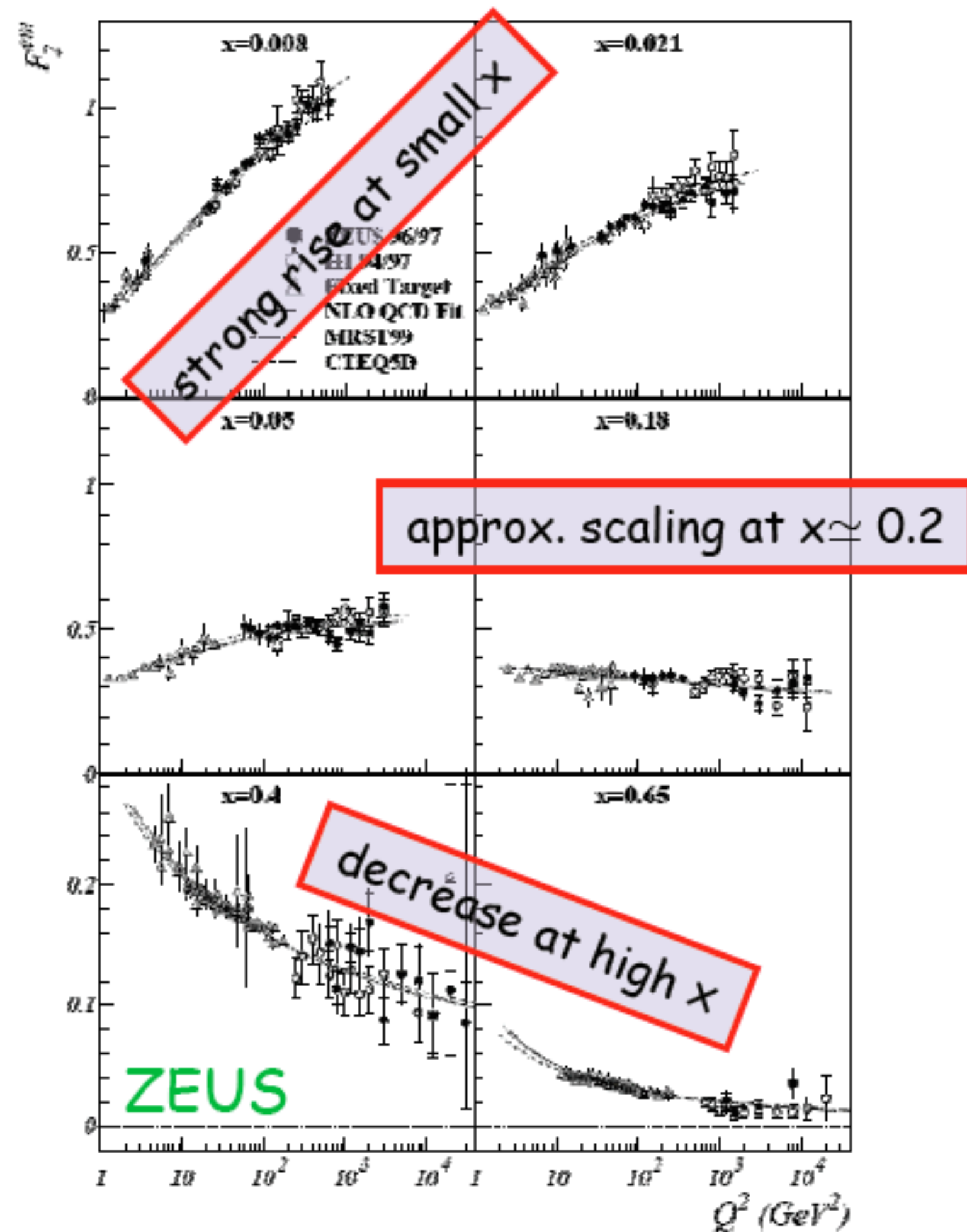


???

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

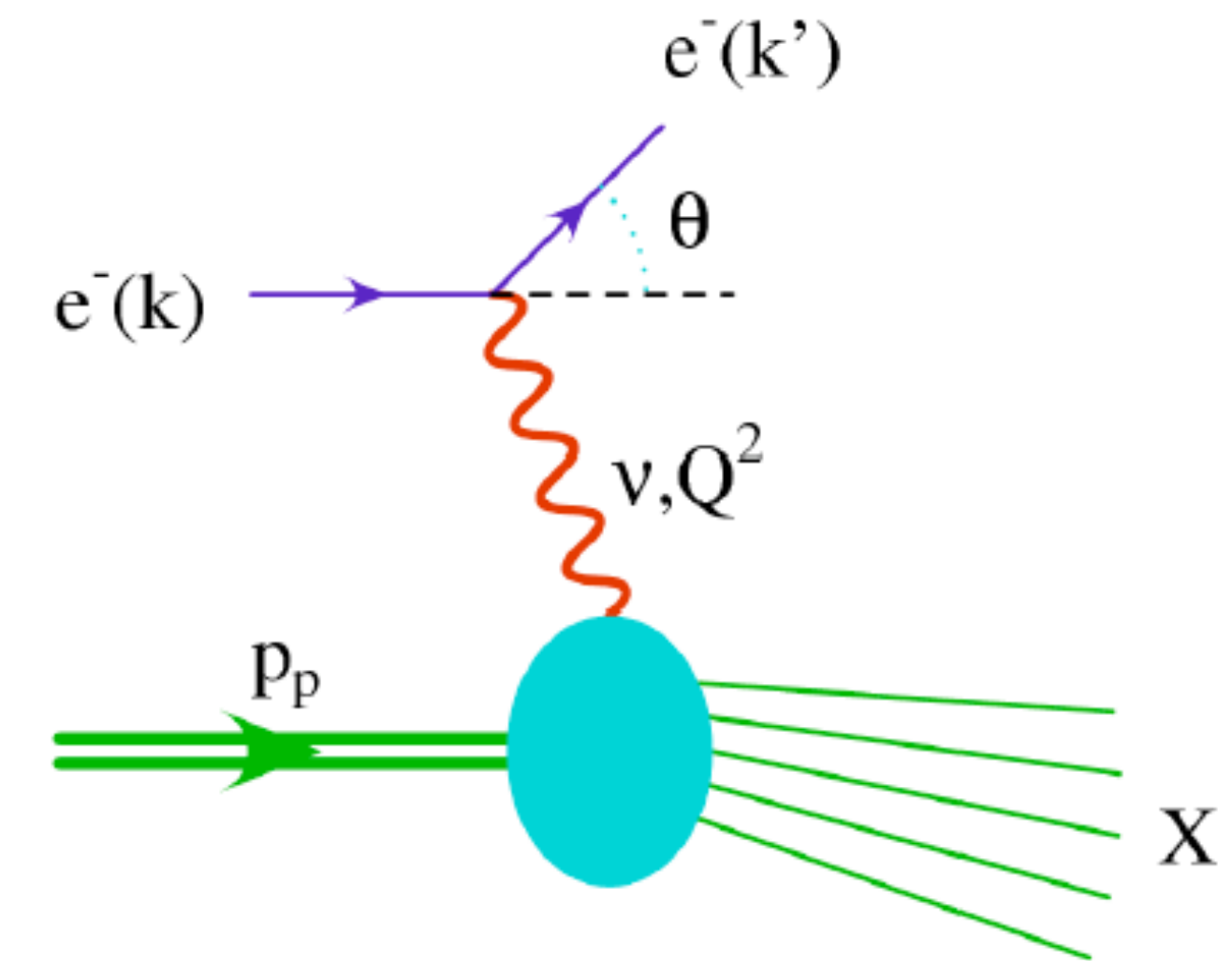
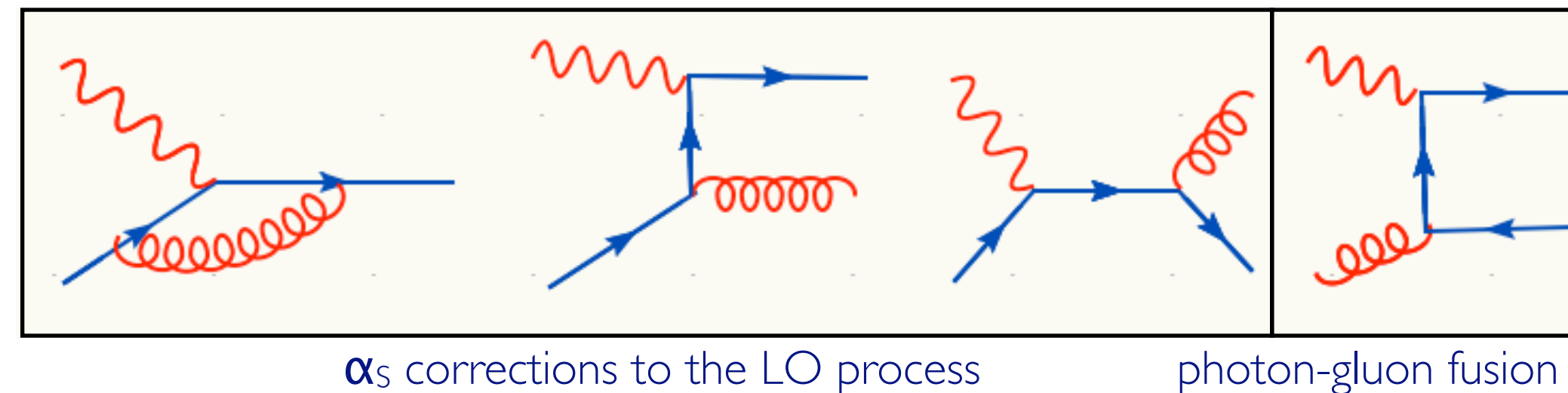
QCD improved parton model

The parton model predicts scaling. Experiment shows:

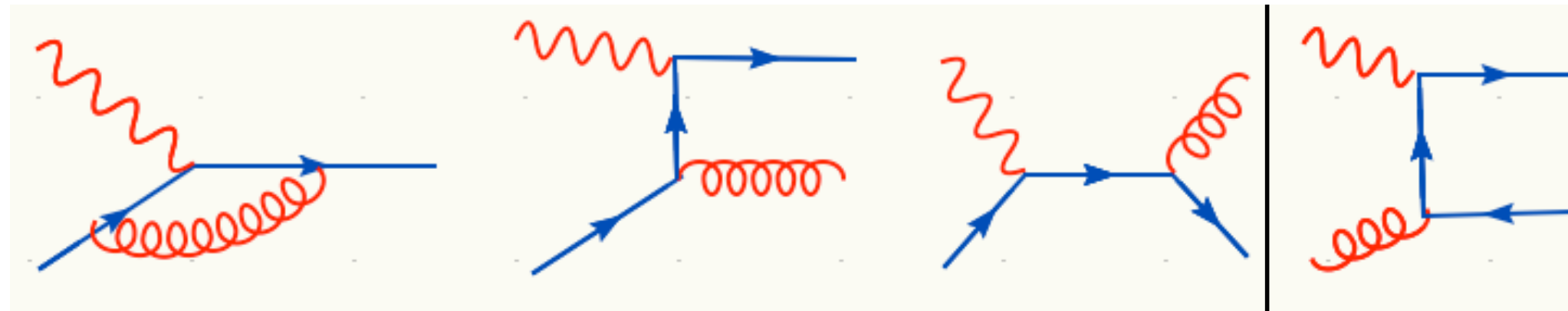


Scaling violation

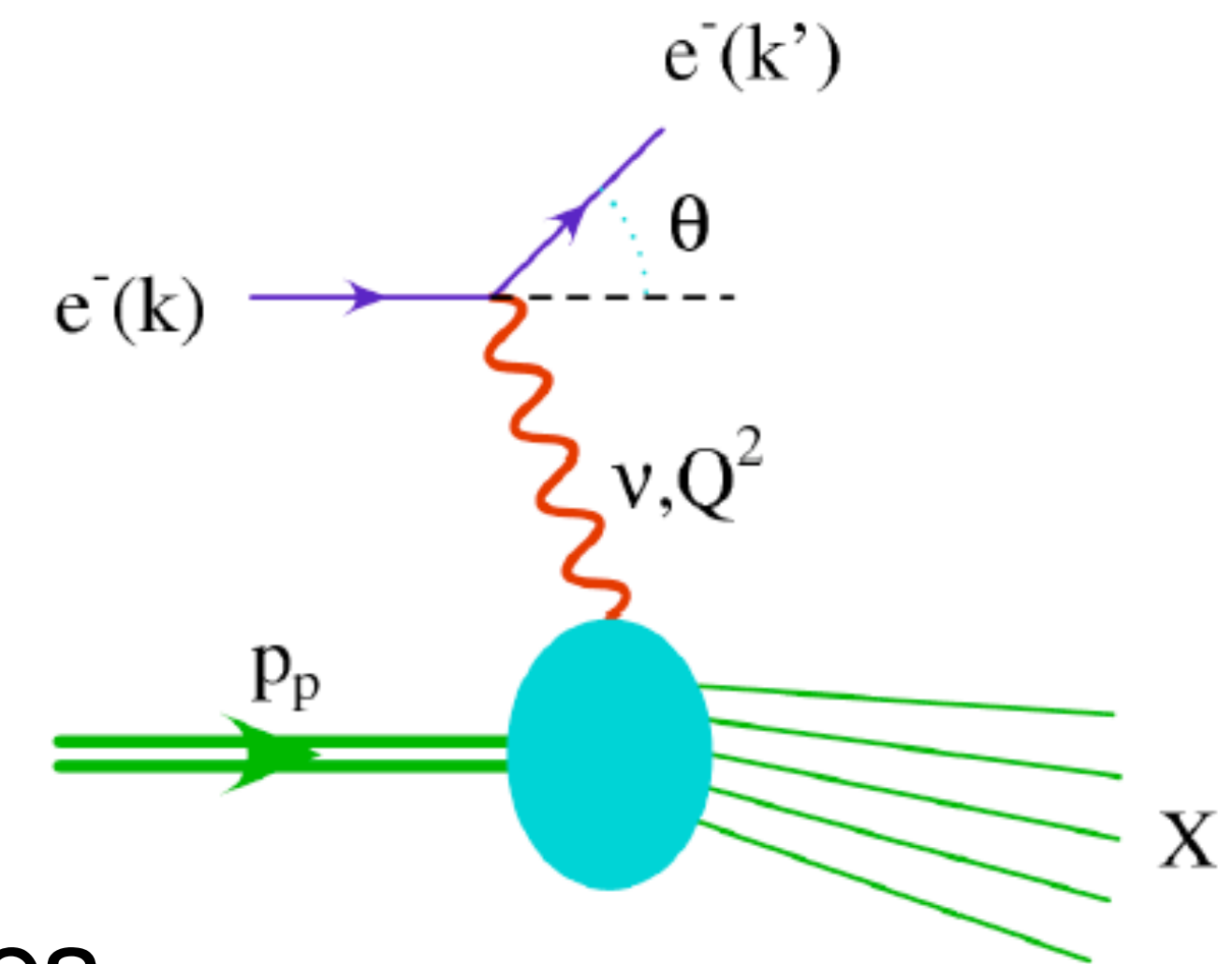
What are we missing?



QCD improved parton model



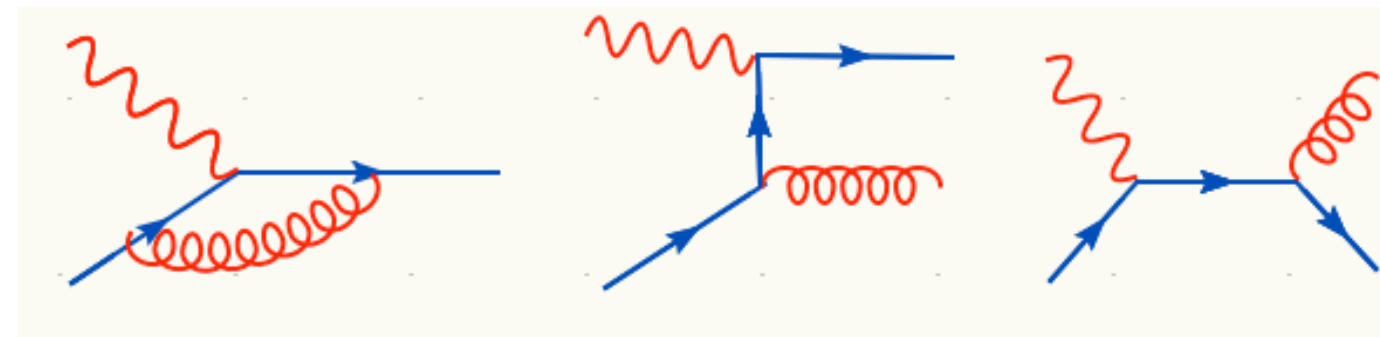
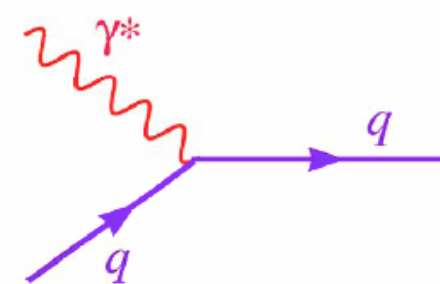
What do we expect?



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

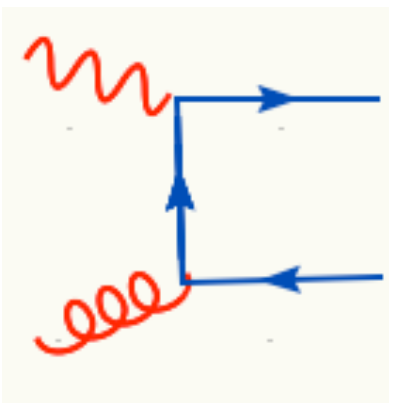
We need to regulate these, and hope that they cancel!

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

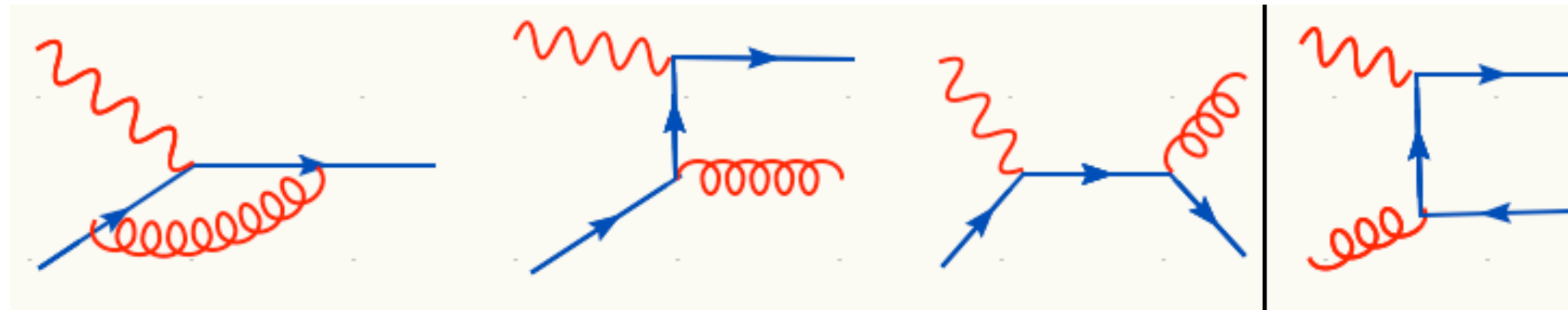


Soft and UV divergences cancel but a collinear divergence remains:

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



QCD improved parton model



Soft and UV divergences cancel but a collinear divergence remains:

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

IR cut-off

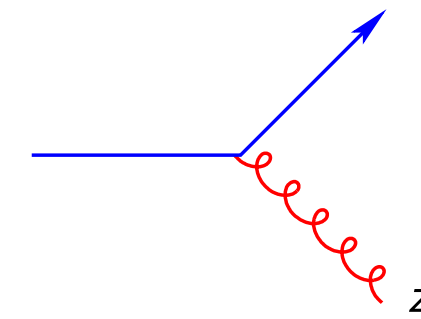
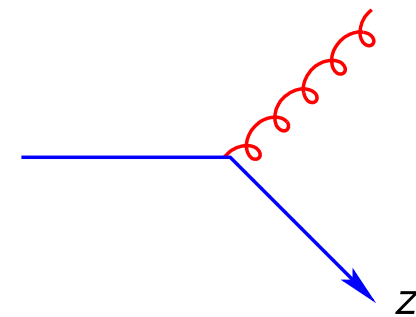
What are functions P_{qq} and P_{qg} ?

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

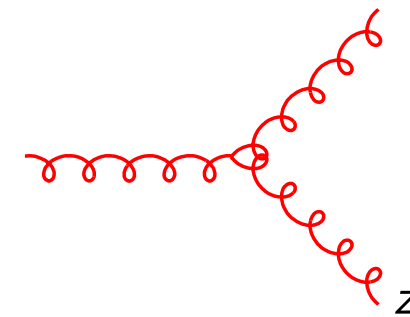
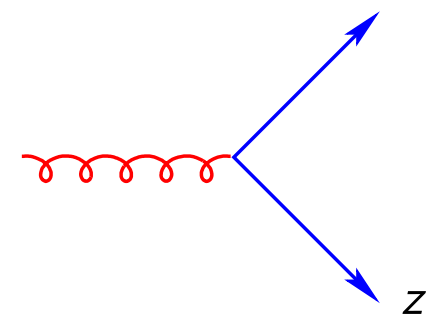
Altarelli-Parisi Splitting functions

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

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



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



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:

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

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

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

Renormalised PDFs!

Factorisation

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

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

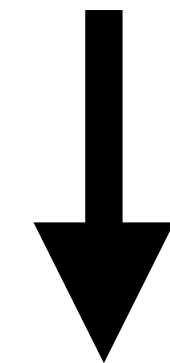
Long distance physics is universally factorised into the PDFs, which now depend on μ_f . PDFs are not calculable in perturbation theory. PDFs are universal, they don't depend on the process.

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

LHC Master Formula

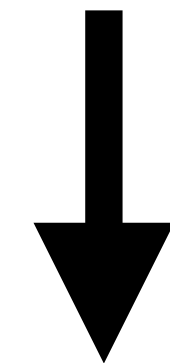
$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{PS} f_a(x_1) f_b(x) \hat{\sigma}(\hat{s})$$

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

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


DGLAP

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

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

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

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

↑ ↑ ↑

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

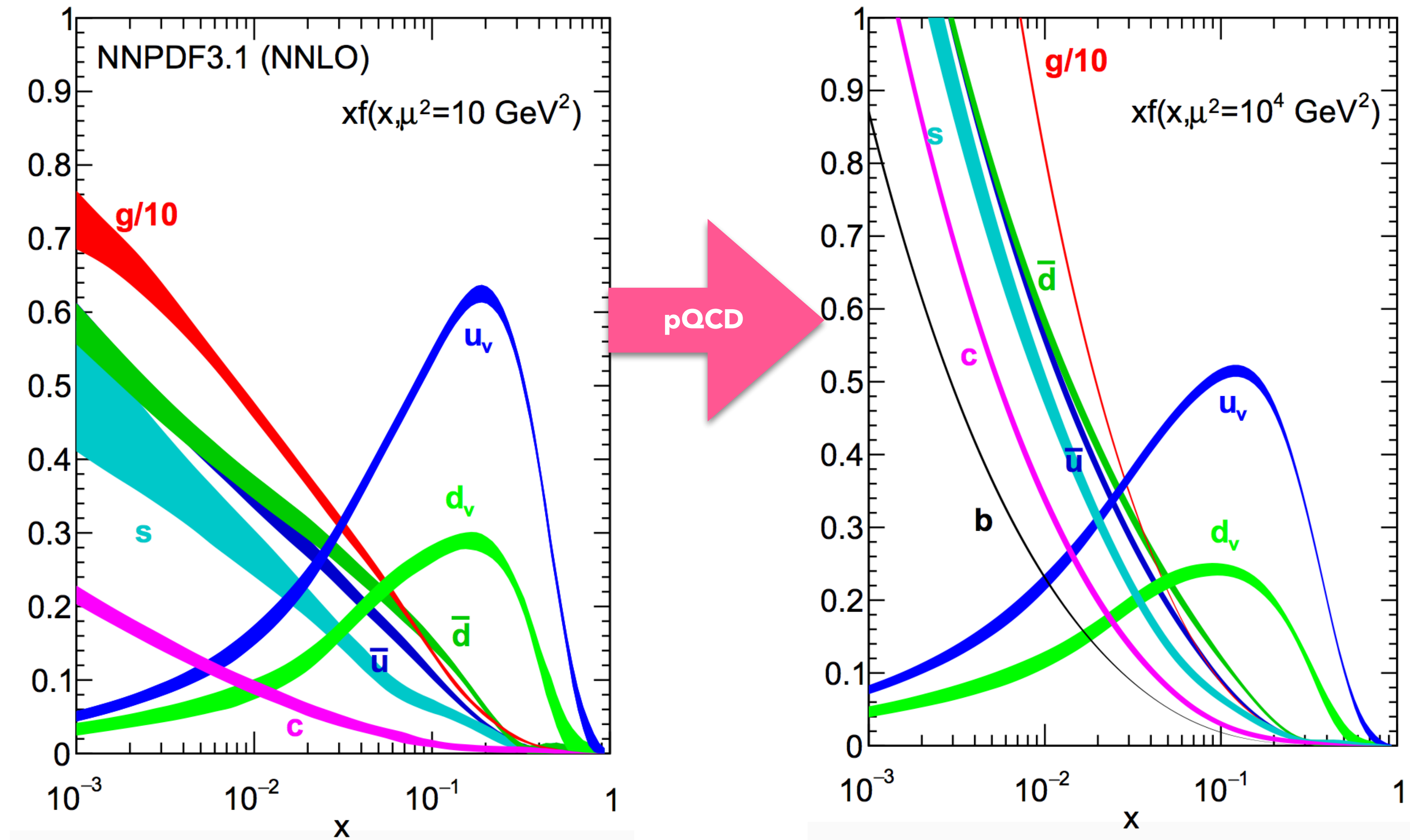
Splitting functions improved in perturbation theory!

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

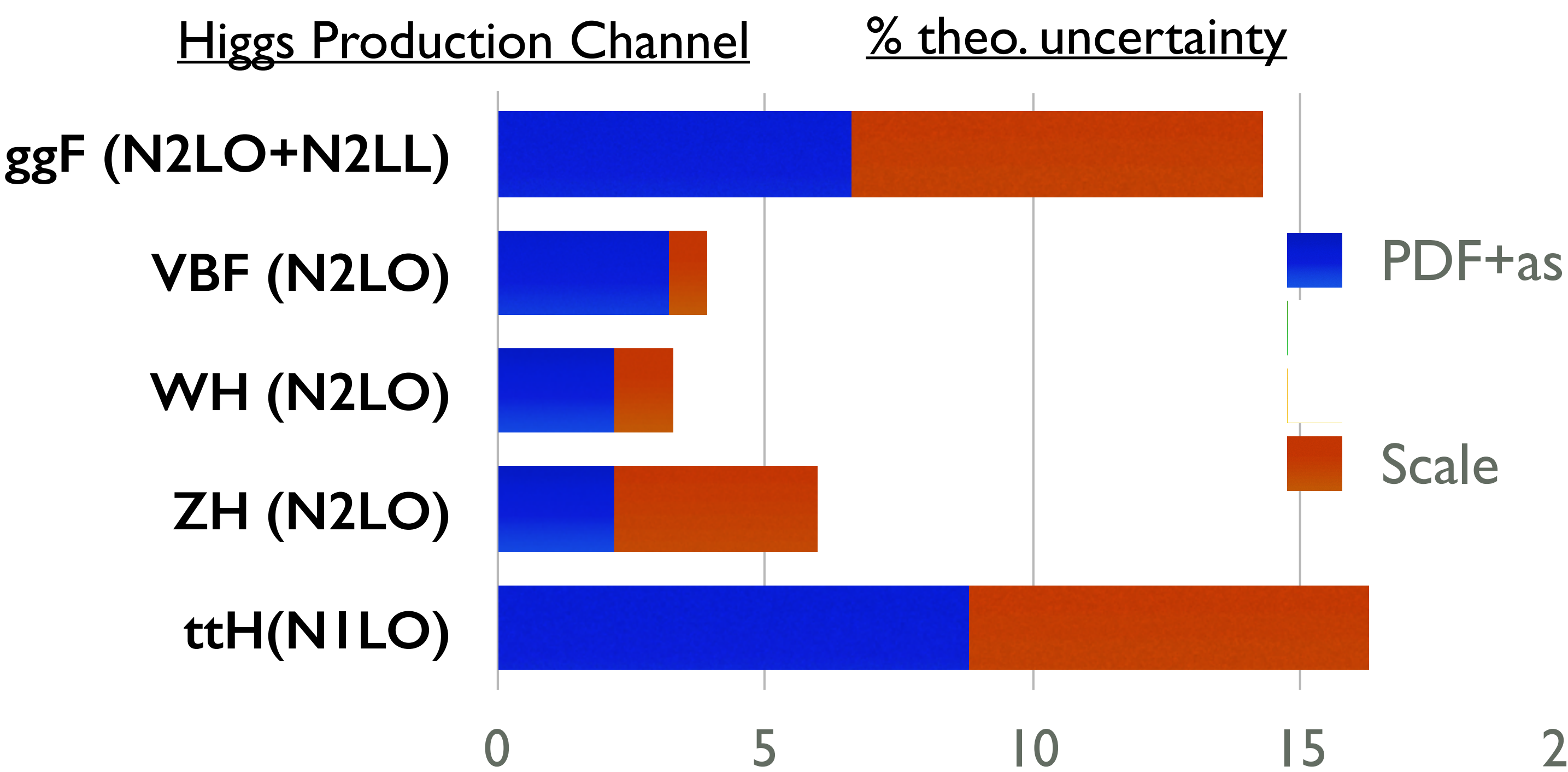
NLO Floratos, Ross, Sachrajda; Floratos, Lacaze, Kounnas
Gonzalez-Arroyo, Lopez, Yndurain; Curci, Furmanski
Petronzio, (1981)

NNLO - Moch, Vermaseren, Vogt, 2004

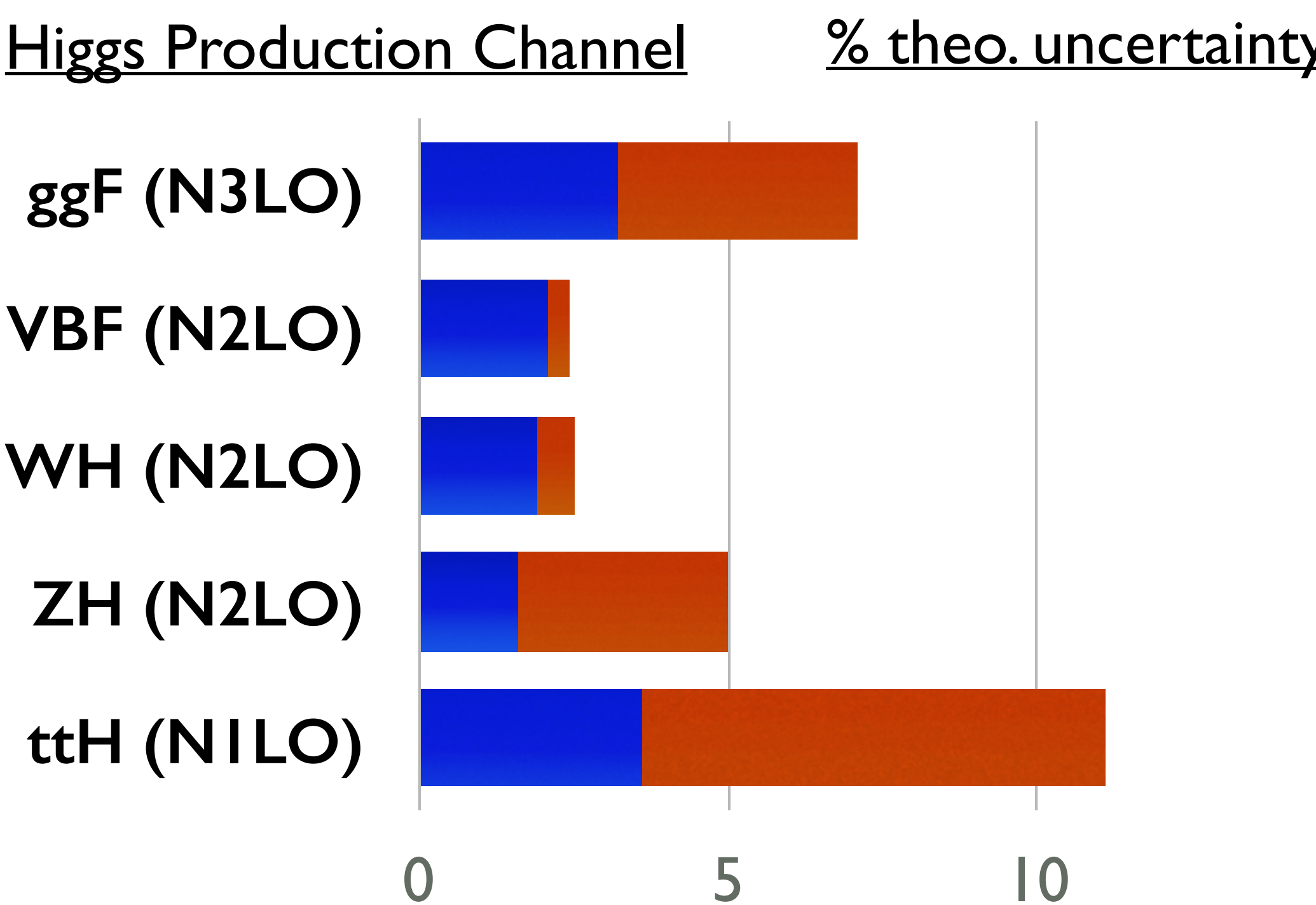
PDF evolution



Impact of PDF uncertainties



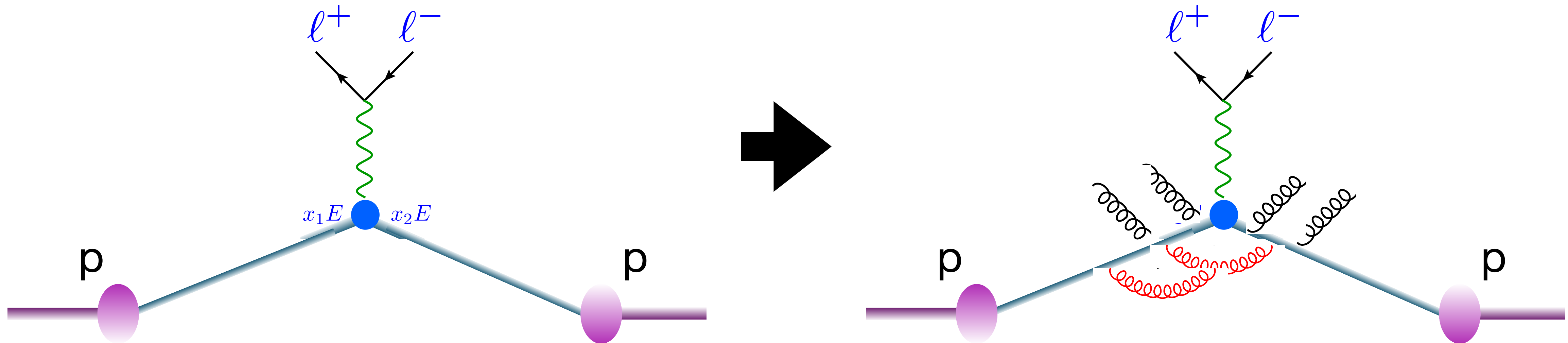
Yellow Report 3 (2013)



Yellow Report 4 (2016)

Progress in PDFs!

Fixed order computations



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

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

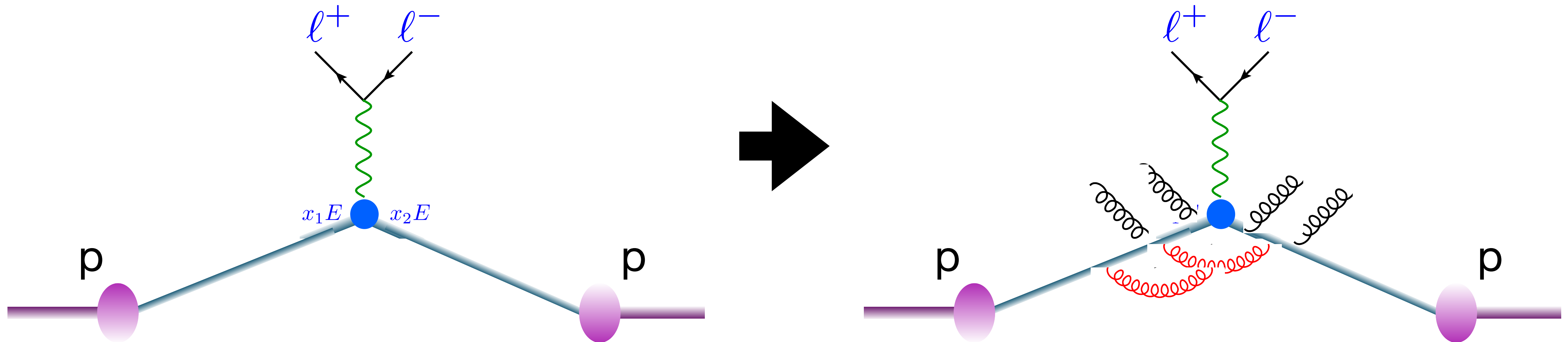
LO

NLO

NNLO

N3LO

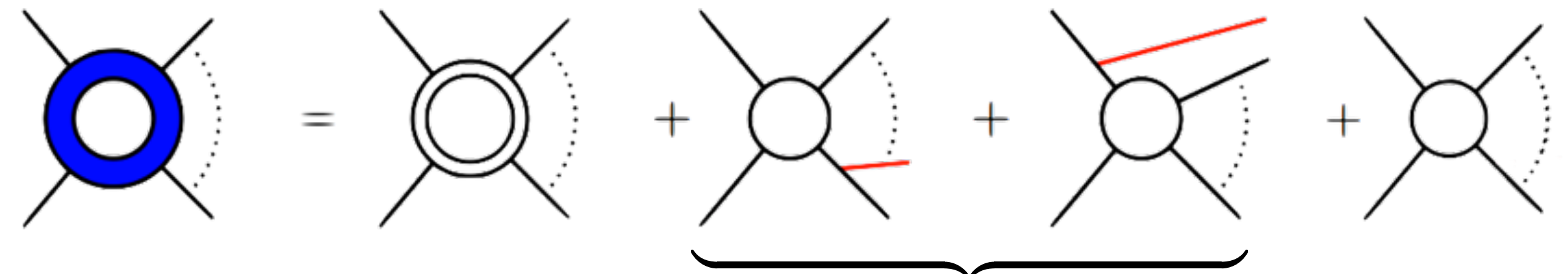
Fixed order computations



*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



$$\sigma^{\text{NLO}} = \underbrace{\int_m d^{(d)} \sigma^V}_{\text{Virtual part}} + \underbrace{\int_{m+1} d^{(d)} \sigma^R}_{\text{Real emission part}} + \int_m d^{(4)} \sigma^B \quad \text{Born}$$

Difficulties:

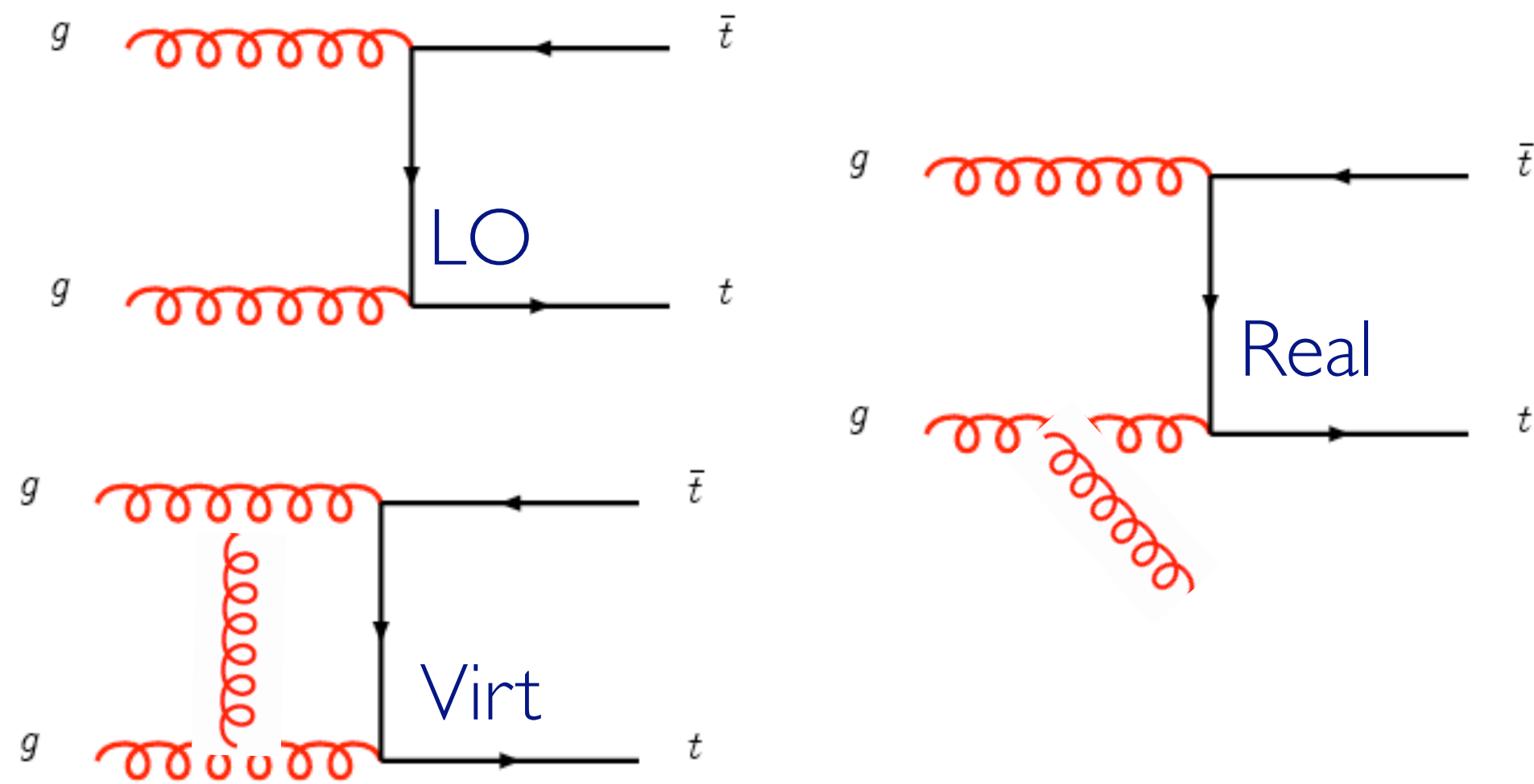
- Loop calculations: tough and time consuming
- Divergences: Both real and virtual corrections are divergent
- More channels, more phase space integrations

Difficulty



A note about NLO

Example: top pair production



NLO

Which observables do we compute at NLO?

Total cross-section ✓

pT of a top quark ✓

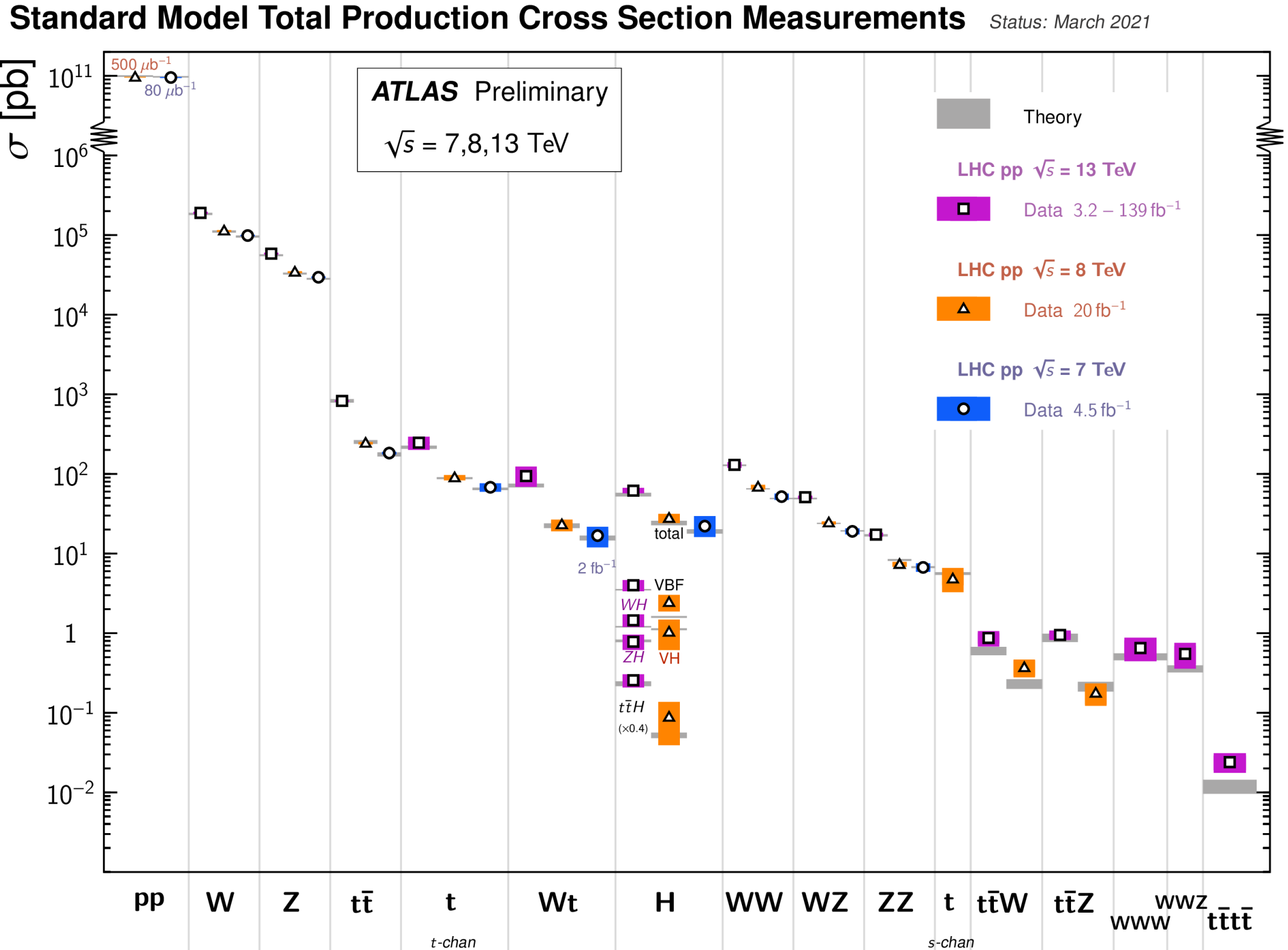
pT of top pair ✗

pT of hardest jet ✗

tt invariant mass ✓

It is certain observables which are computed at NLO

Need for higher-orders



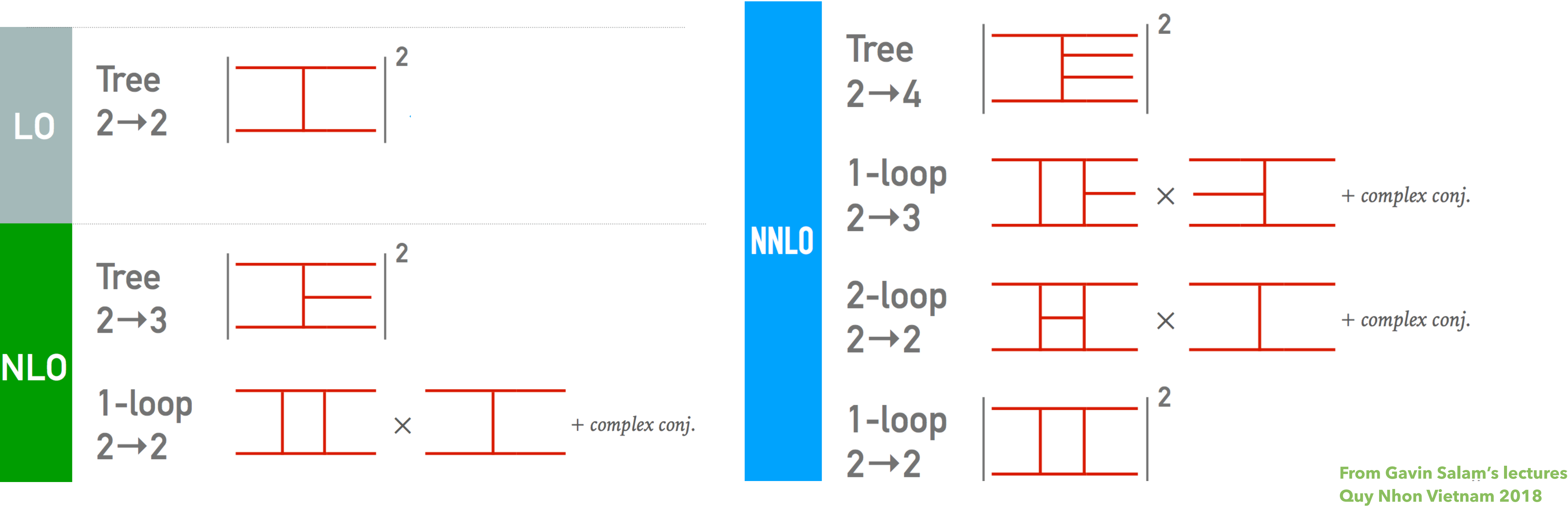
Reminder:

Level of experimental precision demands precise theoretical predictions

Theorists are not simply having fun!!!

There are processes whose measurement is limited by theoretical uncertainties

Higher order computations



Complexity rises a lot with each N!

Status of hard scattering cross-sections

LO automated

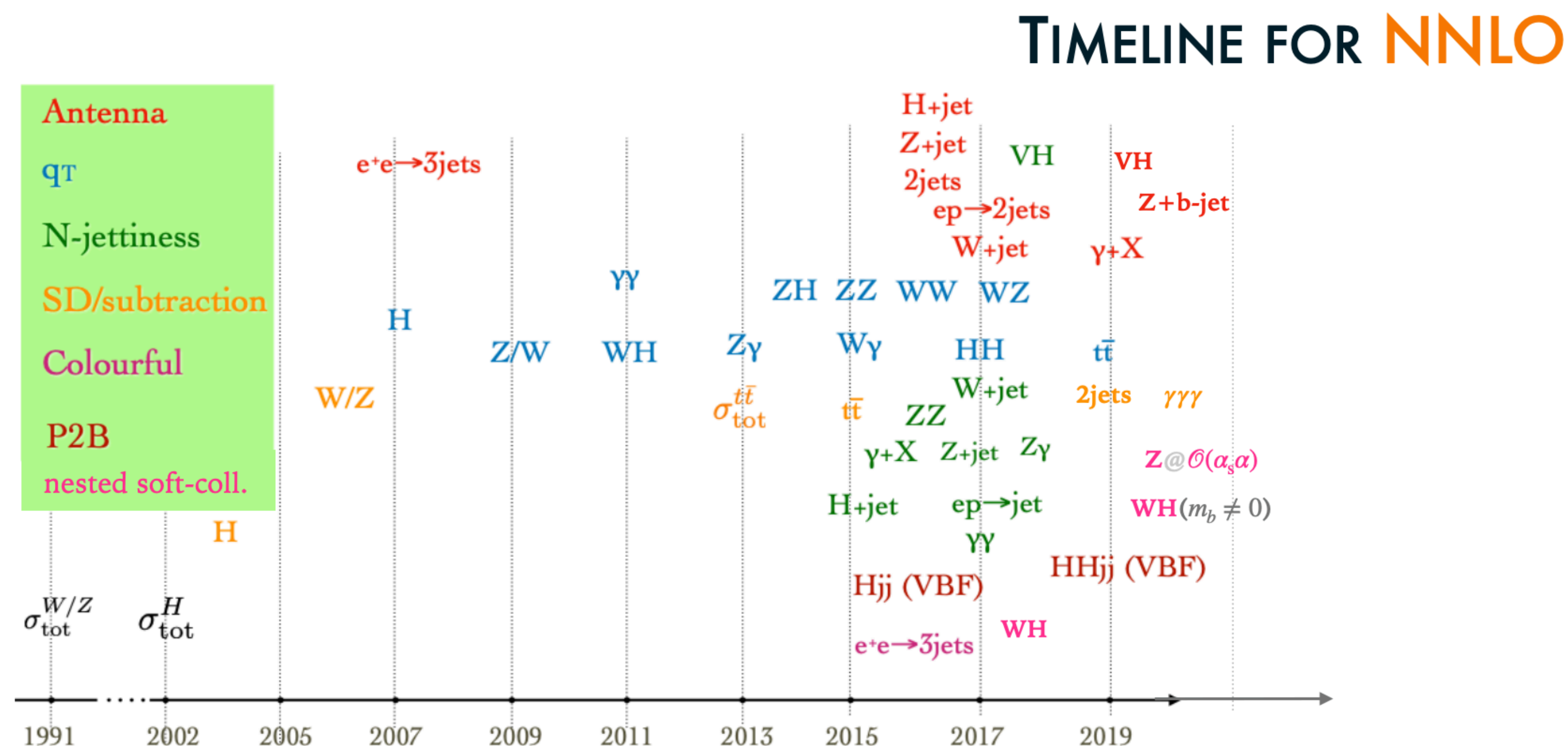
NLO automated

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

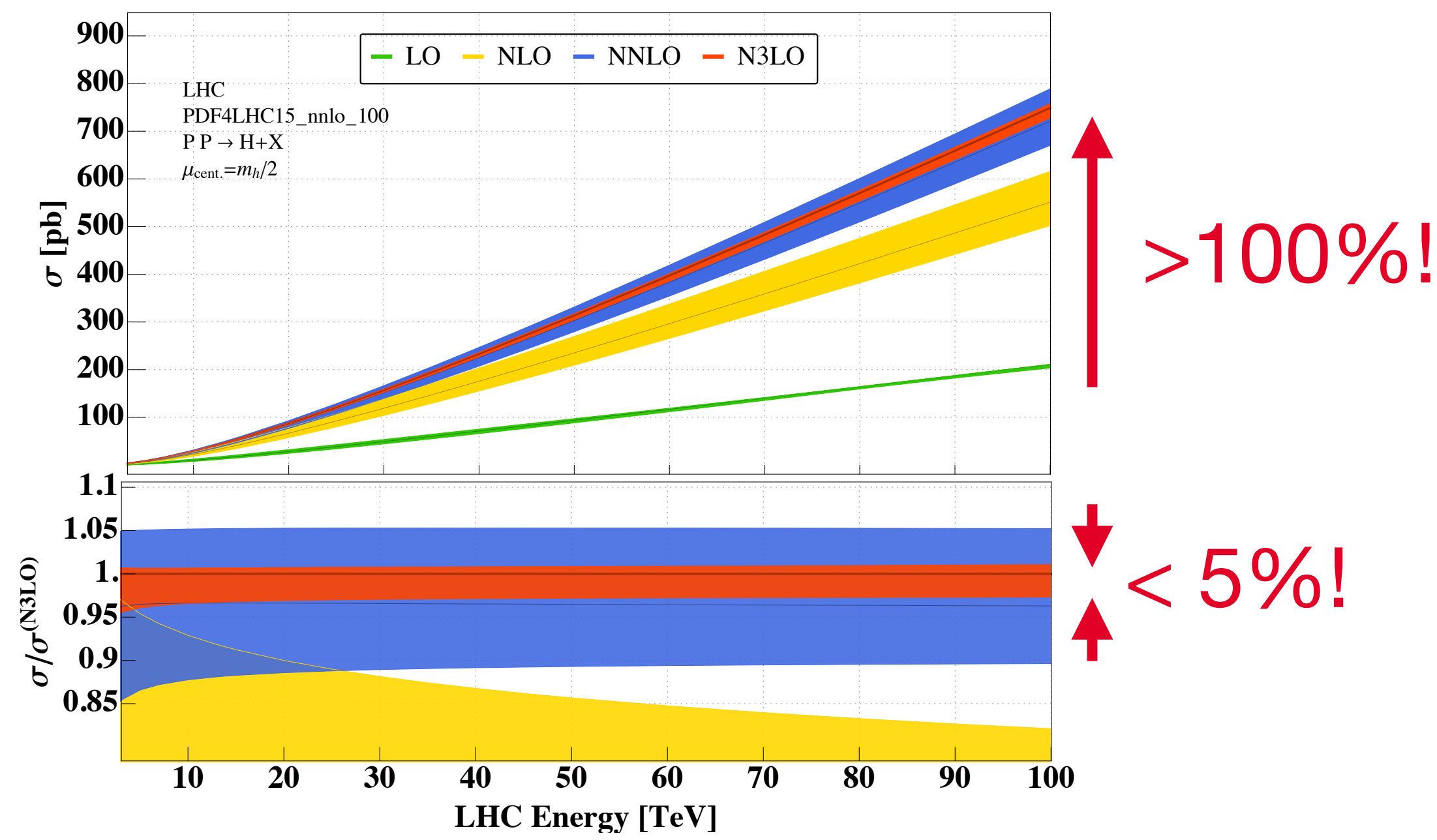


A. Huss, QCD@LHC-X 2020

Hard scattering cross-section

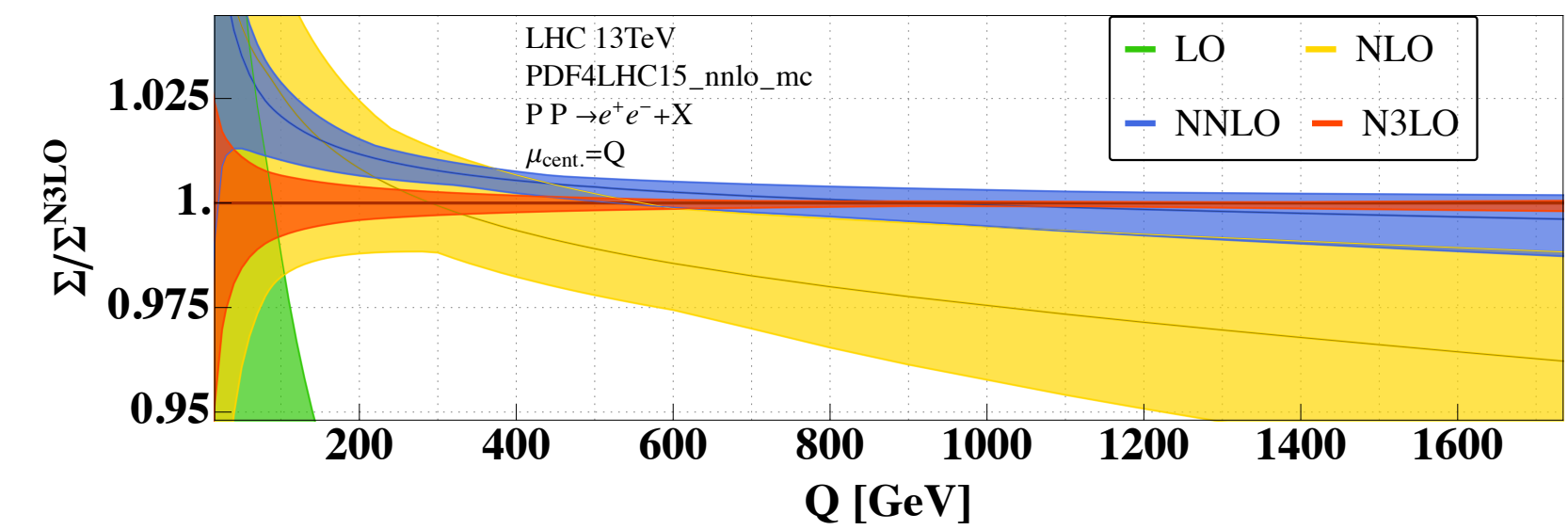
$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \underbrace{\frac{\alpha_s}{2\pi} \sigma^{(1)}}_{\text{NLO}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)}}_{\text{NNLO}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)}}_{\text{N3LO}} + \dots \right)$$

LO
NLO
NNLO
N3LO



Higgs production

Improved accuracy and precision



Dilepton production

arXiv:2203.06730

Uncertainties in theory predictions

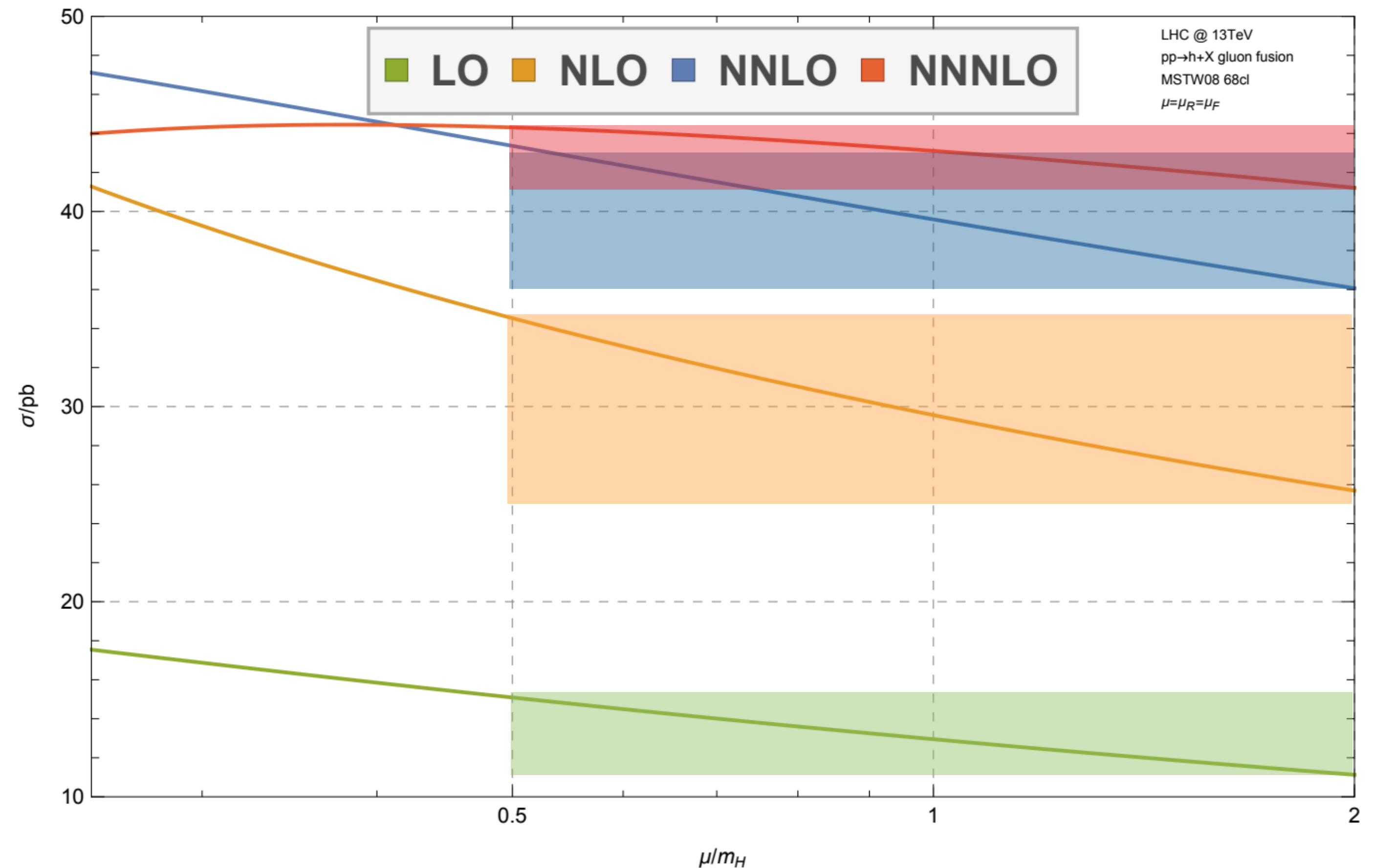
How do we estimate uncertainties?

Vary the renormalisation and factorisation scale

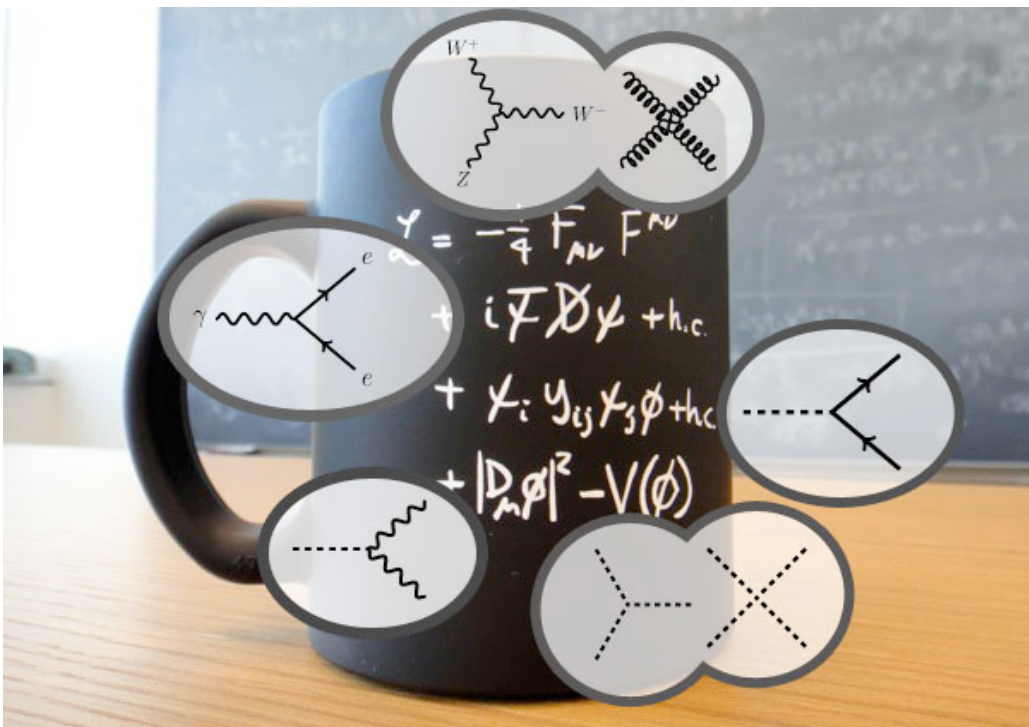
Typically pick some central scale μ_0 and vary the scale up and down by a factor of 2

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

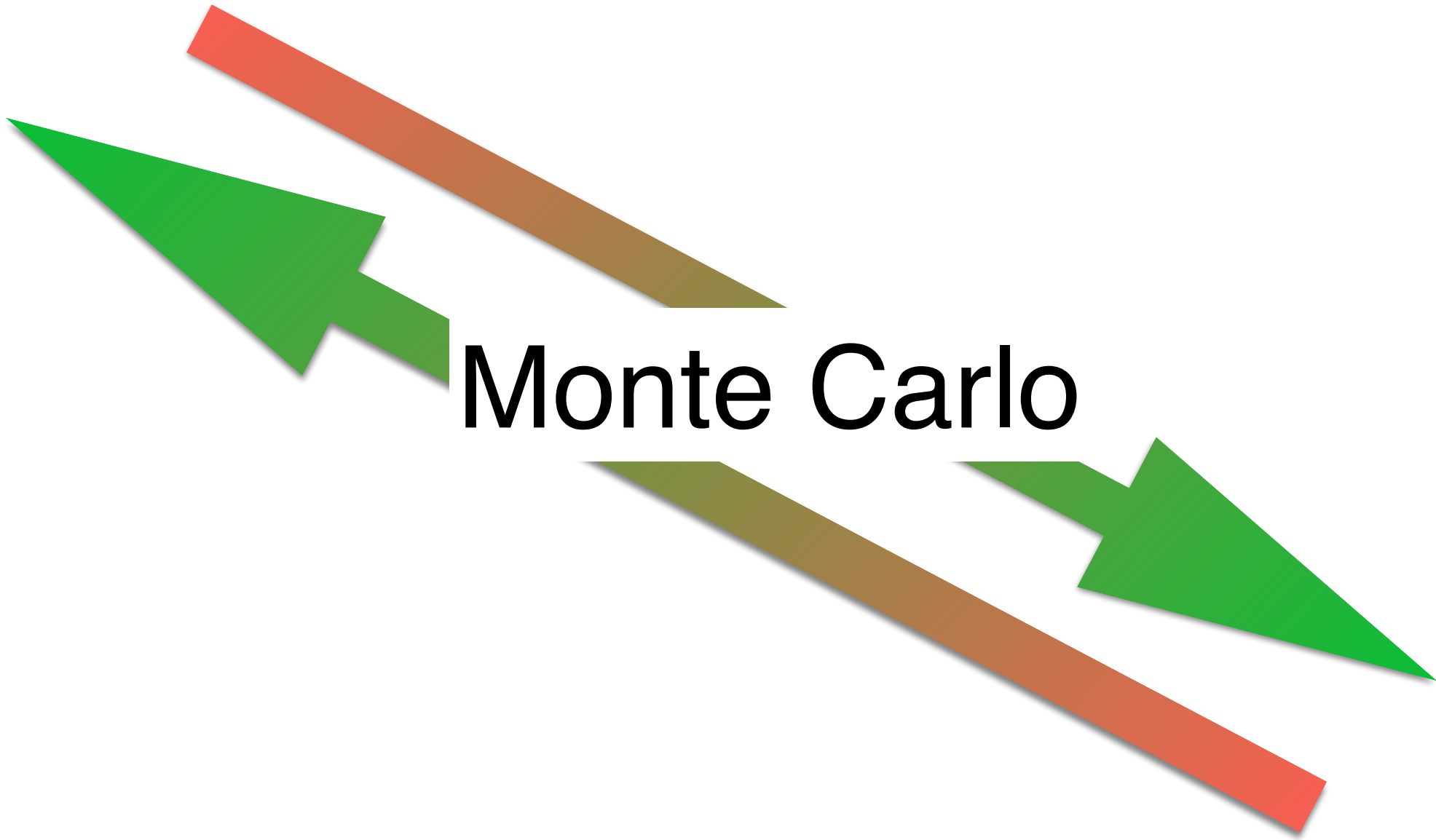
“All orders” result should be μ independent



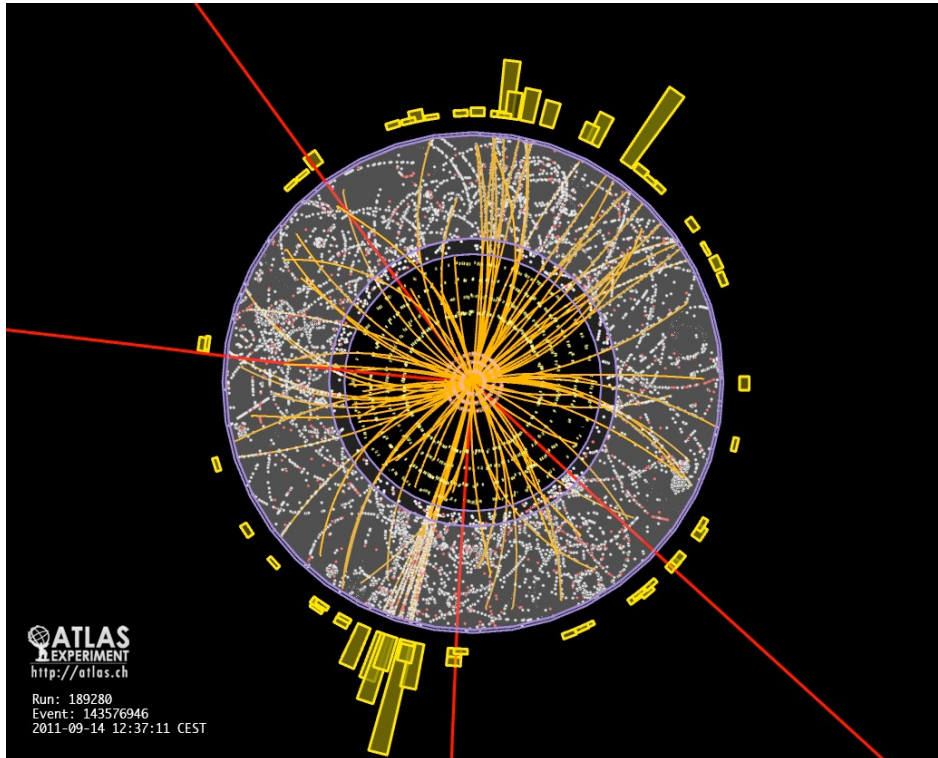
How do we actually compute all of these?



Theory



Experiment



Focusing on LO

Example: 3 jet production in pp collisions

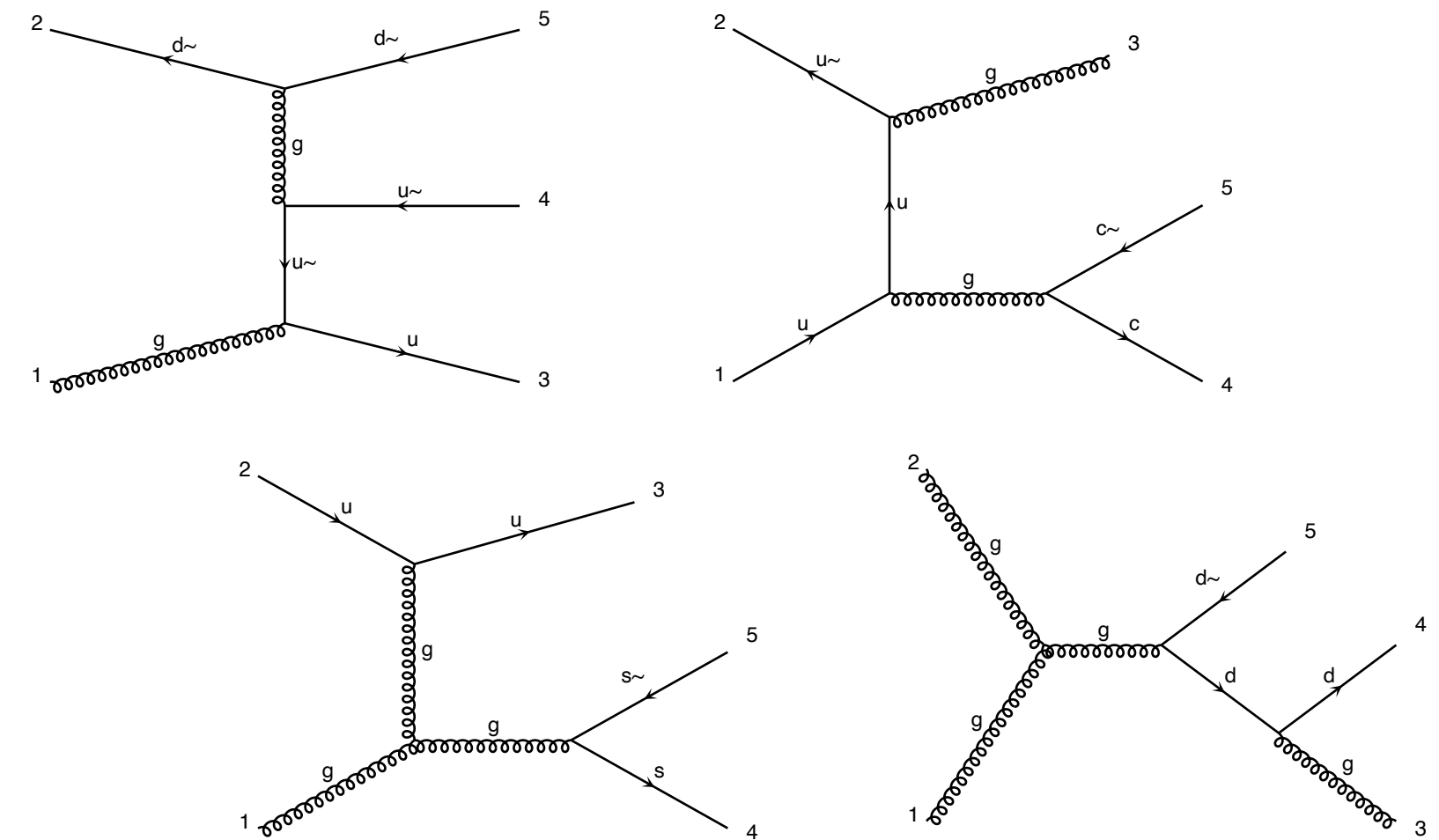
1. Know the Feynman rules (SM or BSM)
2. Find all possible Subprocesses

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

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



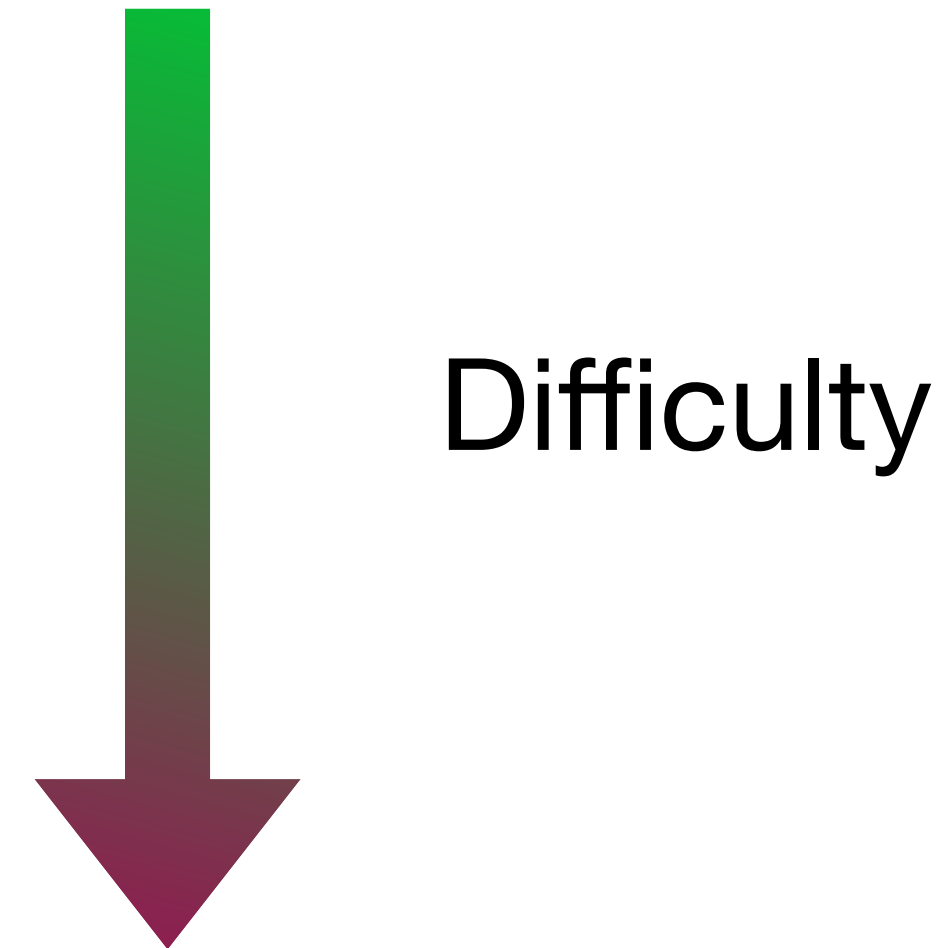
LO calculation of a cross-section

How many subprocesses?

Amplitude computation (Feynman diagrams)

Square the amplitude, sum over spin and colour

Integrate over the phase space



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)

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

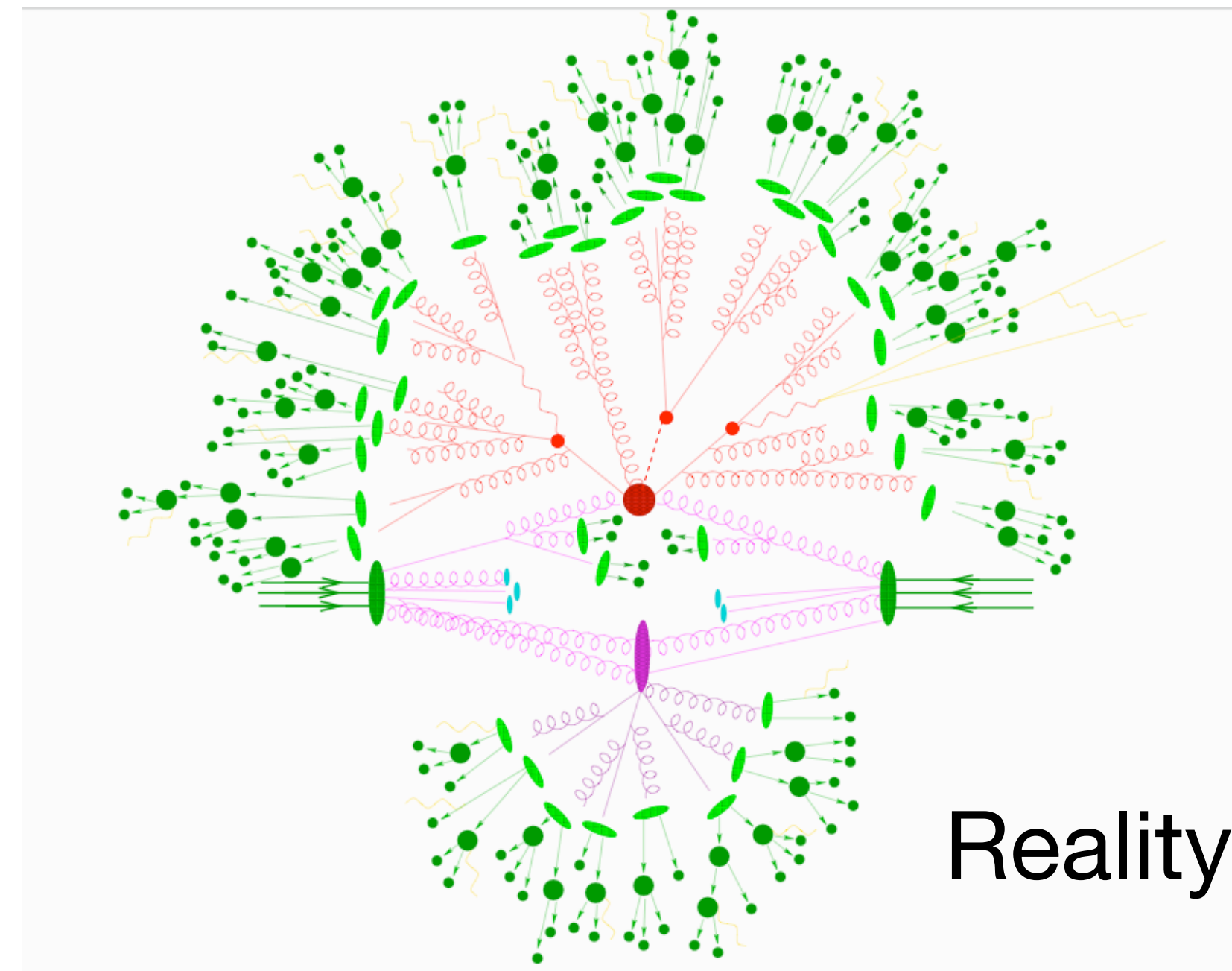
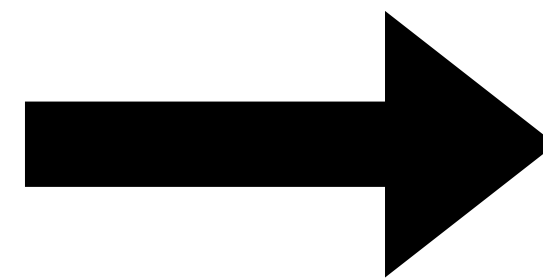
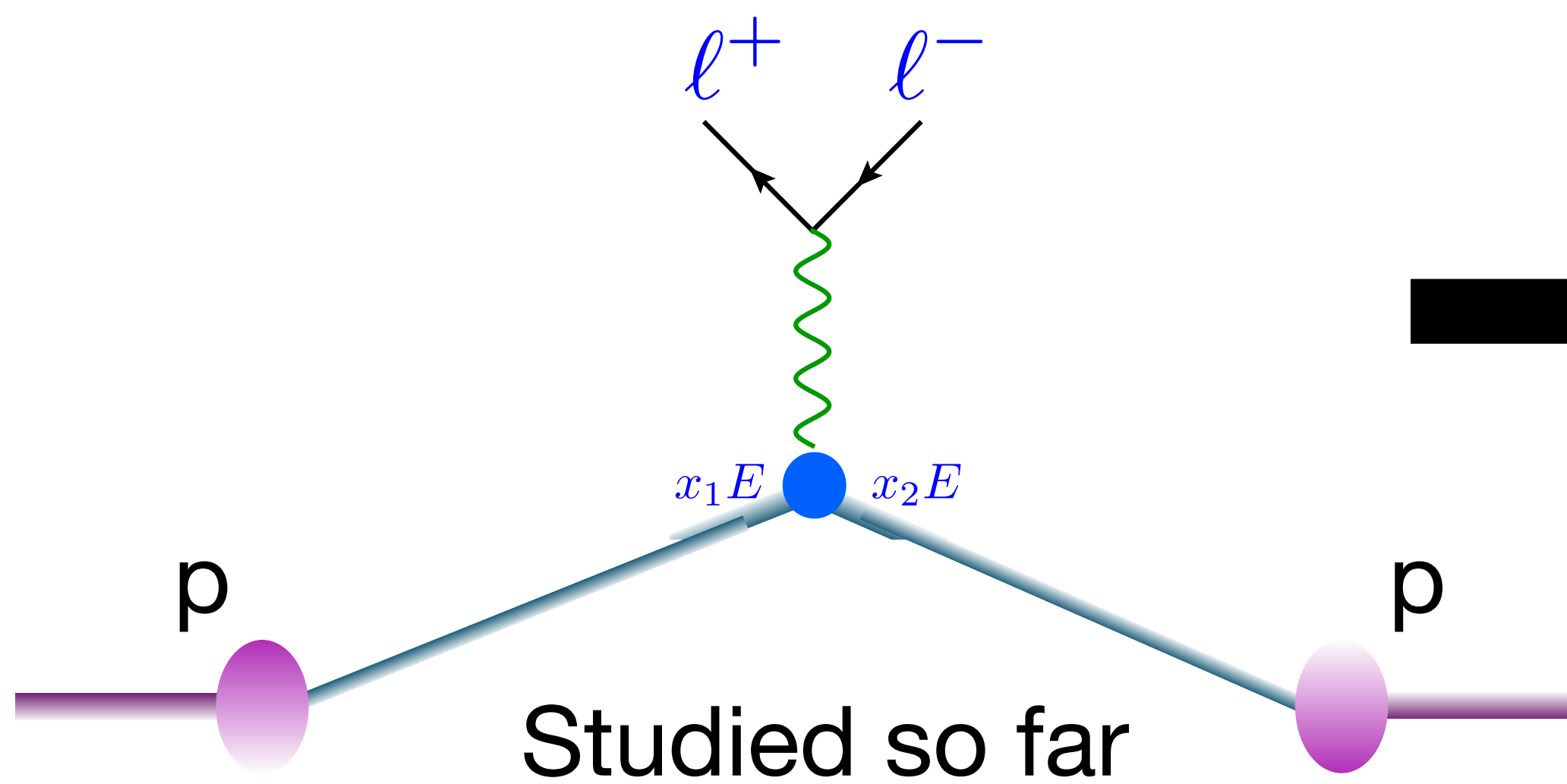
Available public MC generators

Matrix element generators (and integrators):

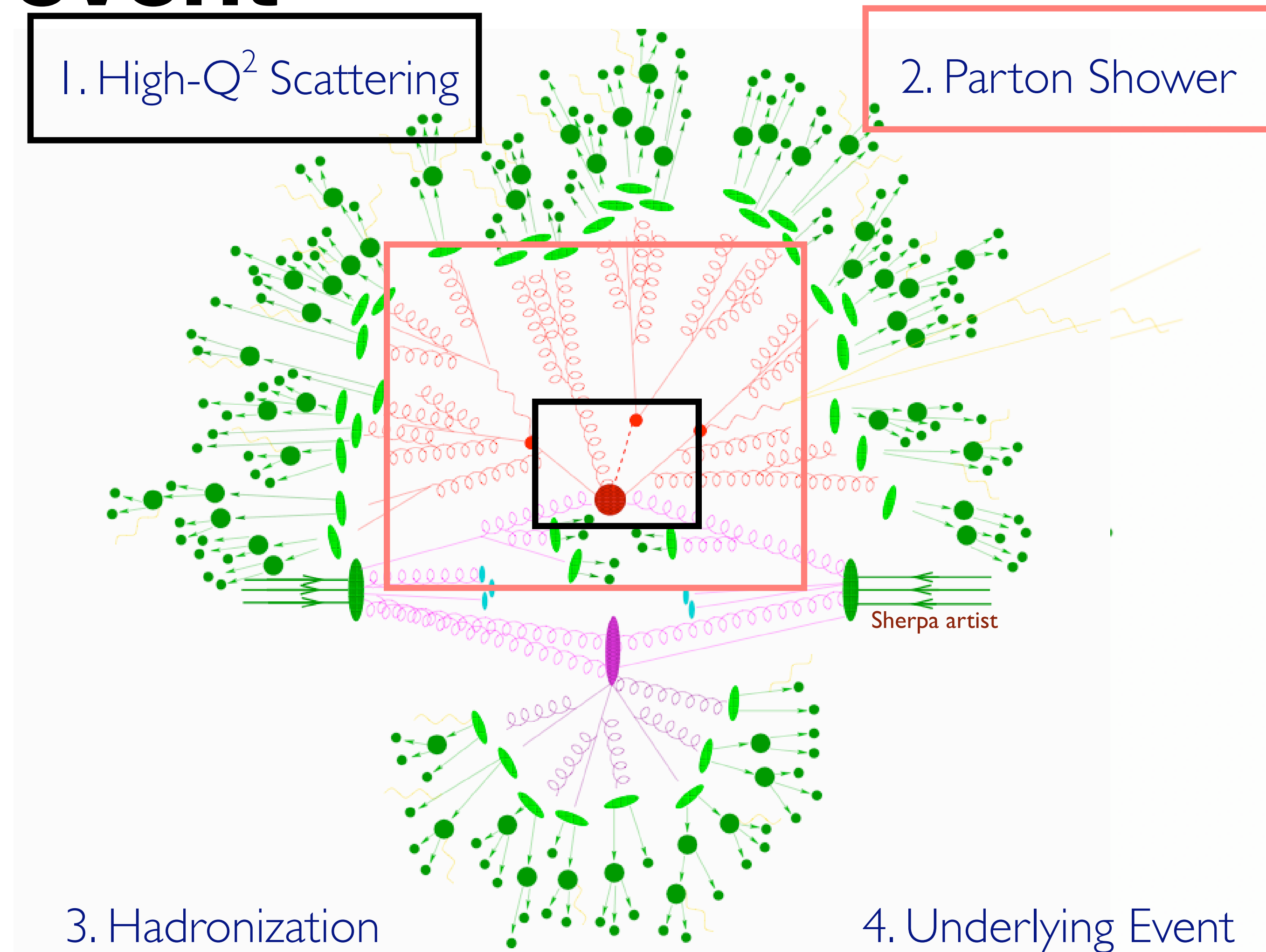
- MadGraph/MadEvent
- Comix/AMEGIC (part of Sherpa)
- HELAC/PHEGAS
- Whizard
- CalcHEP/CompHEP

Is Fixed Order enough?

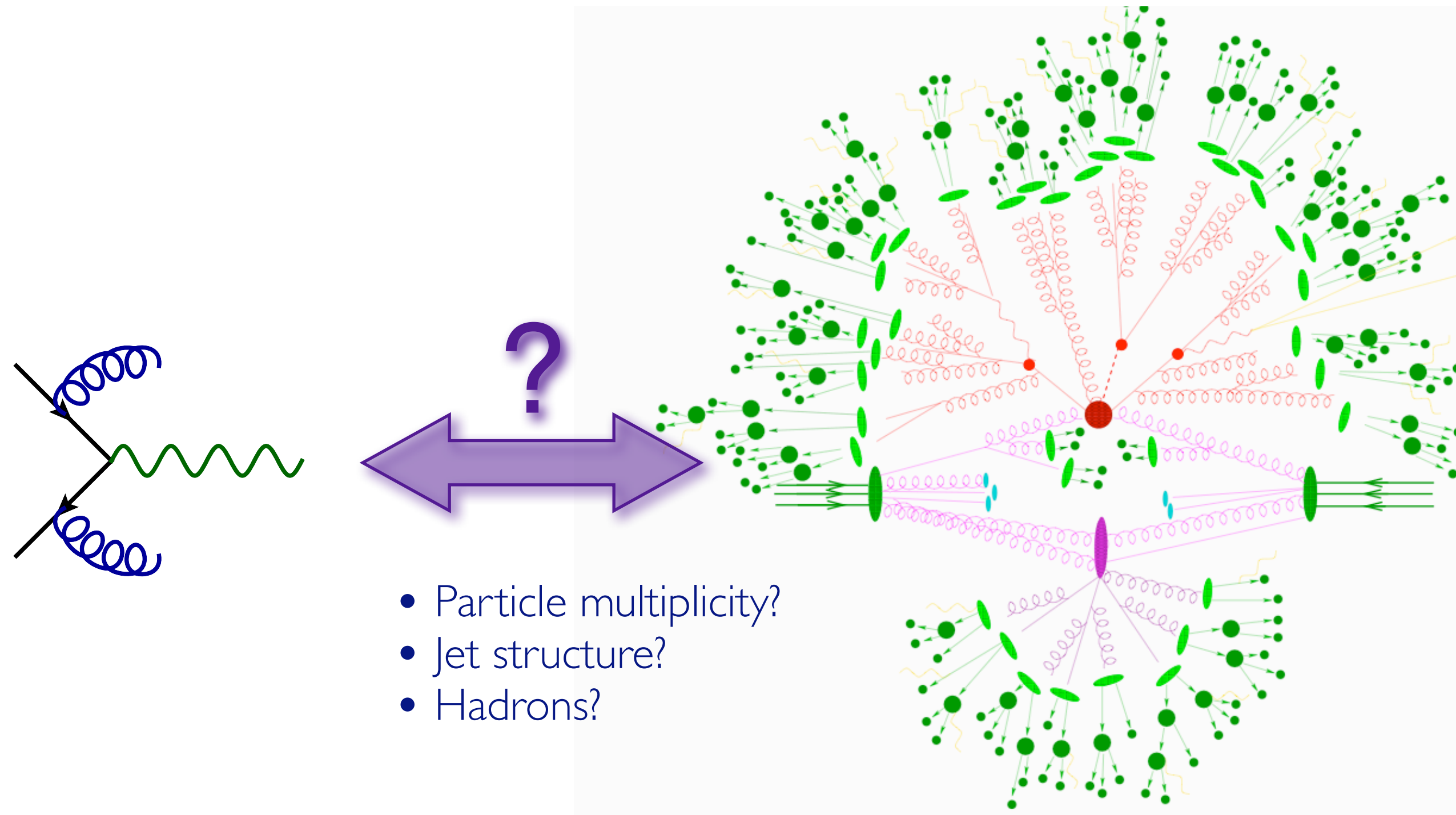
Fixed order computations can't give us the full picture of what we see at the LHC



An LHC event



Is fixed order enough?



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

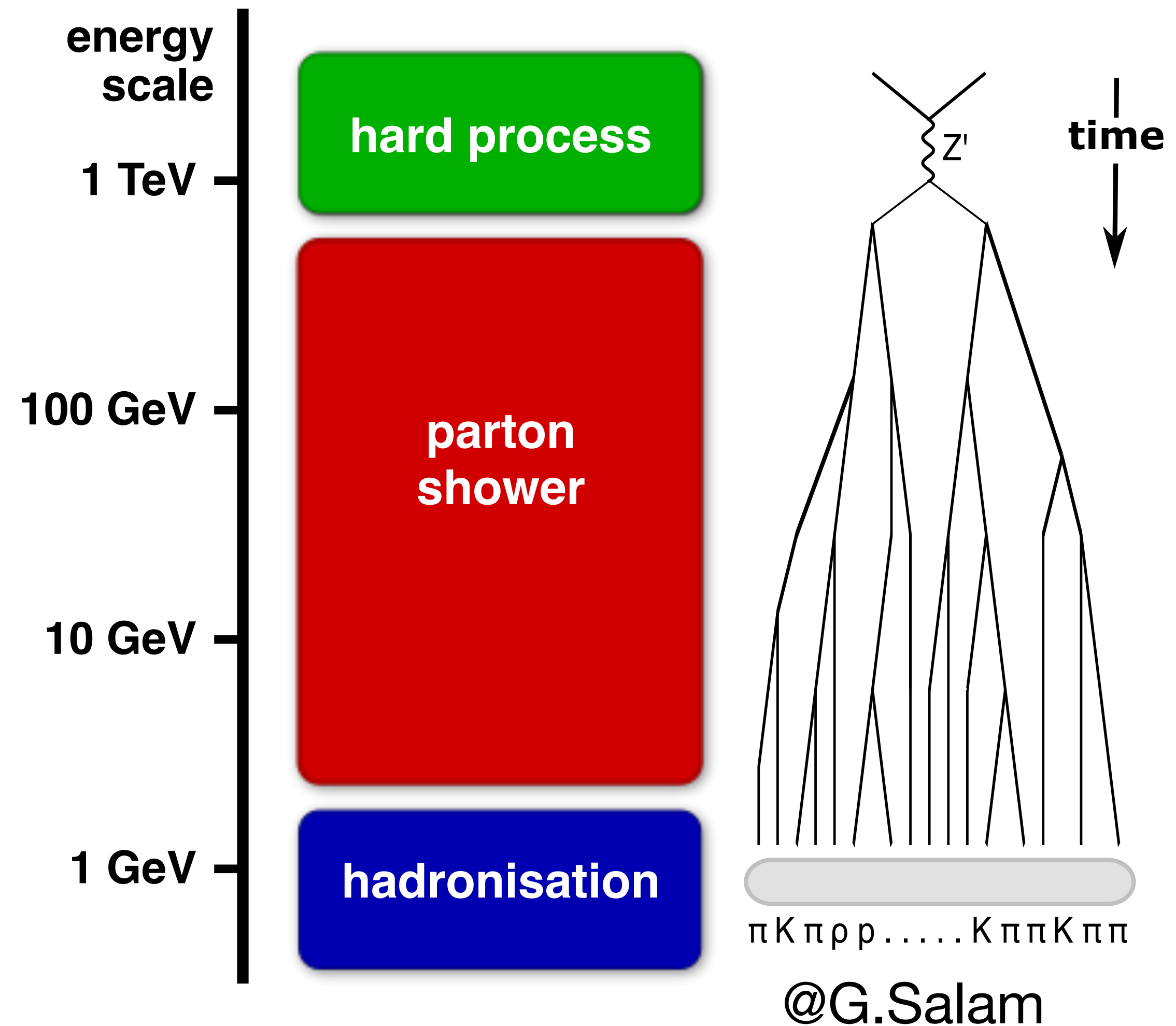
A multiscale story

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

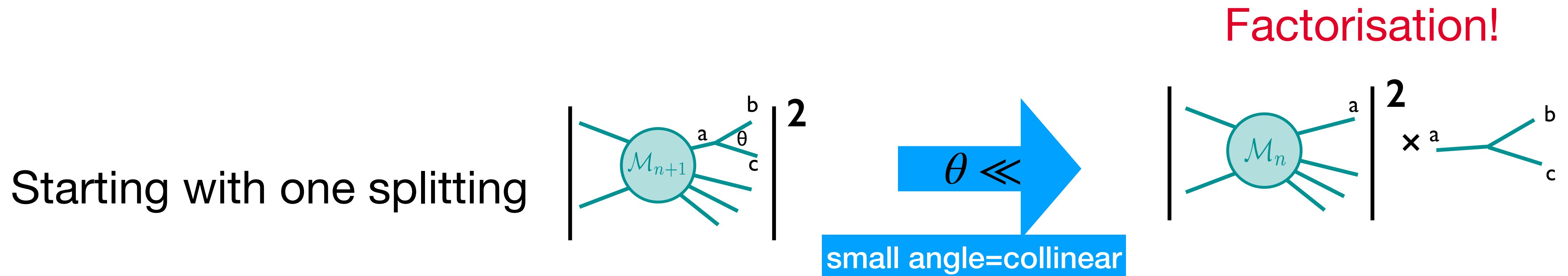
Underlying event: low Q^2 , involves multiple interactions



Parton Shower

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

Basics of parton shower

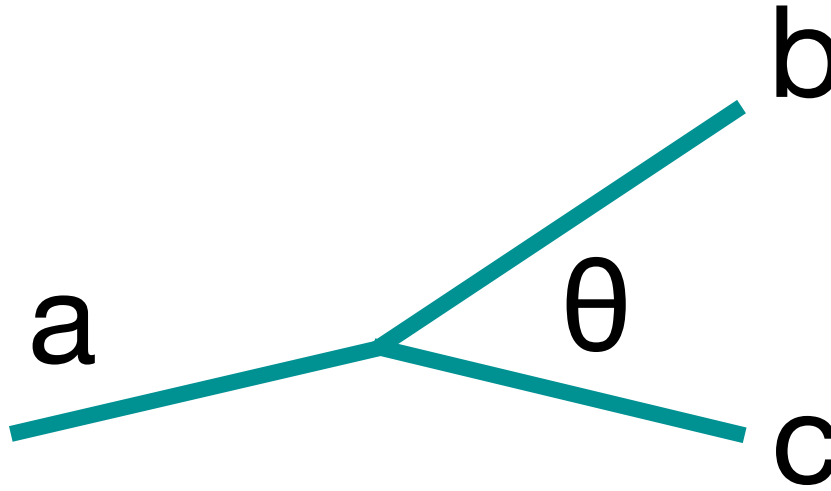


- Time scale associated with splitting much longer than the one of the hard scattering
- This kind of splitting should be described by a branching probability
- The parton shower will quantify the probability of emission

Collinear factorisation:

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

Collinear factorisation and splitting functions

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


- 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 ($z \rightarrow 1$ in the soft limit)
- ϕ azimuthal angle

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

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

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

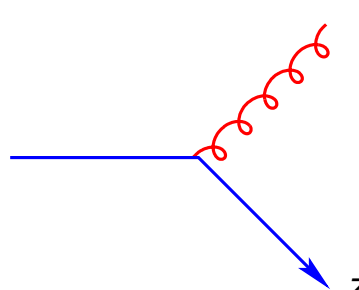
$$t \in \{\theta^2, k_{\perp}^2, Q^2\}$$

Altarelli-Parisi Splitting functions

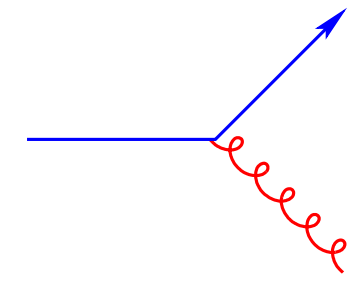
Branching has a universal form given by the Altarelli-Parisi splitting functions (as we saw in DIS)

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

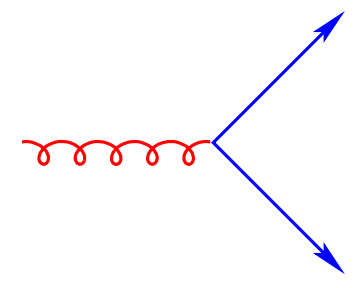
➔



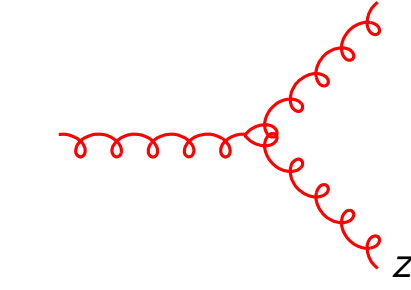
$$P_{q \rightarrow qg}(z) = C_F \left[\frac{1+z^2}{1-z} \right],$$



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



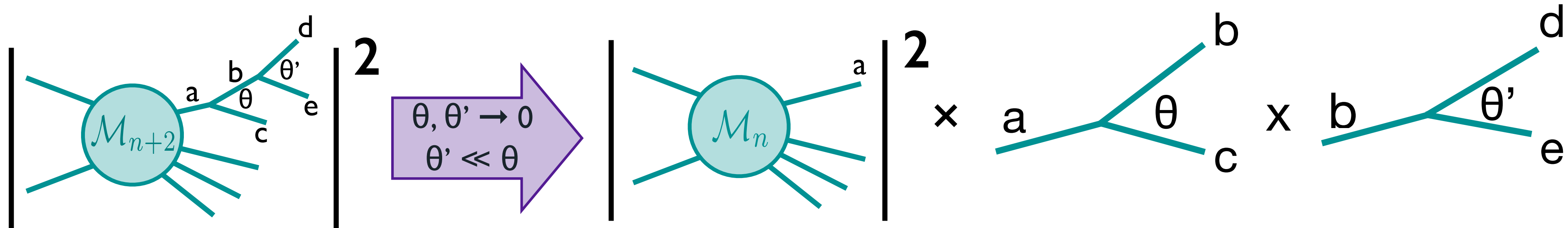
$$P_{g \rightarrow qq}(z) = T_R [z^2 + (1-z)^2],$$



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

These functions are universal for each type of splitting

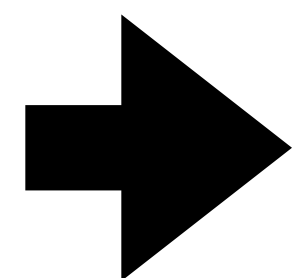
Multiple emissions



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

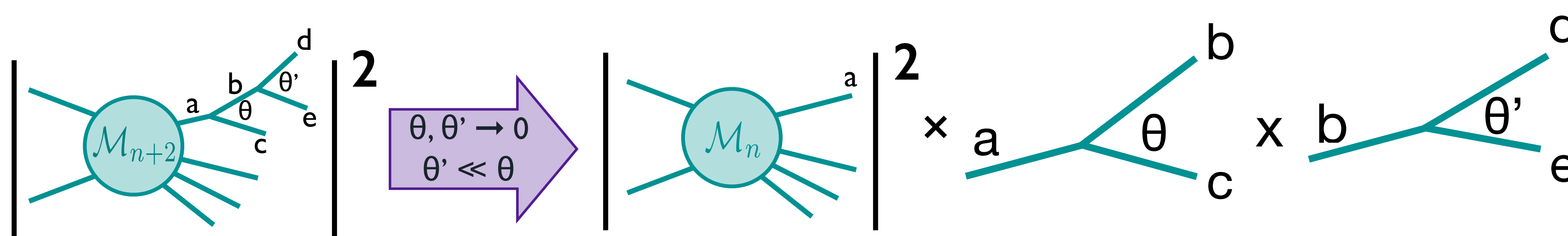
We can generalise this for an arbitrary number of emissions

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:

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

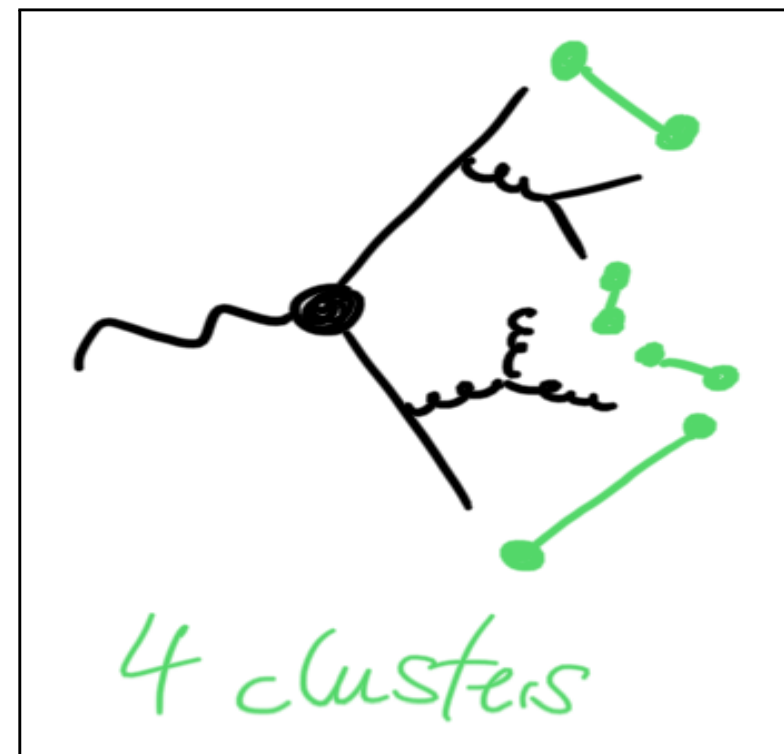
- Q is the hard scale and Q_0 is an infrared cut off (separating non-perturbative regime)
- Each power of α_s comes with a logarithm (breakdown of perturbation theory when large)

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: sums logs to all orders
 - Bridge between fixed order and hadronisation
- Parton shower is **unitary**
 - Sum over all possible branching histories = 1
 - Preserve hard scattering cross section

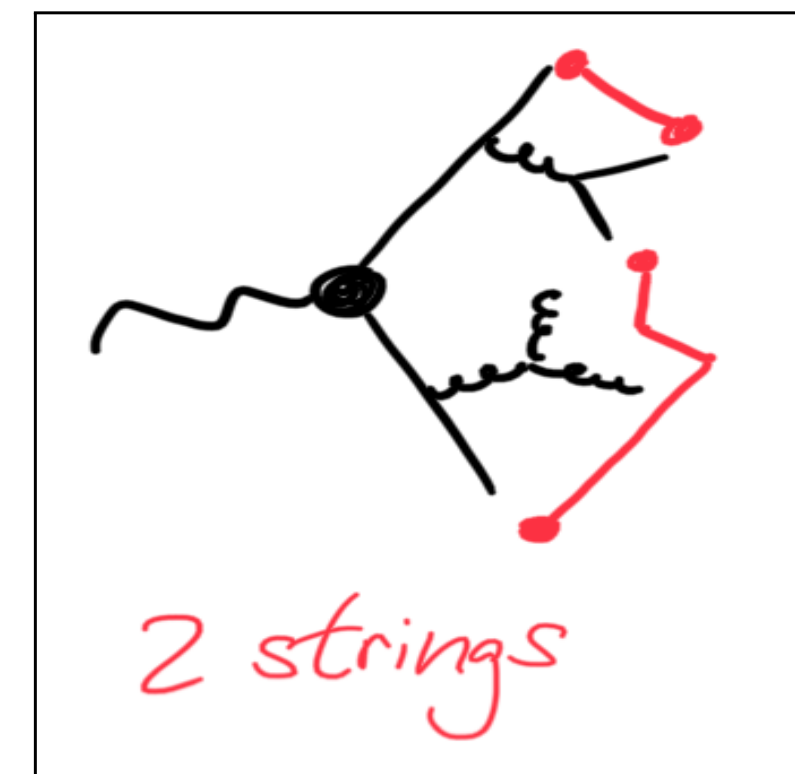
Hadronisation

- 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

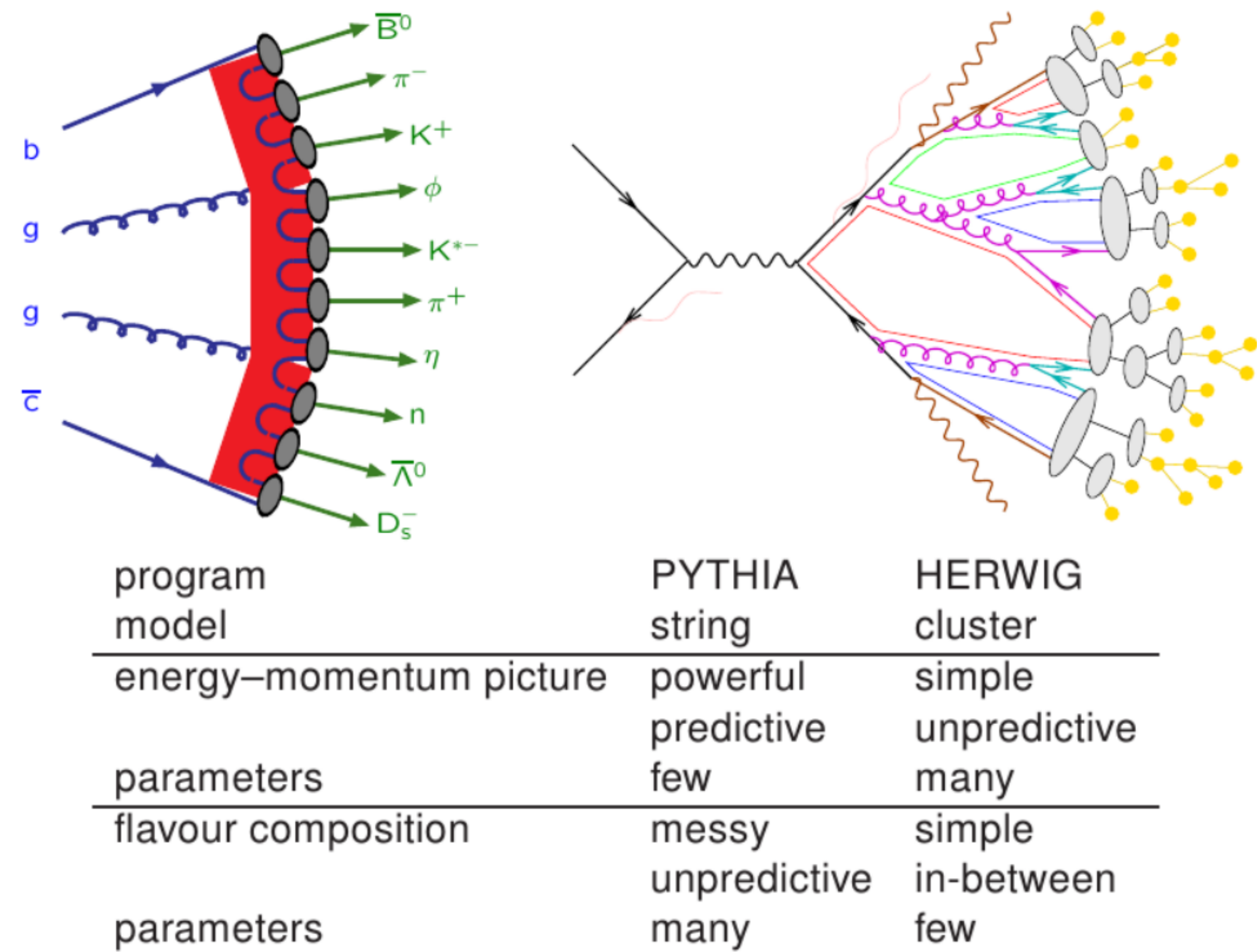


Create strings from color string, with gluons “stretching the string” locally. It uses non-perturbative insights

String hadronisation

Hadronisation

Sjöstrand, Durham '09



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 provides 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

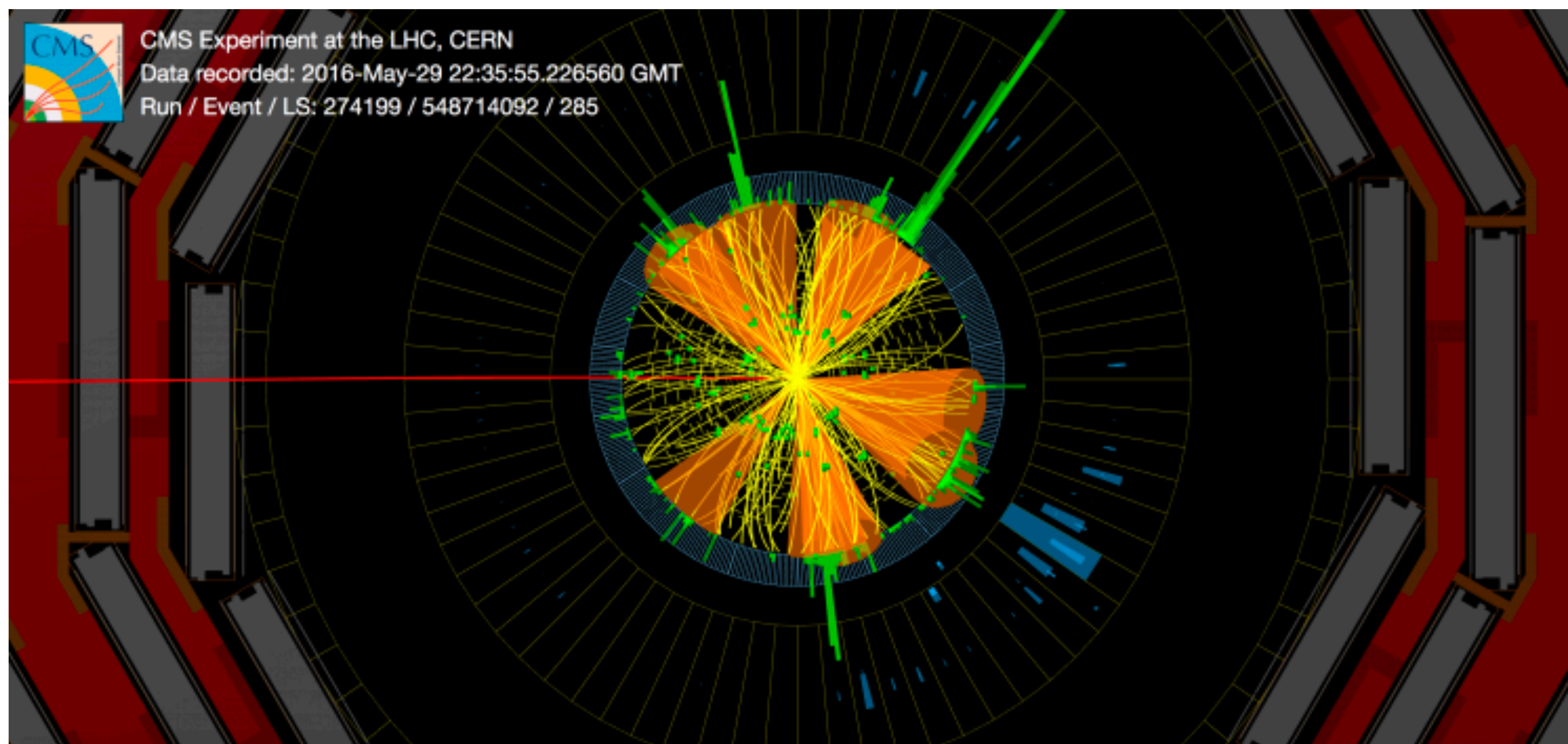
Parton shower programs



Current release series	Hard matrix elements	Shower algorithms	MPI	Hadronization
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

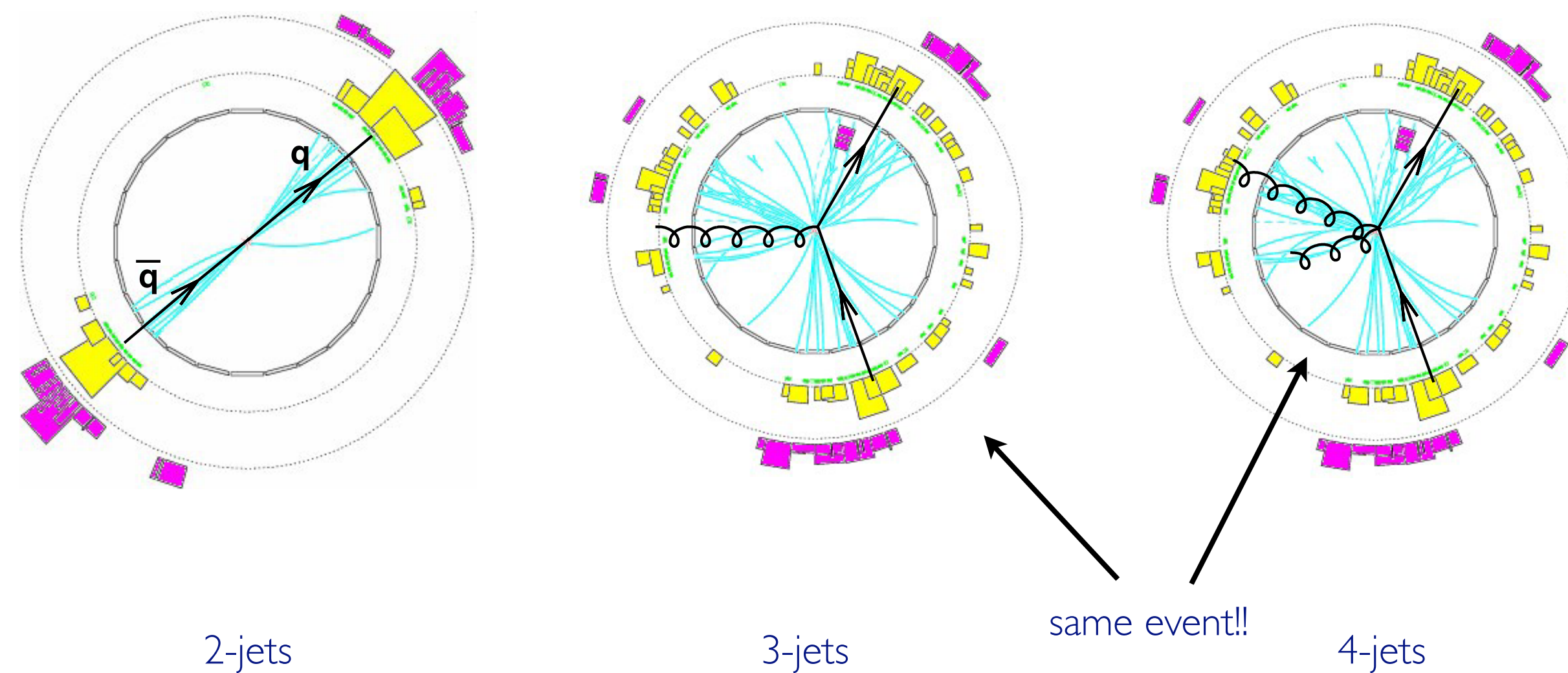
Herwig and Pythia use LHE files e.g. produced in MG5_aMC

What do we see in the detectors?



Collimated sprays of particles: Jets!

Jets

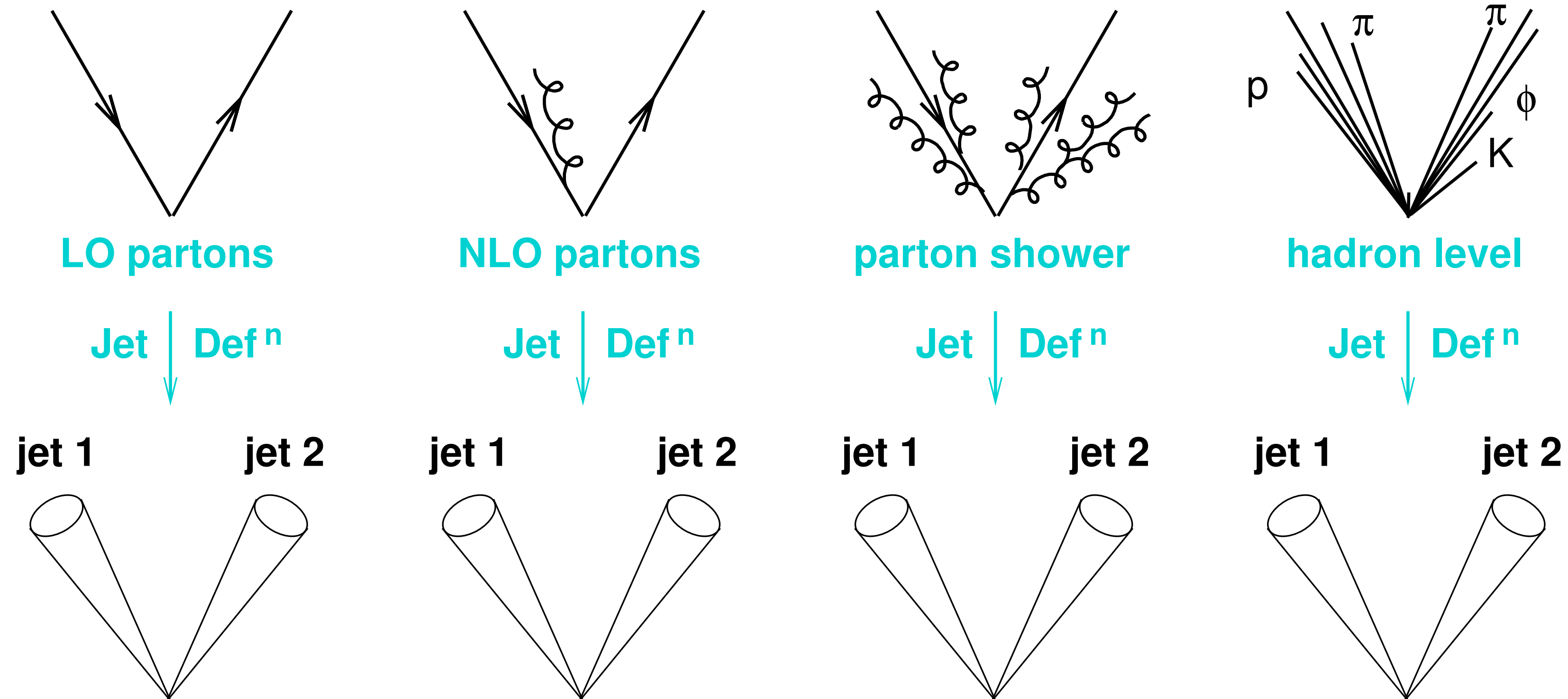


How do we decide?

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

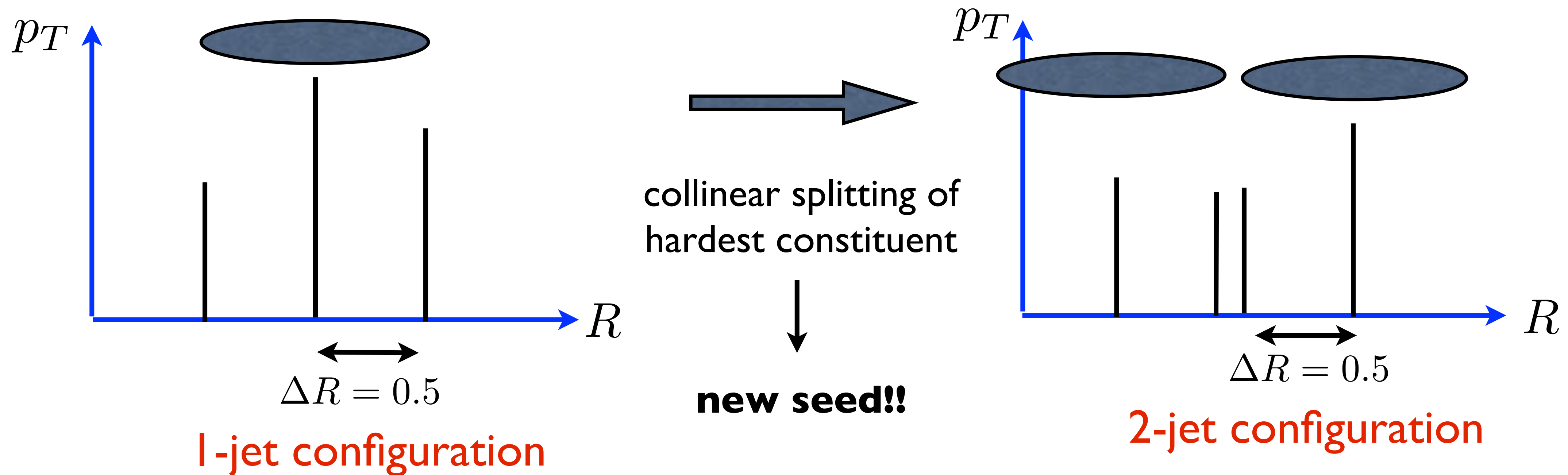
- Bottom-up: combine particles starting from closest ones
- How? Choose a distance measure, iterate recombination until few objects left, call them jets
- Usually trivially made IRC safe, but algorithmically complex
- Examples: Jade, k_t , Cambridge/Aachen, anti- k_t ...

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

Start with a collection of “particles” defined by their 4-momenta

Distance
measure

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

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

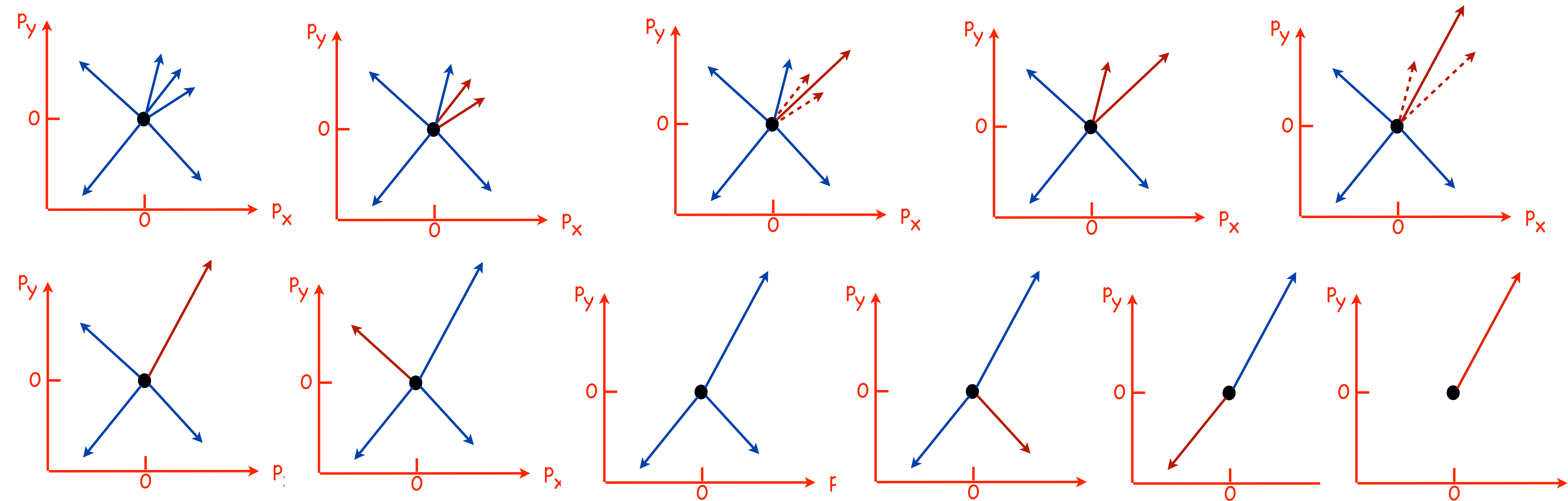
Steps:

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 1. 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

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

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

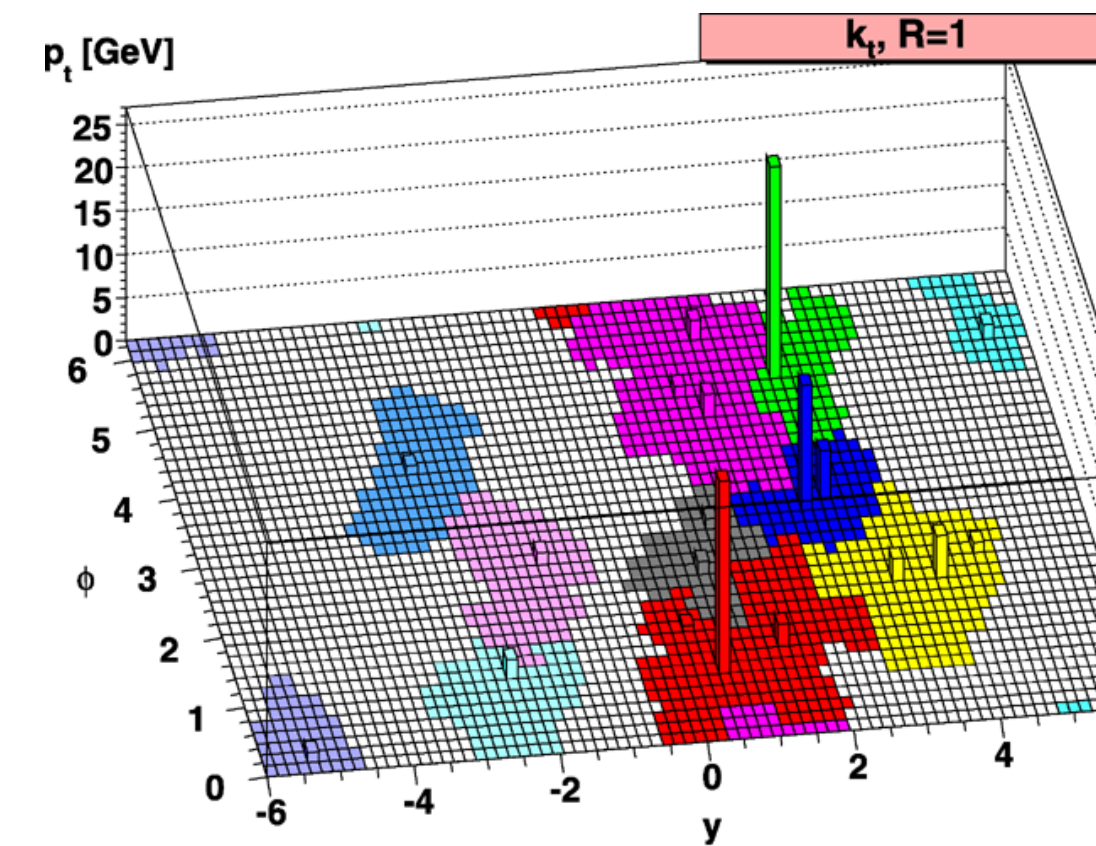
Anti-KT algorithm

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

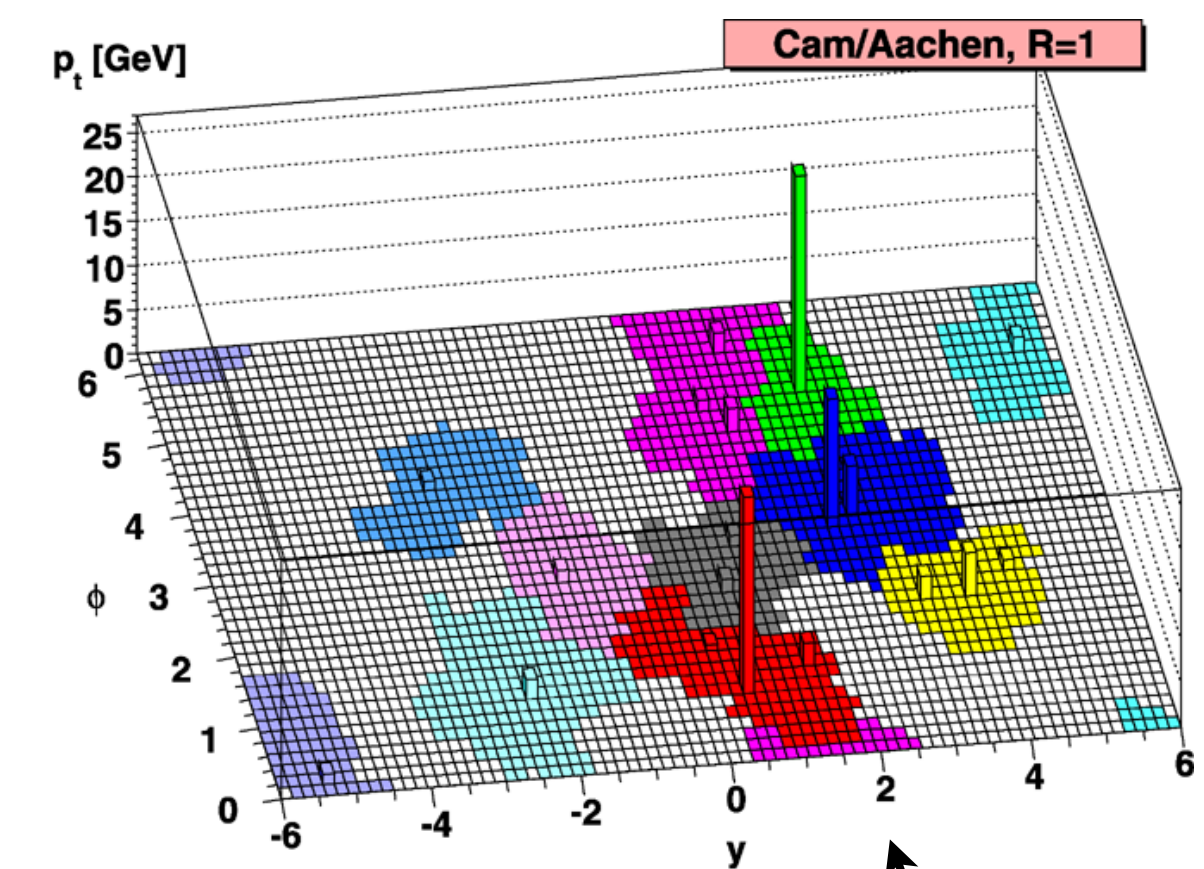
$$d_{iB} = \frac{1}{p_{ti}^2}$$

Cambridge/Aachen

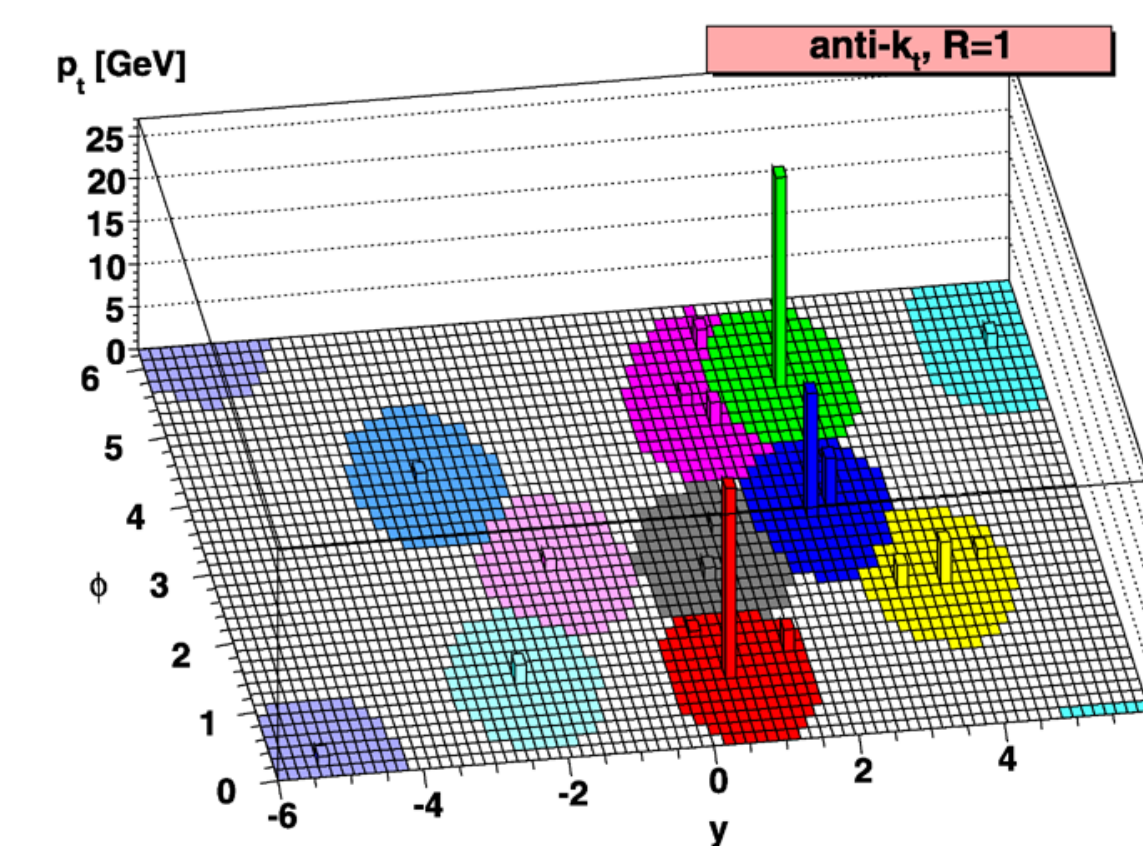
$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = 1$$



soft jet
more
circular



shape independent
of jet pT



hard jet
more
circular

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

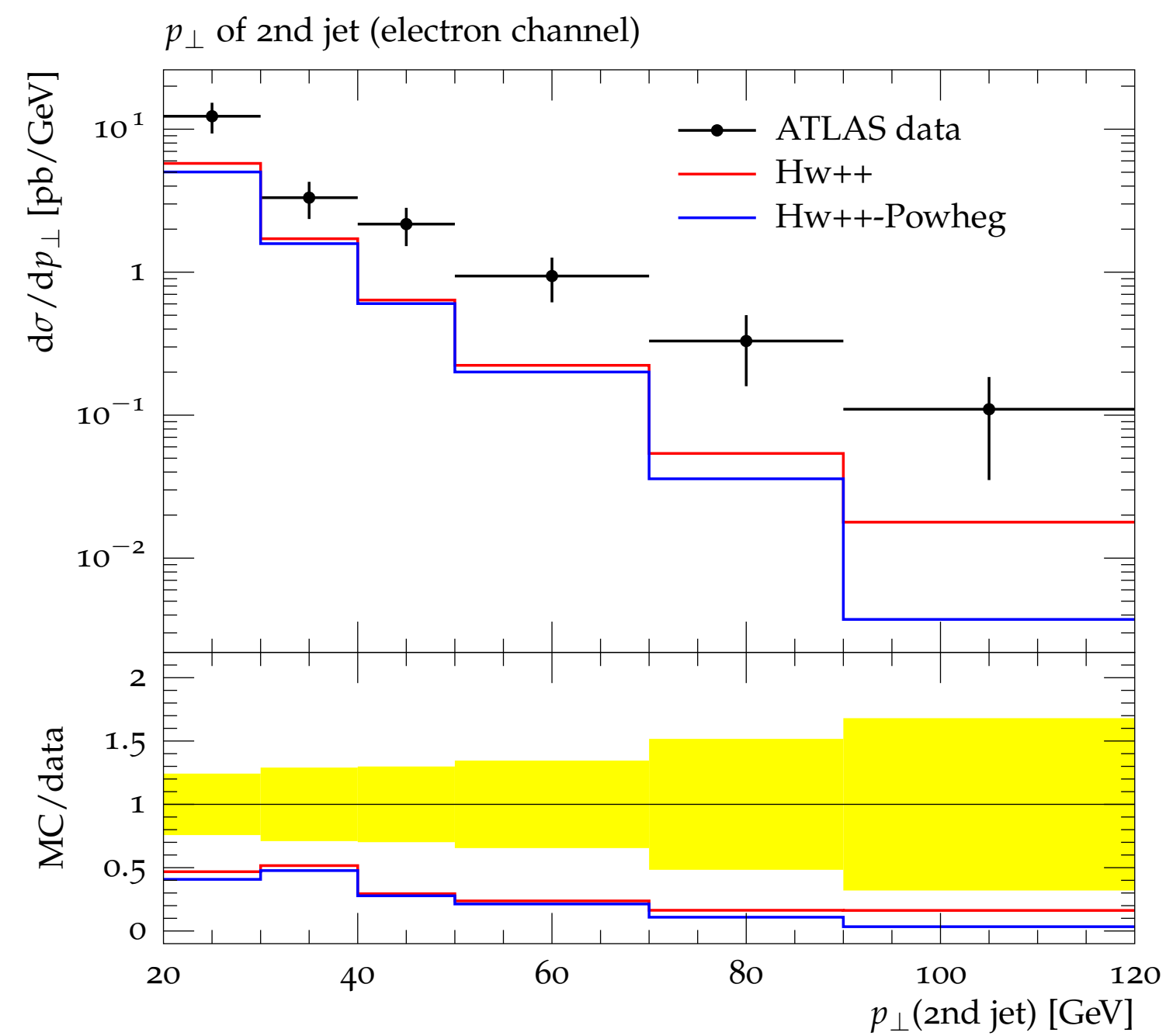
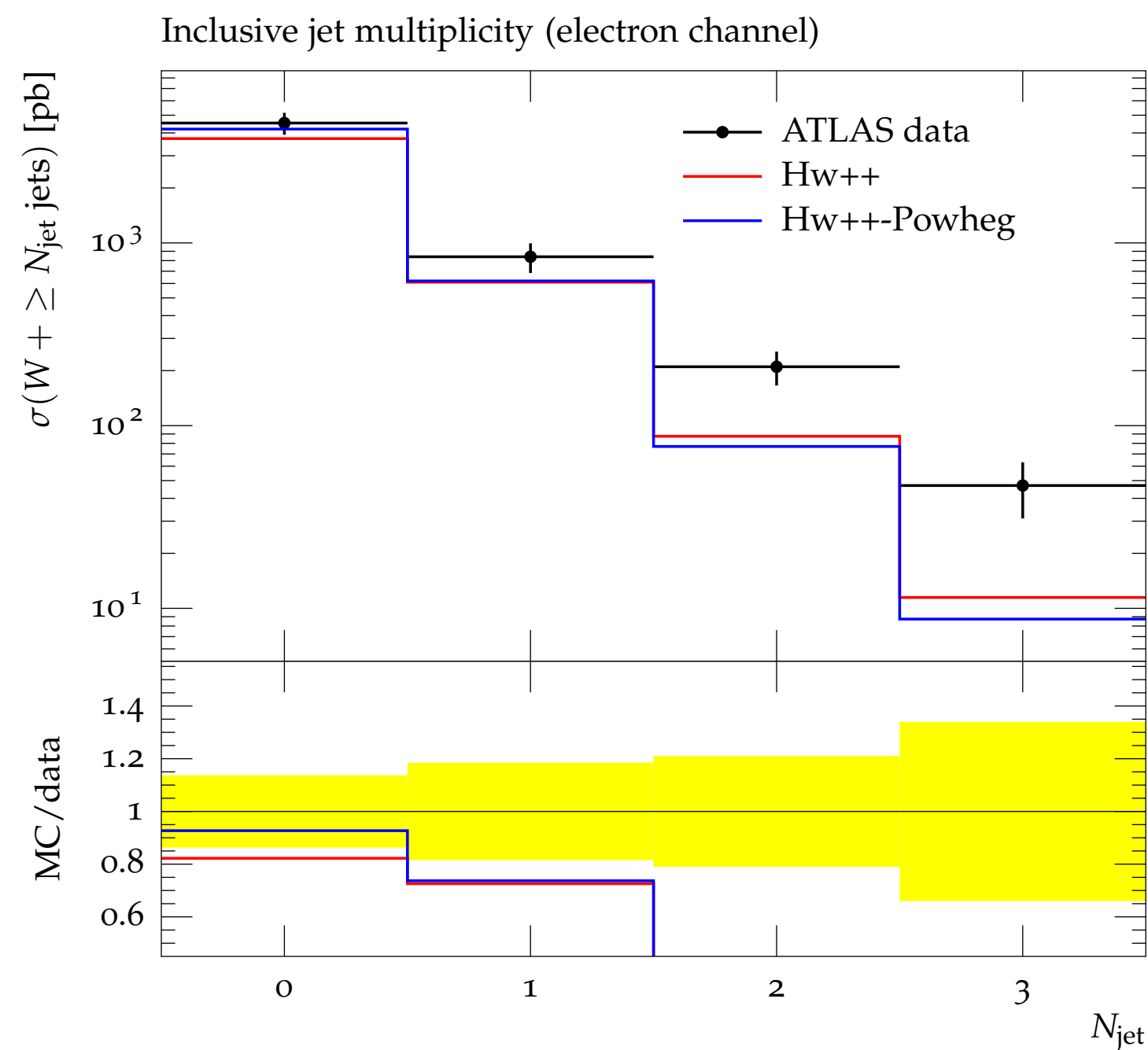
For hard radiation we need input from the matrix element

Two directions of improving parton shower Monte Carlo

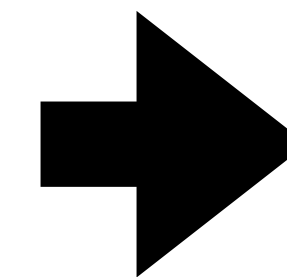
- **ME+PS merging**: include higher multiplicity (but leading order) matrix elements
- **NLO+PS matching**: include NLO corrections to the matrix elements to reduce theoretical uncertainties and then match to the parton shower

Parton shower results

$W + \text{jets}$, LHC 7 TeV.

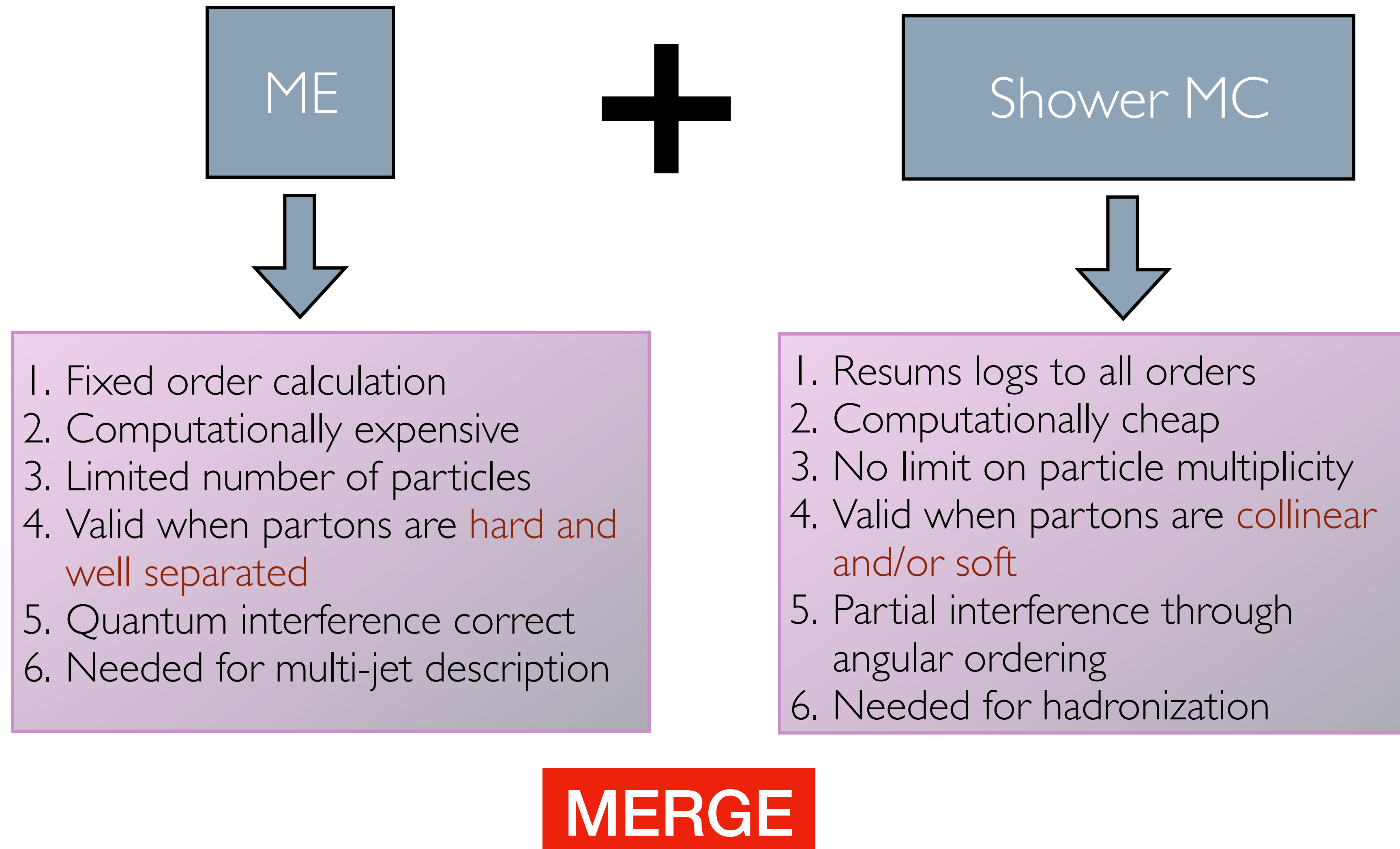


Parton shower can't describe high multiplicity hard jet events

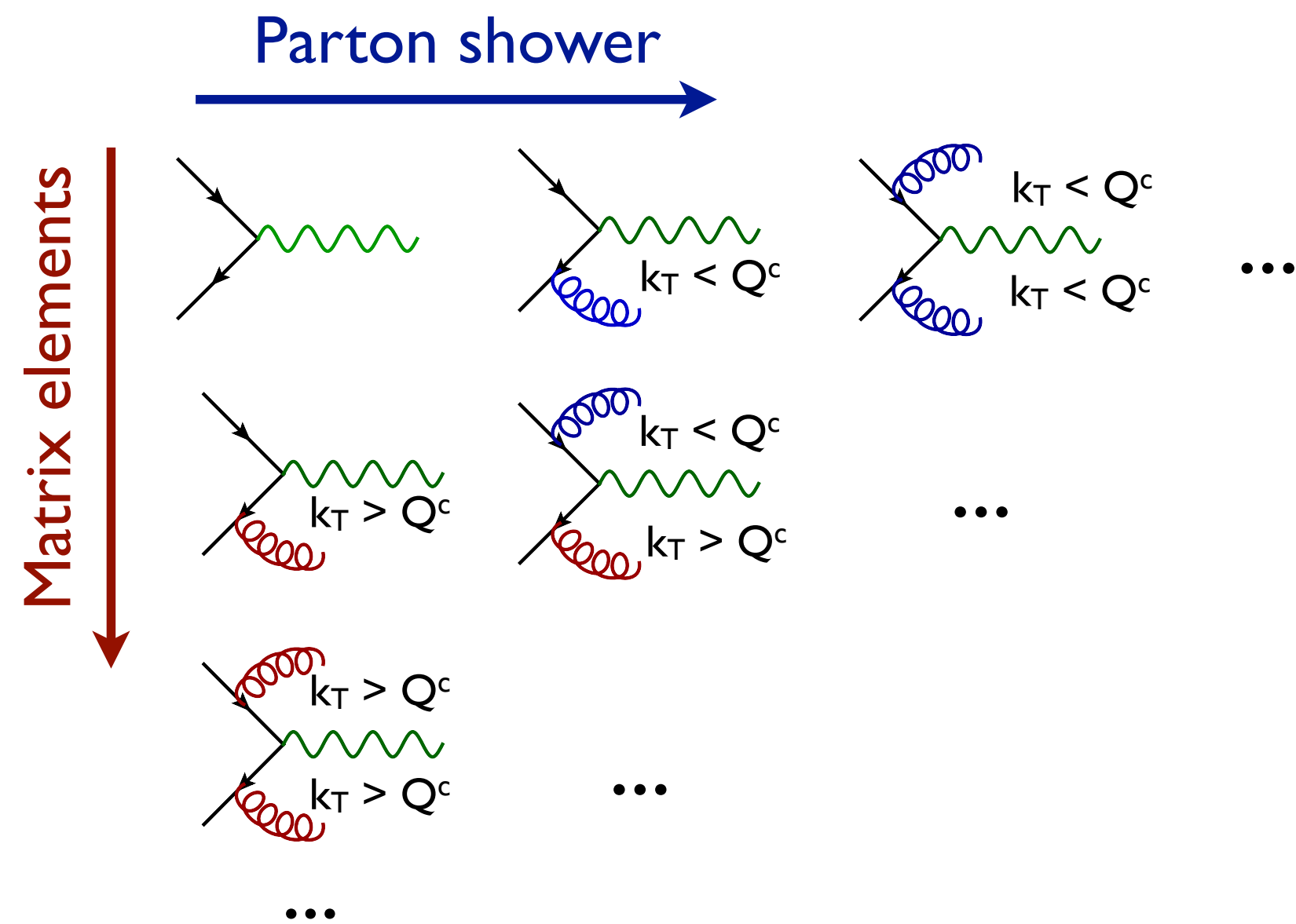


Need input from the matrix element

Towards LO merging

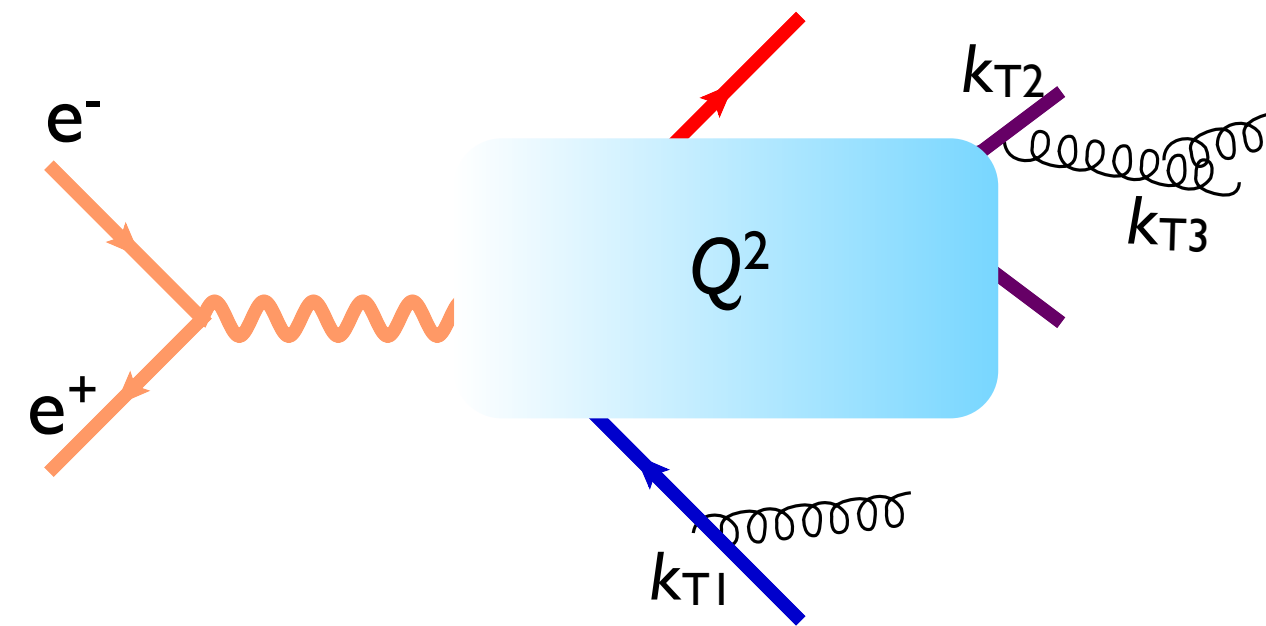


Double counting



- 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

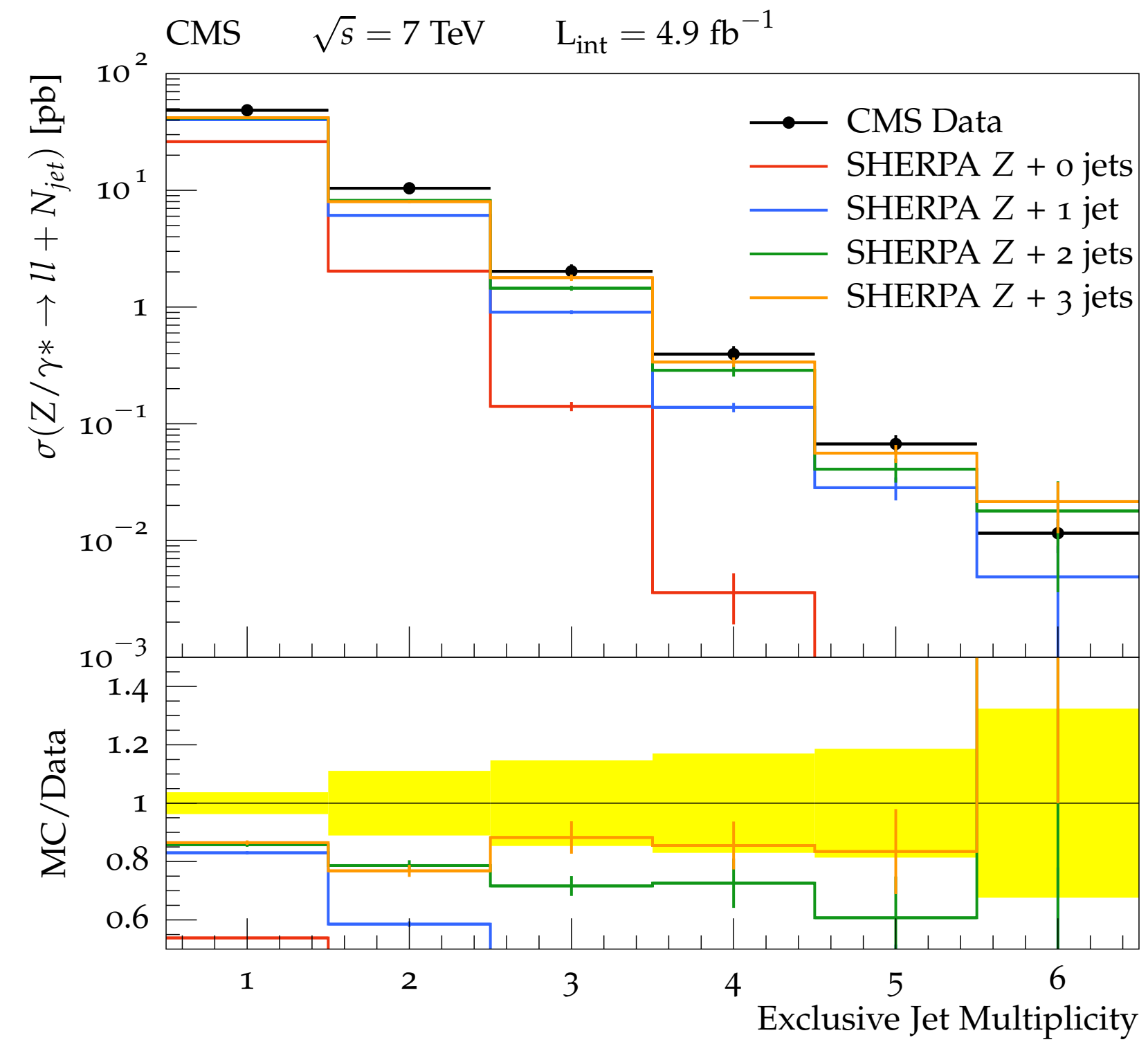
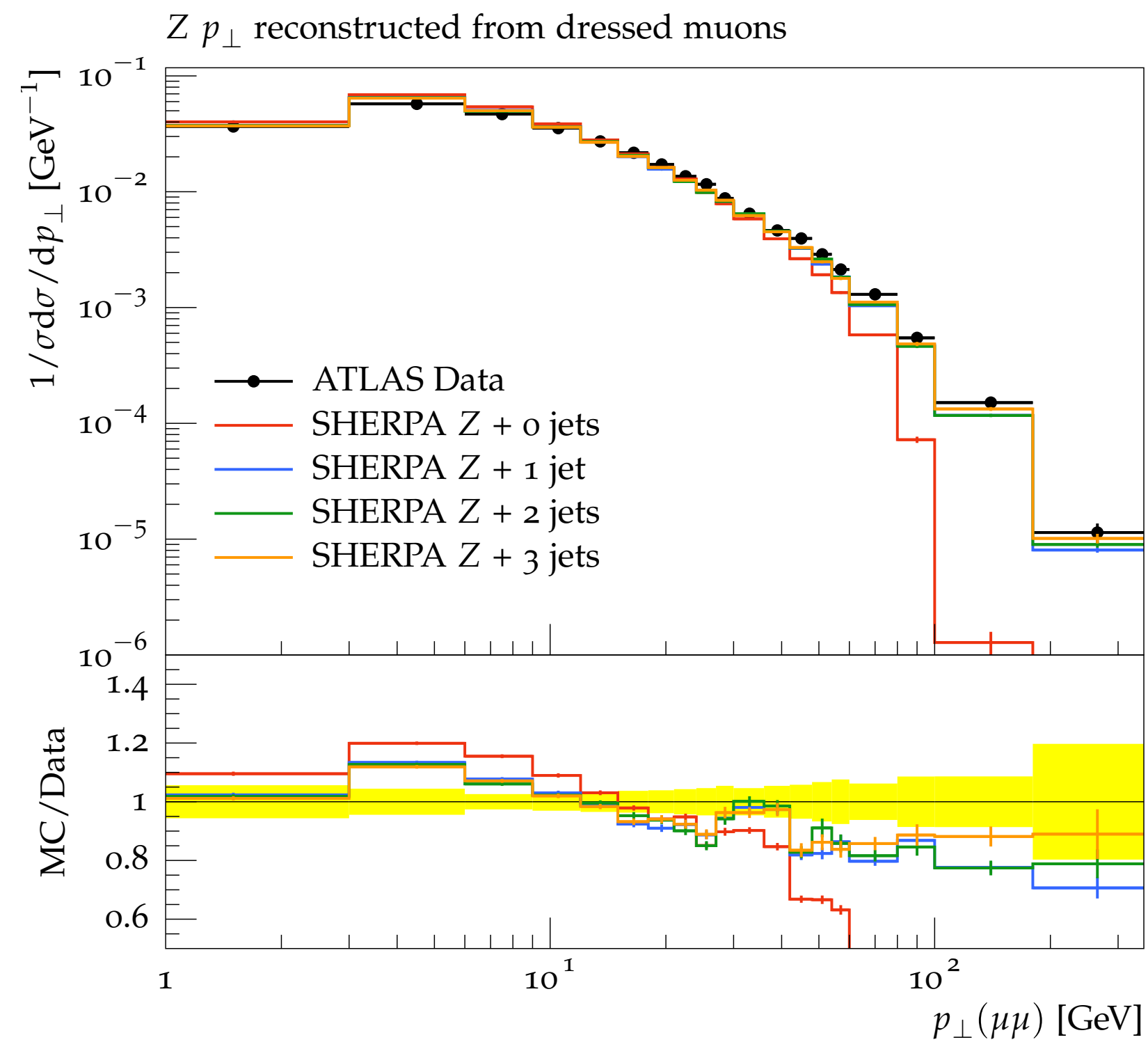
Example: MLM merging



[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

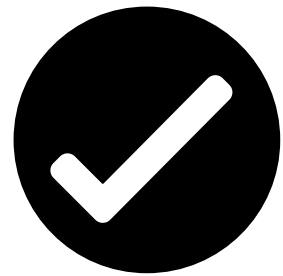
Exp vs Theory



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

Much better agreement with experiment!

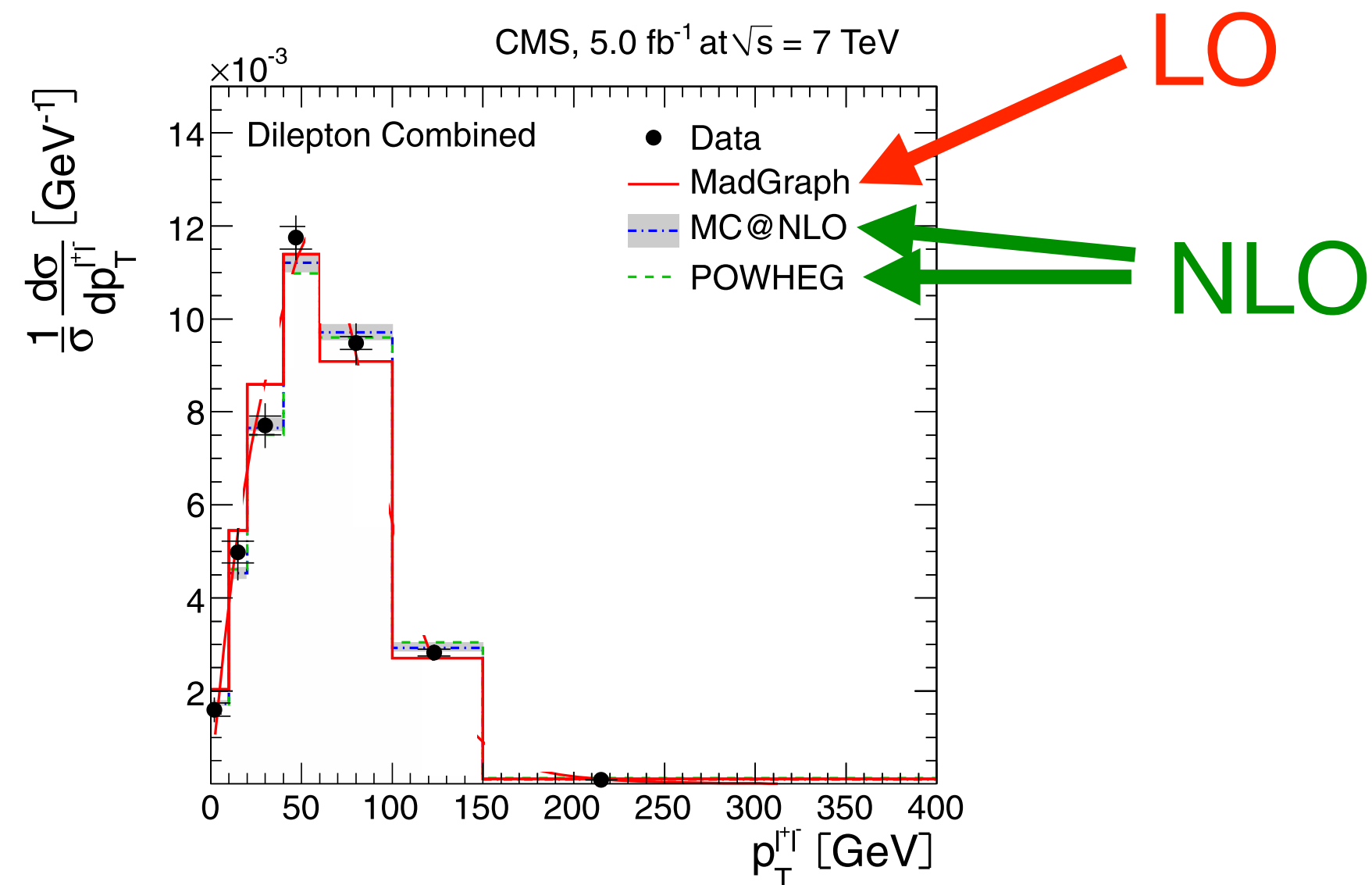
Summary: LO merging

- 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?

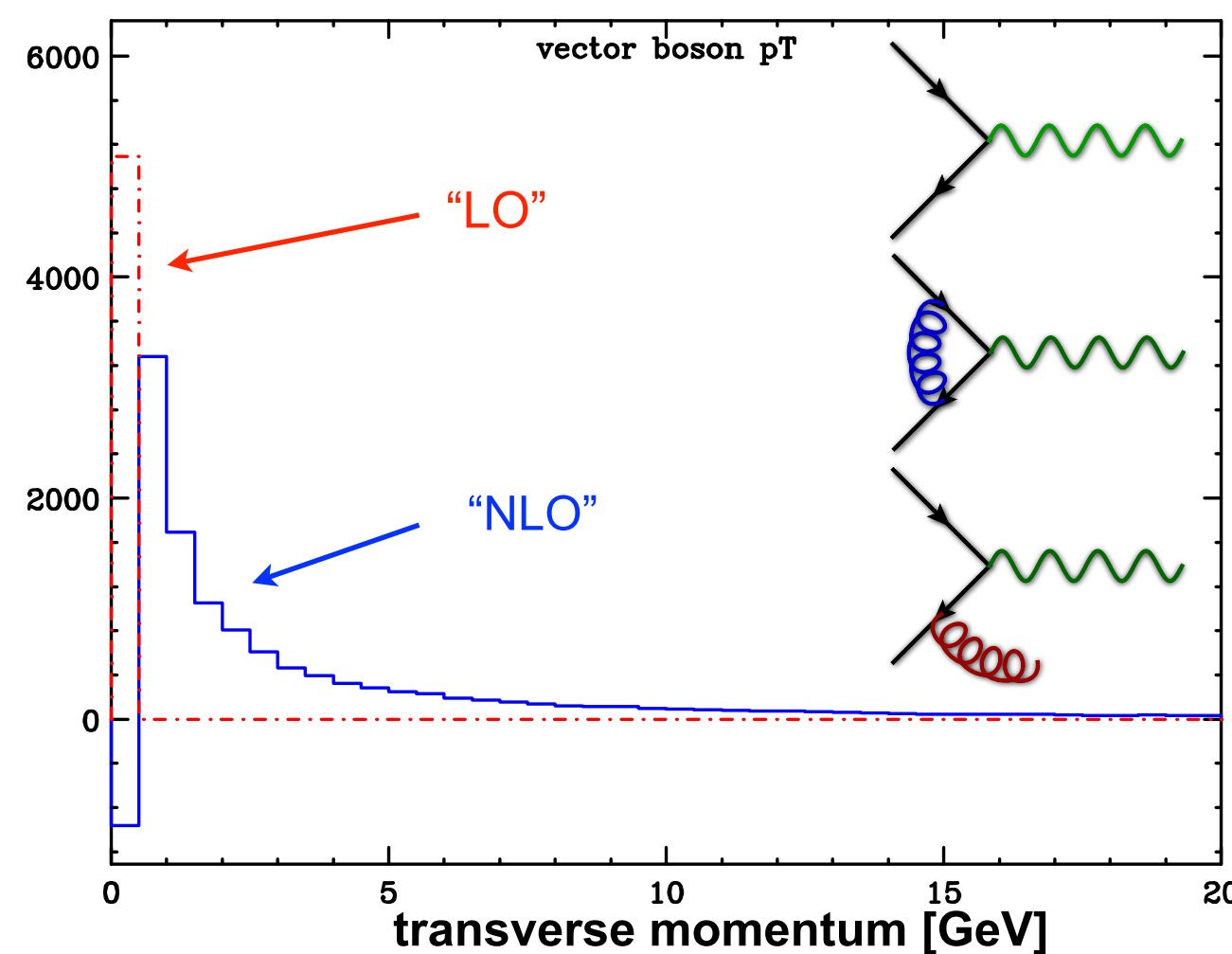
We have seen the importance of higher-order corrections to predict rates and distributions and reduce uncertainties

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

NLO+PS

Two main methods:

MC@NLO: Frixione, Webber 2002

POWHEG: Nason 2004

also

KRKNLO, Vincia, Geneva

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

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"

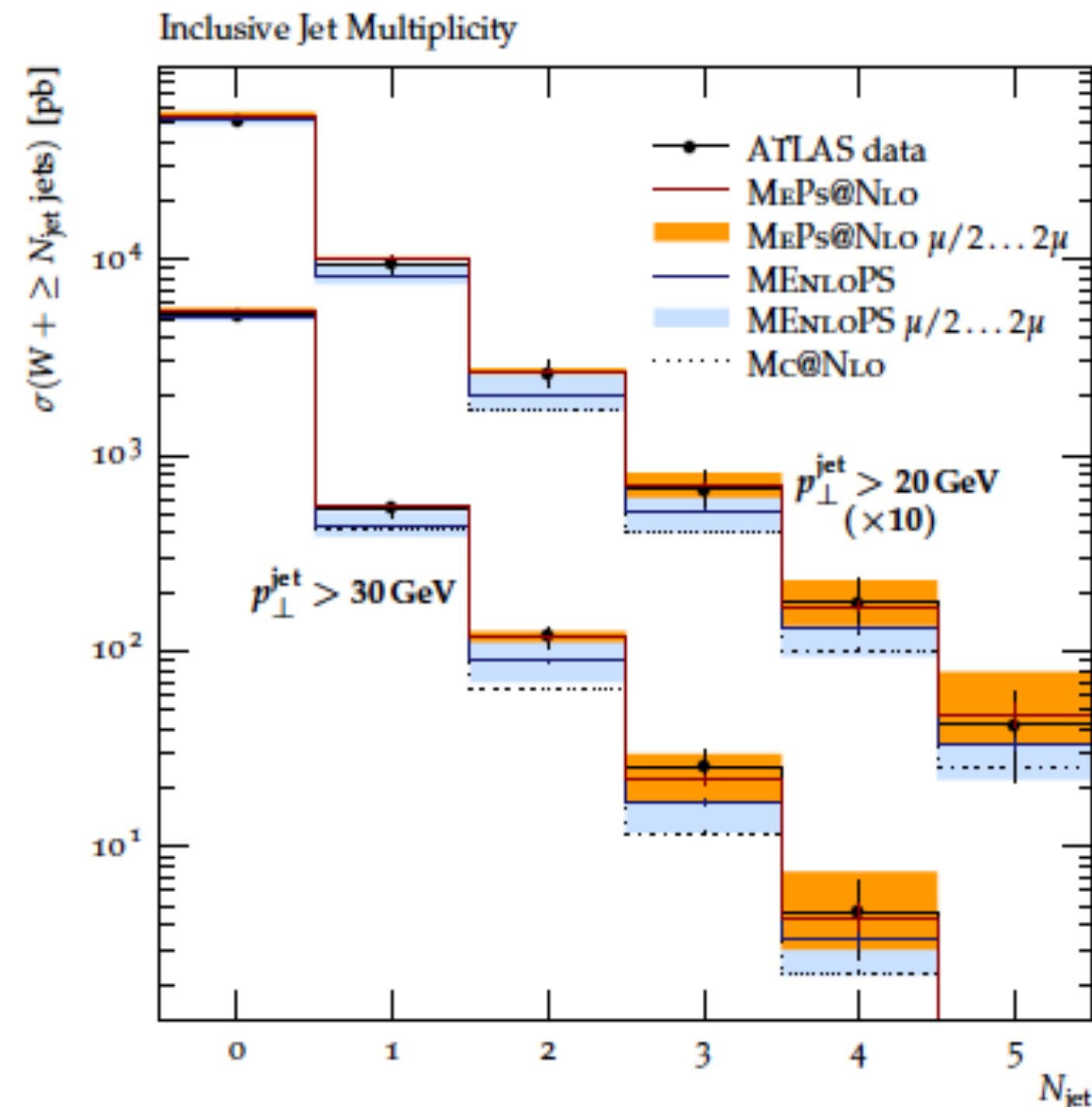
CKKW from hard scale down to the scale of the softest jet not affected by veto;

- 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]

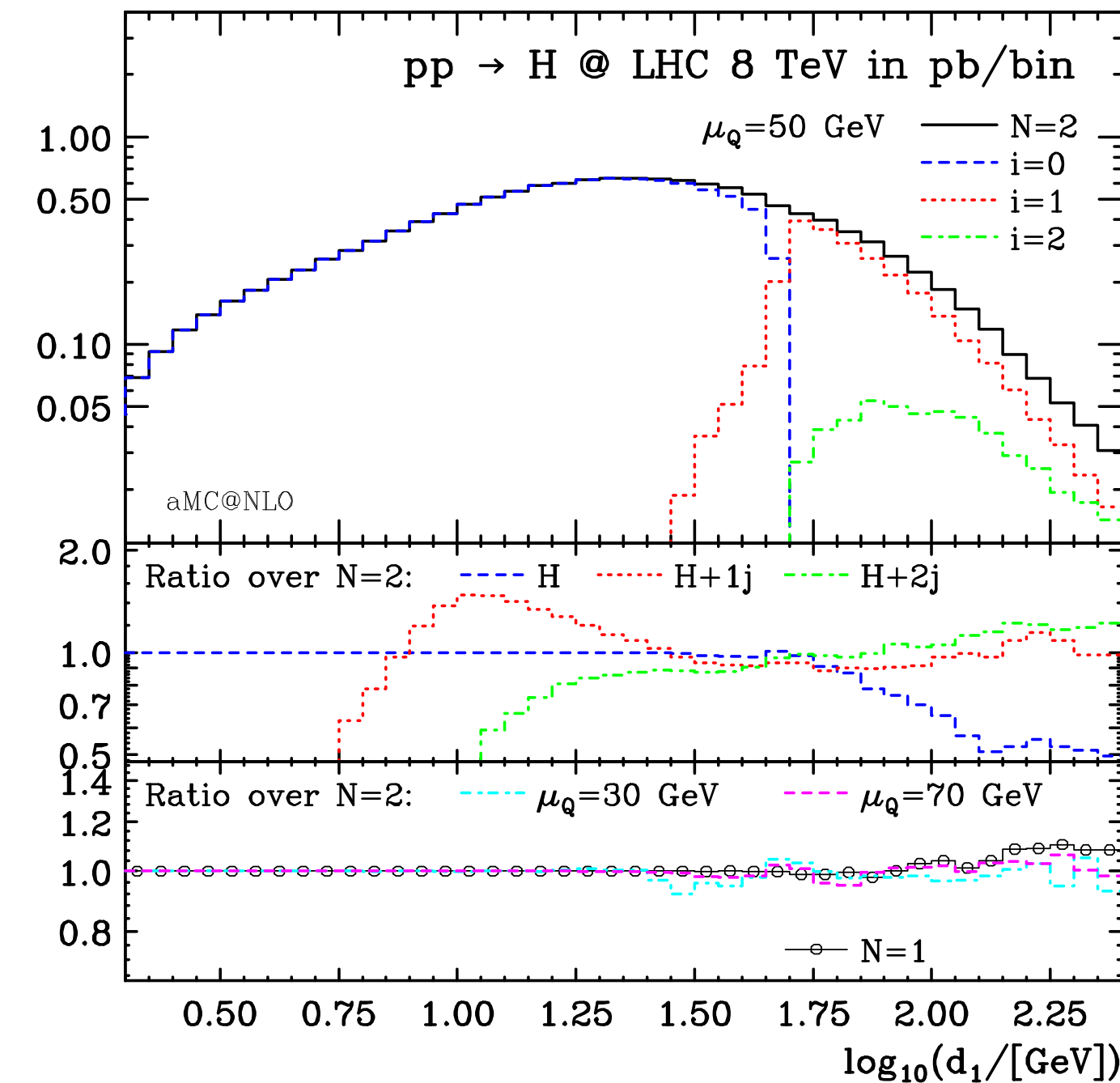


W + jets: up to 3-jets@NLO

Jet multiplicity

Good agreement with LHC data

[Frederix, Frixione, 1209.6215]

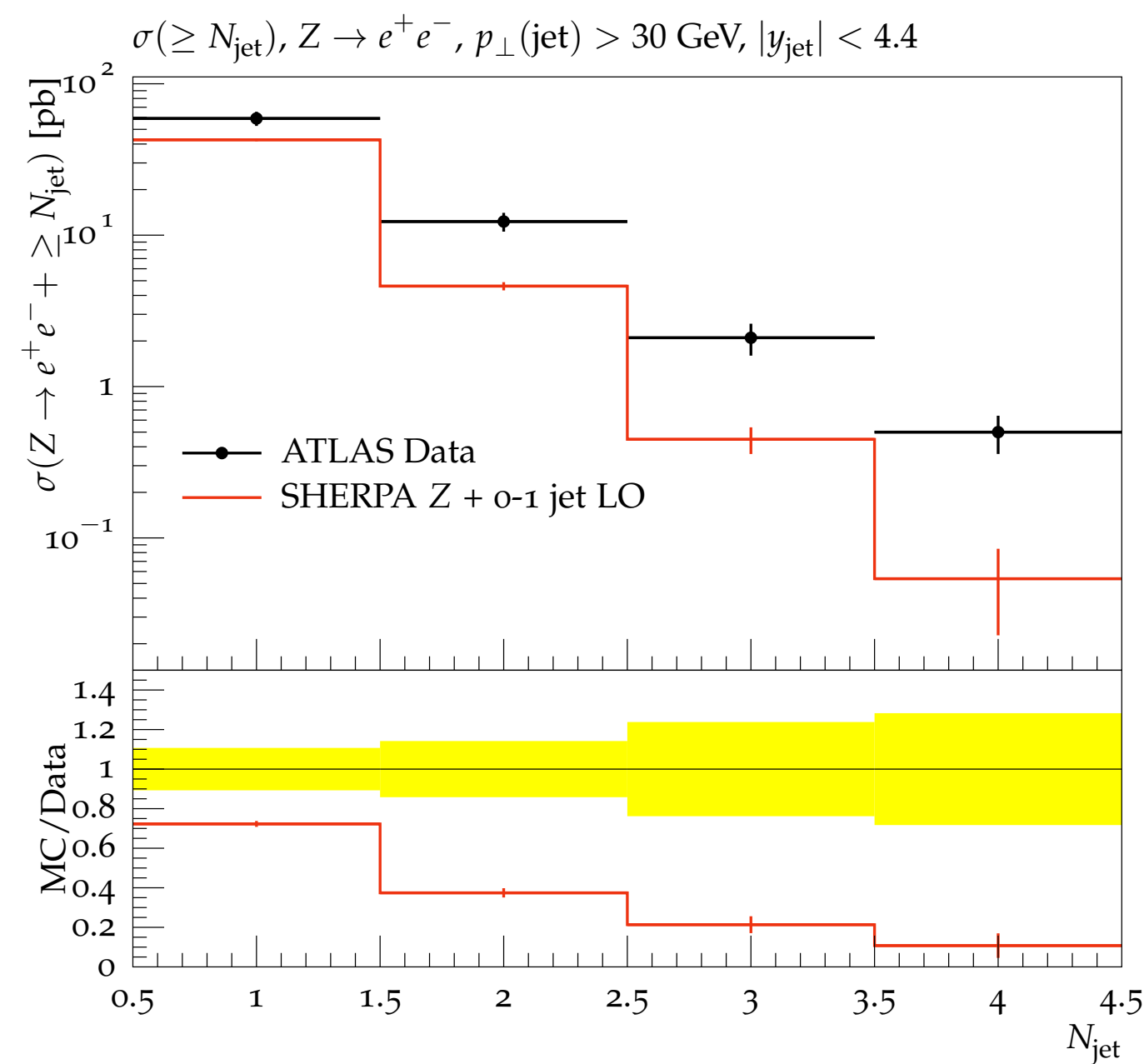


H + jets: up to 2-jets@NLO

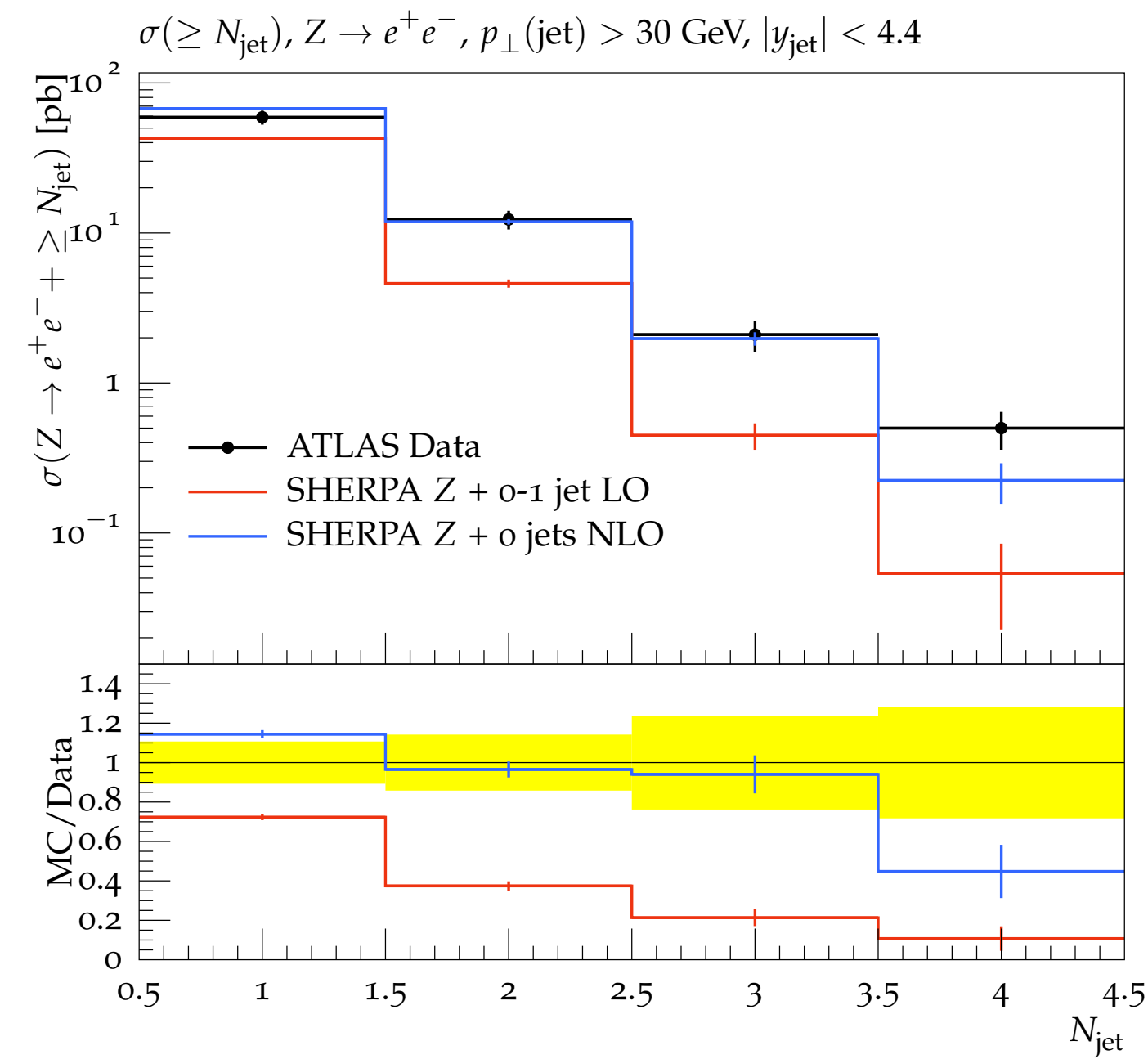
Differential jet rate

Very mild merging scale dependence

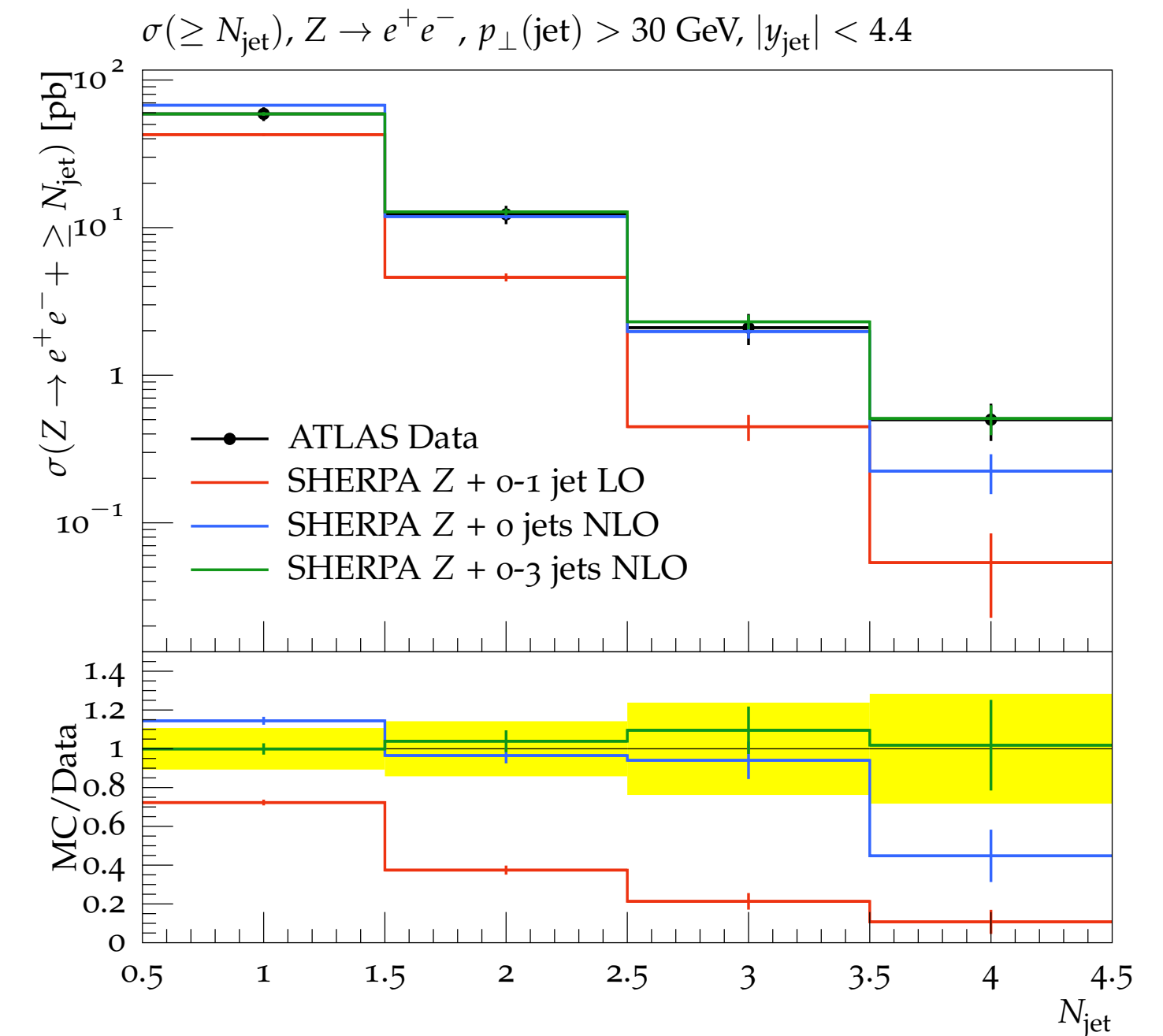
Is this progress relevant?



Merging at LO



NLO+PS



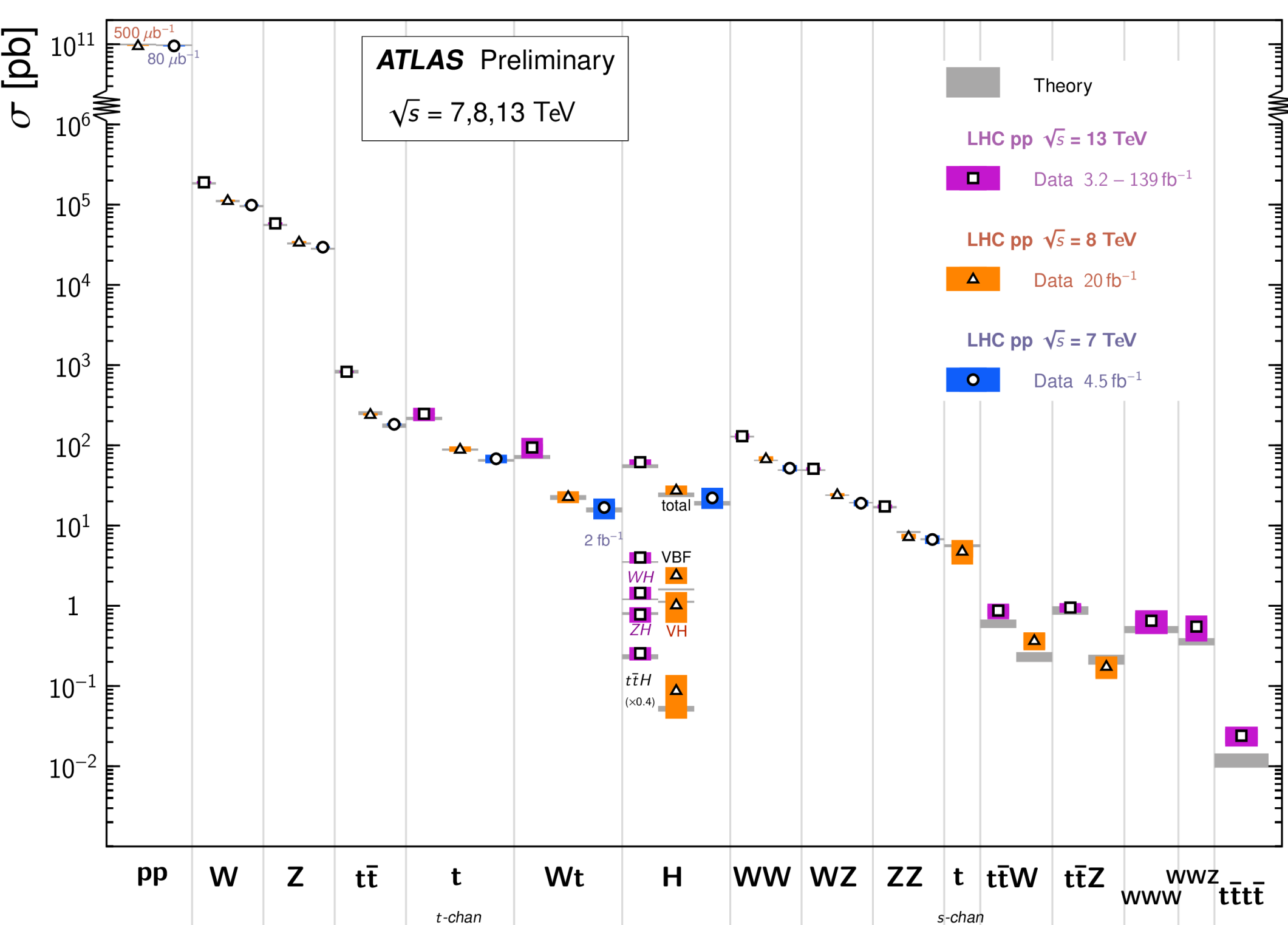
NLO+PS merging

Impressive improvement in description of data!

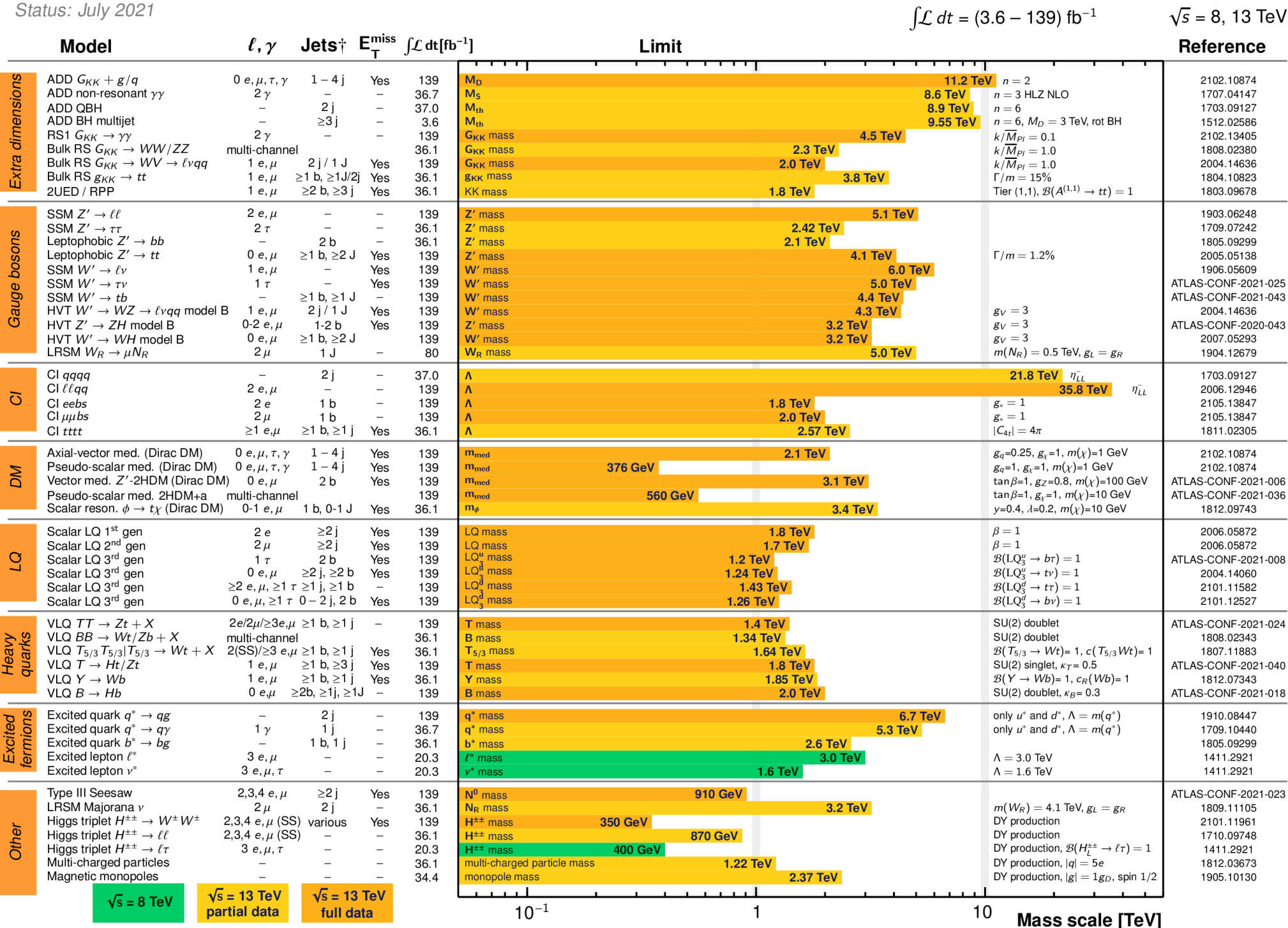
LHC status

Exploring & refining the SM

Standard Model Total Production Cross Section Measurements Status: March 2021



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits Status: July 2021



*Only a selection of the available mass limits on new states or phenomena is shown.

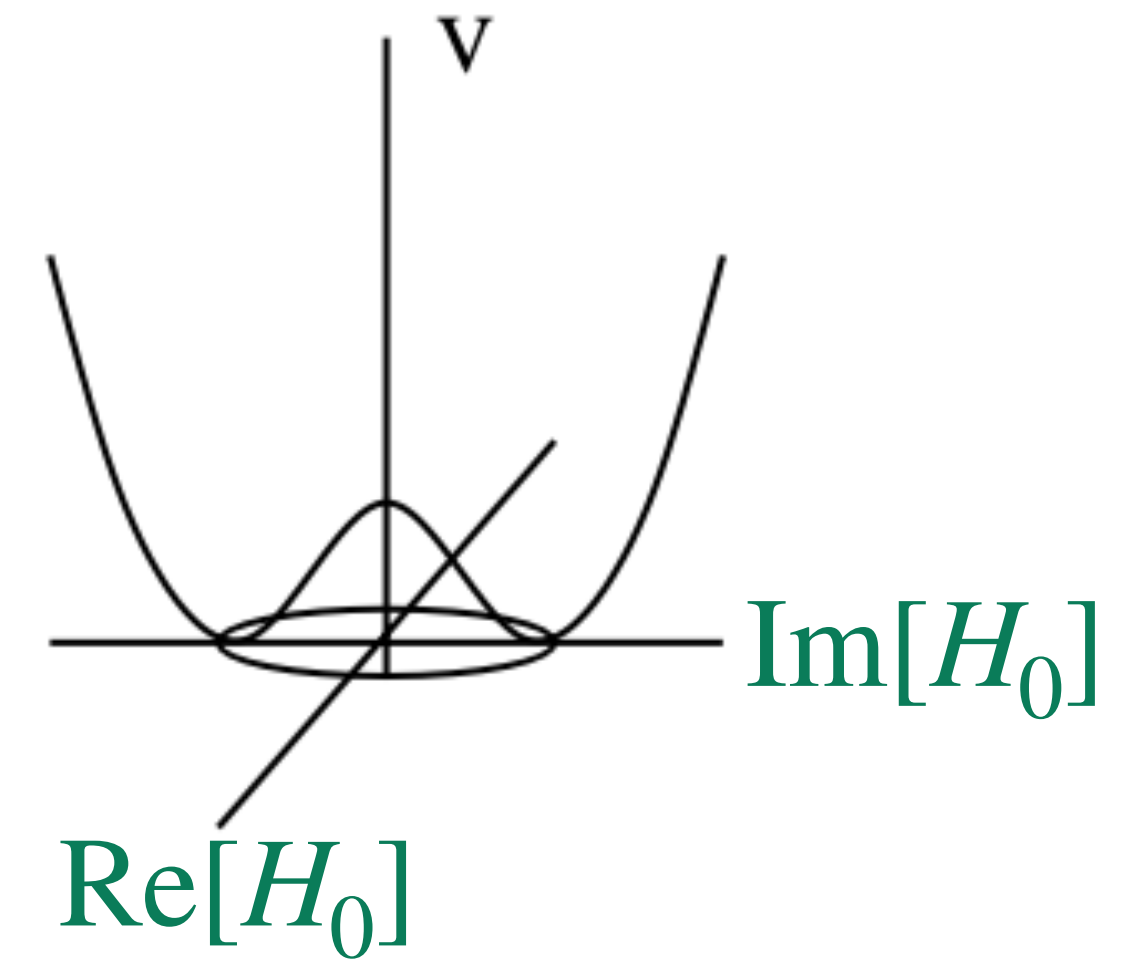
†Small-radius (large-radius) jets are denoted by the letter j (J).

Good agreement with the SM

Higgs phenomenology

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

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



Generates mass for all fundamental particles

- Higgs boson (h) couplings are proportional to mass

Gauge $(D^\mu H)^\dagger (D_\mu H) \supset (gv)^2 V^\mu V_\mu, g^2 v h V^\mu V_\mu, g^2 h h V^\mu V_\mu$

$\sim m_V^2$ $\sim m_V^2/v$ $\sim m_V^2/v^2$

Yukawa $y_f \bar{F}_L H f_R \supset y_f v f \bar{f}, y_f h f \bar{f}$

$\sim m_f$ $\sim m_f/v$

Potential $V(H) \supset \lambda v^2 h^2, \lambda v h^3, \lambda h^4$

$\sim m_h^2$ $\sim m_h^2/v$ $\sim m_h^2/v^2$

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

$$\mathcal{H} \equiv (i\sigma_2 H^*, H) = \begin{pmatrix} H_0^* & H_+ \\ -H_+^* & H_0 \end{pmatrix} \Rightarrow \begin{aligned} \text{Tr}[\mathcal{H}^\dagger \mathcal{H}] &= 2H^\dagger H \\ V(H) &= -\frac{\mu^2}{2} \text{Tr}[\mathcal{H}^\dagger \mathcal{H}] + \frac{\lambda}{4} \text{Tr}[\mathcal{H}^\dagger \mathcal{H}]^2 \end{aligned}$$

Custodial symmetry

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

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

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

SM: global $\rightarrow$ gauge symmetries

- Completely gauge $SU(2)_L$ but only gauge T_R^3 : $D^\mu \mathcal{H} = \partial_\mu \mathcal{H} - ig W_\mu^I \sigma_I \mathcal{H} - i \frac{g'}{2} B_\mu \mathcal{H} \sigma_3$

- 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

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

Suppose we completely gauged $SU(2)_R$

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

$$\tilde{D}^\mu \mathcal{H} = \partial_\mu \mathcal{H} - ig W_\mu^I \sigma_I \mathcal{H} - ig' B_\mu^I \mathcal{H} \sigma_I$$

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

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

- H & H^* have opposite charge
- $SU(2)_V$ imposes $m_W^2 = m_Z^2 c_W^2$

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

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

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

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

$$F_L = \begin{pmatrix} f_L^u \\ f_L^d \end{pmatrix}, F_R = \begin{pmatrix} f_R^u \\ f_R^d \end{pmatrix} \quad \mathcal{L}_f \sim y_F \bar{F}_L \mathcal{H} F_R \underset{y_{fu} = y_{fd}}{\neq} y_{fd} \bar{F}_L H f_R^d + y_{fu} \bar{F}_L \tilde{H} f_R^u$$

$y_{fu} \neq y_{fd}$

- 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 $\Delta\rho_{\text{SM}}$

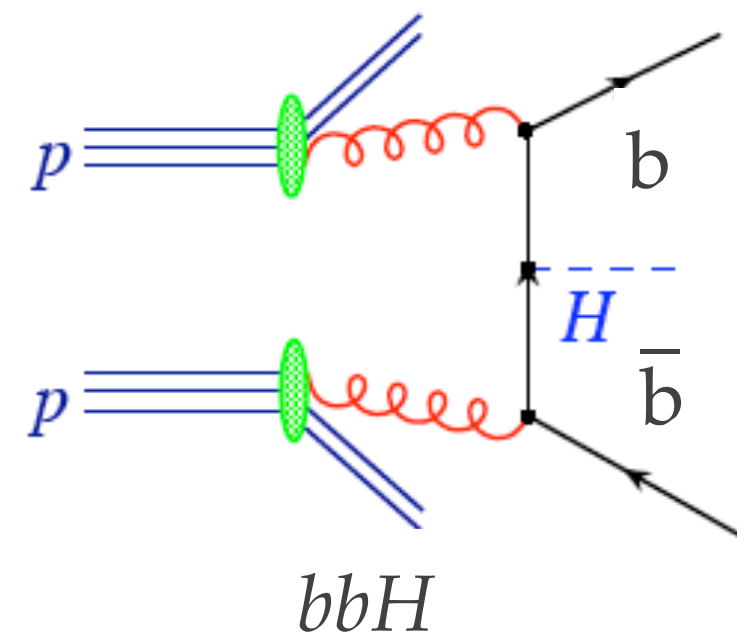
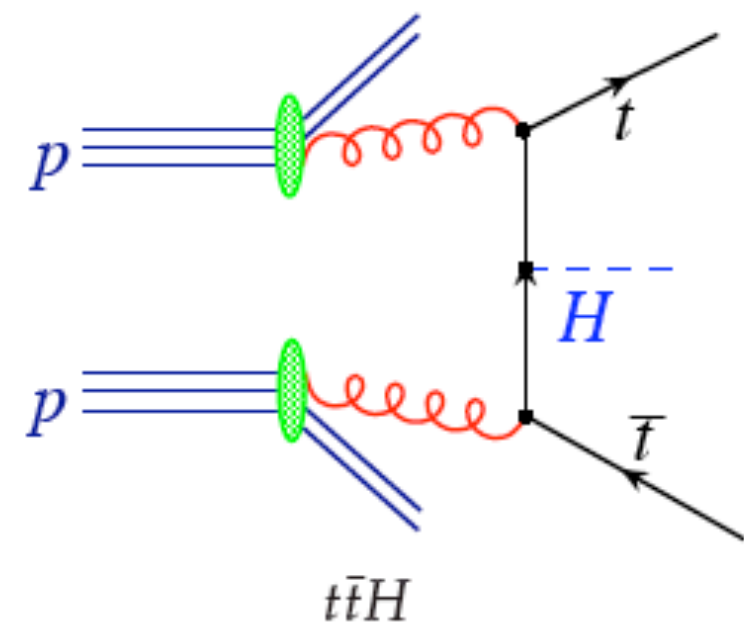
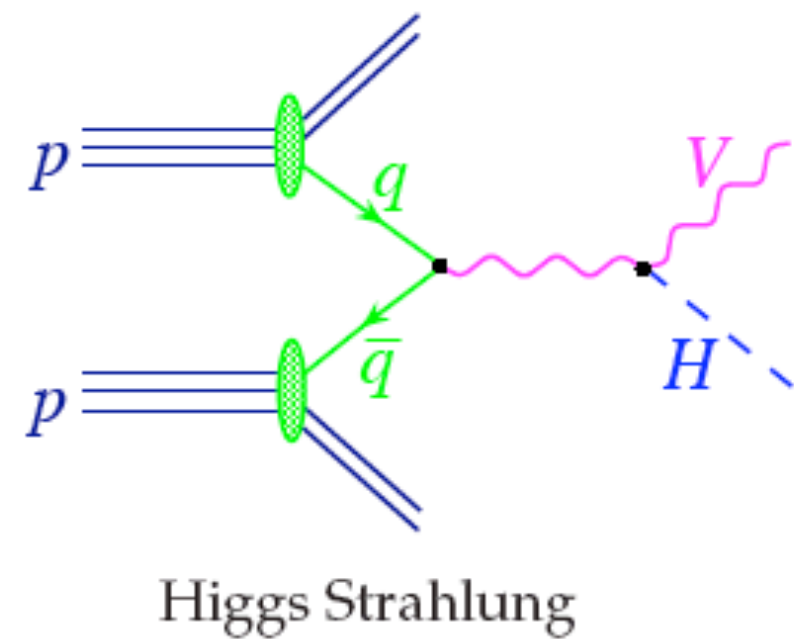
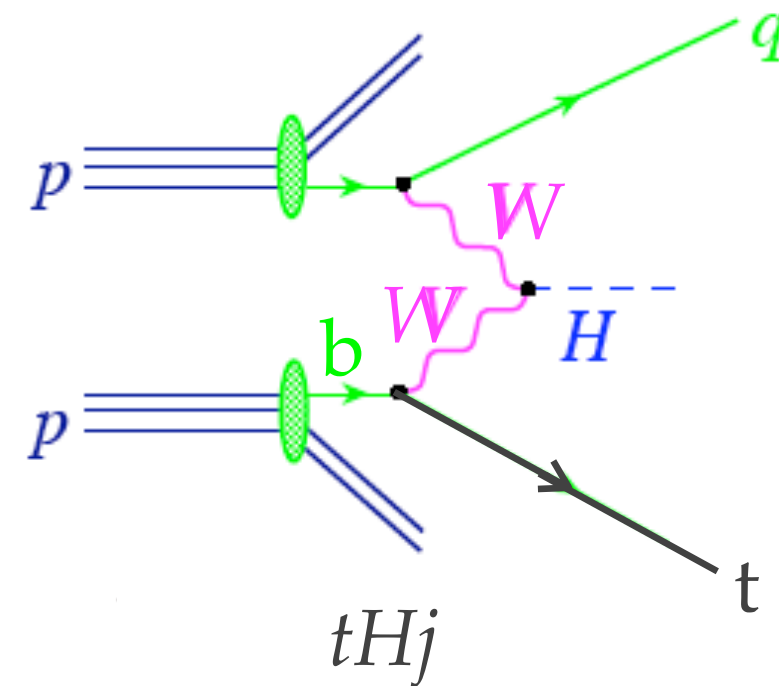
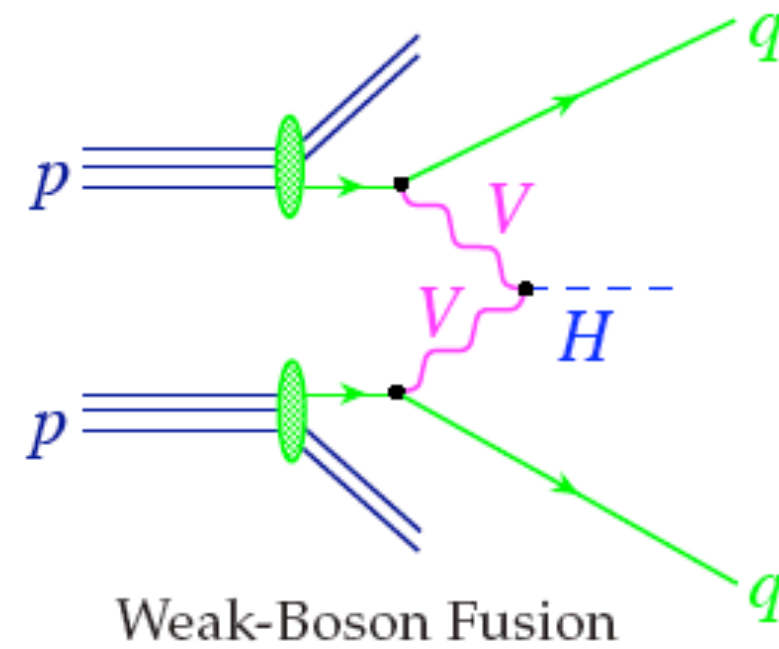
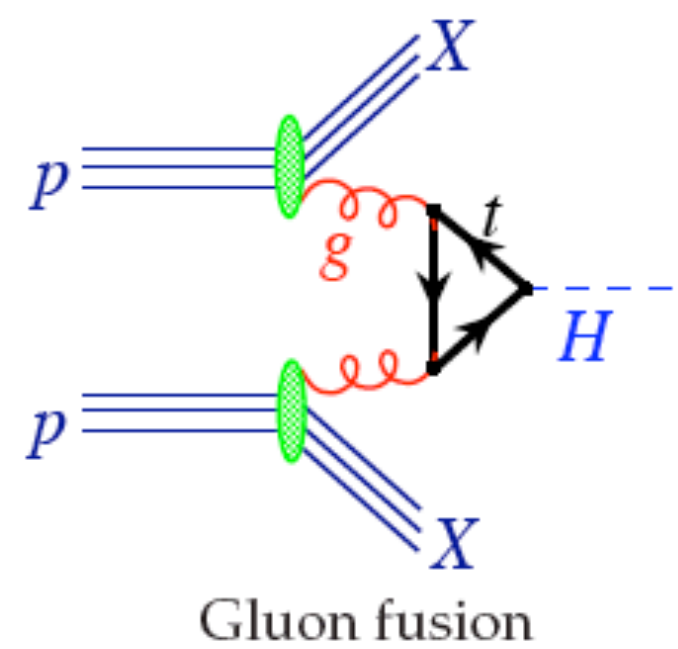
We can test the SM by searching for deviations $\Delta\rho_{\text{BSM}}$

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

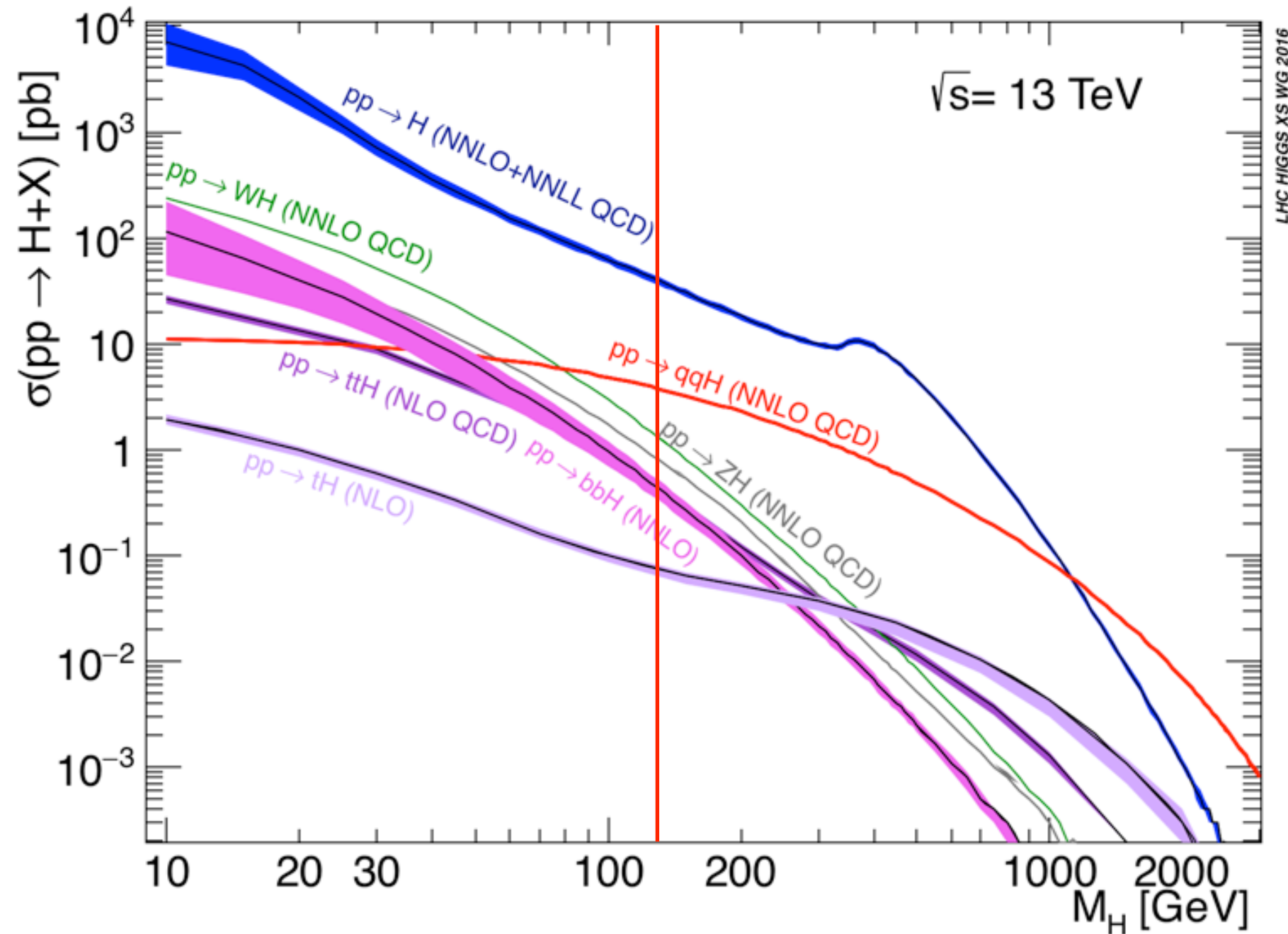
$$\rho_{\text{tree}} = \frac{\sum_j |v_j|^2 [T_j(T_j + 1) - Y_j^2]}{2 \sum_j |v_j|^2 Y_j^2}$$

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

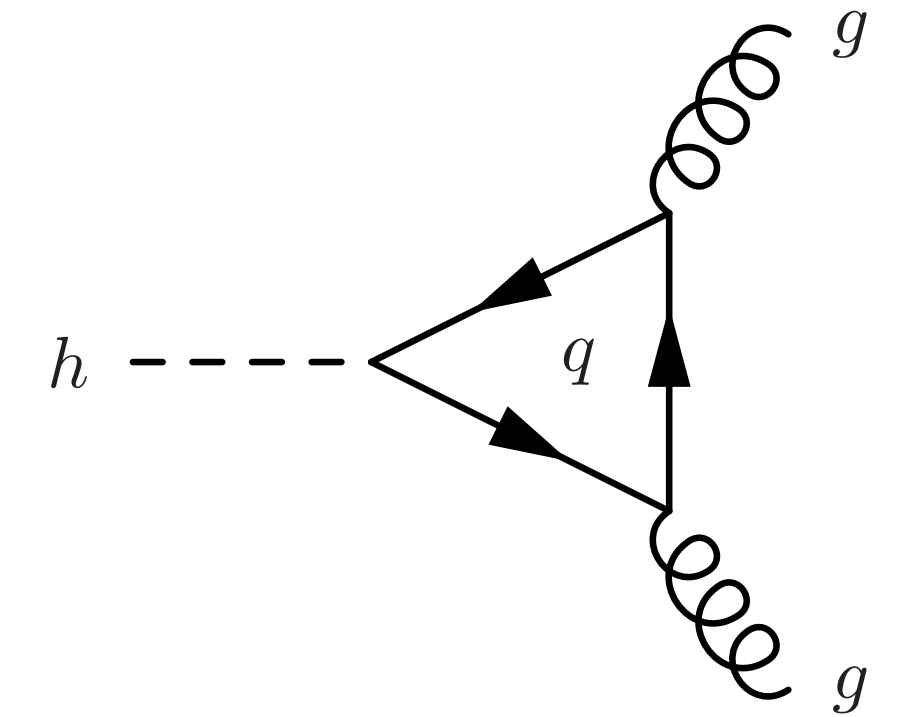
Higgs production @ hadron colliders



$m_h = 125 \text{ GeV}$



Gluon fusion



Higgs boson coupling to gluons induced by quark loops

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

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

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

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

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

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

- Non-decoupling behaviour!

Coupling $\propto$ mass

$$m_q \rightarrow \infty \Leftrightarrow y_q \rightarrow \infty$$

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

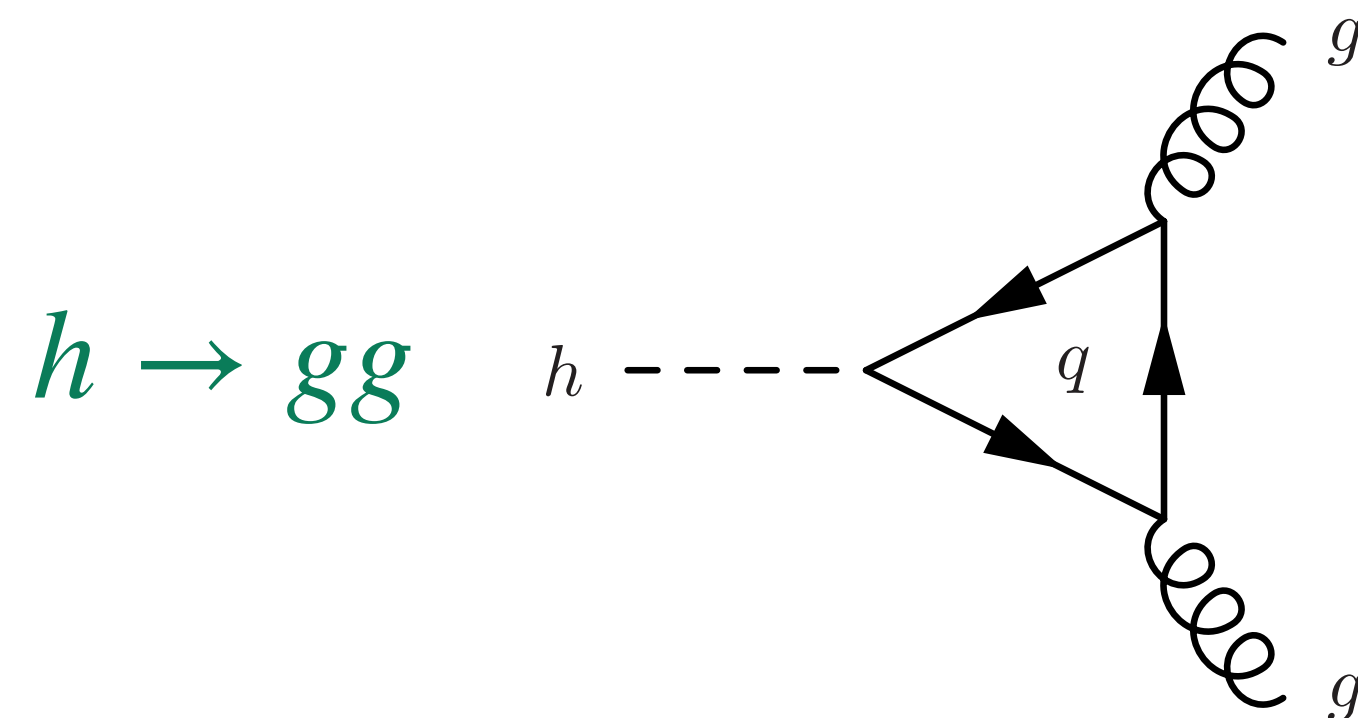
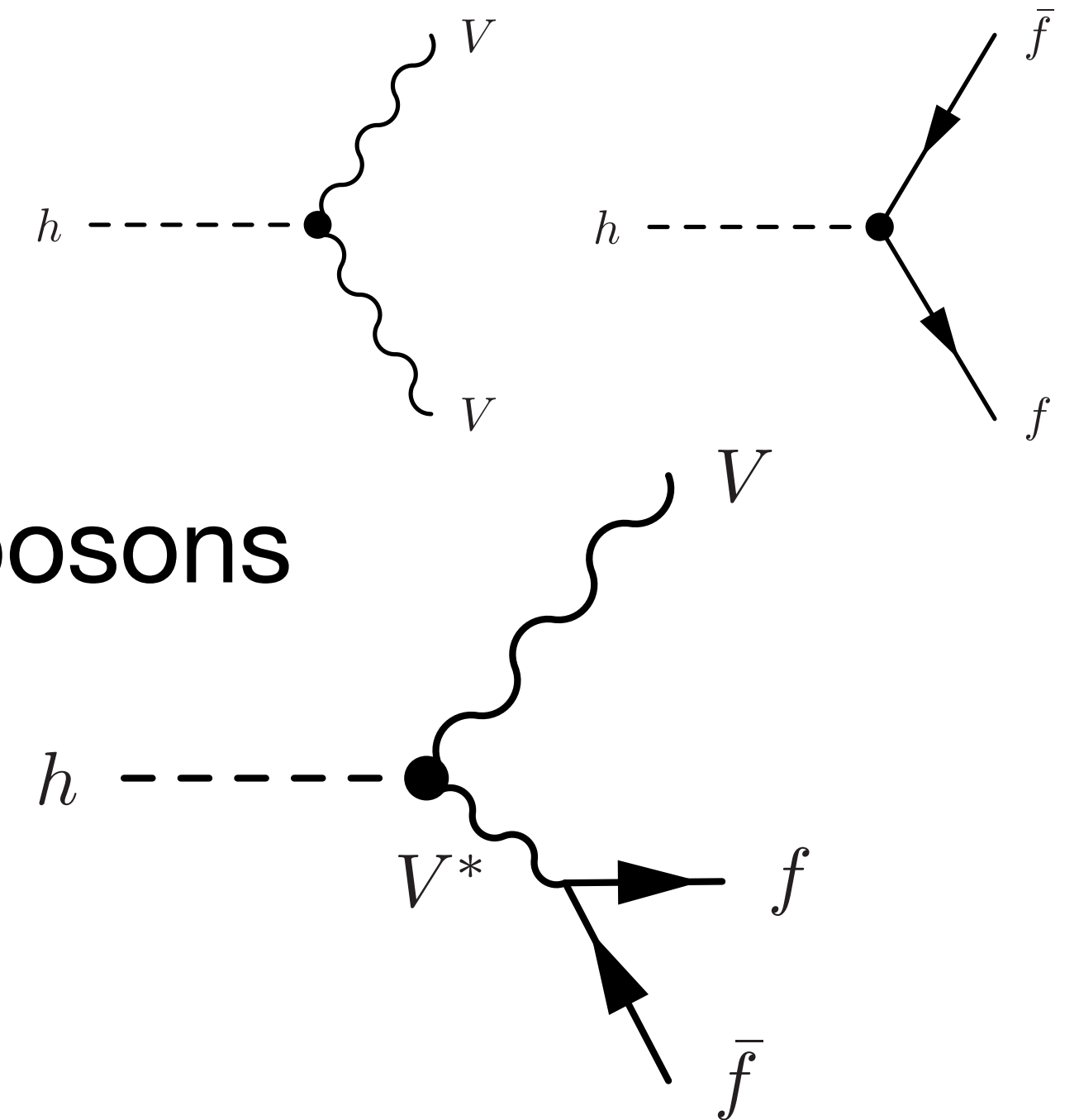
Higgs decay

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

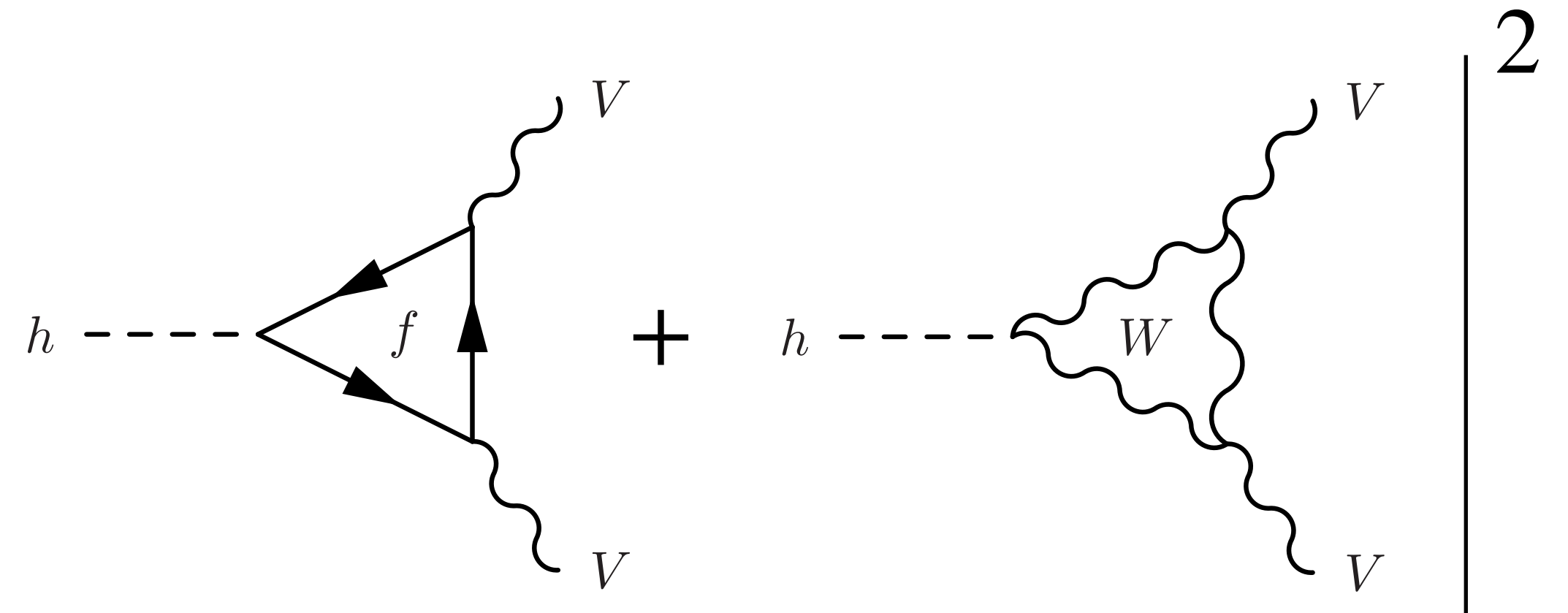
- For $m_h < 2m_V$, off shell contributions can be relevant

Loop level: decays to massless gauge bosons

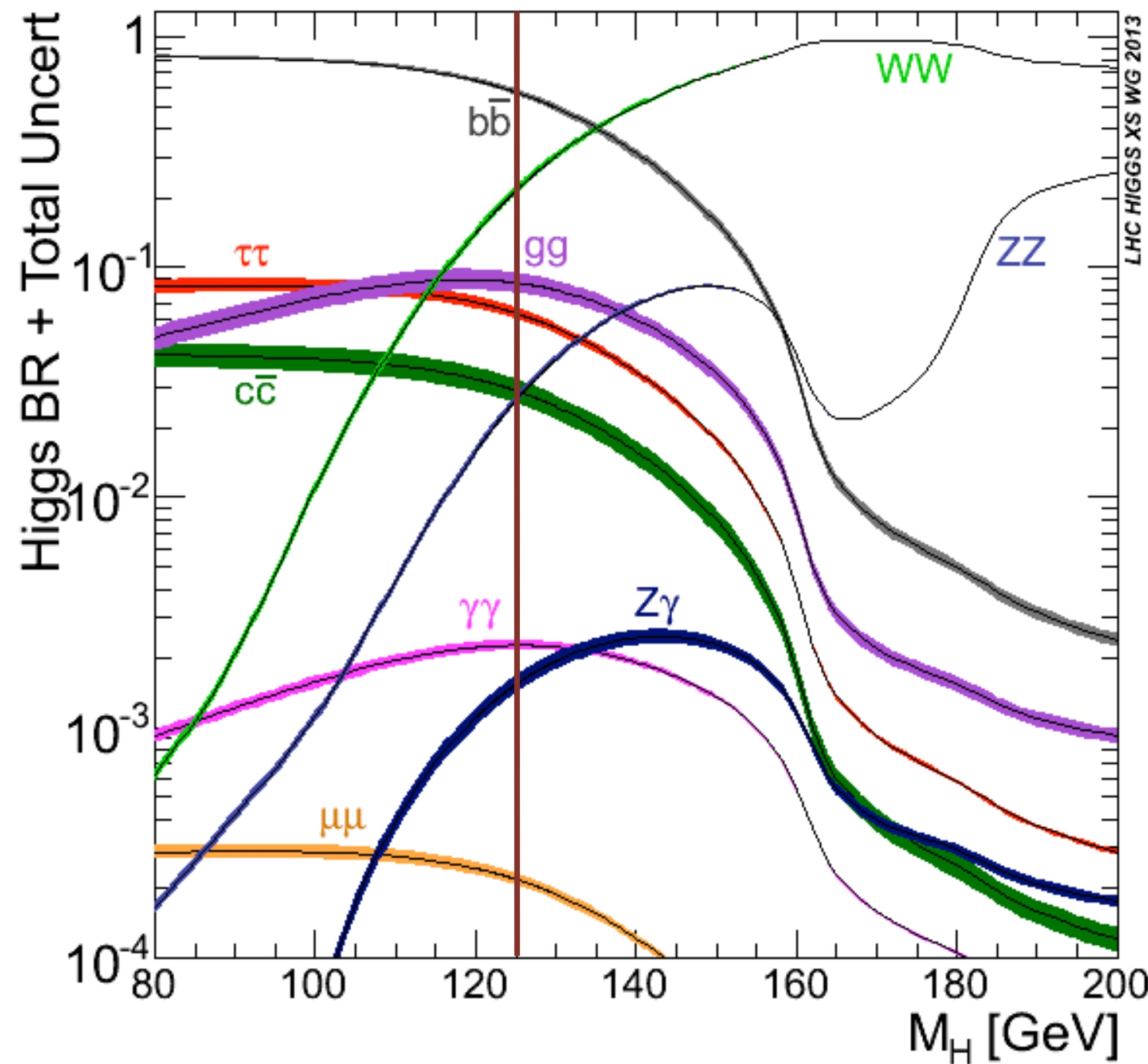
- $gg, \gamma\gamma$ & $Z\gamma$
- c.f. gluon fusion & non-decoupling behavior



$h \rightarrow \gamma\gamma/Z\gamma$



Higgs branching fractions

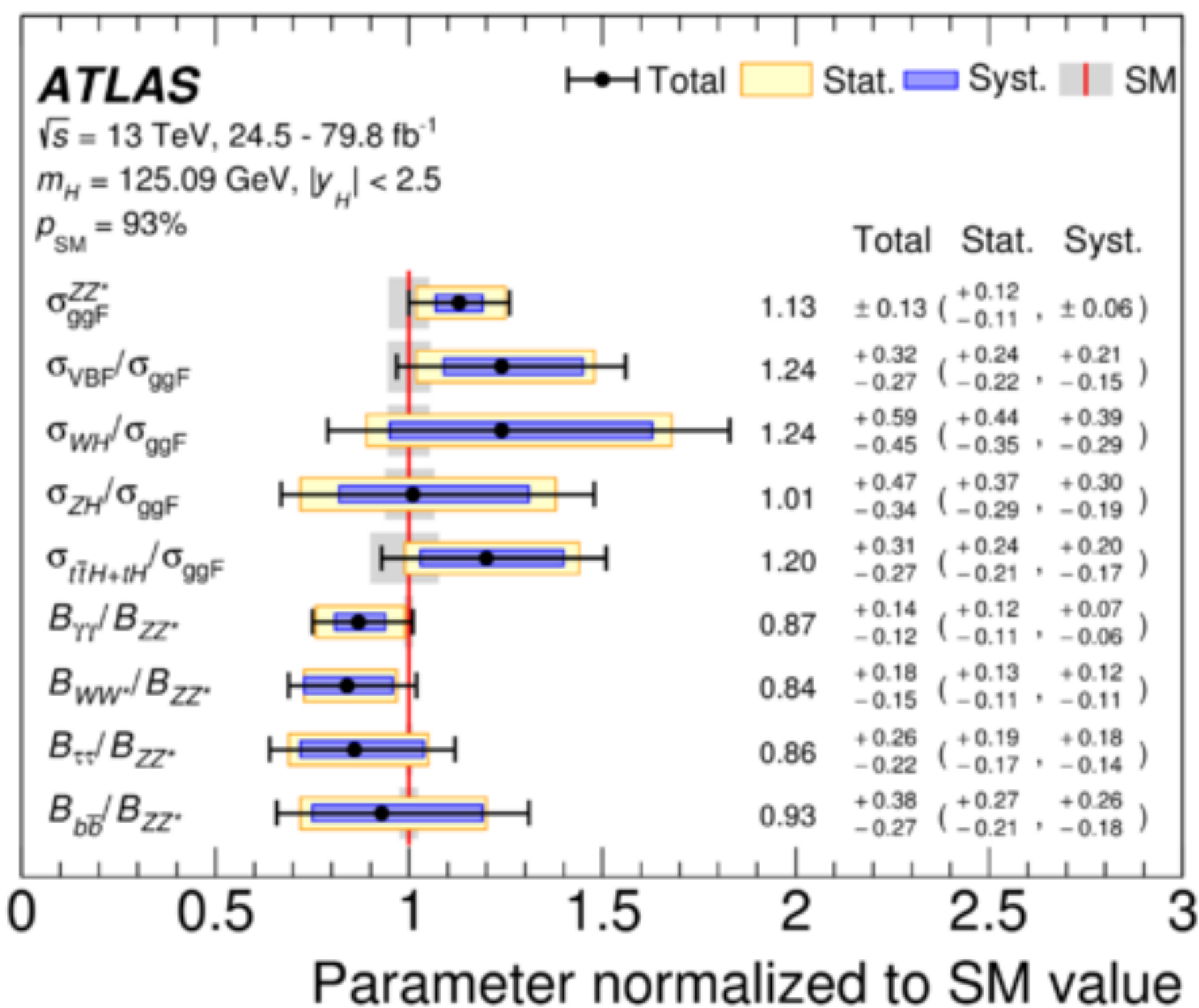
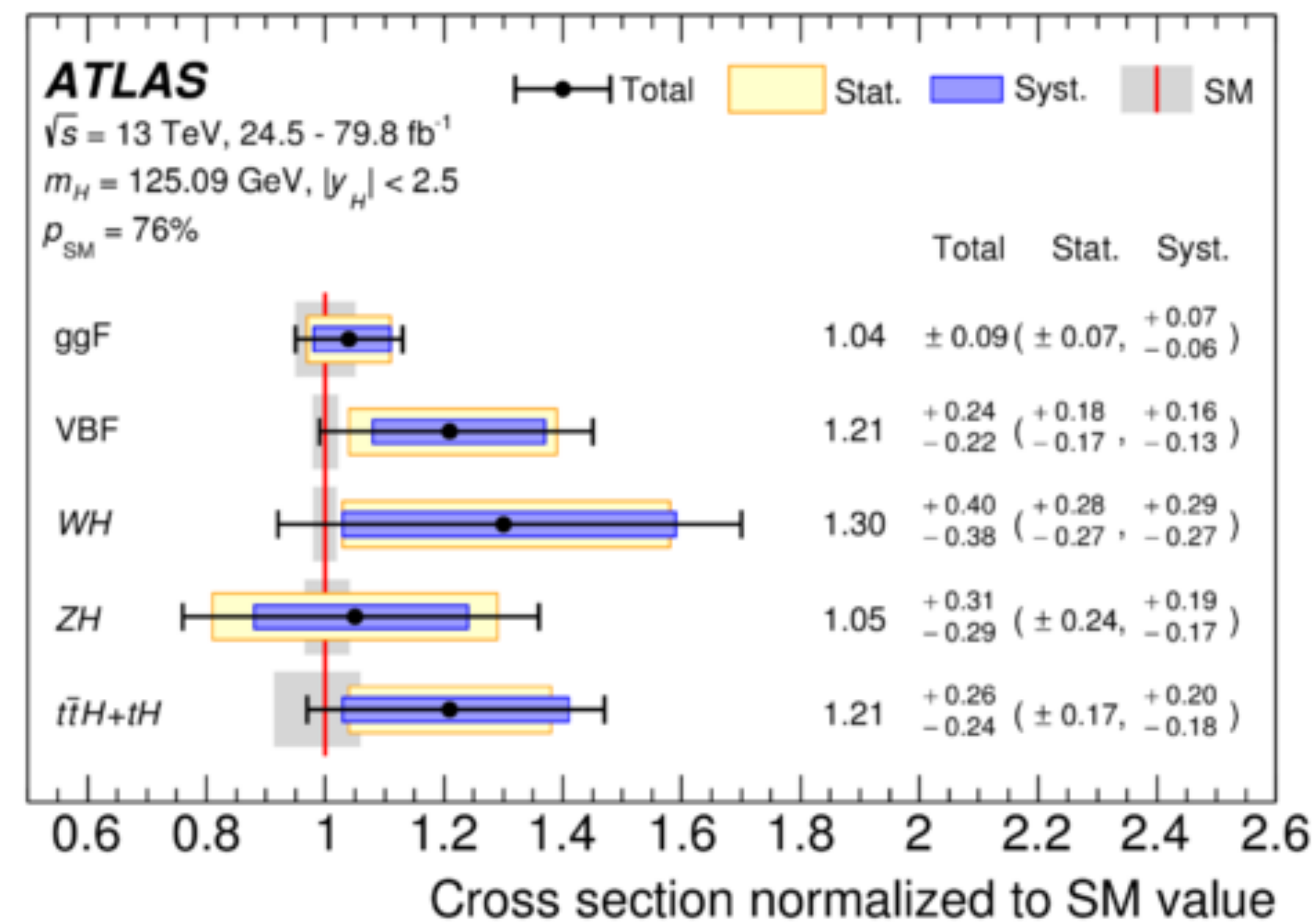


- Wealth of decay channels for 125 GeV, rich phenomenology
- Very narrow! $\Gamma \sim 4 \text{ MeV}$
- Diphoton and $ZZ^* \rightarrow 4\ell$ final state are the cleanest signatures
- Hadronic channels are hard at the LHC because of the backgrounds, but accessible through boosted techniques!

Higgs measurements

‘Signal strengths’ $\mu_i = \sigma^{\text{exp.}} / \sigma_{\text{SM}}^{\text{th.}}$

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



Characterising the Higgs boson

We measure combinations of Higgs production modes & decay channels

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

$$\begin{aligned}\sigma_{pp}(ii \rightarrow h \rightarrow ff) &\simeq \sigma_{pp}(ii \rightarrow h) \times BR(h \rightarrow ff) + O(\Gamma_h^2/m_h^2) \\ &= \sigma_{pp}(ii \rightarrow h) \times \Gamma(h \rightarrow ff)/\Gamma_h\end{aligned}$$

- Define ‘modifiers’ for SM Higgs couplings, $\kappa_i = y_i/y_i^{\text{SM}}$:

$$\sigma_{ii \rightarrow h} = \kappa_i^2 \sigma_{ii}^{\text{SM}}, \quad \Gamma_{ff} = \kappa_f^2 \Gamma_{h \rightarrow ff}^{\text{SM}}, \quad \Gamma_h = \kappa_h^2 \Gamma_h^{\text{SM}}$$

$$\Rightarrow \sigma_{pp}(ii \rightarrow h \rightarrow ff) = \sigma_{pp}^{\text{SM}}(ii \rightarrow h \rightarrow ff) \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_h^2} \quad \mu_{ii \rightarrow ff} = \frac{\sigma_{ii \rightarrow ff}}{\sigma_{ii \rightarrow ff}^{\text{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_h^2}$$

Kappa framework

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

$$\kappa_g^2(\kappa_t, \kappa_b) = \frac{\Gamma_{h \rightarrow gg}}{\Gamma_{h \rightarrow gg}^{\text{SM}}} = \frac{\hat{\sigma}_{gg \rightarrow h}}{\hat{\sigma}_{gg \rightarrow h}^{\text{SM}}} \quad \kappa_{\gamma/Z\gamma}^2(\kappa_t, \kappa_b, \kappa_Z, \kappa_W) = \frac{\Gamma_{h \rightarrow \gamma\gamma/Z\gamma}}{\Gamma_{h \rightarrow \gamma\gamma/Z\gamma}^{\text{SM}}}$$

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

BSM interpretations: Higgs-scalar mixing

- Scalar singlet with Higgs portal coupling

$$\mu_S S_0 (H^\dagger H) \rightarrow \mu_S v S_0 h_0$$

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

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

- two-Higgs-Doublet Model (2HDM)

$$\kappa_V = \sin(\beta - \alpha) \quad \text{'Type I'}$$

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

$$\kappa_V = \sin(\beta - \alpha) \quad \text{'Type II'}$$

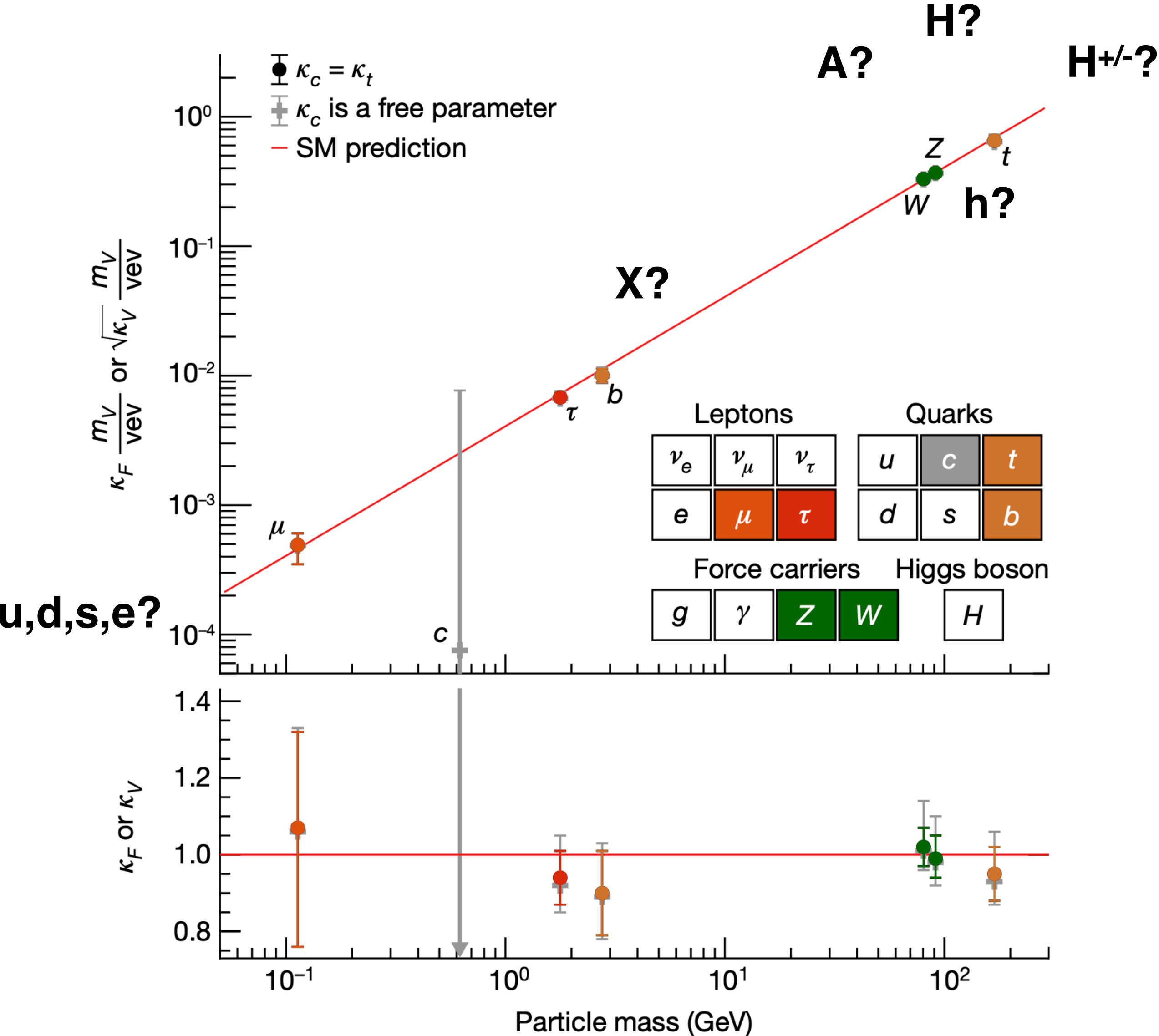
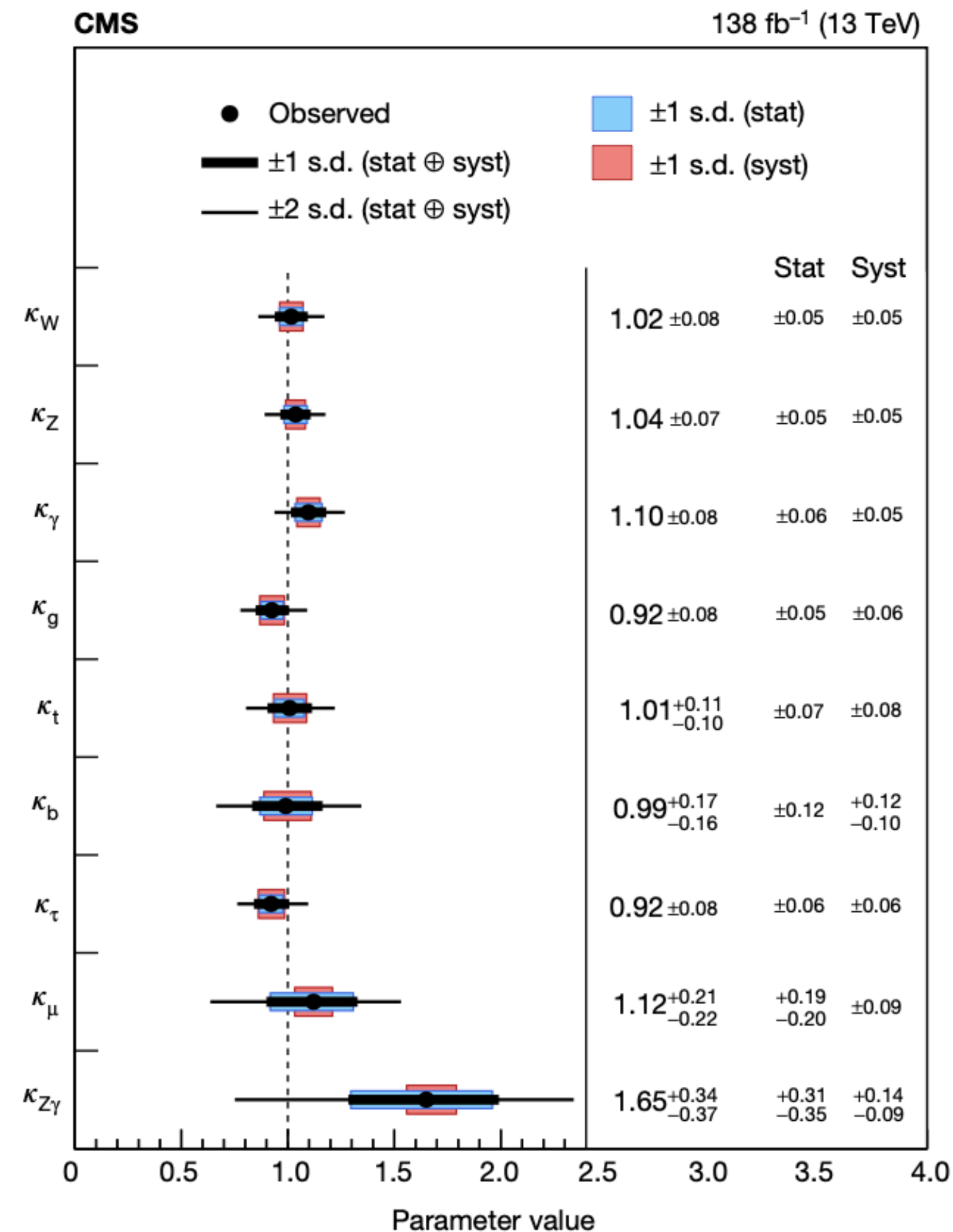
$$\kappa_u = \cos(\beta - \alpha)/\tan \beta + \sin(\beta - \alpha)$$

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

Knowns and Unknowns

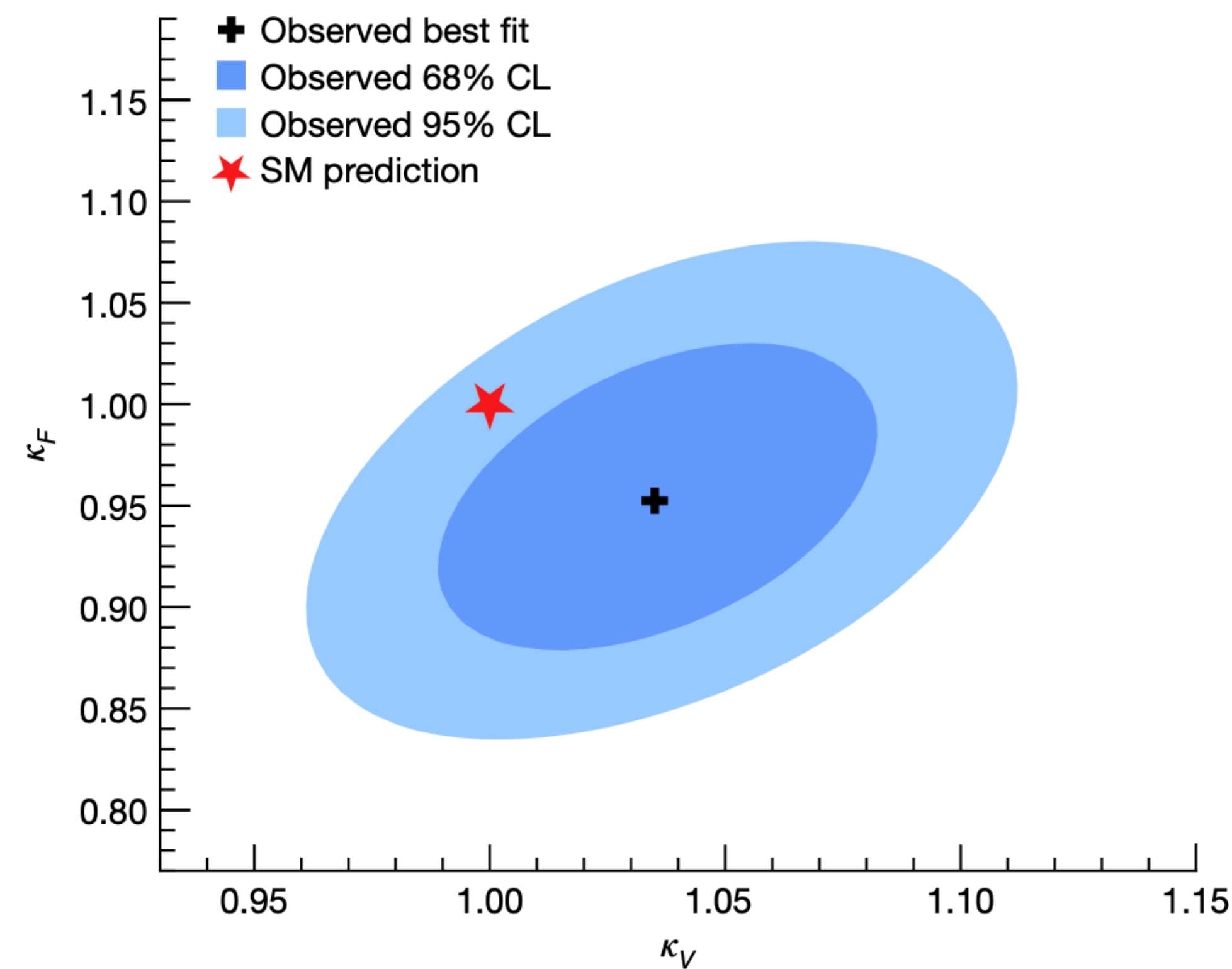
[CMS; 2207.00043]

[ATLAS; 2207.00092]



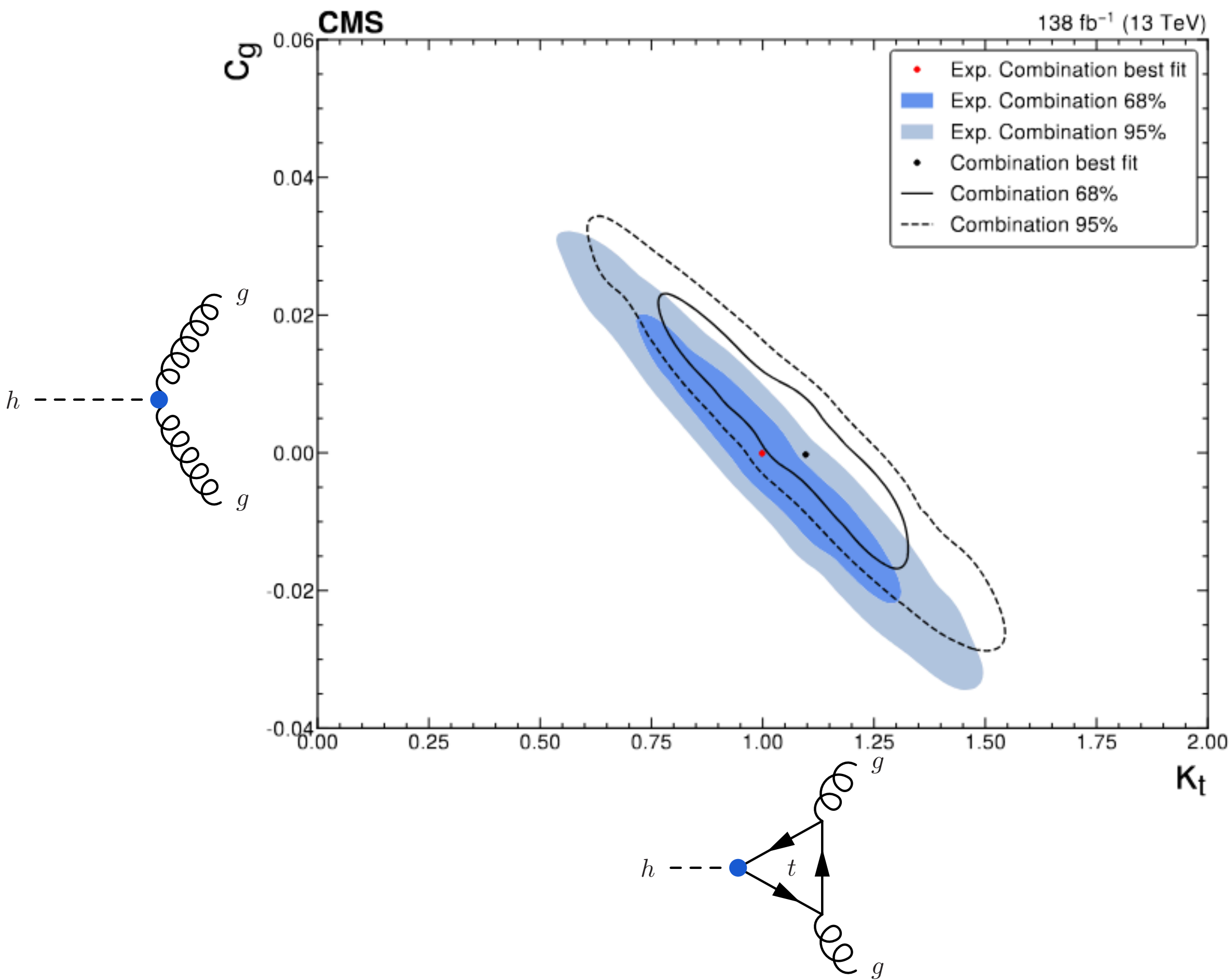
Correlations

[ATLAS; 2207.00092]



$$\kappa_{t,b,c,\dots} = \kappa_F \quad \kappa_{Z,W} = \kappa_V$$

[CMS; 2504.13081]



Bound on new scalars

Singlet

2HDM

[ATLAS; 2402.05742]

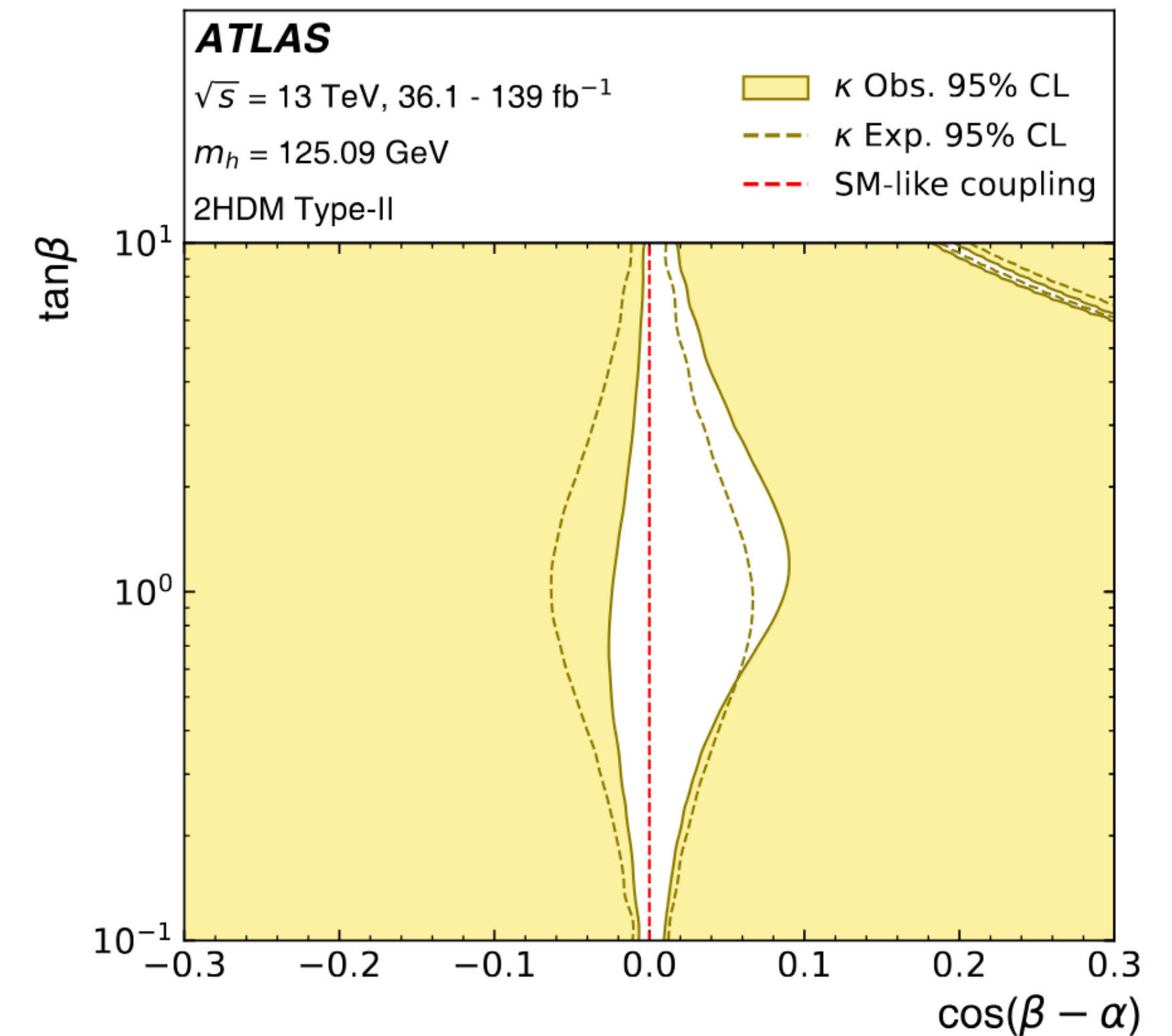
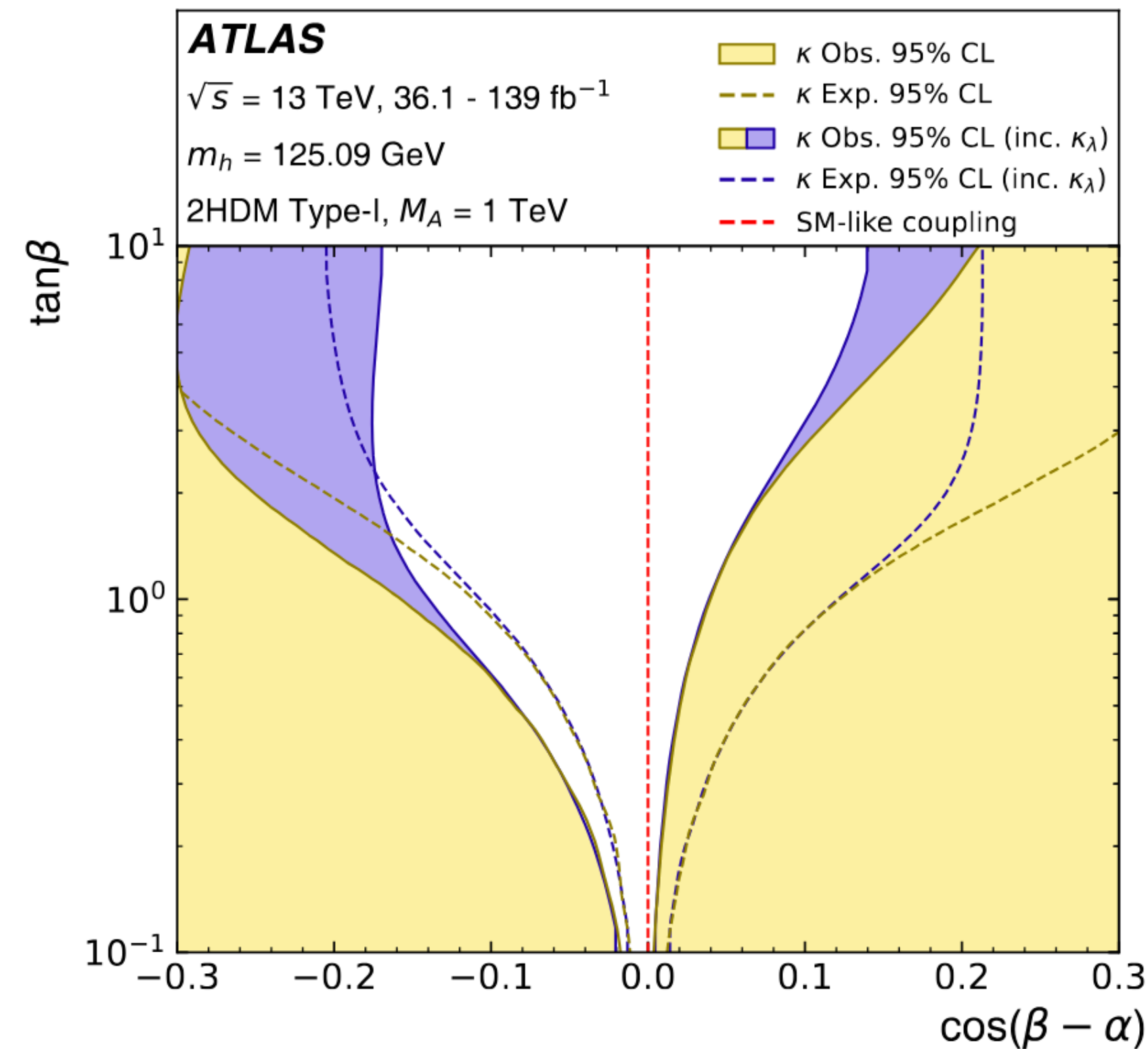
$$\kappa_i = \cos \alpha$$

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

(BRs unchanged)

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

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



~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

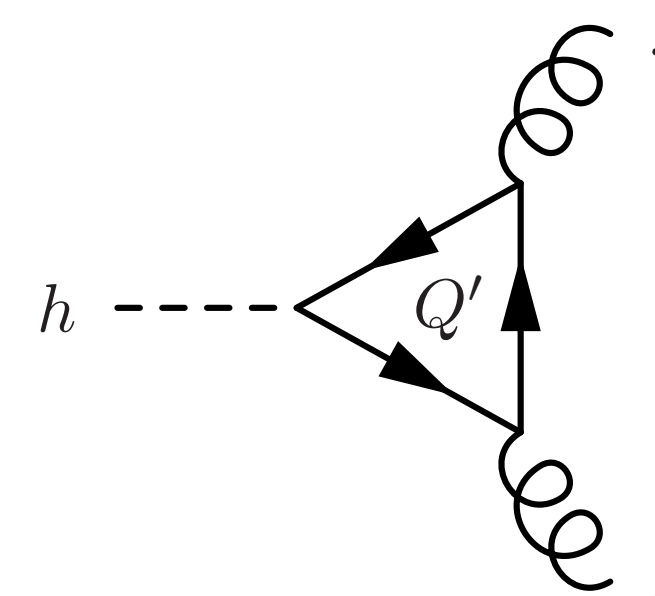
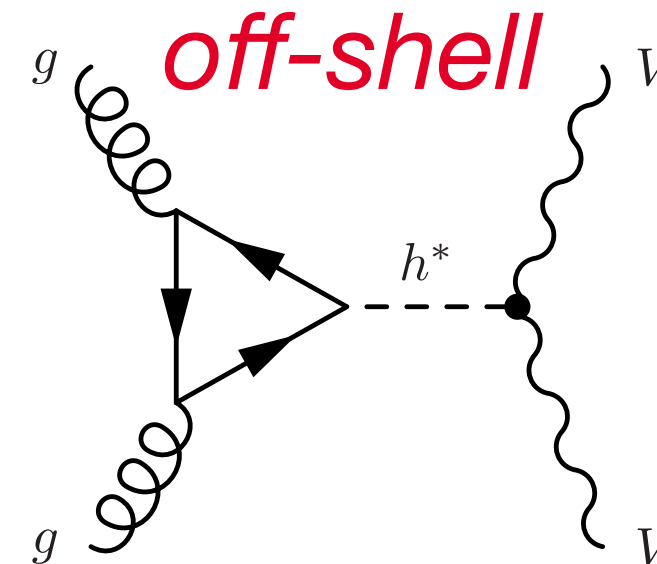
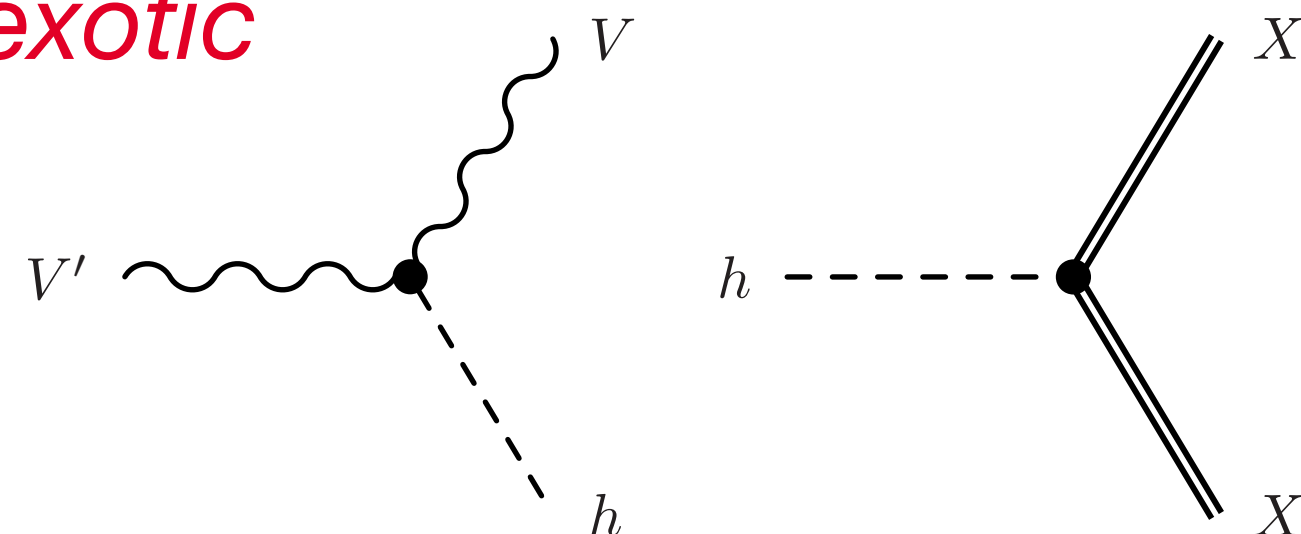
SM: $hV_\mu V^\mu$

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

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

e.g. heavy quark loop

exotic



$\Rightarrow f(q^2, M_Q^2) \cdot h G_{\mu\nu}^A G_A^{\mu\nu}$

Beyond kappa-framework?

Theoretical consistency

- Its not a theory! no Lagrangian, Feynman rules

Lets try...

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

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

$$\propto s$$

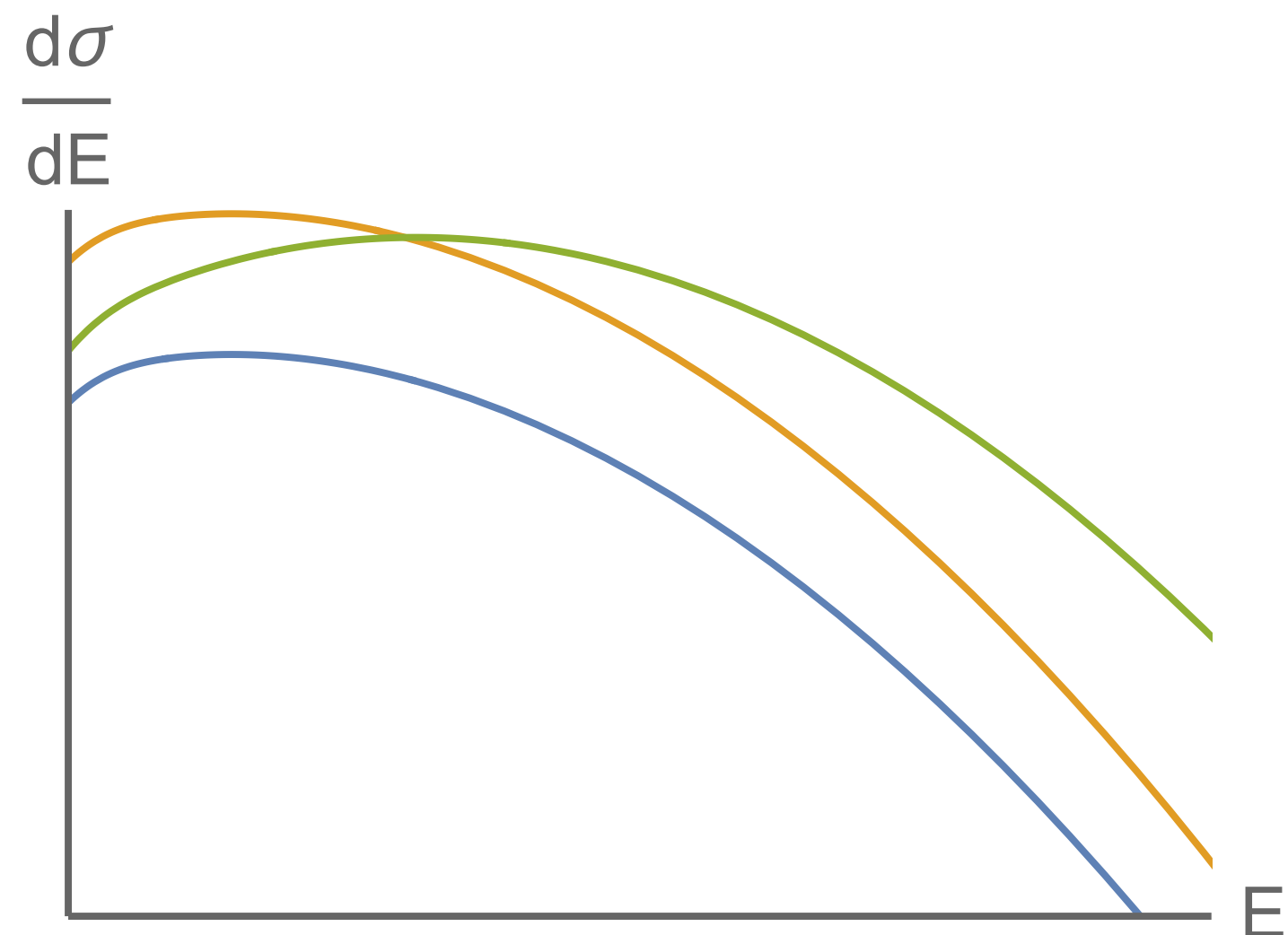
Need EFT framework, see later

Differential measurements

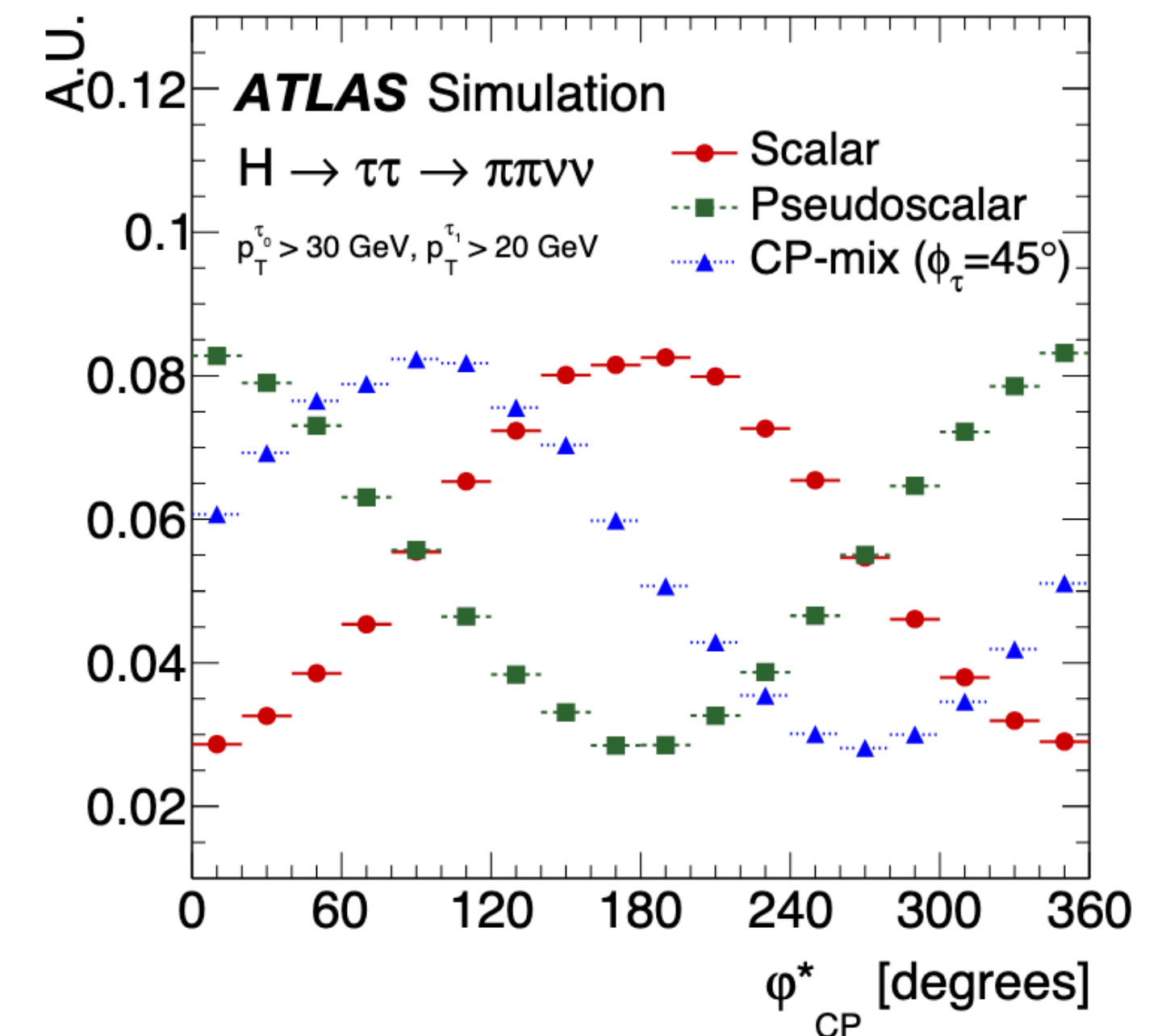
$$\sigma_{pp \rightarrow X} = \sum_{ab} \int_0^1 \frac{d\tau}{\tau} \cdot \mathcal{L}_{ab}(s, \tau) \cdot \left[\hat{s} \hat{\sigma}_{ab}(\hat{s}, p_X) \right]$$

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

- Measure energy dependence of scattering
- Angular dependence $\Rightarrow$ spin information



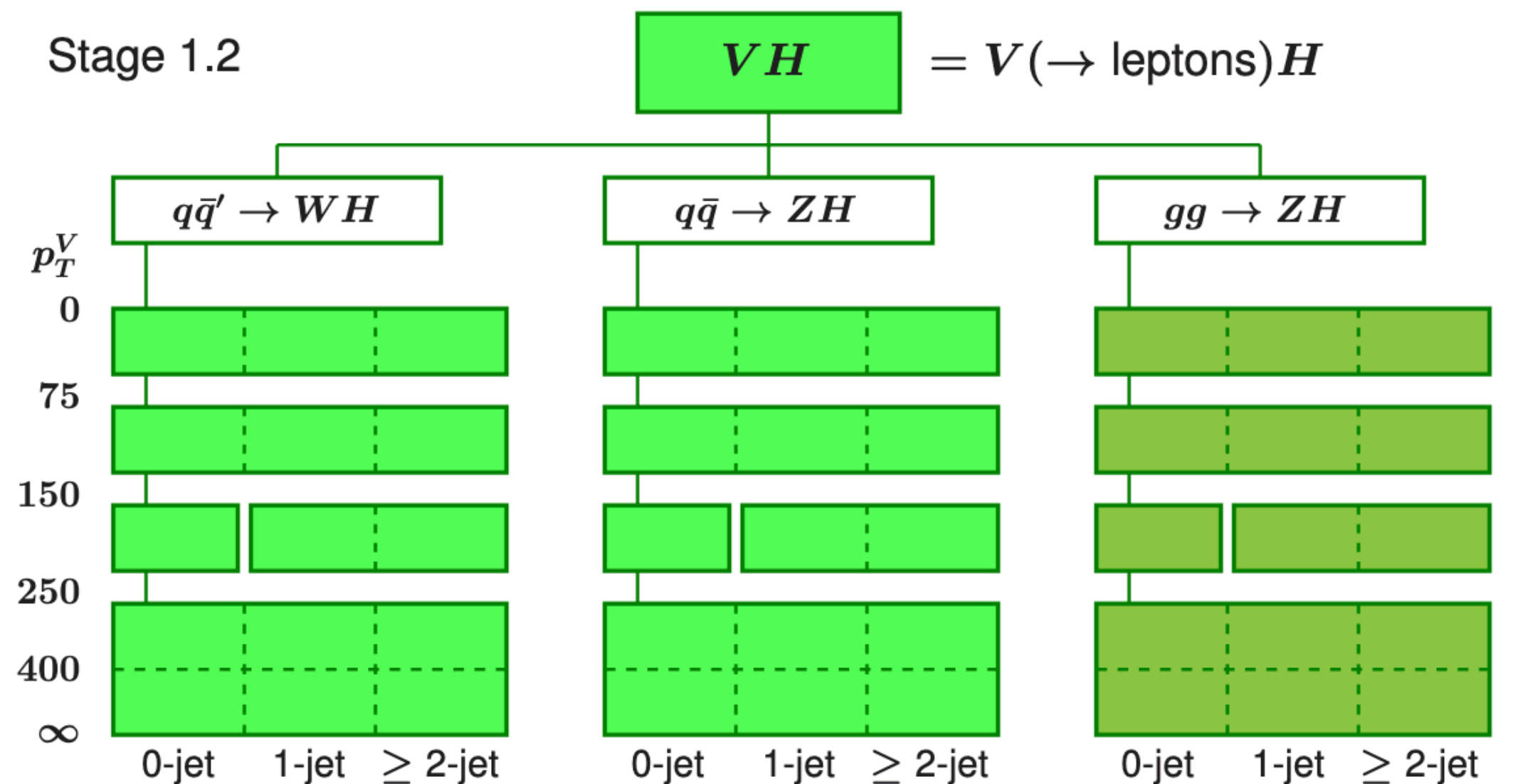
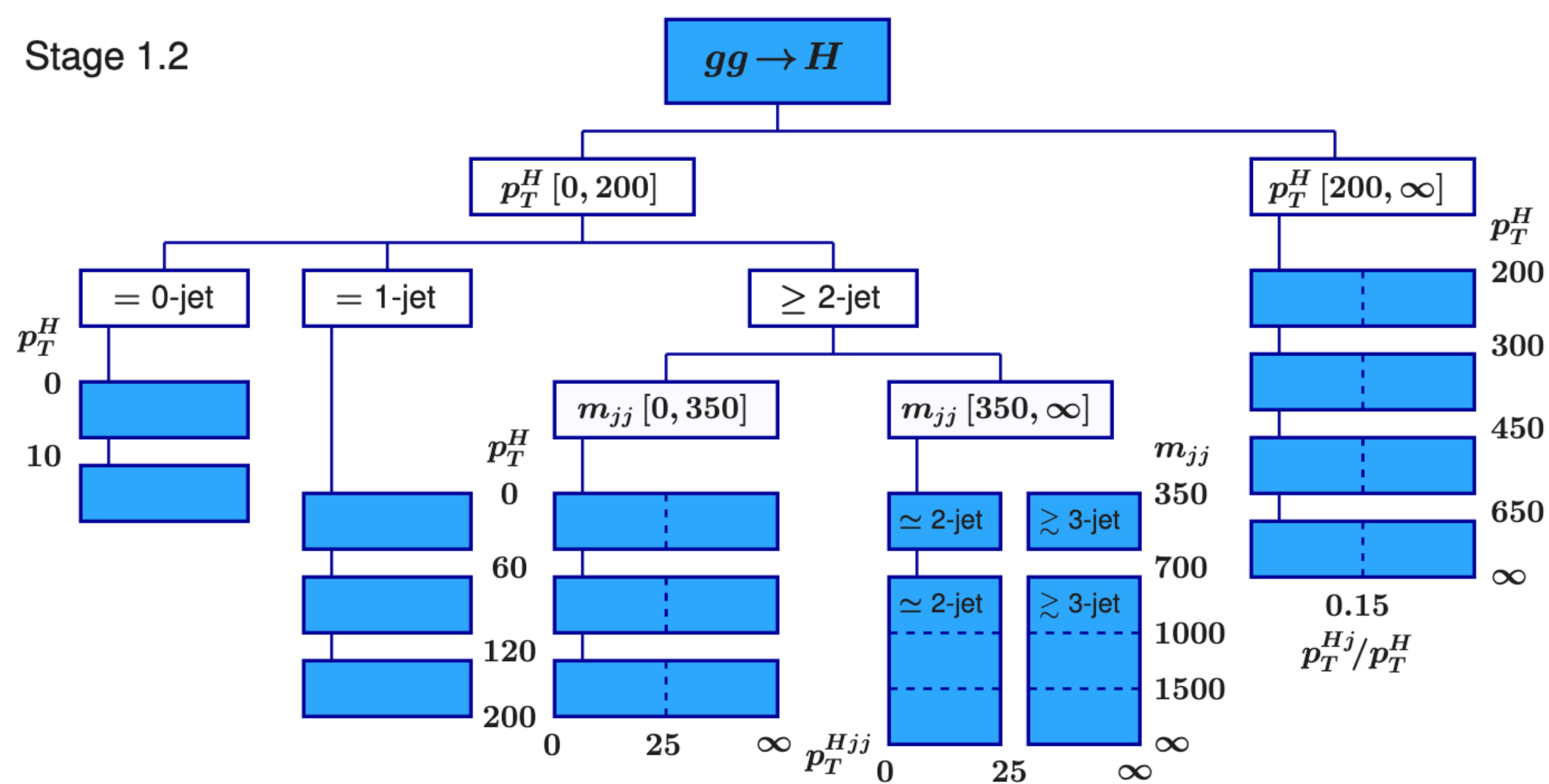
[ATLAS; 2212.05833]



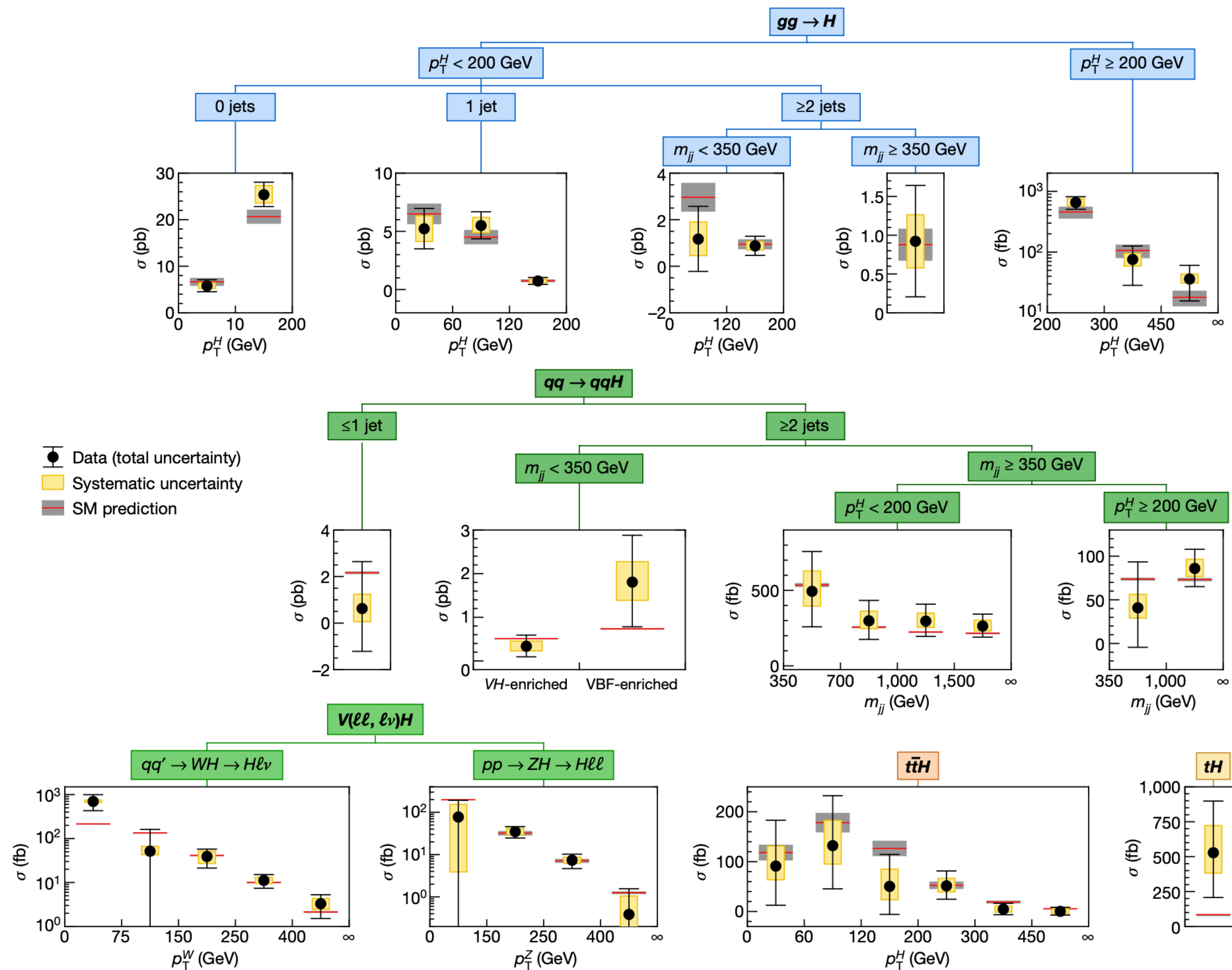
Simplified Template Cross Sections (STXS)

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

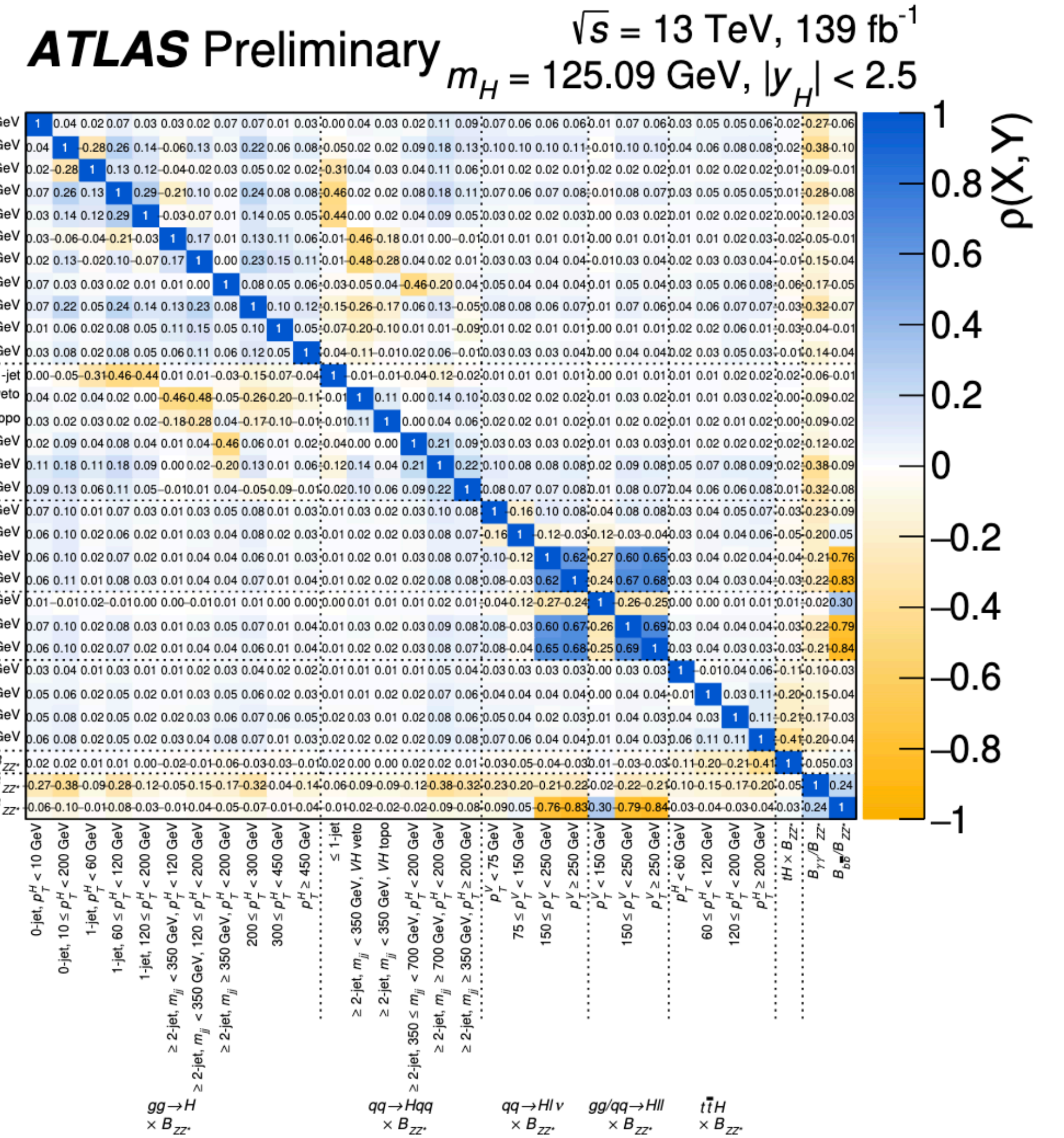
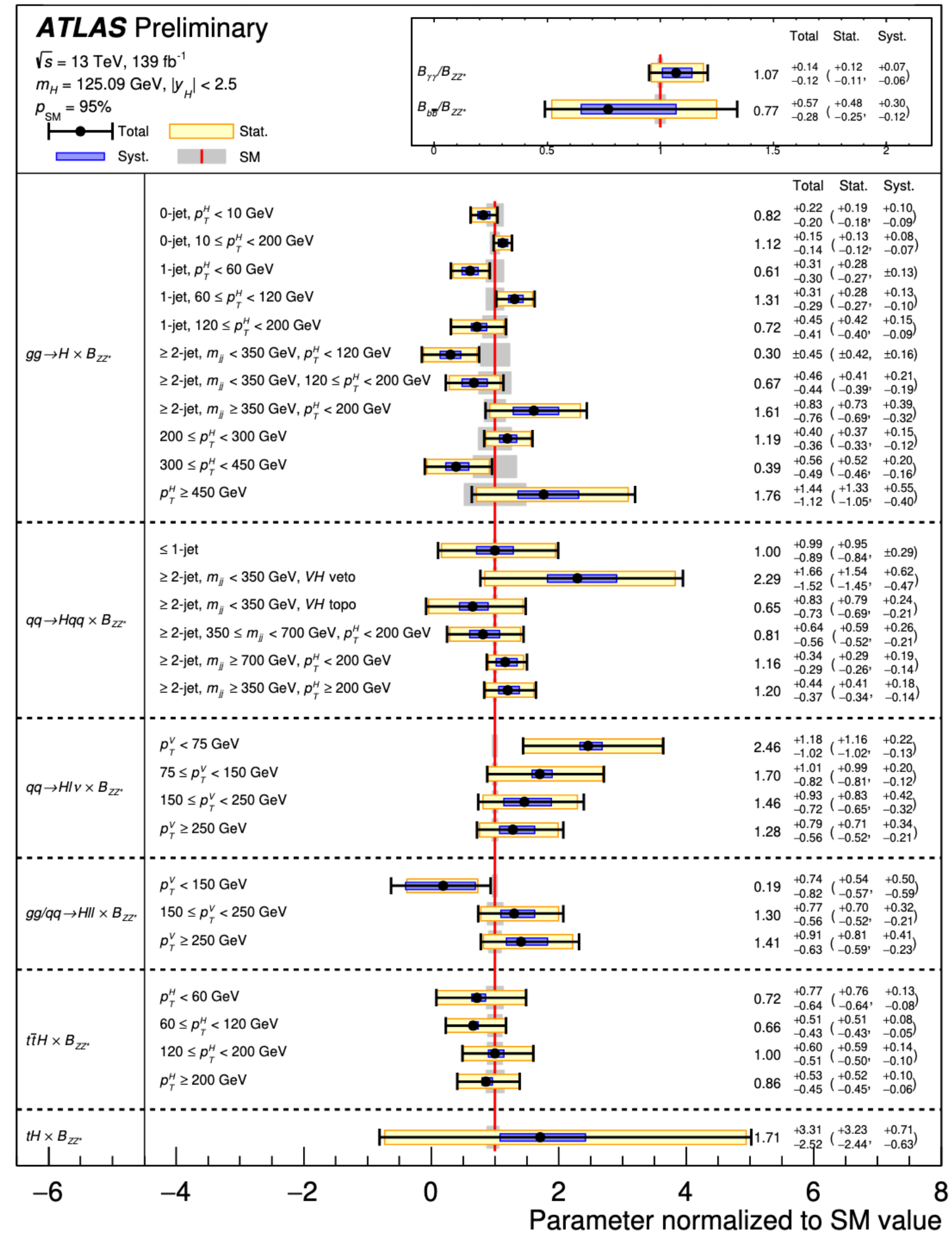


STXS



STXS [ATLAS-CONF-2020-027]

Correlation information crucial!
Interpret beyond κ 's e.g. EFT

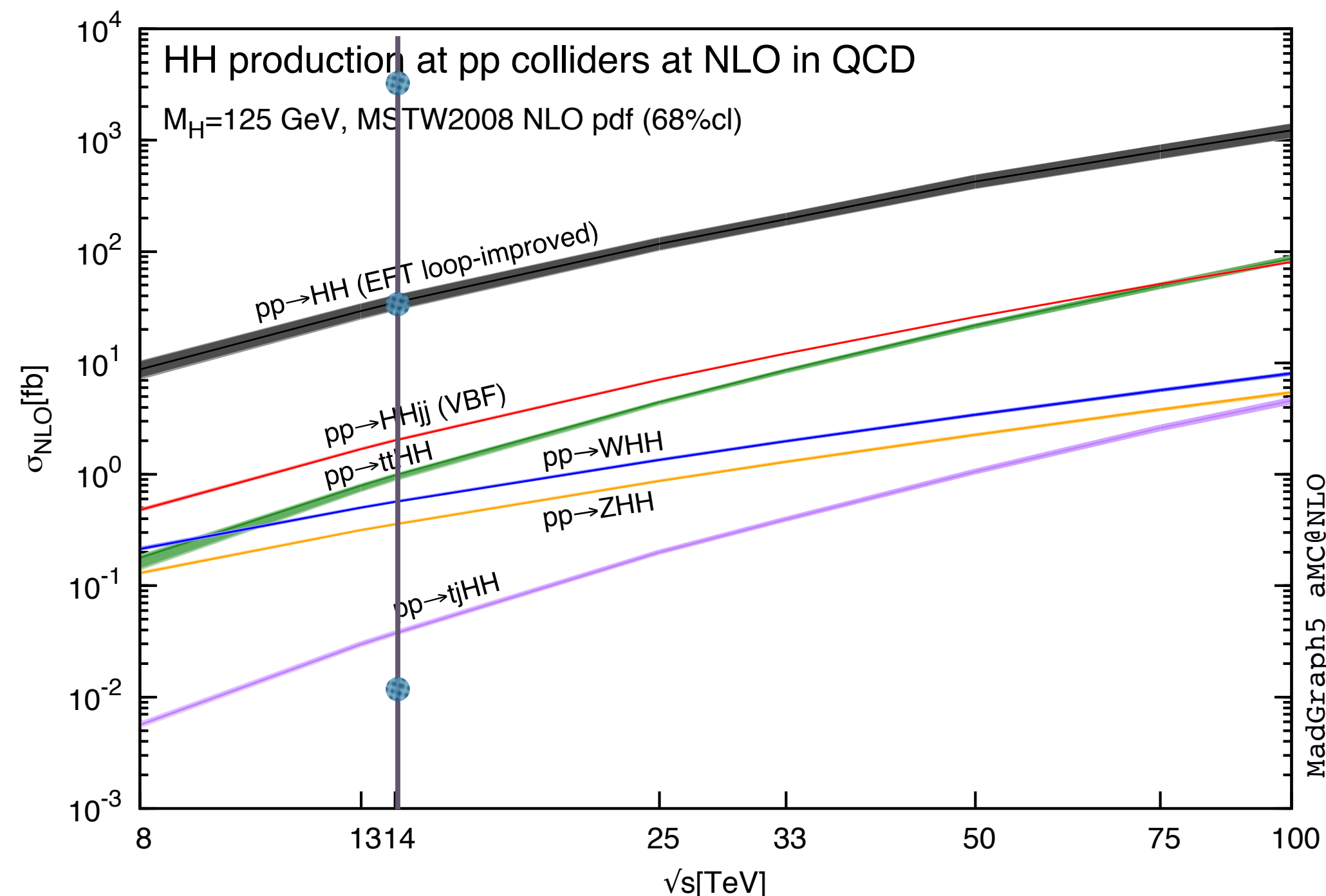


Higgs self-couplings

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

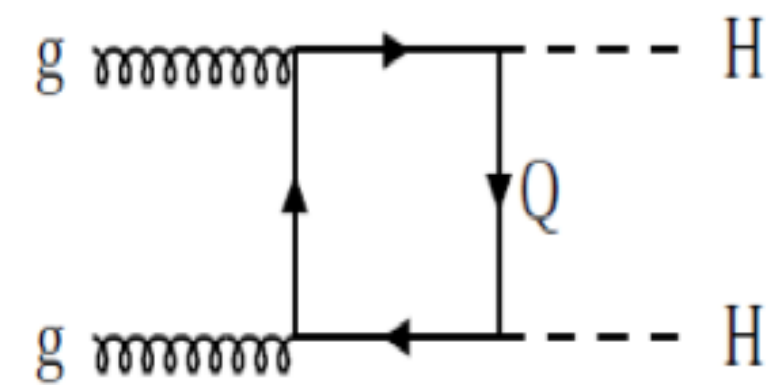
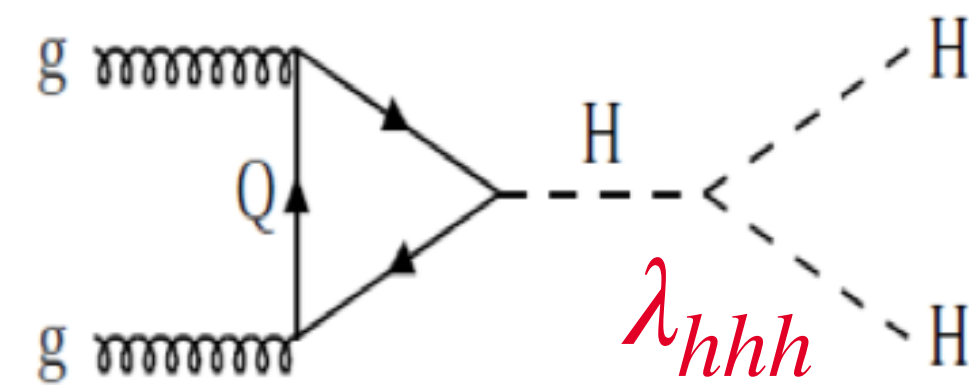
- Measuring λ_{hhh} , λ_{hhhh} tests the SM: **How?**

Multi-Higgs production



Fixed values in the SM

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



At 14 TeV from gg fusion:

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

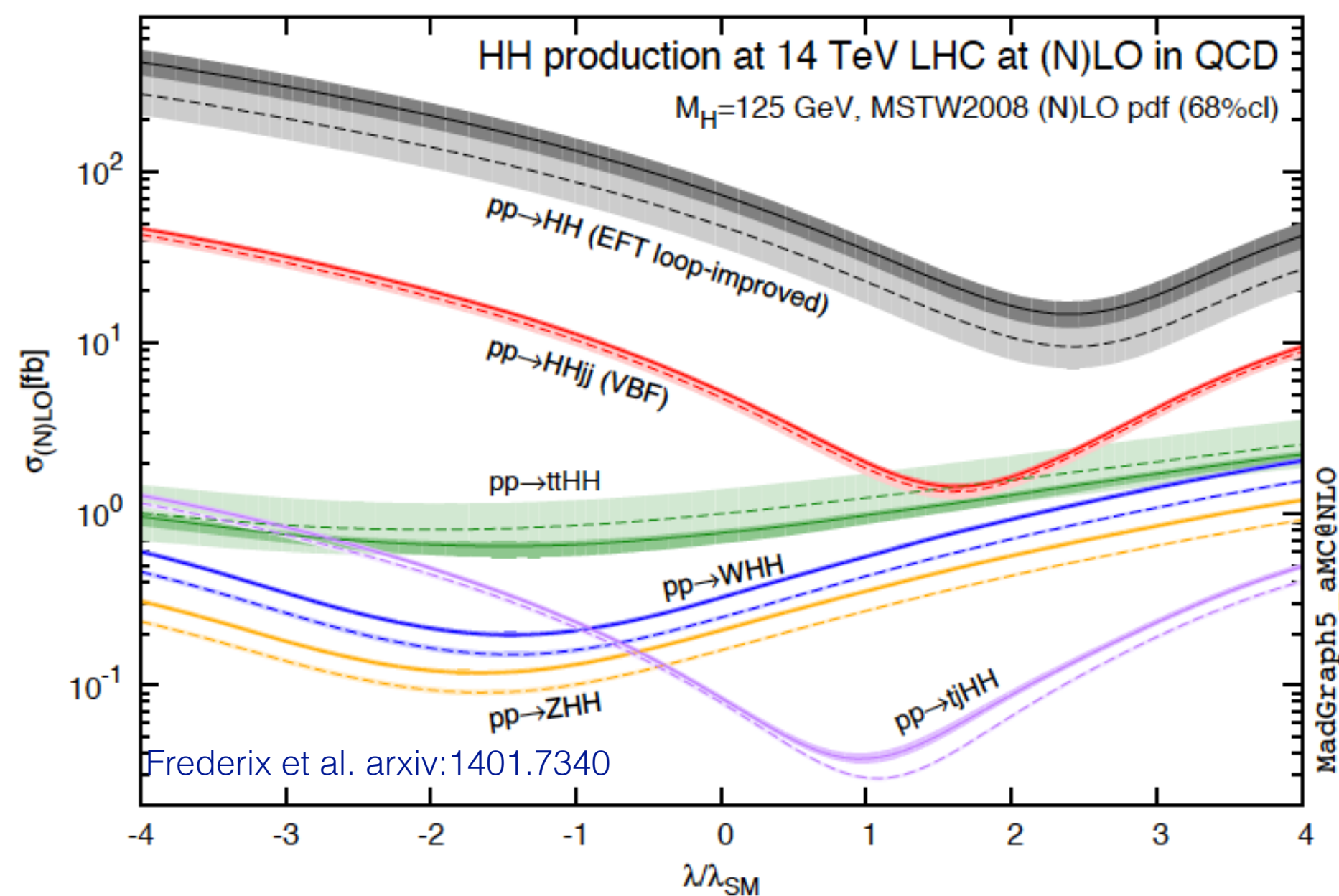
$$\sigma_{HH} = 44 \text{ fb}$$

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

$\times 10^{-3}$
 $\times 10^{-3}$

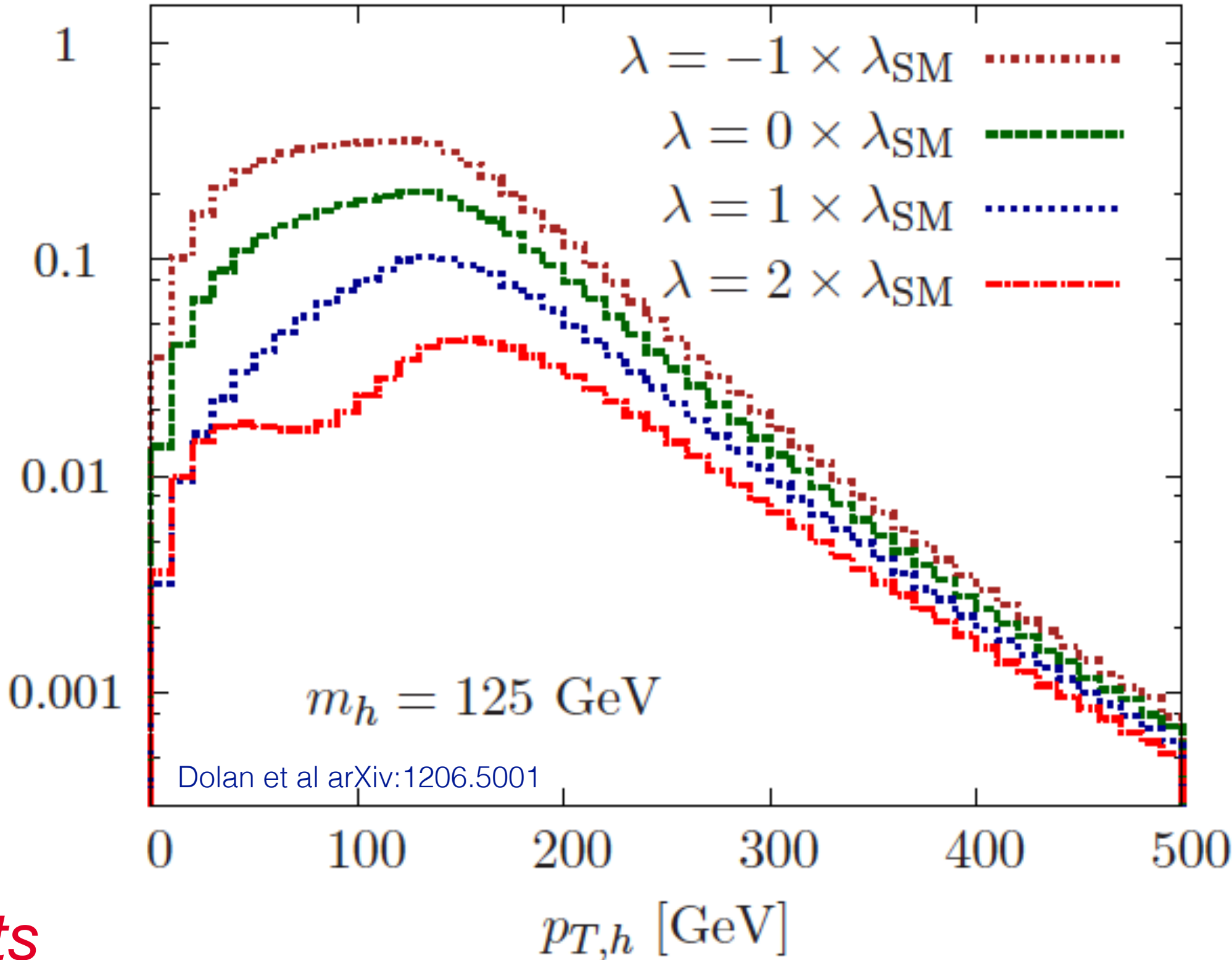
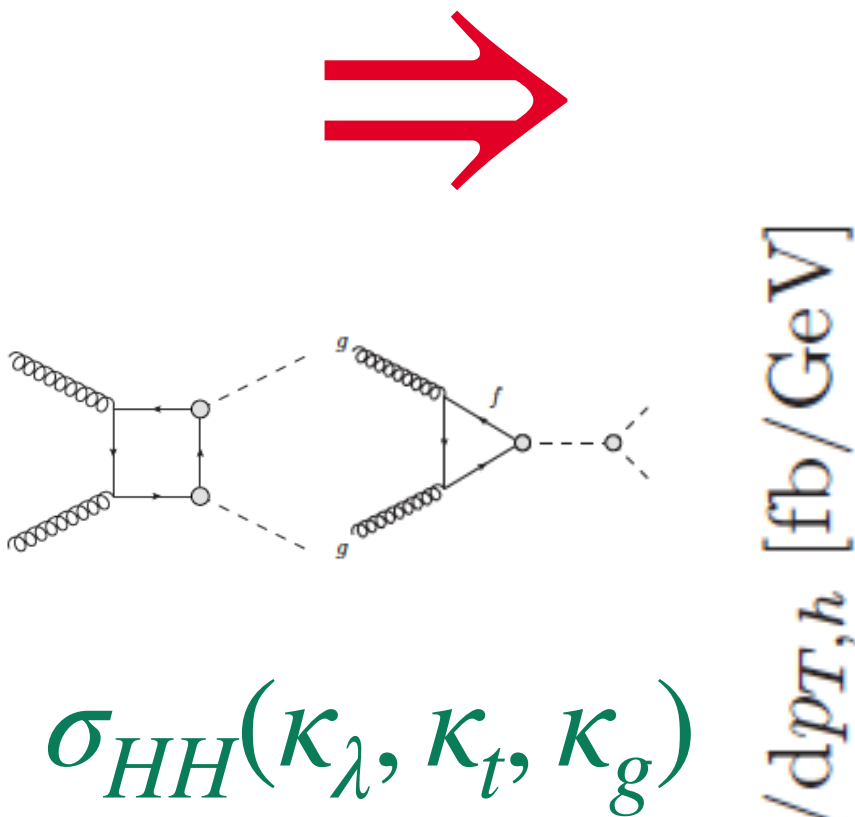
SM: not enough hhh events for HL-LHC ($3ab^{-1}$)

How to extract the Higgs self-coupling



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

Grazzini et al arXiv:1803.02463

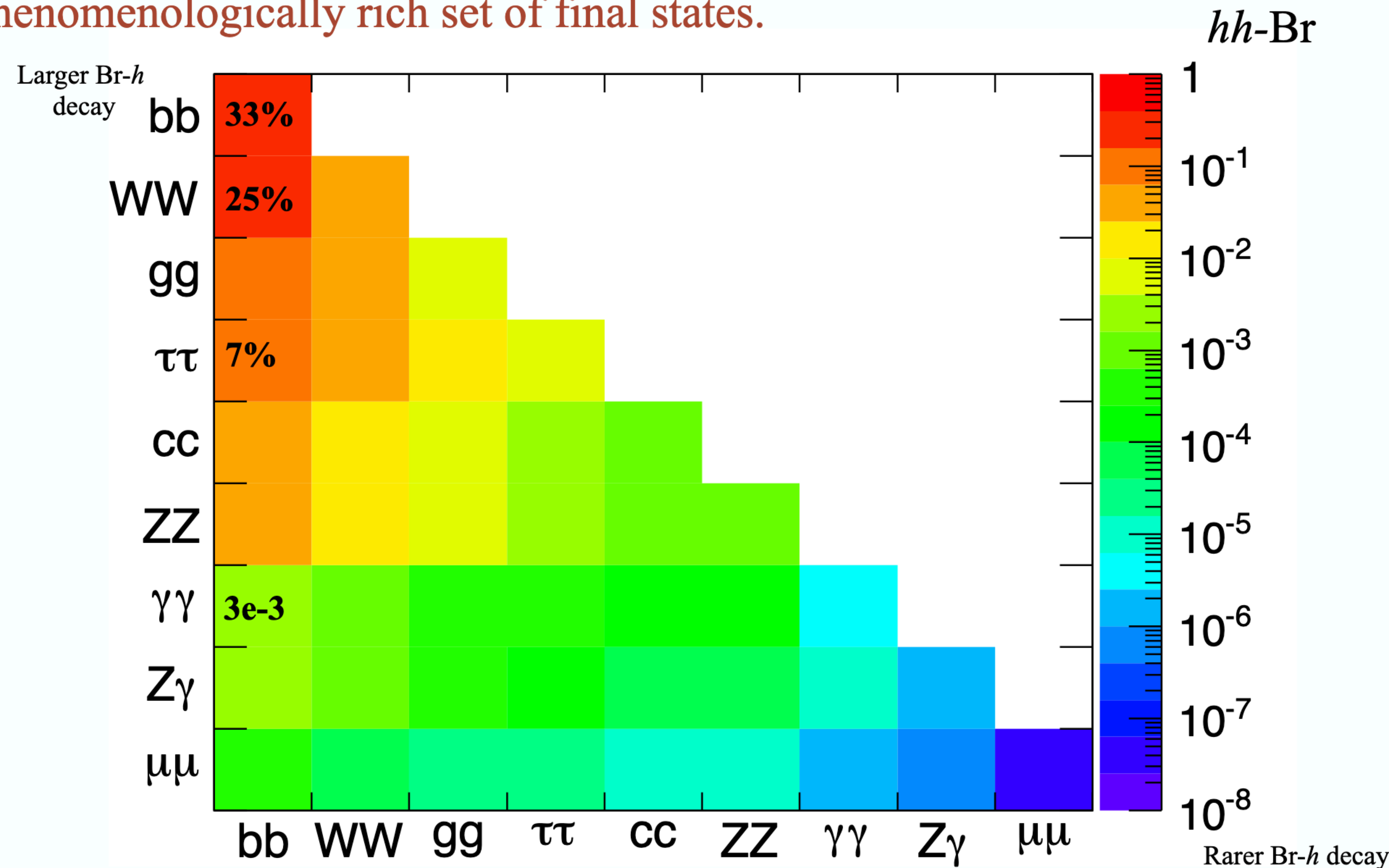


Interference effects
between triangle &
box diagrams

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

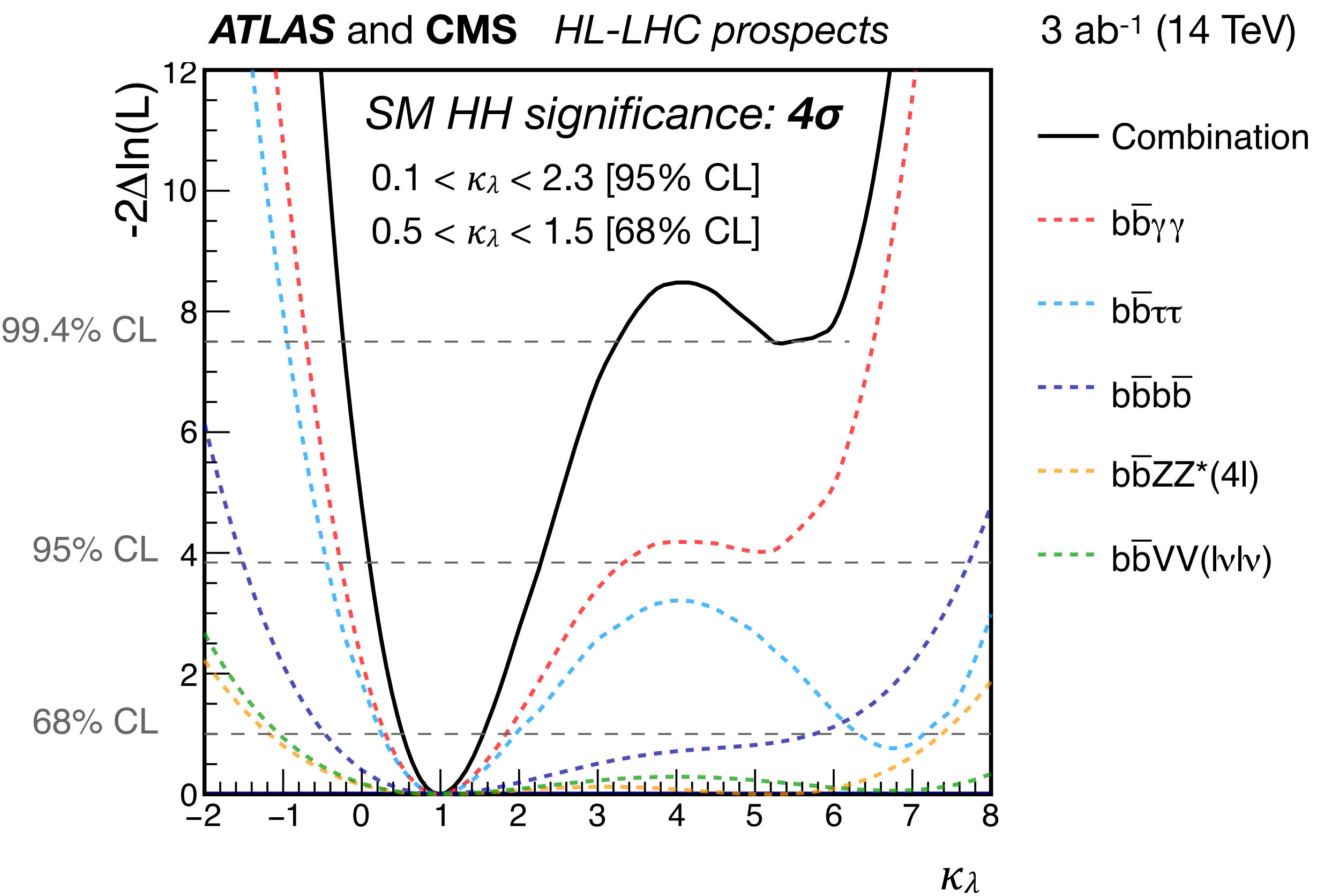
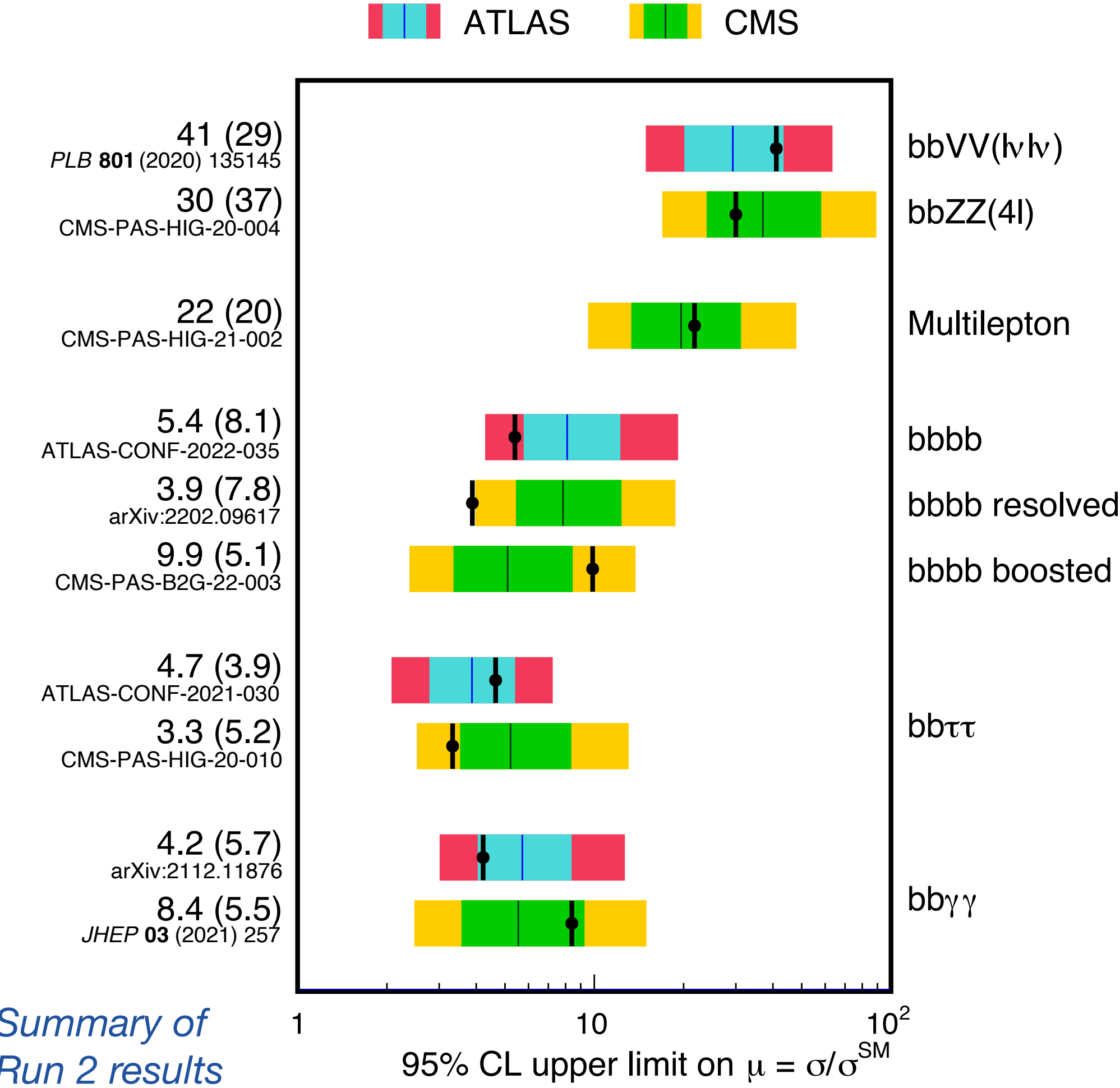
- Missing energy from neutrinos

$\tau\tau$: 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



A challenge even for the HL-LHC

Higgs width

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

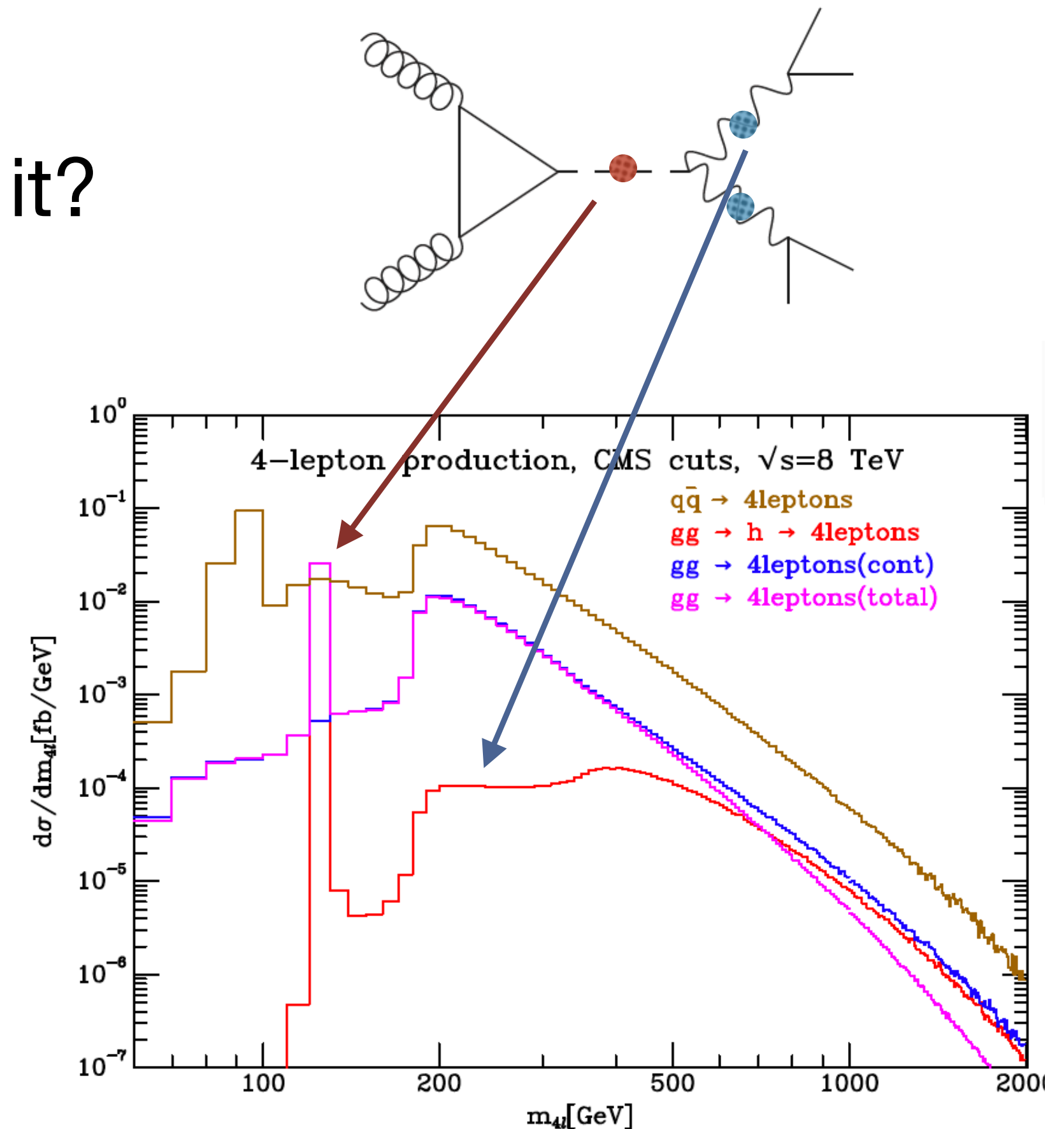
On-shell/Off-shell : $gg \rightarrow ZZ \rightarrow 4\text{leptons}$

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

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

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

$$\text{CMS: } \Gamma_H = 3.2_{-1.7}^{+2.4} \text{ MeV}$$



beware: model dependent

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 $h \rightarrow \chi\chi$
- Light scalar or vector $m_X < m_H - m_Z$: $h \rightarrow ZX$

Higgs is a natural portal to new physics:

- No symmetries to prevent BSM coupling via portal

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

$|H|^2 \mathcal{O}_{\text{BSM}}$ ($= \chi\bar{\chi}, SS, \dots$)

- If light new physics exists, there is a good chance that the Higgs might decay into it

For $h \rightarrow XY$ 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 $\Gamma_h = \Gamma_h^{\text{SM}} + \Gamma_{\text{unobs.}}$

- If nothing else about the Higgs couplings is modified

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

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

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

Strong assumption!

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

Indirect constraints

μ_i combination

Fix $B_{i,u} = 0$

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

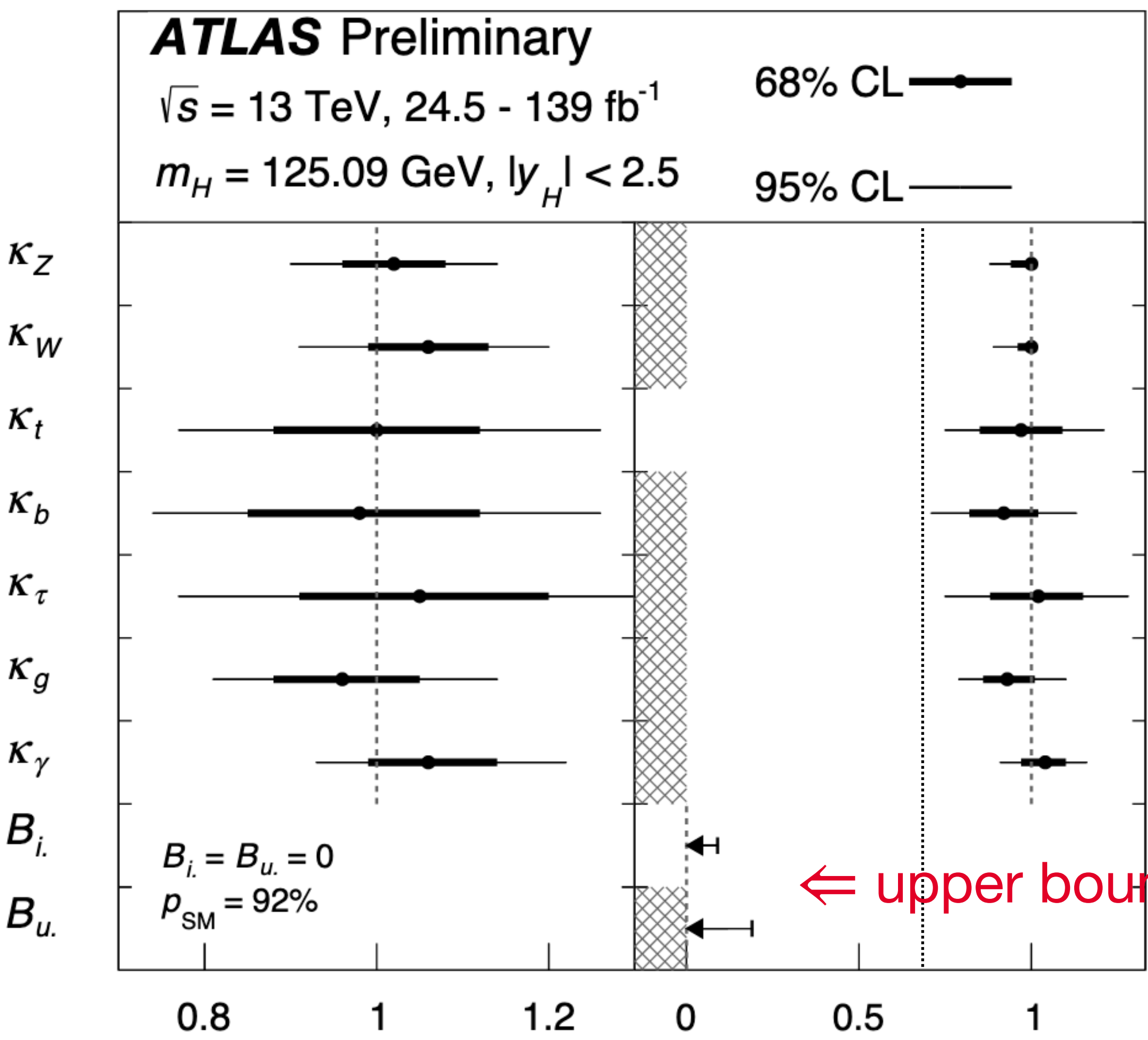
$\kappa_{Z,W} < 0$

Not possible otherwise

Moderate impact
on other κ_i

$h \rightarrow$ invisible

$h \rightarrow$ unobserved



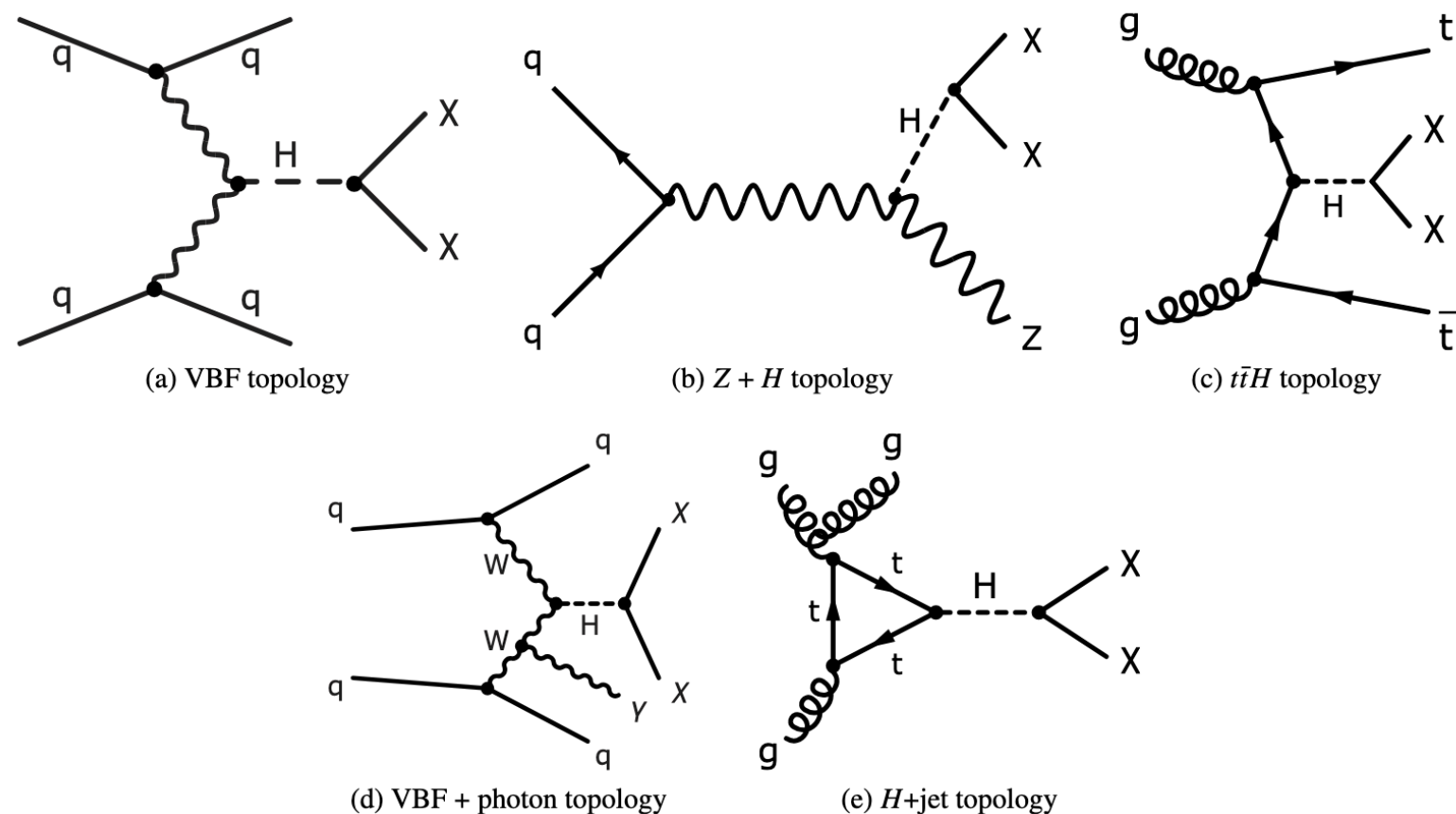
Parameter	(a) $B_i = B_u = 0$	(b) B_i free, $B_u \geq 0, \kappa_{W,Z} \leq 1$
κ_Z	1.02 ± 0.06	> 0.88 at 95% CL
κ_W	1.06 ± 0.07	> 0.89 at 95% CL
κ_b	$0.98^{+0.14}_{-0.13}$	0.92 ± 0.10
κ_t	1.00 ± 0.12	0.97 ± 0.12
κ_τ	$1.05^{+0.15}_{-0.14}$	$1.02^{+0.13}_{-0.14}$
κ_γ	$1.06^{+0.08}_{-0.07}$	$1.04^{+0.06}_{-0.07}$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

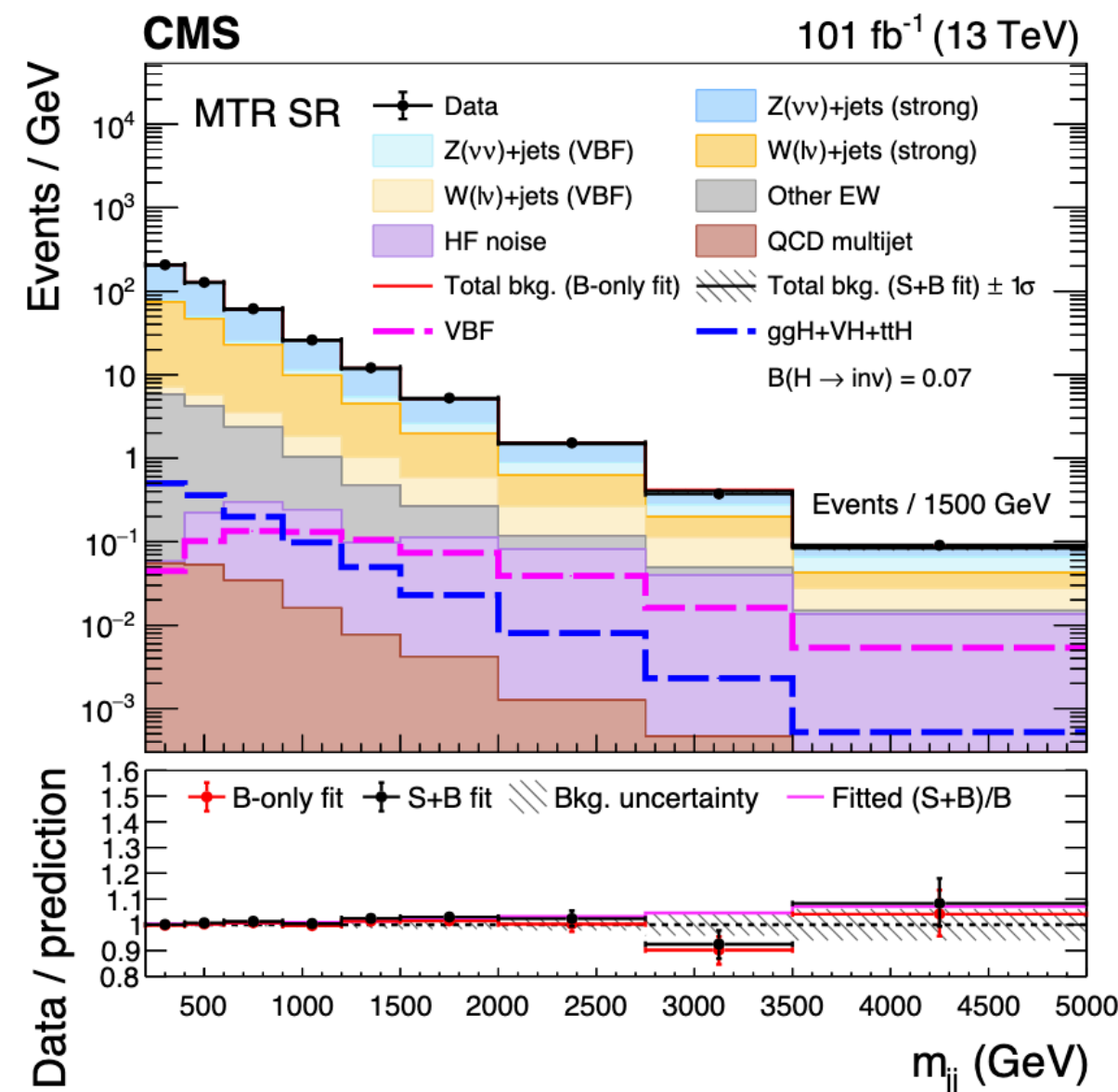
$$pp \rightarrow X + (h \rightarrow \text{MET})$$

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)

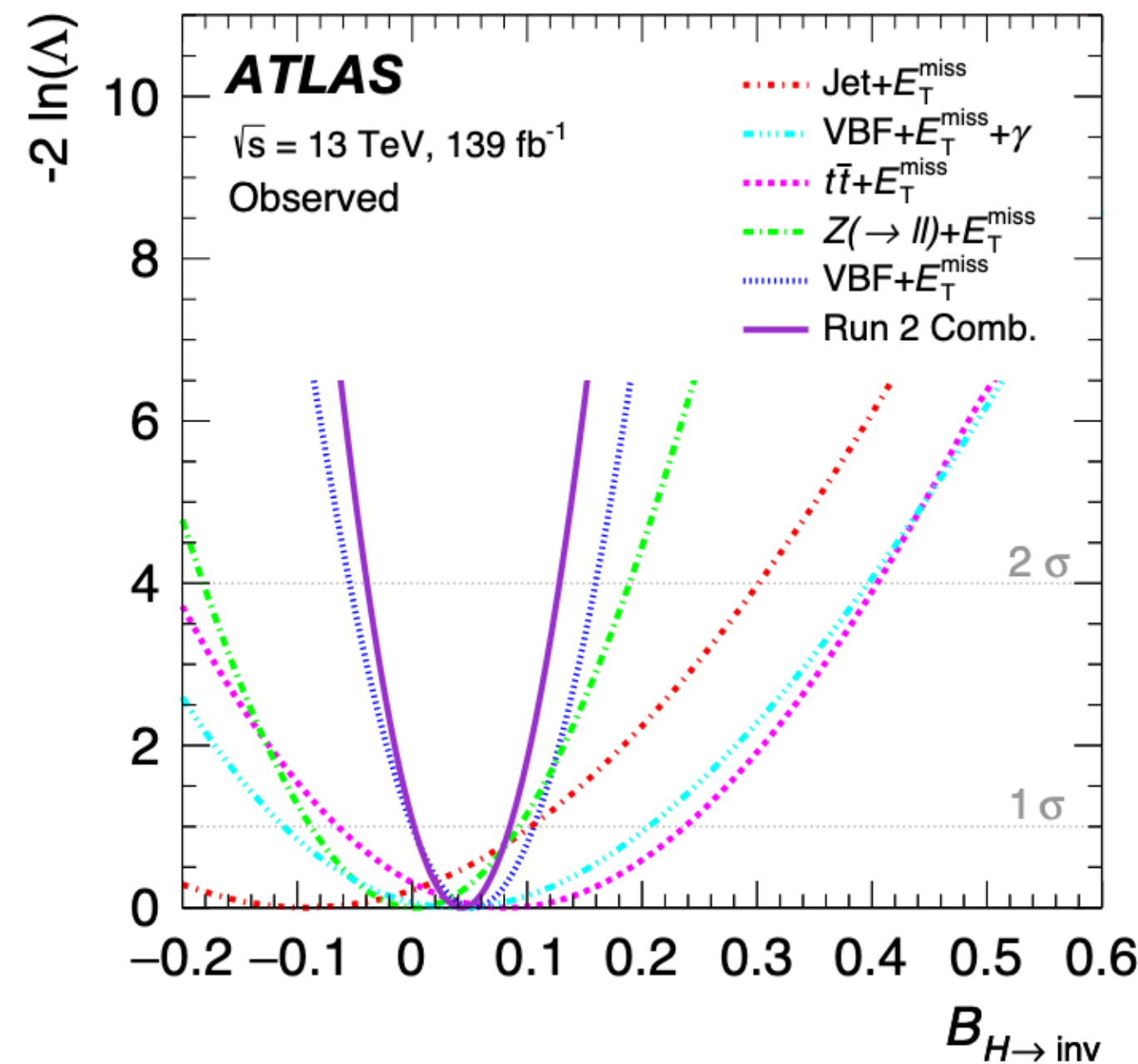


VBF: [\[CMS; 2201.11585\]](#)

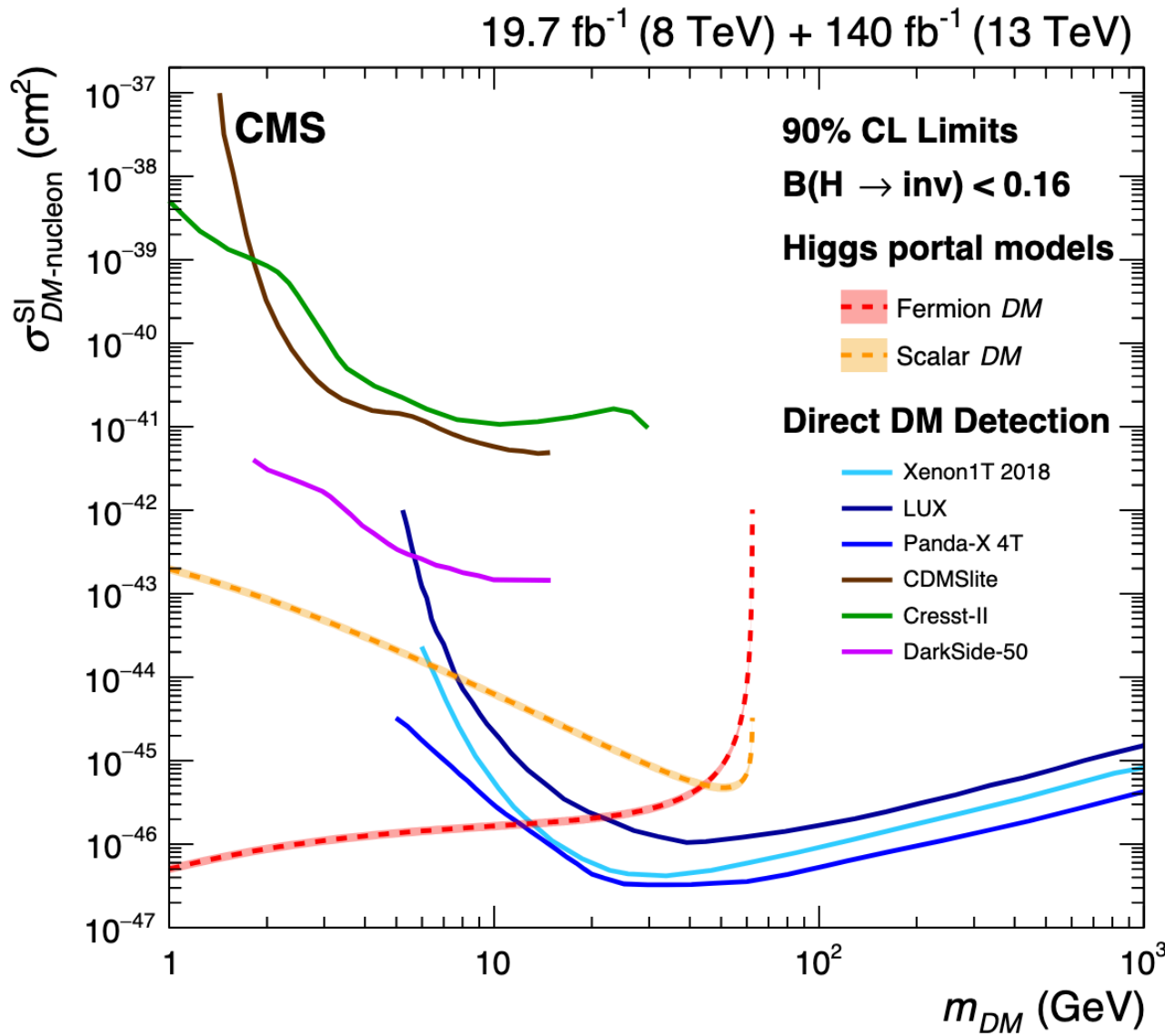
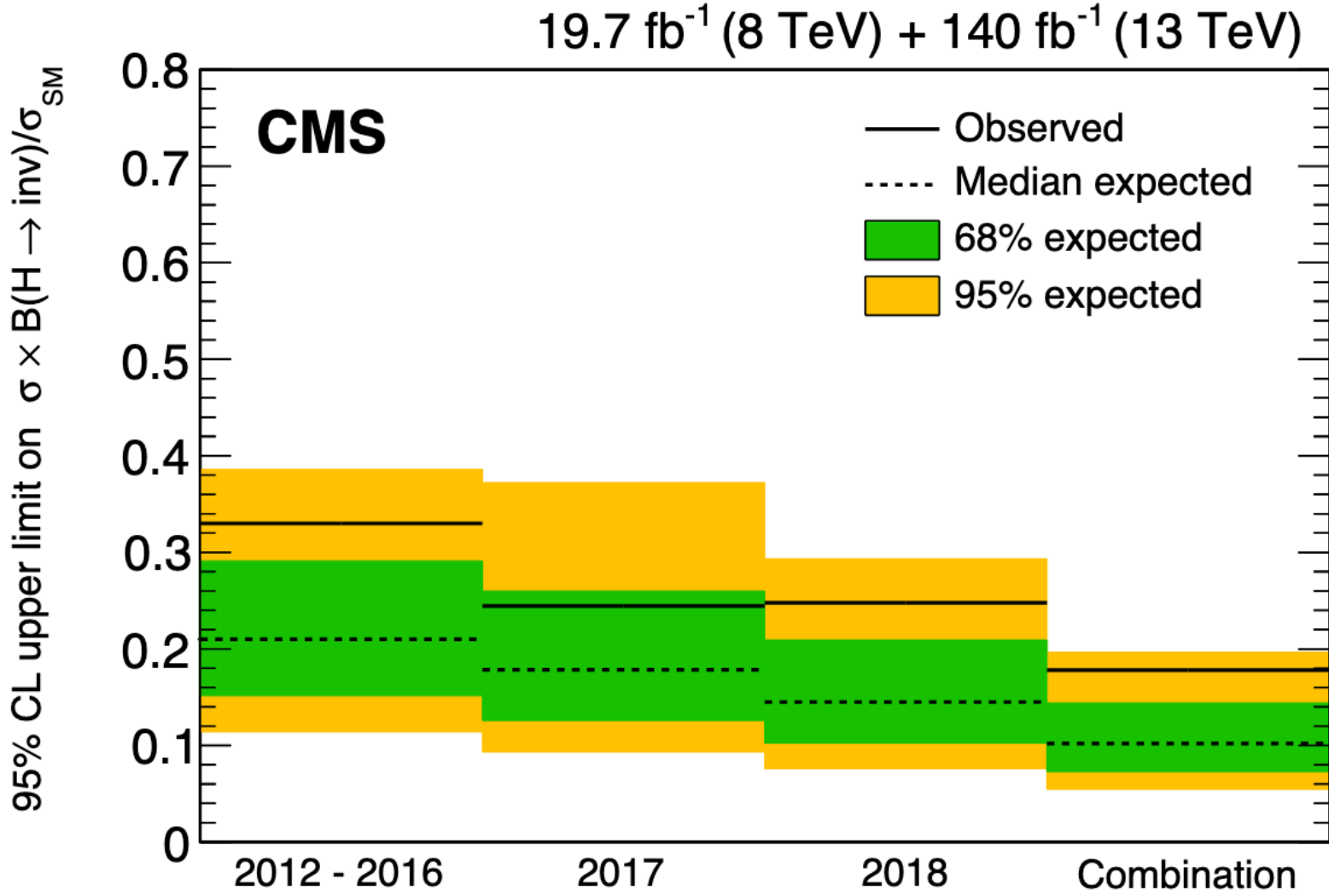


[\[ATLAS; 2301.10731\]](#)

$BR_{inv.} < 0.113$ @ 95% C.L.

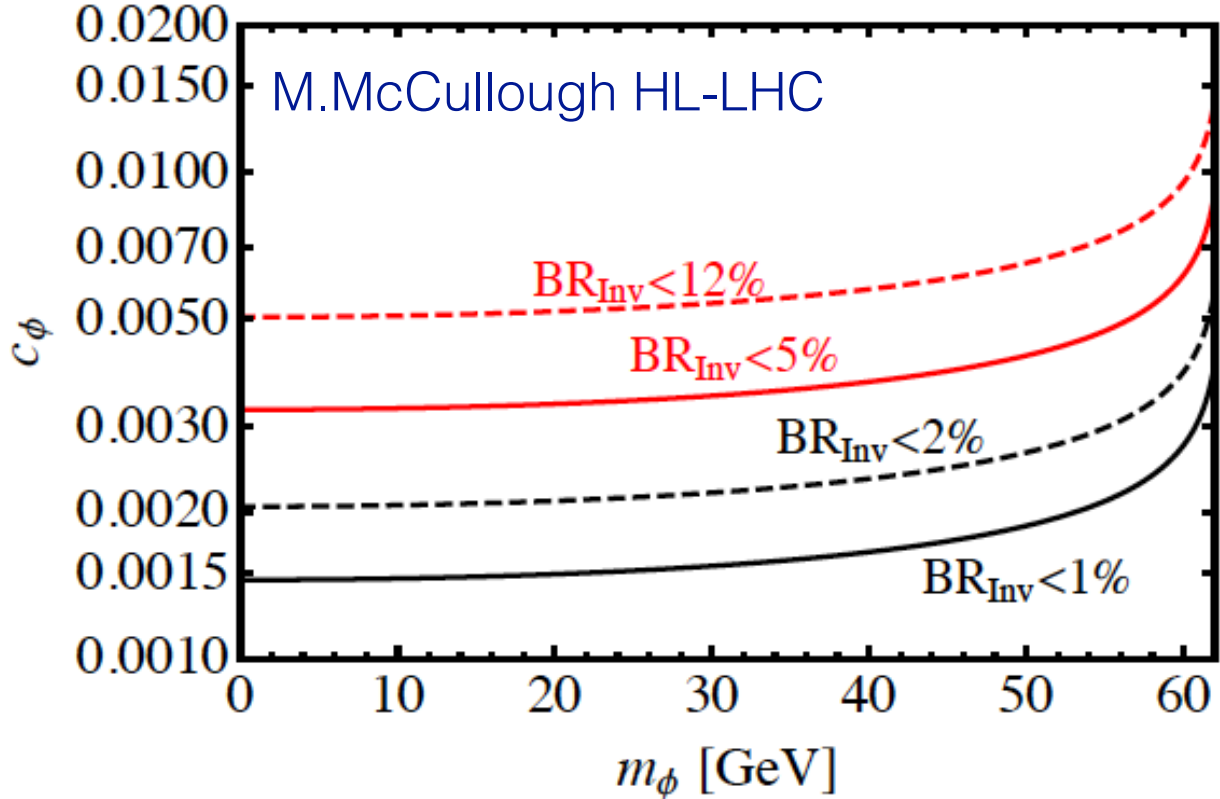


Searching for the invisible



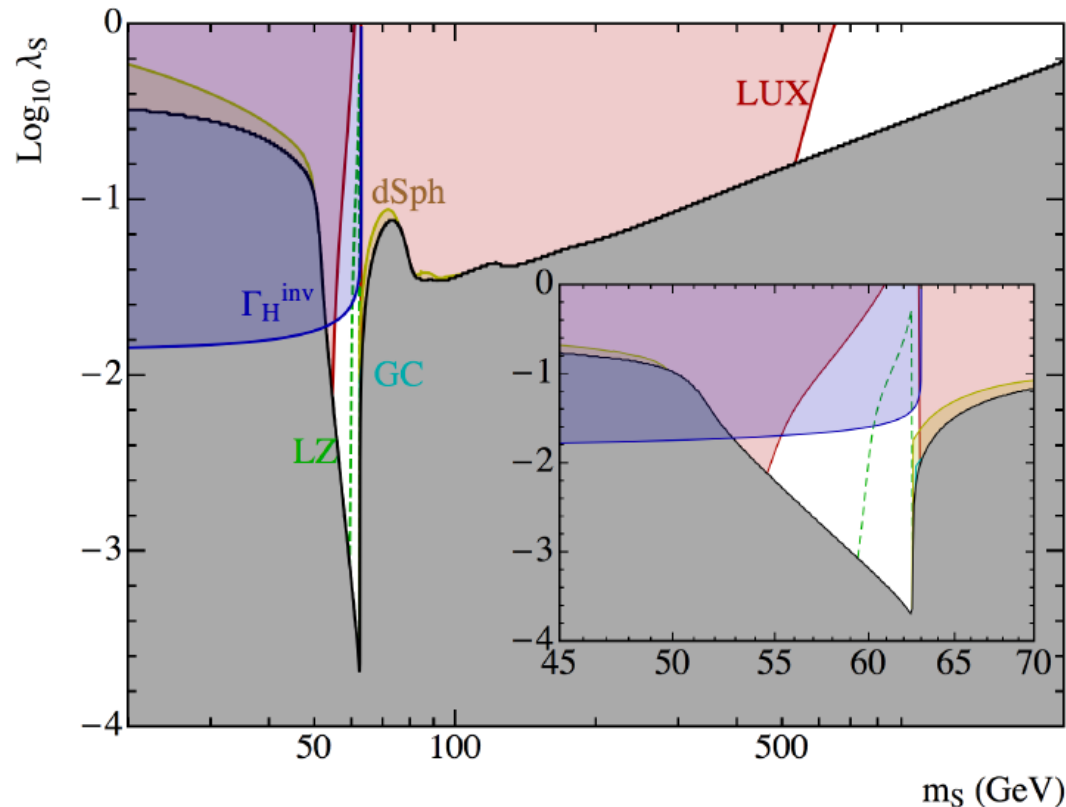
Important
Dark Matter
implications

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



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

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

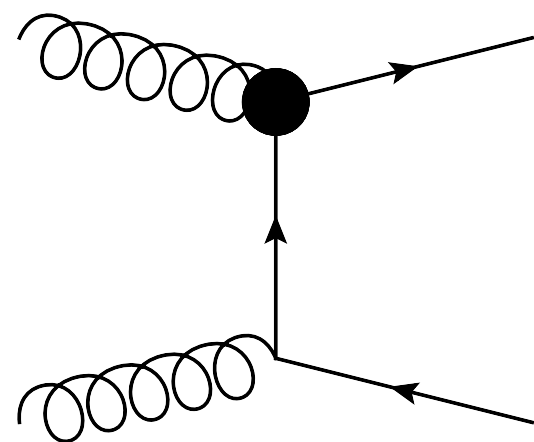


Casas et al arXiv:1701.08134

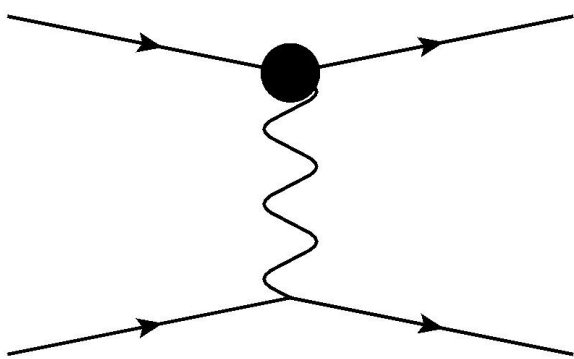
LHC is a top factory

Rich phenomenology:

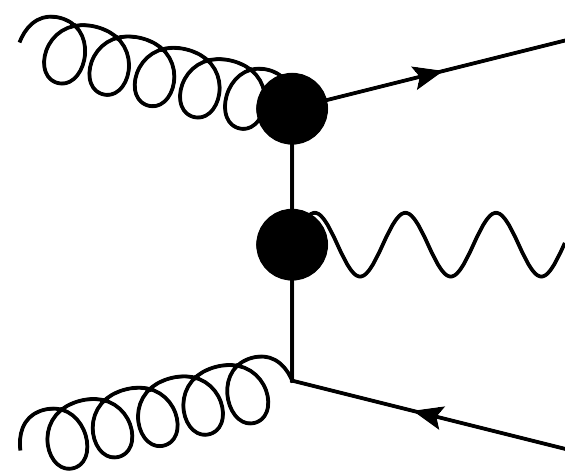
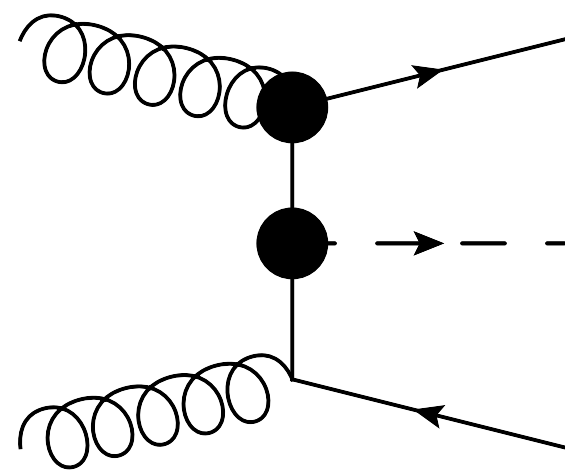
pair production



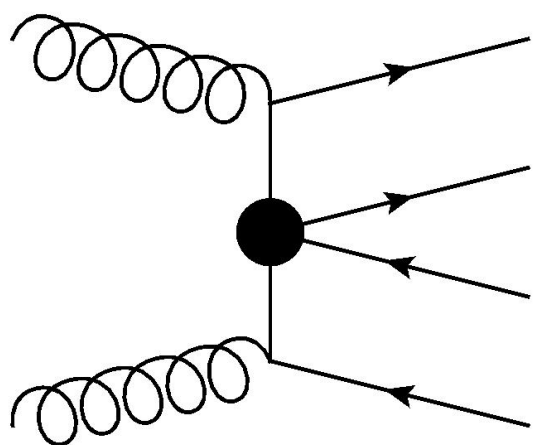
single



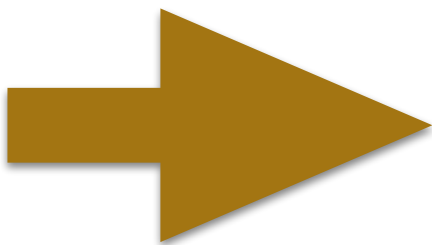
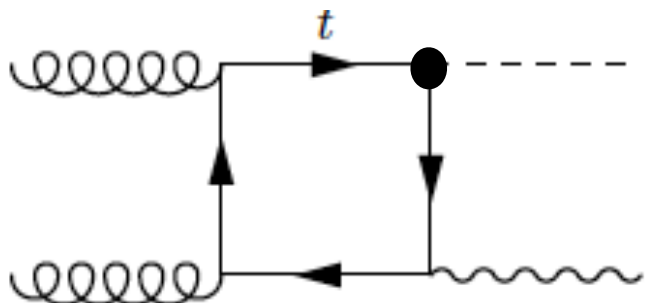
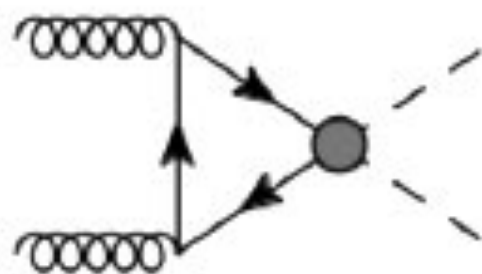
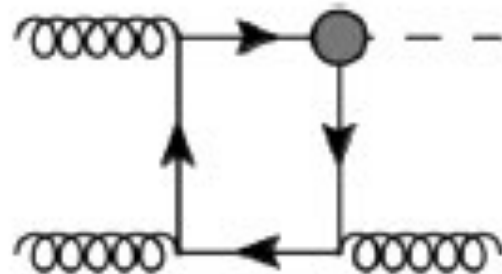
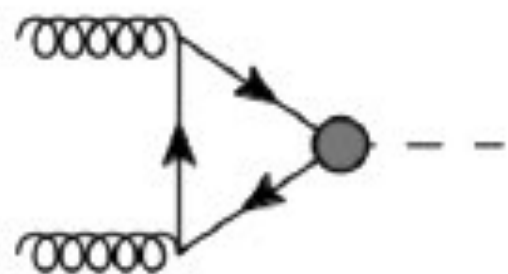
associated production



4 tops



top loops



connection to Higgs physics

Top physics

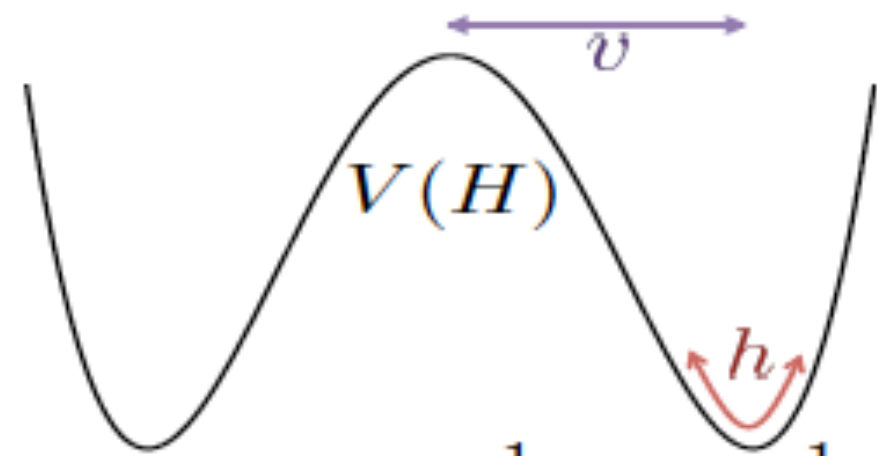
Why study the top quark ?

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

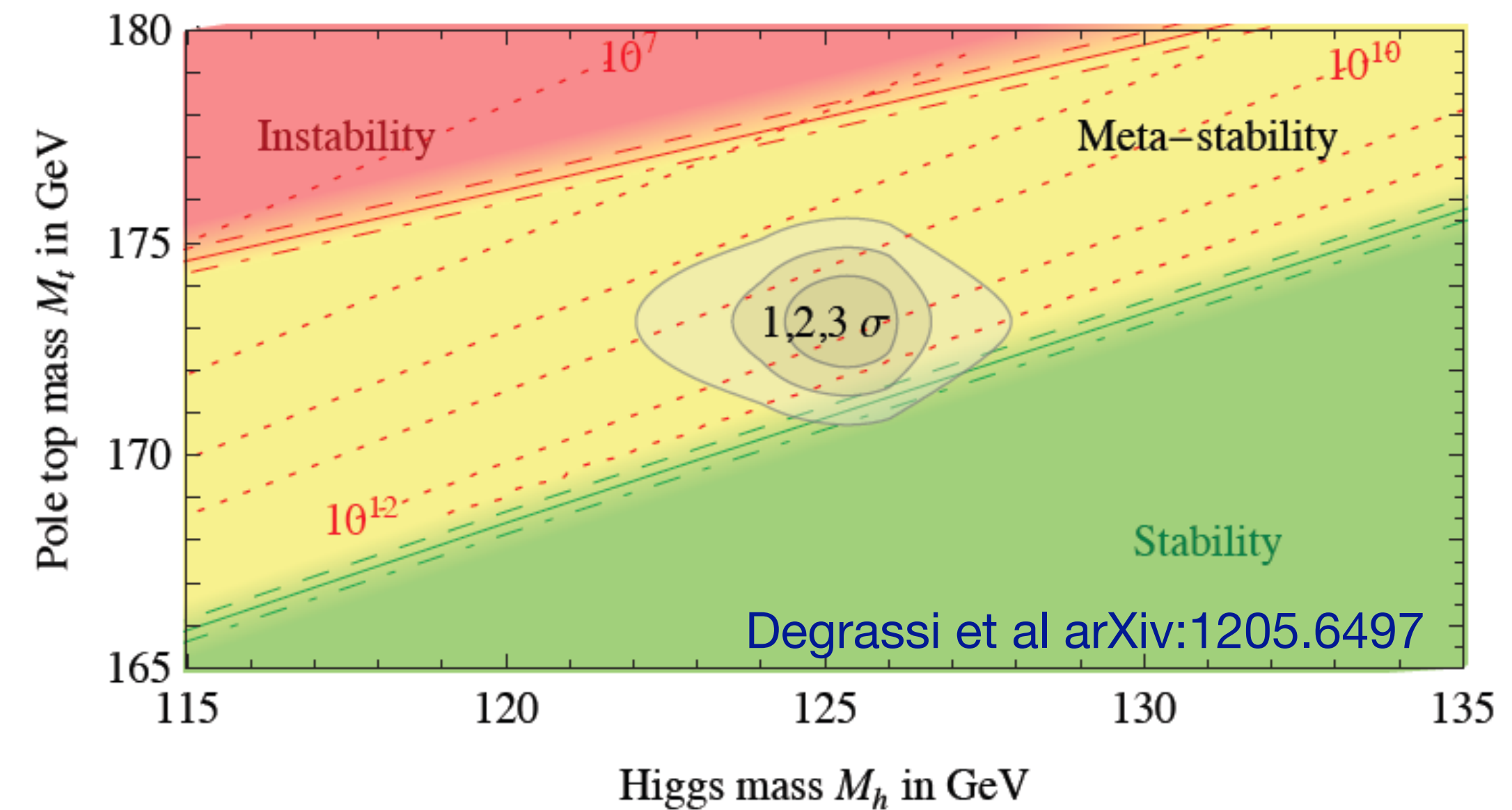
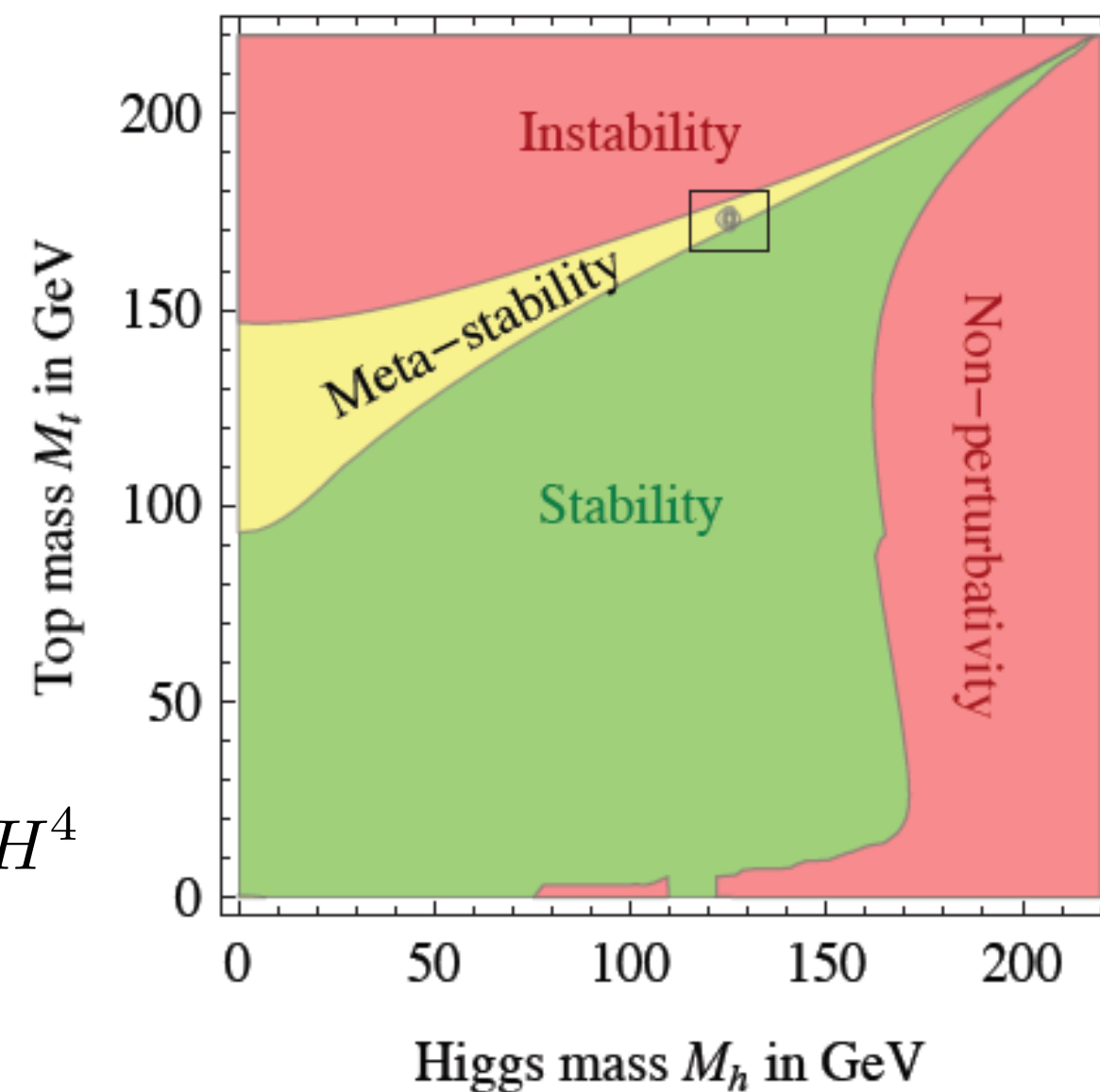
Top has a special place in the Universe

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)!

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

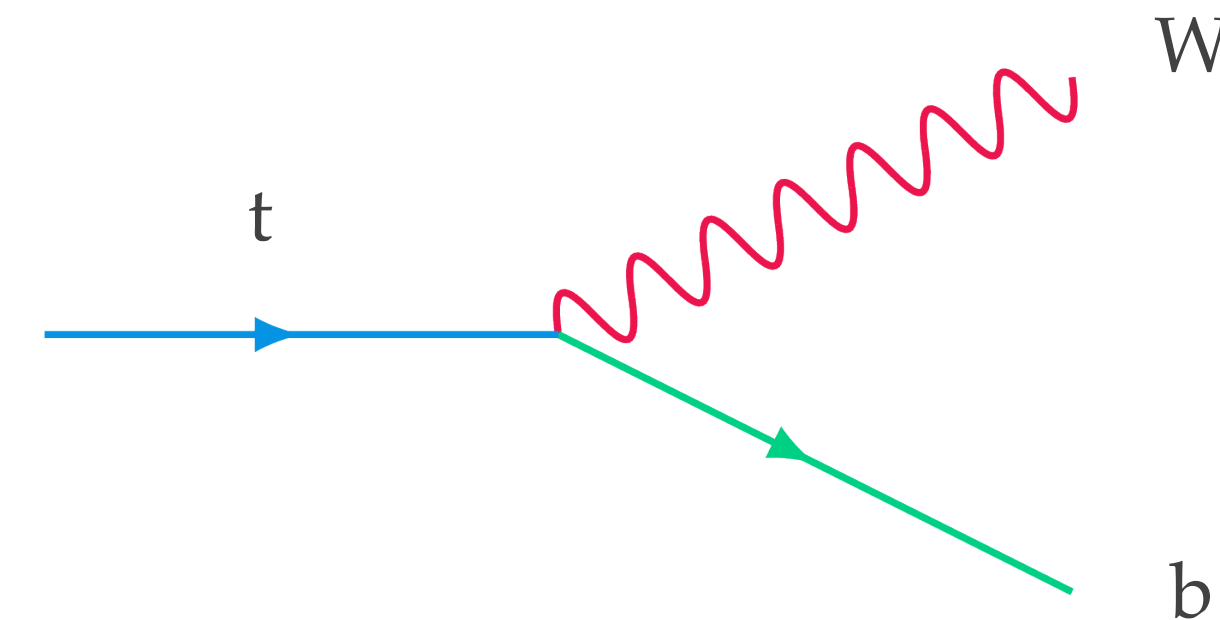
$$h_t(M_t) = 0.93587 + 0.00557 \left(\frac{M_t}{\text{GeV}} - 173.15 \right) \dots \pm 0.00200_{\text{th}} \quad \text{Top Yukawa!}$$

Top quark is a special quark

Spin Correlations

The top decays before hadronising

Spin information is preserved!

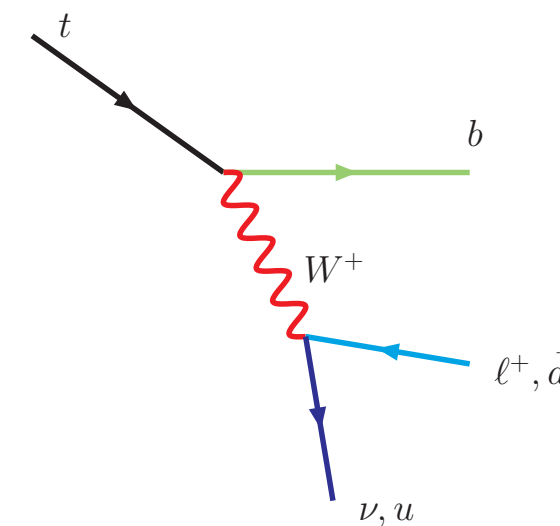


$$\tau_{\text{had}} \approx \hbar/\Lambda_{\text{QCD}} \approx 2 \cdot 10^{-24} \text{ s}$$

$$\tau_{\text{top}} \approx \hbar/\Gamma_{\text{top}} = 1/(GF m_t^3 |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25} \text{ s}$$

(with $\hbar = 6.6 \cdot 10^{-25} \text{ GeV s}$)

Top Spin effects



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

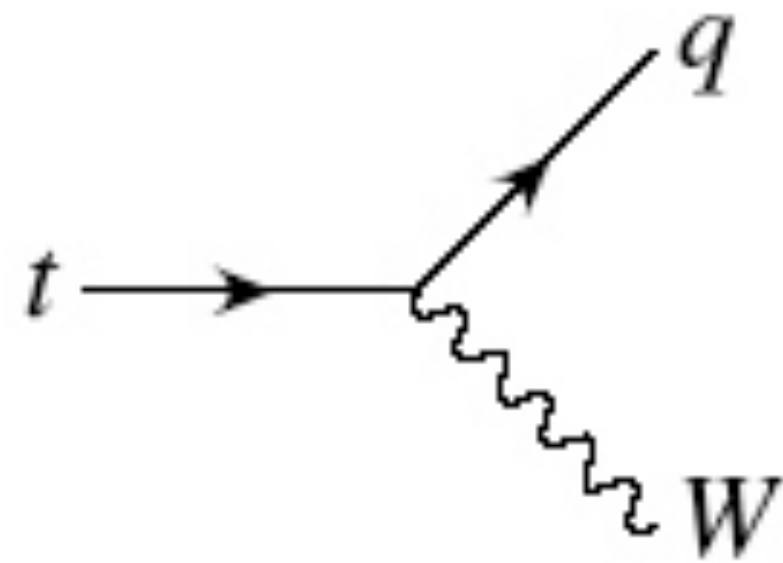
k_i	ℓ^+	$\bar{d}$	u	b
LO:	1	1	-0.32	-0.39
NLO:	0.999	0.97	-0.31	-0.37

Lepton+ or d emitted in the top spin direction

Spin analysing power

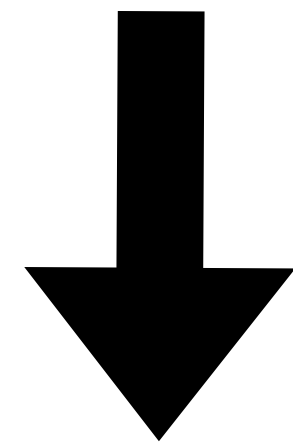
We can check how the top is produced!

Weak interaction and W polarisation

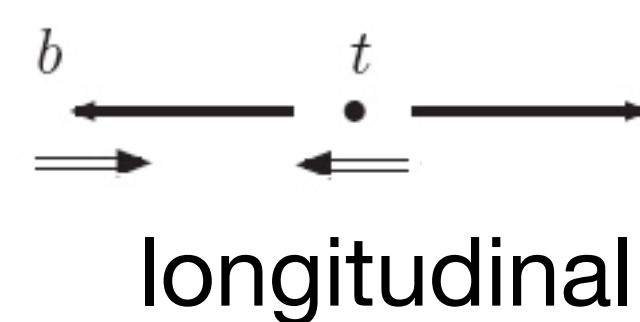


$$-i \frac{g}{\sqrt{2}} V_{tq} \gamma^\mu \frac{1}{2} (1 - \gamma^5)$$

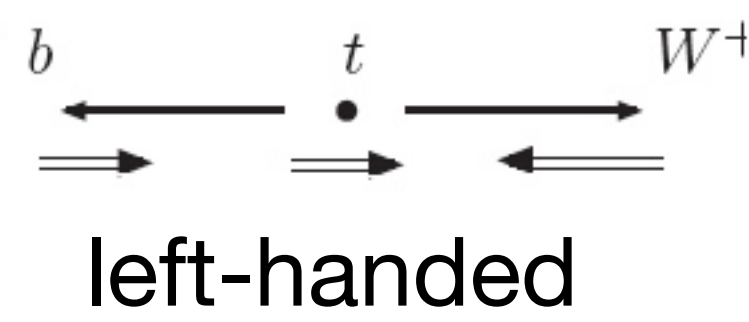
Only left-handed tops in the decay!



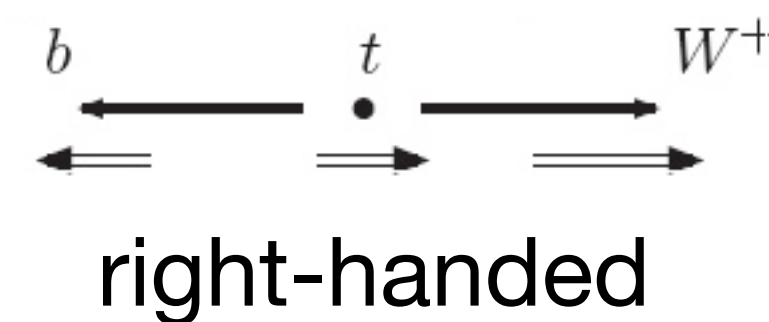
Helicities of W bosons



?



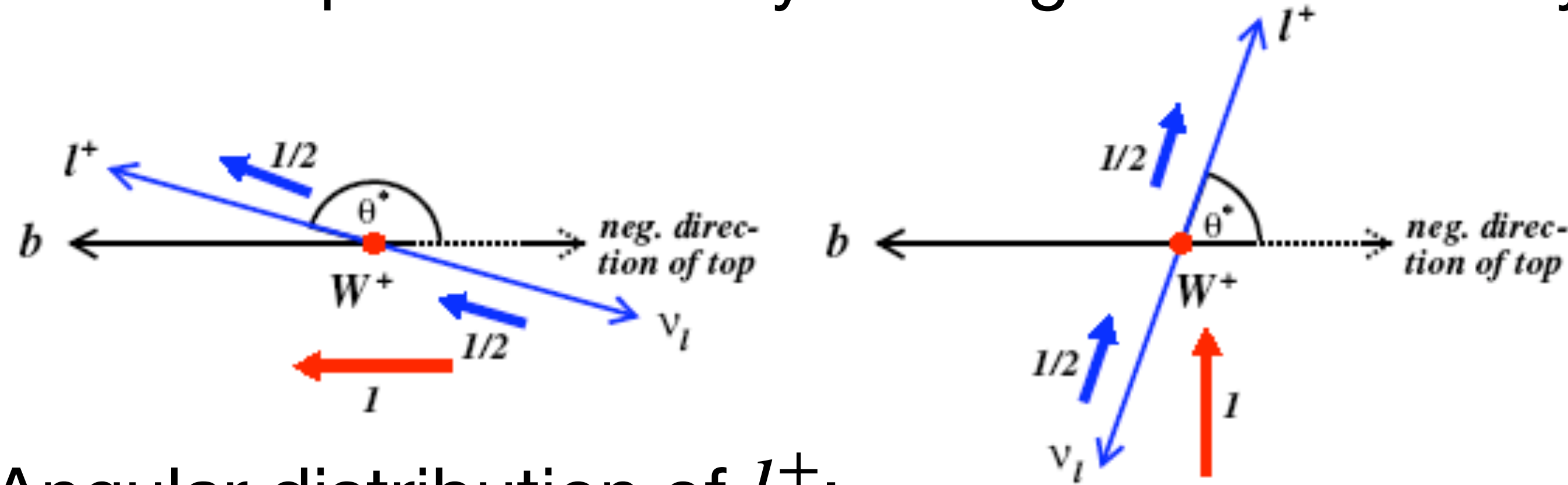
?



?

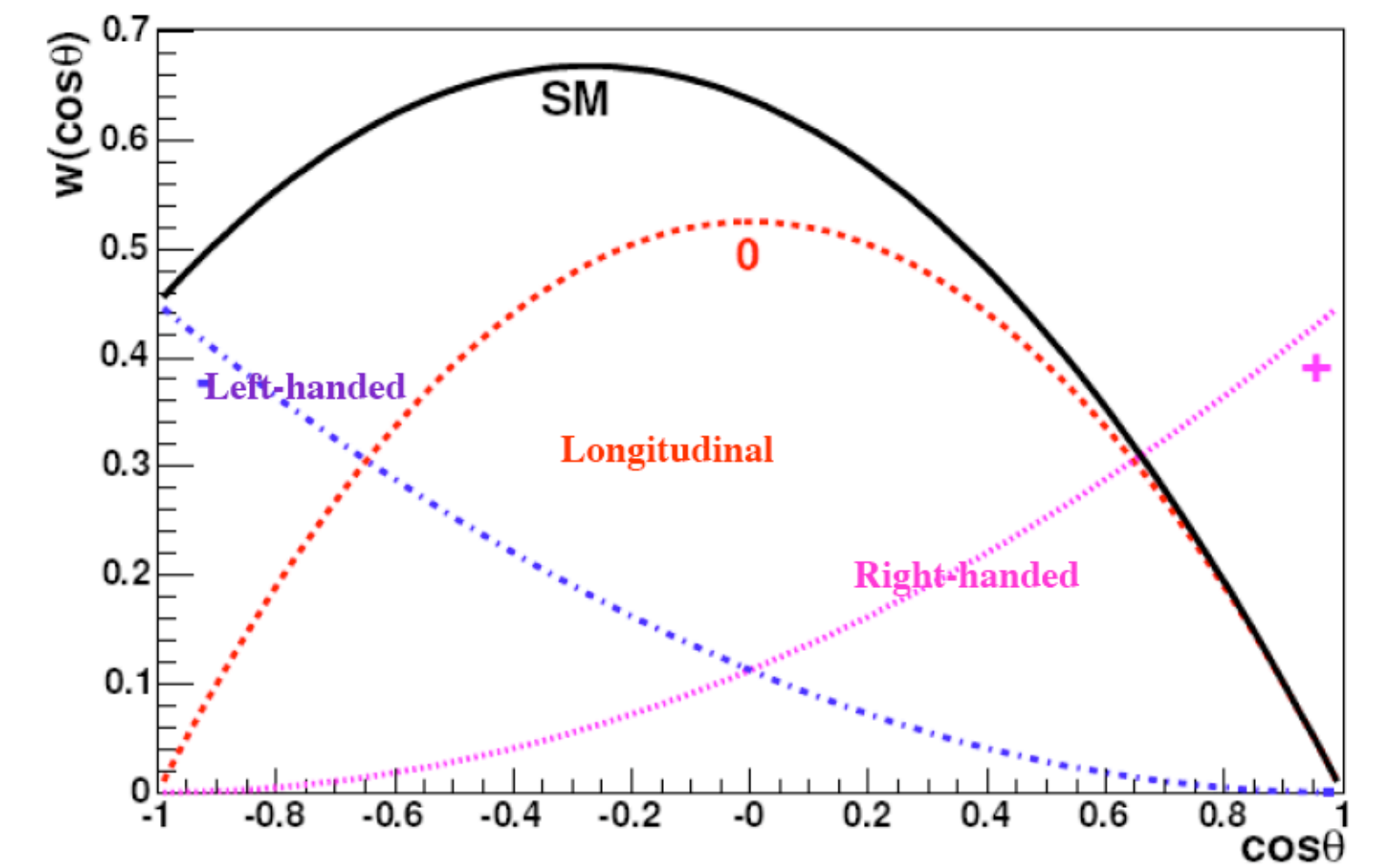
Weak interaction and W polarisation

Extract W polarisation by looking at the W decay products:



Angular distribution of l^+ :

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



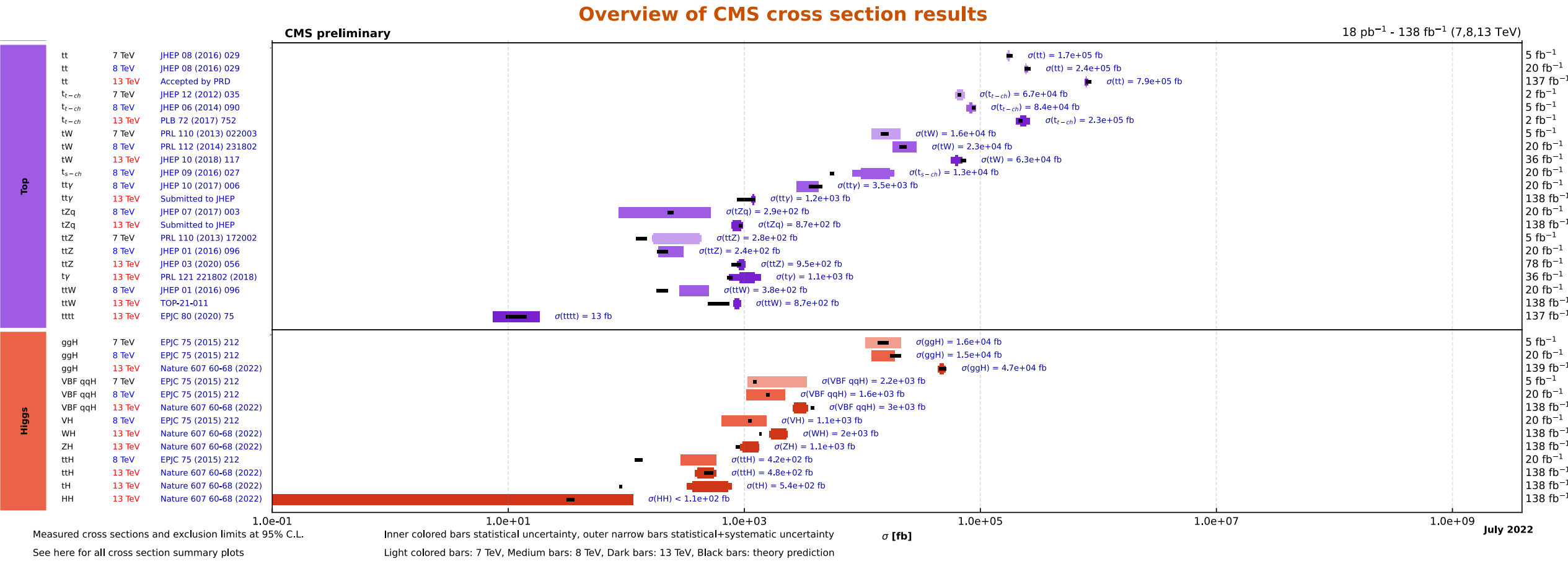
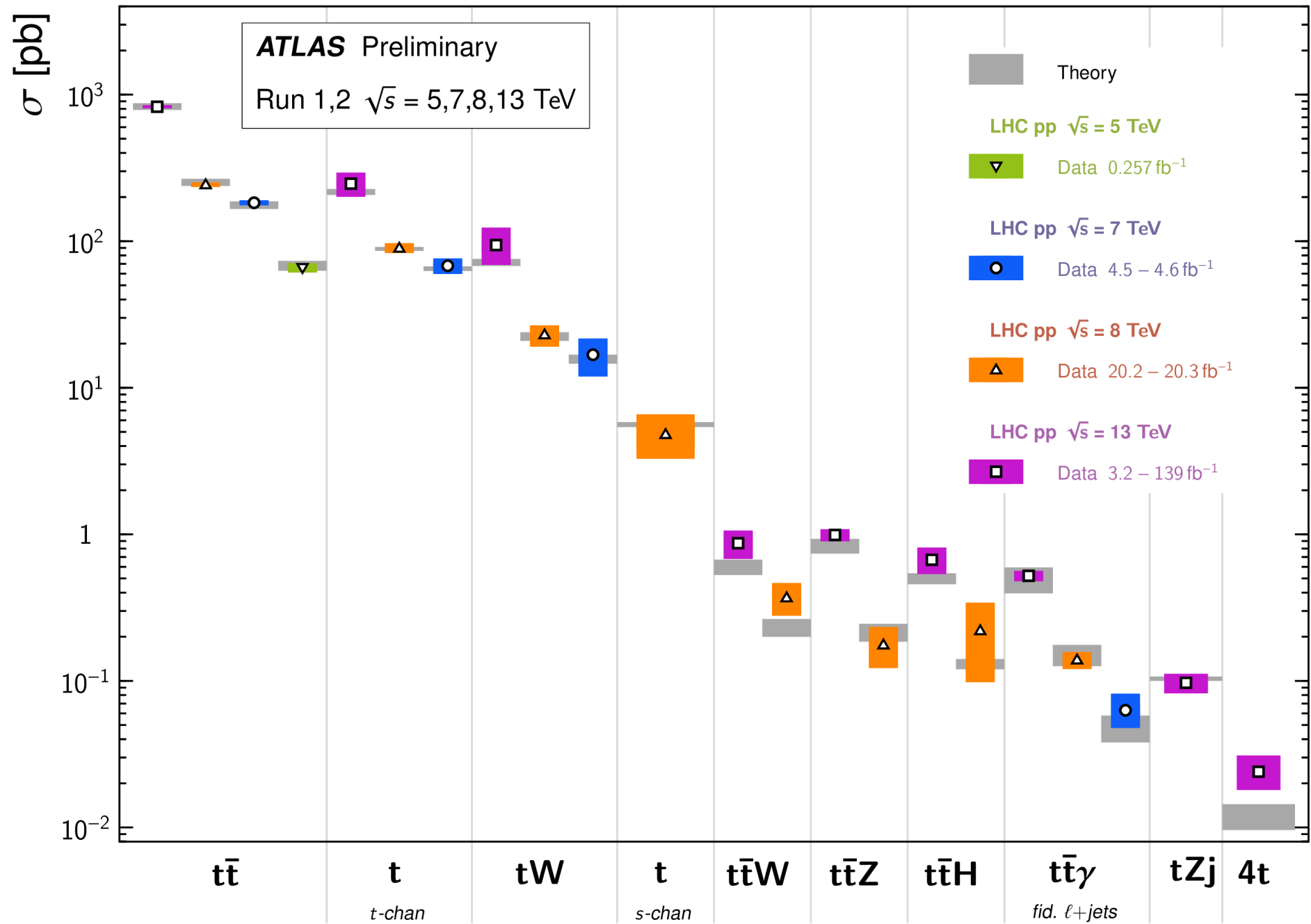
$$f_0 = \frac{m_t^2}{2m_W^2 + m_t^2} \sim 70 \% \quad f_L = \frac{2m_W^2}{2m_W^2 + m_t^2} \sim 30 \% \quad f_R \sim 0 \% \quad \text{for } m_b = 0$$

Check of Wtb interaction!

Status of top measurements

Top Quark Production Cross Section Measurements

Status: March 2022



Model	E_{CM} [TeV]	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Measurement
$t\bar{t}$	13	36.1 fb ⁻¹	$\sigma = 826.4 \pm 3.6 \pm 19.6 \text{ pb}$
$t_{t\text{-chan}}$	13	3.2 fb ⁻¹	$\sigma = 247 \pm 6 \pm 46 \text{ pb}$
$t\bar{t}W$	13	36.1 fb ⁻¹	$\sigma = 870 \pm 130 \pm 140 \text{ fb}$
$t\bar{t}Z$	13	139 fb ⁻¹	$\sigma = 990 \pm 50 \pm 80 \text{ fb}$
$t\bar{t}H$	13	80 fb ⁻¹	$\sigma = 670 \pm 90 \pm 110 - 100 \text{ fb}$
$t\bar{t}\gamma$	13	36.1 fb ⁻¹	$\sigma = 521 \pm 9 \pm 41 \text{ fb}$
tZj	13	139 fb ⁻¹	$\sigma = 97 \pm 13 \pm 7 \text{ fb}$
$4t$	13	139 fb ⁻¹	$\sigma = 24 \pm 7 - 6 \text{ fb}$

Theory
$\sigma = 832 + 40 - 45 \text{ pb}$ (top++ NNLO+NNLL)
$\sigma = 217 \pm 10 \text{ pb}$ (NLO+NLL)
$\sigma = 600 \pm 72 \text{ fb}$ (Madgraph5 + aMCNLO)
$\sigma = 840 + 90 - 100 \text{ fb}$ (NLO QCD + EW)
$\sigma = 507 + 35 - 50 \text{ fb}$ (LHCHXSWG NLO QCD + NLO EW)
$\sigma = 495 \pm 99 \text{ fb}$ (PRD 83 (2011) 074013)
$\sigma = 102 + 5 - 2 \text{ fb}$ (Madgraph5 + aMCNLO (NLO))
$\sigma = 12.0 \pm 2.4 \text{ fb}$ (JHEP 02 (2018) 031)

Very precise measurements!

In some cases:

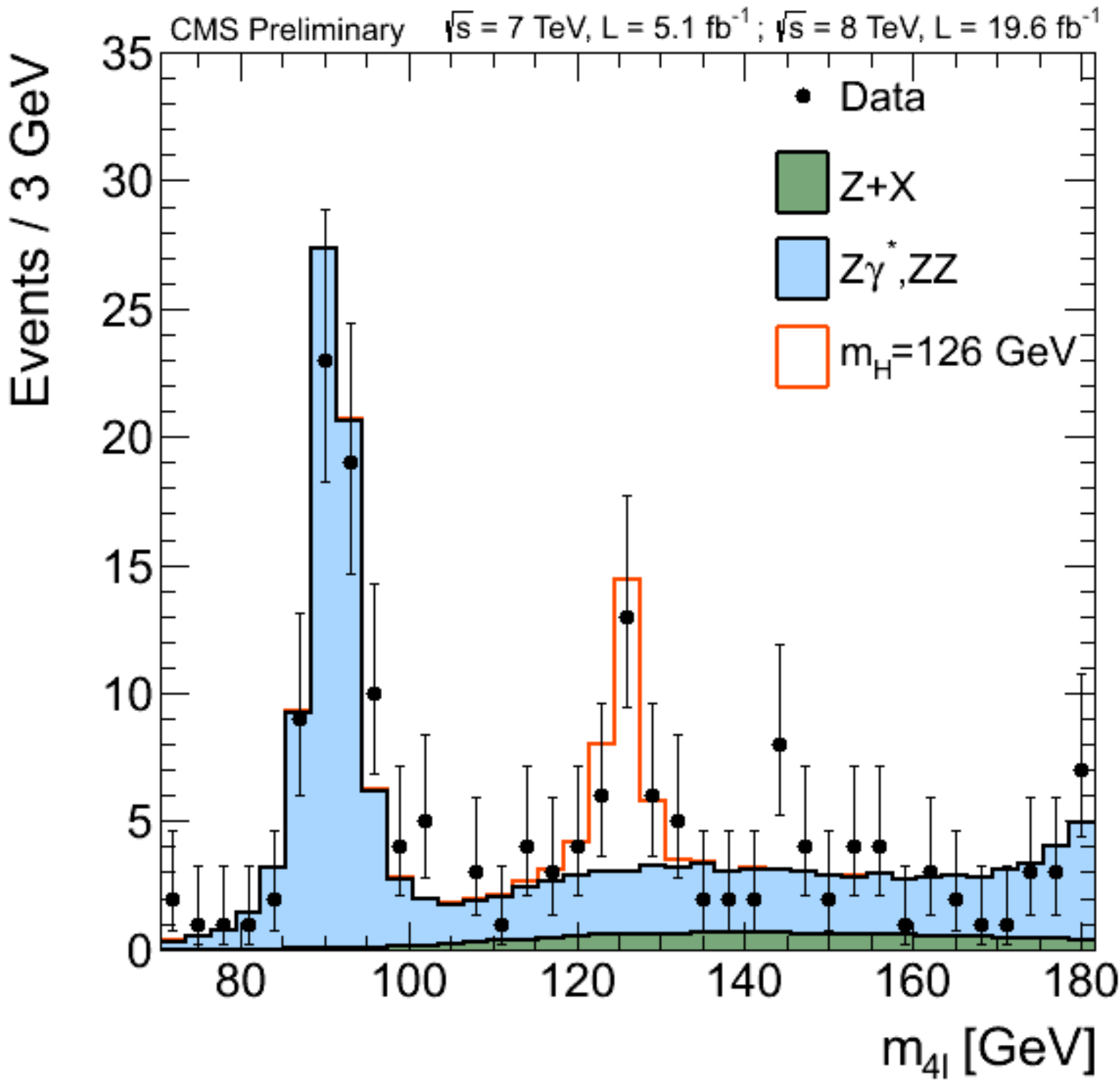
$\Delta_{EXP} < \Delta_{TH}$

New Physics searches at the LHC

Model-dependent

SUSY, 2HDM...

New particles

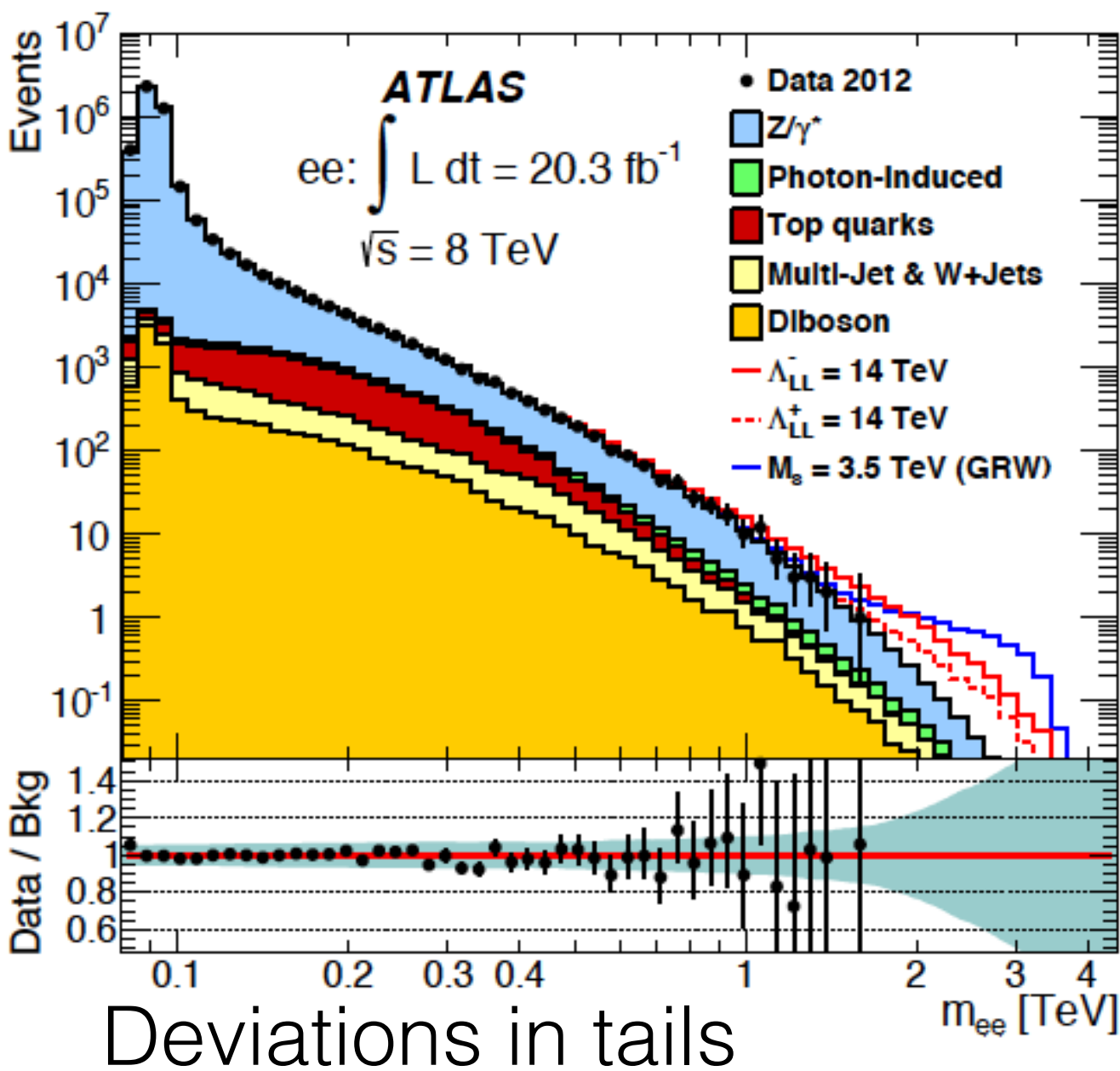


Model-Independent

simplified models, EFT

New Interactions of SM particles

anomalous couplings, EFT



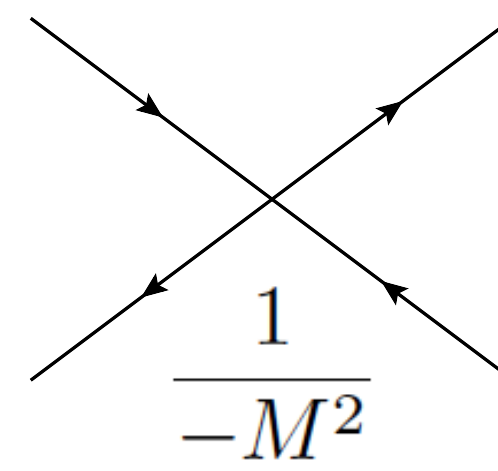
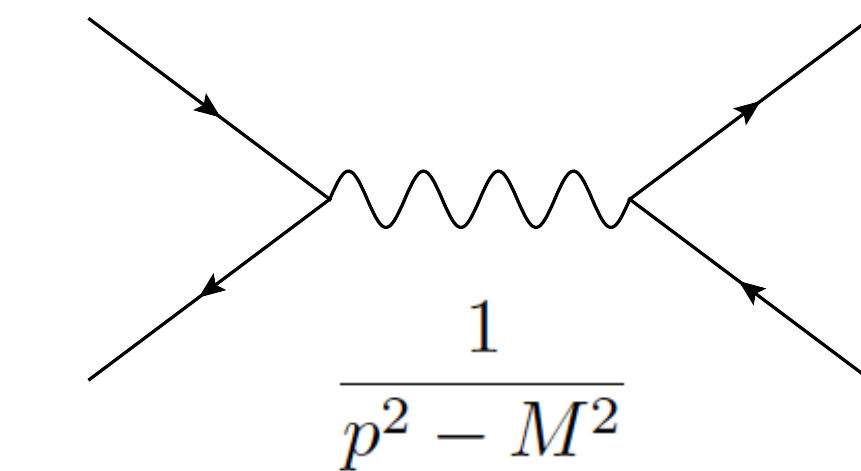
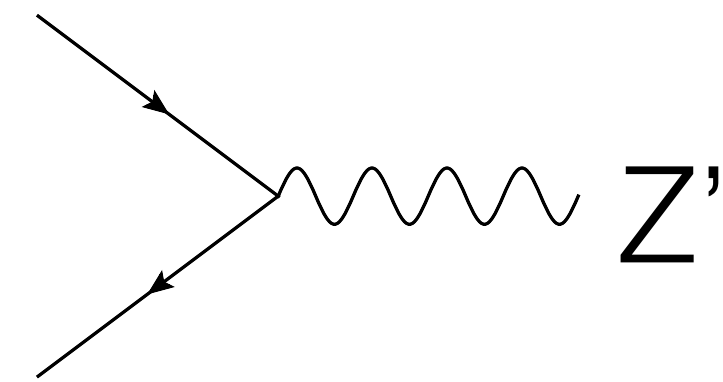
$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

EFT: What is it all about?

Energy
New Physics

Λ

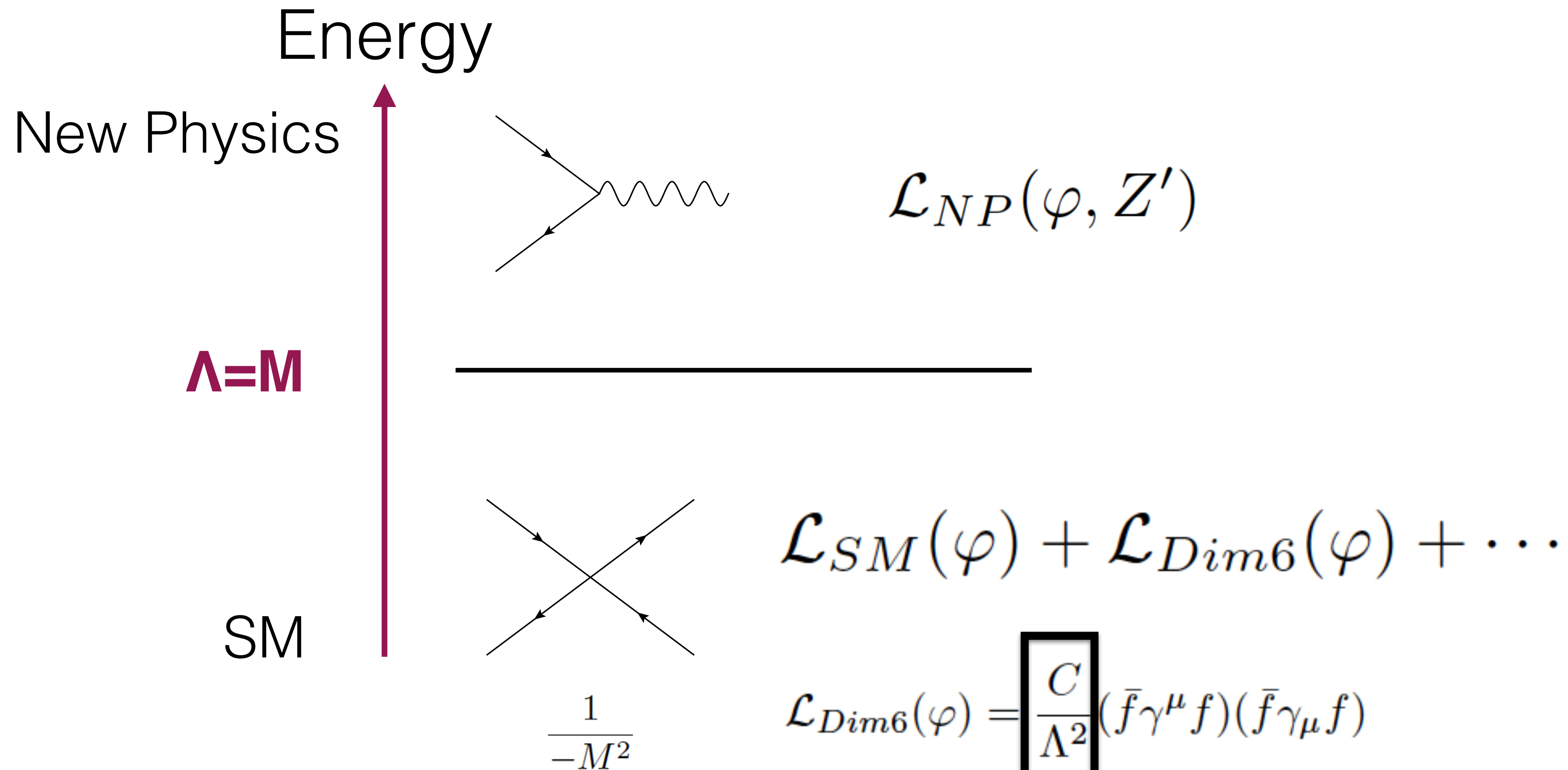
SM



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

We have integrated out the Z'

EFT: What is it all about?

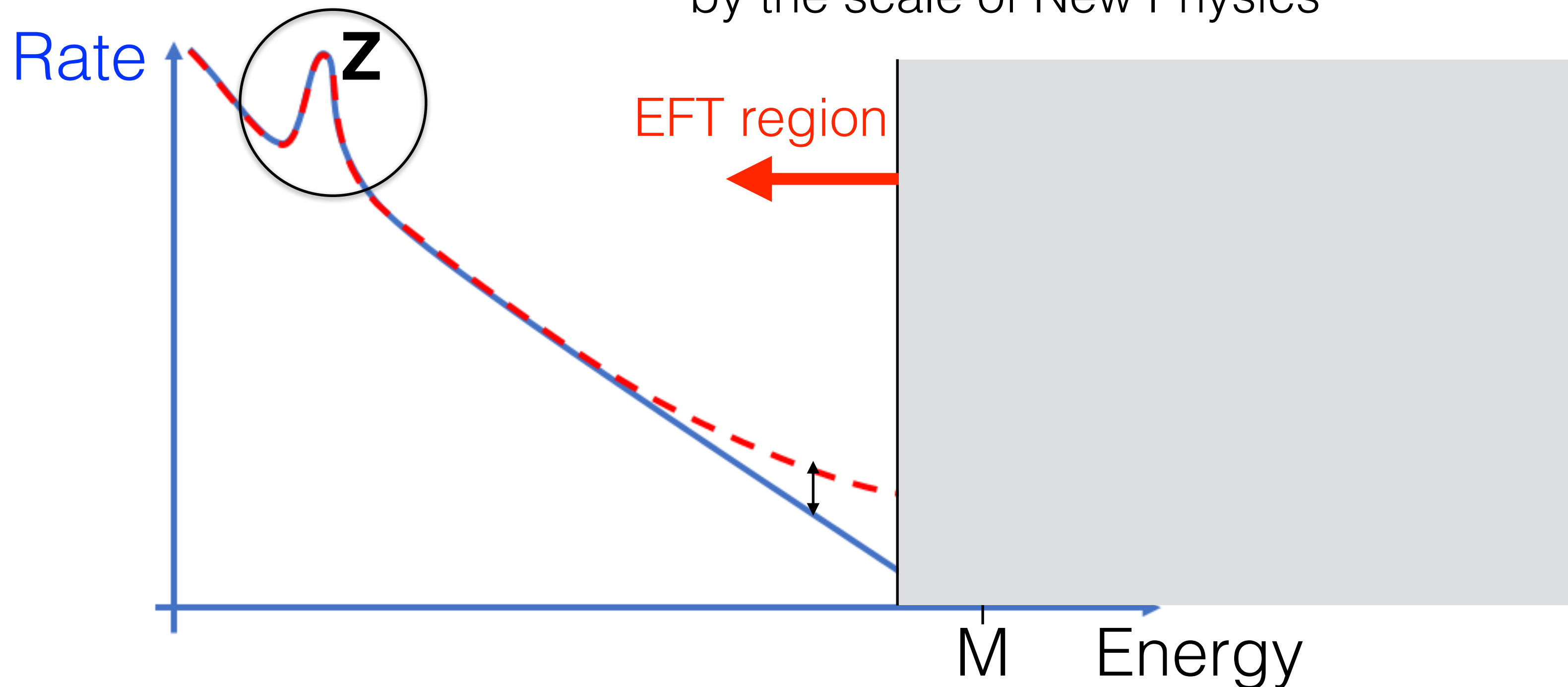
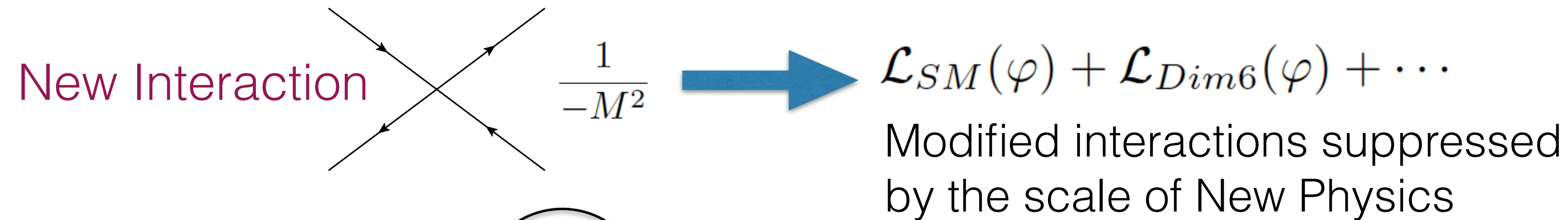


$$\mathcal{L}_{Dim6}(\varphi) = \frac{C}{\Lambda^2} (\bar{f} \gamma^\mu f) (\bar{f} \gamma_\mu f)$$

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

EFT for New Physics

Low Energy Effective Theory without the Z'

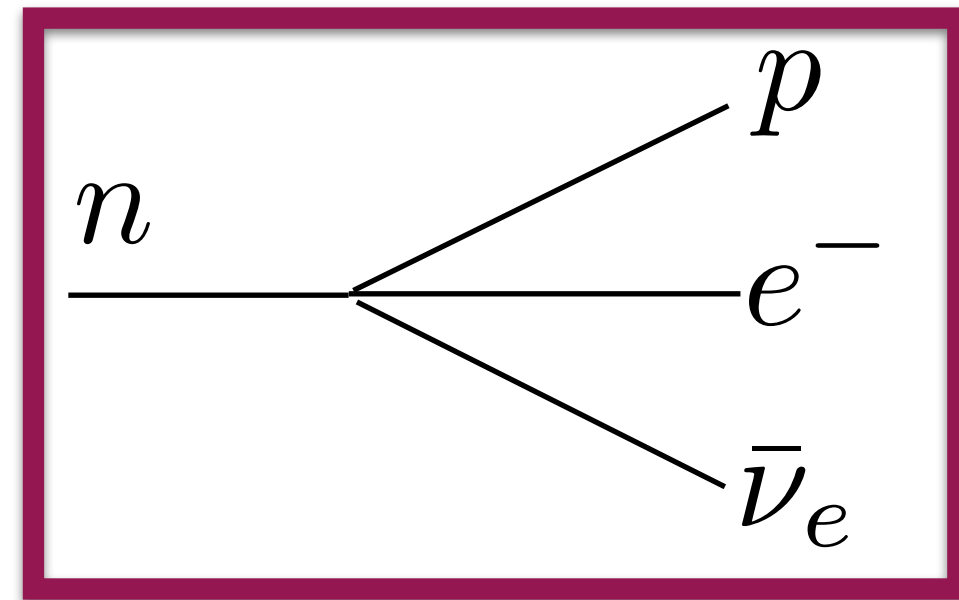


The way to probe New Physics in the absence of light states

Does the effective theory work?

An example of a successful EFT:

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

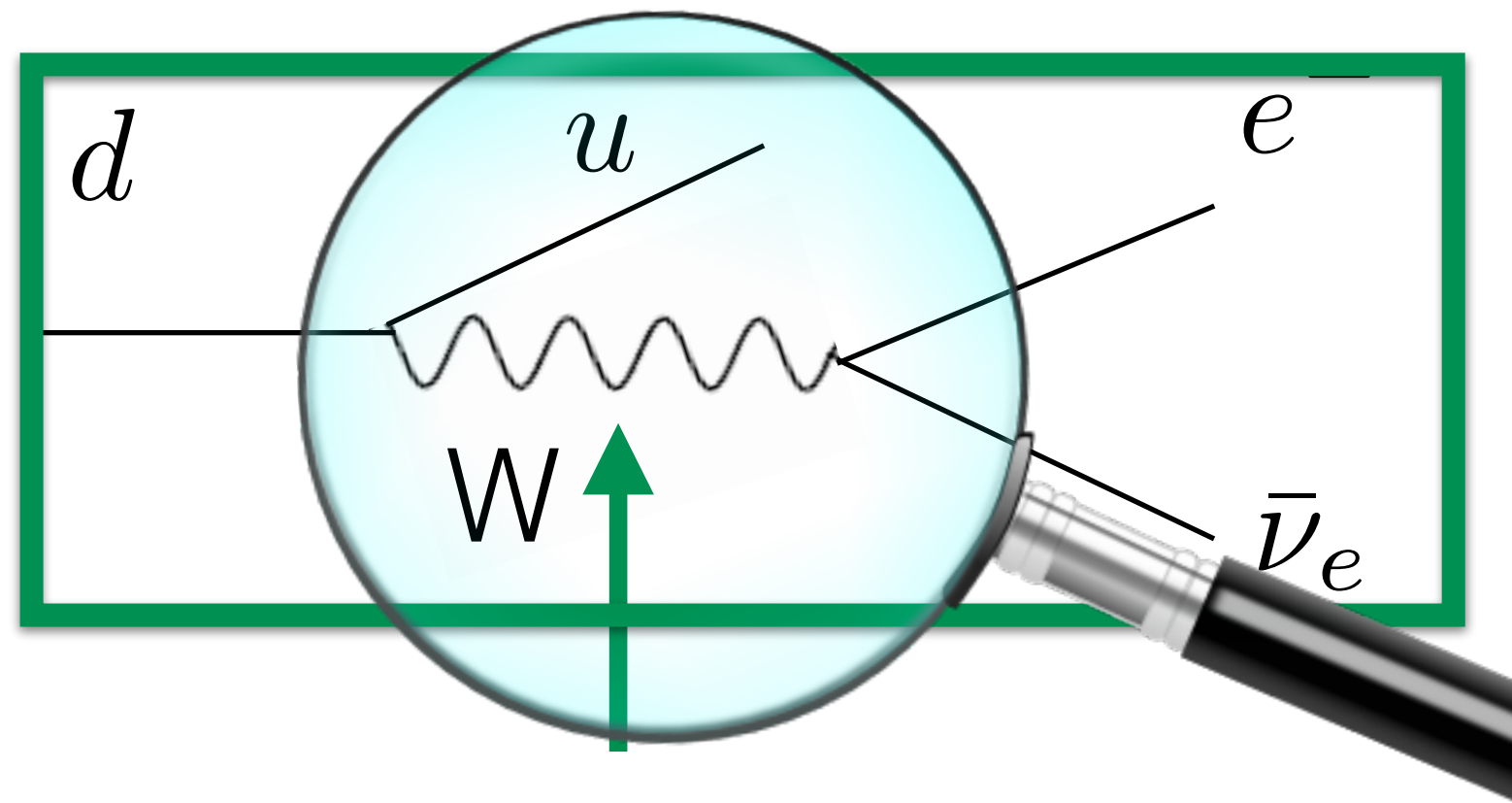


Fermi formulated his theory in the 1930's

It described β -decay data very well

Energy of β -decay: $\sim \text{MeV}$

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

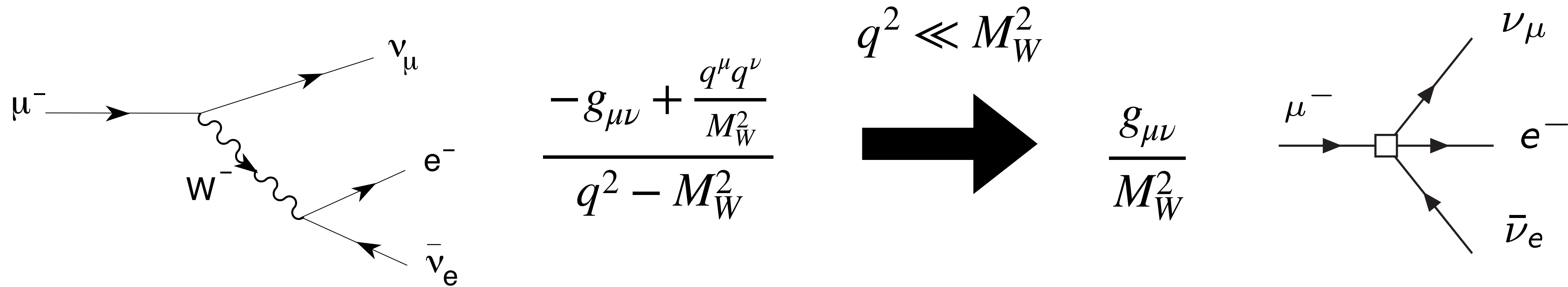


1983 Discovery of W-boson at CERN UA1 and UA2
 $M_W = 80 \text{ GeV} \gg Q_\beta$

Energy borrowed from the vacuum
A virtual W-boson exchange

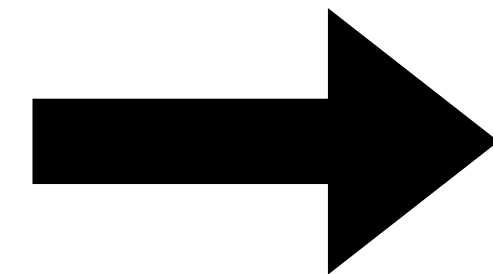
Low energy weak interactions

Muon Decay



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

$$q^2 \ll M_W^2$$



$$\frac{g_{\mu\nu}}{M_W^2}$$

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

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

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e^2}{m_\mu^2}\right)$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

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](https://arxiv.org/abs/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)

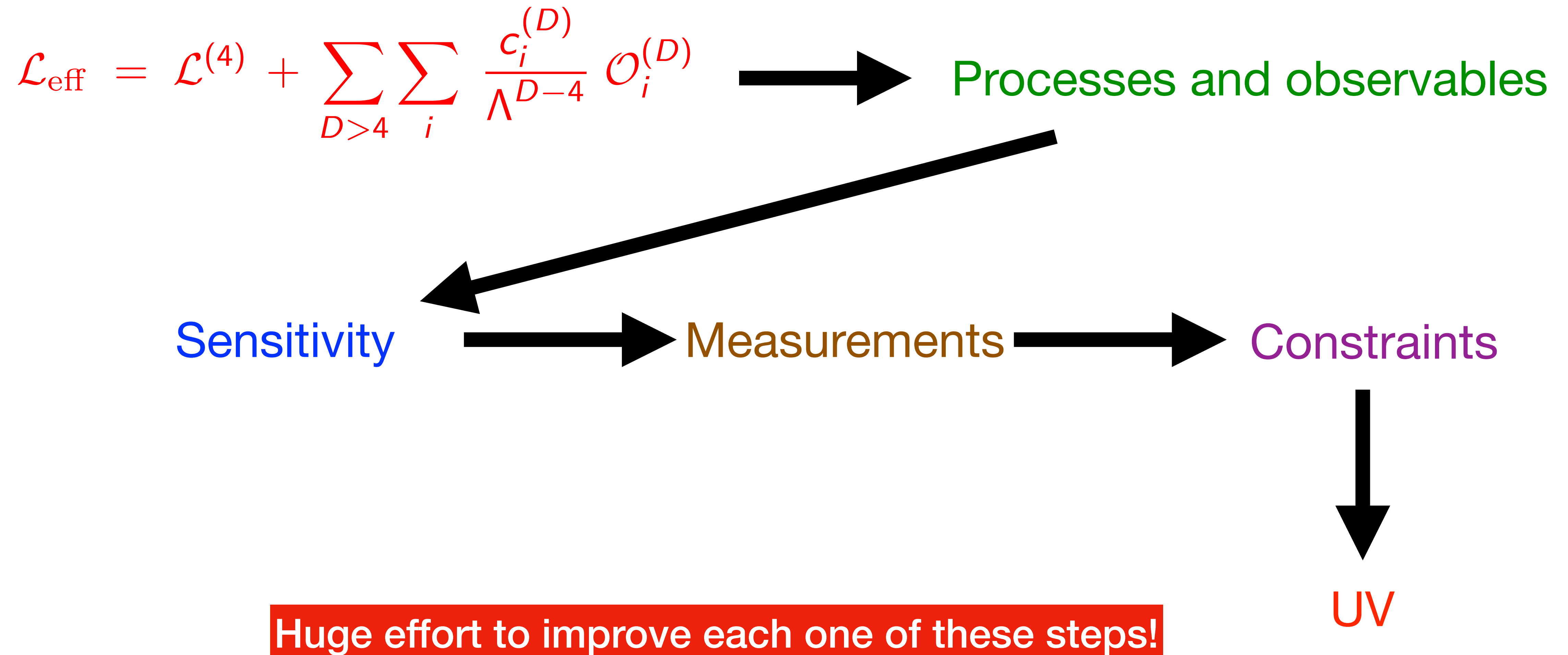
SMEFT for New Physics

- Focus on SMEFT:
 - only SM fields
 - respecting SM symmetries ✓
 - valid below scale Λ
- Gauge invariant ✓
- Higher-order corrections: renormalisable order by order in $1/\Lambda$ ✓

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

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

Let's take a tour of SMEFT



SMEFT dimension-5

One lepton number violating operator at dim-5

Weinberg (1979)

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

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

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

Possible UV completion: see-saw model

$$\mathcal{L} = -y_D \bar{L} \epsilon \phi^* \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R + \text{H.c.} \quad \longrightarrow \quad \begin{array}{l} \nu \sim \nu_L \\ N \sim \nu_R \end{array} \quad \begin{array}{l} m_\nu \sim m_D^2 / M_R \\ M_R \end{array}$$

Not relevant for LHC physics

SMEFT@dim-6

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

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	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_\tau \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_\tau \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_\tau \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_\tau) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_\tau)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_\tau) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_\tau)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_\tau) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_\tau)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_\tau) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_\tau)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_\tau) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_\tau)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_\tau) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_\tau)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_\tau) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_\tau)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_\tau) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_\tau)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_\tau)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_\tau)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_\tau)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_\tau)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_\tau)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_\tau)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_\tau)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_\tau)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_\tau)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_\tau)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_\tau)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_\tau)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_\tau)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_\tau)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_\tau)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_\tau)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B -violating			
Q_{ledq}	$(\bar{l}_p^j e_\tau)(\bar{d}_s^k q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_\tau^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_\tau) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_\tau^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_\tau) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} [(q_p^{\alpha j})^T C q_\tau^{\beta k}] [(q_s^\gamma)^T C l_t^m]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_\tau) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^{\alpha j})^T C q_\tau^{\beta k}] [(q_s^\gamma)^T C l_t^m]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_\tau) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_\tau^\beta] [(u_s^\gamma)^T C e_t]$		

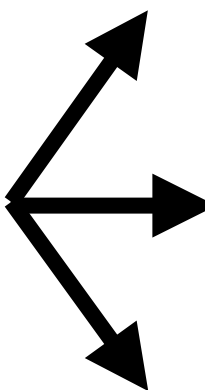
Warsaw basis of dimension-6 operators

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)
	$\psi^4 : (\bar{q}_i \gamma^\mu q_j) (\bar{q}_k \gamma_\mu q_l)$	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

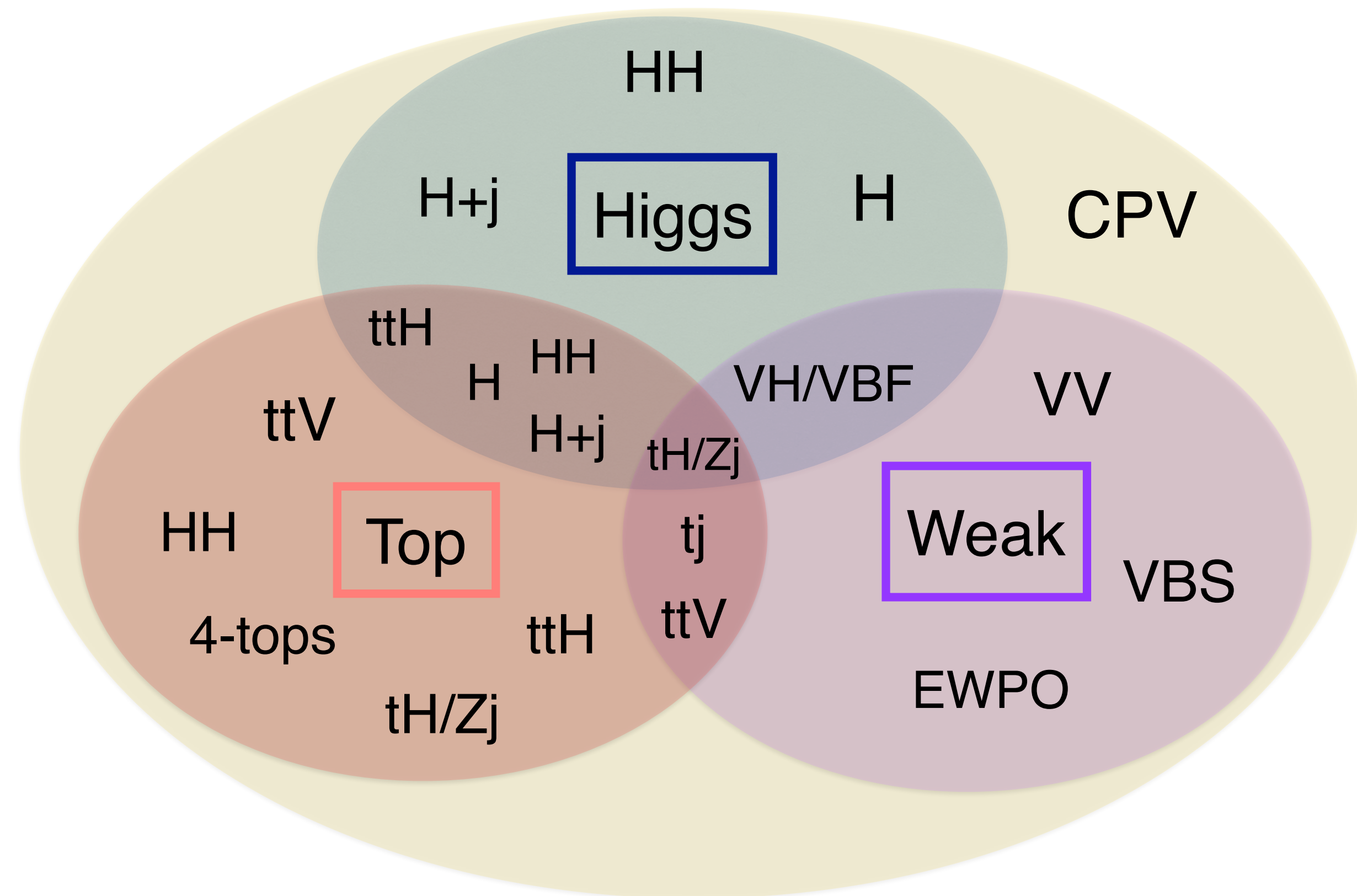
2) New Lorentz structures

(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

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

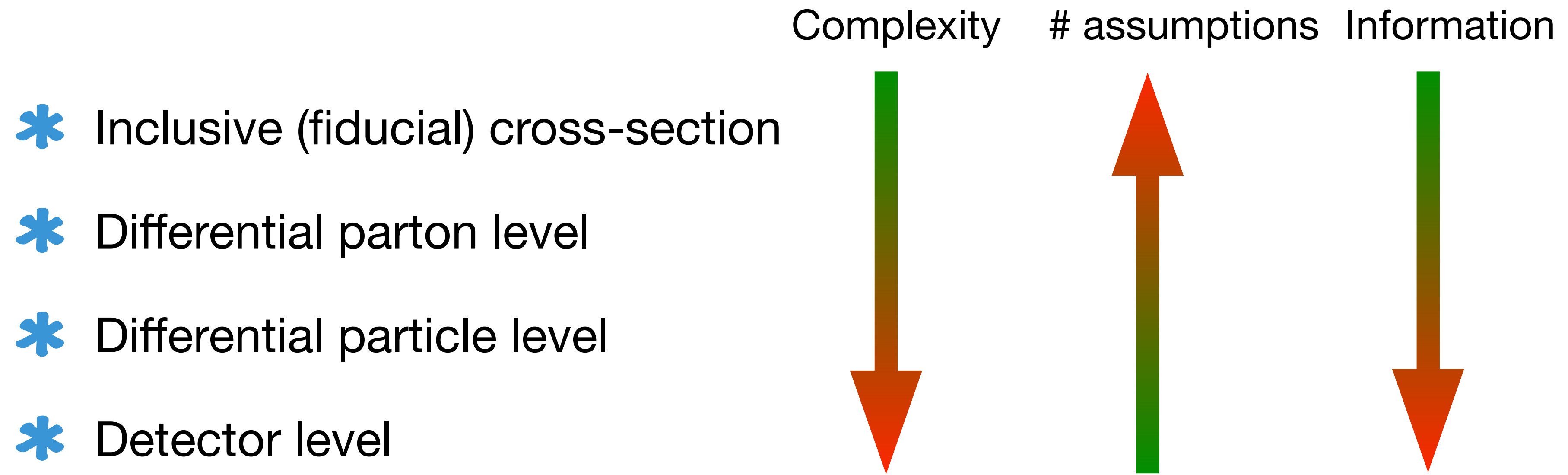
Precise experimental measurements

Precise SM predictions

Precise EFT predictions

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

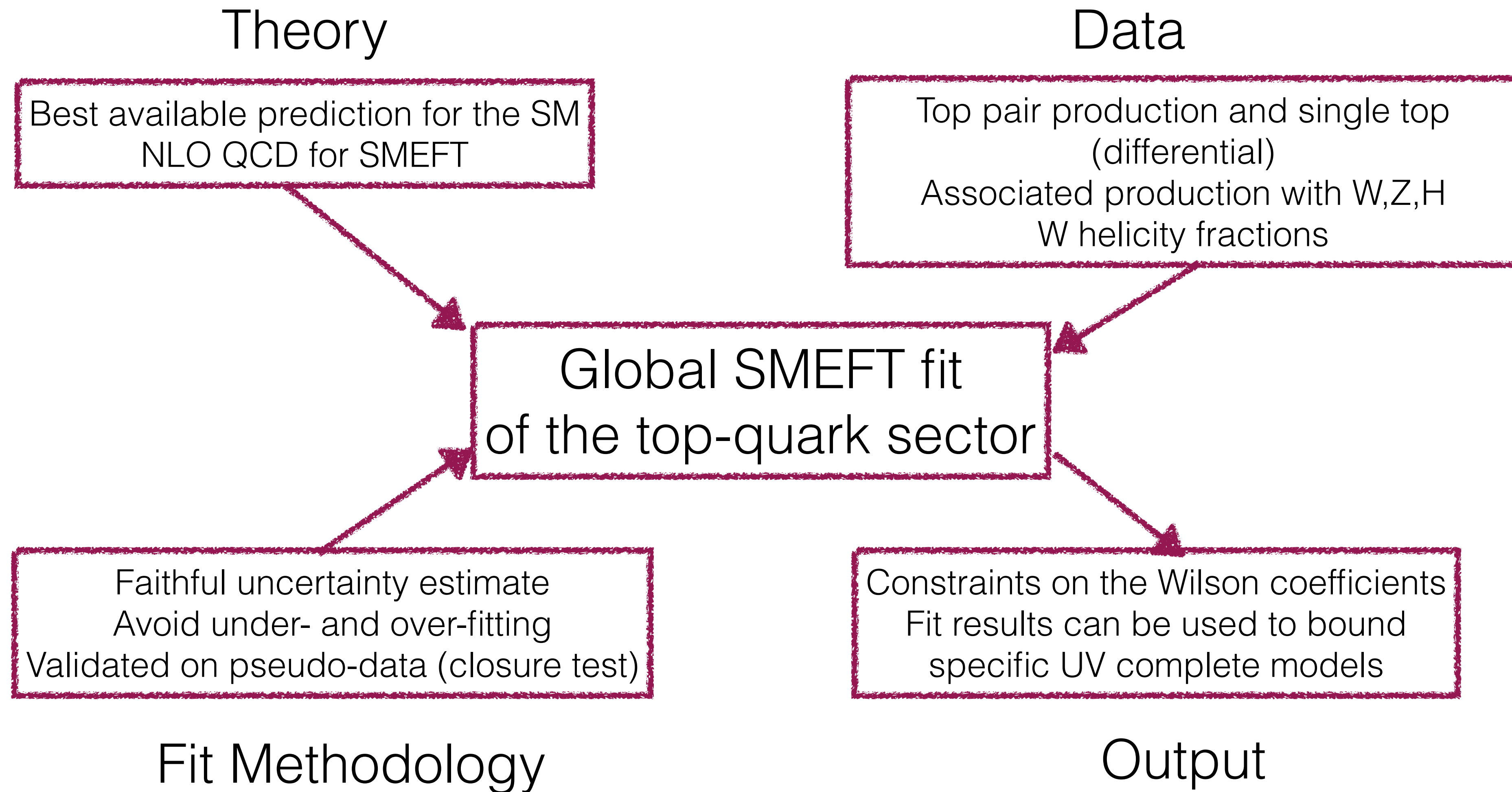
EFT interpretations



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_{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	[37]
ATLAS_tt_AC_13TeV (*)	8 TeV, 20.3 fb ⁻¹	charge asymmetry	A_C	5	[38]

4 tops, ttbb, top-
pair associated
production

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

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	N_{dat}	Ref
CMS_t_tch_8TeV_inc	8 TeV, 19.7 fb ⁻¹	t-channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t})$	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	$\sigma_{\text{tot}}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	8 TeV, 20.3 fb ⁻¹	s-channel	$\sigma_{\text{tot}}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	13 TeV, 3.2 fb ⁻¹	t-channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	13 TeV, 2.2 fb ⁻¹	t-channel	$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t})$	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_{dat}	Ref
ATLAS_tW_8TeV_inc	8 TeV, 20.2 fb ⁻¹	inclusive (dilepton)	$\sigma_{\text{tot}}(tW)$	1	[95]
ATLAS_tW_inc_1lep_8TeV (*)	8 TeV, 20.2 fb ⁻¹	inclusive (single lepton)	$\sigma_{\text{tot}}(tW)$	1	[101]
CMS_tW_8TeV_inc	8 TeV, 19.7 fb ⁻¹	inclusive	$\sigma_{\text{tot}}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	13 TeV, 3.2 fb ⁻¹	inclusive	$\sigma_{\text{tot}}(tW)$	1	[97]
CMS_tW_13TeV_inc	13 TeV, 35.9 fb ⁻¹	inclusive	$\sigma_{\text{tot}}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	13 TeV, 36.1 fb ⁻¹	inclusive	$\sigma_{\text{tot}}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	13 TeV, 139.1 fb ⁻¹	inclusive	$\sigma_{\text{fid}}(t\bar{t}^+ \ell^- q)$	1	[102]
CMS_tZ_13TeV_inc	13 TeV, 35.9 fb ⁻¹	inclusive	$\sigma_{\text{fid}}(Wb\ell^+ \ell^- q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	13 TeV, 77.4 fb ⁻¹	inclusive	$\sigma_{\text{fid}}(t\bar{t}^+ \ell^- q)$	1	[103]

tW, tZ

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

Diboson

STFC HEP school 2026

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

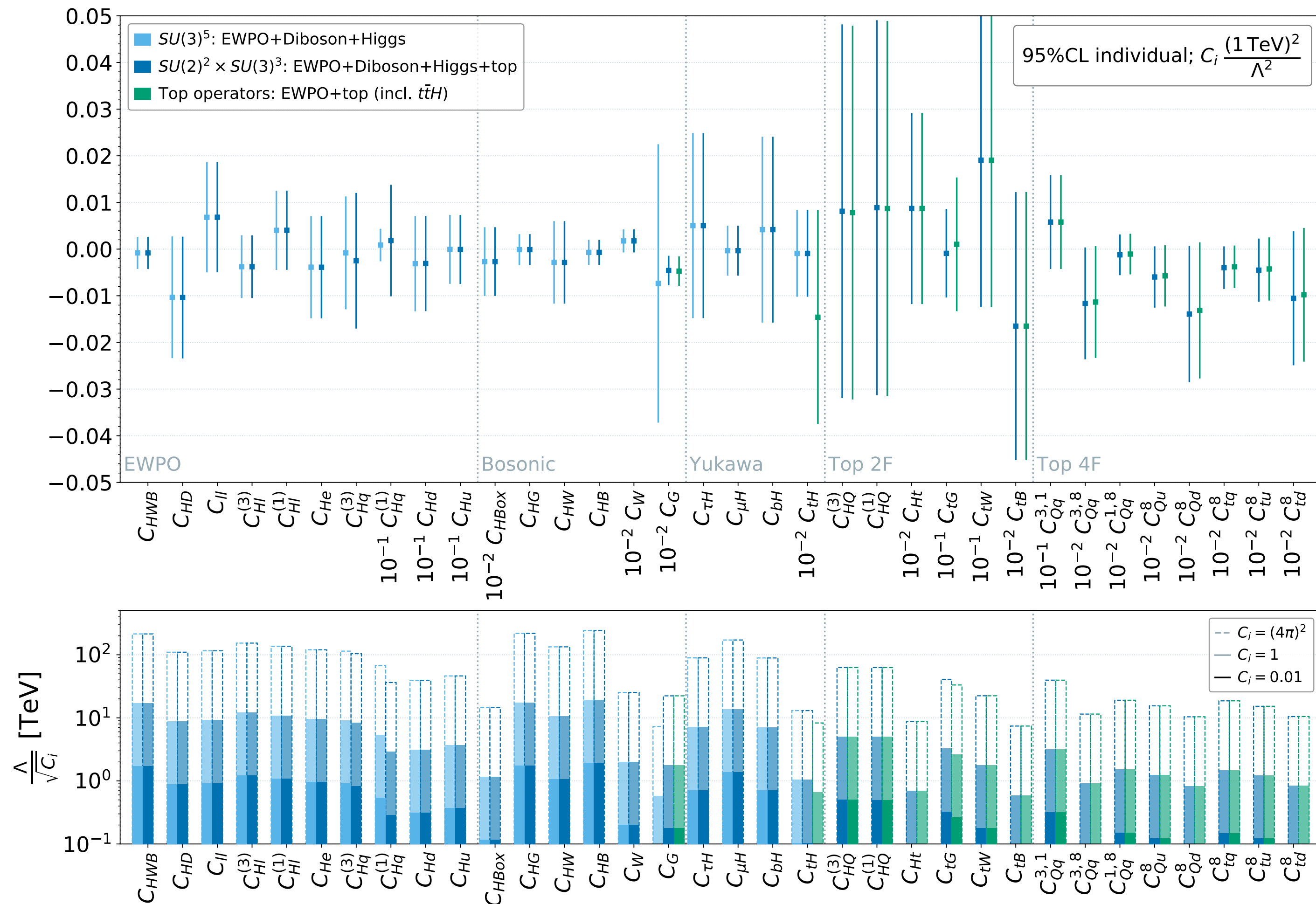
Higgs signal strengths

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

Higgs differential

Category	Processes	n_{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



Individual: only one non-zero c_i
 (optimistic, unrealistic)

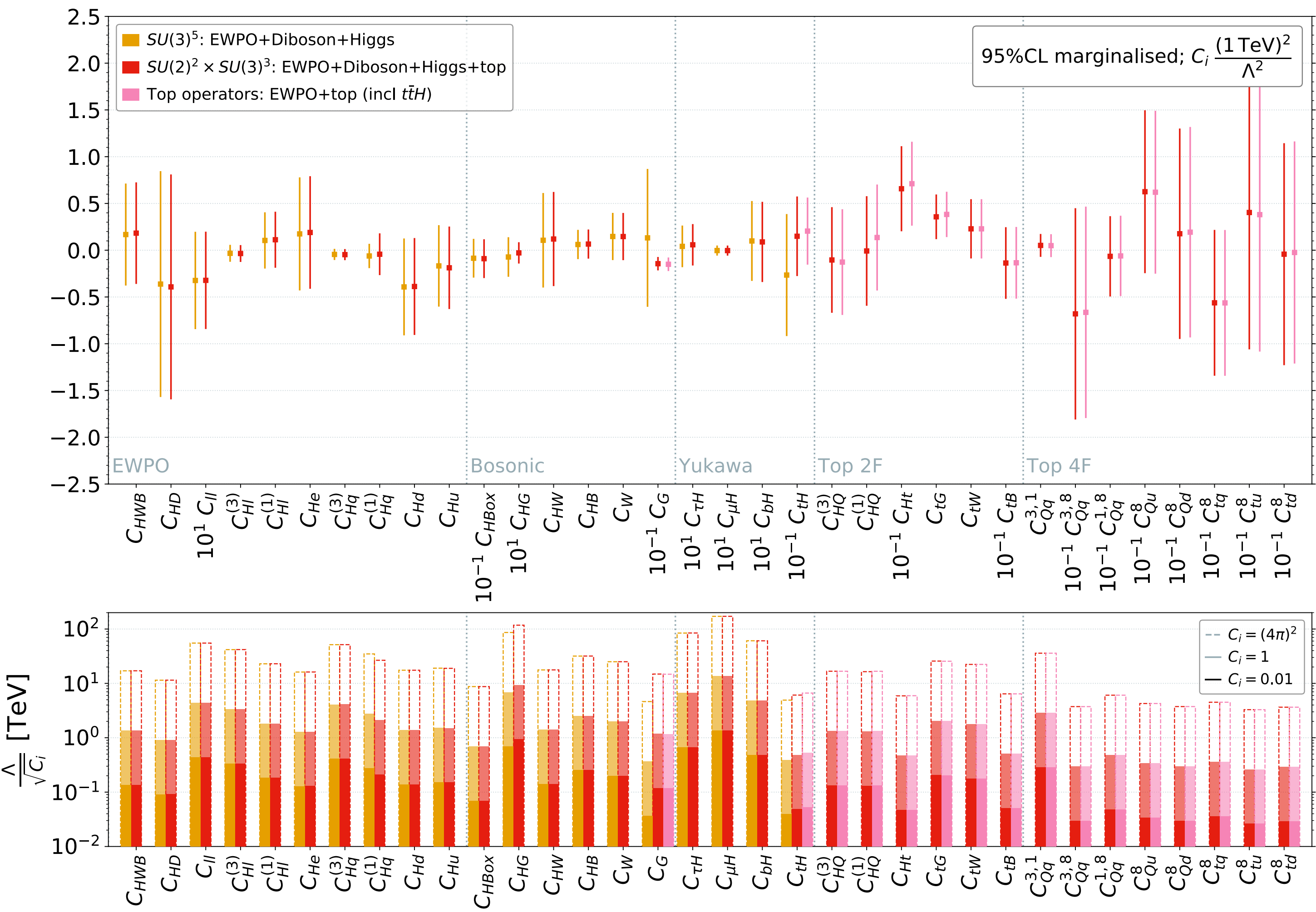
**What does that mean
 for the UV scale?**

Strongly coupled
 Weakly coupled

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

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

Full fit: marginalised



All coefficients allowed to be non-zero

Bounds significantly worse in a marginalised fit

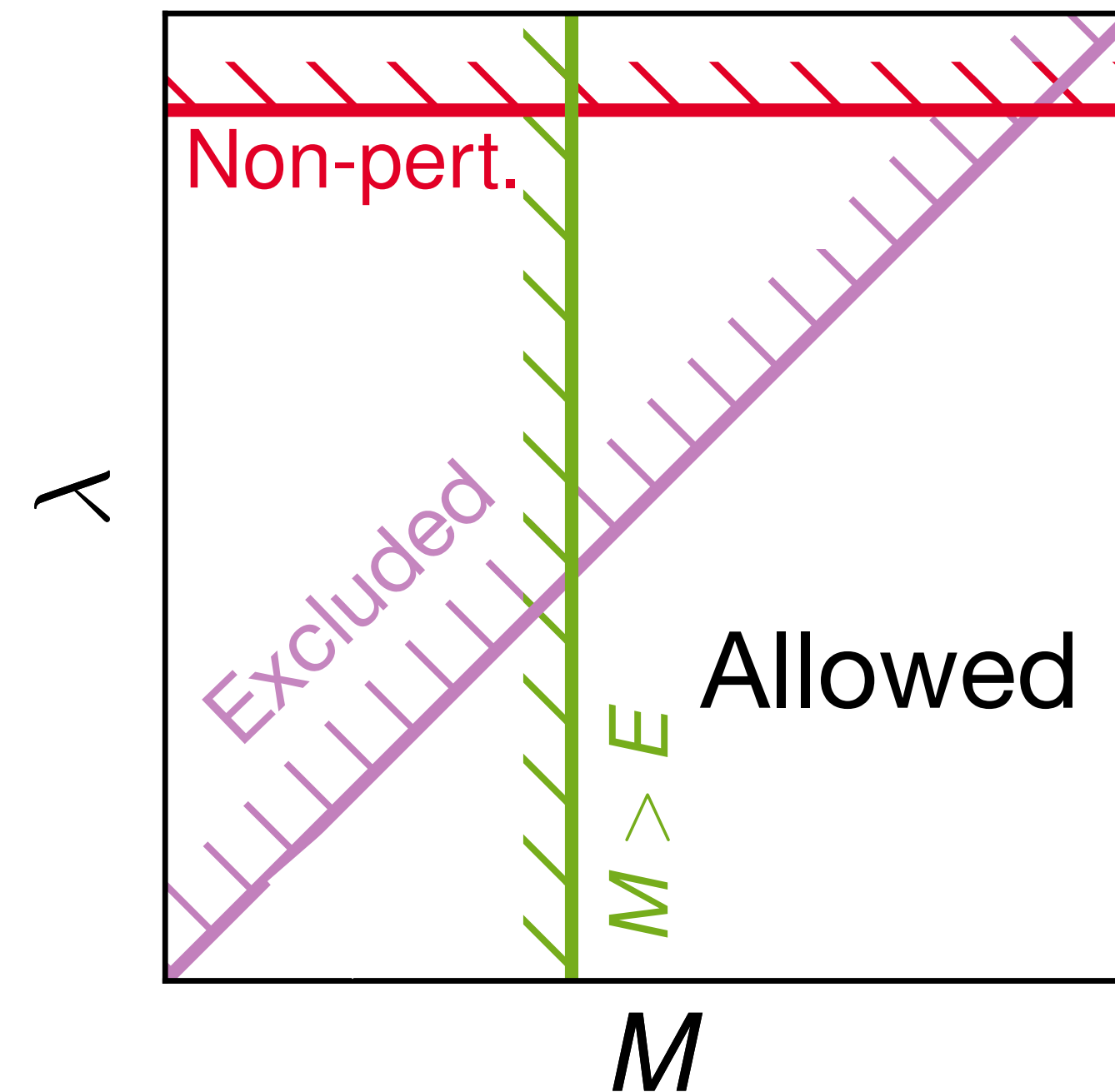
For weakly coupled theories Λ bound below the TeV scale: **EFT Validity???**

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

Scalars

Z'

W'

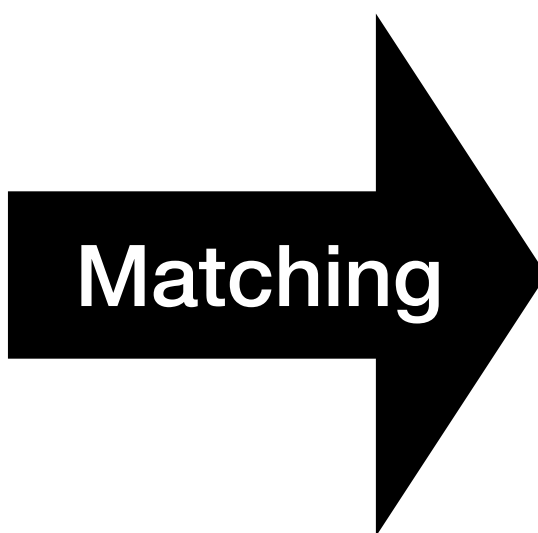
VLL

VLQ

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, 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)
B	1	1	1	0	$(M_B, \hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D, λ_D)
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})
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})
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T, s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB}, s_L^{t,b})$

VLL

VLQ



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			$-\frac{1}{2} \frac{M_T^2}{v^2}$	$\frac{1}{2} \frac{M_T^2}{v^2}$			$y_t \frac{M_T^2}{v^2}$		

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

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

From EFT to UV

Scalars

Z'

W'

VLL

VLQ

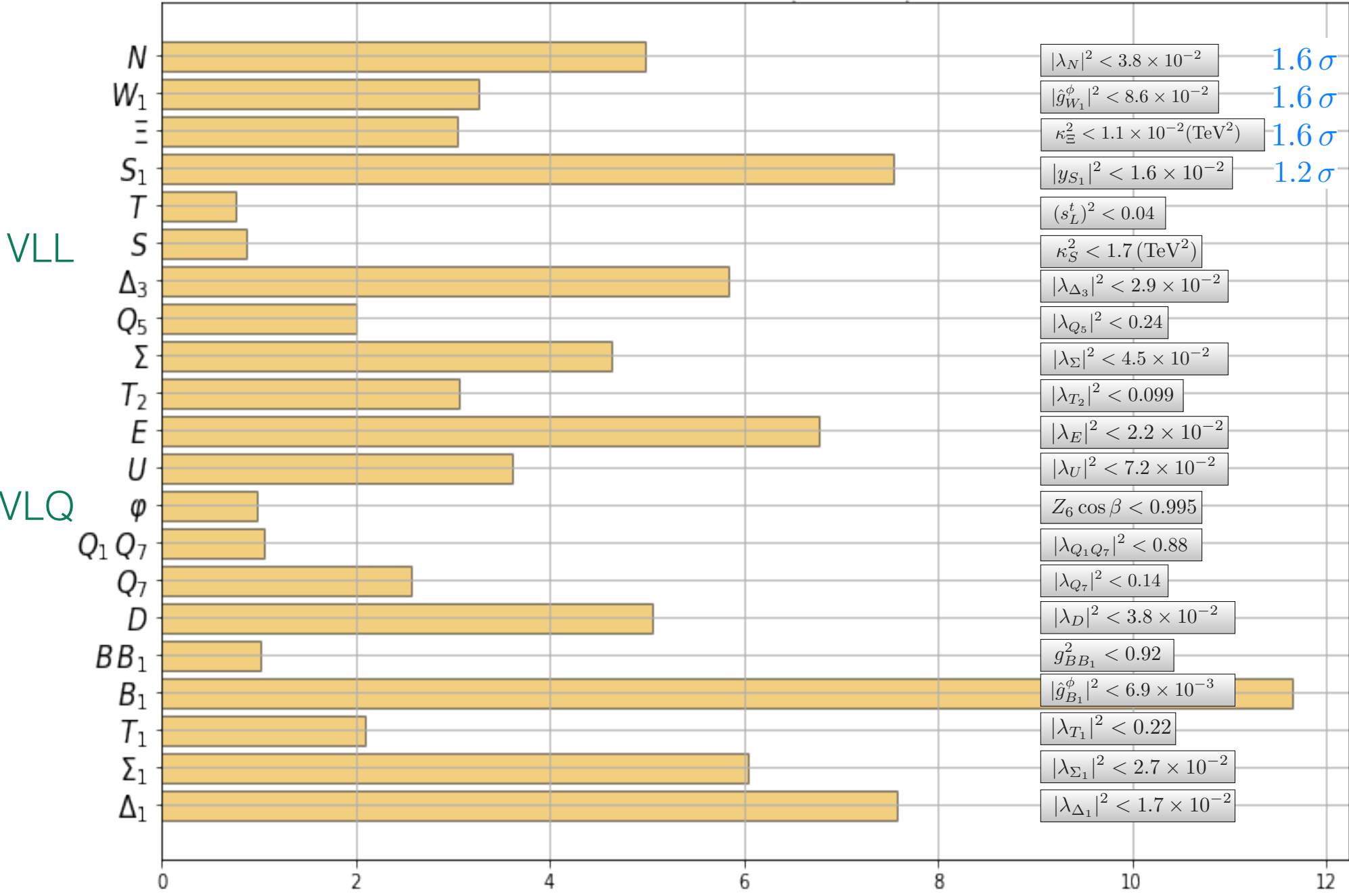
Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.
S	0	1	1	0	(M_S, κ_S)	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1}, \lambda_{\Delta_1})$
S_1	0	1	1	1	(M_{S_1}, y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3}, \lambda_{\Delta_3})$
φ	0	1	2	$\frac{1}{2}$	$(M_\varphi, Z_6 \cos \beta)$	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)
B	1	1	1	0	$(M_B, \hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D, λ_D)
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})
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})
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T, s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB}, s_L^{t,b})$

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

$M(\lambda = 1)$

Mass limits (in TeV)

$\lambda(M = 1 \text{ TeV})$



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

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

THANK YOU