Collider Phenomenology (3)

Eleni Vryonidou

STFC school, Durham
2-6/9/24

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

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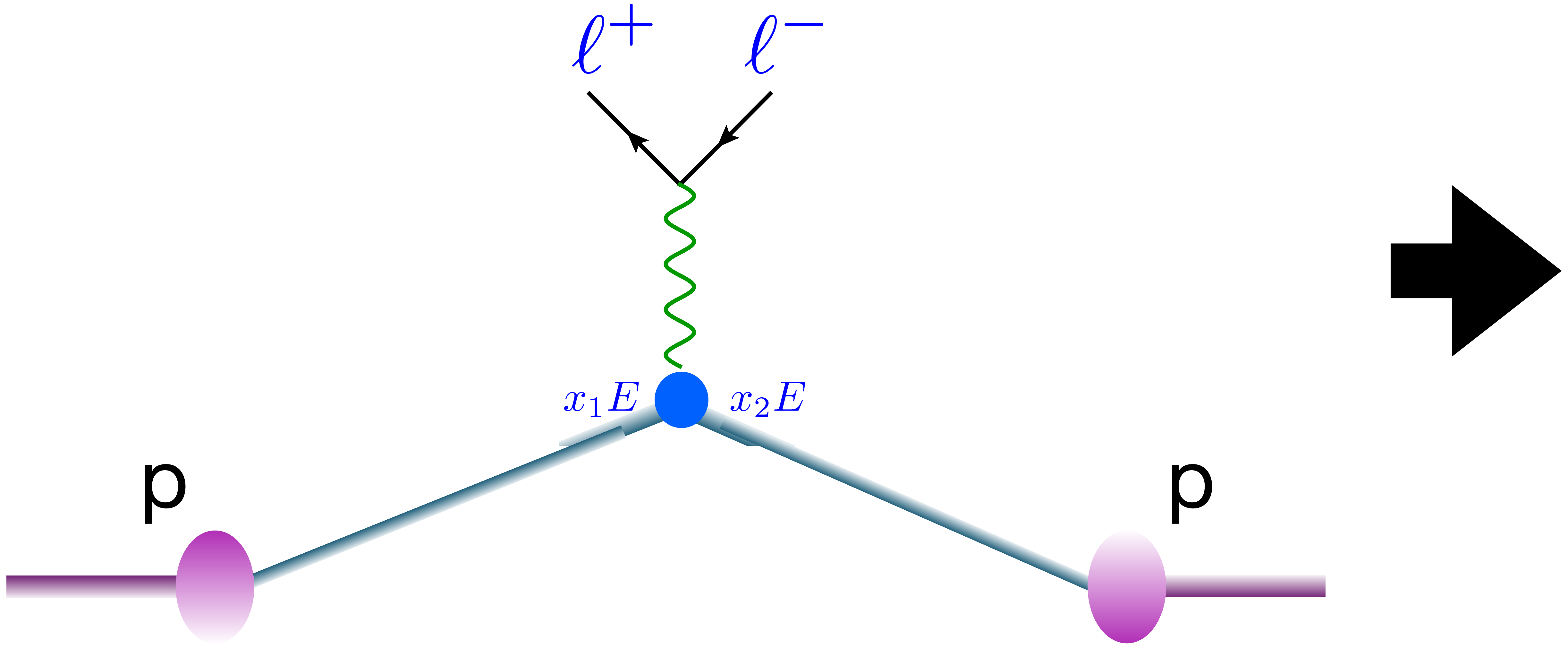
Fixed order computations

Going to higher orders



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

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

LO NLO NNLO N3LO

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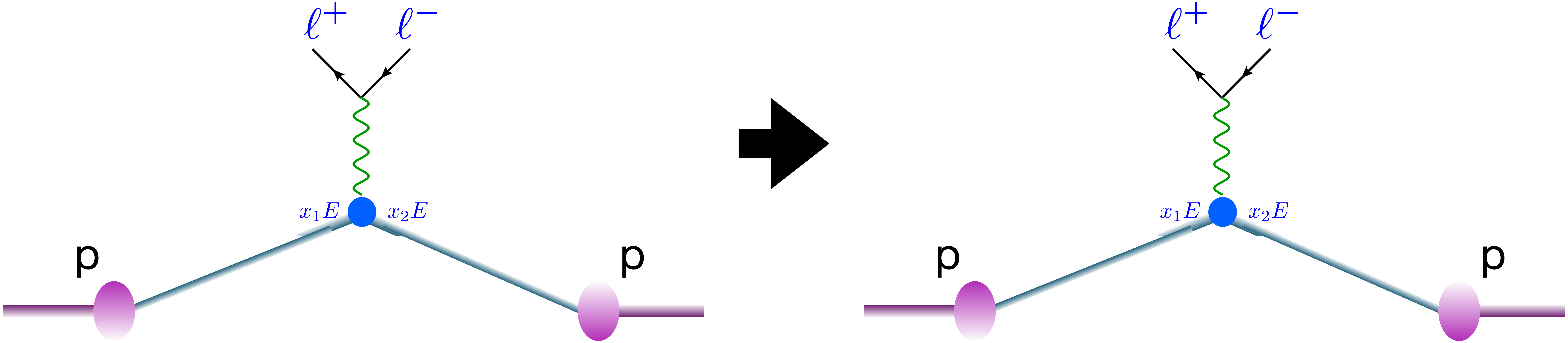

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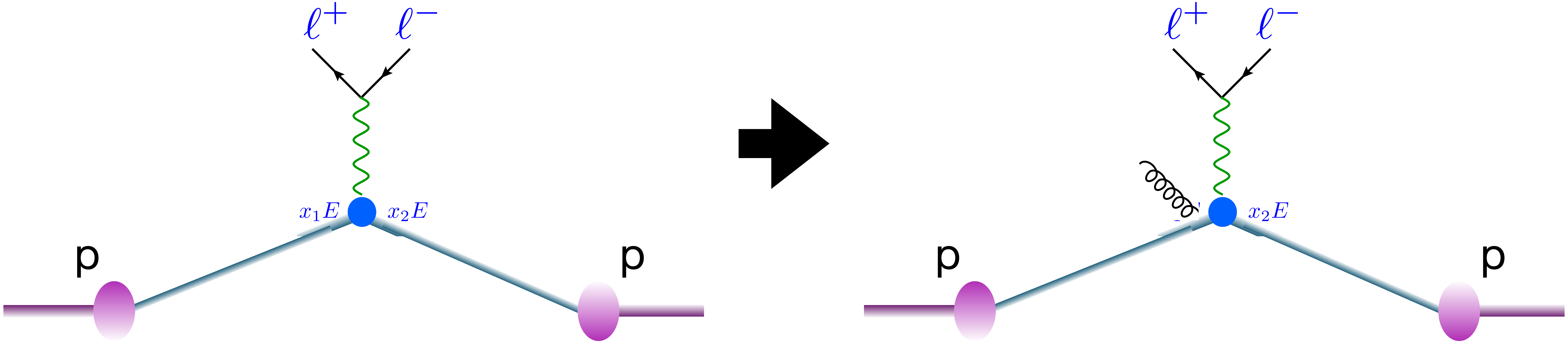

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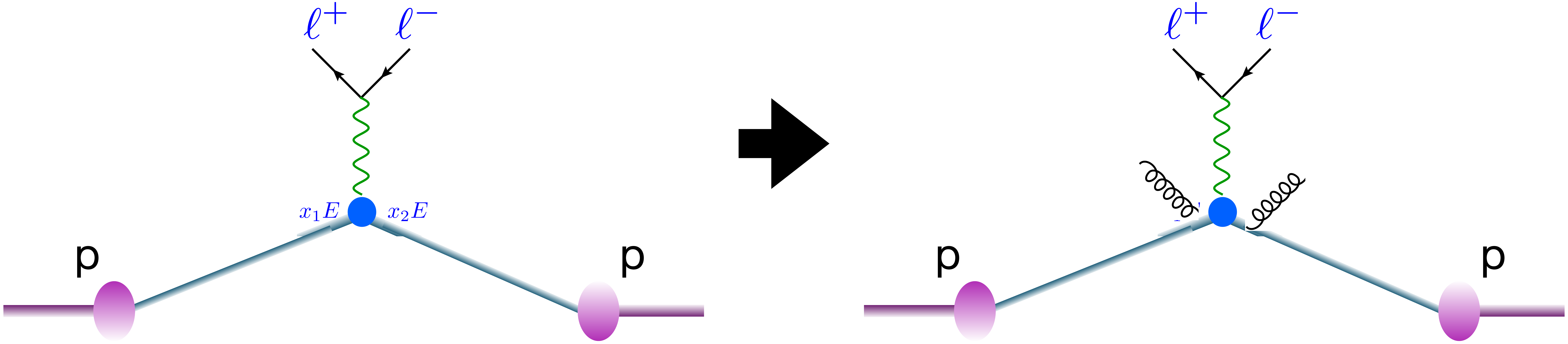

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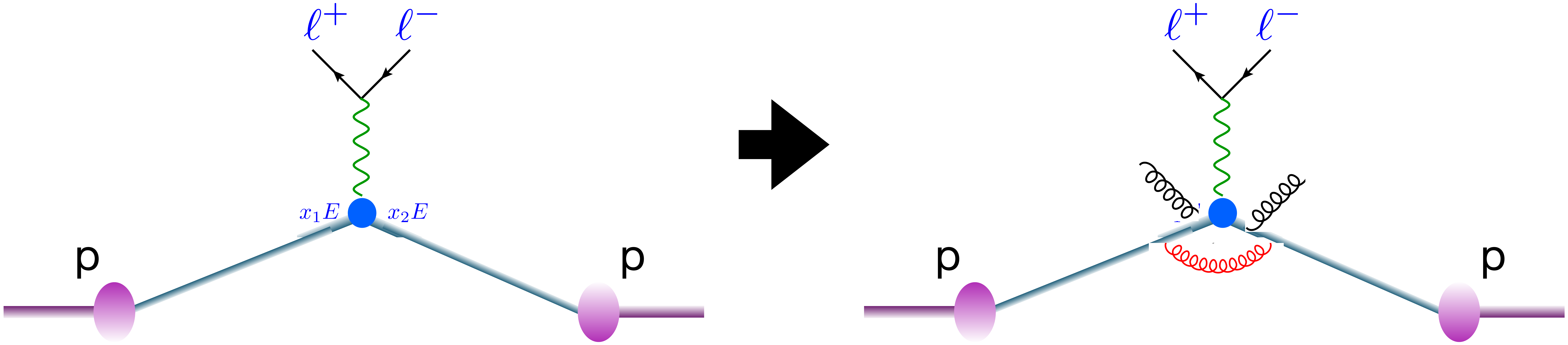

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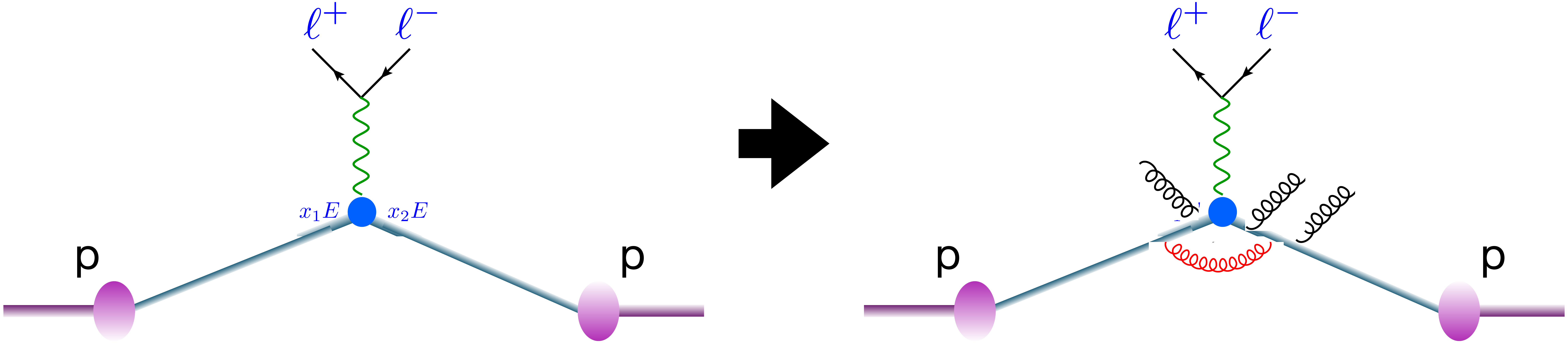

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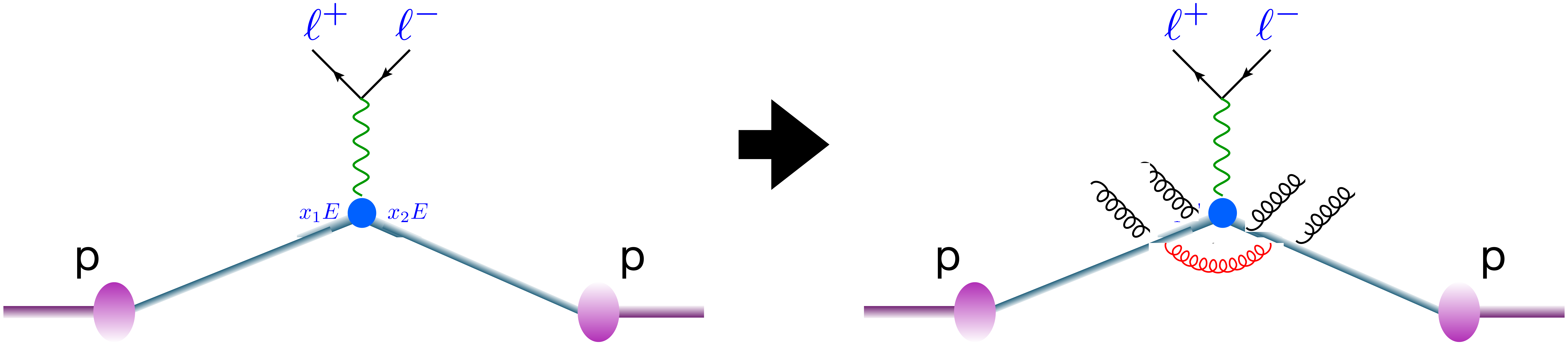

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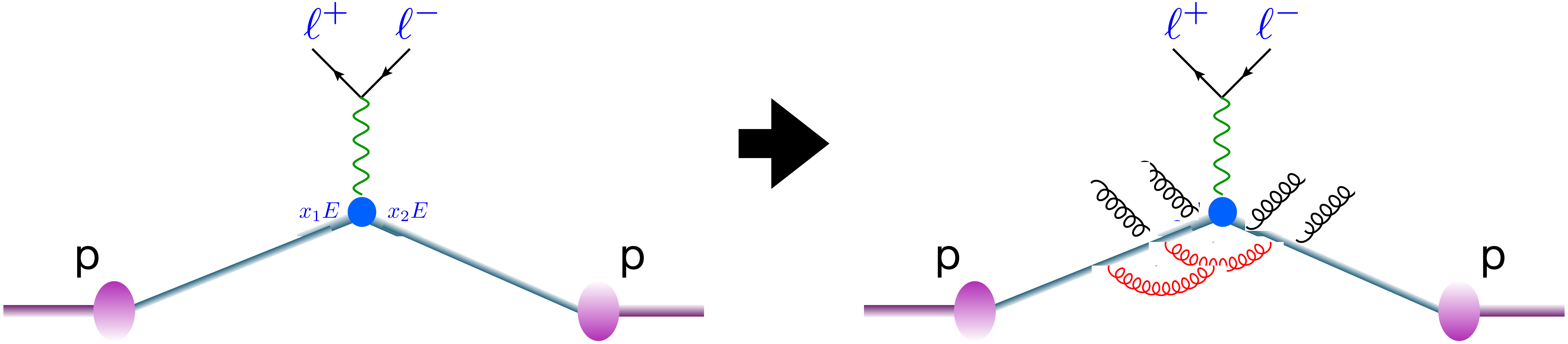

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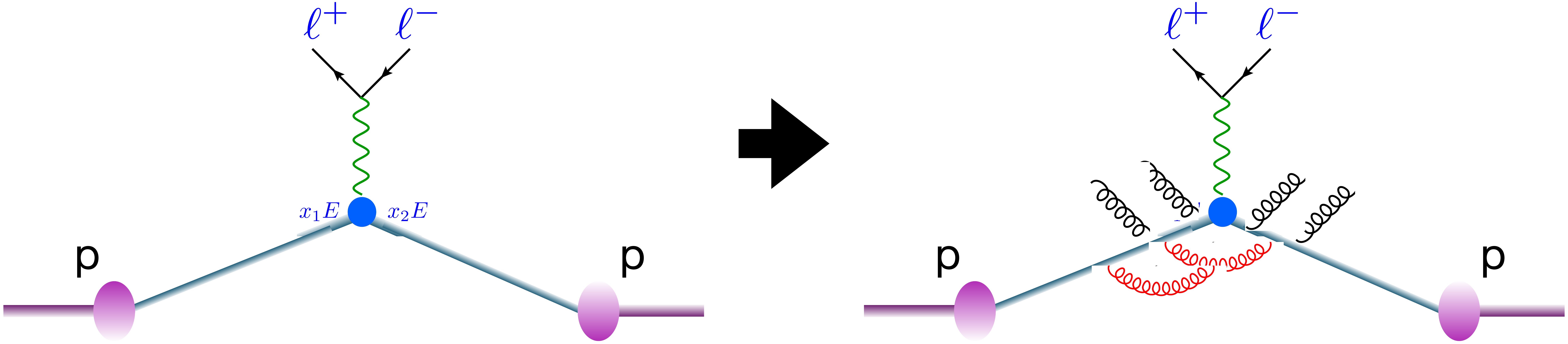
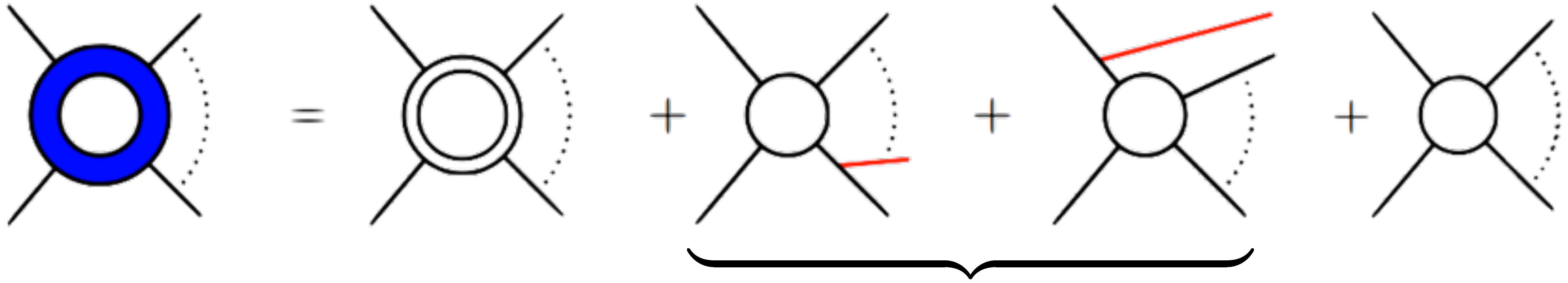


We need to add real and virtual corrections to the hard scattering dealing with singularities

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

Structure of an NLO calculation



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

Virtual part | Real emission part | Born

Difficulties:

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

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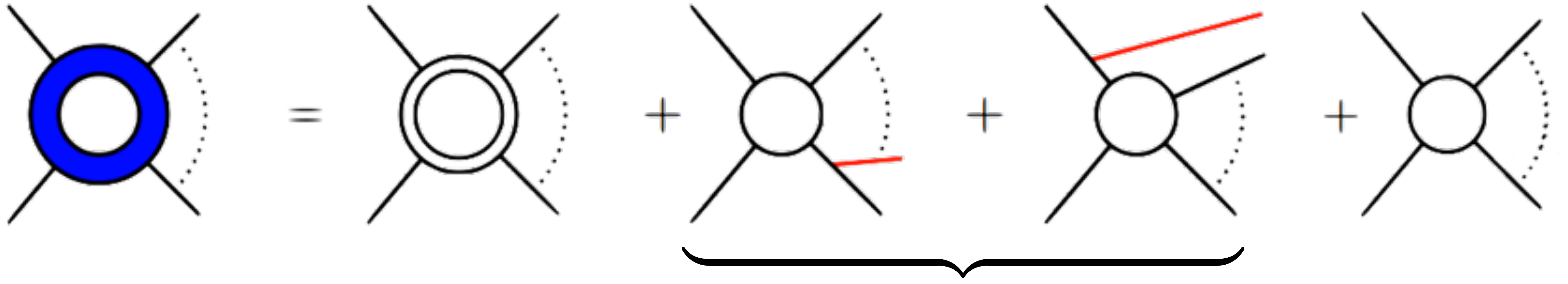

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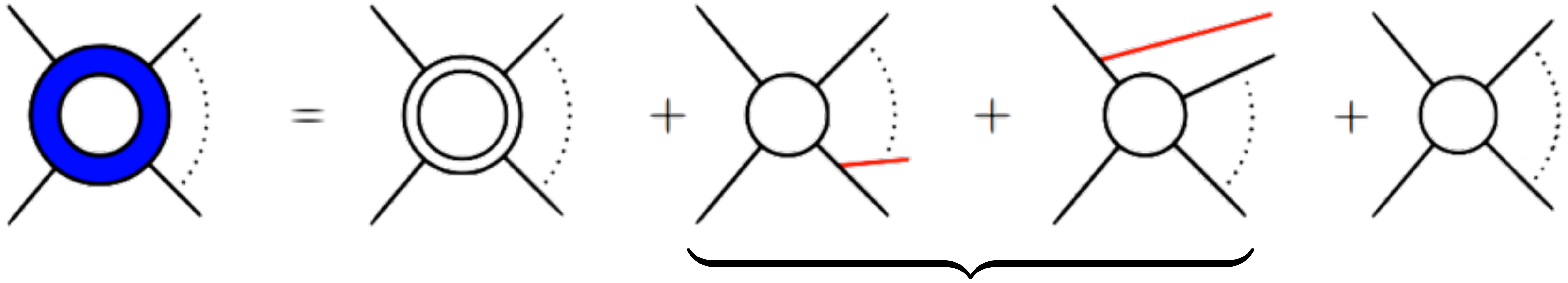

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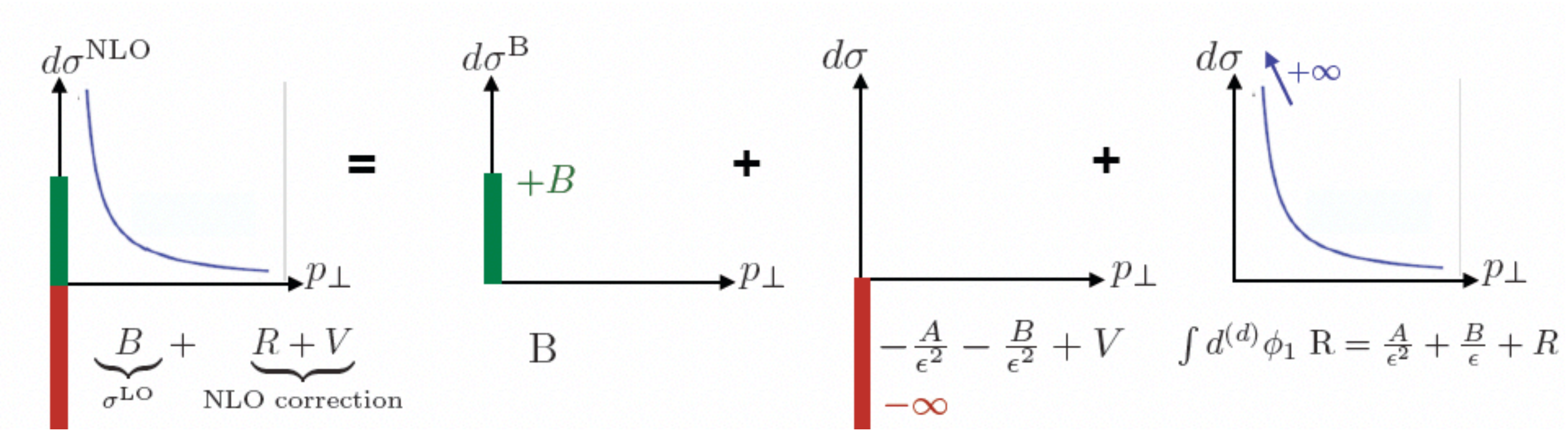
How to deal with NLO in practice?

NLO corrections involve divergences: Divergences are bad for numerical computations



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

Subtraction:

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

finite

finite

Subtraction techniques at NLO

Dipole subtraction

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

FKS subtraction

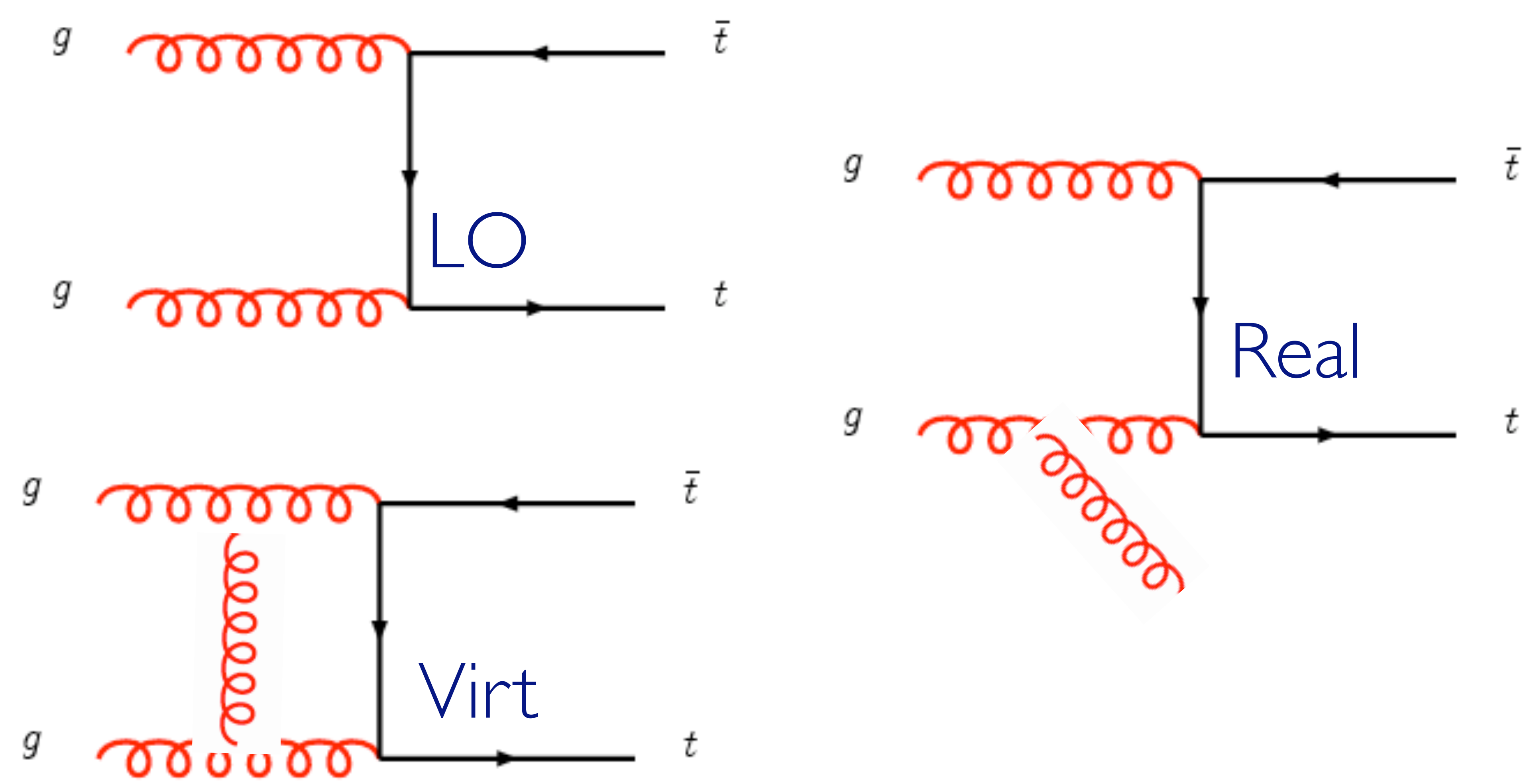
- Frixione, Kunszt, Signer hep-ph/9512328
- Automated in MadGraph5_aMC@NLO and Powheg/Powhel

Detailed discussion of these could be another lecture course!

A note about NLO

NLO is relative

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

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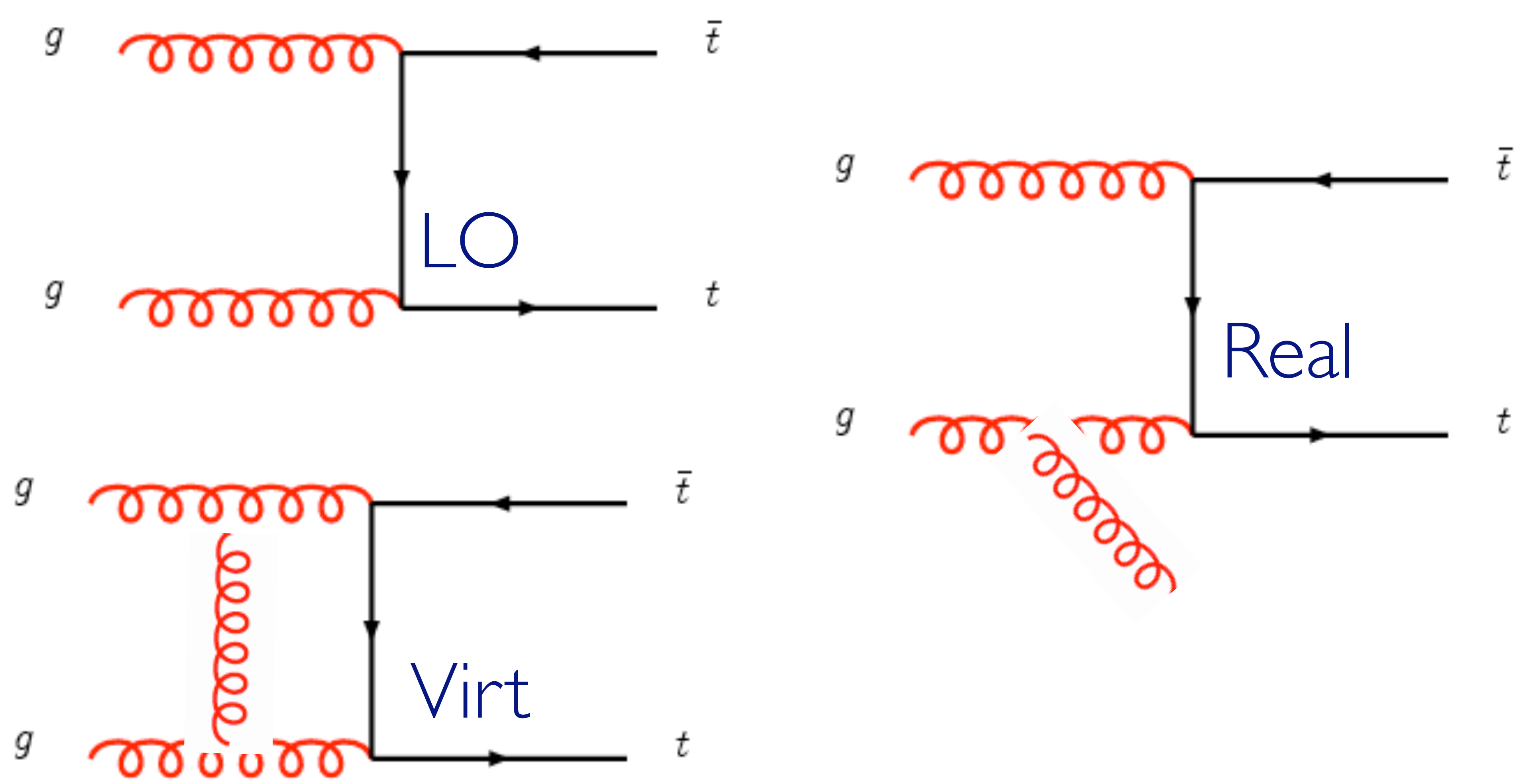

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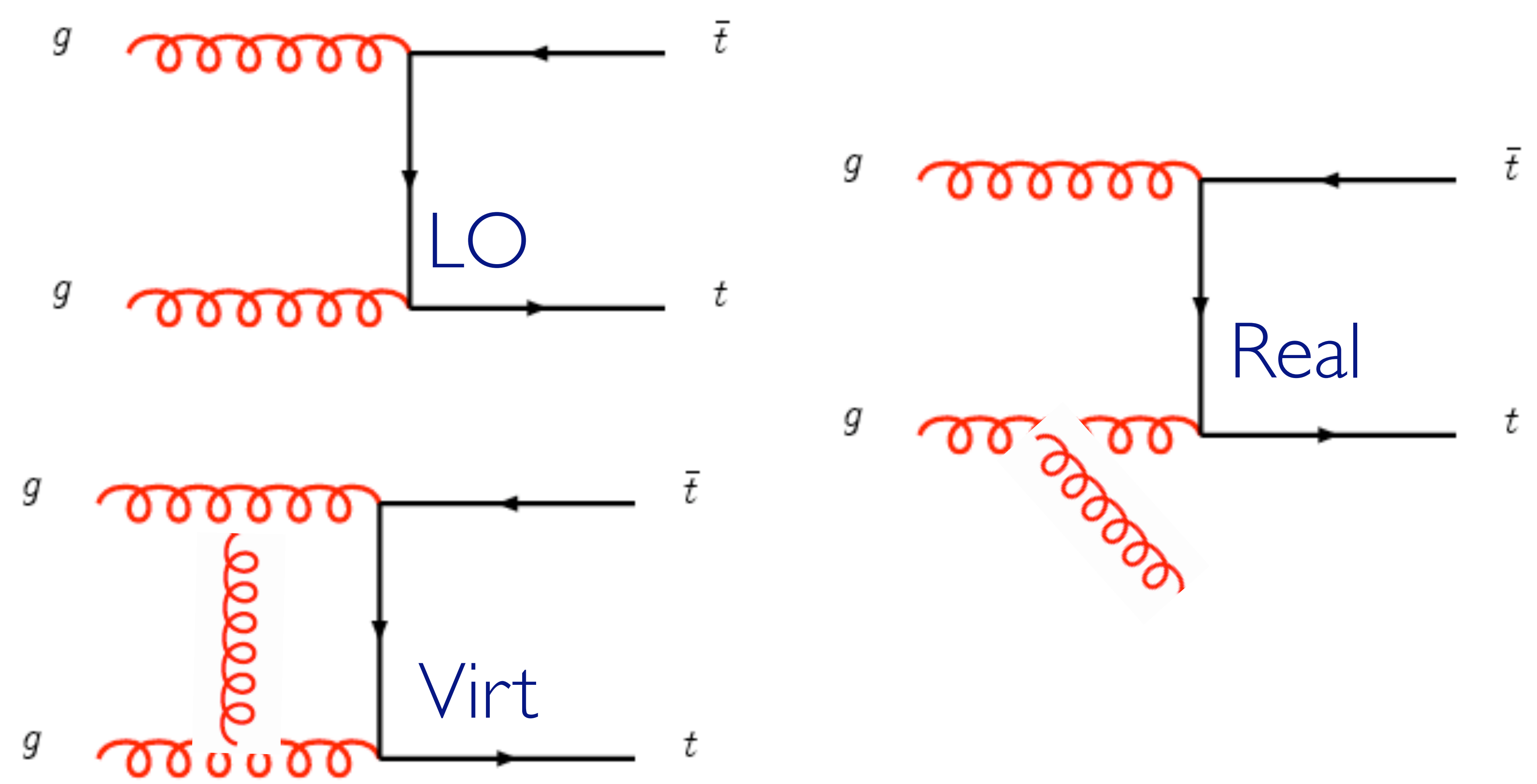

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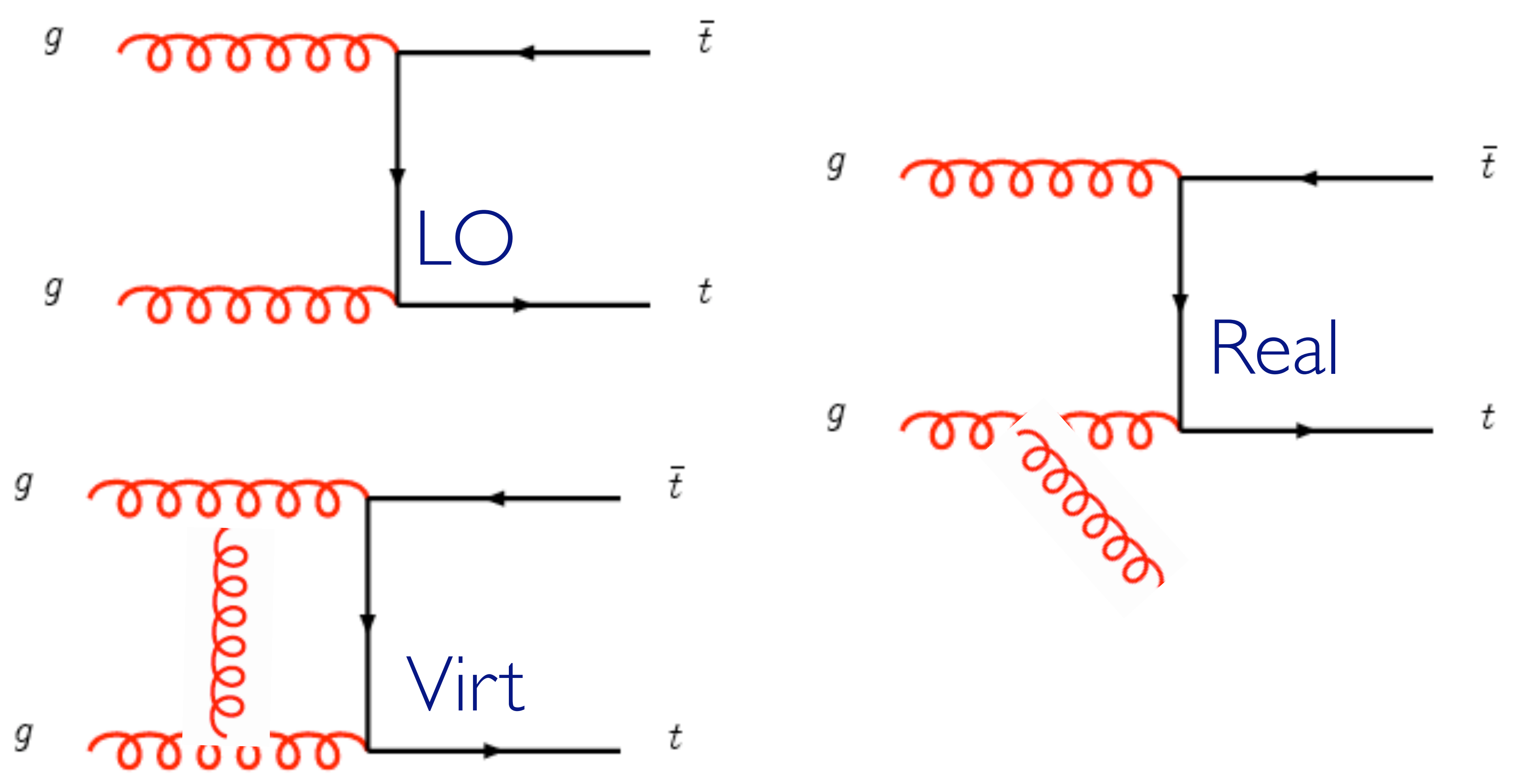

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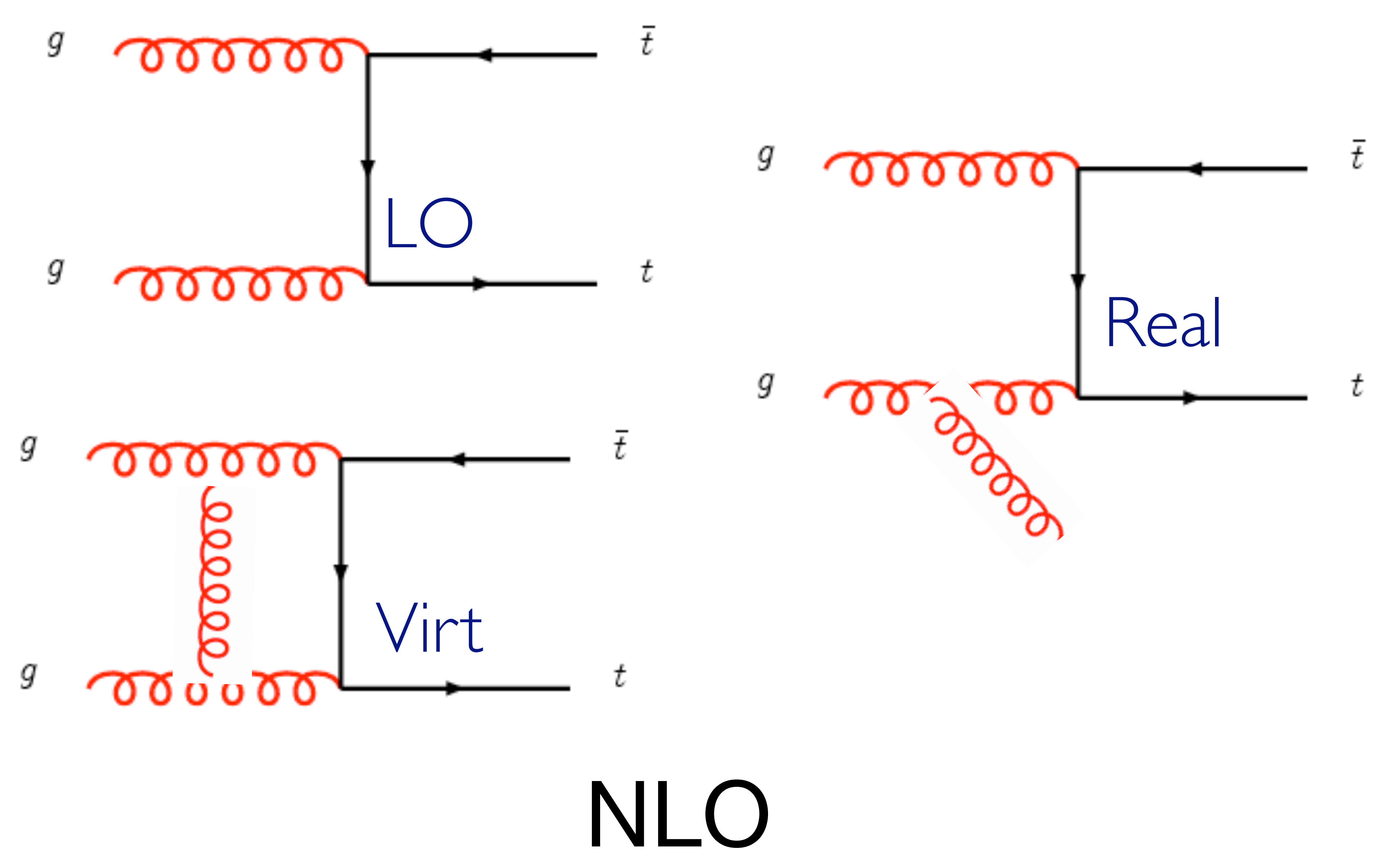

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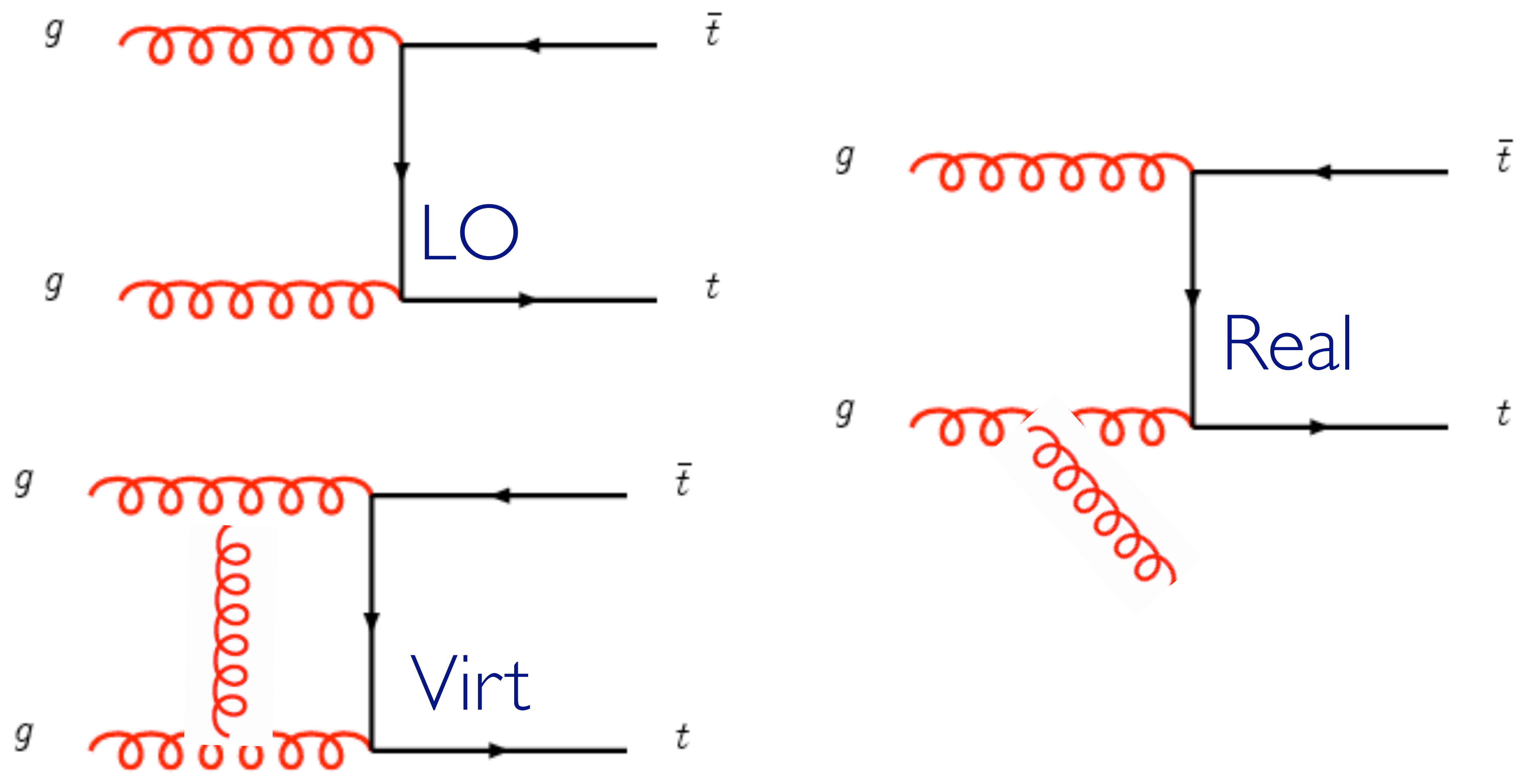

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- Total cross-section ✓
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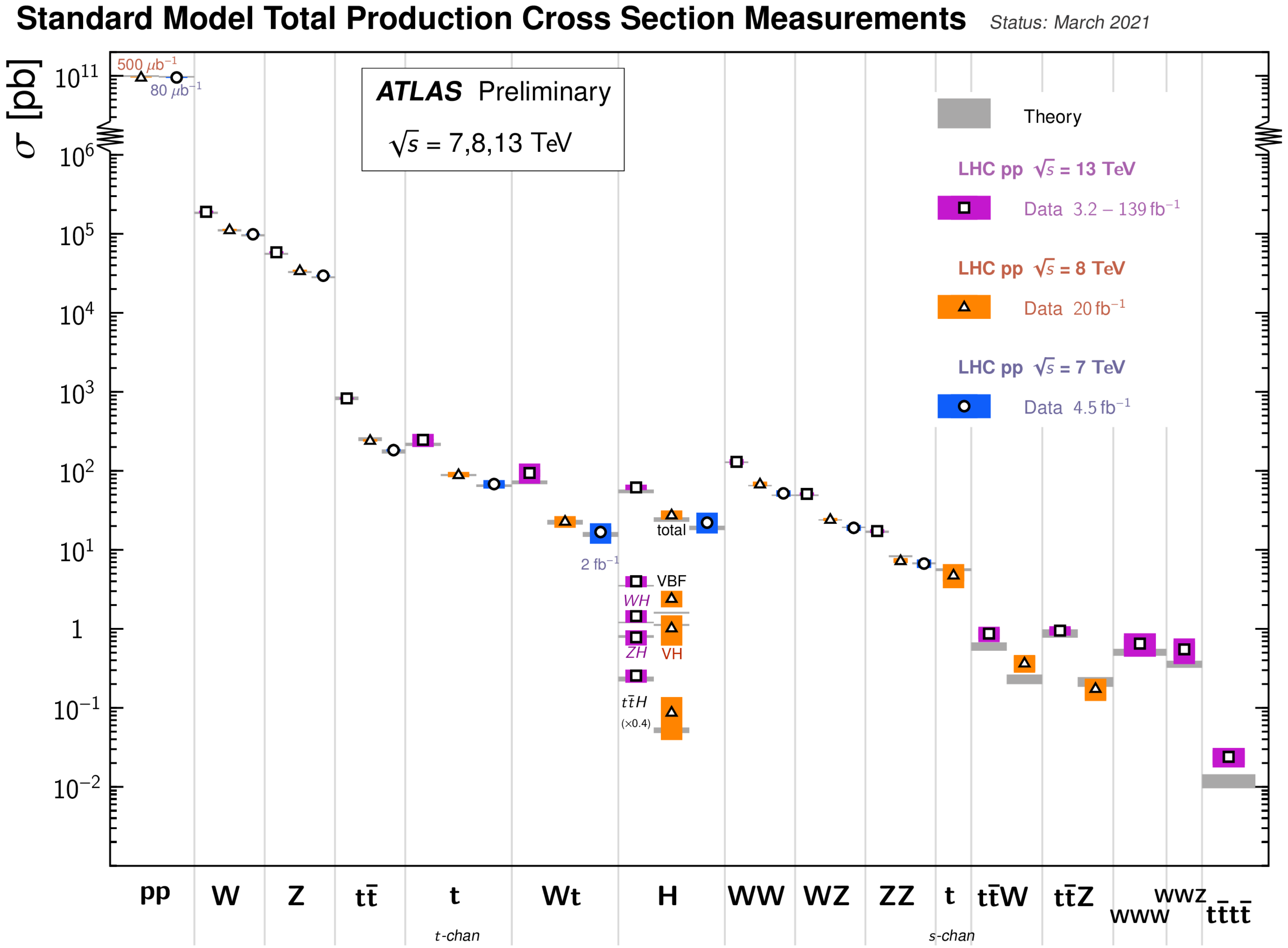
Need for higher-orders

Why is this so important?

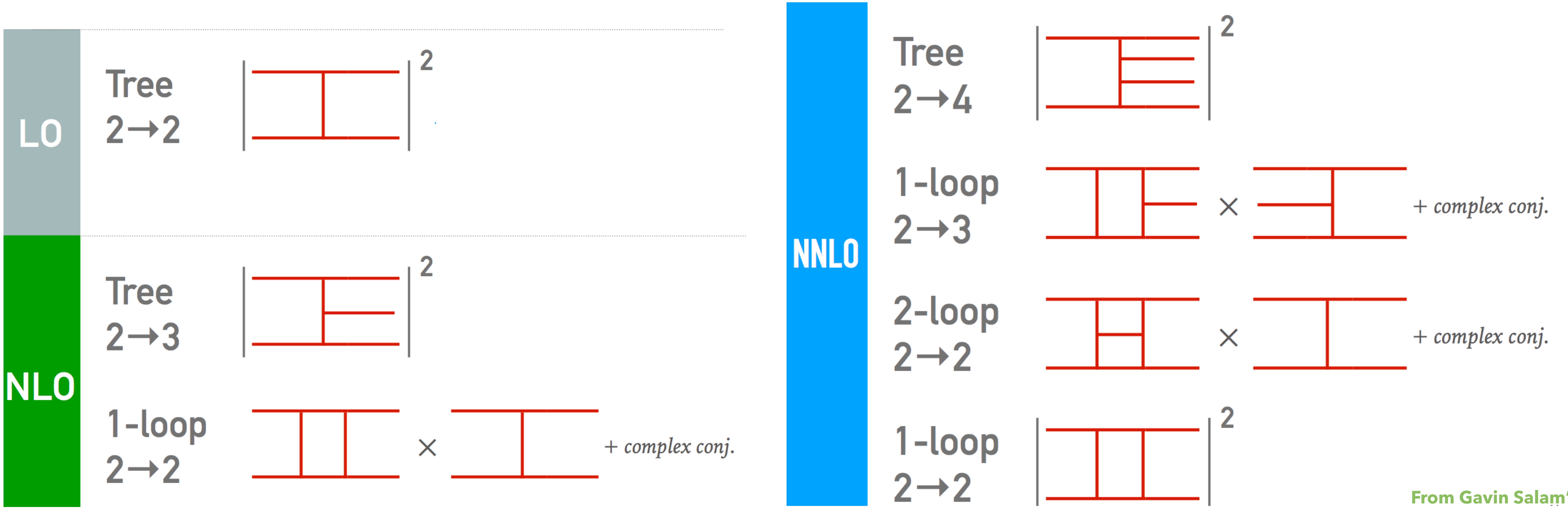


Reminder:

Level of experimental precision demands precise theoretical predictions

Theorists are not simply having fun!!!

Higher order computations



From Gavin Salam's lectures
Quy Nhon Vietnam 2018

Complexity rises a lot with each N!

Status of hard scattering cross-sections

LO automated

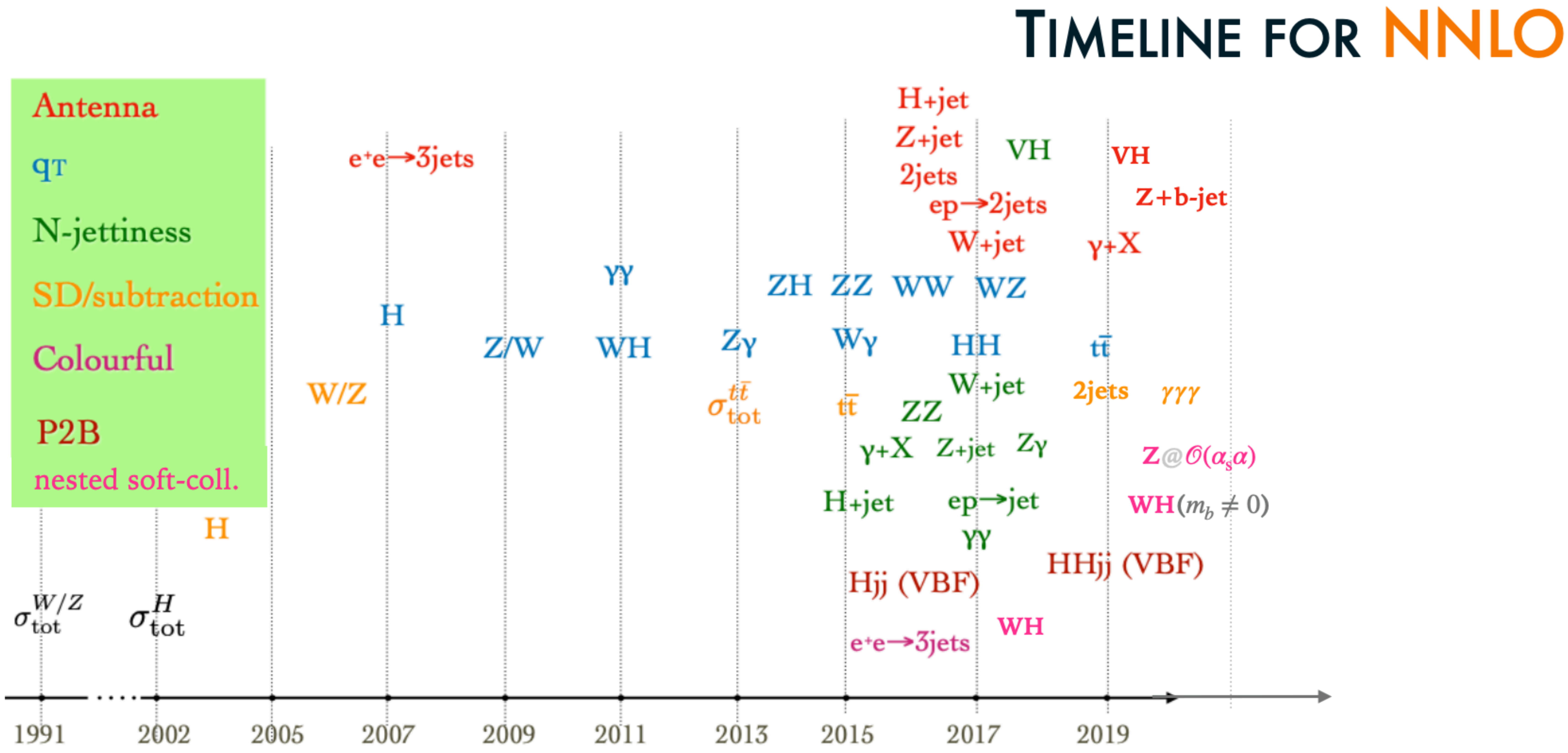
NLO automated

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

NNNLO: only a handful of processes!

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

Progress in higher-order computations



A. Huss, QCD@LHC-X 2020

Hard scattering cross-section

Perturbative expansion

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

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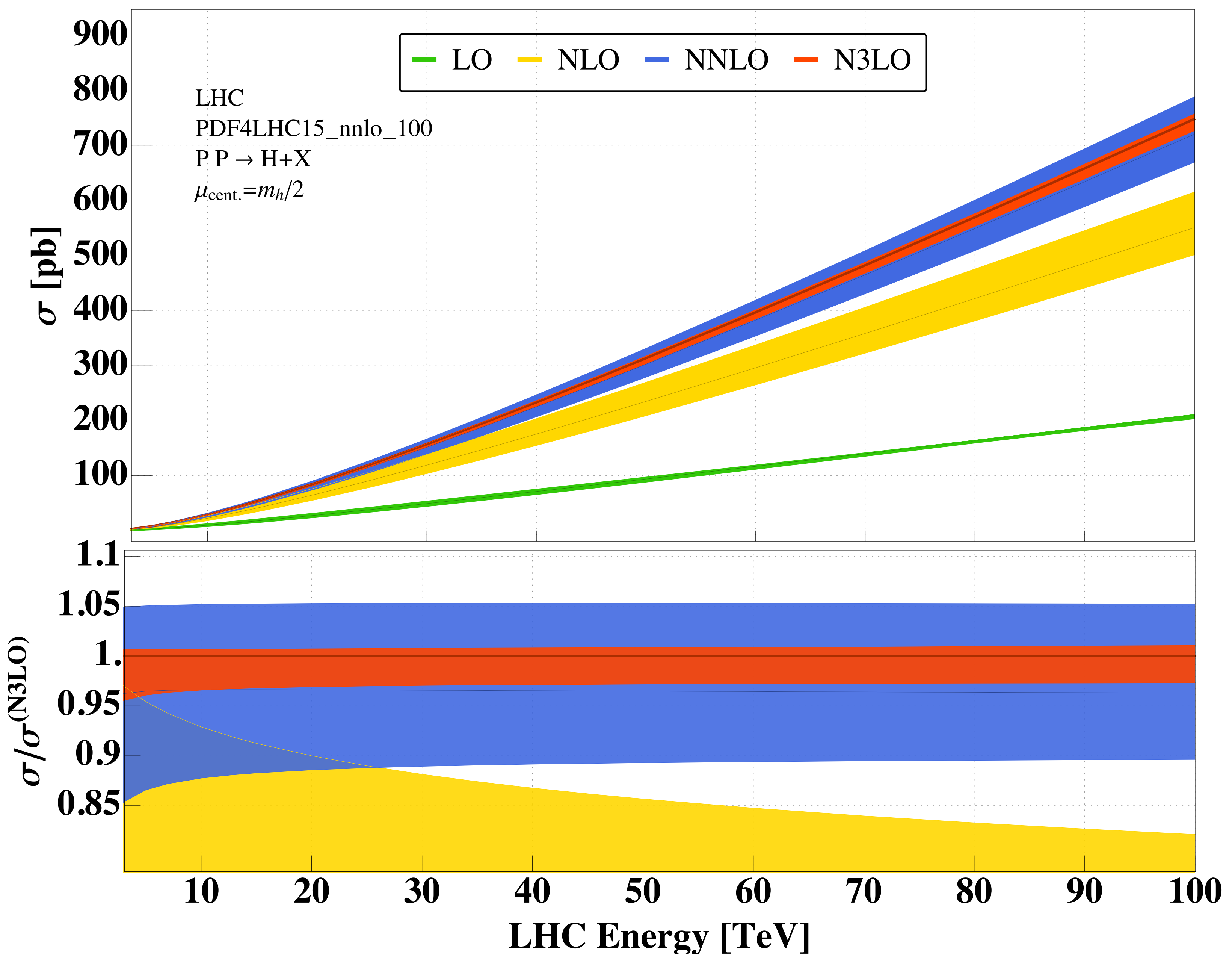
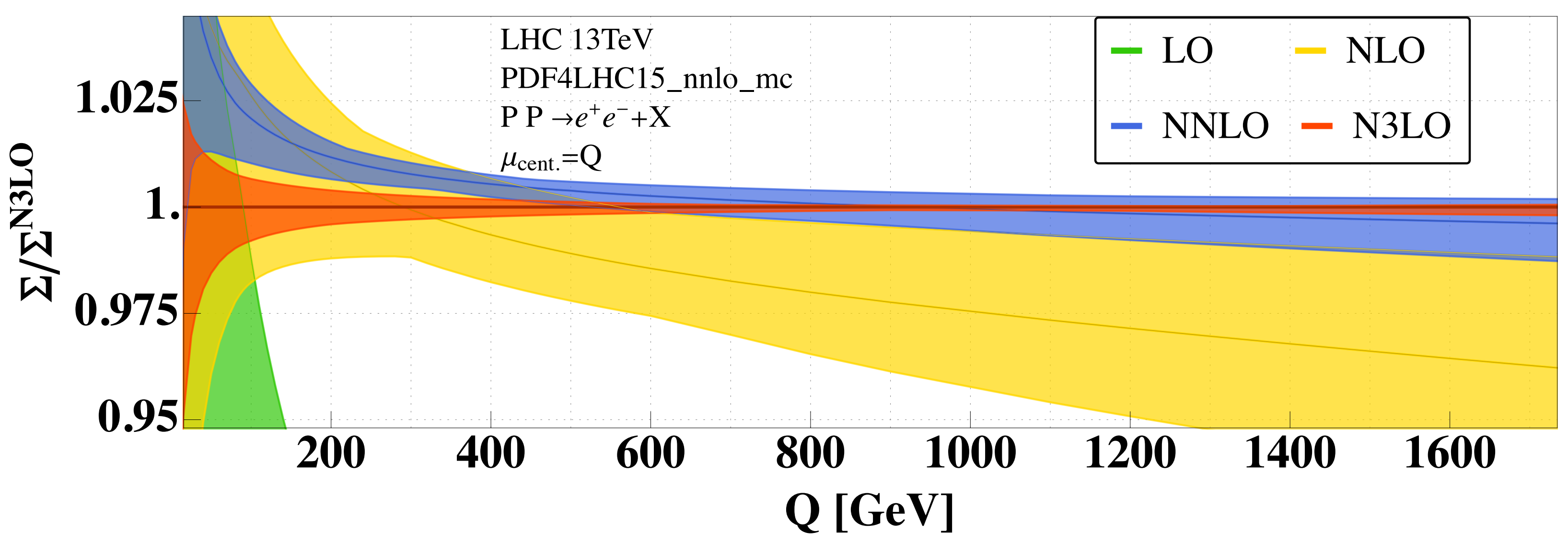


Improved accuracy and precision



Dilepton production

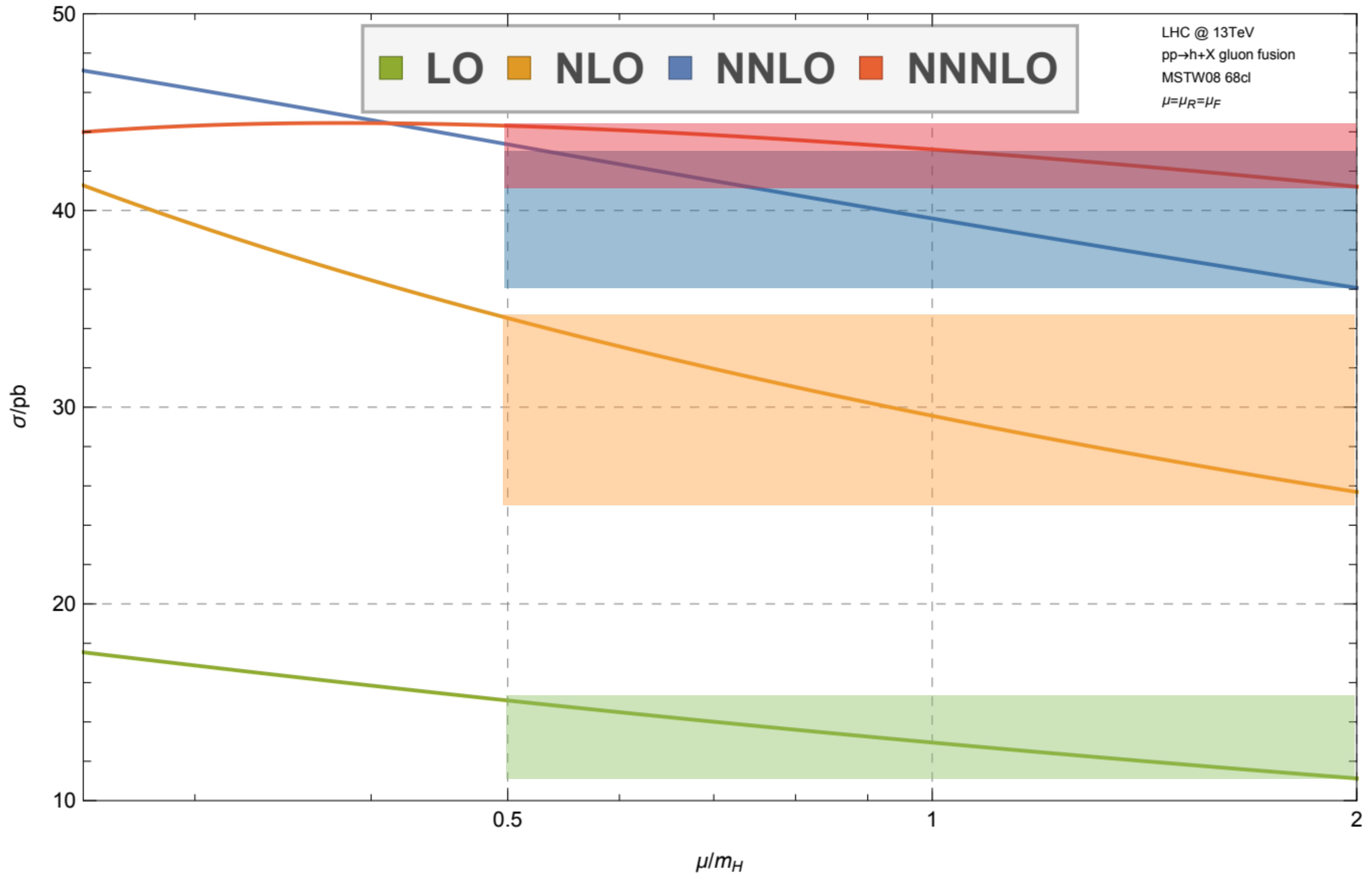
Higgs production arXiv:2203.06730

Uncertainties in theory predictions

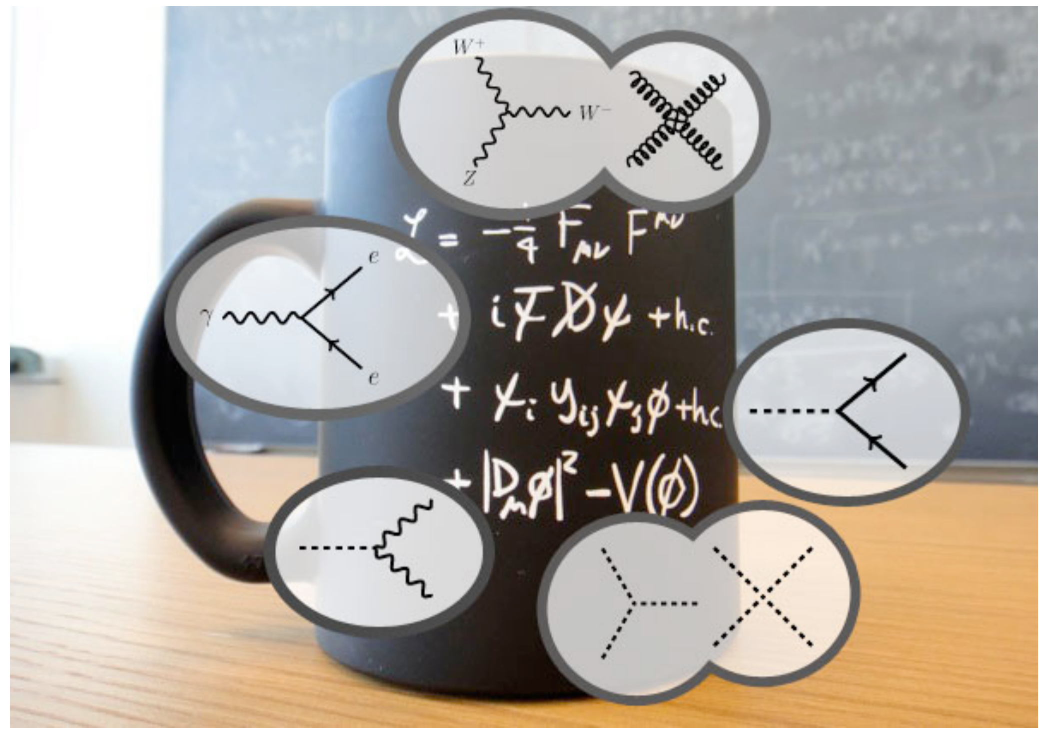
How do we estimate uncertainties?

Vary the renormalisation and factorisation scale

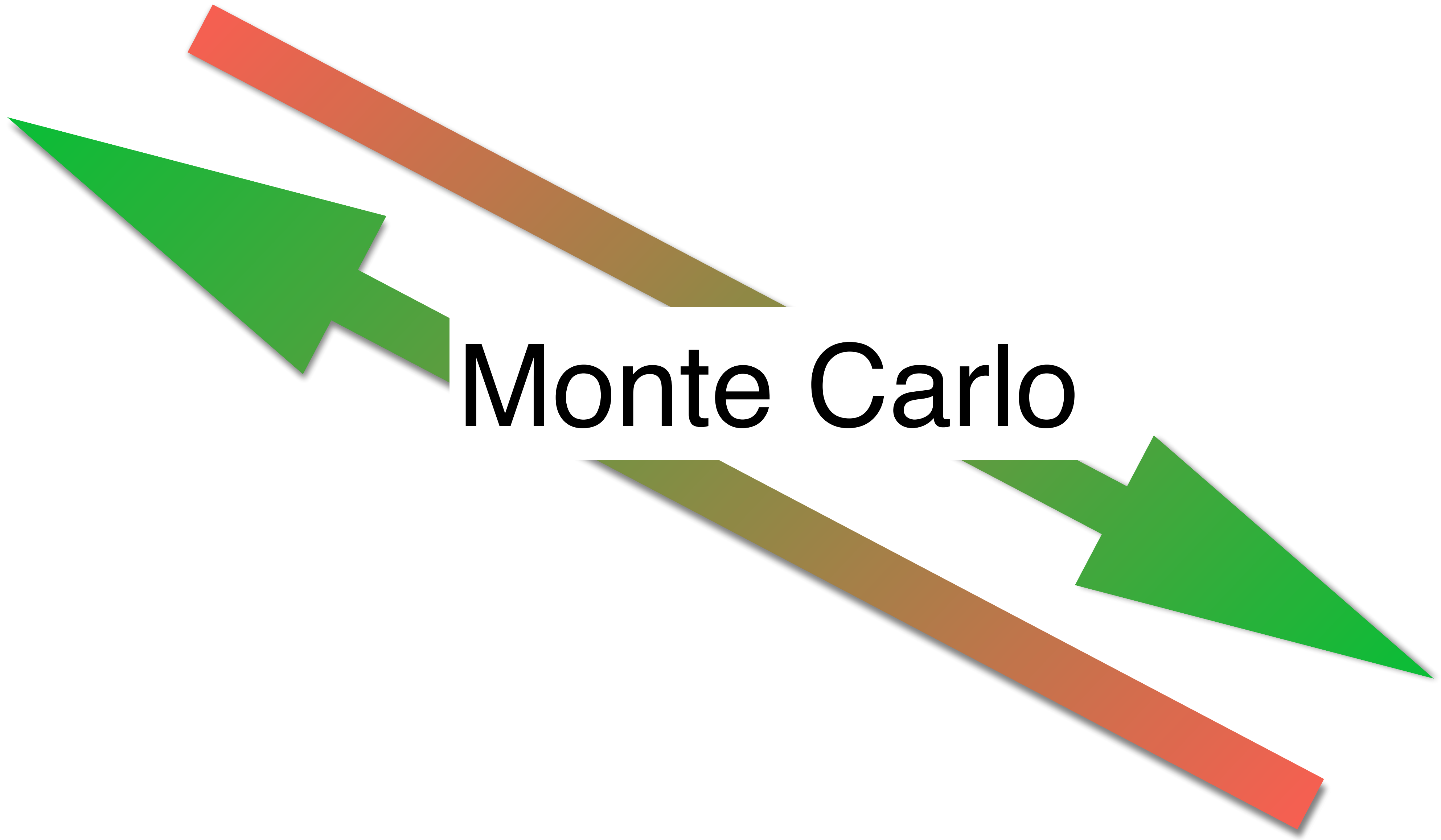
Typically pick some central scale μ_0 and vary the scale up and down by a factor of 2



How do we actually compute all of these?

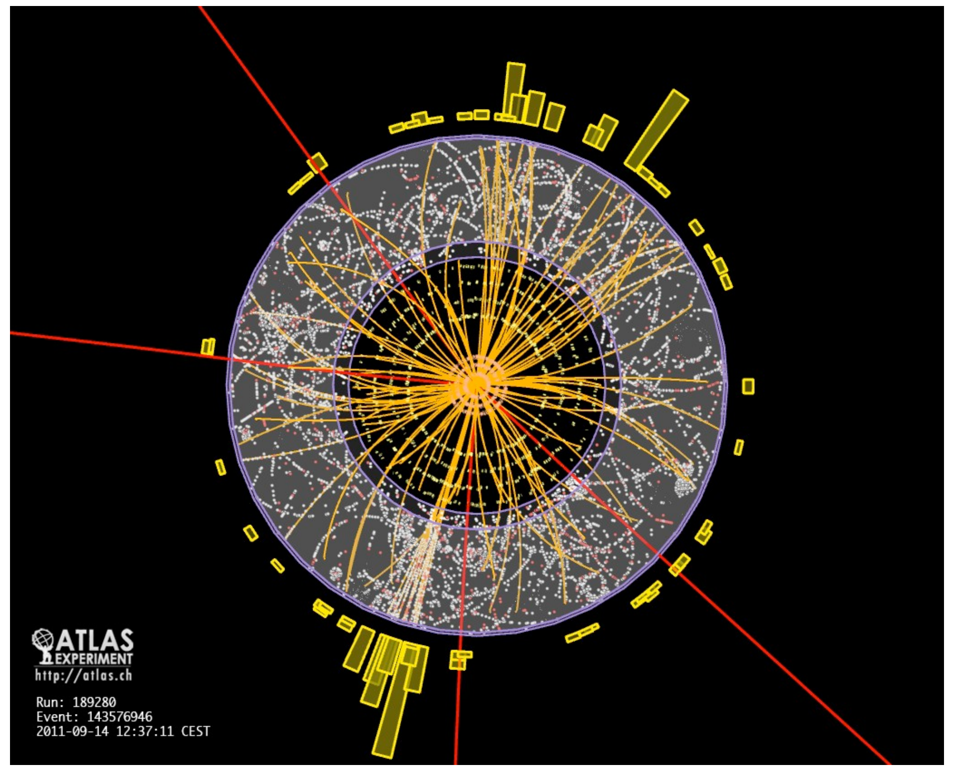


Theory



Monte Carlo

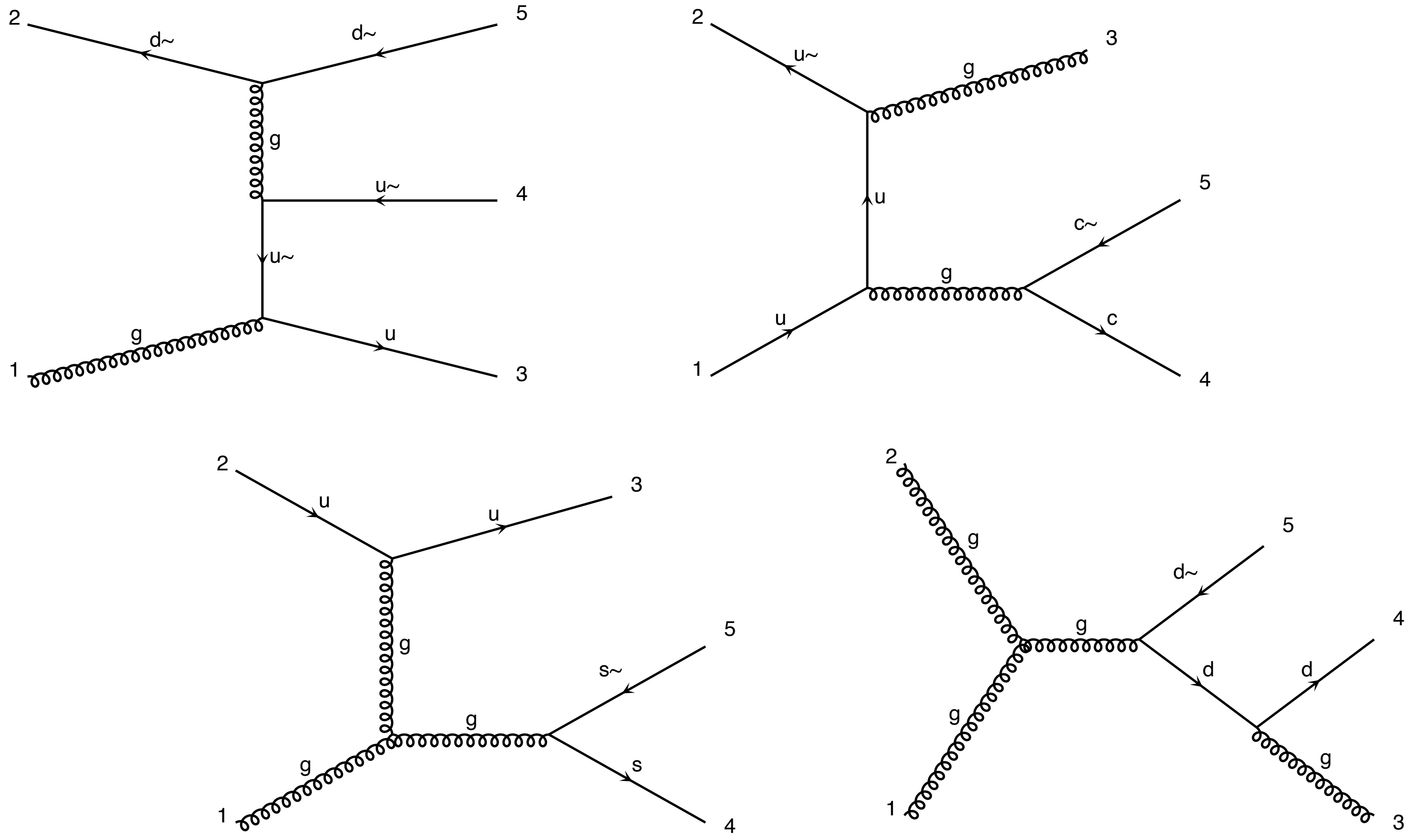
Experiment



Focusing on LO

How to compute a LO cross-section

Example: 3 jet production in pp collisions



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

97 processes with 781 diagrams generated in 2.994 s

Total: 97 processes with 781 diagrams

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

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

LO calculation of a cross-section

How many subprocesses?

Amplitude computation (Feynman diagrams)

Square the amplitude, sum over spin and colour

Integrate over the phase space

Difficulty

Complexity increases with

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

Structure of an automated MC generator

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

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Next: Shower+Hadronisation
Detector simulation and reconstruction

Output of LO MC generators

Les houches events

Example: gg>ZZ

```
<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

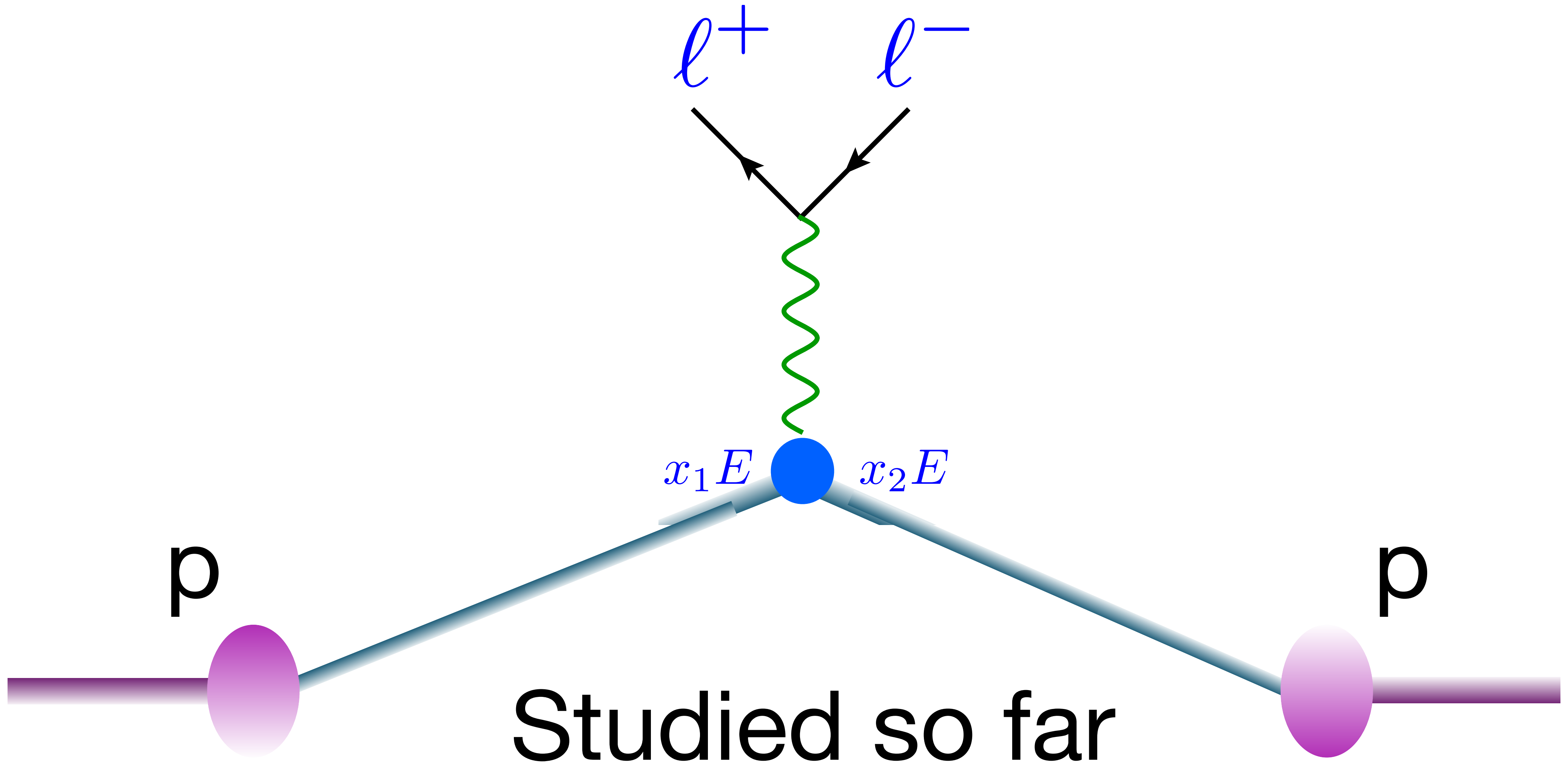
Available public MC generators

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



Studied so far

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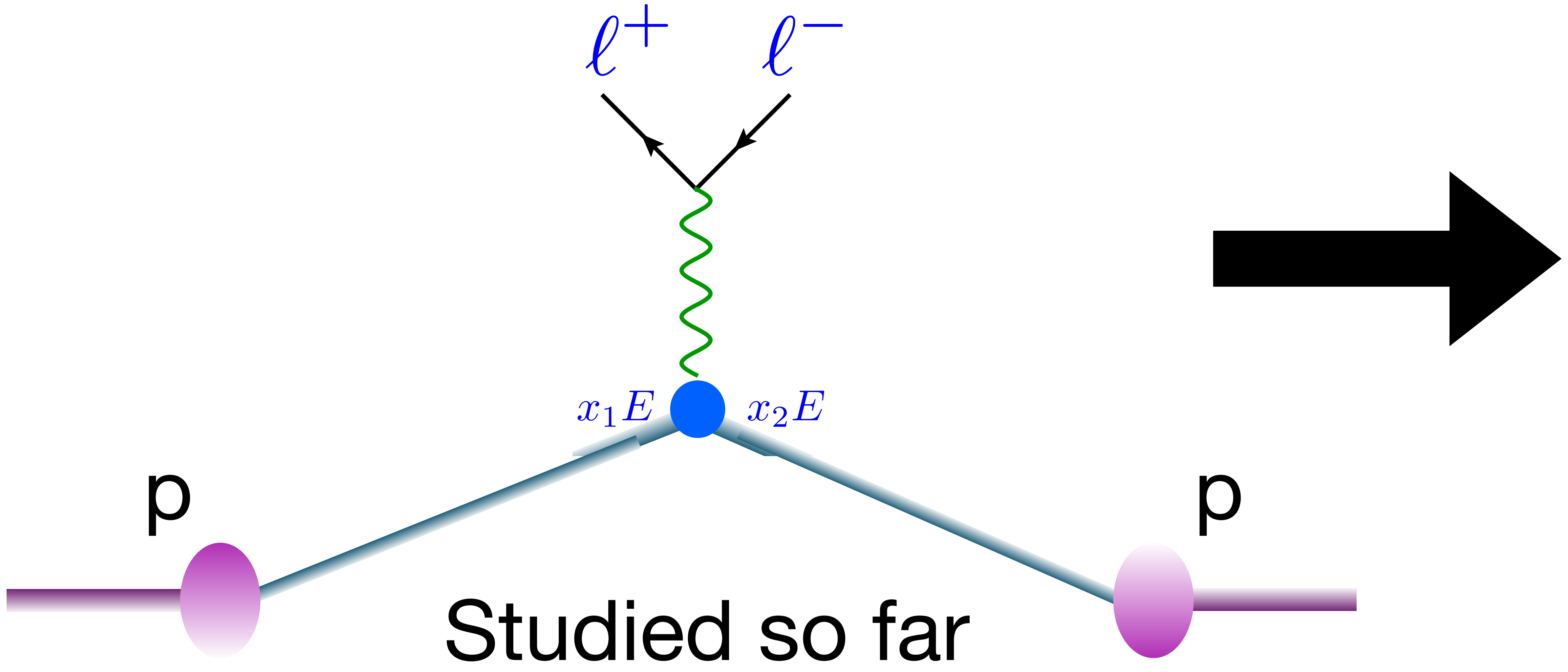
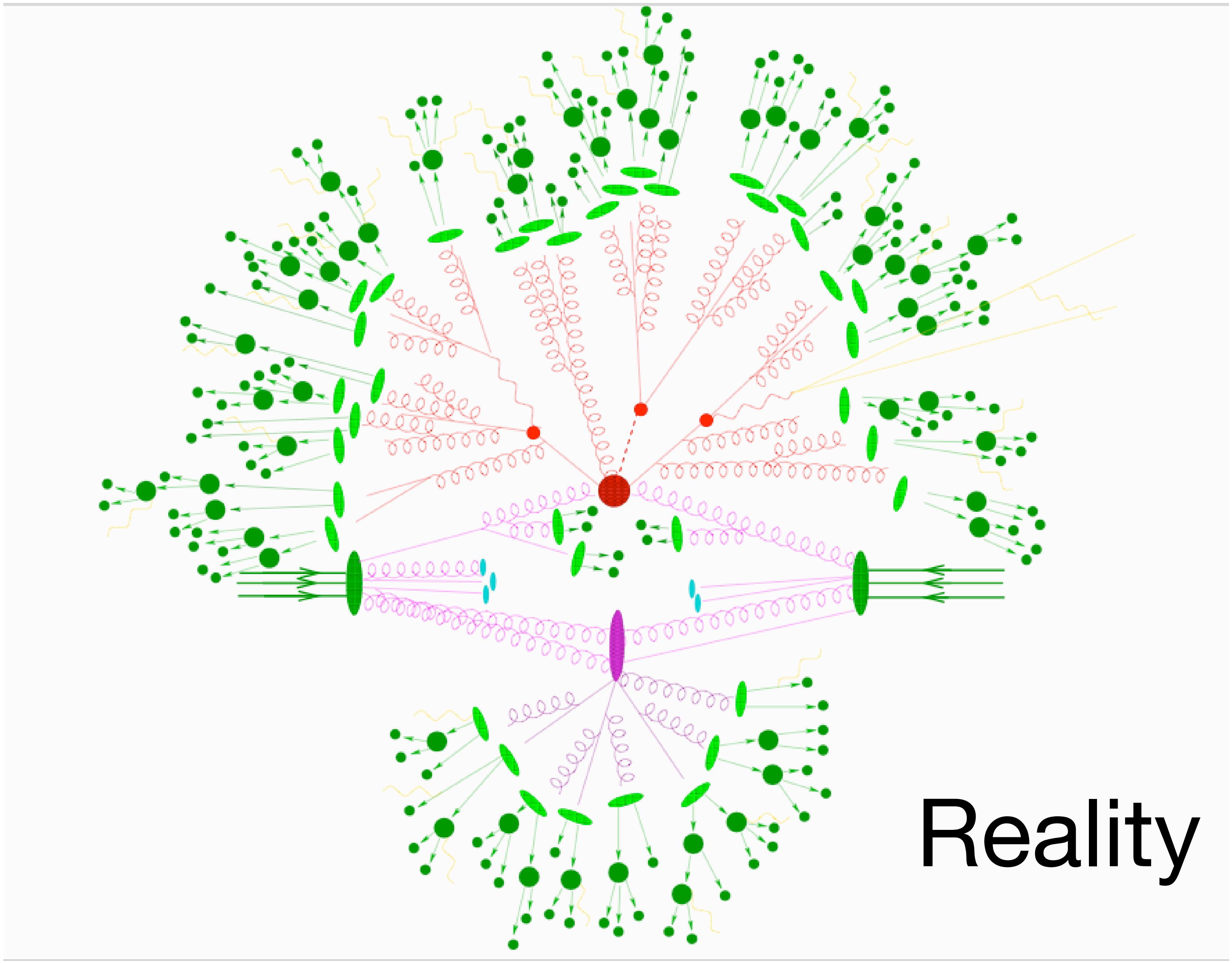
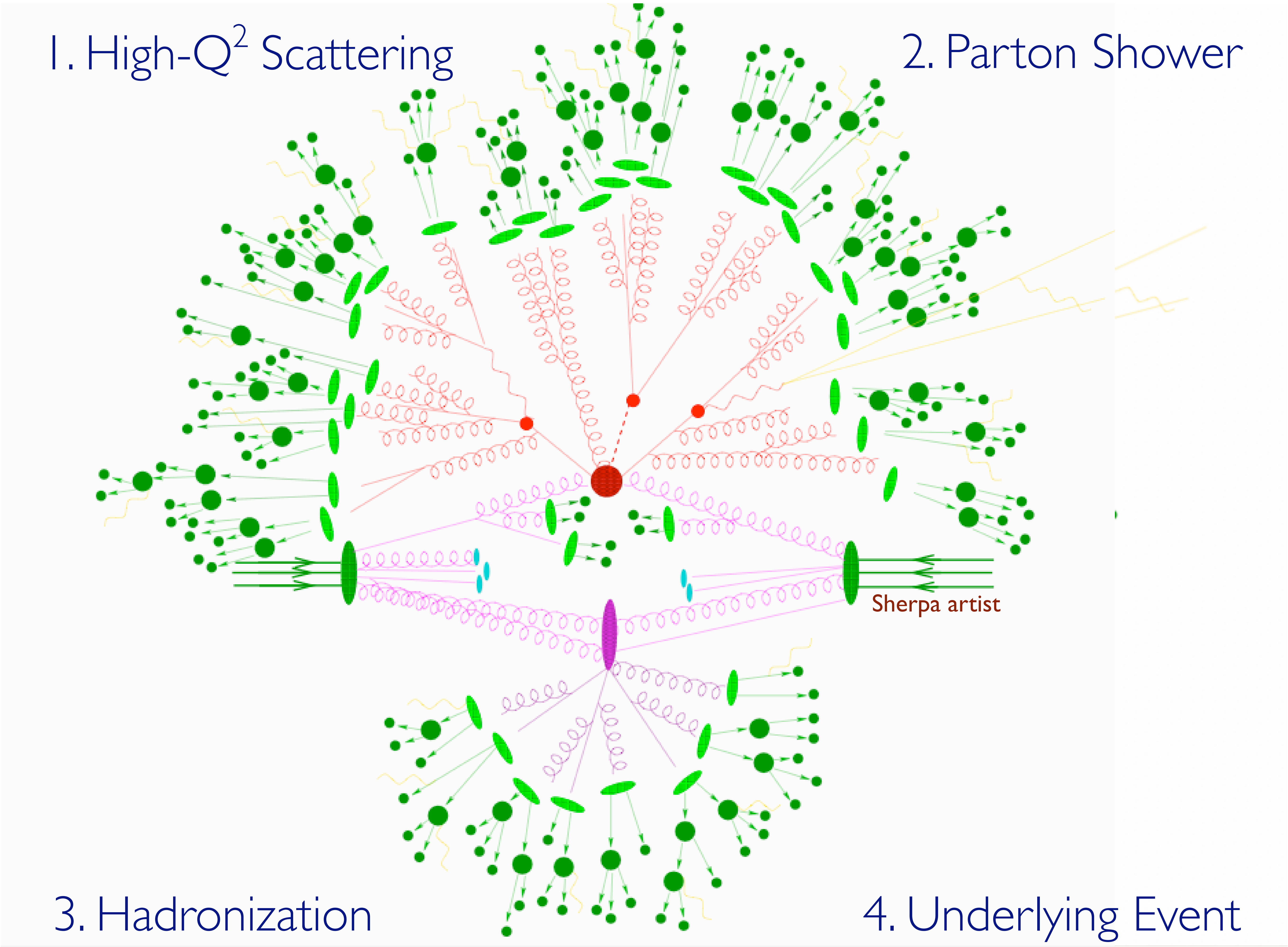


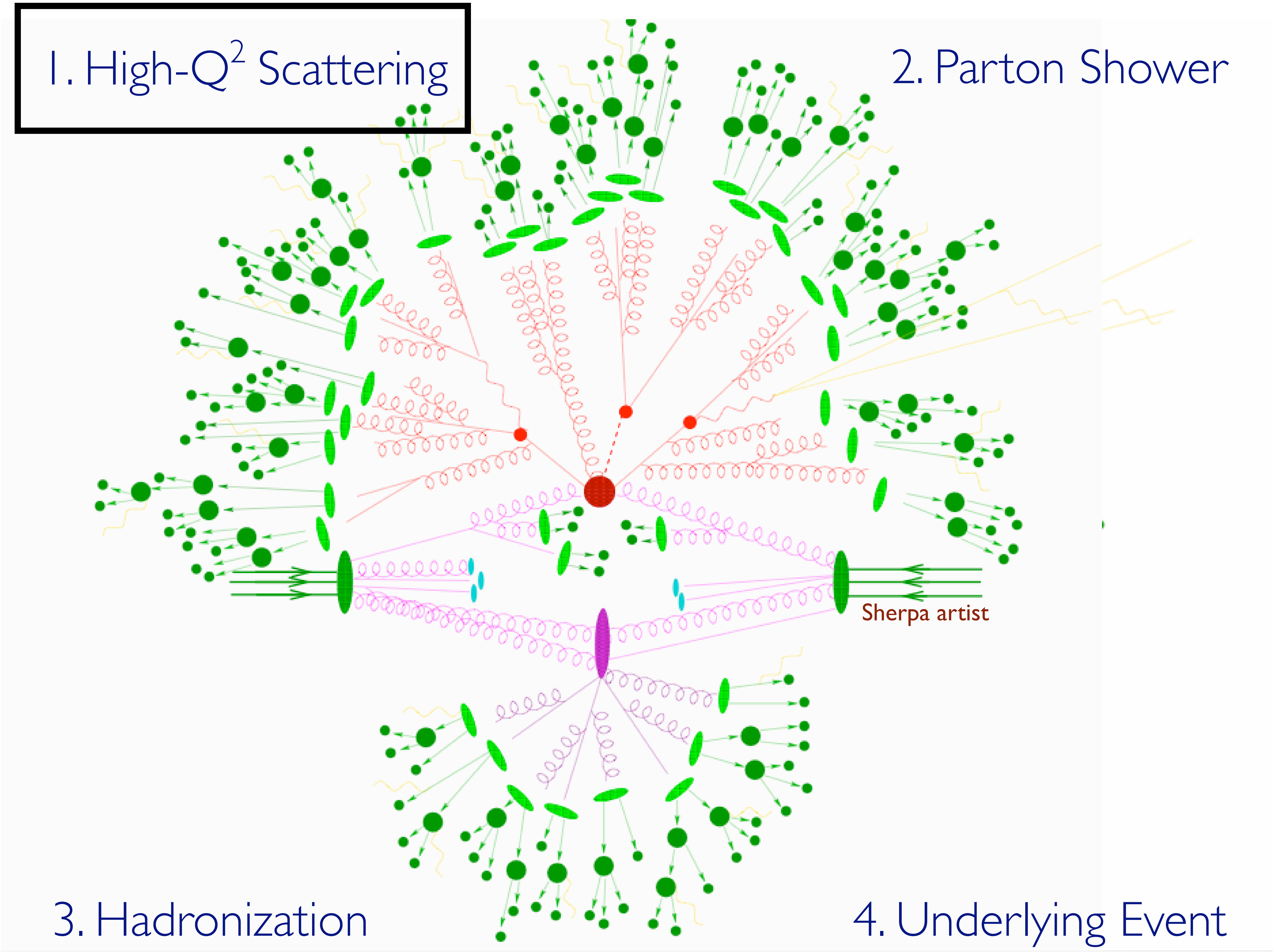


An LHC event



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

An LHC event



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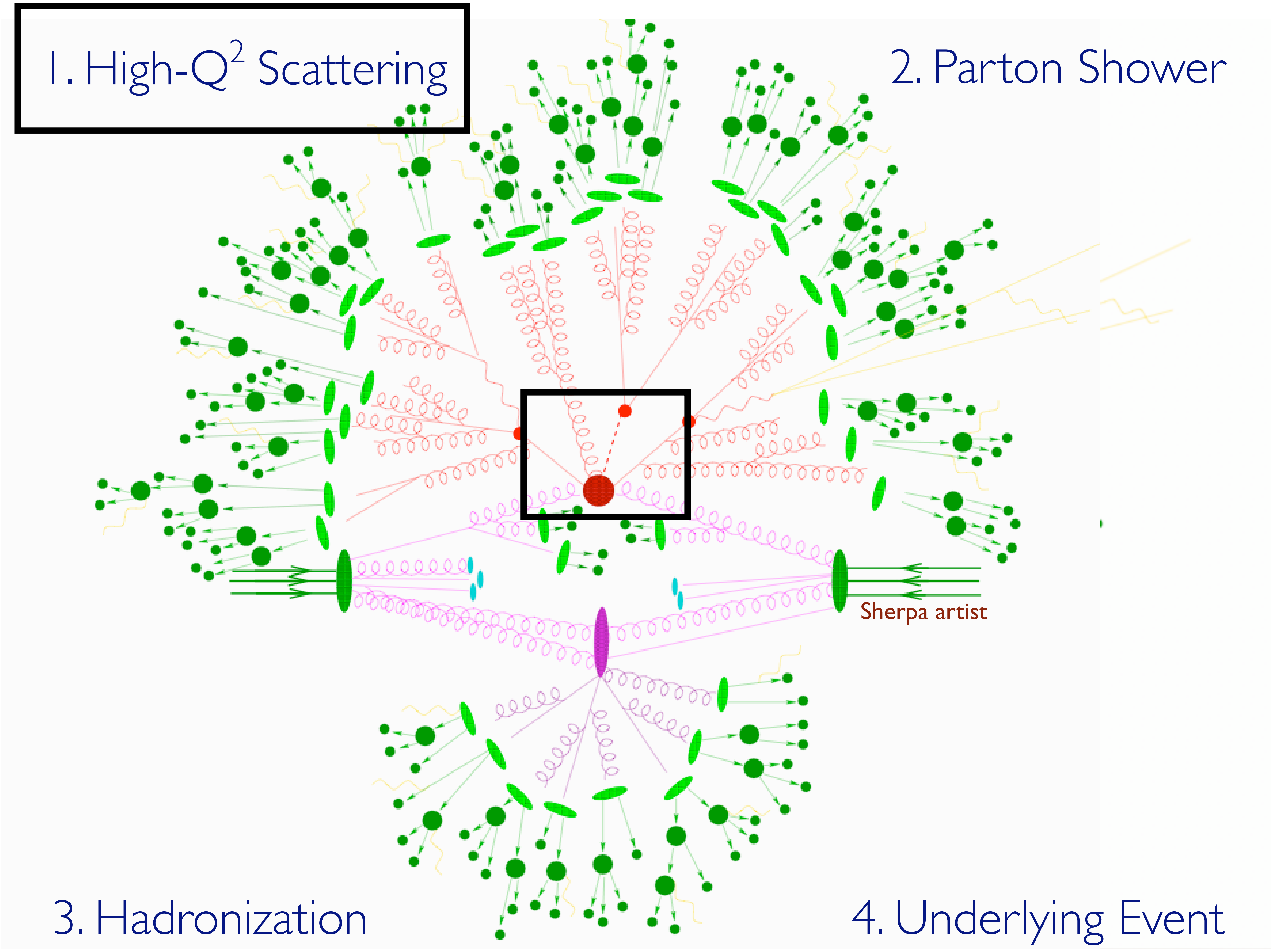
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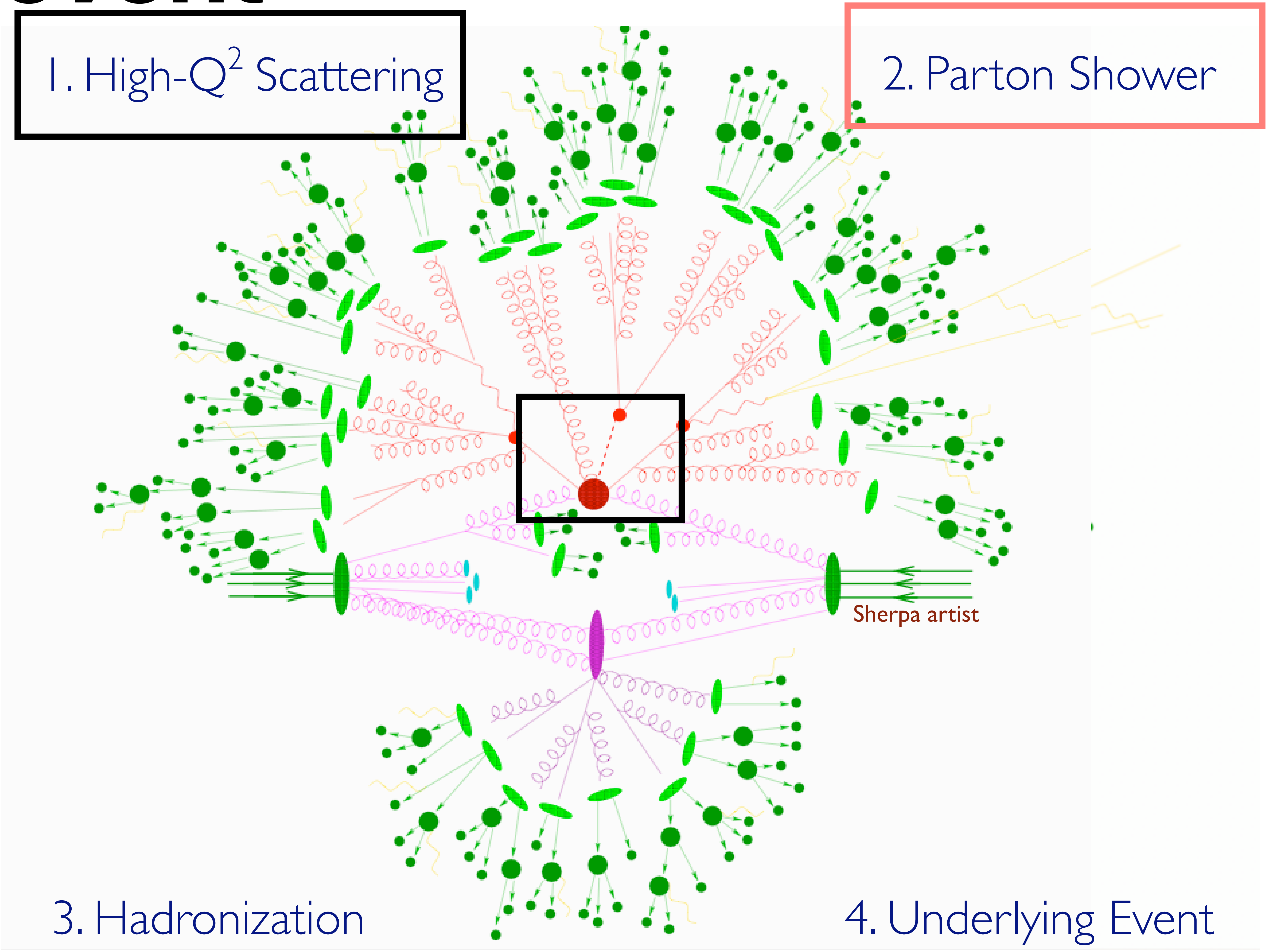

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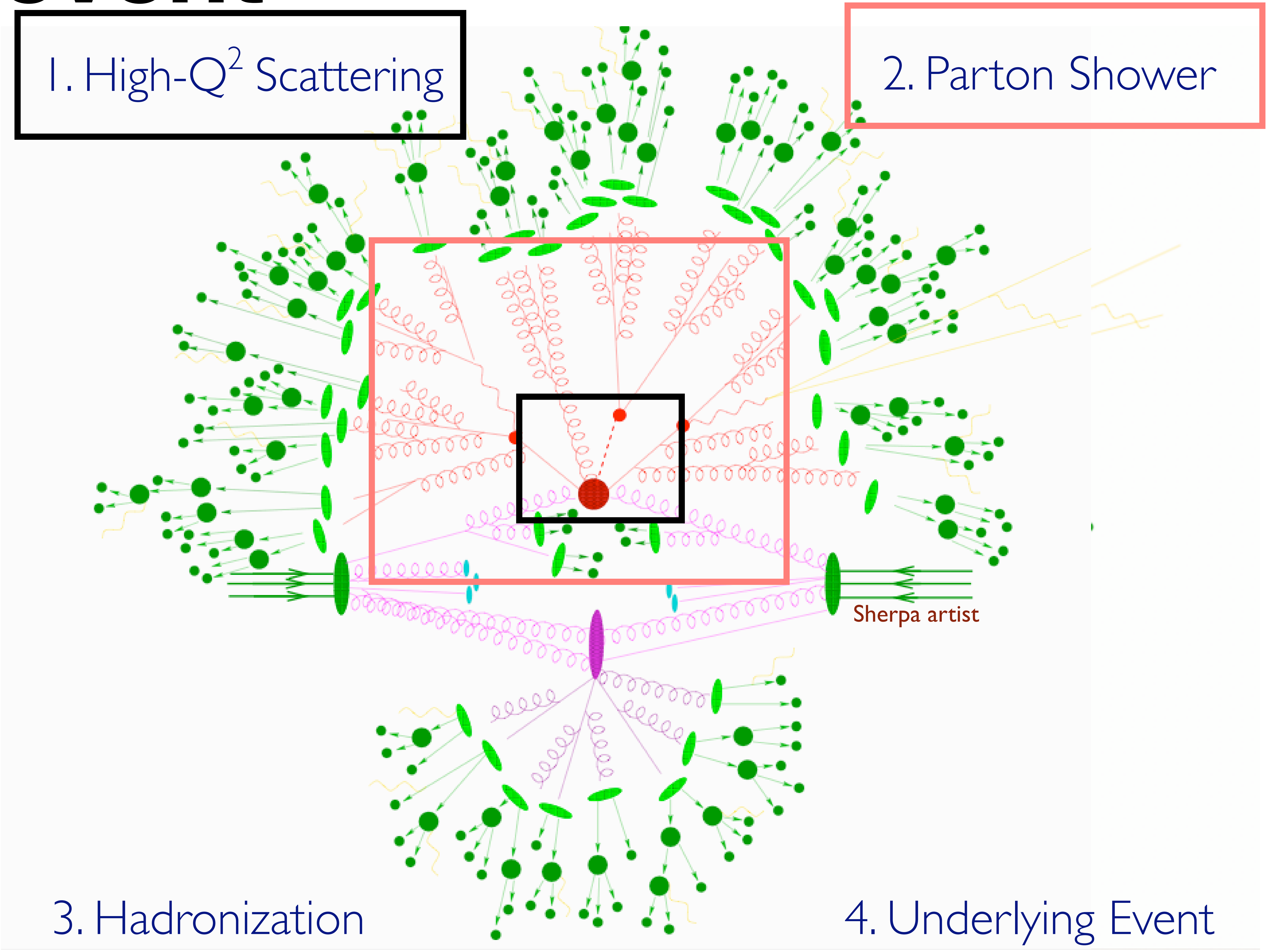
An LHC event



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

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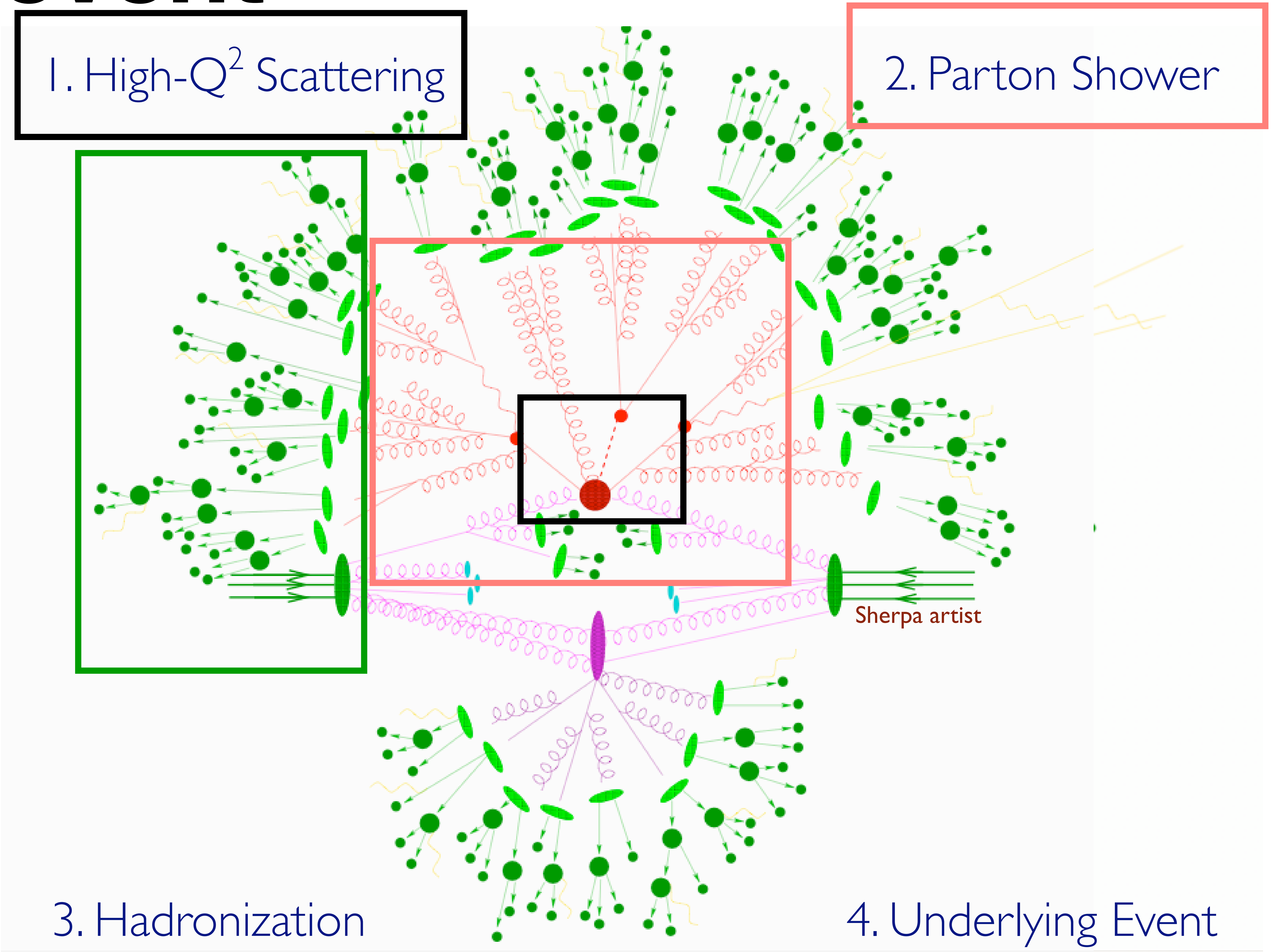

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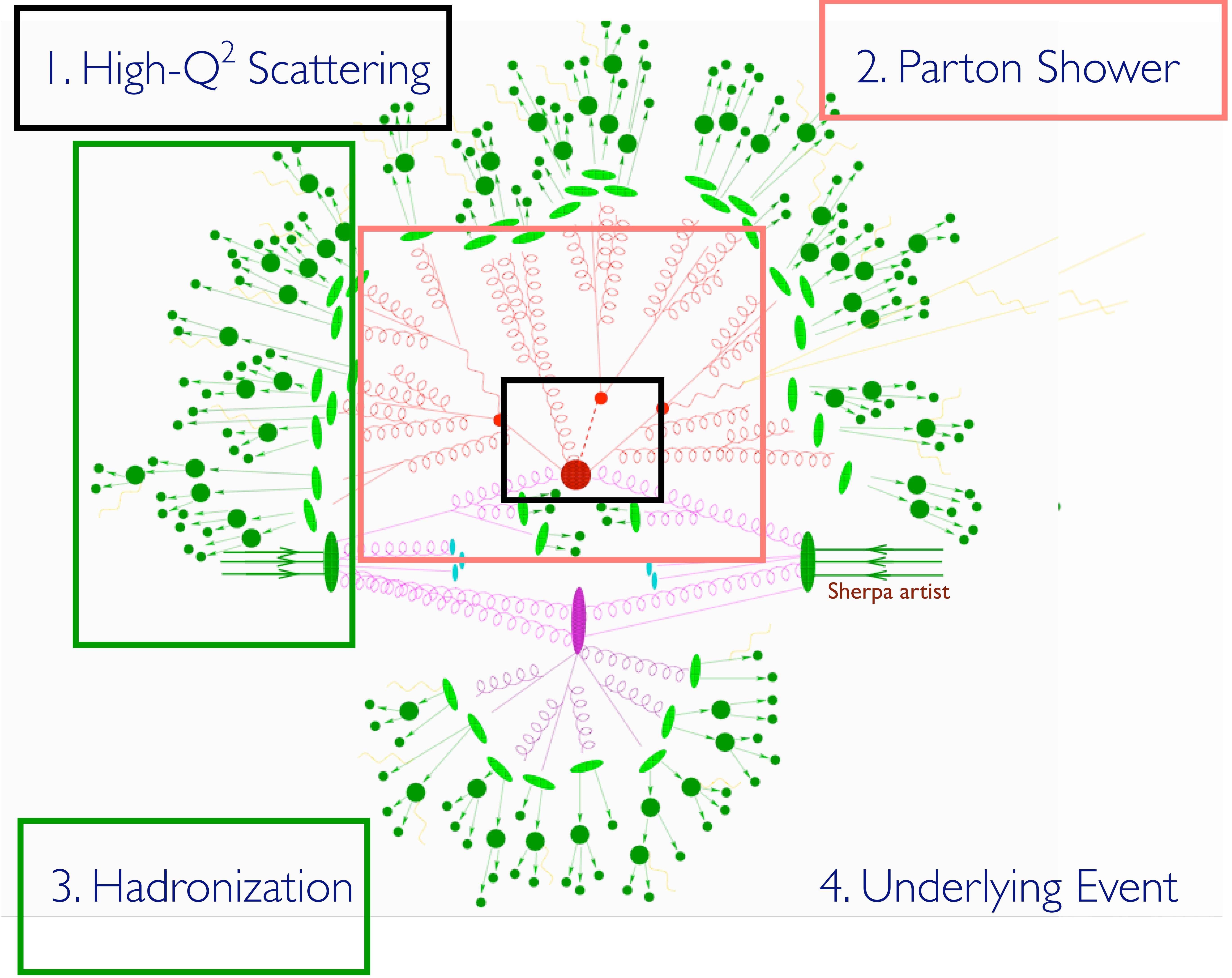

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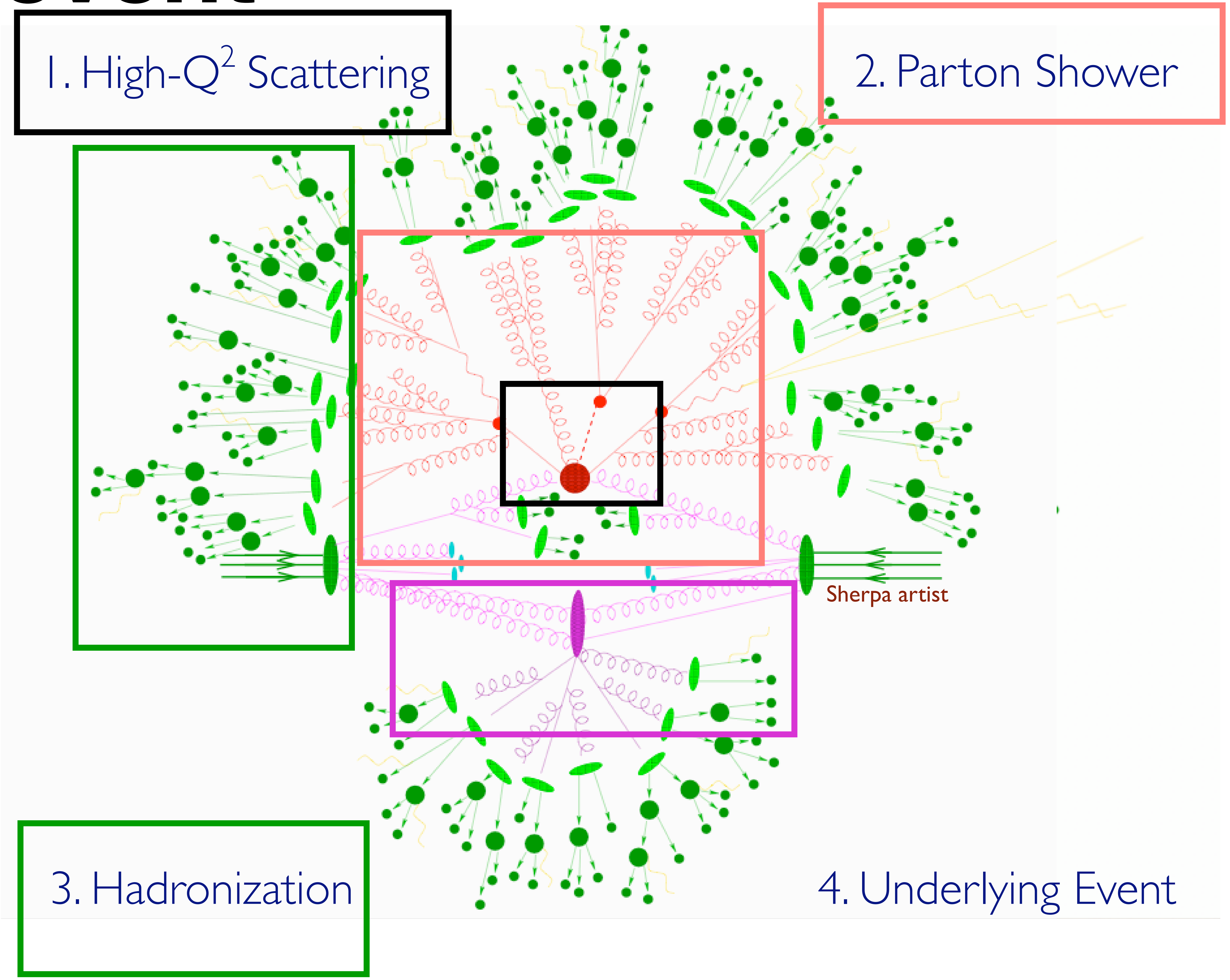

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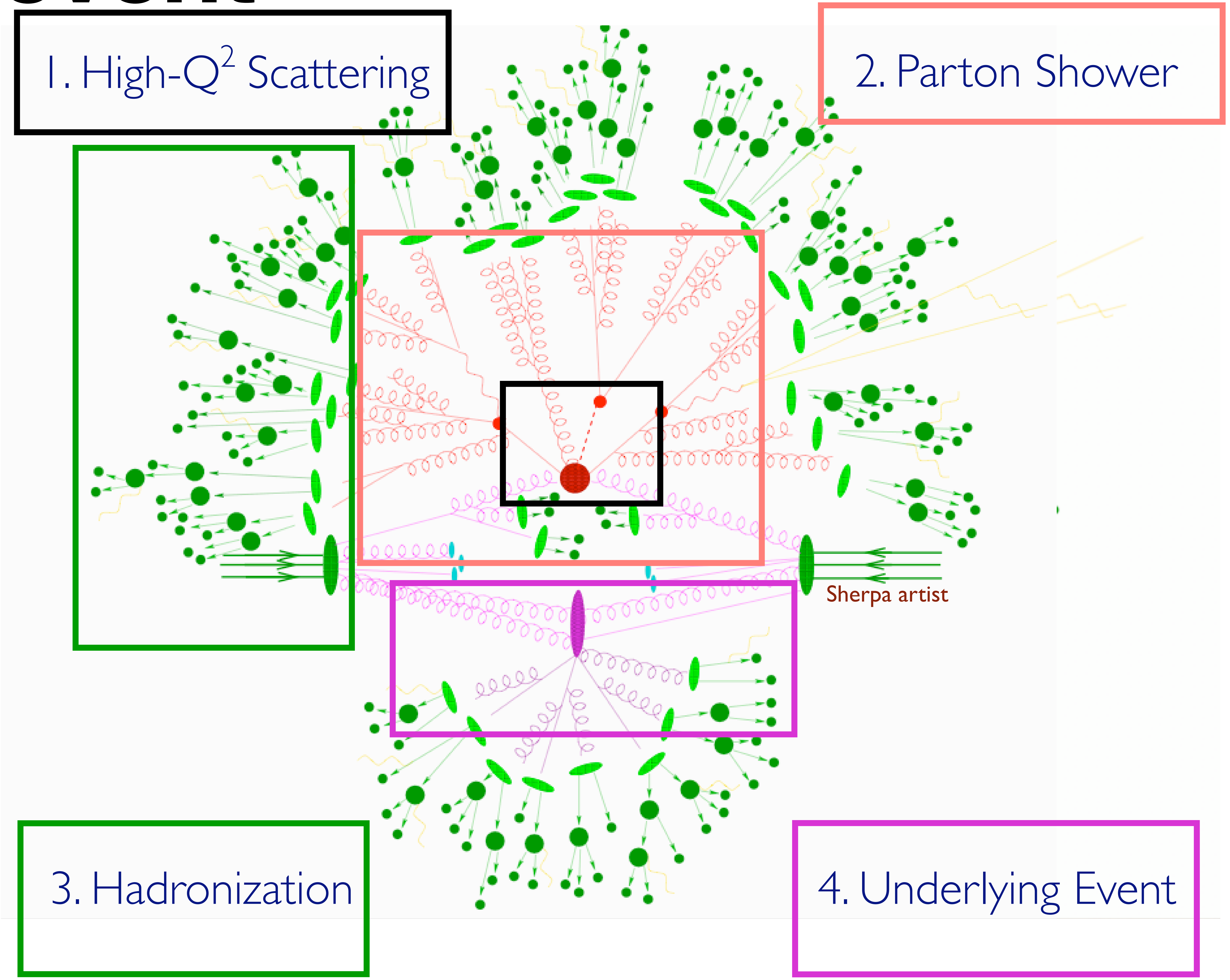

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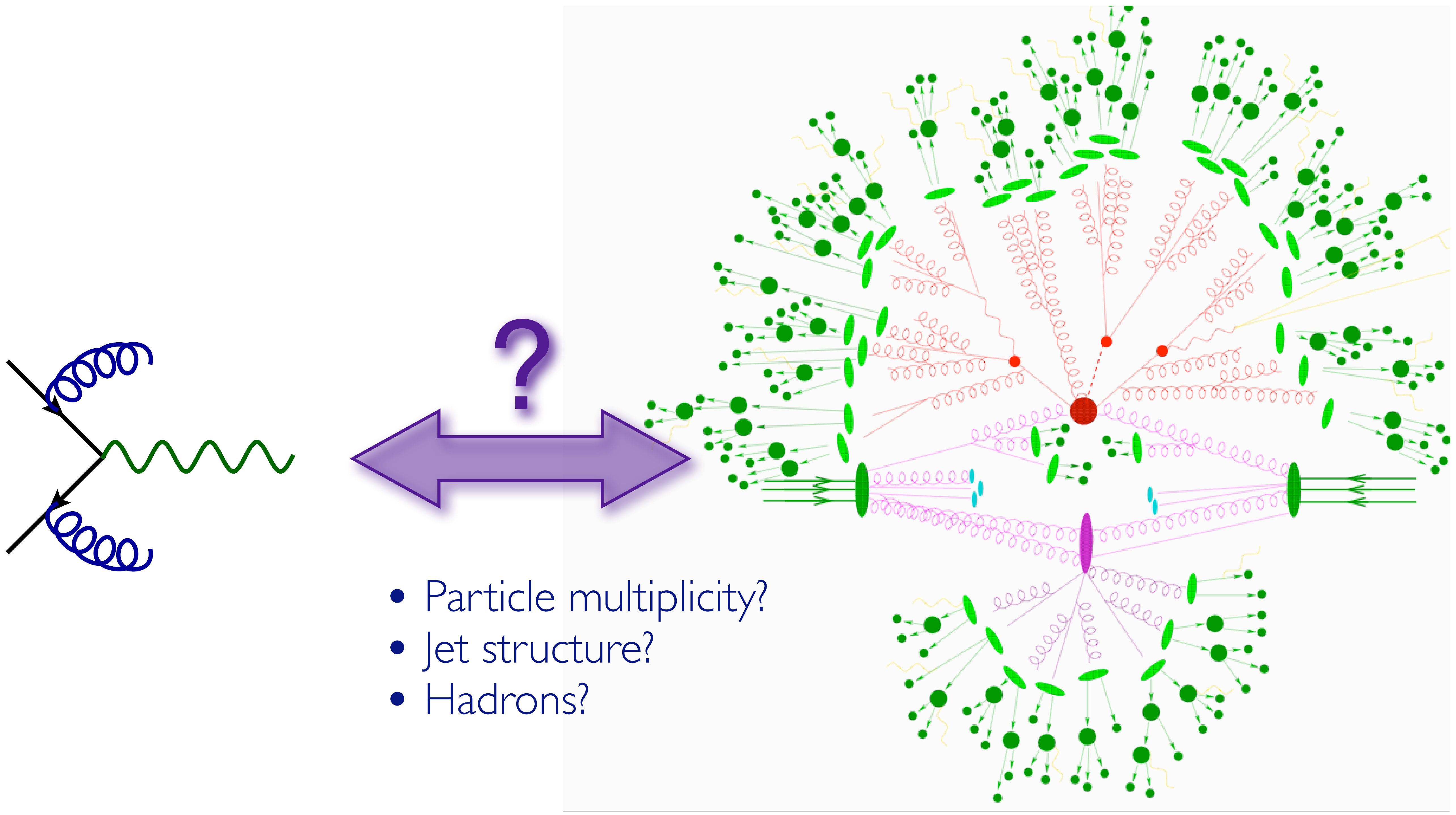
Is fixed order enough?



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

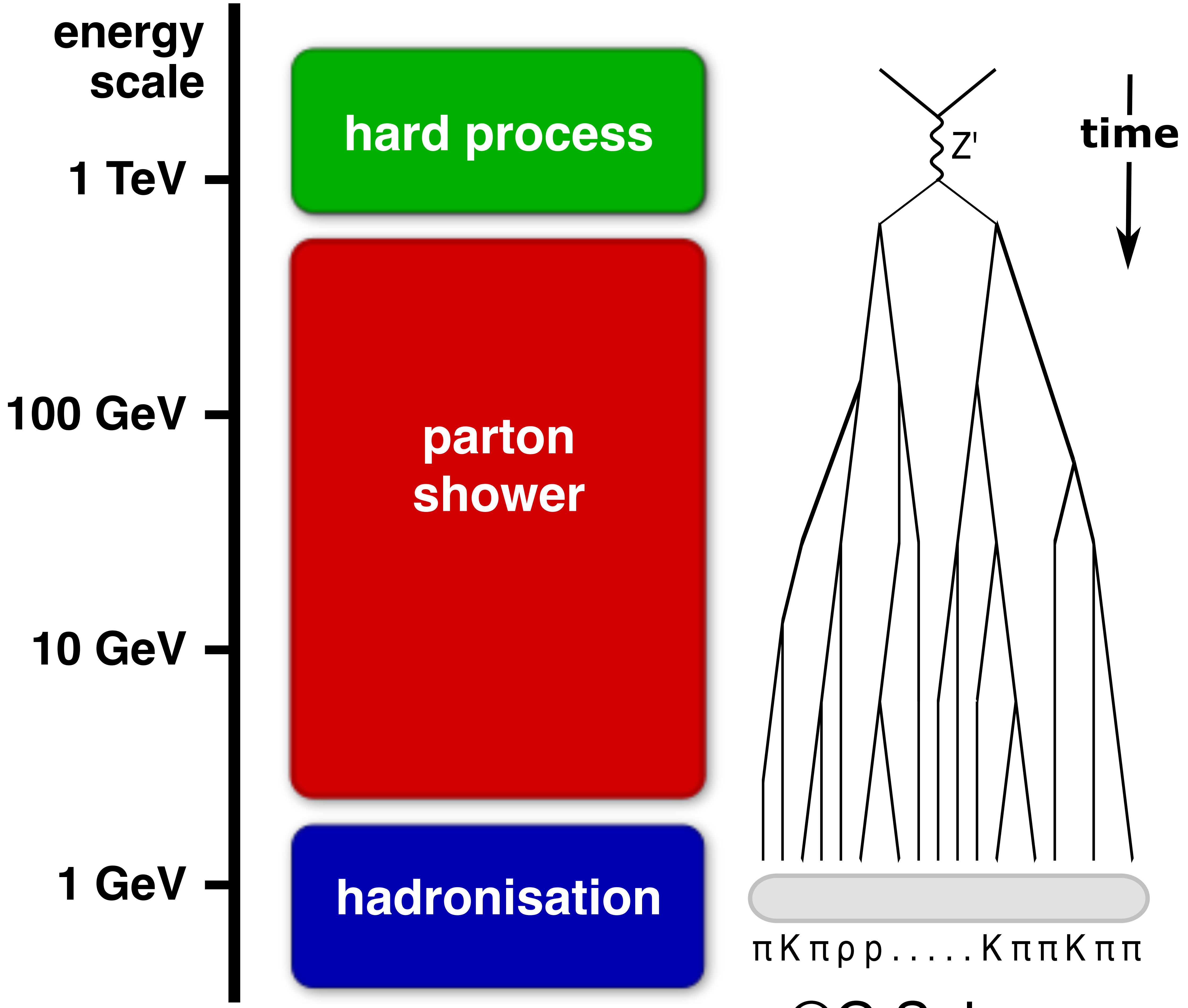
A multiscale story

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



@G.Salam

Parton Shower

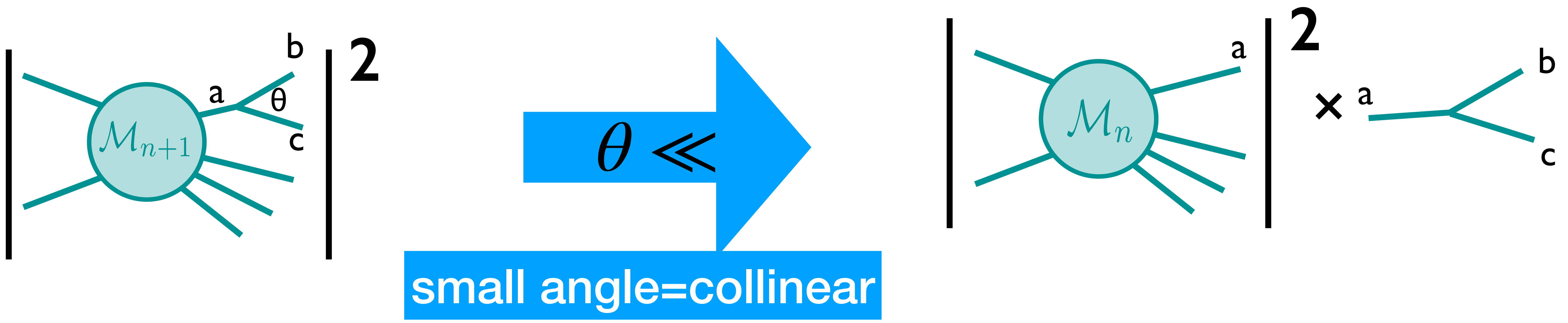
What does the parton shower do/should do?

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

Basics of parton shower

Collinear factorisation

Starting with one splitting



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

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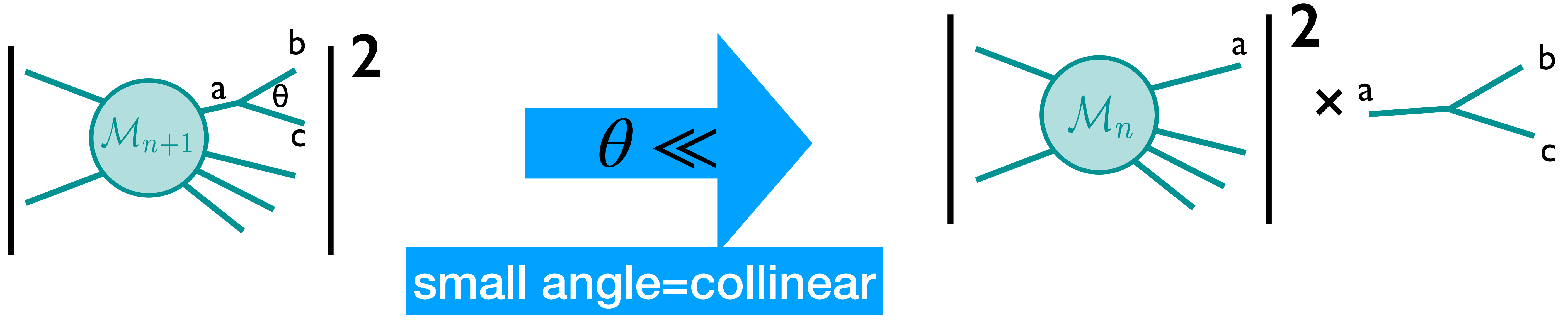

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- This kind of splitting should be described by a branching probability
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Collinear factorisation:

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

Collinear factorisation and splitting functions

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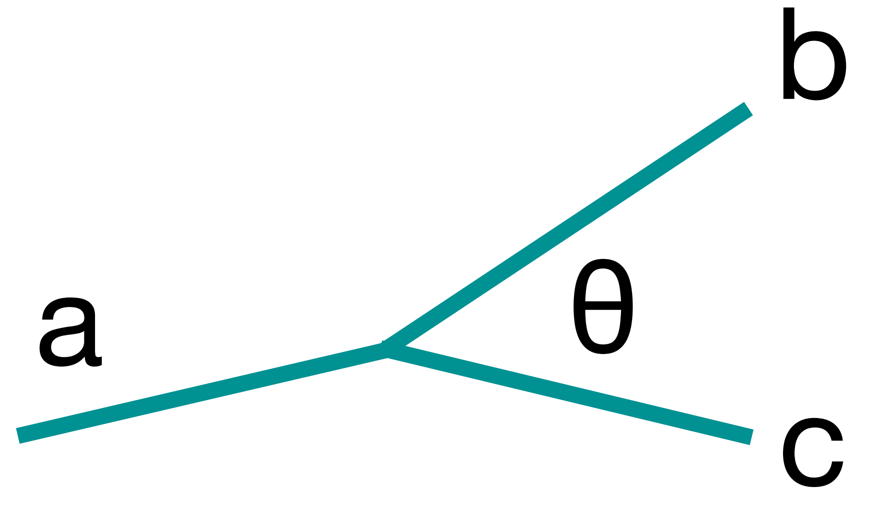

- t is the evolution variable
  - t tends to zero in the collinear limit (this factor is singular)
- z energy fraction transferred from parton a to parton b in splitting ($z \to 1$ in the soft limit)
- ϕ azimuthal angle

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

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

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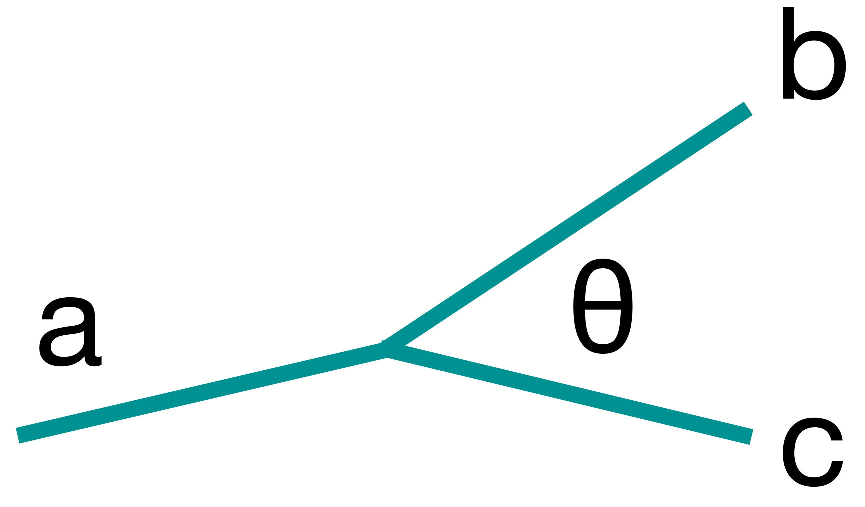

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$$\frac{d\theta^2}{\theta^2} = \frac{dk_\perp^2}{k_\perp^2} = \frac{dQ^2}{Q^2}$$

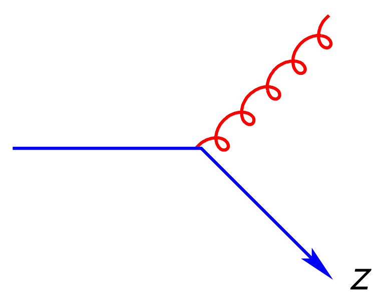
$$t \in \{\theta^2, k_\perp^2, Q^2\}$$

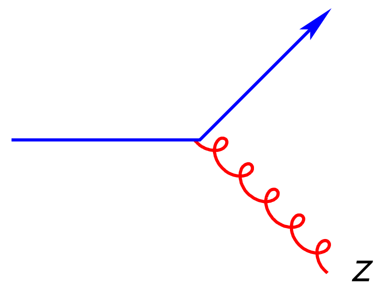
Altarelli-Parisi Splitting functions

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

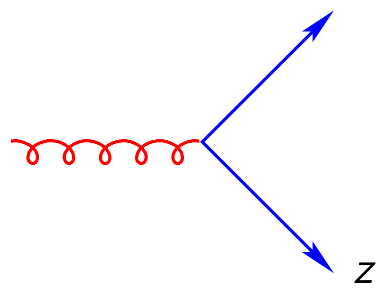
$$\frac{dt}{t}dz\frac{d\phi}{2\pi}\frac{\alpha_S}{2\pi}P_{a\to bc}(z)$$

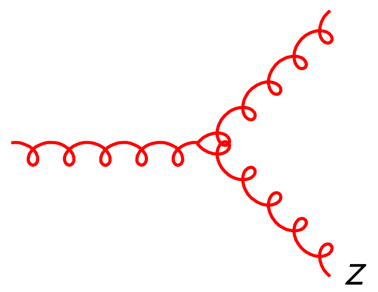
$$P_{q\to qg}(z) = C_F\left[\frac{1+z^2}{1-z}\right], \qquad P_{q\to gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right].$$





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





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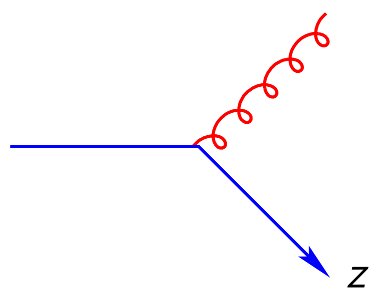

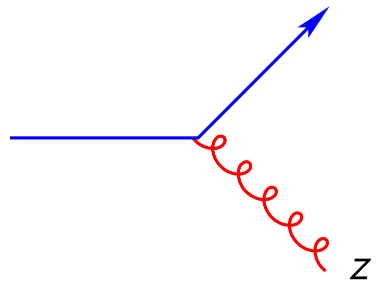

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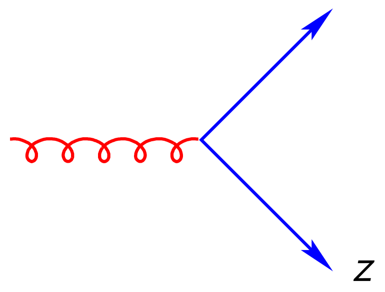
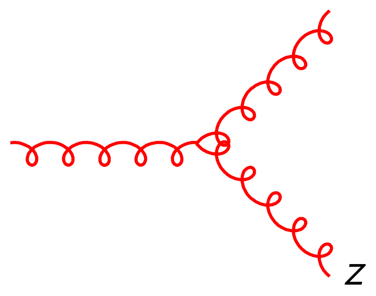
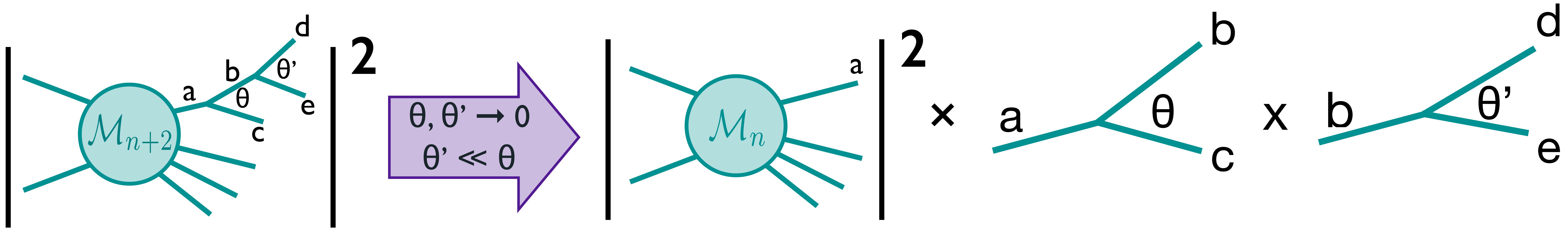




These functions are universal for each type of splitting

Multiple emissions

How does this change with multiple emissions?



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

We can generalise this for an arbitrary number of emissions

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

Multiple emissions

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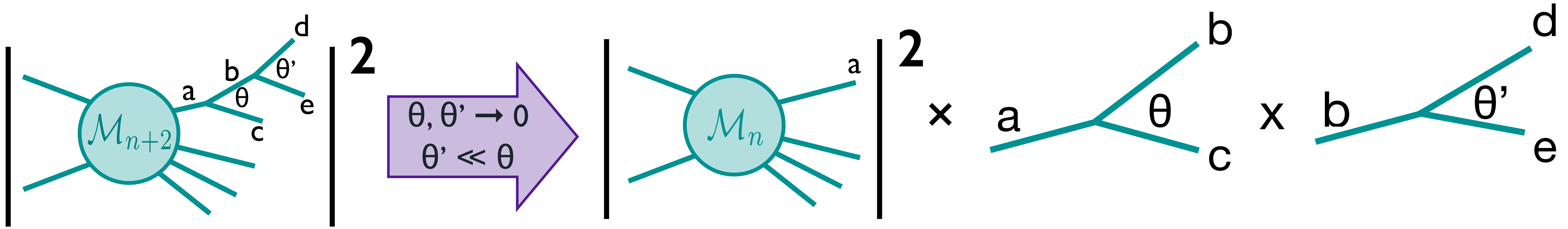

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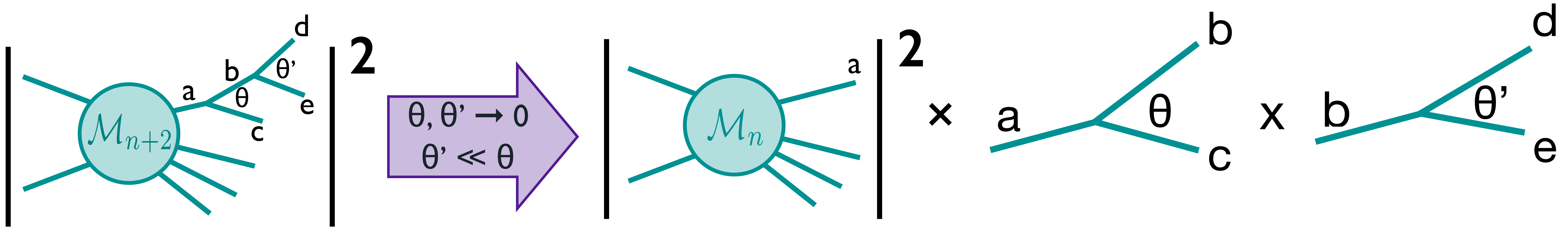

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→ **No interference: Classical**

Multiple emissions

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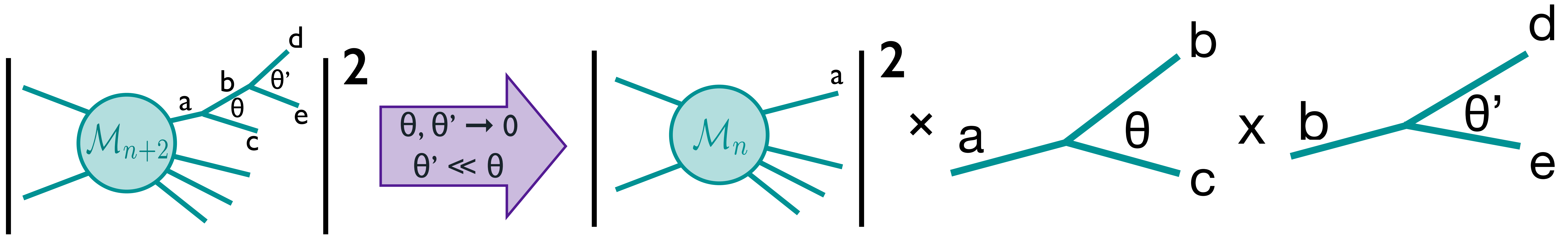

Dominant contribution comes from subsequent emissions which satisfy strong ordering $\theta \gg \theta' \gg \theta''$

For k emissions the rate takes the form:

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

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

Basics of PS

What we saw so far

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

Sudakov form factor

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

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

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

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

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

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

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

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Sudakov form factor

Sudakov form factor = No emission probability

Sudakovs

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

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

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

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

Unitarity

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

Probability of k ordered splittings:

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

Integrating this gives us:

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

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

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

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Probability is conserved

Evolution parameter in parton shower

A parton shower is constructed:

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

Other variables can be used as evolution parameter:

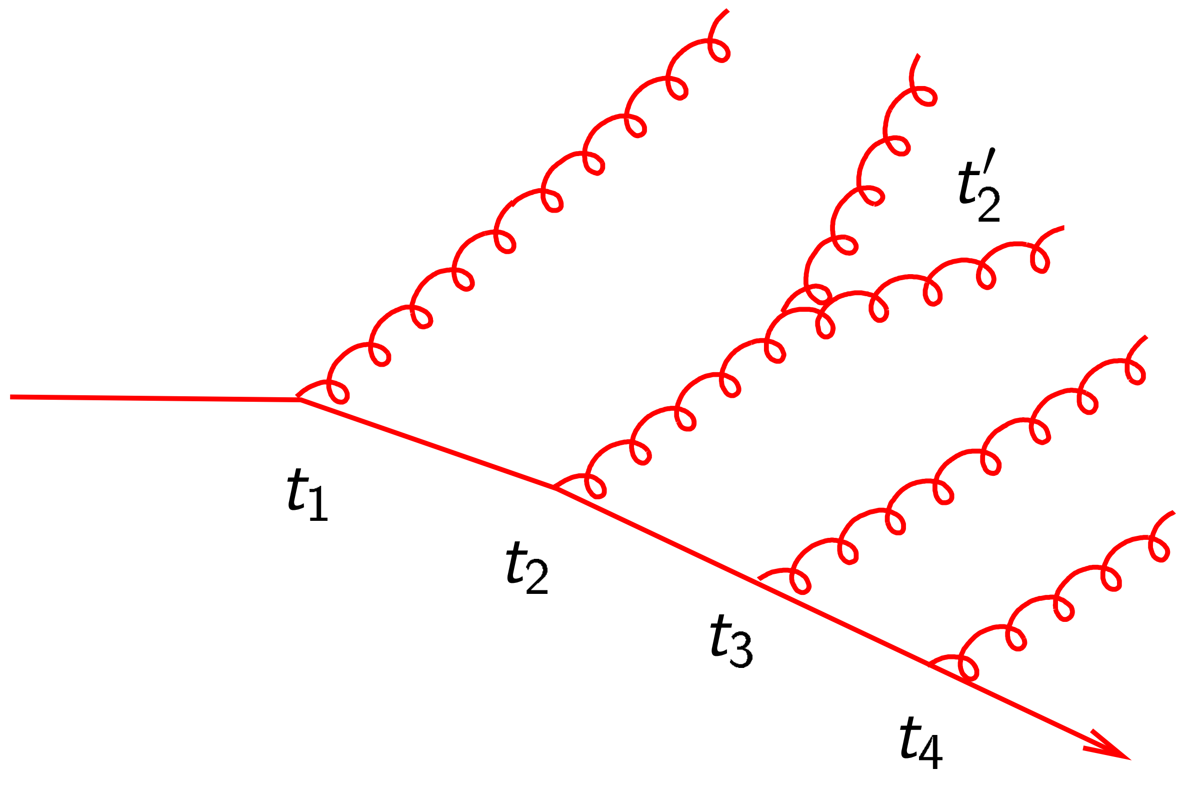
$$\frac{d\theta^2}{\theta^2} \sim \frac{dQ^2}{Q^2} \sim \frac{dp_\perp^2}{p_\perp^2} \sim \frac{d\tilde{q}^2}{\tilde{q}^2} \sim \frac{dt}{t}$$

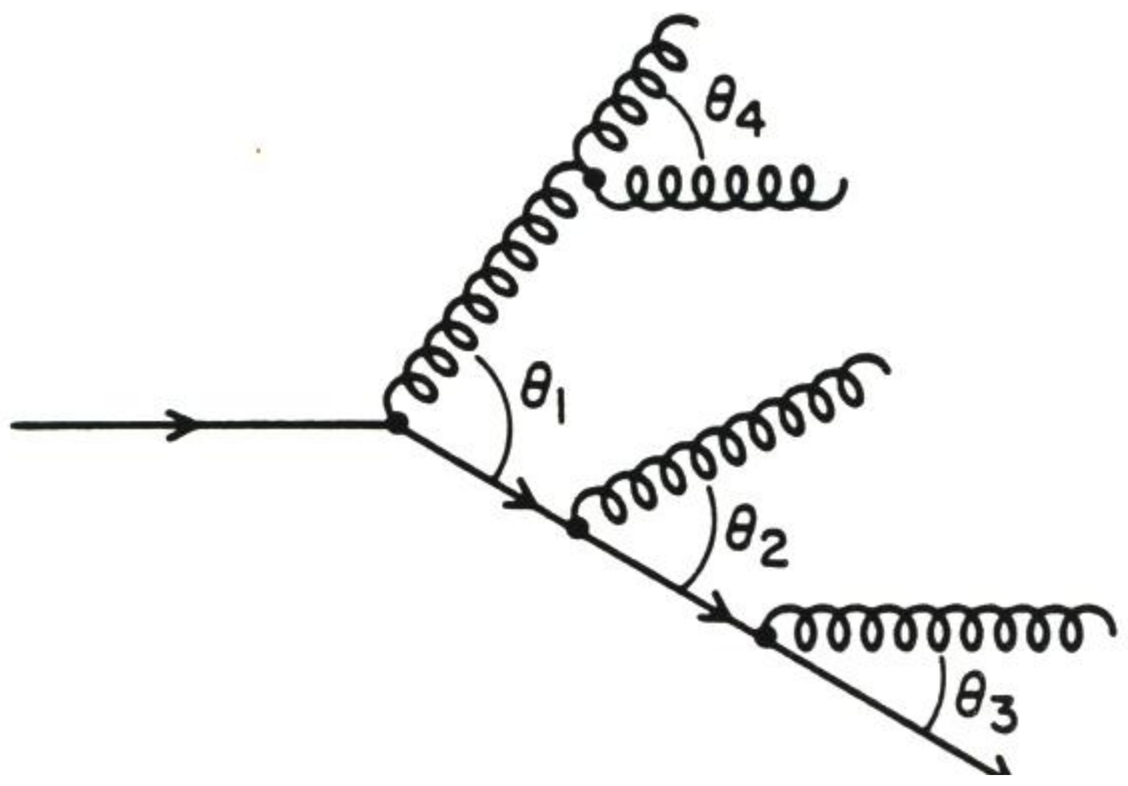
- θ: HERWIG
- Q^2: PYTHIA ≤ 6.3, SHERPA.
- $p_\perp$: PYTHIA ≥ 6.4, ARIADNE, Catani–Seymour showers.
- $\tilde{q}$: Herwig++.

Same collinear behaviour, differences in the soft limit

Ordered branchings

Angular ordering





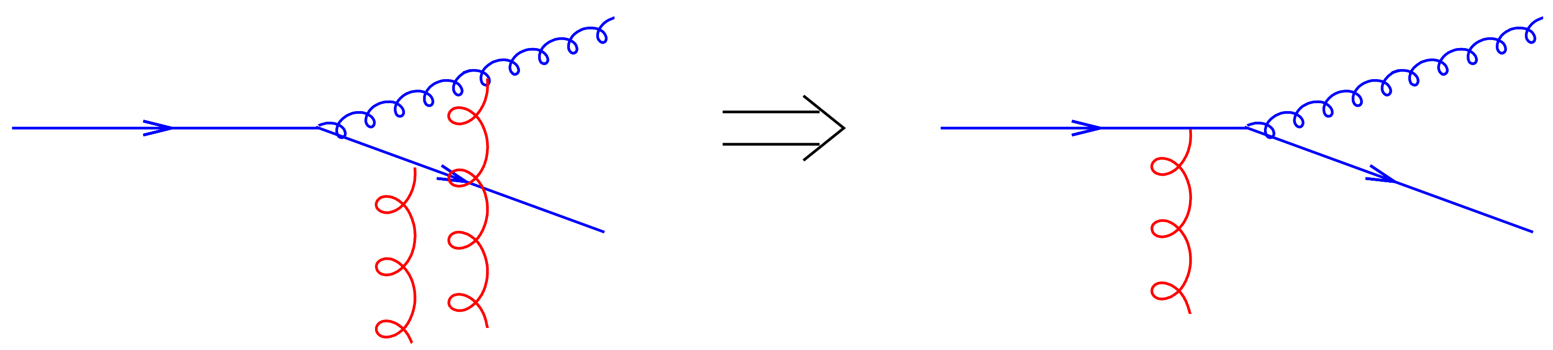
Shower is based on ordered splittings

$t_1 \gg t_2 \gg t_3 \gg t_4$ and $t_2 \gg t_2'$

Emission with smaller and smaller angles

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

Note:



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

Hadronisation

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

Color-singlet parton pairs end up "close" in phase space. This is called preconfinement.
Involves collecting $q\bar{q}$ pairs into color-singlet clusters.

Cluster hadronisation

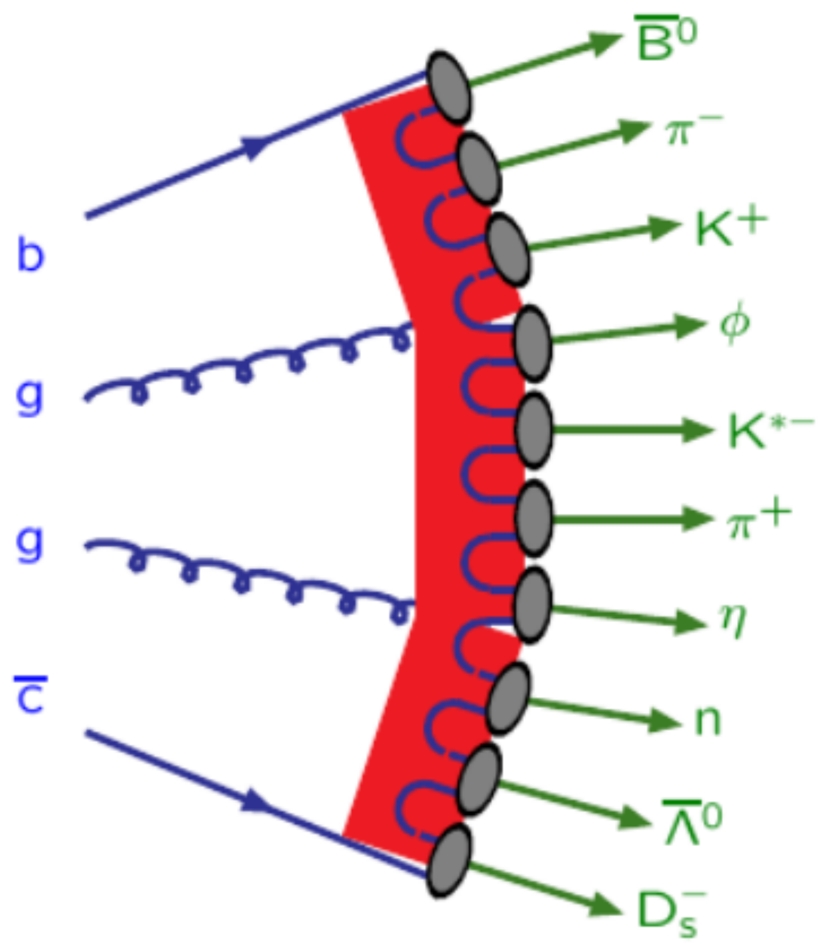
Create strings from color string, with gluons "stretching the string" locally. It uses non-perturbative insights

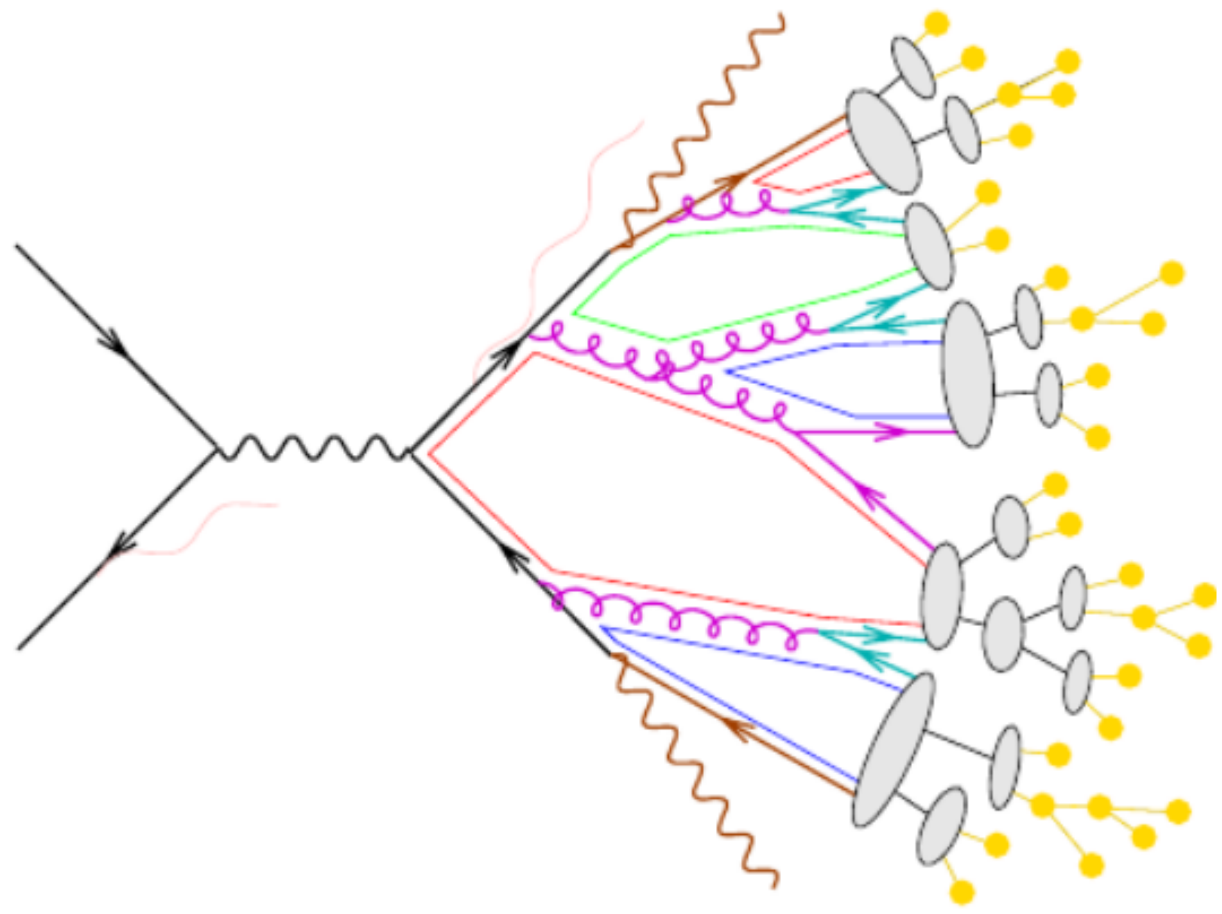
String hadronisation

Hadronisation

String vs Cluster

Sjöstrand, Durham '09





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

Summary: Parton shower

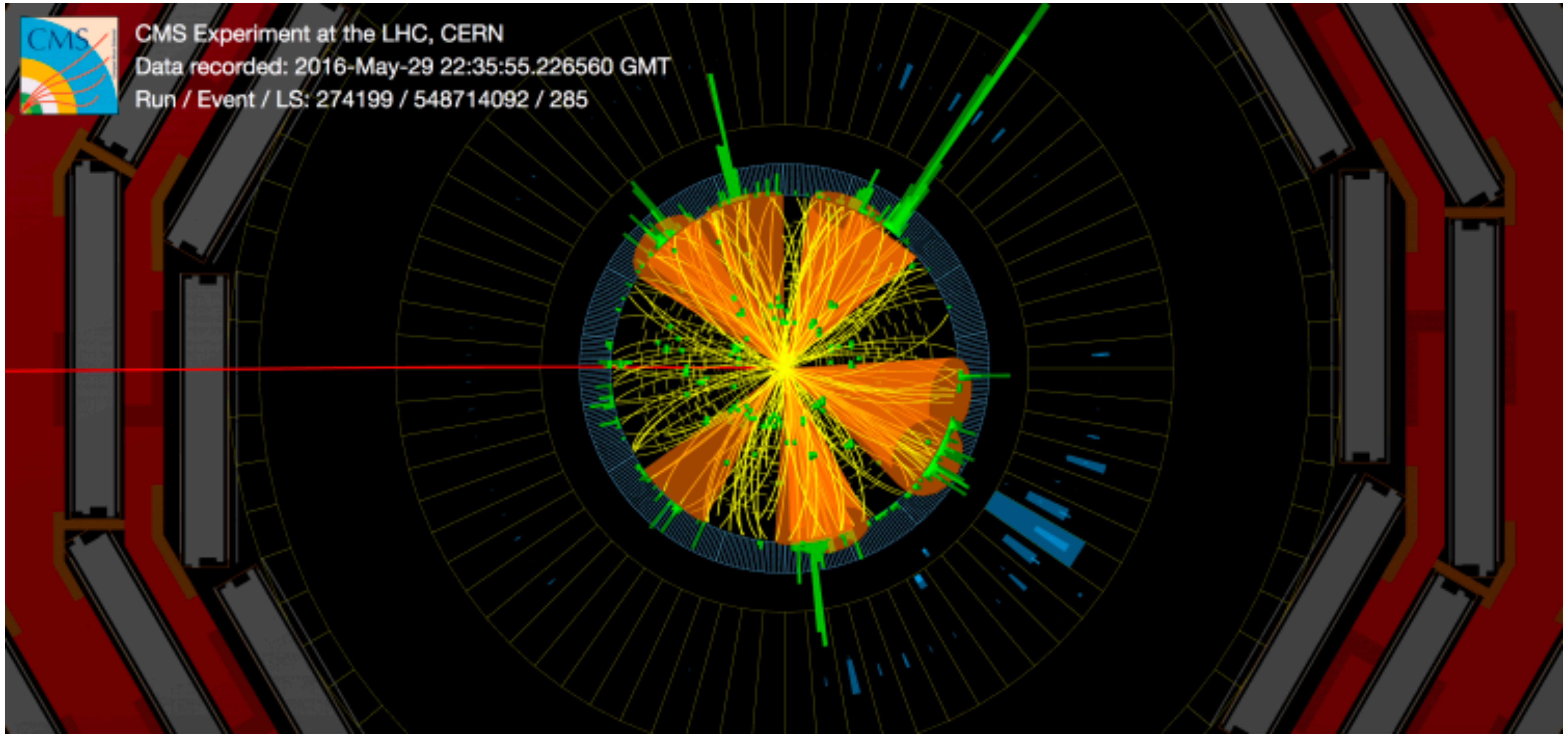
- A parton shower dresses partons with radiation such that the sum of probabilities is one.
  - Predictions become exclusive.
  - General-purpose, process-independent tools
  - Based on collinear factorisation and build around the Sudakov form factors provide a resummed prediction
  - Similar ideas can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

Parton shower programs

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

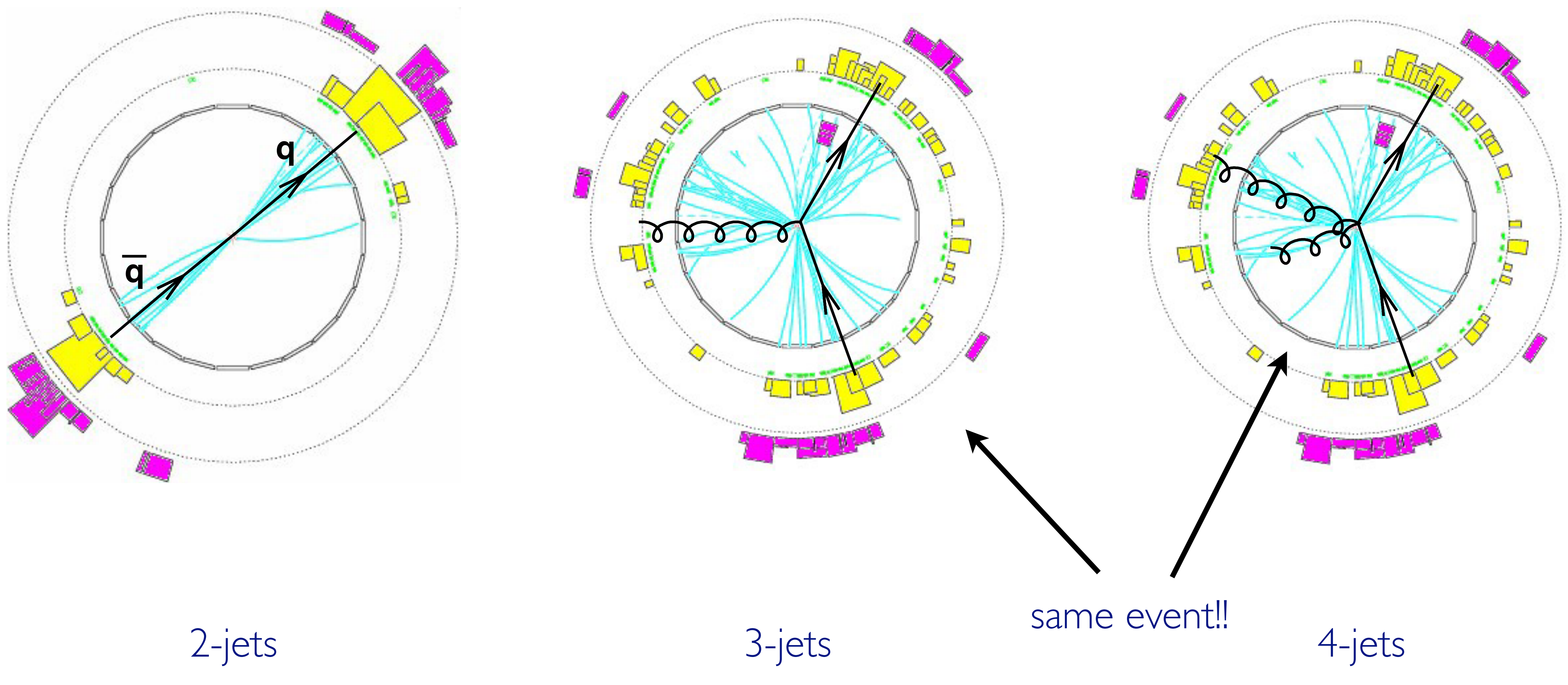
Herwig and Pythia use LHE files e.g. produced in MG5_aMC

What do we see in the detectors?



Collimated sprays of particles: Jets!

Jets

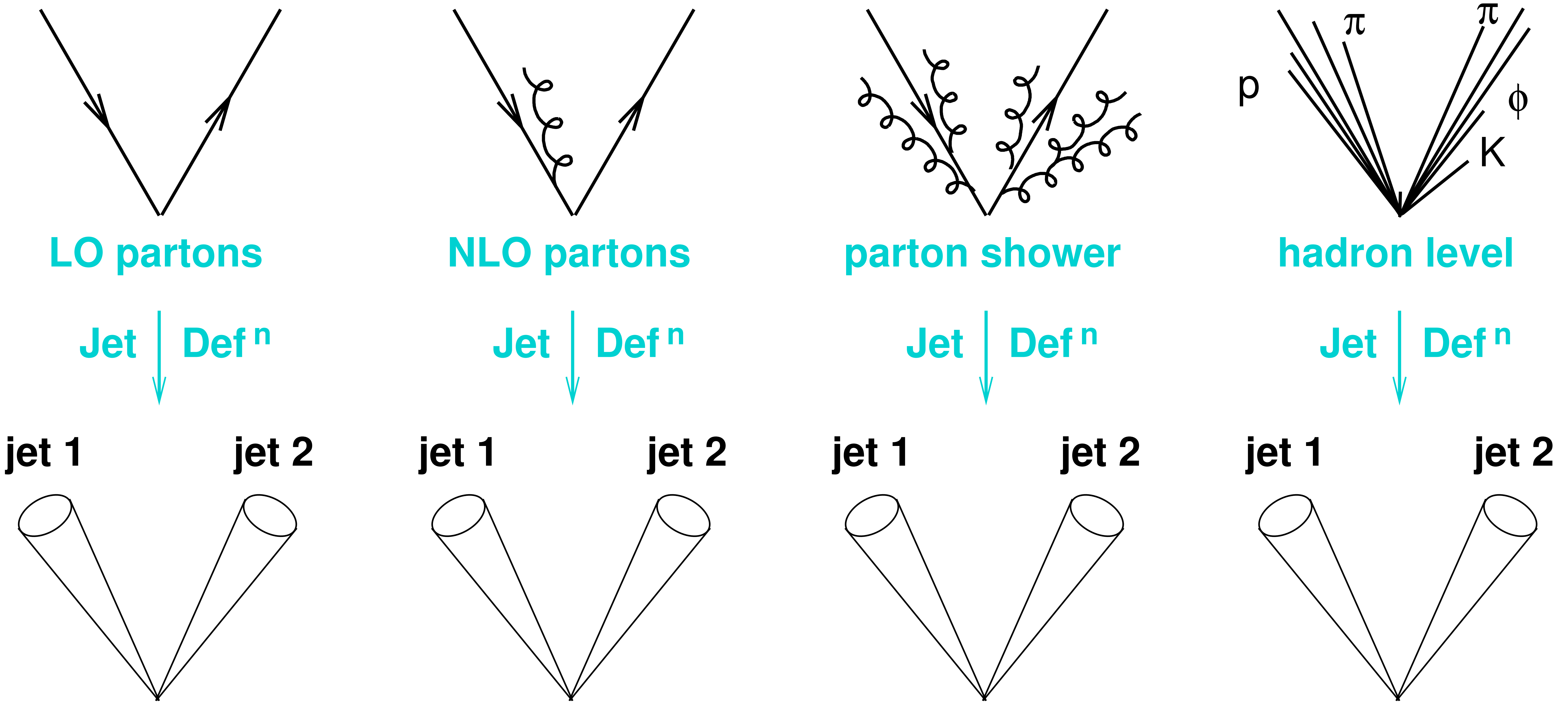


How do we decide?

Jet algorithms:

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

Jet algorithms



Procedure needs to be IRC safe!

Example of jet algorithms

Sequential recombination algorithm

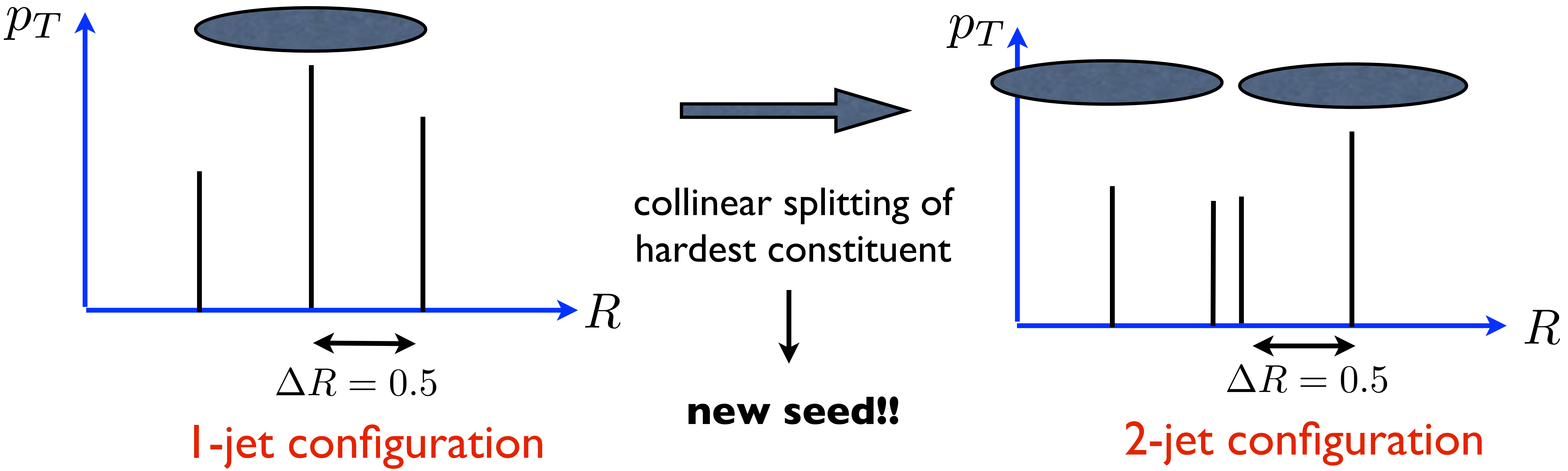
- Bottom-up: combine particles starting from closest ones
- How? Choose a distance measure, iterate recombination until few objects left, call them jets
- Usually trivially made IRC safe, but their algorithmically complex
- Examples: Jade, k_t, Cambridge/ Aachen, anti-k_t ...

Cone:

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

IR safety and cone algorithms

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



Sensitive to collinear emission! Not IRC!

Example of jet algorithm

kT algorithm

Distance measure

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

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

Steps:

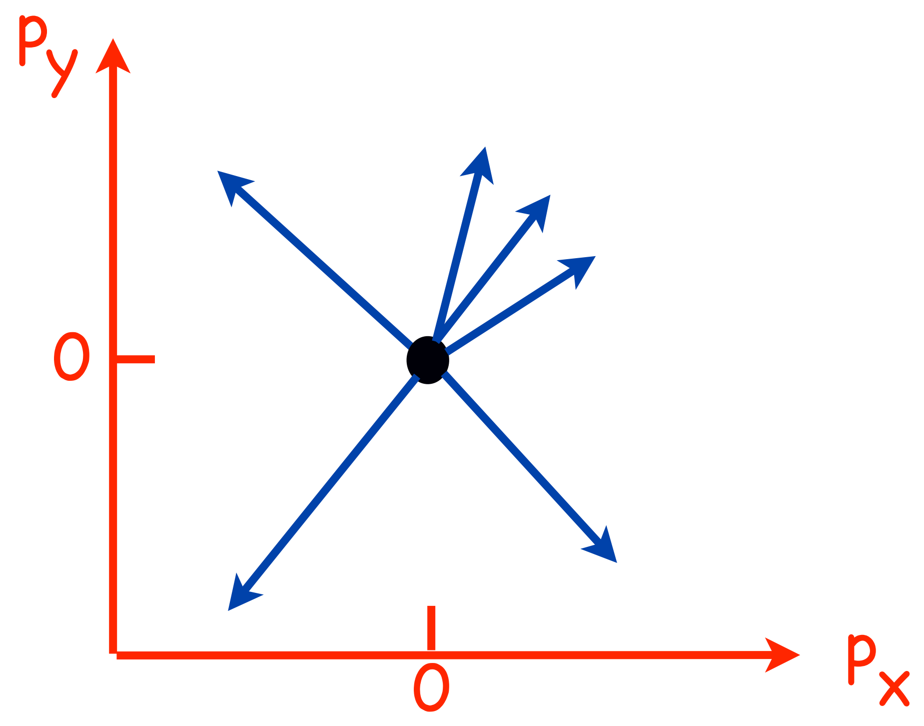
1. Find the smallest of d_{ij}, d_{iB}
2. If ij recombine them
3. If iB call i a jet and remove from particles
4. Repeat from I until no particles left

Minimum distance between jets is R

Number of jets above p_{Tj} is IR safe

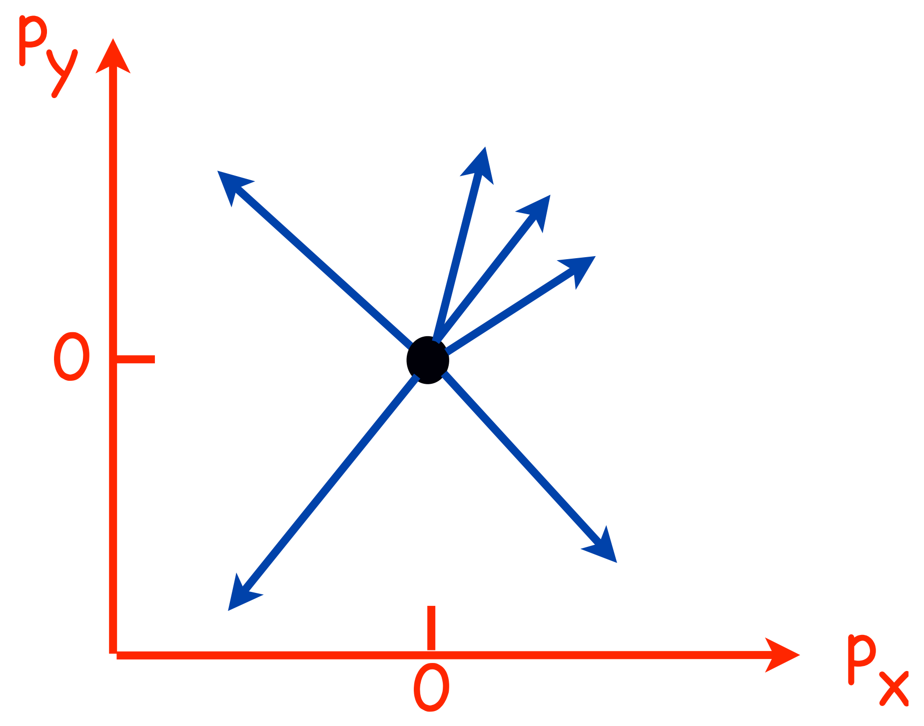
Example of jet algorithm

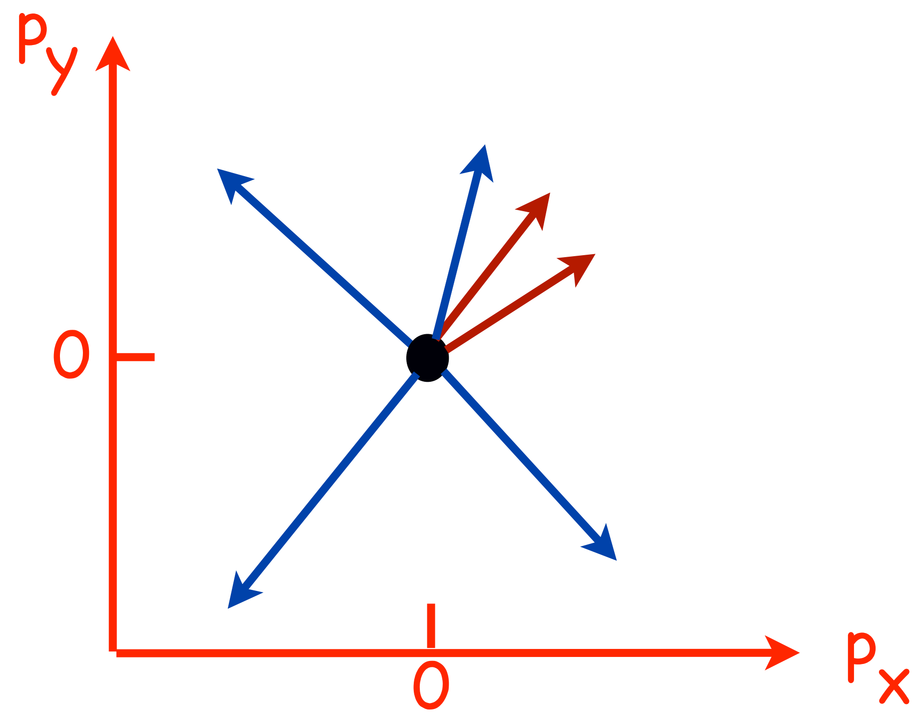
kT algorithm



Example of jet algorithm

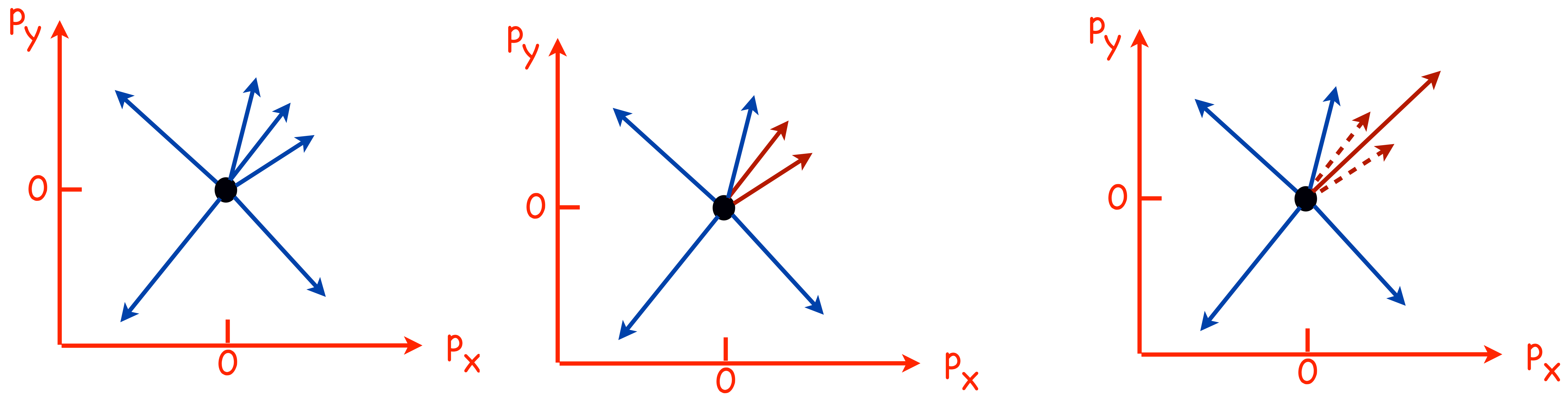
kT algorithm





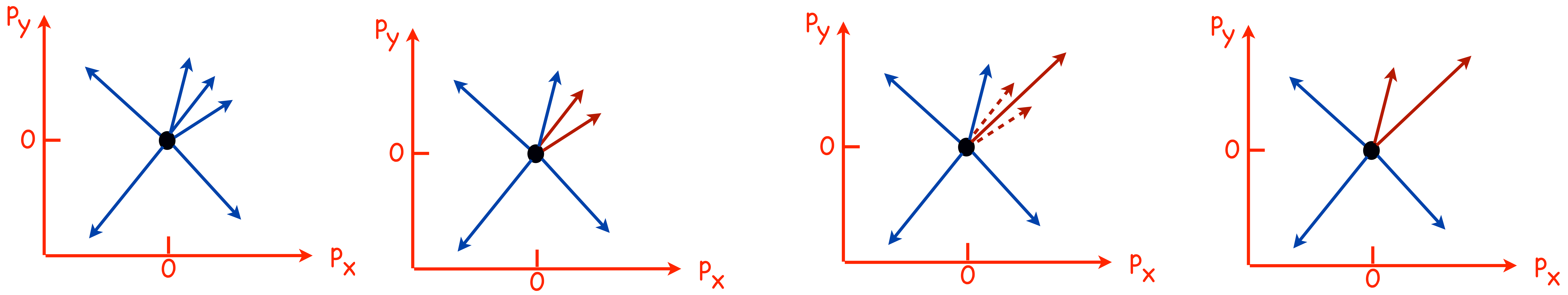
Example of jet algorithm

kT algorithm



Example of jet algorithm

kT algorithm



Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

Example of jet algorithm

kT algorithm

4-jets found!

Example of jet algorithms

kT algorithm

KT algorithm

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

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

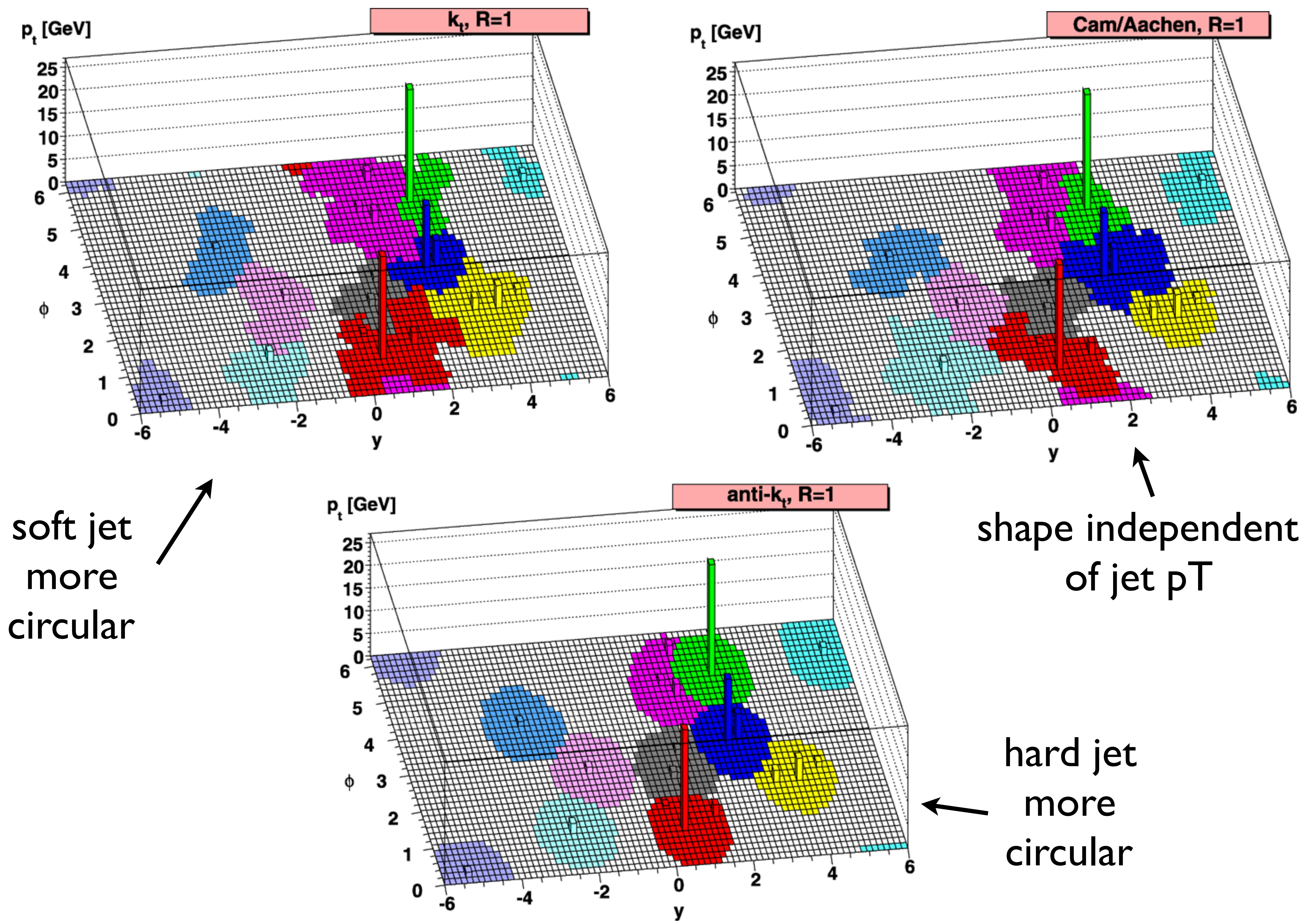
Anti-KT algorithm

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

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

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

See exercises!



G. Salam

Summary so far

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

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Summary so far

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- We identify jets using IRC jet algorithms ✓

Any room for improvement?

Fixed order vs parton shower

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

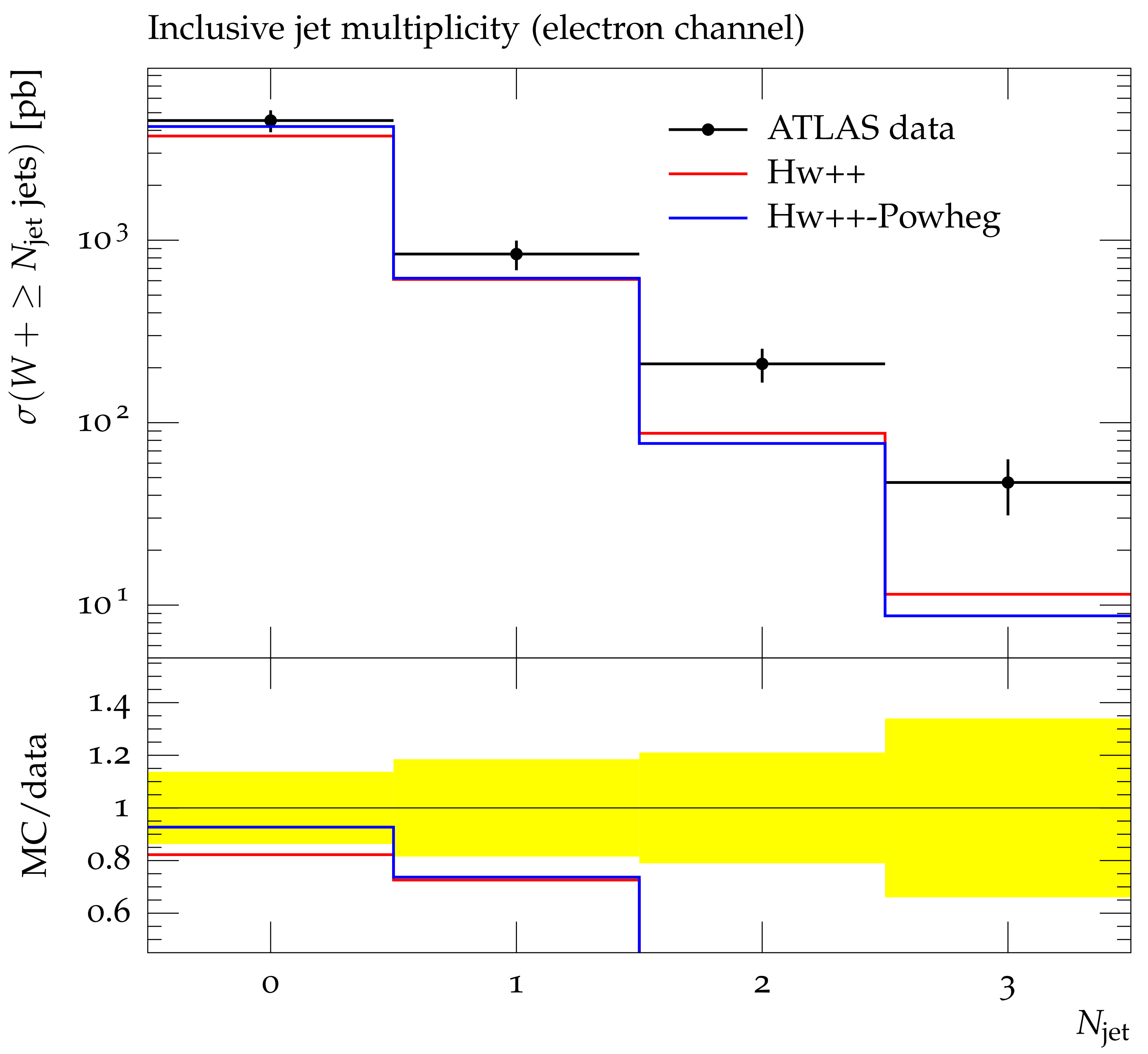
For hard radiation we need input from the matrix element

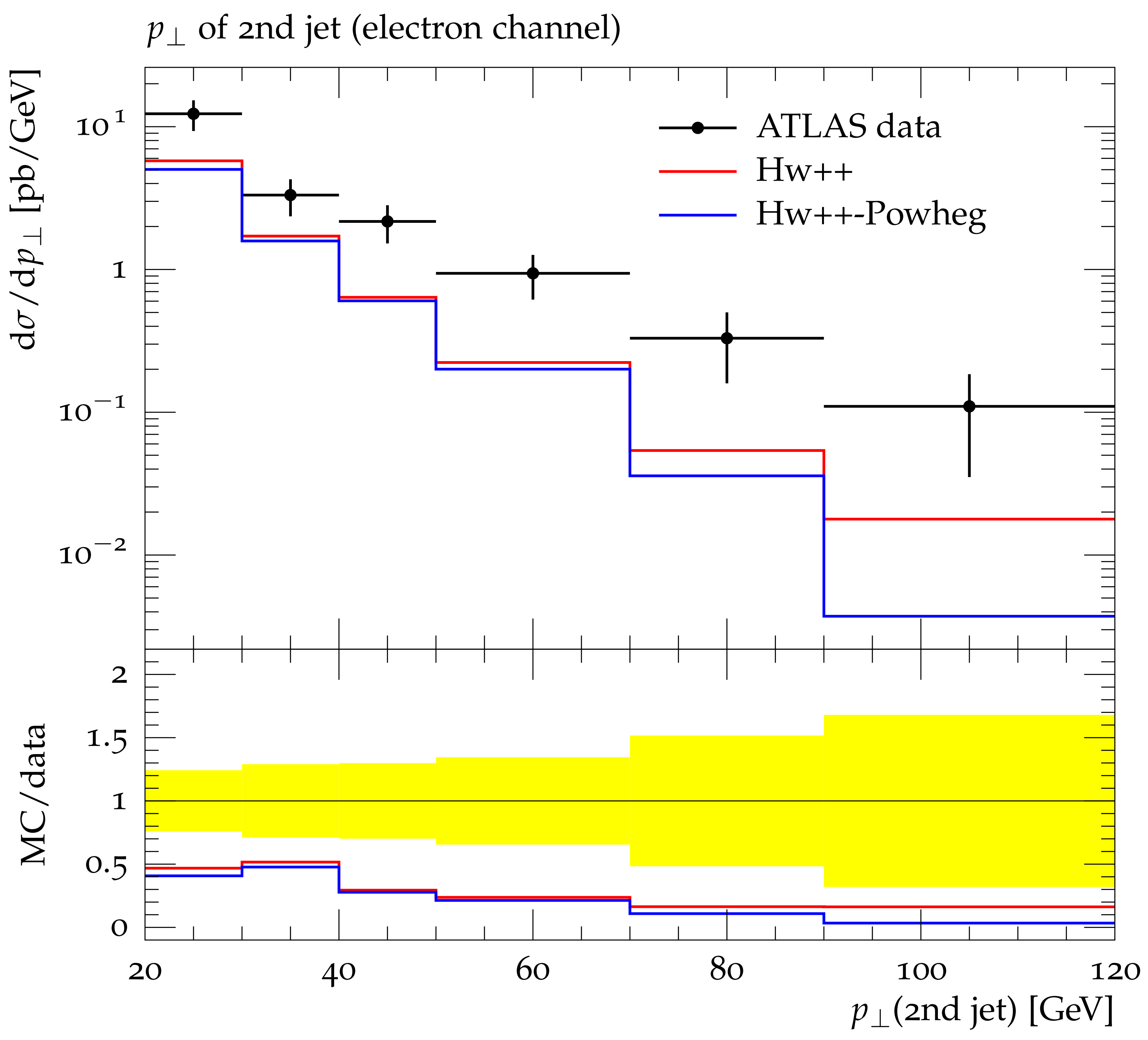
Two directions of improving parton shower Monte Carlo

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

Parton shower results

$W +$jets, LHC 7 TeV.





Parton shower can't describe high multiplicity hard jet events

Parton shower results

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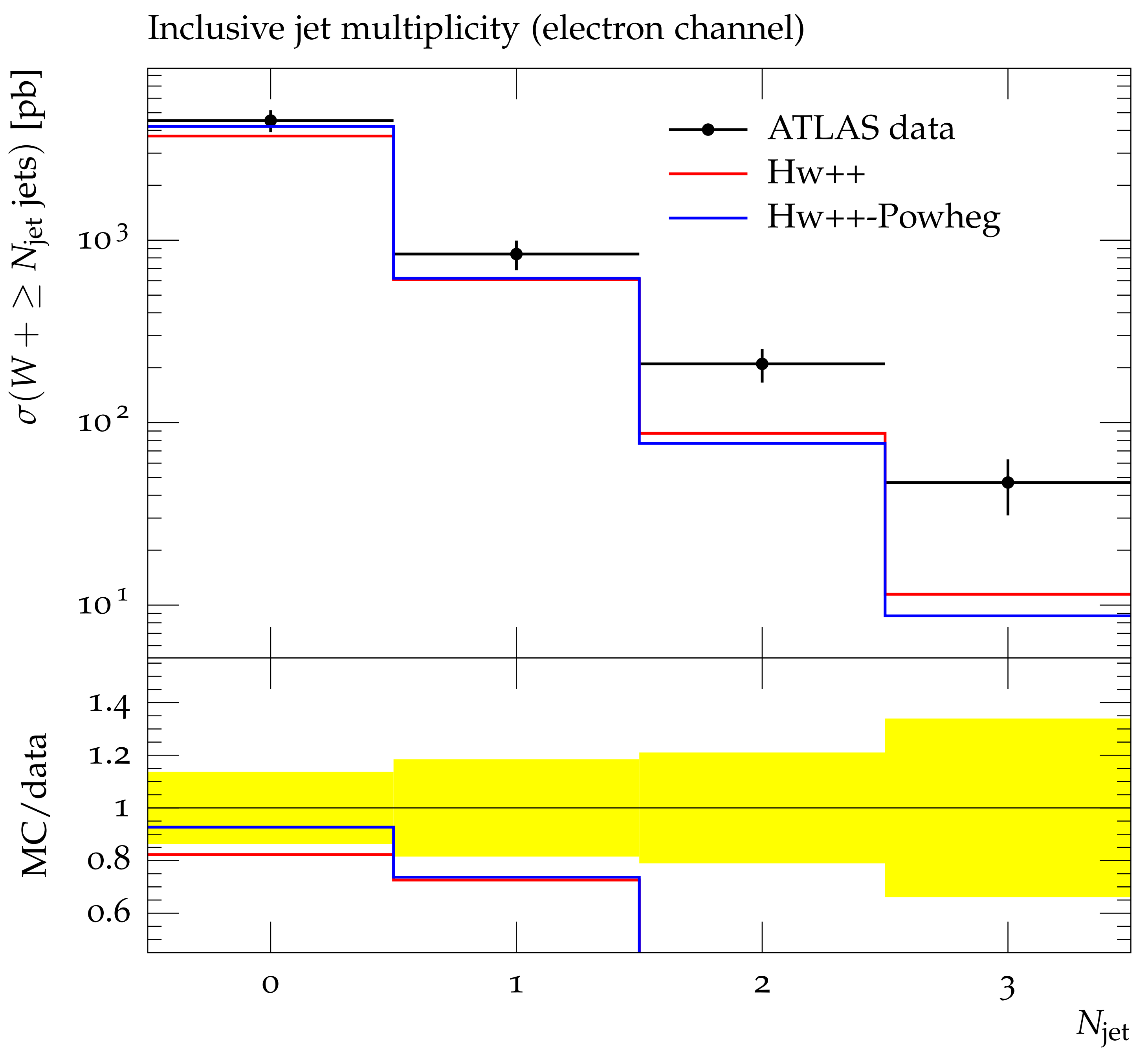

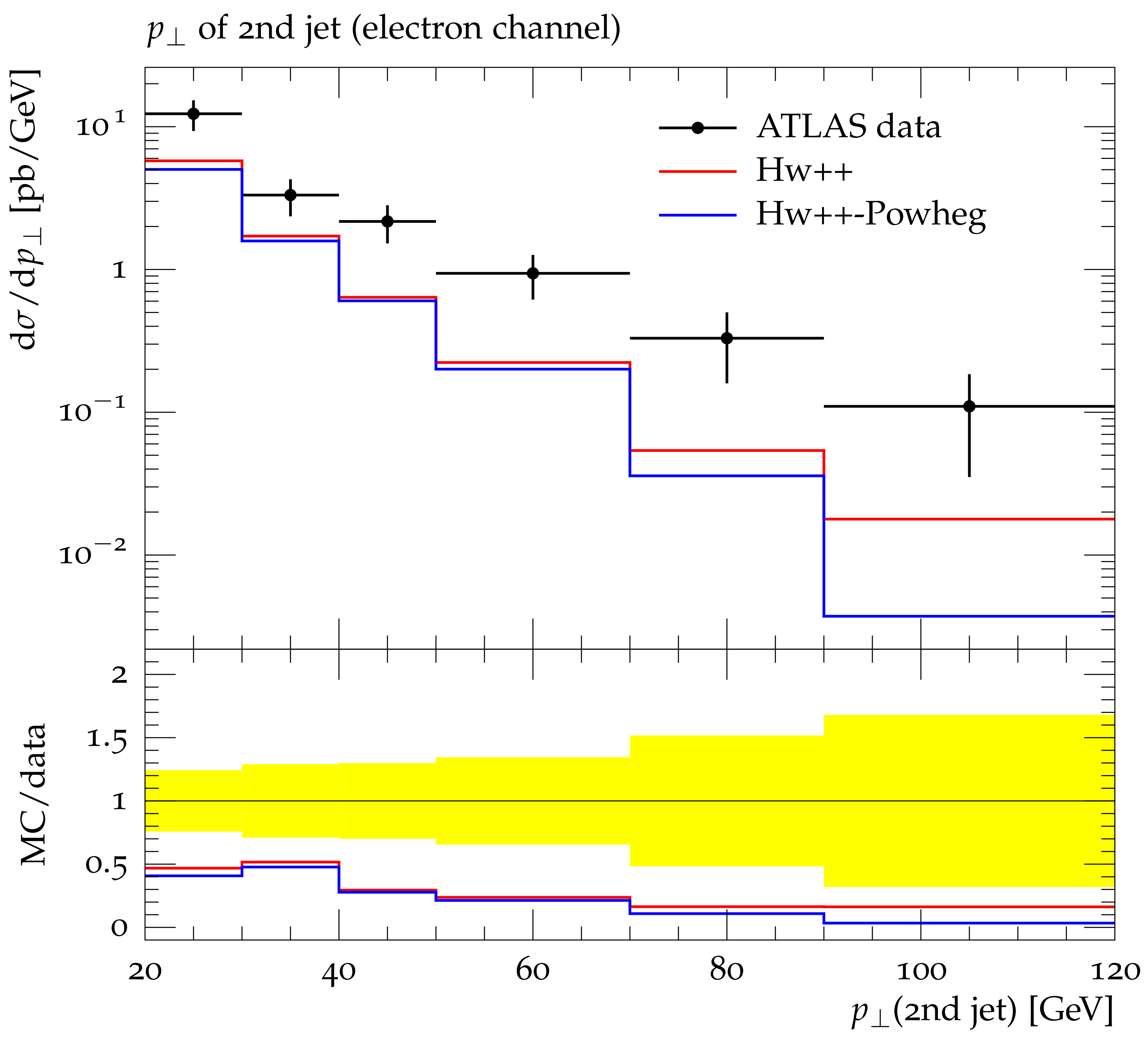

Parton shower can't describe high multiplicity hard jet events

➡ Need input from the matrix element

Towards LO merging

ME

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

Shower MC

1. Resums logs to all orders
2. Computationally cheap
3. No limit on particle multiplicity
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Towards LO merging

ME + Shower MC

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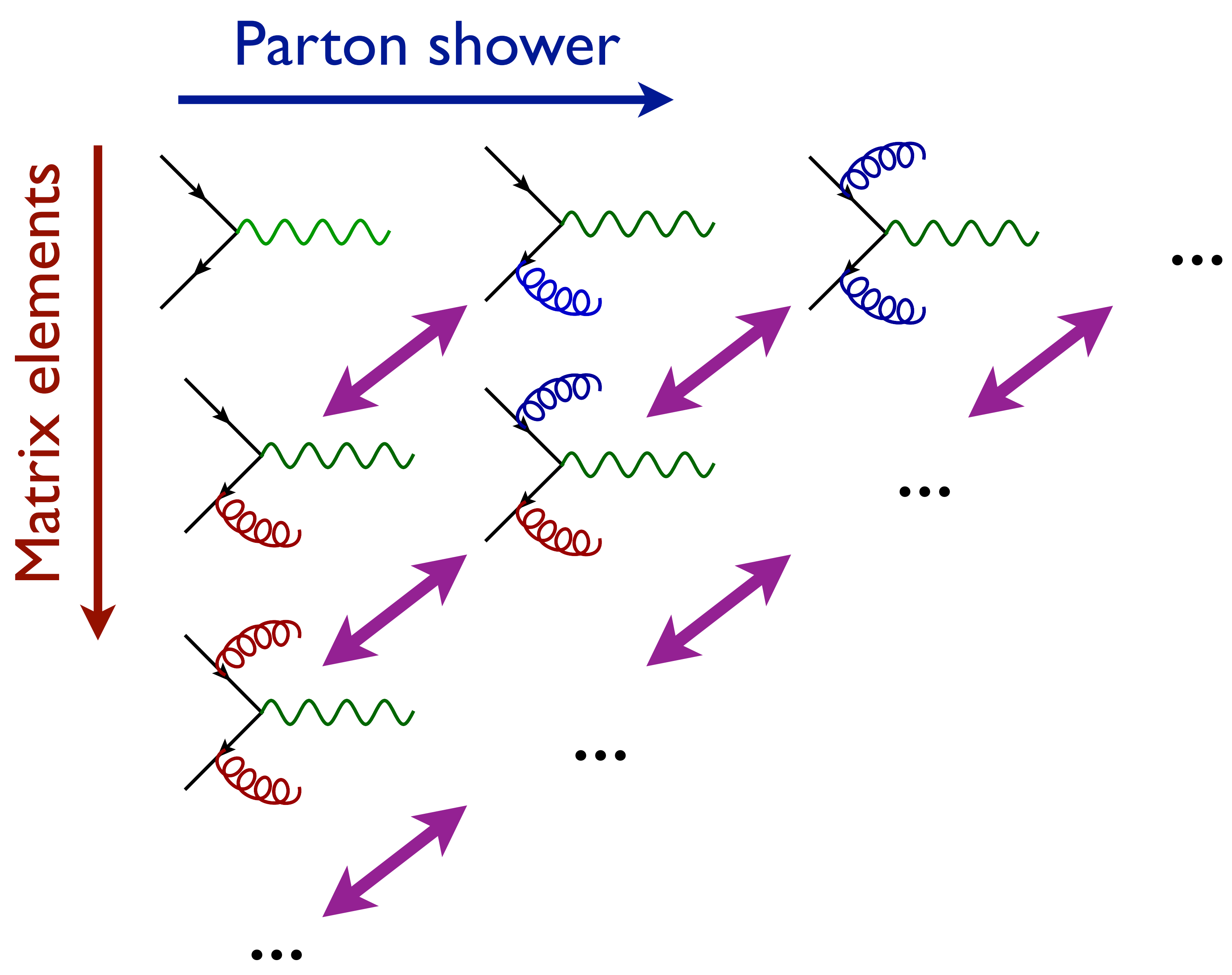
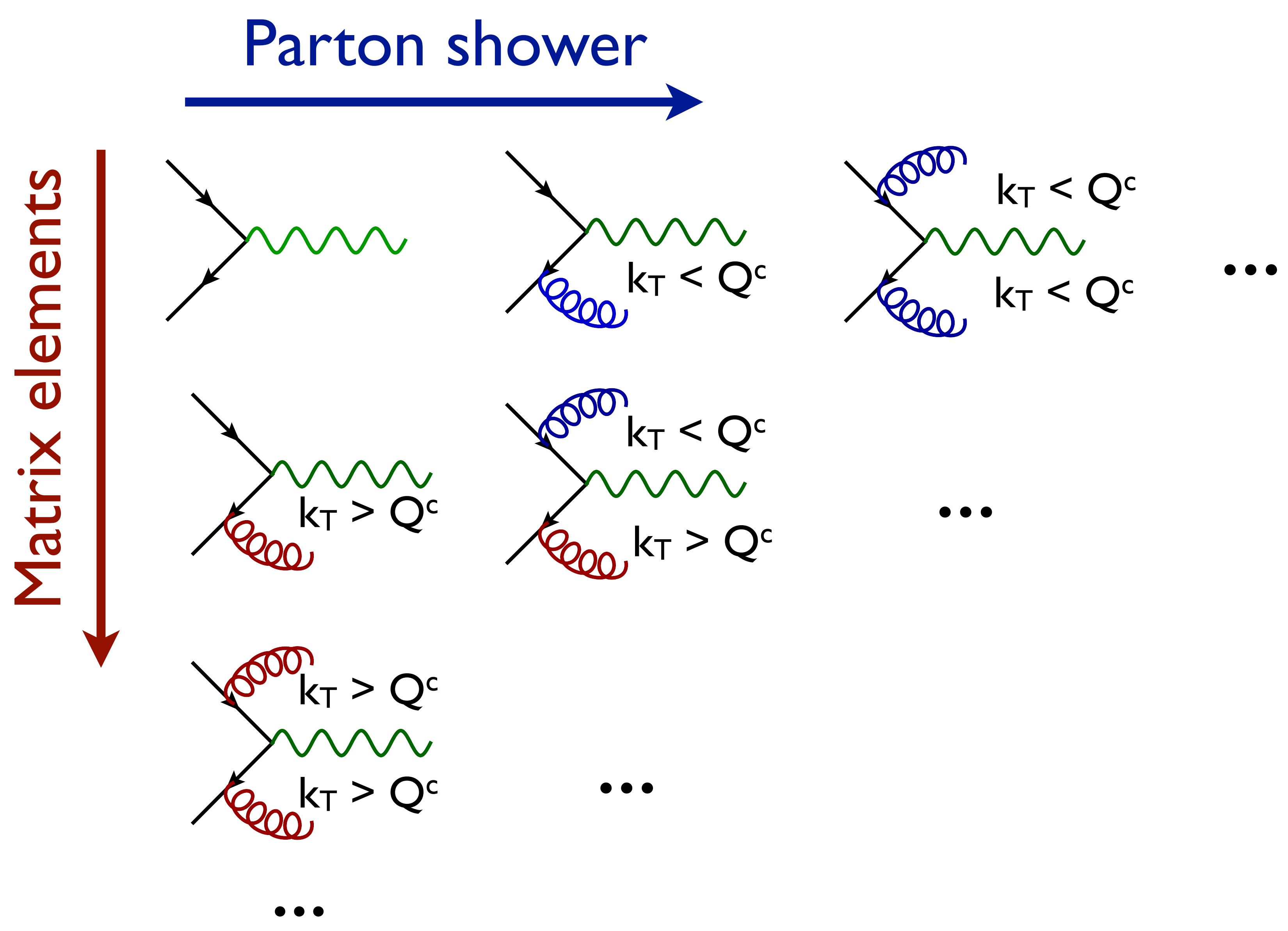
MERGE

Double counting



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

Double counting



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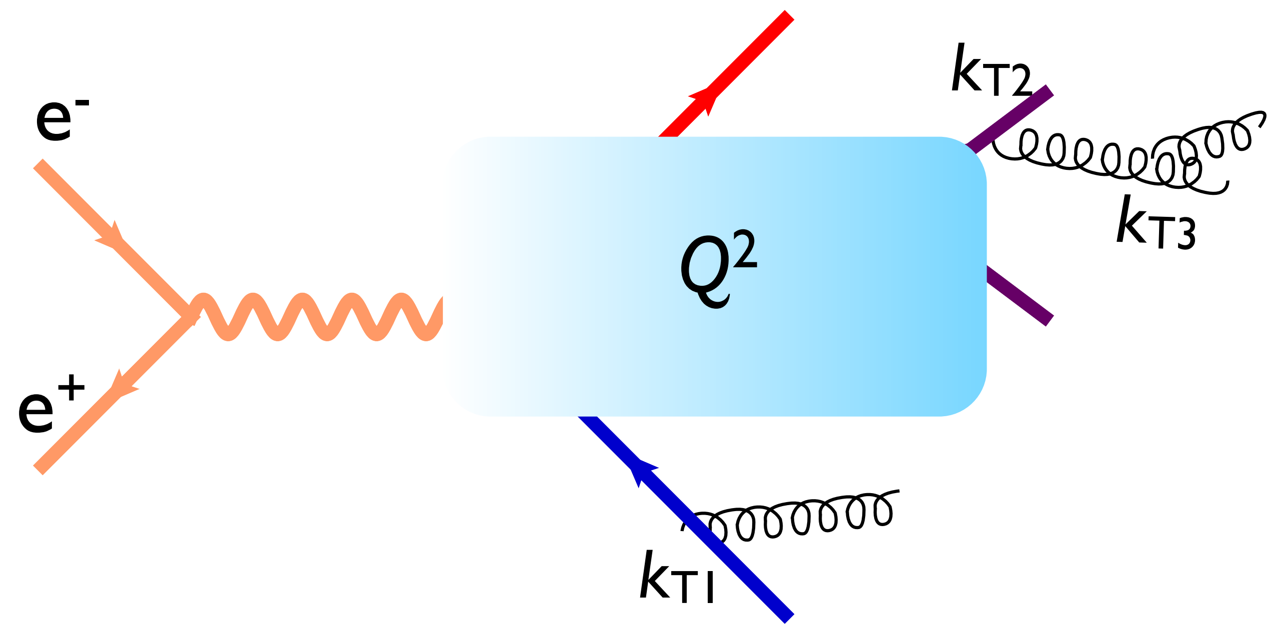
Example: MLM merging

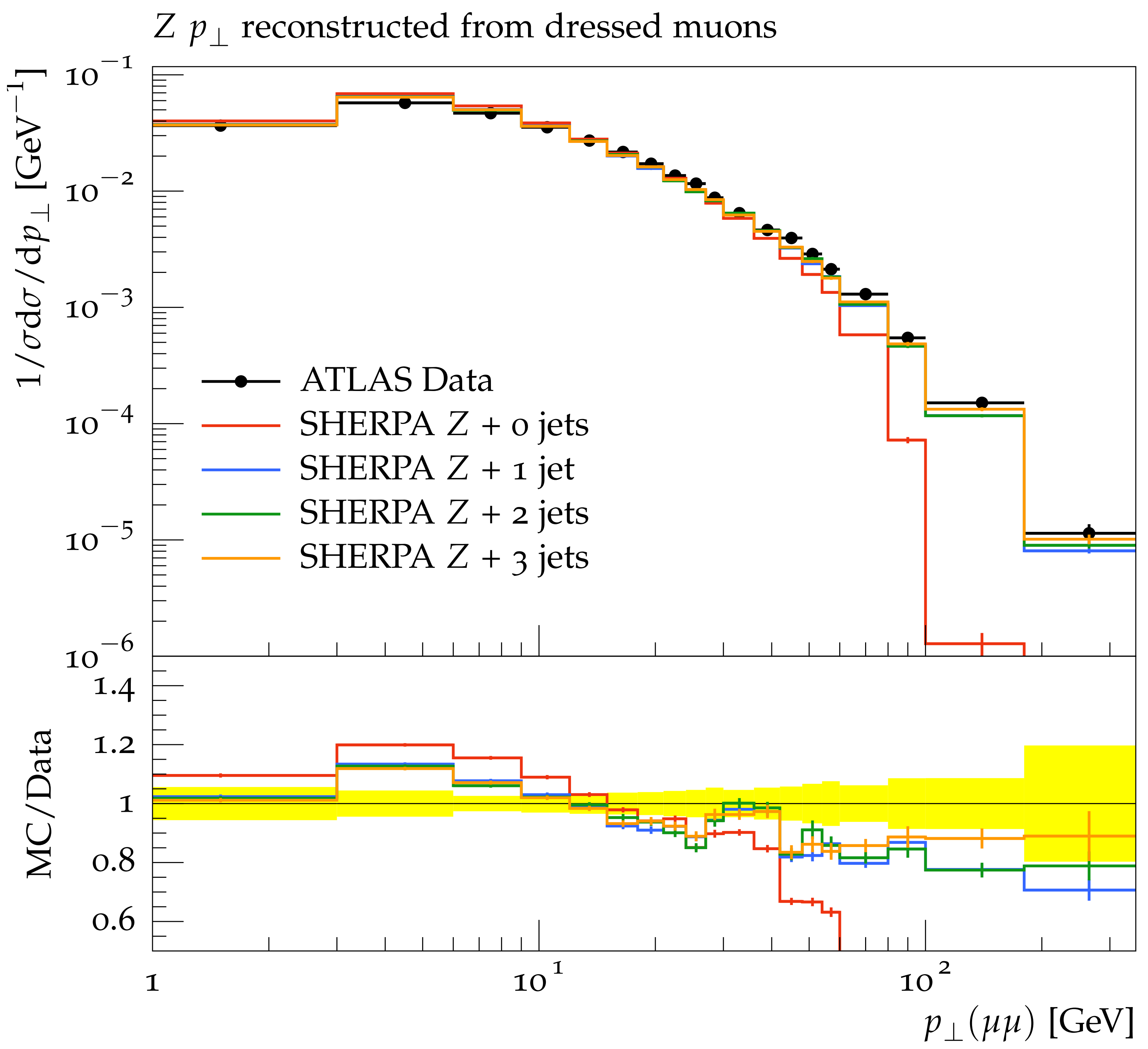


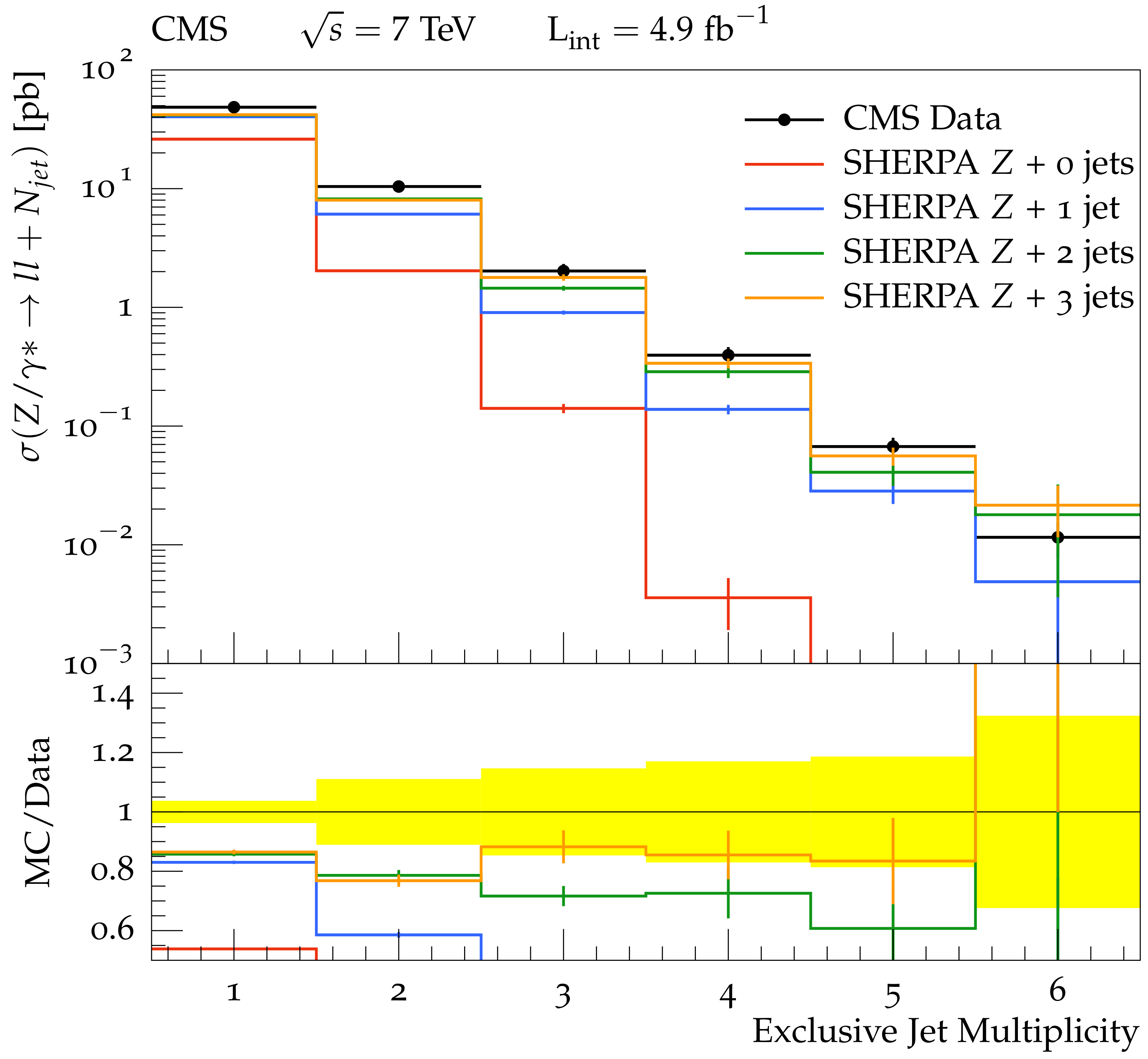
[M.L. Mangano, 2002, 2006]
[J. Alwall et al 2007, 2008]

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

Merged results





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

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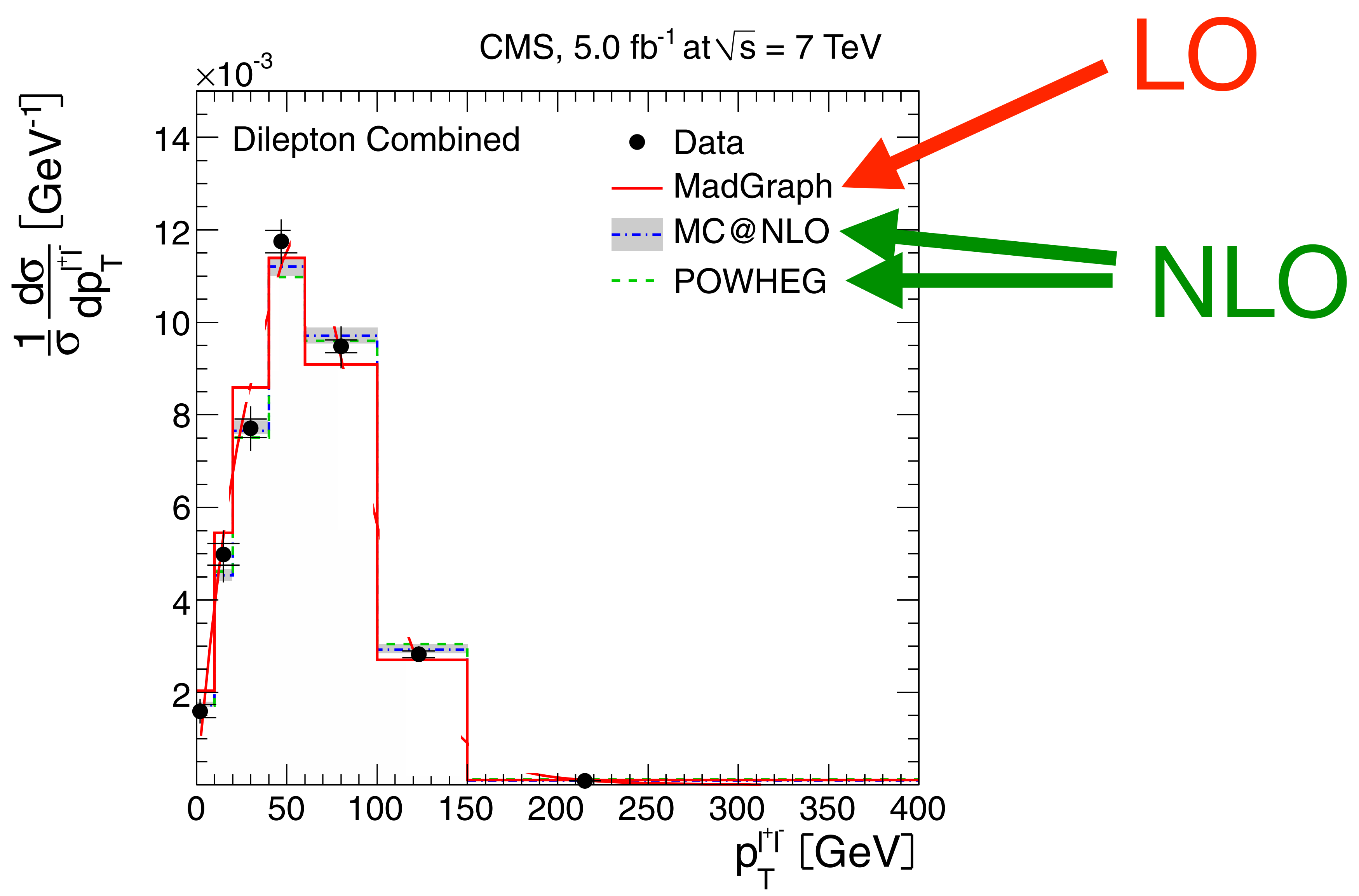
Is LO merging enough?

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!



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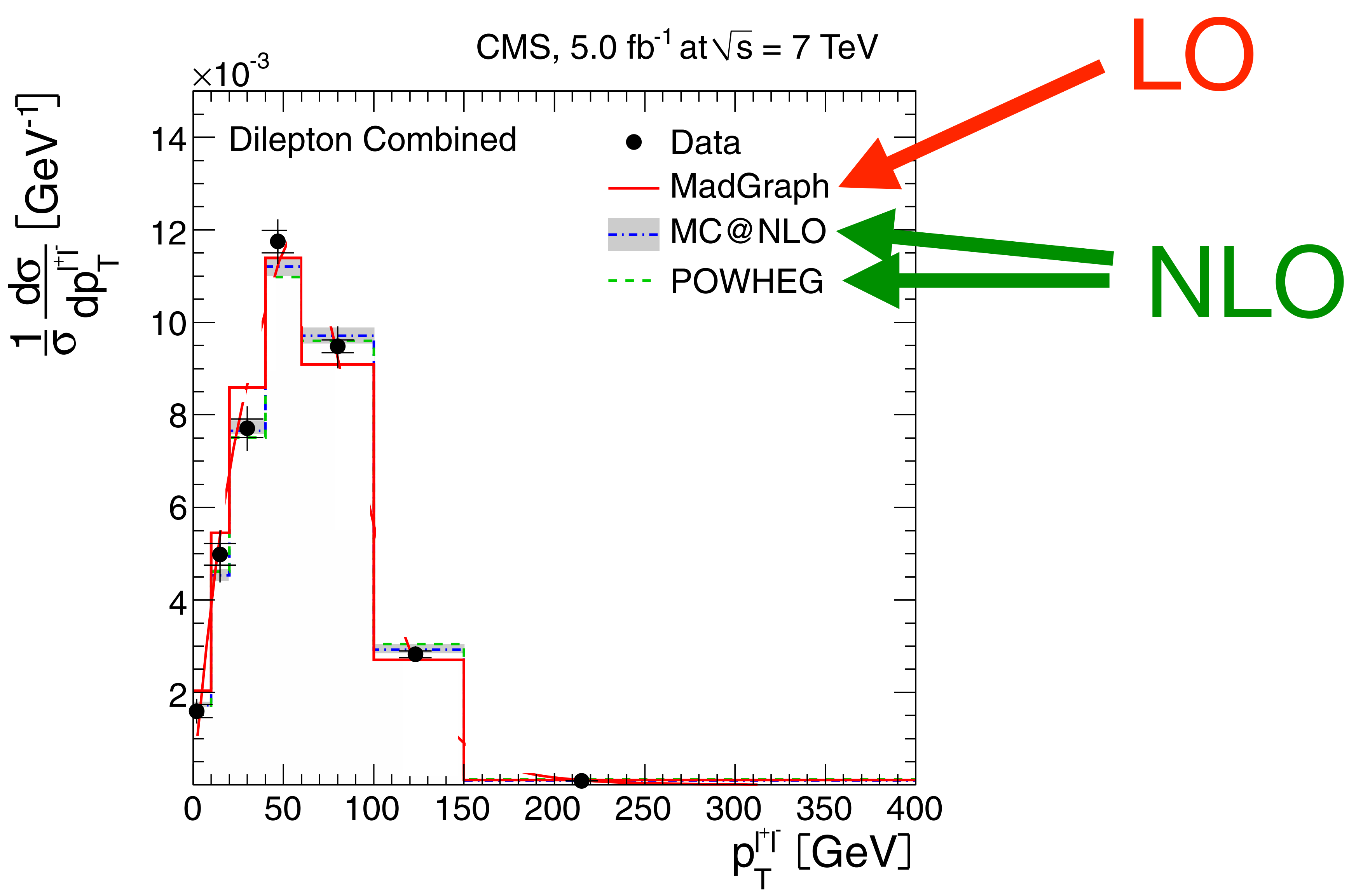
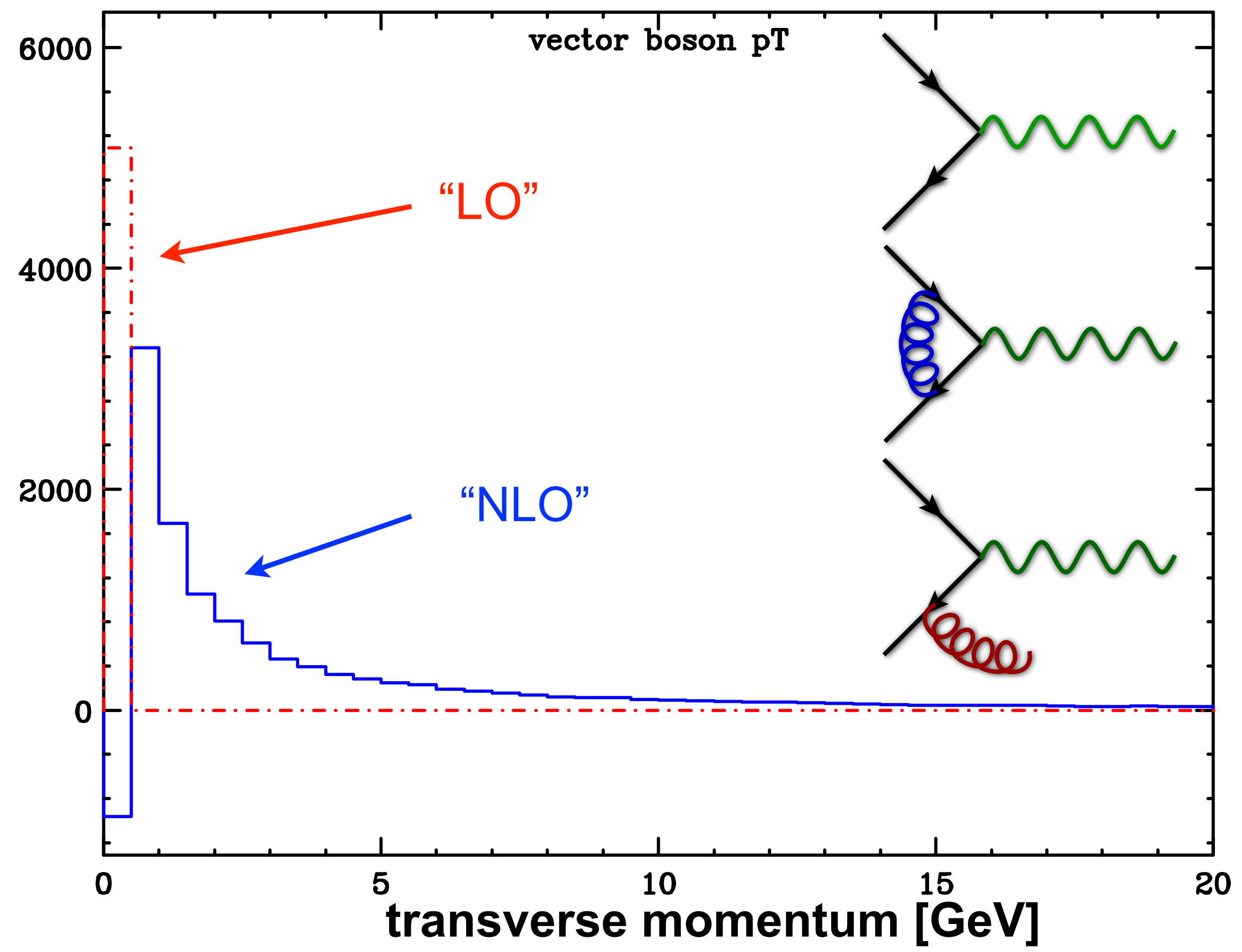


Let's match NLO predictions to the parton shower

Higher orders and PS matching

Issues with matching NLO+PS



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

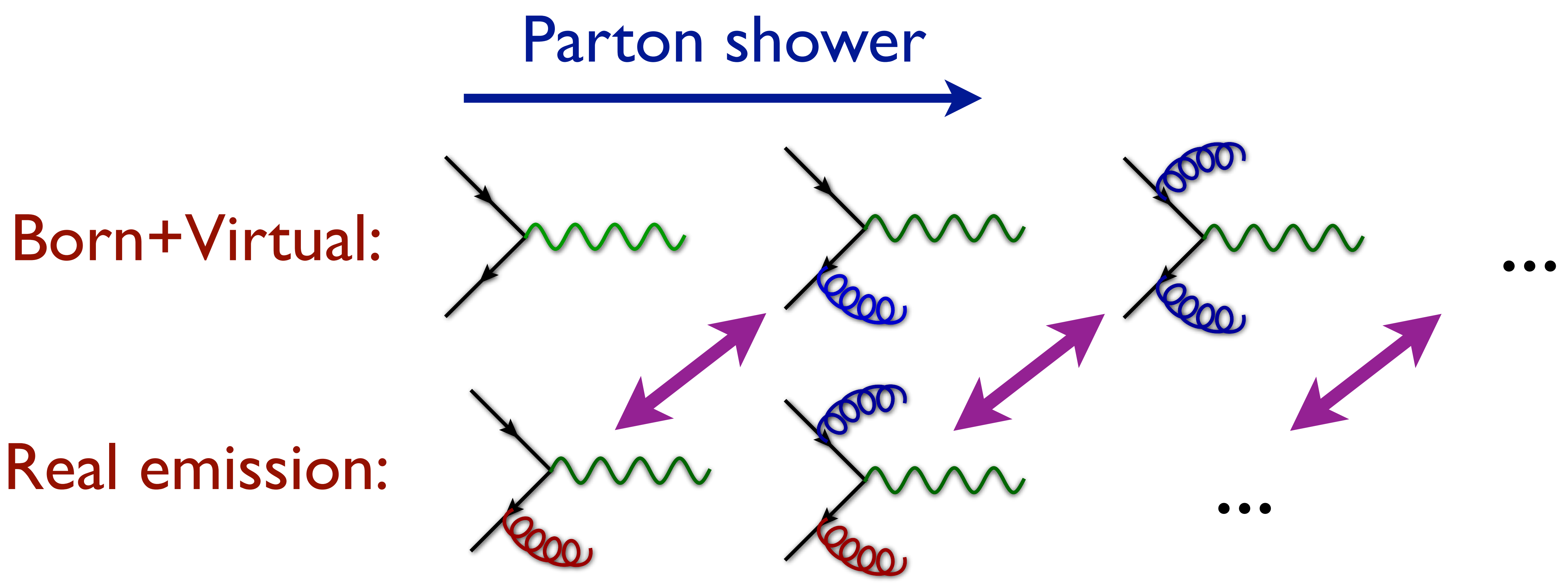
NLO has divergences in virtual and real corrections

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

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

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

Double counting @NLO



Double counting between the shower and the real emission matrix element

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

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

That means Δ contains contributions from the virtual corrections

→ Double counting

NLO+PS

How to avoid double counting?

Two main methods:

MC@NLO: Frixione, Webber 2002

POWHEG: Nason 2004

also

KRKNLO, Vincia, Geneva

MC@NLO matching

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

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

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

MC@NLO features

Good features of including the subtraction counter terms

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

Not so nice feature:

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

Summary: NLO+PS

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

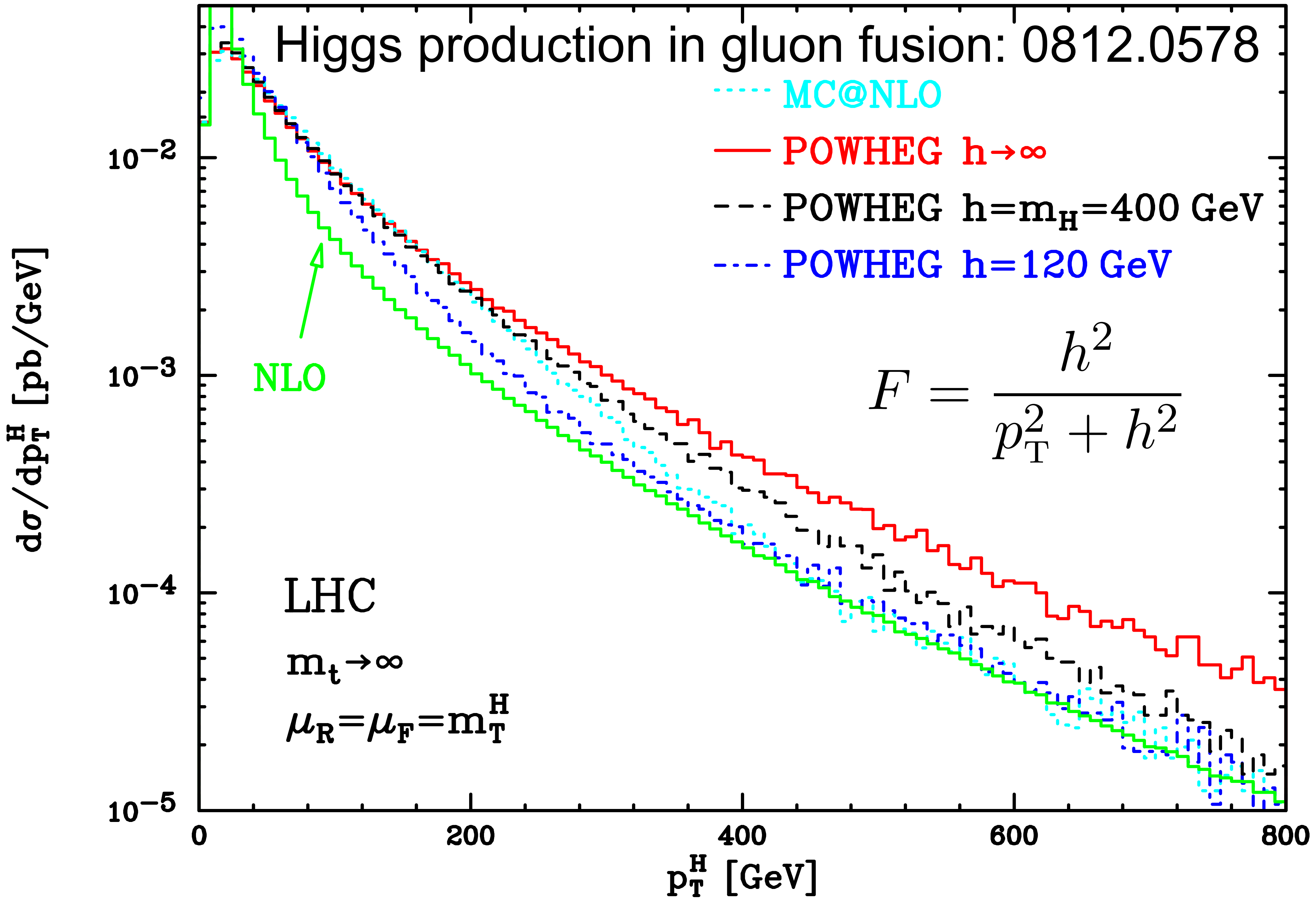
MC@NLO: subtraction term avoids double counting between NLO and parton shower

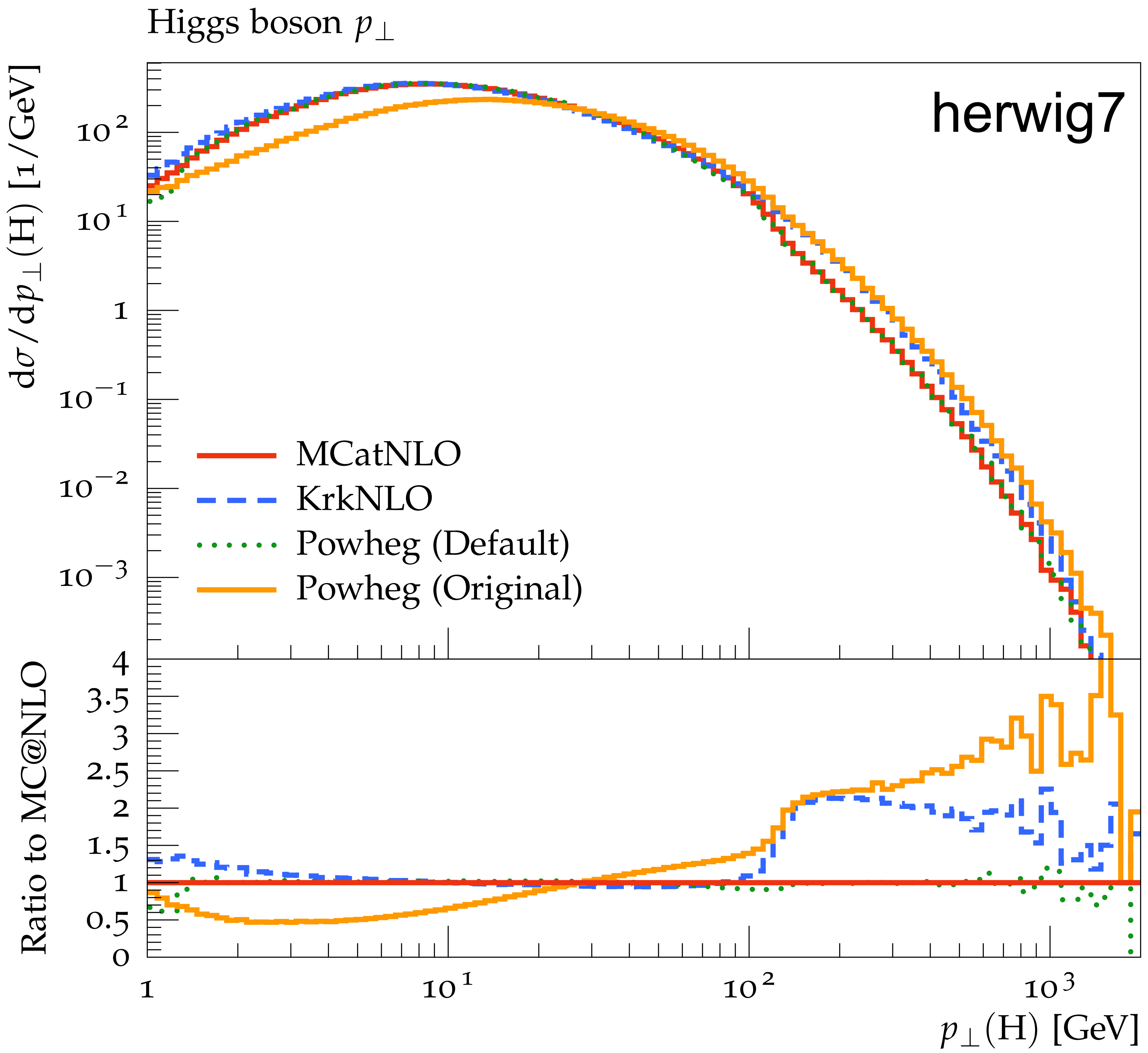
Other NLO+PS method:

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

Showered results

Higgs production NLO+PS





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

Showered results

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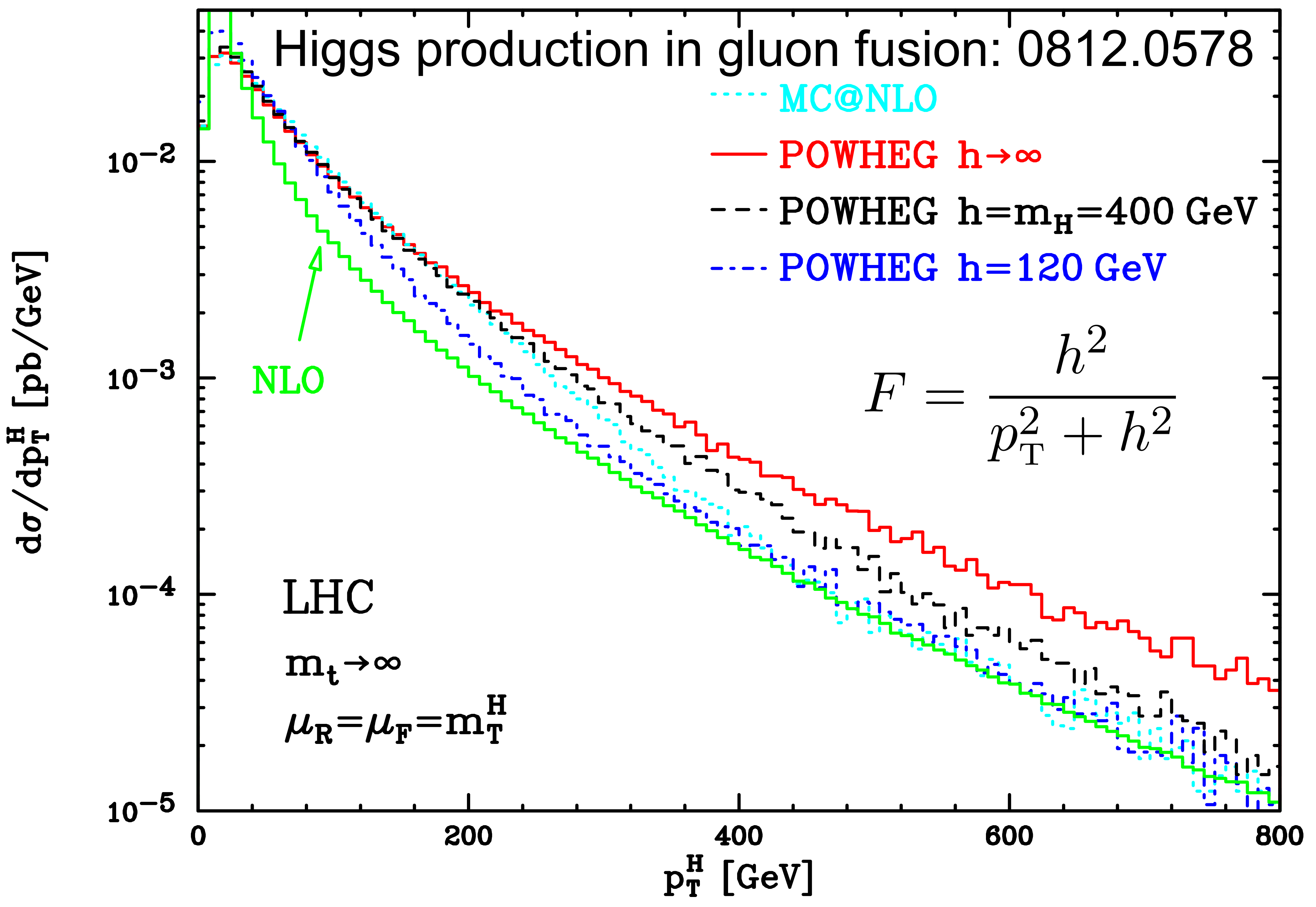

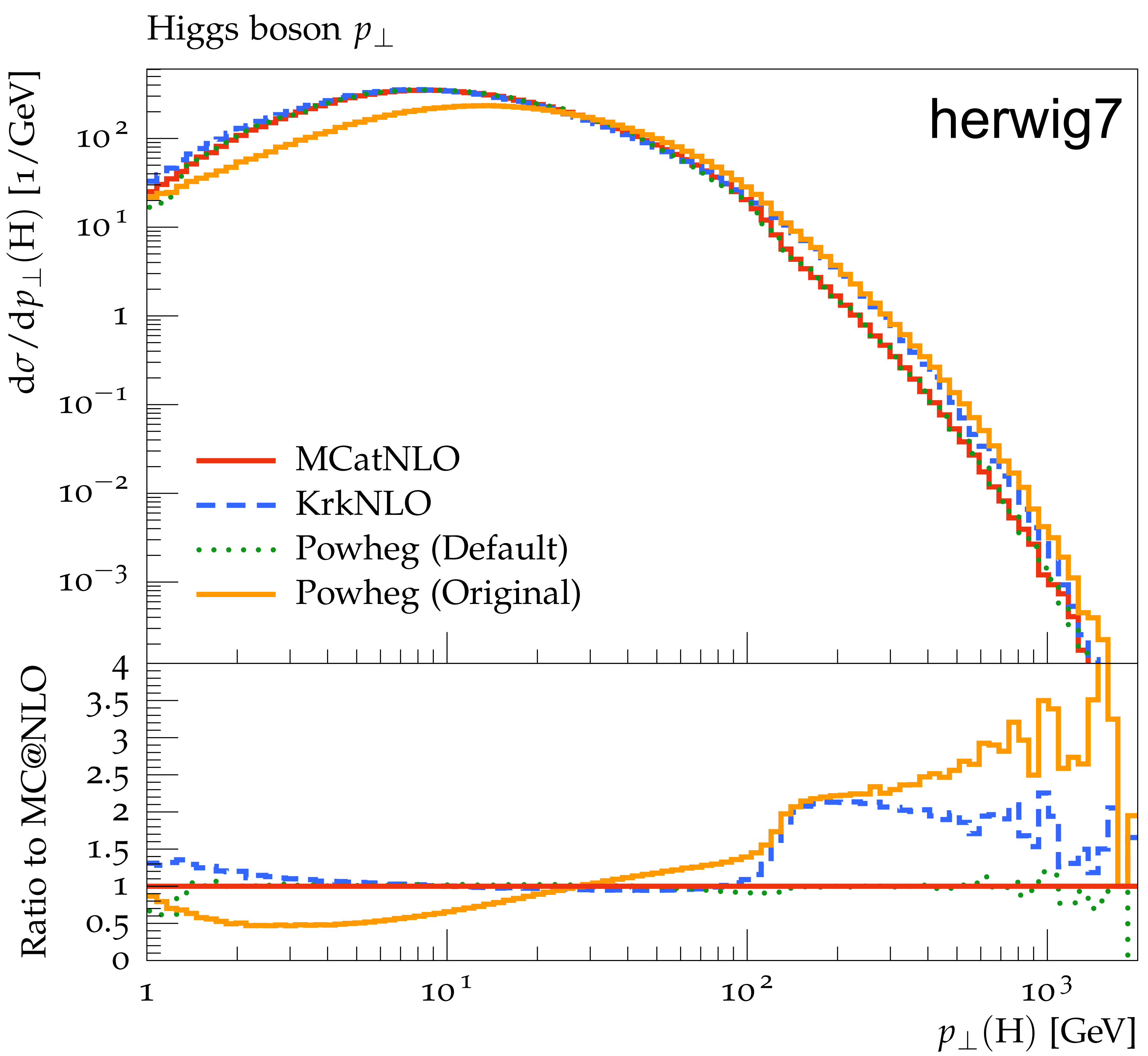

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Original Powheg was giving too hard tails

Improved Powheg very close to MC@NLO

Merging@NLO

Best of both worlds

To improve both high multiplicity regions and rates

Two main methods of merging@NLO

- FxFx
- MEPS@NLO

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

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

Used in Sherpa's "MEPS@NLO"

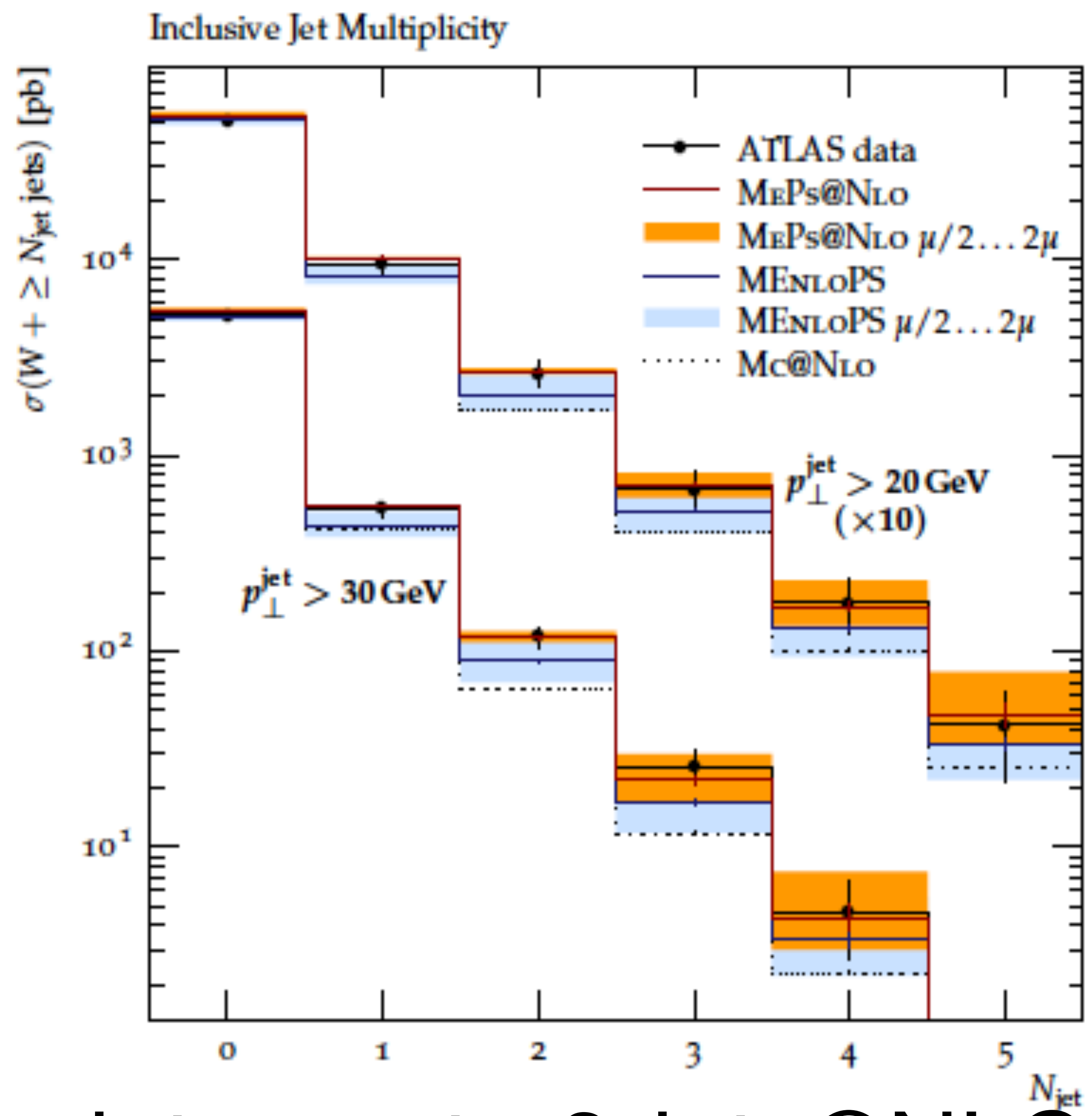
CKKW from hard scale down to the scale of the softest jet not affected by veto;

- MLM-type rejection from there down to merging scale

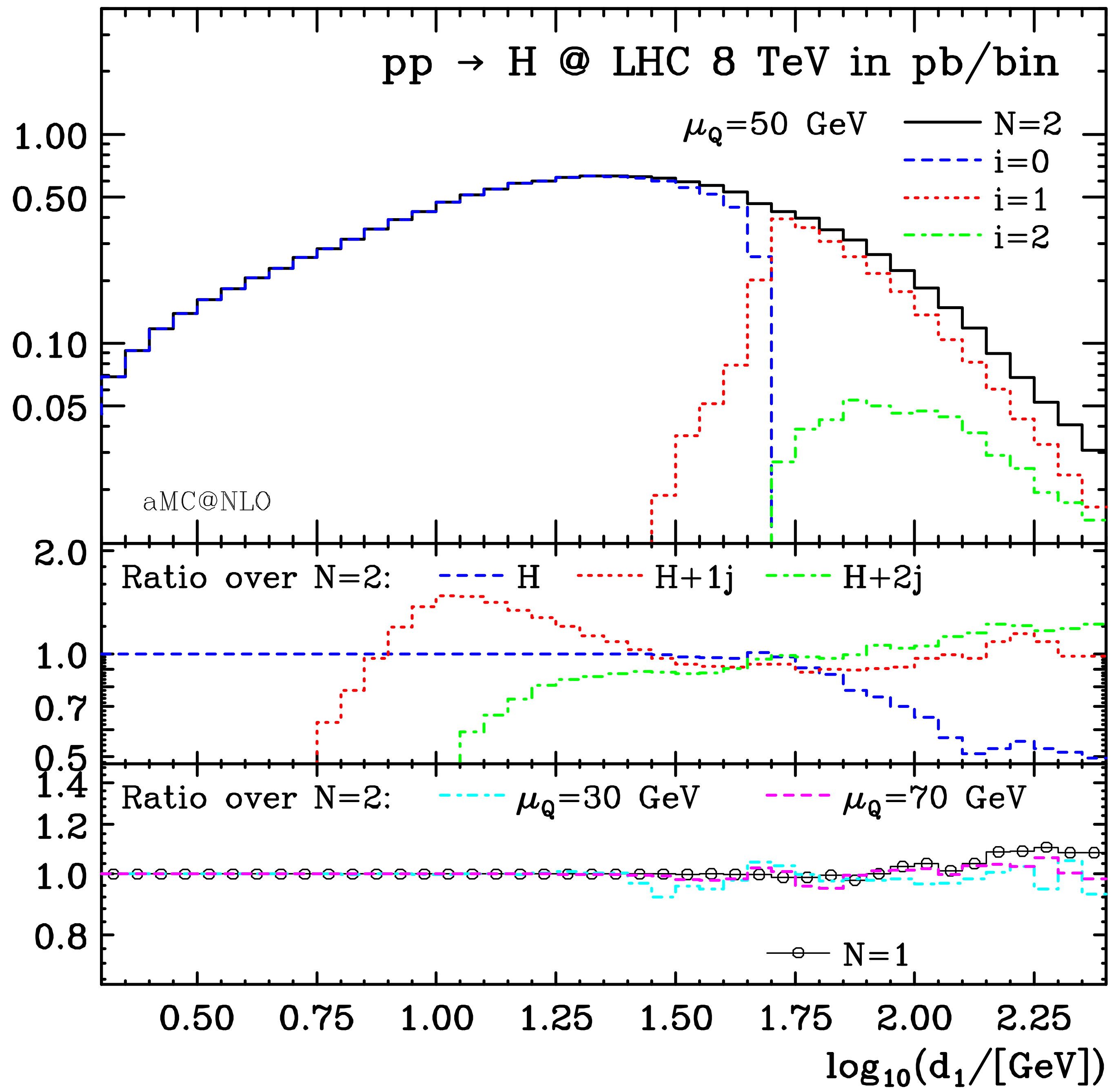
Used in MadGraph5_aMC@NLO with Pythia or Herwig: "FxFx merging"

Merging@NLO

[Hoeche et al. , 1207.5030]



[Frederix, Frixione, 1209.6215]



W + jets: up to 3-jets@NLO

Jet multiplicity

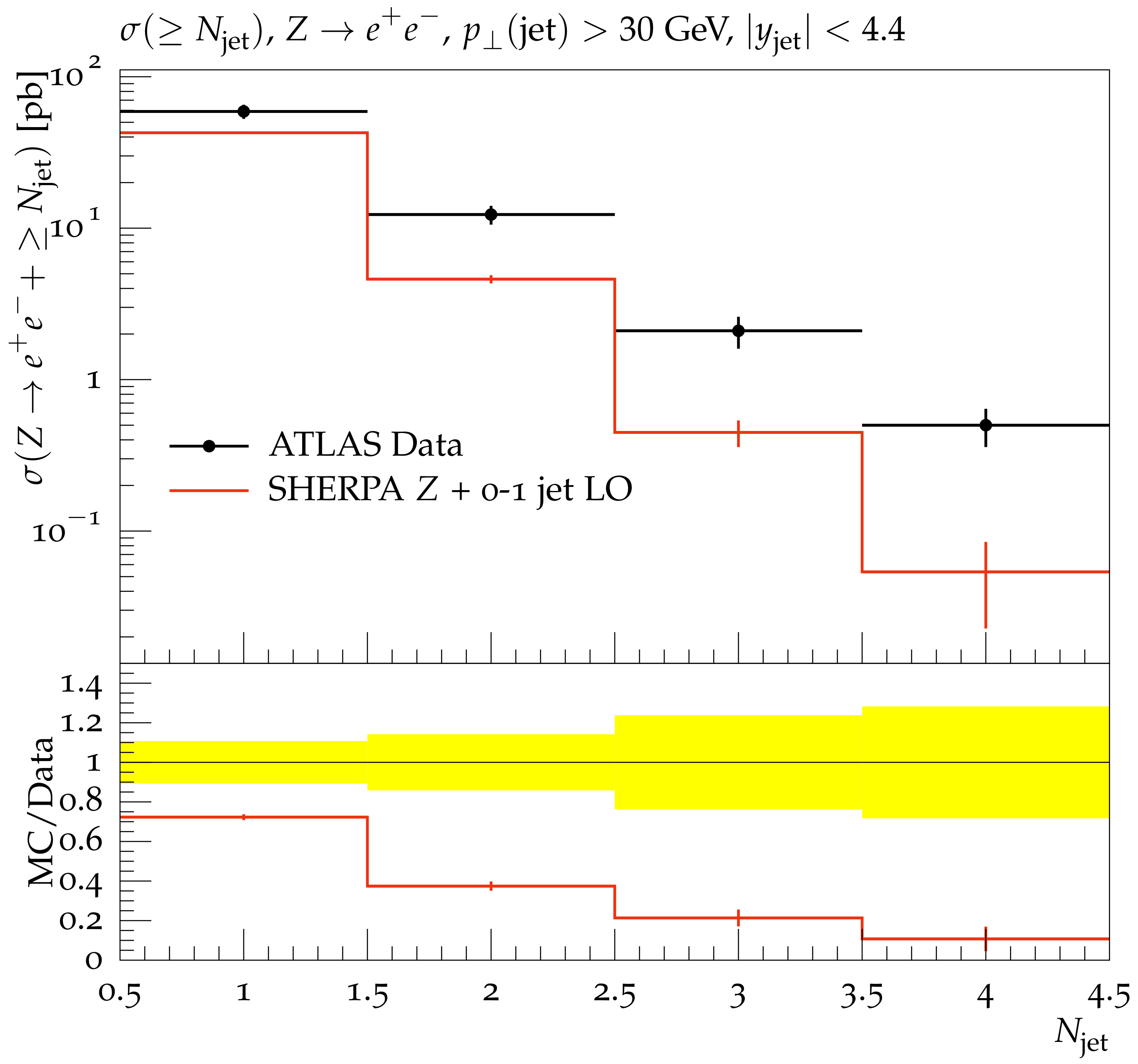
Good agreement with LHC data

H + jets: up to 2-jets@NLO

Differential jet rate

Very mild merging scale dependence

Is this progress relevant?



Merging at LO

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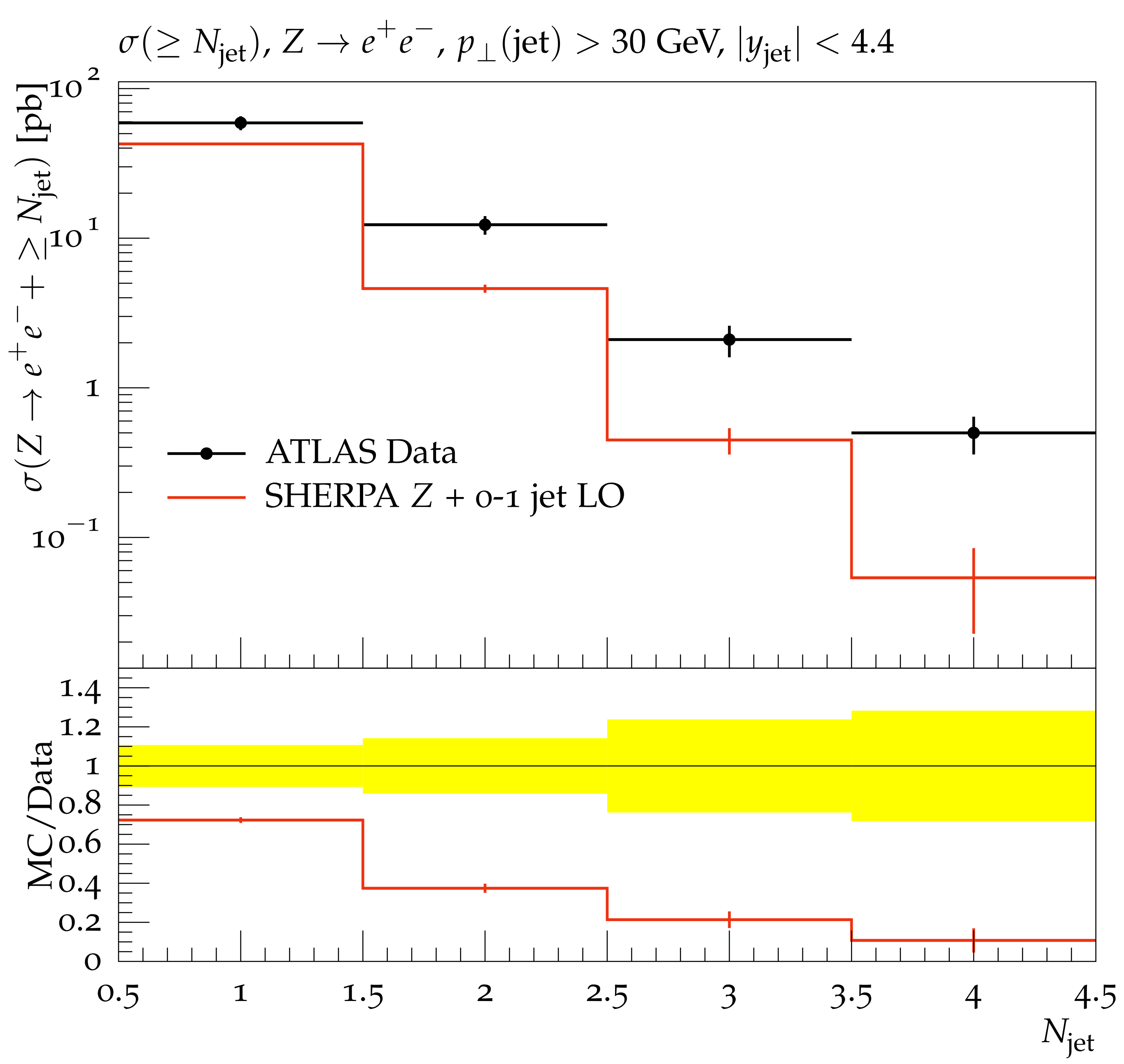

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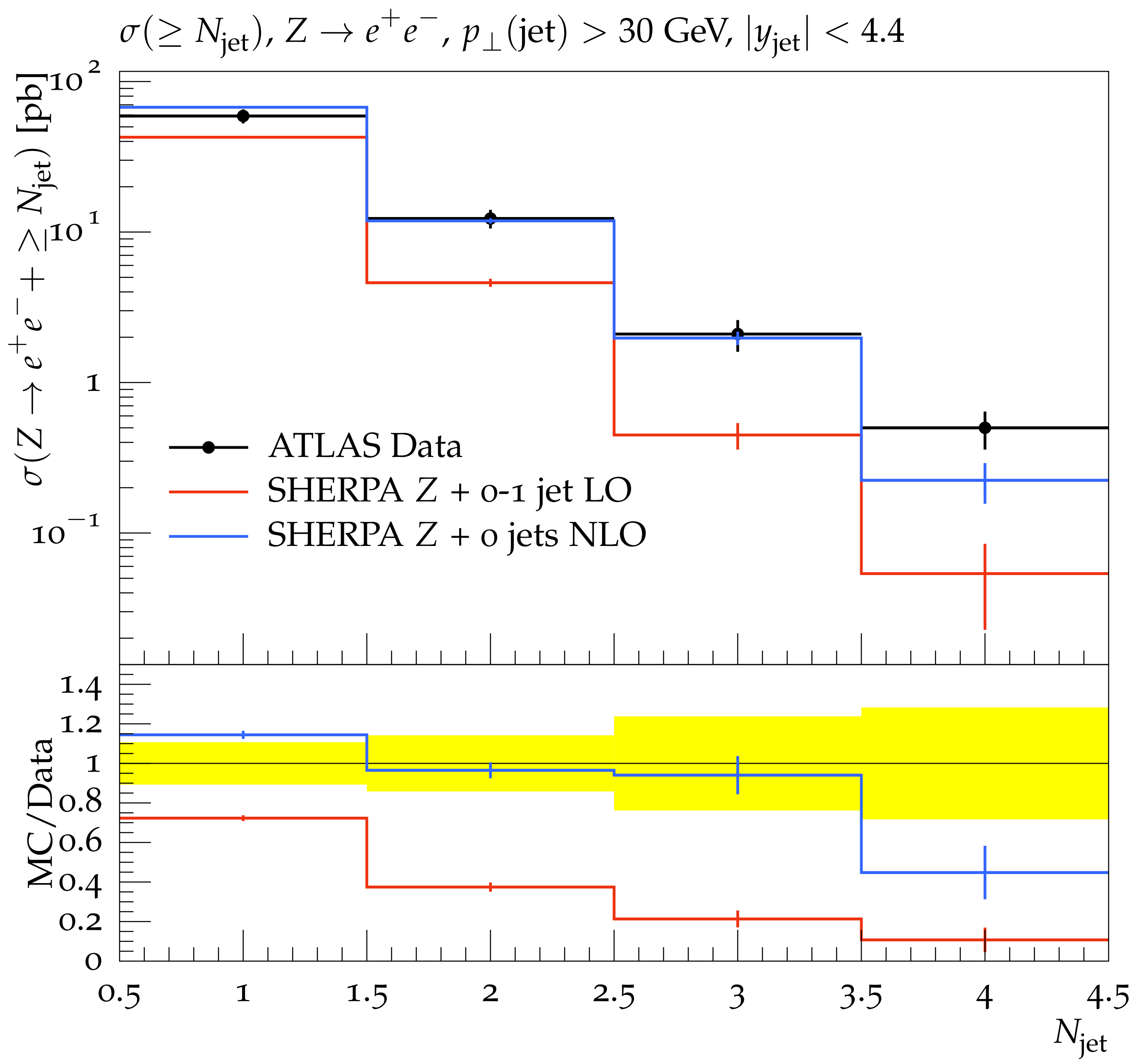

NLO+PS

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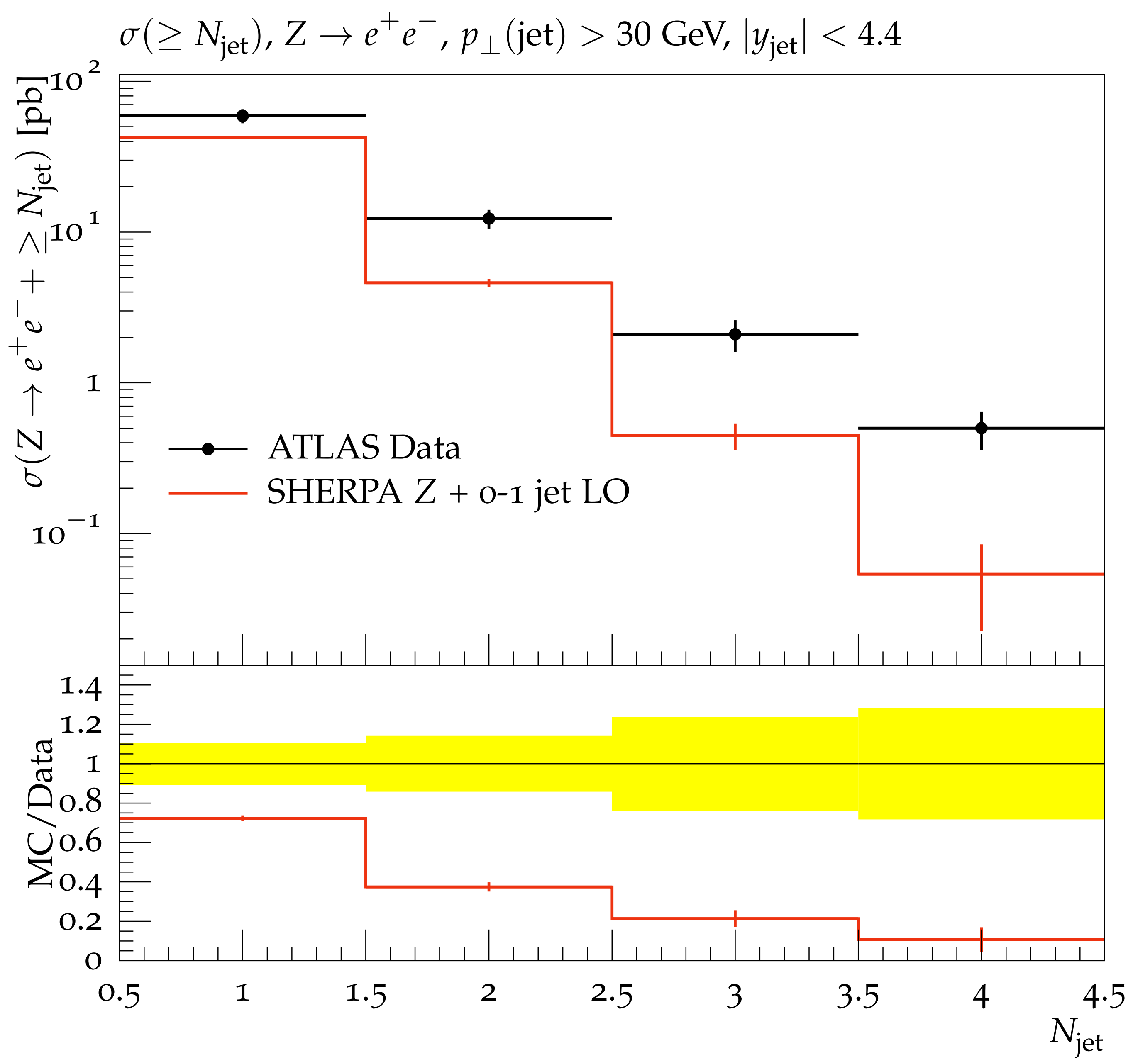
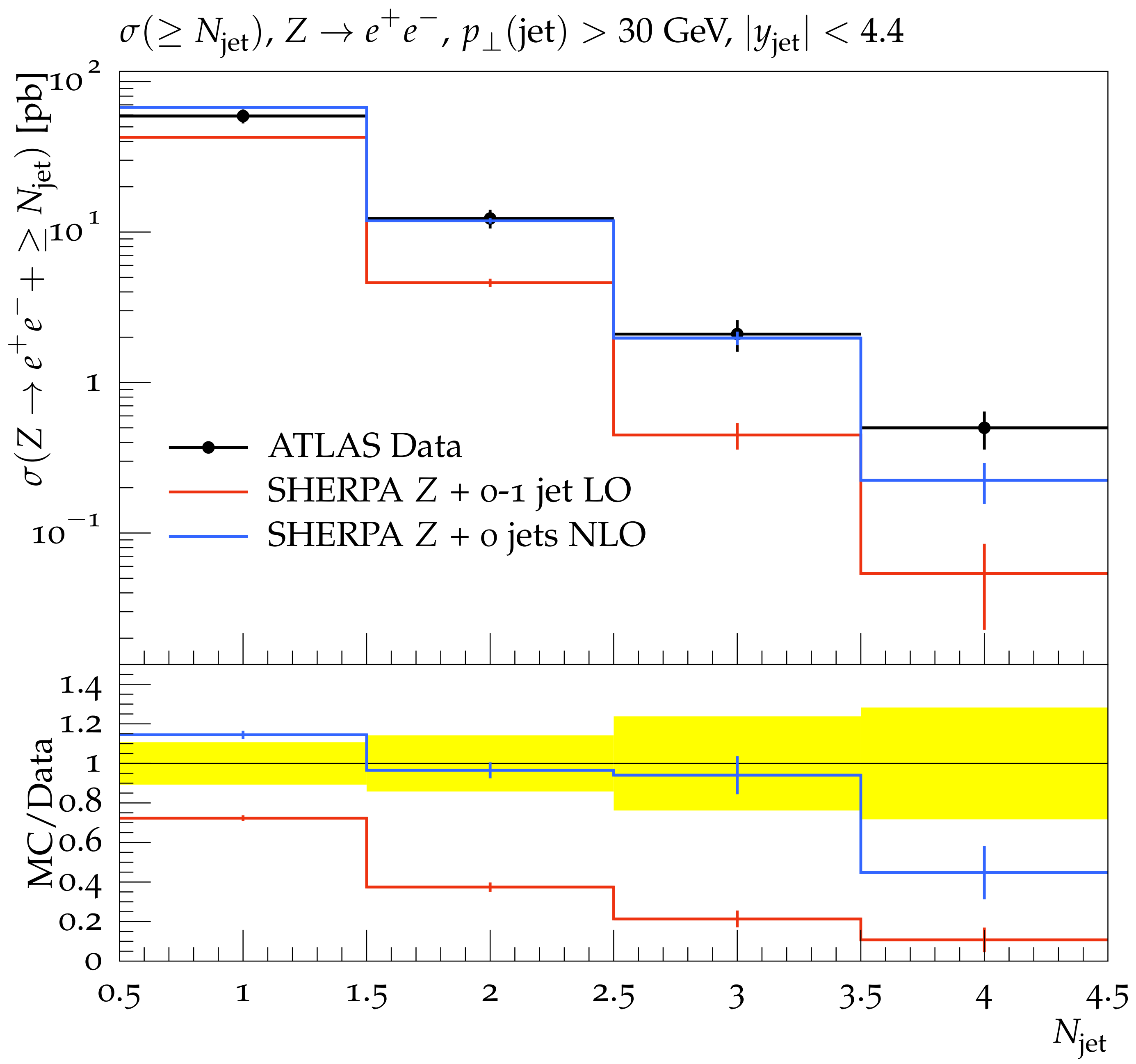
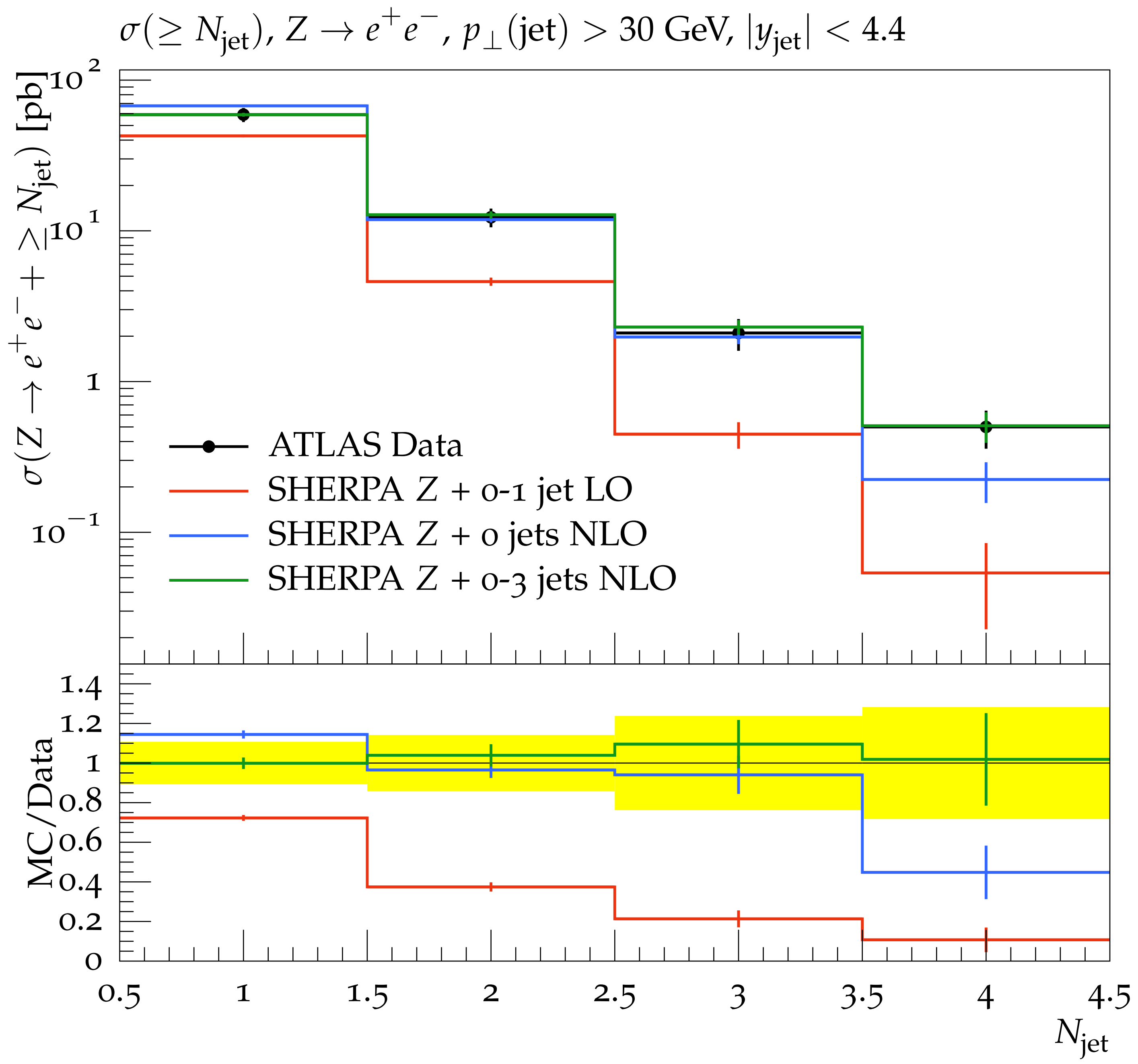


Merging at LO

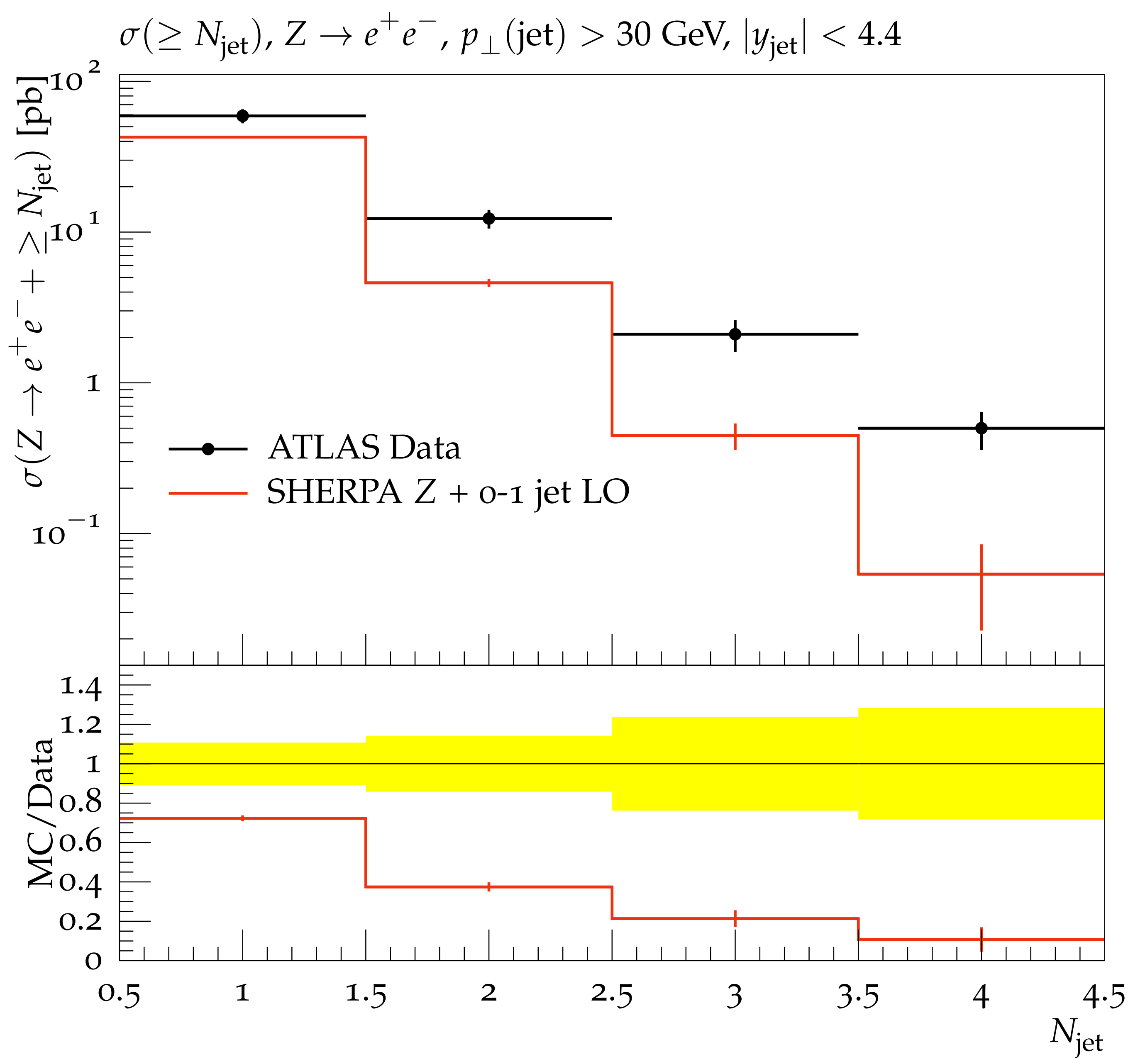


NLO+PS

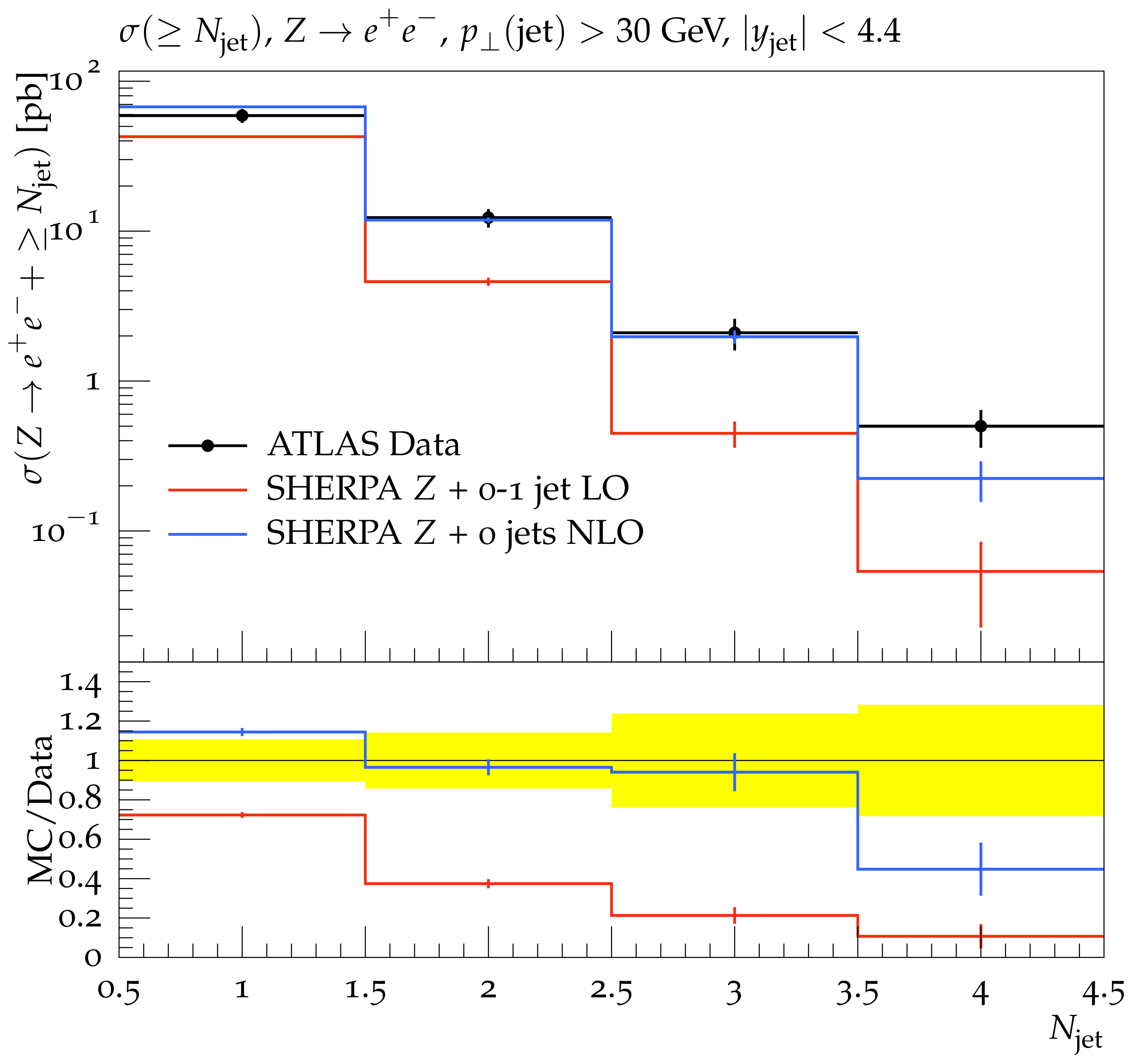


NLO+PS merging

Is this progress relevant?



Merging at LO



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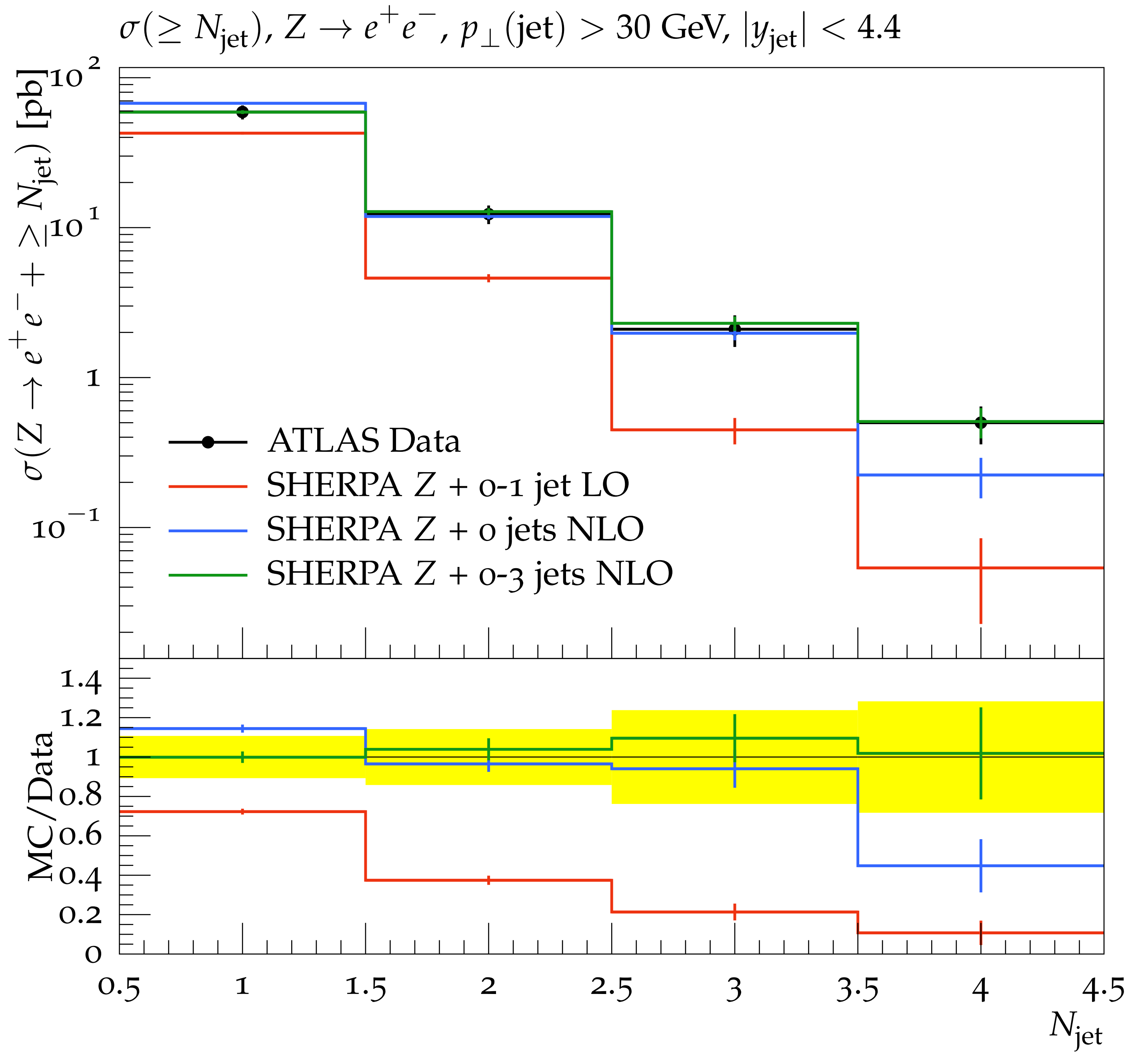
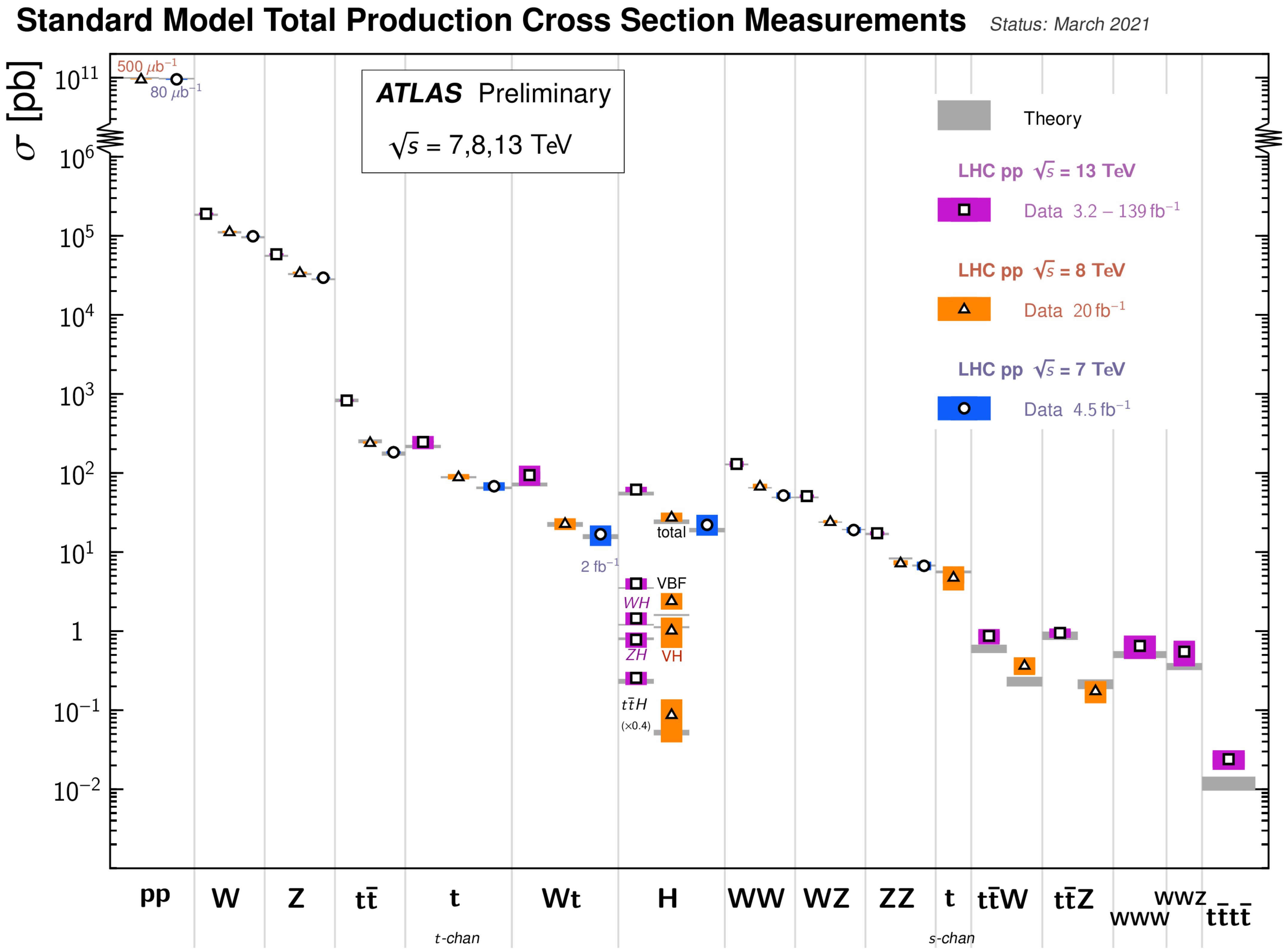


NLO+PS merging

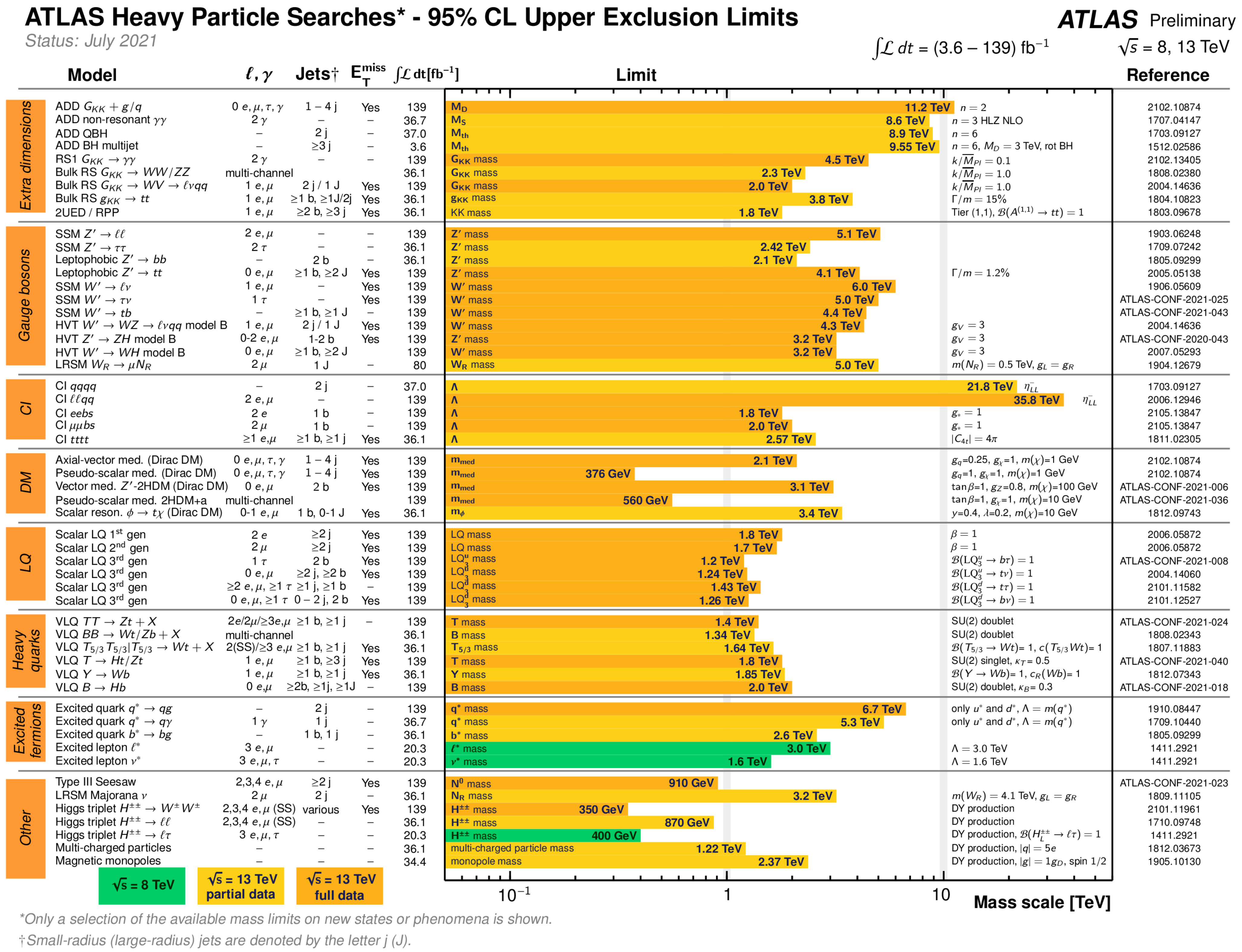
Impressive improvement in description of data!

LHC status

Rediscovering the SM



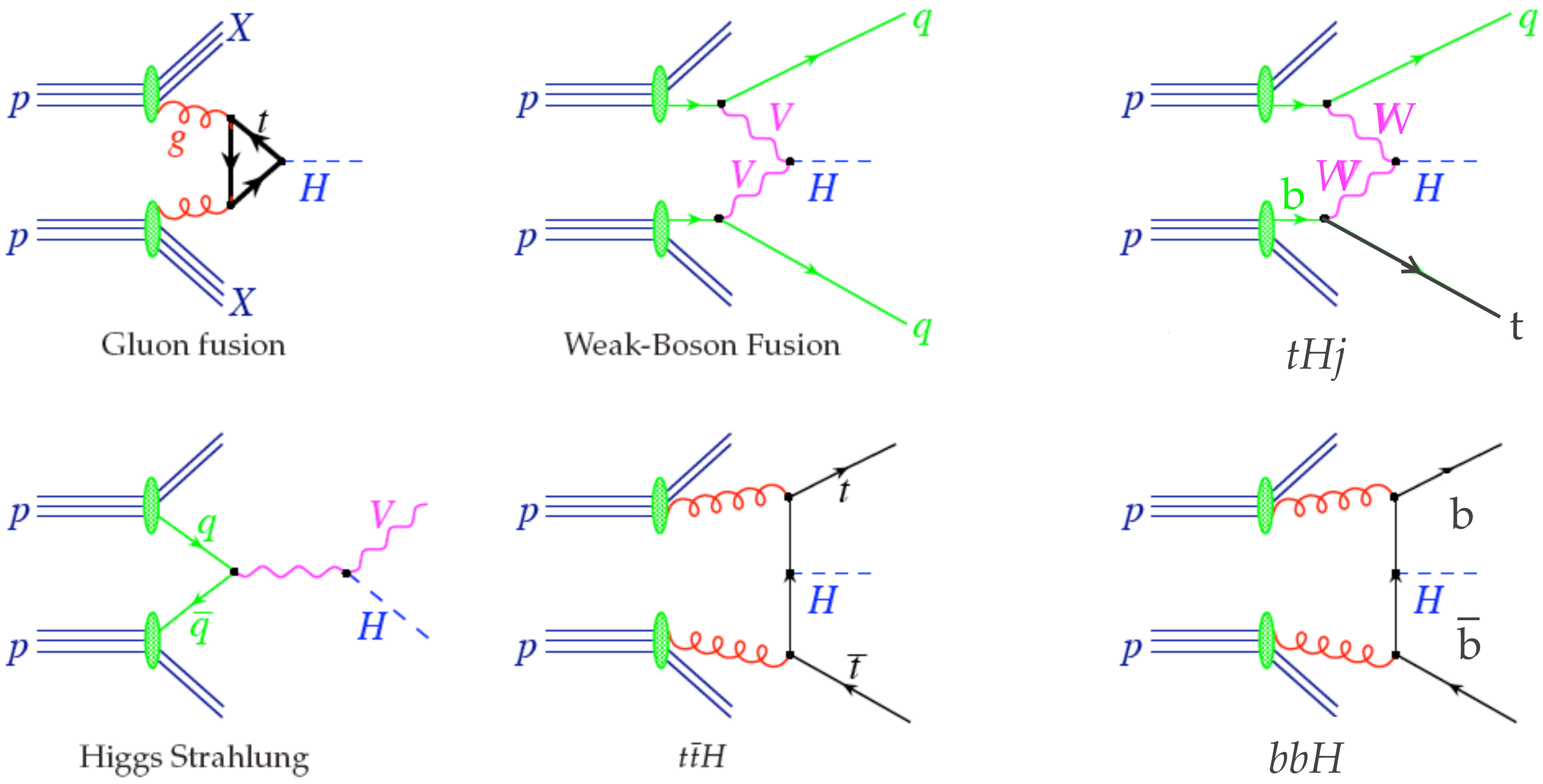
Searching for the unknown

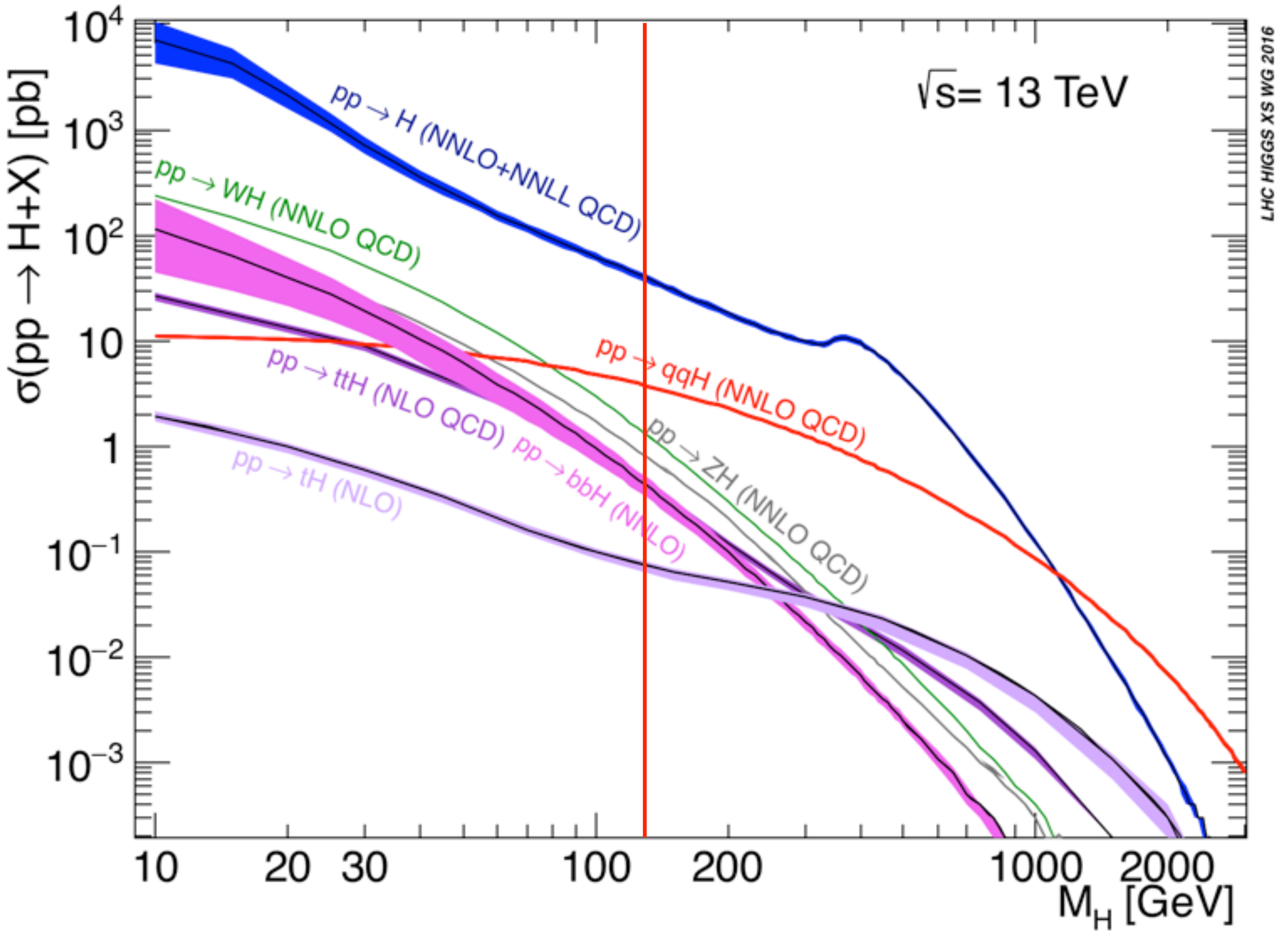


Good agreement with the SM

Higgs phenomenology

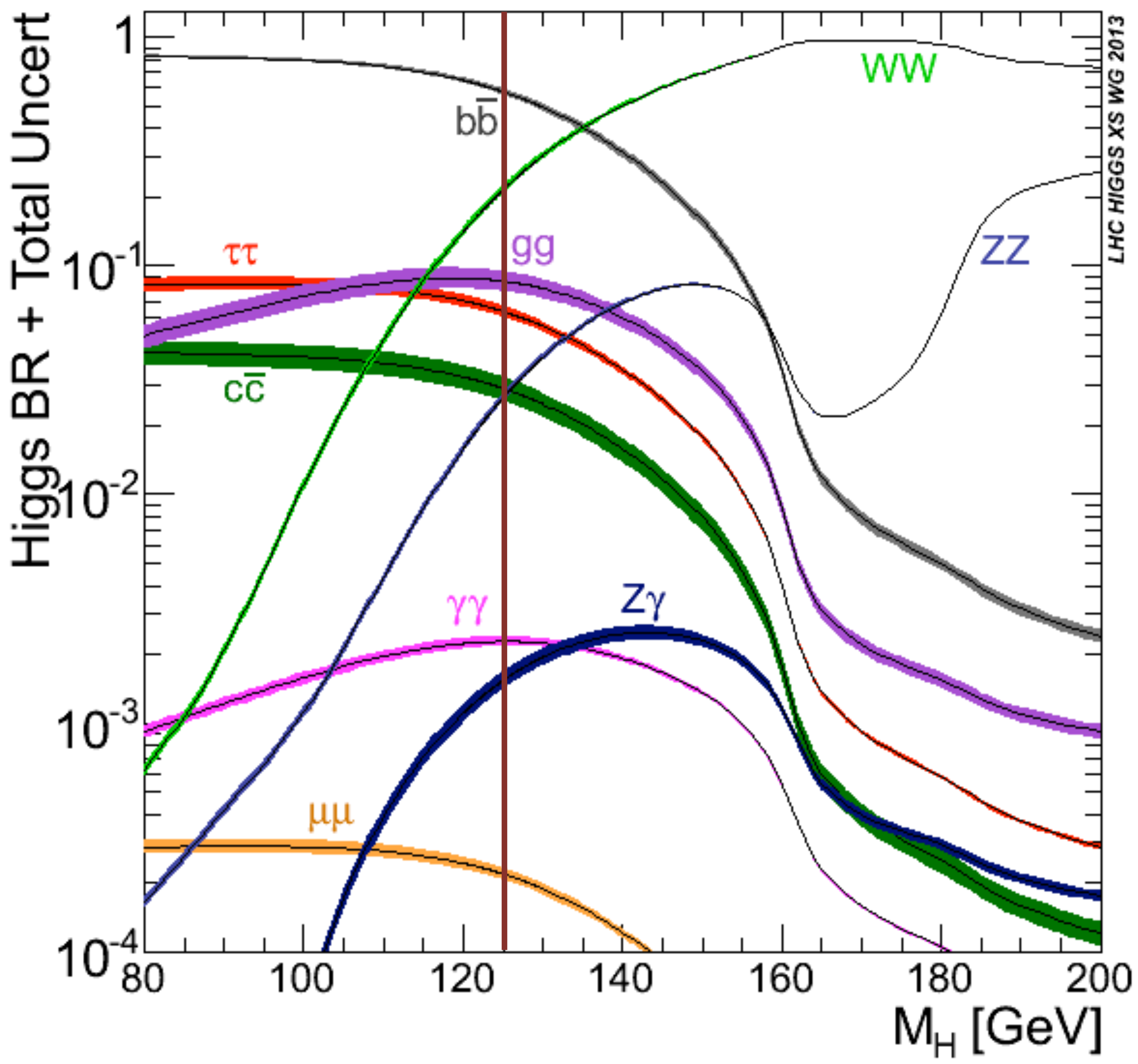
Higgs production





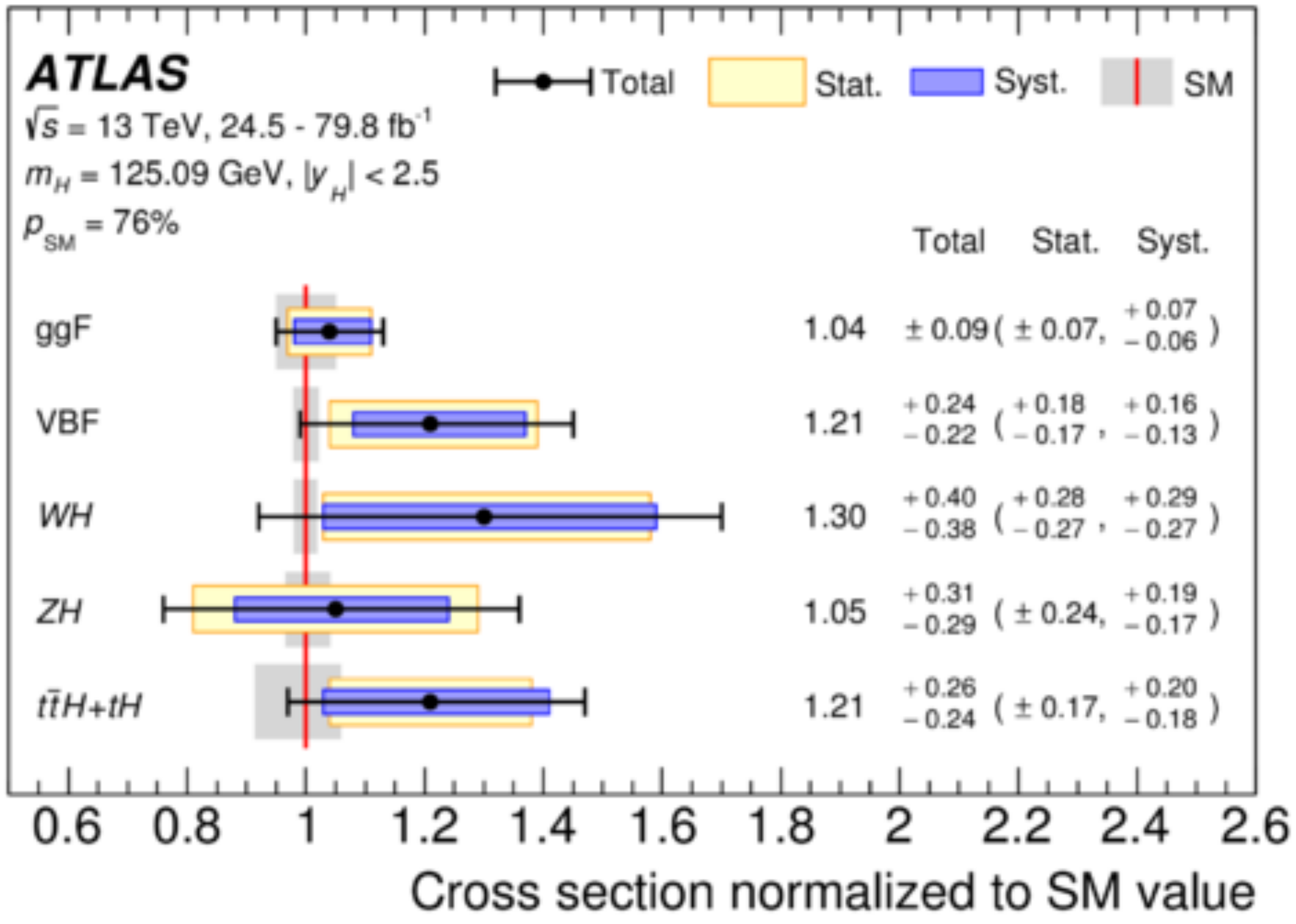
Higgs phenomenology

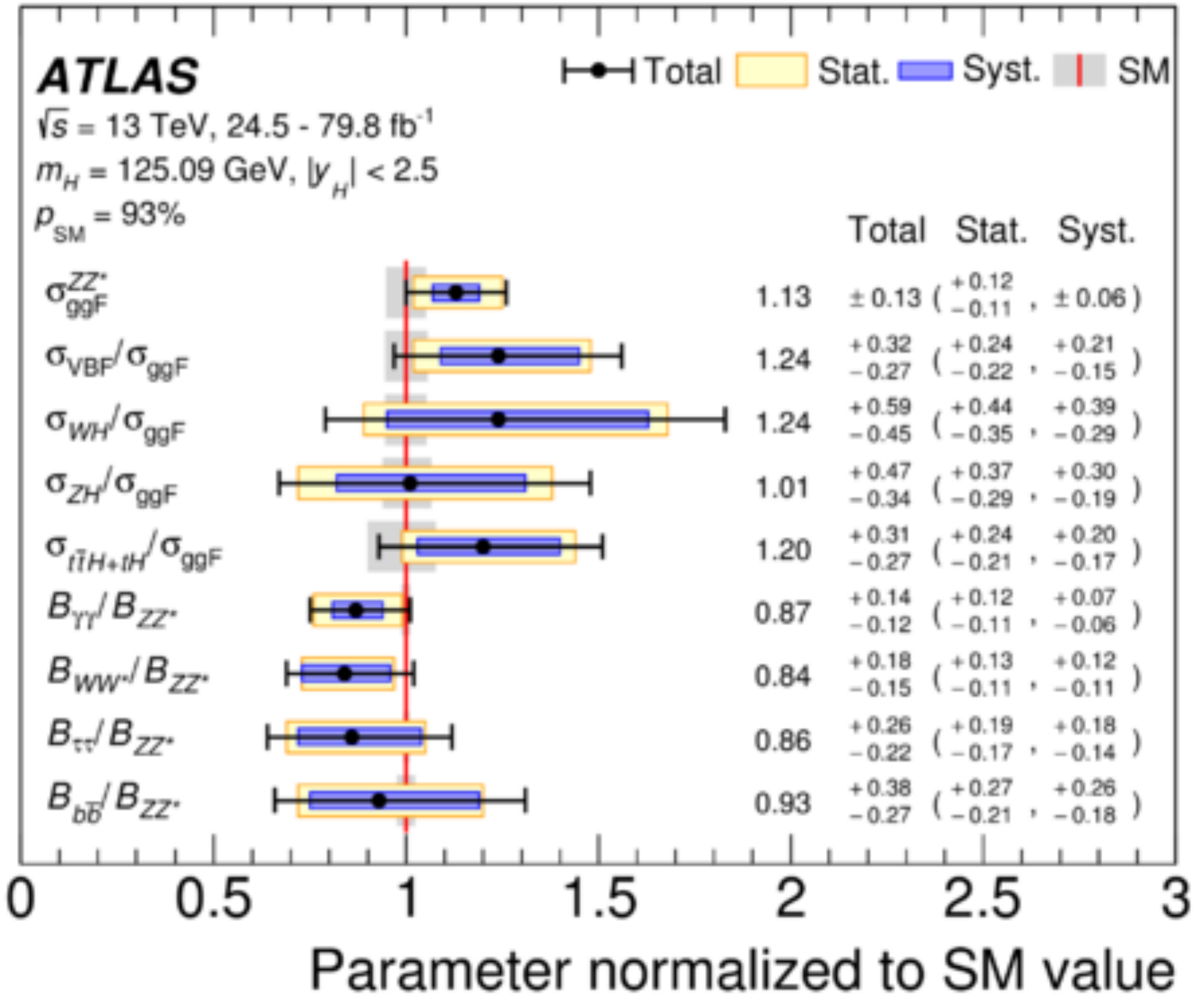
Higgs decays



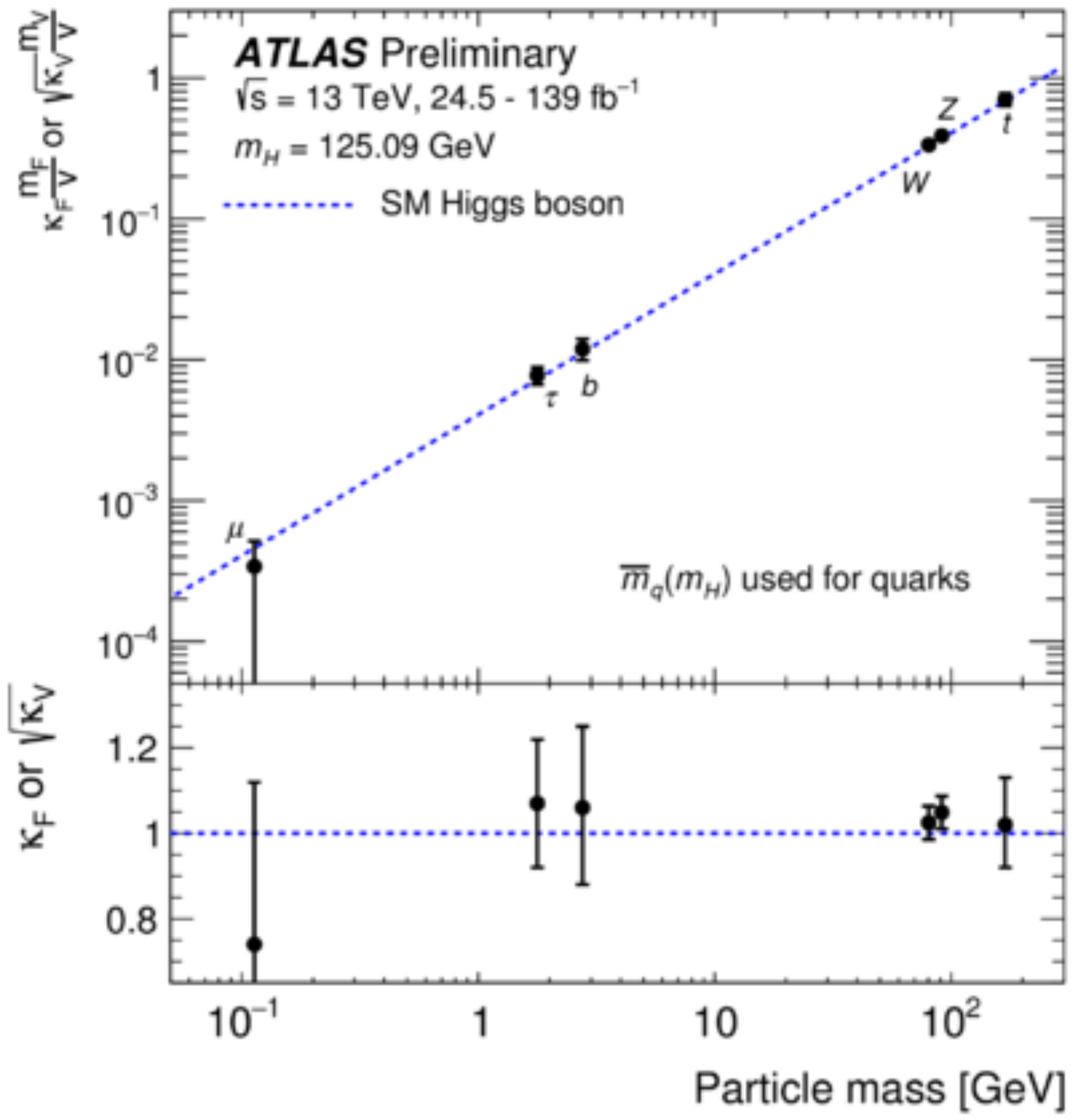
- Weath of decay channels for 125 GeV, rich phenomenology
- Very narrow!
- Diphoton and 4lepton final state are the cleanest signatures
- Hadronic channels are hard at the LHC because of the backgrounds, but accessible through boosted techniques!

Higgs measurements





Knowns and Unknowns



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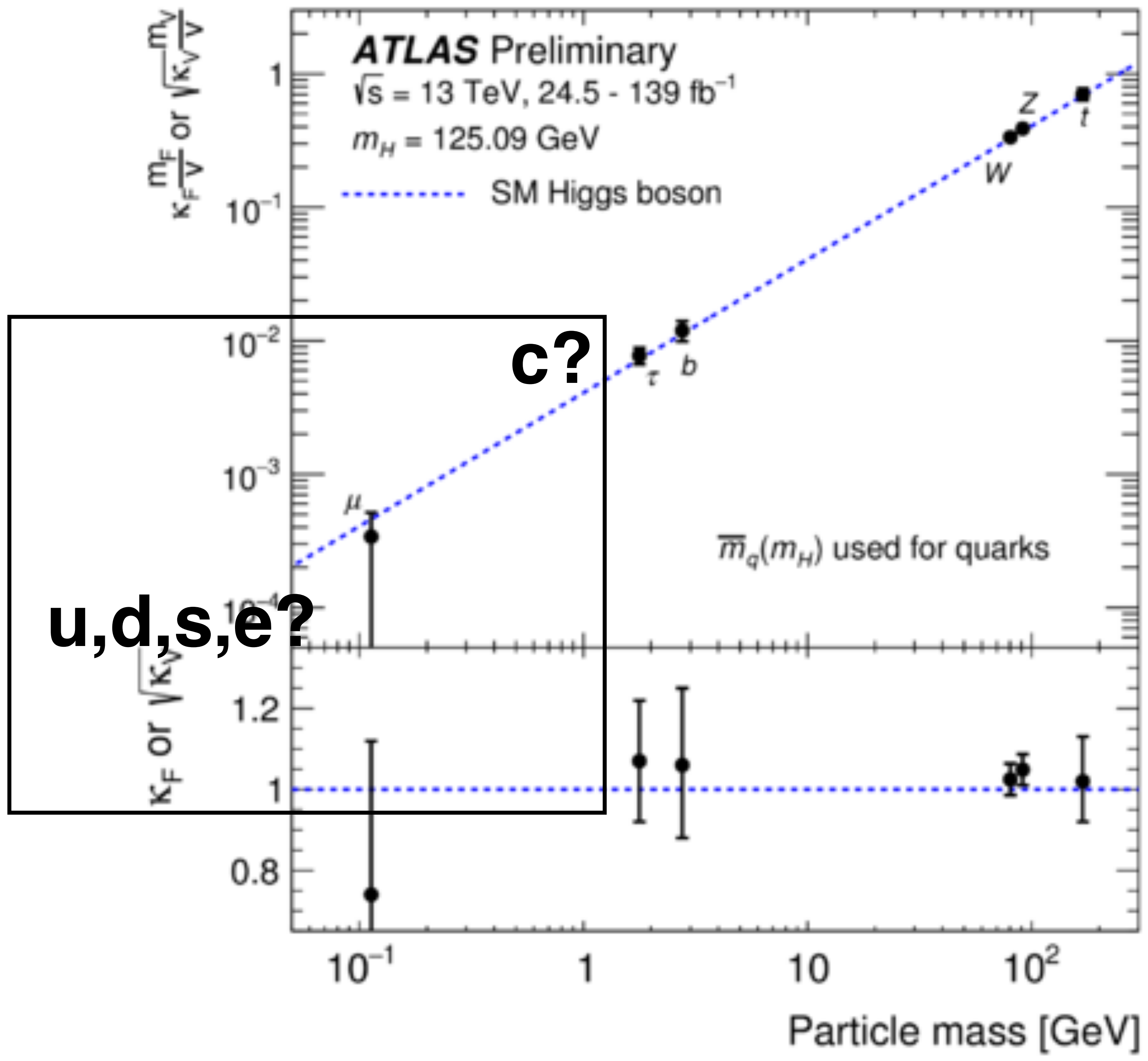

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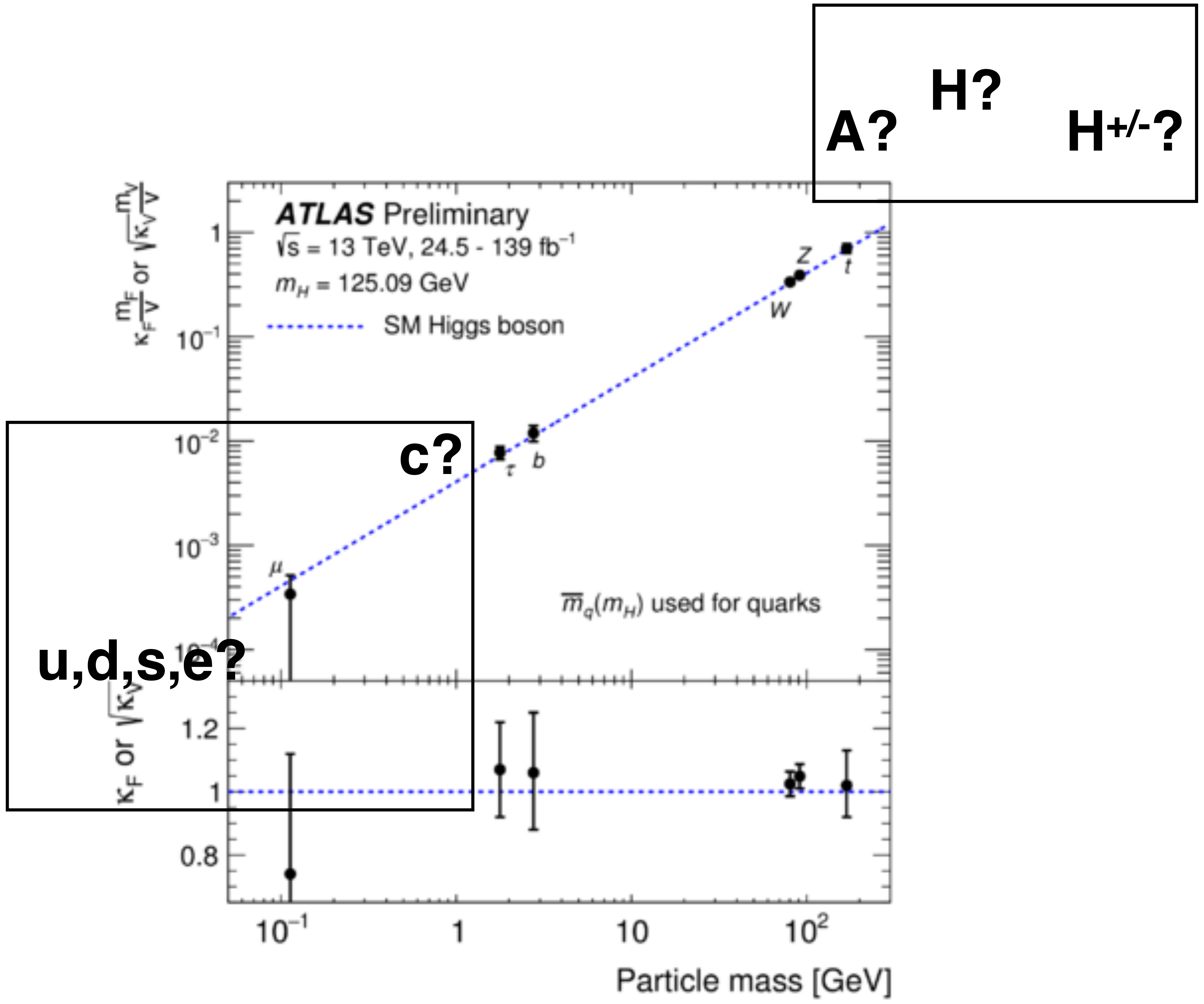

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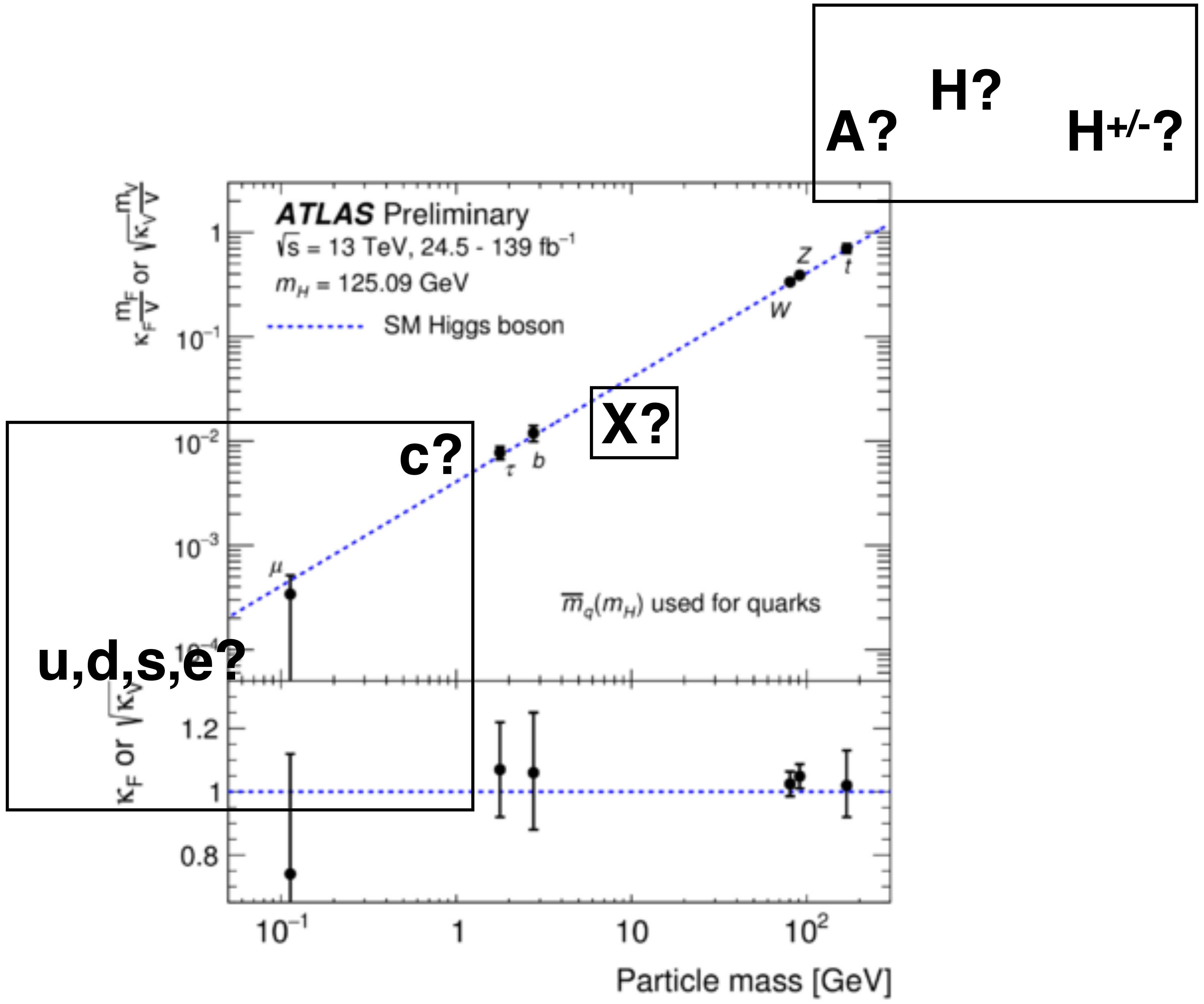

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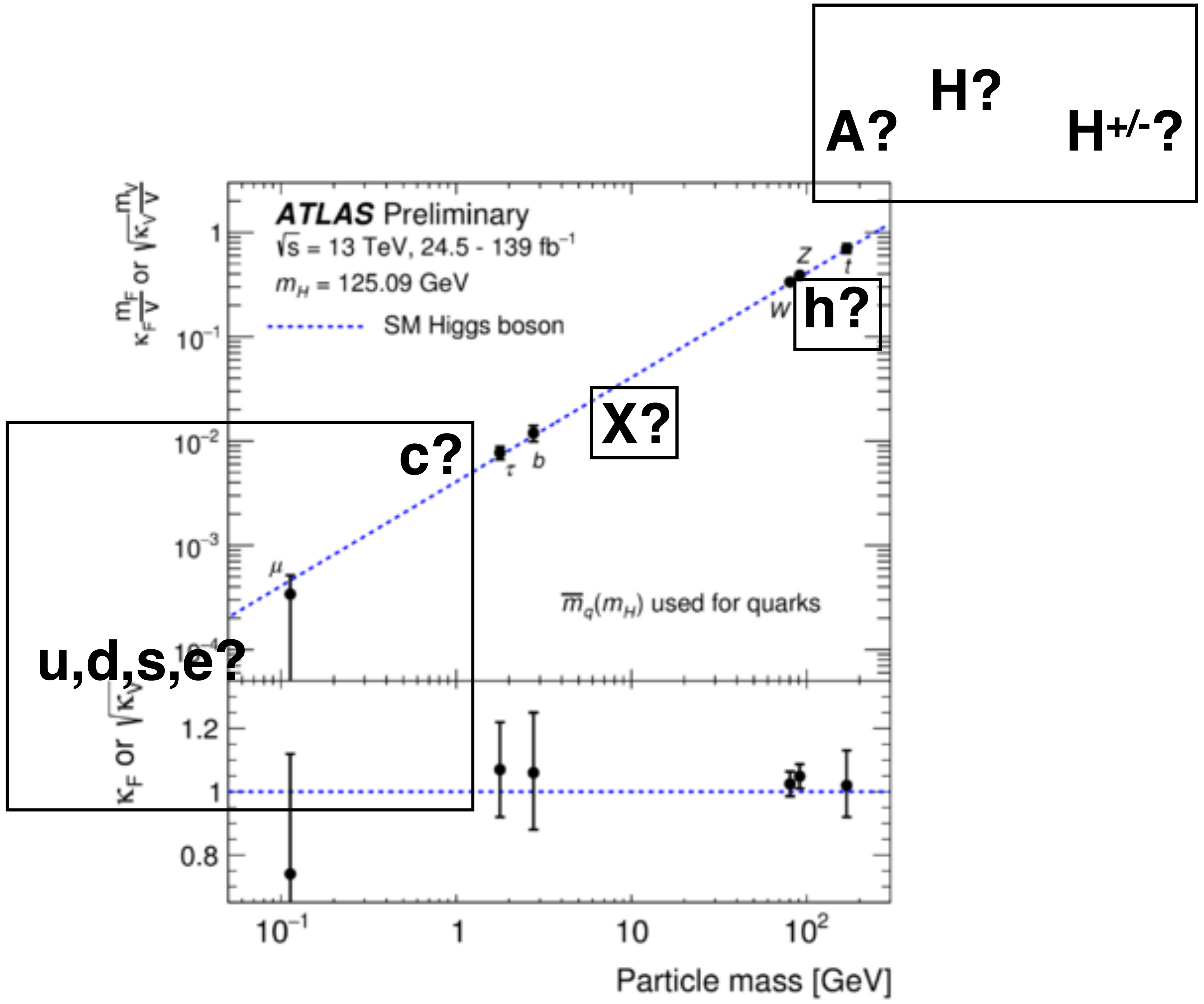

Higgs self-coupling

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

Fixed values in the SM: $$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

How do we measure it?

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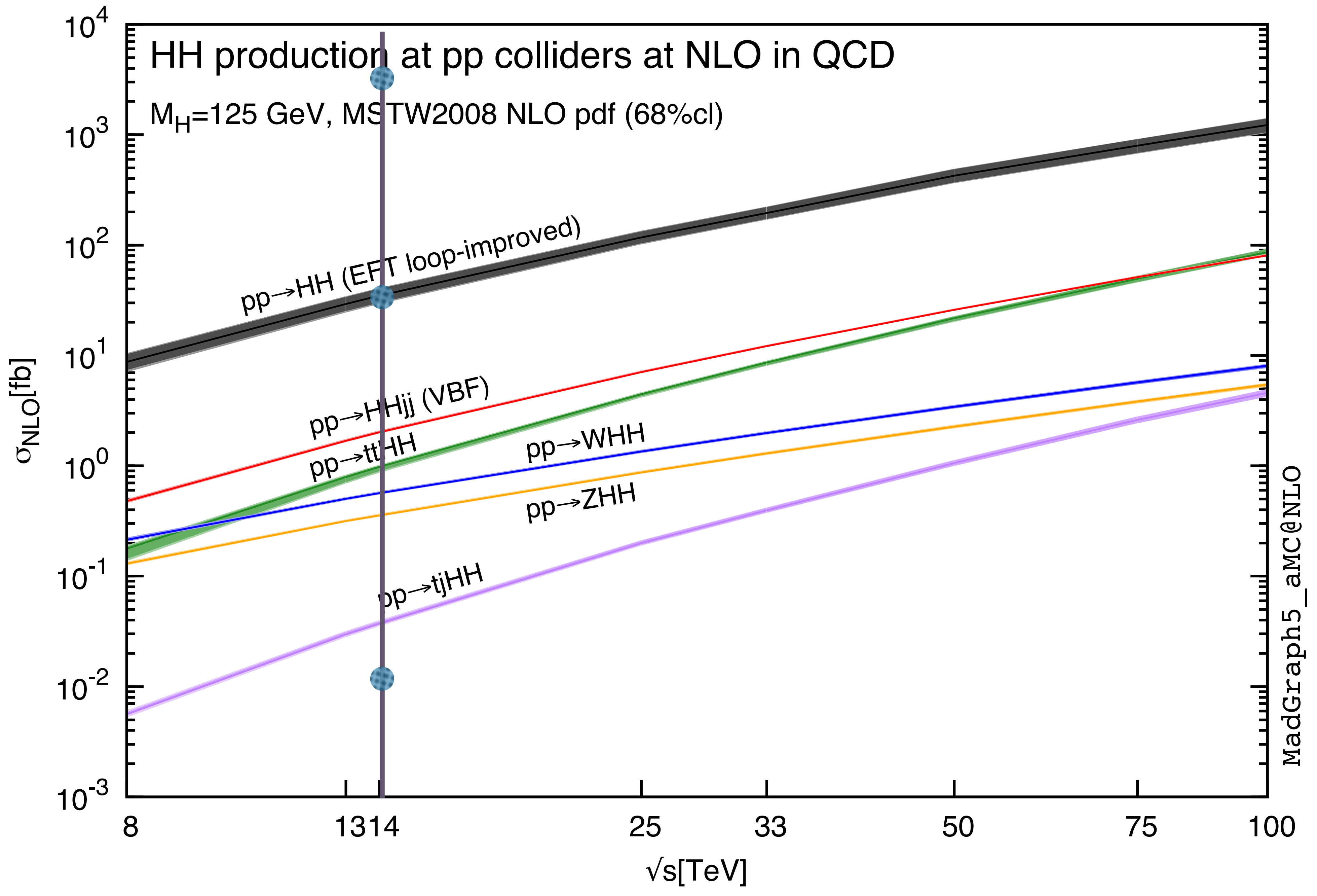
[Frederix et al. '14]

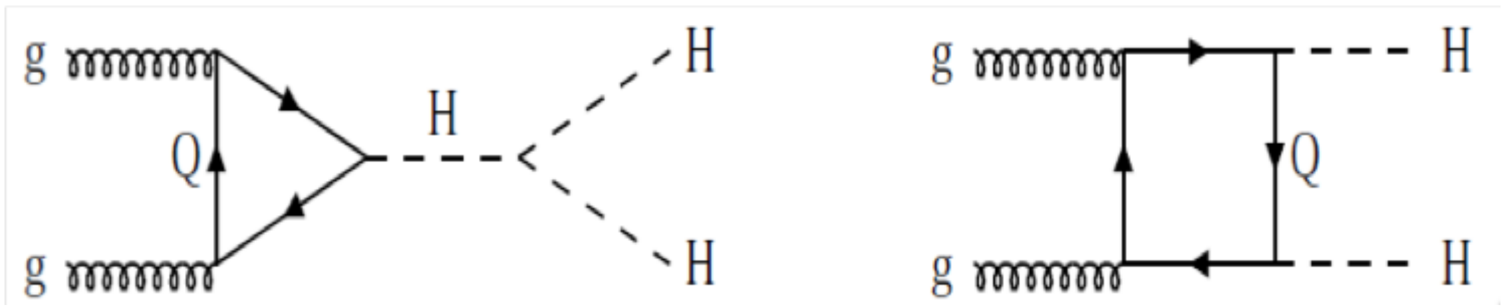


At 14 TeV from gg fusion:

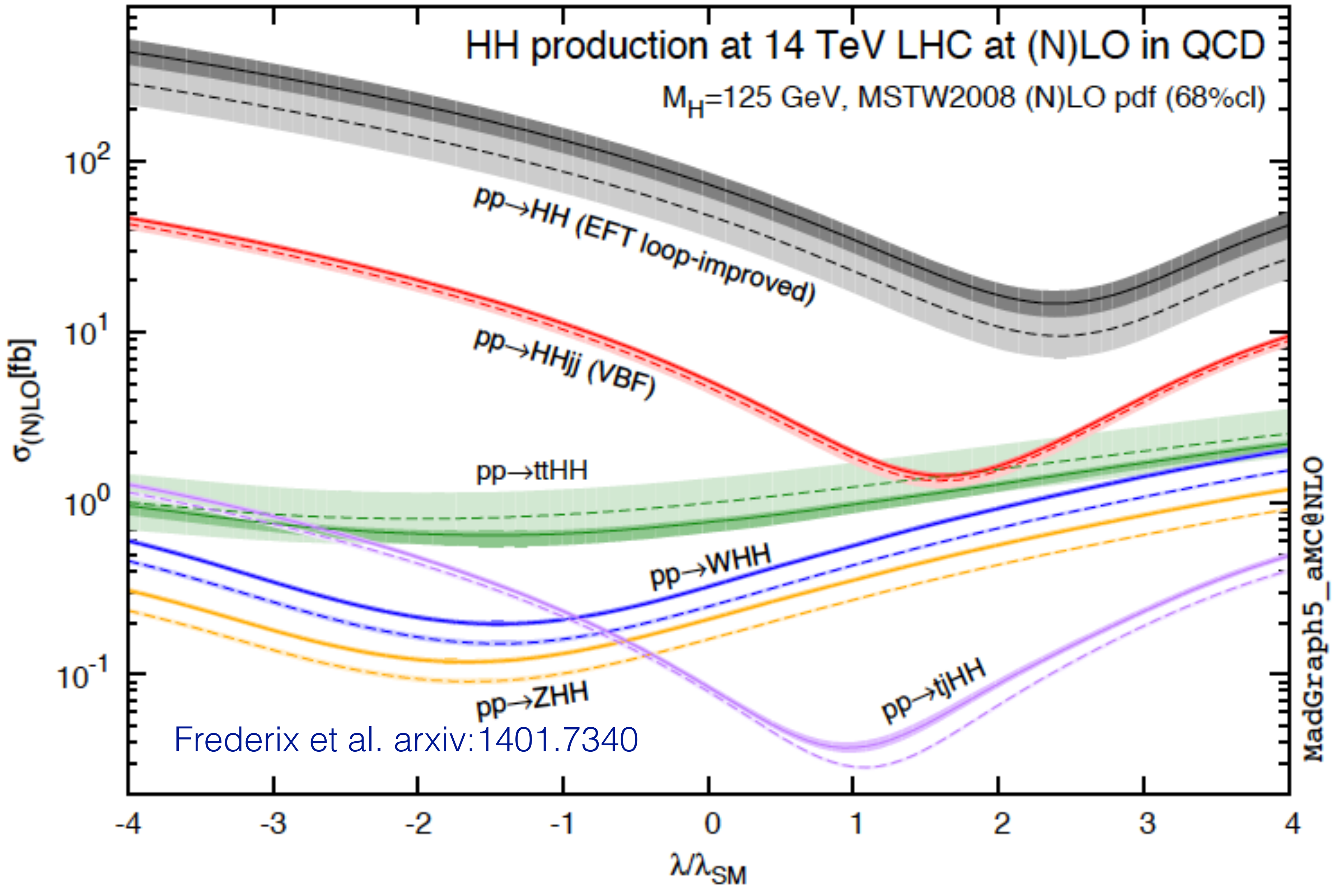
$$\sigma_H = 55 \text{ pb}$$

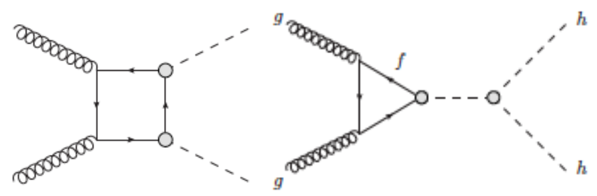
$$\sigma_{HH} = 44 \text{ fb}$$

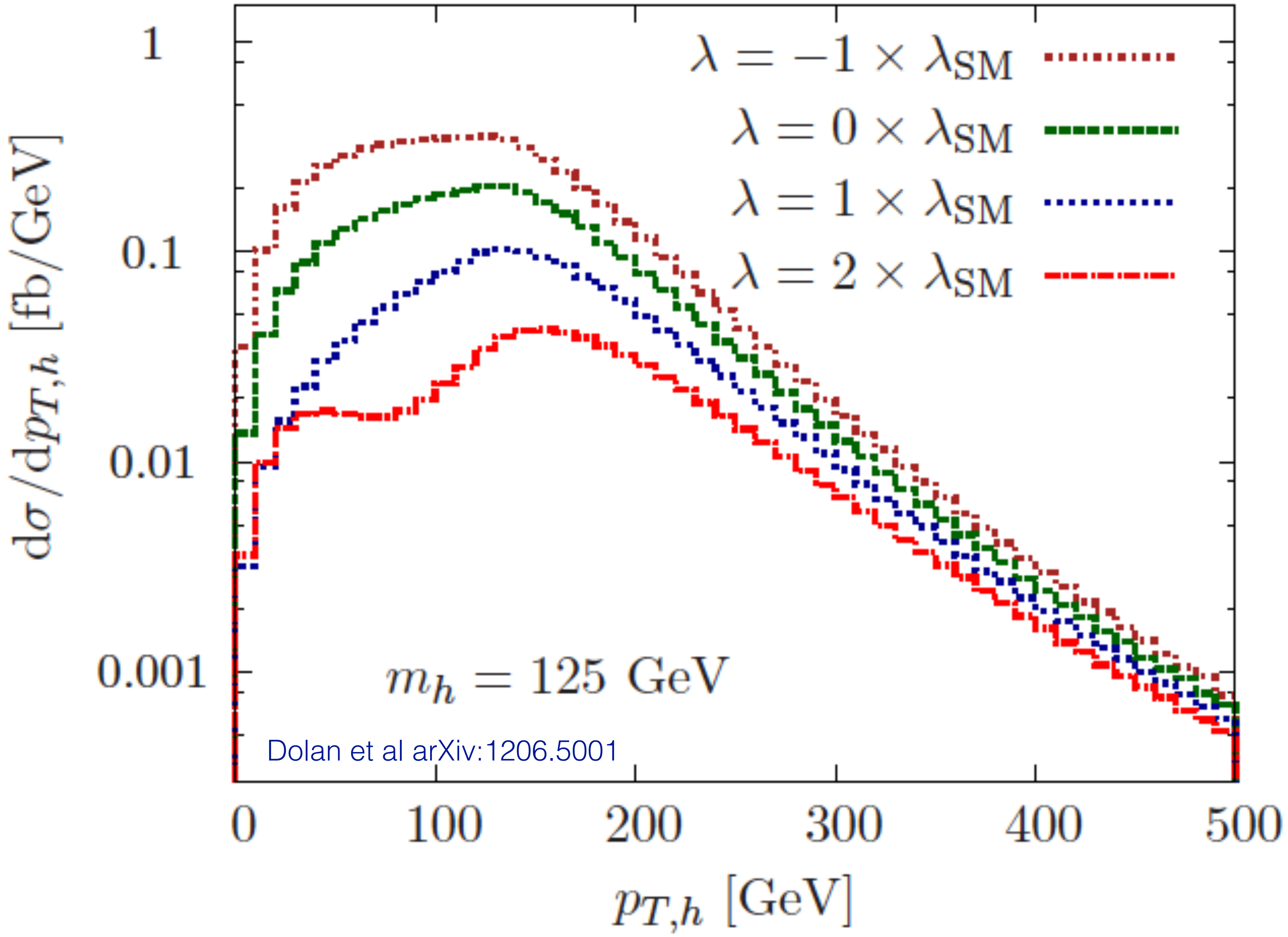
$$\sigma_{HHH} = 110 \text{ ab}$$



How to extract the Higgs self-coupling







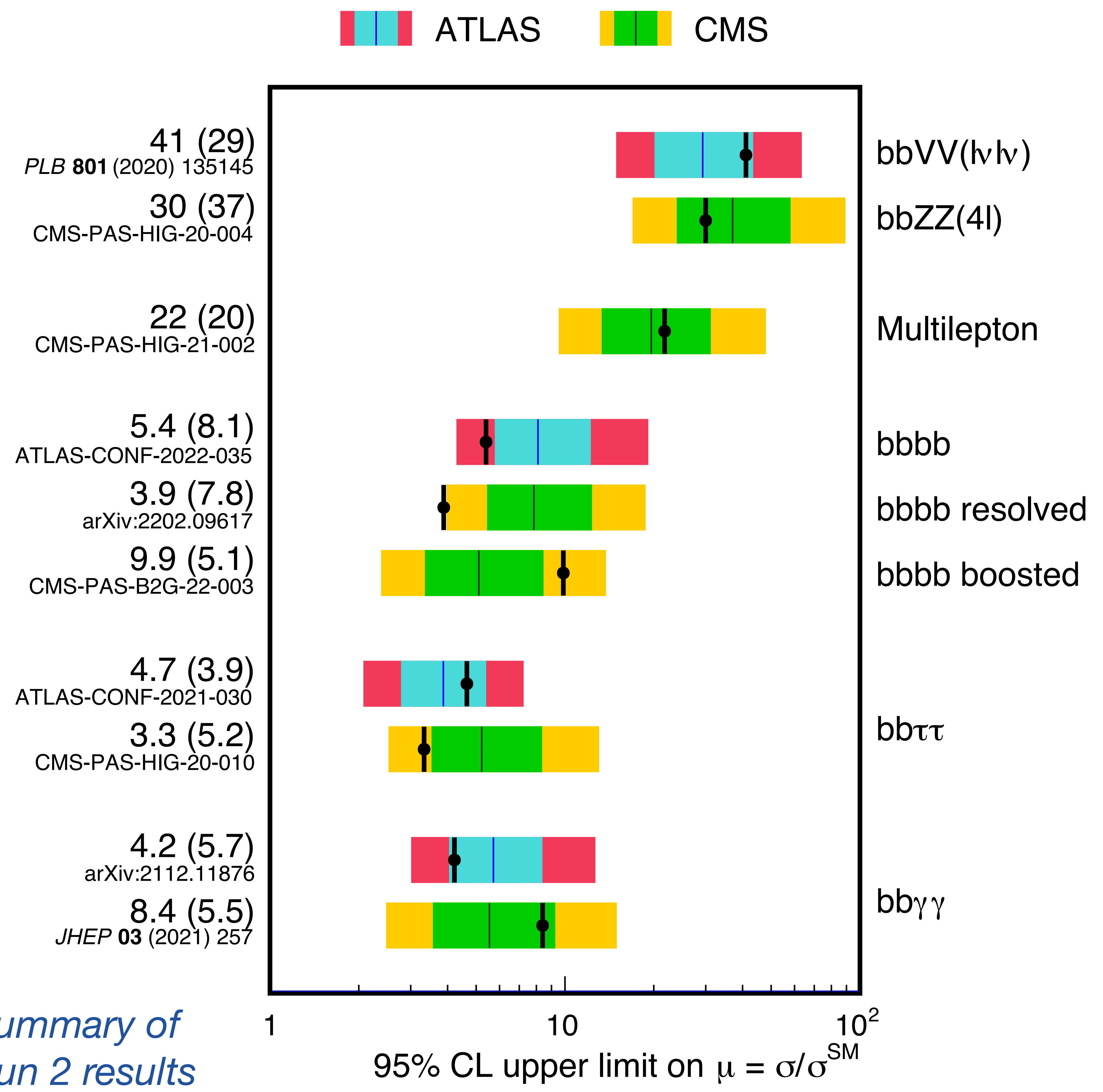
SM cross sections

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

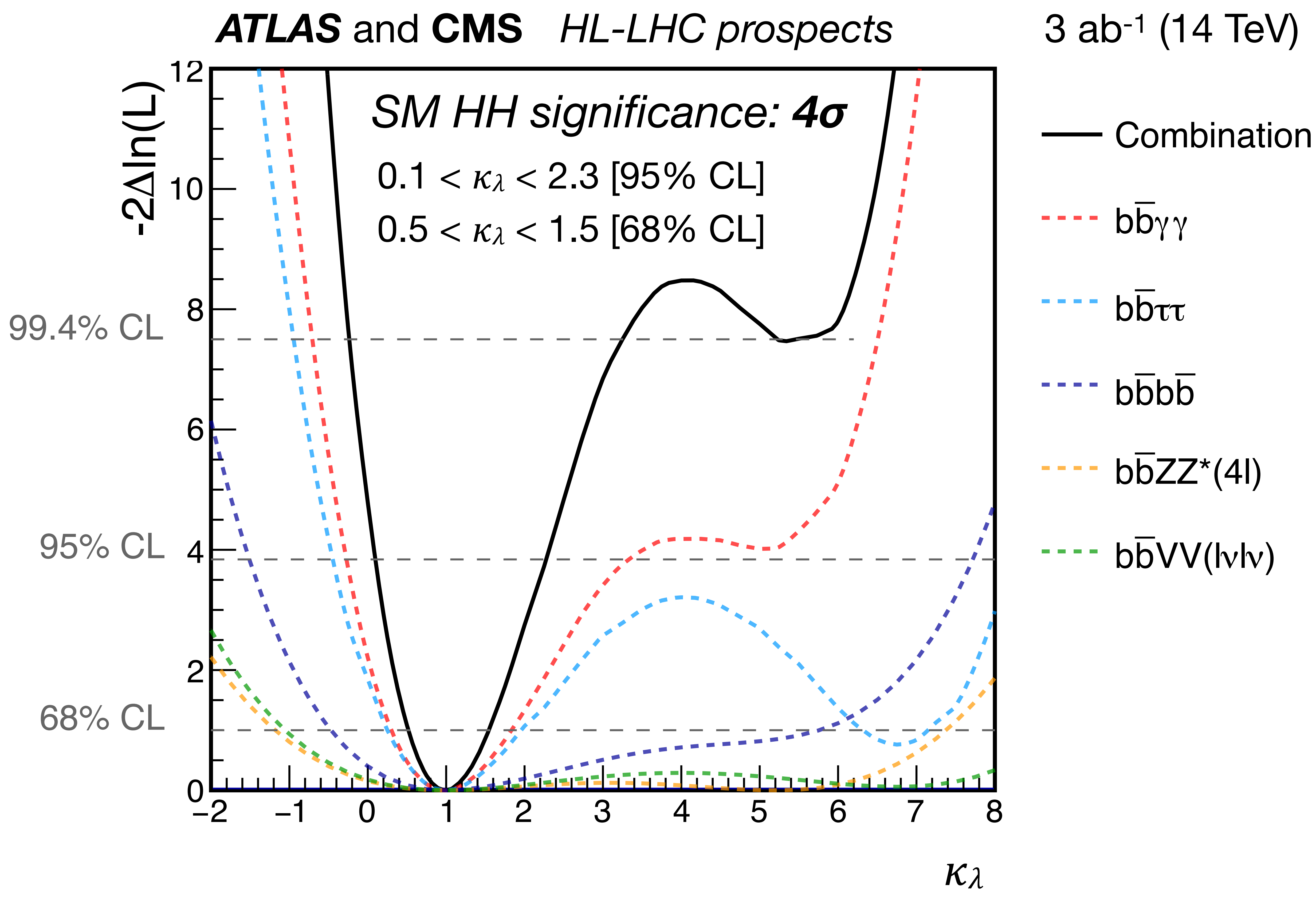
Grazzini et al arXiv:1803.02463

Need for differential information

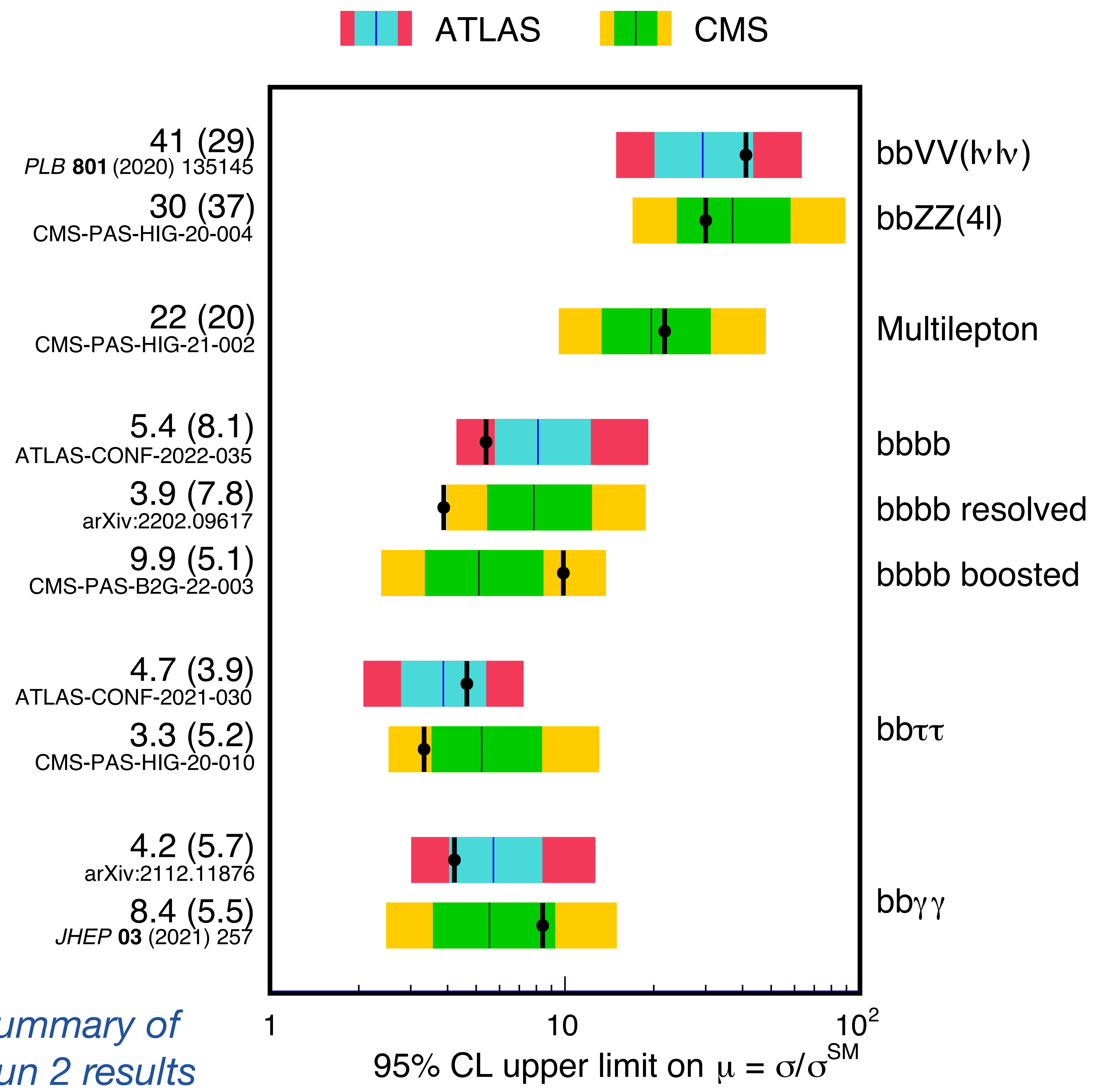
How to extract the Higgs self-coupling



Summary of Run 2 results



How to extract the Higgs self-coupling



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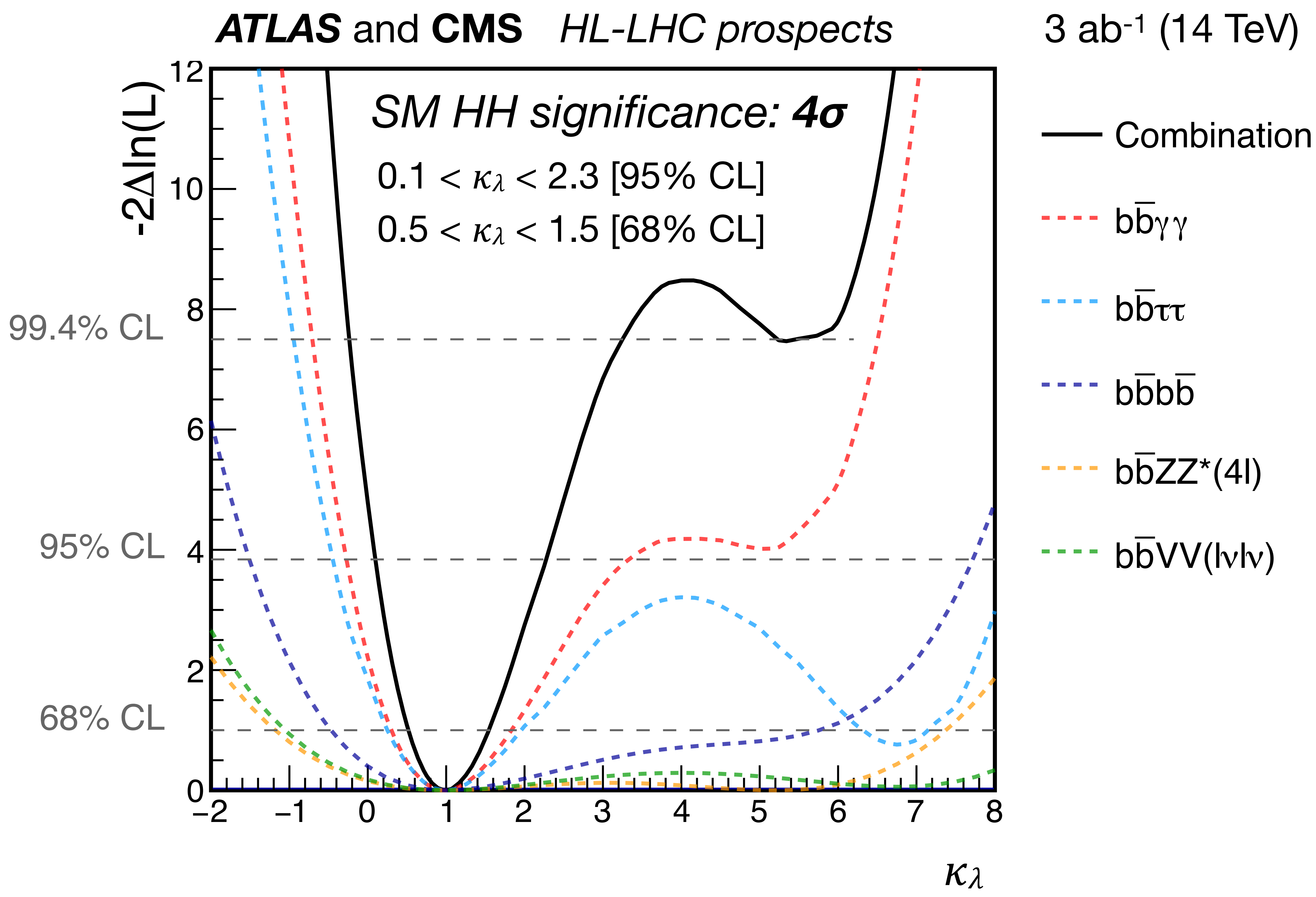


A challenge even for the HL-LHC

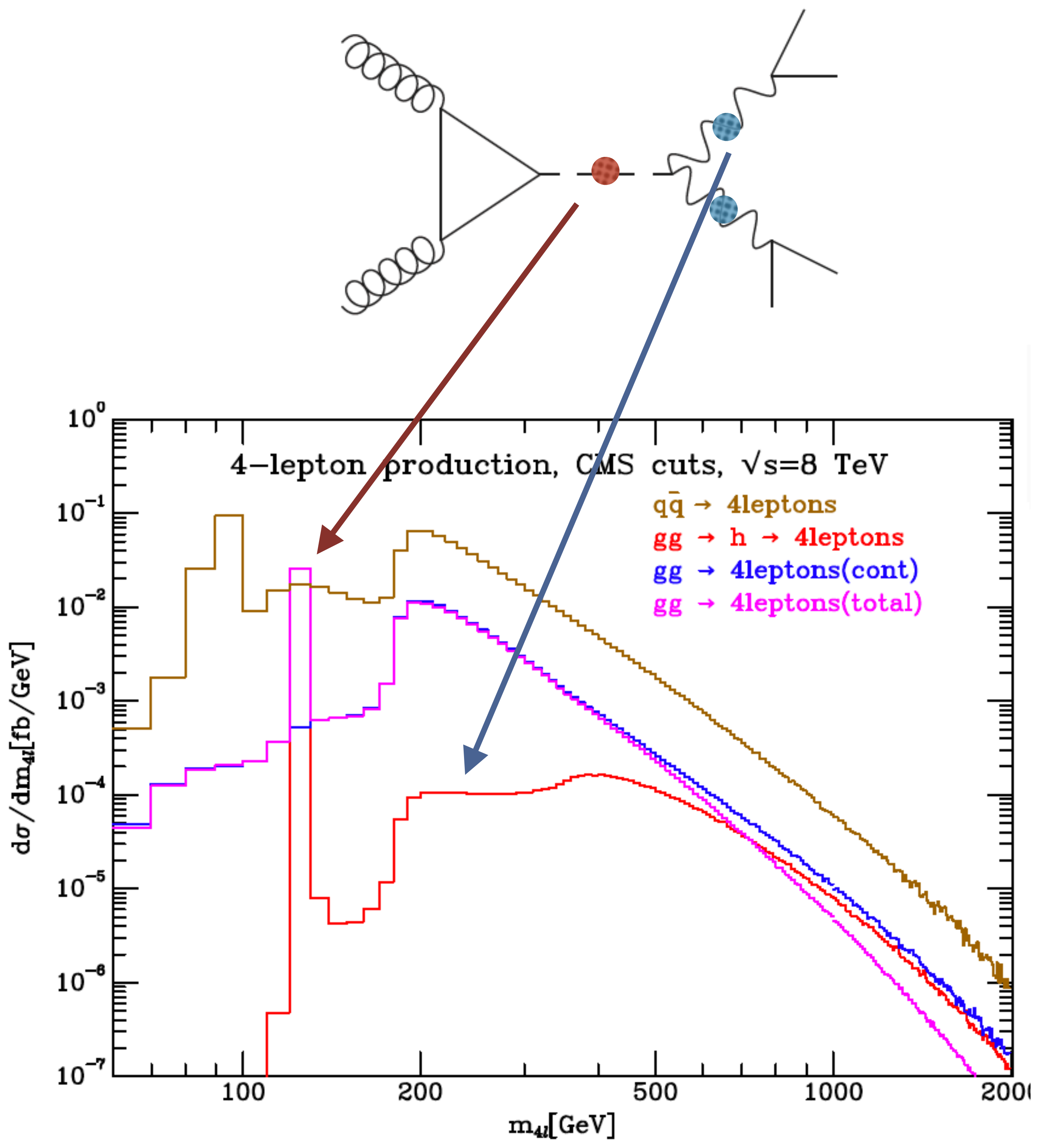
Higgs width

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

On-shell/Off-shell : gg→ZZ→4leptons

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

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



beware: model dependent

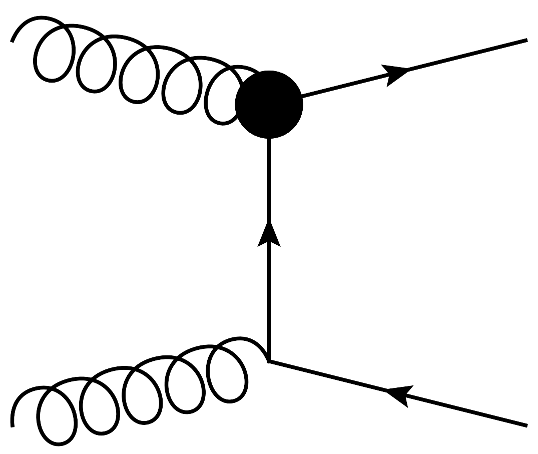
$$\sigma^{\text{above}} / \sigma^{\text{on-peak}} \sim \Gamma_H$$

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

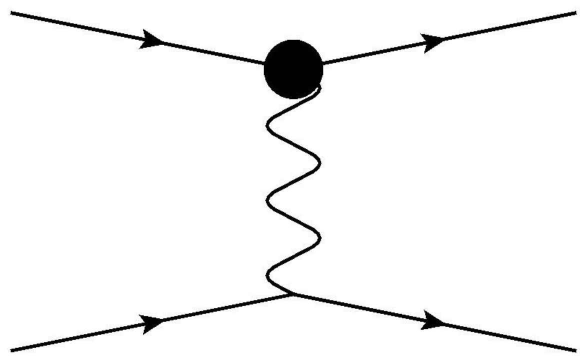
LHC is a top factory

Rich phenomenology:

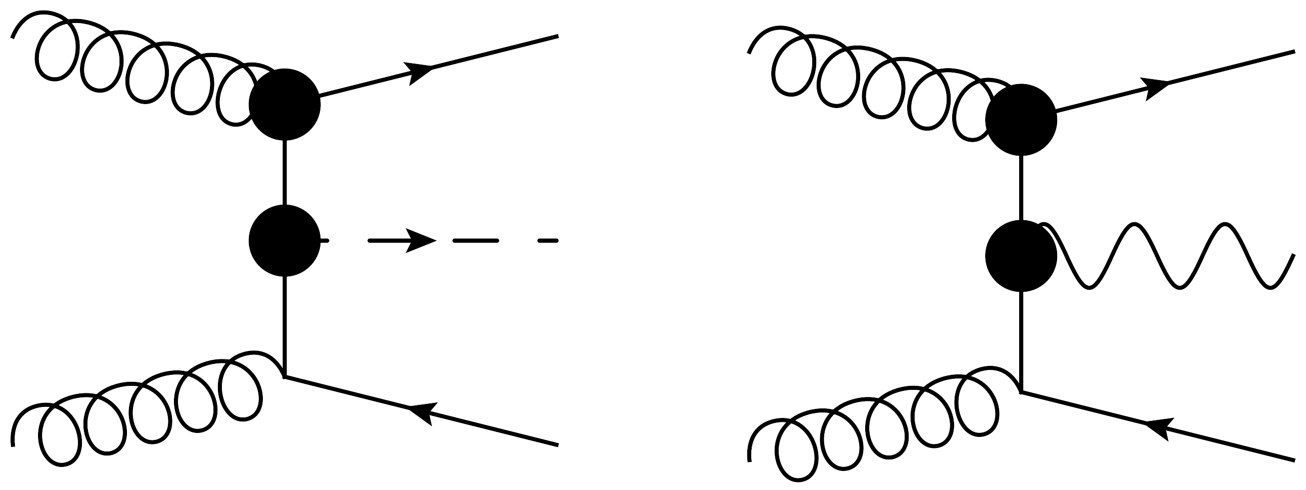
pair production



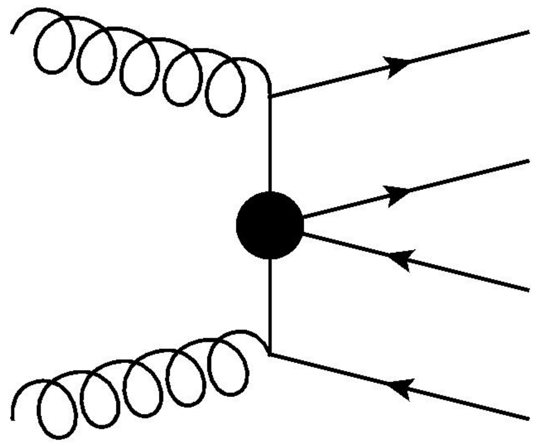
single



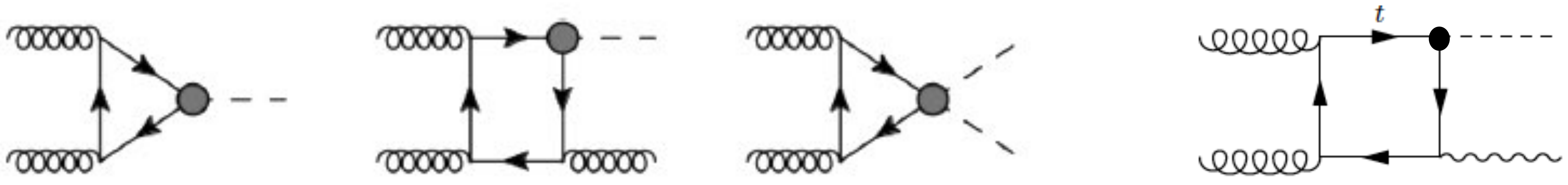
associated production



4 tops



top loops



connection to Higgs physics

Top physics

Why study the top quark ?

1. Heaviest known particle: Strong coupling to the Higgs

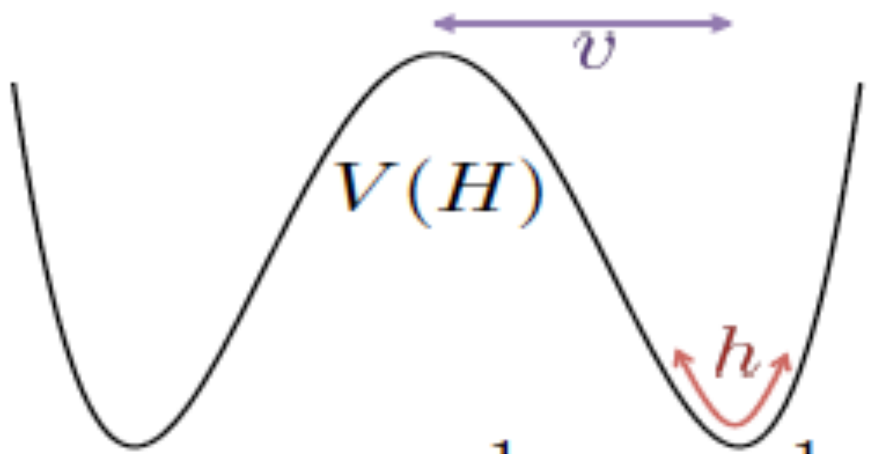
2. Portal to new physics: e.g. EWSB, composite Higgs

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

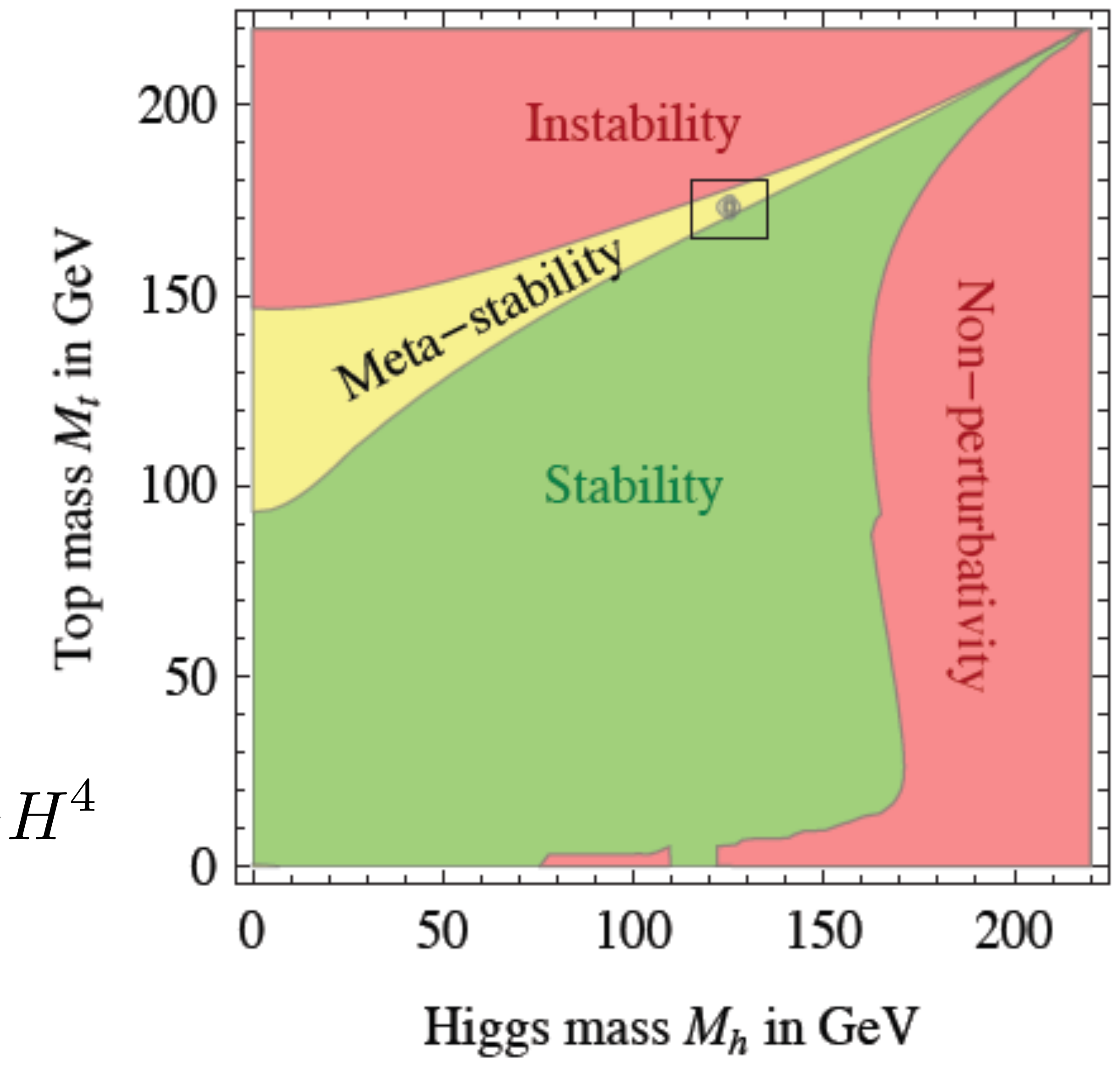
Top has a special place in the Universe

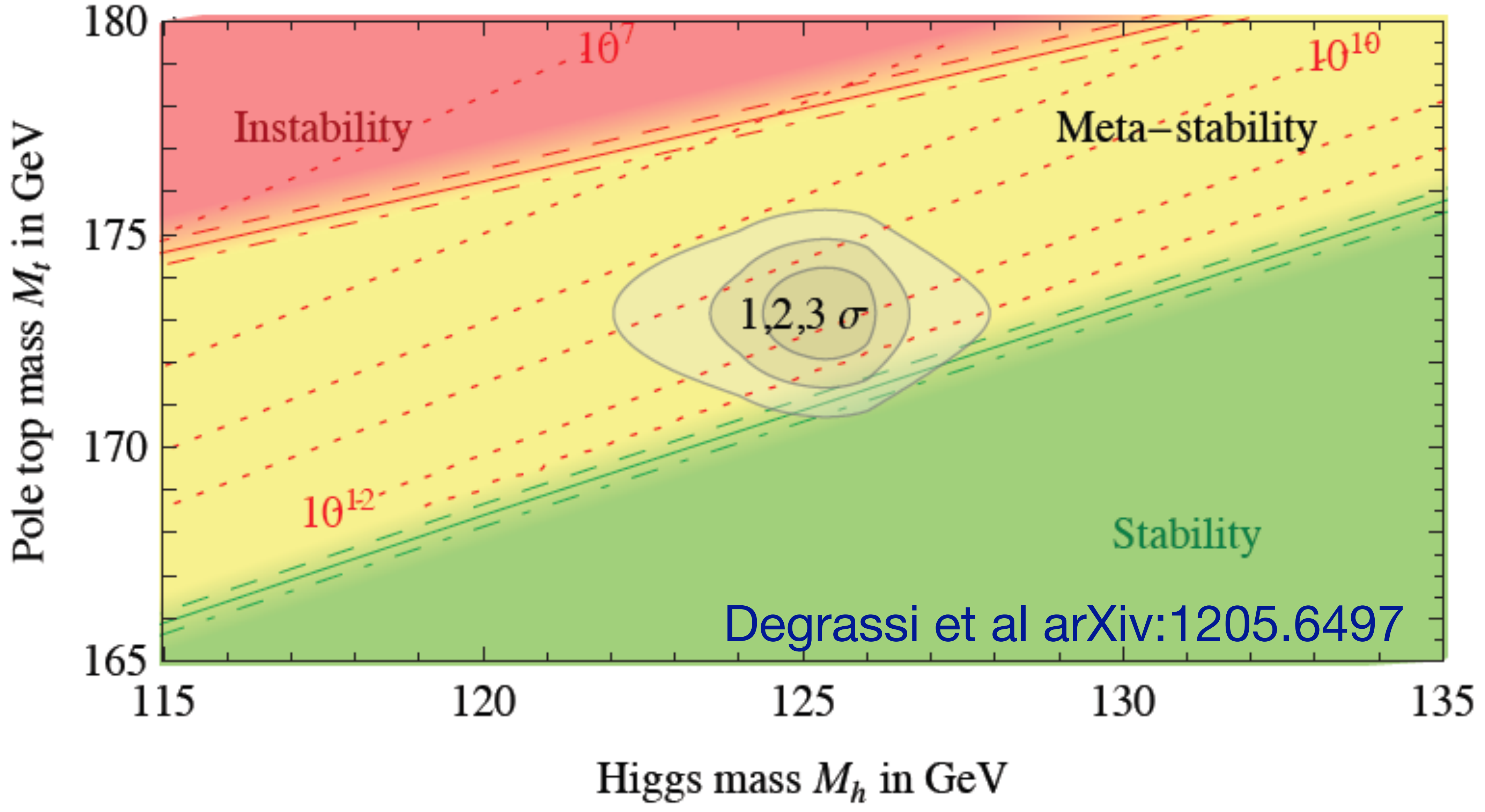
Stability of the vacuum

Higgs potential:



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





Degrassi et al arXiv:1205.6497

Need λ to be positive (and remain positive)!

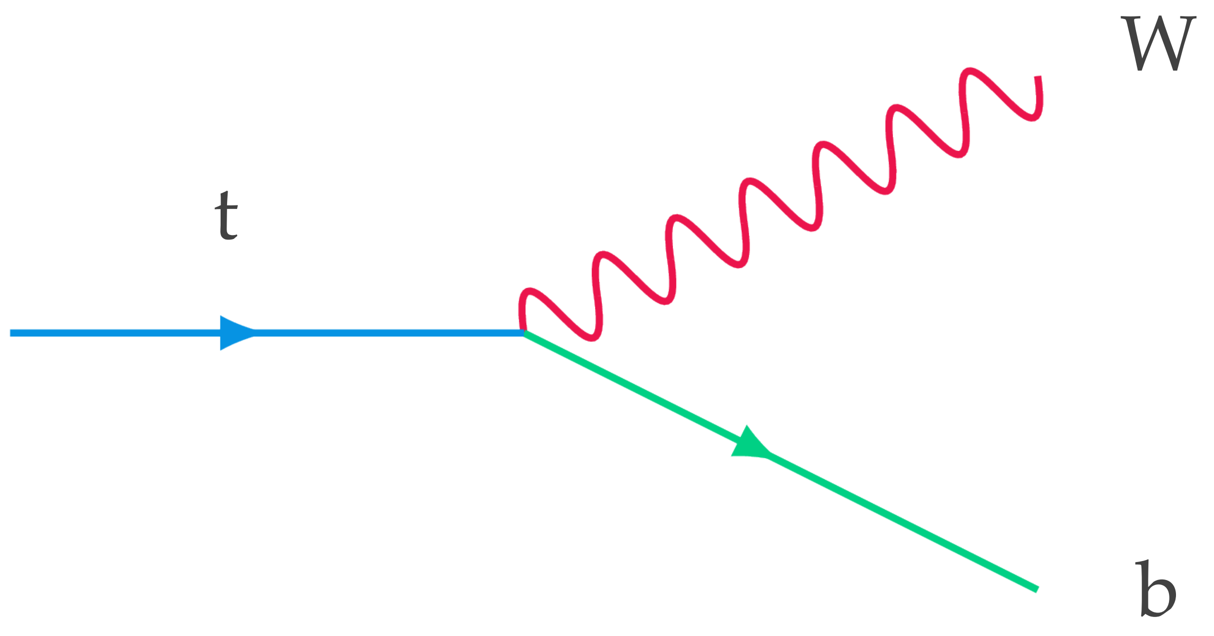
$$\frac{d\lambda(\mu)}{d\log\mu^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + \frac{3}{8}g^4 + \frac{3}{16}\left(g^2 + g'^2\right)^2 - 3h_t^4 - 3\lambda g^2 - \frac{3}{2}\lambda\left(g^2 + g'^2\right) + 6\lambda h_t^2\right] \qquad m_t = \frac{h_t v}{\sqrt{2}} \qquad m_H^2 = 2\lambda v^2$$

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

Top quark is a special quark

Spin Correlations

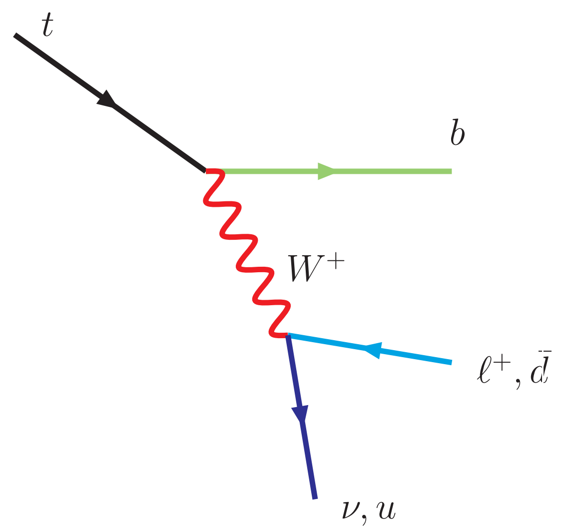
The top decays before hadronising



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

Spin information is preserved!

Top Spin effects



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

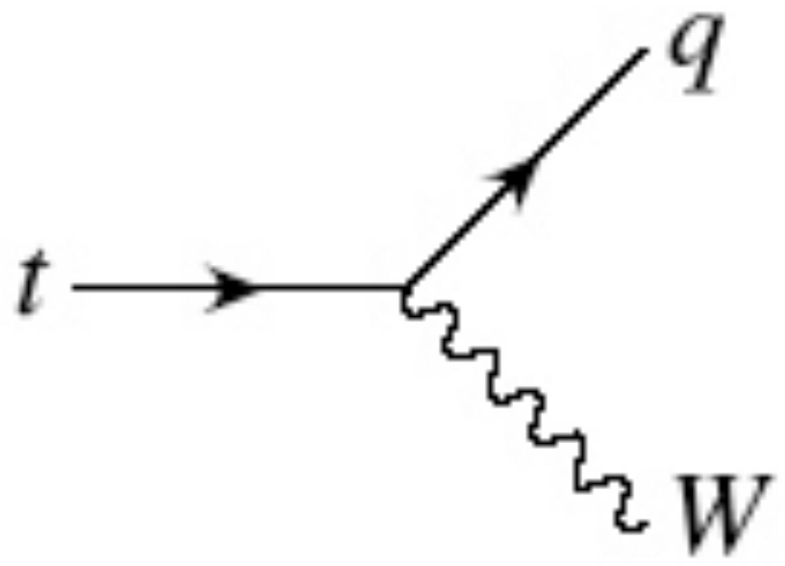
k_i	ℓ^+	$\bar{d}$	u	b
LO:	1	1	-0.32	-0.39
NLO:	0.999	0.97	-0.31	-0.37

Lepton+ or d emitted in the top spin direction

Spin analysing power

We can check how the top is produced!

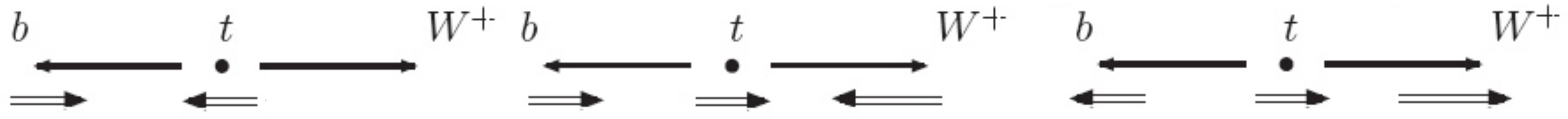
Weak interaction and W polarisation



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

Only left-handed tops in the decay!

Helicities of W bosons

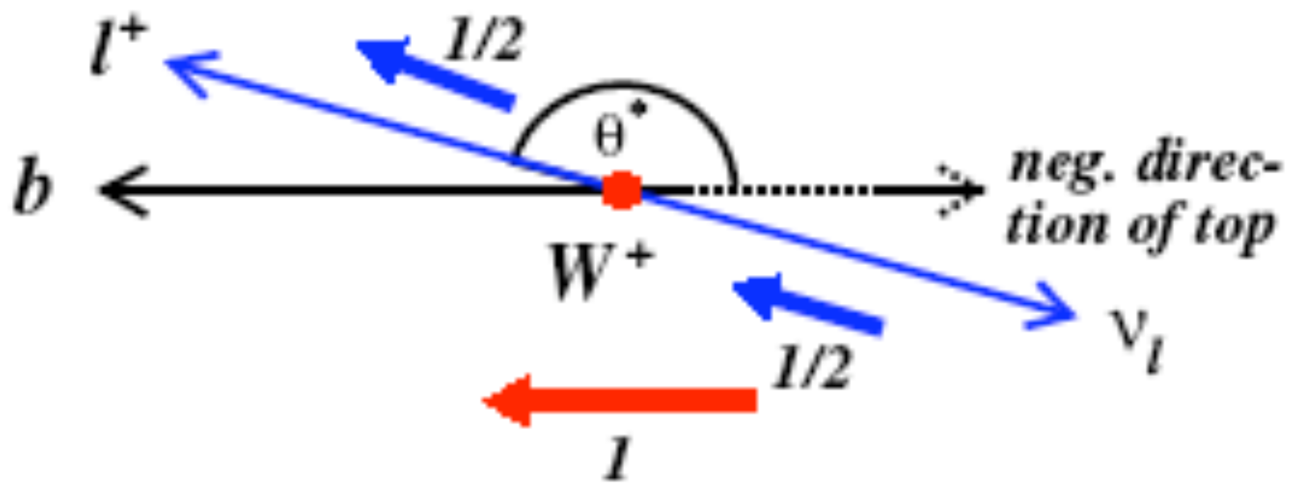


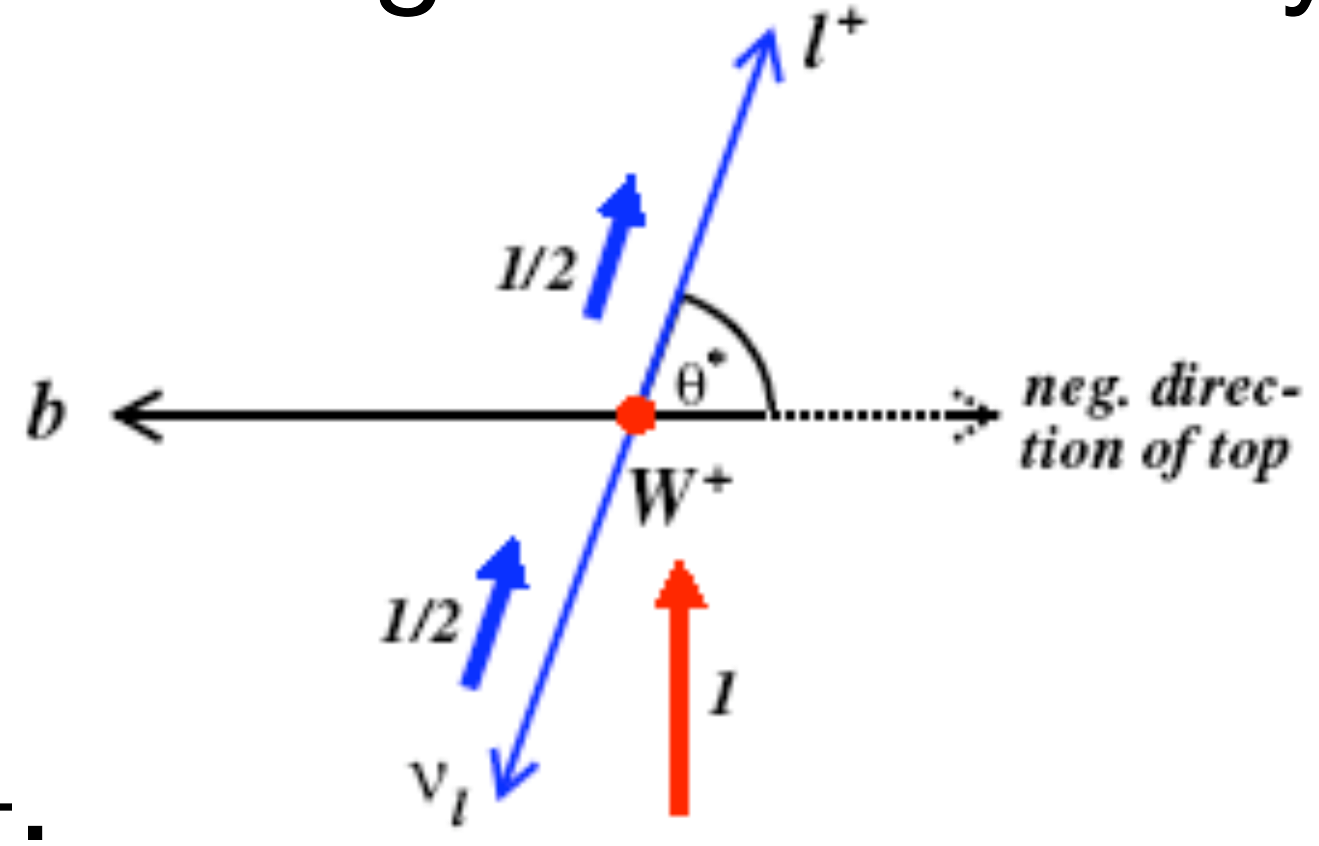
longitudinal left-handed right-handed

? ? ?

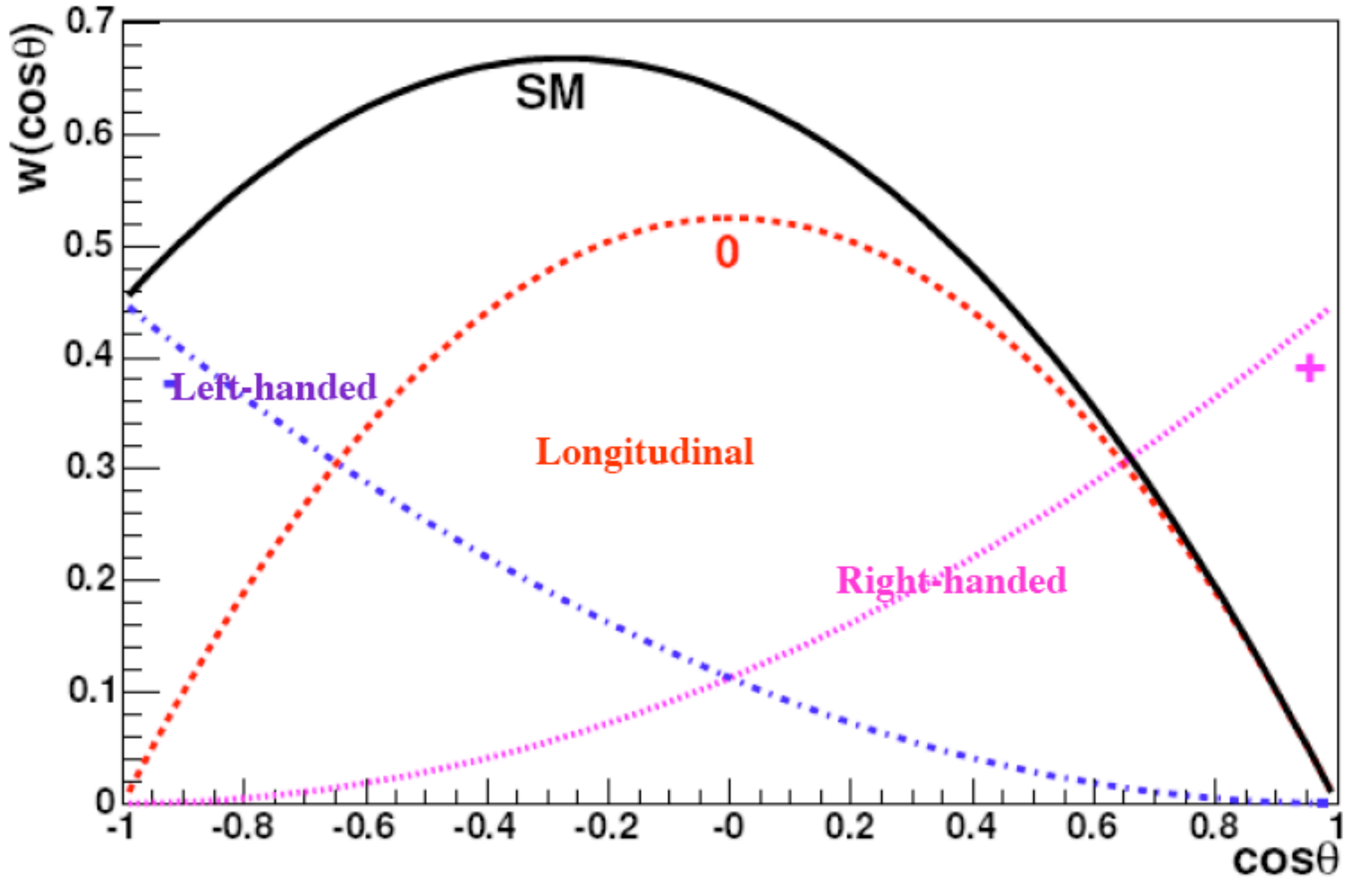
Weak interaction and W polarisation

Extract W polarisation by looking at the W decay products:





Angular distribution of l^+:

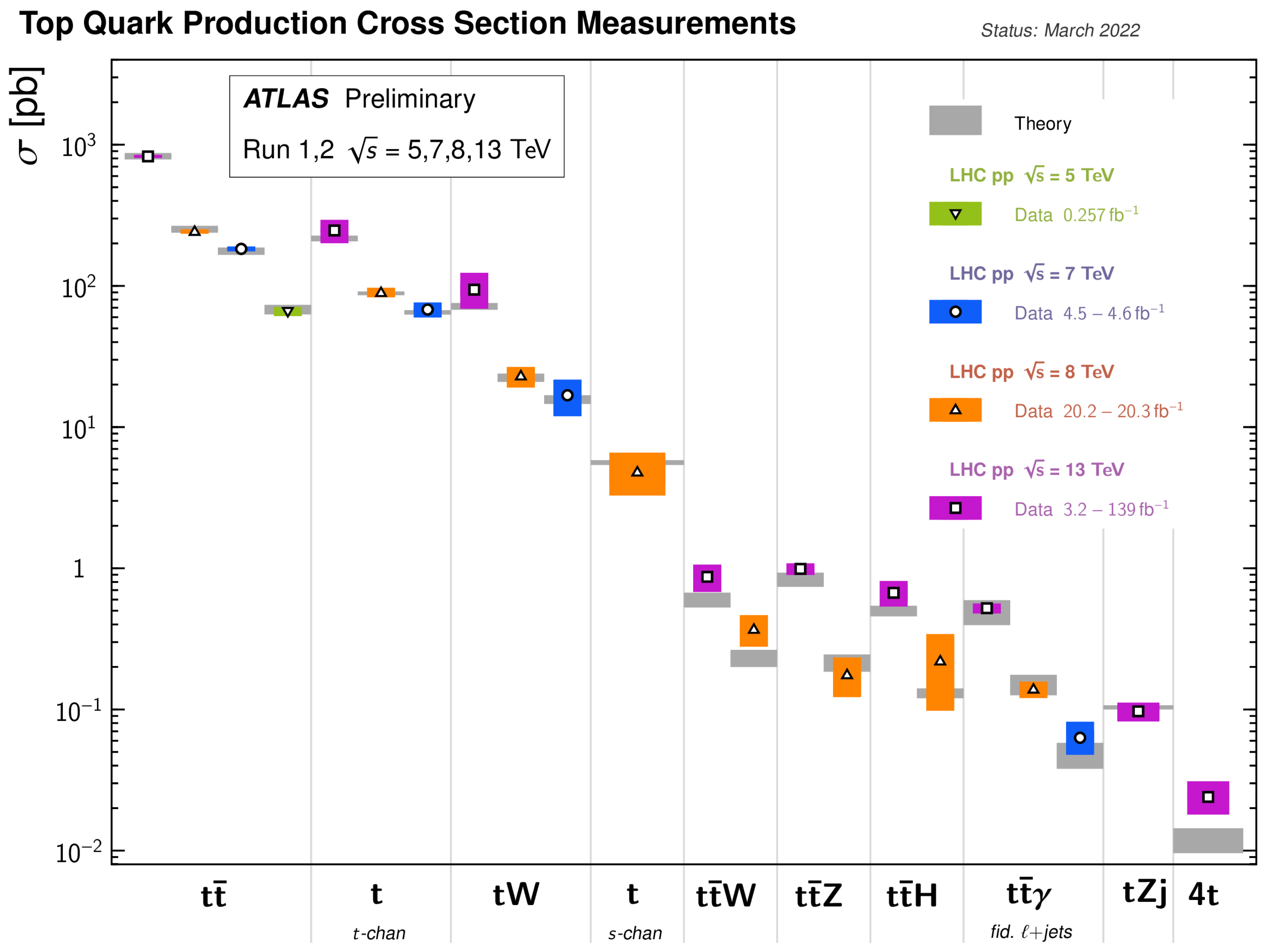


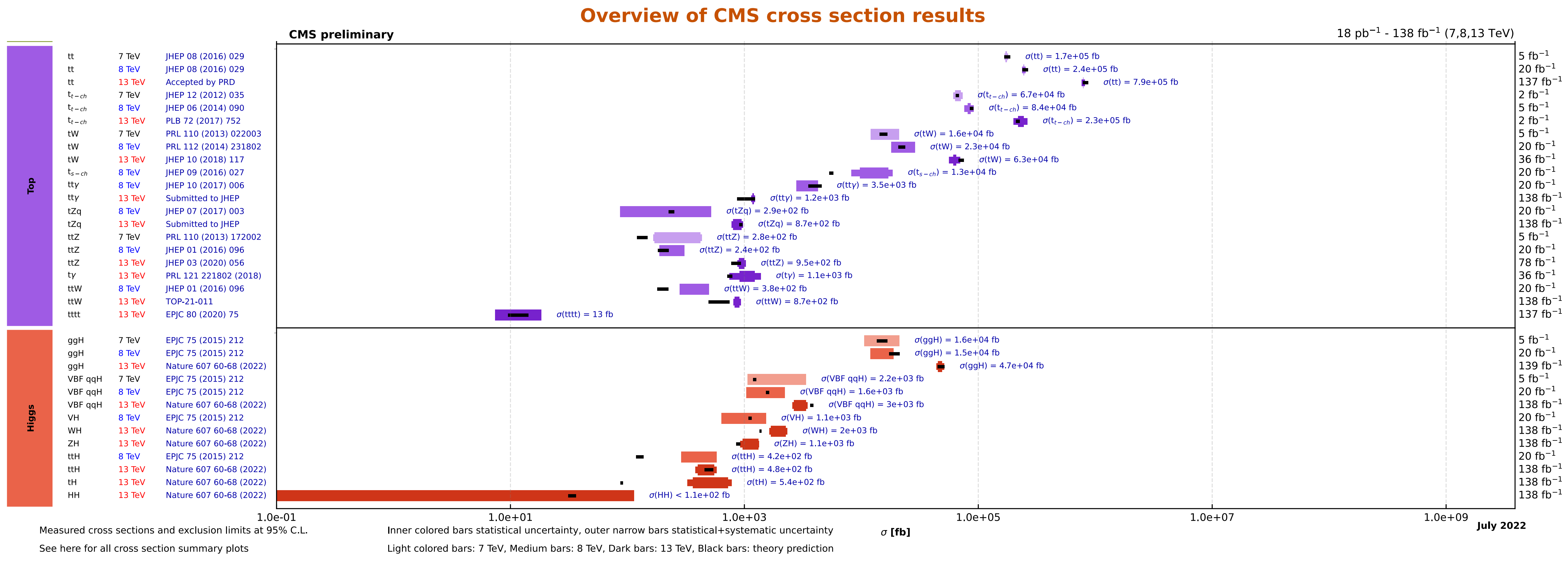
$$\frac{1}{N}\frac{dN(W\to l\nu)}{dcos\theta} = K\left[f_0\sin^2\theta + f_L(1-\cos\theta)^2 + f_R(1+\cos\theta)^2\right]$$

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

Check of Wtb interaction!

Status of top measurements





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

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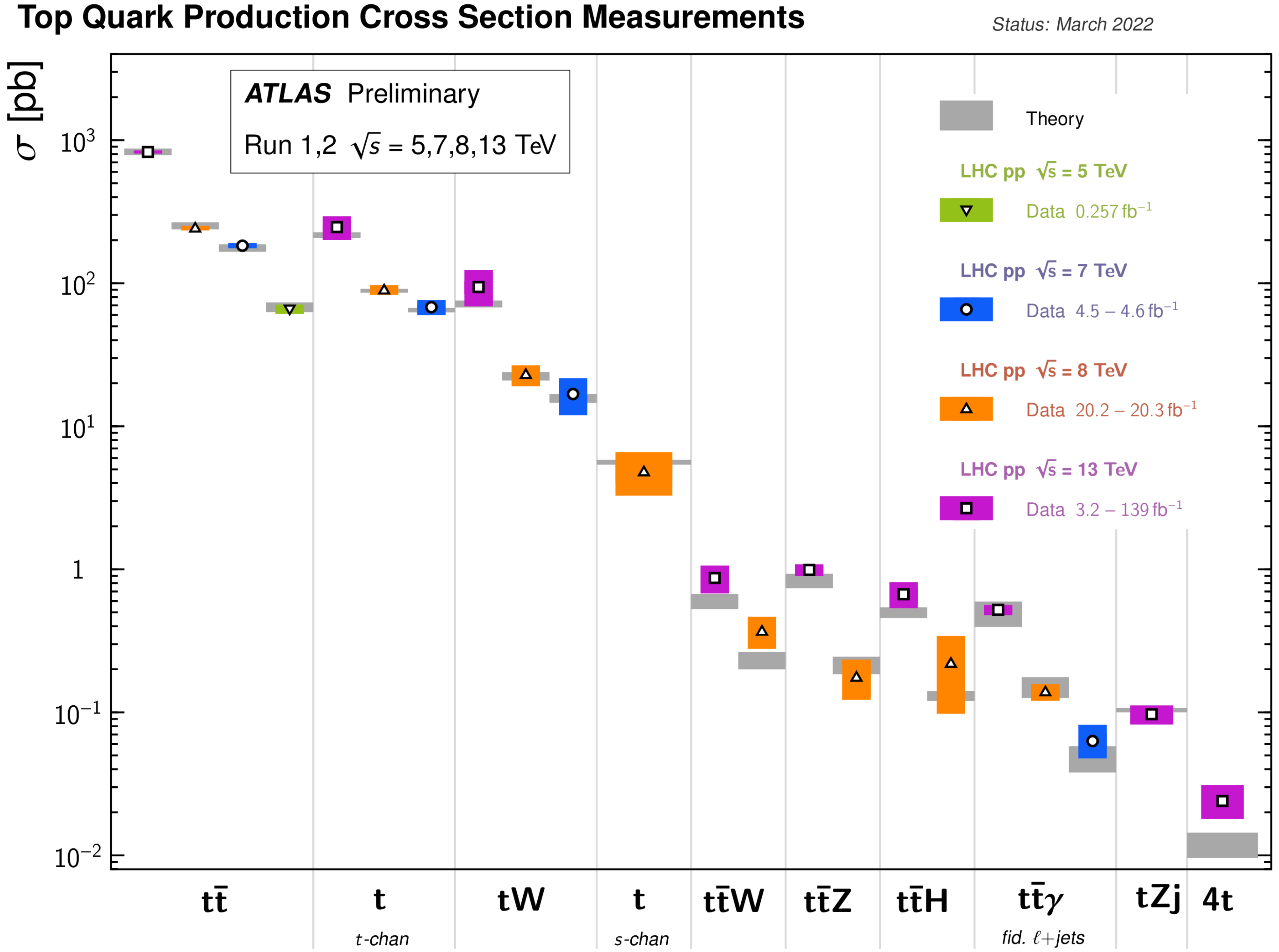

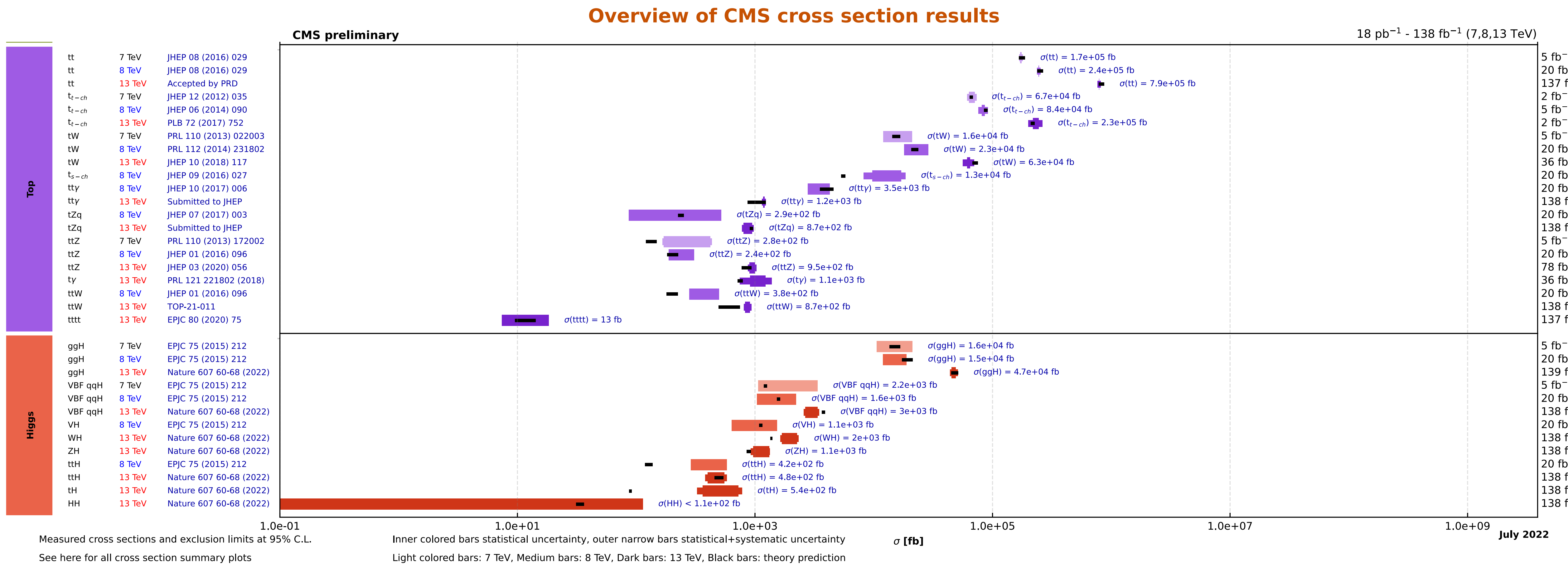

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Very precise measurements!

In some cases:

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