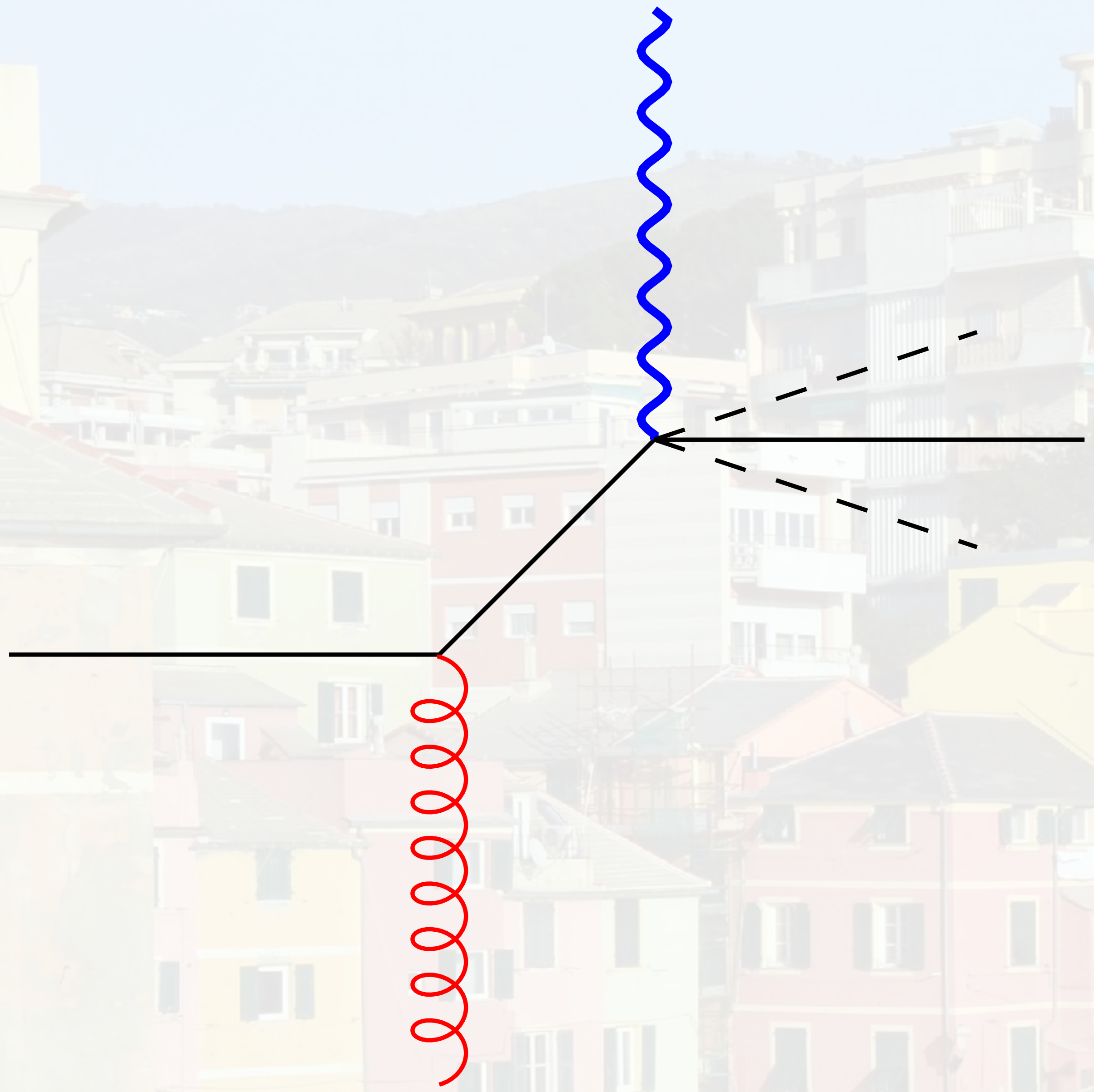
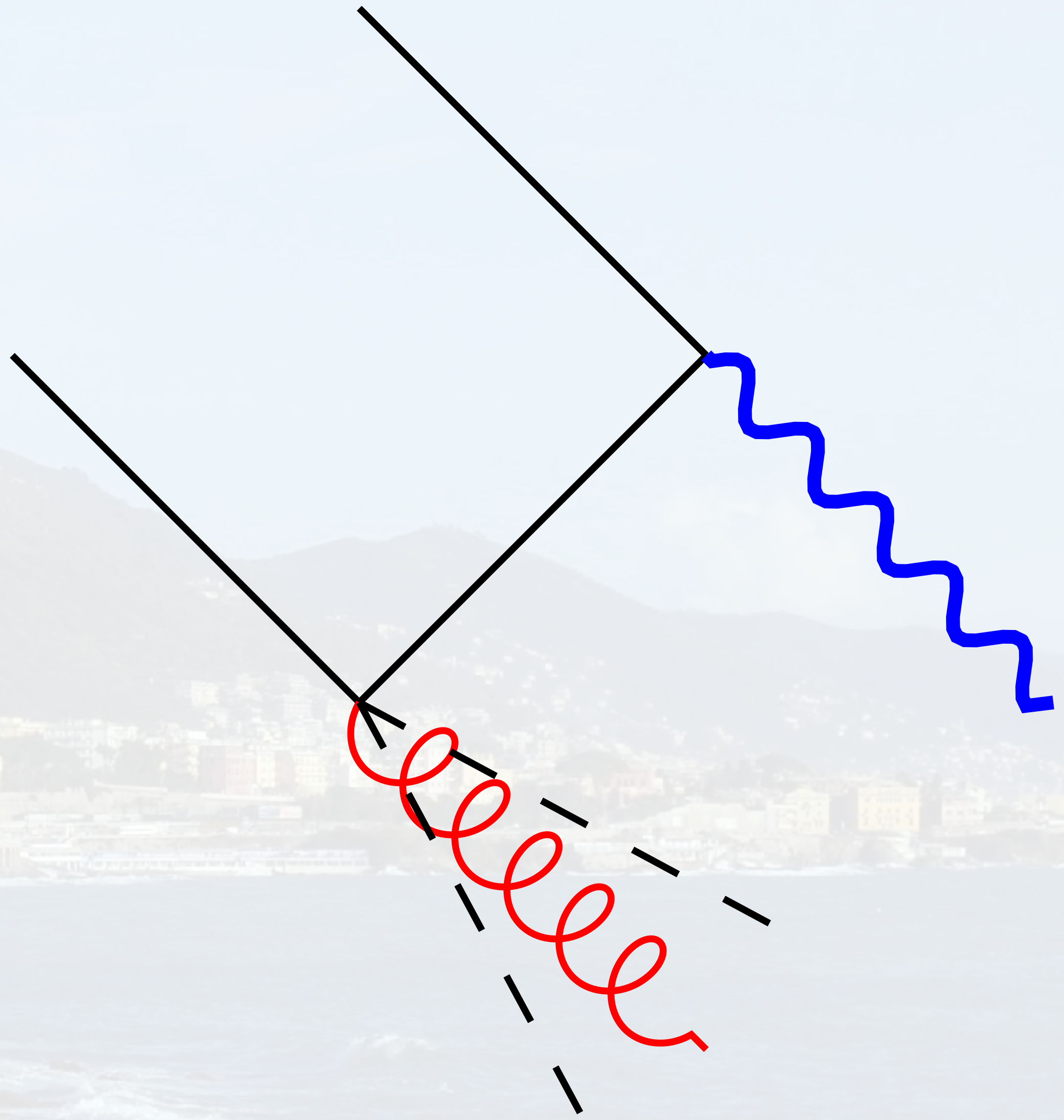
Precise predictions for V+jet production

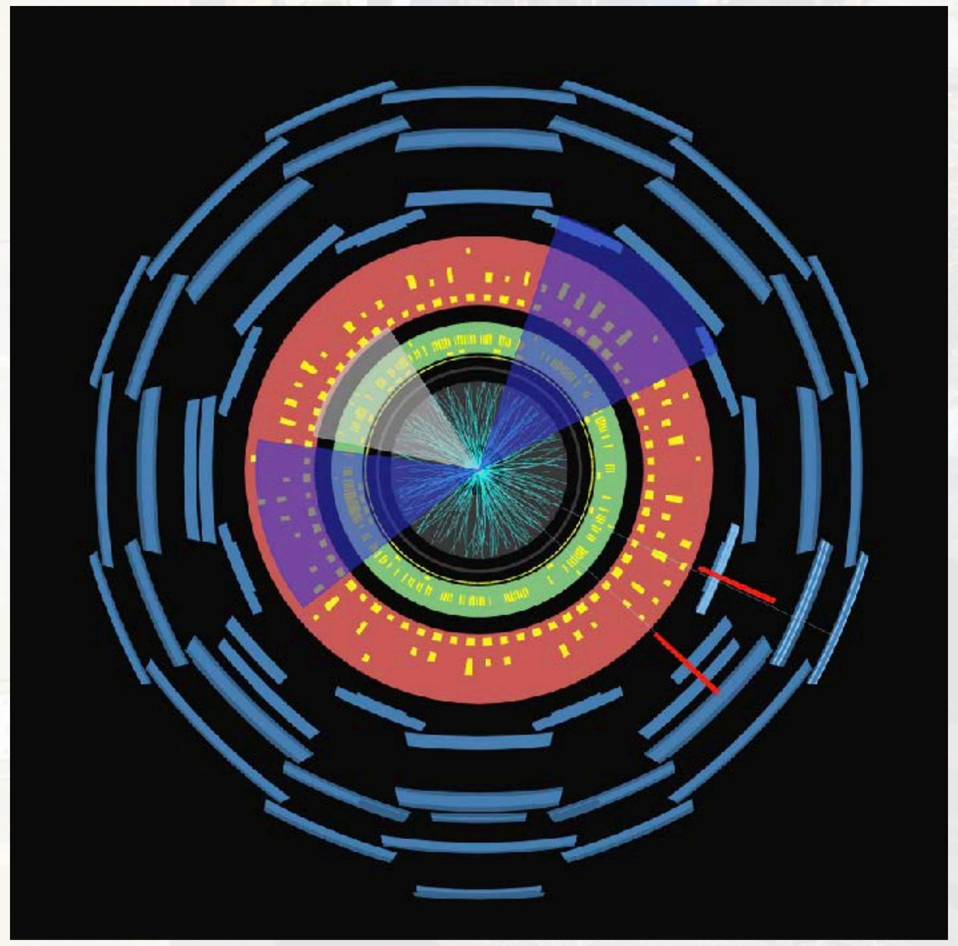


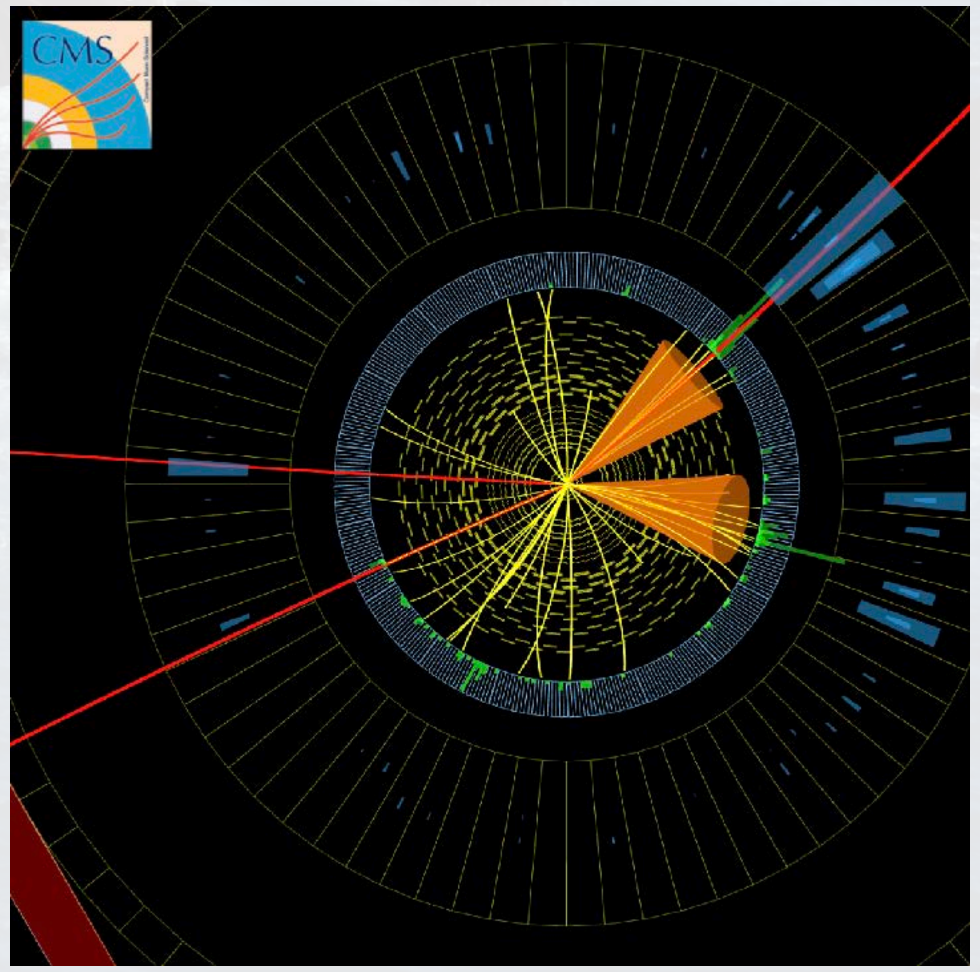


Giovanni Stagnitto
(Milano Bicocca University & INFN)

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN





Seminari di Fisica Teorica, Genova, 26/02/2025

Outlook of this talk

1. (Rather long and pedagogical) introduction

2. Flavoured jets at the LHC:
Z+c-jet and W+c-jet production

3. Towards NNLO+PS for V+jet:
improving slicing methods for V+jet production

Biased selection of recent results where I personally contributed.
Minimal inclusion of references, apologies for any relevant omission.

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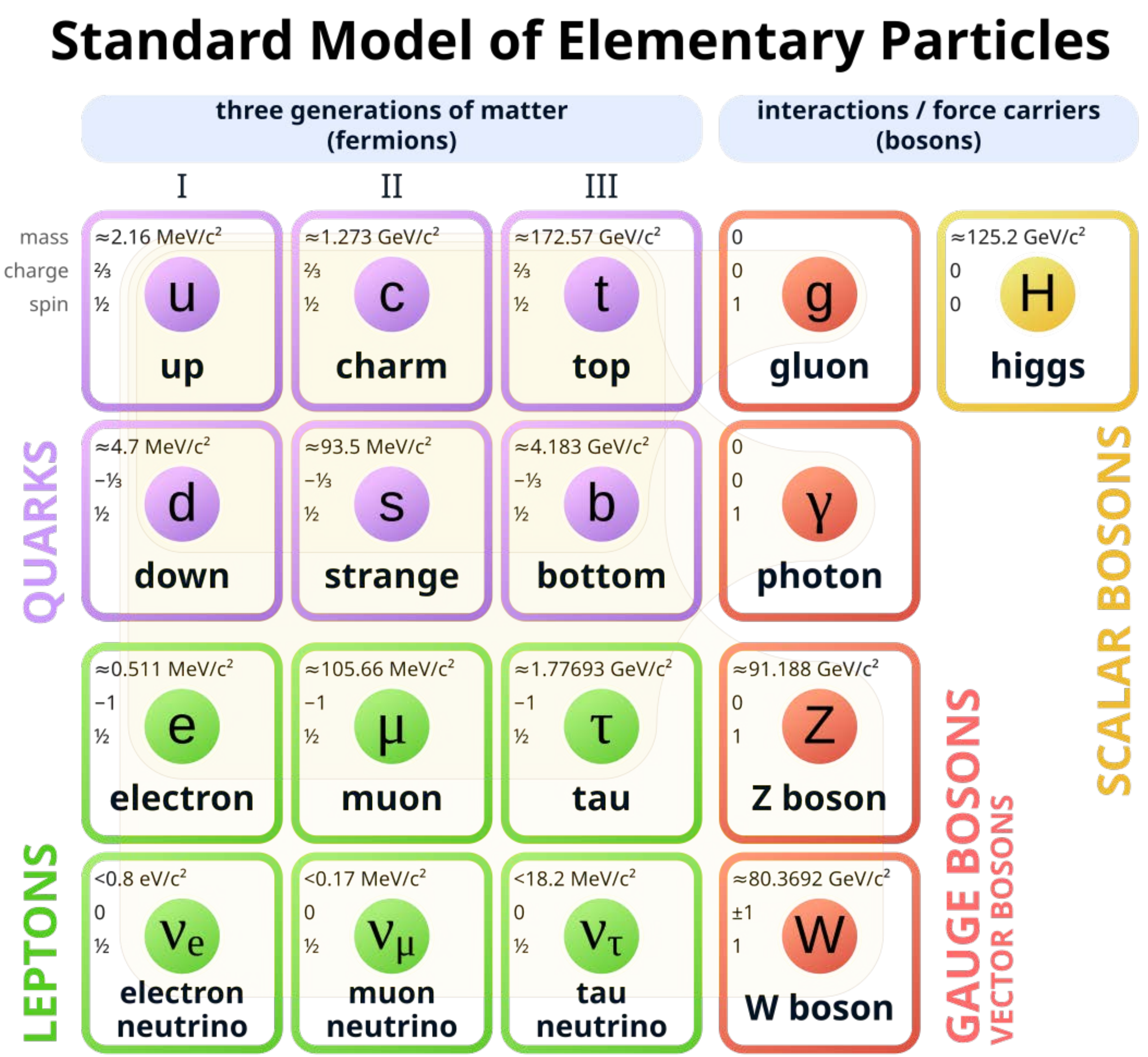


Very successful theory, BUT:

Open *experimental* puzzles:
- what is dark matter?
- origin of neutrino masses?
- what is dark energy?
- baryogenesis?
- ...

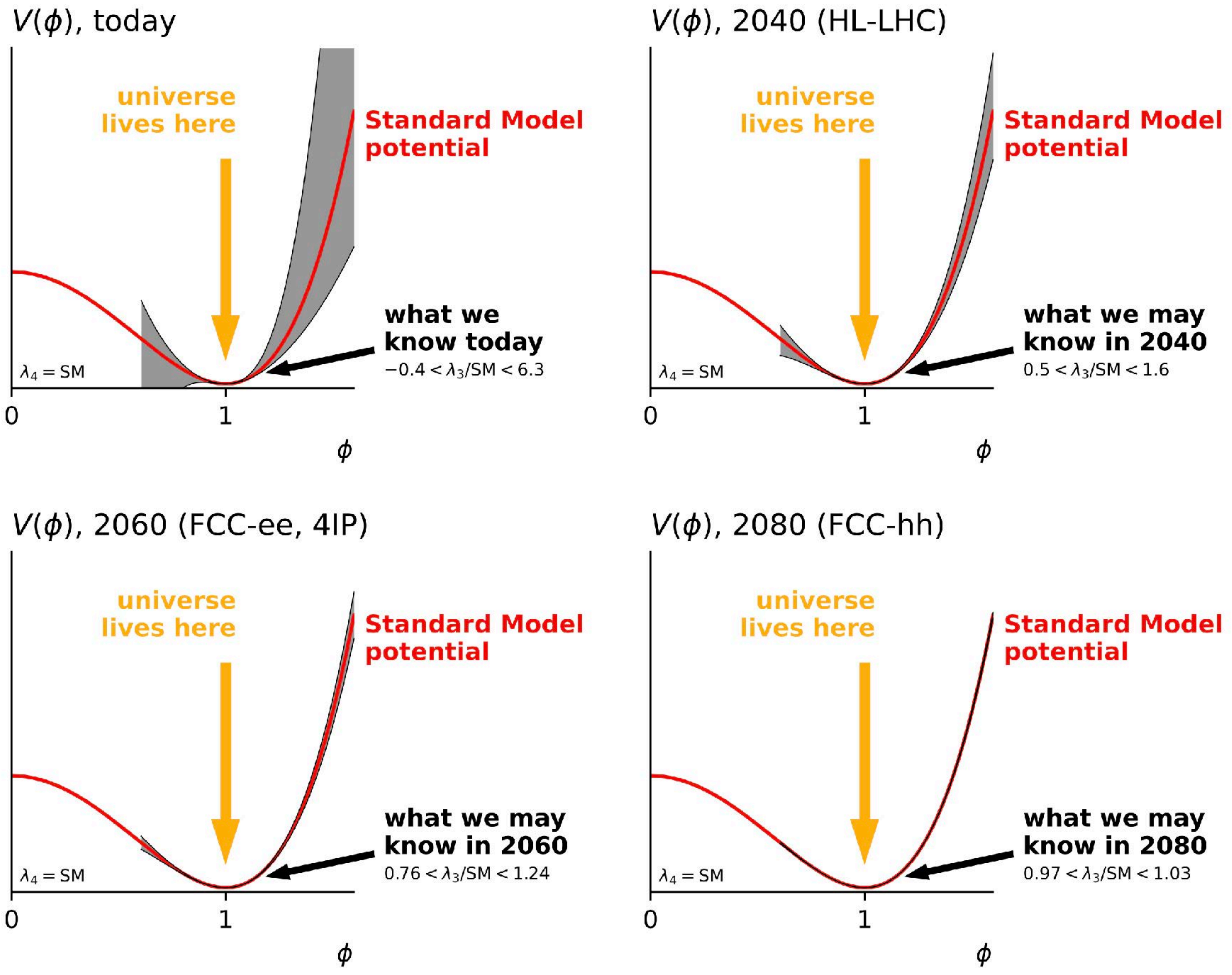
Open *theory* puzzles:
- origin of EWSB?
- hierarchy problem?
- origin of flavour?
- ...

Plethora of Beyond Standard Model (BSM) scenarios to offer solutions

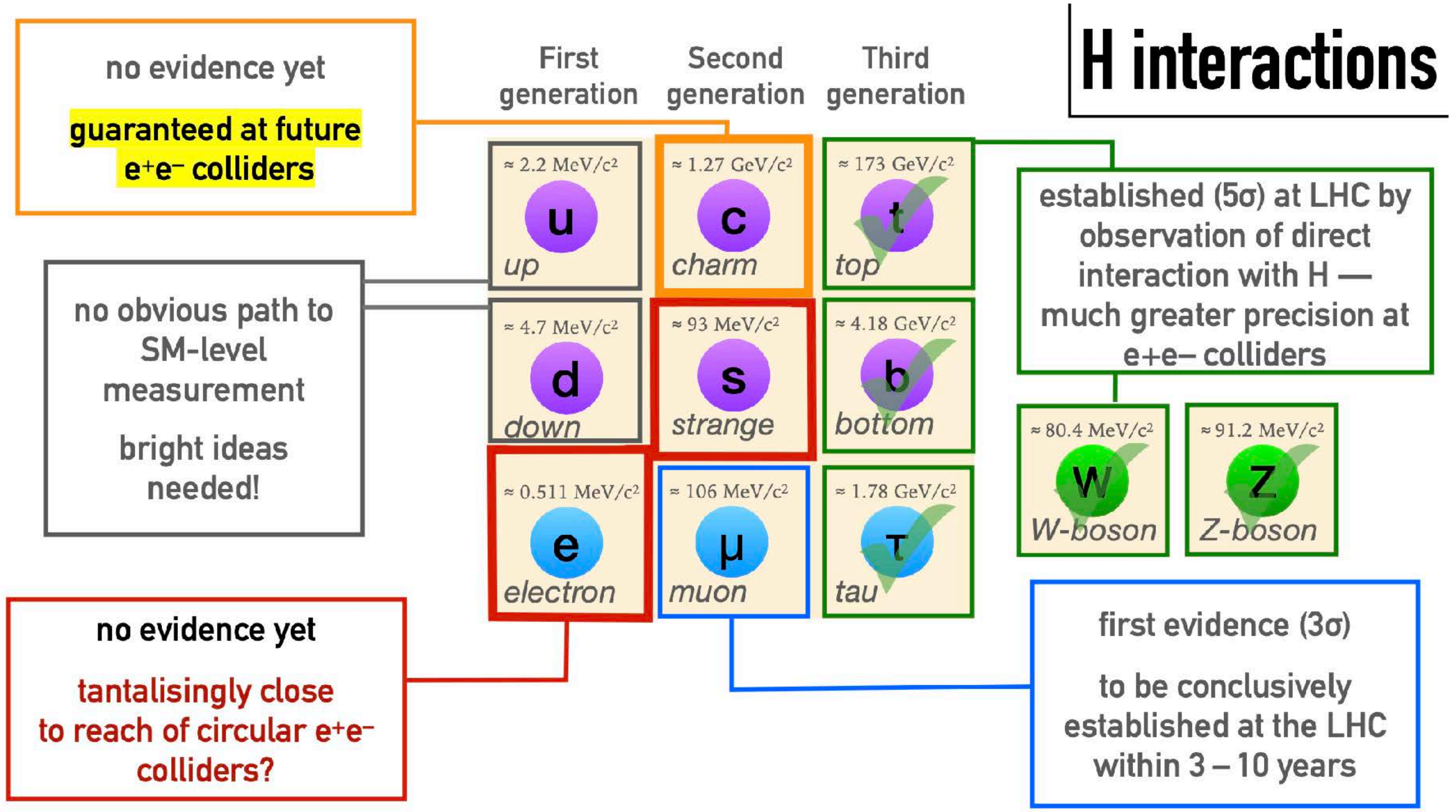
Higgs physics: a "guaranteed discovery"

We have just started the exploration of the Higgs sector of the SM

Higgs potential



Yukawa interactions

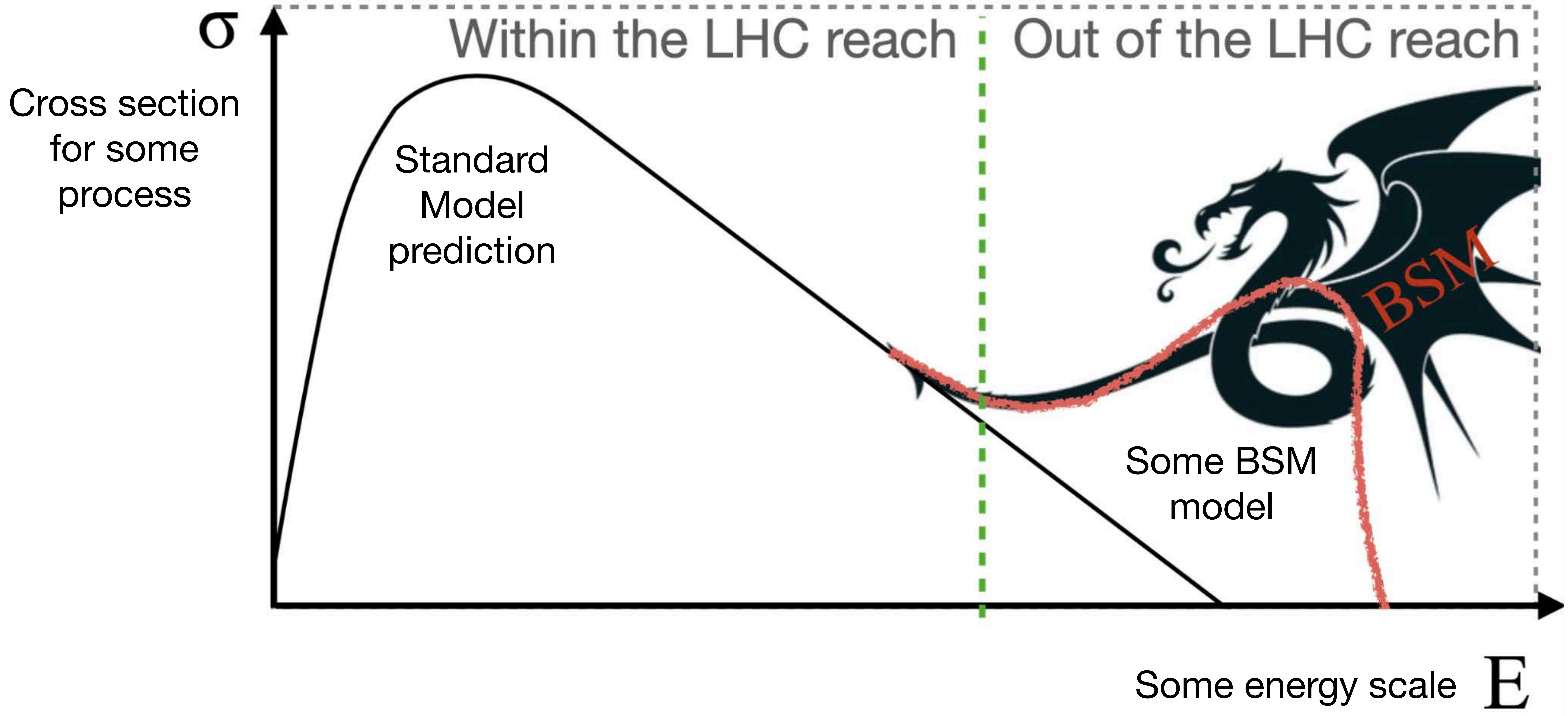


G. Salam

The Large Hadron Collider

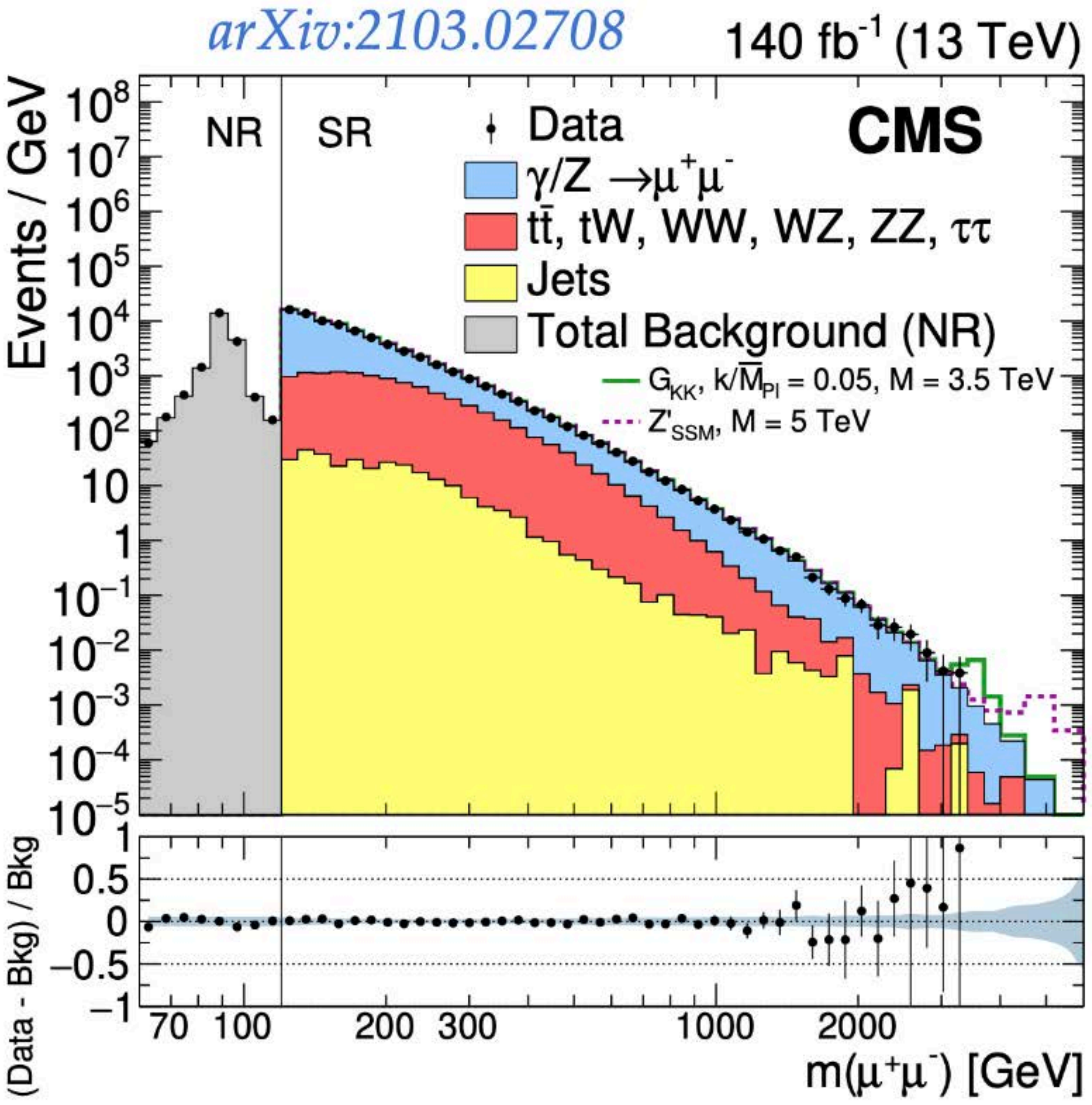
Why precise Standard Model Phenomenology is important?

Direct searches



Why precise Standard Model Phenomenology is important?

Direct searches



mass window [GeV]	stat. unc. 140fb^{-1}	stat. unc. 3ab^{-1}
$600<m_{\mu\mu}<900$	1.4%	0.2%
$900<m_{\mu\mu}<1300$	3.2%	0.6%

Why precise Standard Model Phenomenology is important?

Indirect searches e.g. value of mass of W-boson

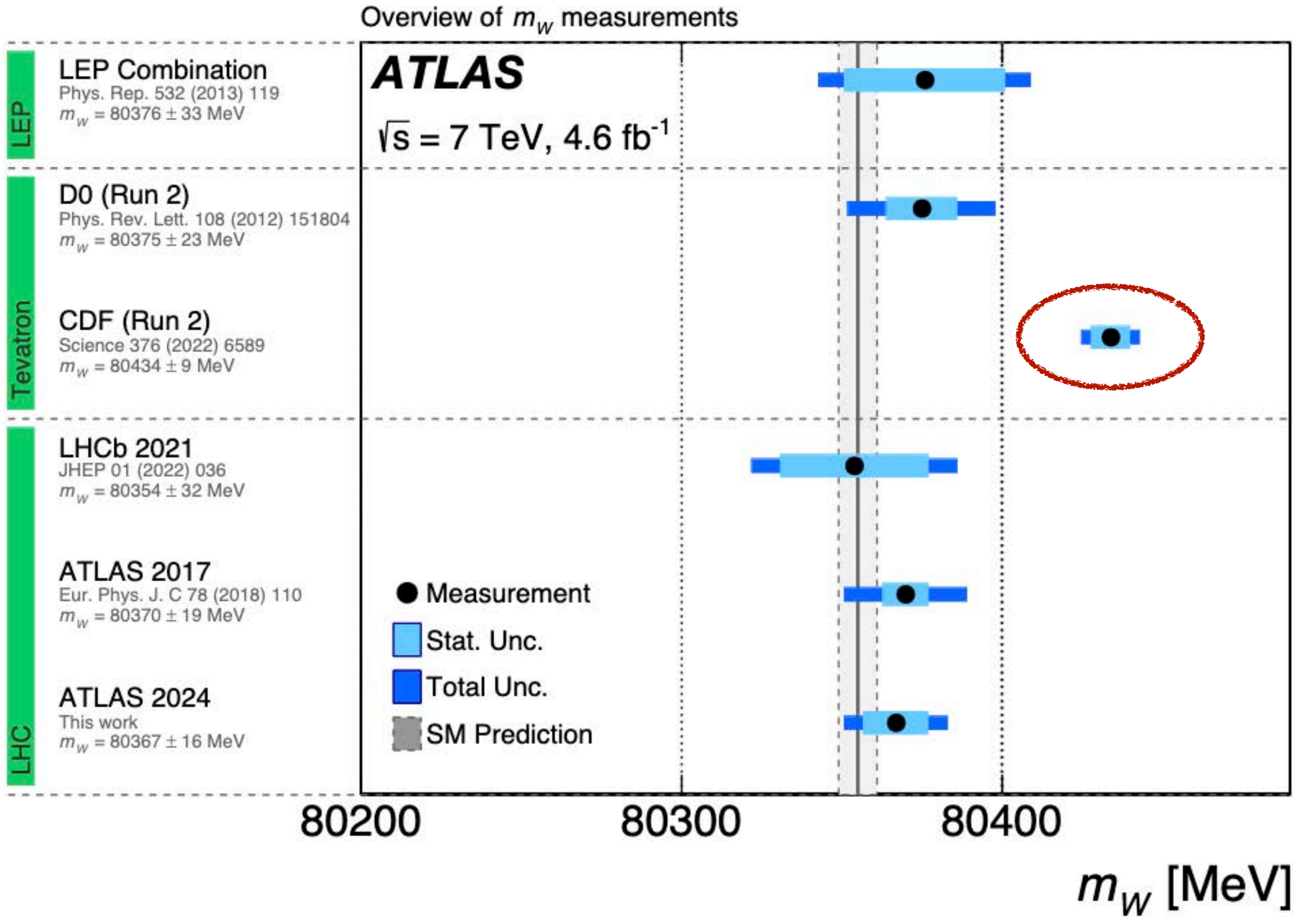
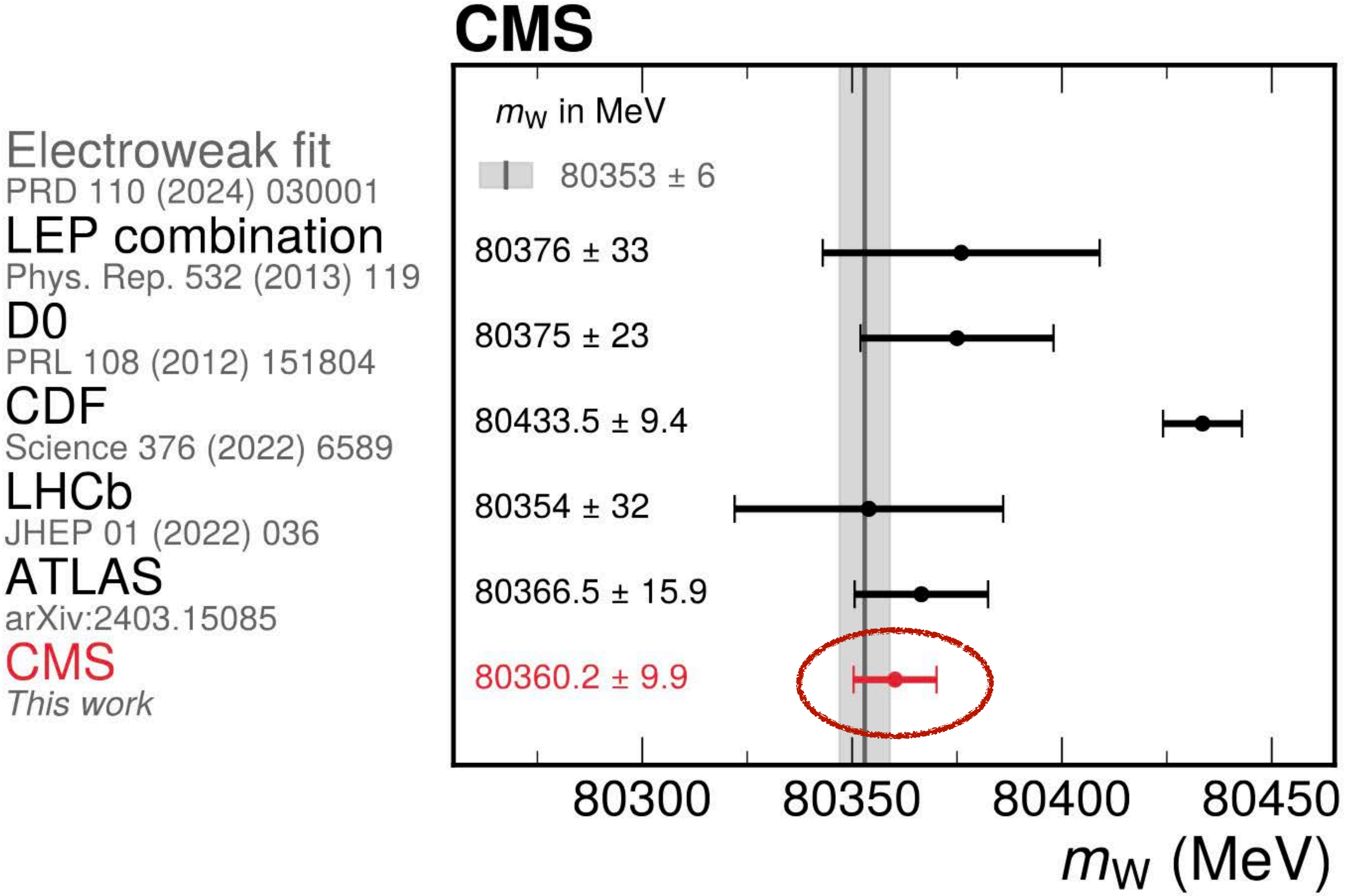


Table 2. Uncertainties on the combined M_W result. CDFII uncertainties

Source	Uncertainty (MeV)	
Lepton energy scale	3.0	Exp. systematics
Lepton energy resolution	1.2	
Recoil energy scale	1.2	
Recoil energy resolution	1.8	
Lepton efficiency	0.4	
Lepton removal	1.2	
Backgrounds	3.3	
p_T^Z model	1.8	Th. systematics
p_T^W/p_T^Z model	1.3	
Parton distributions	3.9	
QED radiation	2.7	
W boson statistics	6.4	Statistics
Total	9.4	

Why precise Standard Model Phenomenology is important?

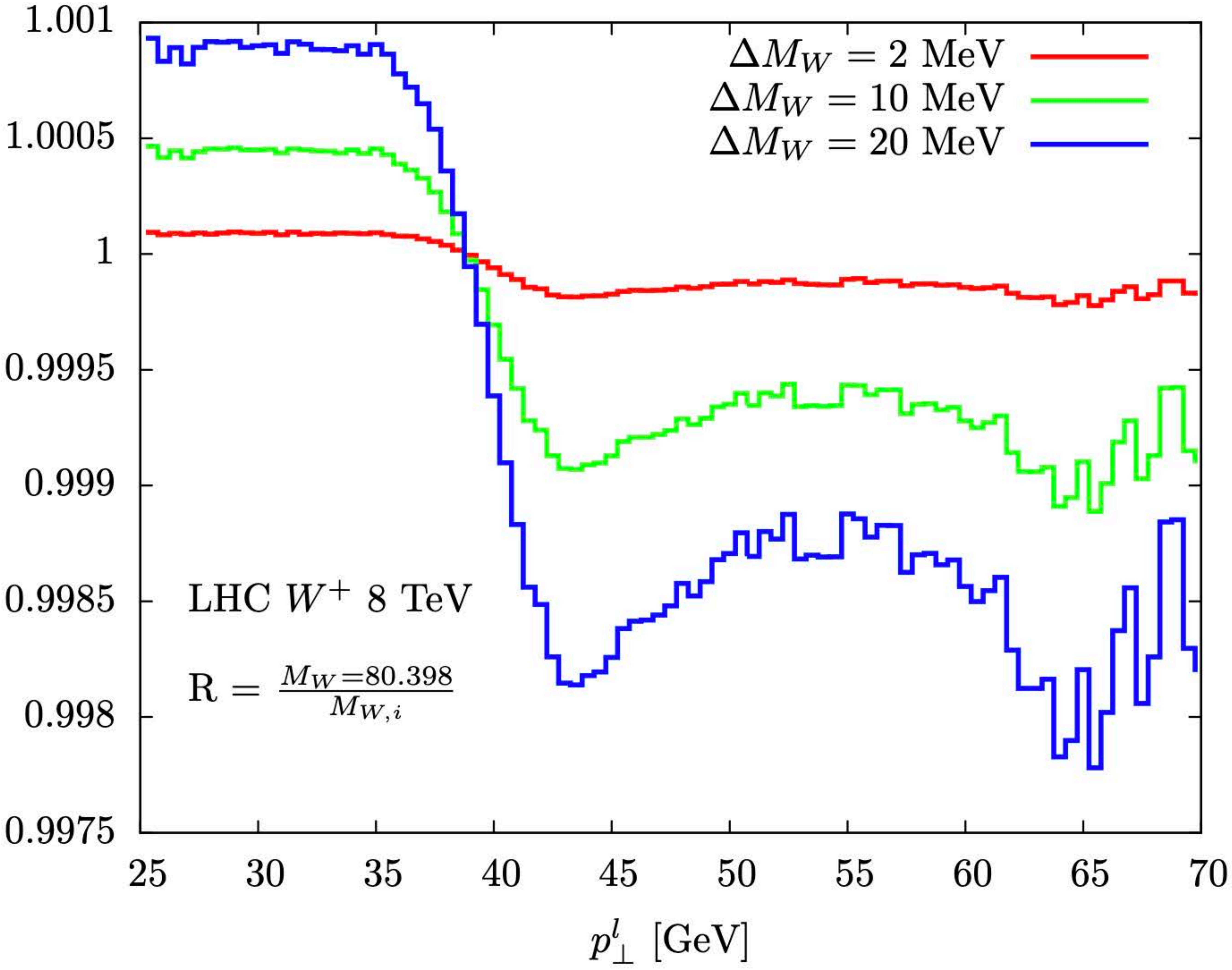
Indirect searches e.g. value of mass of W-boson



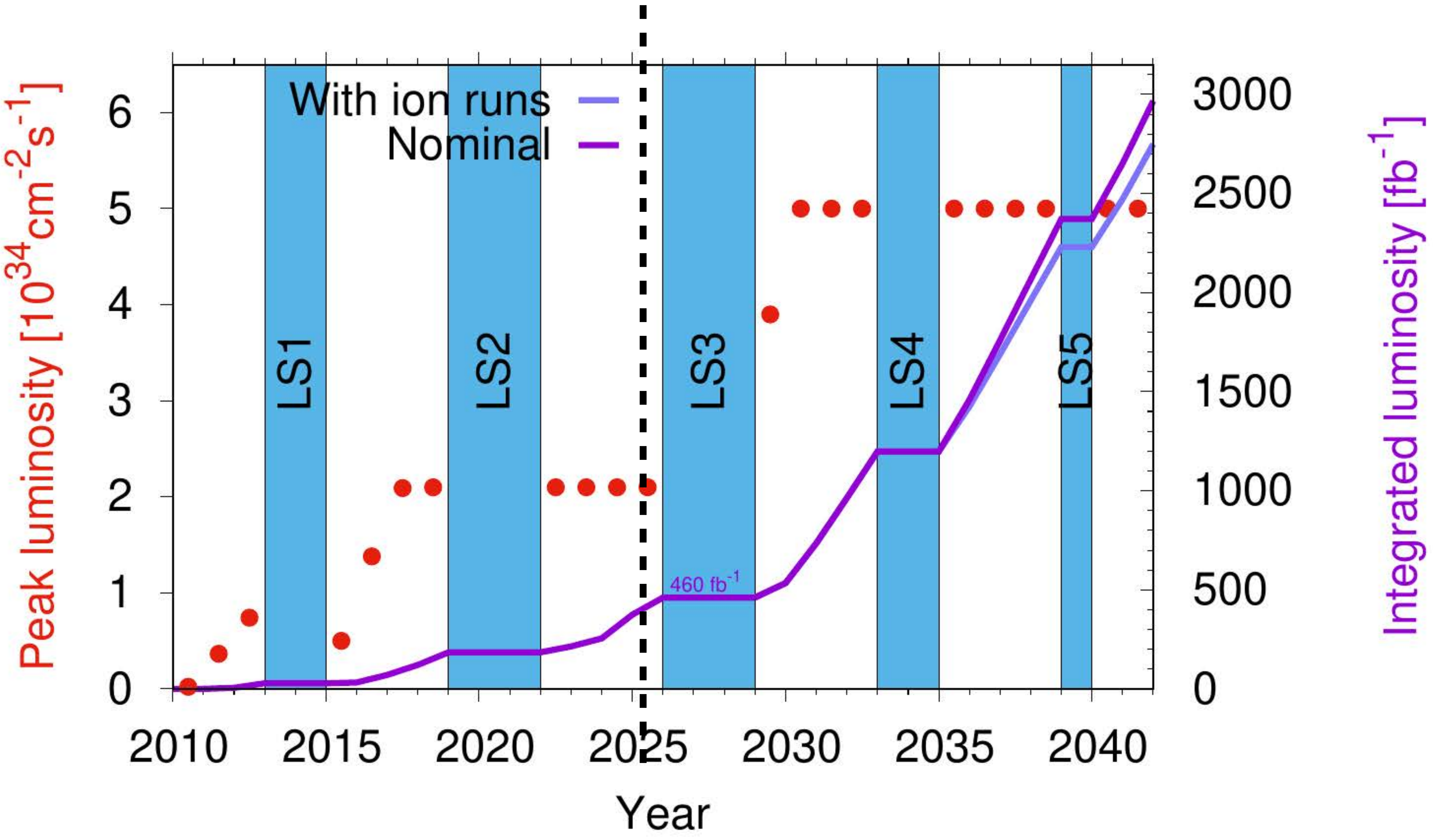
Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

Why precise Standard Model Phenomenology is important?

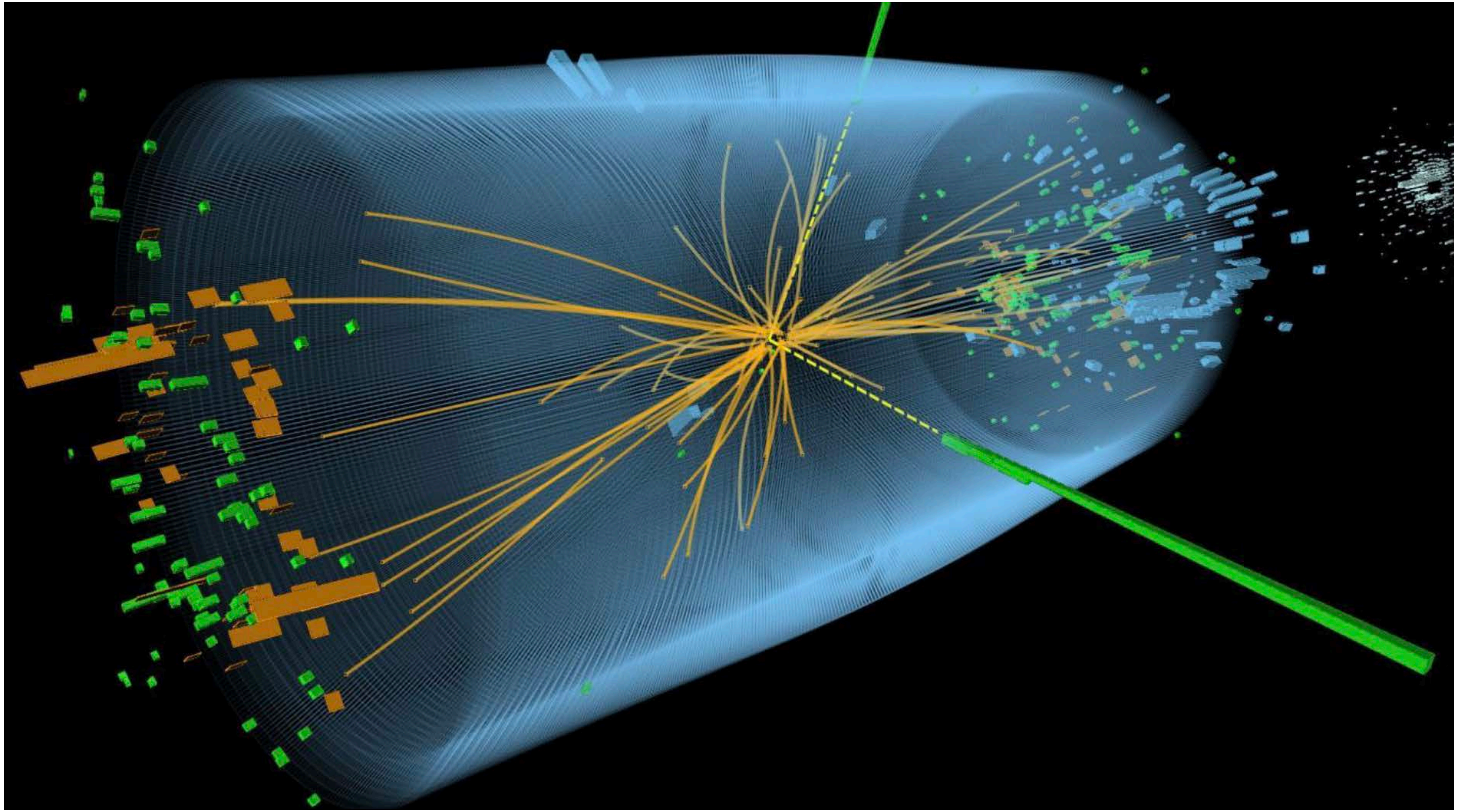
Indirect searches e.g. value of mass of W-boson



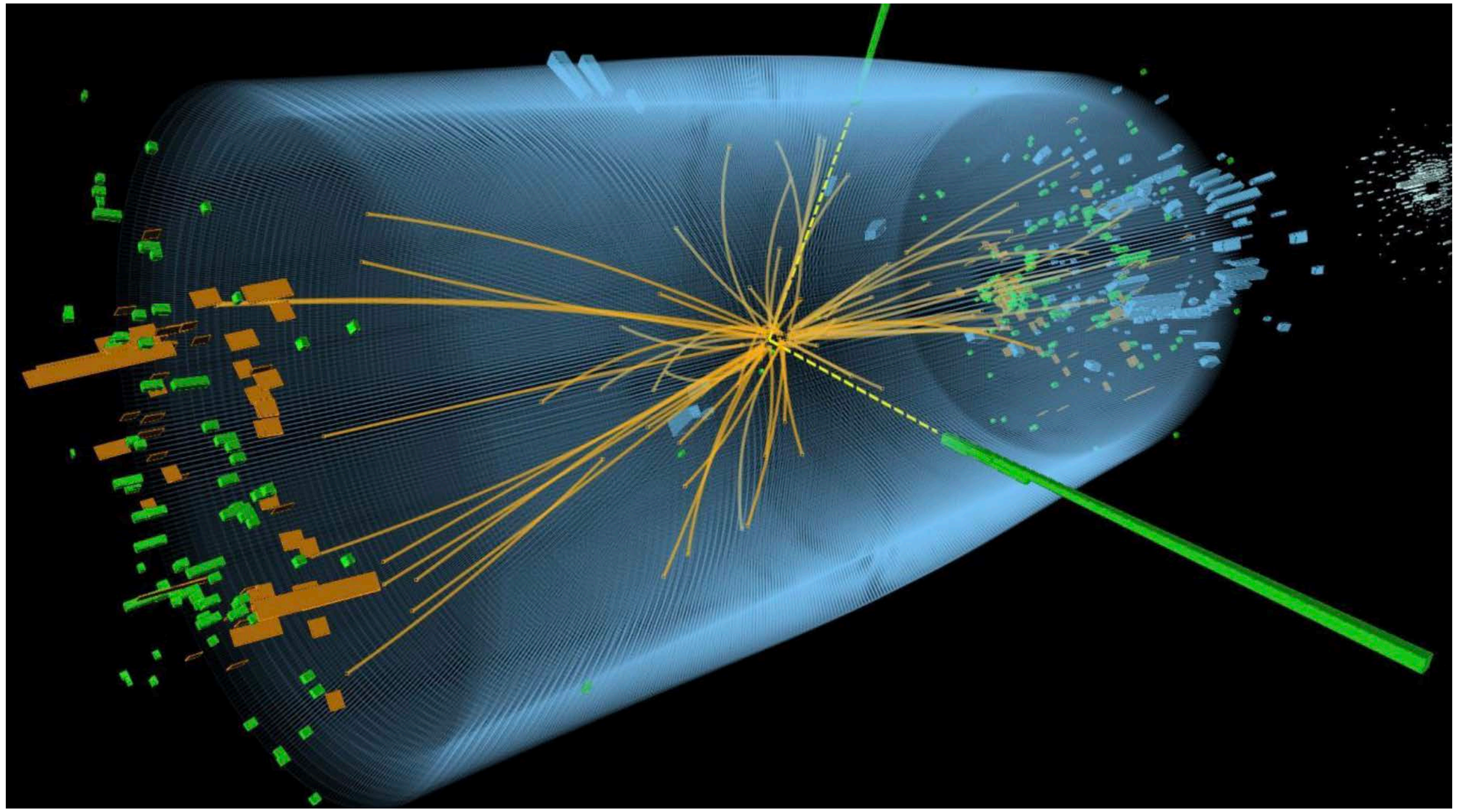
~90% of LHC collisions yet to be delivered!

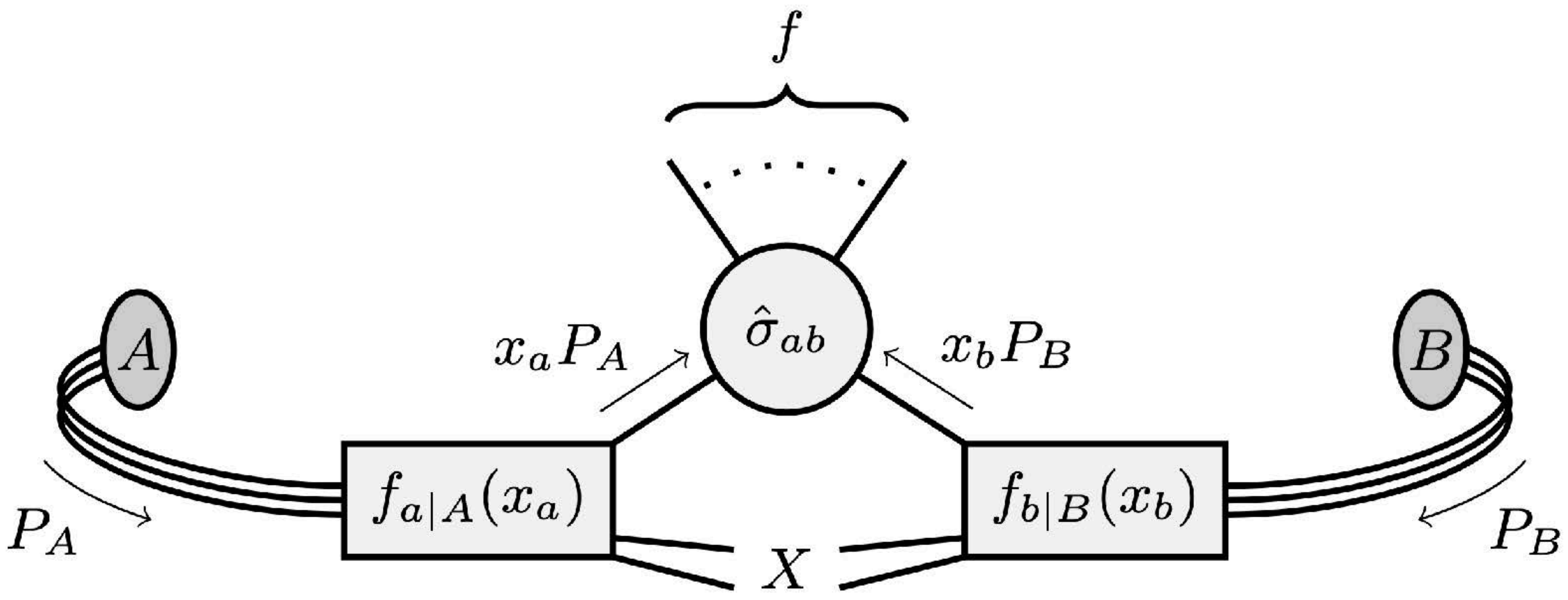


How can we describe collider events?



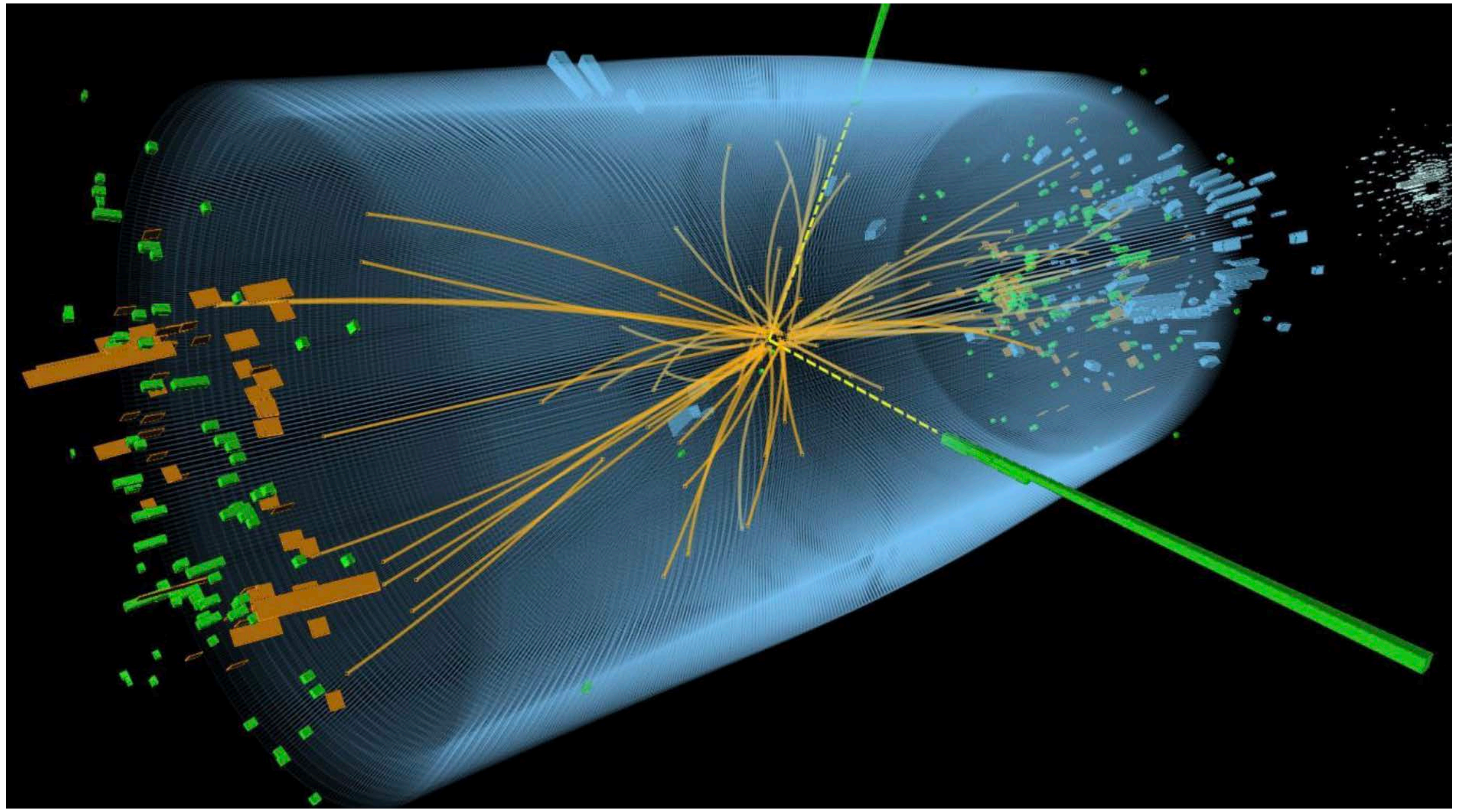
Collider events and their theoretical description

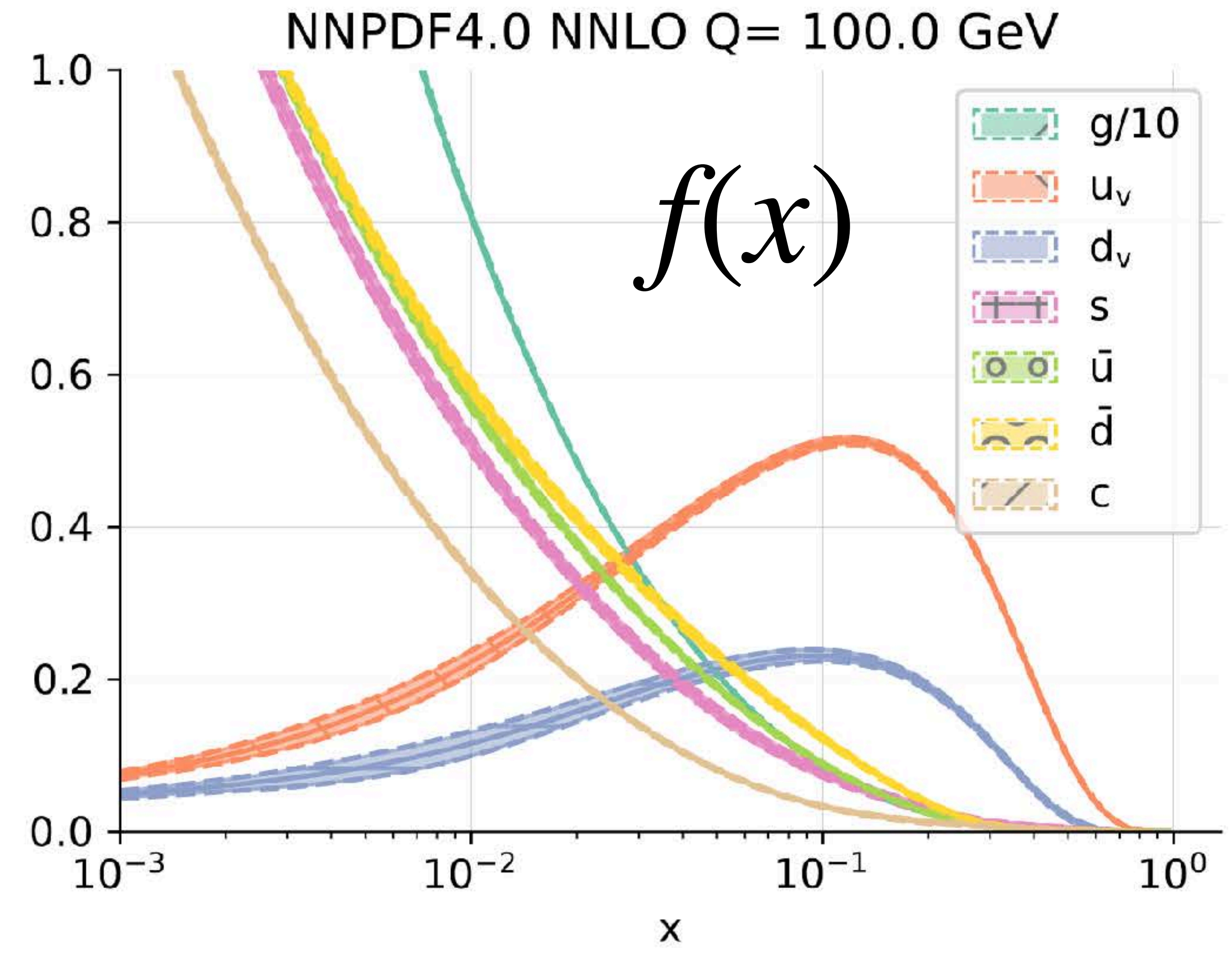


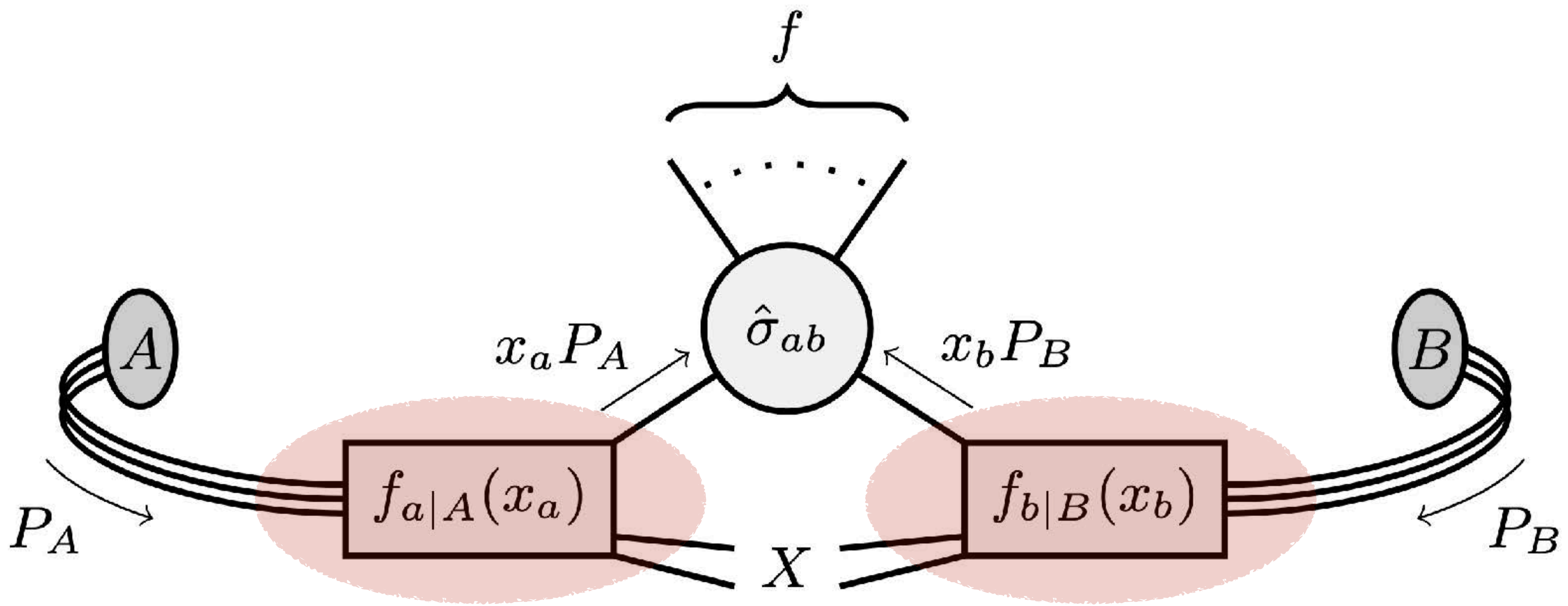


$$\mathrm{d}\sigma_{AB} = \sum_{ab} f_{a|A} \otimes f_{b|B} \otimes \mathrm{d}\hat{\sigma}_{ab}$$

Collider events and their theoretical description (1/3)





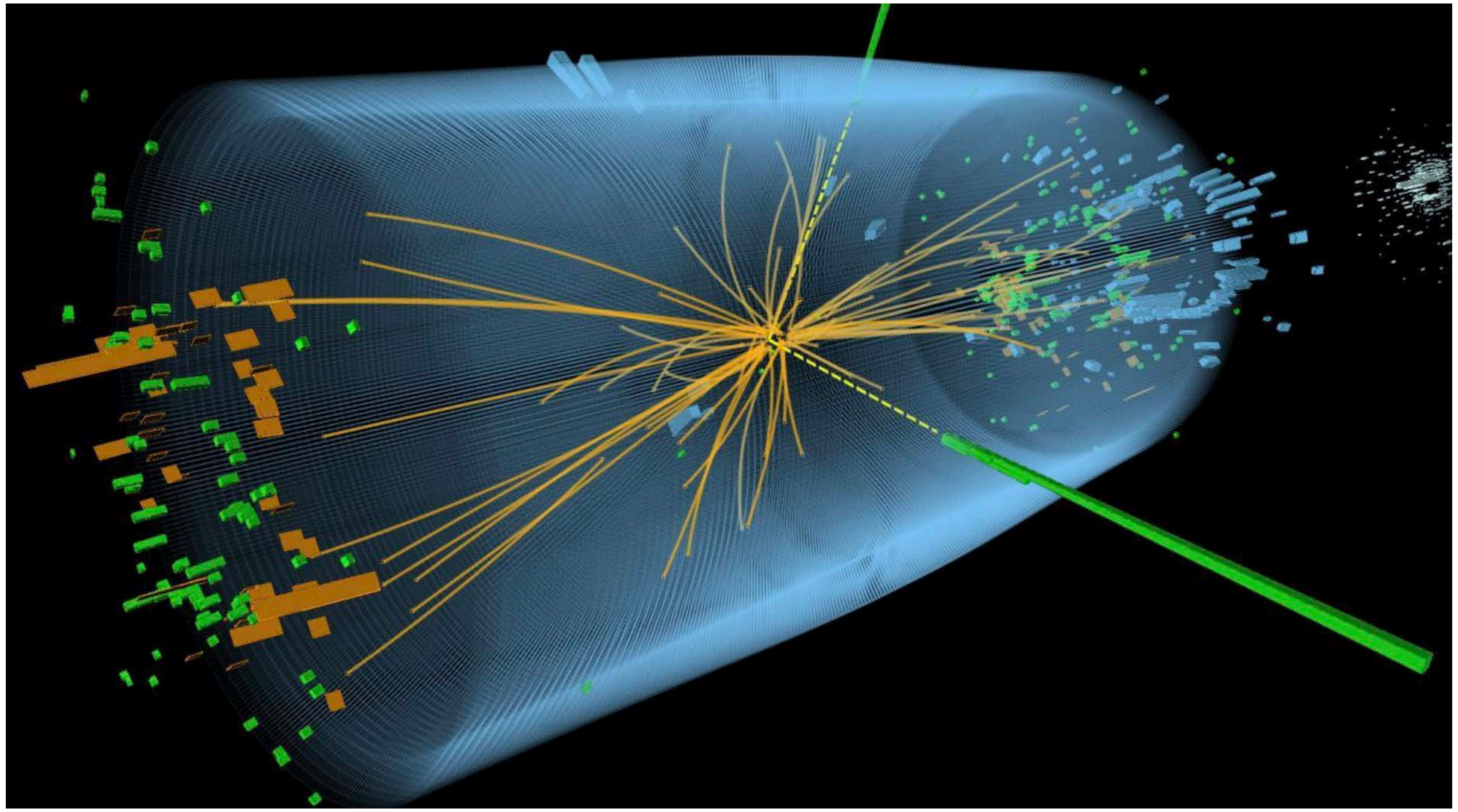


Parton Distributions Functions (PDFs)

Non-perturbative functions describing momentum distribution of quark and gluons inside the proton

$$d\sigma_{AB} = \sum_{ab} f_{a|A} \otimes f_{b|B} \otimes d\hat{\sigma}_{ab}$$

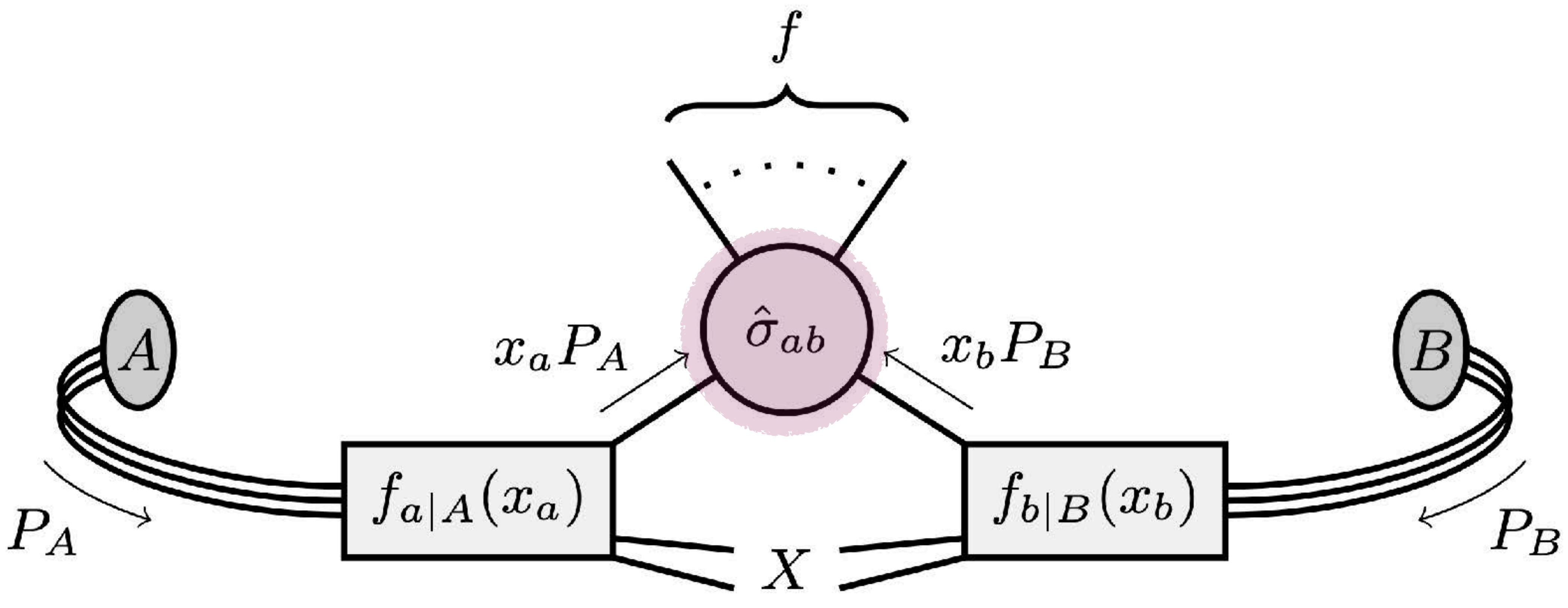
Collider events and their theoretical description (2/3)



LO NLO NNLO N^{3}LO

$$\hat{\sigma} = \hat{\sigma}_0 + \alpha_s \hat{\sigma}_1 + \alpha_s^2 \hat{\sigma}_2 + \alpha_s^3 \hat{\sigma}_3 + \mathcal{O}(\alpha_s^4)$$

$\hat{\sigma}_k$ is the N^{k}LO cross section

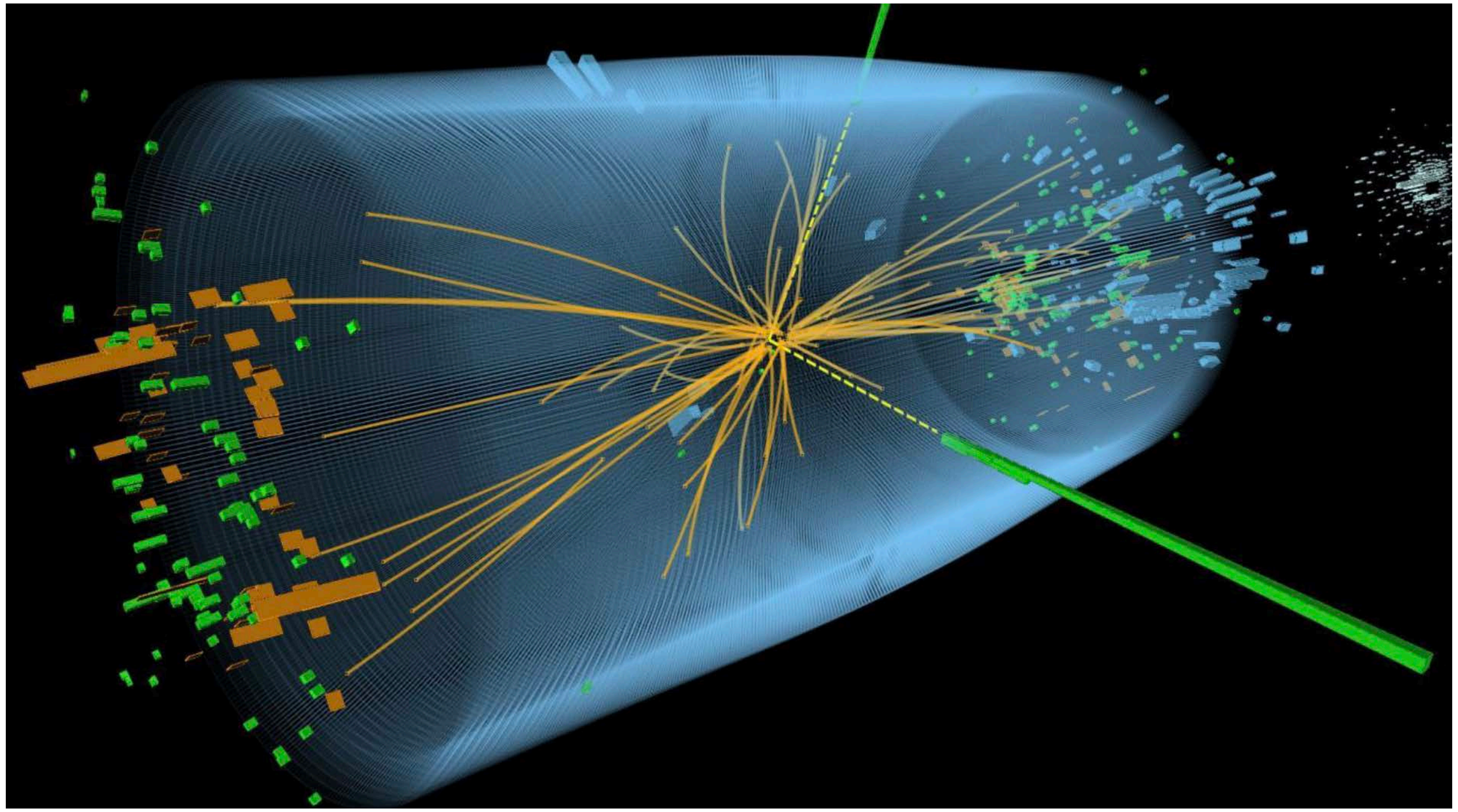


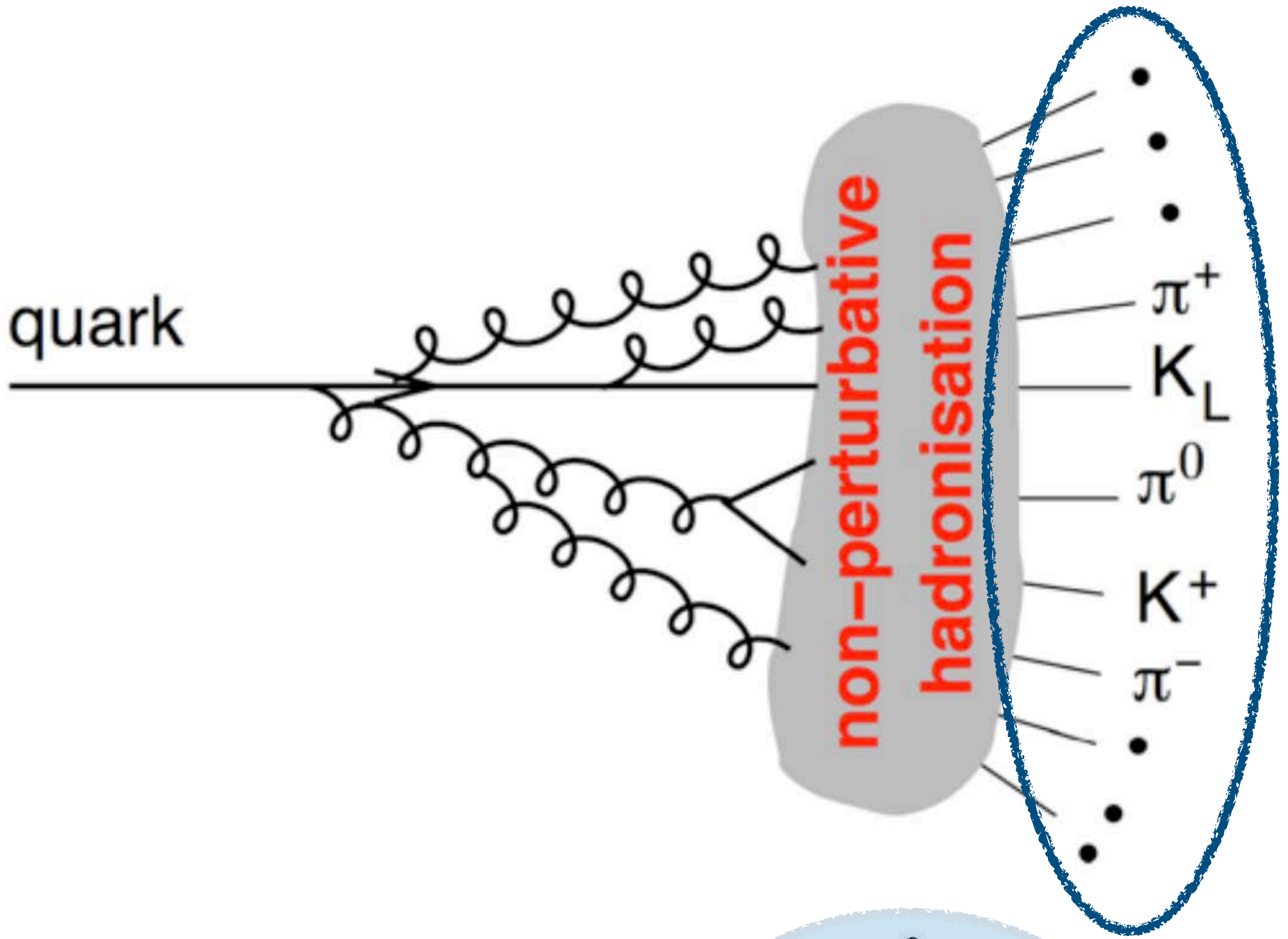
$$d\sigma_{AB} = \sum_{ab} f_{a|A} \otimes f_{b|B} \otimes d\hat{\sigma}_{ab}$$

Short-distance cross section

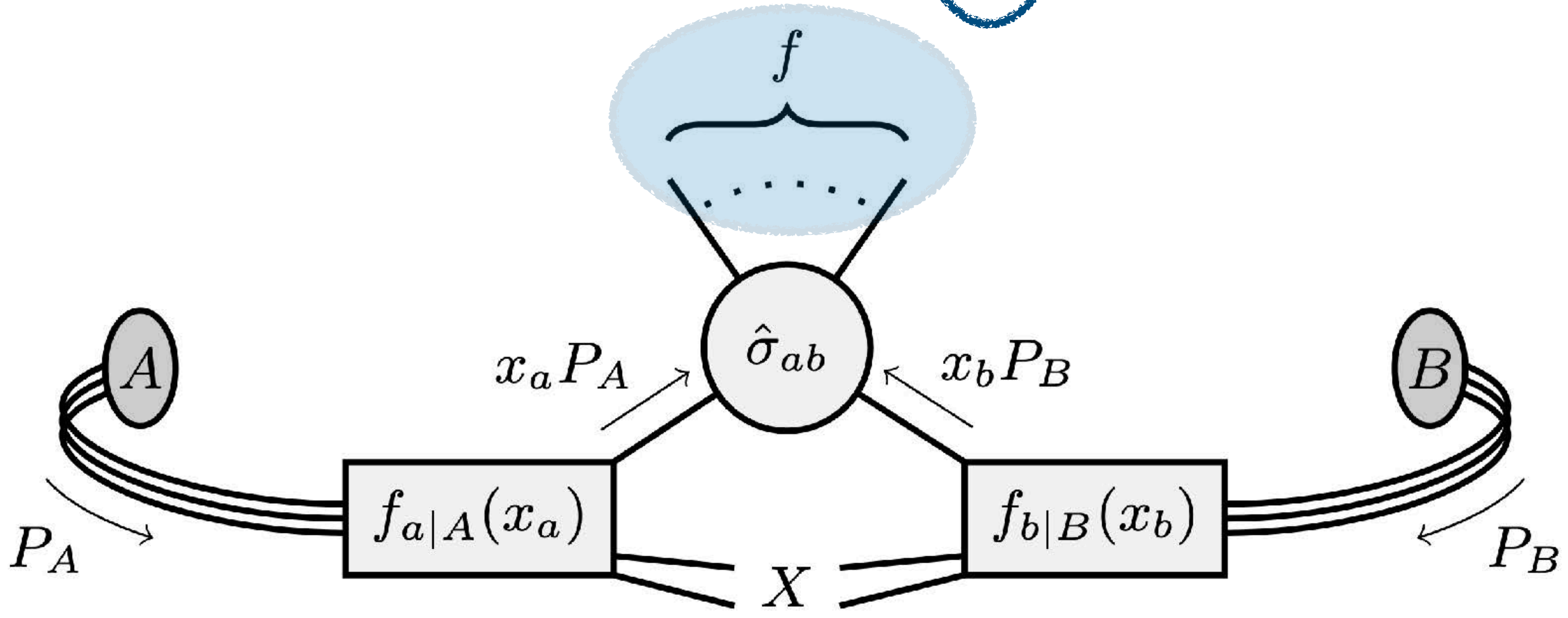
The strong coupling constant α_s is small at high energies, $\alpha_s(Q \sim 100 \text{ GeV}) \sim 0.1$, so we can work in perturbation theory

Collider events and their theoretical description (3/3)





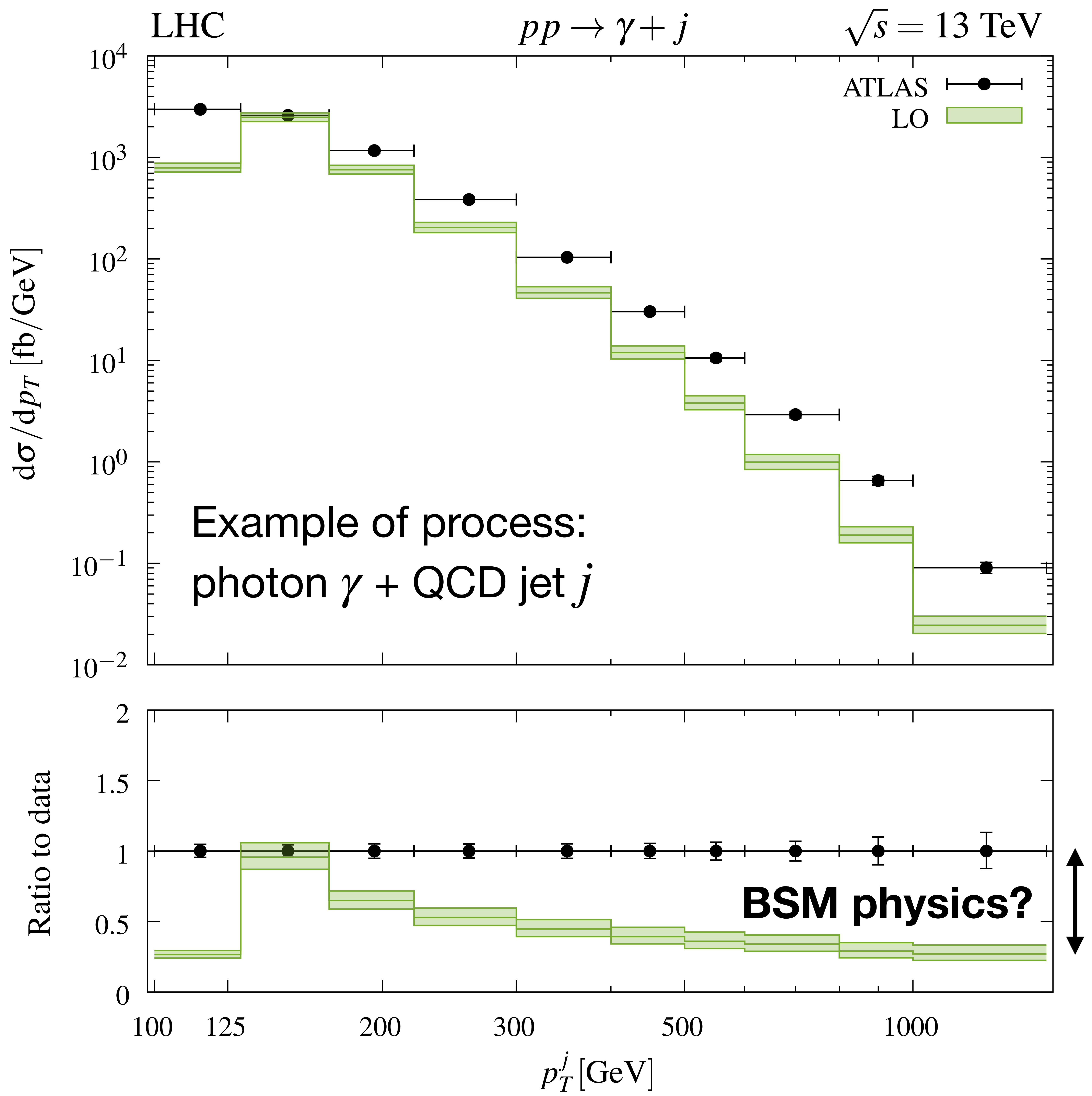
Hadronic *jet* (proxy for hard quark)



Experiments do not see quarks and gluons, but composite QCD particles (*hadrons)*

Measurement and predictions in terms of jets (~ clusters of particles close in angle)

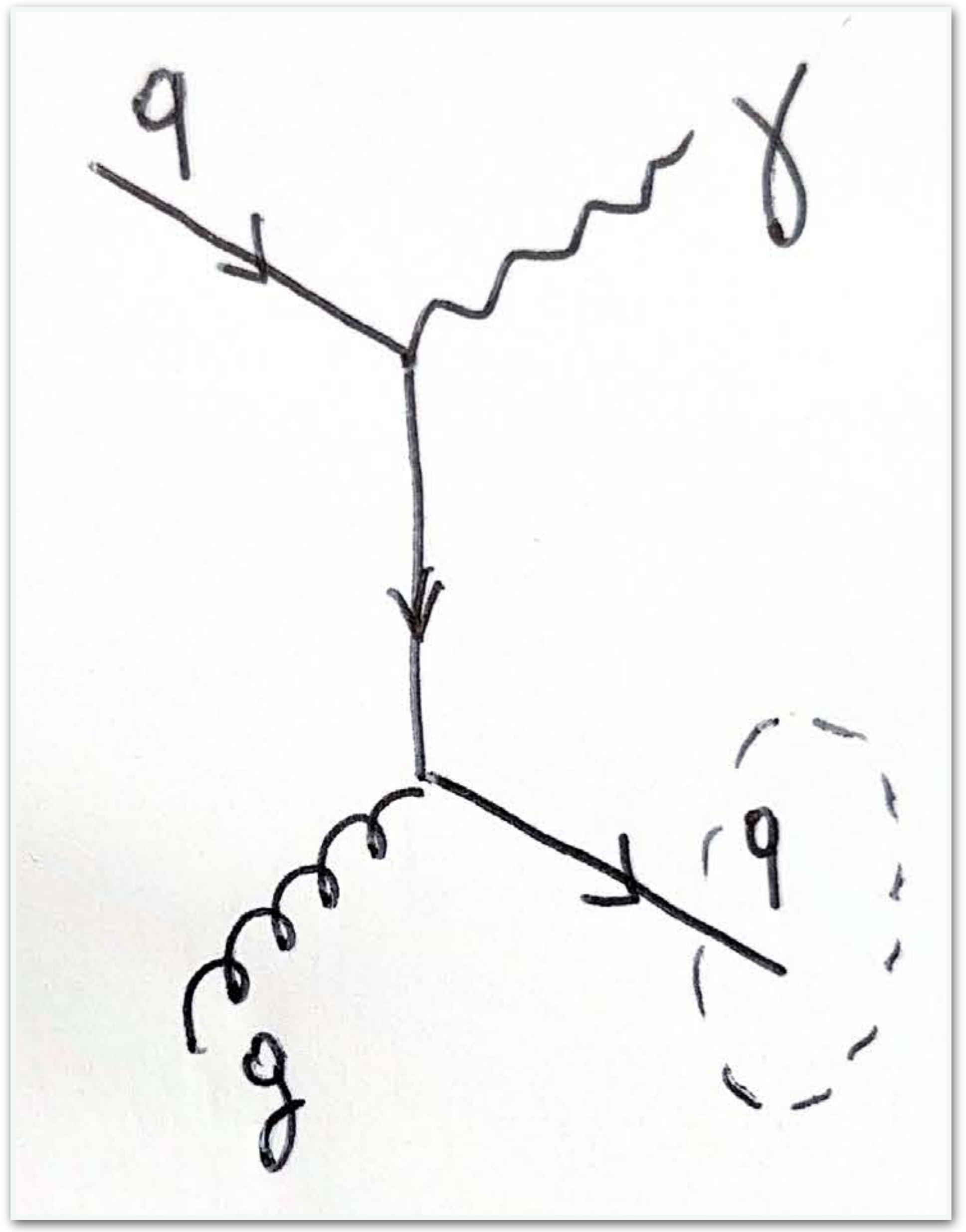
$$d\sigma_{AB} = \sum_{ab} f_{a|A} \otimes f_{b|B} \otimes d\hat{\sigma}_{ab}$$

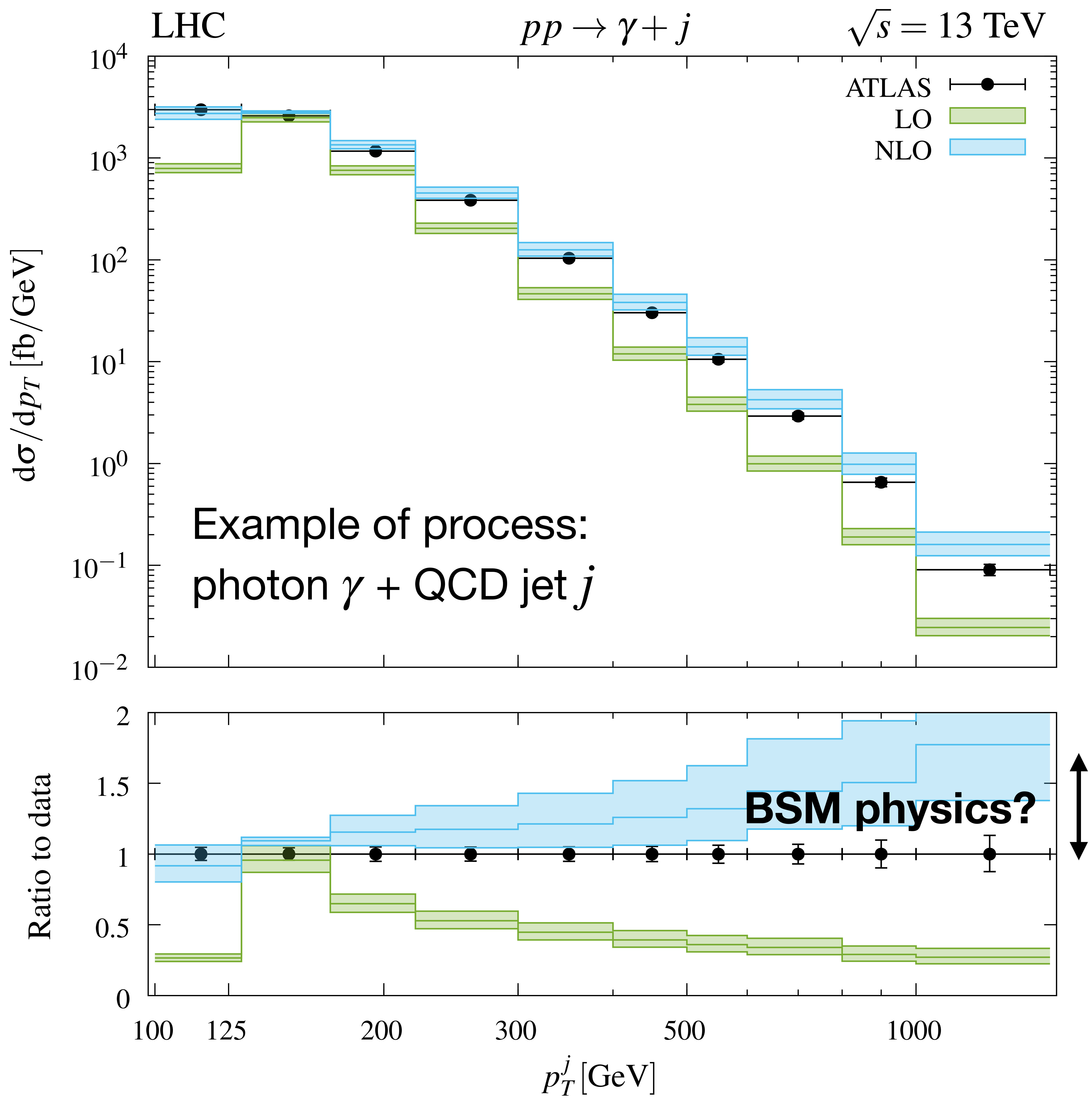


Precise description of hard scattering

Leading Order (LO)

$$\sigma = \underline{\sigma_0} + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \mathcal{O}(\alpha_s^3)$$

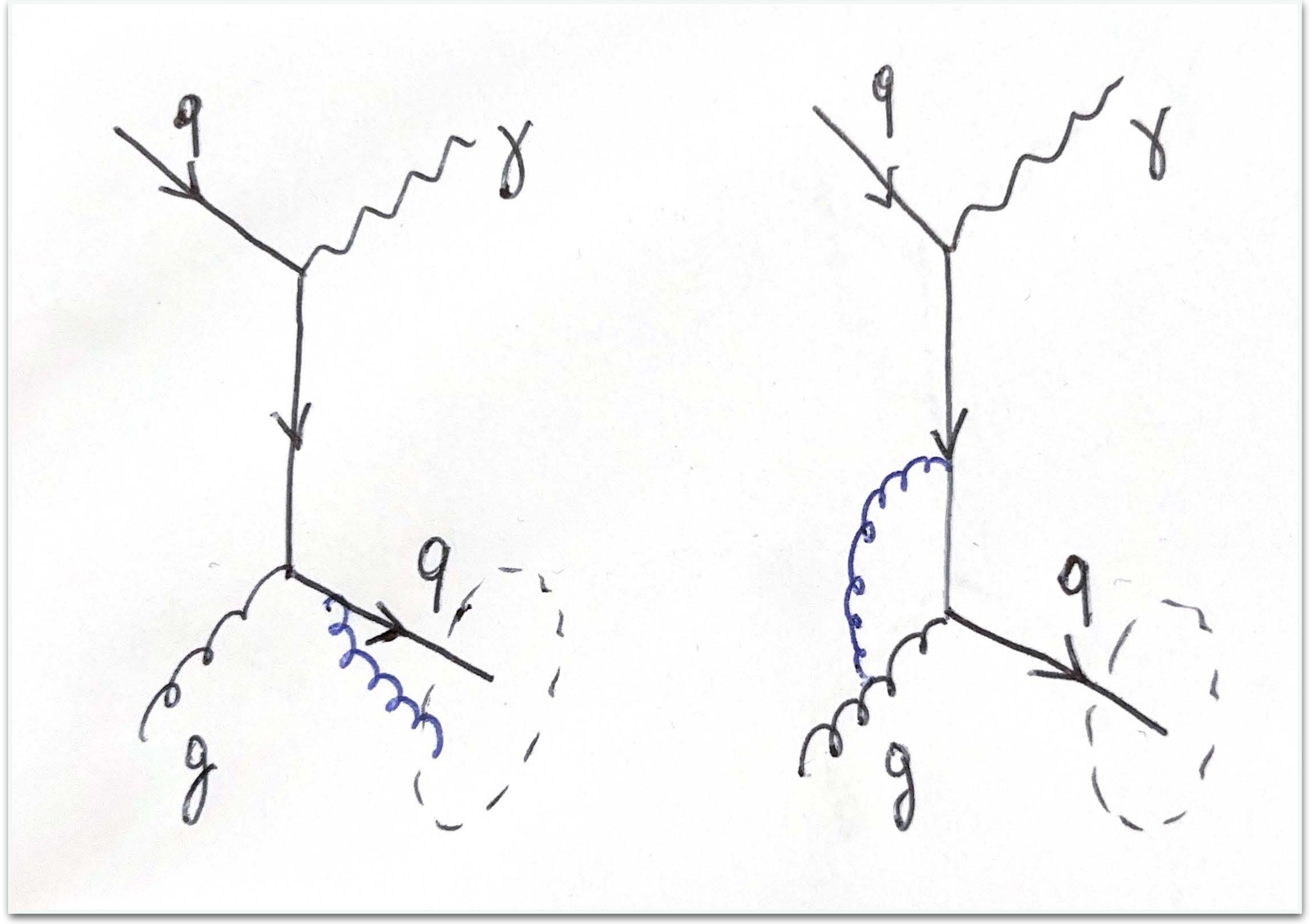




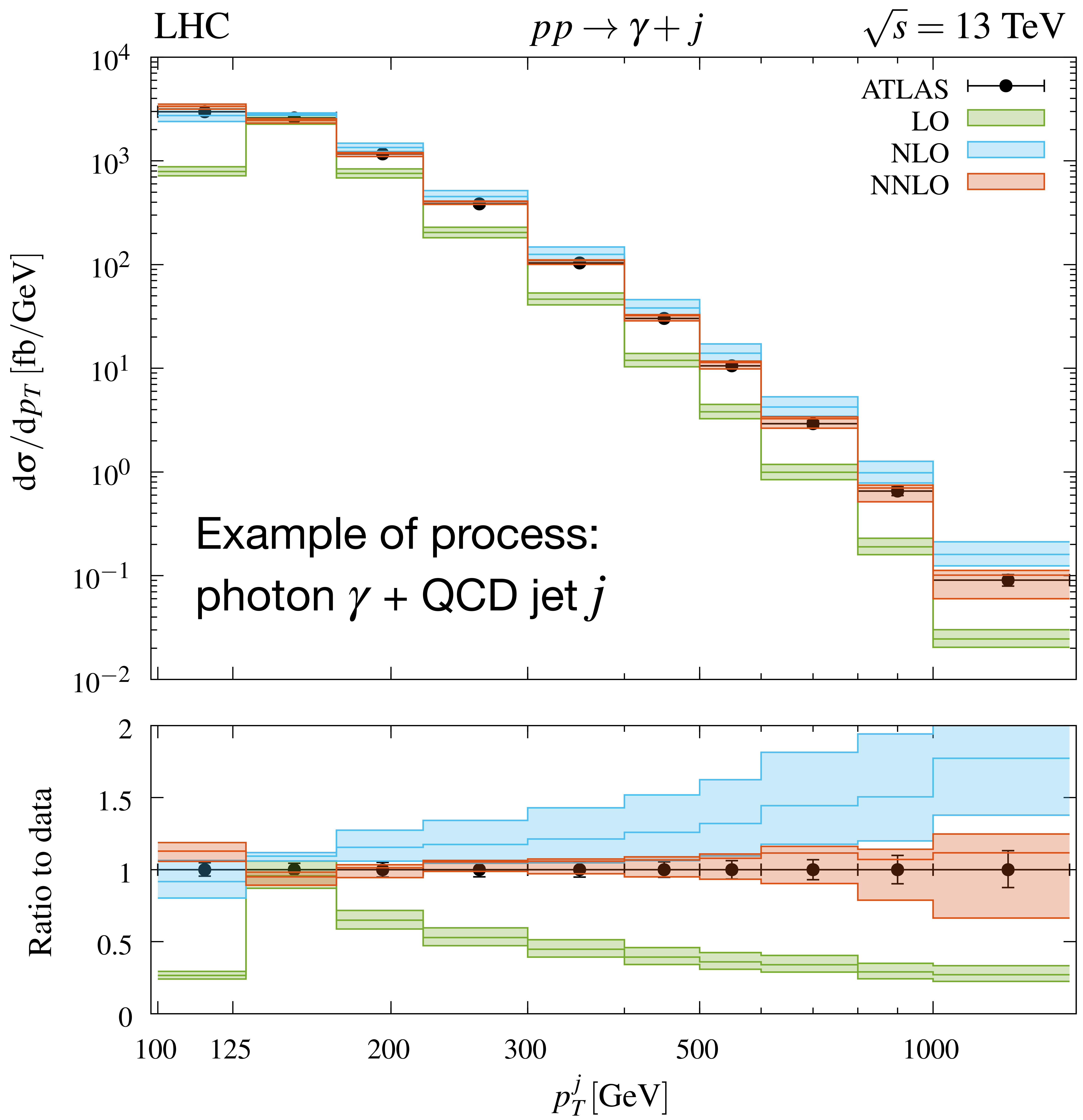
Precise description of hard scattering

Next-to-Leading Order (NLO)

$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \mathcal{O}(\alpha_s^3)$$



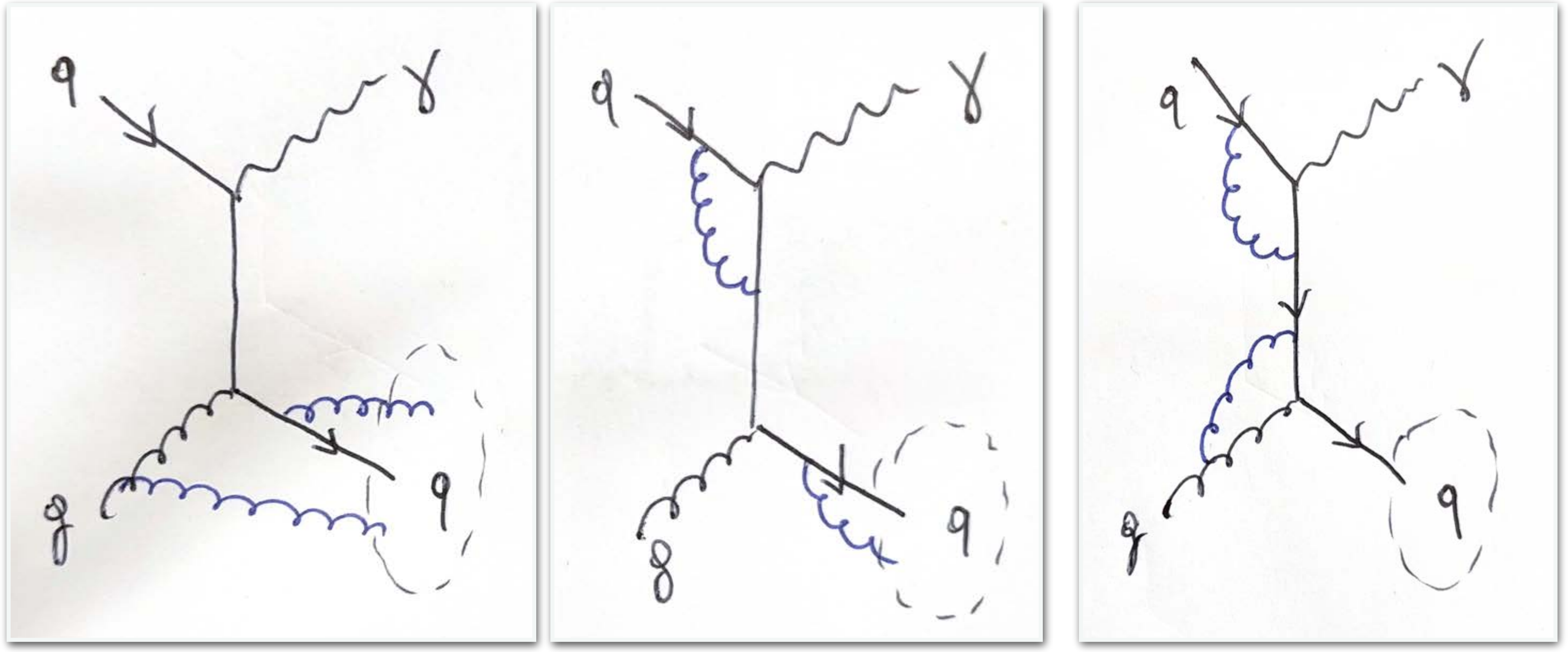
Real gluon *Virtual* gluon



Precise description of
hard scattering

Next-to-Next-to-Leading Order (NNLO)

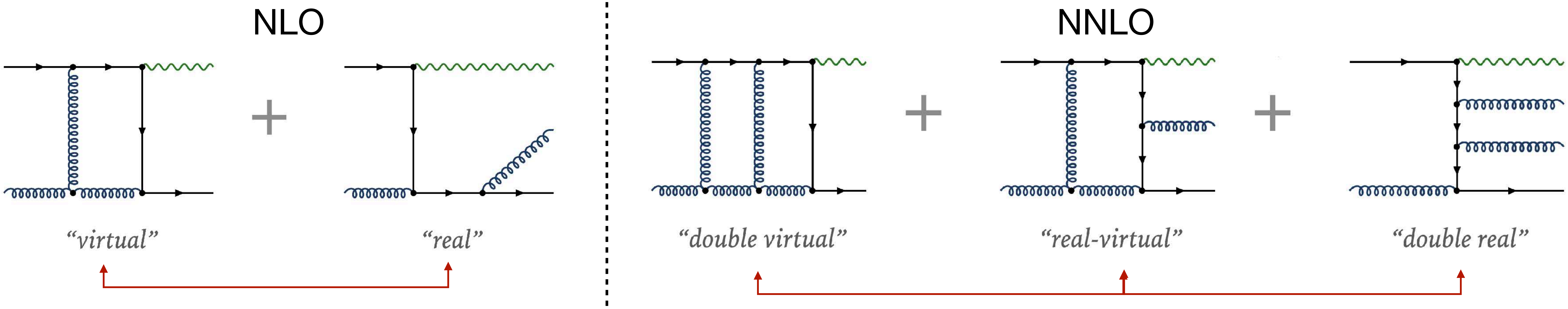
$$\sigma = \underline{\sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2} + \mathcal{O}(\alpha_s^3)$$



Real-real *Real-virtual* *Virtual-virtual*

Fixed-order calculations: dealing with infrared singularities in QCD

Infrared singularities appearing when particles are *soft* (low energy) and/or *collinear* (close in angle)



Toy model: parameter ϵ acting as regulator; F complicated "measurement" function over the "emission phase space" x (e.g. energy of emitted particle or angle between particles)

Real
Implicit divergence as $x \to 0$
(regulated by x^ϵ)

$$I = \lim_{\epsilon \to 0} \left\{ \int_0^1 \frac{dx}{x} x^\epsilon F(x) - \frac{1}{\epsilon} F(0) \right\}$$

Virtual
Explicit divergence
(pole in $1/\epsilon$)

Two class of methods to tackle this issue: *subtraction* or *slicing*

Fixed-order calculations: dealing with infrared singularities in QCD

Two class of methods to tackle this issue: *subtraction* or *slicing*

Subtraction: add and subtract a term
mimicking the divergent limit under integration AND simple to integrate.
Analytical cancellation of poles and leftover integral can be integrated numerically

$$I = \lim_{\epsilon \to 0} \left\{ \int_0^1 \frac{dx}{x} x^\epsilon (F(x) - F(0)) + \int_0^1 \frac{dx}{x} x^\epsilon F(0) - \frac{1}{\epsilon} F(0) \right\}$$

$$= \int_0^1 \frac{dx}{x} (F(x) - F(0)) \, ,$$

Established NLO methods: Catani-Seymour, FKS, …

NNLO methods: antenna subtraction, sector-improved residue subtraction,
nested soft-collinear subtraction, local analytic sector subtraction, …

Antenna subtraction implemented in the NNLOJET code

SPAM

Stay tuned for the first public release: https://nnlojet.hepforge.org/

NNLOJET: a parton-level event generator for jet cross sections at NNLO QCD accuracy

NNLOJET Collaboration

A. Huss[1,⋆], L. Bonino[2], O. Braun-White[3], S. Caletti[4], X. Chen[5], J. Cruz–Martinez[1], J. Currie[3], R. Gauld[6], W. Feng[2], E. Fox[3], G. Fontana[2], A. Gehrmann–De Ridder[2,4], T. Gehrmann[2], E.W.N. Glover[3], M. Höfer[7], P. Jakubčik[2], M. Jaquier[8], M. Löchner[2], F. Lorkowski[2], I. Majer[4], M. Marcoli[3], P. Meinzinger[2], J. Mo[2], T. Morgan[3], J. Niehues[3,9], J. Pires[10], C. Preuss[11], A. Rodriguez Garcia[4], K. Schönwald[2], V. Sotnikov[2], R. Schürmann[2], G. Stagnitto[12], D. Walker[3], S. Wells[3], J. Whitehead[13], T.Z. Yang[2] and H. Zhang[8]

Processes available in version 1.0, all at NNLO accuracy:

- $pp \to Z$+jet
- $pp \to W^{\pm}$+jet
- $pp \to H$+jet
- $pp \to \gamma$+jet
- $pp \to$ 1/2 jet
- $e^{\pm}p \to$ 2/3 jets
- $e^{+}e^{-} \to$ 2/3 jets

Fixed-order calculations: dealing with infrared singularities in QCD

Two class of methods to tackle this issue: *subtraction* or *slicing*

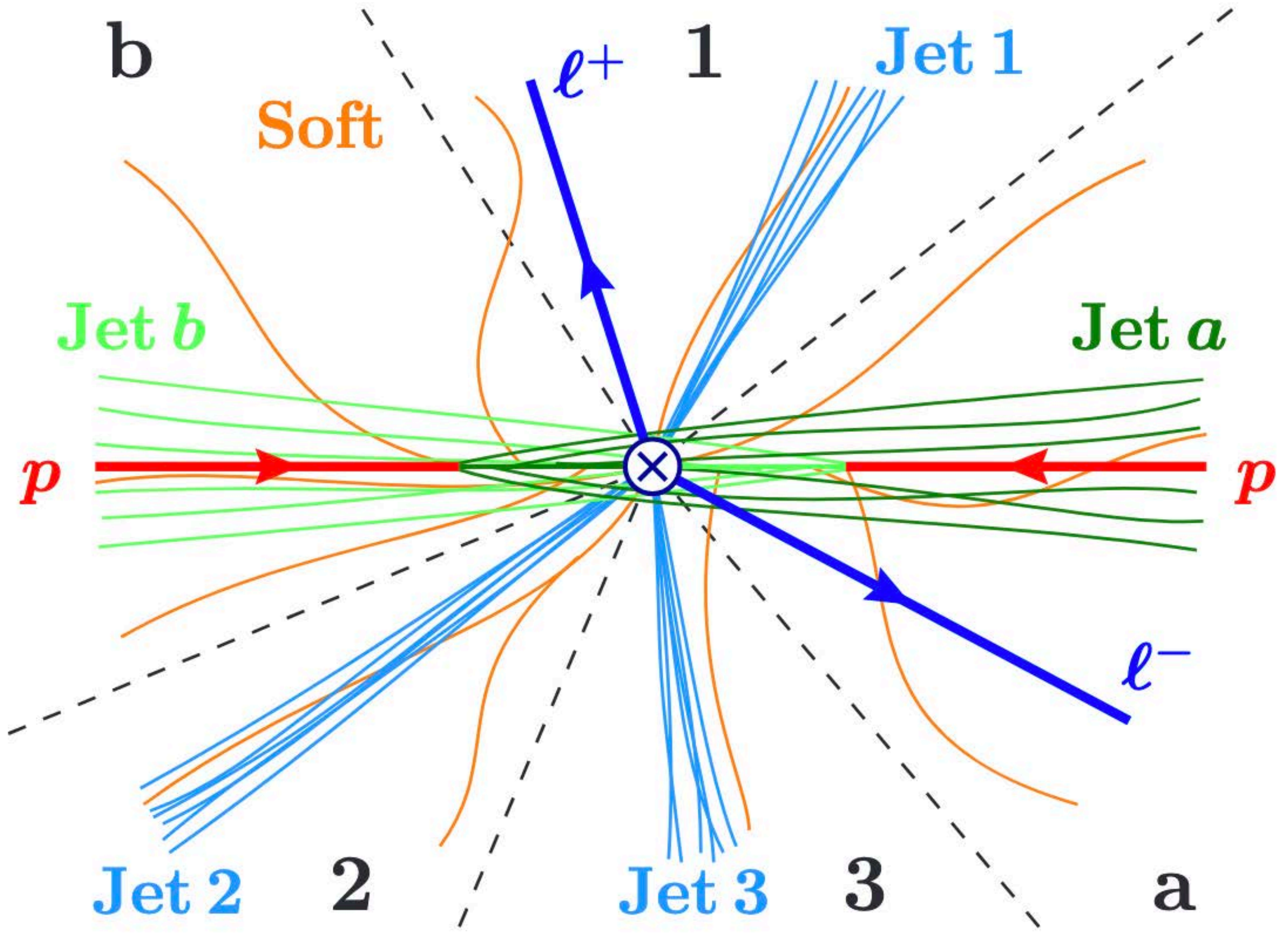
Slicing: introduce a small parameter δ, such that:
- for $x > \delta$, we avoid all divergences (and we can compute it numerically)
- for $x < \delta$, we can approximate it analytically (usually neglecting powers $\delta^{n>0}$)

$$
\begin{aligned}
I &= \lim_{\epsilon \to 0} \left\{ \int_0^{\delta} \frac{dx}{x} x^{\epsilon} F(0) + \int_{\delta}^{1} \frac{dx}{x} x^{\epsilon} F(x) - \frac{1}{\epsilon} F(0) \right\} \\
&= \lim_{\epsilon \to 0} \left\{ \cancel{\frac{1}{\epsilon} F(0)} + \log(\delta) F(0) + \int_{\delta}^{1} \frac{dx}{x} x^{\epsilon} F(x) - \cancel{\frac{1}{\epsilon} F(0)} \right\} \\
&= \log(\delta) F(0) + \int_{\delta}^{1} \frac{dx}{x} F(x) \,.
\end{aligned}
$$

Variants at NNLO: q_T-subtraction, N-jettiness subtraction, …

N-jettiness: a global event shapes at hadron colliders

[Stewart, Tackmann, Waalewijn '10]



$$\tau_N = \frac{2}{Q^2} \sum_k \min\{q_a \cdot p_k,\, q_b \cdot p_k,\, q_1 \cdot p_k,\, \ldots,\, q_N \cdot p_k\}$$

q_a, q_b and $q_1, \ldots, q_N$ are massless reference momenta

It vanishes for exactly N infinitely narrow jets

The limit $\tau_N \to 0$ encapsulates all the singularities of the $V + N$-jet process
-> it can be used as slicing variable for fixed-order calculations

Fixed-order calculations: dealing with infrared singularities in QCD

$$\int_0^1 \frac{dx}{x}(F(x) - F(0))$$

$$\log(\delta)F(0) + \int_\delta^1 \frac{dx}{x}F(x)$$

SUBTRACTION

PROS:
- *local* subtraction (more stable numerically)
- general and/or automated formulations

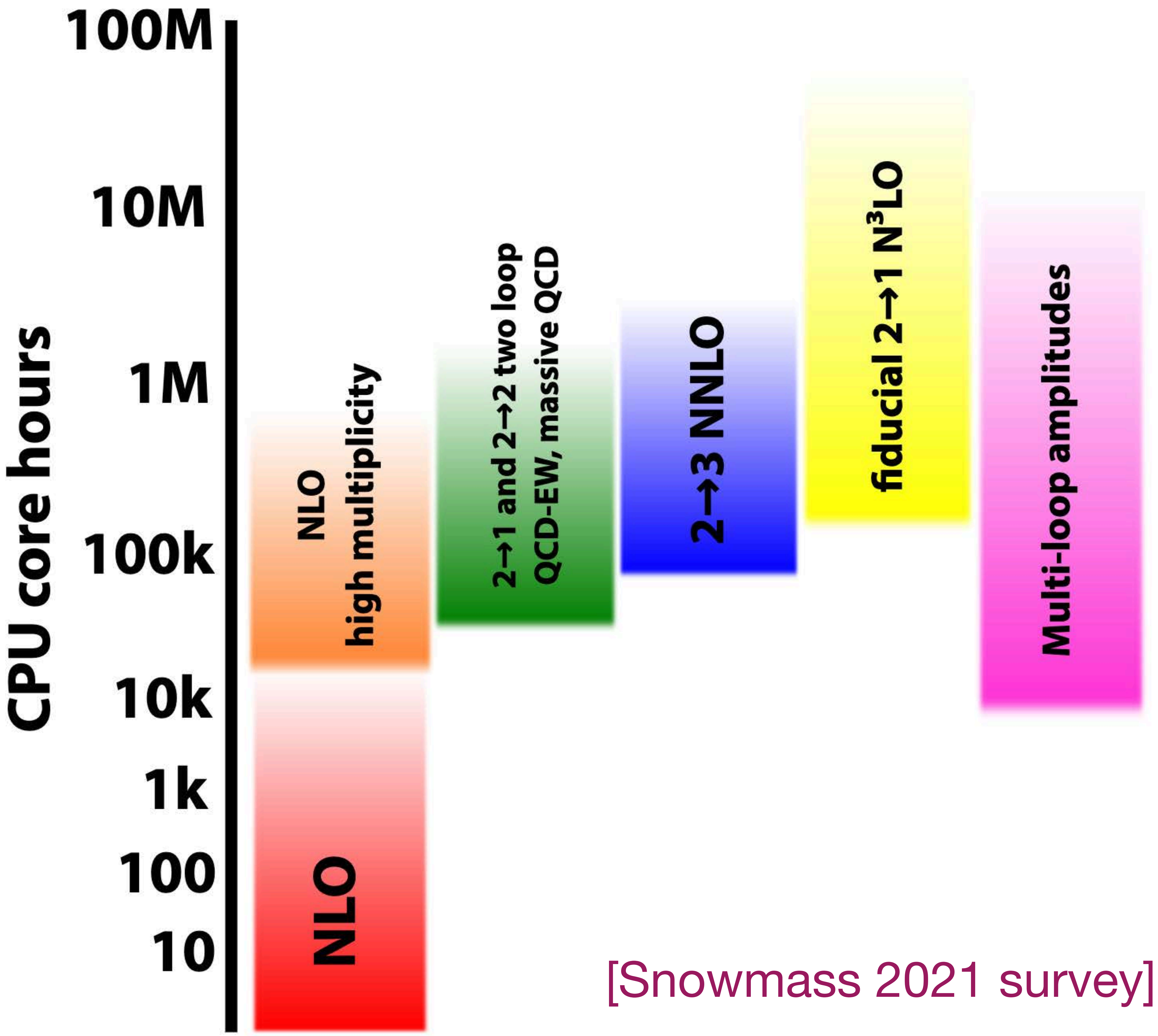
CONS:
- numerical implementation challenging
- integration of counter-terms may be tough (either analytically or numerically)

SLICING

PROS:
- simpler to implement numerically
- matching to parton showers easier

CONS:
- *global* subtraction (large numerical cancellations)
- need analytical knowledge of $\delta \to 0$
- extrapolation for obtain the $\delta \to 0$ limit

Both techniques require significant computing resources at NNLO or at NLO with many particles



[Snowmass 2021 survey]

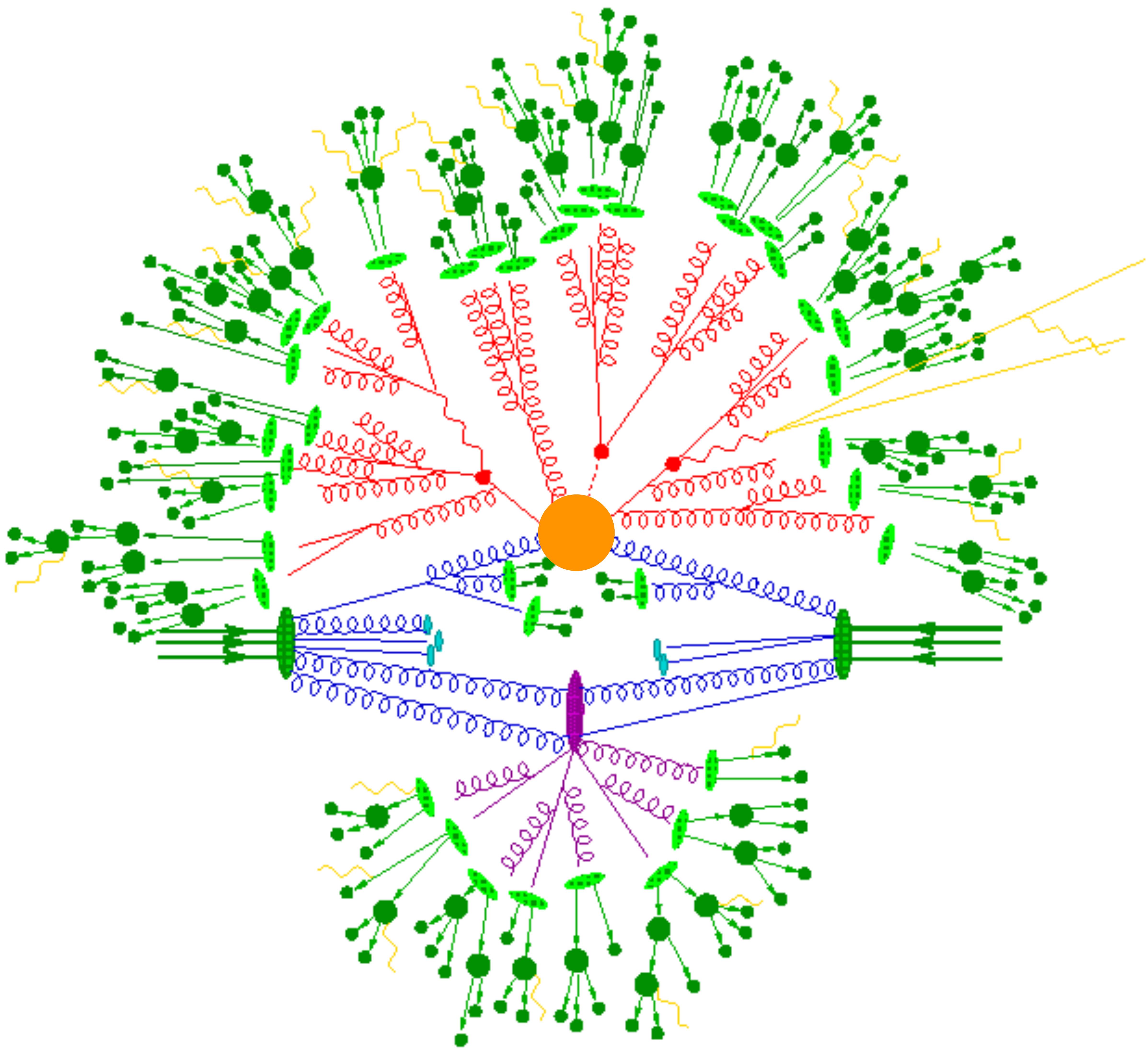
Open questions

How to efficiently store/deliver predictions?
E.g. grids or (un)weighted events?

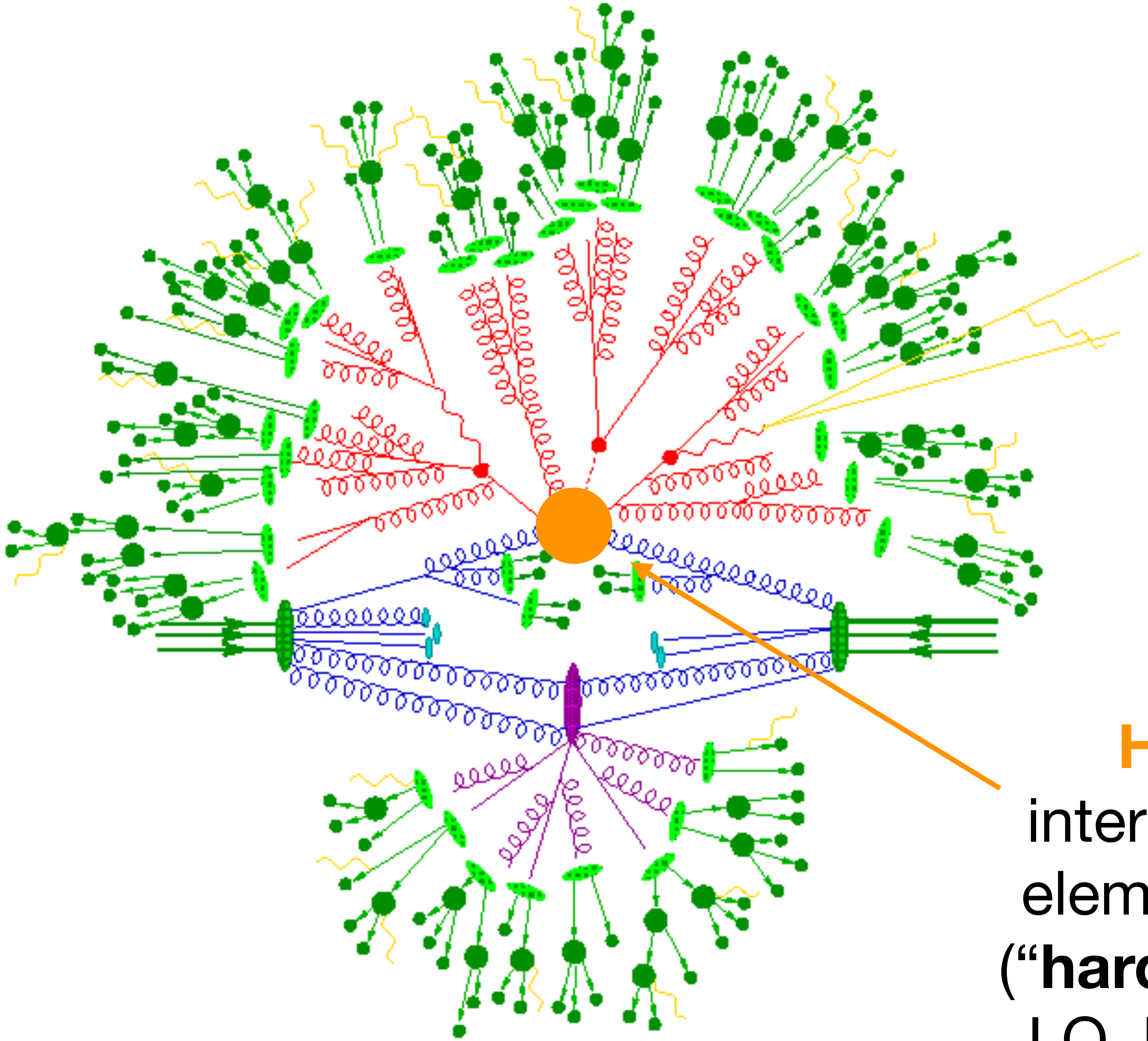
How to optimise Monte Carlo integration?
E.g. machine learning?

How to exploit advantages of GPUs?
E.g. Redesign our (Fortran) codes?

From hard scattering to realistic events



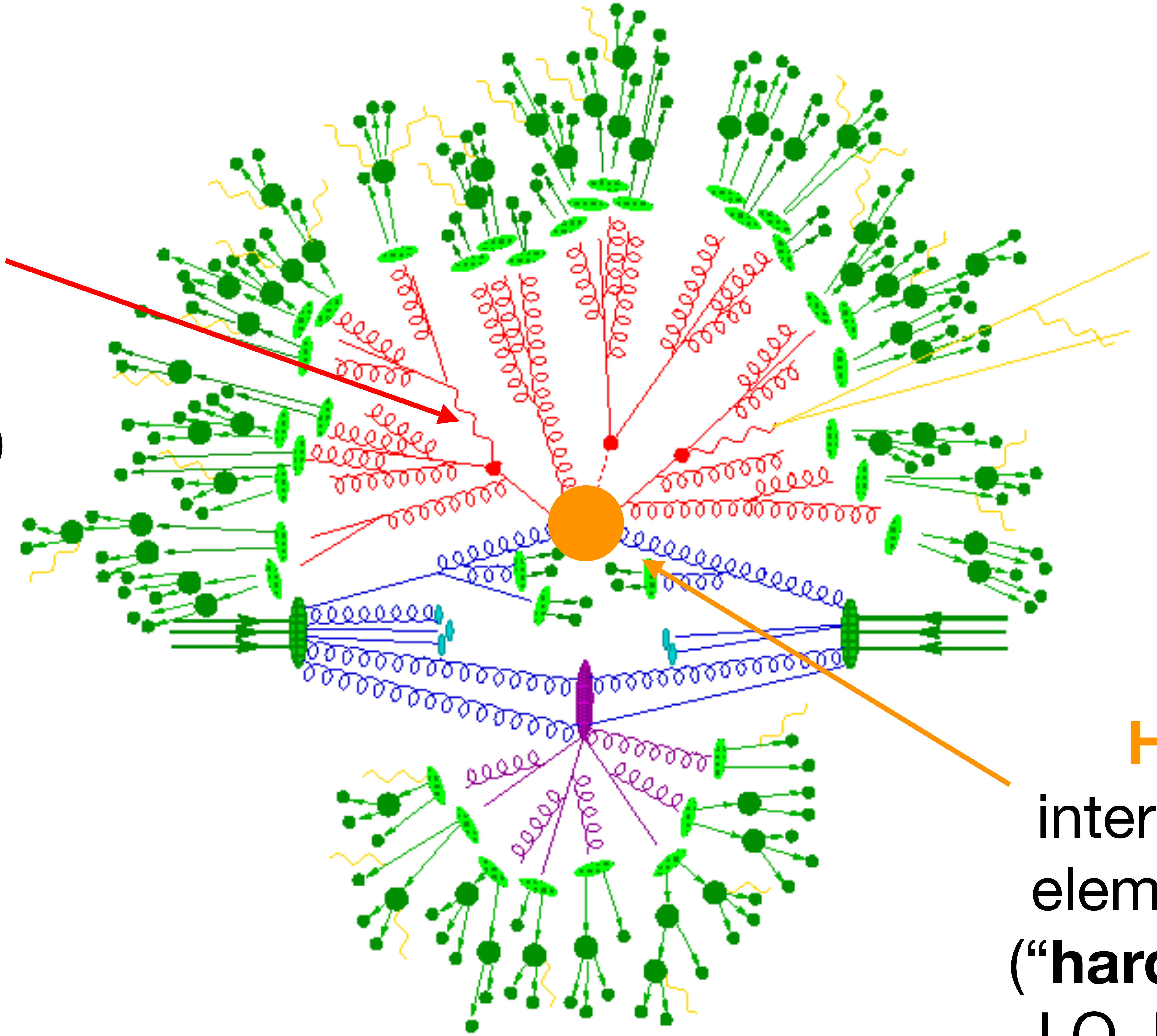
From hard scattering to realistic events



High-energy interaction between elementary particles (“**hard scattering**”) at LO, NLO, NNLO, …

From hard scattering to realistic events

From high-energy to low-energy with emission of (mostly) collinear and/or soft quark and gluons (“**parton shower**”, PS)



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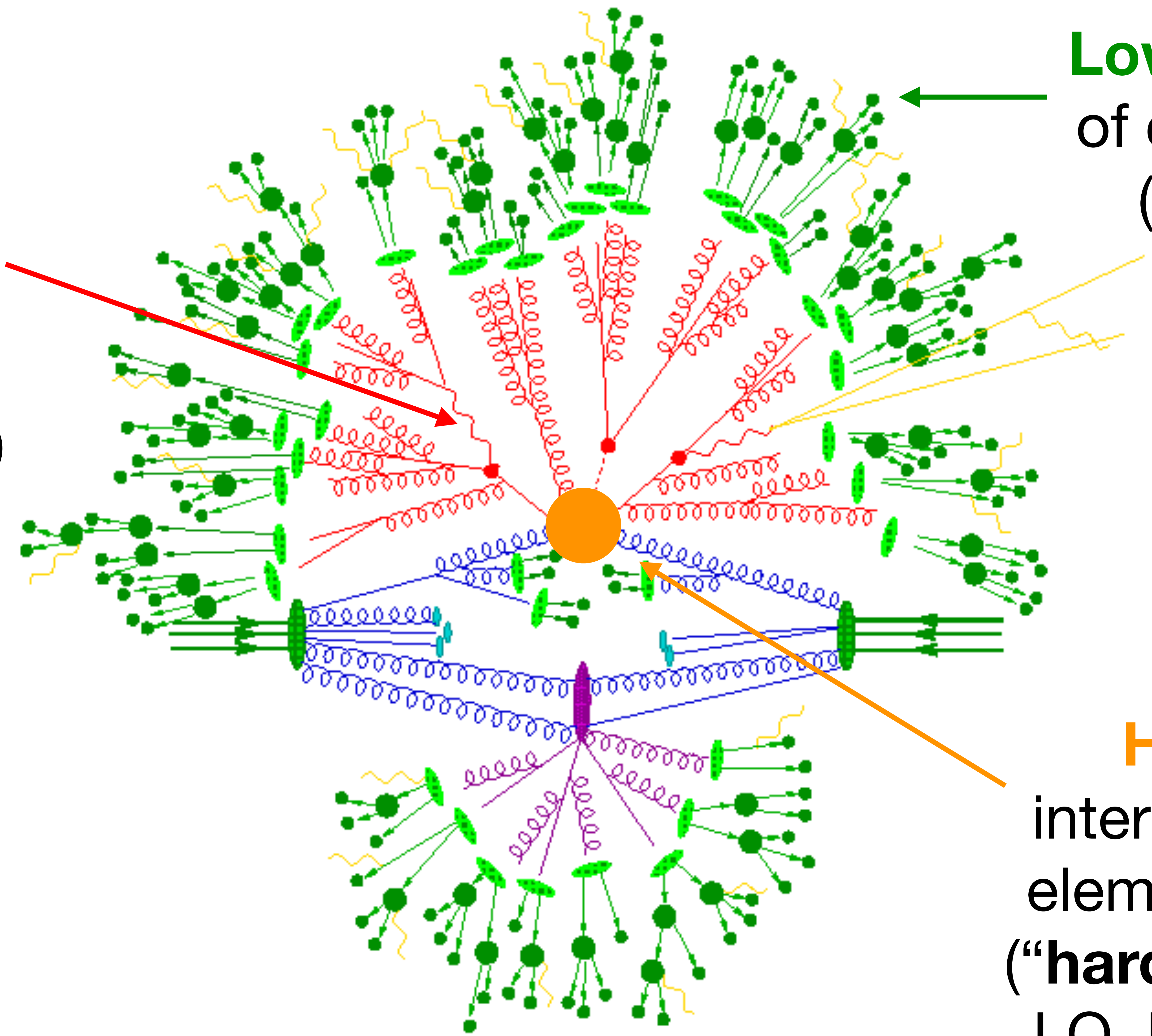
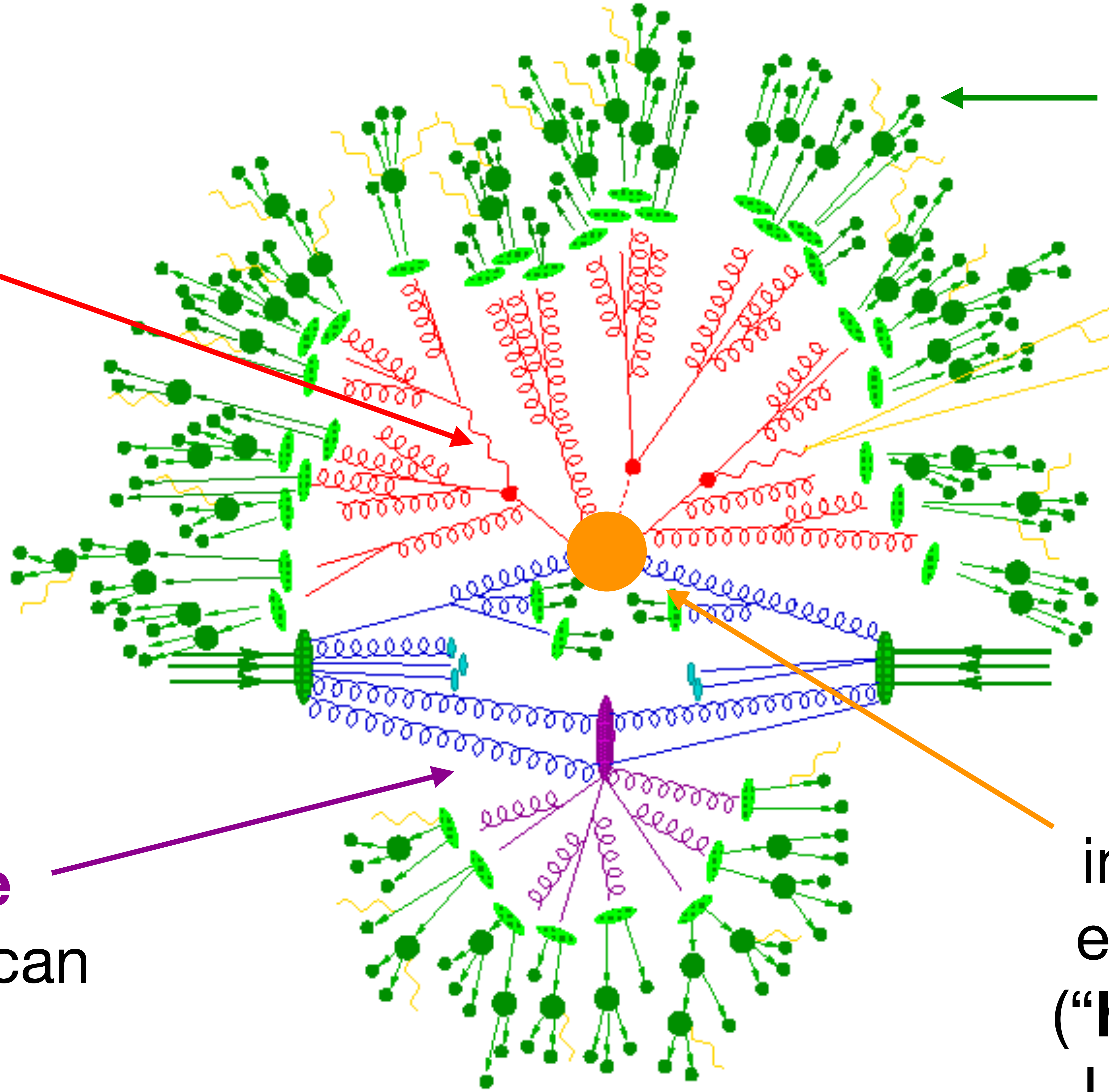


Low-energy formation of composite particles ("**hadronization**")

High-energy interaction between elementary particles ("**hard scattering**") at LO, NLO, NNLO, …

From hard scattering to realistic events

From high-energy to low-energy with emission of (mostly) collinear and/or soft quark and gluons (“**parton shower**”, PS)



Low-energy formation of composite particles (“**hadronization**”)

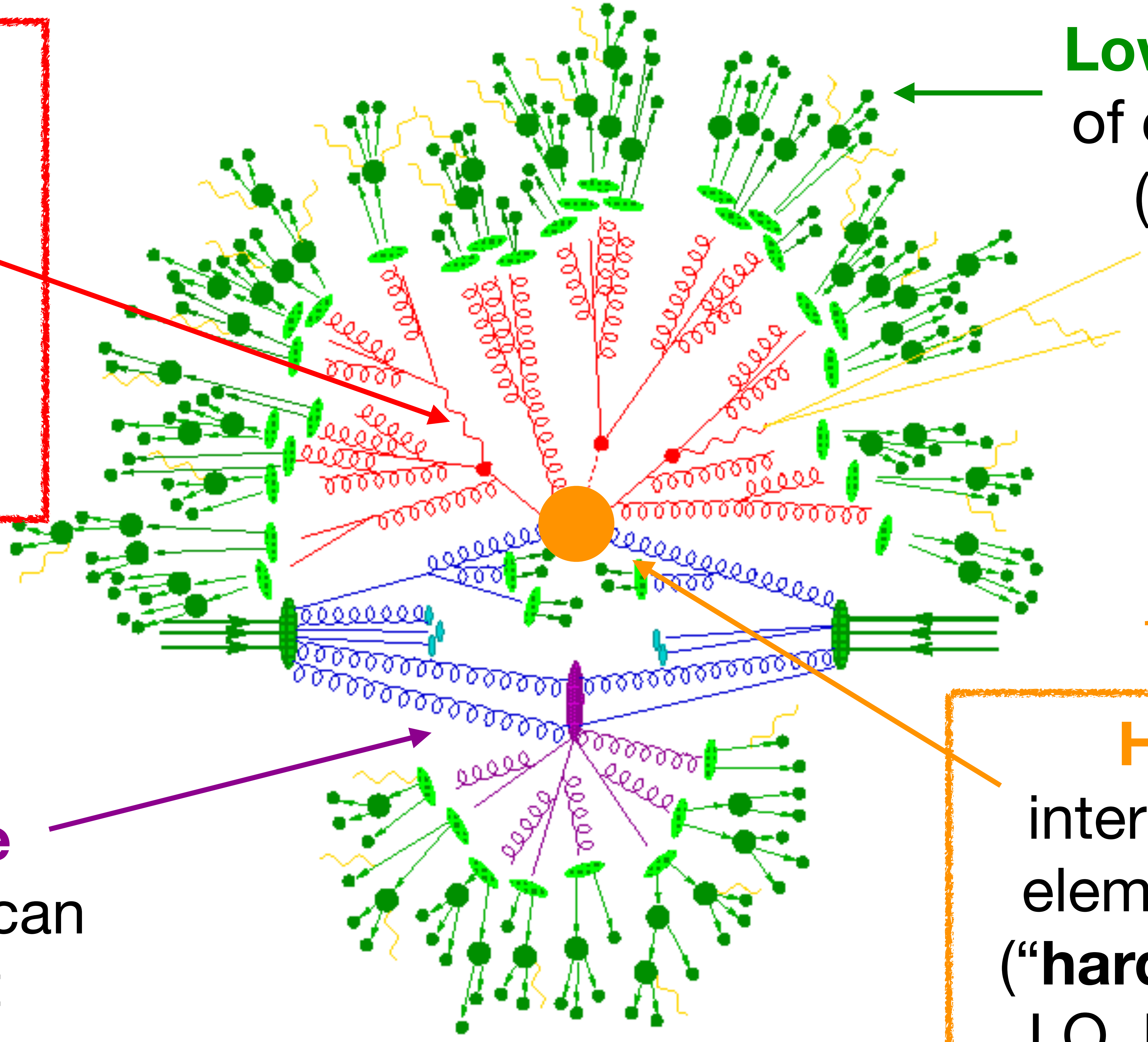
Multiple Particle Interactions (MPI) can pollute the event

High-energy interaction between elementary particles (“**hard scattering**”) at LO, NLO, NNLO, …

From hard scattering to realistic events

From high-energy to low-energy with emission of (mostly) collinear and/or soft quark and gluons (“**parton shower**”, PS)

Approximate multiple emissions

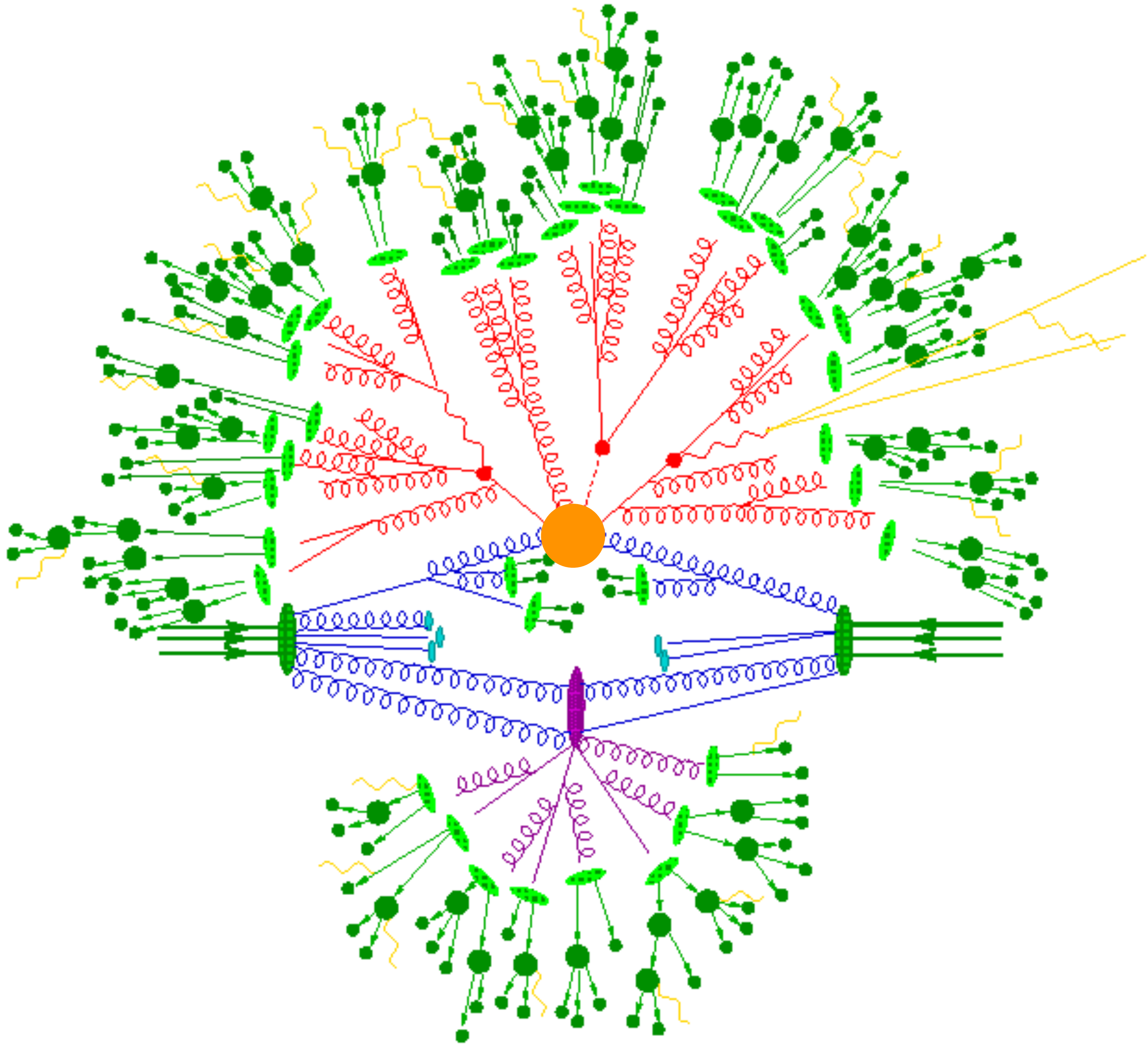


Low-energy formation of composite particles (“**hadronization**”)

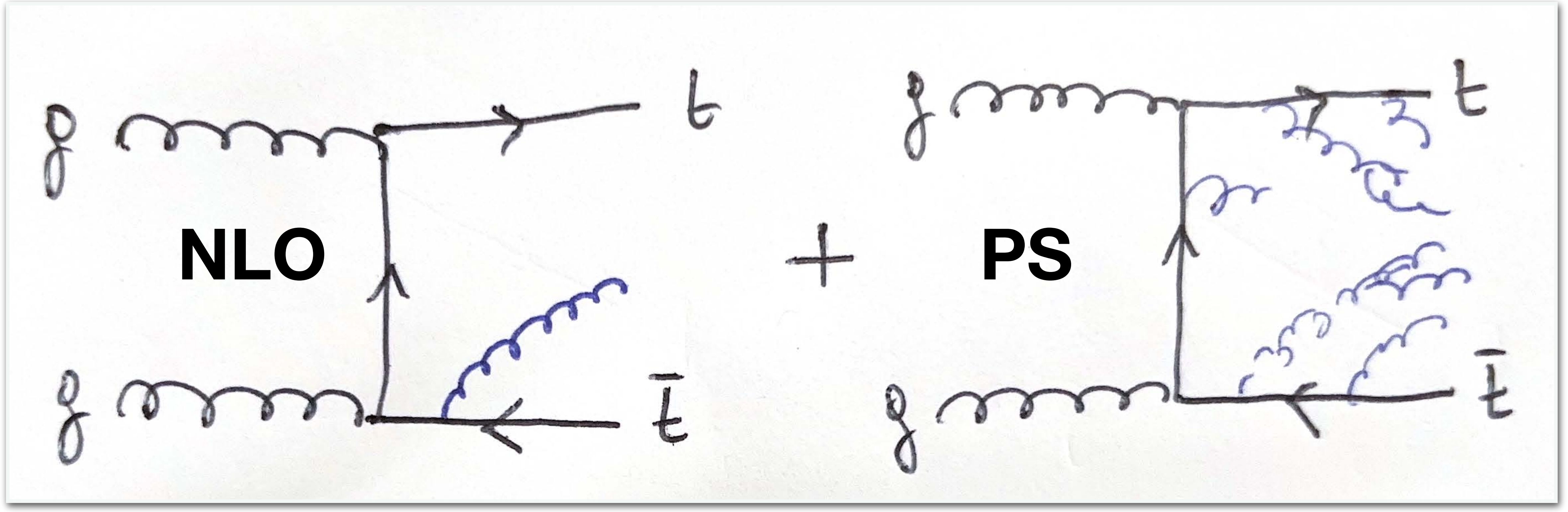
Exact 1/2/3/… emissions

Multiple Particle Interactions (MPI) can pollute the event

High-energy interaction between elementary particles (“**hard scattering**”) at LO, NLO, NNLO, …



Example: top + anti-top production



Exact one gluon emission

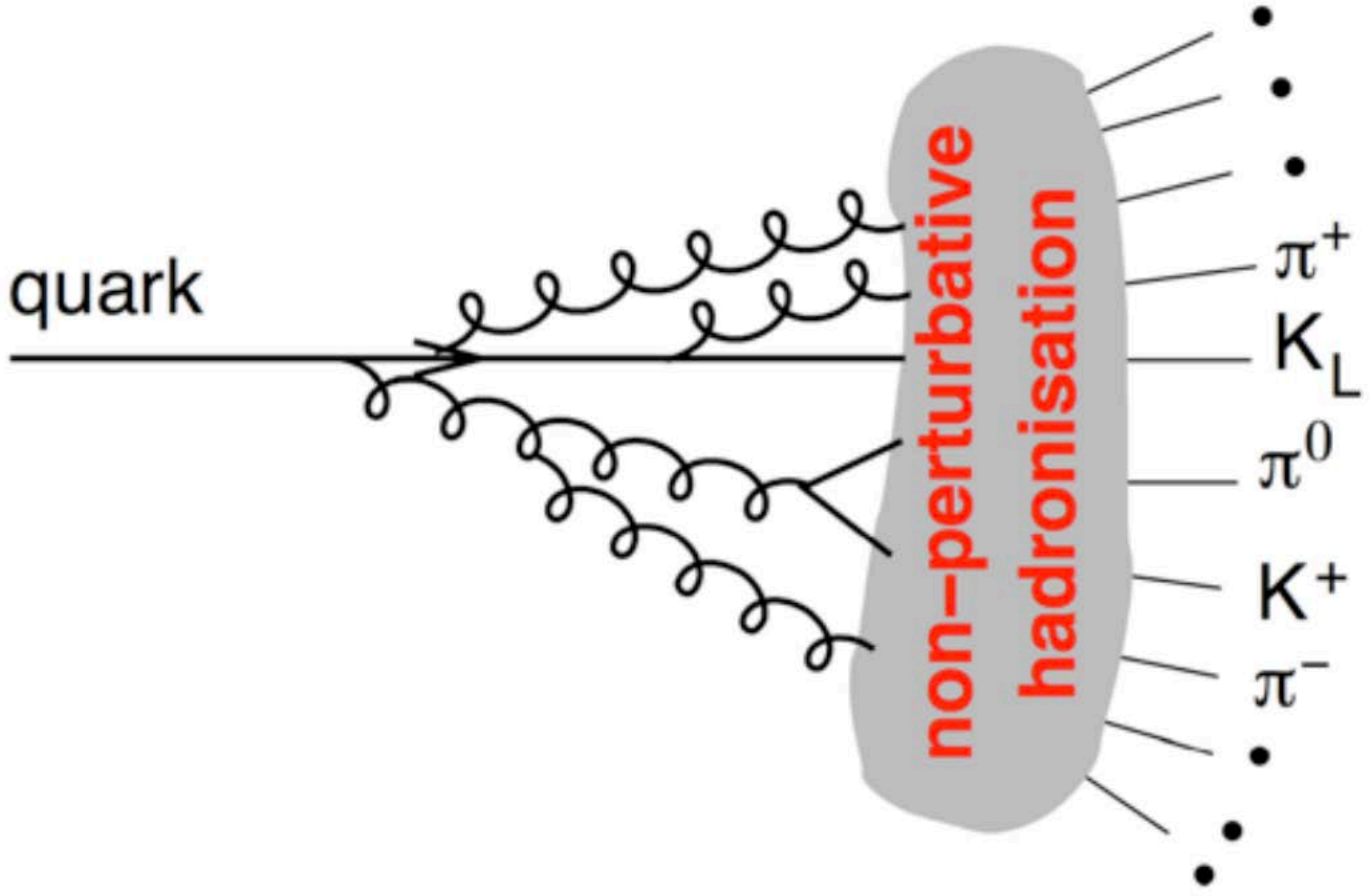
Approximate multiple gluon emissions

How to match
fixed-order (LO, NLO, NNLO)
to **parton shower** (PS)
without loosing accuracy
and without "double counting"?

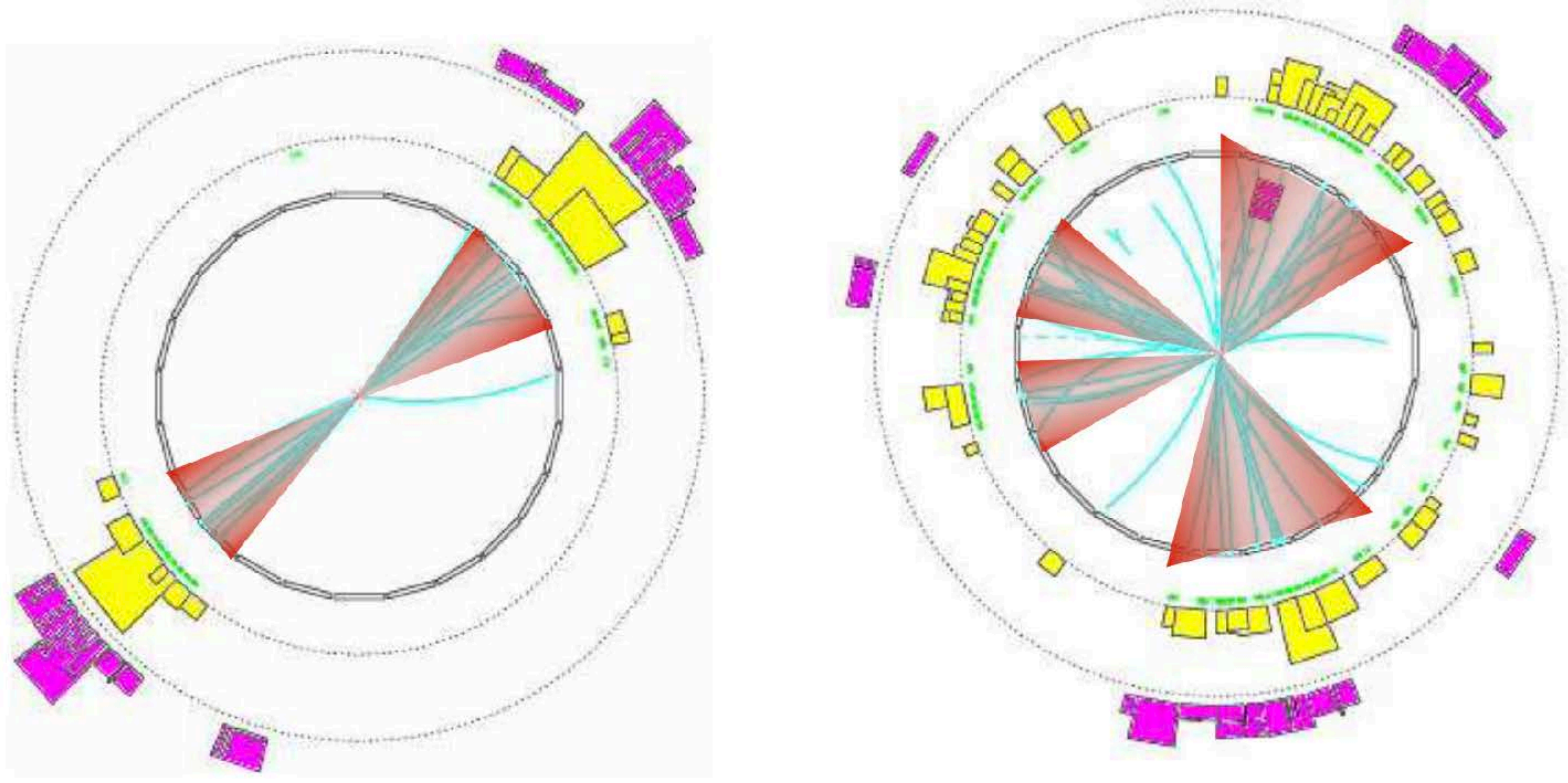
Well established methods for **NLO+PS** predictions:
MC@NLO, POWHEG, …

Methods for **NNLO+PS** predictions still in development:
GENEVA, MiNNLOPS, …

On the definition of jets



Naive definition:
collimated bunch of hadrons
flying roughly in the same direction



2 clear jets

3 jets?
or 4 jets?

Proper definition:
a collection of hadrons
defined by means of a **jet algorithm**

"*Jet [definitions] are legal contracts between theorists and experimentalists*"
MJ Tannenbaum

Jet definition must satisfy IRC safety

An observable is **infrared and collinear safe** if, in the limit of a **collinear splitting**, or the **emission of an infinitely soft** particle, the observable remains **unchanged:**

$$O(X; p_1, \ldots, p_n, p_{n+1} \to 0) \to O(X; p_1, \ldots, p_n)$$

$$O(X; p_1, \ldots, p_n \parallel p_{n+1}) \to O(X; p_1, \ldots, p_n + p_{n+1})$$

This property ensures cancellation of **real** and **virtual** divergences in higher order calculations

If we wish to be able to calculate a jet rate in perturbative QCD the jet algorithm that we use must be IRC safe:
soft emissions and collinear splittings must not change the hard jets

M. Cacciari

Jets at the LHC usually defined by means of a sequential clustering algorithm

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

Distance between particles i and j

Distance between particle i and the beam

p = 1 k_t algorithm

S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187
S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

p = 0 Cambridge/Aachen algorithm

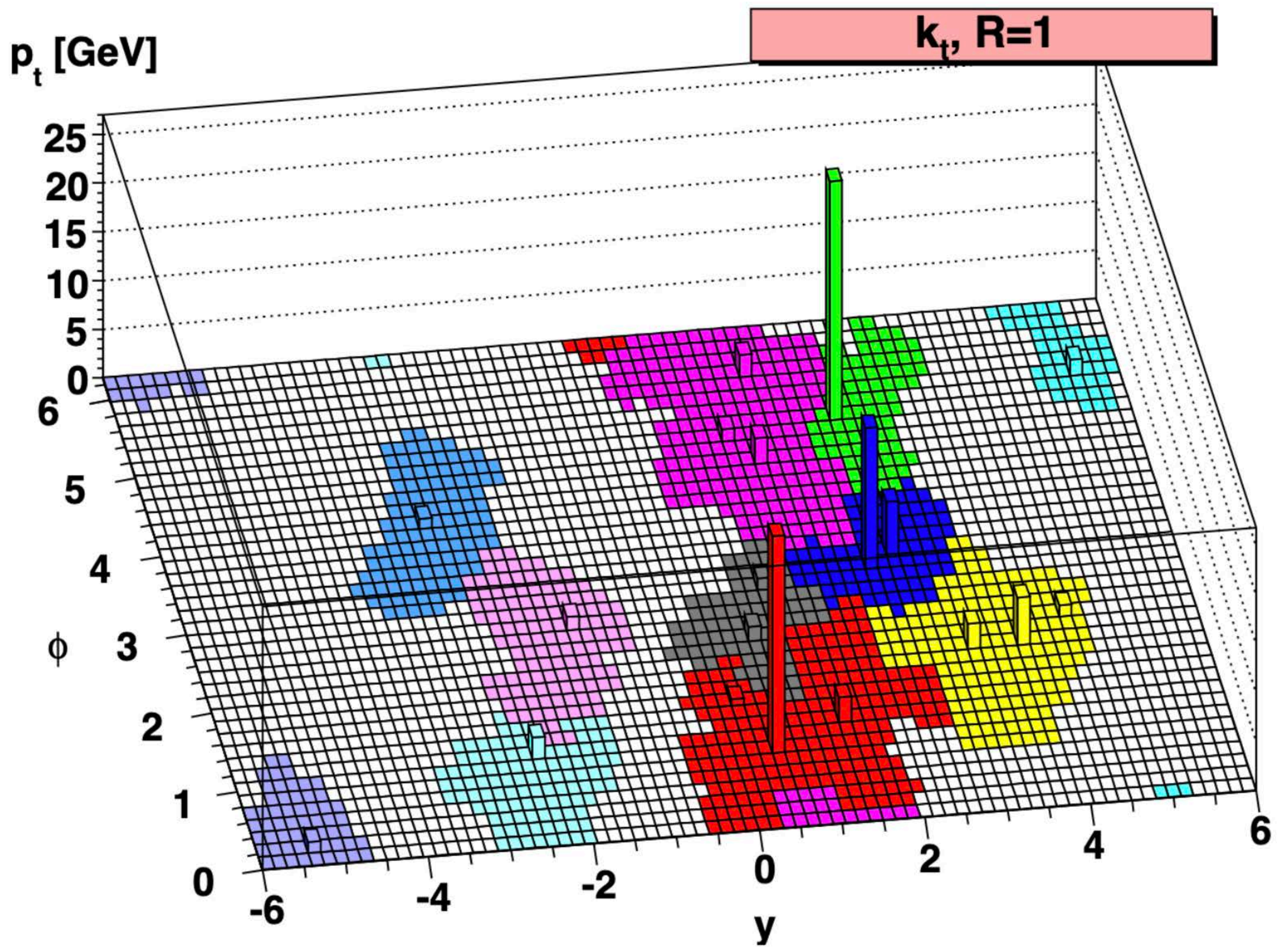
Y. Dokshitzer, G. Leder, S.Moretti and B. Webber, JHEP 08 (1997) 001
M. Wobisch and T. Wengler, hep-ph/9907280

p = -1 **anti-k_t algorithm**

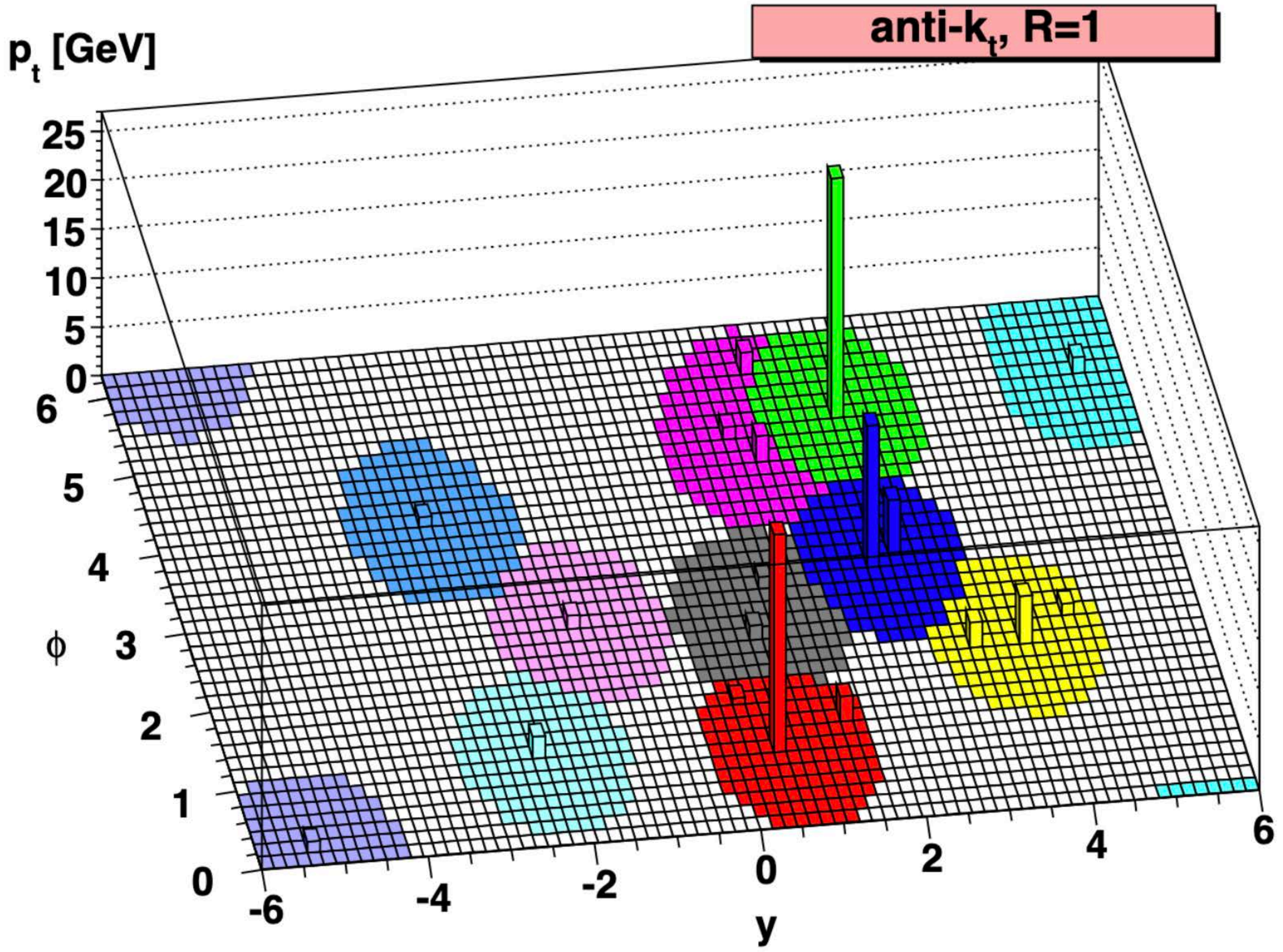
MC, G. Salam and G. Soyez, arXiv:0802.1189

NB: in anti-kt pairs with a **hard** particle will cluster first: if no other hard particles are close by, the algorithm will give **perfect cones**

M. Cacciari



p = 1 k_t algorithm



p = -1 anti-k_t algorithm

The anti-k_t acts as IRC safe "cone" algorithm

Outlook of this talk

1. (Rather long and pedagogical) introduction

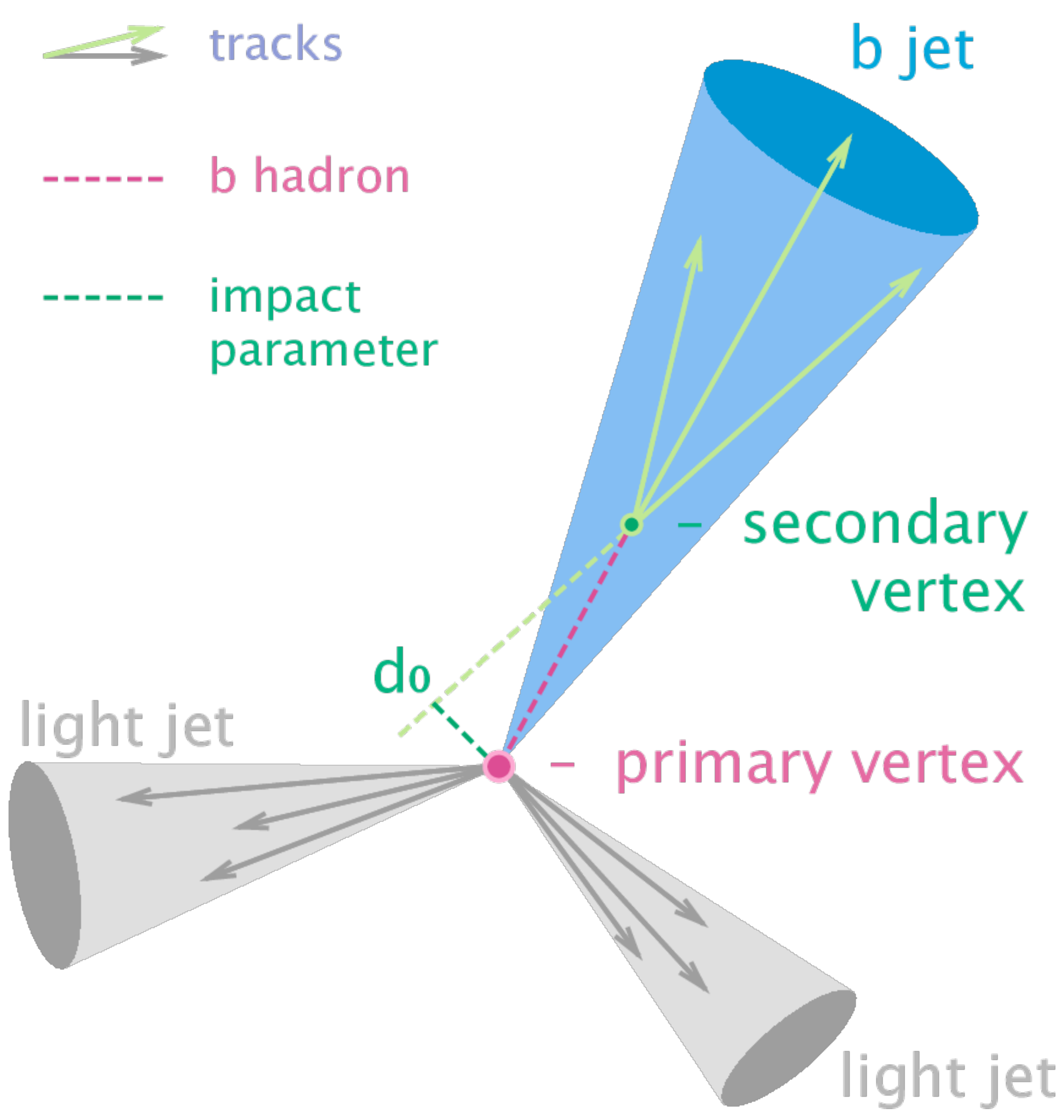
2. Flavoured jets at the LHC:
Z+c-jet and W+c-jet production

3. Towards NNLO+PS for V+jet:
improving slicing methods for V+jet production

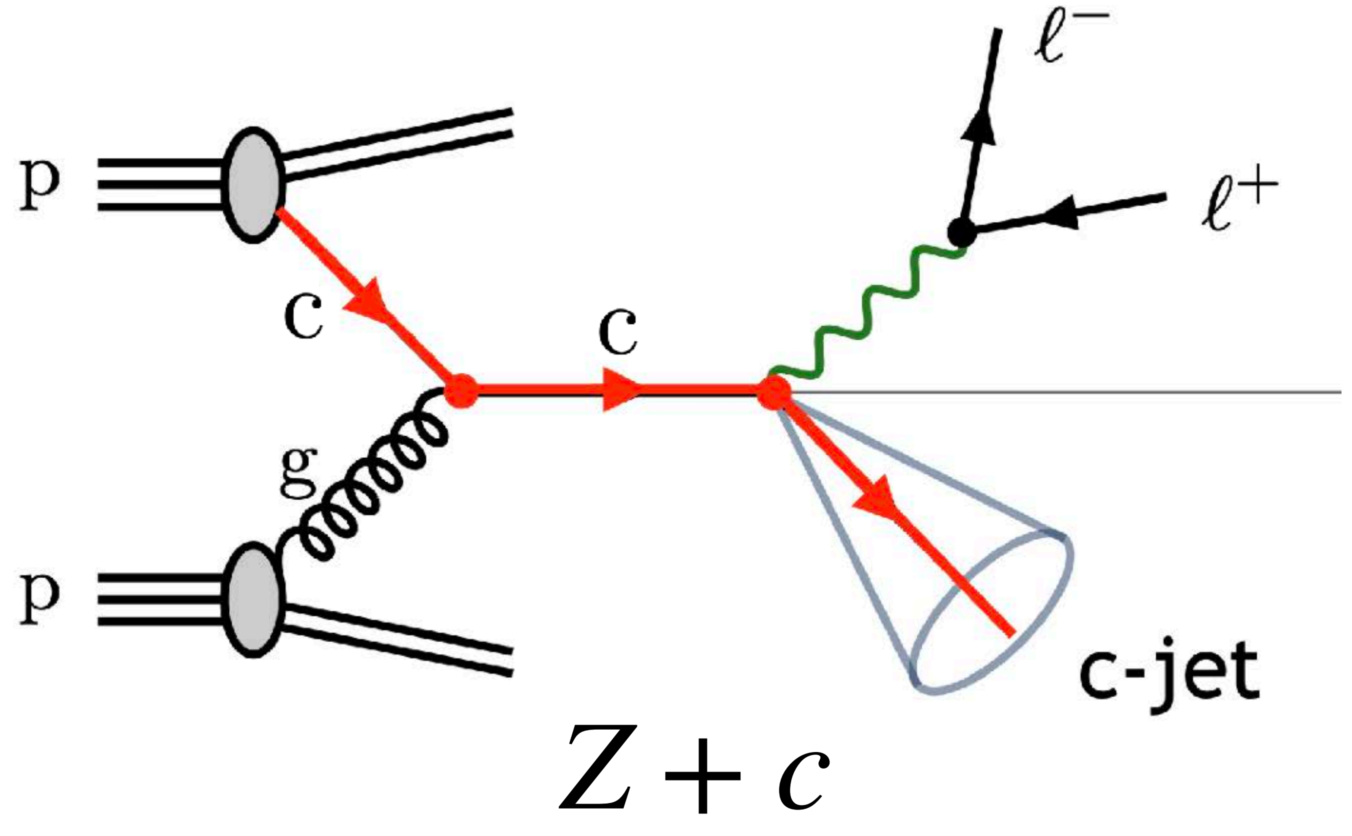
Biased selection of recent results where I personally contributed.
Minimal inclusion of references, apologies for any relevant omission.

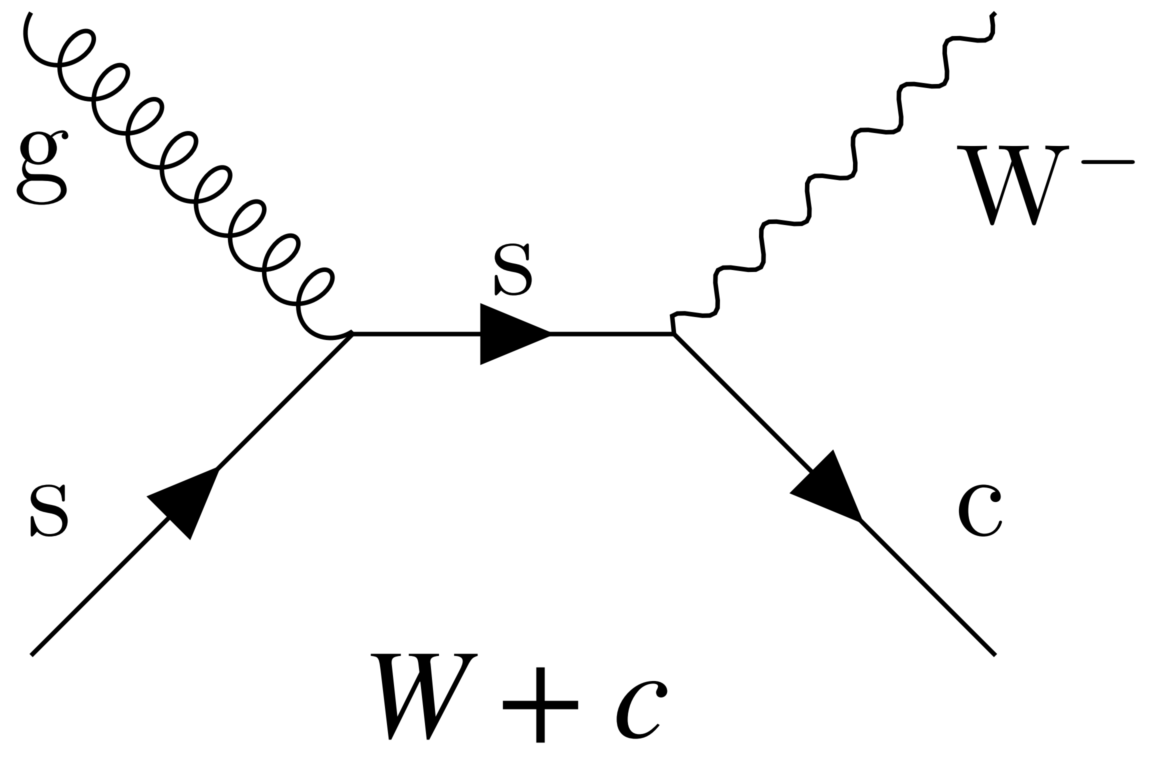
What do we mean by *flavoured* jets?

Jets initiated by charm (m ~ 1.5 GeV) or bottom (m ~ 4.2 GeV) quarks that leaves specific signatures in the detector

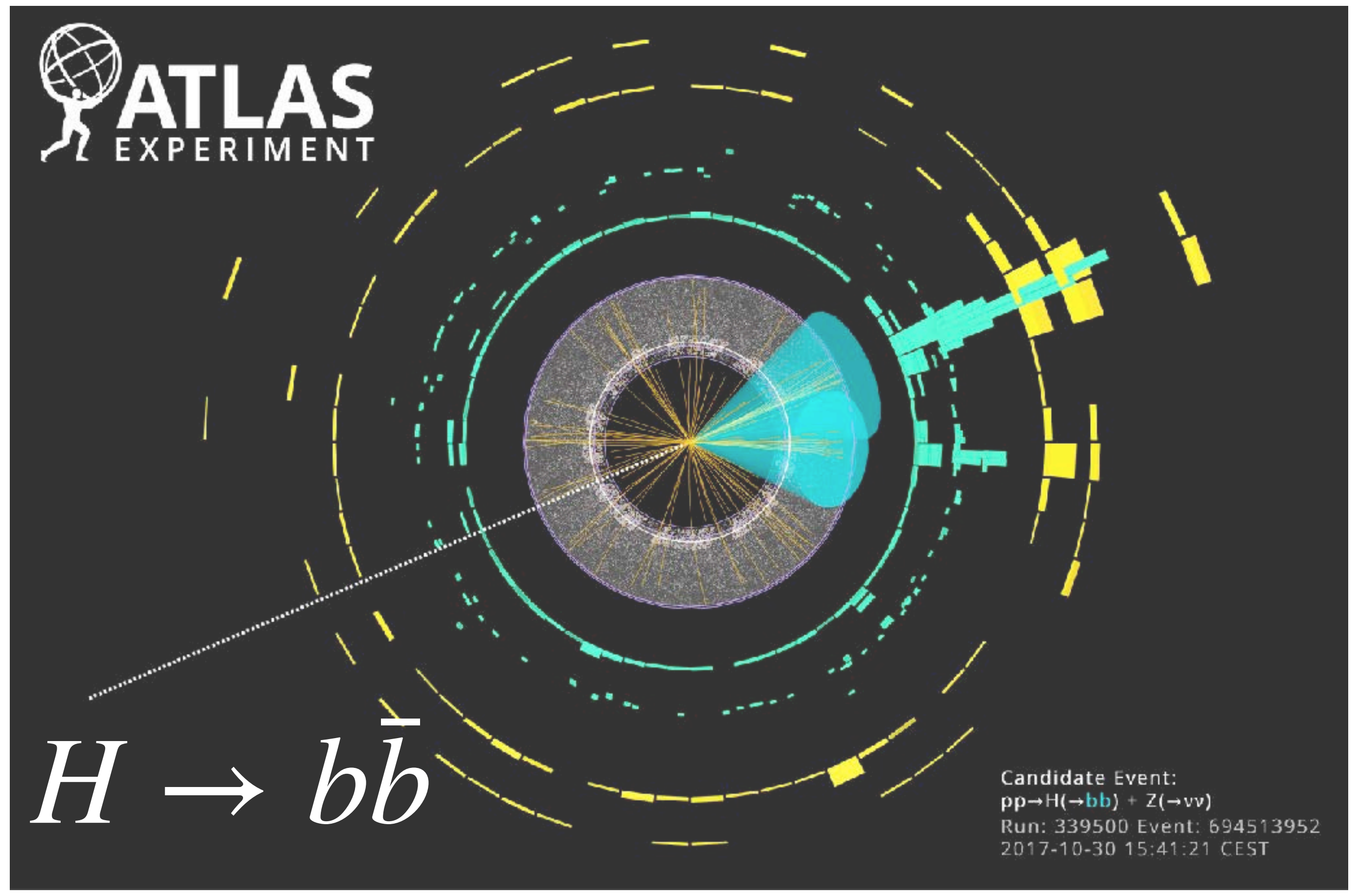


e.g. lifetime of B-hadron long enough to travel a macroscopic distance before decaying



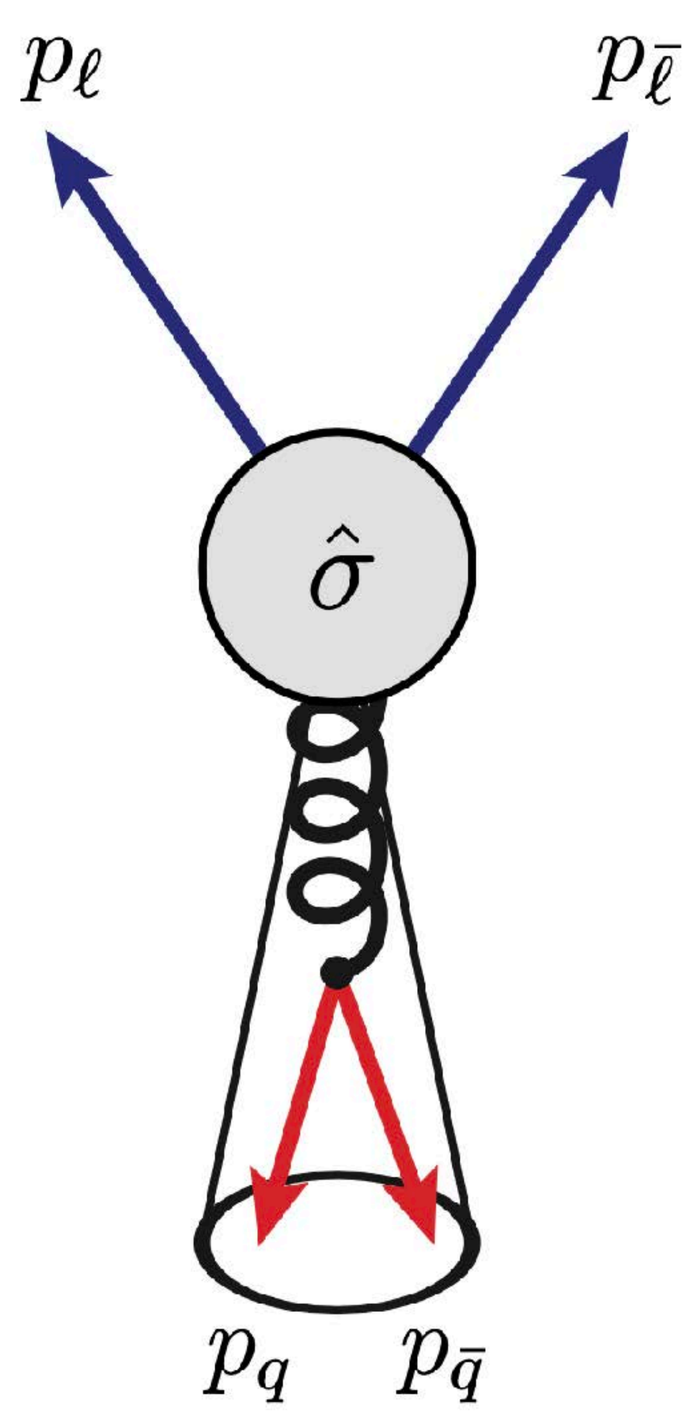


Flavoured jets useful to disentangle quark flavours inside the proton and special role in Higgs physics

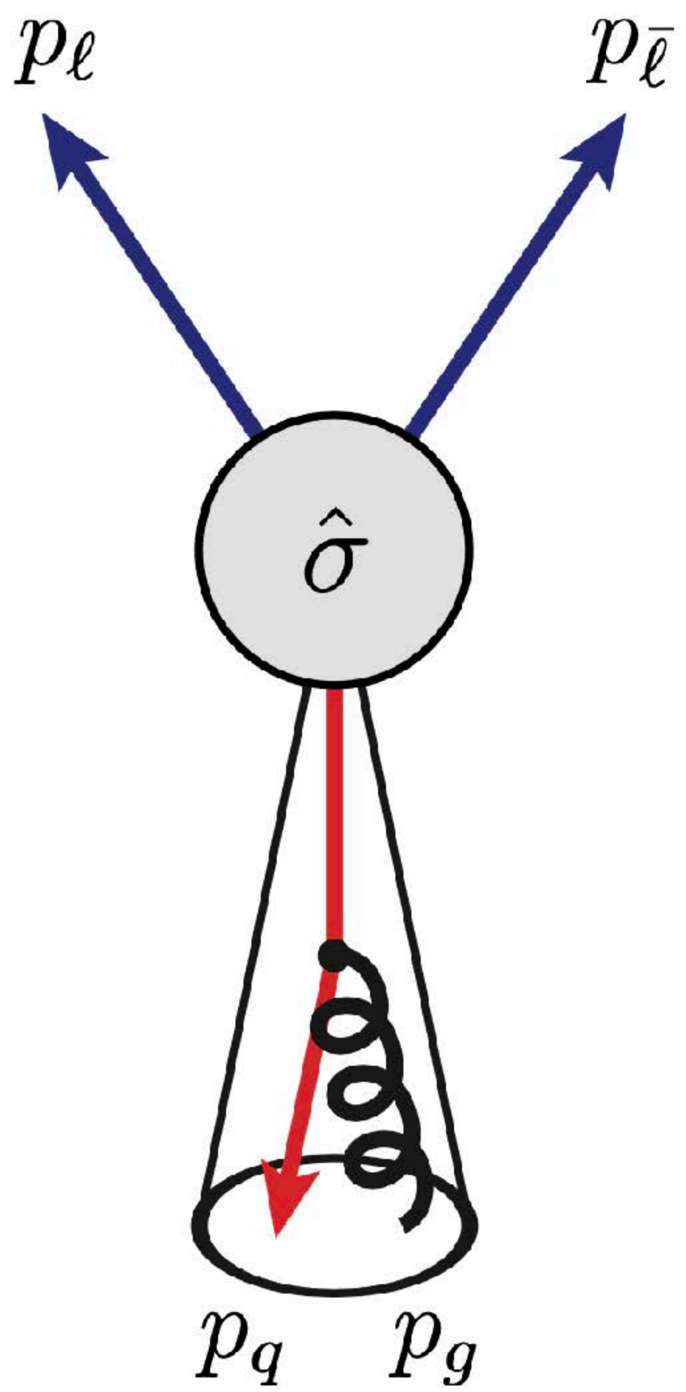


Problem: definition of flavoured jet in perturbative QCD calculations

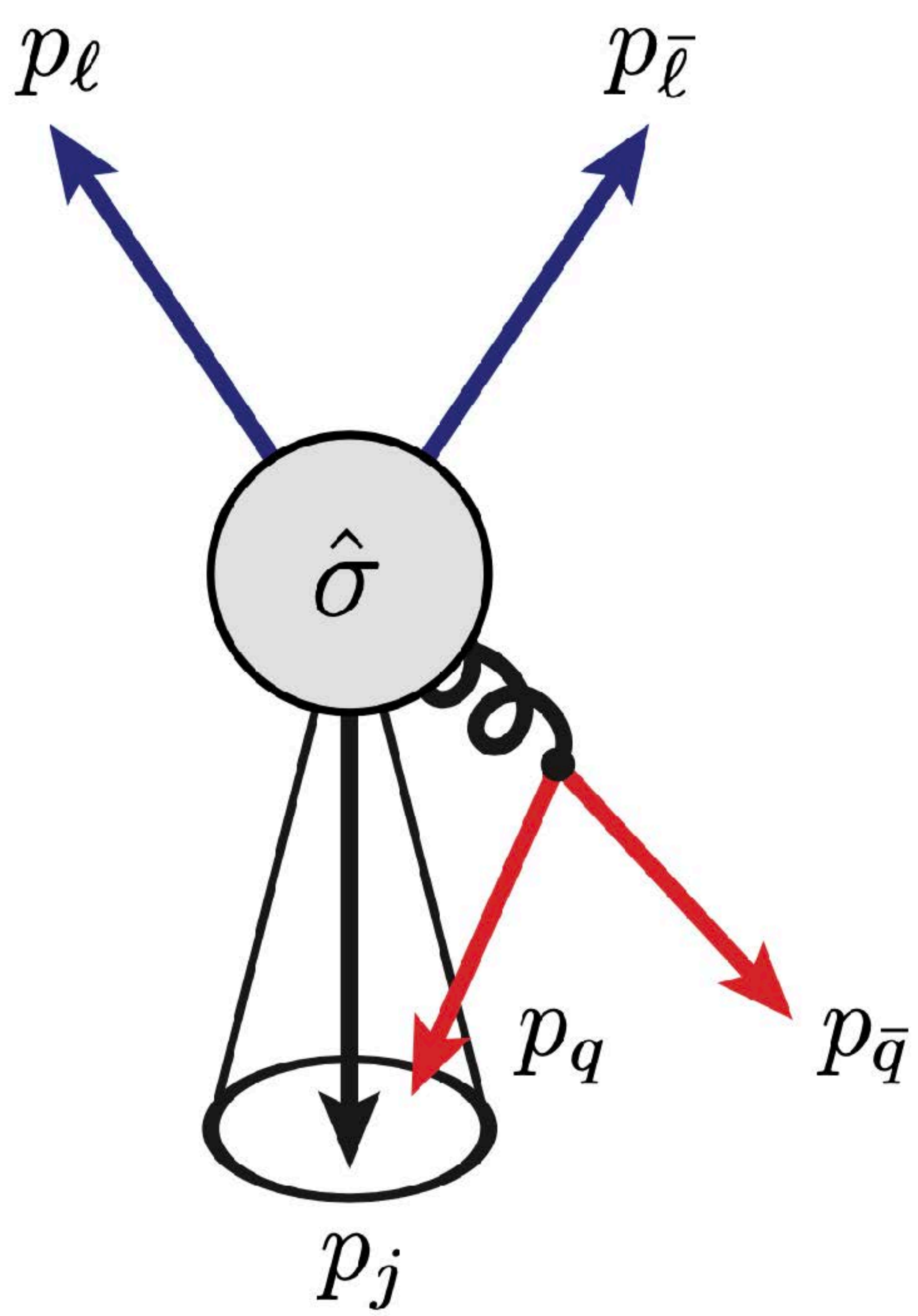
“A (anti-k_t) jet is flavoured if it contains a flavoured quark inside it with some minimal energy”



$g \to q\bar{q}$ is always flavoured even in the collinear limit
-> **collinear unsafe**



$q \to qg$ collinear with a hard gluon leads to a flavourless jet
-> **collinear unsafe**



Soft large-angle $g \to q\bar{q}$ polluting the flavour of other jets
-> **soft unsafe**

Solution: new generation of infrared safe flavoured jet algorithms (2022 - …)

4 new proposals, IRC safe to all orders (or up to high order) with exact (or close to exact) anti-k_t kinematics

[Caletti, Larkoski, Marzani, Reichelt (2205.01109)] **SDF**

[Czakon, Mitov, Poncelet (2205.11879)] **CMP**

[Gauld, Huss, GS (2208.11138)] **GHS**

[Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2306.07314)] **IFN**

A FastJet implementation of all algorithms available in fjcontrib from version 1.101

https://fastjet.hepforge.org/contrib/

Solution: new generation of infrared safe flavoured jet algorithms (2022 - …)

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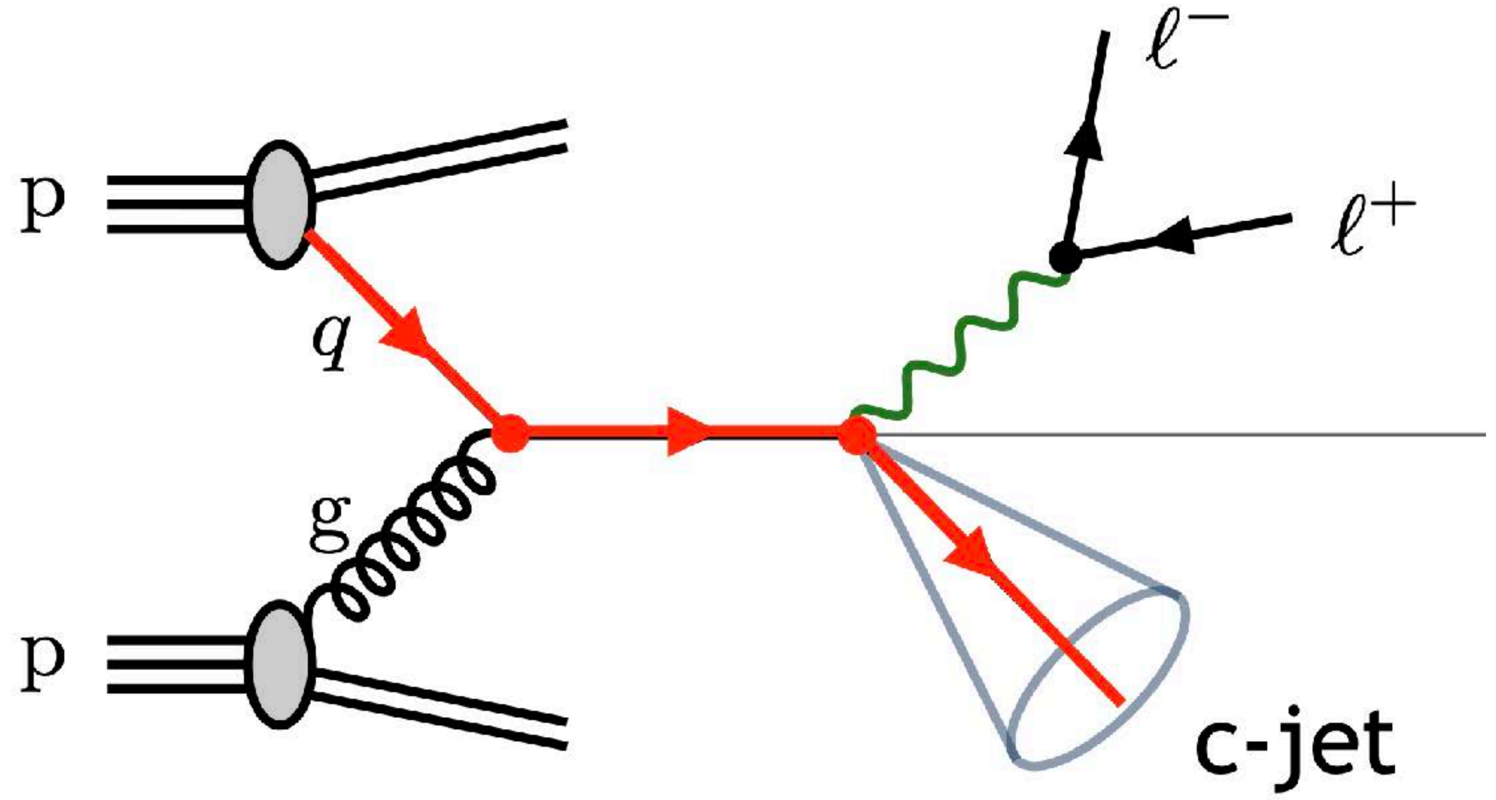
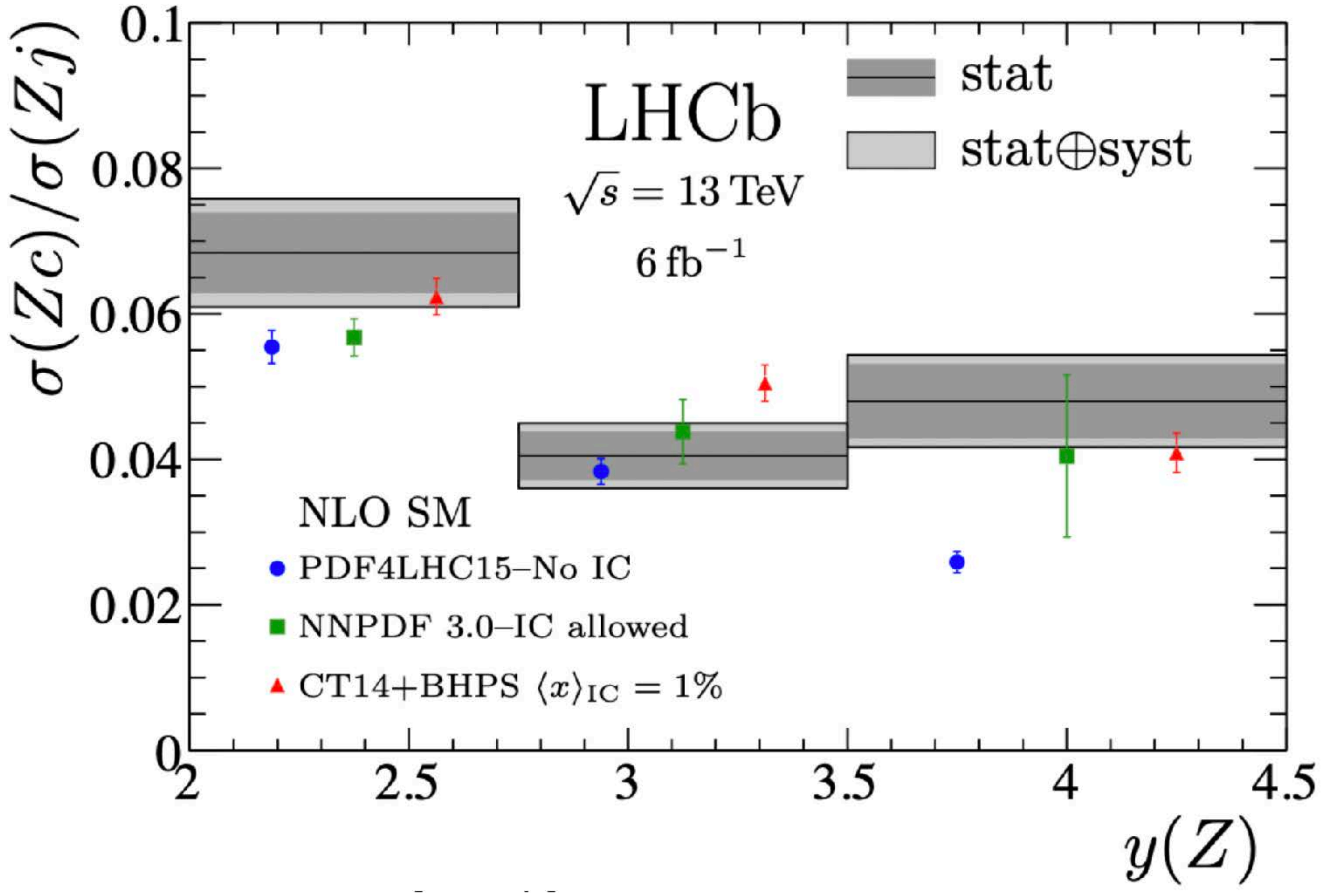
Here I will focus on some QCD NNLO results about Z+c-jet [2302.12844] and W+c-jet [2311.14991] with GHS algorithm

These NNLO predictions were obtained with NNLOJET by tracking flavour of final-state particles in all layers of the calculation

$Z + c$-jet in the forward region (LHCb)

Measurement sensitive to **intrinsic charm in the proton**





Z bosons	$p_T(\mu) > 20\,\text{GeV},\ 2.0 < \eta(\mu) < 4.5,\ 60 < m(\mu^+\mu^-) < 120\,\text{GeV}$
Jets	$20 < p_T(j) < 100\,\text{GeV},\ 2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c\text{ hadron}) > 5\,\text{GeV},\ \Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

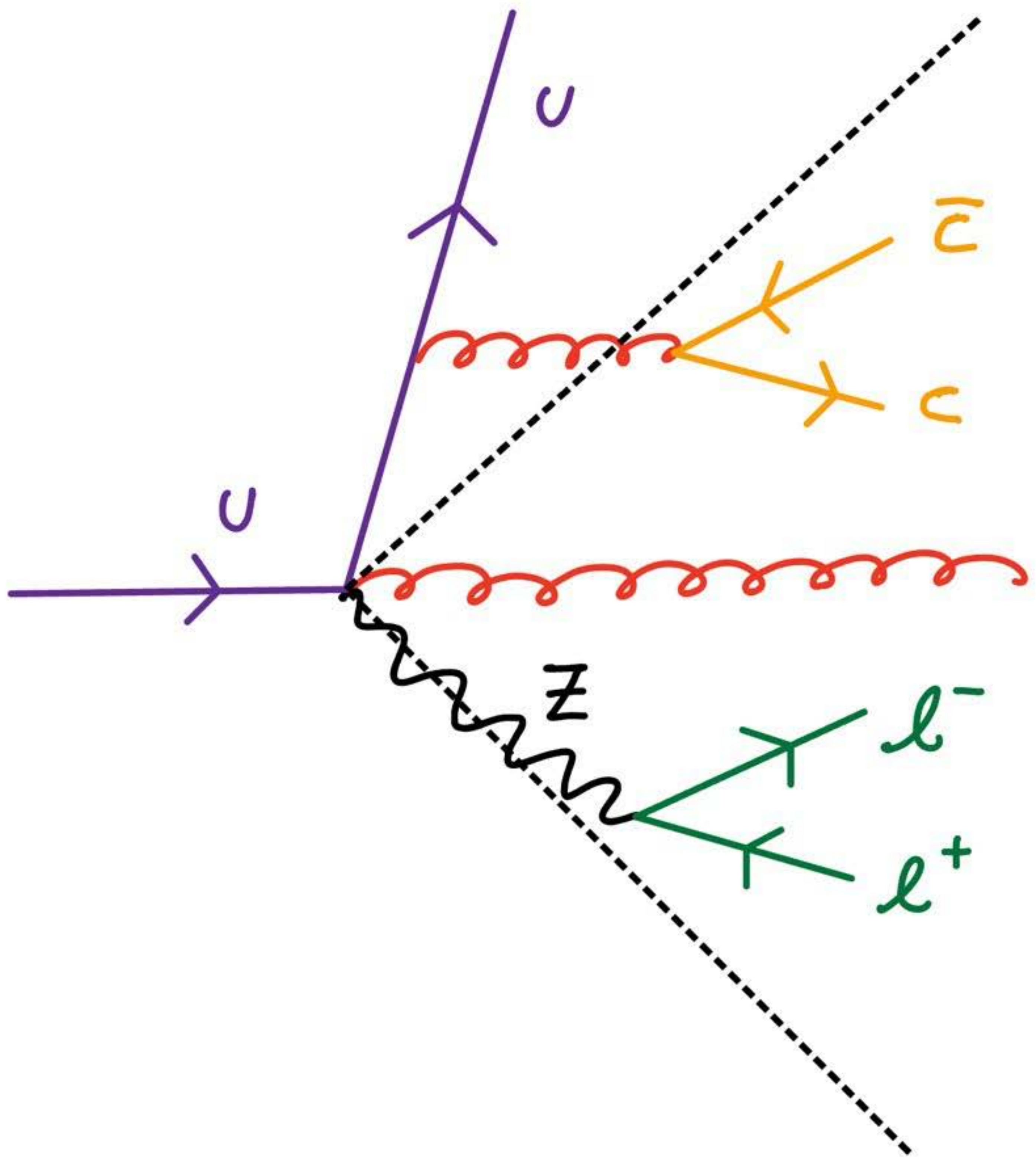
Very unique fiducial region of the measurement:

Z bosons	$p_{\mathrm{T}}(\mu) > 20\,\mathrm{GeV},\ 2.0 < \eta(\mu) < 4.5,\ 60 < m(\mu^+\mu^-) < 120\,\mathrm{GeV}$
Jets	$20 < p_{\mathrm{T}}(j) < 100\,\mathrm{GeV},\ 2.2 < \eta(j) < 4.2$
Charm jets	$p_{\mathrm{T}}(c\ \mathrm{hadron}) > 5\,\mathrm{GeV},\ \Delta R(j, c\ \mathrm{hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

We explore a theory-driven cut:

$$p_{\mathrm{T}}(Z + \mathrm{jet}) < \mathrm{p}_{\mathrm{T,jet}}$$

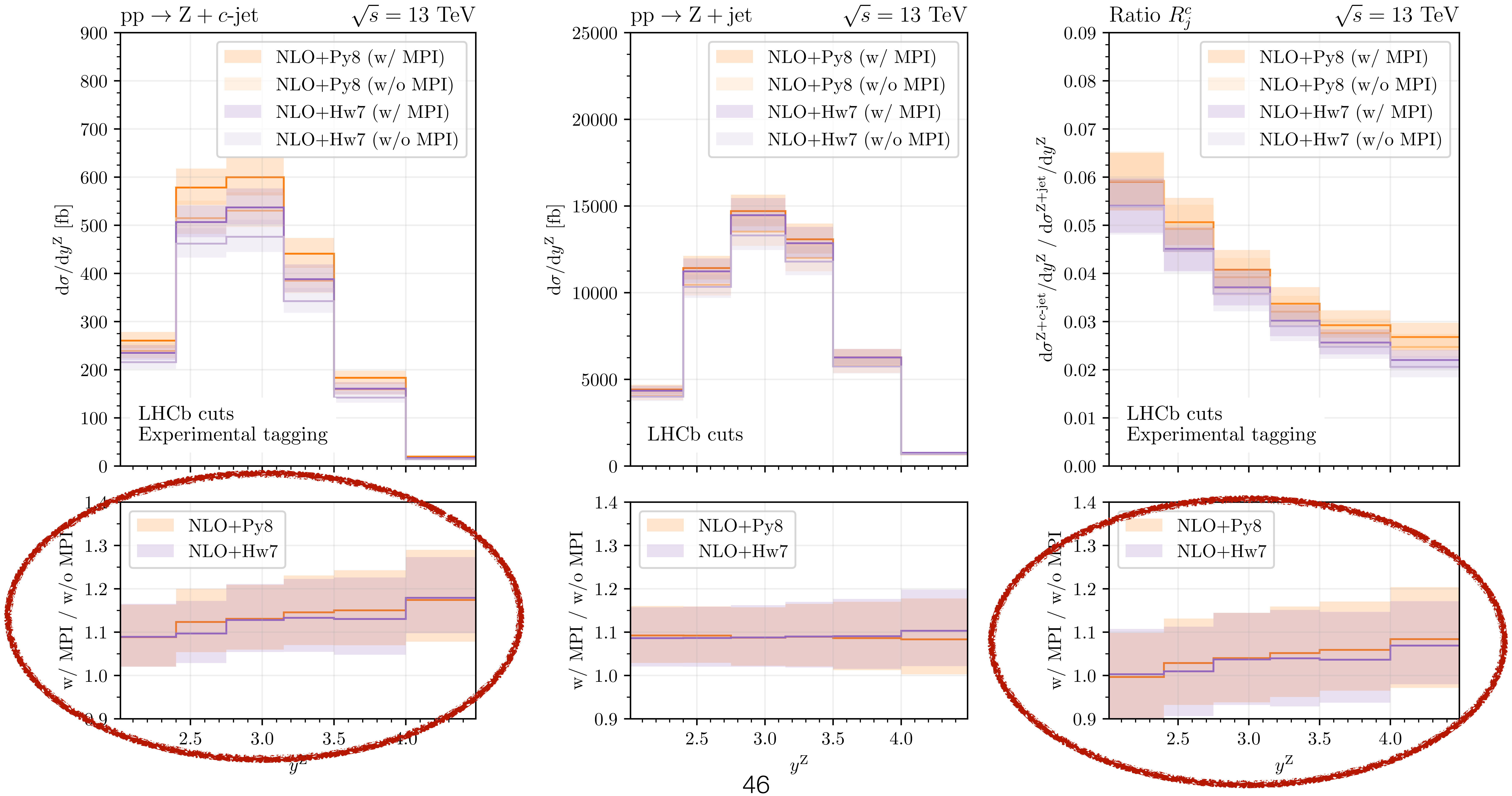
At Born level, the p_{T} of the Z+jet system vanishes, hence the cut limits the hard QCD radiation outside the LHCb acceptance in a dynamical way.

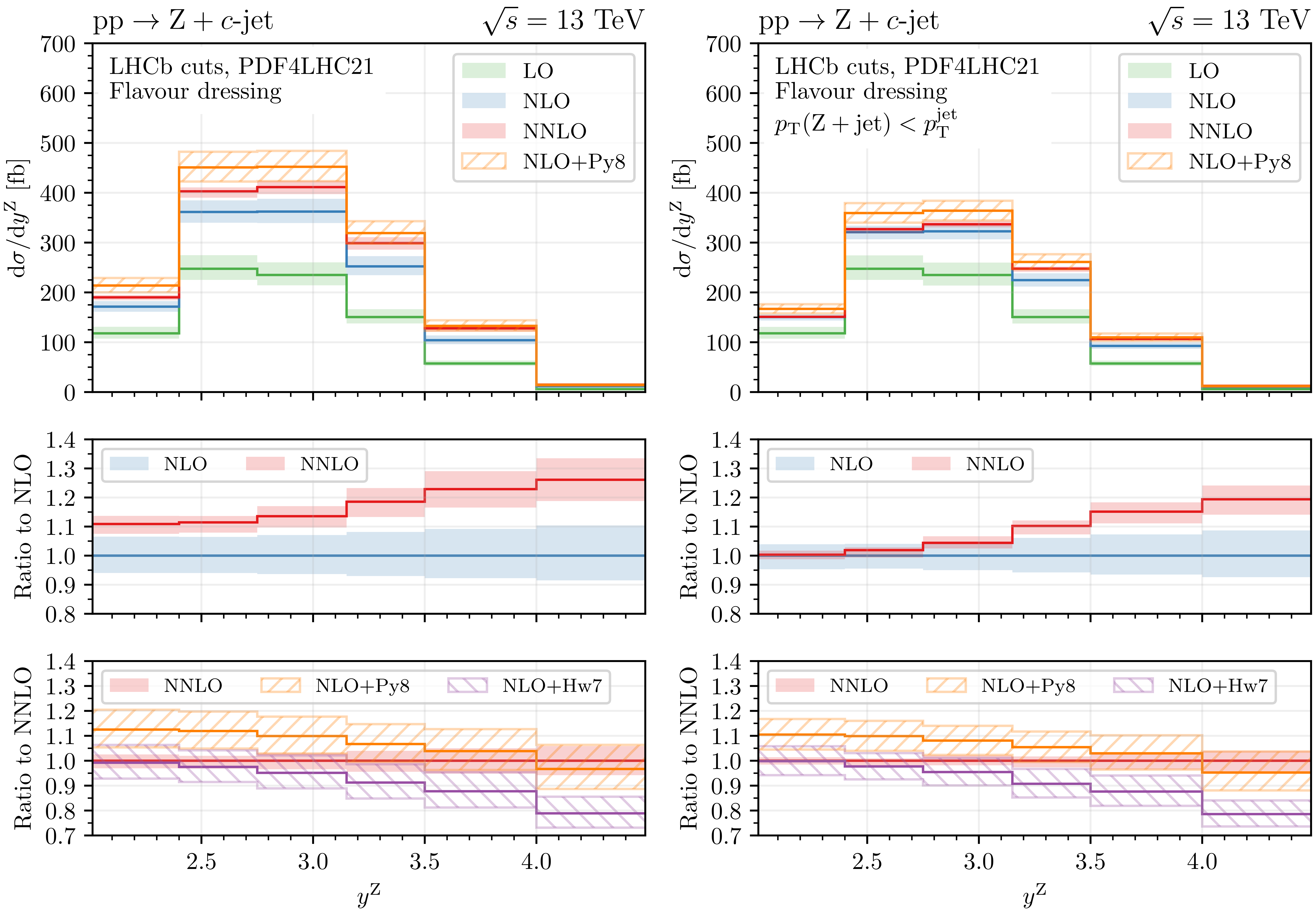


We refrain from making a comparison to the LHCb data

1) definition of flavoured jet adopted by LHCb not IRC safe

2) significant contamination from MPI

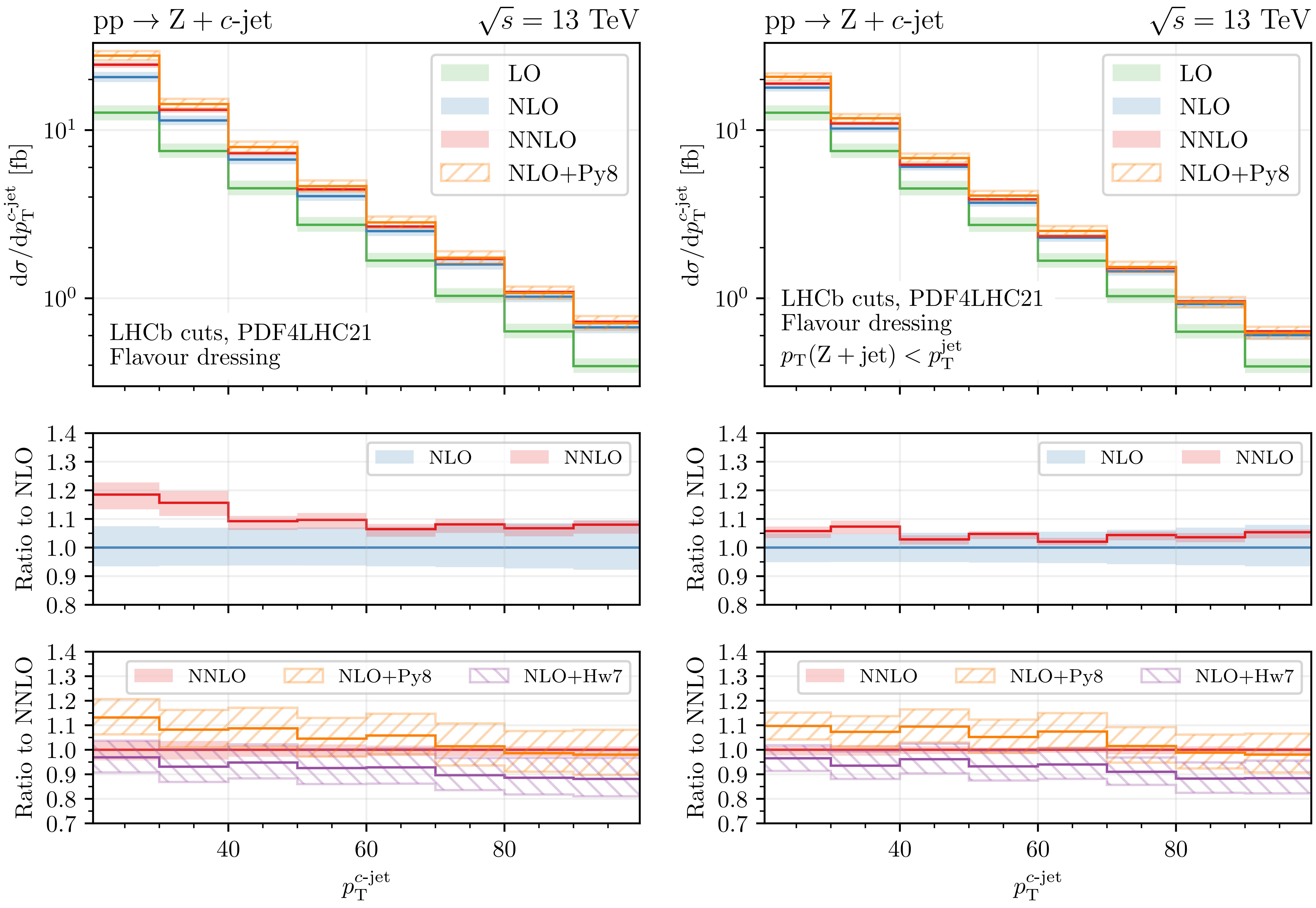




NNLO lies between NLO+PS predictions with different PS.

Reduction of theory uncertainties by a factor of 2.

Theory-driven cut improves perturbative convergence.



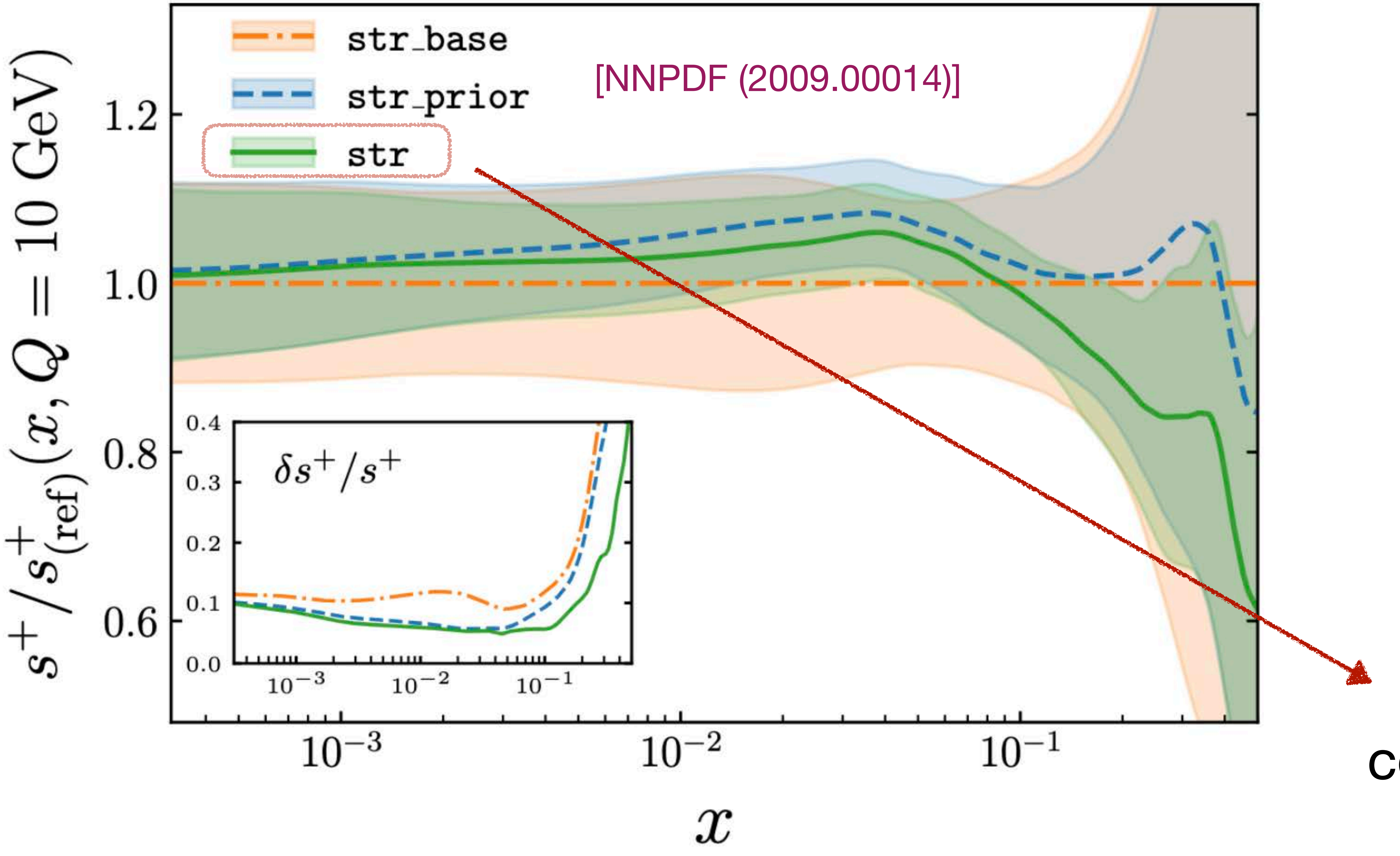
NNLO lies between NLO+PS predictions with different PS.

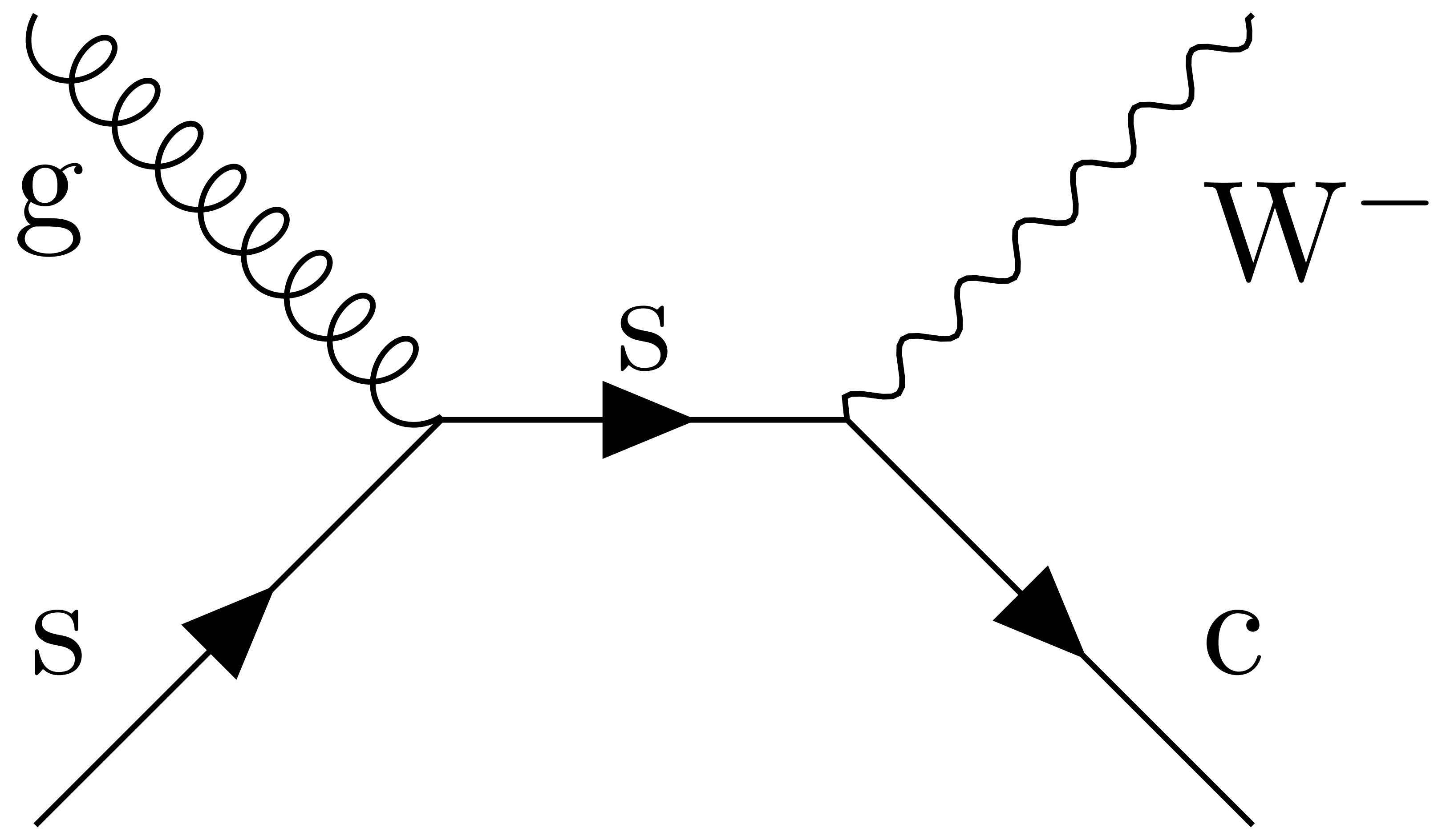
Reduction of theory uncertainties by a factor of 2.

Theory-driven cut improves perturbative convergence.

$W + c$-jet in the central region (ATLAS/CMS)

Unique probe into the **strange PDF**





contain [ATLAS (1402.6263)] and [CMS (1310.1138)] 7 TeV data

Fiducial region, LHC 13 TeV

Jet defined with anti-k_t, R = 0.4, flavour assignment with GHS algorithm

$$p_{T,\ell} > 27\ \mathrm{GeV}, \quad |y_\ell| < 2.5, \quad p_{T,j} > 20\ \mathrm{GeV}, \quad |\eta_j| < 2.5,$$
$$E_{T,\mathrm{miss}} > 20\ \mathrm{GeV}, \quad M_{T,W} > 45\ \mathrm{GeV}, \quad \Delta R(j,\ell) > 0.4.$$

We keep the full CKM matrix in our results!

Definitions:

Inclusive: at least one c-jet

Exclusive: exactly one c-jet

OS: events with lepton from W-decay with opposite charge of that the c-jet

SS: events with lepton from W-decay with same charge of that the c-jet

<u>OS-SS subtraction should remove events where the charm is radiatively generated</u>

Results for fiducial cross sections

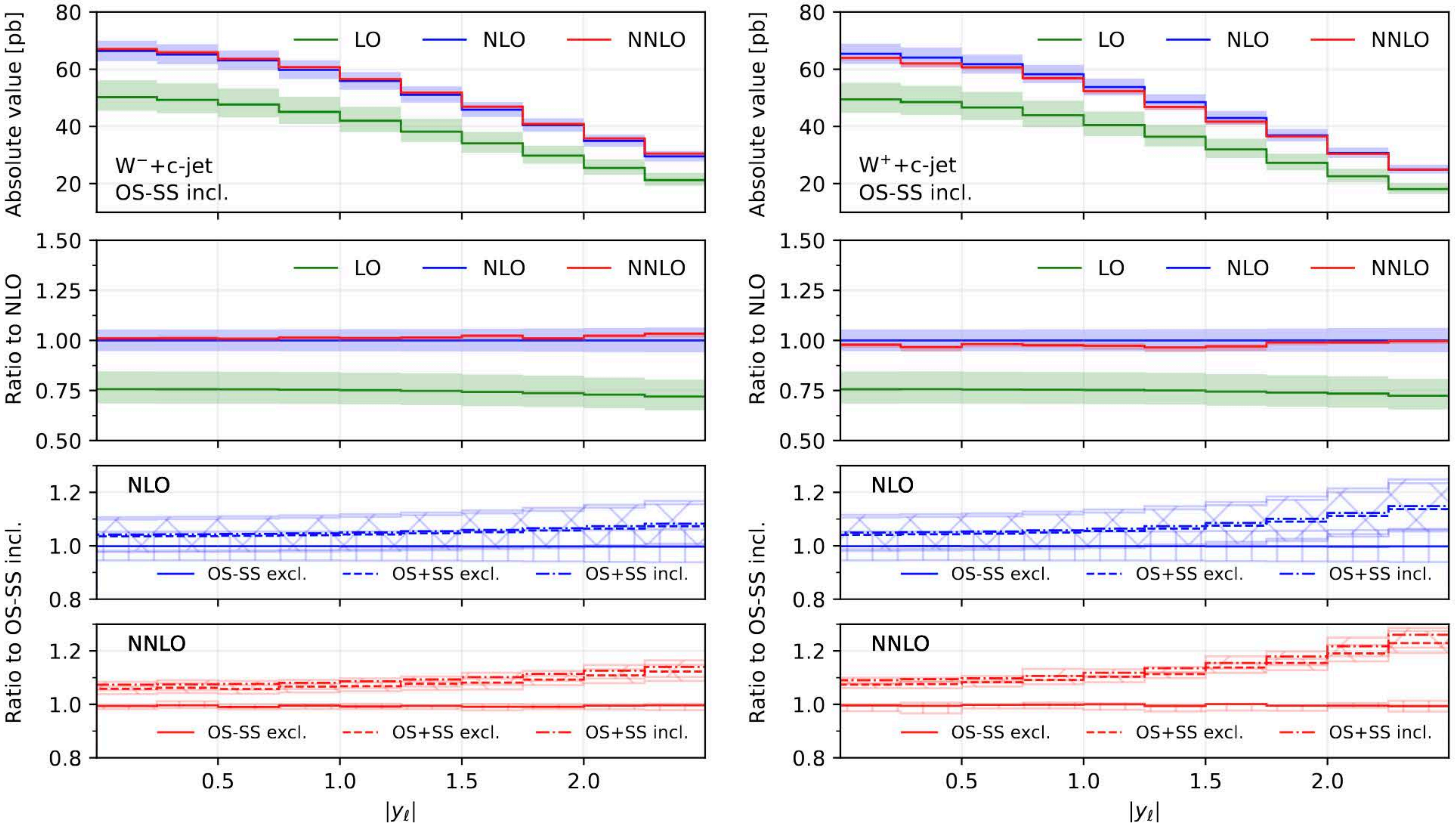
$W^+ + c$-jet	OS−SS incl.	OS−SS excl.	OS+SS incl.	OS+SS excl.
$\sigma^{\rm LO}$	$91.34(1)^{+11.7\%}_{-9.5\%}$	$91.34(1)^{+11.7\%}_{-9.5\%}$	$91.34(1)^{+11.7\%}_{-9.5\%}$	$91.34(1)^{+11.7\%}_{-9.5\%}$
$\Delta\sigma^{\rm NLO}$	$30.45(4)$	$30.24(4)$	$39.23(4)$	$38.12(4)$
$\sigma^{\rm NLO}$	$121.79(4)^{+5.6\%}_{-5.4\%}$	$121.58(4)^{+5.6\%}_{-5.4\%}$	$130.56(4)^{+6.9\%}_{-6.3\%}$	$129.46(4)^{+6.8\%}_{-6.2\%}$
$\Delta\sigma^{\rm NNLO}$	$-2.3(8)$	$-2.7(7)$	$4.5(7)$	$3.2(7)$
$\sigma^{\rm NNLO}$	$119.5(8)^{+0.4\%}_{-1.8\%}$	$119.0(7)^{+0.1\%}_{-1.6\%}$	$135.1(8)^{+1.2\%}_{-1.9\%}$	$132.7(7)^{+0.6\%}_{-1.5\%}$

$W^- + c$-jet	OS−SS incl.	OS−SS excl.	OS+SS incl.	OS+SS excl.
$\sigma^{\rm LO}$	$95.782(4)^{+11.7\%}_{-9.5\%}$	$95.782(4)^{+11.7\%}_{-9.5\%}$	$95.782(4)^{+11.7\%}_{-9.5\%}$	$95.782(4)^{+11.7\%}_{-9.5\%}$
$\Delta\sigma^{\rm NLO}$	$32.244(8)$	$32.004(8)$	$39.011(8)$	$38.043(8)$
$\sigma^{\rm NLO}$	$128.026(9)^{+5.7\%}_{-5.5\%}$	$127.786(9)^{+5.7\%}_{-5.5\%}$	$134.794(9)^{+6.6\%}_{-6.1\%}$	$133.826(9)^{+6.5\%}_{-6.0\%}$
$\Delta\sigma^{\rm NNLO}$	$2.9(5)$	$2.5(5)$	$8.2(5)$	$7.1(5)$
$\sigma^{\rm NNLO}$	$130.9(5)^{+0.7\%}_{-1.5\%}$	$130.3(5)^{+0.9\%}_{-1.5\%}$	$143.0(5)^{+1.5\%}_{-2.5\%}$	$141.0(5)^{+1.1\%}_{-2.4\%}$

Reduction of theory uncertainties at increasing orders

Smaller NNLO corrections for OS-SS subtraction

Results for differential distributions

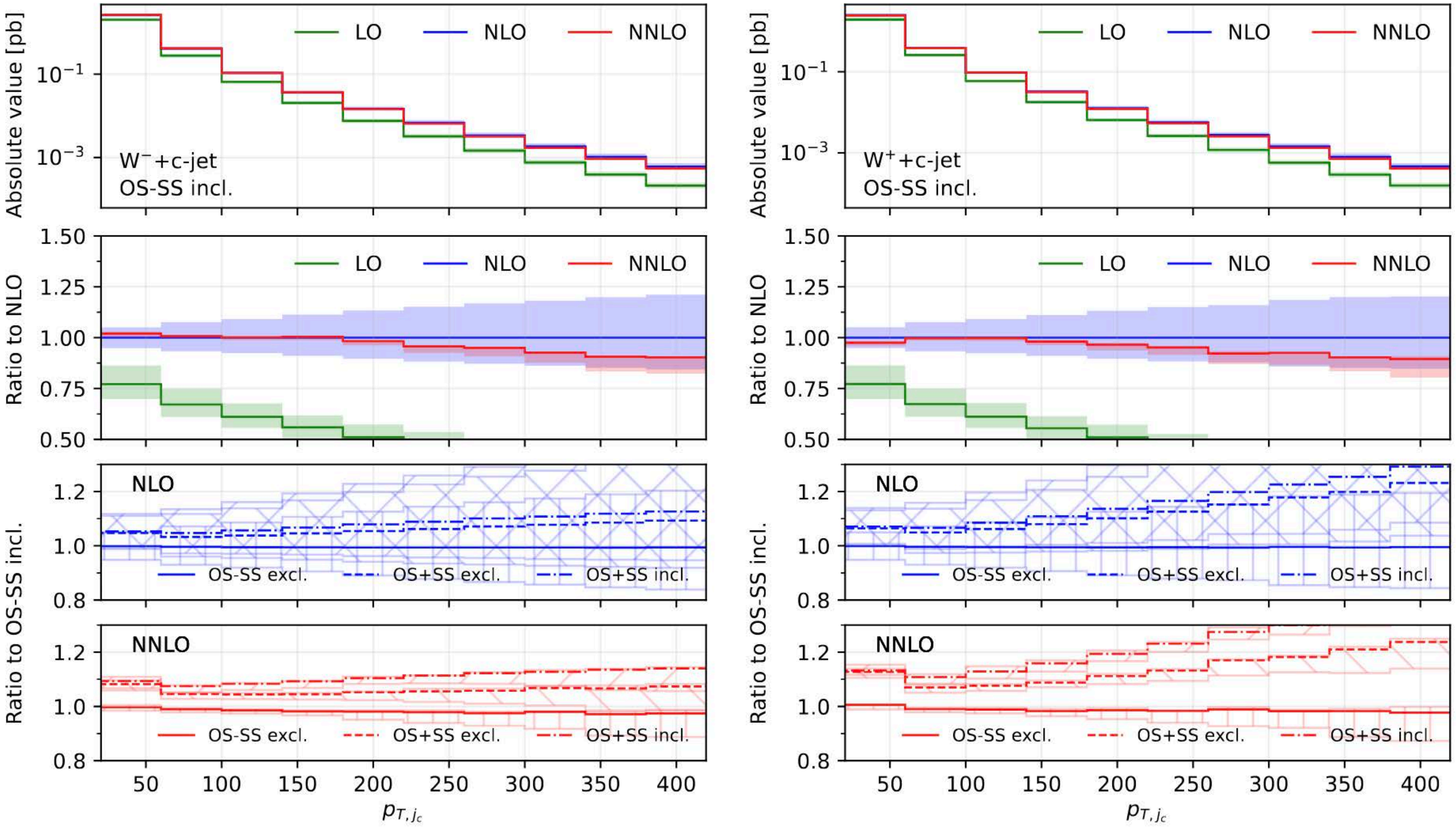


Good perturbative convergence

OS-SS incl. very similar to OS-SS excl. (OS-SS very efficient in discarding events with more than one c-jet)

OS-SS vs. OS+SS increasing at large values of $|y_\ell|$ and p_{T,j_c}, difference more pronounced at NNLO

Results for differential distributions



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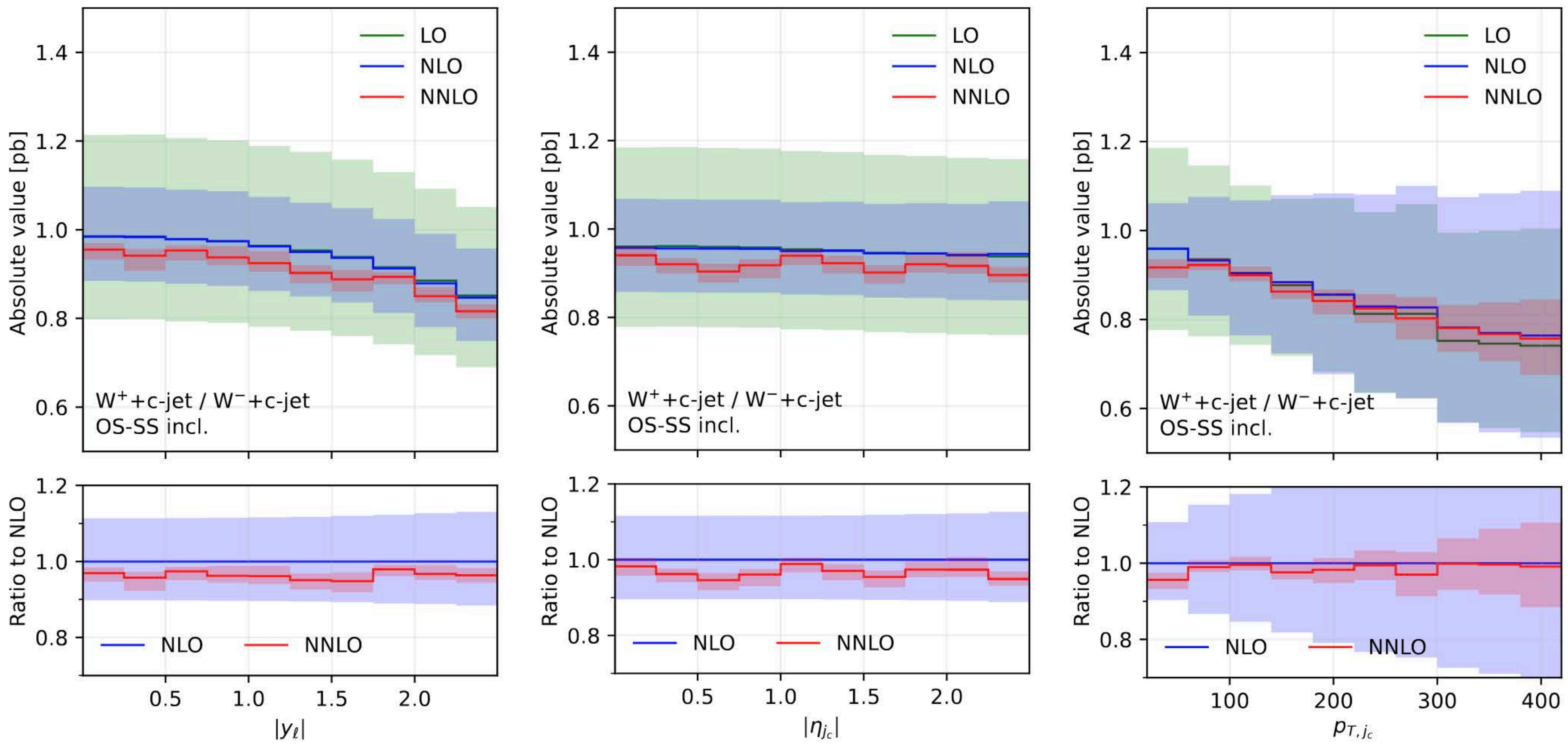
OS-SS vs. OS+SS increasing at large values of $|y_\ell|$ and p_{T,j_c}, difference more pronounced at NNLO

Results for ratio W^++c-jet / W^-+ c-jet

$\mathcal{R}_c^{\pm}$	OS−SS incl.	OS−SS excl.	OS+SS incl.	OS+SS excl.
LO	$0.9536(3)^{+23.4\%}_{-19.0\%}$	$0.9536(3)^{+23.4\%}_{-19.0\%}$	$0.9536(3)^{+23.4\%}_{-19.0\%}$	$0.9536(3)^{+23.4\%}_{-19.0\%}$
NLO	$0.951\ (1)^{+13.9\%}_{-12.1\%}$	$0.952(1)^{+13.6\%}_{-11.9\%}$	$0.968(1)^{+13.9\%}_{-12.1\%}$	$0.967(1)^{+13.6\%}_{-11.9\%}$
NNLO	$0.91(1)^{+1.9\%}_{-2.7\%}$	$0.91(1)^{+1.6\%}_{-2.5\%}$	$0.94(1)^{+3.7\%}_{-3.3\%}$	$0.94(1)^{+3.0\%}_{-2.6\%}$

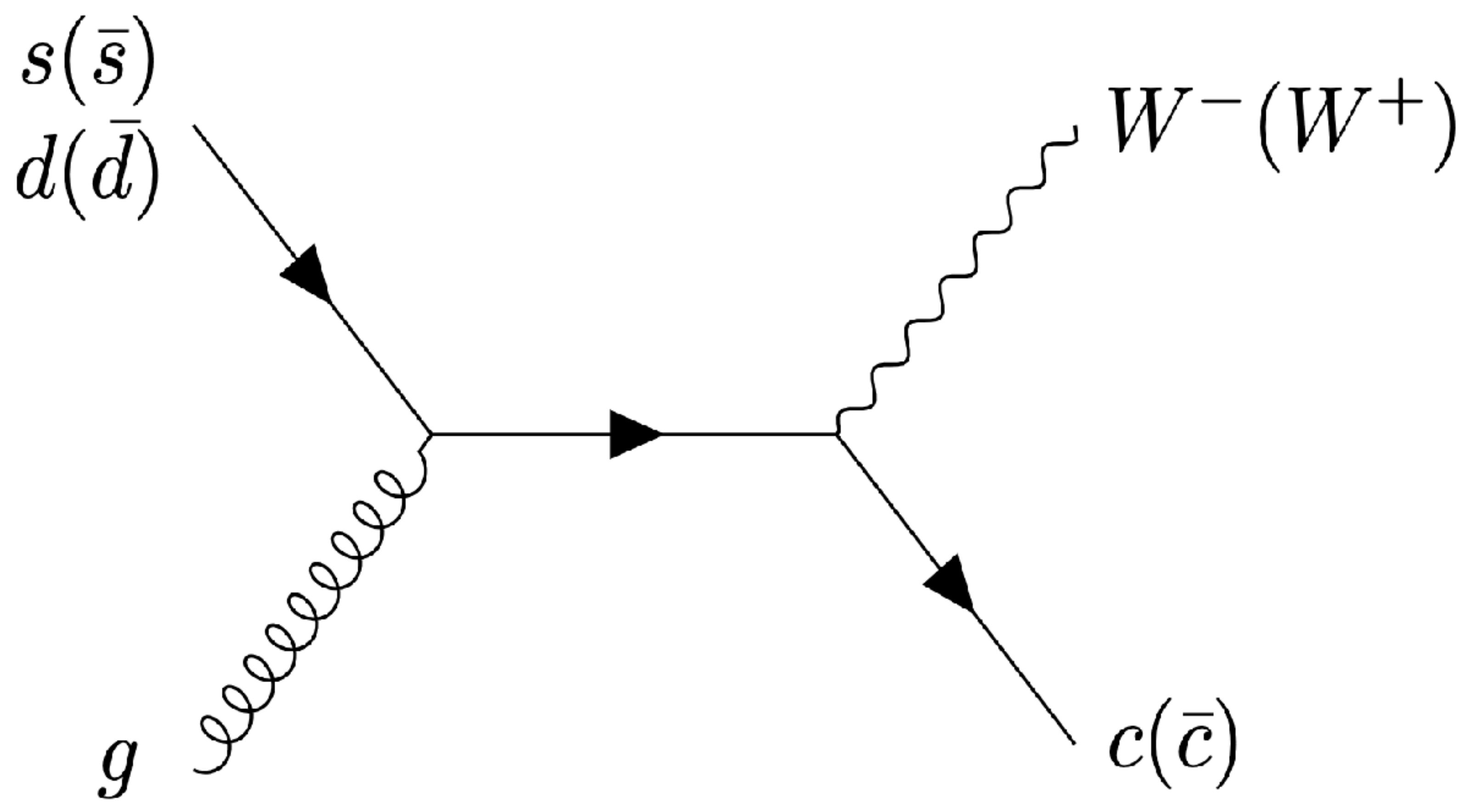


Very nice convergence

Ratio always smaller than 1

i.e. W^- always larger than W^+

Physical interpretation at LO: contribution from the $gs(\bar{s})$ channel similar, because s and $\bar{s}$ PDF are similar. But subdominant gd channel is numerically different from $g\bar{d}$ channel, because d PDF feature a valence component!



Channel breakdown for fiducial cross sections

W^-+c-jet	OS LO	OS NLO	SS NLO	OS NNLO	SS NNLO
$c(\bar{c})s(\bar{s})$	0.0	−0.1225(3)	0.4852(2)	−0.05(2)	0.842(3)
$c(\bar{c})c(\bar{c})$	0.0	0.2158(1)	0.2062(2)	0.360(2)	0.351(1)
$c(\bar{c})q(\bar{q})$	0.0	1.2392(3)	1.3132(4)	1.958(4)	2.088(4)
$s(\bar{s})q(\bar{q})$	0.0	−0.651(3)	0.03134(1)	−1.1(2)	0.0537(2)
$s(\bar{s})s(\bar{s})$	0.0	−0.2549(3)	0.0	−0.42(3)	0.0
$q(\bar{q})q(\bar{q})$	0.0	1.0314(7)	0.9838(4)	1.73(2)	1.676(6)
$gq(\bar{q})$	8.9255(6)	12.700(1)	0.0	12.7(2)	0.405(3)
$gs(\bar{s})$	86.857(4)	123.002(8)	0.0	128.9(3)	−0.0353(6)
$gc(\bar{c})$	0.0	0.0	0.0	−0.14(2)	−0.057(2)
gg	0.0	−6.355(3)	0.0	−8.31(1)	0.0
total	95.782(5)	130.806(1)	3.020(1)	135.6(5)	5.324(9)

Dominant channel is $gs(\bar{s})$, followed by $gq(\bar{q})$

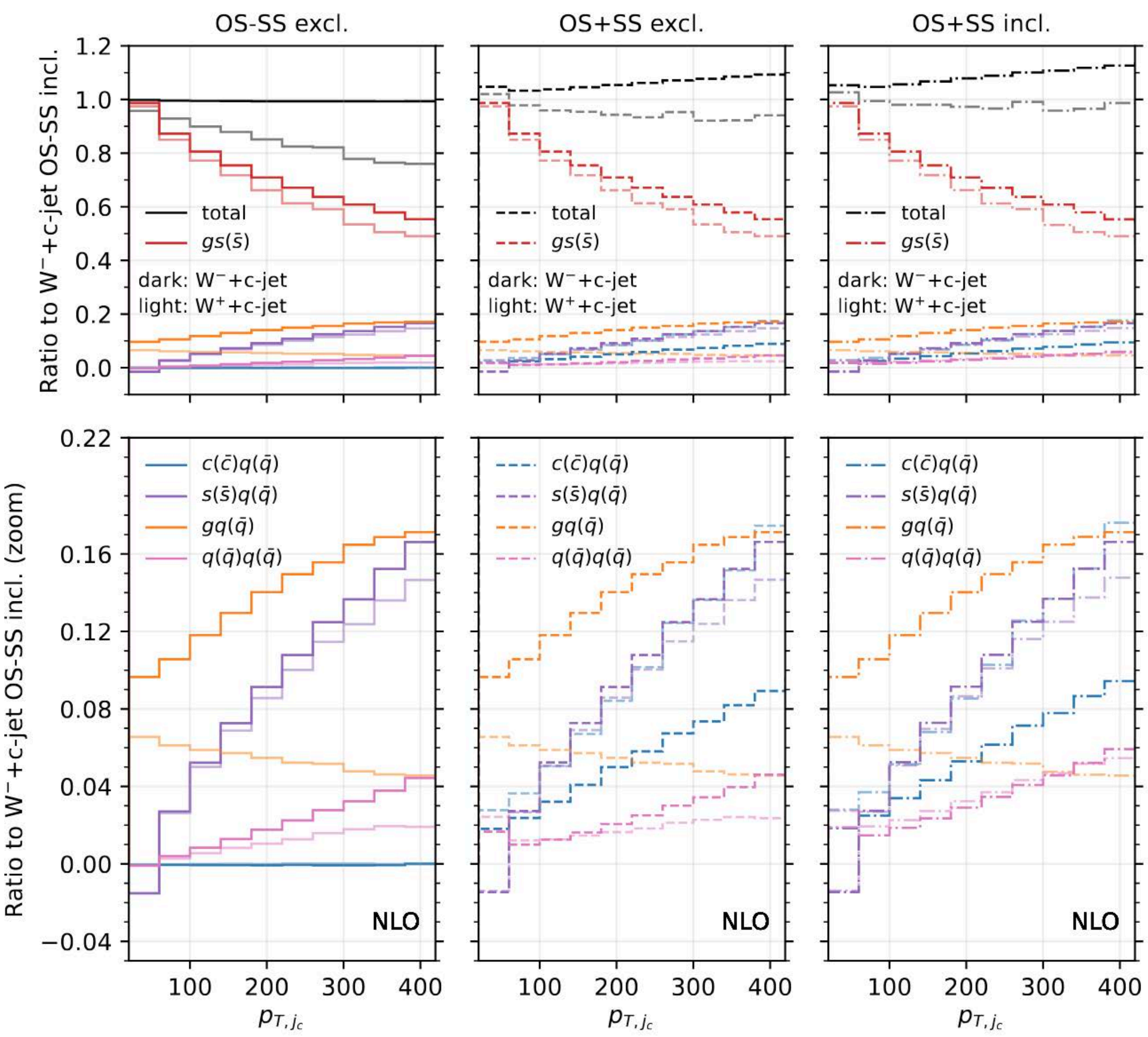
The $c(\bar{c})c(\bar{c})$, $c(\bar{c})q(\bar{q})$ and $q(\bar{q})q(\bar{q})$ channels are very similar between SS and OS: then OS-SS basically removes them

Channel breakdown for fiducial cross sections

W^++c-jet	OS LO	OS NLO	SS NLO	OS NNLO	SS NNLO
$c(\bar{c})s(\bar{s})$	0.0	$-0.1191(9)$	0.4752(4)	$-0.13(2)$	0.838(1)
$c(\bar{c})c(\bar{c})$	0.0	0.2151(3)	0.2047(3)	0.3316(5)	0.3246(6)
$c(\bar{c})q(\bar{q})$	0.0	1.948(3)	1.988(4)	2.945(6)	3.038(6)
$s(\bar{s})q(\bar{q})$	0.0	$-0.649(9)$	0.0673(1)	$-1.9(3)$	0.1157(3)
$s(\bar{s})s(\bar{s})$	0.0	$-0.258(1)$	0.0	$-0.55(5)$	0.0
$q(\bar{q})q(\bar{q})$	0.0	1.431(2)	1.409(2)	2.35(2)	2.423(6)
$gq(\bar{q})$	5.8299(7)	8.257(2)	0.0	10.1(4)	0.508(4)
$gs(\bar{s})$	85.51(1)	121.04(3)	0.0	126.3(6)	$-0.0430(4)$
$gc(\bar{c})$	0.0	0.0	0.0	0.02(2)	$-0.0293(7)$
gg	0.0	$-6.34(1)$	0.0	$-13.62(6)$	0.0
total	91.34(1)	125.51(4)	4.146(4)	125.9(7)	7.17(1)

Dominant channel is $gs(\bar{s})$, followed by $gq(\bar{q})$

The $c(\bar{c})c(\bar{c})$, $c(\bar{c})q(\bar{q})$ and $q(\bar{q})q(\bar{q})$ channels are very similar between SS and OS: then OS-SS basically removes them



Difference OS-SS vs. OS+SS

driven by $c(\bar{c})q(\bar{q})$ channel

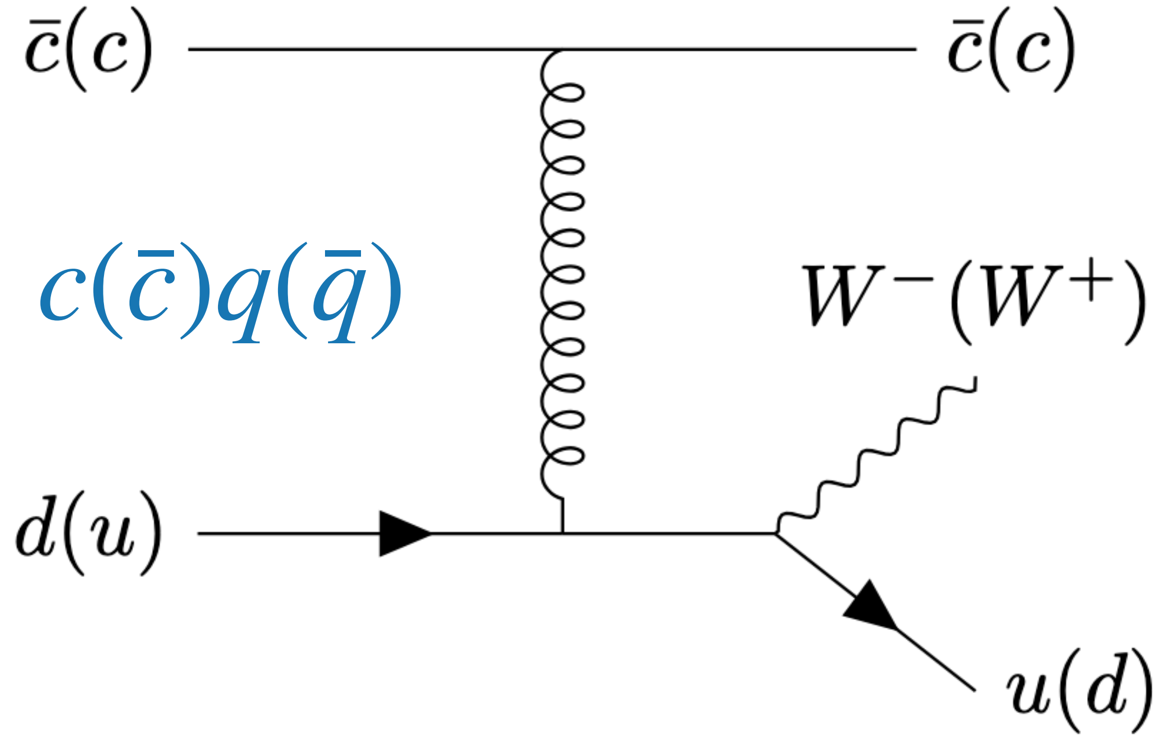
Difference OS+SS excl. vs. OS+SS incl.

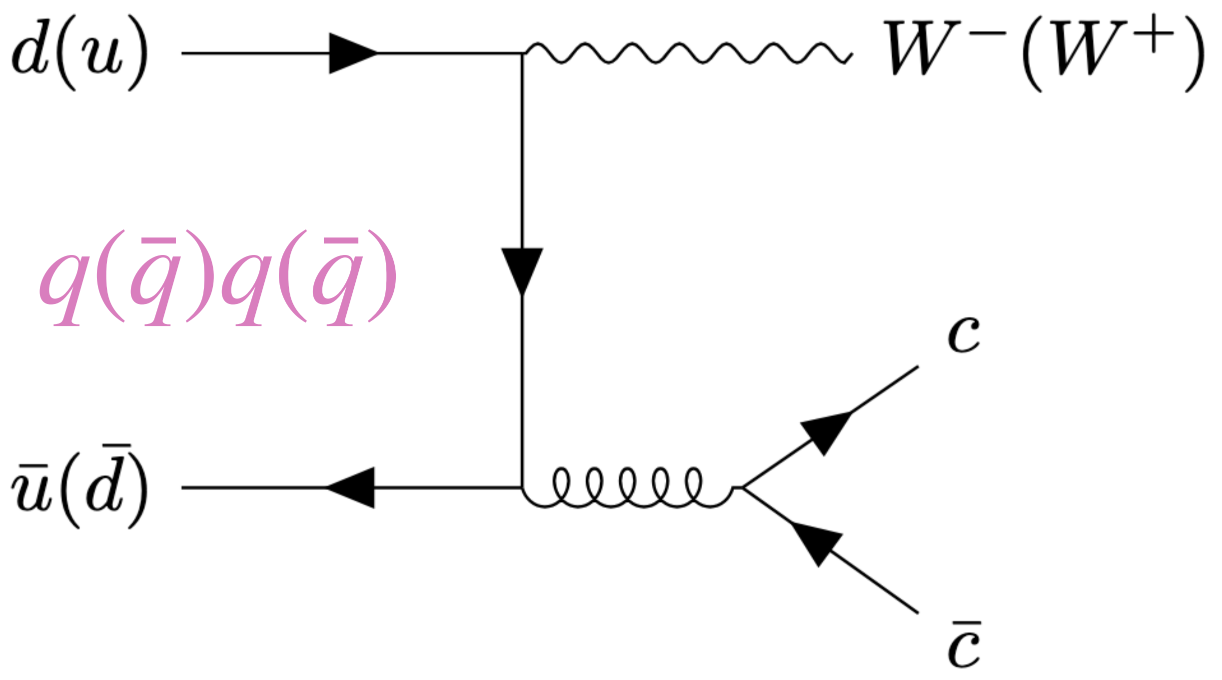
driven by $q(\bar{q})q(\bar{q})$ channel

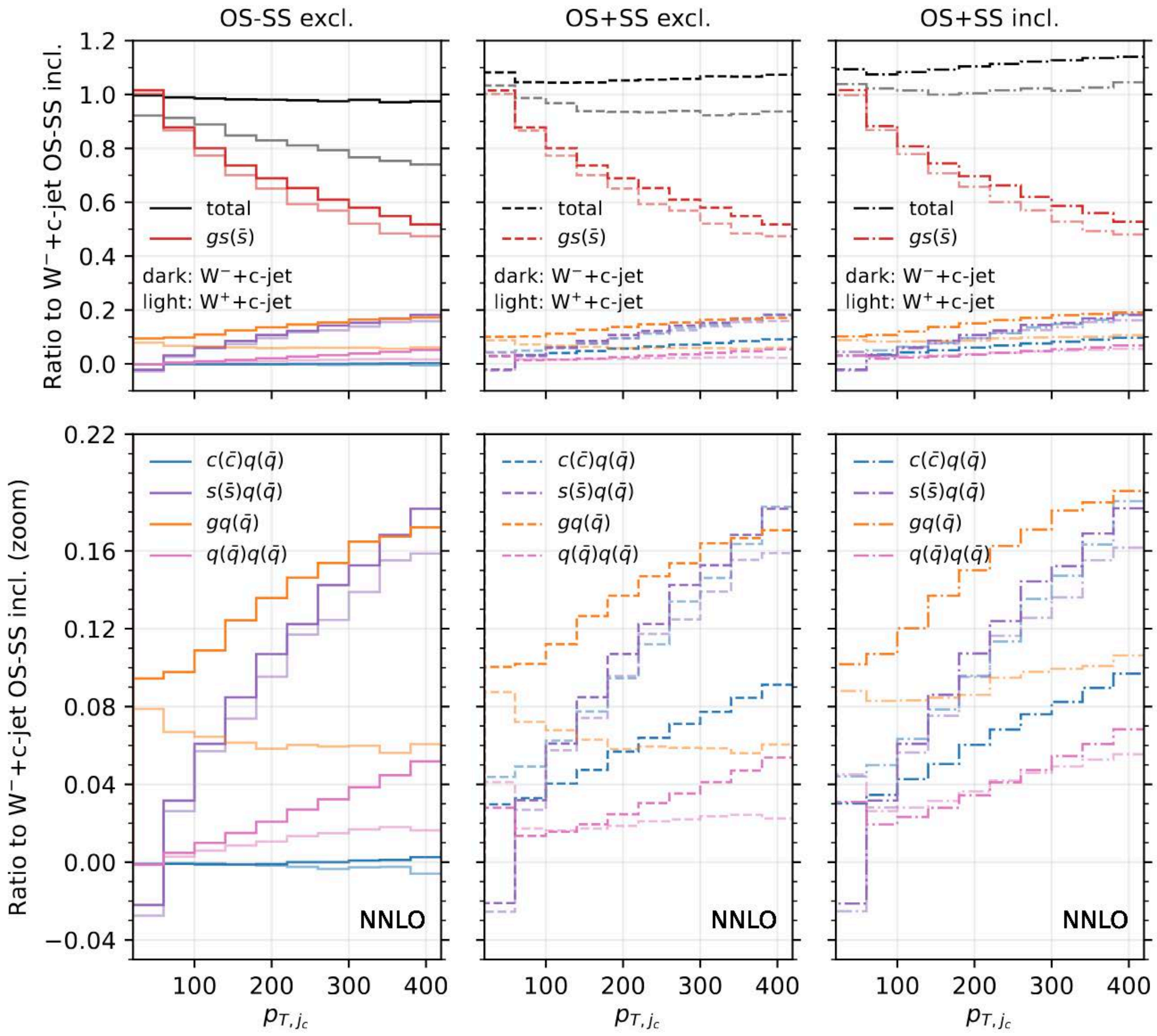
Due to the difference between the size of

u valence PDF and d valence PDF

(u valence is twice the d valence)







Difference OS-SS vs. OS+SS

driven by $c(\bar{c})q(\bar{q})$ channel

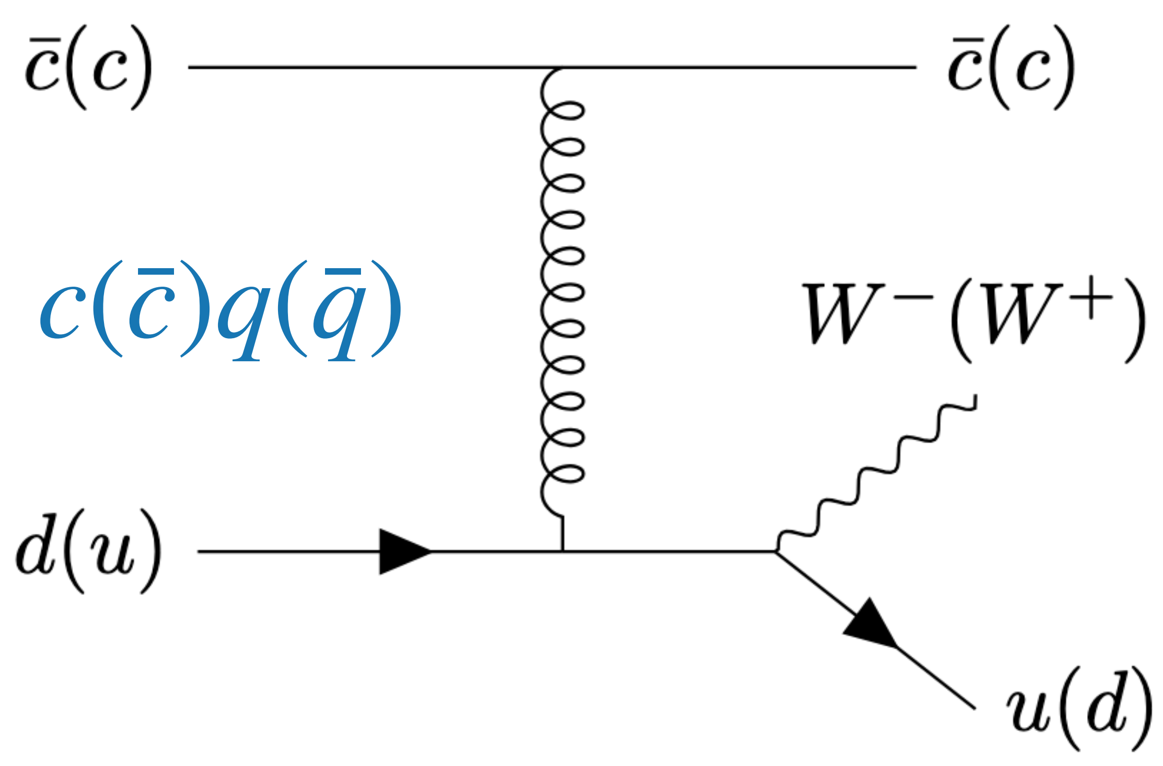
Difference OS+SS excl. vs. OS+SS incl.

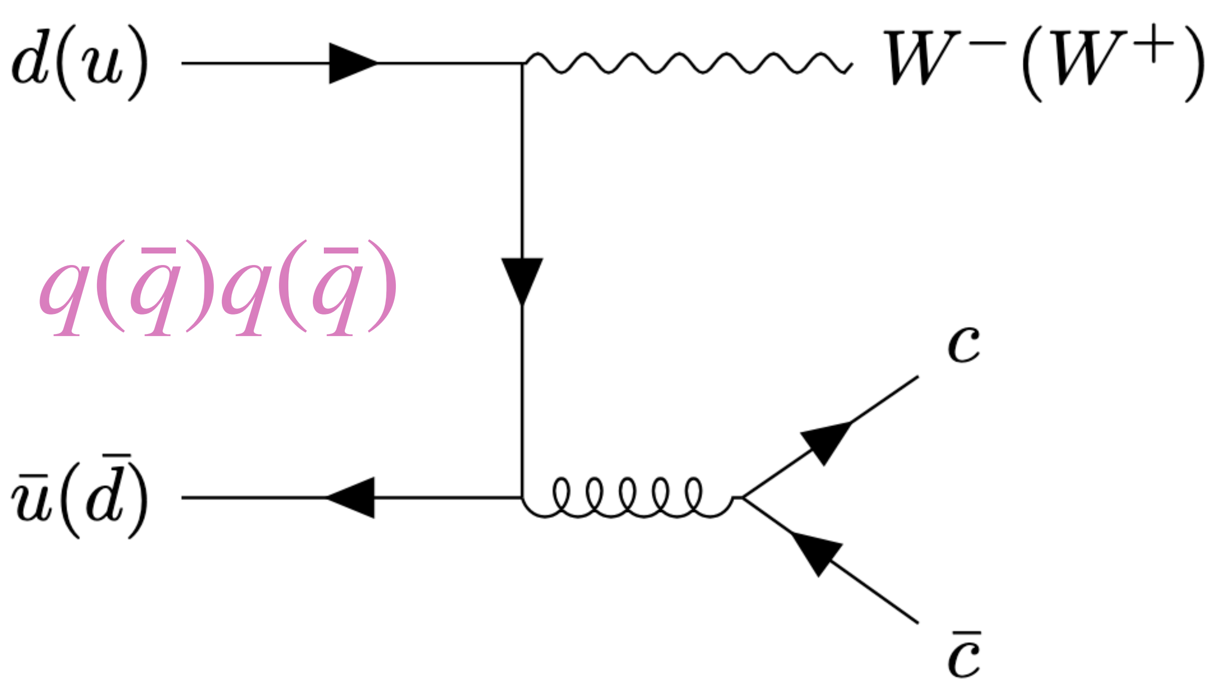
driven by $q(\bar{q})q(\bar{q})$ channel

Due to the difference between the size of

u valence PDF and d valence PDF

(u valence is twice the d valence)





Outlook of this talk

1. (Rather long and pedagogical) introduction

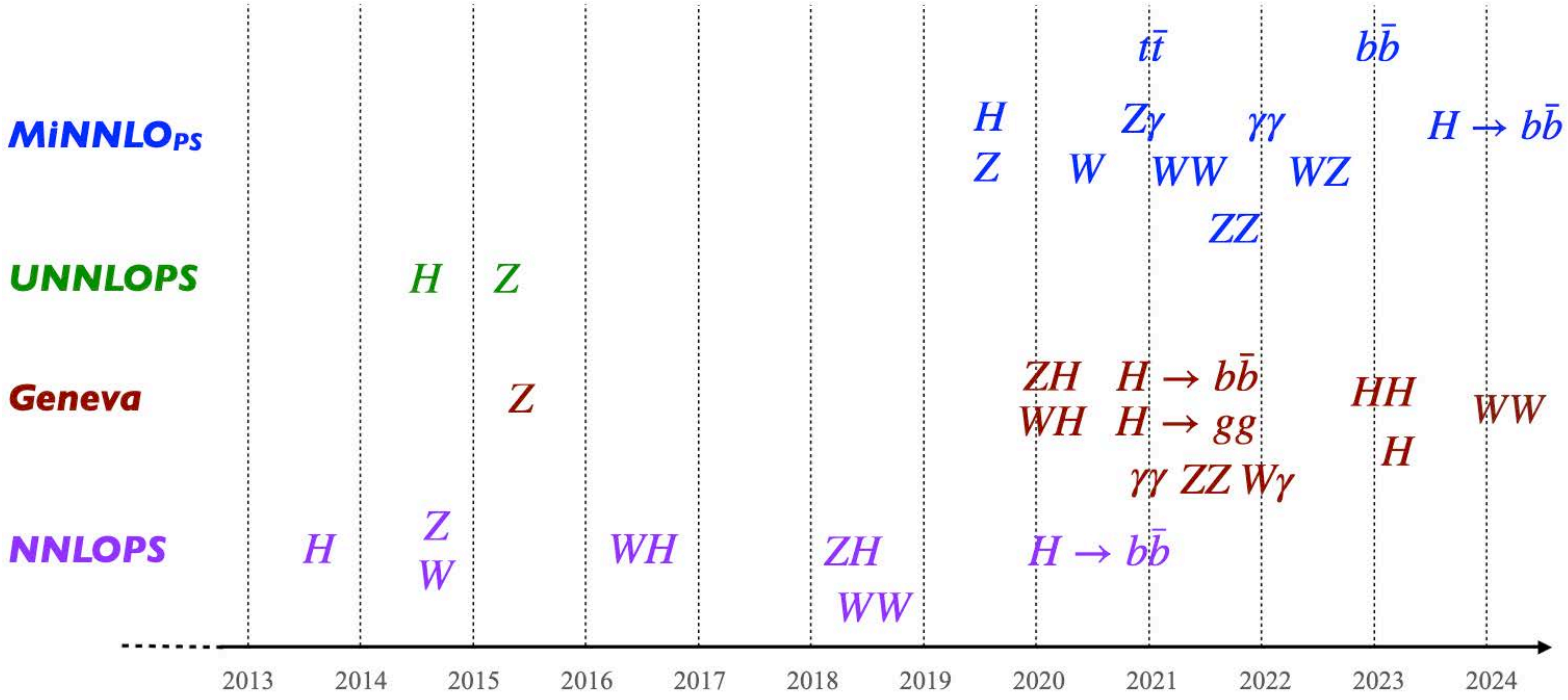
2. Flavoured jets at the LHC:
Z+c-jet and W+c-jet production

3. Towards NNLO+PS for V+jet:
improving slicing methods for V+jet production

Biased selection of recent results where I personally contributed.
Minimal inclusion of references, apologies for any relevant omission.

Status of NNLO+PS

M. Wiesemann



Impressive results in the recent years, but
limited to processes with colour-singlets or heavy quarks in the final state

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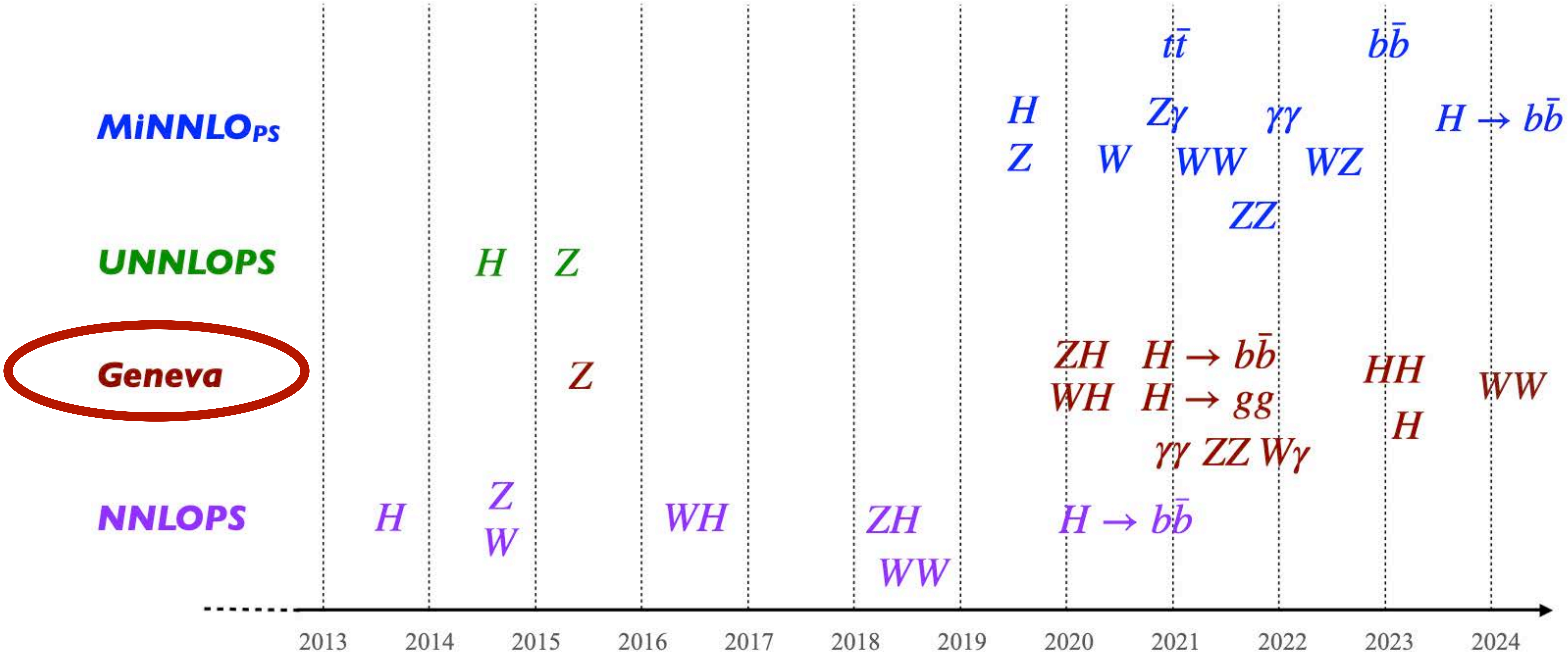

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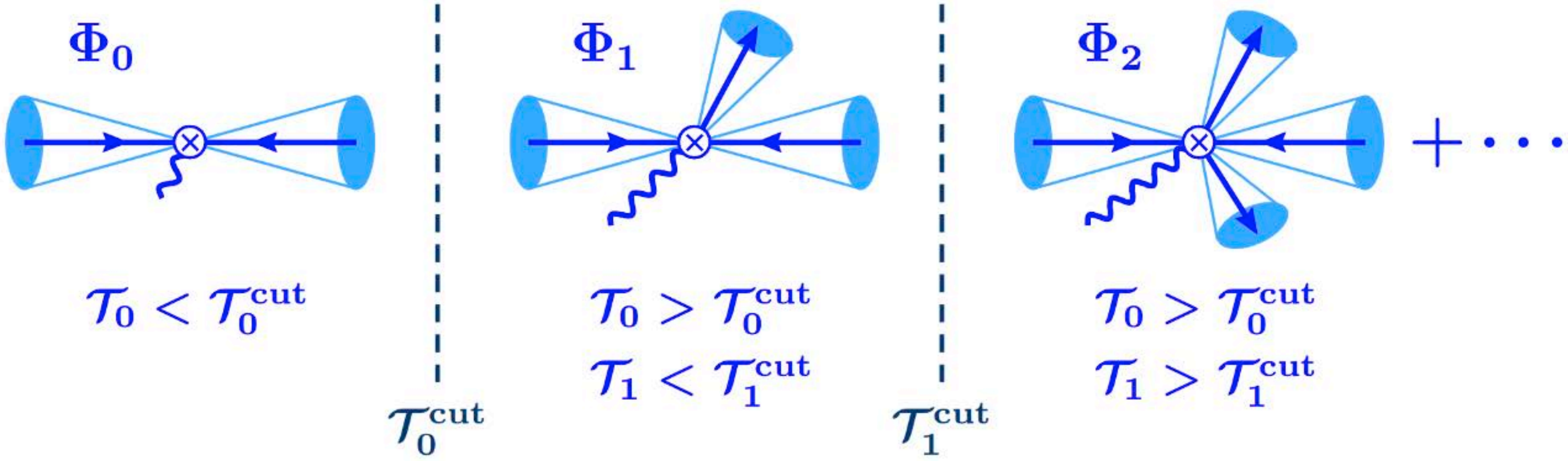
GENEVA in a nutshell (for colour-singlet production)



Division into 0/1/2-jet events dictated by resolution variable(s) $\mathcal{T}_N$

Originally developed for N-jettiness $\mathcal{T}_N$, but later extended to colour-singlet q_T [Alioli, Bauer et al. '21] and leading-jet p_T [Gavardi, Lim et al. '23]

As $\mathcal{T}_N$s regulate IR divergences, large logarithms appear: resummation is required!

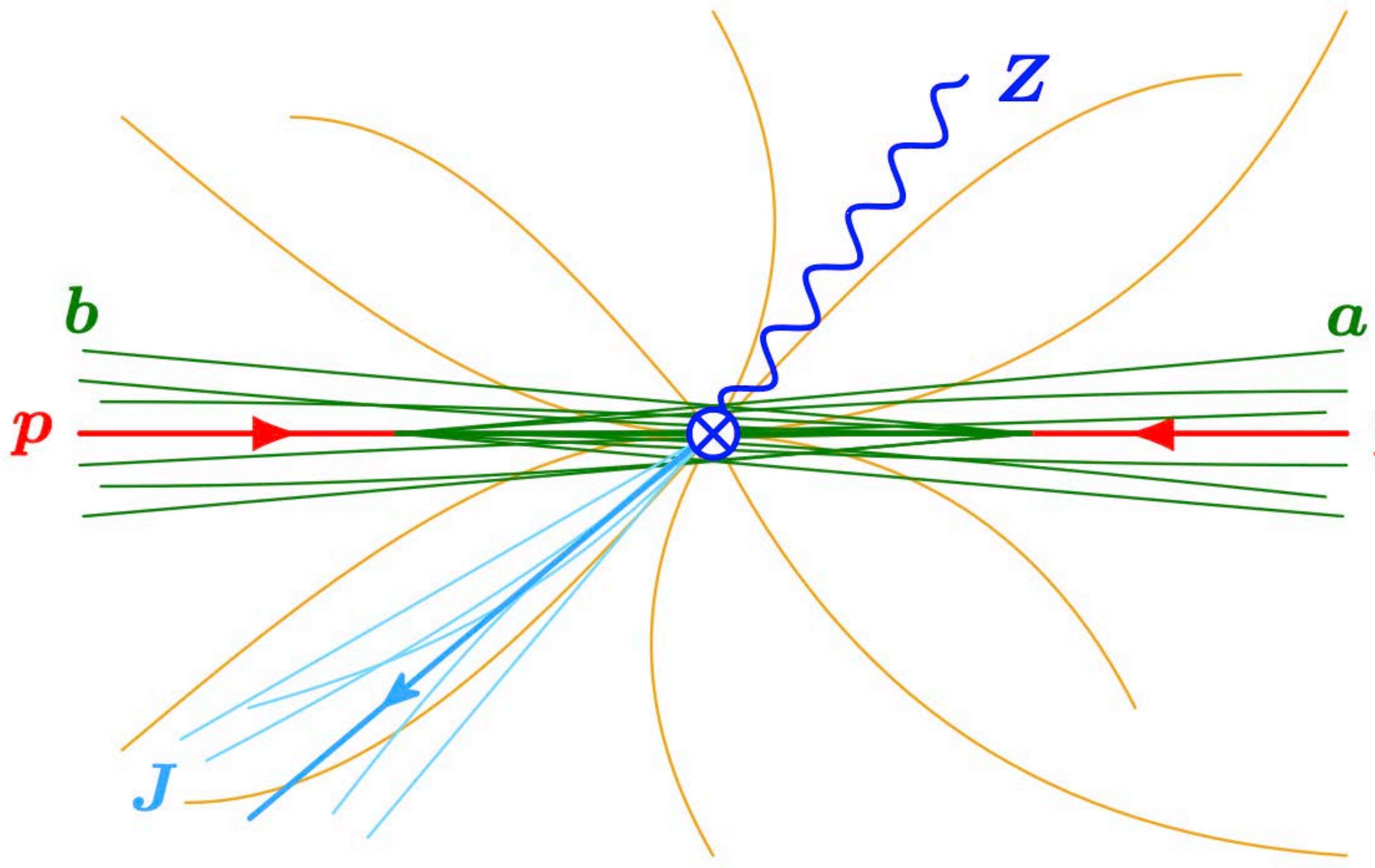
$\mathcal{T}_0$ resummed up to NNLL', $\mathcal{T}_1$ up to NLL

How to extend GENEVA to vector boson plus jet production?

First step: resummation of one-jettiness $\mathcal{T}_1$, performed up to N3LL
[Alioli, Bell, Billis, Broggio, Dehnadi, Lim, Marinelli, Nagar, Napoletano, Rahn '23]

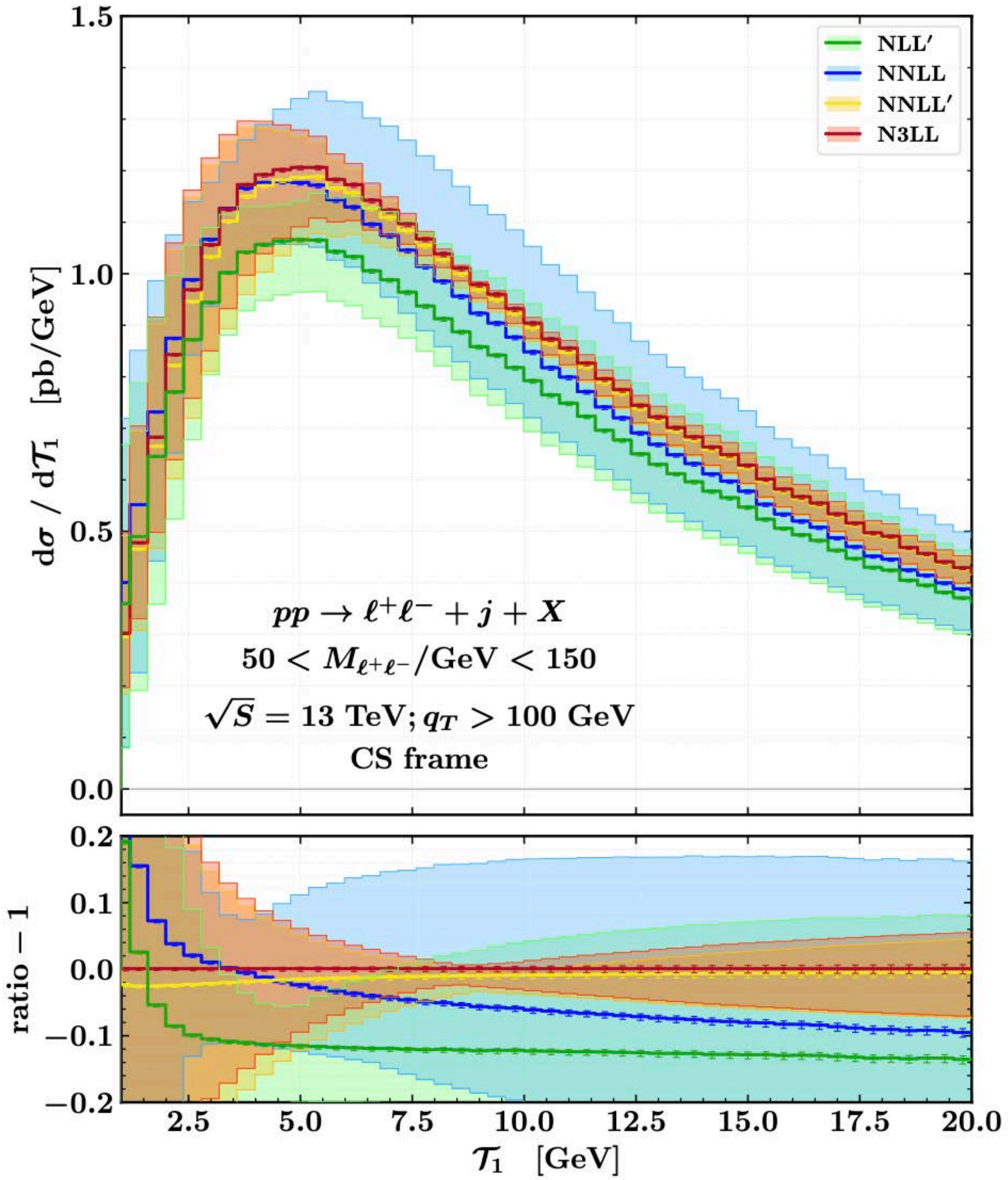
$$\mathcal{T}_1 = \sum_k \min\left\{\frac{2q_a \cdot k}{Q_a}, \frac{2q_b \cdot k}{Q_b}, \frac{2q_J \cdot k}{Q_J}\right\}$$

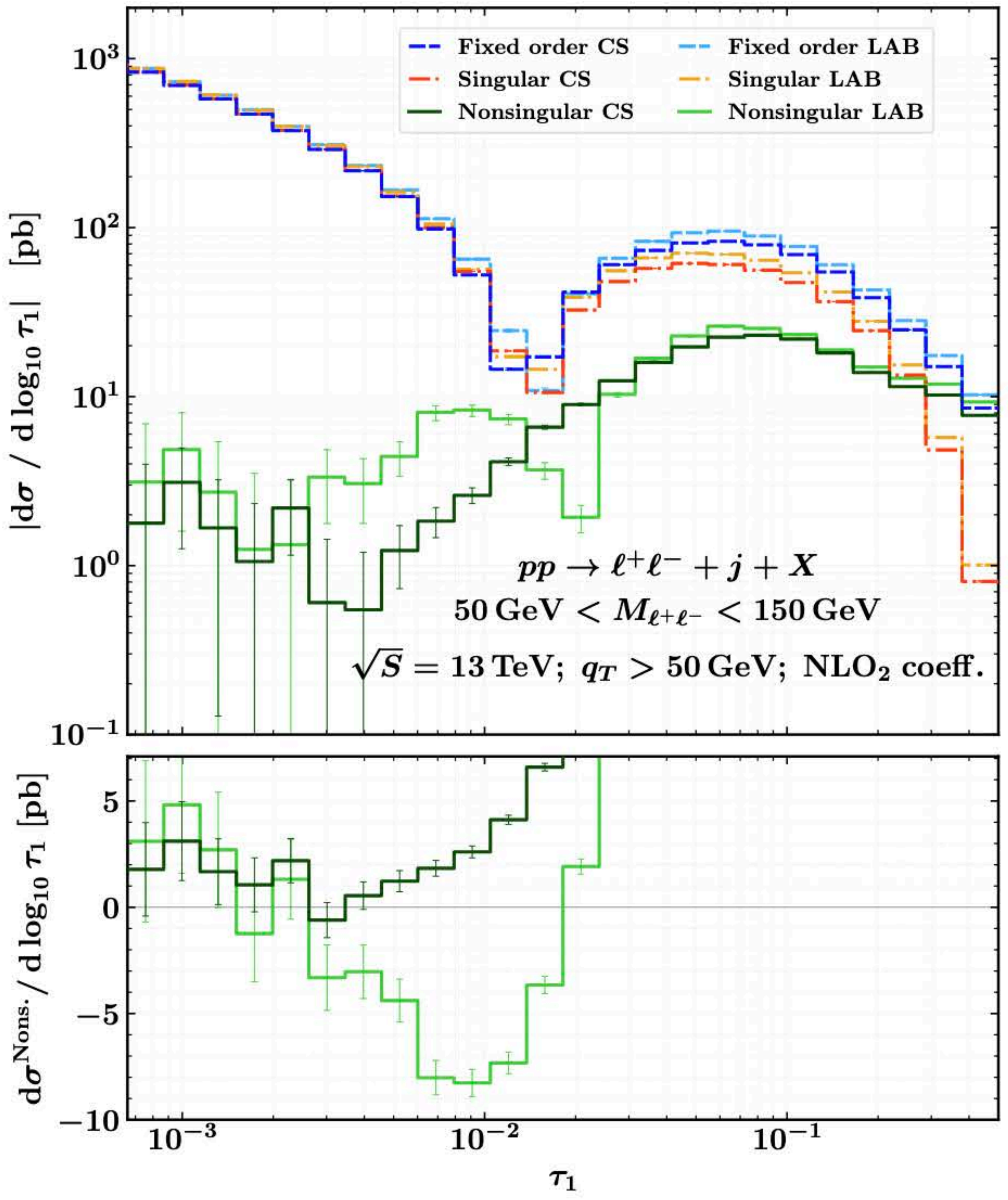
$$Q_i = 2\rho_i E_i$$



Freedom in precise definition of $\mathcal{T}_1$:
dependence on reference frame;
dependence on definition of jet axis
(e.g. obtained recursively with exclusive clustering or a priori with inclusive clustering)

frames	$\rho_{a,b}$	ρ_J
Lab	1	1
Color Singlet (CS)	$e^{\pm Y_V}$	$(e^{Y_V} p_J^- + e^{-Y_V} p_J^+)/E_J$
Underlying Born (UB)	$e^{\pm Y_{VJ}}$	$(e^{Y_{VJ}} p_J^- + e^{-Y_{VJ}} p_J^+)/E_J$





In order to have a finite Born for Z+jet, one adopts a cut on q_T or on $\mathcal{T}_0$

Nonsingular = Fixed order - Singular

$$\tau_1 = \mathcal{T}_1 / m_T$$

$$m_T \equiv \sqrt{M^2_{\ell^+\ell^-} + q_T^2}$$

NLL’ → NNLL → NNLL’ sizeable

NNLL’ → N^{3}LL minor effect

Fixed-order approaches singular as $\tau_1 \to 0$

Power corrections behave better in the CS frame

Second step: recover the NNLO fixed-order result with slicing
[Alioli, Billis, Broggio, GS, in preparation]

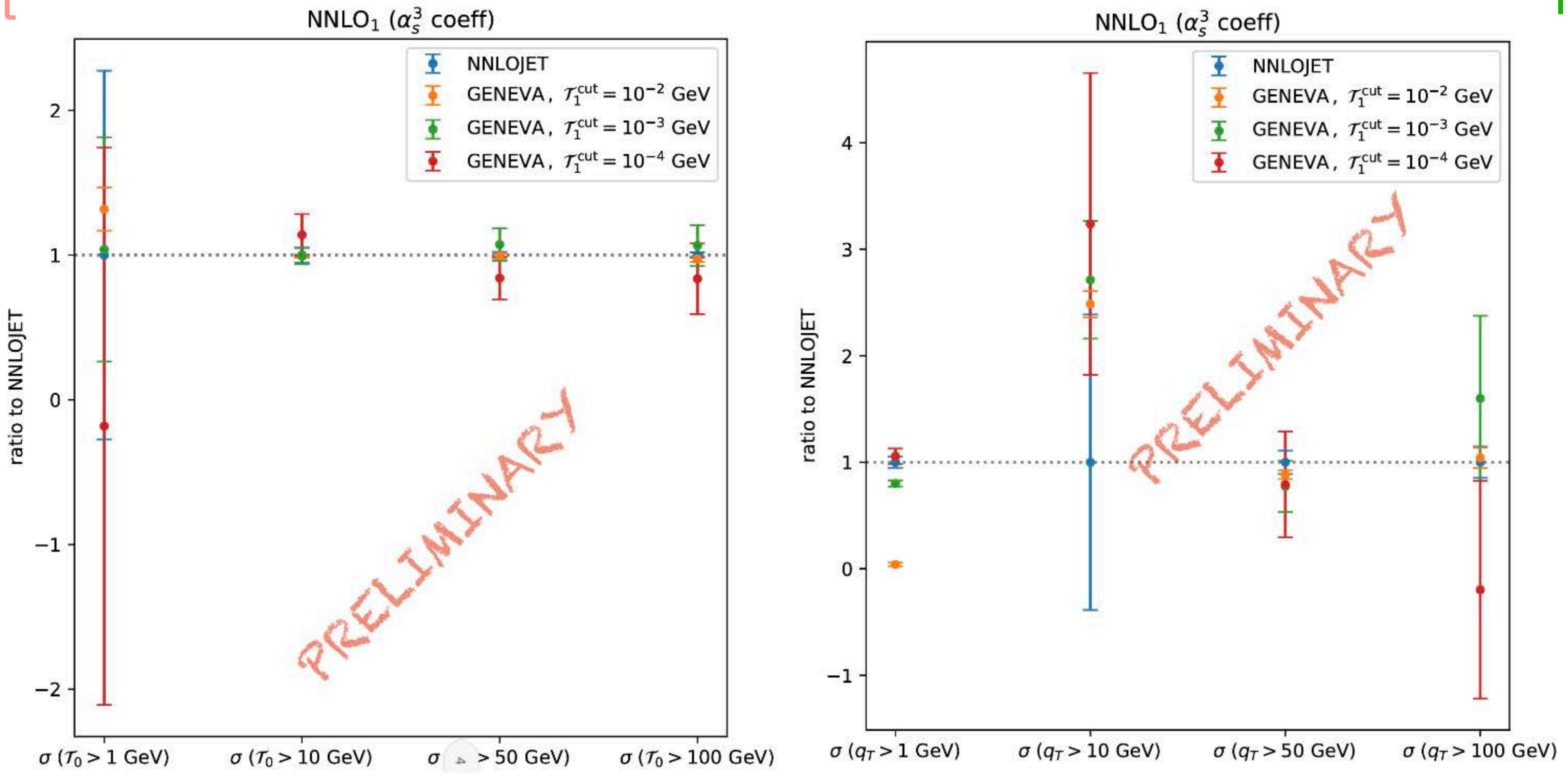
$$O^{\delta \mathrm{NNLO}_1}(\Phi_1) = \frac{d\sigma^{\mathrm{N3LL}}}{d\Phi_1}(\mathcal{T}_1^{\mathrm{cut}})\Big|_{\mathcal{O}(\alpha_s^3)} O(\Phi_1) + \int_{\mathcal{T}_1^{\mathrm{cut}}}^{\mathcal{T}_1^{\max}} \frac{d\Phi_2}{d\Phi_1}\frac{d\sigma^{\delta \mathrm{NLO}_2}}{d\Phi_2} O(\Phi_{\{2,3\}})$$

Analytic cumulant expanded

NLO with local FKS subtraction

Below the cut, resummed result integrated and expanded

Above the cut, fixed-order result for Z+2-jets



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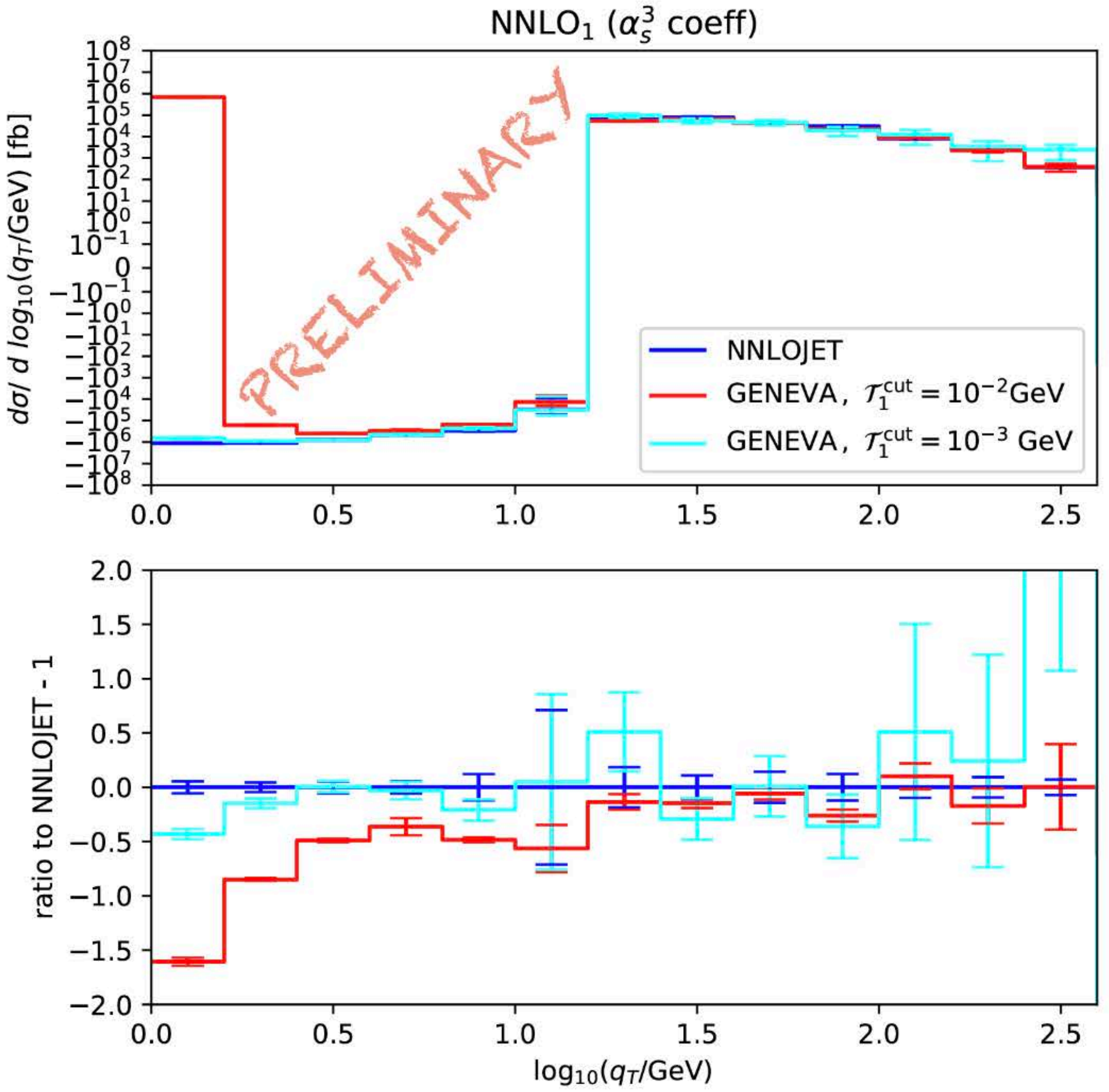

Smaller τ_1^{cut} closer to NNLOJET (=local subtraction), but with increased numerical errors

Larger τ_1^{cut} more stable, but not reproducing NNLOJET result at small q_T

How can we improve the slicing?

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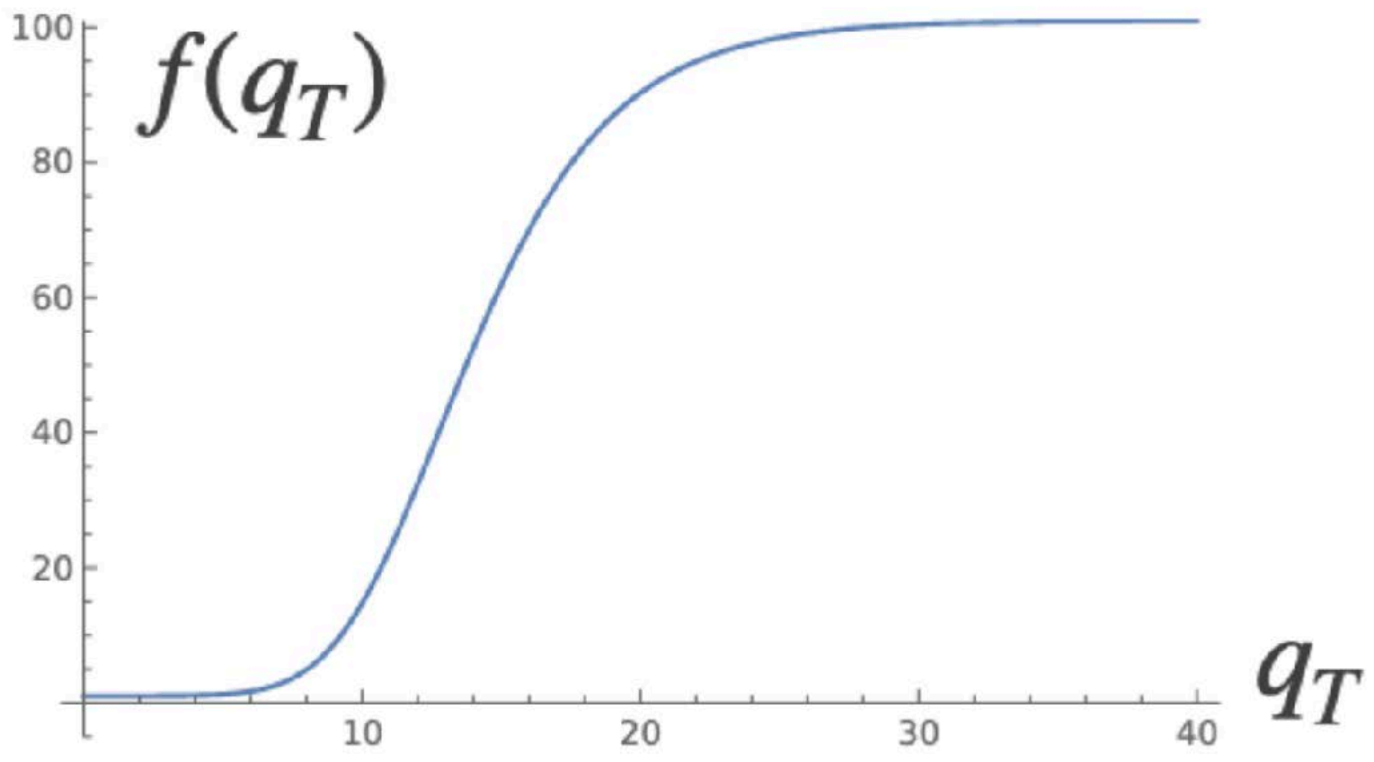
Dynamical cuts:

It is a multiscale problem!
We would like to avoid large logs between τ_1^{cut} and other scales e.g. q_T

$$\mathcal{T}_1^{\mathrm{cut}} = \min\{10^{-4} f(q_T), \mathcal{T}_0/2\}$$



τ_1^{cut} smoothly interpolating between 10^{-2} and 10^{-4}

Local subtraction in τ_1:

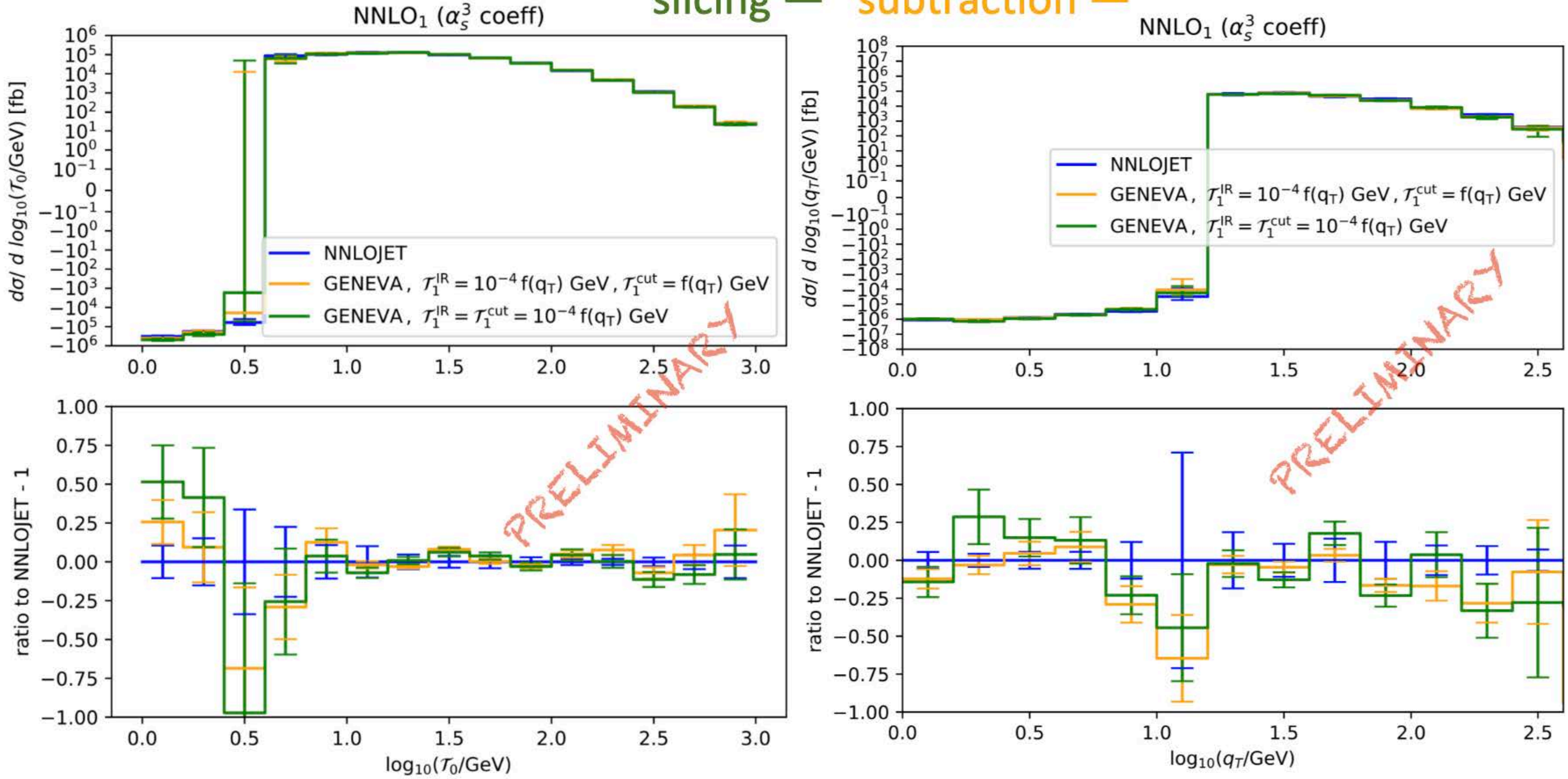
we can subtract the singular spectrum locally in τ_1 between τ_1^{cut} and $\tau_1^{\mathrm{IR}} \ll \tau_1^{\mathrm{cut}}$

$$O^{\delta\mathrm{NNLO}_1}(\Phi_1) = \frac{d\sigma^{\mathrm{N3LL}}}{d\Phi_1}(\mathcal{T}_1^{\mathrm{cut}})\bigg|_{\mathcal{O}(\alpha_s^3)} O(\Phi_1) + \int_{\mathcal{T}_1^{\mathrm{cut}}}^{\mathcal{T}_1^{\mathrm{max}}} \frac{d\Phi_2}{d\Phi_1} \frac{d\sigma^{\delta\mathrm{NLO}_2}}{d\Phi_2} O(\Phi_{\{2,3\}})$$

$$+ \int_{\mathcal{T}_1^{\mathrm{IR}}}^{\mathcal{T}_1^{\mathrm{cut}}} \frac{d\Phi_2}{d\Phi_1} \left[\frac{d\sigma^{\delta\mathrm{NLO}_2}}{d\Phi_2} O(\Phi_{\{2,3\}}) - \frac{d\sigma^{\mathrm{N3LL}}}{d\Phi_1 d\mathcal{T}_1}\bigg|_{\mathcal{O}(\alpha_s^3)} \mathcal{P}(z,\varphi)\, O(\Phi_1) \right]$$

The subtraction term can be any approximation of the exact NNLO result with the same singular behaviour

(here, we adopt the singular spectrum times a normalised splitting function $\mathcal{P}$ to make it differential in the higher-multiplicity phase-space) slicing — subtraction —

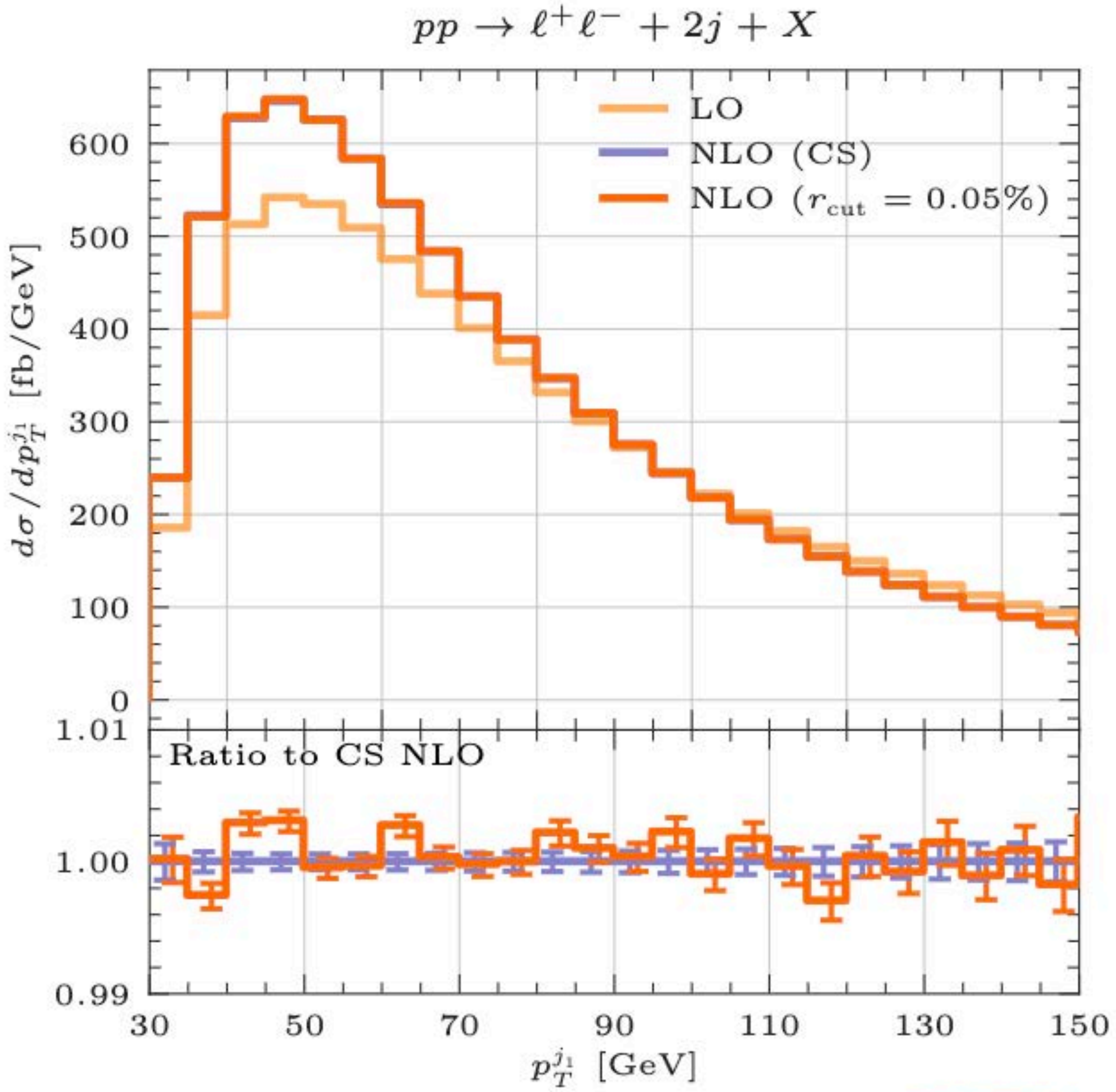


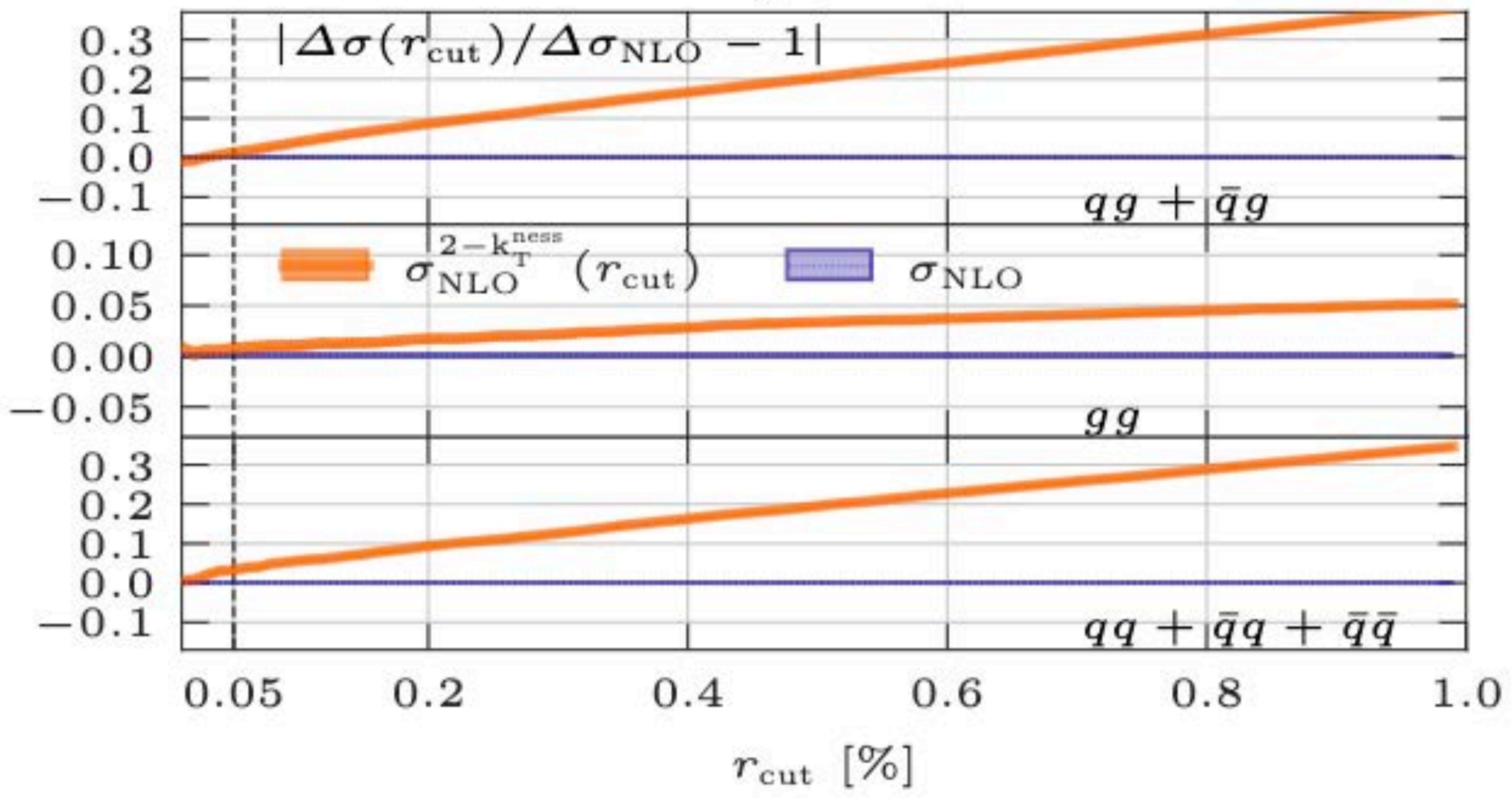
Next steps towards NNLO+PS for Z+jet:

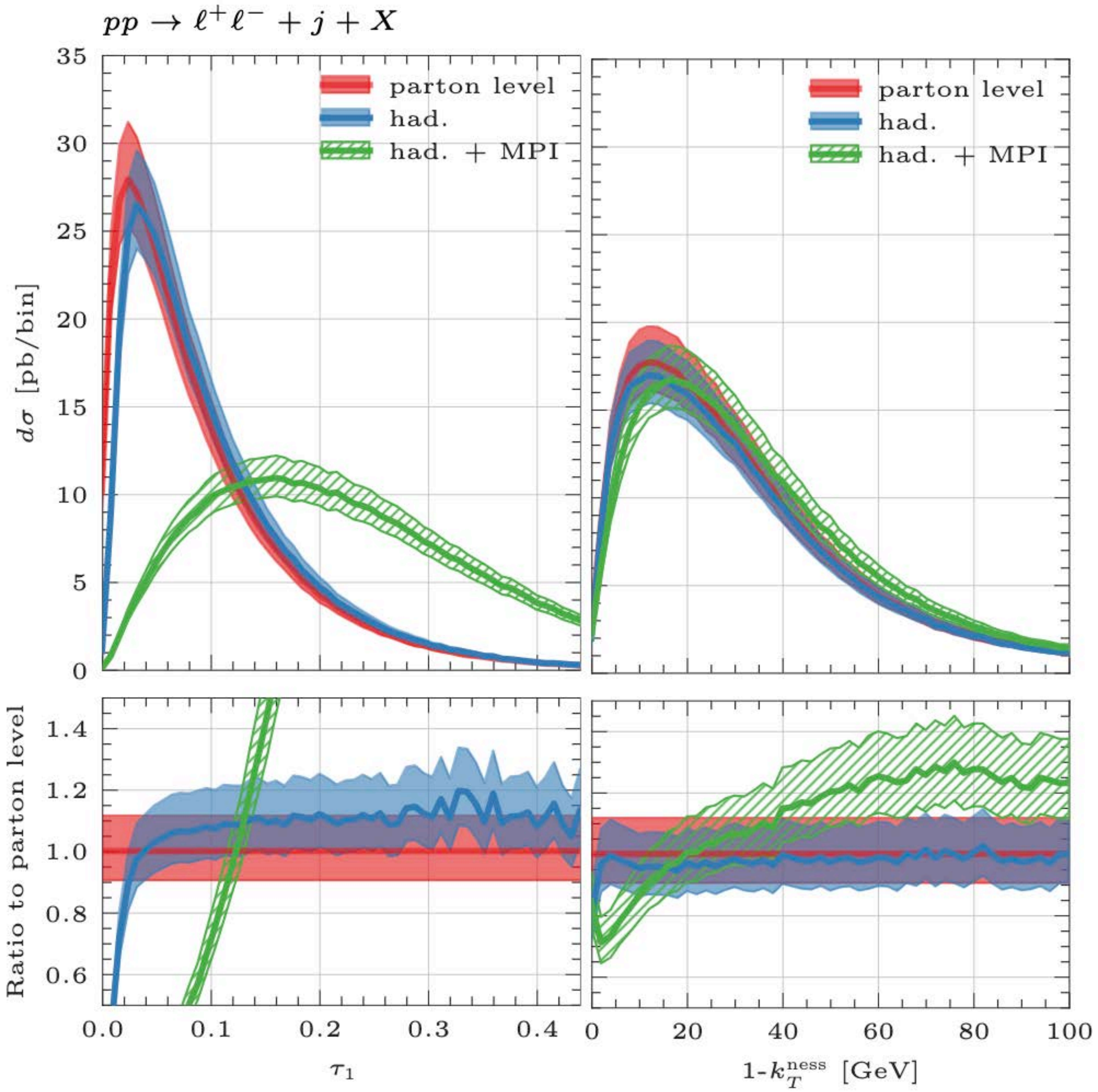
- $\mathcal{T}_1$-preserving mapping
- splitting functions $\mathcal{P}_{2\to3}(\Phi_2)$
- resummation of $\mathcal{T}_2$
- interface to parton shower
- **alternative resolution variables?**

e.g. k_T^{ness}, based on exclusive k_T-clustering algorithm

[Buonocore, Grazzini, Haag, Rottoli, C. Savoini ’22,’23]







More stable than $\mathscr{T}_1$ under non-pert. effects (had. and MPI)

All ingredients at NLO, extension to NNLO WIP

If available, resummation up to NNLL’ would allow for usage in NNLO+PS frameworks

Conclusions

“*At the LHC, with enough luminosity, any measured observable will show a deviation from theory predictions*”

A wise man

We have just entered the precision era of colliders.

We know very well the Standard Model, but not enough.
Precision implies not only to push accuracy of predictions,
but also to revisit basic assumptions and develop new strategies.

To claim percent-level accuracy on SM predictions, there are a lot of things to improve:

- accuracy of hard-scattering (first N3LO results appearing)
- matching to parton shower (progresses towards NNLO+PS for processes with jets)
- accuracy of parton showers (new generation of PS with higher logarithmic accuracy)
- understanding of non-perturbative effects (?)