QCD at the LHC

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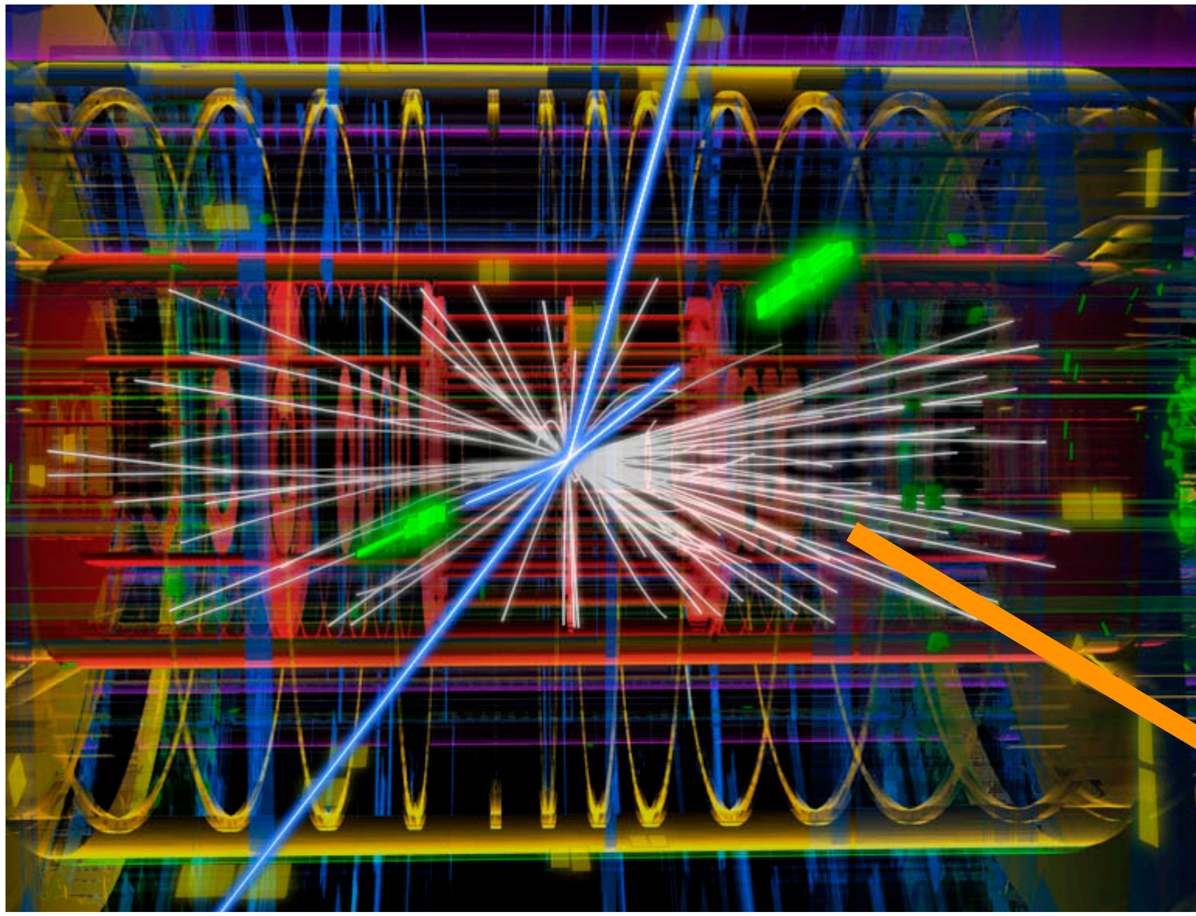
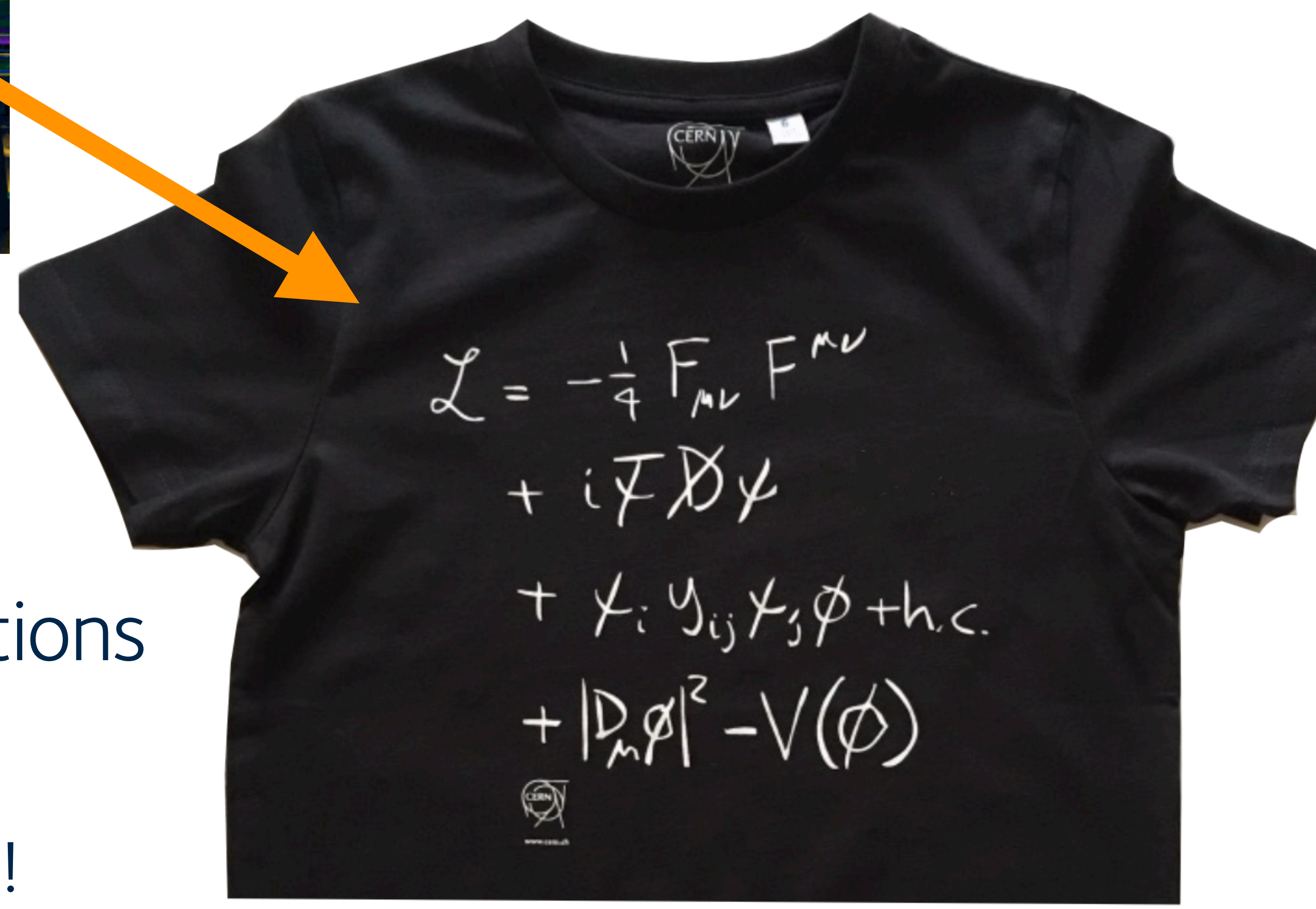
Lake Louise Winter Institute, February 25, 2022

QCD at the LHC: the big goal



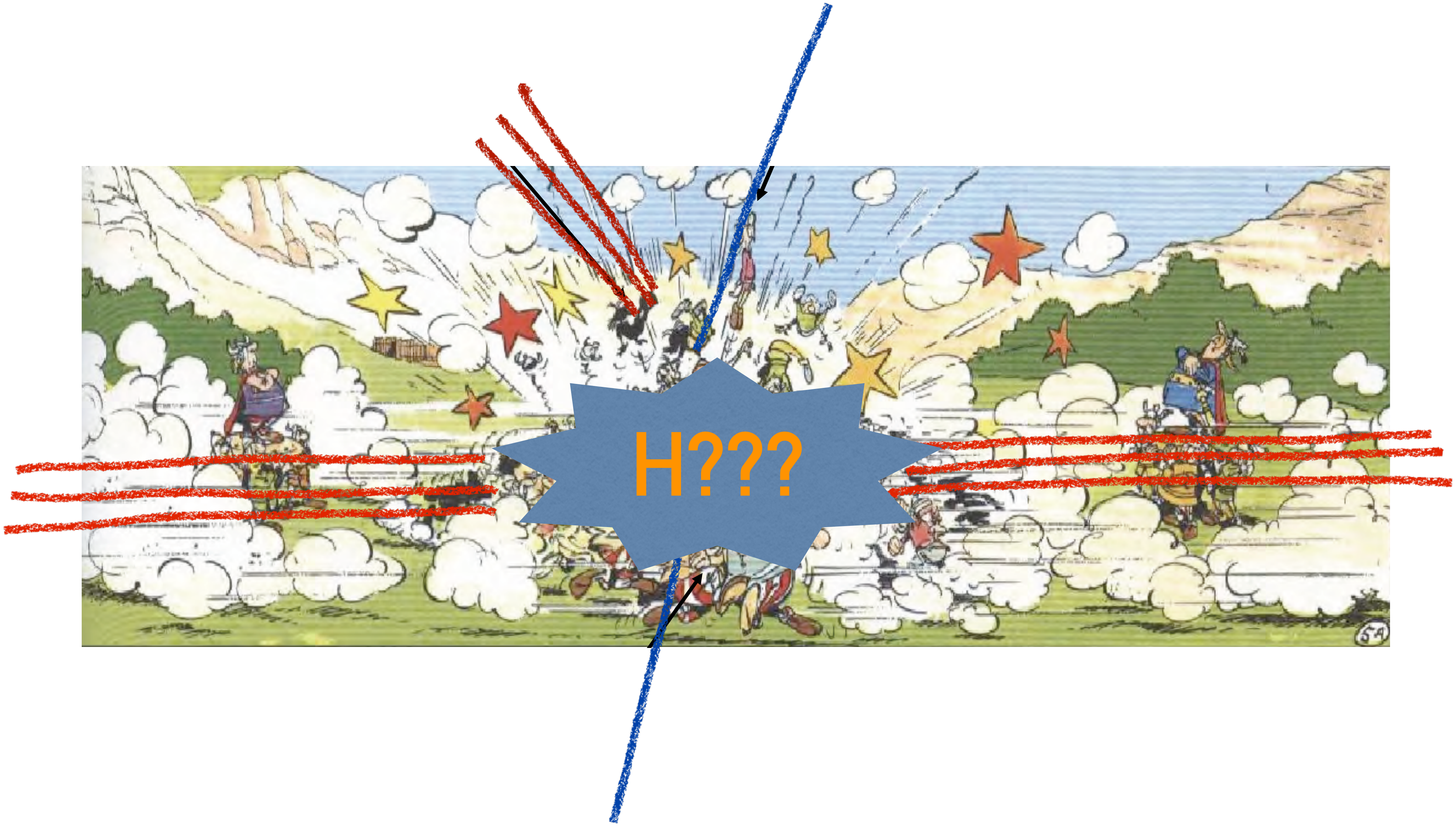
Extract information from a highly-complex environment, from first principles…



… and use it to constraint fundamental particles and interactions

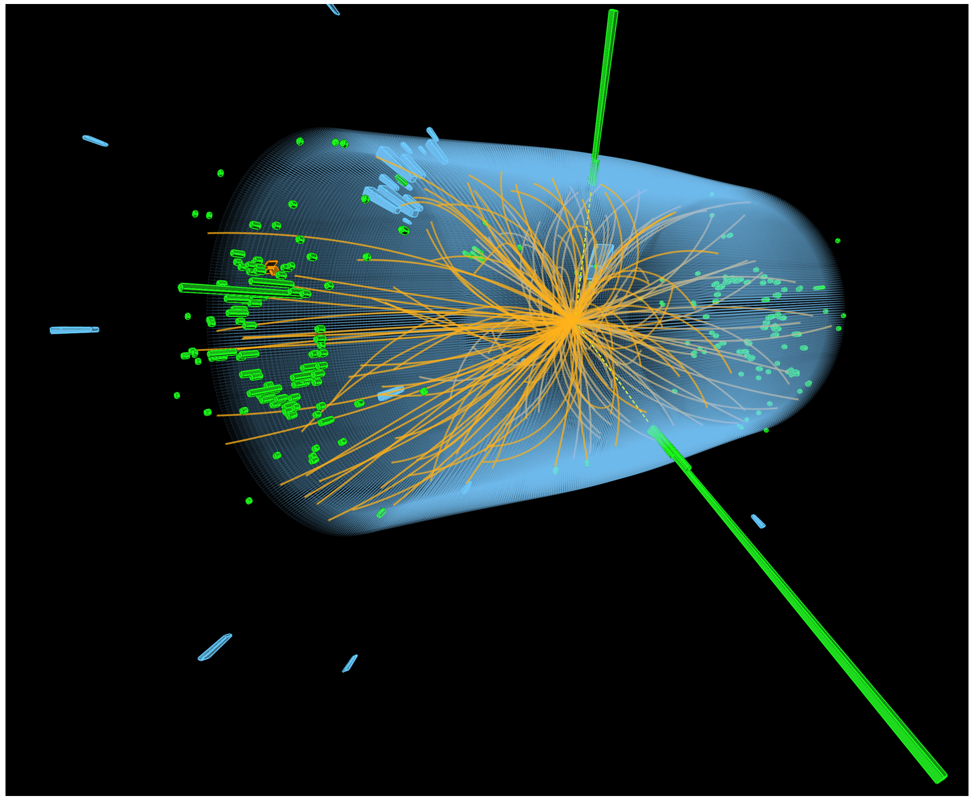
Bonus: QCD is a very interesting theory!

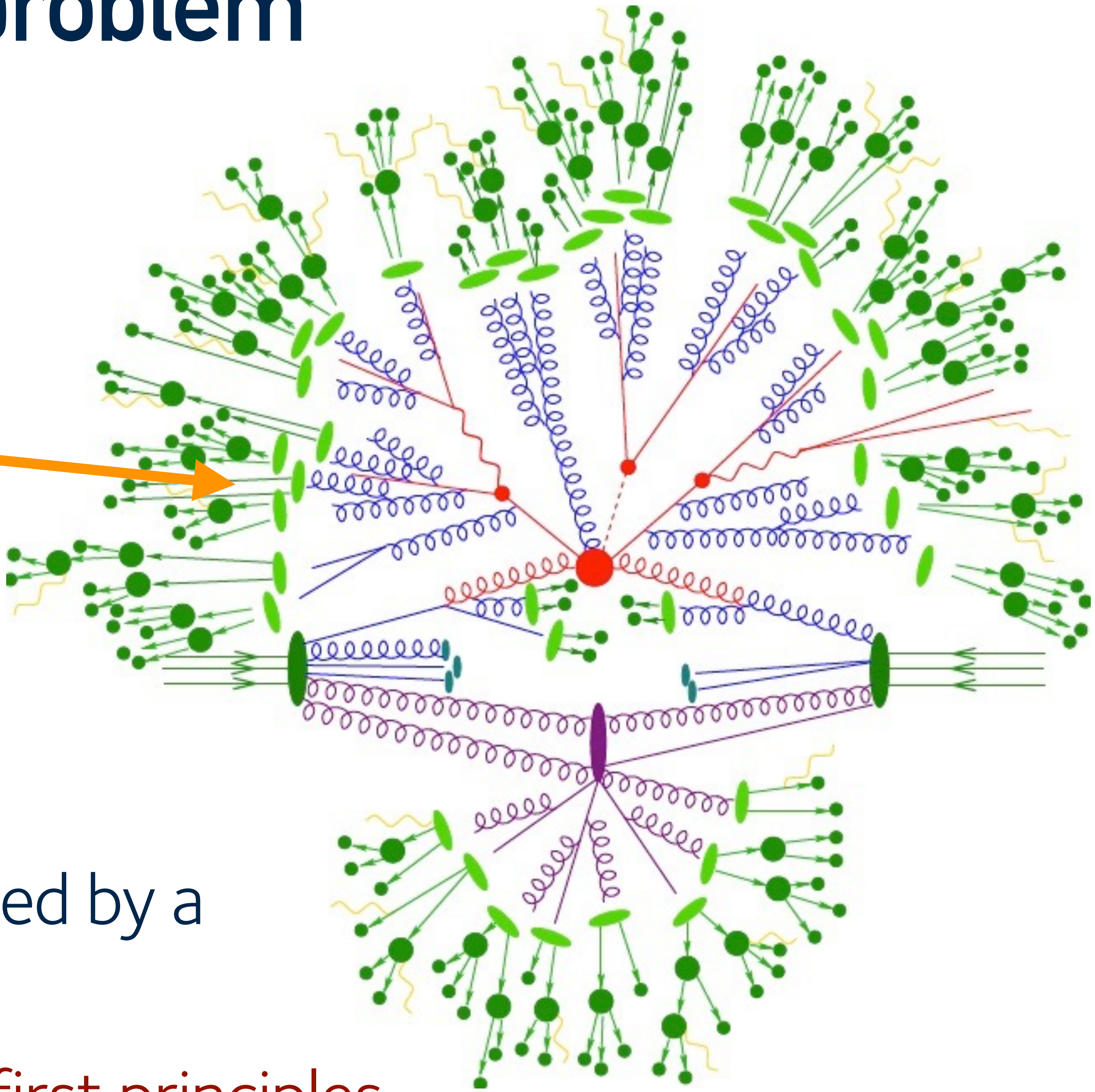
QCD at the LHC: the big goal



``It's like try to learn how a Swiss watch works by taking a bunch of them, smashing against each other and see what comes out"

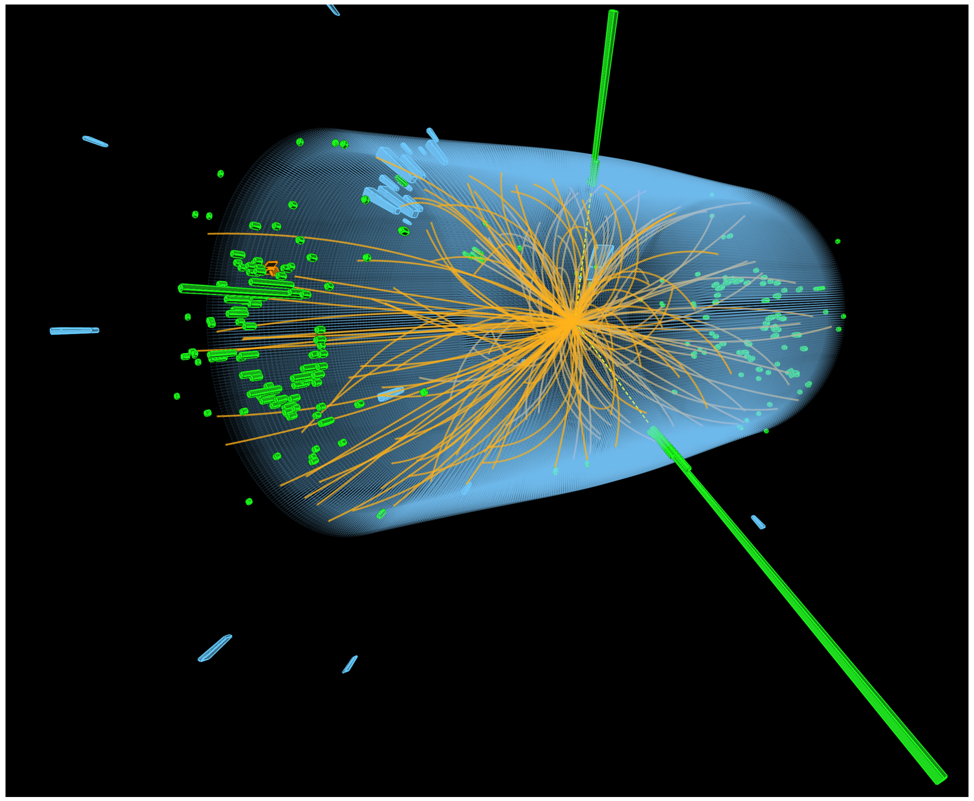
The problem

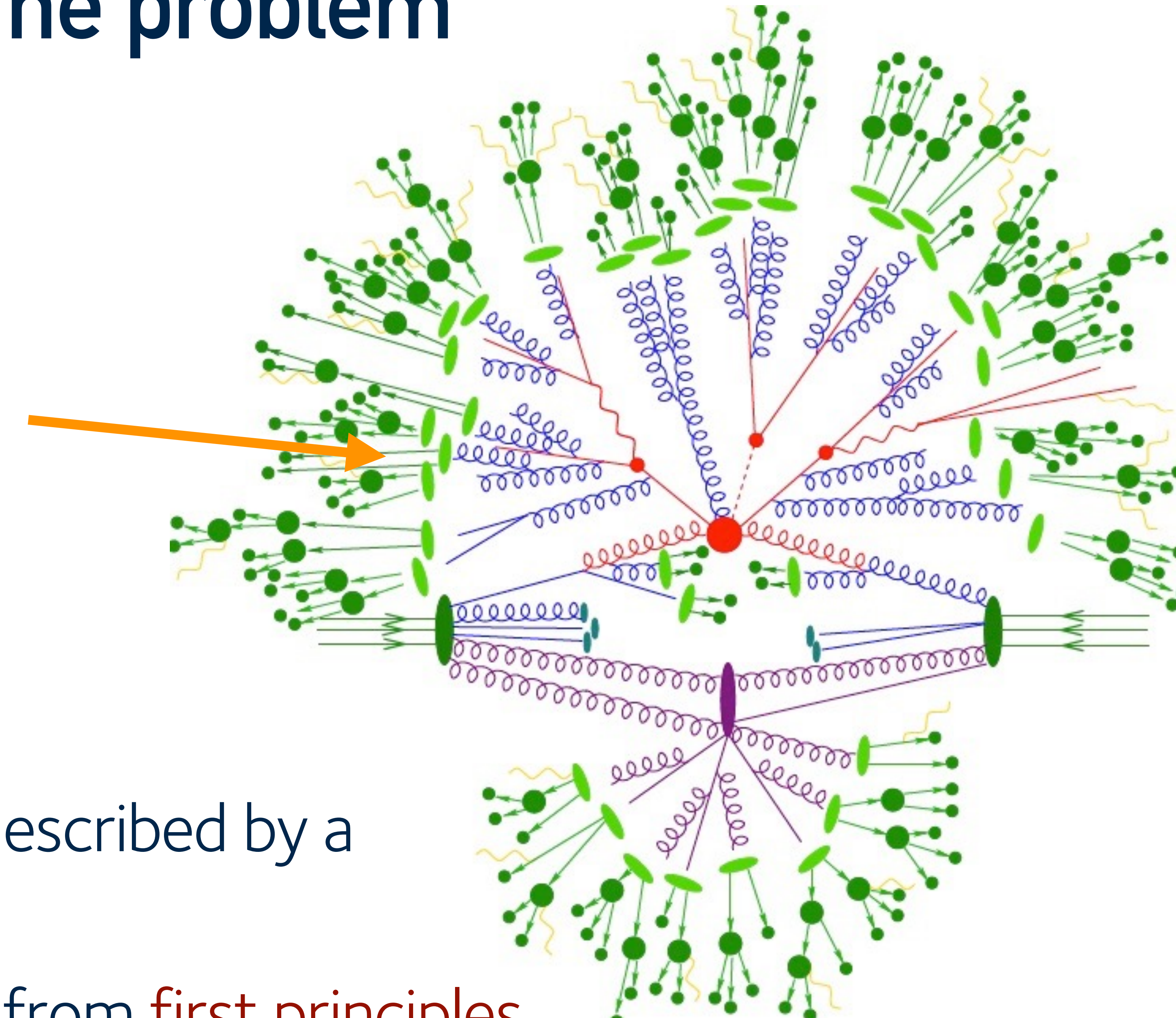




- A complex environment, described by a strongly coupled theory
- We want to understand it from first principles

The problem





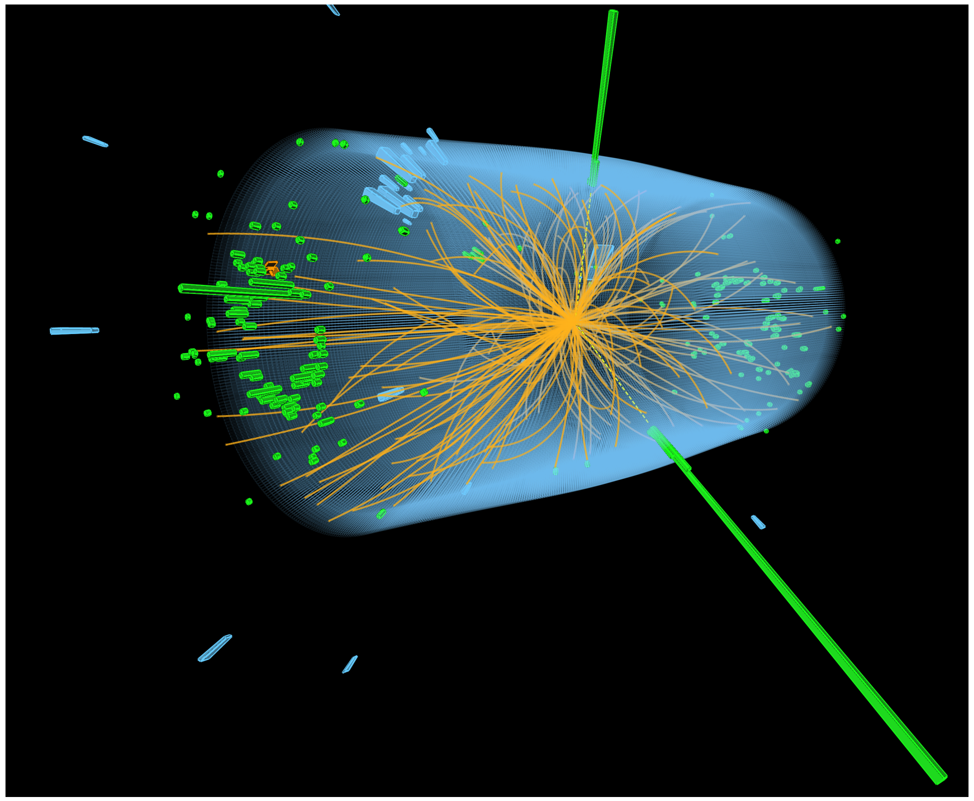
- A complex environment, described by a strongly coupled theory
- We want to understand it from first principles

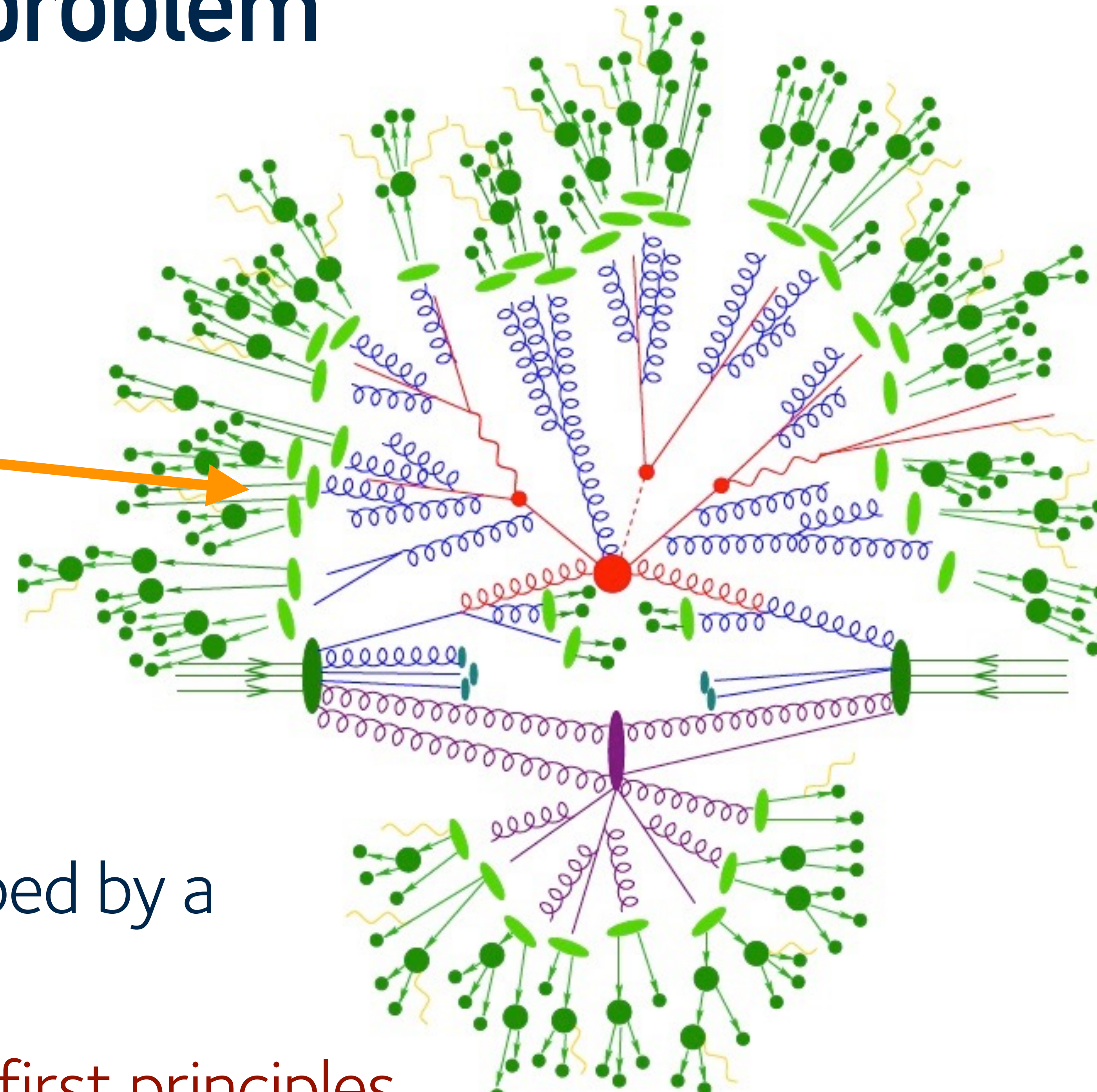
Lattice?

- Resolve the full event → 2 TeV ~ 10^{-4} fm
- Hadronic scale ~ 1fm, boost factor ~ 100 → 10^{4} fm

10^{32} nodes

The problem





- A complex environment, described by a strongly coupled theory
- We want to understand it from first principles

Lattice?

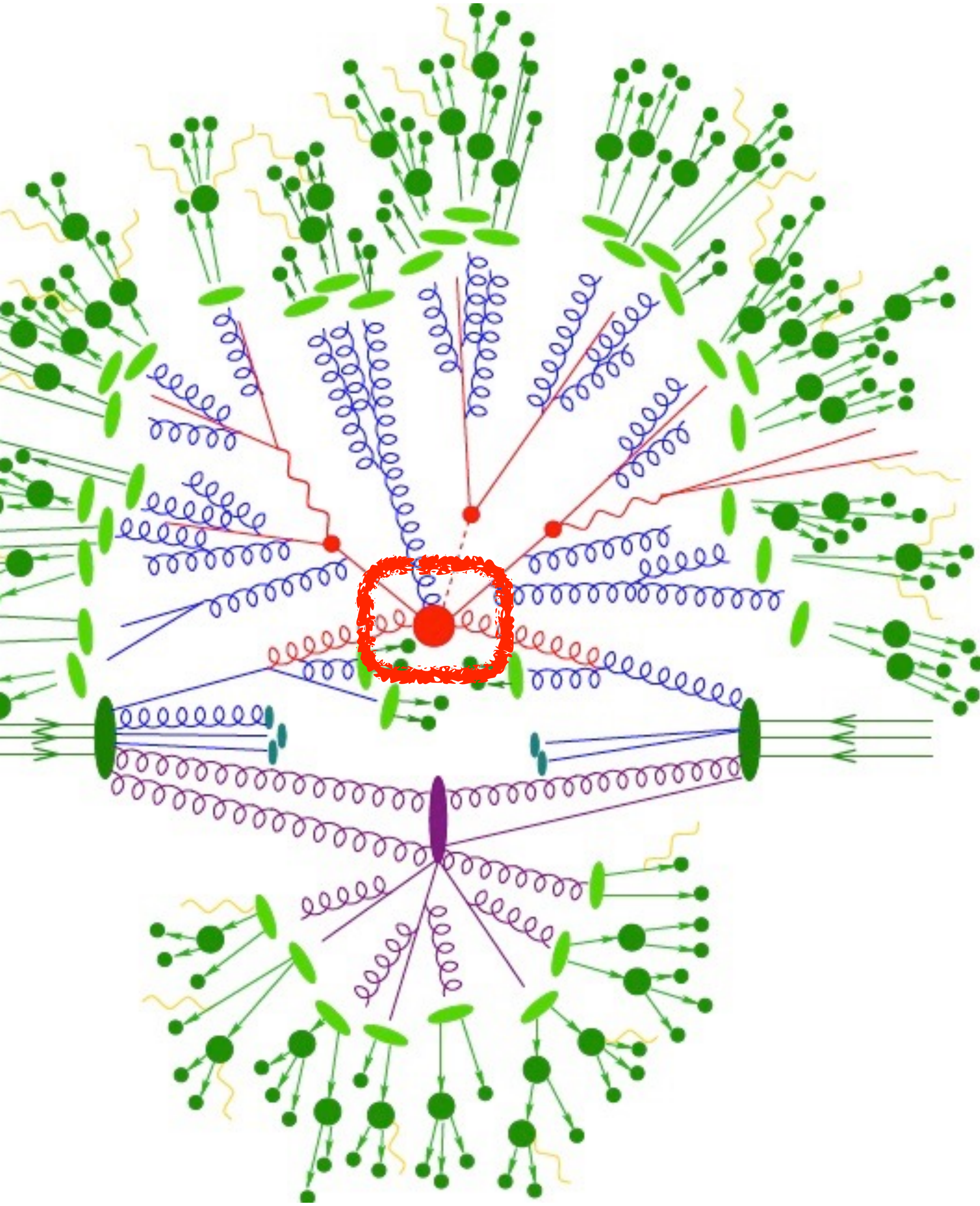
- Resolve the full
- Hadronic

10^{32} nodes

boost factor ~ 100 → 10^4 fm

Quantum computing?

The solution: factorisation



The ``interesting" short distance physics

Q ≳ 100 GeV

The experimental world: hadrons/jets in the detector

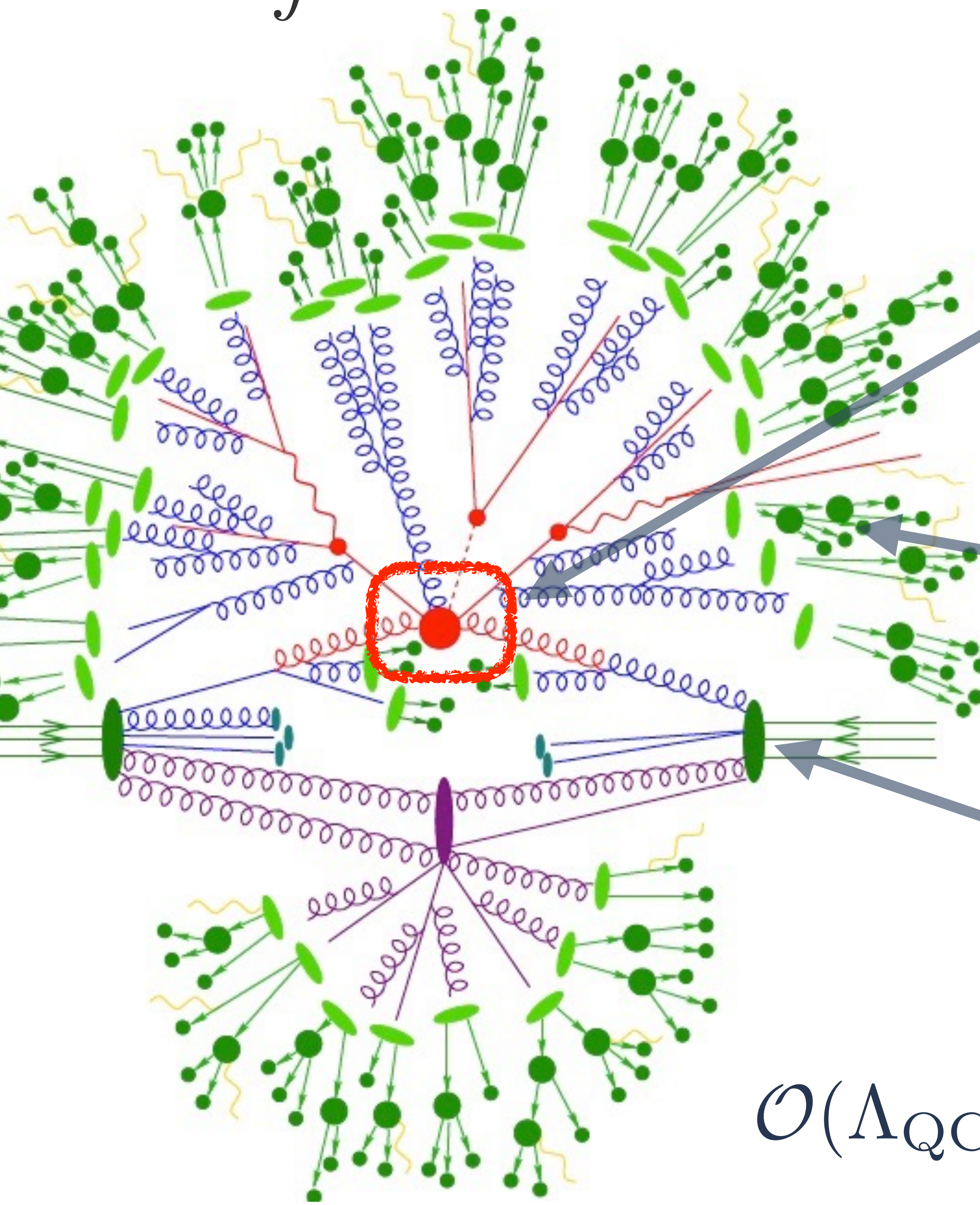
Q ~ 1 GeV

Partons from proton

Different physics at very different scales, can be TREATED SEPARATELY

The solution: factorisation

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$



The interesting short-distance perturbative cross section

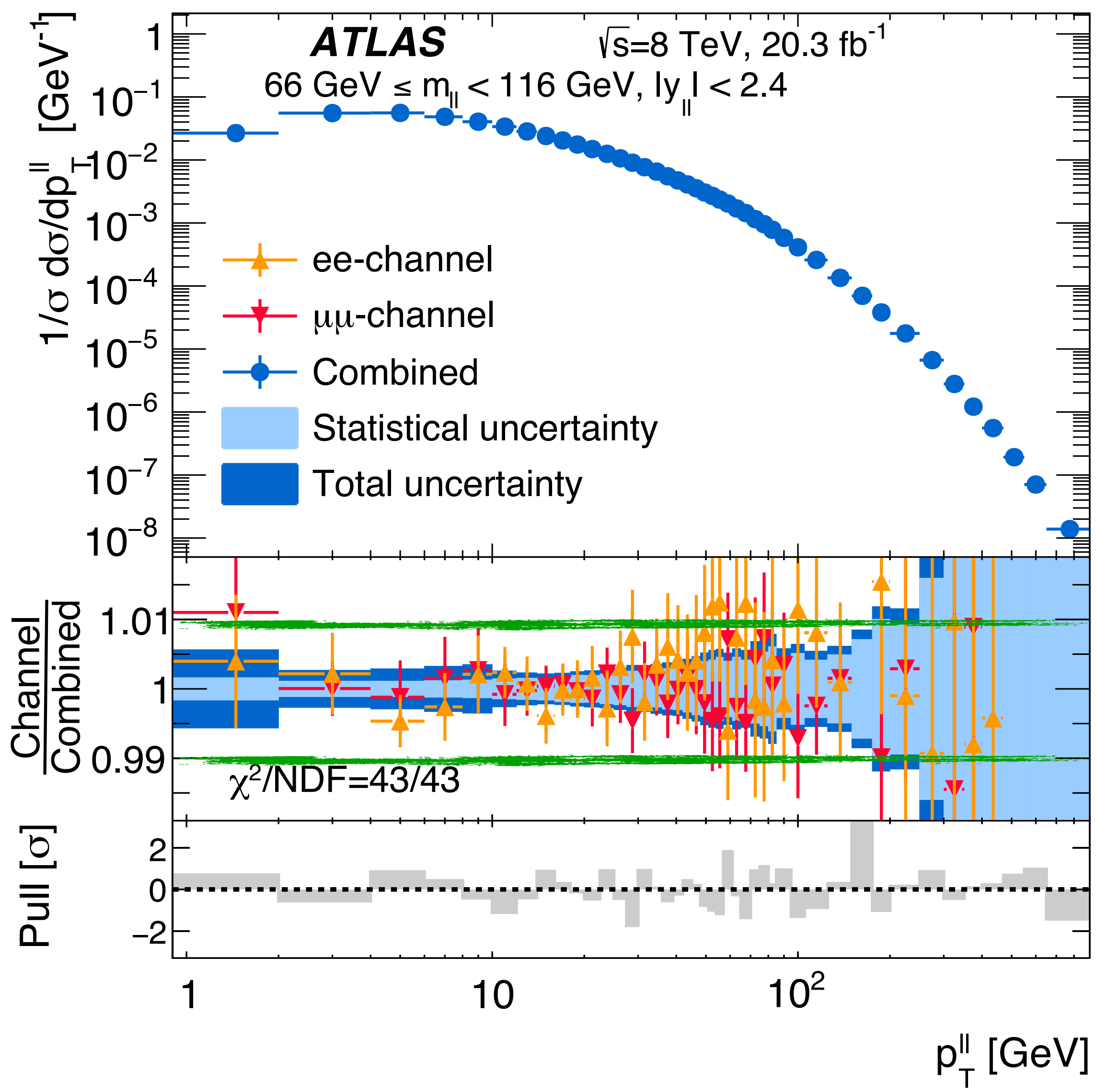
From parton to hadrons: PS

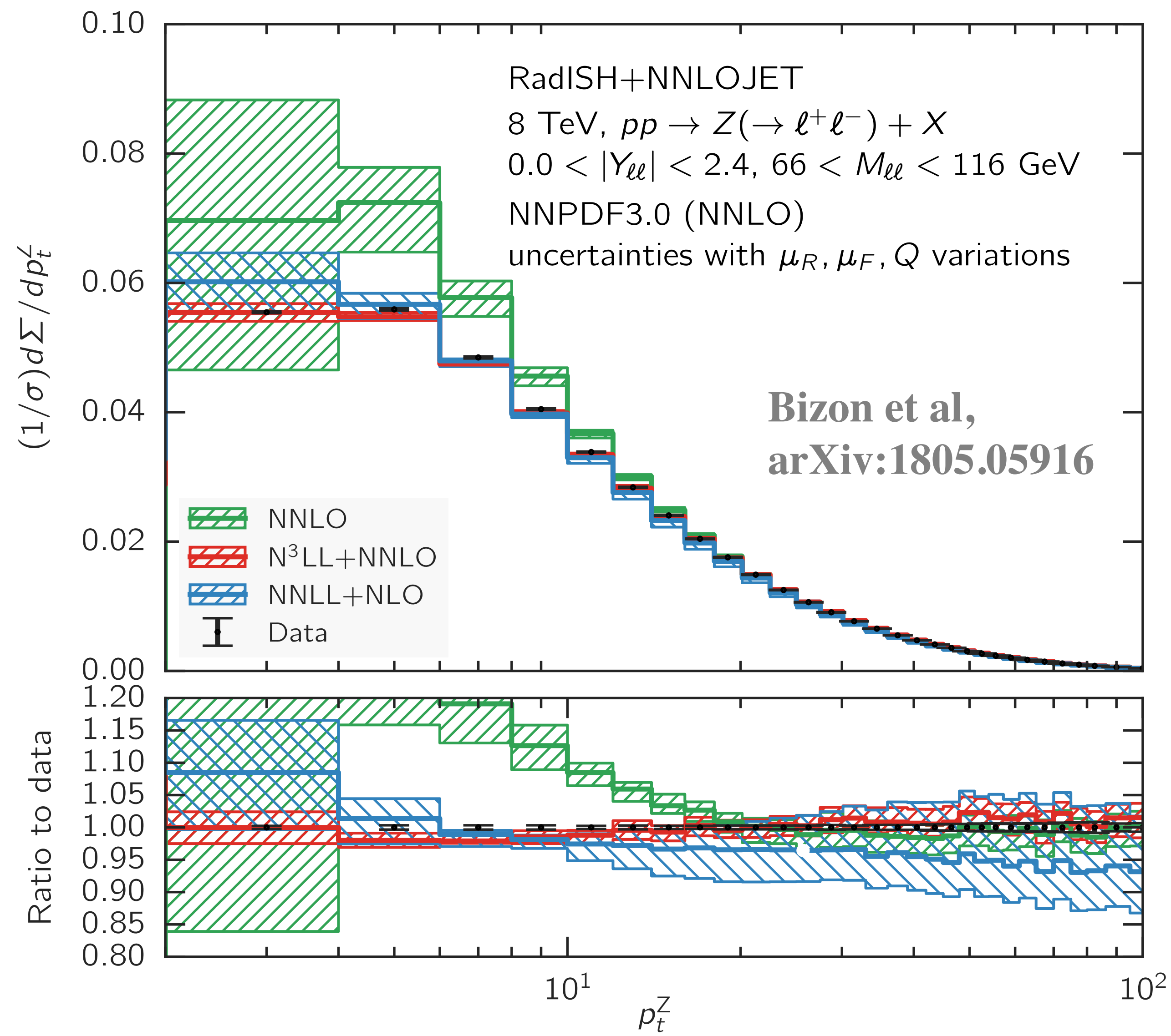
Partons in the proton: PDFs

$\mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)$: this whole construction could break down at the few-percent level!

Precision goals

Drell-Yan





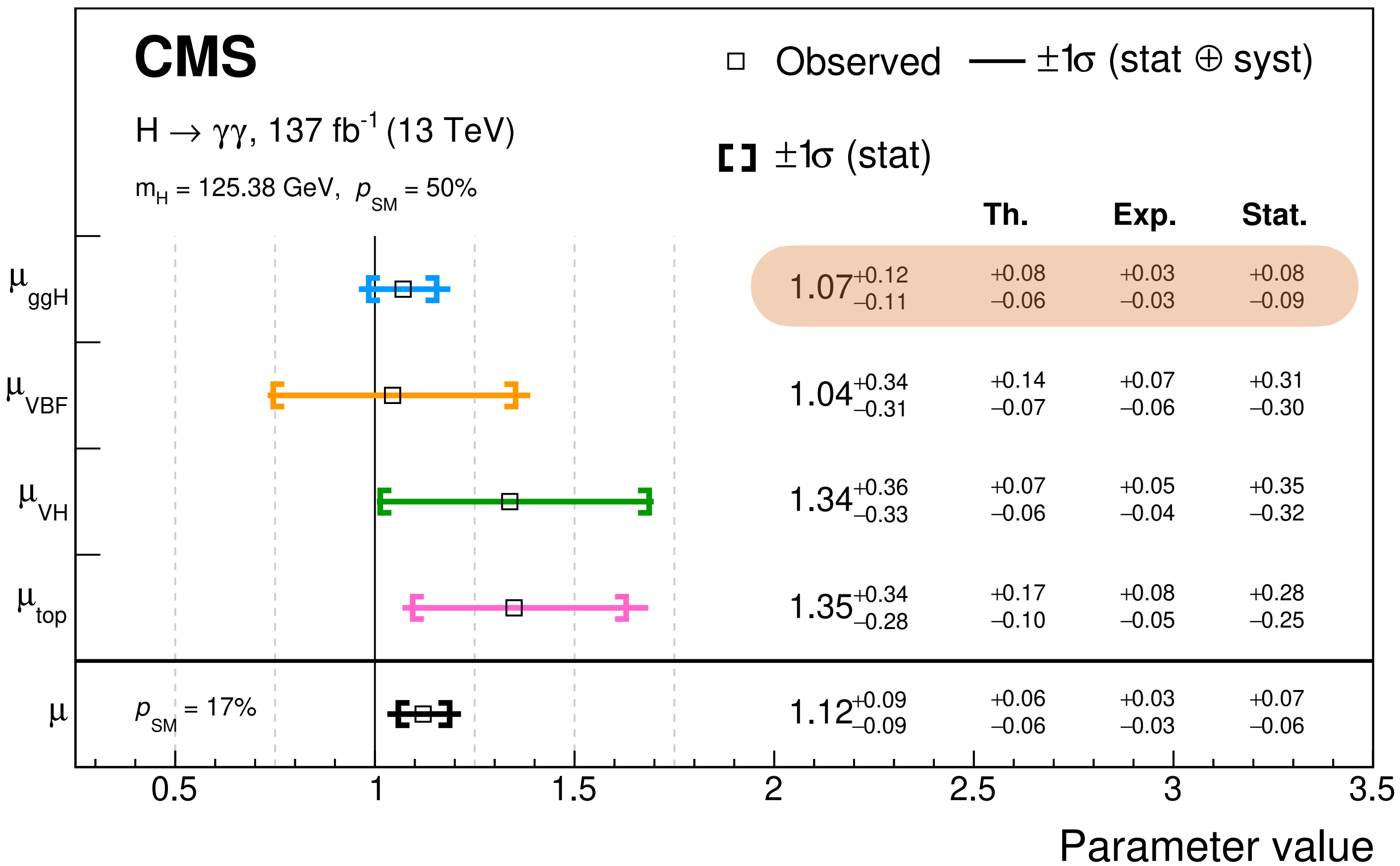
Data: per-mill

Theory: few percent

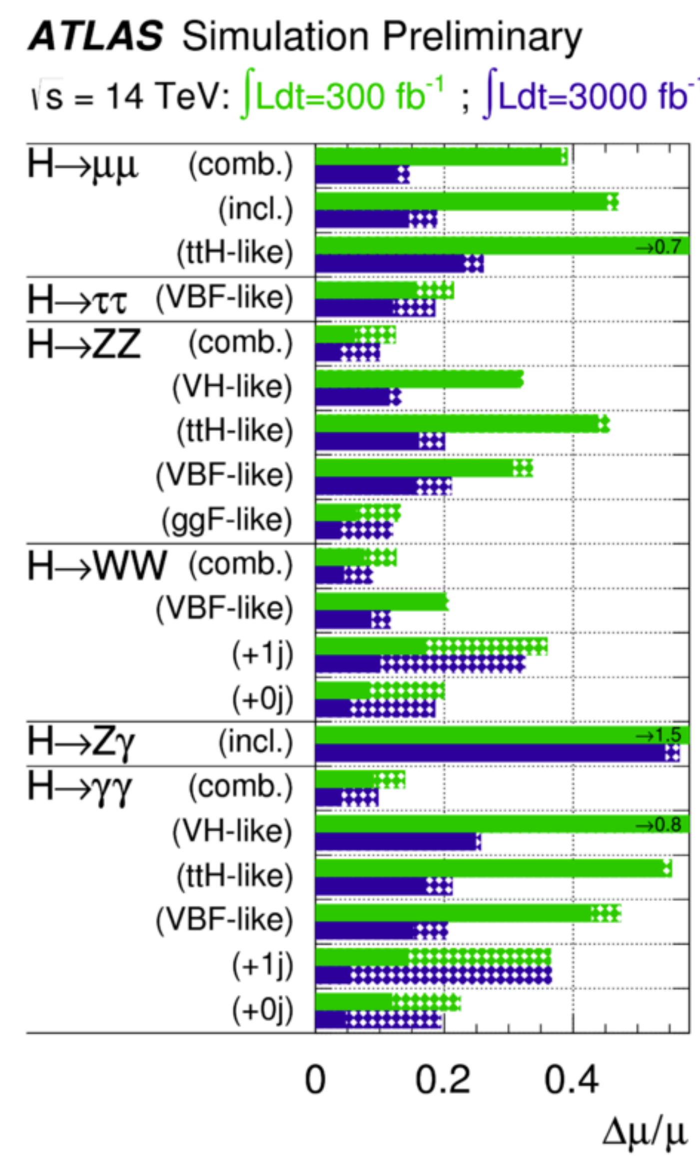
Precision goals

Higgs

ggF Higgs, now

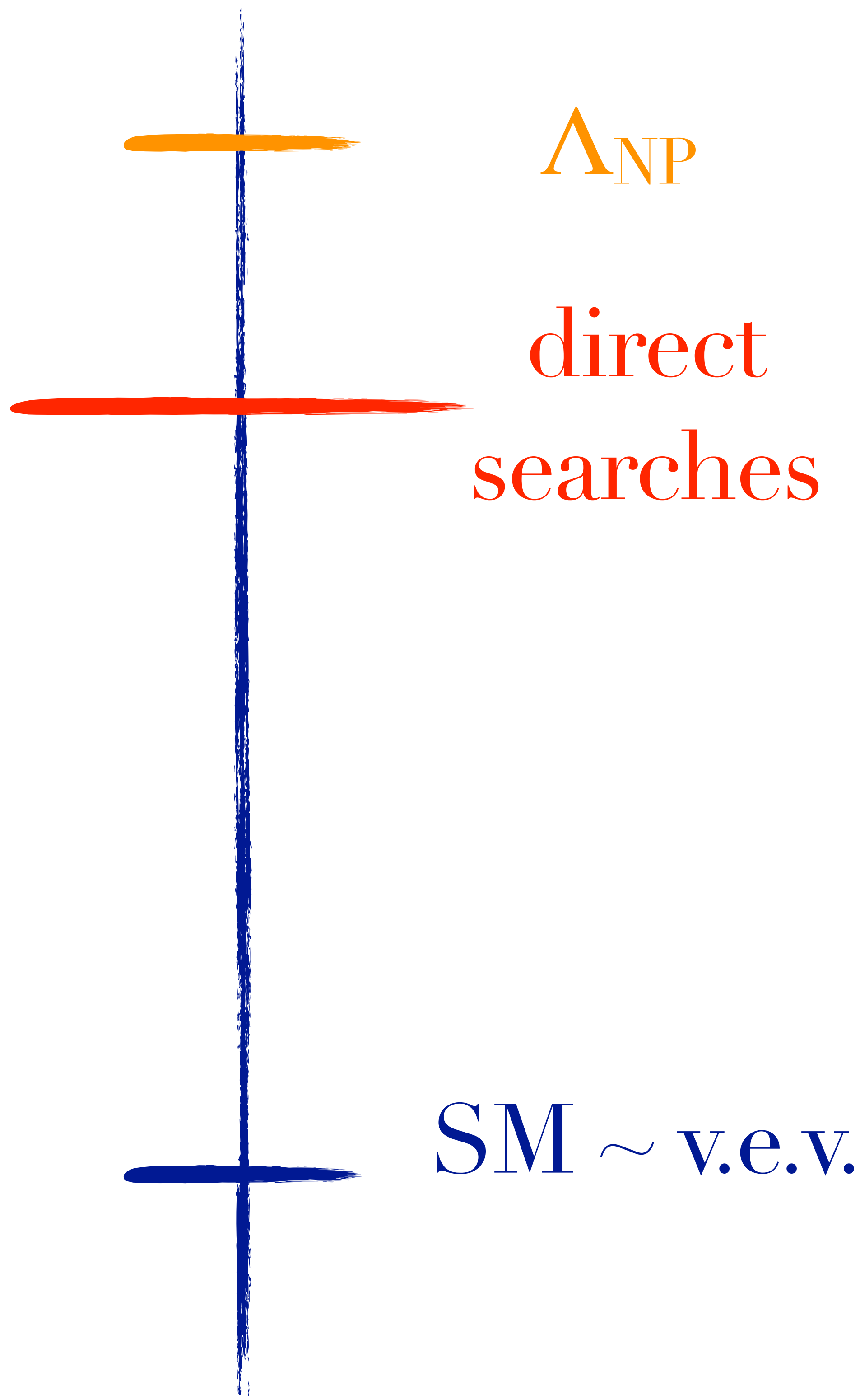


Higgs couplings, HL-LHC



In many interesting cases, physics at the few-percent possible

What does precision buy you



Imagine to have new physics at a (heavish) scale Λ_{NP}

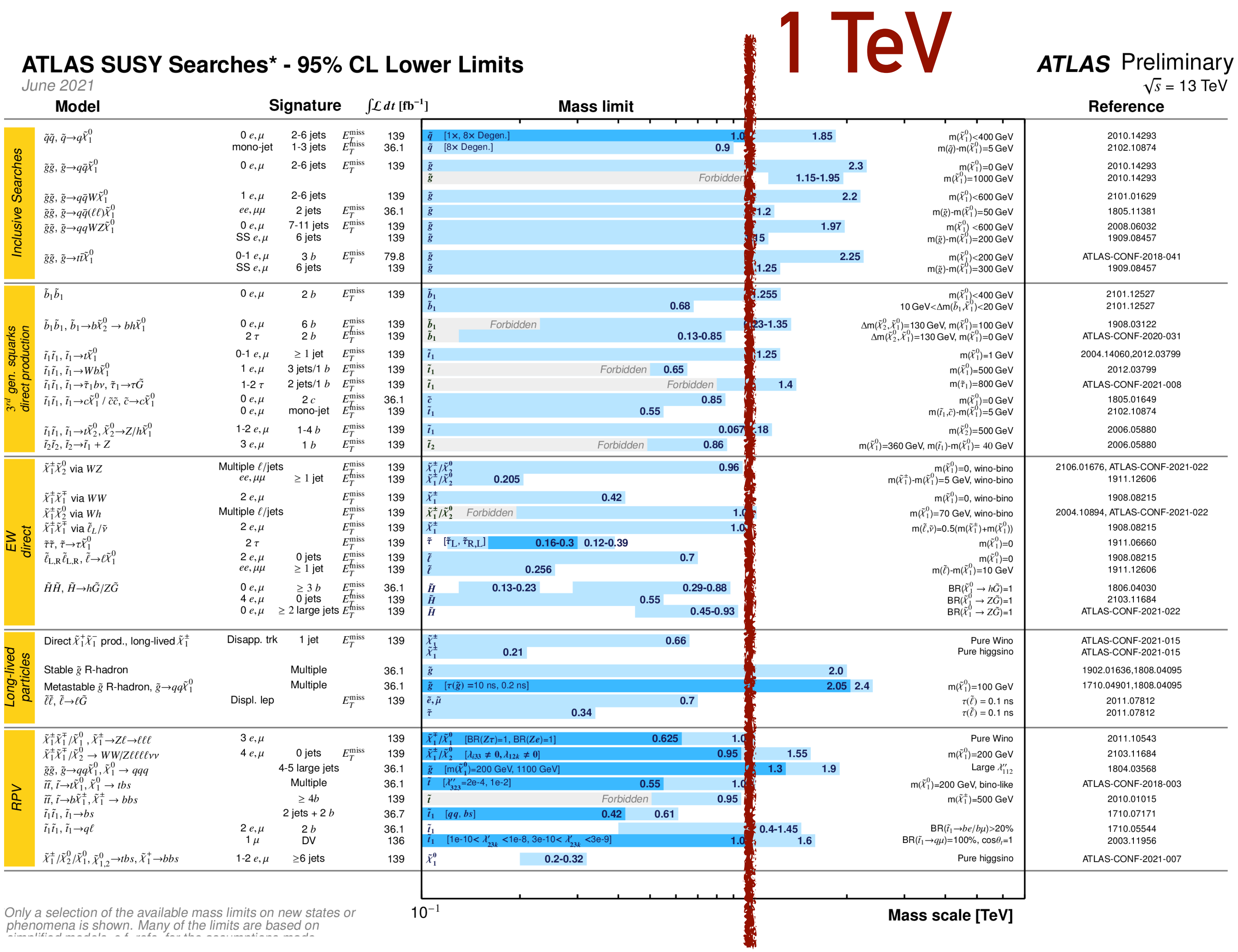
Typical modification to observable w.r.t. standard model prediction:

$\delta O \sim Q^2/\Lambda_{NP}{}^2$

Search strategies:

- Direct searches: energy-limited
- Indirect searches: precision-limited, <u>long-run game</u>

What does precision buy you



Direct searches: probing the TeV scale, already now

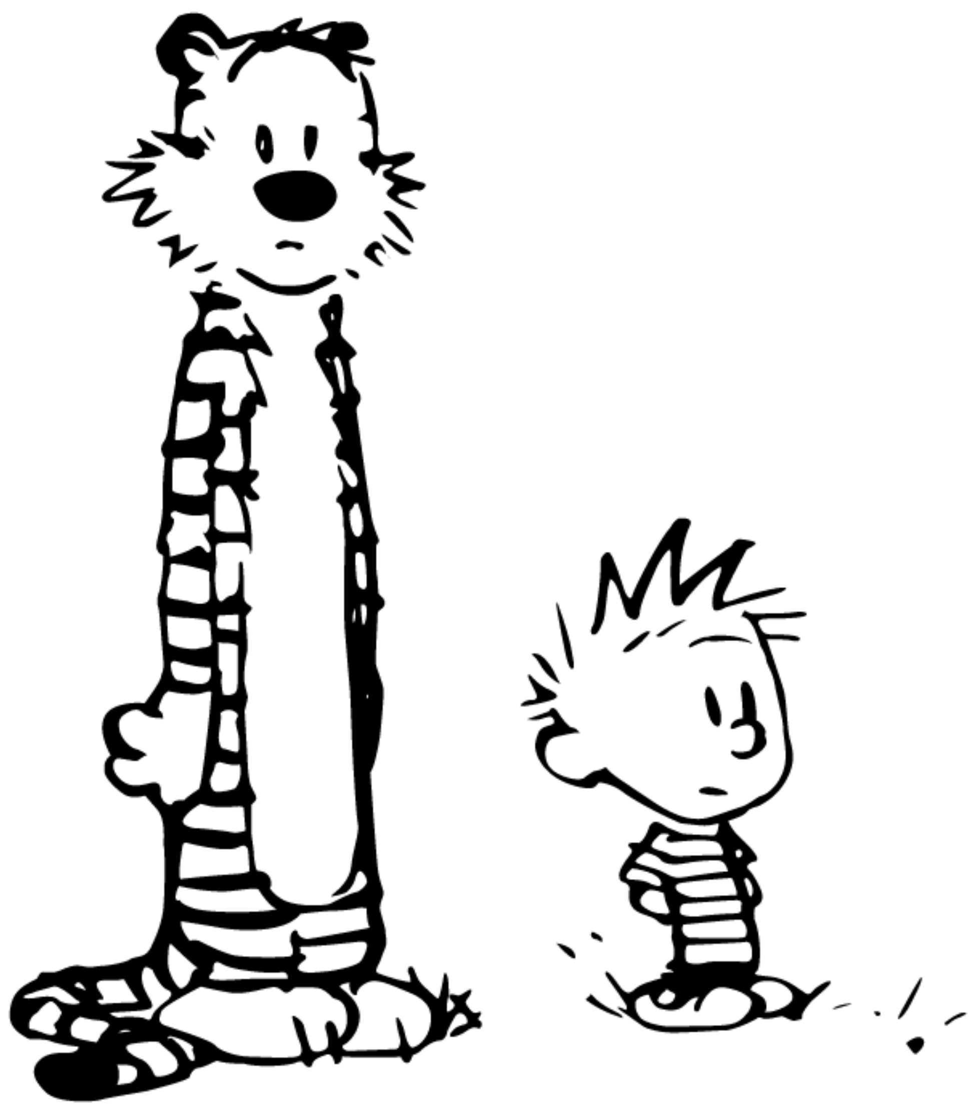
To be competitive:

$\delta = Q^2/\Lambda^2, \quad \Lambda \gtrsim 1$ TeV

δ:
- ~ few percent in the bulk (~100 GeV)
- ~ 10%, 20% in the tails (~500 GeV)

Precision QCD: an oxymoron?

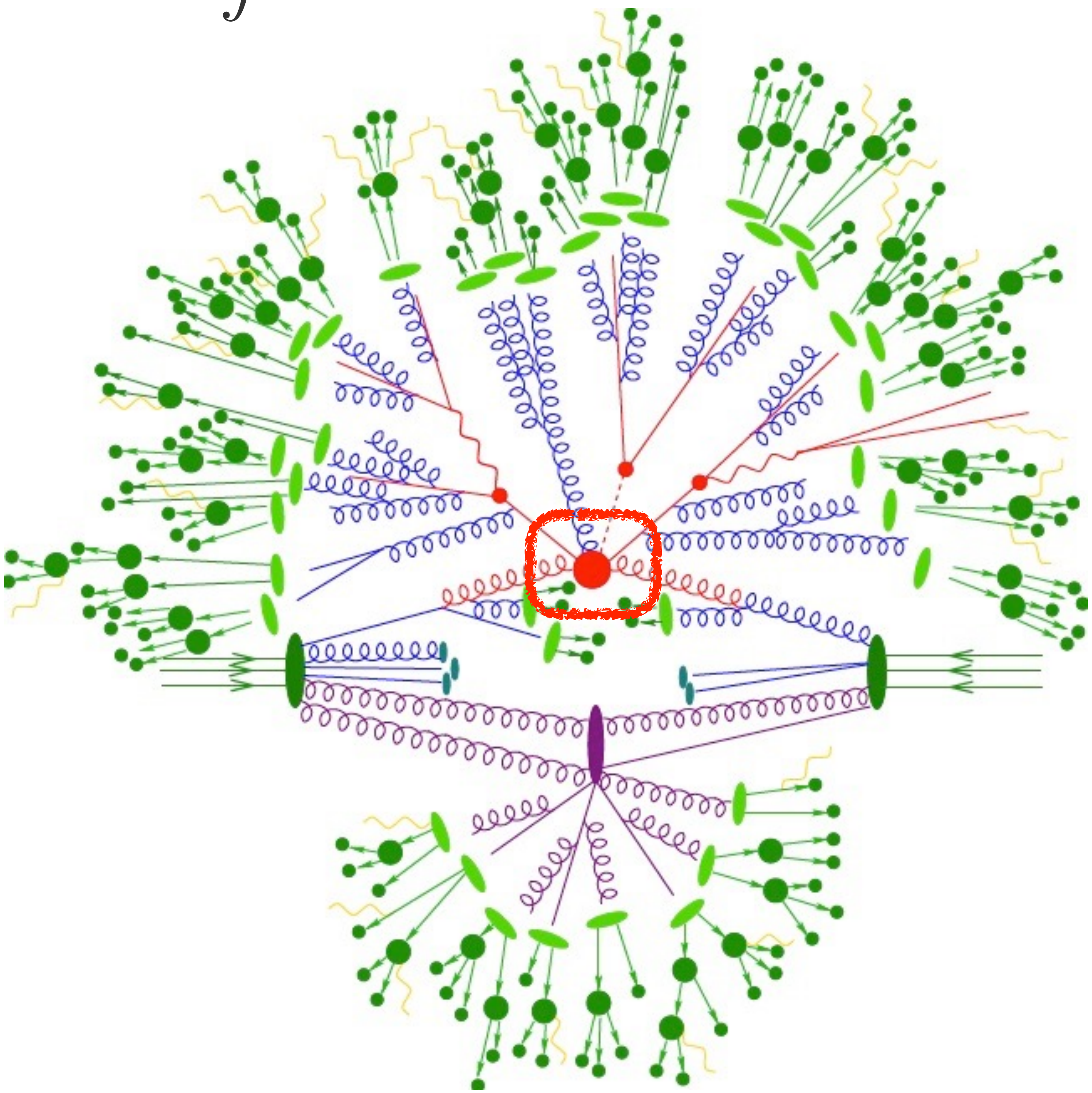
A motivational speech from an old distinguished professor, who pioneered the development of quantum field theory and the Standard Model



- And what about you young man, what are you working on?
- Perturbative QCD
- My dear boy, you should change topic: QCD was established decades ago!
- But we don't want to establish it, we want to use it to extract precision information from the LHC
- Hadron colliders are messy, you cannot do precision physics there

Physics at the few percent

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$



Need control over

Input parameters (PDFs, α_s)

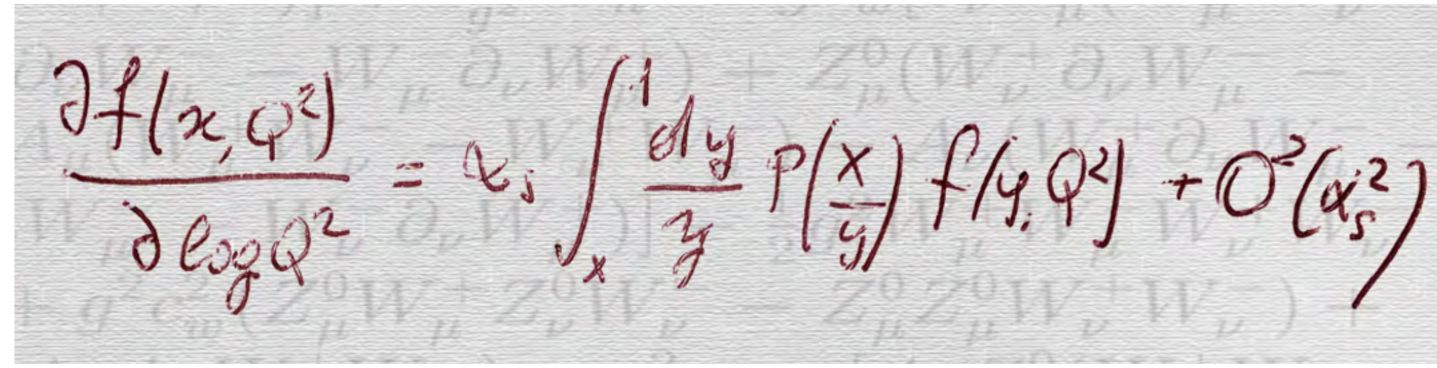
Hard process → th predictions

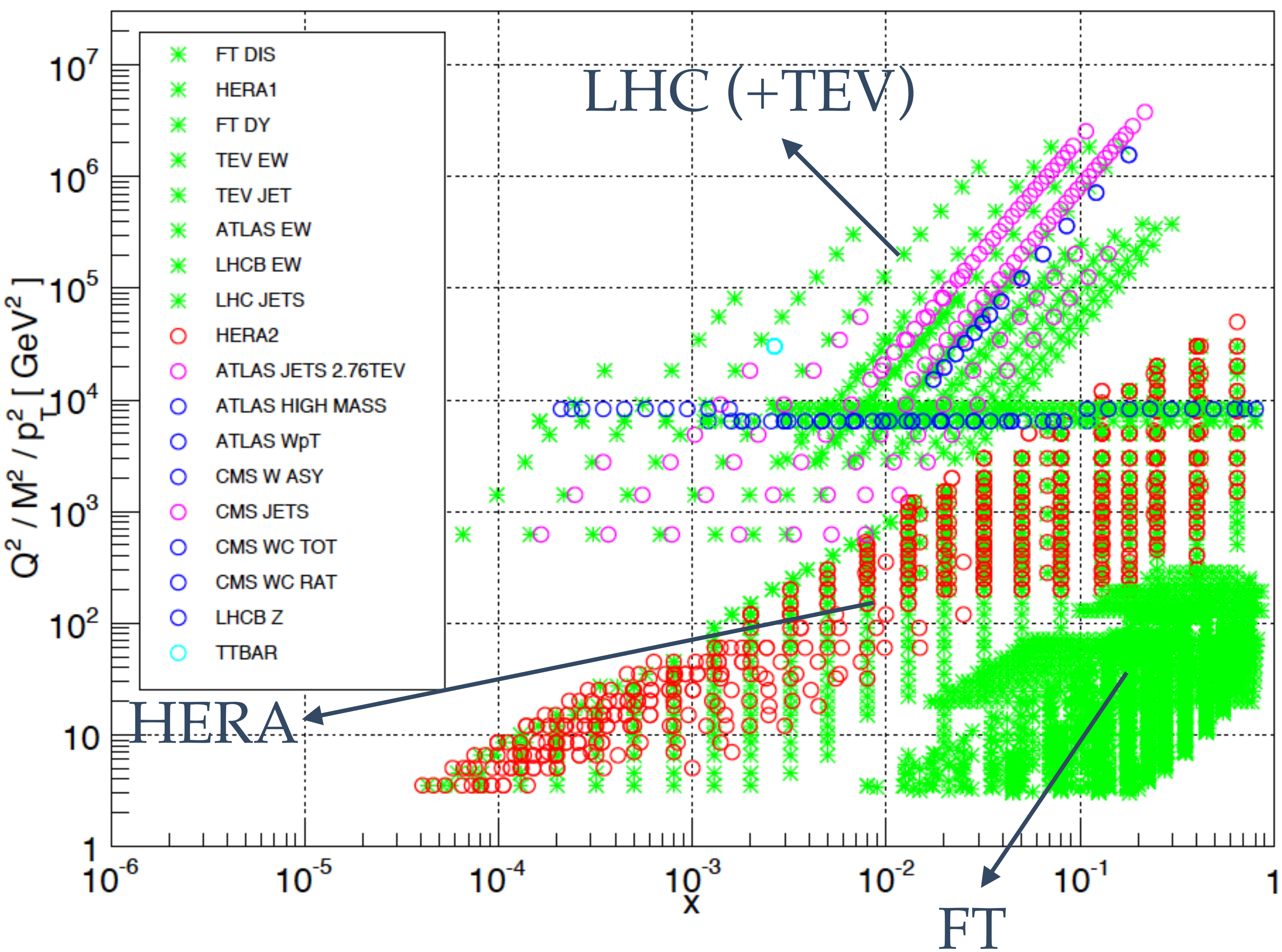
Framework

Non-trivial...

Input parameters: PDFs in the LHC era

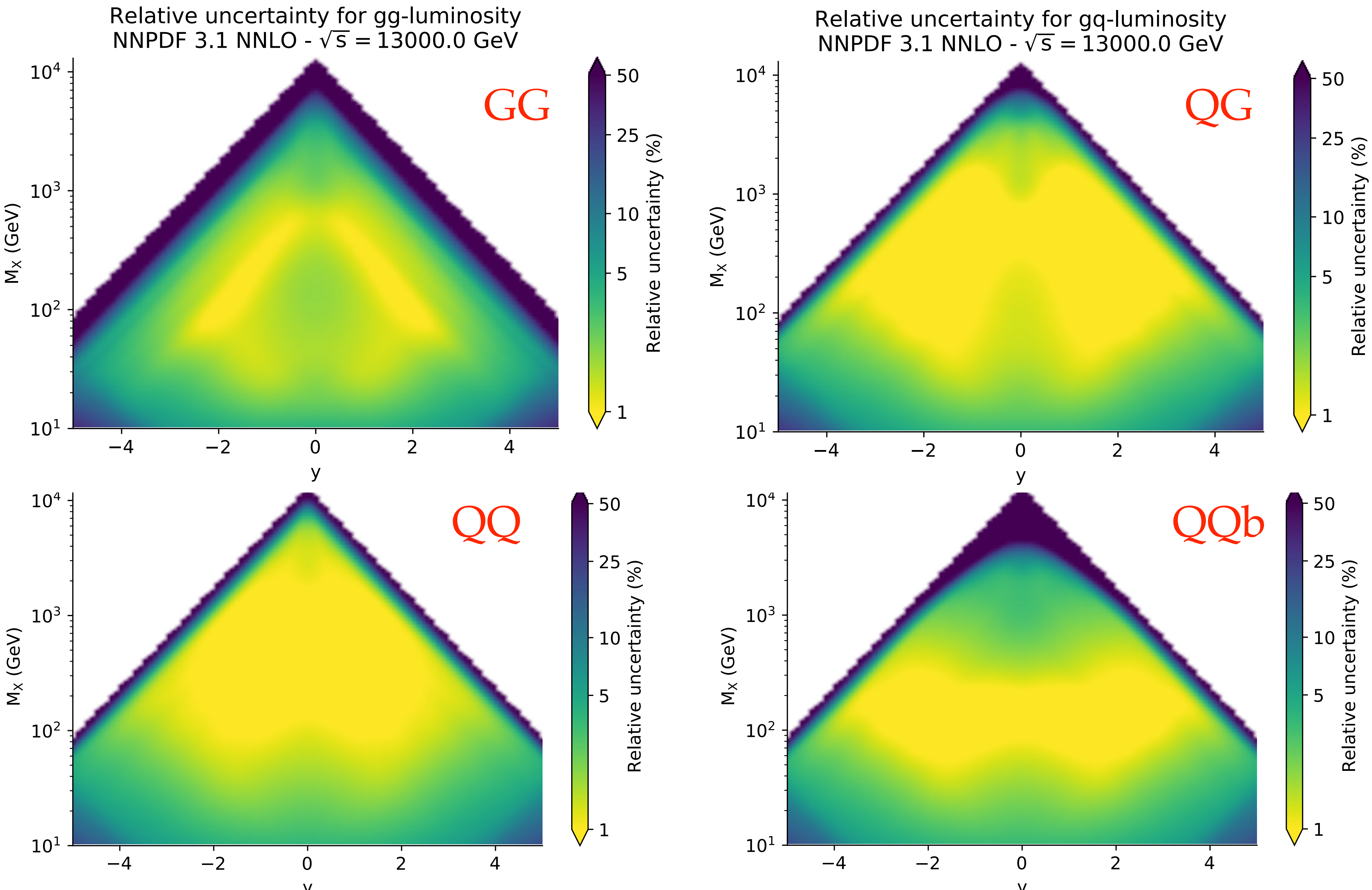
- Parton content of the proton
  non pert → fitted to data
- Data at different scales related by first-principle computable AP evolution → universality





- Results consistent over many orders of magnitude → great test of pQCD
- A lot of precise data from the LHC are already now having great impact (tt, jj, Z/W...)
- We may soon discard `old' low-Q data with limited theoretical control (nuclear corrections...)
- Solid, Robust and `Clean' Determinations

PDFs: the overall precision

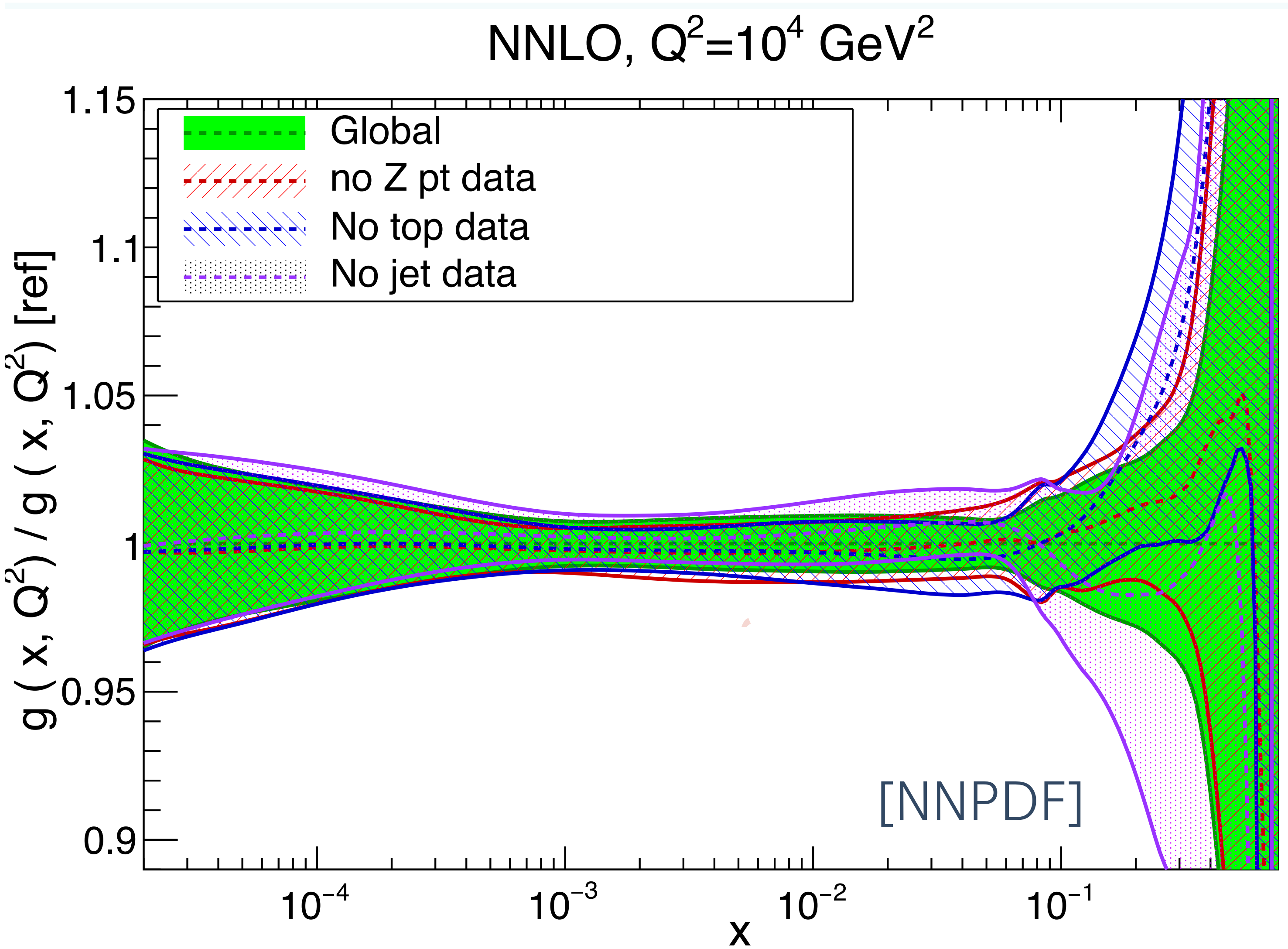


[NNPDF31]

- Big improvement w.r.t. few years ago
- For Central EW Production: percent precision
- Although be careful to take these uncertainties at face value

PDFs: sanity check

How do we make sure we are not fitting new physics away?

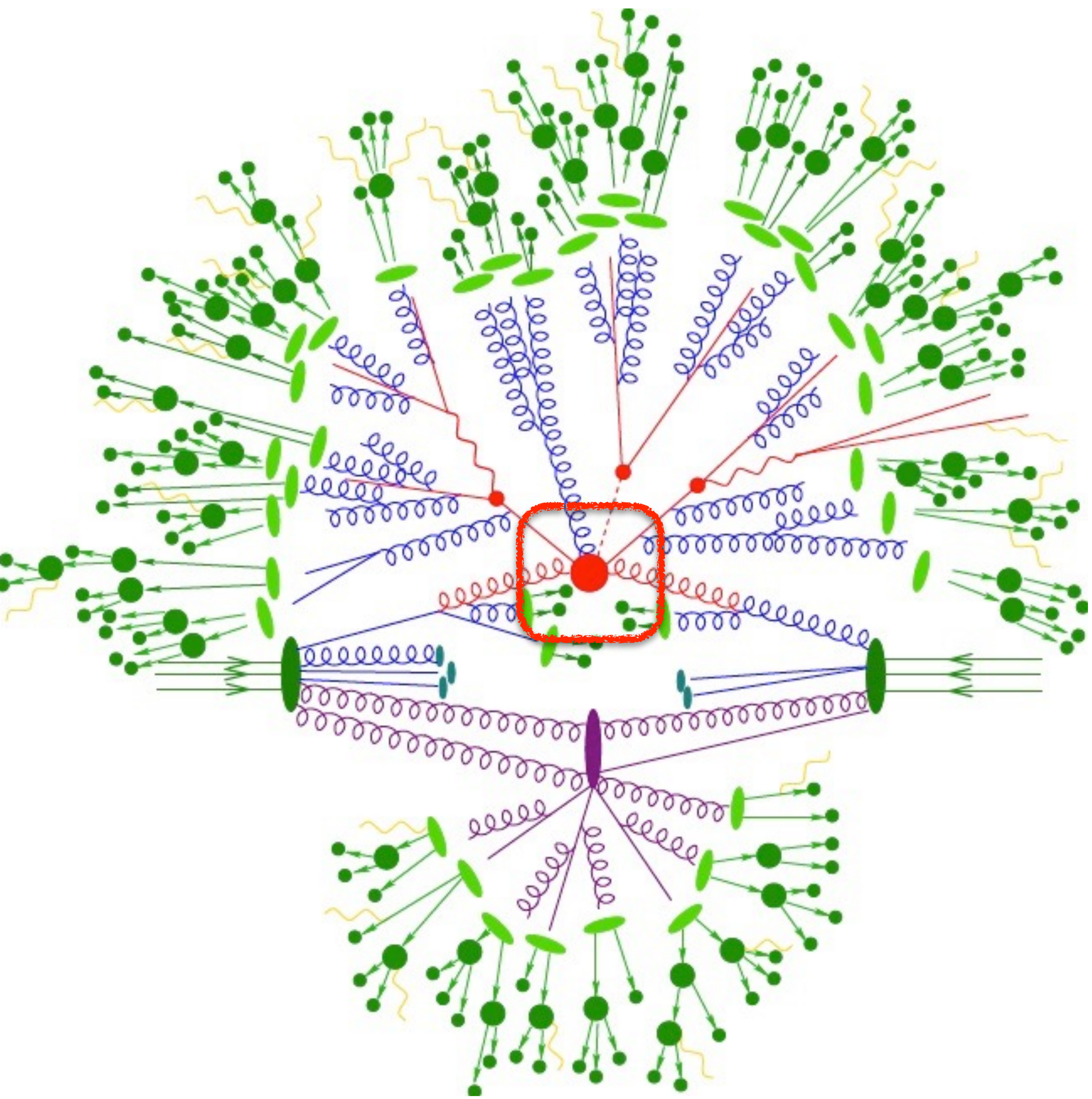


- Fits are stable under inclusion/ exclusion of extra data-set
- Effect of new data: mostly reduction in uncertainty, small change in the central value

- With more and more data, can also try to fit ``safest'' PDFs from kinematic regions which should be free from BSM contaminations (e.g. forward jets…)

The hard process: precision calculations

$$d\sigma = \int dx_1 dx_2 f(x_1) f(x_2) d\sigma_{\text{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q))$$



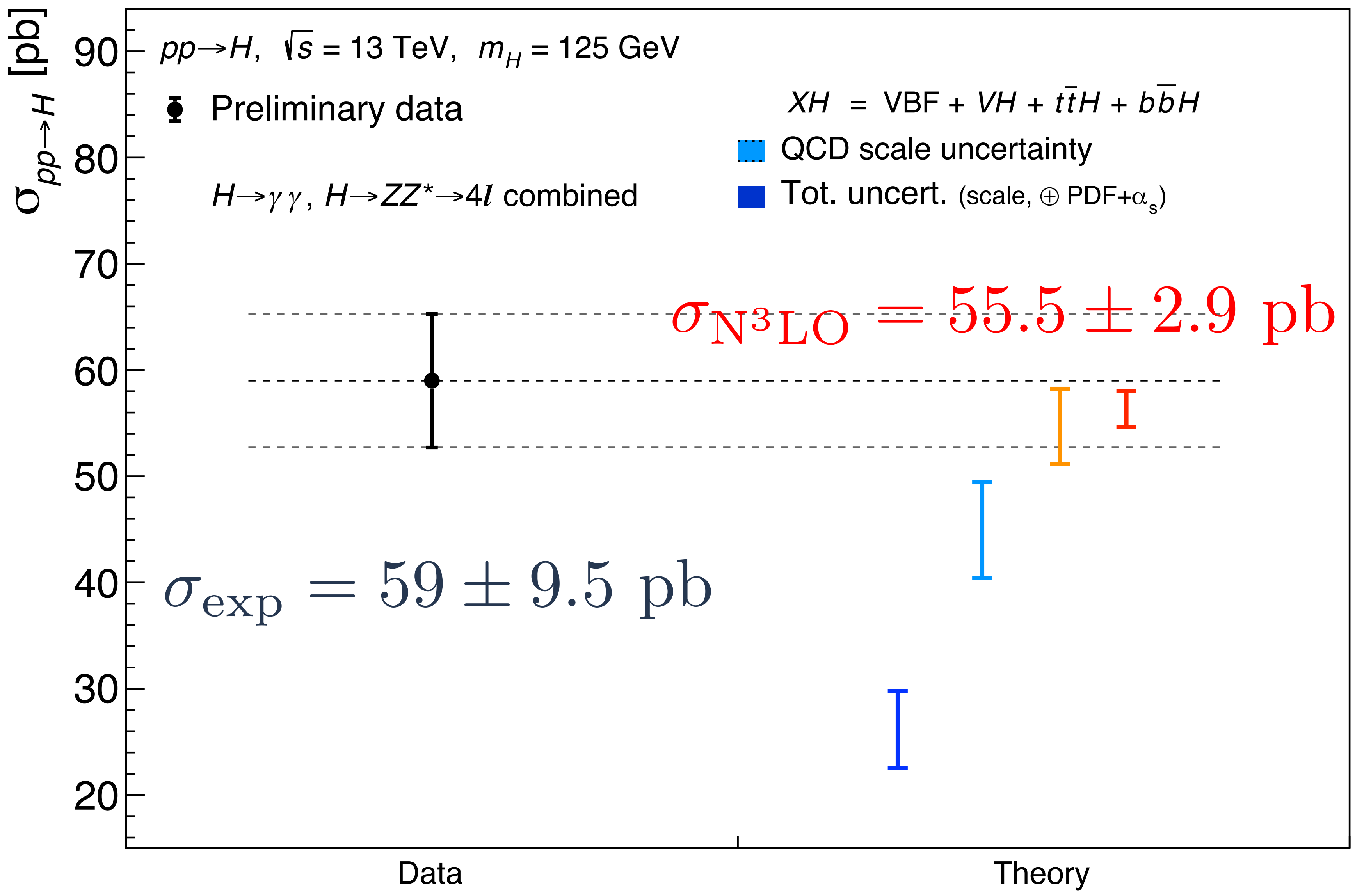
THE ``INTERESTING'' SHORT DISTANCE CROSS-SECTION

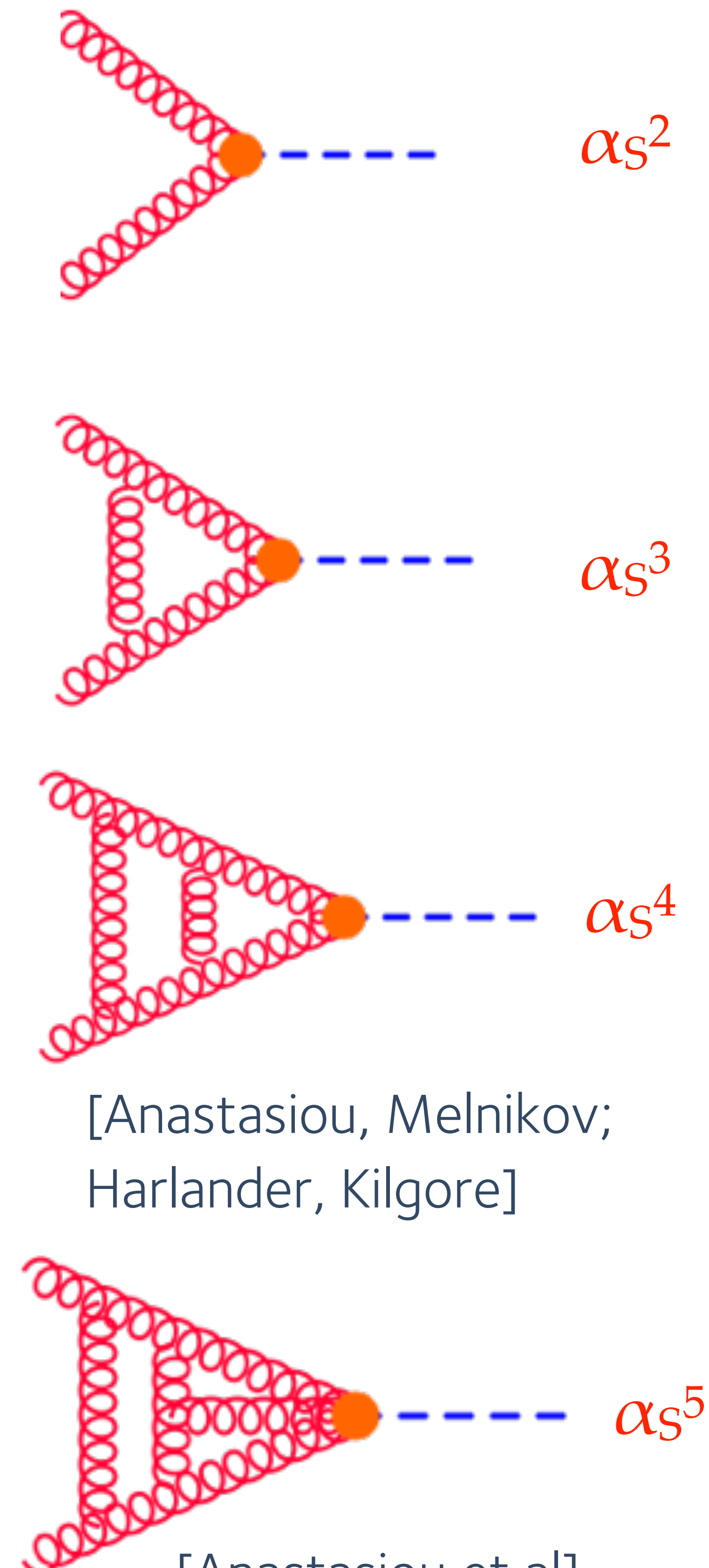
- Asymptotic freedom → at high scale QCD is perturbative
- Still, for typical EW scales $\alpha_S \sim 0.1$
- The path to precision: NLO ~ 10%, NNLO ~ 1%. Gluonic processes (e.g. Higgs): large color charges $\alpha_S C_A \sim 0.3$. Even higher orders may be required (N^3LO…)

The hard process: an ideal world

- In a perfect world (= large luminosities, good S/B control, large energy coverages):
  - find simple high-Q observables, where contamination by IR physics is minimal
  - ``cut-and-count'' like analysis, in the fiducial region → very clean data / theory comparison
- Whenever this is possible: very good theoretical control on our predictions. If the process is simple enough, we can obtain very accurate reliable results via Higher Order Perturbative Computations
- Fixed order (differential) computations:
  - very solid framework
  - they give direct access to the actual fiducial region (i.e. we can put cuts on the final state)

The need for higher orders: Higgs





[Anastasiou, Melnikov; Harlander, Kilgore]

[Anastasiou et al]

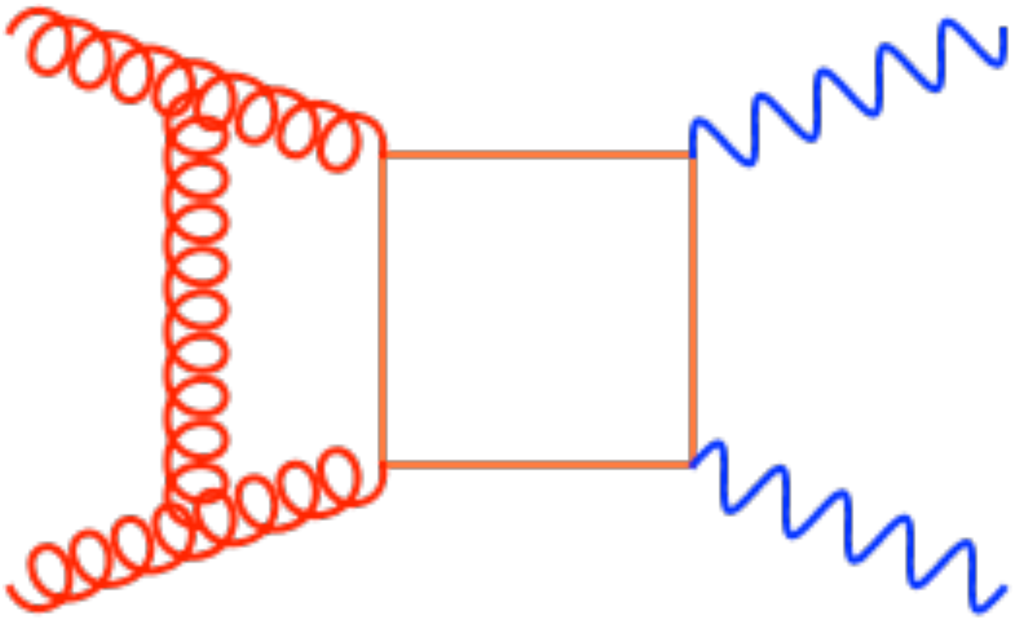
N³LO results needed to establish perturbative convergence / reduce residual theoretical uncertainty

Higher order calculations: amplitudes

A crucial ingredient: multi-loop scattering amplitudes

The problem: complexity grows very fast with number of scales (#legs/masses)

$gg \to \gamma\gamma$



$$
\begin{aligned}
F^{\mathrm{L}}_{--++} = & -(x^2+y^2)\Big[4\mathrm{Li}_4(-x) + \frac{1}{48}Z_+^4 \\
& + (\tilde{Y} - 3\tilde{X})\mathrm{Li}_3(-x) + \Xi\mathrm{Li}_2(-x) \\
& + i\frac{\pi}{12}Z_+^3 + i\frac{\pi^3}{2}X - \frac{\pi^2}{12}X^2 - \frac{109}{720}\pi^4\Big] \\
& + \frac{1}{2}x(1-3y)\Big[\mathrm{Li}_3(-x/y) - Z_-\mathrm{Li}_2(-x/y) \\
& - \zeta_3 + \frac{1}{2}Y\tilde{Z}\Big] + \frac{1}{8}\left(14(x-y) - \frac{8}{y} + \frac{9}{y^2}\right)\Xi \\
& + \frac{1}{16}(38xy-13)\tilde{Z} - \frac{\pi^2}{12} - \frac{9}{4}\left(\frac{1}{y} + 2x\right)\tilde{X} \\
& + \frac{1}{4}x^2\Big[Z_-^3 + 3\tilde{Y}\tilde{Z}\Big] + \frac{1}{4} + \Big\{t \leftrightarrow u\Big\},
\end{aligned}
$$

[Bern, De Freitas, Dixon (2002)]

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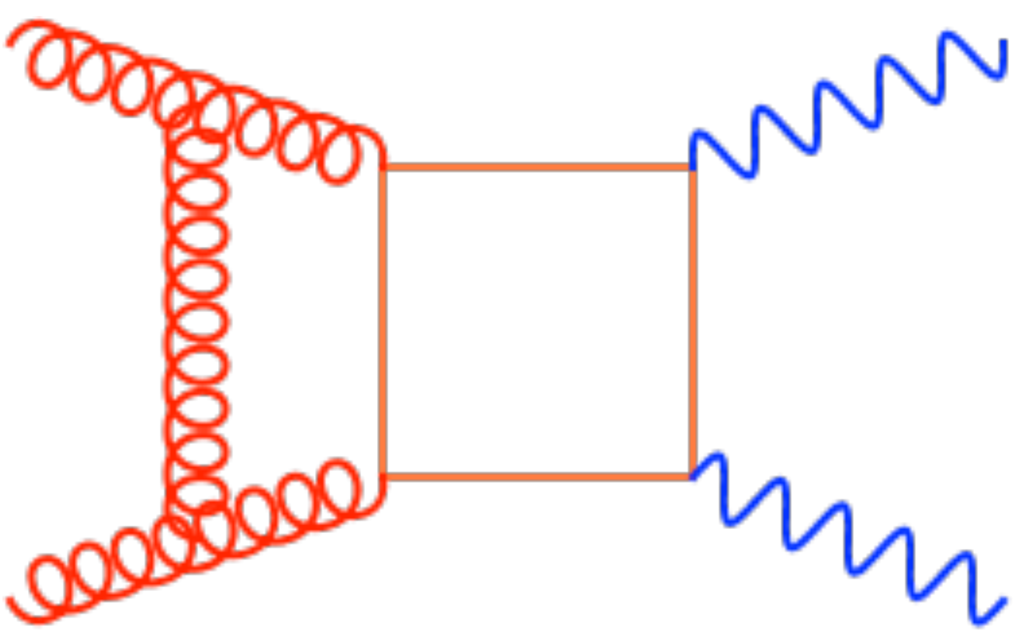
gg→ZZ



```
[766]+n(-13,2)*r[771]+n(19,2)*r[772]+n(43,2)*r[773];
r[12412] = n(-23,2)*r[750]+n(-12)*r[754]+n(2)*r[758]+n(-11,4)*r[759]+n(-11,4)*r[
760]+n(17,2)*r[761]+n(-11,4)*r[765]+n(-11,4)*r[766];
r[12413] = n(-1,4)*r[750]+n(-2)*r[760]+n(2)*r[766]+r[771]+n(-1)*r[772]+n(-2)*r[8
19]+n(5)*r[820]+n(2)*r[821];
r[12414] = n(3,2)*r[750]+n(3,2)*r[984]+n(-3)*r[1333]+n(3)*r[1350]+n(3)*r[1351]+n
(3)*r[1356]+n(3)*r[1520]+n(3)*r[1529];
r[12415] = n(5)*r[750]+n(1,2)*r[759]+n(-1,2)*r[760]+n(-7,2)*r[765]+n(-5,2)*r[766
]+n(7,2)*r[771]+n(-1,2)*r[772]+n(3,2)*r[773];
r[12416] = n(34)*r[750]+n(-5,2)*r[759]+n(-5,2)*r[760]+n(-89,2)*r[765]+n(-89,2)*r
[766]+n(59,2)*r[771]+n(35,2)*r[772]+n(59,2)*r[773];
r[12417] = n(-4)*r[753]+n(-3,2)*r[759]+n(-3,2)*r[760]+n(17,2)*r[762]+n(-3,2)*r[7
65]+n(-3,2)*r[766]+n(-17,2)*r[768]+n(3,2)*r[771];
r[12418] = n(-1)*r[755]+n(115,12)*r[759]+n(-81,4)*r[760]+n(17,2)*r[764]+n(-13,12
)*r[765]+n(71,4)*r[766]+n(-17,2)*r[770]+n(25,4)*r[771];
r[12419] = n(-2,3)*r[755]+n(-605,12)*r[759]+n(15,4)*r[760]+n(-17,2)*r[764]+n(59,
12)*r[765]+n(-161,4)*r[766]+n(17,2)*r[770]+n(73,4)*r[771];
r[12420] = n(-1)*r[756]+n(-565,24)*r[759]+n(7,24)*r[760]+n(17,2)*r[762]+n(347,24
)*r[765]+n(-83,8)*r[766]+n(-17,2)*r[768]+n(721,24)*r[771];
```

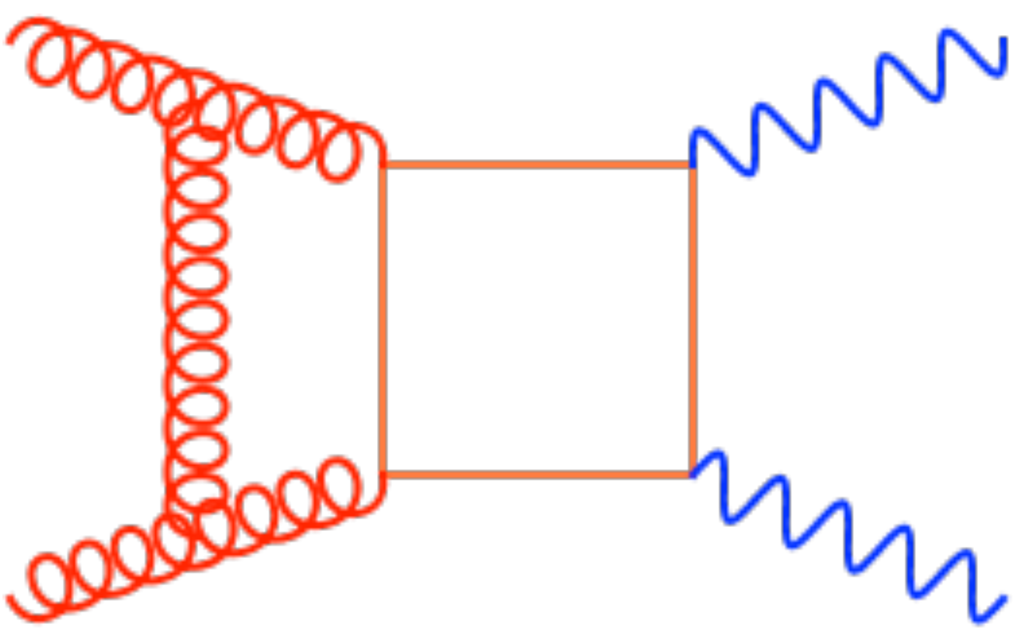
[FC, Henn, Melnikov, Smirnov[2]; Tancredi, von Manteuffel, Weihs, Gehrmann (2015)]

Higher order calculations: amplitudes

A crucial ingredient: multi-loop scattering amplitudes

The problem: complexity grows very fast with number of scales (#legs/masses)

gg→ZZ



```
[766]+n(-13,2)*r[771]+n(19,2)*r[772]+n(43,2)*r[773];
r[12412] = n(-23,2)*r[750]+n(-12)*r[754]+n(2)*r[758]+n(-11,4)*r[759]+n(-11,4)*r[
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r[12416] = n(34)*r[750]+n(-5,2)*r[759]+n(-5,2)*r[760]+n(-89,2)*r[765]+n(-89,2)*r
[766]+n(59,2)*r[771]+n(35,2)*r[772]+n(59,2)*r[773];
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)*r[765]+n(71,4)*r[766]+n(-17,2)*r[770]+n(25,4)*r[771];
r[12419] = n(-2,3)*r[755]+n(-605,12)*r[759]+n(15,4)*r[760]+n(-17,2)*r[764]+n(59,
12)*r[765]+n(-161,4)*r[766]+n(17,2)*r[770]+n(73,4)*r[771];
r[12420] = n(-1)*r[756]+n(-565,24)*r[759]+n(7,24)*r[760]+n(17,2)*r[762]+n(347,24
)*r[765]+n(-83,8)*r[766]+n(-17,2)*r[768]+n(721,24)*r[771];
```

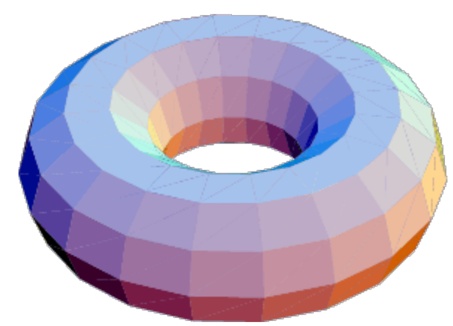
[FC, Henn, Melnikov, Smirnov²; Tancredi,
von Manteuffel, Weihs, Gehrmann (2015)]

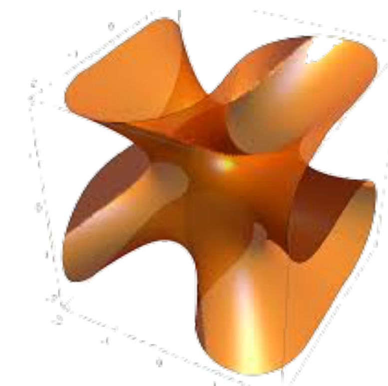
10 MB expression, complex transcendental functions

Massive tops (crucial for high energy): only known numerically

Amplitudes: a lot of recent progress

[Abreu, Badger, Brønnum-Hansen, Bargiela, Borowka, Buccioni, FC, Chawdhry, Chen, Chicherin, Czakon, de Laurentis, Dormans, Duhr, Dunbar, Febres-Cordero, Frellesvig, Gambuti, Gehrmann, Hartanto, Heinrich, Henn, Ita, Jones, Jehu, Liu, Lo Presti, Manteuffel, Ma, Maître, Mitev, Mitov, Page, Peraro, Perkins, Poncelet, Schabinger, Sotnikov, Tancredi, Wasser, Weinzierl, Zhang...]



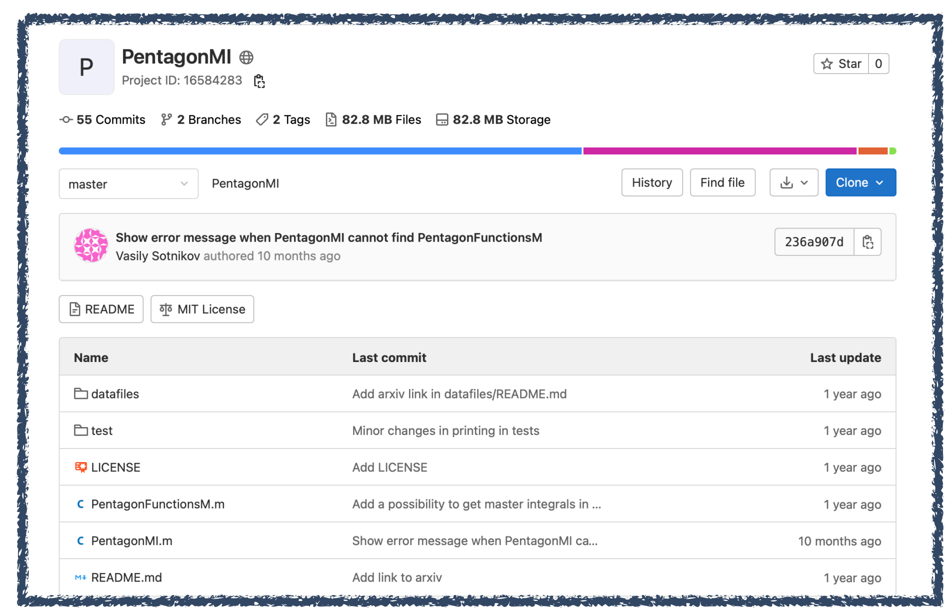


Analytical / theoretical investigations:

- New structures / symmetries
- Interesting mathematical objects

Numerical / implementation:

- Finite-field reconstruction
- Fast numerical evaluation



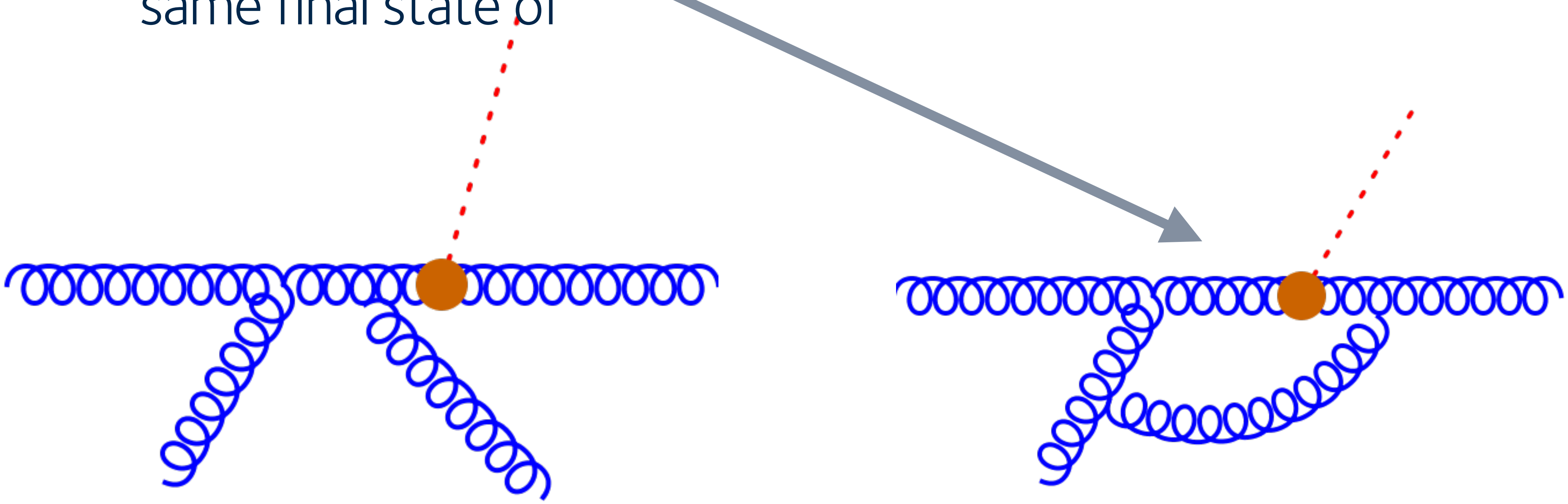
State of the art: 2→2@2L, some 2→3@2L, first results for 2→2@3L

From amplitudes to physics

Quantum mechanics: you should only deal with observables

If 2nd gluon soft/collinear:

same final state of



∞ ∞

Only the sum is well-defined. Proper regulation / combination of the IR effects very complicated

From amplitudes to physics

``Local analytic'' [Magnea, Maina, Pellicciolì, Signorile-Signorile, Torrielli]]

``q_t'' [Catani, Grazzini]

``Antenna'' [Gehrmann-de Ridder, Gehrmann, Glover]

``N-jettiness'' [Boughezal et al, Gaunt et al]

``Sector decomposition+FKS'' [Binoth, Heinrich; Anastasiou, Melnikov, Petriello; Czakon; Czakon, Heymes; Asteriadis, FC, Melnikov, Röntsch]

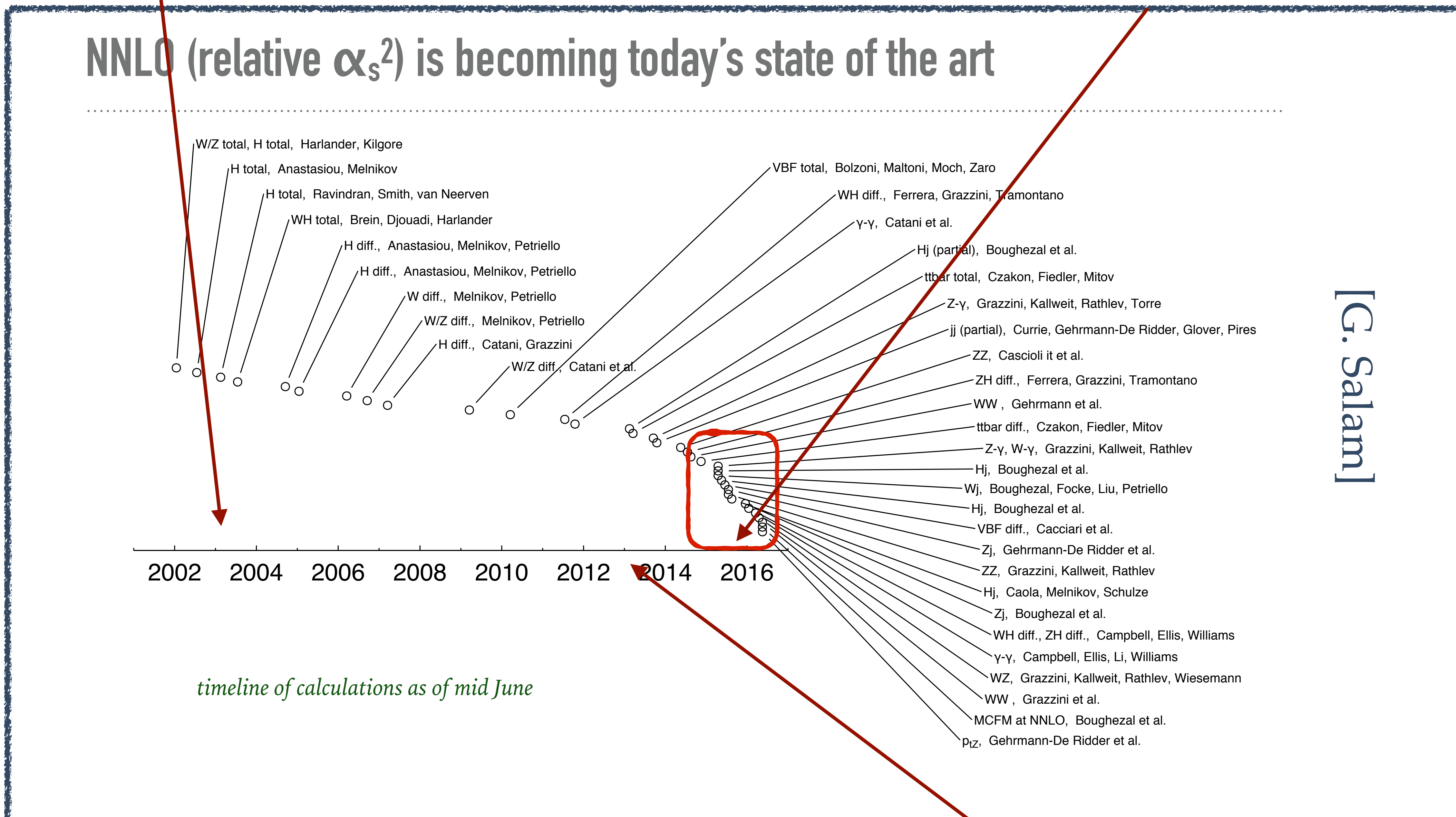
``Projection to Born'' [Cacciari, Dreyer, Karlberg, Zanderighi, Salam]

``Colorful NNLO'' [Del Duca, Duhr, Kardos, Somogyi, Trocsanyi]

The NNLO timeline

1st 2L amplitudes

new ideas/techniques for multi-loop amplitude calculation

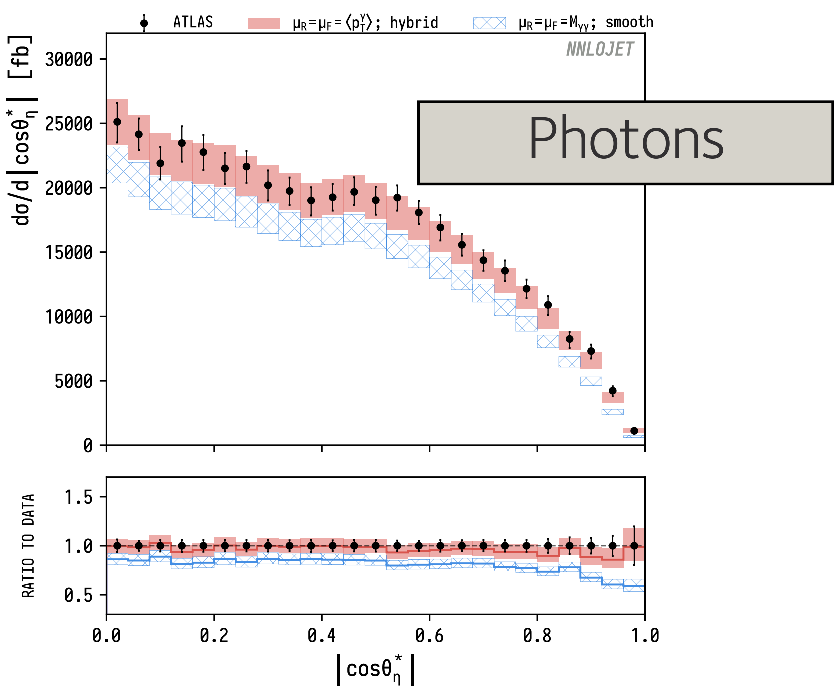


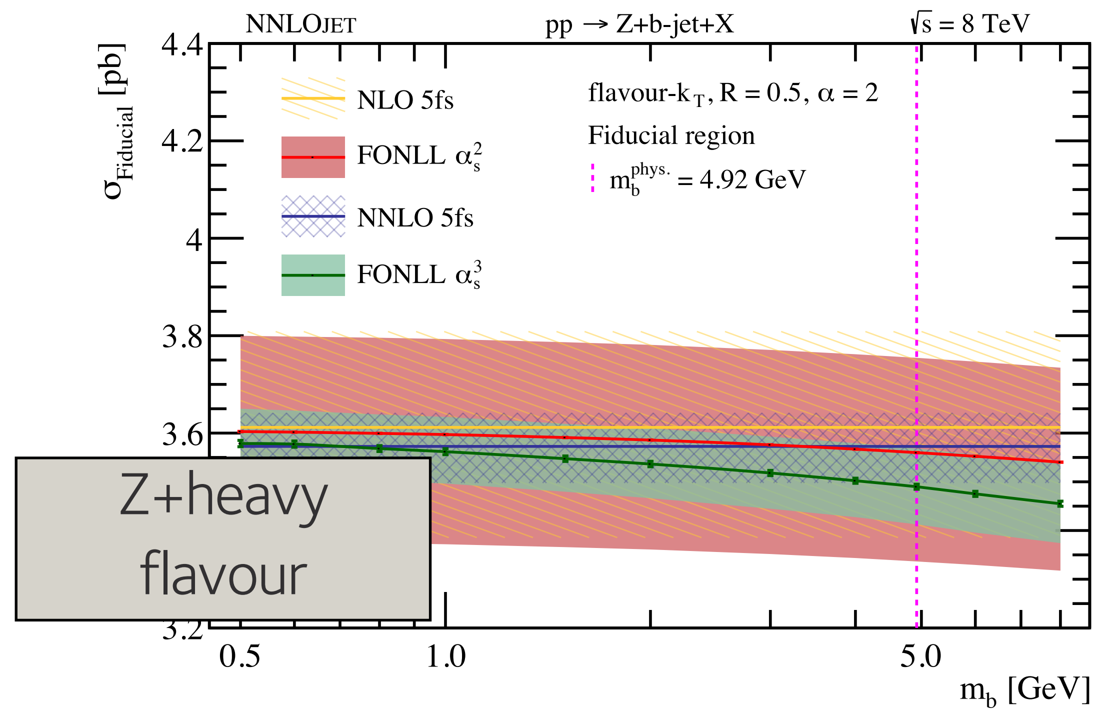
IR organisation for arbitrary processes

Physics: 2→2 NNLO is well-understood

NNLO: from proof of concept to detailed phenomenology

[Gehrmann, Glover, Huss, Whitehead (2020)]

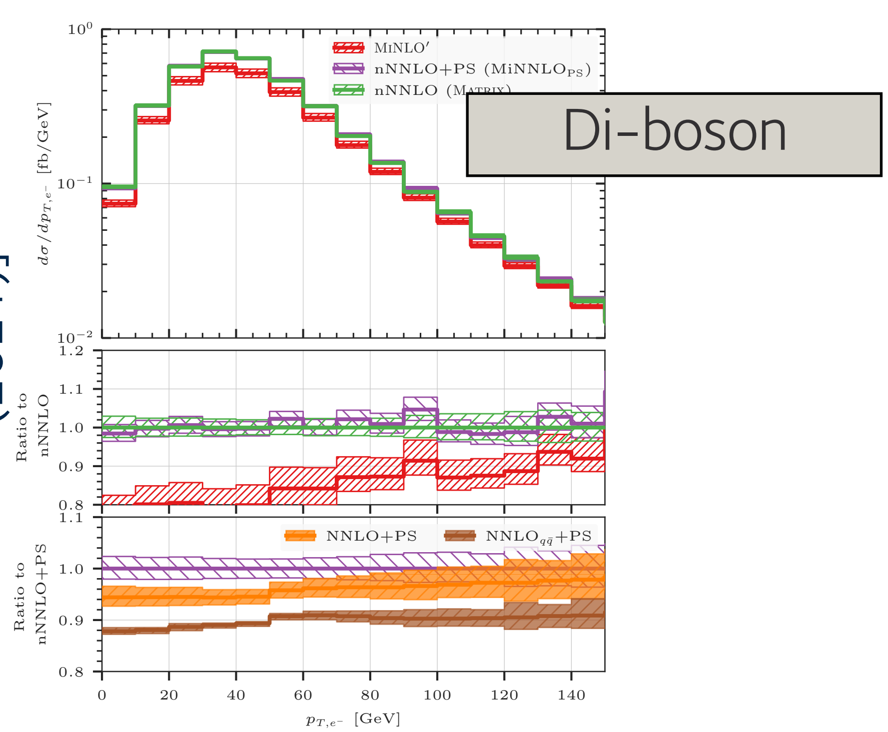


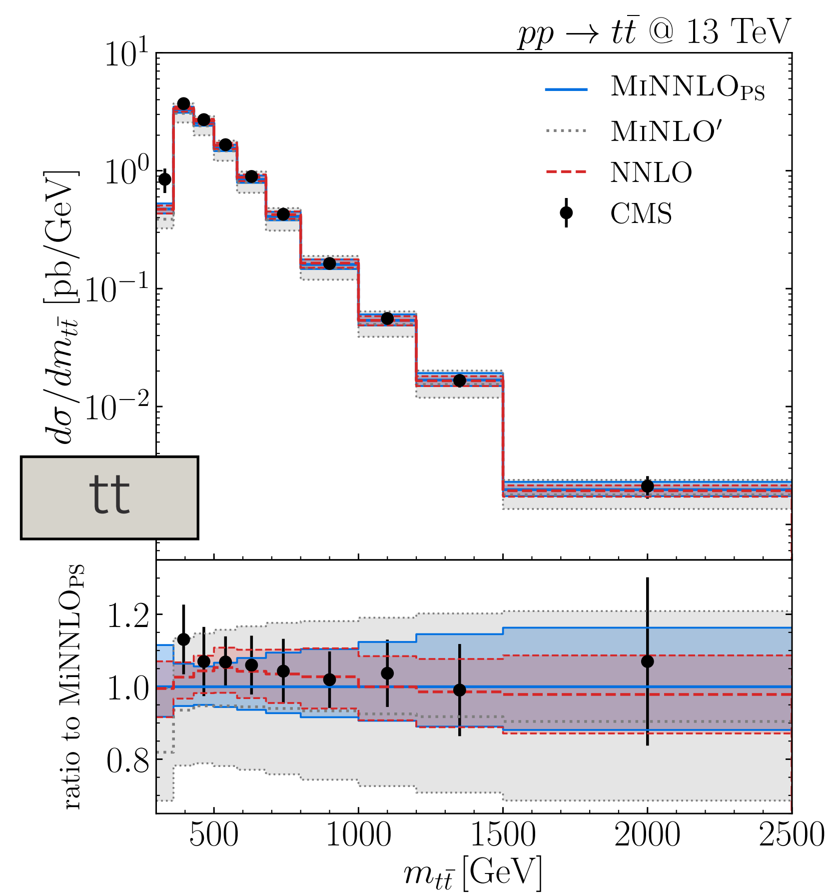


[Gauld, Gehrmann-de Ridder, Glover, Huss, Majer (2020)]

NNLLO + PS becoming a reality

[Buonocore, Koole, Lombardi, Rottoli, Wieseemann, Zanderighi (2021)]



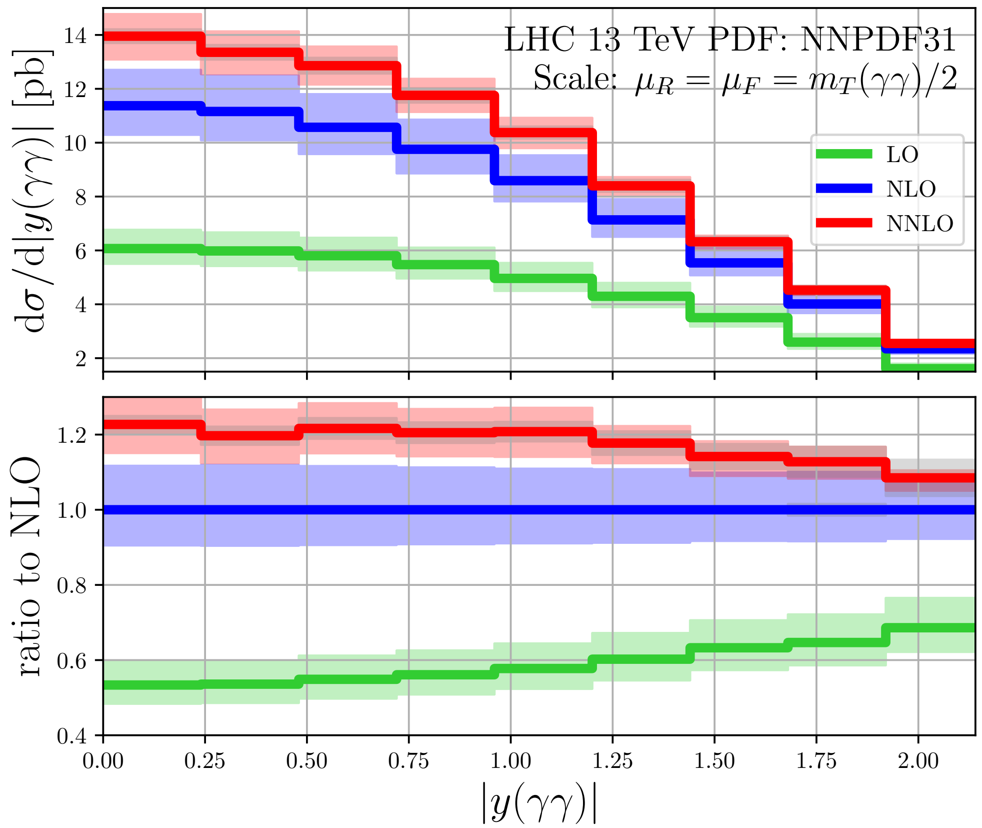


[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi (2021)]

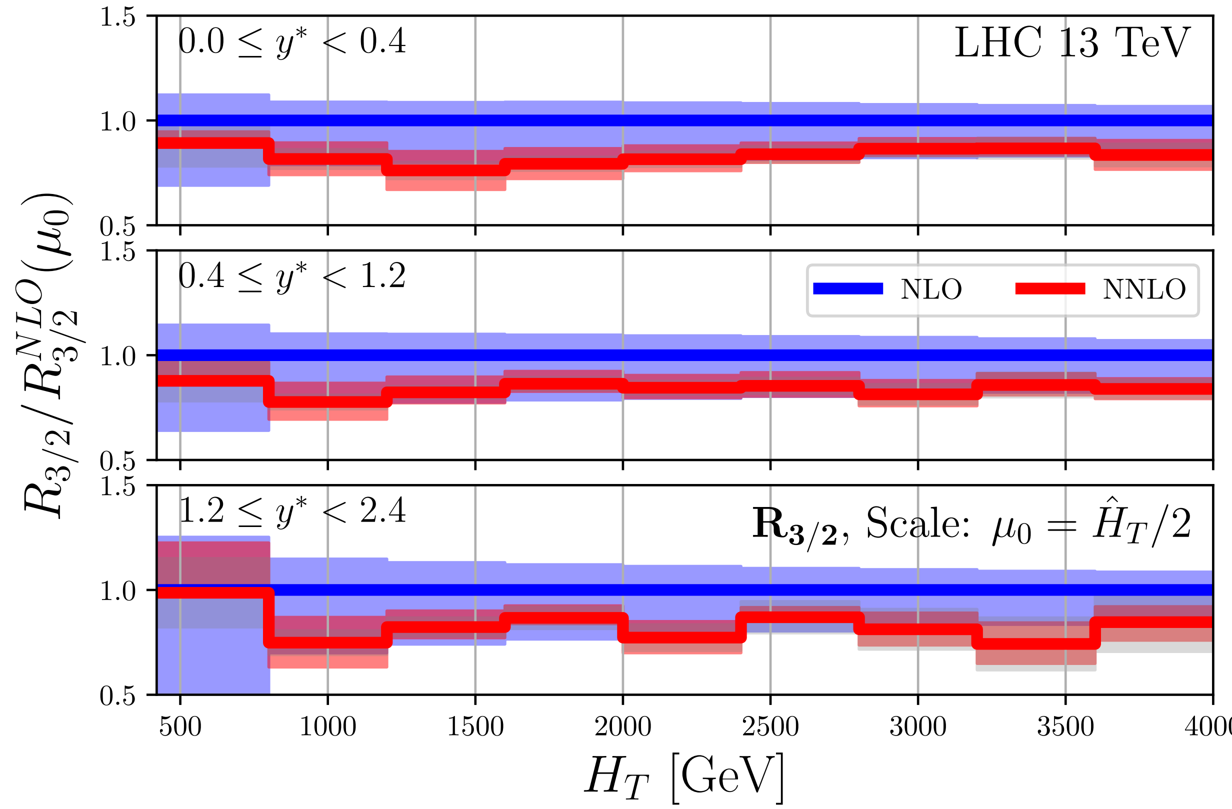
First steps toward more complex processes

[Chawdhry, Czakon, Mitov, Poncelet (2021)]

γγj



jjj

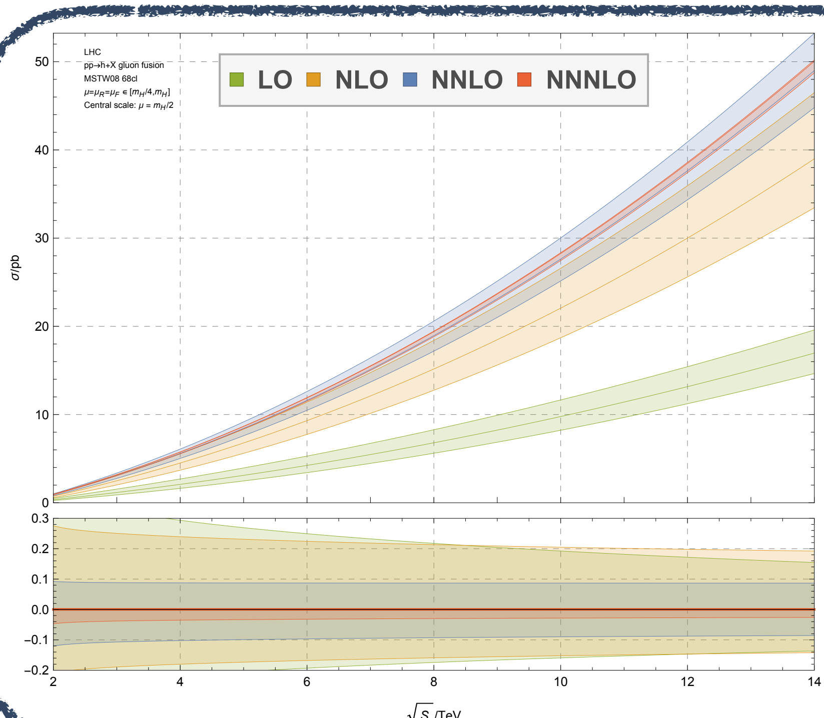


[Czakon, Mitov, Poncelet (2021)]

- jjj: ``Tour de force in QCD”.
- still very much in the exploratory phase
- Gives access e.g. to α_s in the TeV region

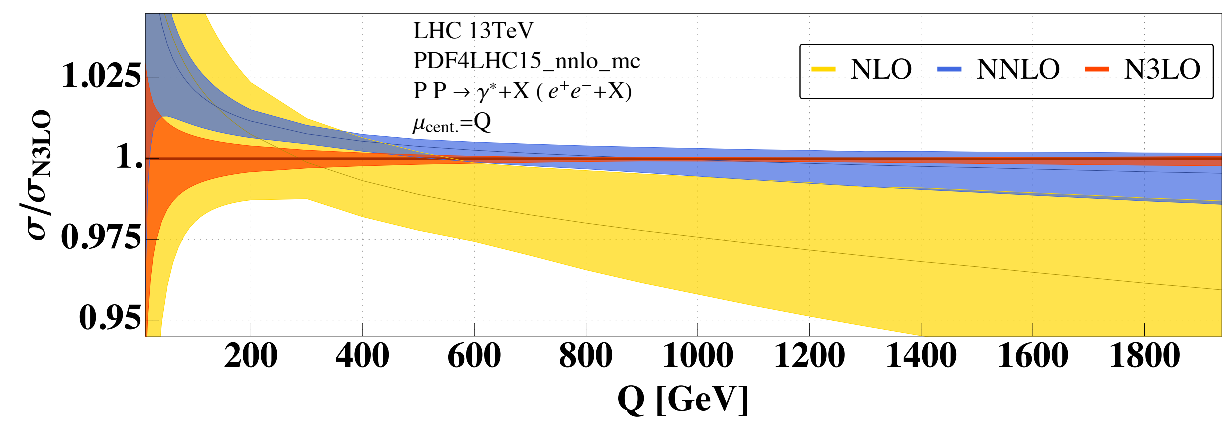
Even more precise: N^{3}LO for standard candles

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger (2016-...);
Duhr, Dulat, Mistlberger (2020-21)]



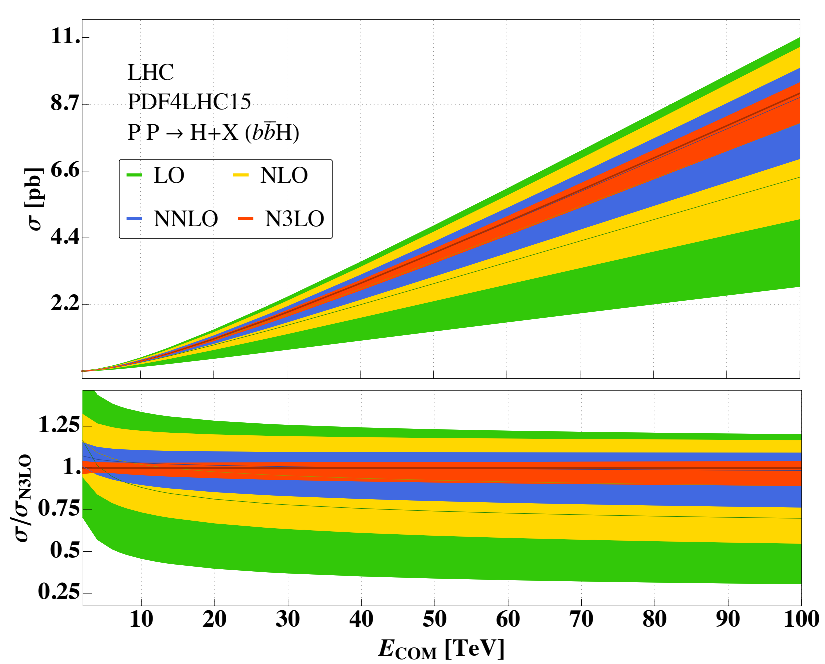
ggH

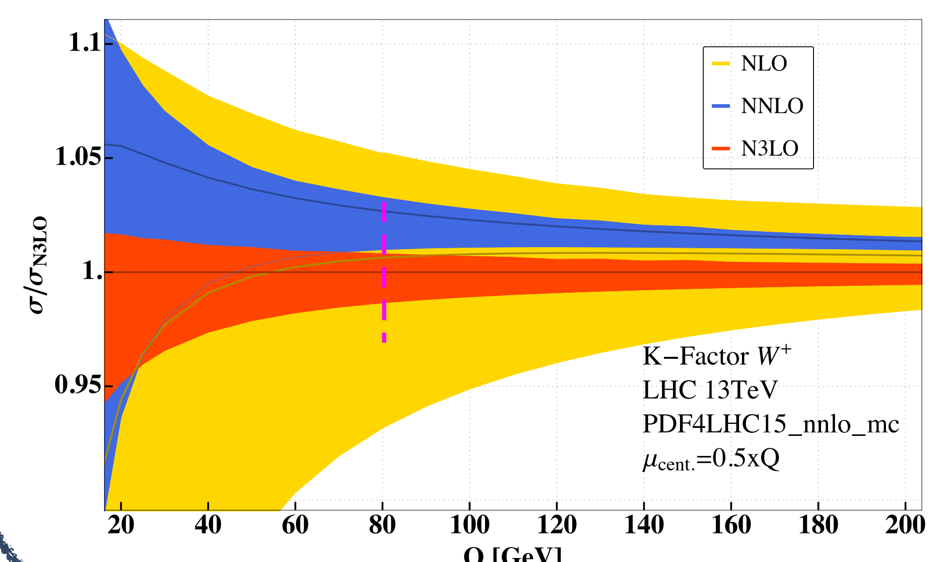
Drell-Yan



γ*

bbH

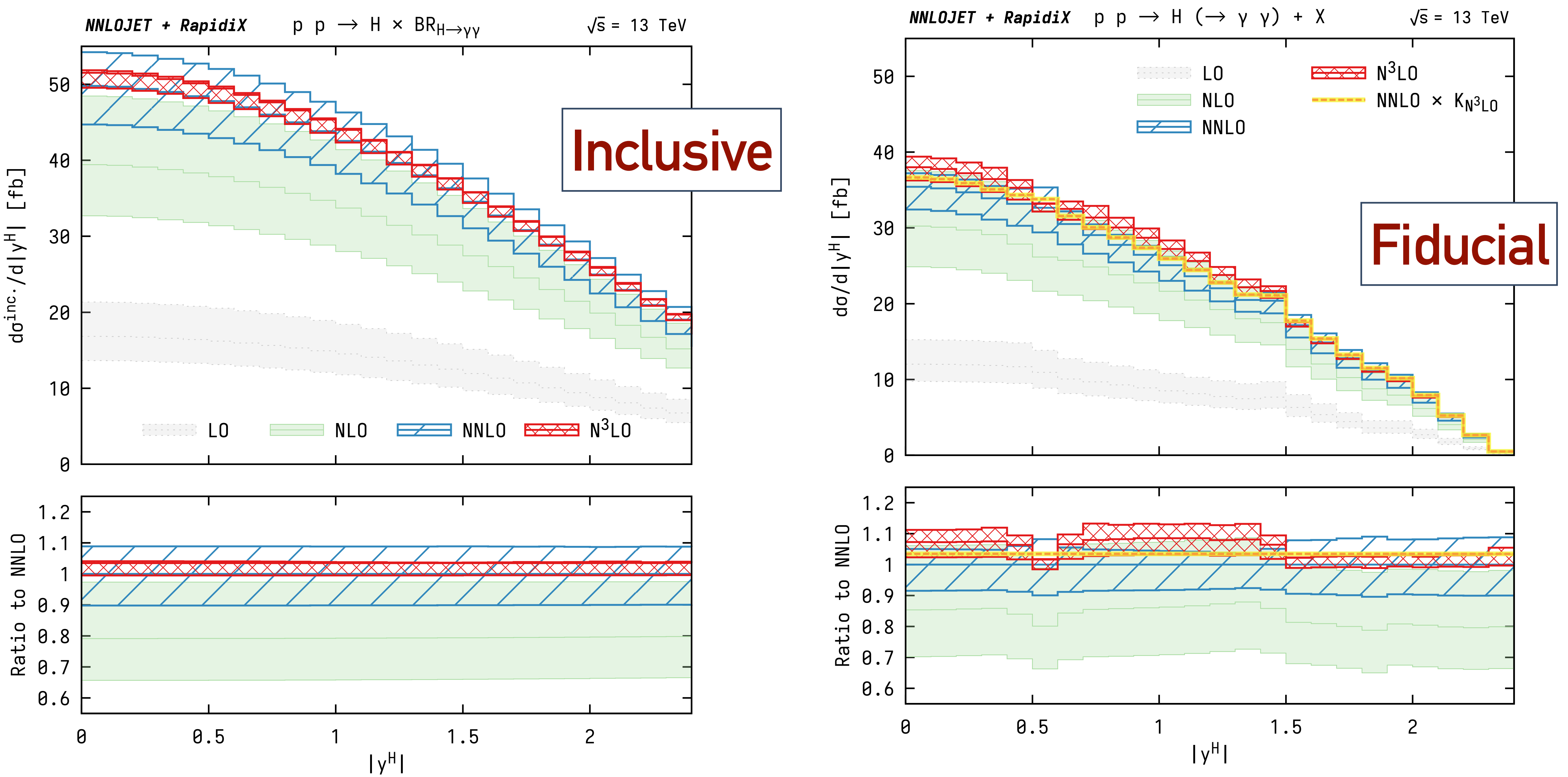




W

Precision studies: lessons learned

Higgs fiducial: $p_{t,\gamma 1} > 0.35\, m_H$, $p_{t,\gamma 2} > 0.25\, m_H$,



[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni (2021)]

- Inclusive: flat K-factor (as for inclusive), tiny error, no structure
- Fiducial: large corrections, large error, non-trivial shapes

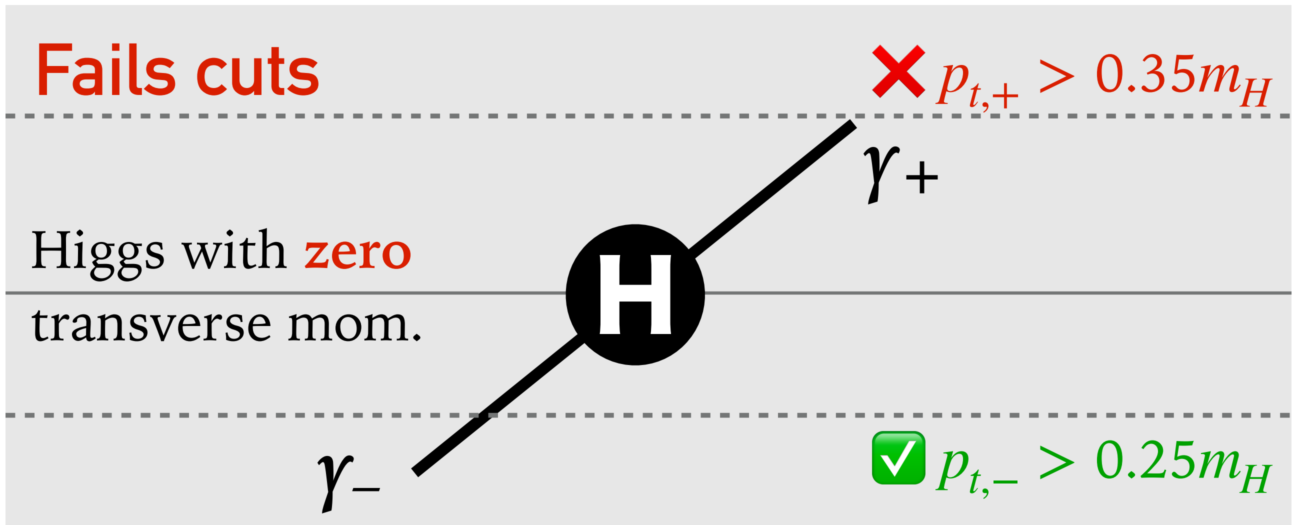
?

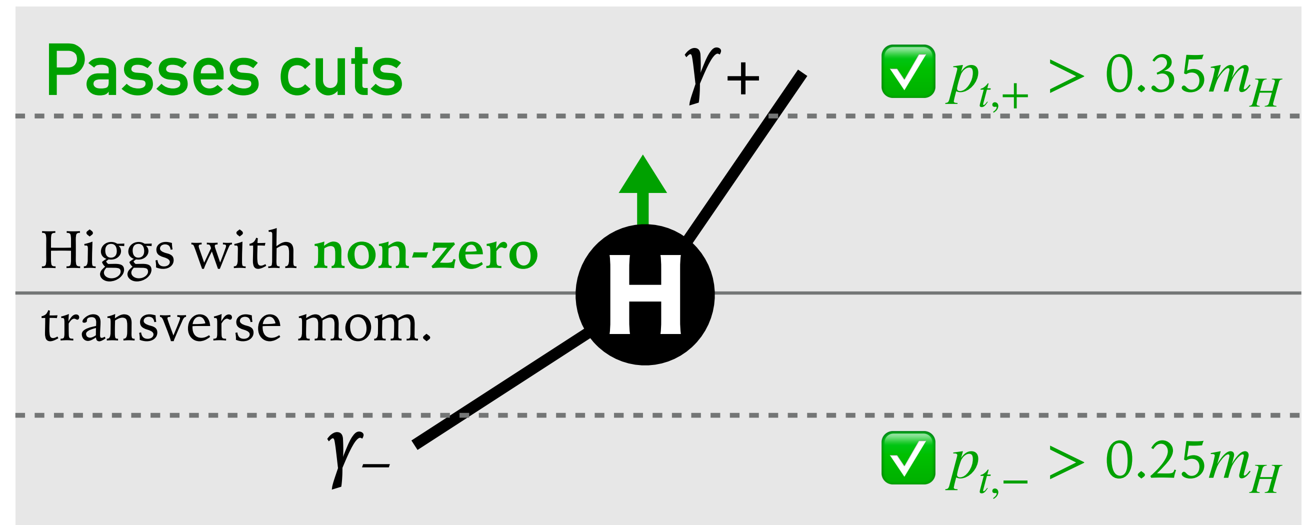
The hard process: an ideal world

- In a perfect world (= large luminosities, good S/B control, large energy coverages):
  - find simple high-Q observables, where contamination by IR physics is minimal
  - ``cut-and-count'' like analysis, in the fiducial region → very clean data / theory comparison
- Whenever this is possible: very good theoretical control on our predictions. If the process is simple enough, we can obtain very accurate reliable results via Higher Order Perturbative Computations
- Fixed order (differential) computations:
  - very solid framework
  - they give direct access to the actual fiducial region (i.e. we can put cuts on the final state)

Precision studies: lessons learned

Higgs fiducial: $p_{t,\gamma 1} > 0.35\, m_H$, $p_{t,\gamma 2} > 0.25\, m_H$,





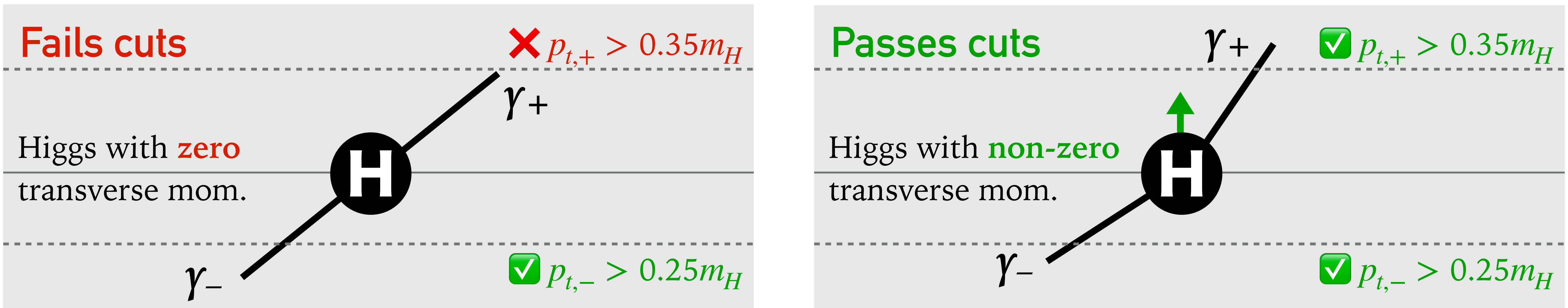
Sensitive to IR physics [Salam, Slade; Billis, Dehnadi, Ebert, Michel, Tackmann (2021)]

$$\frac{\sigma_{\rm asym} - f_0 \sigma_{\rm inc}}{\sigma_0 f_0} \simeq 0.15_{\alpha_s} - 0.29_{\alpha_s^2} + 0.71_{\alpha_s^3} - 2.39_{\alpha_s^4} + 10.31_{\alpha_s^5} + \dots \quad \simeq 0.06$$

IR-sensitivity makes the perturbative expansion factorially divergent →
the more you compute, the worse it gets [Salam, Slade]

Precision studies: lessons learned

Higgs fiducial: $p_{t,\gamma 1} > 0.35\ m_H$, $p_{t,\gamma 2} > 0.25\ m_H$,



Sensitive to IR physics [Salam, Slade; Billis, Dehnadi, Ebert, Michel, Tackmann (2021)]

Way out:

- Resum all-order IR effects [Billis, Dehnadi, Ebert, Michel, Tackmann (2021)]
- Design cuts/observables that are insensitive to IR physics, while retaining good S/B ratio [Salam, Slade]

Precision studies: lessons learned

Higgs fiducial ... 0.35 ... 0.35

Fails ... 35m_H

Higgs ...

transv ...

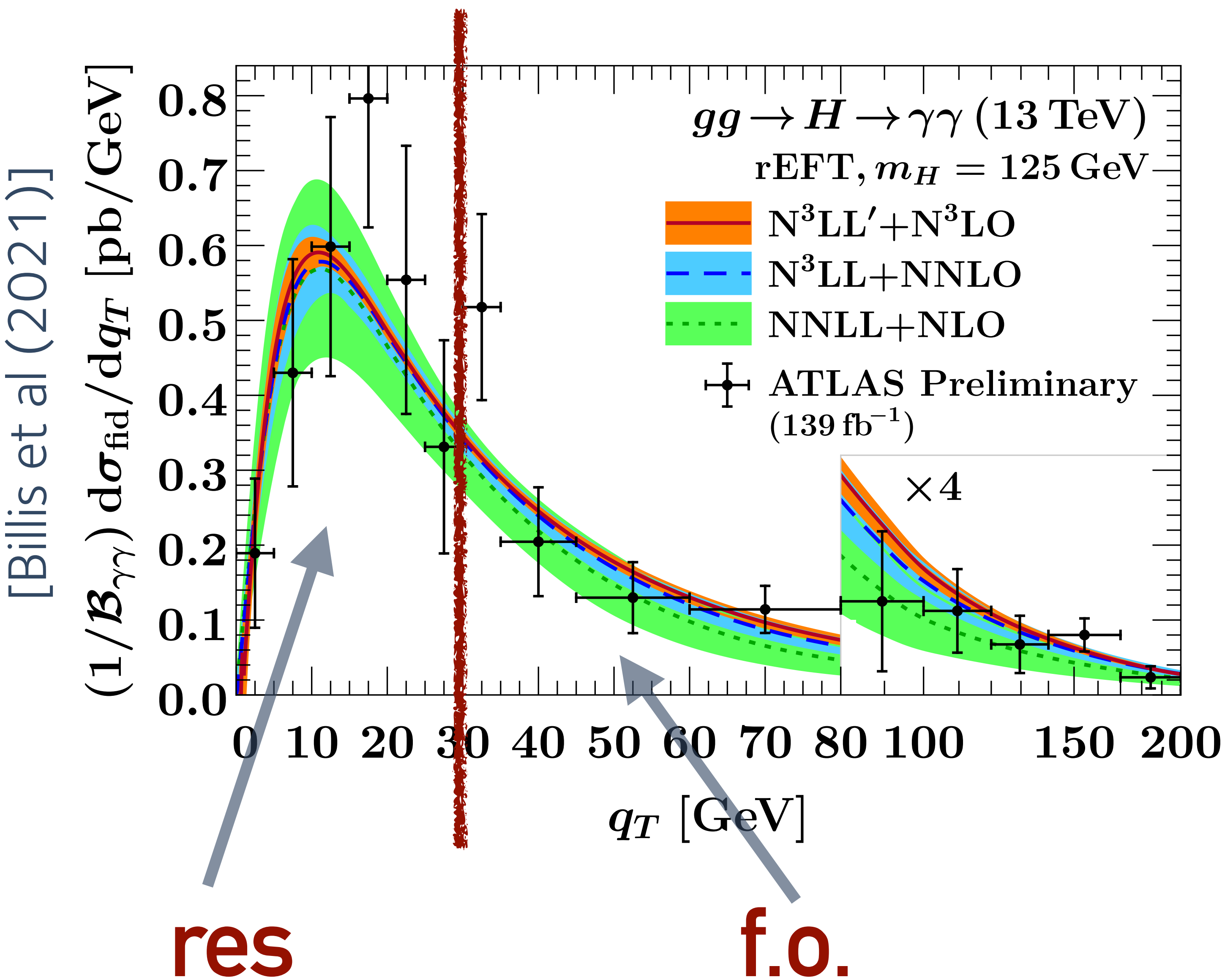
25m_H

As we get more and more precise, and explore the TeV region: careful analysis of common practice become crucial

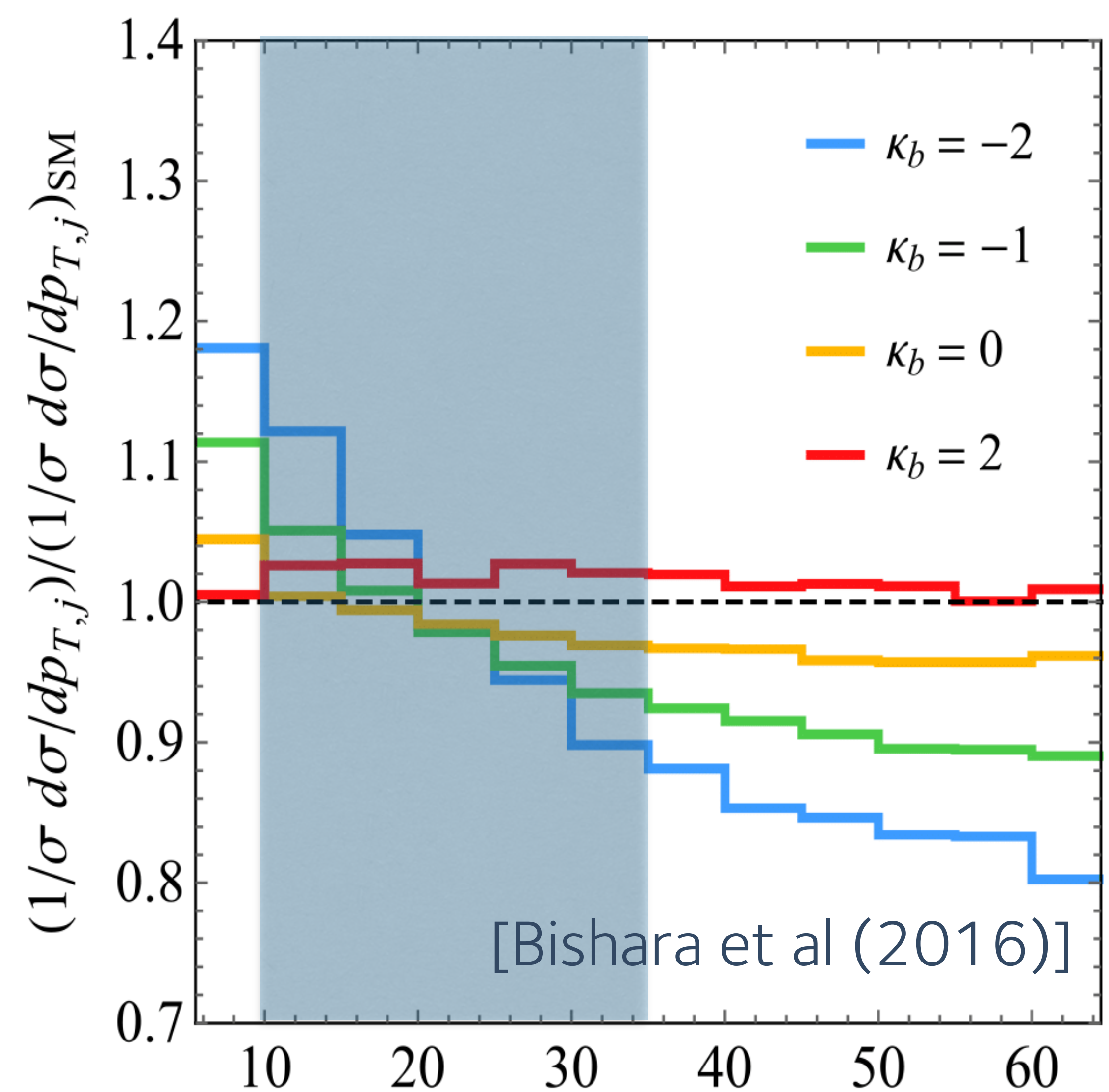
Problems (and in some cases tentative solutions) already known for energetic tops (high-invariant mass tops are IR-sensitive) and heavy flavour

Taming IR physics: all-order resummation

In some cases, we can extend the range of validity of the perturbative approach by doing RGE-improved perturbation theory → resum large class of soft/collinear terms



low-pₜ Higgs: handle on light Yukawa!



Taming IR physics: all-order resummation

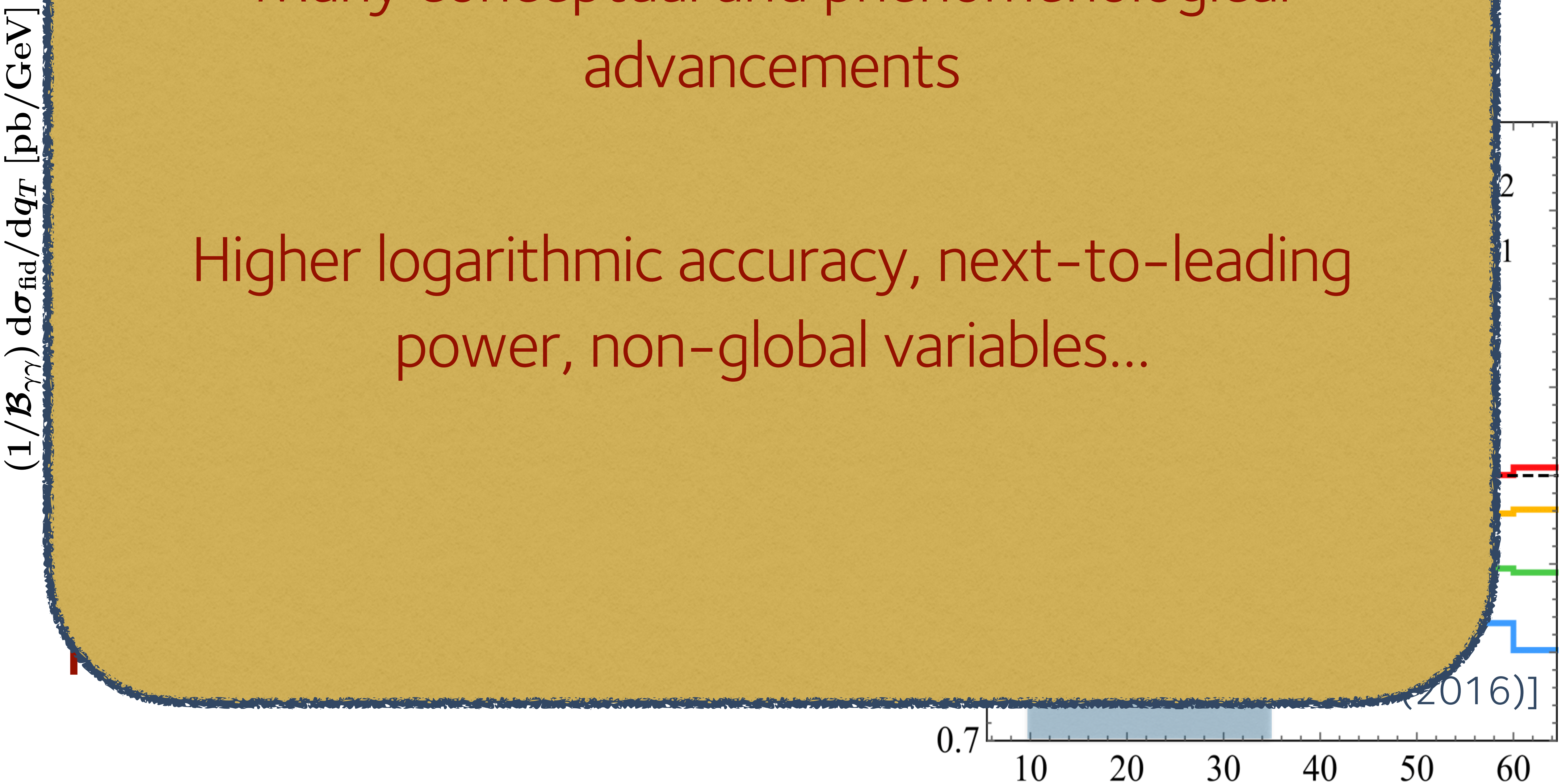
In some cases, we can extend the range of validity of the perturbative approach by

doing … terms

Many conceptual and phenomenological advancements

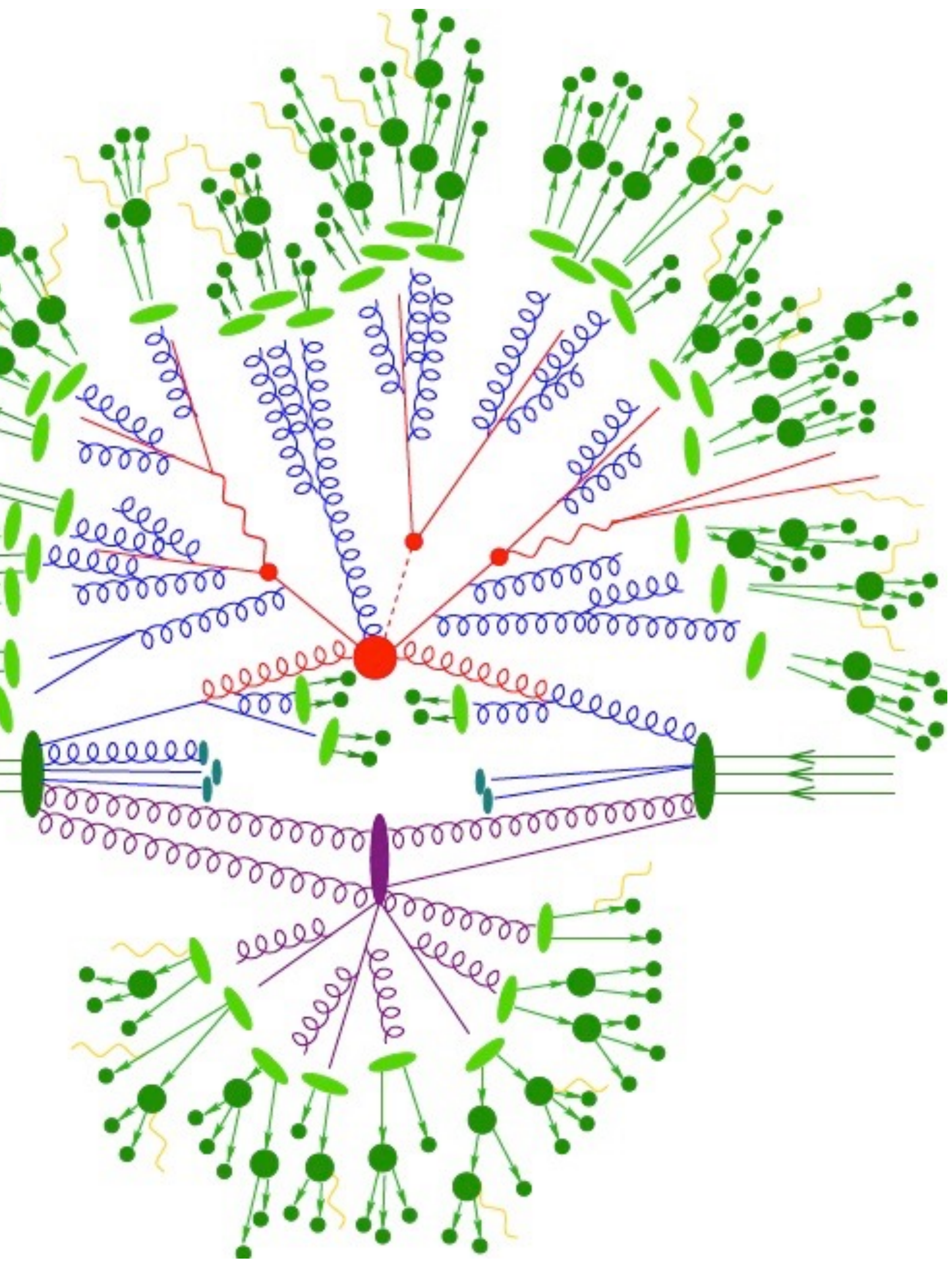
Higher logarithmic accuracy, next-to-leading power, non-global variables…

[Billis et al (2021)]

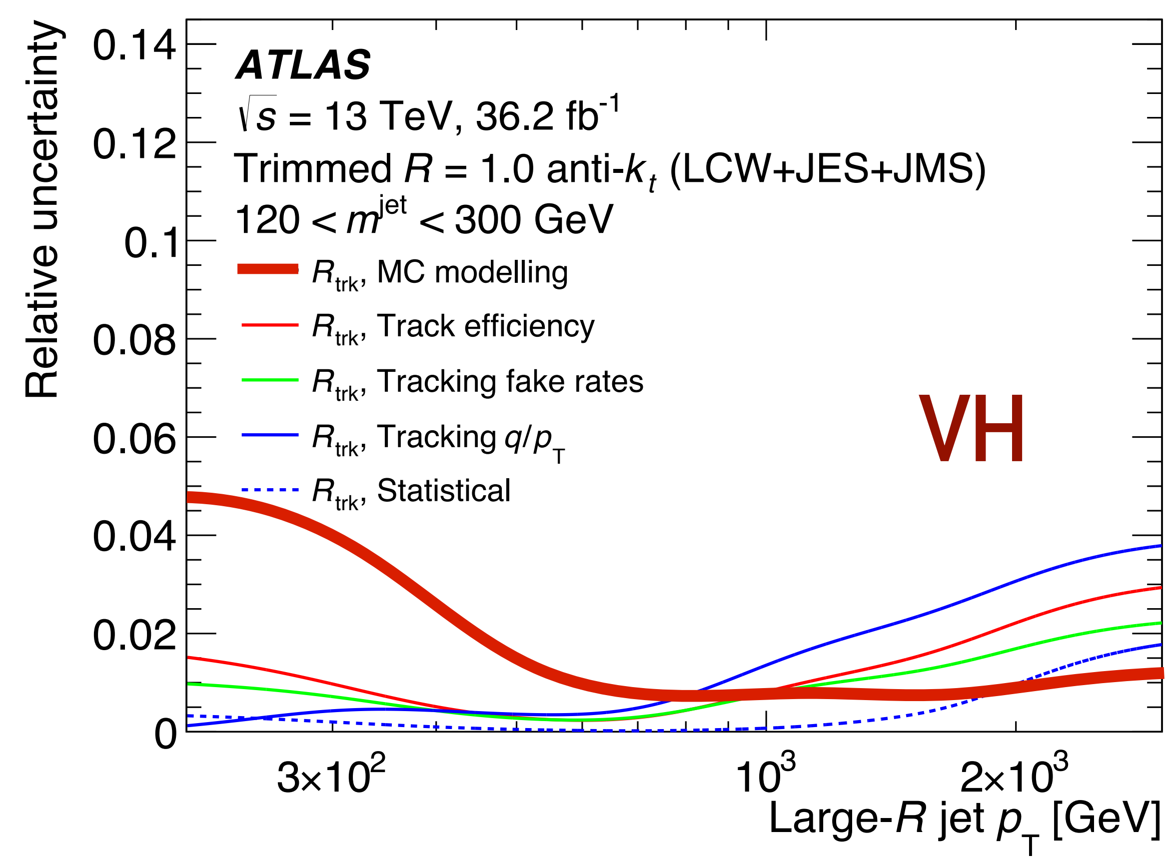


(2016)]

From parton to hadrons: parton showers



- In many cases, we need to connect high-energy scattering to detector reality
- Parton-shower MC, approximate treatment of many-body processes
  - –: lose precision
  - +: gain flexibility
- In many cases: leading TH systematics...



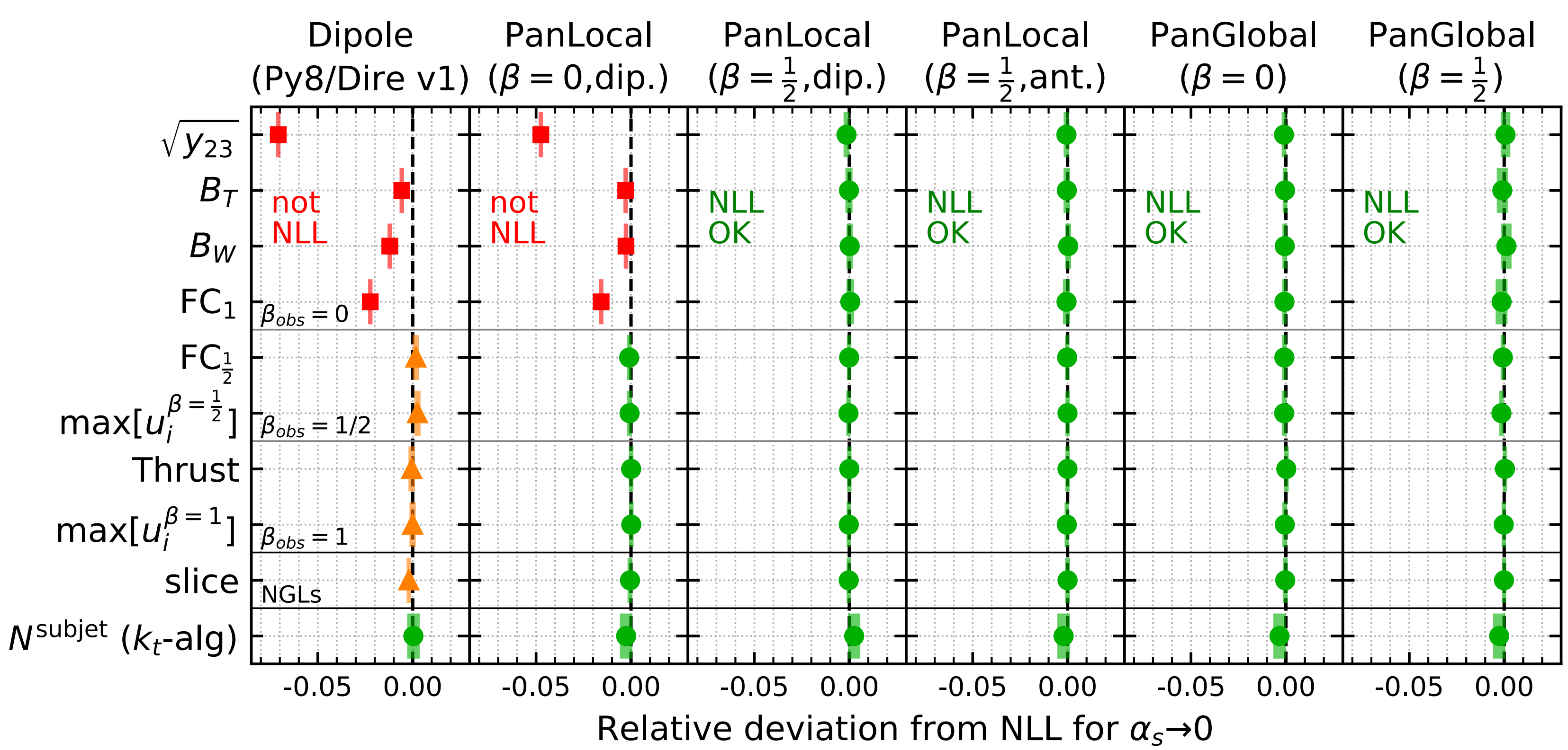
From parton to hadrons: parton showers

- Parton showers have two identities
  - Black boxes with enough handles, to accommodate for data features
  - Predictive tools

- Predictive tool: need to be reliable
  - Especially crucial in the ML world: virtually all the ML algorithms trained on PS

- Recent past: first attempts at making PS under theoretical control and systematically improvable!

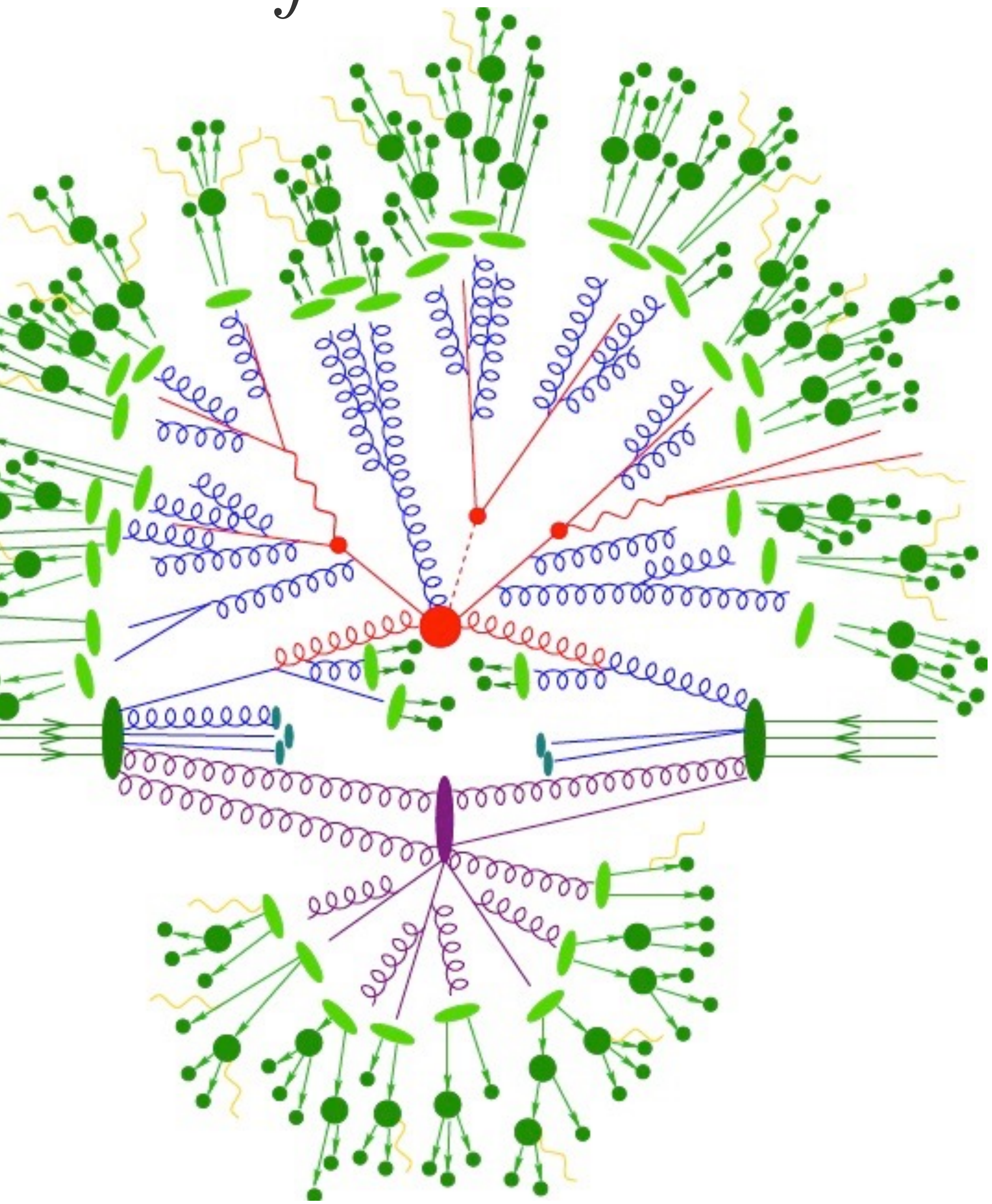
[Panscales (2020)]



First demonstrably ``higher order” showers starting to appear

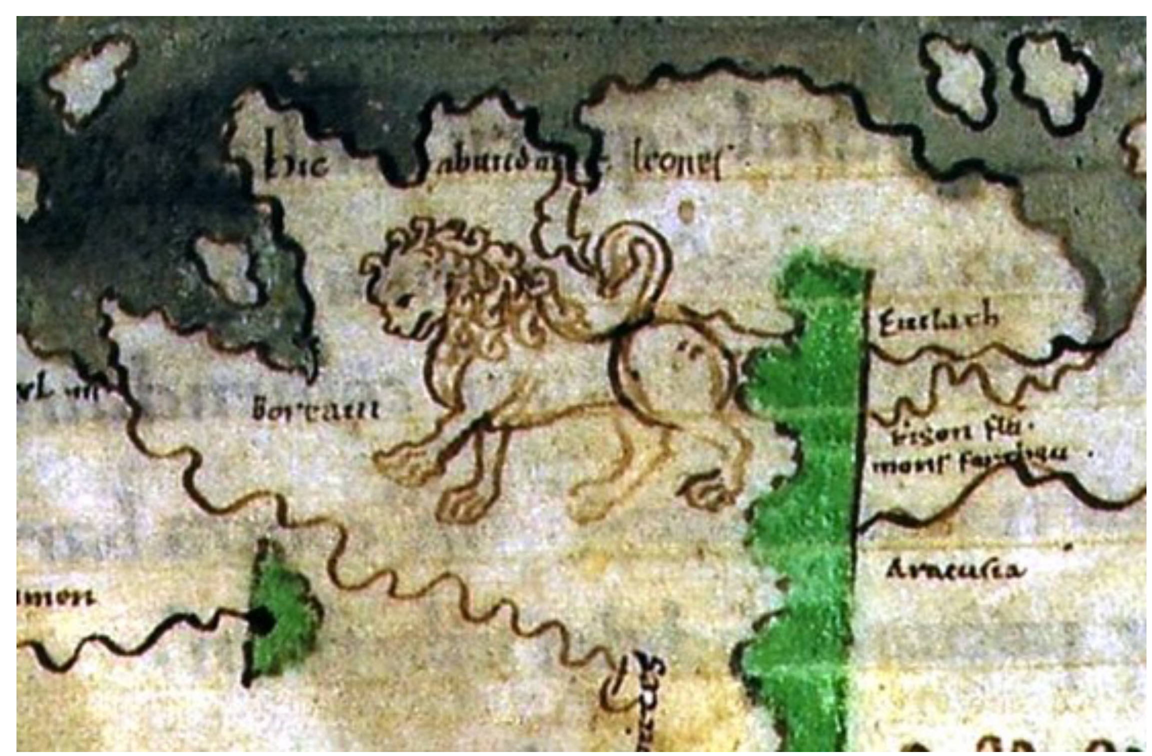
Can we trust factorisation?

$$d\sigma = \int dx_1 dx_2 f(x_1) f(x_2) d\sigma_{\text{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q))$$



At the end, we cannot escape some contamination from soft physics

- Λ_{QCD} ~ GeV, Q ~ 100 GeV → can be 1% effect!
- Non-perturbative → out of control



Can we trust factorisation?

$$\mathrm{d}\sigma = \int dx_1 dx_2 f(x_1) f(x_2)\, \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J \,\left(1 + \mathcal{O}(\Lambda^p_{\mathrm{QCD}}/Q^p)\right)$$

Can we at least establish the scaling?

In practice, a very big difference between p=1 (problem) and p > 1 (irrelevant)

- $e^+e^- \to$ hadrons: $p \geqslant 4$
- For DIS: solid proof that $p \geqslant 2$

- Hadron colliders:
  - for inclusive quantities (e.g. DY total xsec): leading NP corrections should have p=2 (non-trivial!)
  - For more exclusive quantities: potential sources of linear power corrections.
  - Top, Jets are known to have linear power corrections. What about colour singlet?

Can we trust factorisation?

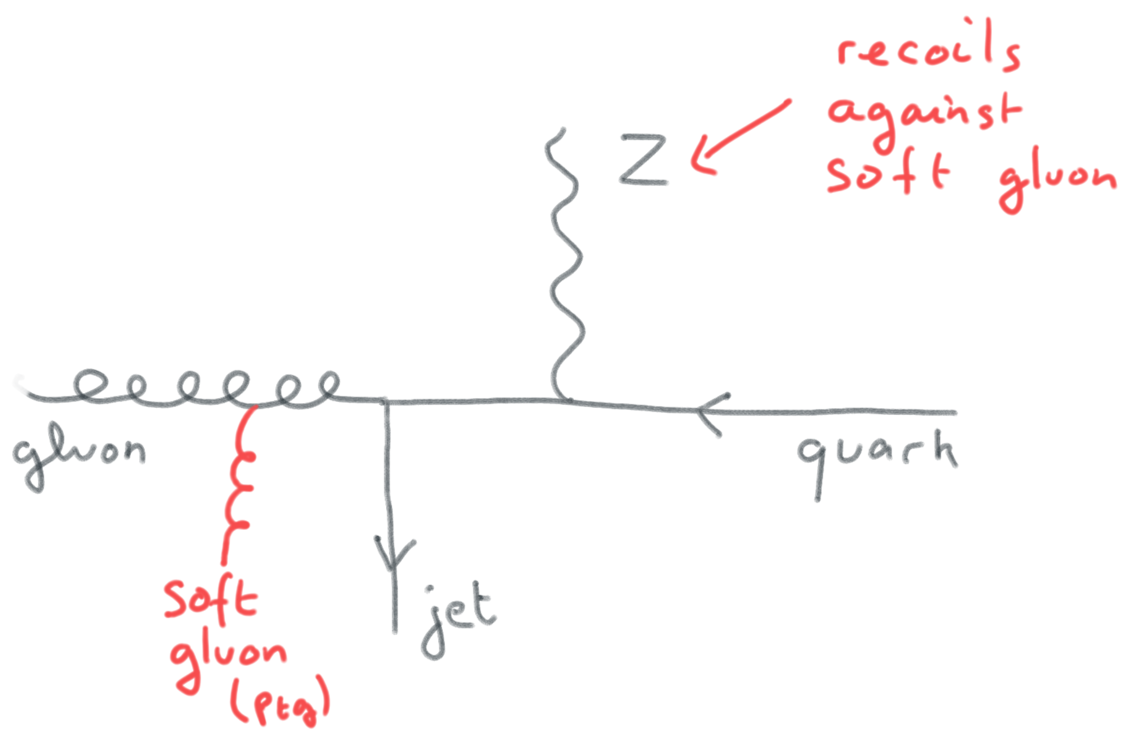
Mechanisms that could generate linear power corrections are there…

QCD power corrections ↔ sensitivity to IR physics

Basic idea: find good ``probe” of the IR, and ask ``can we generate p=1 terms?”

E.g.: Z transverse momentum distribution (example from G.P. Salam)

[G.P. Salam]



$$\sigma \sim \int \frac{dp_\perp}{p_\perp} \alpha_s(p_\perp)$$

Because of azimuthally asymmetric color flow: linear terms could be generated

Integrate over soft d.o.f. → NP

Beyond pQCD

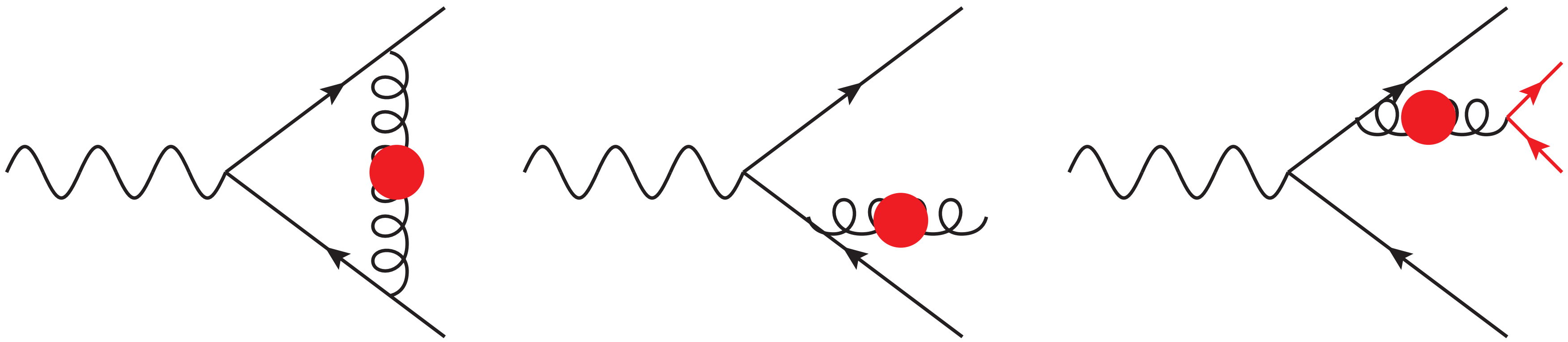
The obvious problem: at colliders, we cannot deal with QCD non-perturbatively

However: we know one source of NP that ``creeps" into perturbative results.

When integrating over soft momenta → Landau pole ambiguity

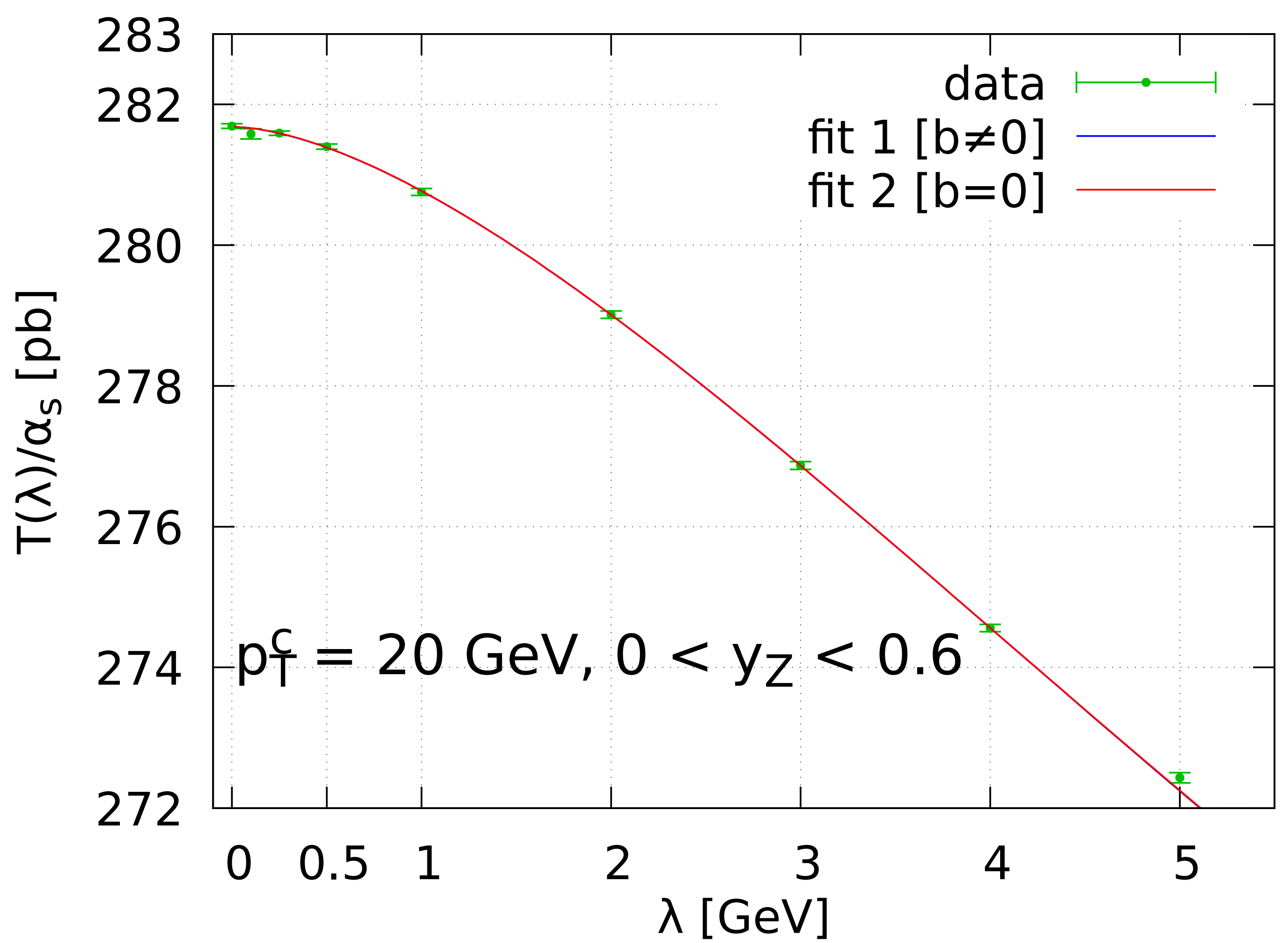
Lead to divergent behaviour of perturbative expansion → can get info from PT theory itself!

Renormalons, calculations in the $n_f \to -\infty$ limit



Z p_t and linear renormalons

[Ferrario Ravasio, Limatola, Nason (2020)]: Numerical study based on renormalon calculus



Compute Z p_t with massive gluons, and extrapolate to $m_g \to 0$

$$f(\lambda) = a\left[1 + b\left(\frac{\lambda}{p_T^c}\right) + c\left(\frac{\lambda}{p_T^c}\right)^2 \log^2\left(\frac{\lambda}{p_T^c}\right) + d\left(\frac{\lambda}{p_T^c}\right)^2 \log\left(\frac{\lambda}{p_T^c}\right)\right]$$

Fit consistent with b=0 → no linear power corrections

Z p_t and linear renormalons

[Ferrario Ravasio, Limatola, Nason (2020)]: Numerical study based on renormalon calculus

Very recently: towards a theoretical understanding.

``No linear power corrections for observables inclusive w.r.t. QCD radiation”

Towards strong foundations for the precision program

[FC, Ferrario Ravasio, Limatola, Melnikov, Nason (2021)]

Conclusions and outlook

- Progress in precision QCD phenomenology keeps proceeding at a remarkable pace
  - N^3LO, complex NNLO, QCD-EW, EW…
  - More and more elaborate resummations
  - Parton shower…
  - Computational tools (→ ingredients for N^3LL resummation)
  - SM/BSM interplay: EFTs…
  - ML to extract the most from data

- This is necessary but not sufficient for physics at the few percent. Many unexpected issues that keep popping up

- A better understanding of NP corrections may be required

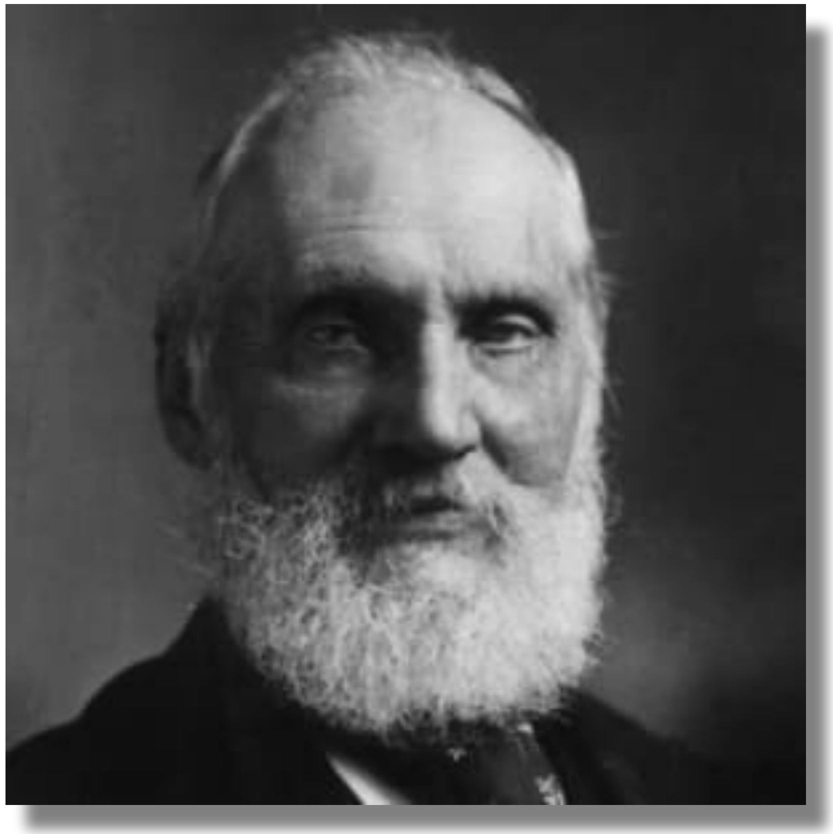
- Future ahead: not only computations. Very interesting analysis, from hardcore pheno to subtle QFT…

Precision physics at the LHC and beyond

With the Higgs, the Standard Model may be a complete theory. What is the point of looking at the next decimal digit?

> ``physics is complete, all we need to do is to measure some known quantities to a great degree of precision''

Lord Kelvin, ca 1900



5 years later: special relativity.

Less than 30 years later: quantum mechanics, general relativity

Thank you very much for your attention!