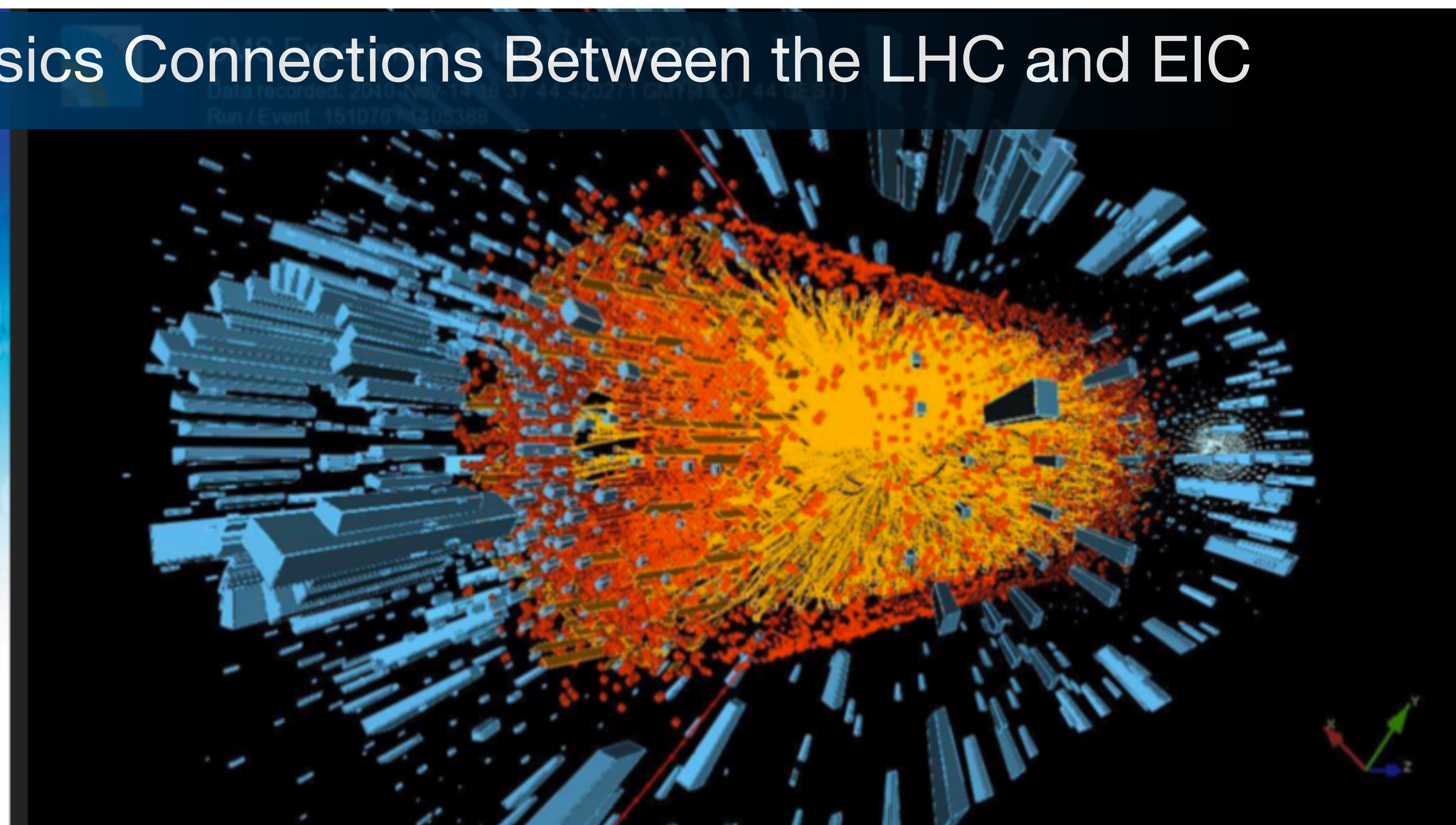
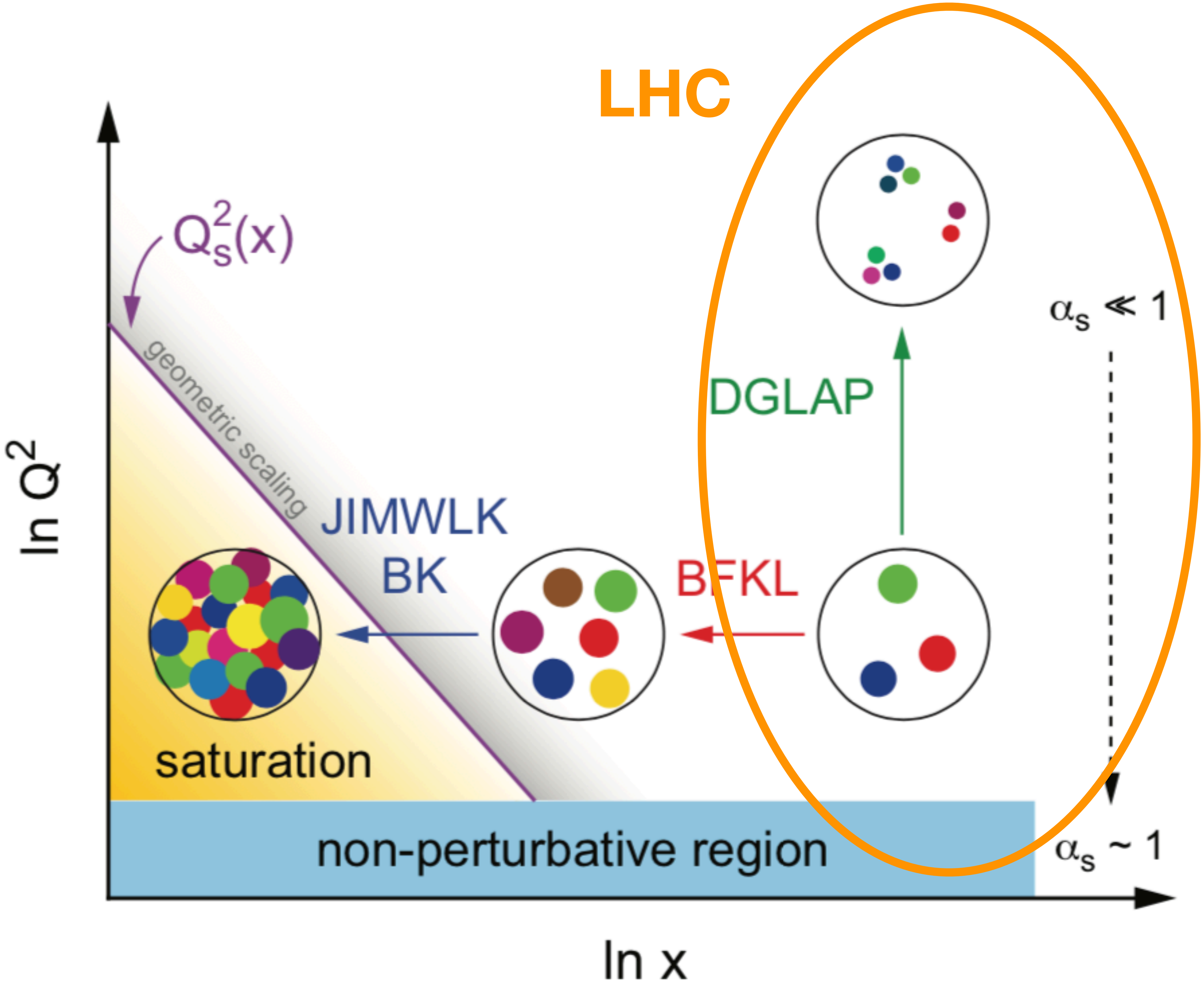
Perturbative QCD: status and opportunities

John Campbell, Fermilab

Workshop on Physics Connections Between the LHC and EIC



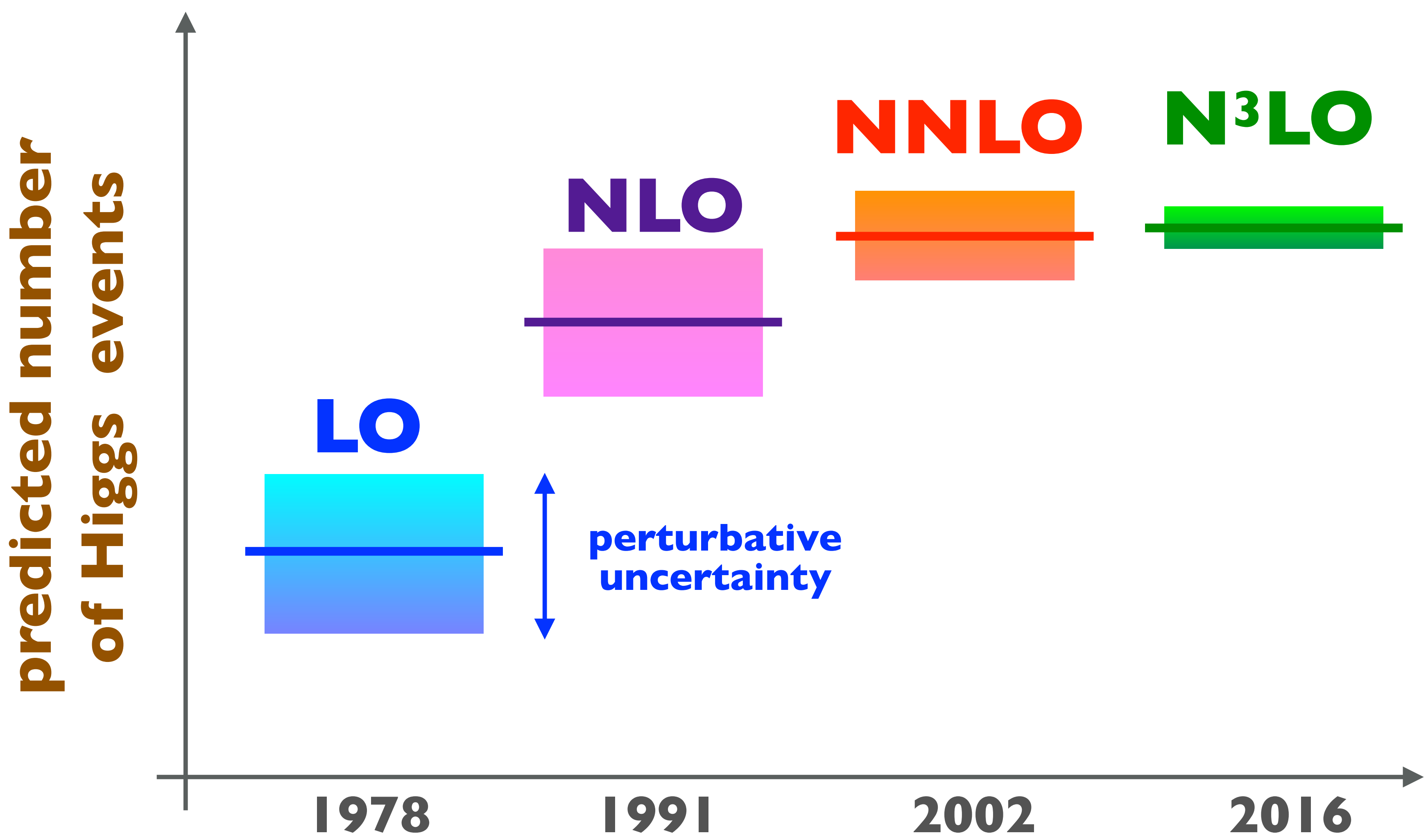
The landscape

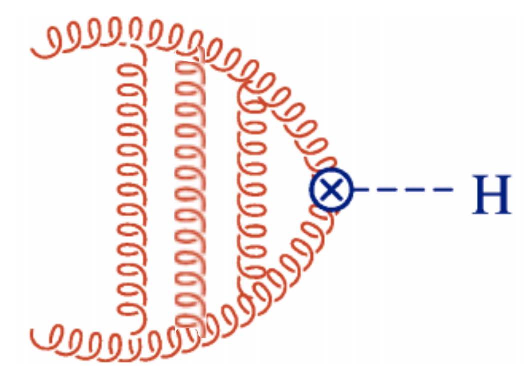


- Making the bulk of LHC predictions is “simplified” by properties of QCD: asymptotic freedom and factorization.
- Collinear factorization works well (enough) for colliding protons.
- Perturbation theory is a powerful tool!

Higher orders

- Systematic improvement in the prediction at each order of perturbation theory:
  - better description (partons initiating hard process, radiation in final state)
  - reduced dependence on unphysical renormalization and factorization scales.
- But still hard work; primary emphasis on best bang-for-buck!





Anastasiou, Dulat, Mistlberger et al (2016-)

LO and NLO

- Any process can (in principle) be computed up to NLO using off-the-shelf tools
- For producing cross-sections, observables and events
  - Madgraph5/aMC@NLO, SHERPA, Herwig, …
- Accessing all necessary matrix elements (further assembly required!)
  - OpenLoops, RECOLA, GoSam, NLOX, …

- All thanks to advances in understanding multiple elements of the calculation
  - importance of recursion (recycling)
  - universal and efficient methods to handle infrared singularities (subtraction)
  - knowledge of analytic behavior of amplitudes (unitarity methods)
  - structure of one-loop integrals
  - efficient phase-space integration
  - ….
- Of course, all of the above applies not just to hadron-hadron colliders.

Beyond NLO

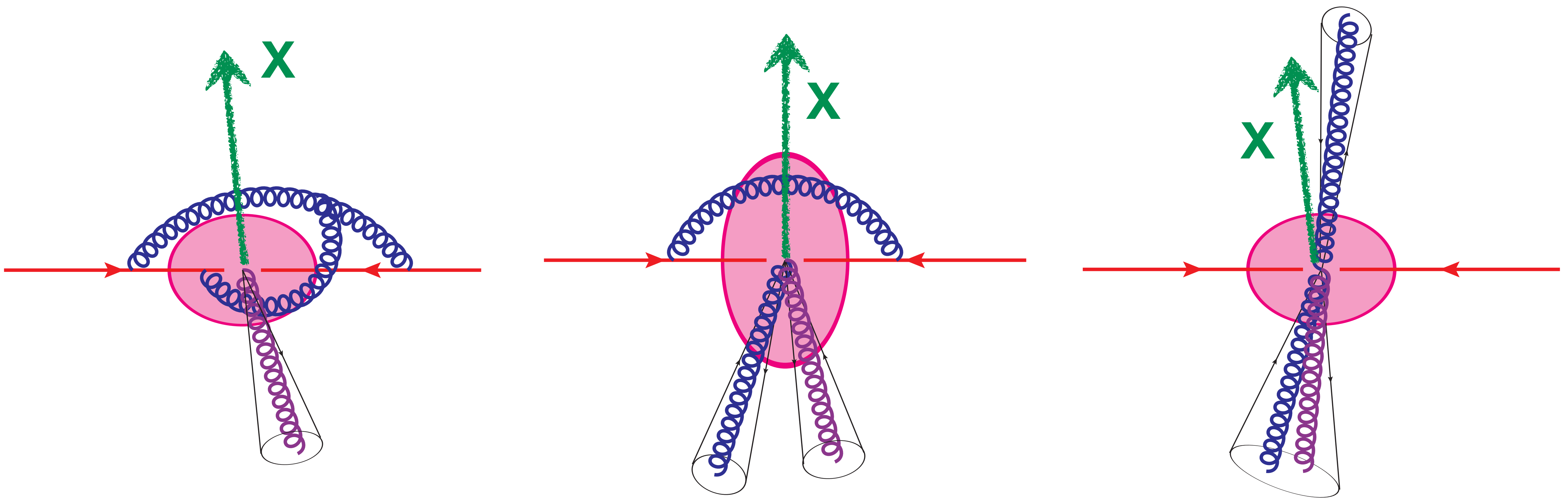
- Two main areas requiring attention:
  - calculation of multi-loop diagrams beyond 2→2 topology
  - cancellation of infrared singularities: multiple strategies currently in use, all computationally challenging, no clear consensus on best approach

Example of infrared complications: X+jet @ NNLO

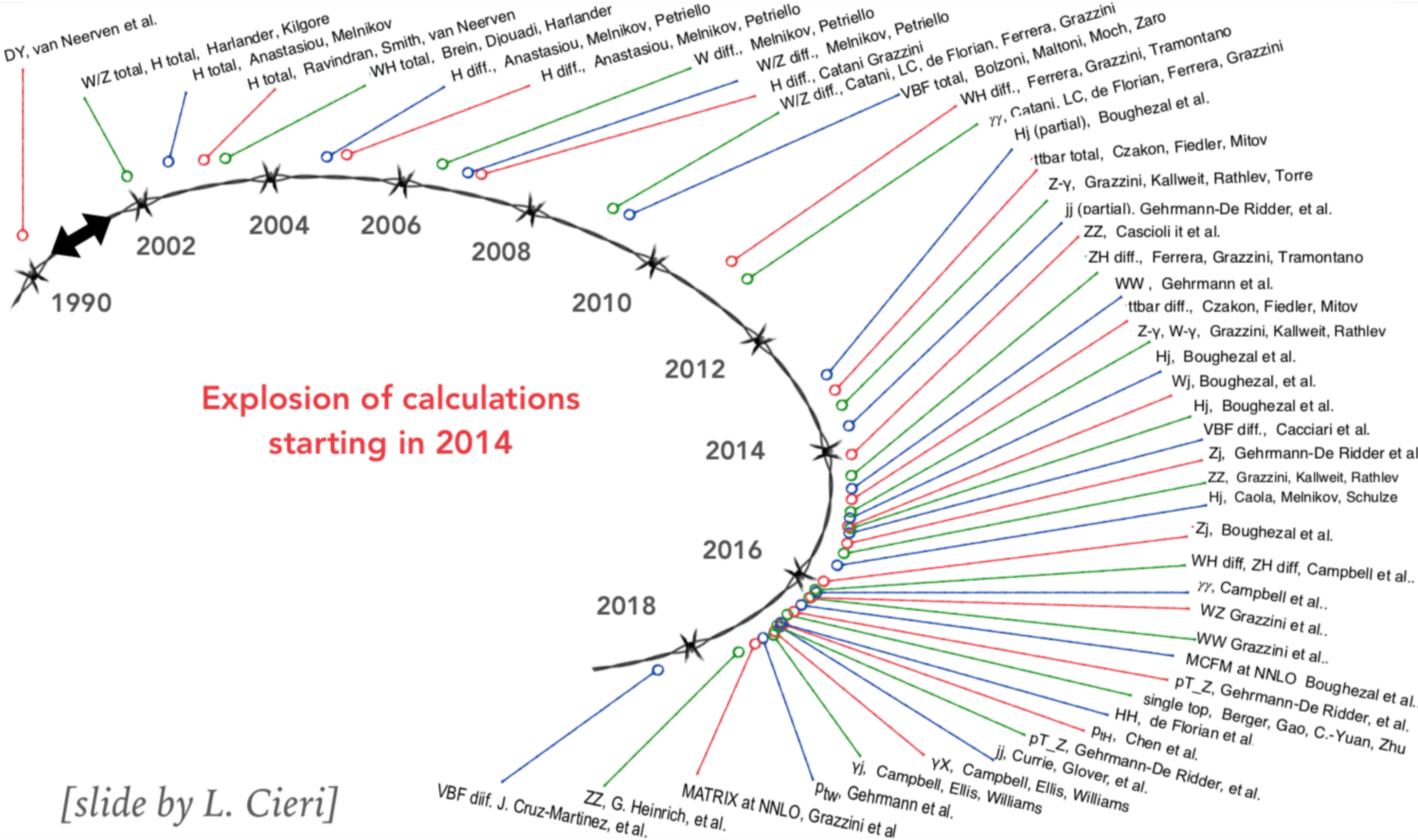
"Pure virtual", e.g. 2-loop diagrams (Born topology)

"Real-virtual", 1-loop with an additional parton

"Real-real", two additional partons



NNLO progress



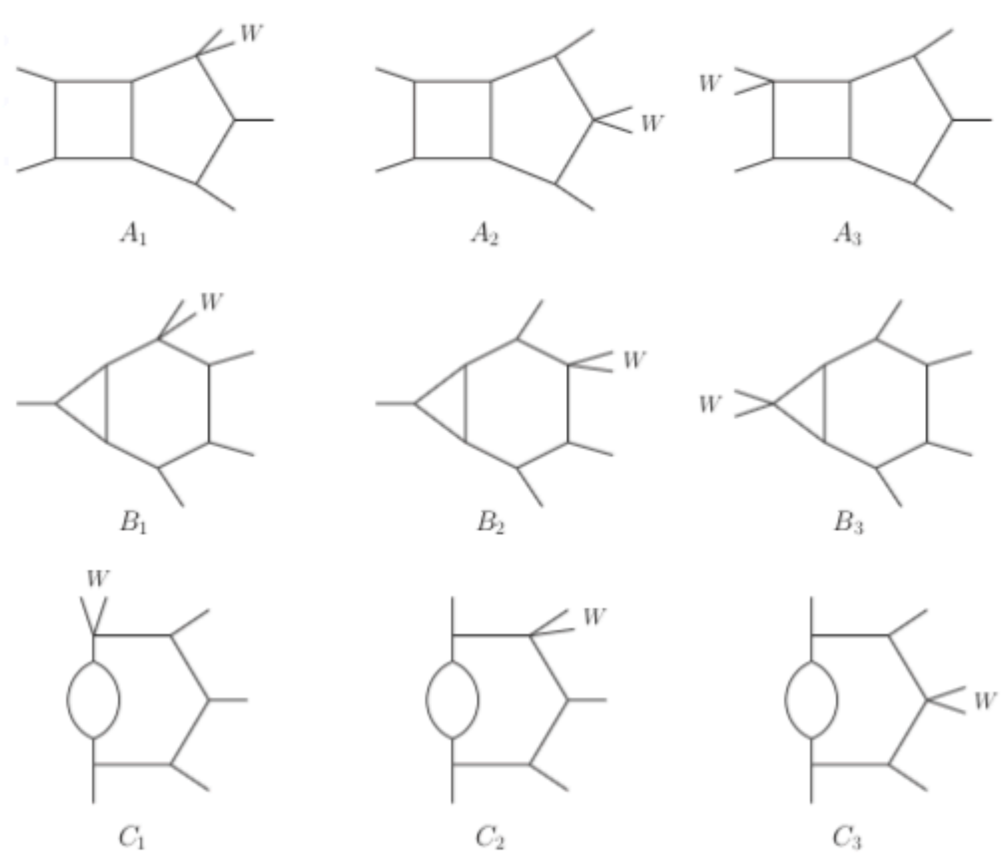
[slide by L. Cieri]

NNLO: hot topics and prospects

- Pushing beyond the current 2→2 frontier desirable for many reasons:
  - Higgs: ttH and Higgs+2 jets
  - Precision SM: 3 jets, W/Z/photon + 2 jets
- Requires deeper understanding of two-loop amplitudes: analytic structure, new (elliptic) integrals, numerical techniques for handling integrals.

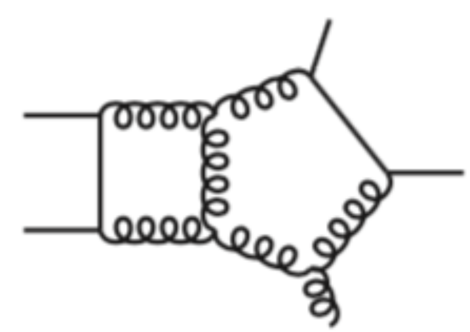
numerical evaluation of planar 2-loop W+4 parton amplitudes

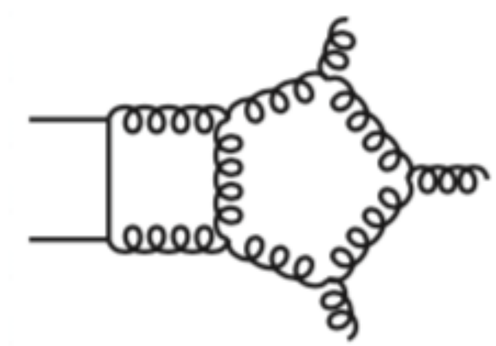
Hartanto, Badger, Bronnum-Hansen, Peraro (2019)



analytic 2-loop leading-color 5-parton amplitudes

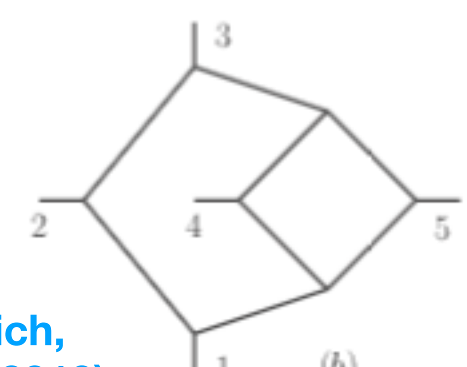
Abreu, Dormans, Febres Cordero, Ita, Page, Sotnikov (2019)





full analytic 5-parton +++++ amplitude

Badger, Chicherin, Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zola (2019)



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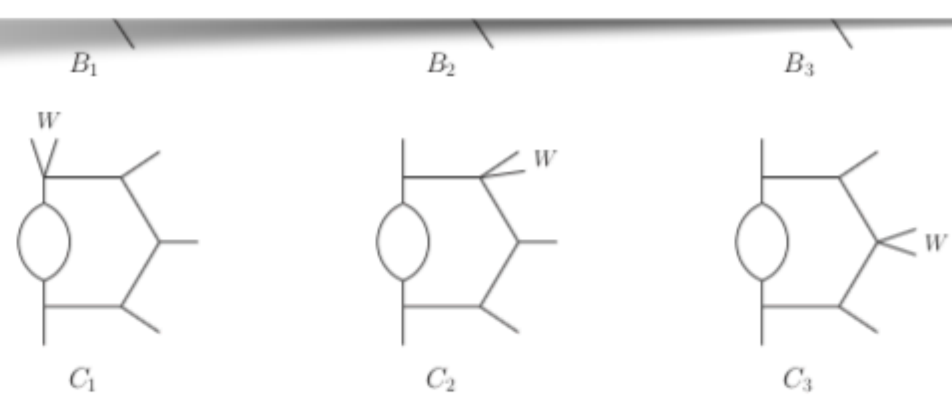
$$\mathcal{H}_1^{(2,0)} = \sum_{S_{\mathcal{T}_1}} \left\{ -\kappa \frac{[45]^2}{\langle 12\rangle\langle 23\rangle\langle 31\rangle} I_{123;45} + \kappa^2 \frac{1}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle} \left[5\, s_{12}s_{23} + s_{12}s_{34} + \frac{\mathrm{tr}_+^2(1245)}{s_{12}s_{45}} \right] \right\}$$

$$\mathcal{H}_{13}^{(2,1)} = \sum_{S_{\mathcal{T}_{13}}} \left\{ \kappa \frac{[15]^2}{\langle 23\rangle\langle 34\rangle\langle 42\rangle} \left[I_{234;15} + I_{243;15} - I_{324;15} - 4\, I_{345;12} - 4\, I_{354;12} - 4\, I_{435;12} \right] \right.$$
$$\left. - 6\,\kappa^2 \left[\frac{s_{23}\,\mathrm{tr}_-(1345)}{s_{34}\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle} - \frac{3}{2}\frac{[12]^2}{\langle 34\rangle\langle 45\rangle\langle 53\rangle} \right] \right\},$$



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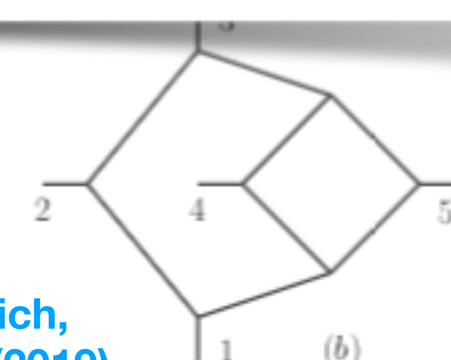
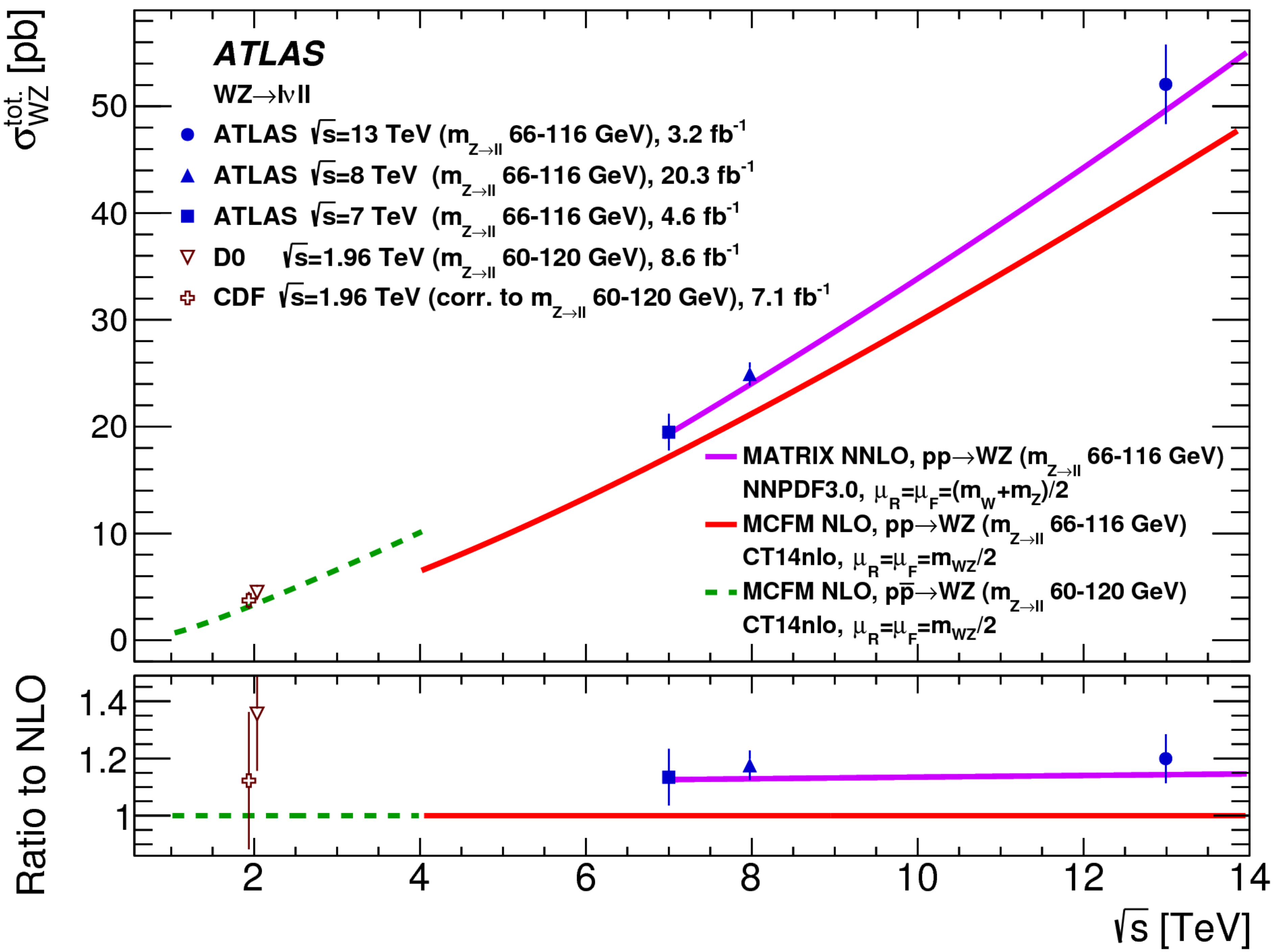


What does it mean?

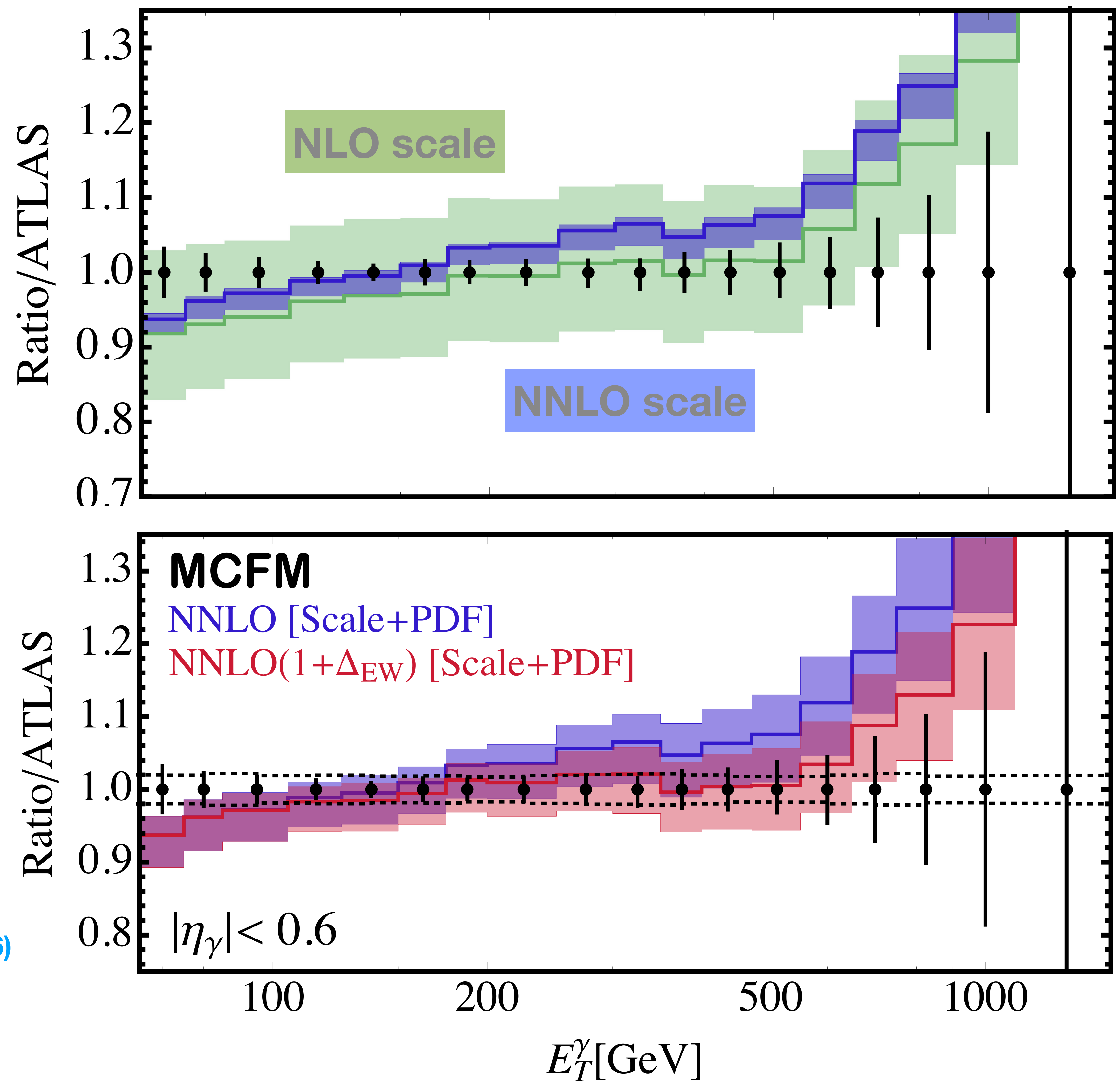
- The increasing availability of calculations at NNLO is essential to properly describe much of the data taken at the LHC.



Precision

- Much-reduced scale dependence yields percent-level theory uncertainties that can be competitive with experimental ones
  - new opportunities for measurements and constraints
  - at this level, often need to consider electroweak effects as well (especially in tails of distributions)

Ellis, Williams, JC (2016)

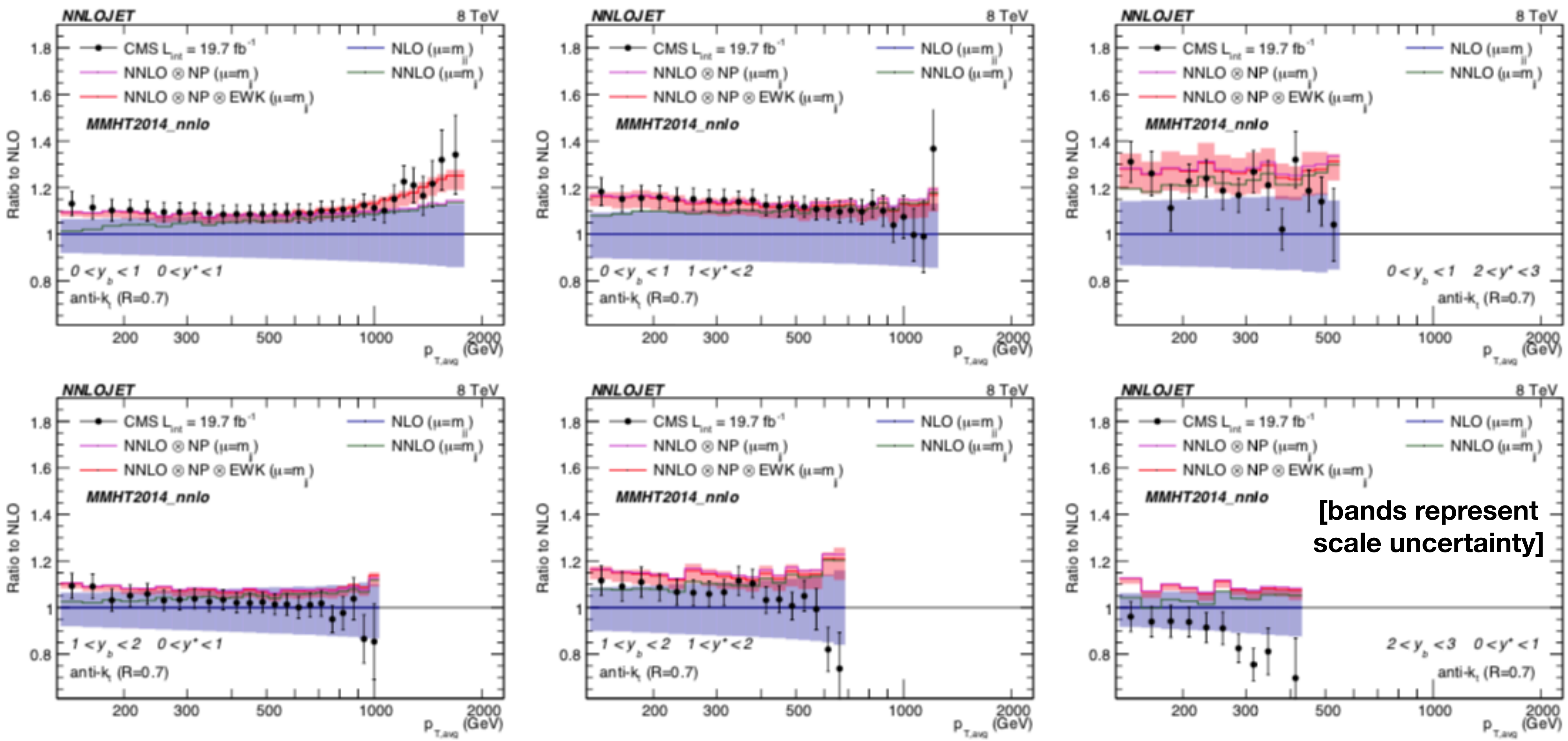


Differential jet cross-sections

Gehrmann-de Ridder, Gehrmann, Glover, Huss, Pires (2019)

$$x_{1,2} = \frac{2p_{T,\mathrm{avg}}}{\sqrt{s}}\, e^{\pm y_b} \cosh y^*$$

dijet rapidity separation $y^* = \frac{1}{2}|y_1 - y_2|$

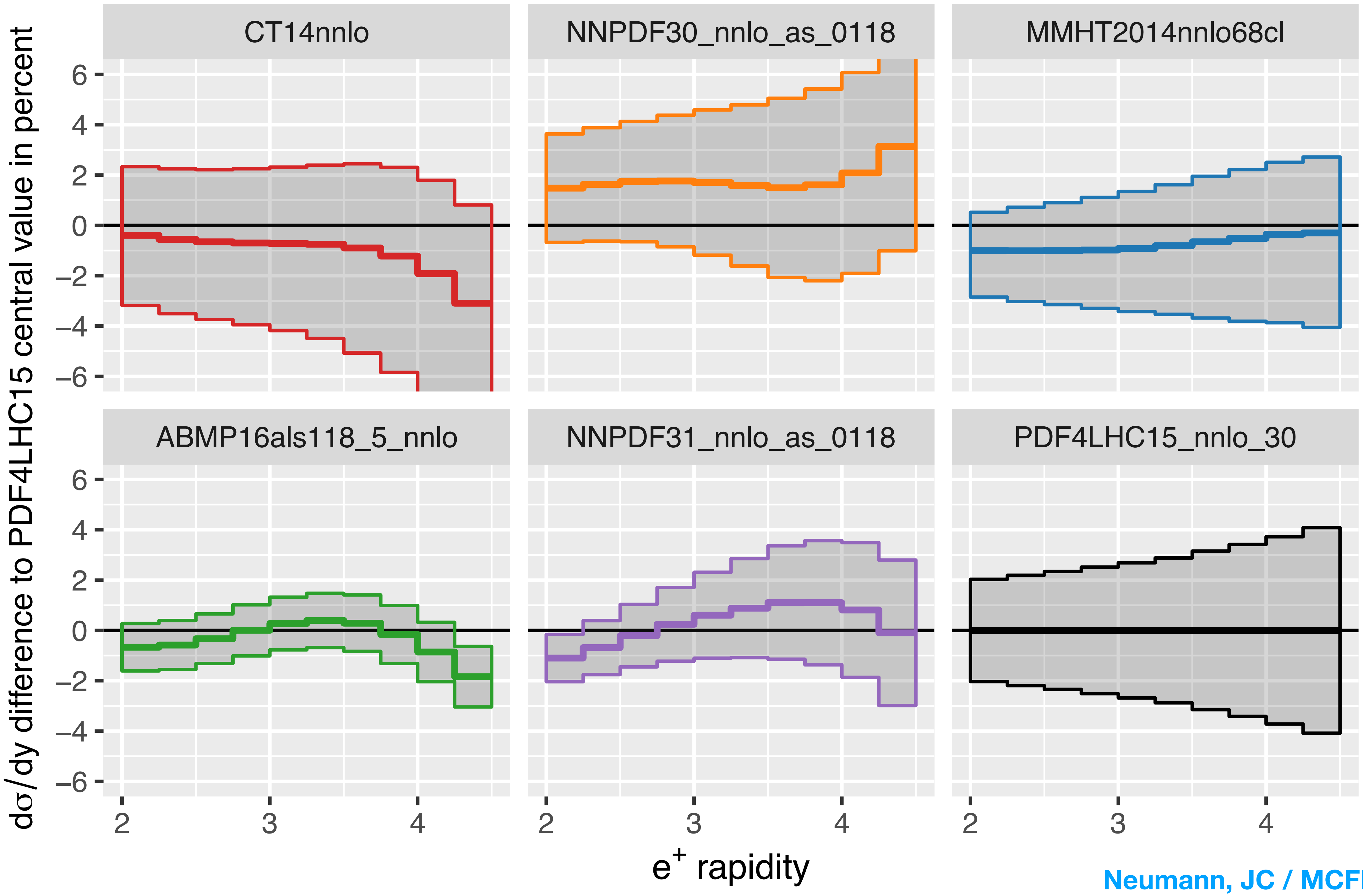


boost of dijet system $y_b = \frac{1}{2}|y_1 + y_2|$

- Smaller uncertainties, better agreement with data (especially low boost)
- At large boost (and jet p_T) disagreement an opportunity to refine high-*x* PDF

PDF studies

- Need tools able to compute NNLO predictions for multiple PDFs, precisely enough to see differences, both for assessing compatibility and eventually for global fitting.

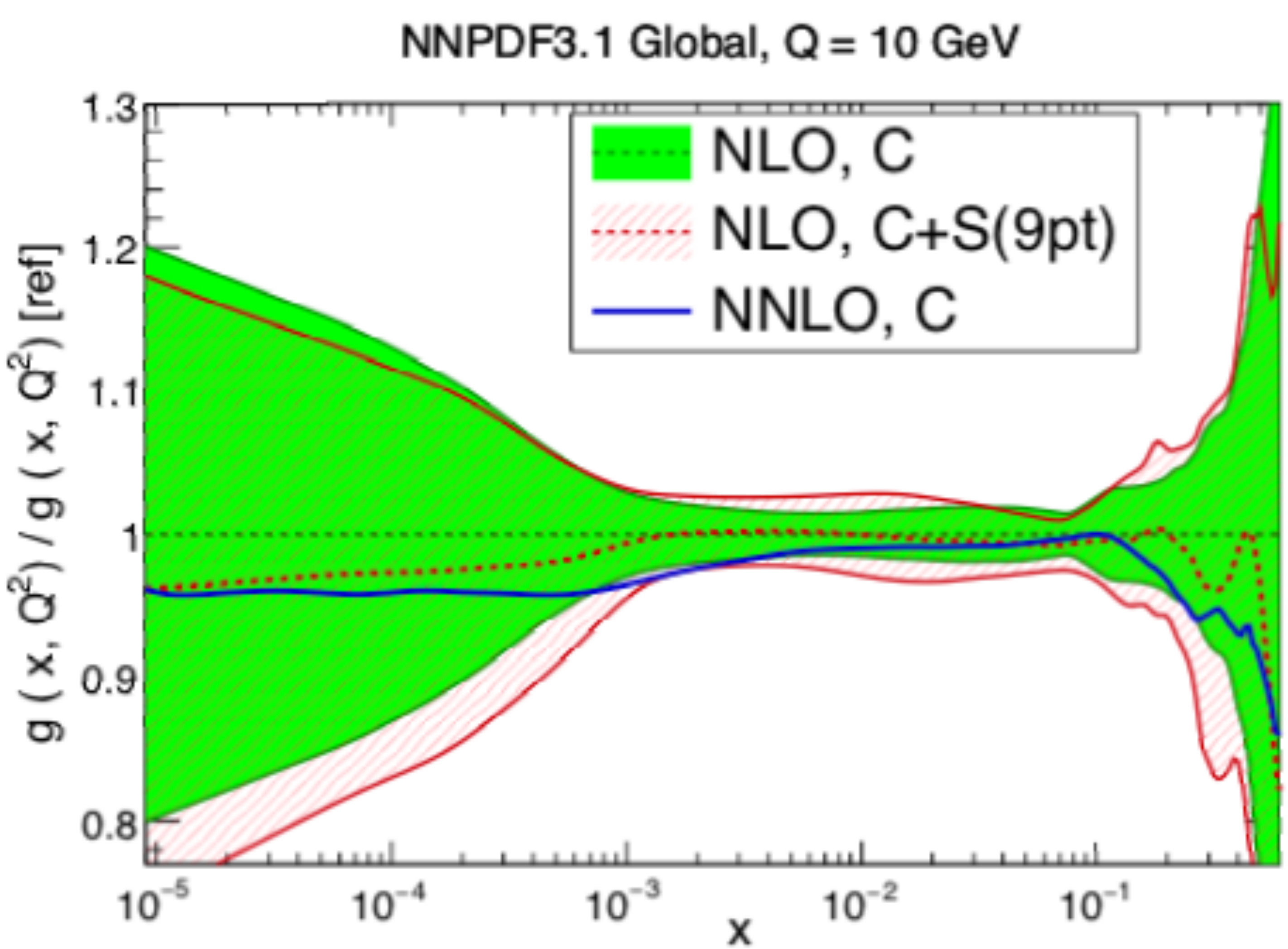


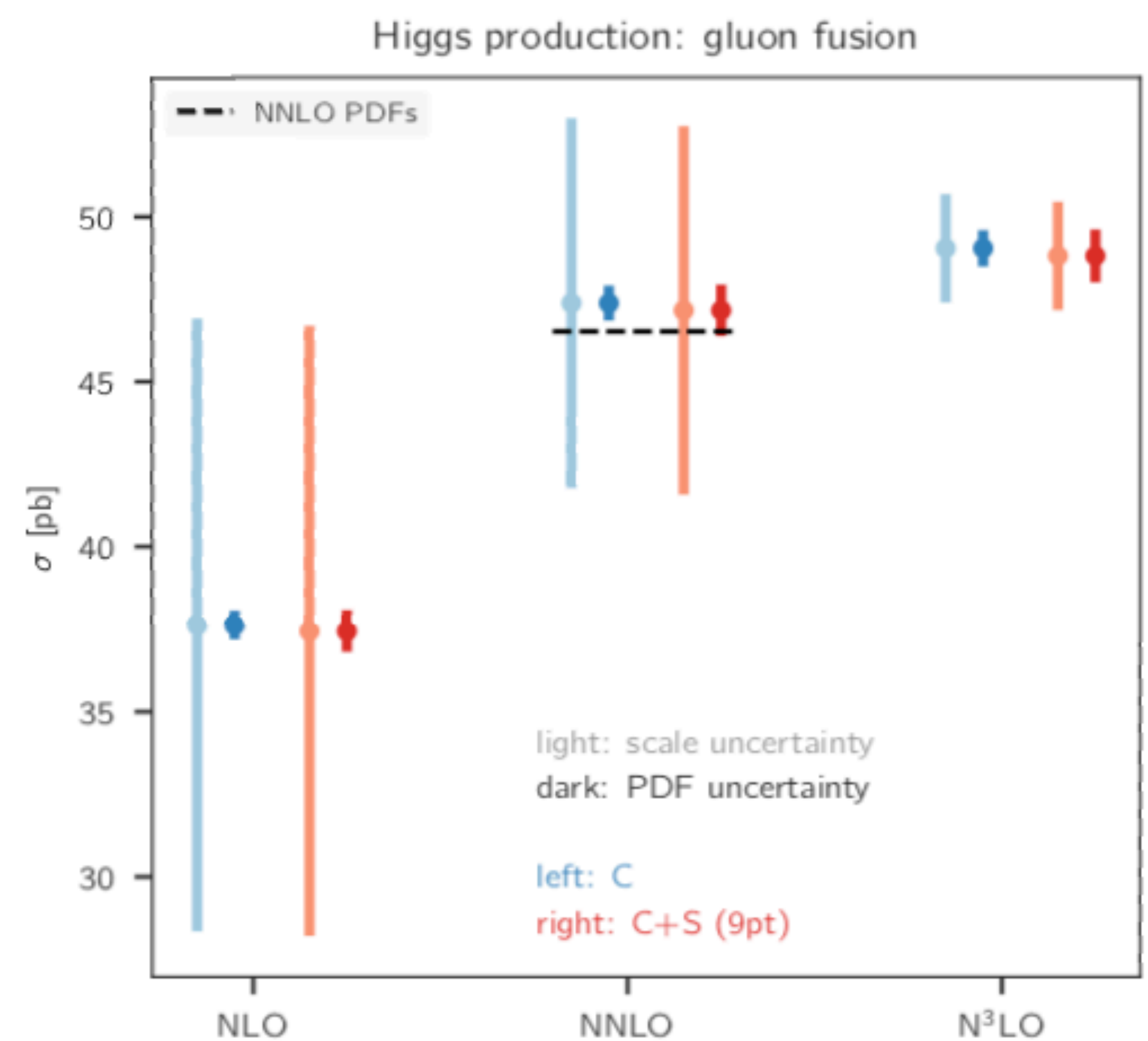
Neumann, JC / MCFM-9.0 (2019)

Higher-order uncertainty in fits

- Attempt to capture uncertainty in fits due to missing higher orders (scale uncertainty)
  - so far only to NLO where all calculations are readily available.
  - general formalism worked out, also applicable to nuclear & higher-twist corrections

Abdul Khalek, Ball, Carrazza, Forte, Giani, Kassabov, Nocera, Pearson, Rojo, Rottoli, Ubiali, Voisey, Wilson / NNPDF (2019)

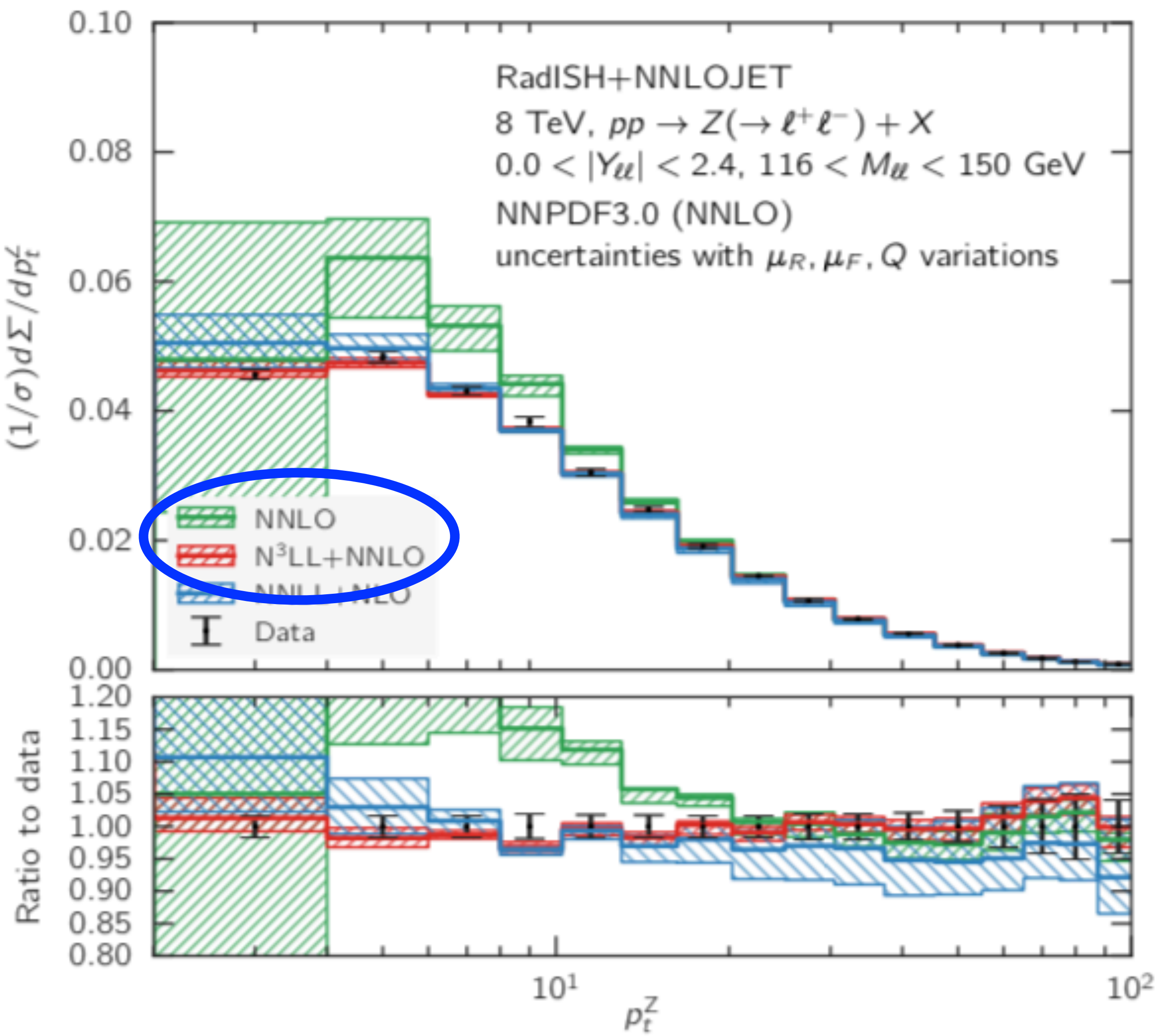


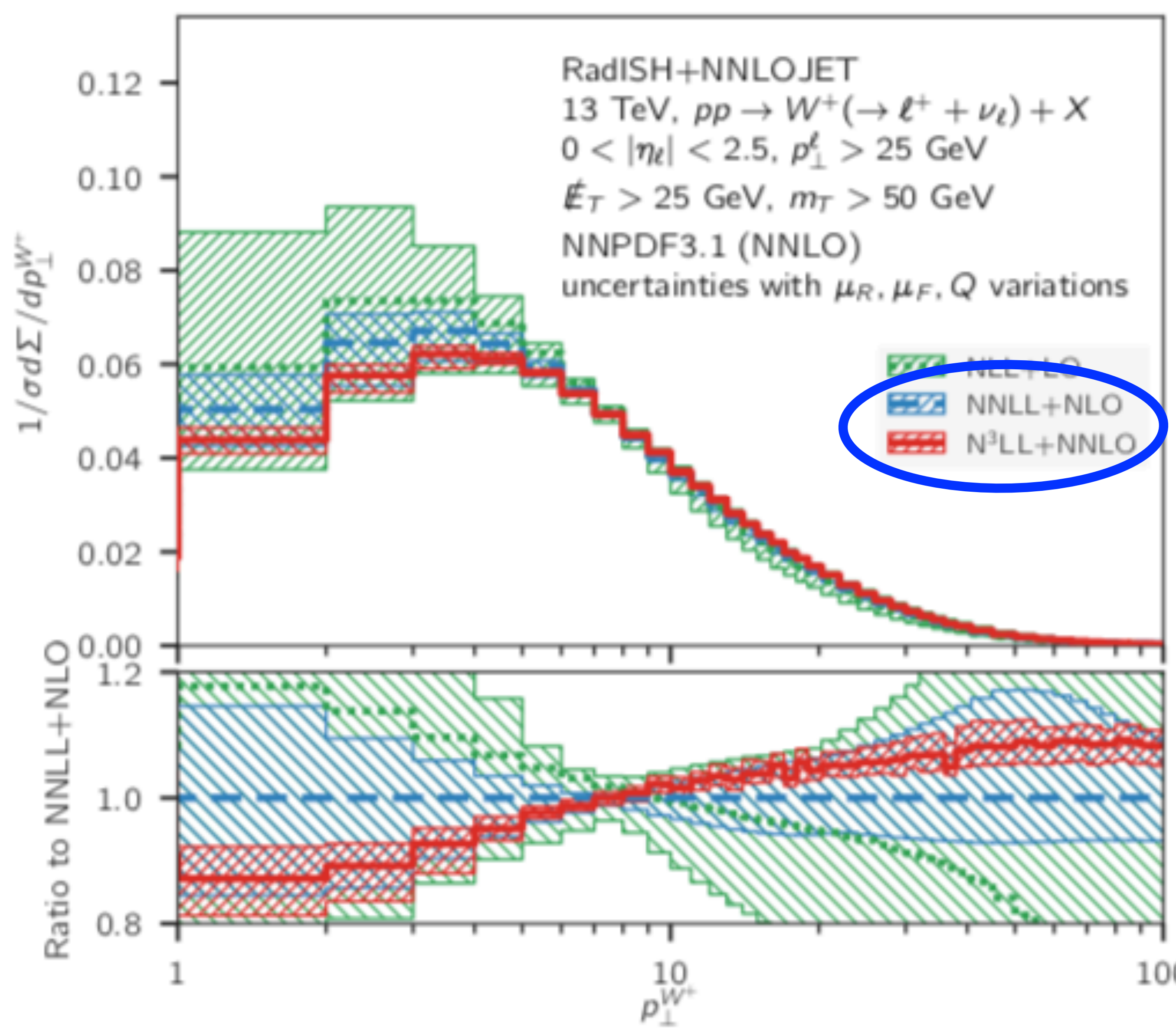


Not just fixed order

- W and Z p_T spectrum important for PDF determination, W mass (also H for BSM effects)
- State-of-the-art combines NNLO fixed order with N^3LL large-log resummation

Bizon, Chen, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli (2018)
Bizon, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Walker (2019)





resummation crucial ← → **NNLO sufficient**

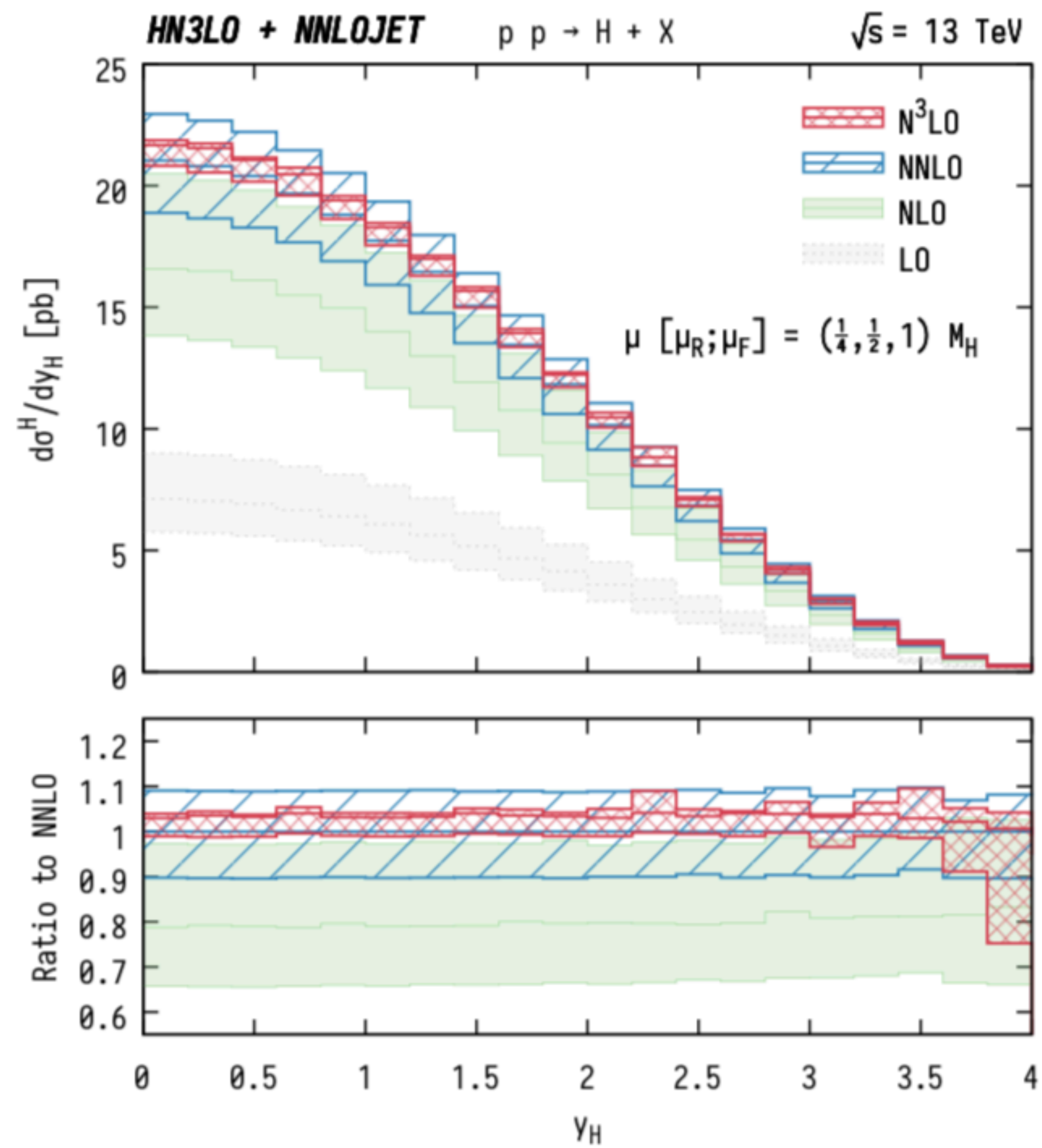
significant shape change (up to ~10%) wrt NNLL+NLO, residual uncertainty < 5%

Beyond NNLO

- Only a handful of N^{3}LO results, focussed on Higgs production
  - inclusive cross-sections for gluon fusion and VBF
  - W and Z production notably absent!
- Aside from experimental considerations, pure theoretical interest
  - first order at which all parton channels are computed to at least NLO
  - how does series converge?
- Latest results: completely-differential calculation of Higgs production at N^{3}LO

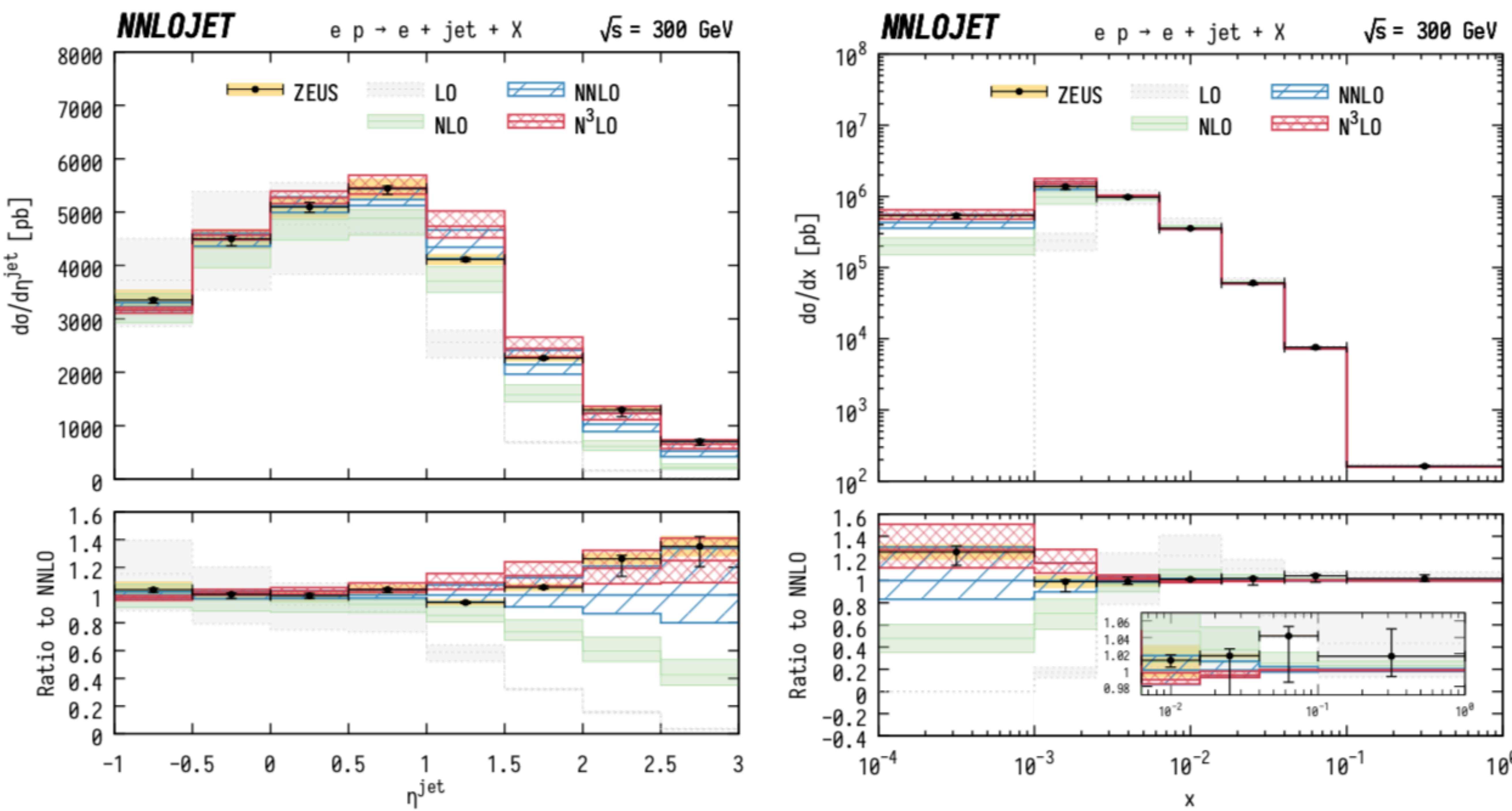
  Cieri, Chen, Gehrmann, Glover, Huss (2018)
  - excellent agreement with earlier (threshold expansion) calculation

    Dulat, Mistlberger, Pelloni (2018)
- Open question: how does perturbative stability look after fiducial cuts?



Steps towards the EIC

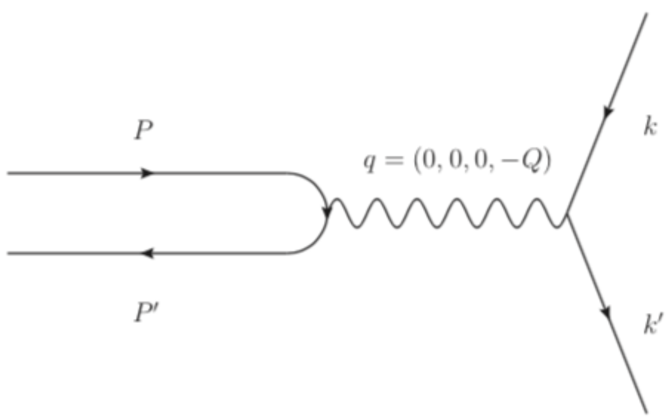
- N^3LO jet production in DIS in the lab frame Currie, Gehrmann, Glover, Huss, Niehues, Vogt (2017)
    - overlapping uncertainty bands, factor two smaller uncertainties, better description even in regions with lower accuracy or susceptible to large logs.

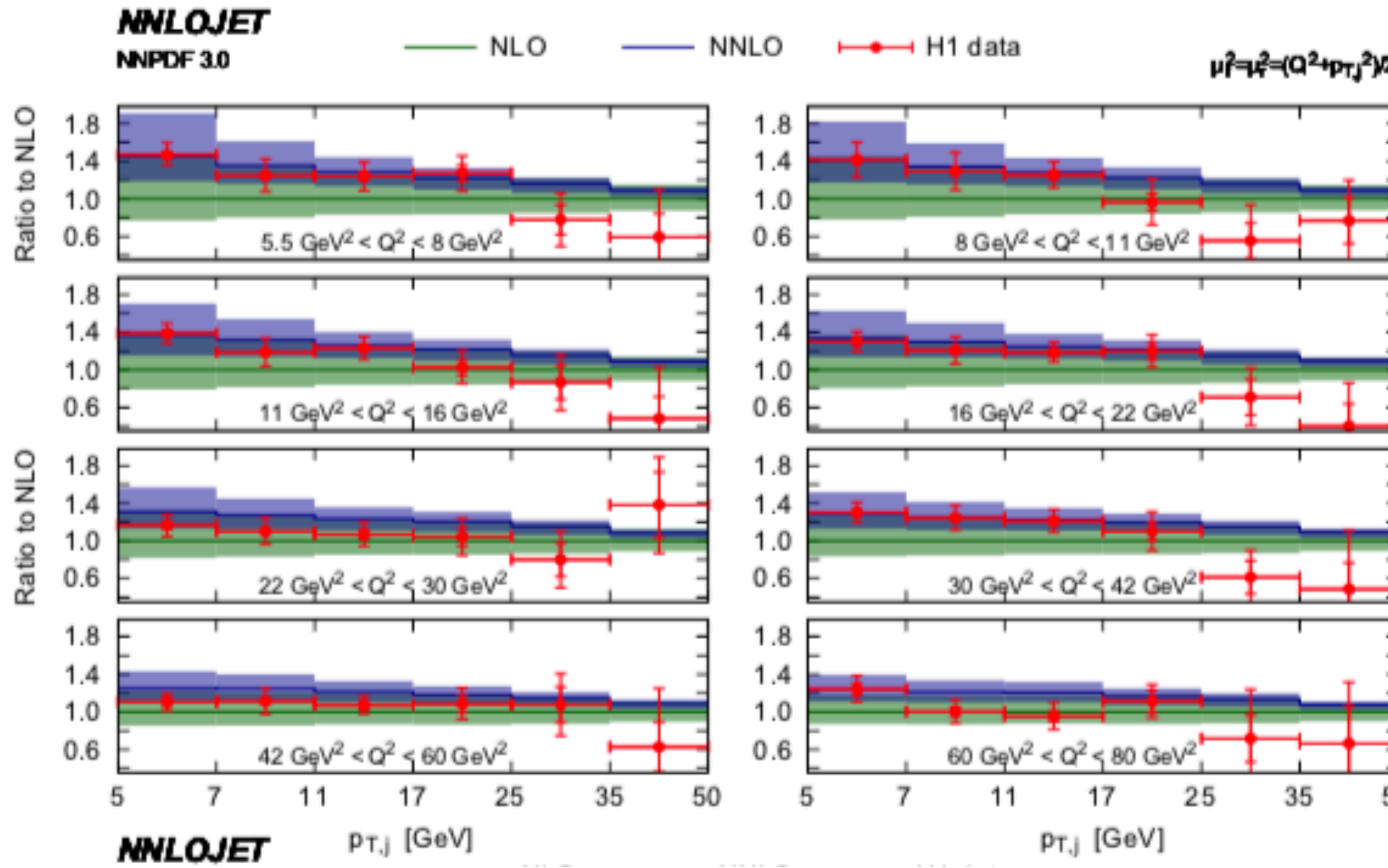


NNLO calculations for DIS

- NNLO corrections to DIS jet and dijet production in the Breit frame

  Currie, Gehrmann, Huss, Niehues (2017)

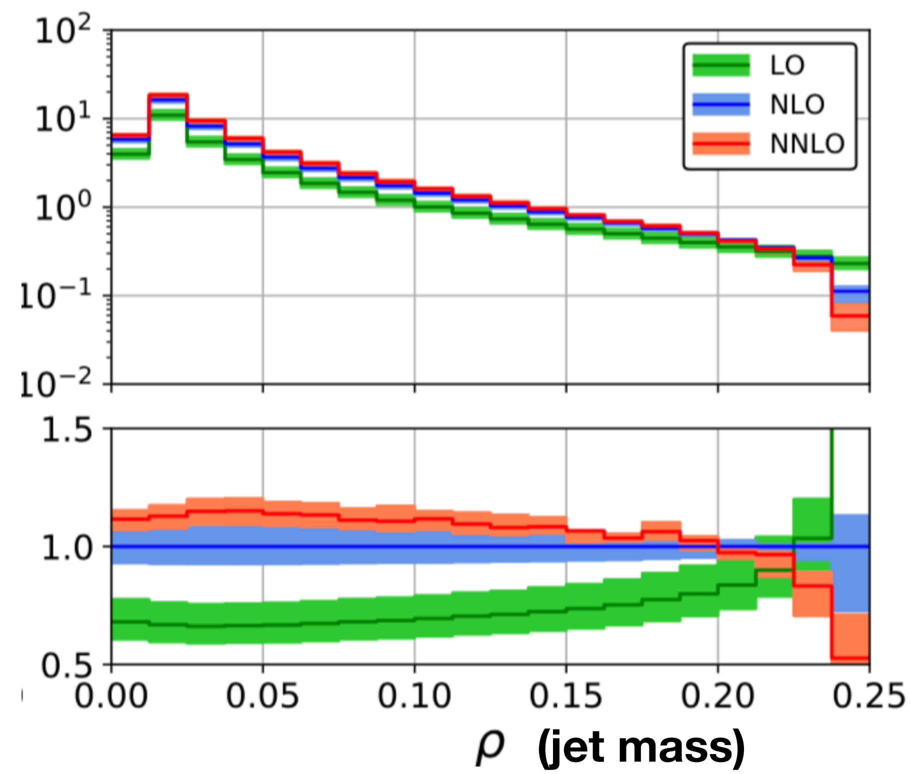




- inclusive jet: substantial corrections at low Q^2 and p_T, up to 60%, much improved description of data

- Corresponding results for event-shape distributions

  Gehrmann, Huss, Mo, Niehues (2019)



In general up to 20% corrections, non-uniform, decreased scale uncertainty but small overlap with NLO

Non-perturbative effects

- Description of data requires the addition of power corrections to account for parton-hadron transition.
- Dispersive model (also used at LEP) shifts differential distribution:

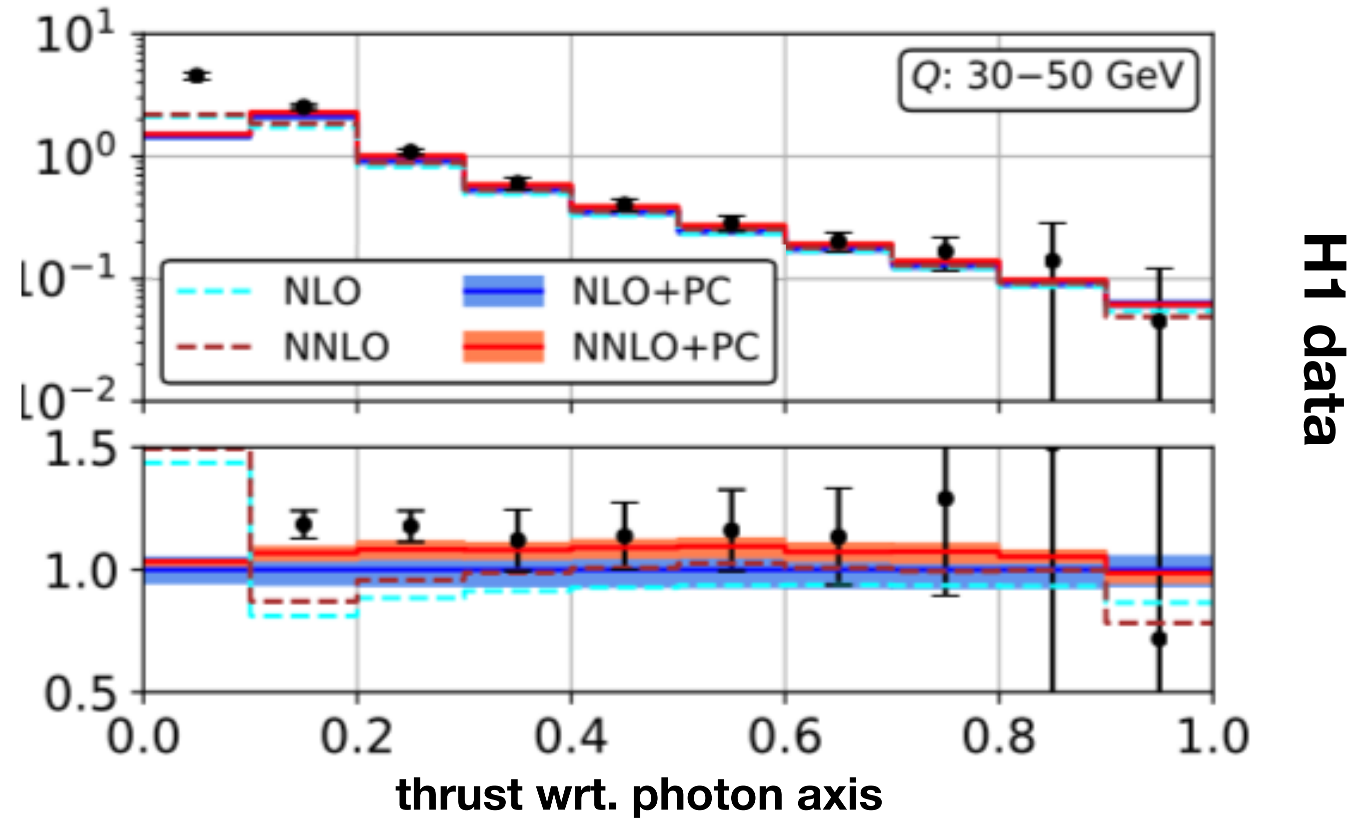
$$\frac{\mathrm{d}\sigma^{\mathrm{hadron}}(F)}{\mathrm{d}F} = \frac{\mathrm{d}\sigma^{\mathrm{parton}}(F - a_F P)}{\mathrm{d}F}$$

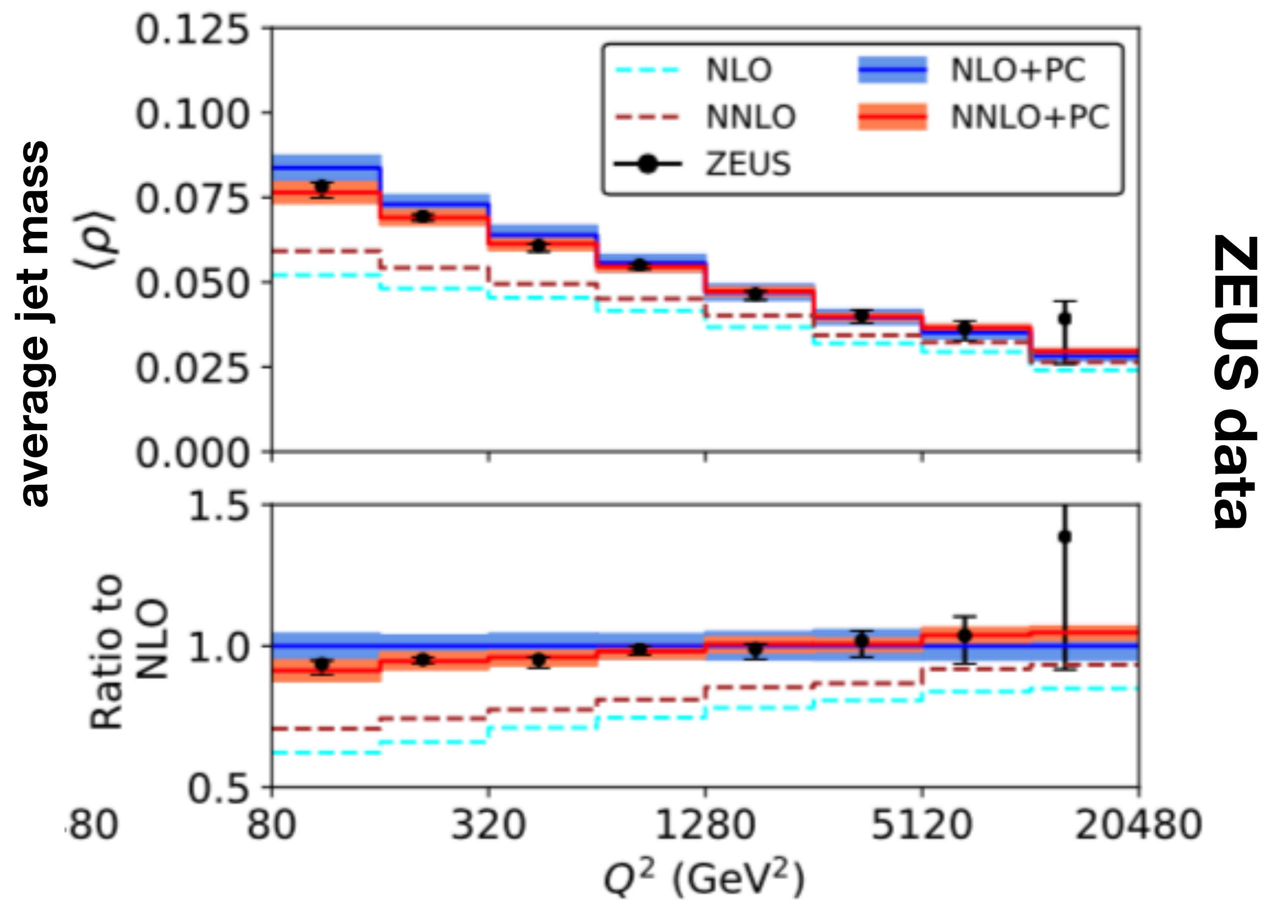
and mean values correspondingly:

$$\langle F \rangle = \langle F \rangle^{\mathrm{pert.}} + a_F\, P,$$

(universal *P*, a_F varies by event shape)

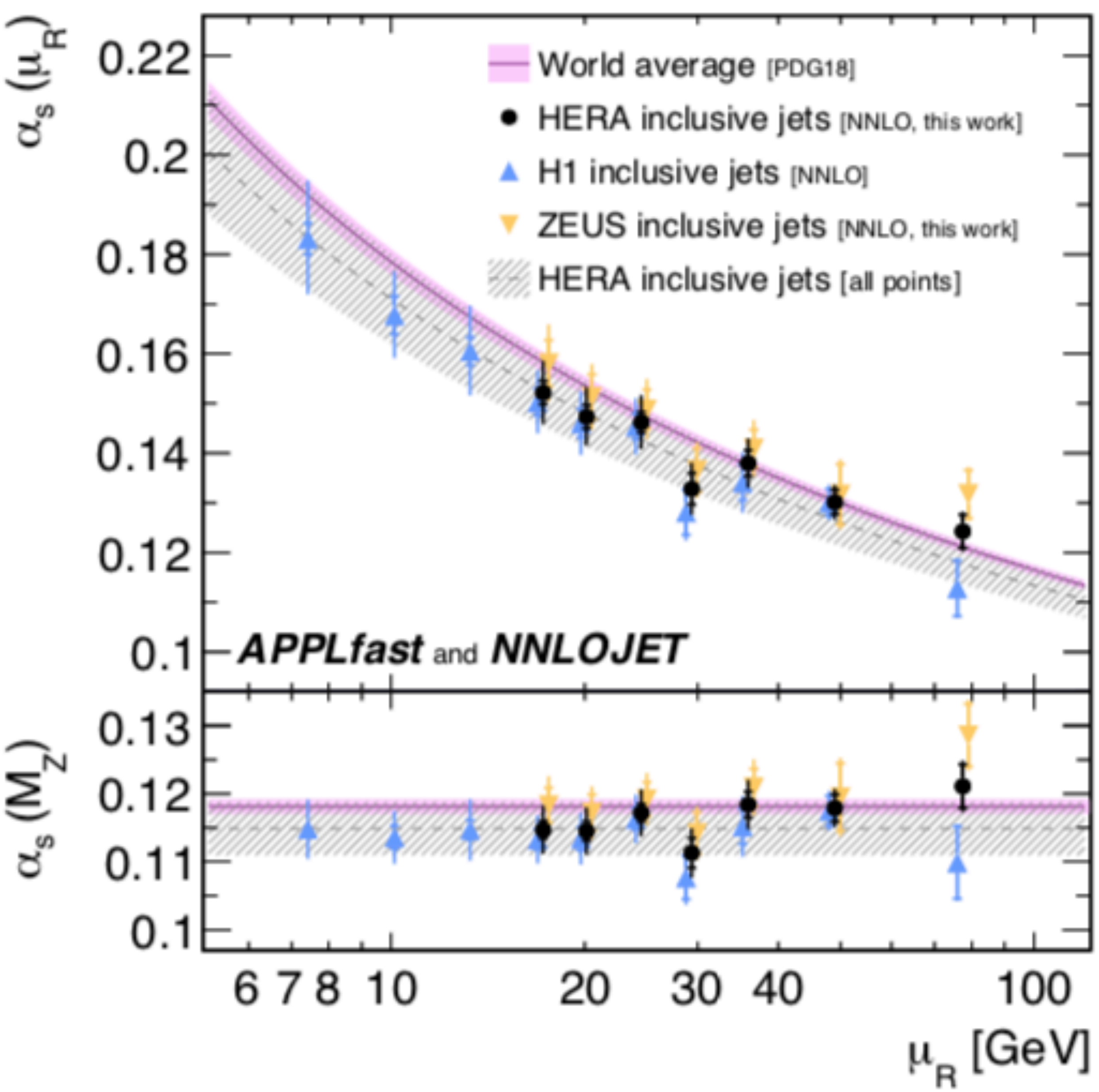
- Precision QCD studies now possible through reanalyses of HERA data
  - opportunity for EIC

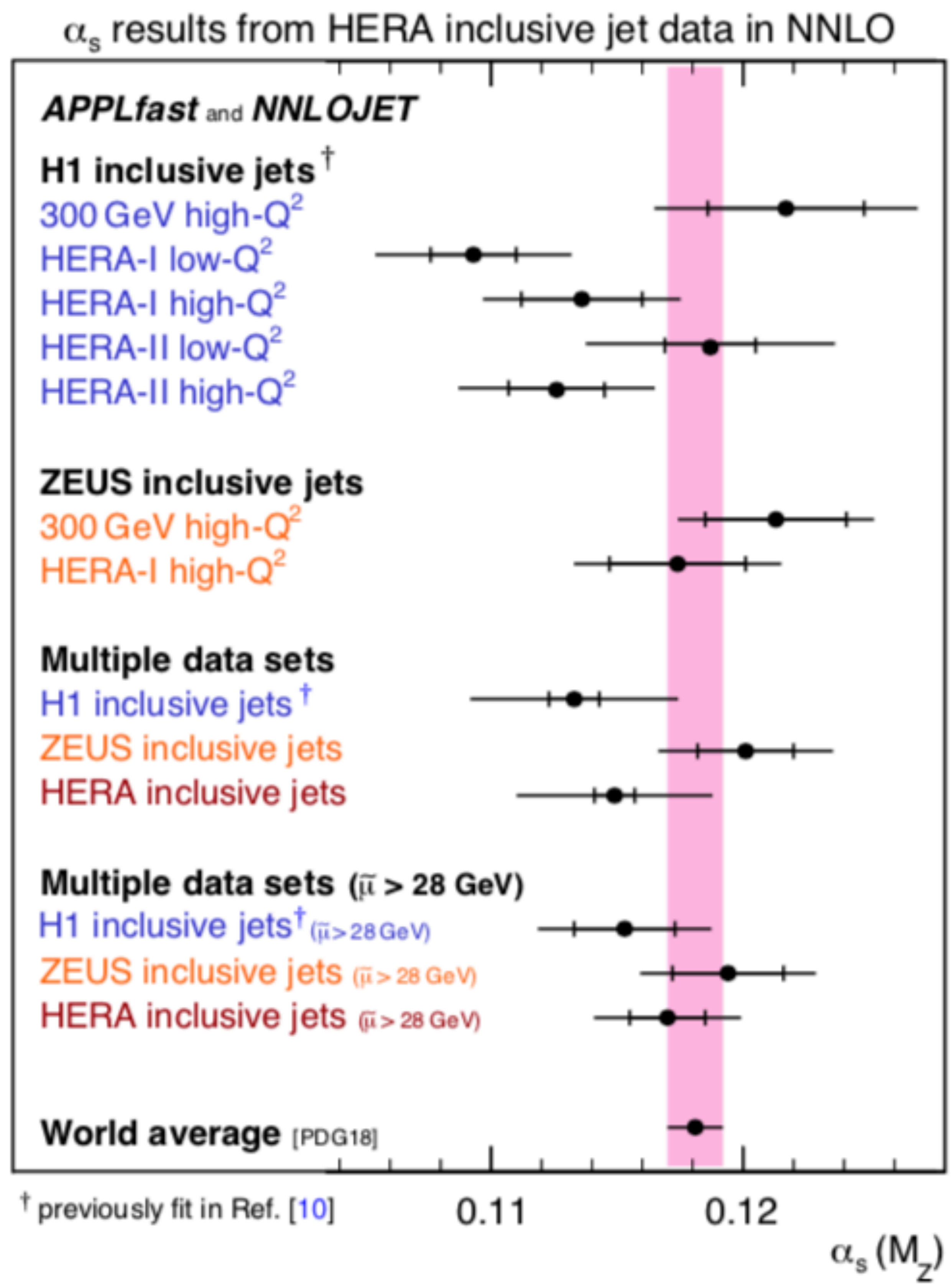




Extraction of α_s from HERA data

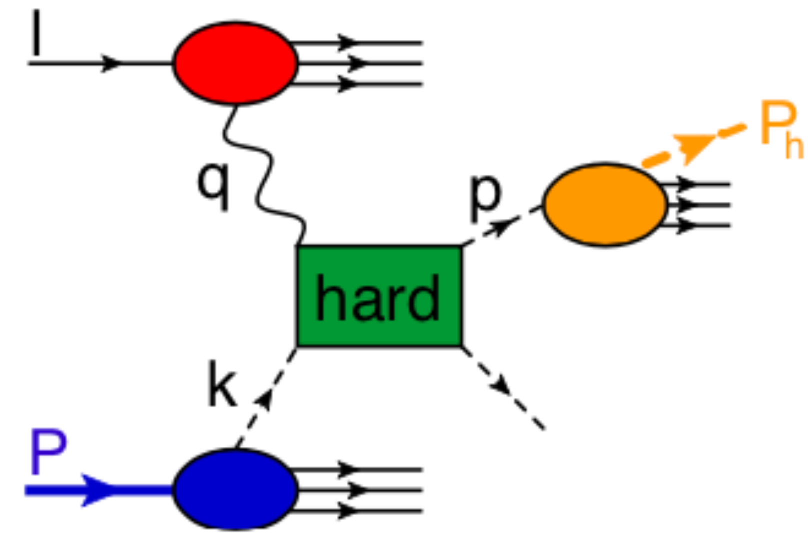
- Demonstration for APPLfast project
  Britzger et al (2019)
  - uses perturbative input from NNLO (NNLOJET) to produce interpolation tables for a posteriori PDF analyses



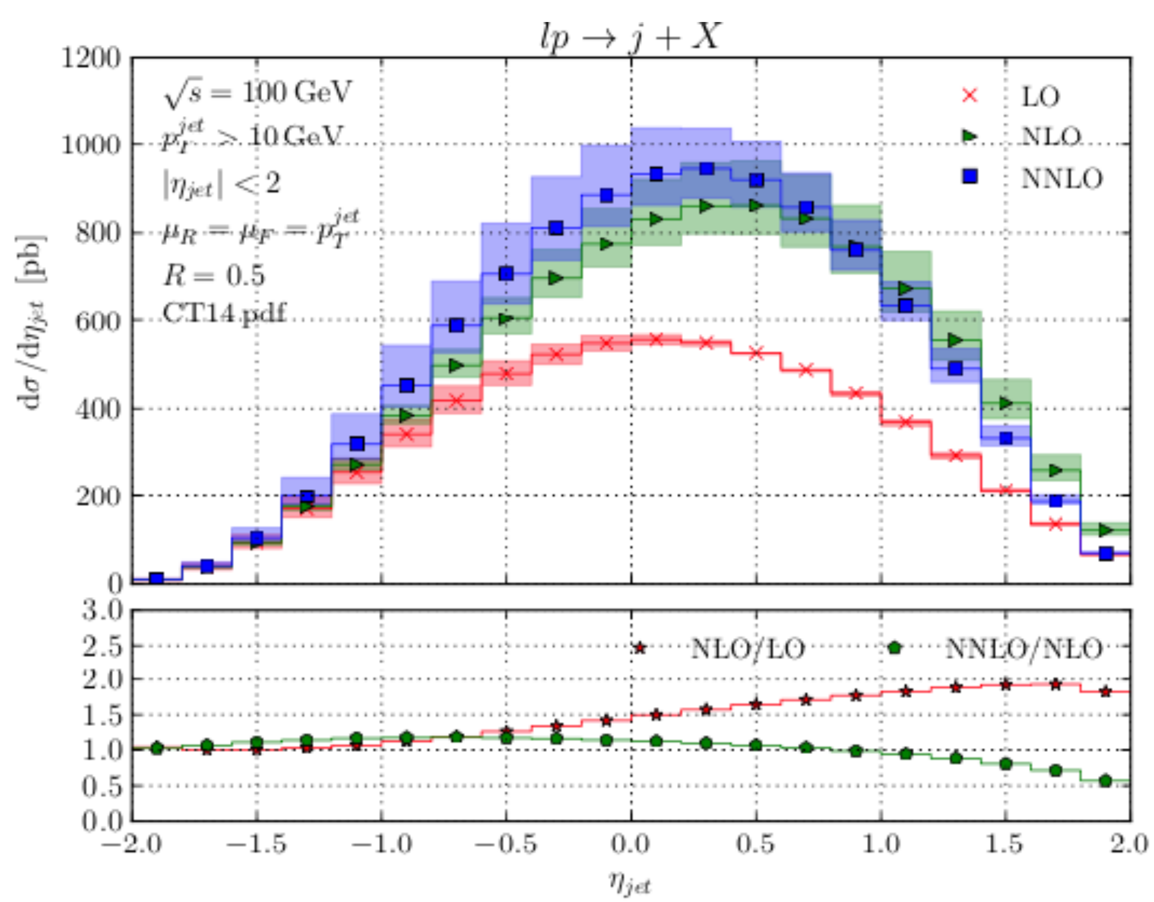


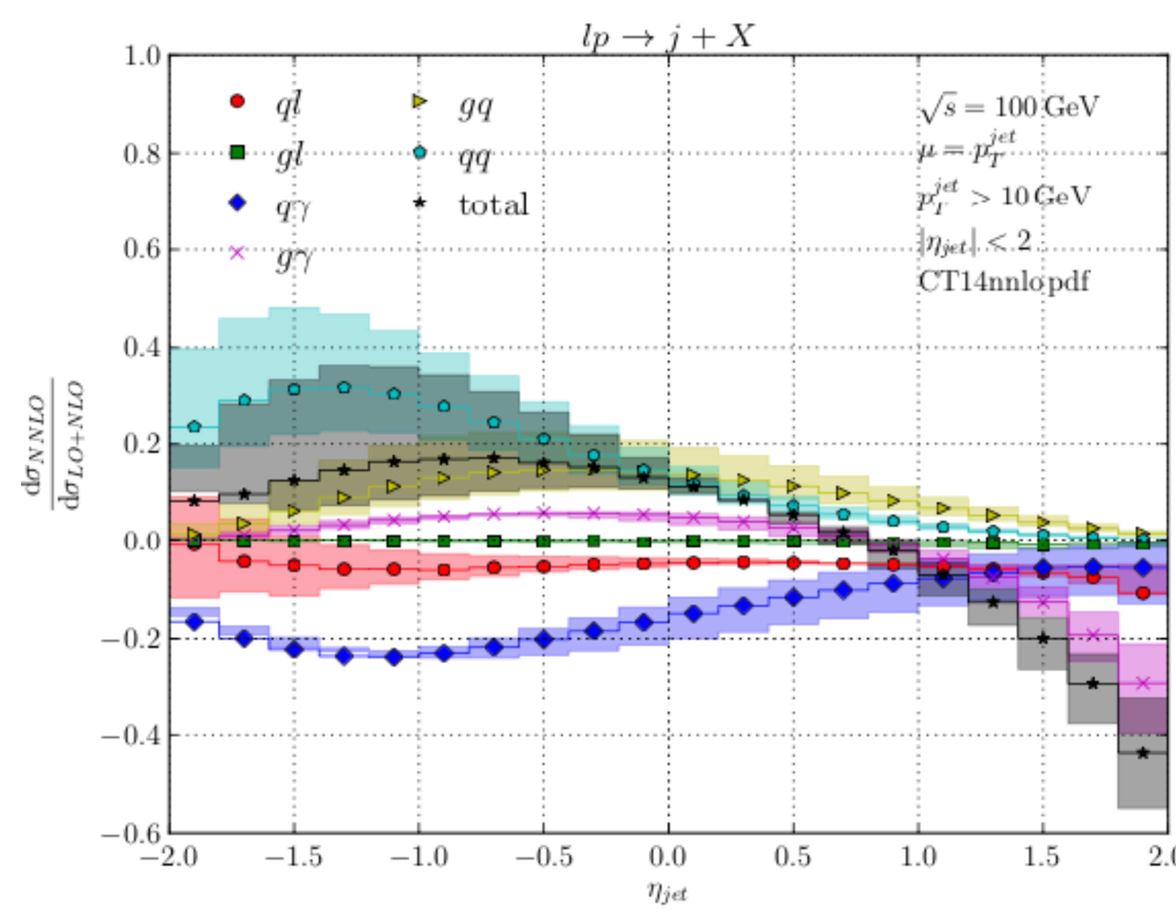
Single-inclusive production at an EIC

- Need predictions for single-inclusive hadron production: no lepton observed.
- However, when inclusive of the lepton, must also account for configurations resulting from quasi-real photon (lepton travels down the beam pipe).
    - can capture through Weizsacker-Williams approach (lepton structure function) **Hinderer, Schlegel, Vogelsang (2015)**
- Recently used to compute NNLO predictions for EIC



Abelof, Boughezal, Liu, Petriello (2016)





Summary

- Perturbation theory at NLO a workhorse of the LHC.
- Many calculations at NNLO (even N^3LO) have emerged over the last 5-10 years that are suited to precision studies:
  - describe data over a wider kinematic range;
  - exhibit uncertainties smaller than, or at least competitive with, data.
- Turning complex calculations into tools for data analysis still a challenge
  - new tools making better use of CPU resources, interpolation techniques
- Some attention from the LHC precision community turning to topics closer to EIC
  - variety of calculations for DIS in particular

- Areas ripe for cross-fertilization:
  - inclusion of higher-order corrections in Monte Carlo tools
  - extraction of PDFs at higher perturbative orders, “ultimate” LHC precision
  - understanding remaining non-perturbative effects, e.g. in event shapes