Frontiers of perturbative QCD

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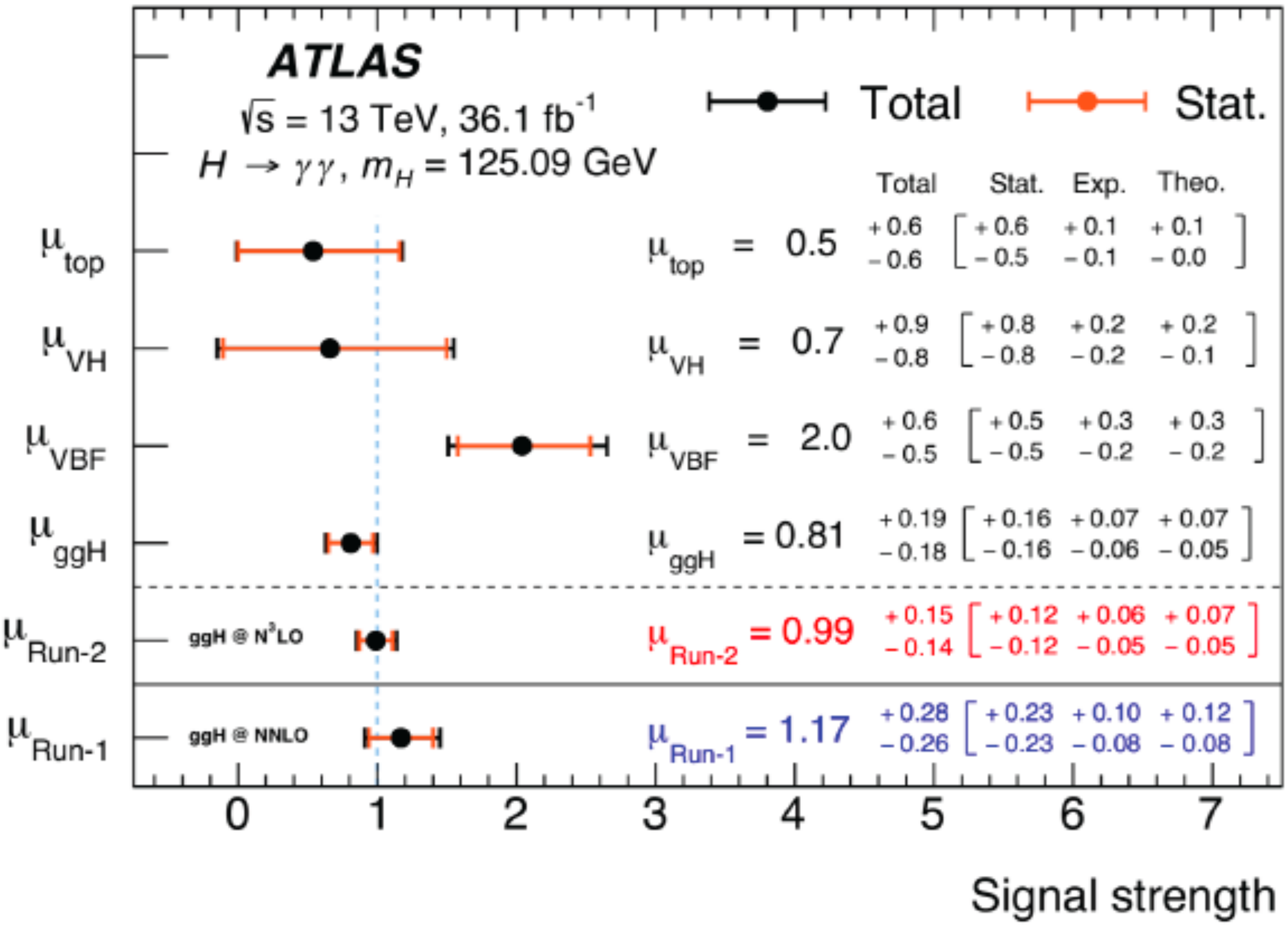
Outline

- The why: why do we need perturbative QCD and what have we learned from it so far in the LHC era?
- The how: review of the theoretical framework
- The details:
  - Precision jet cross sections and future directions in higher-order calculations
  - Advances in PDFs: theory uncertainties and lattice input
  - Logarithmic accuracy of parton shower simulations
  - SMEFT and global fitting of precision LHC data

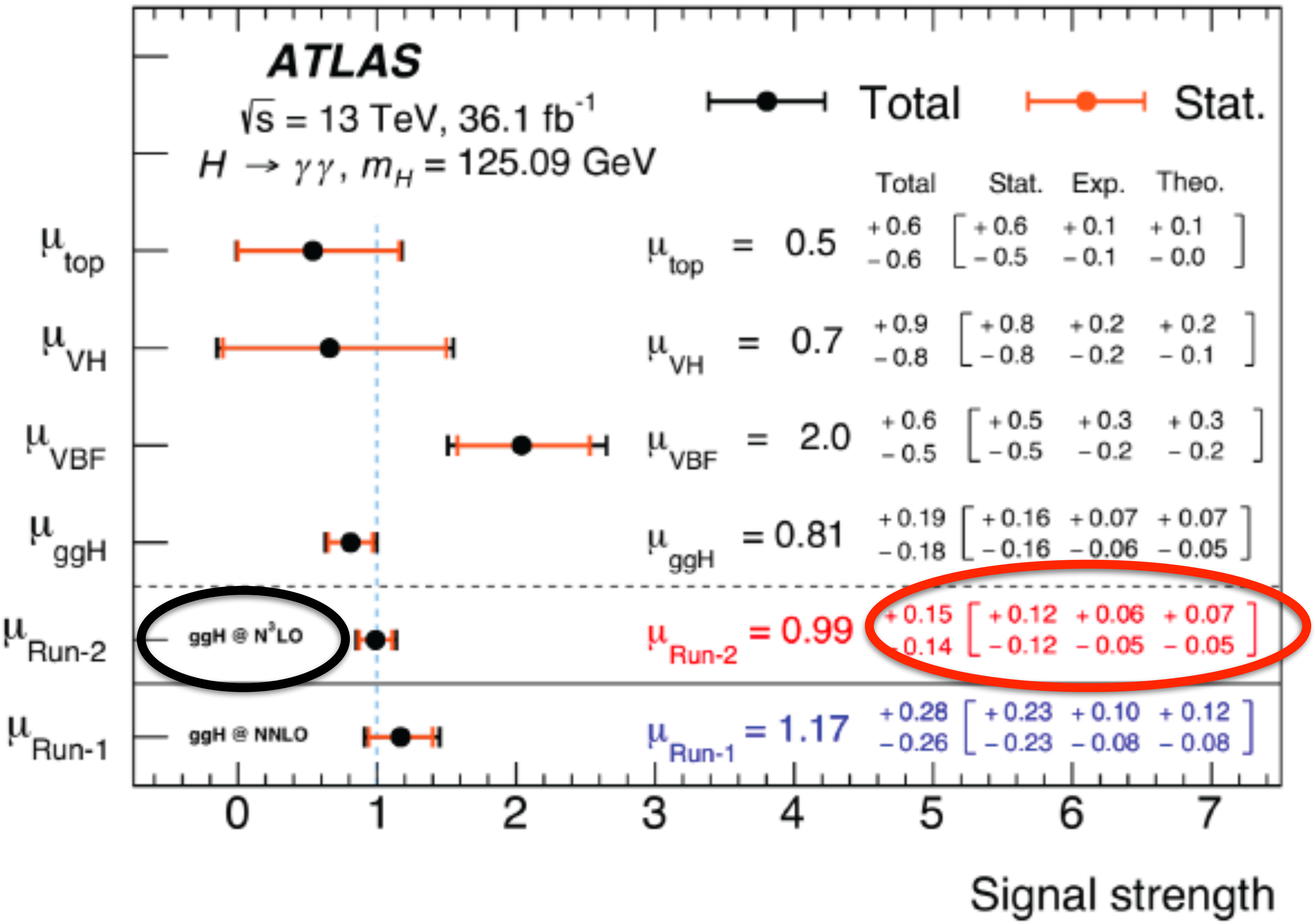
Focus on results from last two years; apologies for omissions!

Why pQCD?



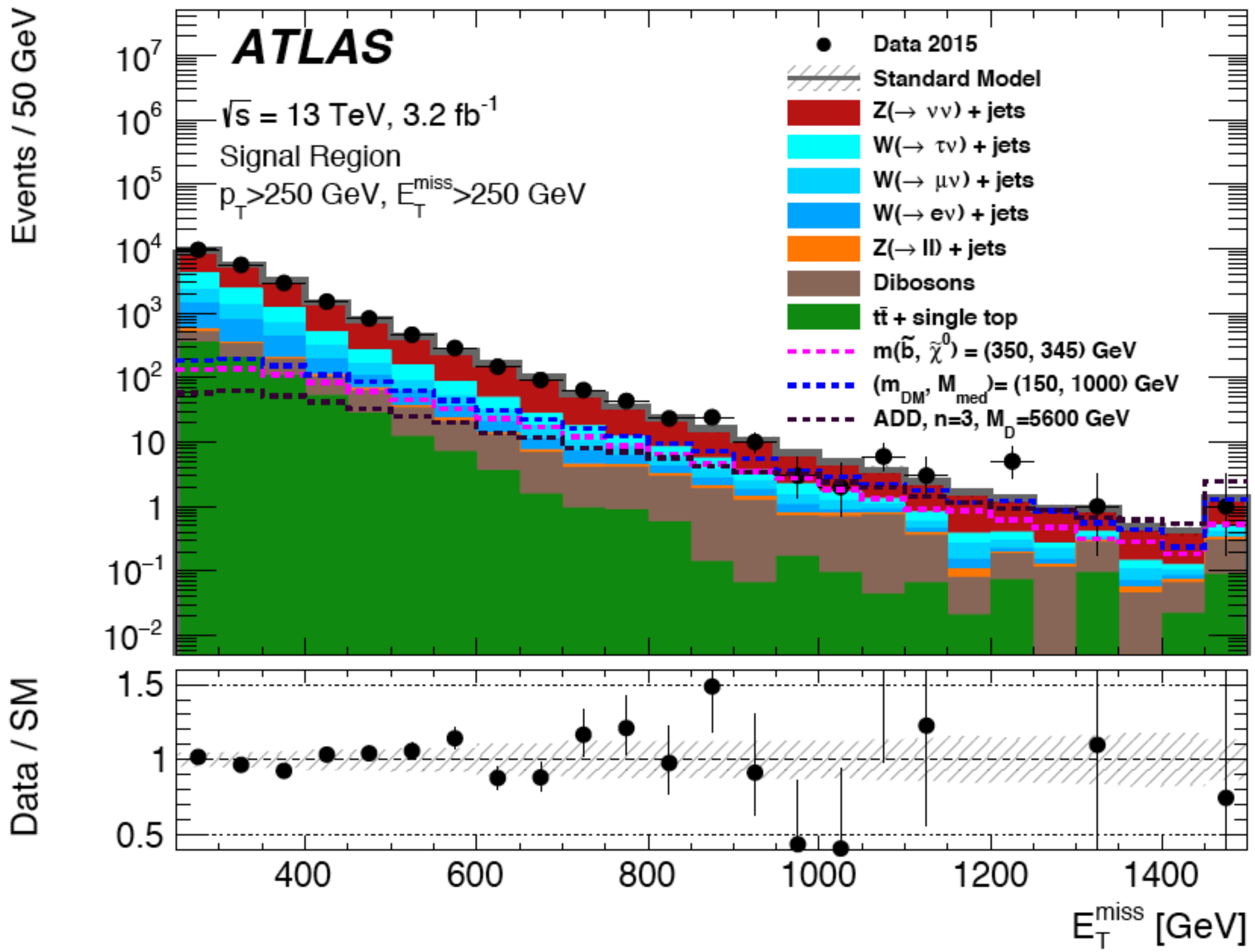
Indispensable in understanding measurements at the LHC and whether they agree with the Standard Model. Poised to become more so with higher integrated luminosity

Why pQCD?



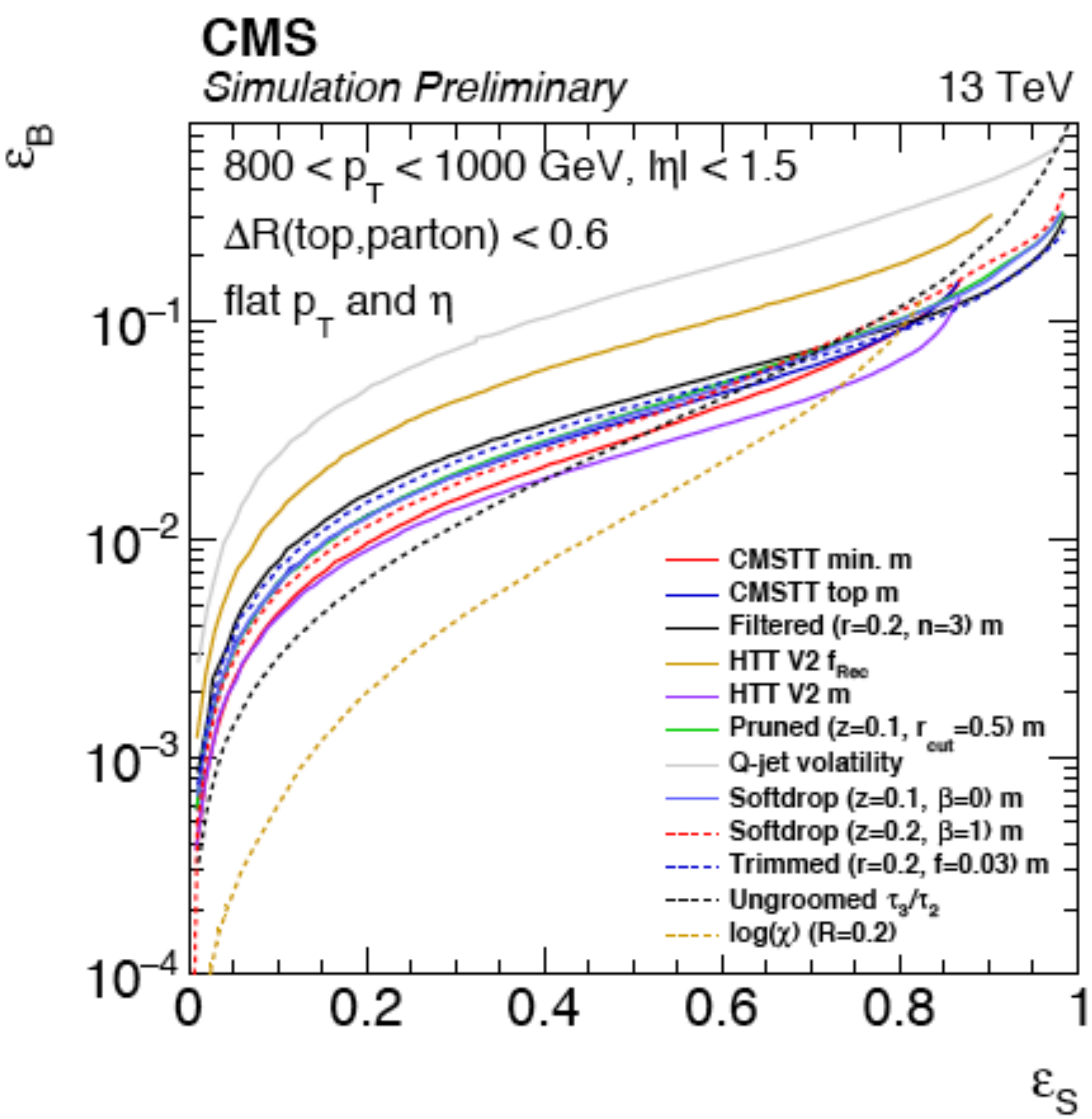
Even with N^{3}LO pQCD prediction (Anastasiou et al. 1602.00695) theory uncertainties substantial!

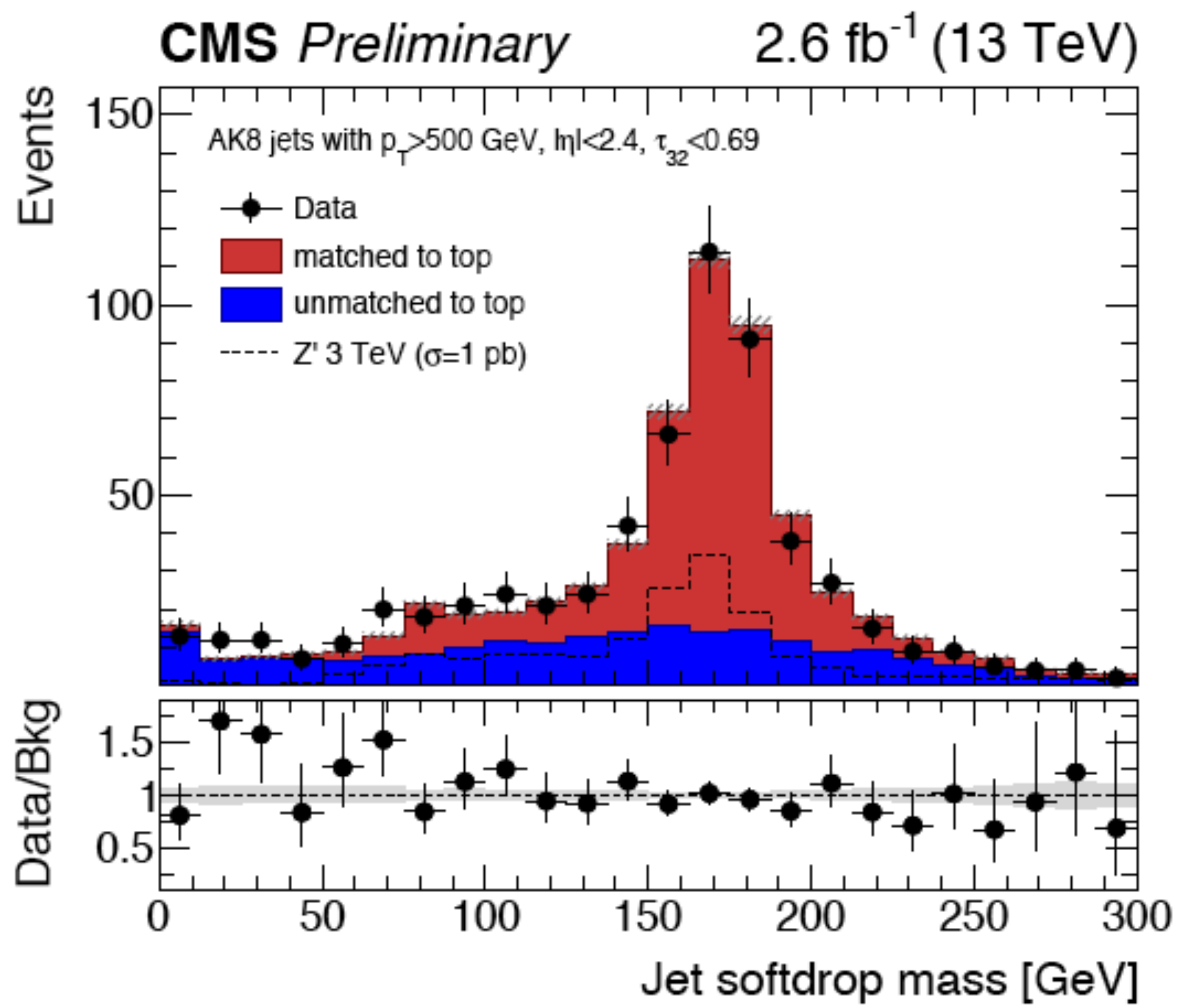
Why pQCD?



QCD tools needed to understand sometimes subtle kinematic differences between background and signal in BSM searches

Why pQCD?

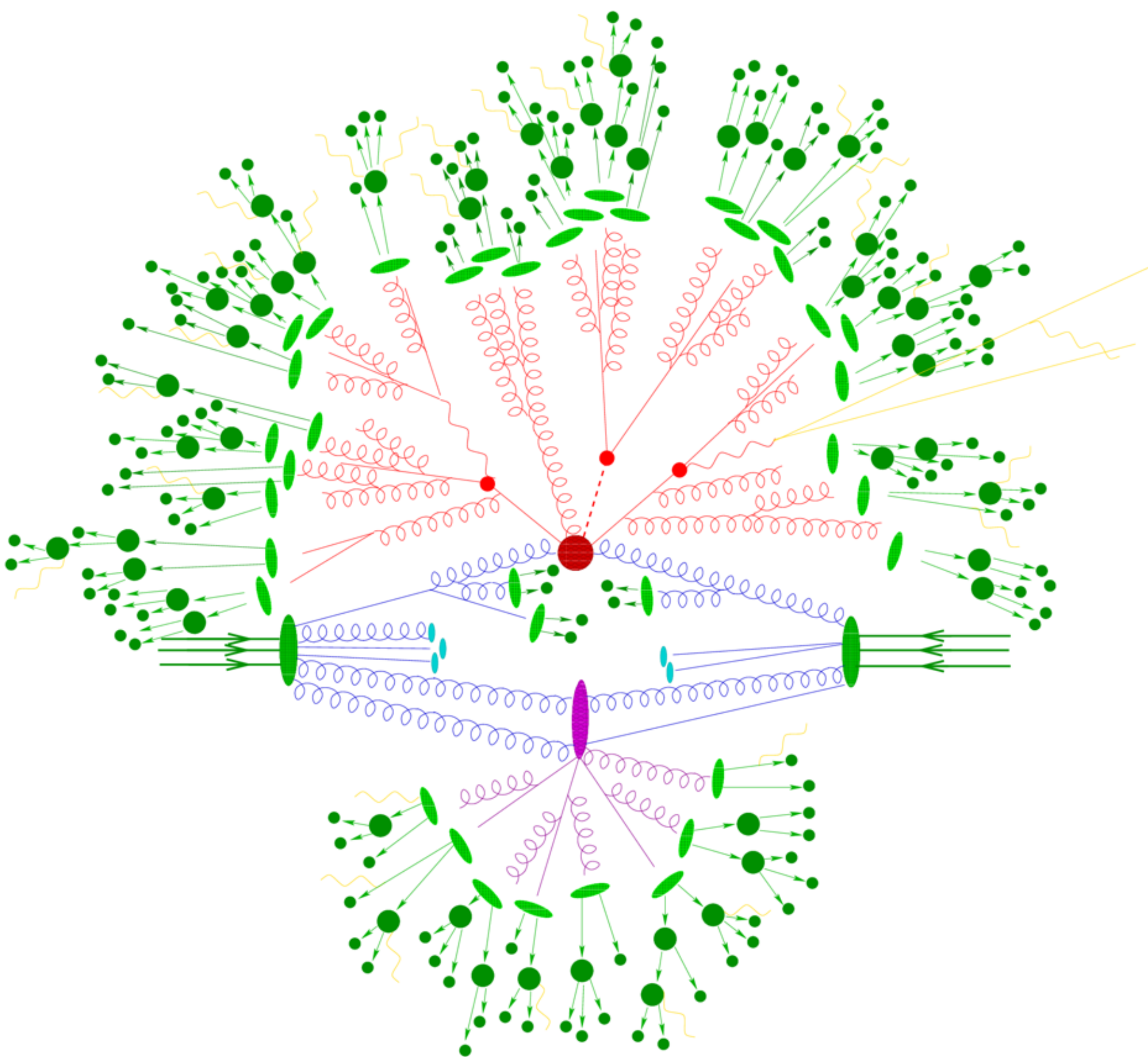


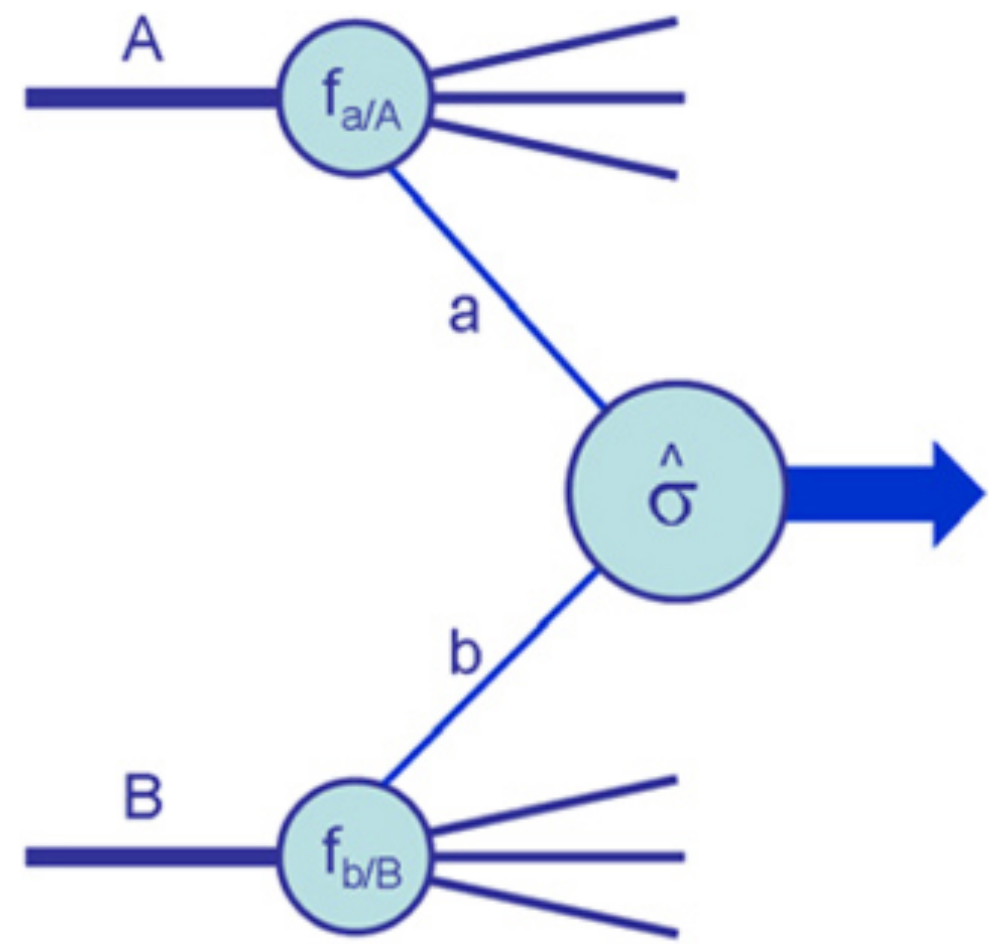


New ideas: Understanding of QCD has led to new tools to search for physics beyond the SM, such as jet substructure

Structure of QCD at the LHC

Key principle: factorization of long and short distance physics





Structure of QCD at the LHC

Key principle: factorization of long and short distance physics

long distance: 1/GeV | short distance: 1/TeV

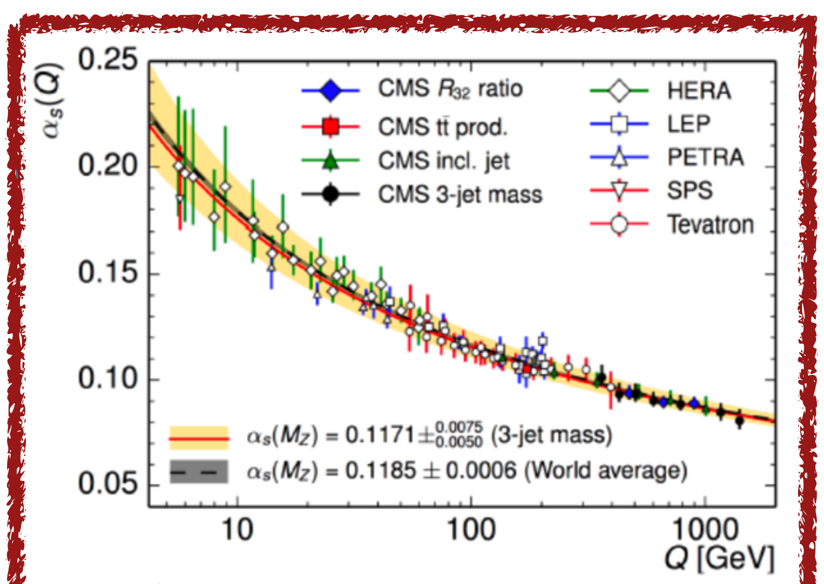
$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\hat{\sigma}_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

measure → $\sigma_{h_1 h_2 \to X}$

extract from data → PDFs

calculate → partonic cross section

small for many LHC observables → power corrections



Asymptotic freedom →

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

LO predictions | NLO corrections | NNLO corrections | NNNLO corrections

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QCD prediction checklist:

- ☑ Partonic cross section to high enough order in α_S
- ☑ Parton distribution functions
- ☑ The value of α_S
- ☑ For some measurements, parton showers to tie together the hard interaction scale and hadronization at Λ_{QCD}

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Covered here

- ☑ Partonic cross section to high enough order in α_S
- ☑ Parton distribution functions
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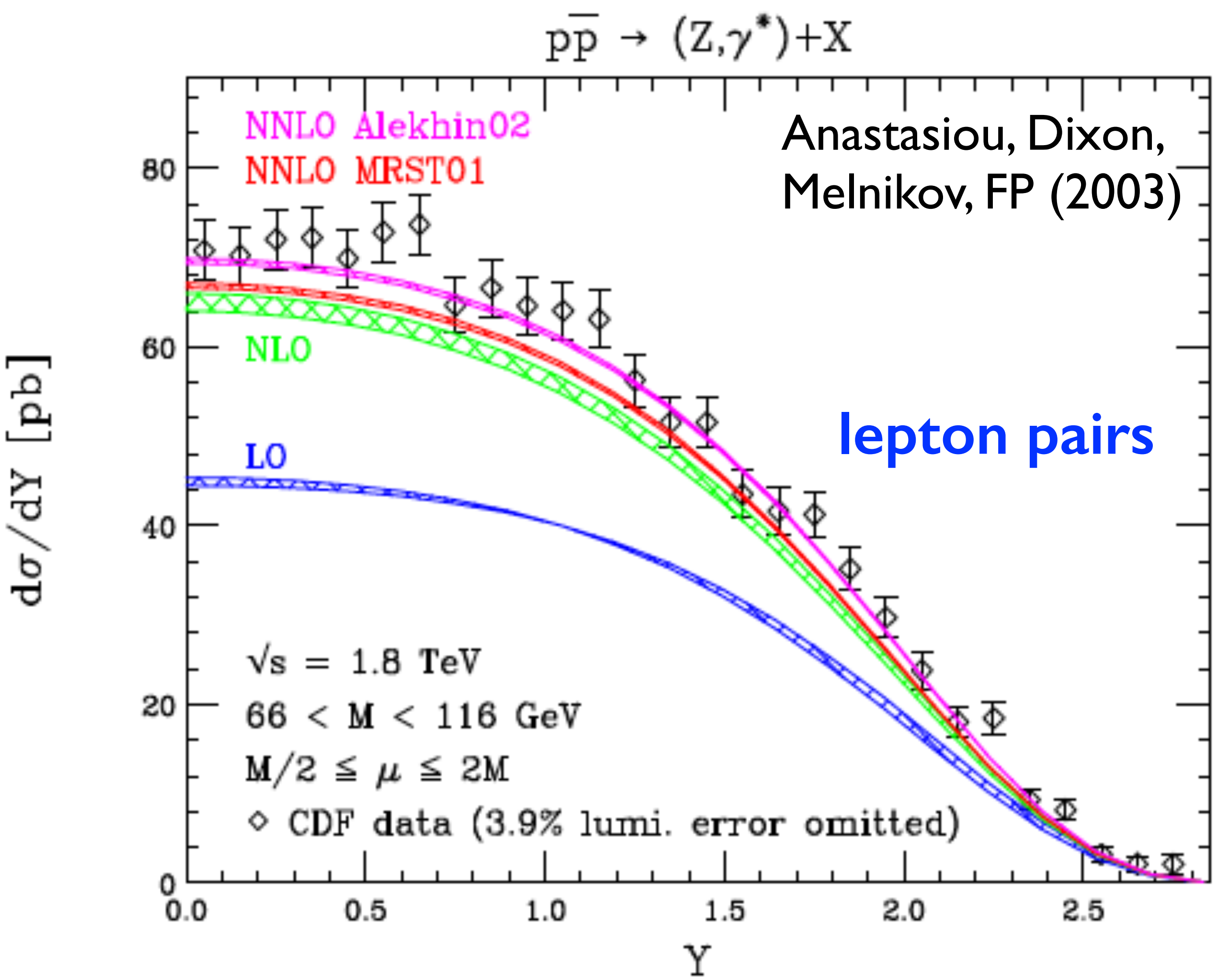
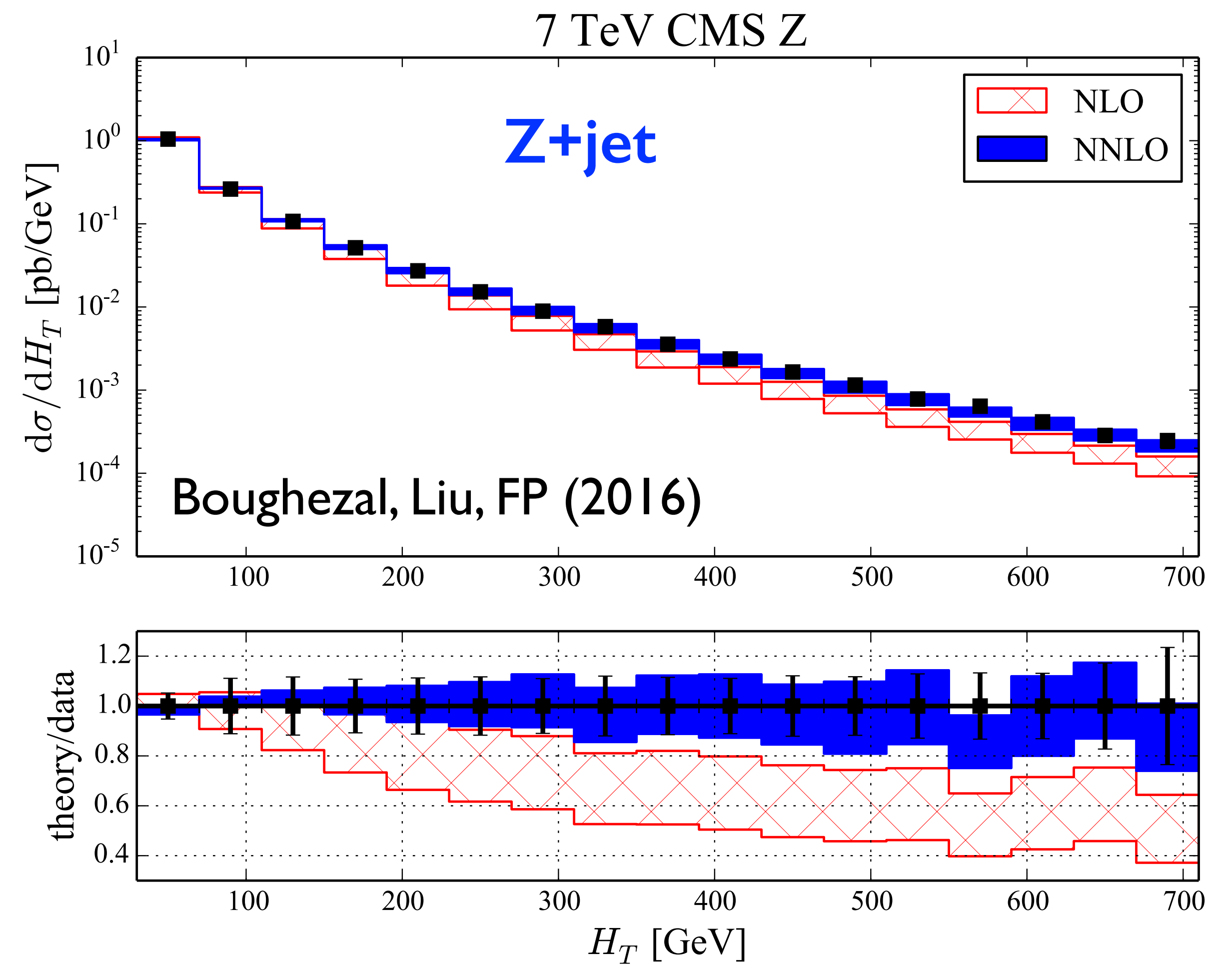
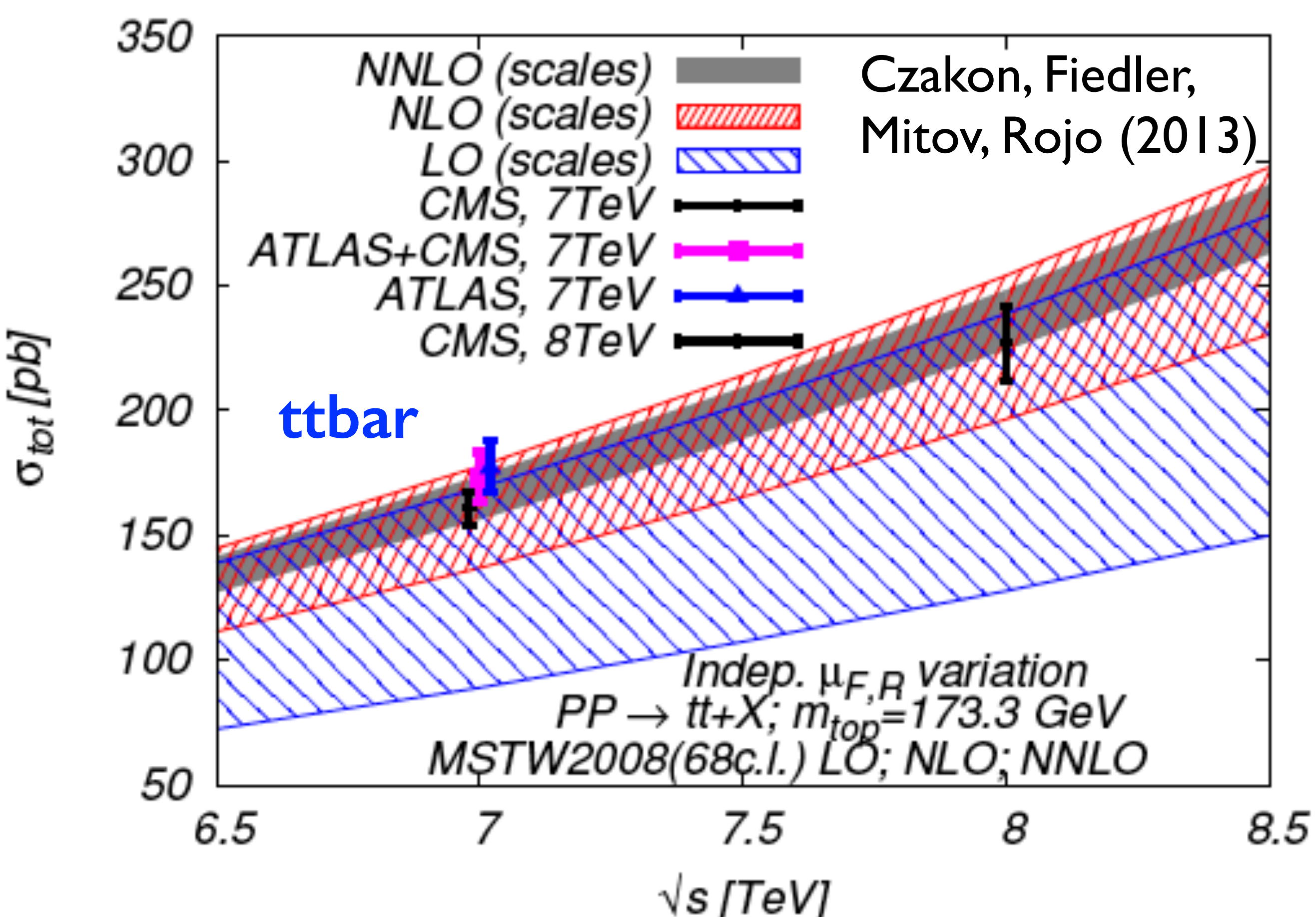
- ☑ For some measurements, parton showers to tie together the hard interaction scale and hadronization at Λ_{QCD}

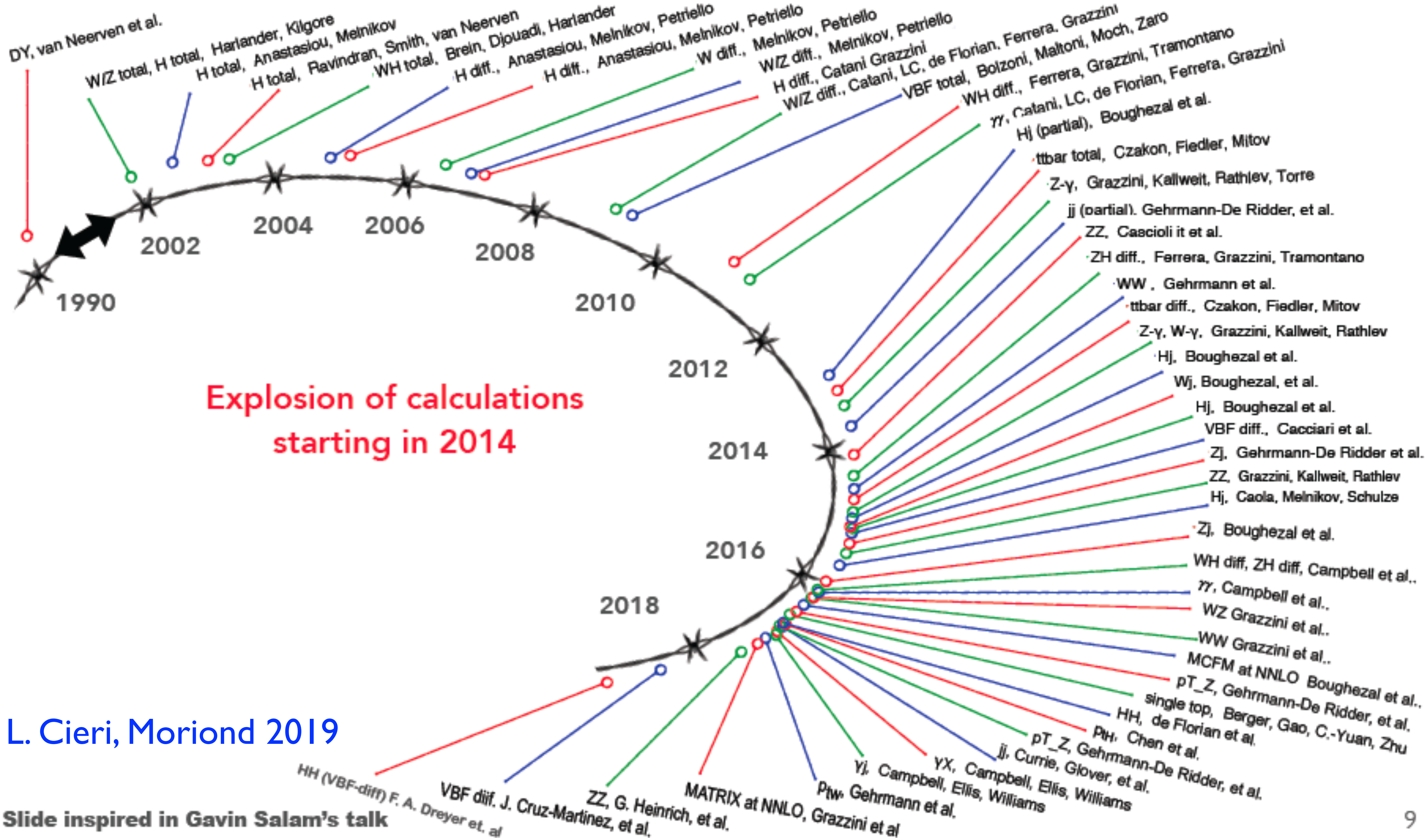






Many examples show that:

LO: rough estimate only
NLO: first quantitative estimate
NNLO: needed for precision!



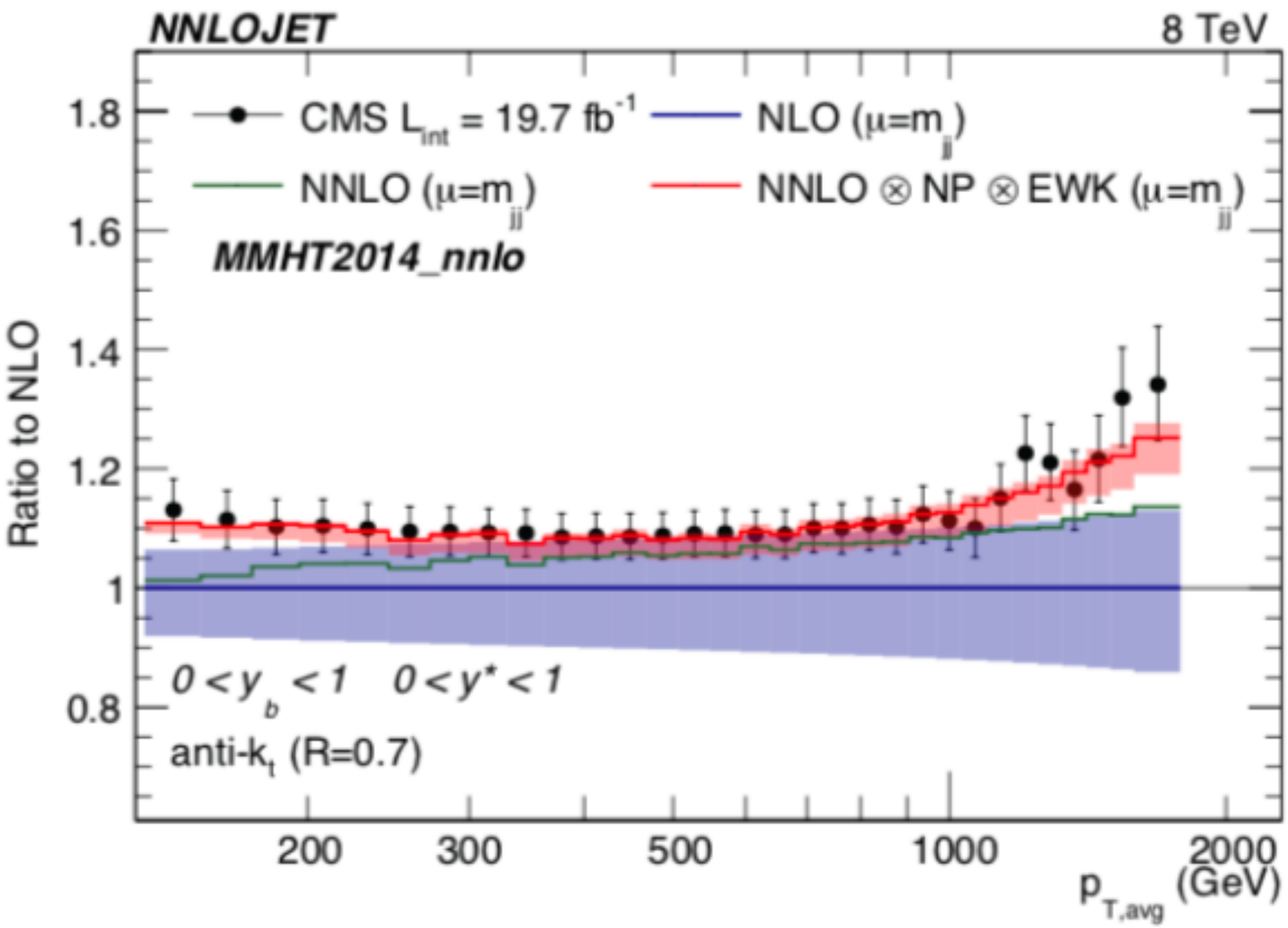
L. Cieri, Moriond 2019

Slide inspired in Gavin Salam's talk

Major recent themes: NNLO for 2→2, especially with final-state jets, and detailed comparisons to experimental data

Di-jet production

- Numerous applications: searches for new physics in the form of new resonances or contact interactions; measurements of α_s, high-x gluon



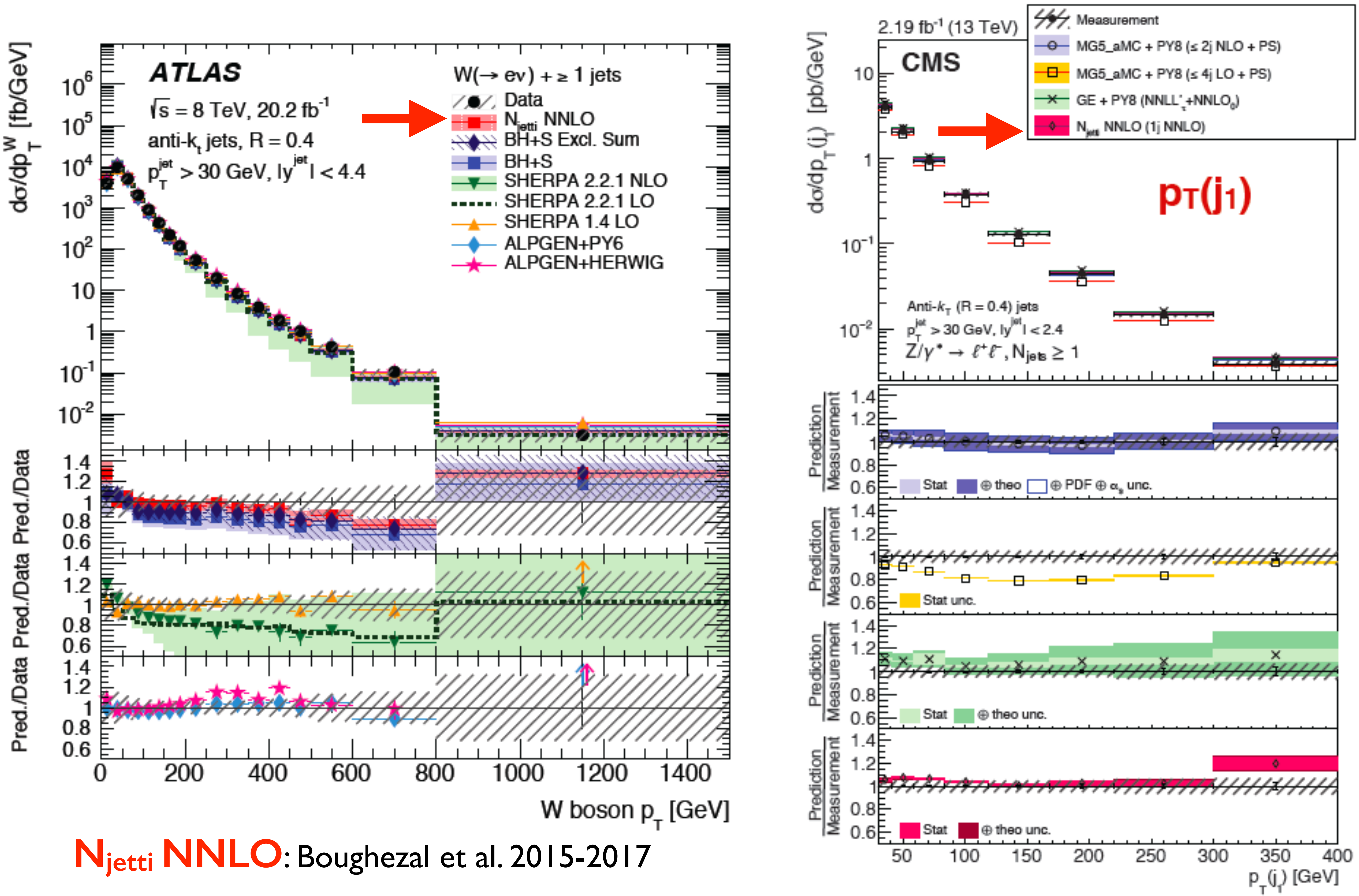
Gehrmann-De Ridder et al. 1905.09047

Large NNLO QCD corrections at high transverse momentum

Large electroweak corrections at high transverse momentum

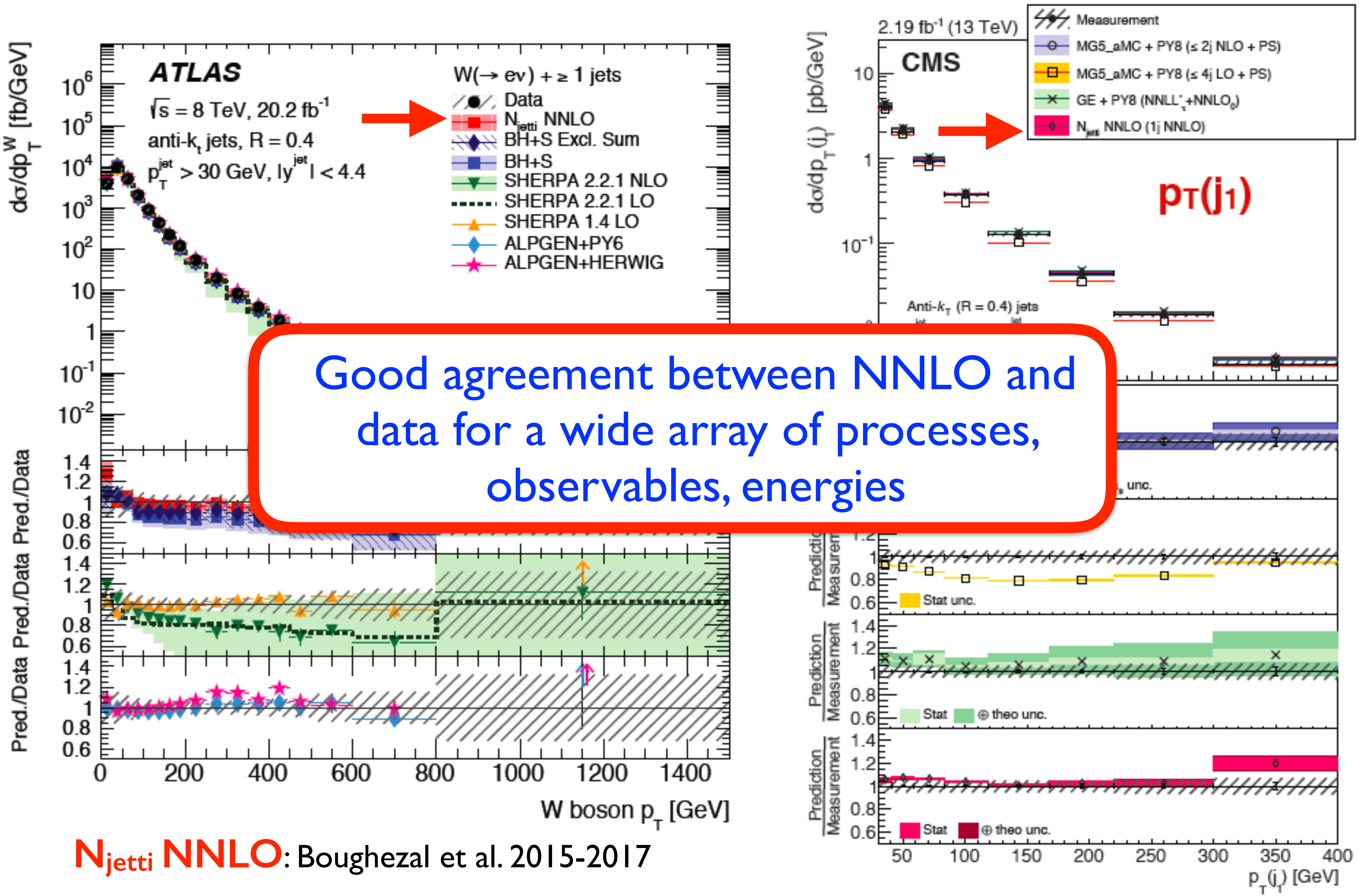
Markedly improved description of data when NNLO is included

V+jet production



N$_{jetti}$ NNLO: Boughezal et al. 2015-2017

V+jet production

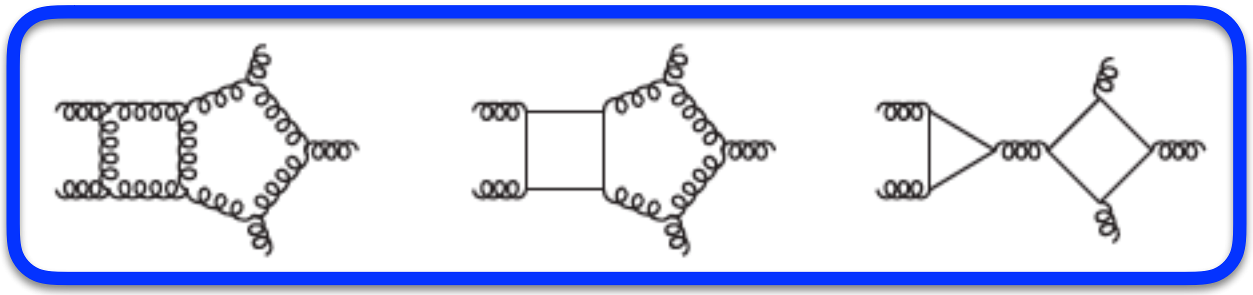


Good agreement between NNLO and data for a wide array of processes, observables, energies

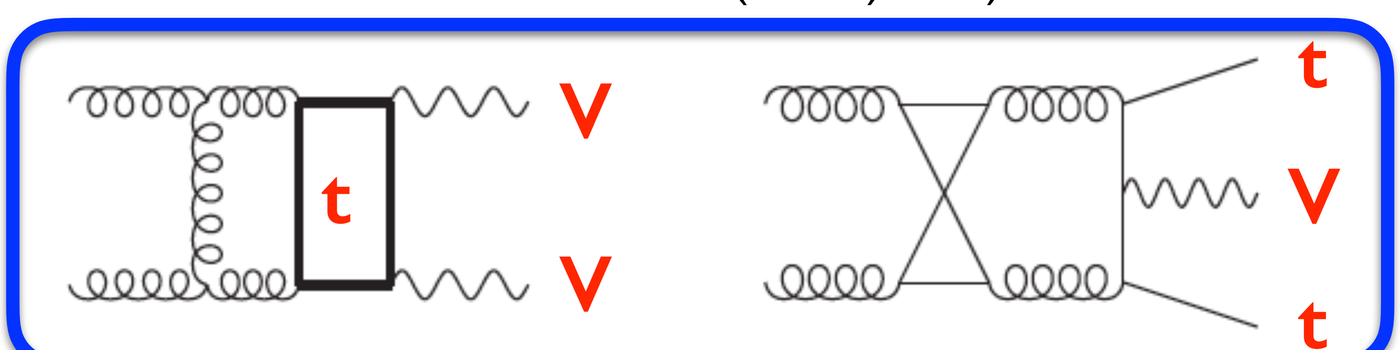
N_{jetti} NNLO: Boughezal et al. 2015-2017

Future directions at NNLO

- **Current topic**: 2-loop amplitudes for 2→3 processes. Currently an active subject of study, with initial results for 3-jet amplitudes appearing (Gehrmann, Henn, Lo Presti (2016); Badger, Bronnum-Hansen, Hartanto, Peraro (2017-2019); Abreu, Febres Cordero, Ita, Page, Zeng (2017-2019); Badger, Chicherin, Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zoia (2019); …)



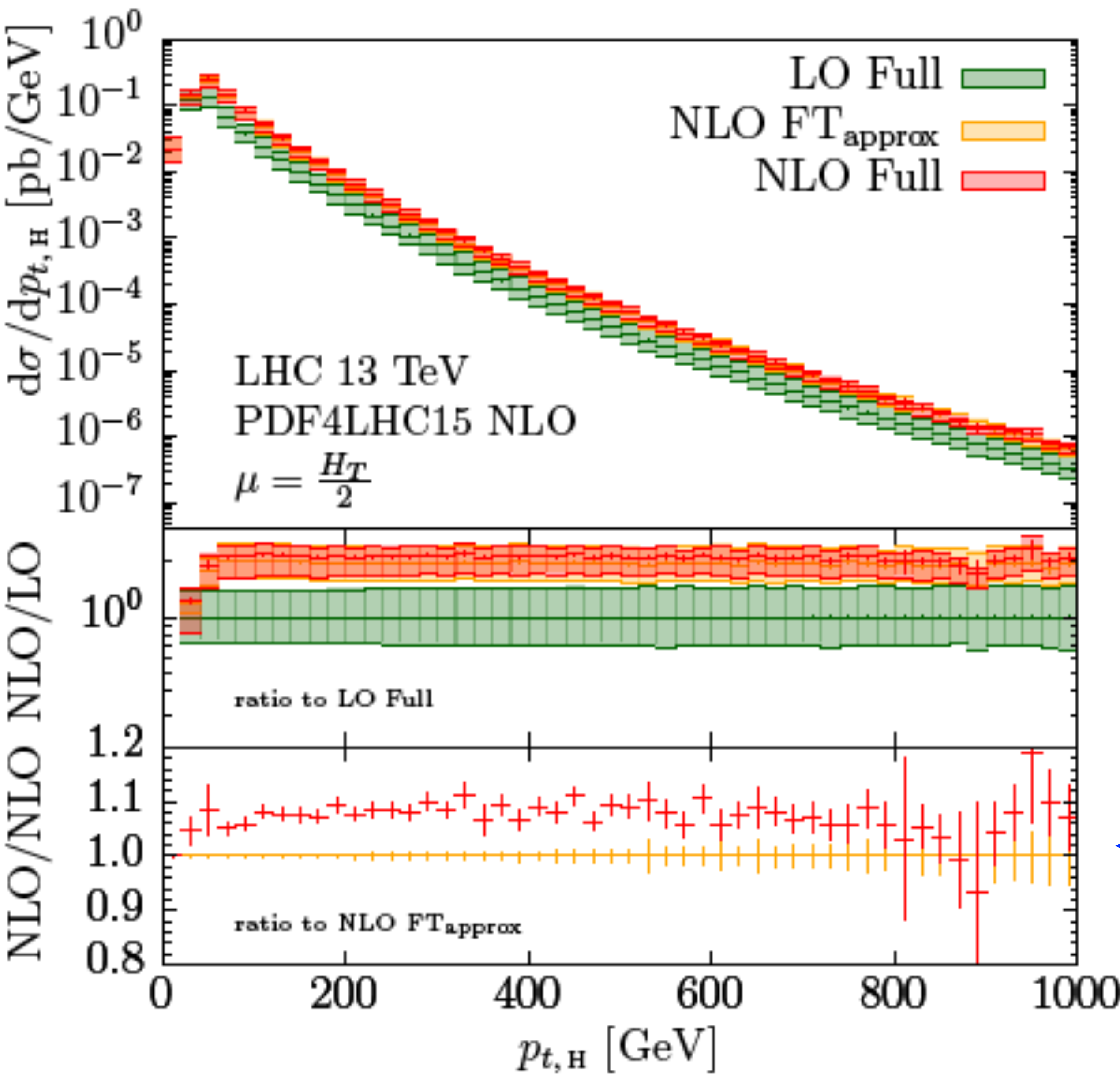
- **Current topic**: multi-scale 2-loop amplitudes with massive internal particles, relevant for Higgs, top, vector boson production. New mathematical structures beyond multiple polylogarithms appear (Remiddi, Tancredo (2016); Bonciani et al (2016); Weinzierl et al (2016-2019); Ablinger et al (2017); Broedel, Duhr, Dulat, Marzucca, Penante, Tancredi (2019); …)



Multi-scale 2-loop: Higgs p_T spectrum

- Critical to look for BSM effects in the Higgs sector, and to break coupling degeneracies that appear given only the total cross section:

$$\Delta\mathcal{L} = -c_t \frac{m_t}{v} + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v} G^a_{\mu\nu} G^{a,\mu\nu} \Rightarrow \frac{\sigma(c_t,\kappa_g)}{\sigma_{SM}} \approx (c_t+\kappa_g)^2$$



NLO for finite m_t now known

Jones, Kerner, Luisoni 1802.00349

Numerical evaluation of the necessary 2-loop integrals using sector decomposition

Binoth, Heinrich hep-ph/0004013

Previous best approximation got shape correct; exact NLO larger by 6-8%

Advances in PDFs

- Past few years have seen many updates to global PDF determinations

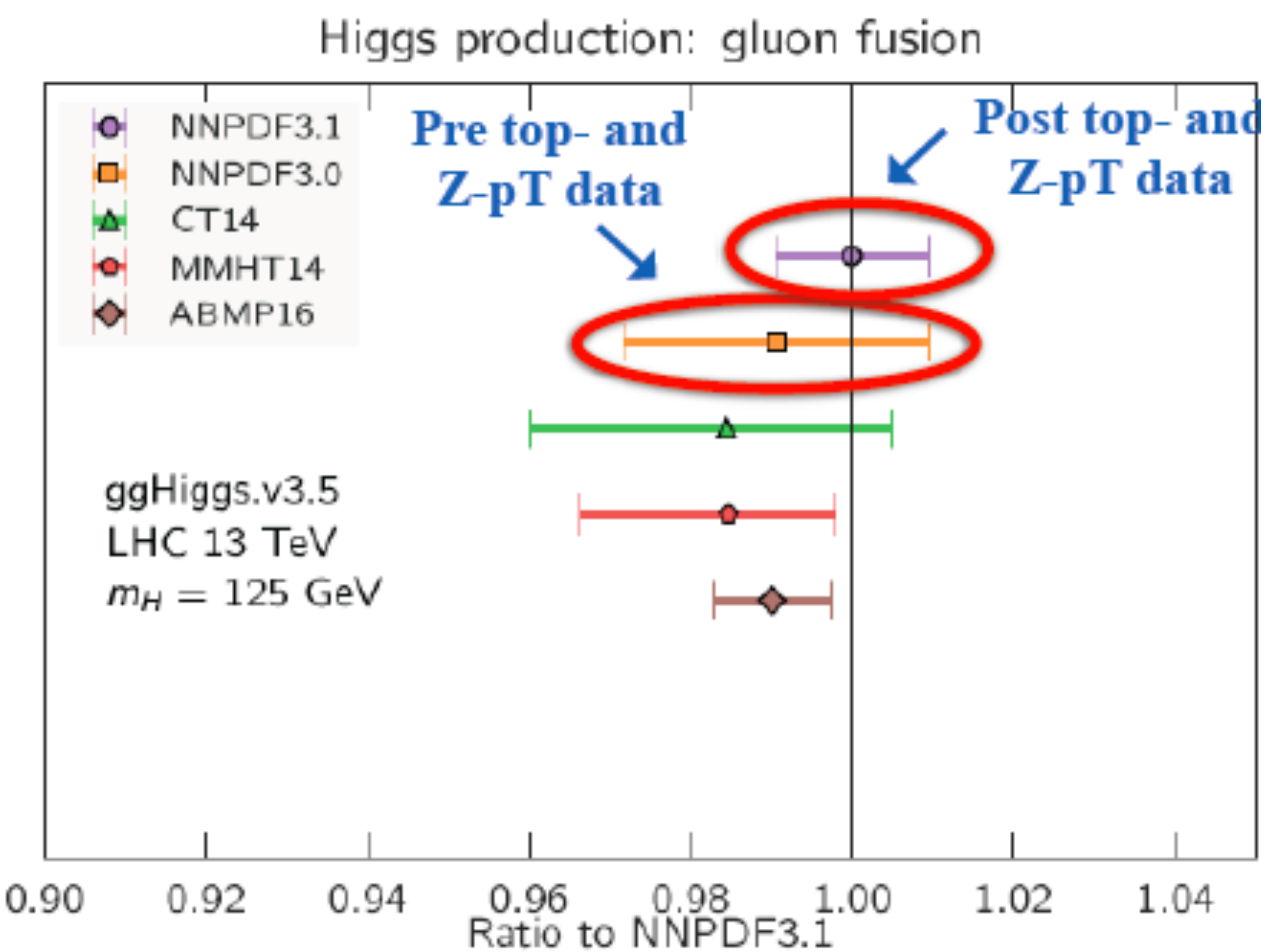
  ABMP: new W, Z, top data included; updated α_s=0.1145(9) (1701.05838)

  CTEQ: new technique to visualize impact of data sets in fits (1803.02777)

  MMHT: study of PDF sensitivity to jet production data (1711.05757)

  NNPDF: first time incorporating Z-p_T and top pair data (1706.00428)

  Additional studies on strangeness, charm; methodology improvements

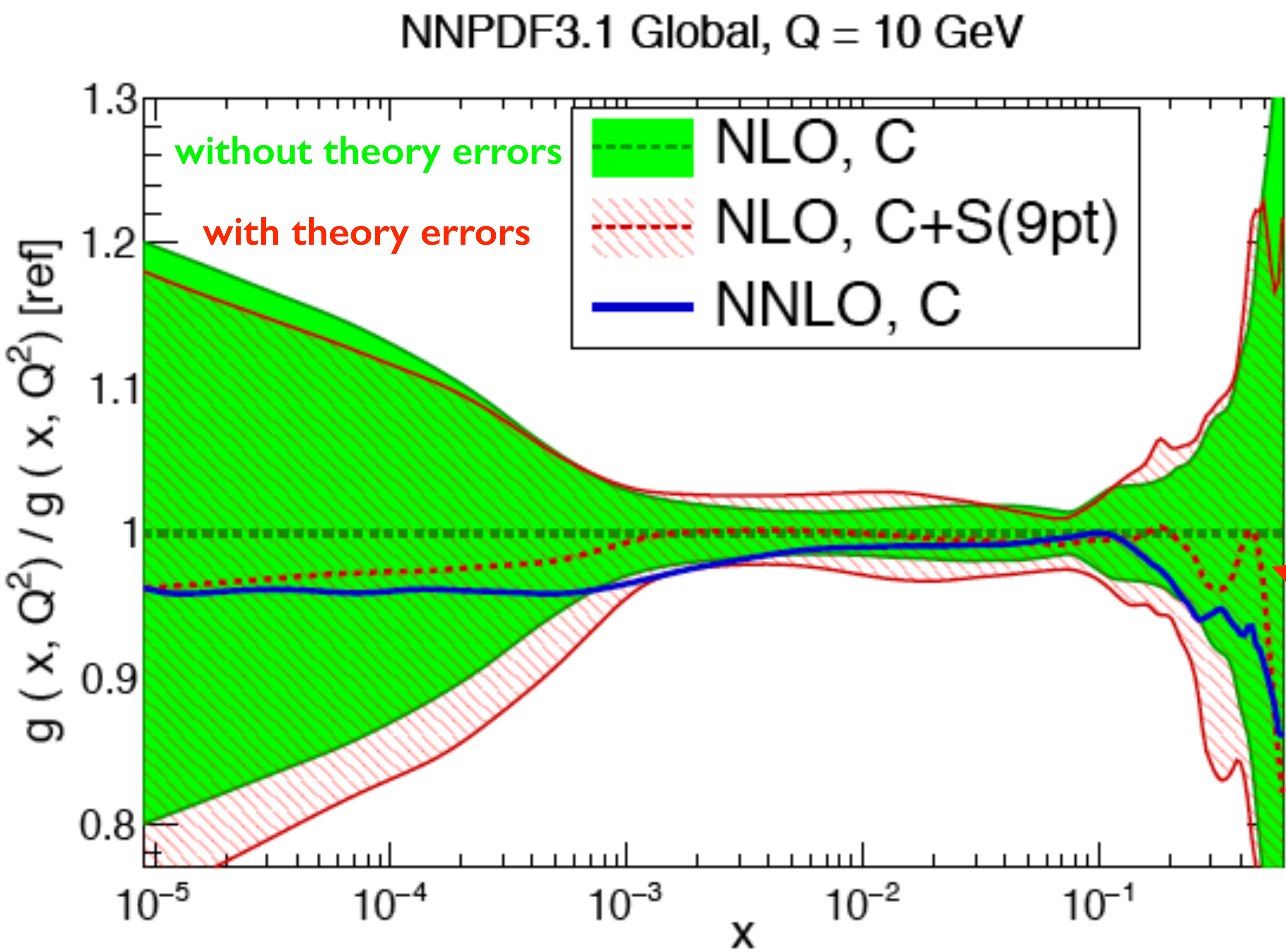


Good agreement between different fits with estimated uncertainties on ggH approaching one percent

Theory uncertainties in PDFs

- New: extend PDF uncertainties to include theoretical uncertainties from the underlying process from which they're fit, not just experimental errors

NNPDF 1905.04311, 1906.10698



NLO validation:

Only slight increase of PDF errors; theory errors relax some tensions between data sets

Central value moves closer to NNLO fit

Theory uncertainties in PDFs

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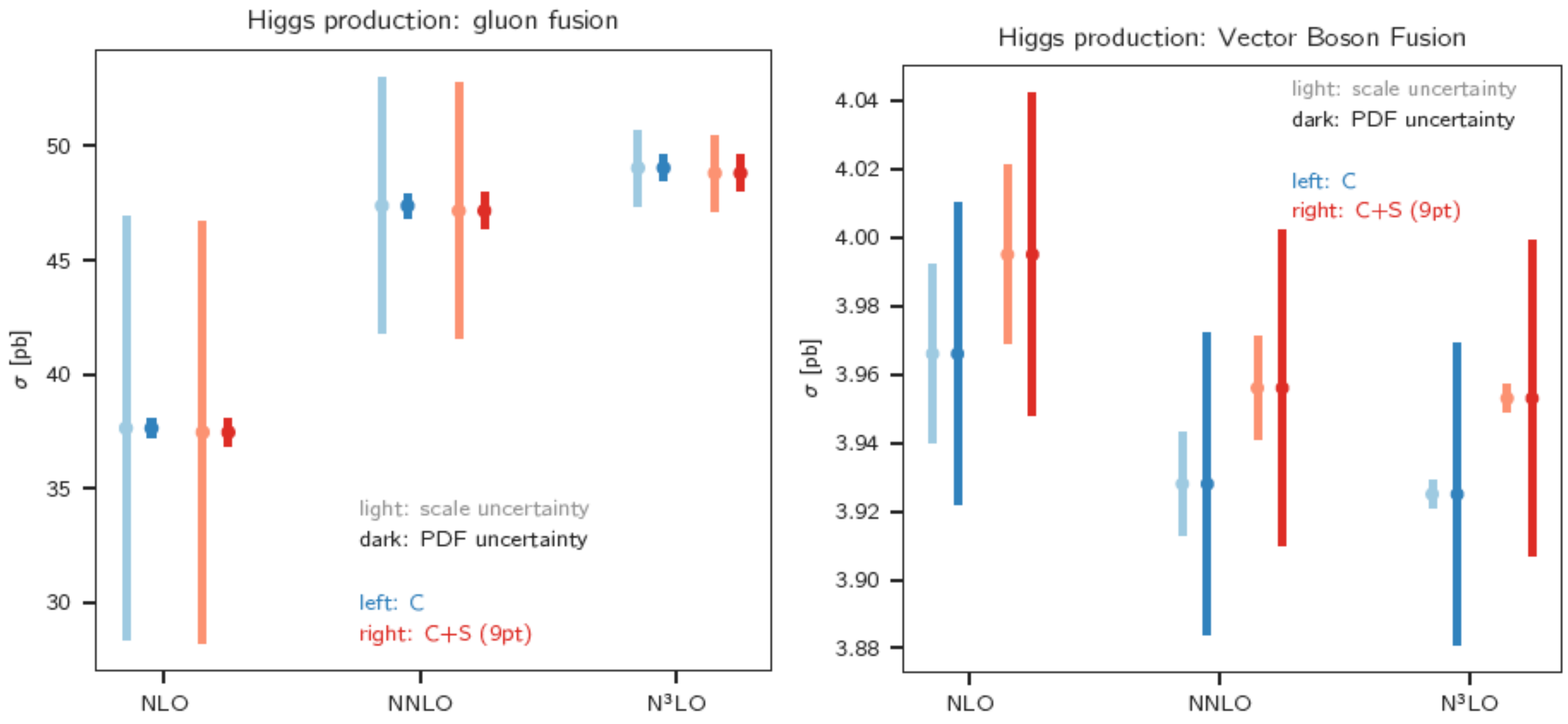
NNPDF 1905.04311, 1906.10698

Preliminary pheno implications:

ggH: few per-mille increase of PDF uncertainty, <1% cross section shift

VBF: PDF uncertainty almost unchanged, 1% upwards cross section shift



PDFs from lattice QCD

- **New idea**: x-dependent PDFs can be obtained directly from lattice QCD calculations using effective field theory to relate them to lattice-calculable quasi-PDFs or pseudo-PDFs (Ji 1305.1539; Radyushkin 1705.01488)

$$\widetilde{q}(x,\Lambda,p_z) = \int_{-1}^{1} \frac{dy}{|y|} Z\left(\frac{x}{y},\frac{\mu}{p_z},\frac{\Lambda}{p_z}\right)_{\mu^2=Q^2} q(y,Q^2) + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{p_z^2},\frac{M^2}{p_z^2}\right)$$

↑ quasi-PDF from lattice

↑ calculable matching coefficient

↑ regular PDF

Proof-of-principle lattice determinations exist (see Lin et al., 1711.07916 for a review)

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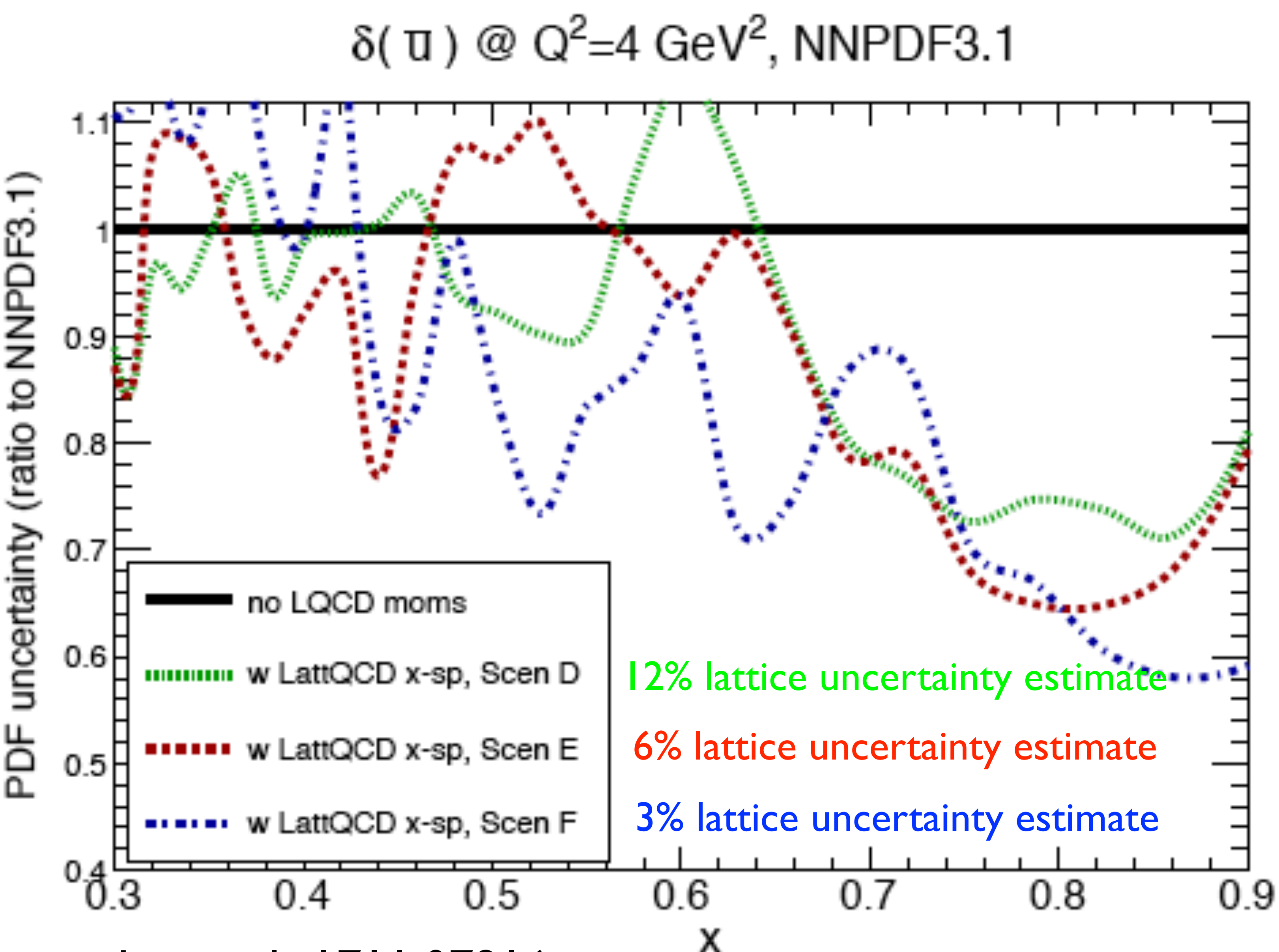


Lin et al., 1711.07916

Sea-quark uncertainties in the high-x region may be reduced by up to 40%; this region important for high-mass BSM searches

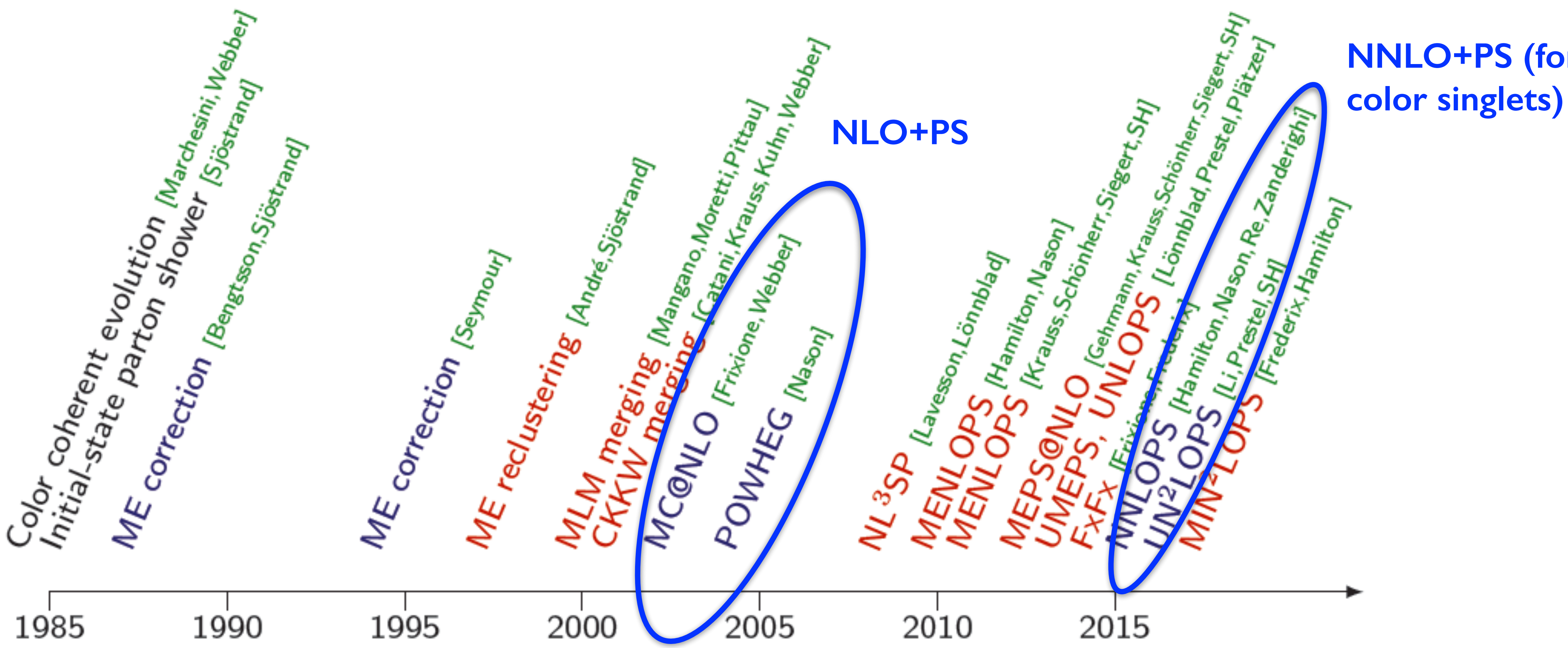
Stay tuned!

Progress on parton showers

- **Parton shower Monte Carlo event generators:** bridge the hard interaction and the Λ_{QCD}-scale hadronization, resum logs of disparate scales in a flexible way applicable to multiple observables

Merging related
Matching related

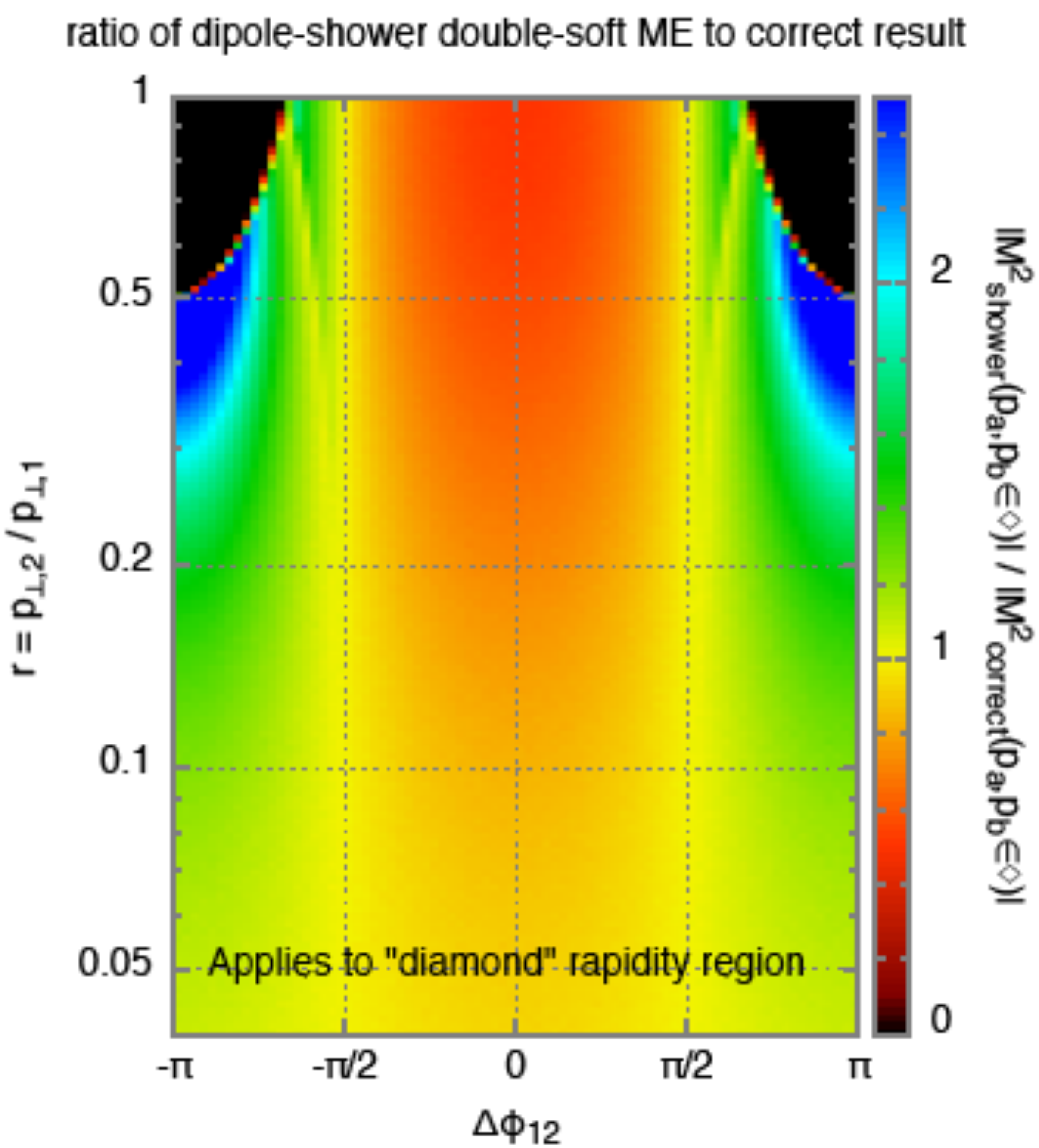
Past decade: improve description of hard interaction in parton showers through matching (more loops) or merging (more legs)



from S. Hoeche

Systematic study of shower accuracy

- **New:** a systematic framework to study the accuracy of the shower itself
  Dasgupta, Dreyer, Hamilton, Monni, Salam 1805.09327



Two criteria:

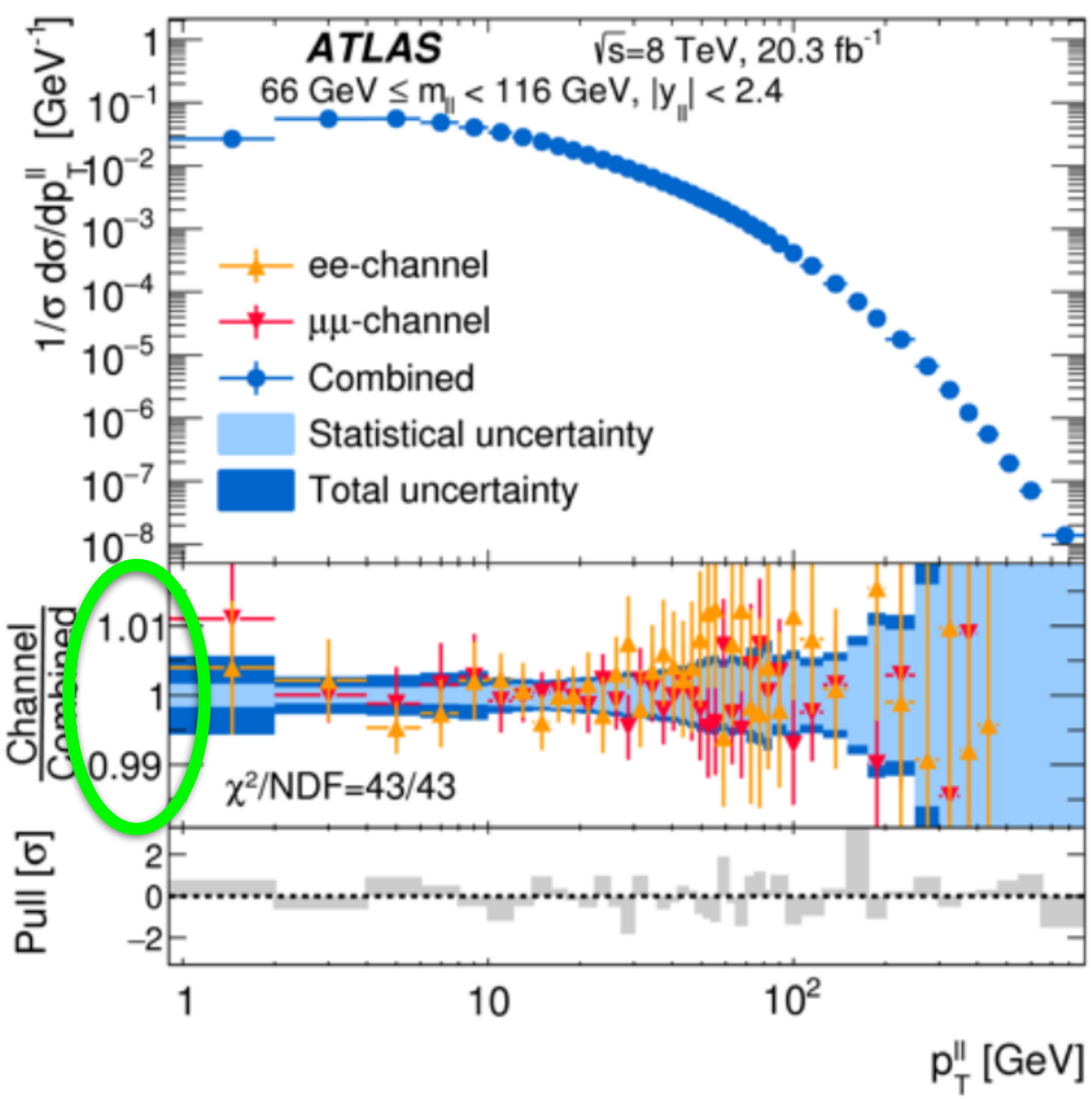
- Do they reproduce known singular limits of multi-parton amplitudes?
- Do they match known analytic logarithmic resummation formulae?

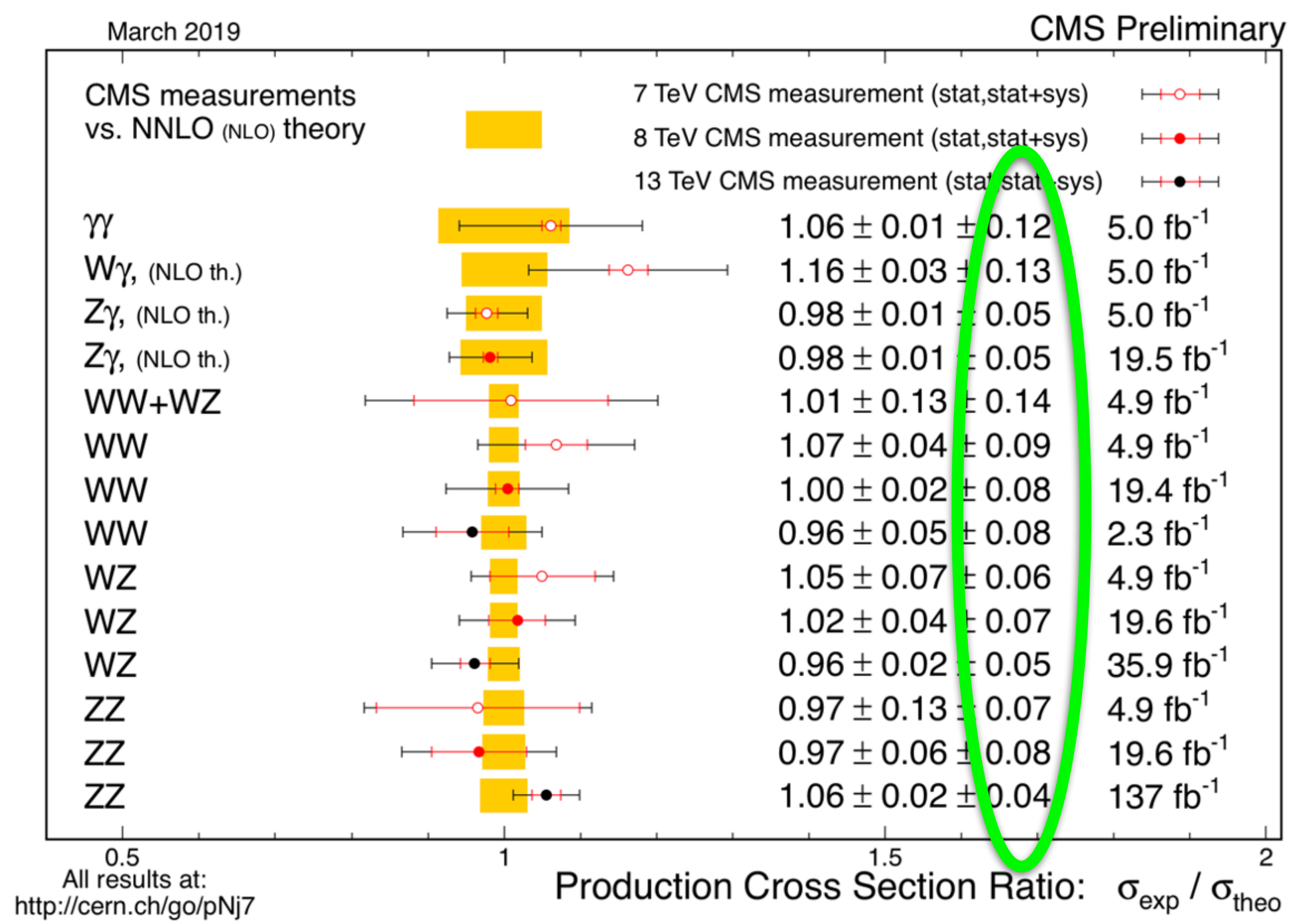
Example: at leading N_C, 100% mismatches in double-soft region for p_T-ordered showers (DIRE, PYTHIA); appears at NLL

Potential impact on precision measurements, jet substructure; stay tuned!

Future of precision QCD at the LHC

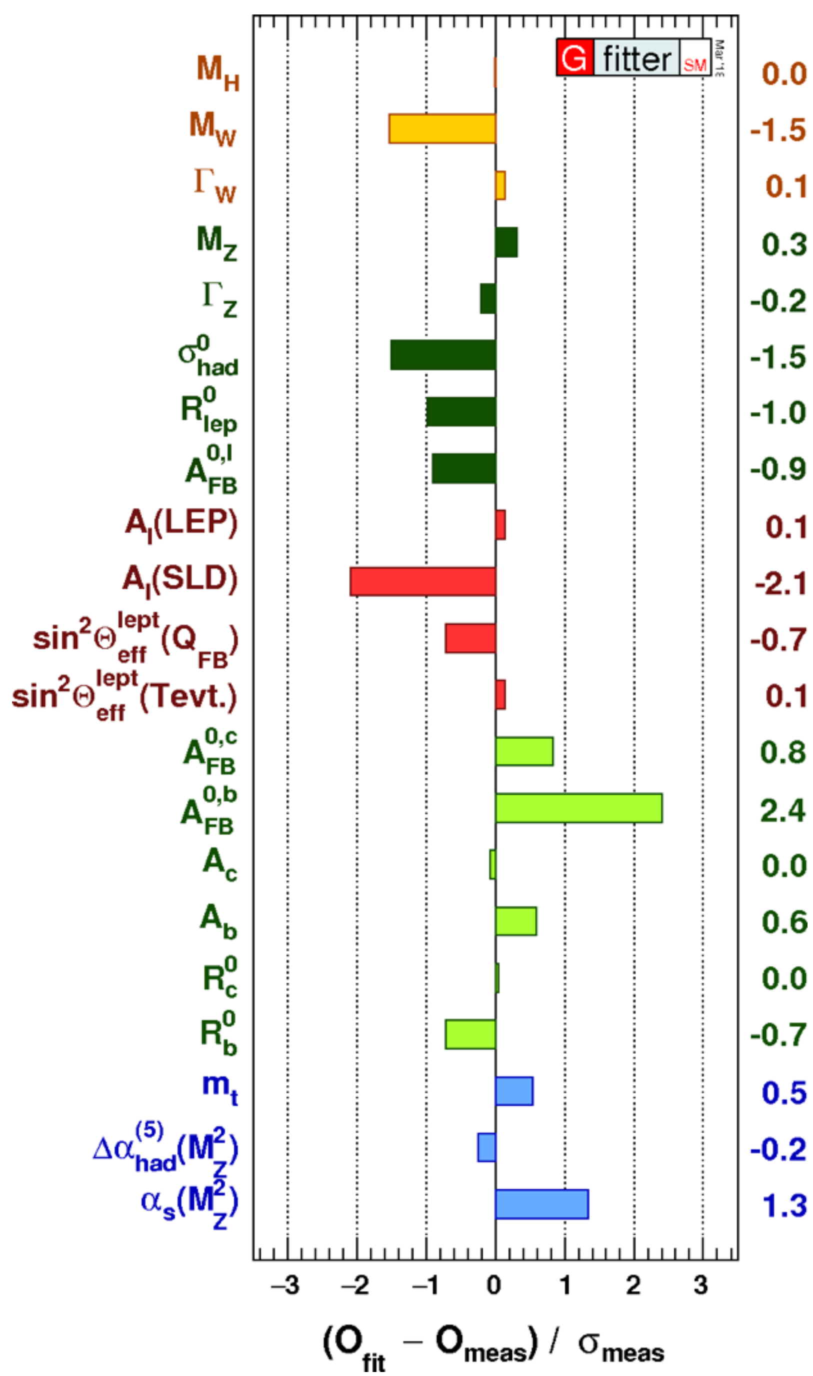
- LHC is a precision machine; measurements approaching few-percent level or better in numerous channels



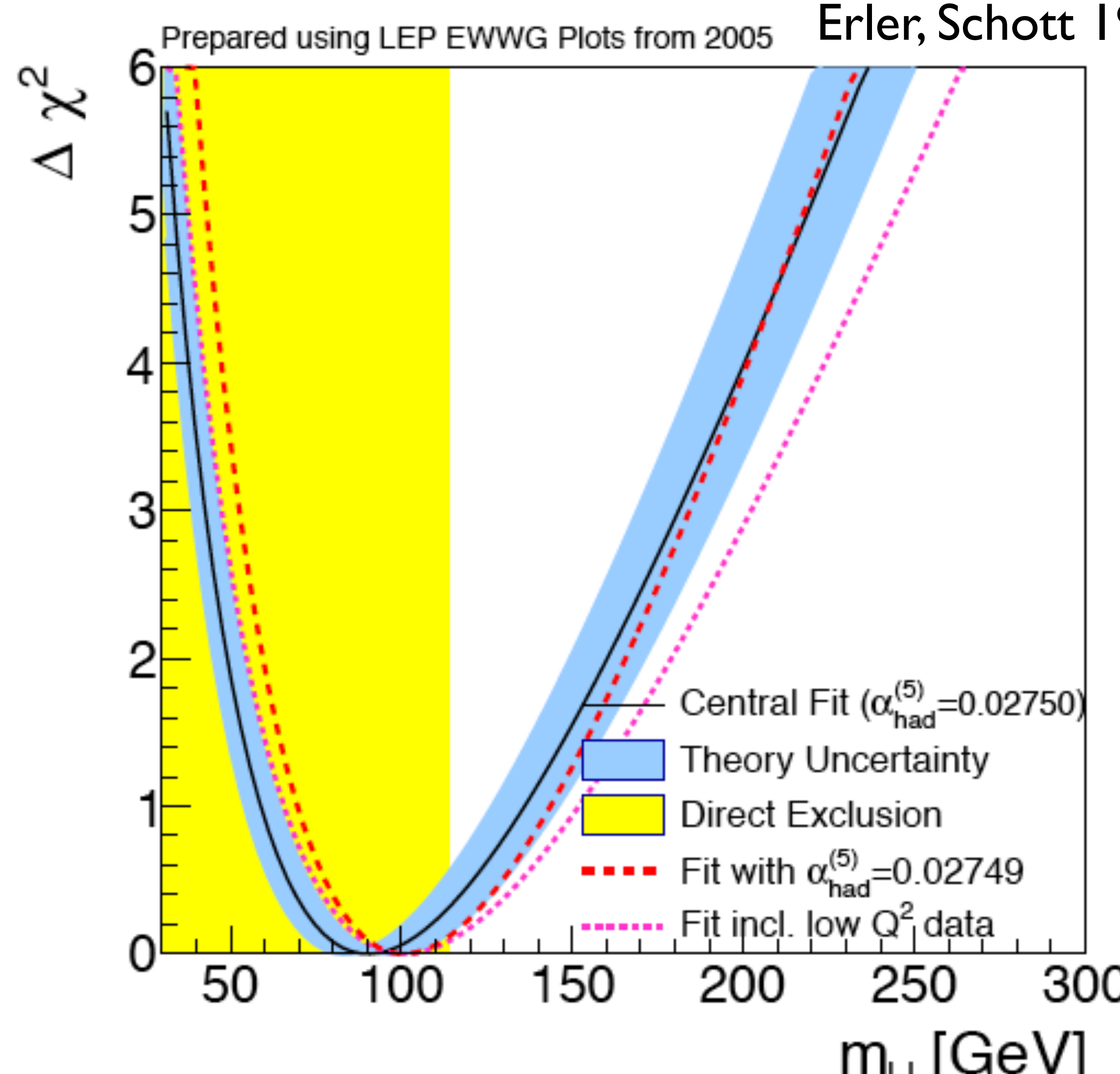


Legacy of the global EW fit

- Lasting legacy of indirect precision measurements from LEP and other experiments teaching us about high-scale physics: light Higgs, SUSY, technicolor



Erler, Schott 1902.05142



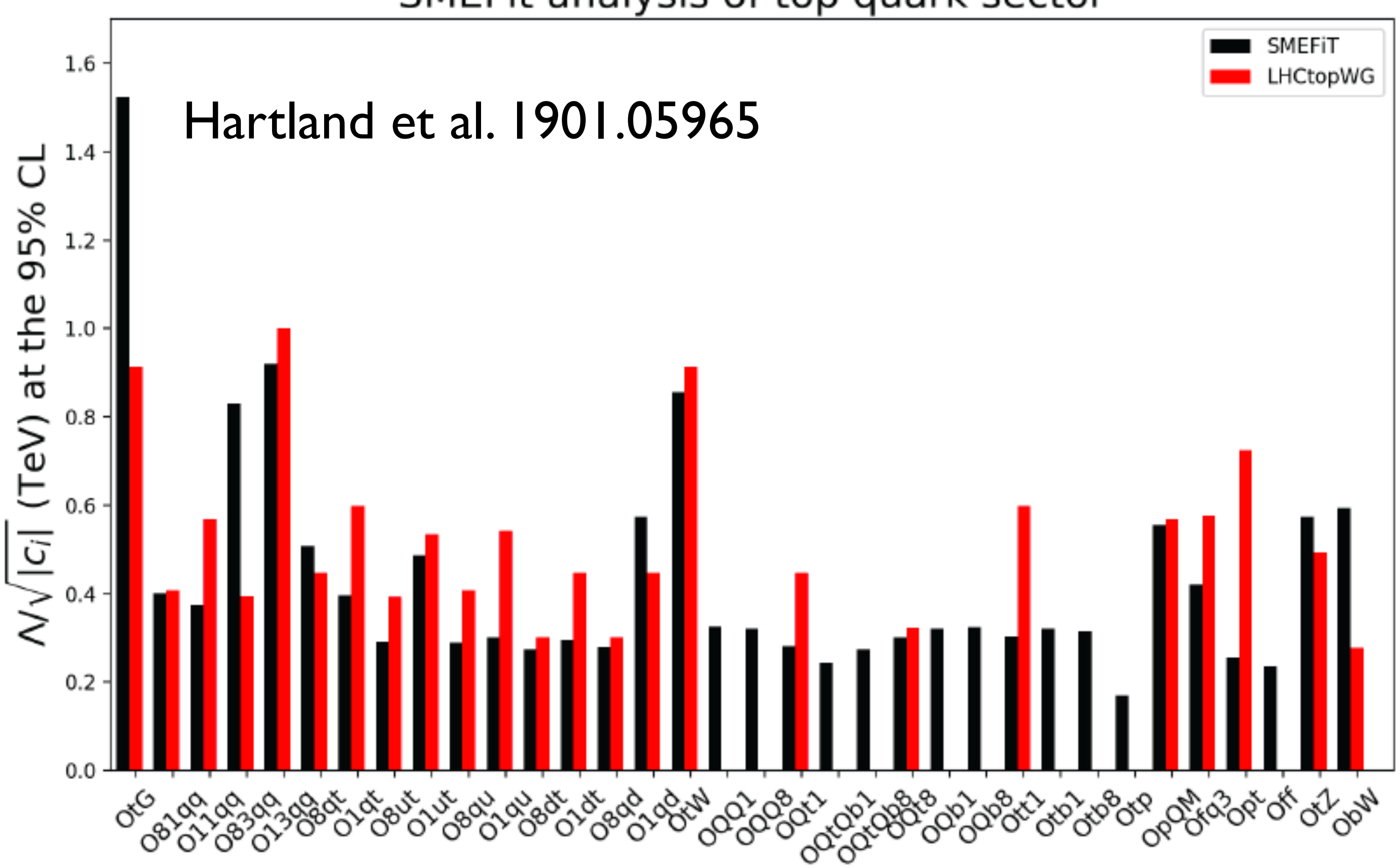
NLO QCD global fit of LHC observables

- New direction: global fits of LHC data to the Standard Model Effective Theory (SMEFT). The study of SMEFT will be a legacy of the LHC era, like the global EW fit was for the LEP era

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$

Λ=scale of underlying UV theory

SMEFit analysis of top quark sector



Example: global study of top quarks with NLO QCD leads to limits on Λ up to 1.5 TeV

Stay tuned!

Conclusions

- Could only scratch the surface of the work being done
  - Higher-order pQCD, resummation, jets: *Felix Ringer, Monday afternoon QCD parallel*
  - Jet substructure: *Yang-Ting Chien, Matt LeBlanc, Christine McLean; Tuesday afternoon QCD parallel*
  - Precision SMEFT analyses: *Daniel Wiegand, Tuesday afternoon BSM parallel; Junping Tian, Tuesday afternoon Higgs parallel*

Thanks for your attention!