Overview of Precision QCD Calculations for Jet Processes

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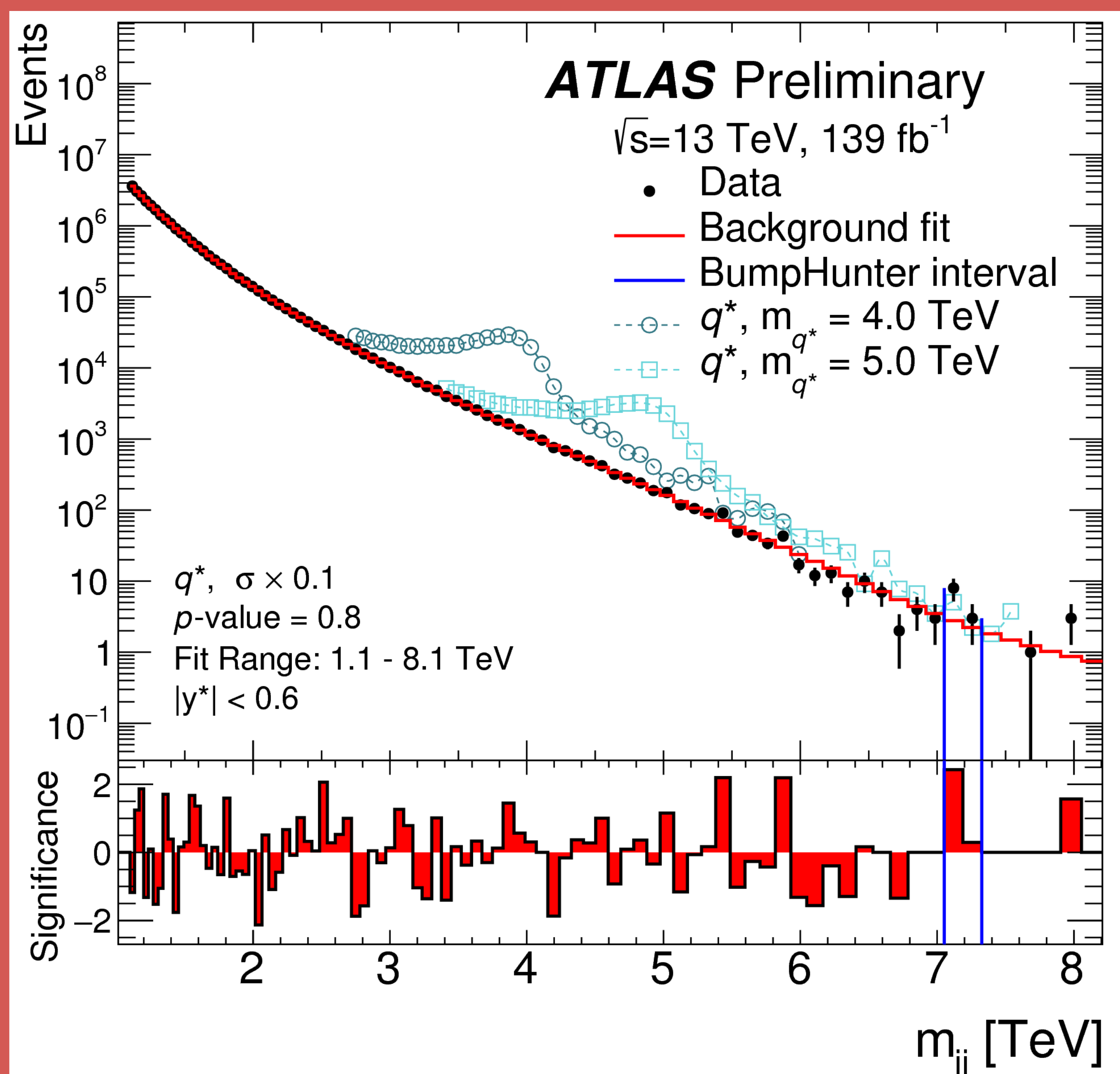
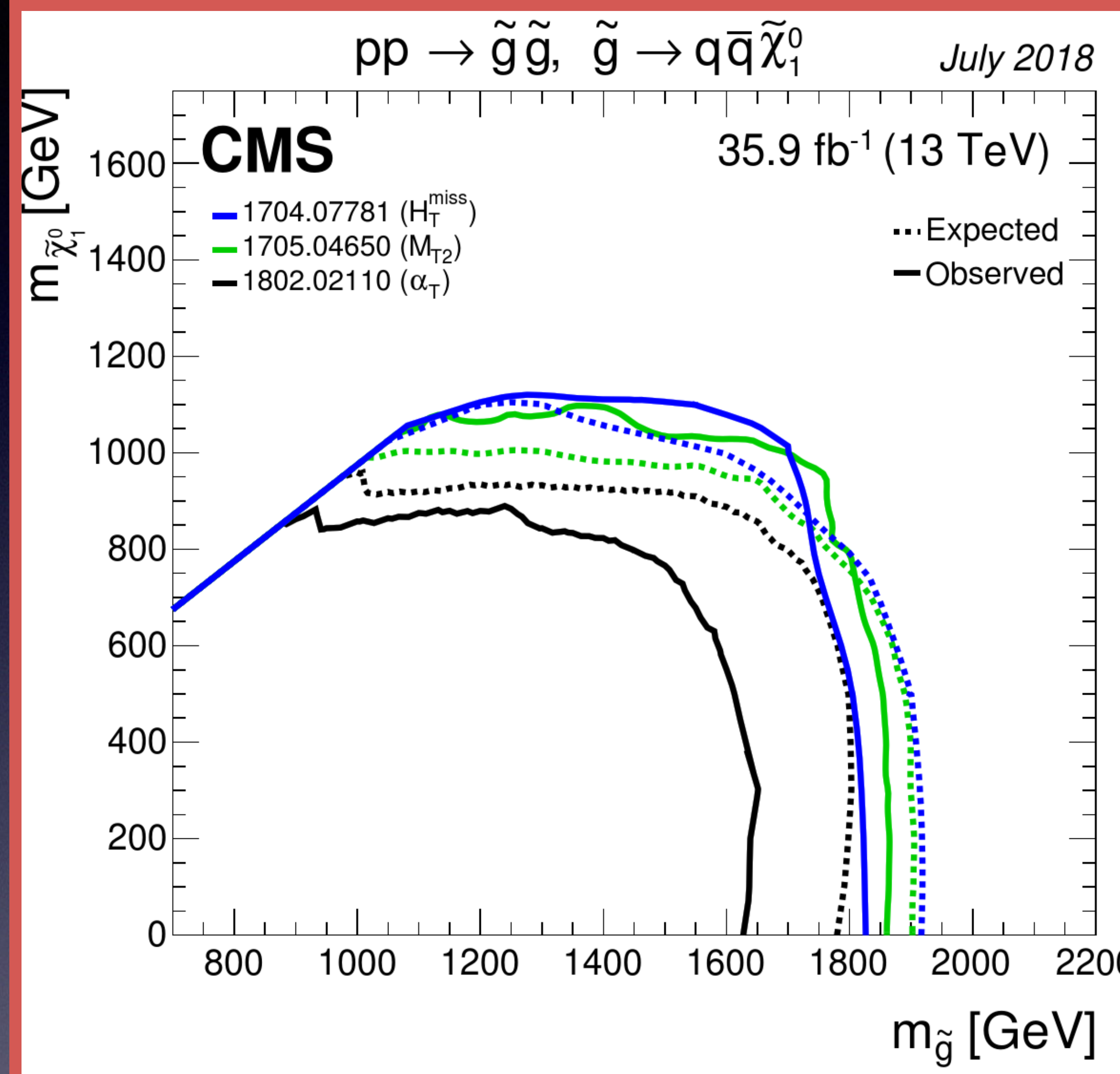
LHCP 2019 , Puebla Mexico, May 20-25, 2019

Why are jets interesting?

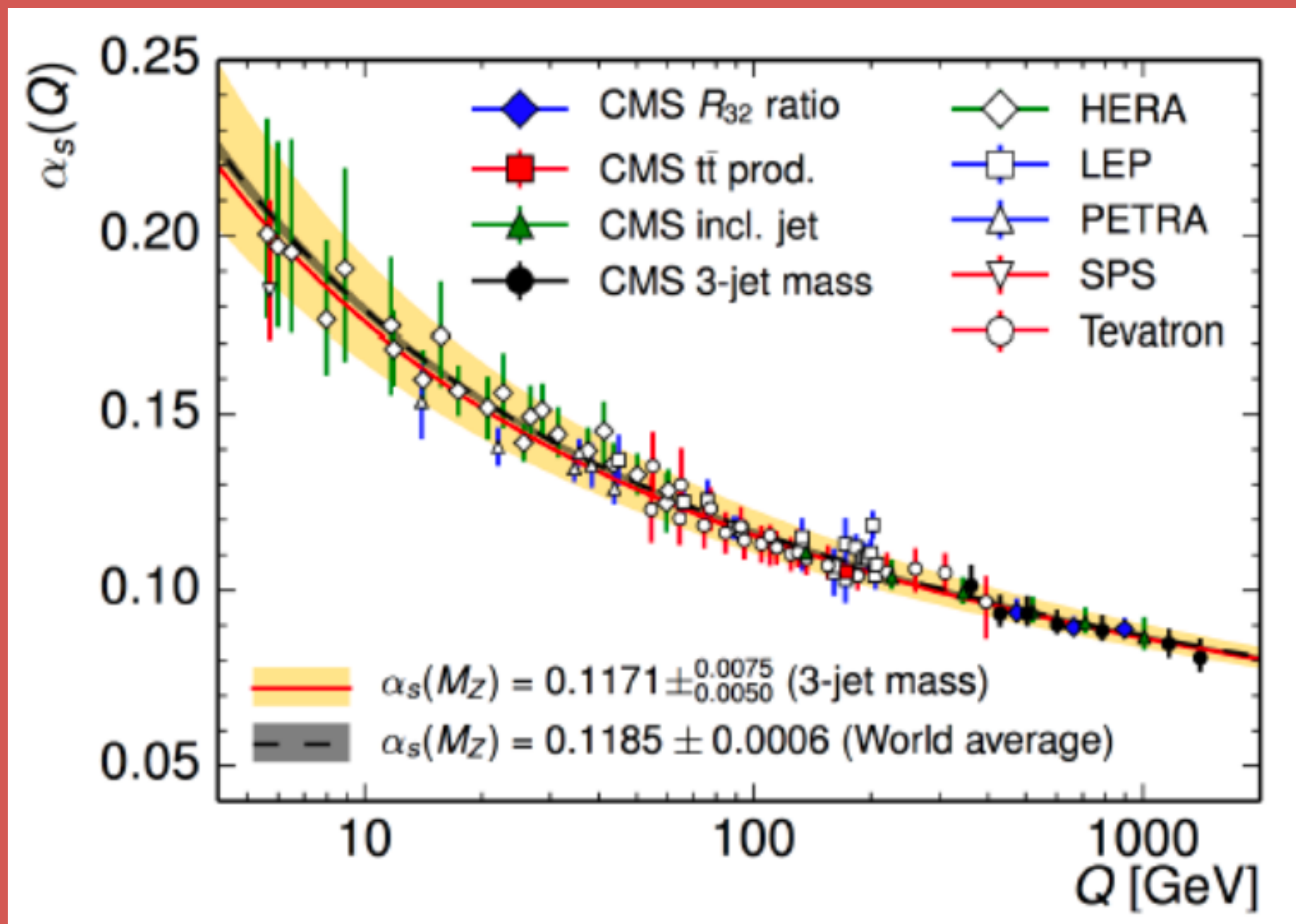


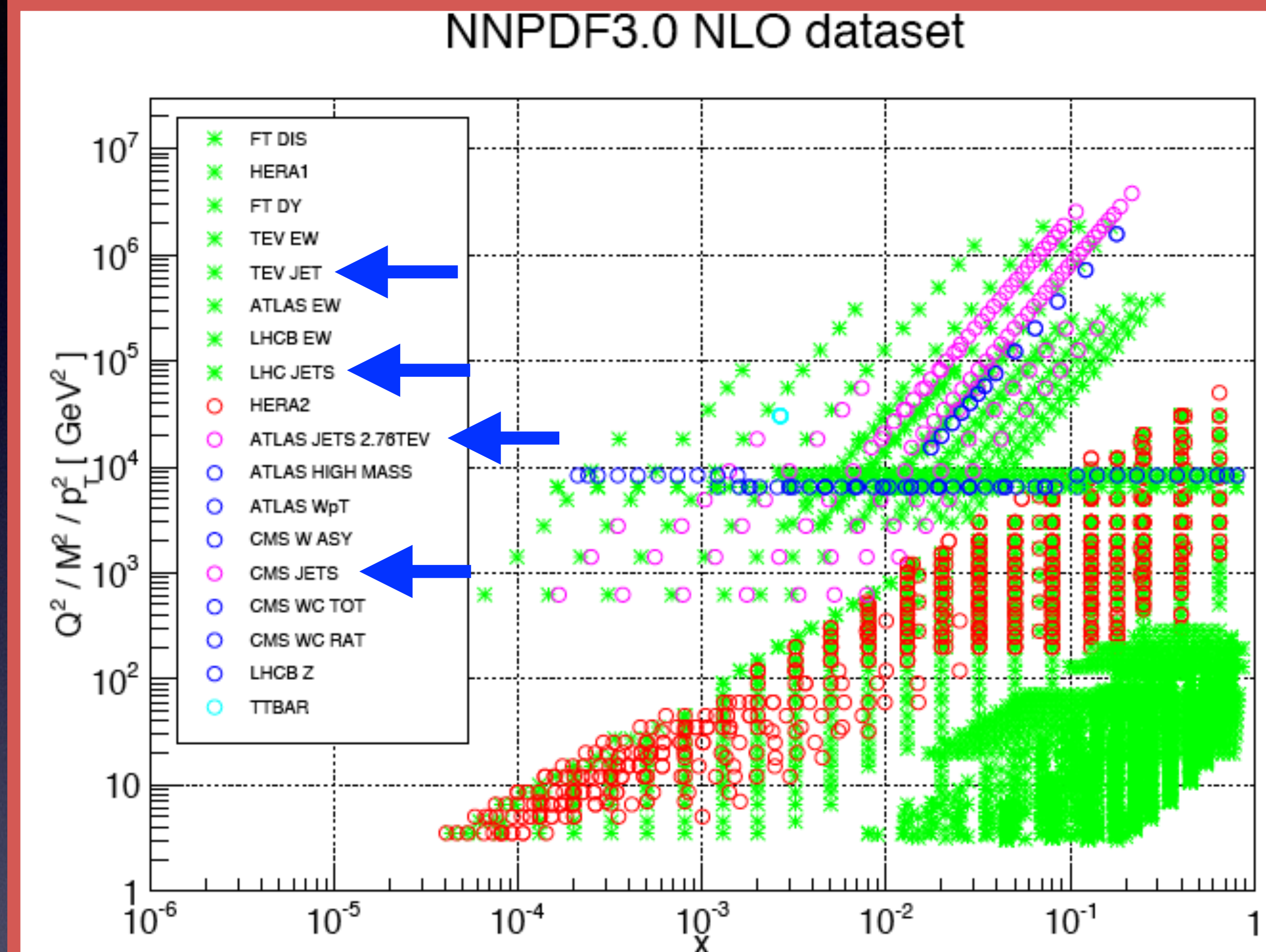


Di-jet resonance searches probe the highest accessible energy scales at the LHC

Jets are a hallmark of many BSM signatures, including much of SUSY parameter space

Why are jets interesting?





Through jets we access fundamental parameters and predictions of QCD such as $\alpha_S(M_Z)$ and α_S running

Jets form a critical input to current PDF fits

How do we study jets?

- Parton-shower Monte Carlo simulations (HERWIG, PYTHIA, SHERPA,…)
- Jet substructure (Grooming, Trimming, Soft-Drop,…)
- **Perturbative QCD**

Jets amenable to first-principle, systematically improvable QCD calculations!

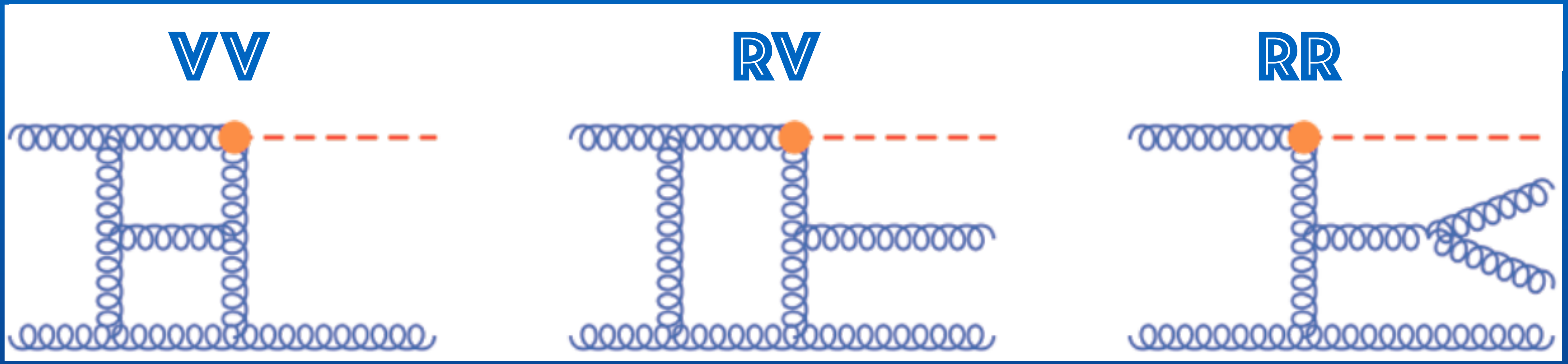
$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \ldots\right)$$

LO predictions | NLO corrections | NNLO corrections | NNNLO corrections

Current frontier: next-to-next-to leading order (NNLO) in α_S

Ingredients for NNLO calculations

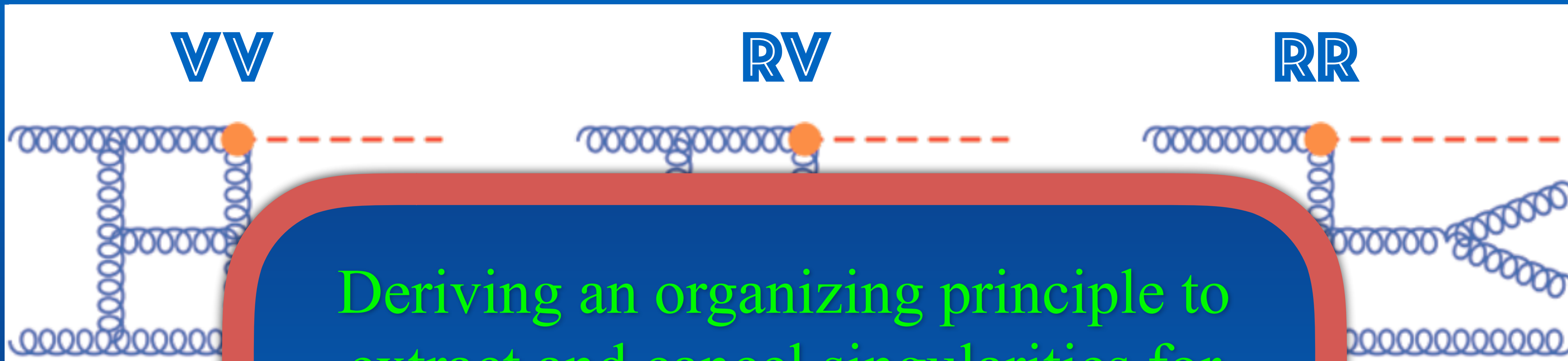
Three basic ingredients for NNLO calculations:



- IR soft/collinear singularities cancel in the sum of real and virtual corrections and mass factorization counter terms, but only after integrating over the real radiation phase space
- Real corrections have implicit IR poles that need to be extracted in the presence of final state kinematic cuts

Ingredients for NNLO calculations

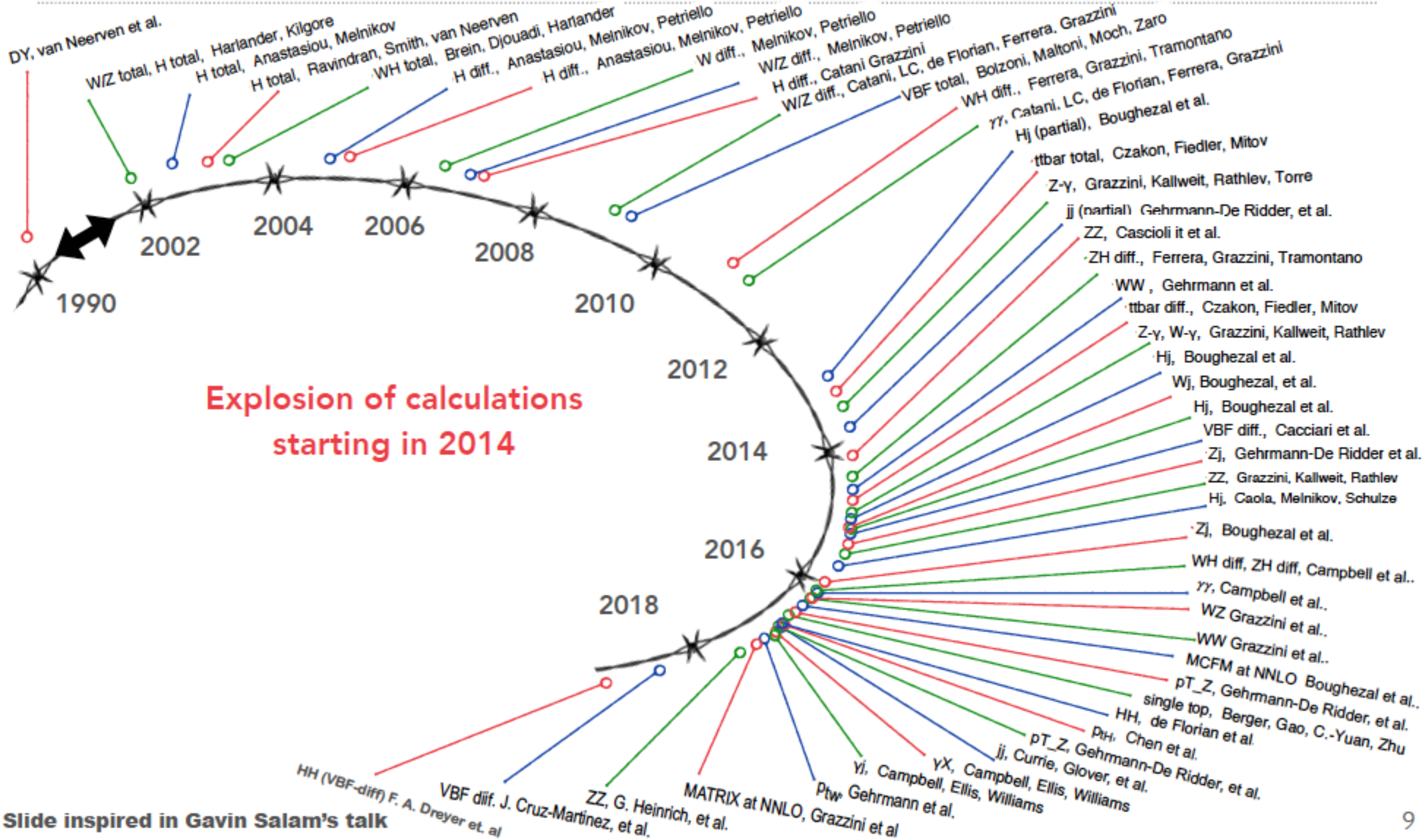
Three basic ingredients for NNLO calculations:



Deriving an organizing principle to extract and cancel singularities for arbitrary observables was a major obstacle in obtaining NNLO predictions

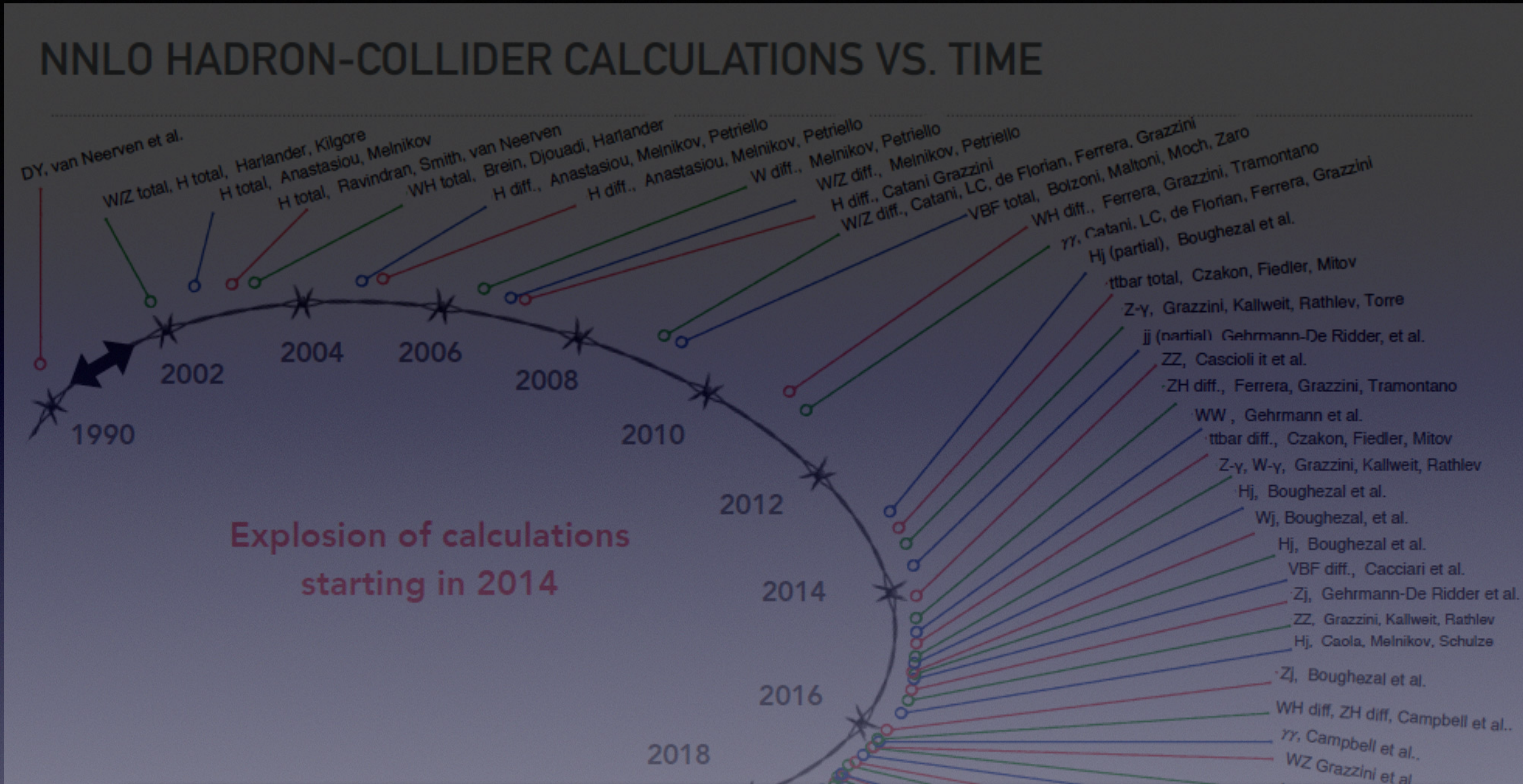
- IR soft/c … and virtual corrections … only after integrating over the real radiation phase space
- Real corrections have implicit IR poles that need to be extracted in the presence of final state kinematic cuts

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME



Slide inspired in Gavin Salam's talk

L. Cieri, Moriond 2019



This explosion of new NNLO results was made possible thanks to several ideas!

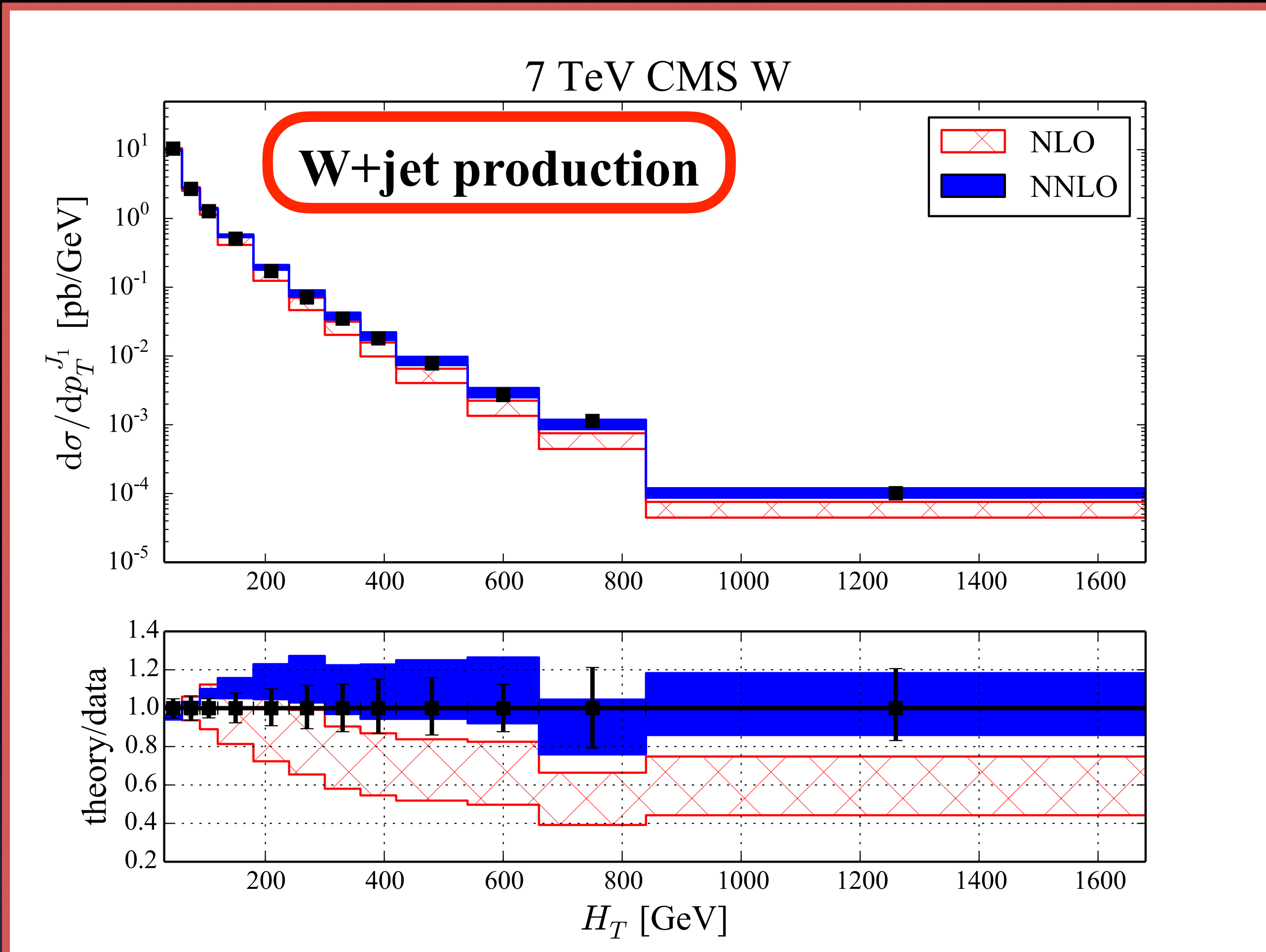
L. Cieri, Moriond 2019

Cancellation of IR divergences @ NNLO

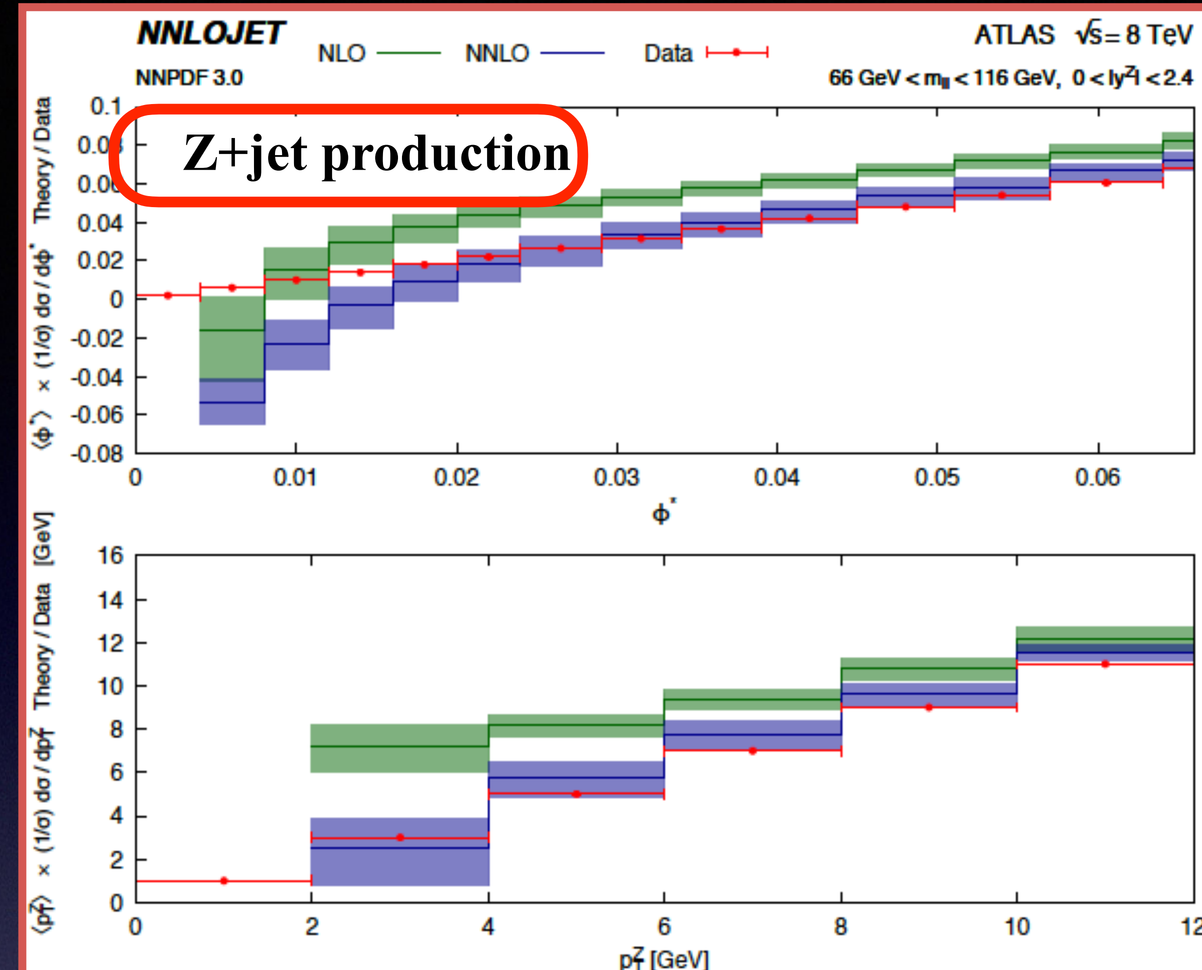
- **Effective field theory methods:**
  - qT subtraction Catani, Grazzini; for processes without jets
  - N-jettiness subtraction RB, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh; applicable for all processes including jet production

- **Subtraction methods:**
  - Sector decomposition Anastasiou, Melnikov, Petriello; Binoth, Heinrich
  - Antenna subtraction Kosower; Gehrmann, Gehrmann De Ridder, Glover
  - Sector Improved Residue Subtraction Czakon; RB, Melnikov, Petriello; Czakon, Heymes; Caola, Melnikov, Rontsch
  - Colorful subtraction Del Duca, Duhr, Kardos, Somogyi, Trocsanyi
  - Projection to Born Cacciari, Dreyer, Karlberg, Salam, Zanderighi

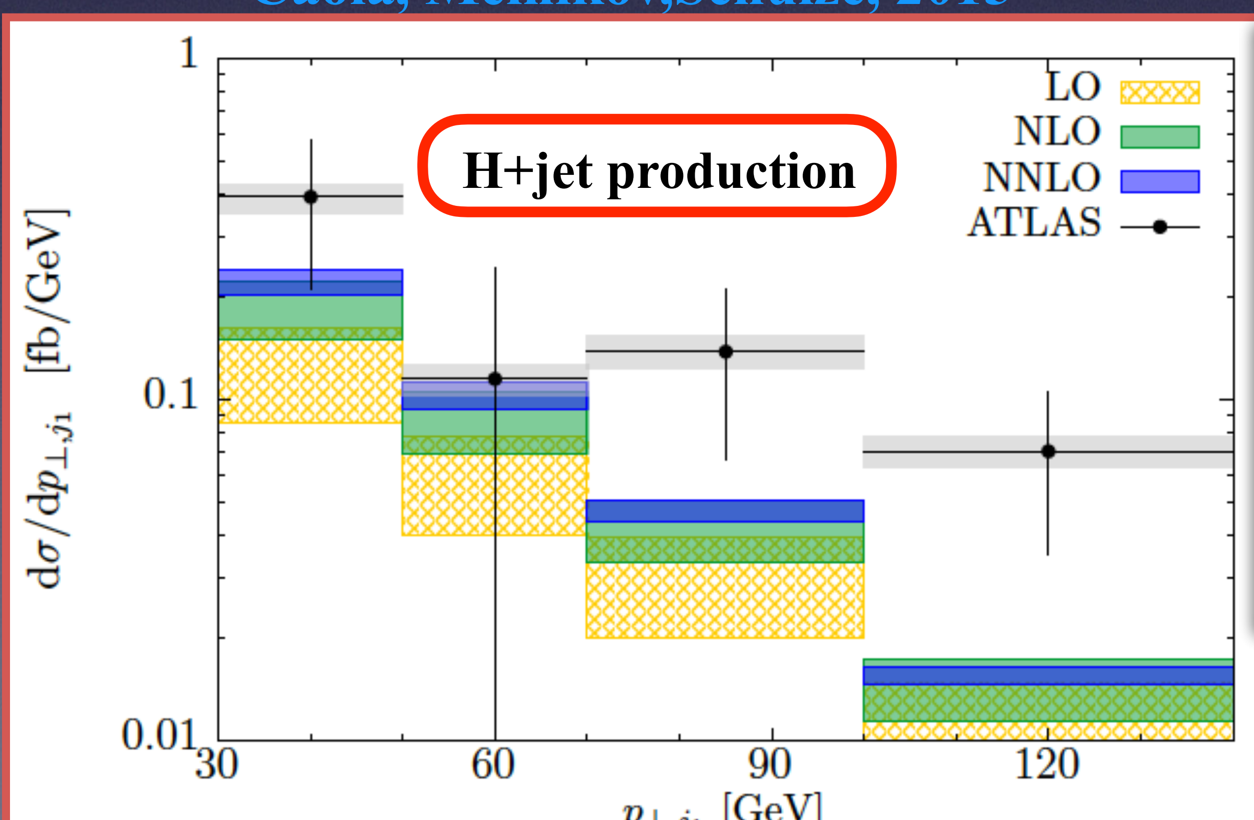
RB, Liu, Petriello, 2016



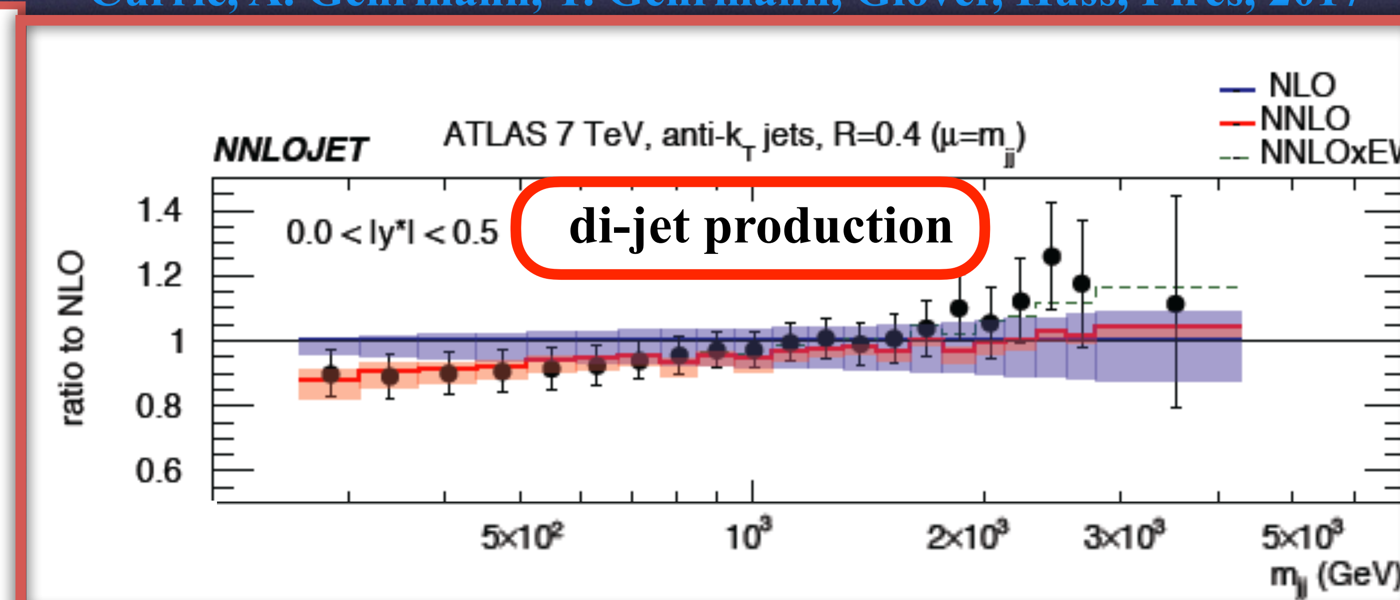
A. Gehrmann, T. Gehrmann, Glover, Huss, Morgan, 2016



Caola, Melnikov, Schulze, 2015



Currie, A. Gehrmann, T. Gehrmann, Glover, Huss, Pires, 2017



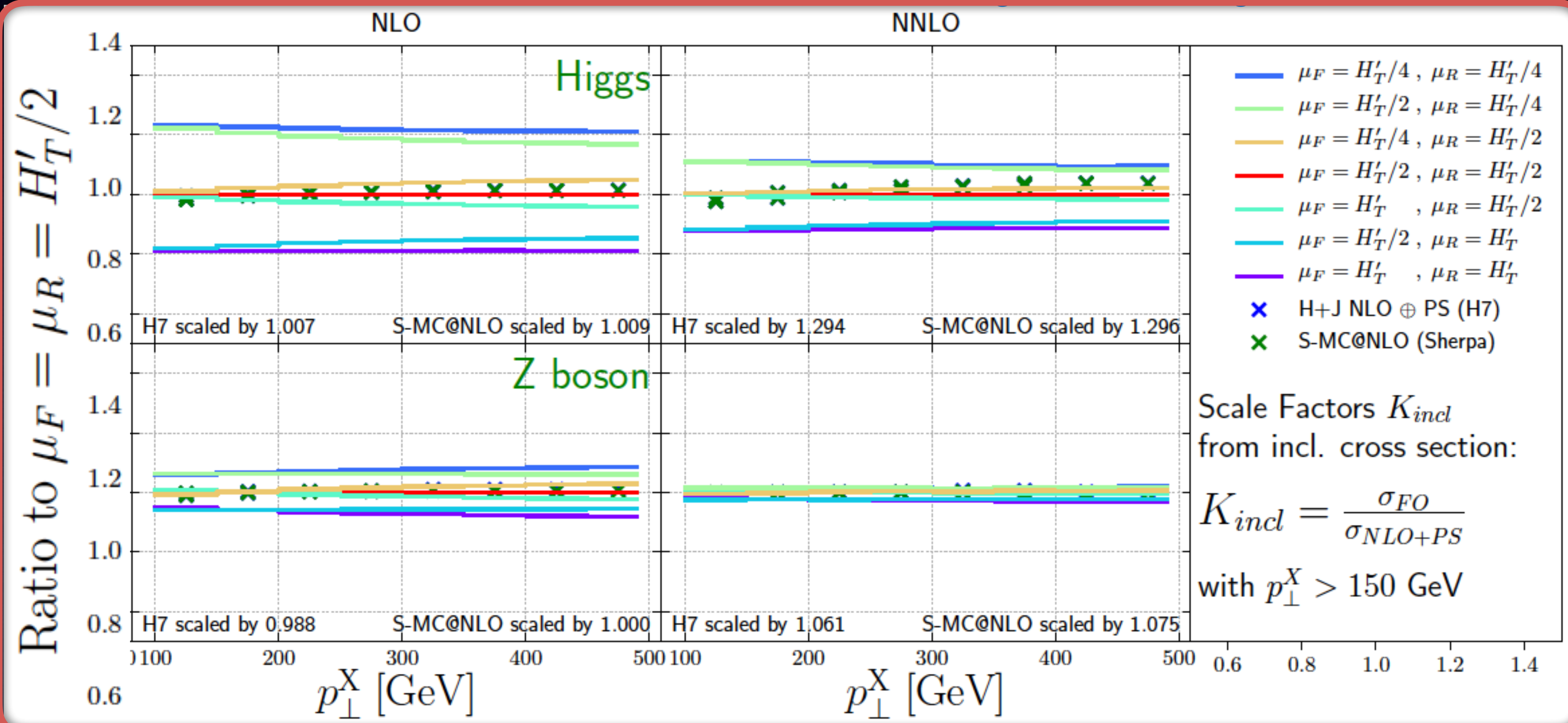
… as well as single-inclusive jet, di-jet in diffractive DIS, photon+jet production…

Highlights of NNLO Jet Phenomenology

(that fit in the allocated talk time!)

Comparison of NNLO Z+j & H+j results with NLO+parton shower

NNLOJET **X= (H, Z) in H+j and Z+j**



Bellm et al, arXiv:1903.12563

$$\mu_0 = \frac{H_{T,j}}{2} = \frac{1}{2}\left(\sqrt{m_X^2 + p_{T,X}^2} + \sum_{\text{jets}} p_{T,j}\right)$$

Scale variation shown for the fixed order results only

Comparison of NNLO Z+j & H+j results with NLO+ parton shower

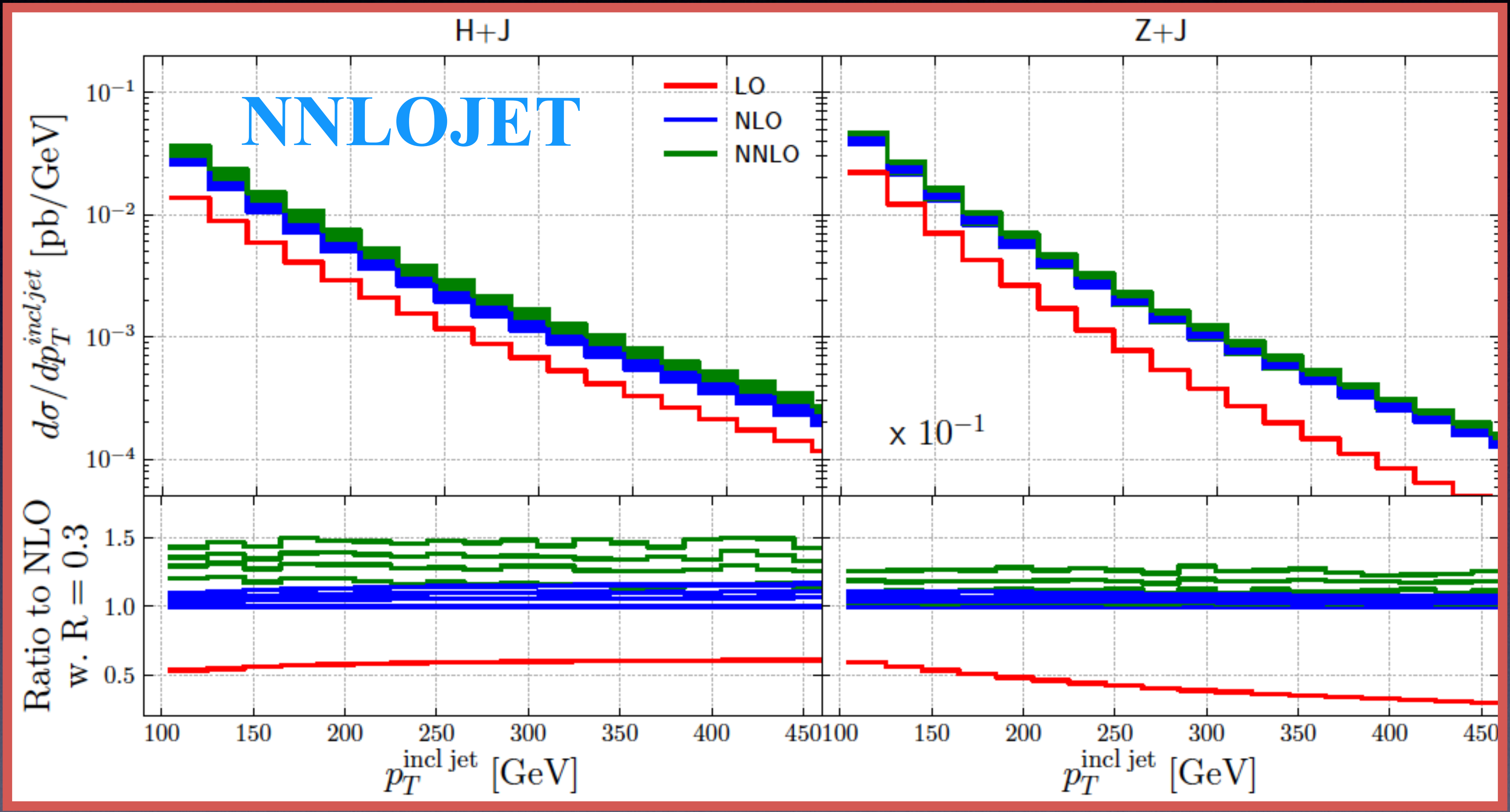
- Visible reduction in scale dependence as we move from NLO to NNLO
- Parton shower scaled by K_{incl} for $p_{T(H,Z)}>150$ GeV to account for missing corrections when comparing to FO
- Very good agreement between the scaled NLO parton shower results of Sherpa and Herwig with the NNLO FO result over the entire studied pT range.
- Can reliably use these generators to predict heavy boson pT spectra in boosted Higgs- and Z-boson analyses.

$$\mu_0 = \frac{H_{T,j}}{2} = \frac{1}{2}\left(\sqrt{m_X^2 + p_{T,X}^2} + \sum_{\text{jets}} p_{T,j}\right)$$

Scale variation shown for the fixed order results only

Jet Radius dependence in the prediction

Study of the spread of the cross section induced by R= {0.3, 0.5, 0.7, 1.0}

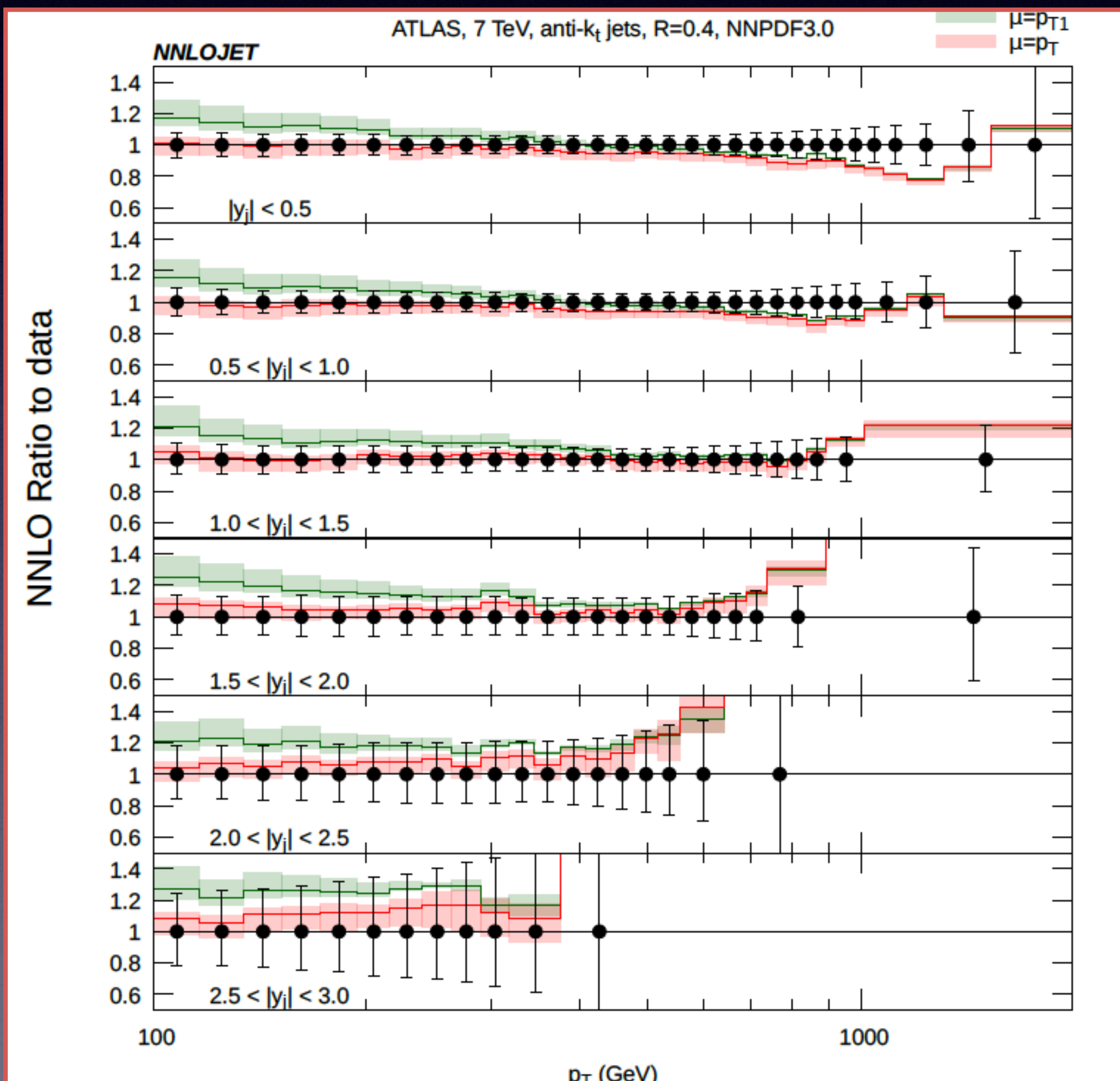


- Larger R-dependence for H+>=1jet at NNLO than at NLO
- Relatively smaller R-dependence for Z+>=1jet at NNLO

Need to understand the R-dependence better

Single-inclusive jet production and the scale choice

- Recent studies have shown that agreement between data and NNLO predictions for single-inclusive jet and di-jet production is sensitive to the scale choice



Currie, Glover, A. Gehrmann,T. Gehrmann, Huss, Pires, 2017

- If $\mu R = \mu F = p_{T1}$, where p_{T1} is the leading jet pT, for all the binned jets in the event, **poor agreement with data is observed**

- If $\mu R = \mu F = p_T$, where p_T is the transverse momentum of each individual binned jet in the event, **good agreement with data is observed**

- $\mu R = \mu F = p_T$ leads to larger corrections from NLO to NNLO while $\mu R = \mu F = p_{T1}$ leads to smaller corrections

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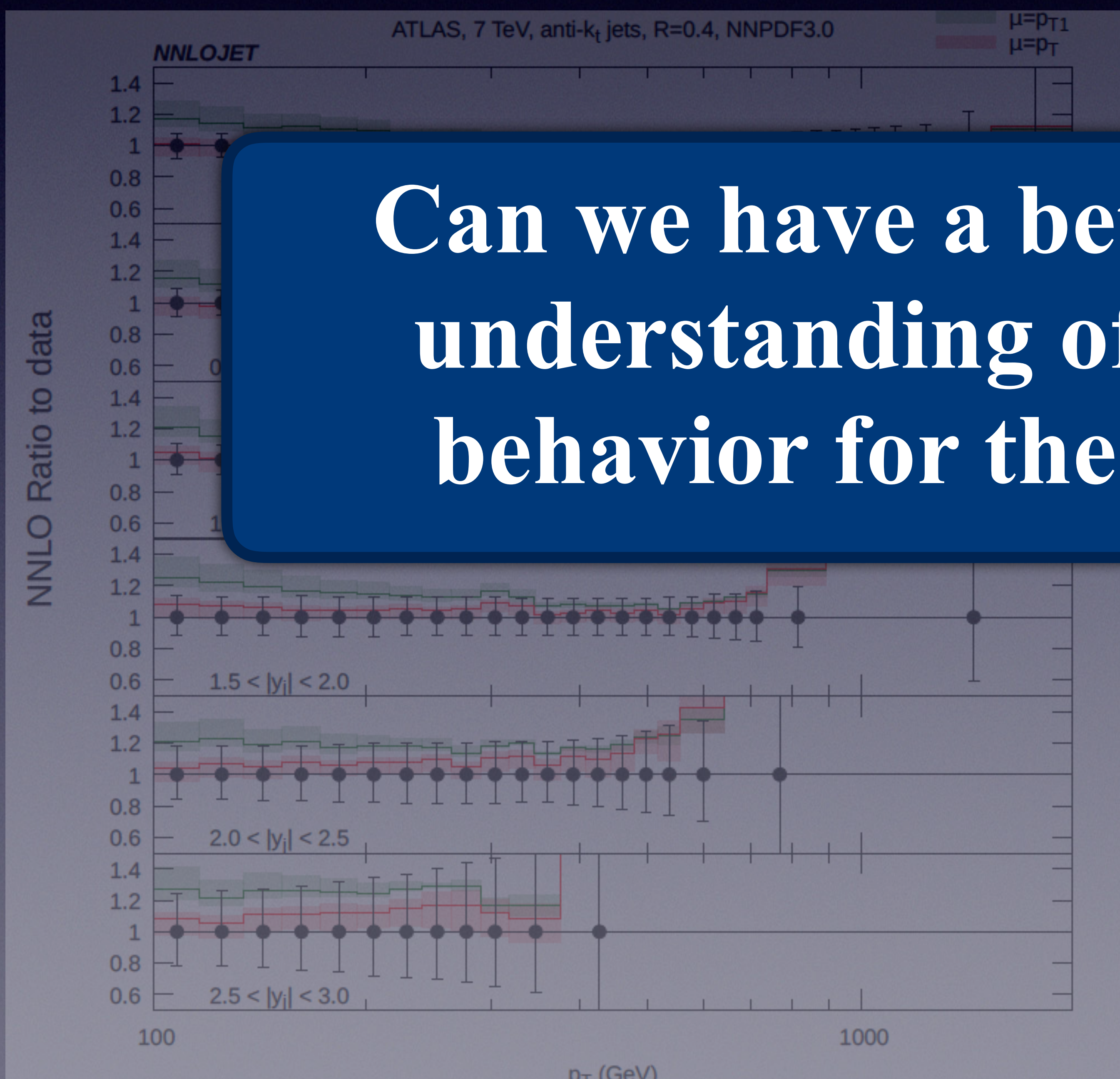


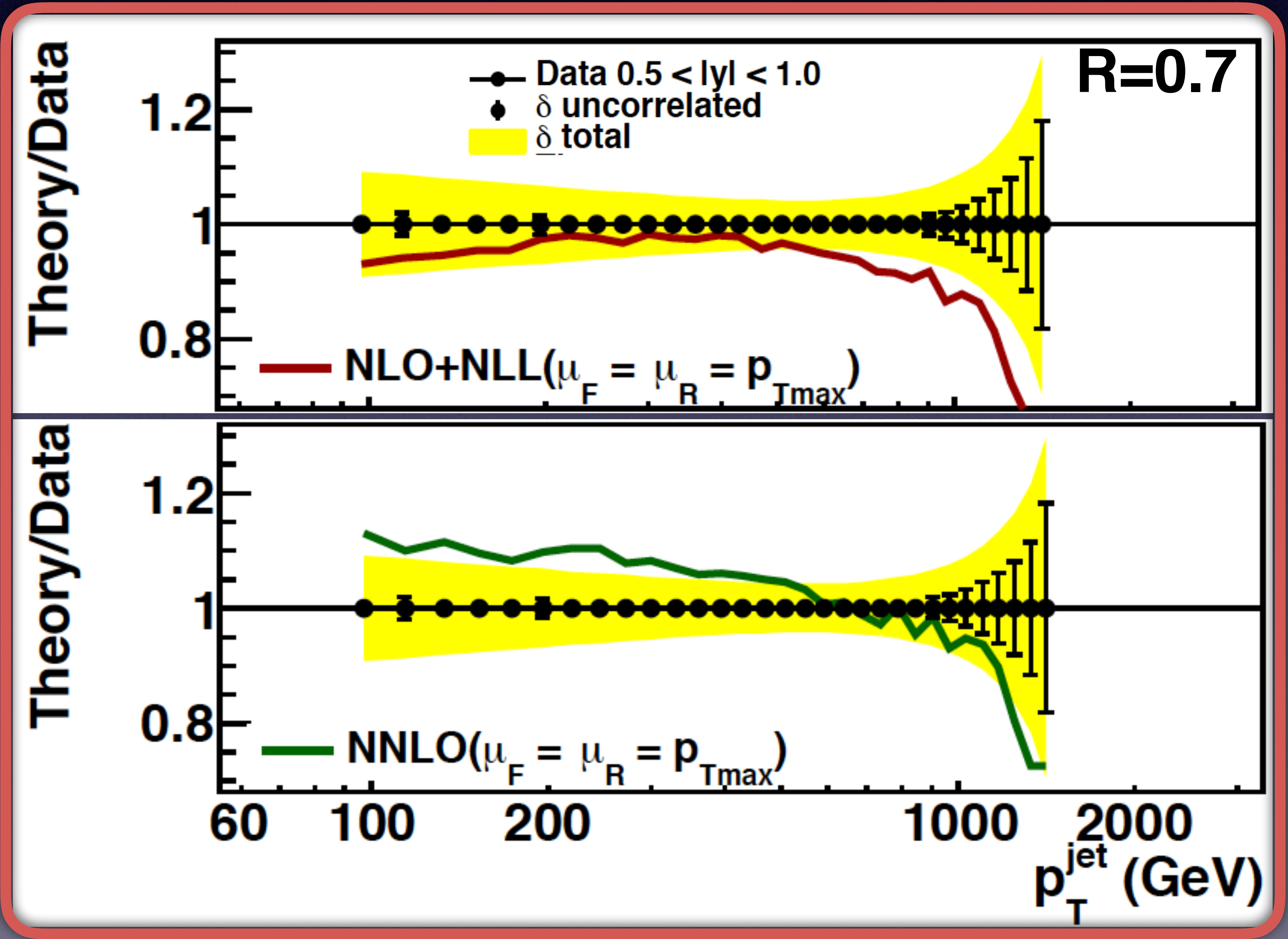
Currie, Glover, A. Gehrmann,T. Gehrmann, Huss, Pires, 2017

- If $\mu_R = \mu_F = p_{T1}$, where pT1 is the leading jet pT, for all the … or … served
- … is the … ch … event, **good agreement with data is observed**
- $\mu_R = \mu_F = p_T$ leads to larger corrections from NLO to NNLO while $\mu_R = \mu_F = p_{T1}$ leads to smaller corrections

Can we have a better theoretical understanding of the observed behavior for the scale choice?

Single-inclusive jet production and the scale choice

- There is sensitivity to threshold logarithms at large jet P_T. There are also cone size dependent logarithms to consider: $\alpha_s^n \log^k(R)$, $k \leqslant n$. Both should be resummed.

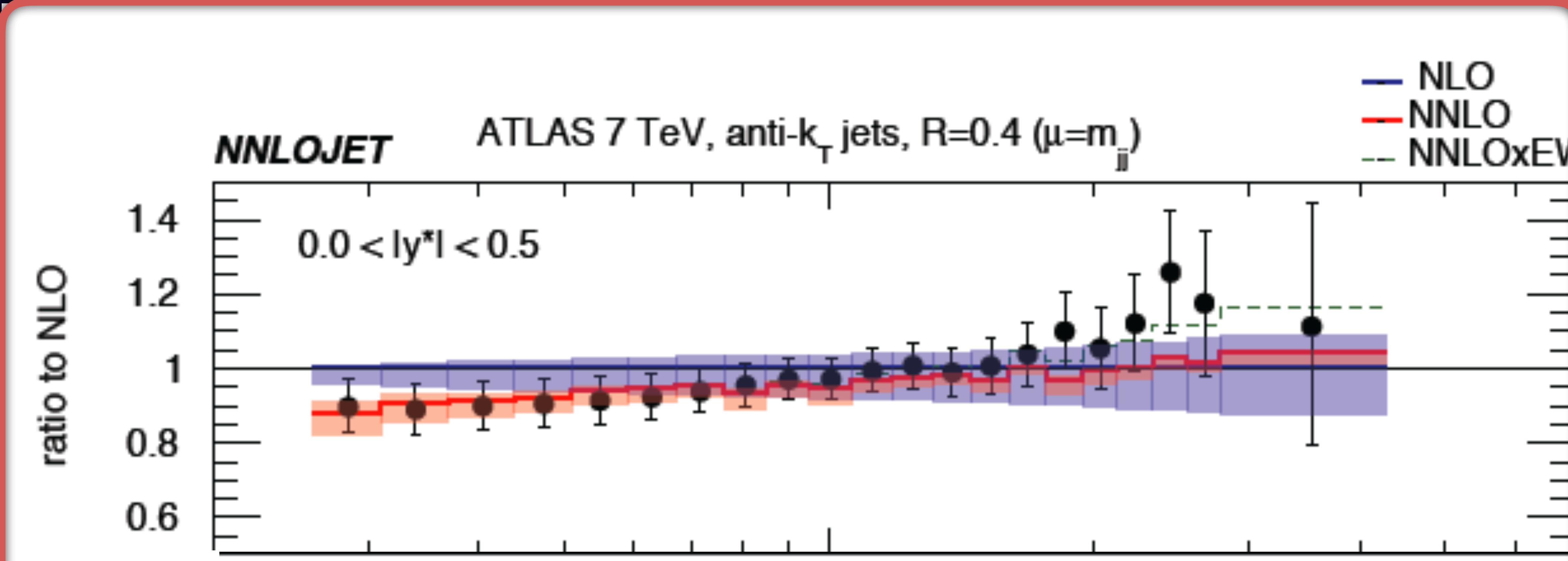


Liu, Moch, Ringer, 2018

- Resummation was done at NLO+NLL for $\mu R = \mu F = p_{Tmax}$.
- Better agreement with data was observed at lower p_T^{jet} values for this scale choice
- Expected further improvement when NNLO+NNLL becomes available

Di-jet @ NNLO

- Numerous applications of di-jet production at the LHC, including searches for new physics, measurements of α_s, and determination of the high-x gluon.



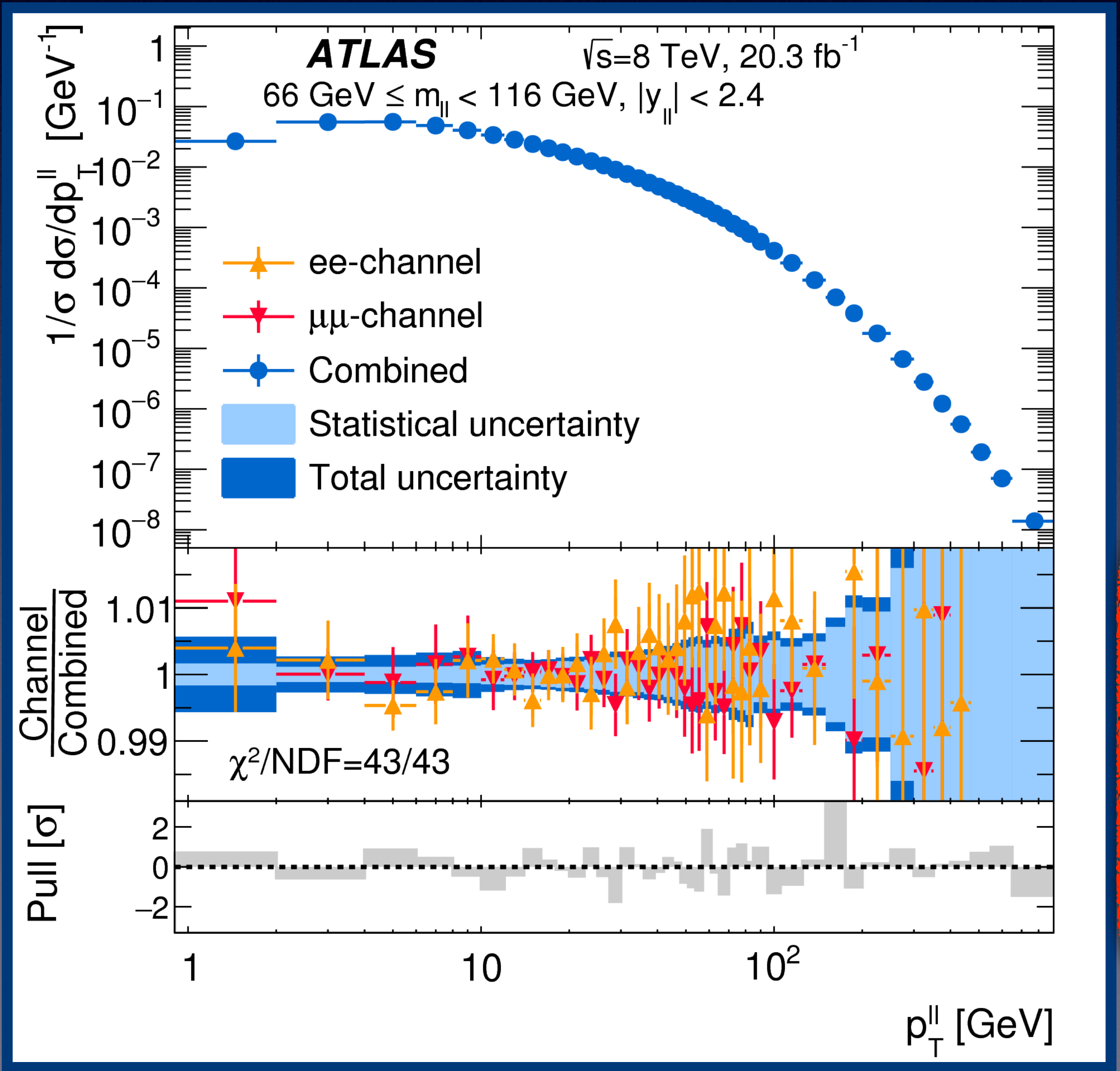
$$y^* = \frac{1}{2}(y_{j_1} - y_{j_2})$$

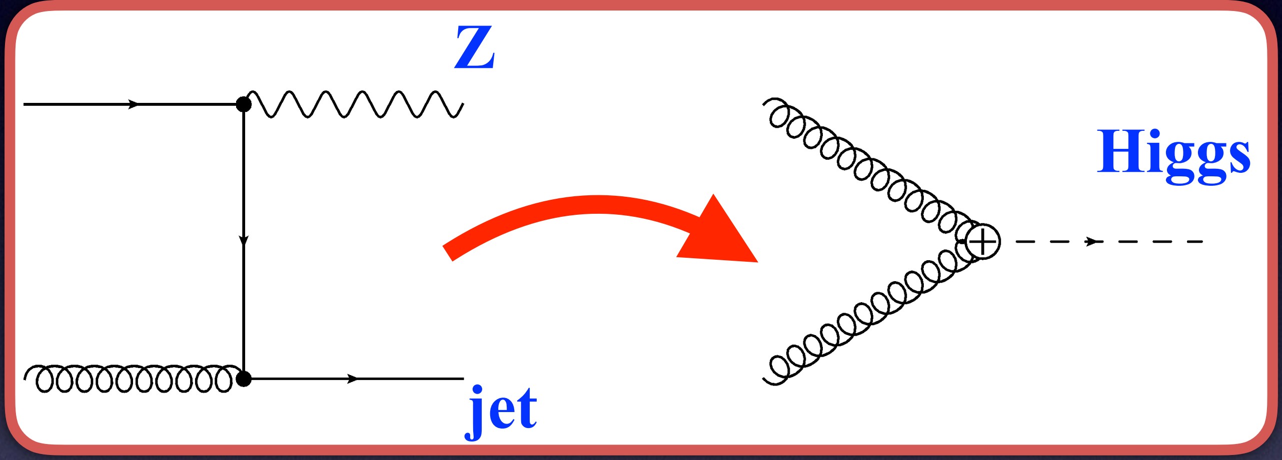
Currie, Gehrmann-de Ridder, Gehrmann, Glover, Huss, Pires (2017)

Improved data/theory agreement in the central y* region!

Z+jet and the Z p_T

- The Z-boson transverse momentum spectrum measurement has reached a remarkable precision at the LHC, with errors below 1% over a large range

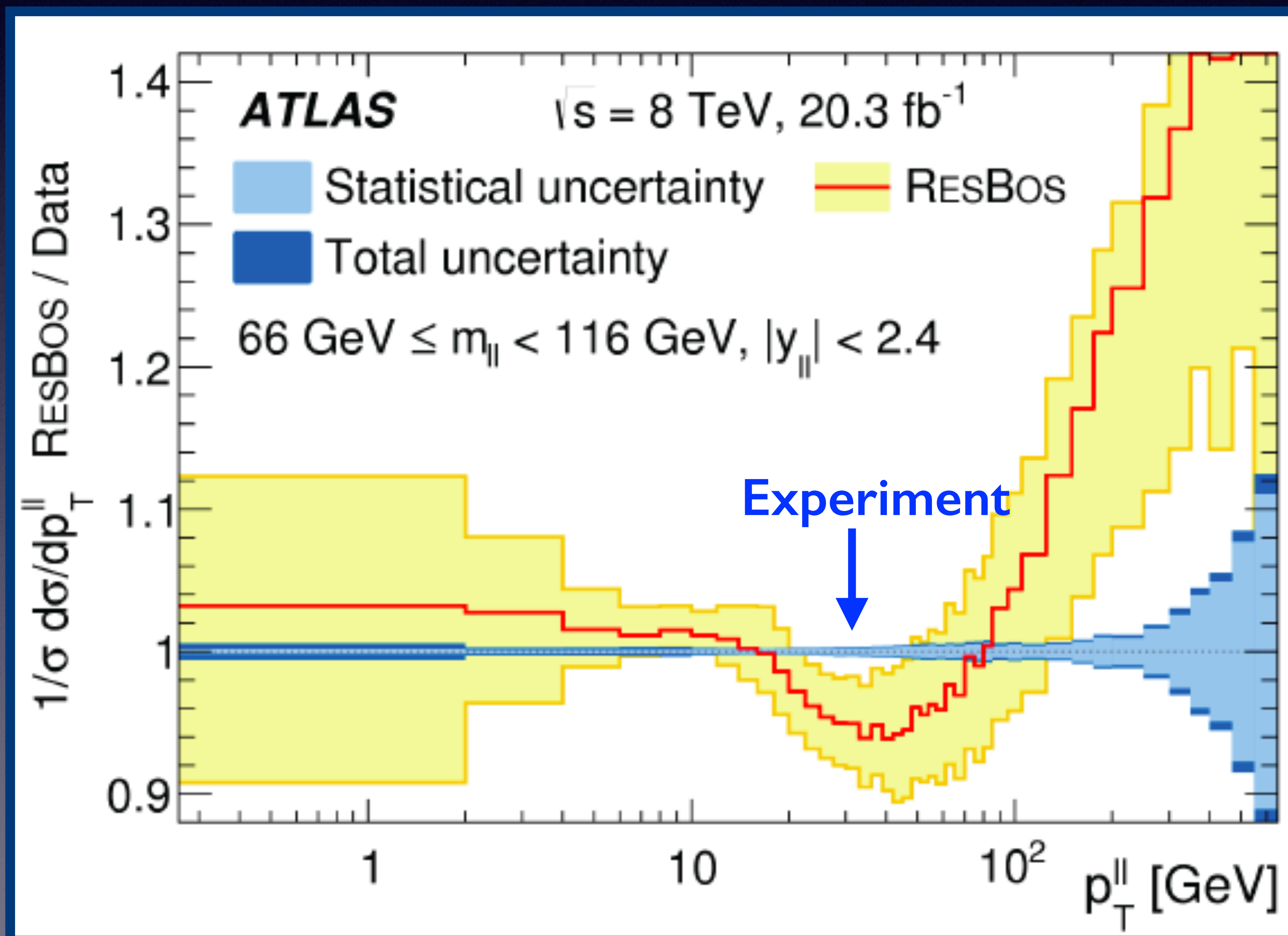




The leading-order cross section for this process depends on the gluon PDF; we can learn about the gluon distribution entering Higgs production from this data!

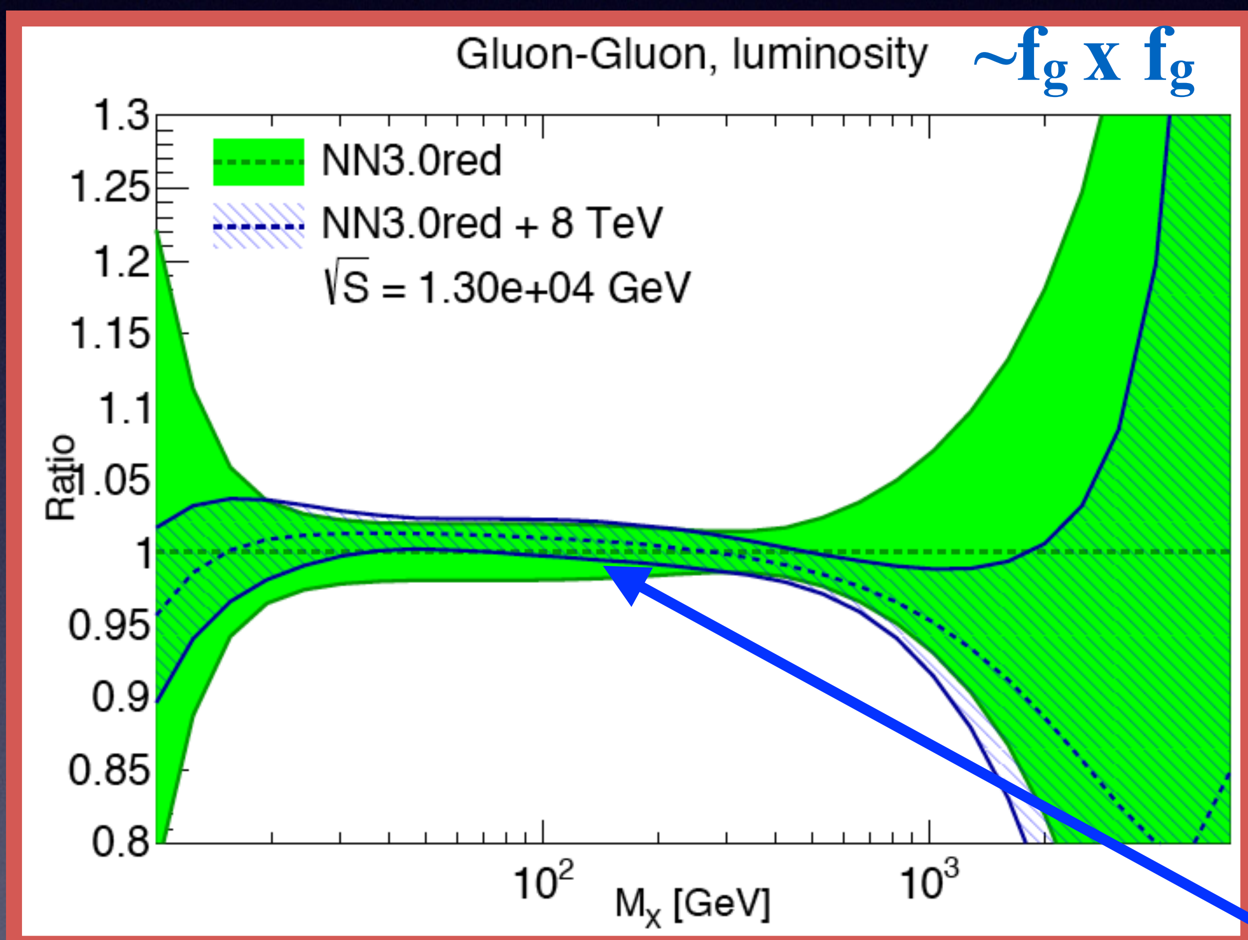
Comparison with NLO theory

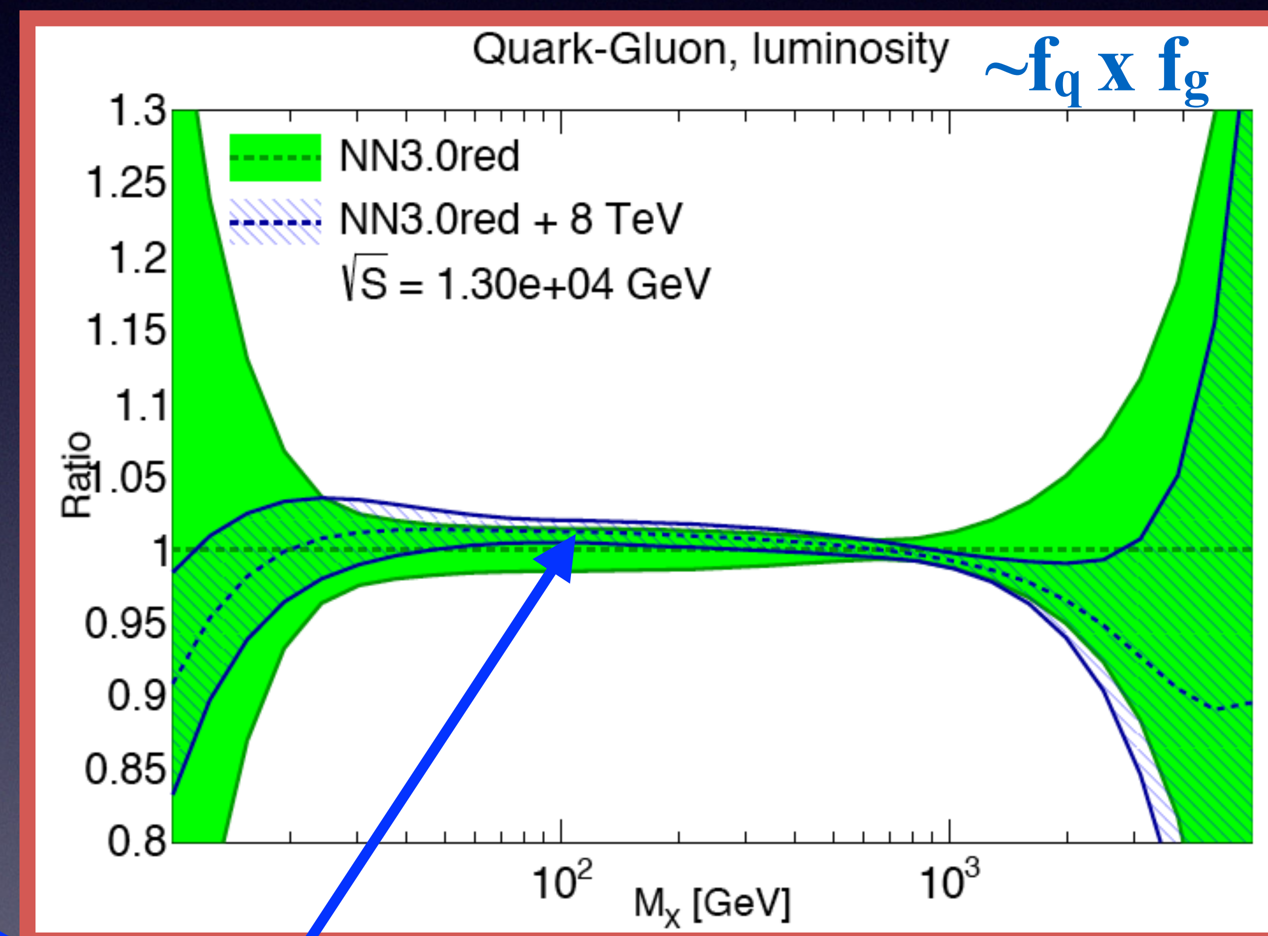
- NLO theory errors more than an order of magnitude larger than the experimental ones; Can't use these data to learn about the gluon PDF without NNLO



Impact on PDFs from Z-pT

- After incorporating NNLO, theory error shrunk to the point that this data can be used. Improvements with respect to a pre Z-pT baseline fit:



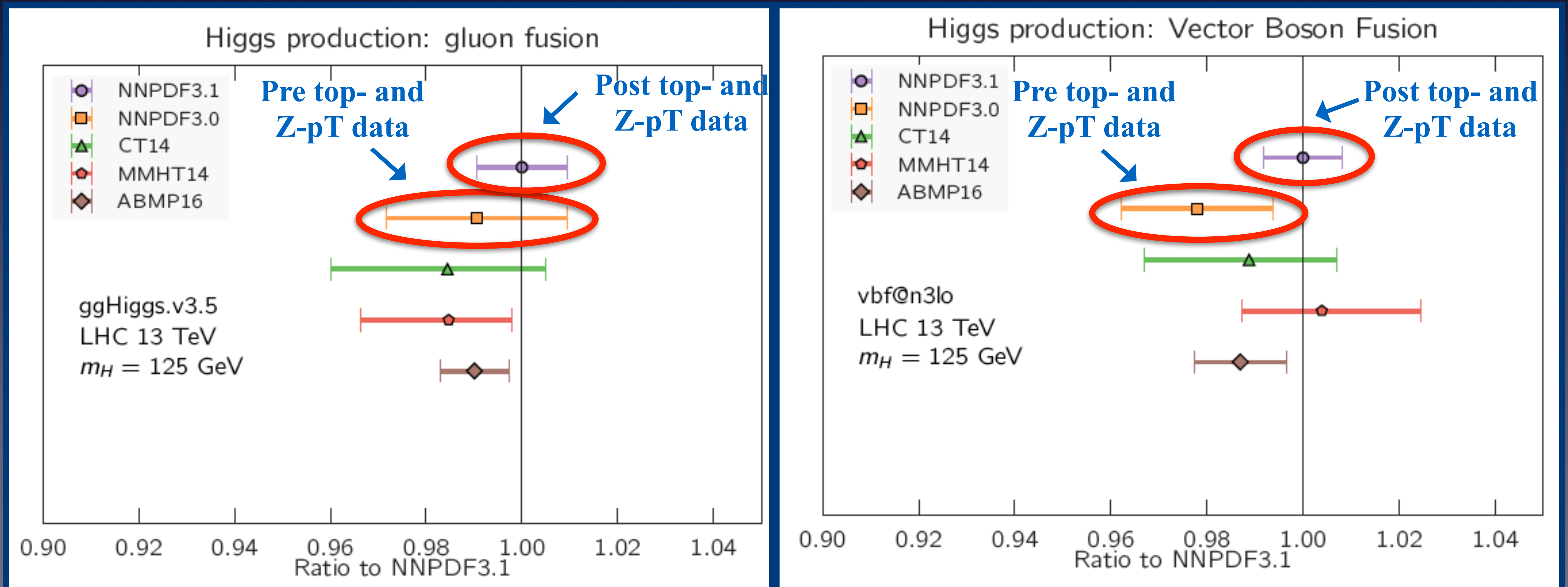


RB, Guffanti, Petriello, Ubiali (2017)

Gluon-gluon and quark-gluon luminosity errors reduced right near M_X~m_H=125 GeV!

Impact on global fit from Z-pT

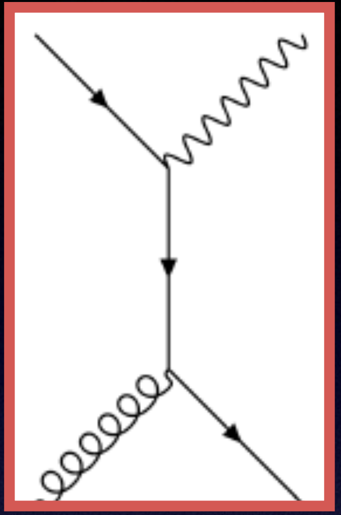
In the NNPDF 3.1 global fit, when also combined with the top-quark and jet production now available at NNLO, the PDF errors on the gluon-fusion and VBF production modes are reduced by nearly a factor of 2 with respect to NNPDF 3.0

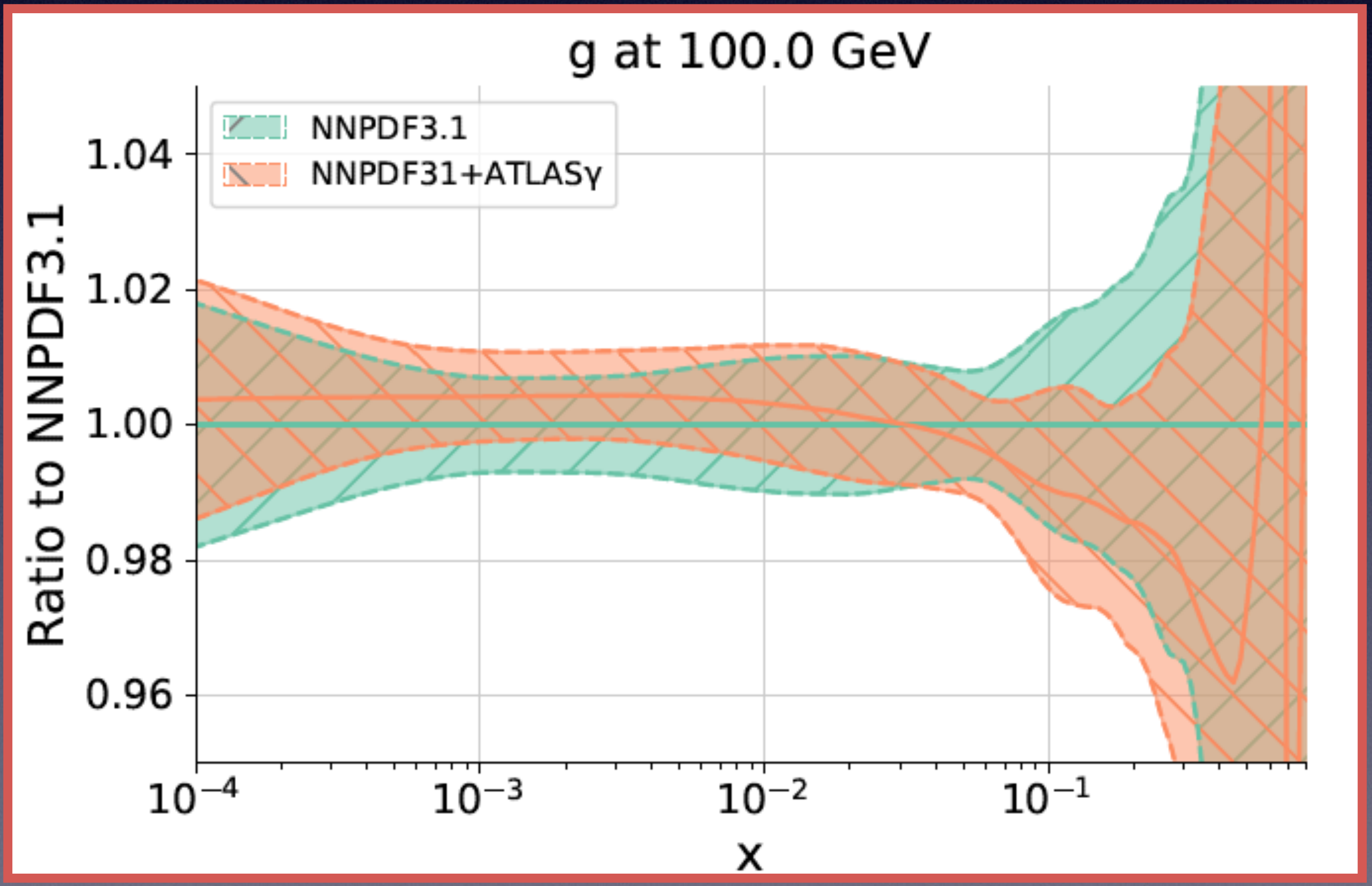


NNPDF3.1

PDFs from γ+jet

- Can also learn about gluon PDFs from direct photon production at the LHC. Sensitivity occurs already at LO through QCD Compton Scattering qg→**γ**q





Campbell, Rojo, Williams, 2018

- Can now use NNLO predictions for **γ**+jet @ LHC
- Moderate reduction of gluon PDF uncertainties in the region $10^{-3} \lesssim x \lesssim 0.4$
- Can incorporate this in future global PDF fits

Future Directions

- All relevant 2→2 predictions for jet processes are now available. For some of these processes approximations were used at NNLO (eg. infinite top mass limit for H+j) that need to be improved upon when studying high pT regions. Work is in progress to go beyond what we have:

  - **Direction 1**: 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, 2018); Abreu, Febres Cordero, Ita, Page, Zeng (2017, 2019); …)

  - **Direction 2**: 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 (2016-2017); Ablinger et al (2017); Broedel, Duhr, Dulat, Tancredi (2017); Caola, Lindert, Melnikov, Monni, Tancredi, Wever (2018),…)

Summary

- All relevant predictions for $2 \to 2$ jet processes are now available at NNLO in QCD. In general good agreement with LHC data was observed. However few theoretical issues still remain to explore (scale choice, jet radius dependence, …)
- These results are having an important impact on improving our understanding of PDFs
- Ongoing work to go beyond the available $2 \to 2$ results and improve the existing approximations for NNLO predictions