NNLO Jet Phenomenology for the LHC

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University of California, Santa Barbara

Outline

- Motivation and introduction
- The need for NNLO QCD
- N-jettiness as a subtraction scheme
- Jet phenomenology at NNLO: W+jet, Z+jet, H+jet at the LHC; comparison with LHC data
- Summary

What is our precision goal for LHC Run II?

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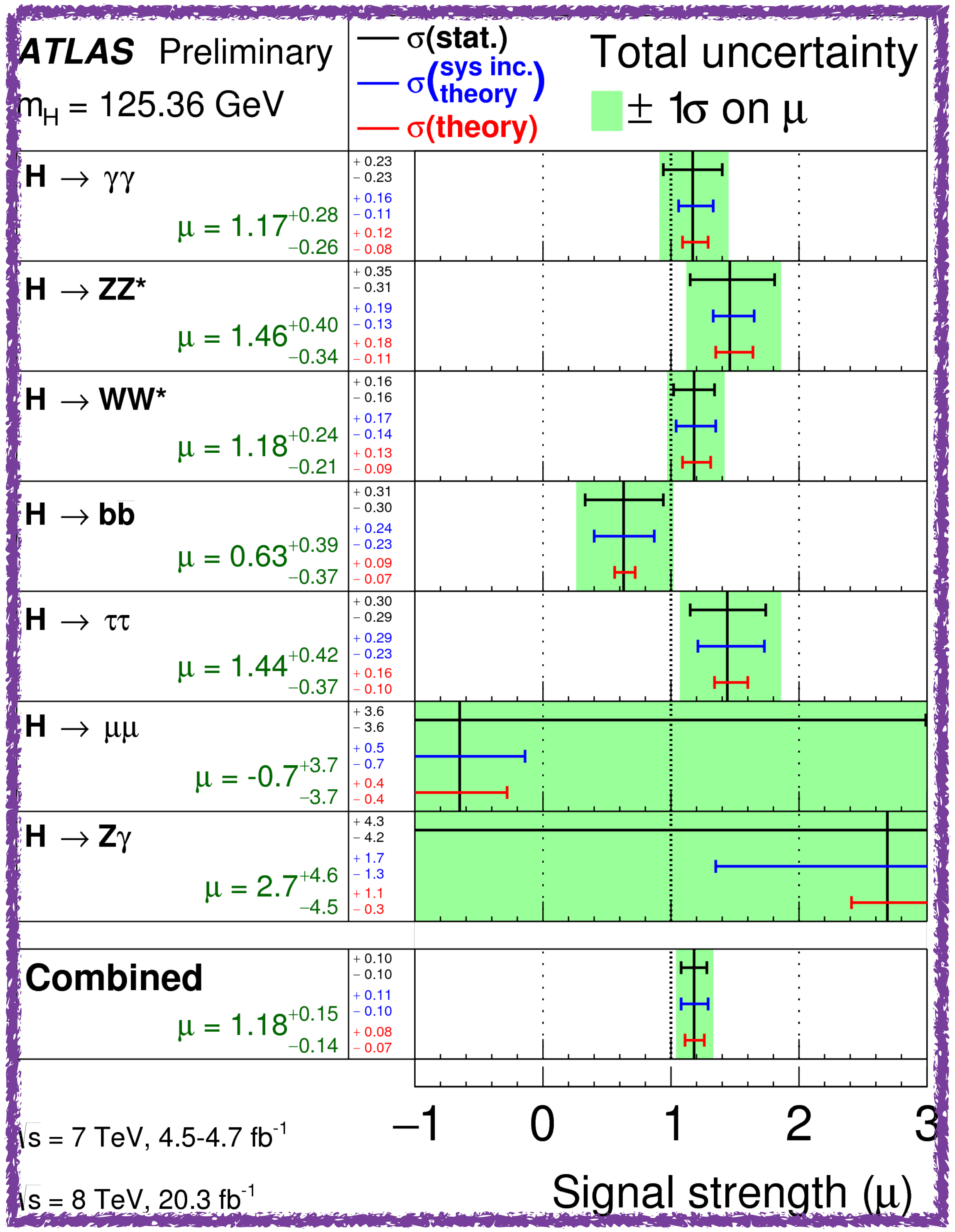
This is set by the experimental accuracy. Consider a few examples.

Higgs production



- The dominant component of the systematic error on the signal strength is theory (~10-15%).
- The statistical error from LHC Run I is the largest (~20%), this however will improve during LHC Run II.

HL-LHC prospects:

x2.5 increase in cross section

x15 increase in luminosity (300 fb^{-1})

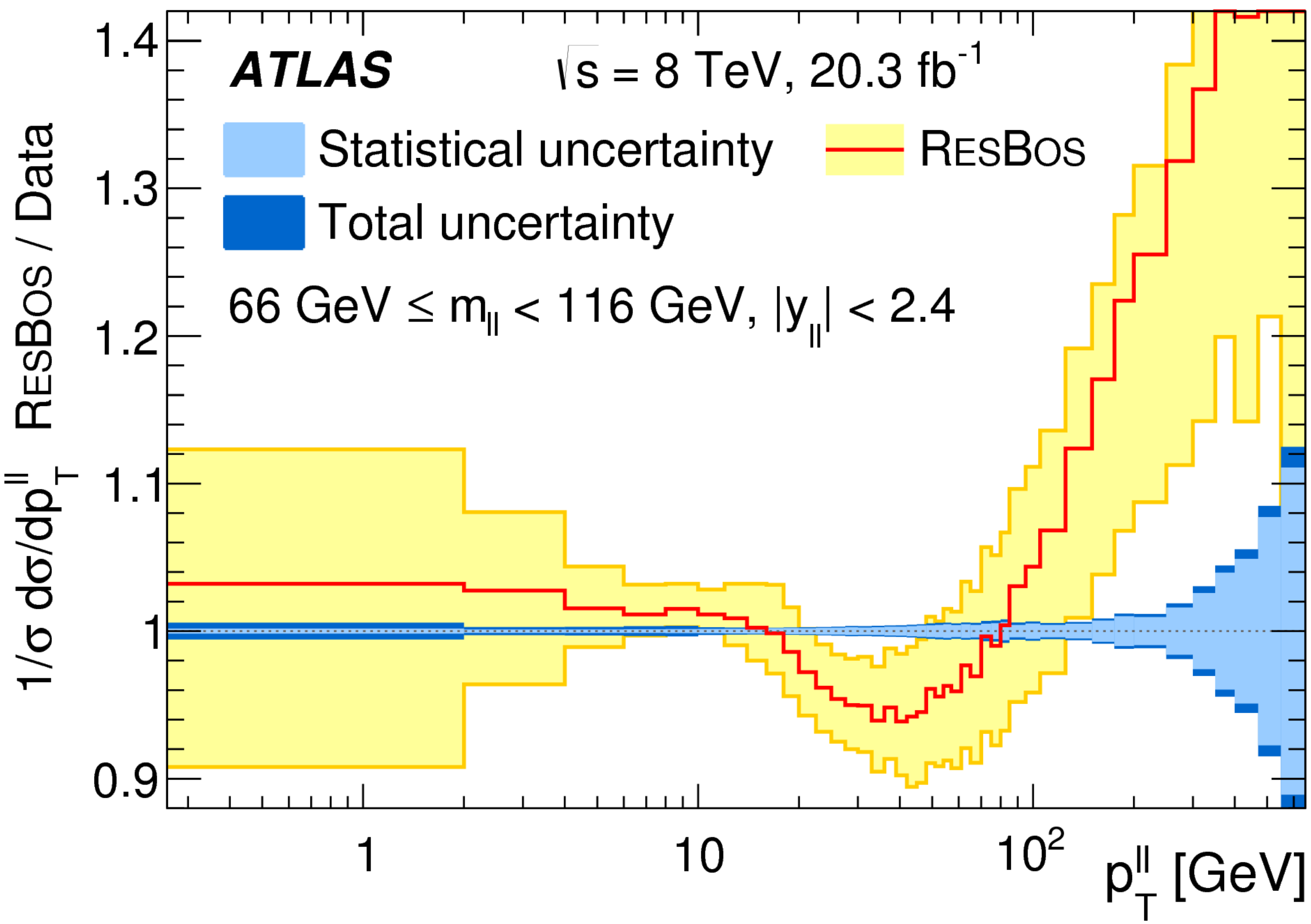
~ 40 times more events

Stat. error in 3-4% range

Theory error becoming a limiting factor in Run II

W/Z+1jet

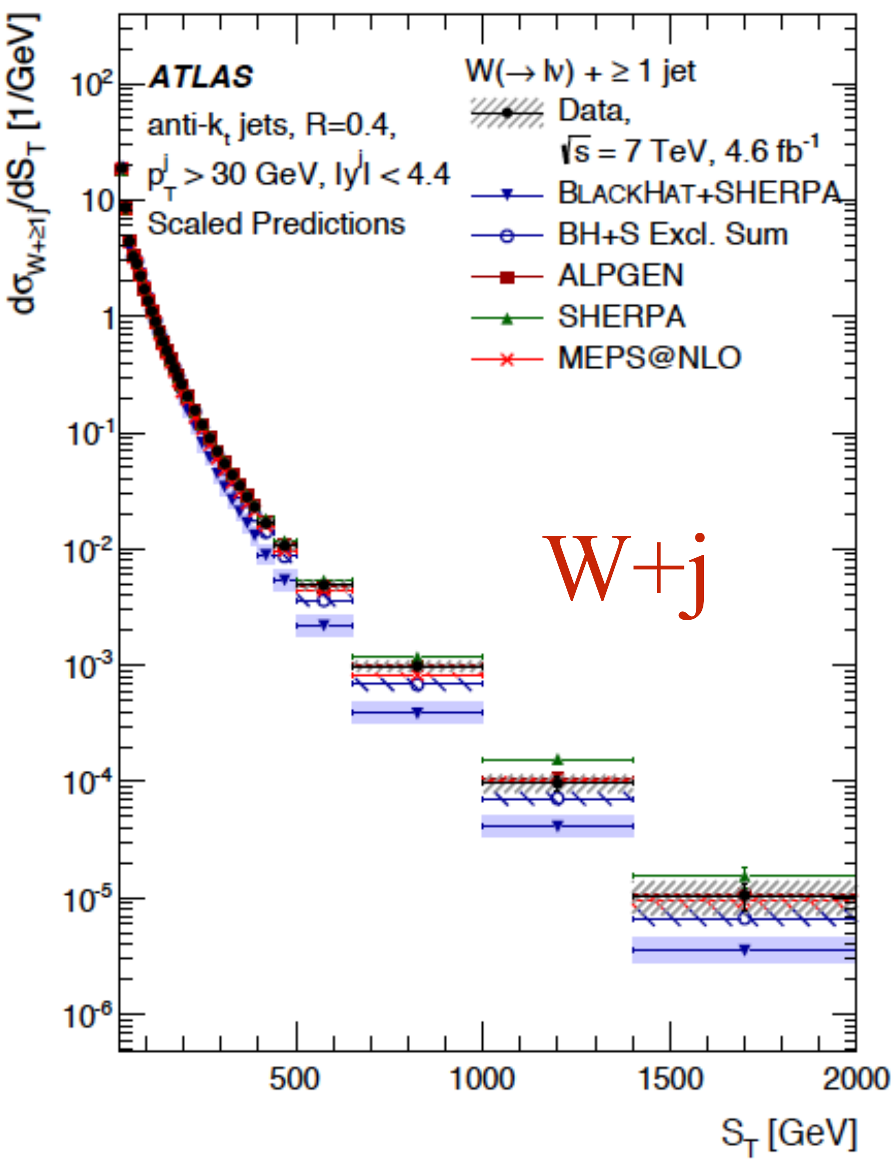
- They provide stringent tests on the SM, as they are measured with small errors over a large energy range. Important for improving PDFs, and detector calibration as well.



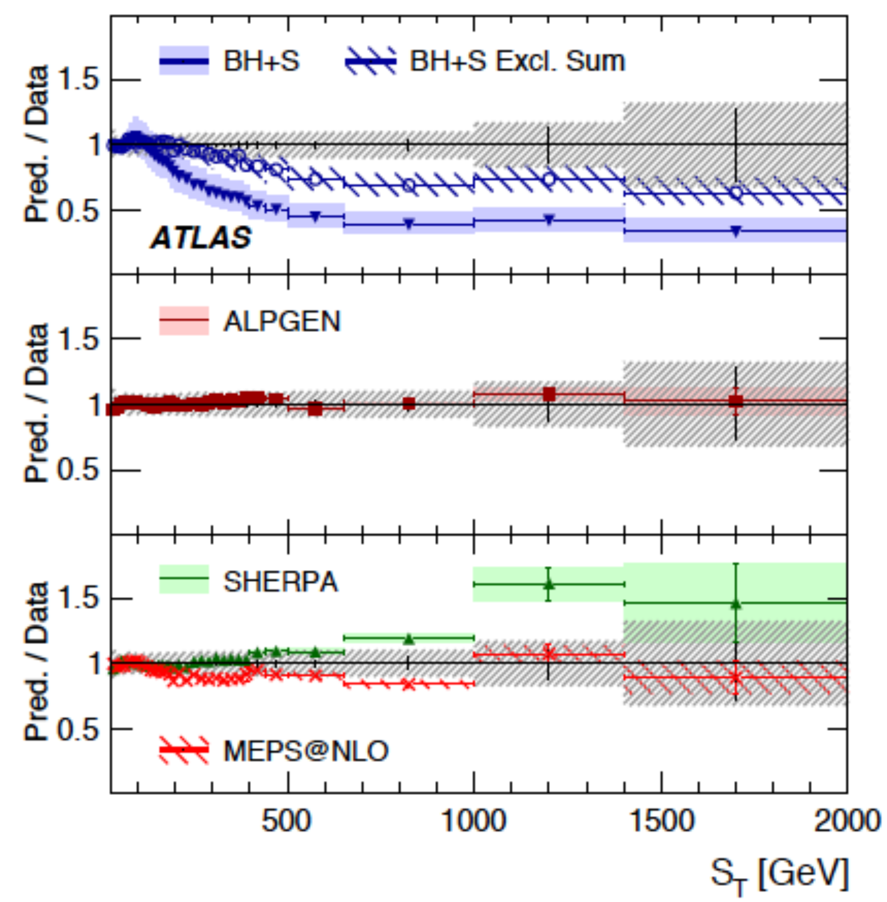
Total experimental uncertainty up to 200GeV for the P_{TZ} is < 1%

H_T Distribution

- An other example: H_T, it is the scalar sum of the transverse momenta of all reconstructed jets, and is called S_T by ATLAS.



1409.8639



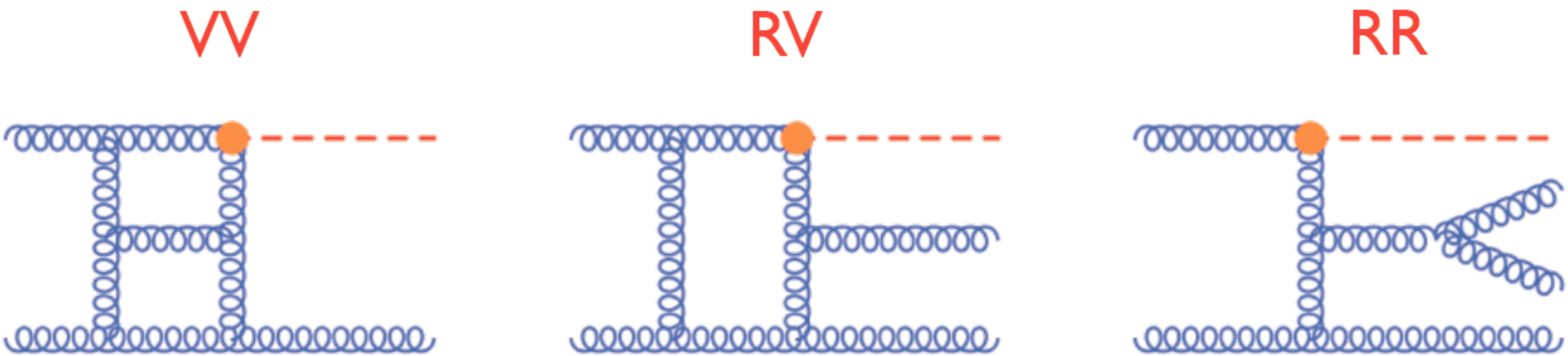
- S_T distributions in W+j and Z+j exhibit mixed agreement with theoretical predictions. NLO QCD predictions and exclusive sum approach **undershoot** the data in the highest-S_T region. Some parton shower simulations **overshoot** the high-S_T data and others don't.

H_T Distribution

NLO QCD and parton showers are not always enough to explain data, need to go beyond

Ingredients for NNLO Calculations

- Need the following ingredients for NNLO cross sections



- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

$$\int \left[\frac{vv_4}{\epsilon^4} + \frac{vv_3}{\epsilon^3} + \frac{vv_2}{\epsilon^2} + \frac{vv_1}{\epsilon} + vv_0\right] \, d\Phi_2$$

$$\int \left[\frac{rv_2}{\epsilon^2} + \frac{rv_1}{\epsilon} + rv_0\right] \, d\Phi_3$$

$$\int [rr_0] \, d\Phi_4$$

Ingredients for NNLO Calculations

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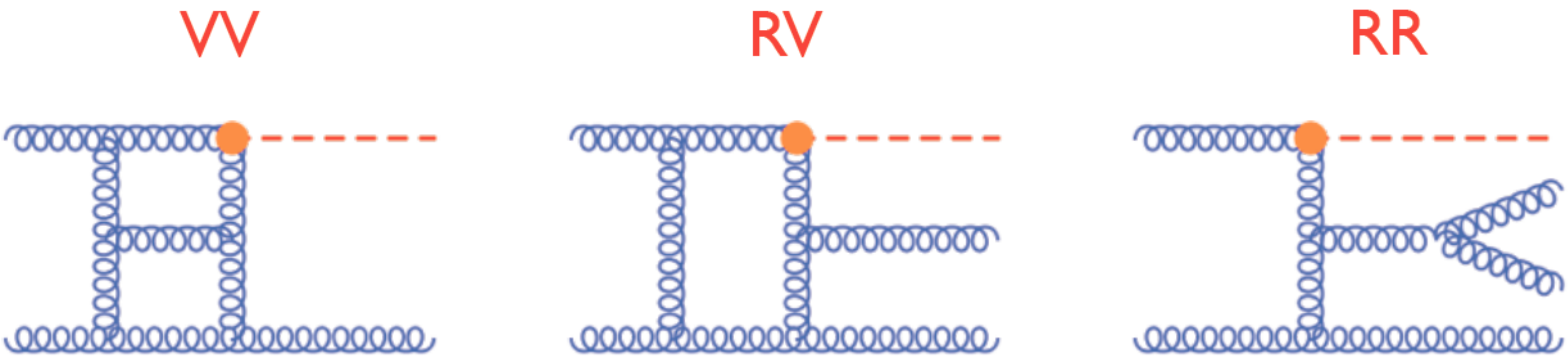

- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations.

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

- A generic procedure to extract IR singularities from RR and RV was unknown when jets in the final state are involved, until very recently.

Techniques for NNLO

- Numerous proposed techniques for handling singularities at NNLO, which can be divided into two distinct categories:

(quasi-)Local: add and subtract counterterms that approximate real-emission matrix elements in all singular limits

Resummation-assisted: leverage knowledge of analytic resummation to remove double-real emission singularities.

Local:

- Sector decomposition: Anastasiou, Melnikov, Petriello; Binoth, Heinrich
- Antennae subtraction: Kosower; Gehrmann, Gehrmann-de Ridder, Glover
- Sector-improved residue subraction: Czakon; RB, Melnikov, Petriello
- Colorful subtraction: Del Duca, Somogyi, Trocsanyi
- Projection-to-Born: Cacciari, Dreyer, Karlberg, Salam, Zanderighi

RG-assisted:

- q_T-subtraction: Catani, Grazzini
- N-jettiness subtraction: RB, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

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N-jettiness

- N-jettiness, τ_N, is an event-shape variable designed to veto final-state jets Stewart, Tackmann, Waalewijn 0910.0467

$$\mathcal{T}_N = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i} \right\}.$$

N=number of final-state jets

Momenta of the two beams and the final-state jets

Measure of the jet hardness (we take $Q_i=2E_i$)

All final-state partons

N jets ← small — $\mathcal{T}_N$ — large → more than N jets

Small N-jettiness vetoes events with more than N-jets

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Momenta of the two beams and the final-state jets

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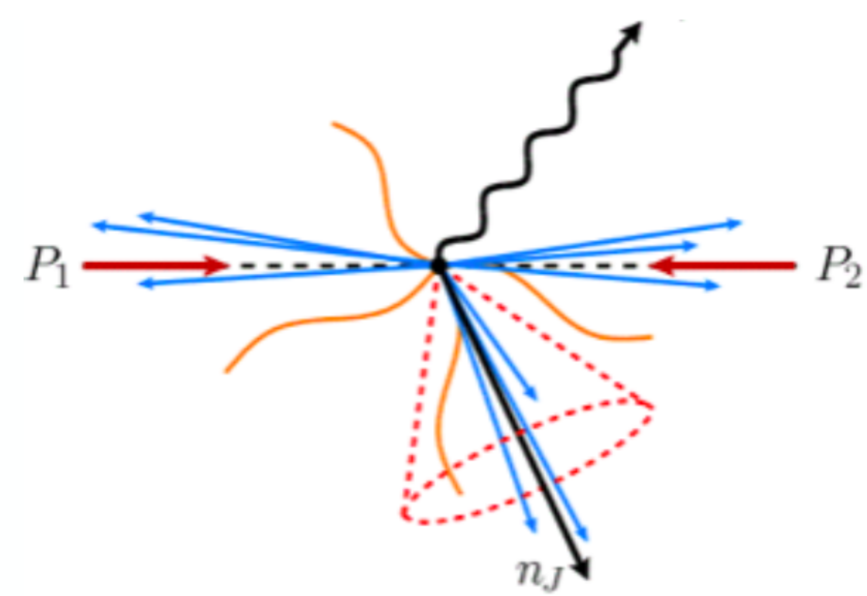
All final-state partons

τ_N=0: all radiation is either soft, or collinear to a beam/jet; at NNLO, gives the double-unresolved limit.



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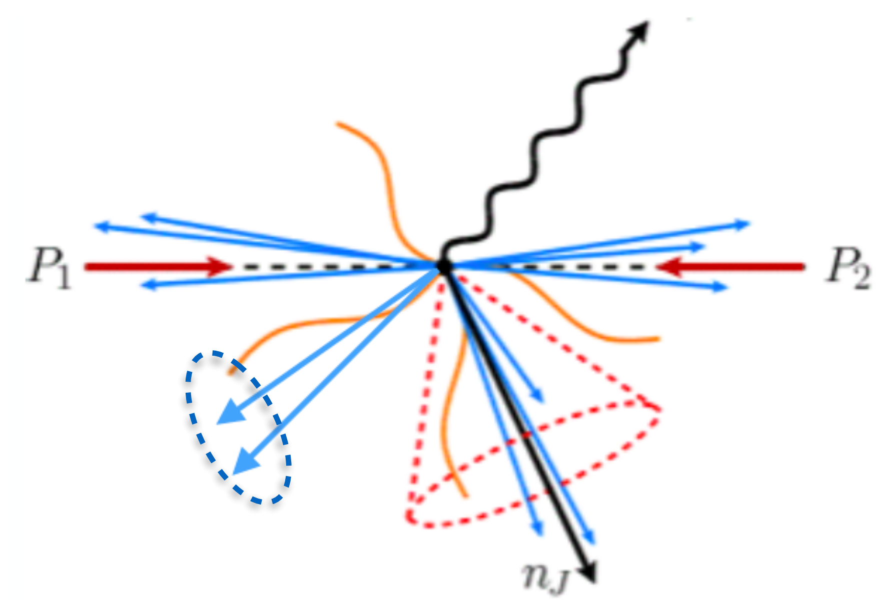
All final-state partons

τ_N>0: at least one additional radiation is resolved; have N+1 final-state jets.



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Momenta of the two beams and the final-state jets

All final-state partons

Measure of the jet hardness (we take Q_i=$2E_i$)

This is the resolution parameter we are looking for!

N-jettiness subtraction

- N-jettiness can be applied to obtain exact NNLO cross sections

RB, Focke, Liu, Petriello 1504.02131

- Introduce τ_N^{cut} that separates the $\tau_N=0$ doubly-unresolved limit of phase space from the single-unresolved and hard regions

$$\sigma_{NNLO}(\mathcal{T}_N < \mathcal{T}_N^{cut})$$

contribution from all double unresolved singularities, including double soft, triple collinear, soft-collinear, etc

$$\sigma_{NNLO}(\mathcal{T}_N > \mathcal{T}_N^{cut})$$

contribution from everything else, with at least N+1 hard radiations present in the final state

N-jettiness subtraction

- For $\tau_N > \tau_N^{cut}$, at least one of the two additional radiations that appear at NNLO is resolved; this region of phase space contains the NLO correction to the N+1 jet process. Can be obtained from any NLO program.

- For $\tau_N < \tau_N^{cut}$, both additional radiations are unresolved. A factorization theorem giving the all-orders result for small N-jettiness was derived Stewart, Tackmann, Waalewijn 0910.0467

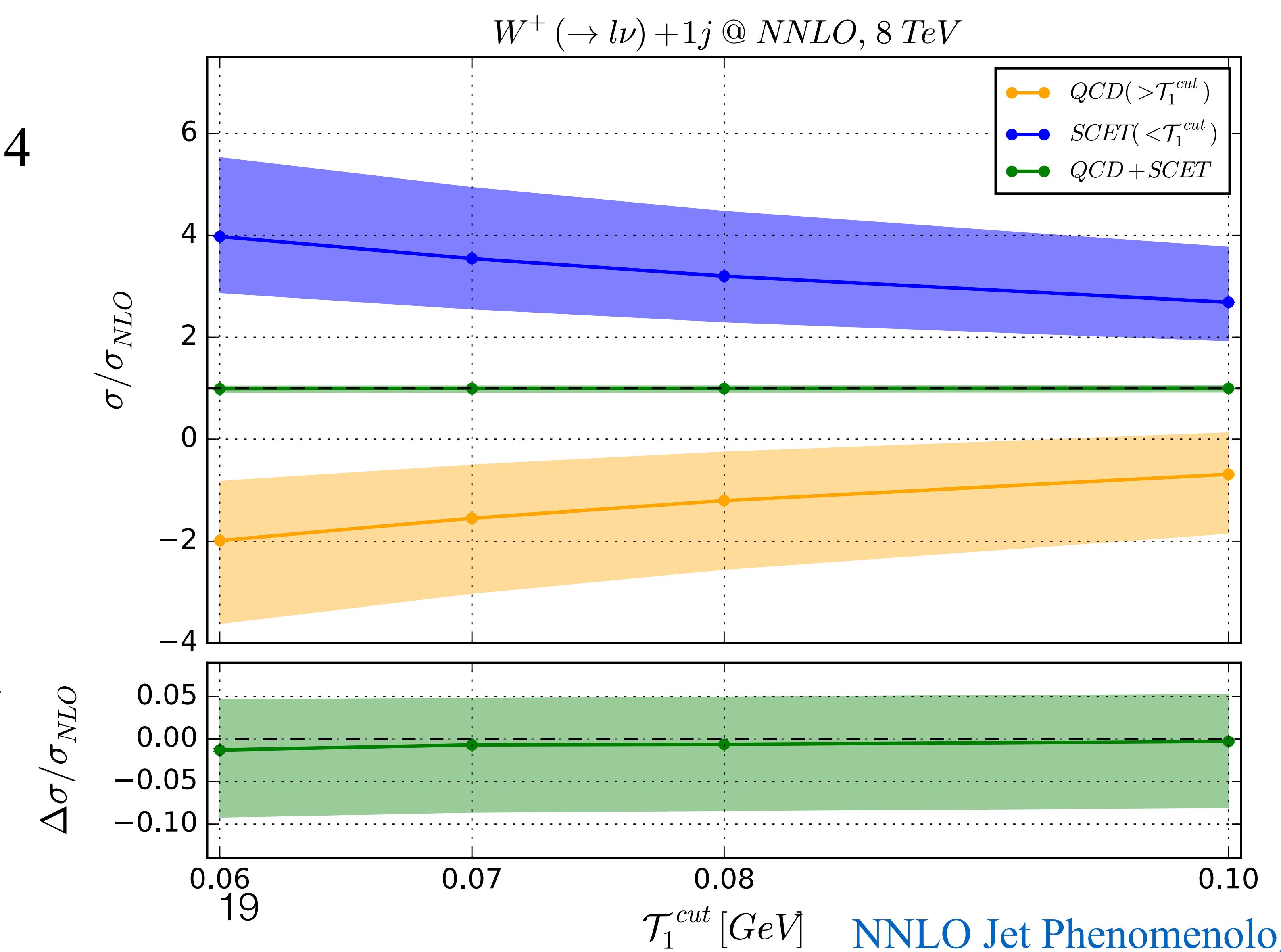
$$\sigma(\tau_N < \tau_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right] + \cdots \; .$$

τ_N^{cut} must be much smaller than any hard scale in the process and any experimental cuts in order to suppress power corrections. Final result must be independent of τ_N^{cut}

W+jet@NNLO: validation

- A powerful check of the N-jettiness subtraction formalism is the independence of the final result from τ_N^{cut}.
- The above-cut and below cut contributions separately depend on $\ln^n(\tau_N^{cut})$, where n ranges from 1 to 4 at NNLO. This dependence must cancel when the two regions are summed.

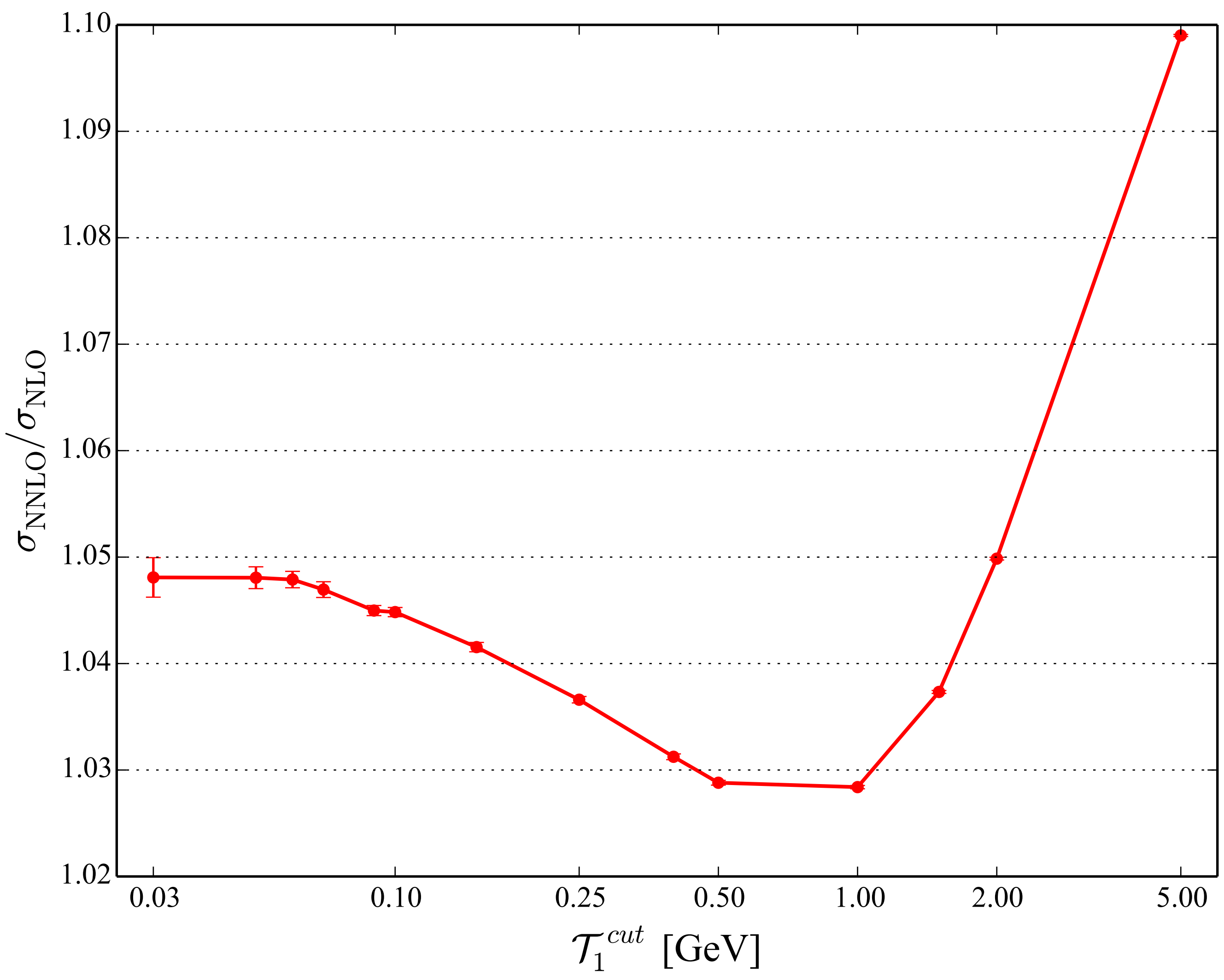
  - CMS cuts: $p_{TJ}>30$ GeV, $|\eta_J|<2.4$
  - CT10 PDFs, $\mu_0=M_W$, vary by factor of 2 to estimate error
  - NLO prediction using N-jettiness agrees with known results.
  - Sum of above-cut and below-cut contributions stable to better than 0.1% of σ_{total}



Z+jet@NNLO: validation

- How do the power corrections in τ^{cut} look like for the Z+j process?

R.B., Campbell, Ellis, Focke, Giele, Liu, Petriello, 2016



- Factorization theorem behaves as expected, the power corrections are important at high τ^{cut}
- Power corrections are not just linear, they contain logarithms of τ^{cut}/Q
- There is a region where we have no dependence on the power corrections. This is the region where the prediction is taken from

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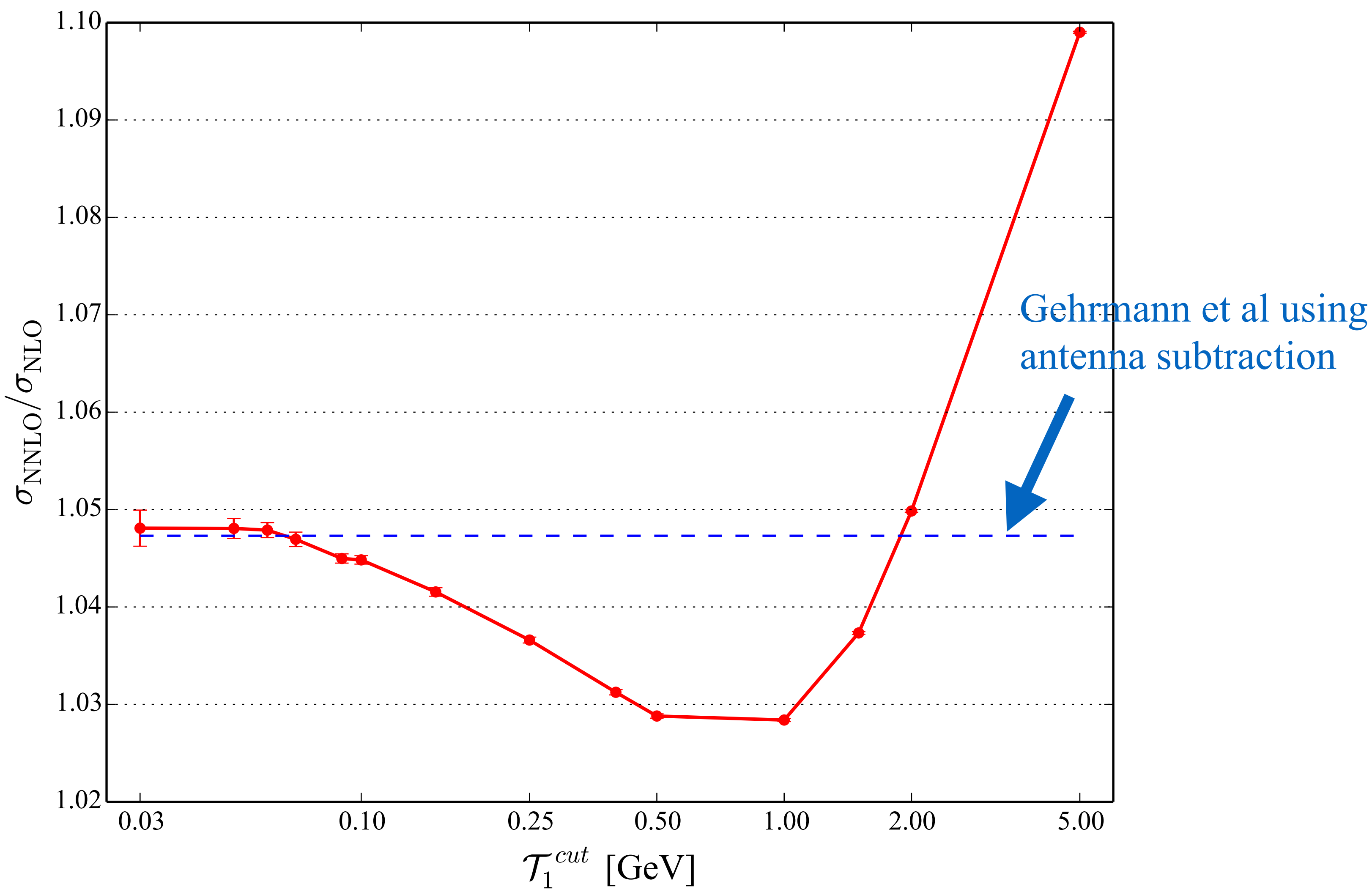

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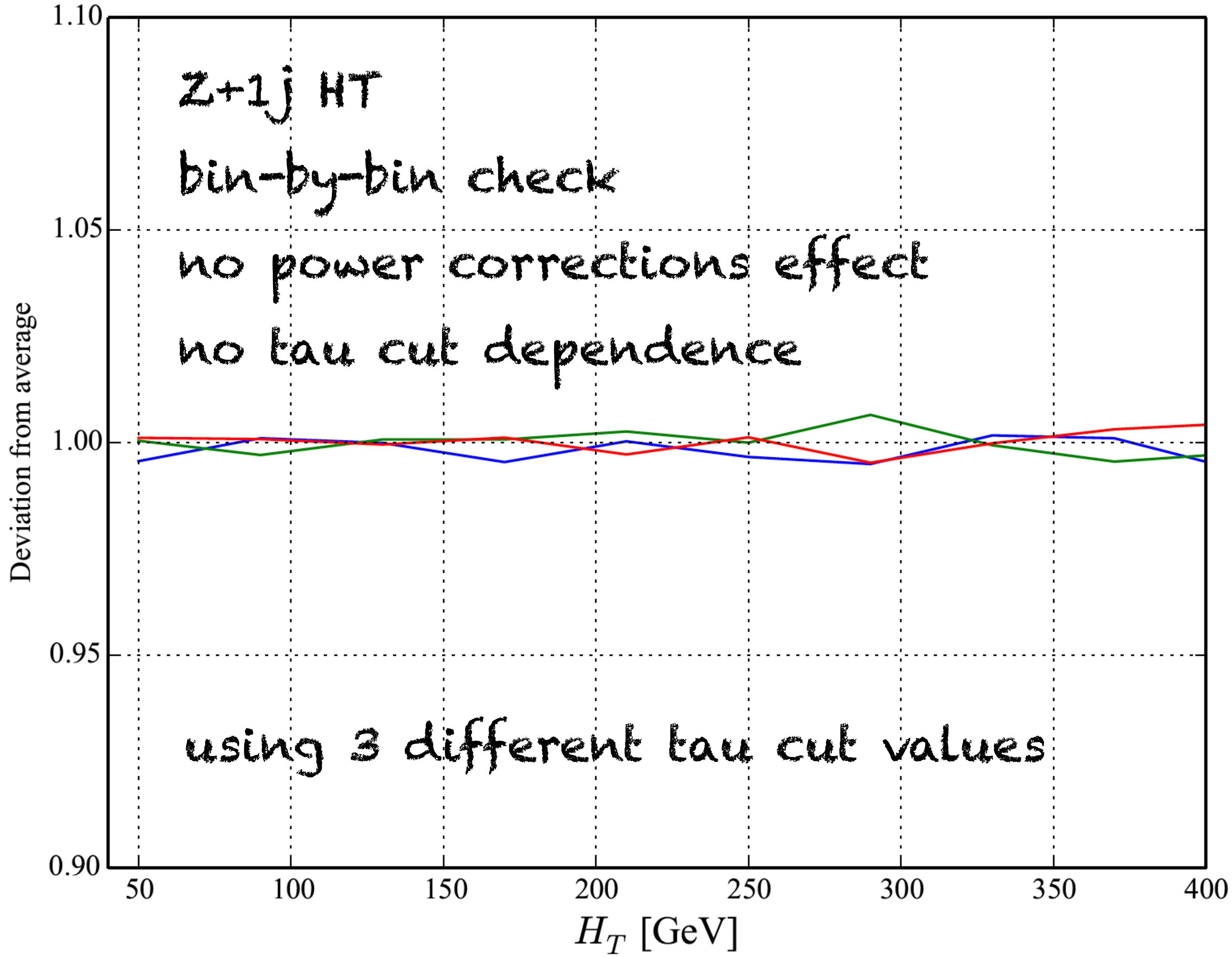


H+jet@NNLO: validation

- The production of the Higgs at high-p_T will provide an important probe of BSM physics in Run II
- Need improvement on two fronts:

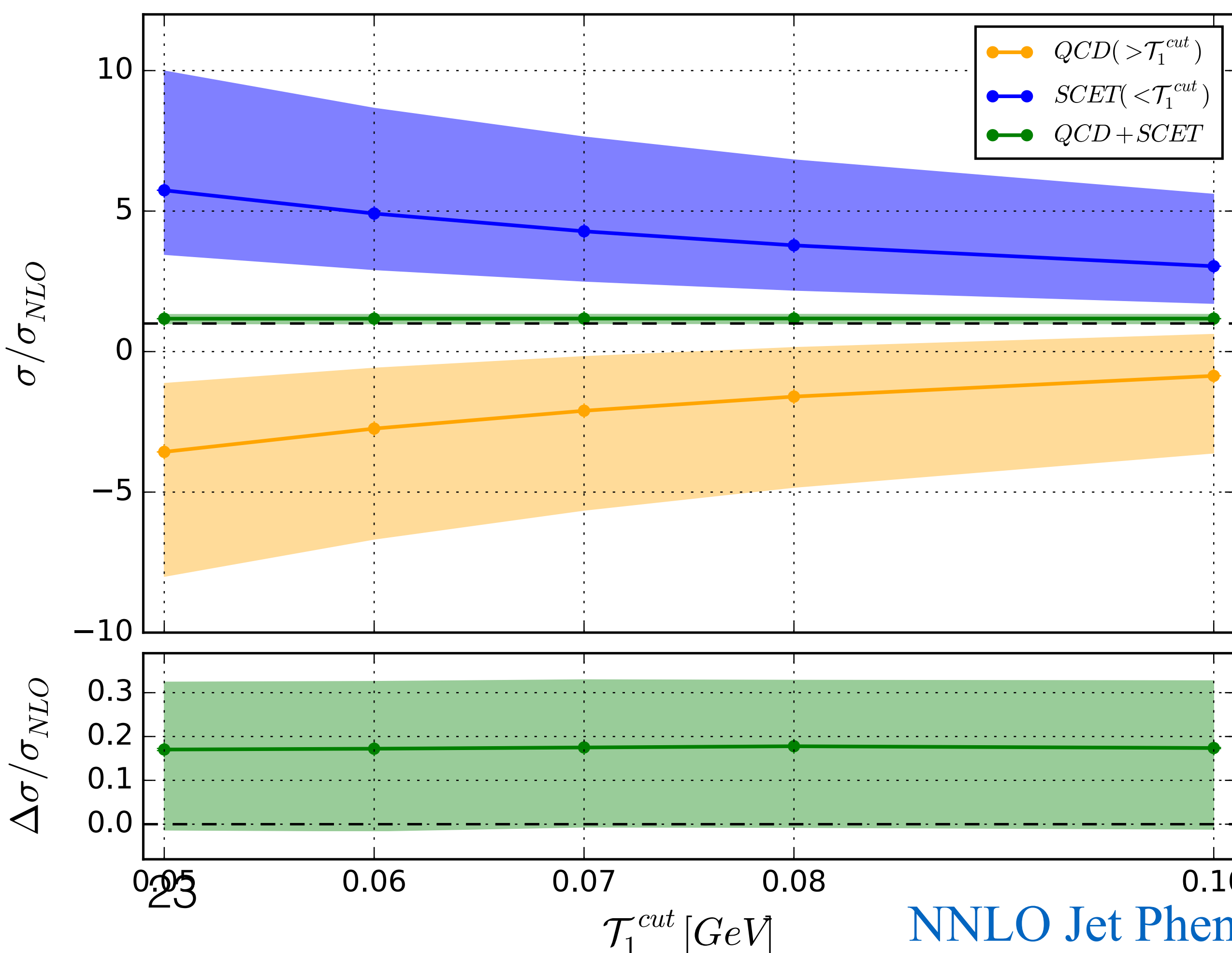
Our focus

O(α_S) corrections to $1/m_t$ suppressed operators

O(α_S^2) correction in the $m_t \to \infty$ limit

Harlander, Neumann, Ozeren 1206.0157;
Dawson, Lewis, Zeng 1409.6299

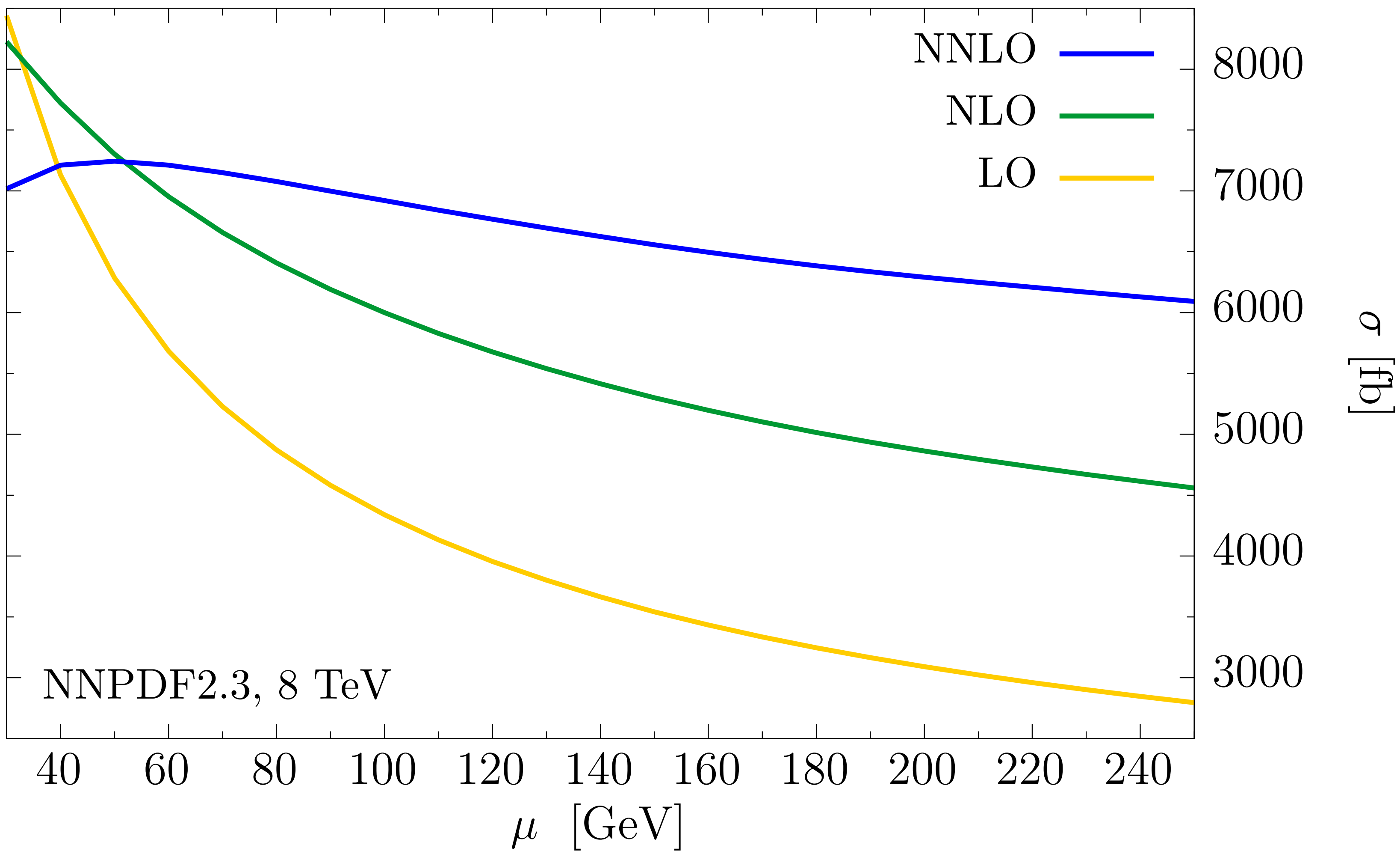
R.B., Focke, Giele, Liu, Petriello 1505.03893



- p_{TJ}>30 GeV, $|\eta_J|$<2.4, R=0.5
- NNPDF PDFs, μ_0=M_H, vary by factor of 2 to estimate error
- Perfect stability with respect to varying τ^{cut}

H+jet@NNLO: validation

- An additional check is possible in this case. The dominant qg and gg scattering channels were also computed using the sector-improved residue subtraction technique R.B., Caola, Melnikov, Petriello, Schulze 1504.07922



- Agreement between the two calculations at the per-mille level
- Effect of missing qq channels in the sector-improved calculation at the 1-2% level
- Reduced scale dependence at NNLO; preference for smaller scales

Important validation of NNLO calculational technology!

H+jet@NNLO: validation

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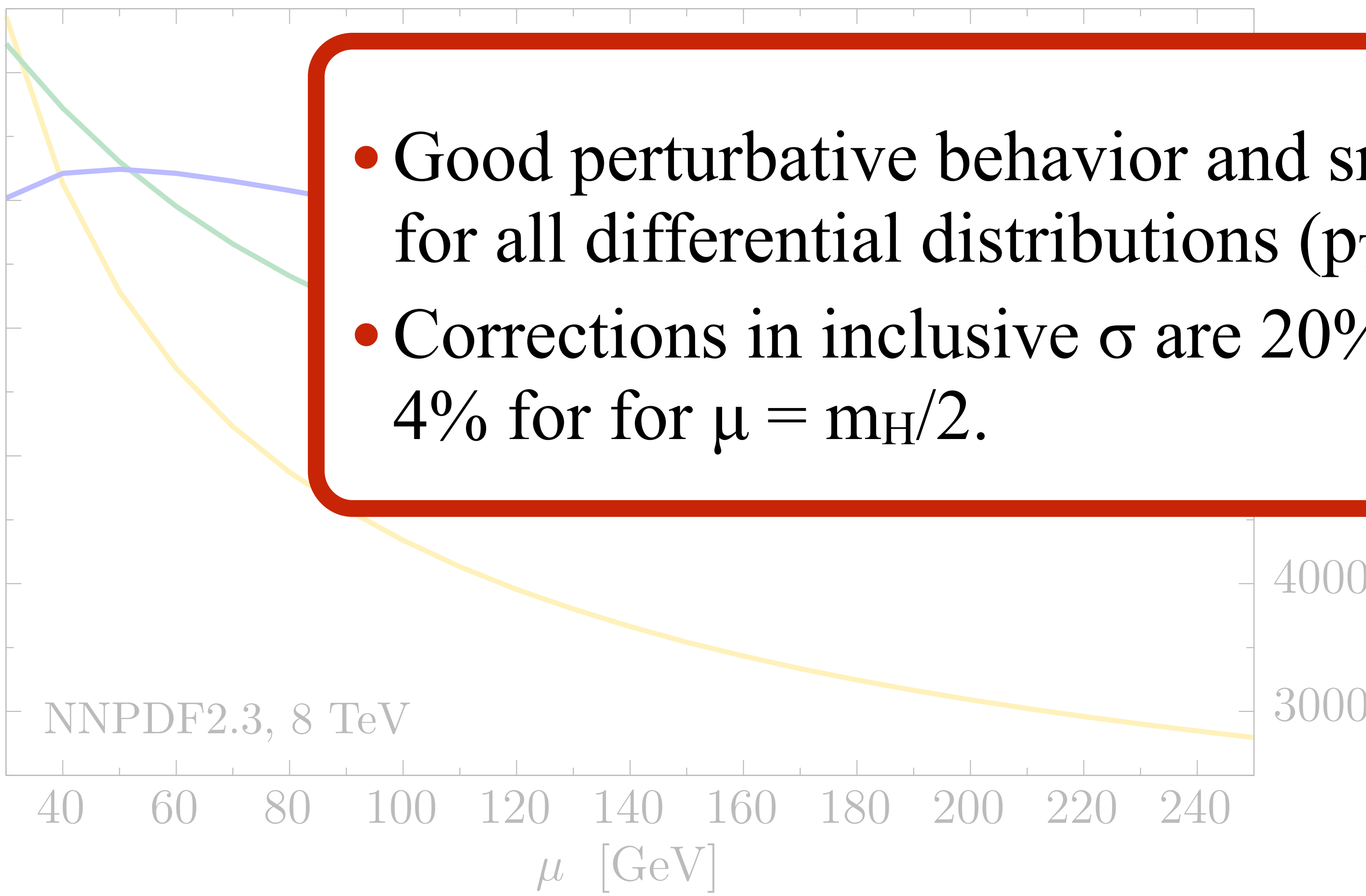

- Good perturbative behavior and smaller uncertainties for all differential distributions (p_{TH}, p_{Tj}, Y_j)
- Corrections in inclusive σ are 20% for for $\mu = m_H$ and 4% for for $\mu = m_H/2$.

...tween the ... at the per-

...ing qq ...ector- ...ation at the 1-2% level

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Important validation of NNLO calculational technology!

Comparison to data

W/Z+jet Processes

- During LHC Run I, ATLAS and CMS probed jet momenta in W/Z+j up to 1TeV. These results were compared for 7 TeV with a wide range of QCD predictions: merged tree level + parton shower, NLO+parton shower, etc. Many distributions had mixed agreement between the data and the available theory predictions.

- In all the comparisons shown next we do the following:
  - Use CT14NNLO PDFs for NNLO results, CT14NLO for NLO results
  - Vary muF and muR independently
  - A correction factor for non-perturbative effects for p_{Tj} and y_j is accounted for for ATLAS (no correction factor was provided by CMS)
  - A correction factor for QED FSR is included for P_{Tj} and y_j for ATLAS (no correction factor was provided by CMS)

Fiducial Cross Sections For Inclusive W+j

RB, Liu, Petriello 1602.05612

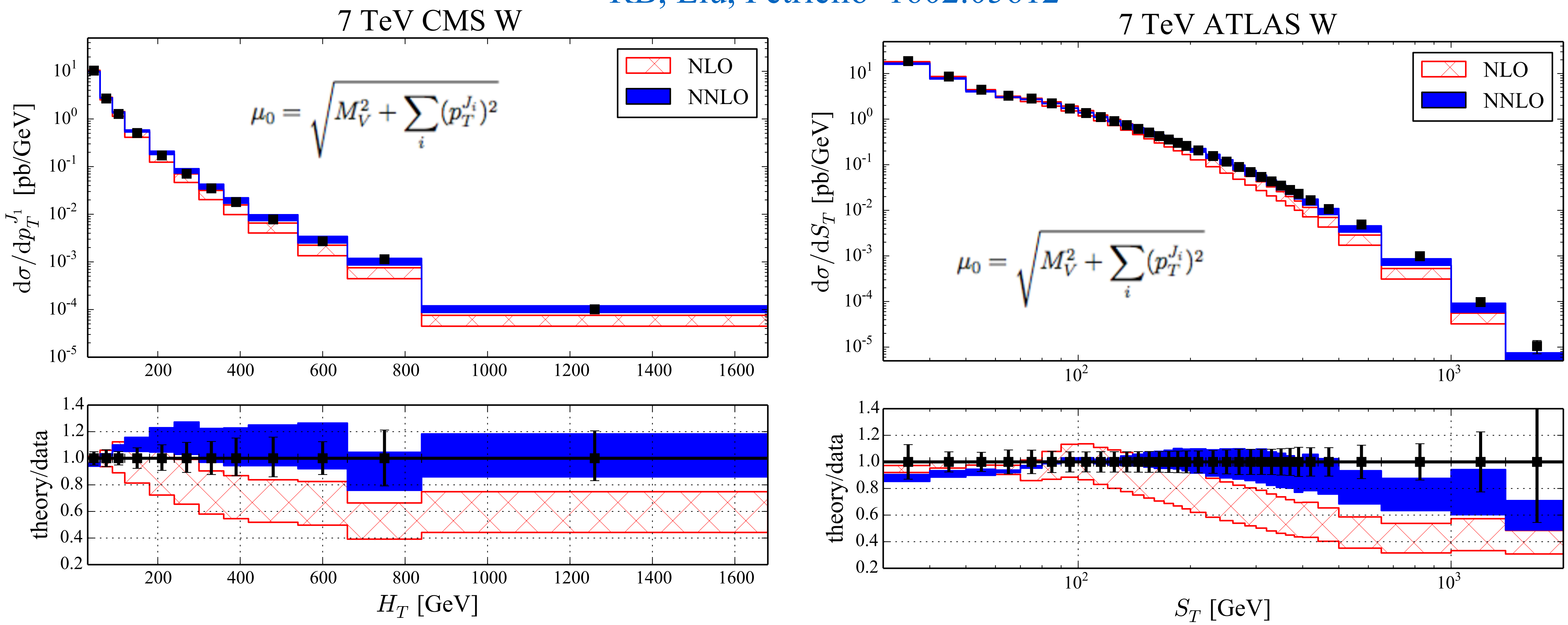
- For CMS cuts NNLO corrections lead to better agreement between the prediction and the measurement.
- For ATLAS cuts NNLO result is slightly below the measured value, but within the 1-σ experimental error.
- NNLO result decreases the residual scale dependence from ±5% at NLO to ±1% at NNLO.

W-boson cuts	ATLAS [10]	CMS [11]
lepton p_T	$p_T^l > 25$ GeV	$p_T^l > 25$ GeV
lepton η	$\|\eta^l\| < 2.5$	$\|\eta^l\| < 2.1$
missing E_T	$E_T^{miss} > 25$ GeV	–
transverse mass	$m_T > 40$ GeV	$m_T > 50$ GeV
jet p_T	$p_T^J > 30$ GeV	$p_T^J > 30$ GeV
jet η	$\|\eta^J\| < 4.4$	$\|\eta^J\| < 2.4$
anti-k_T radius	$R = 0.4$	$R = 0.5$

The H_T Distribution

- H_T is the scalar sum of the transverse momenta of all reconstructed jets, and is called S_T by ATLAS.

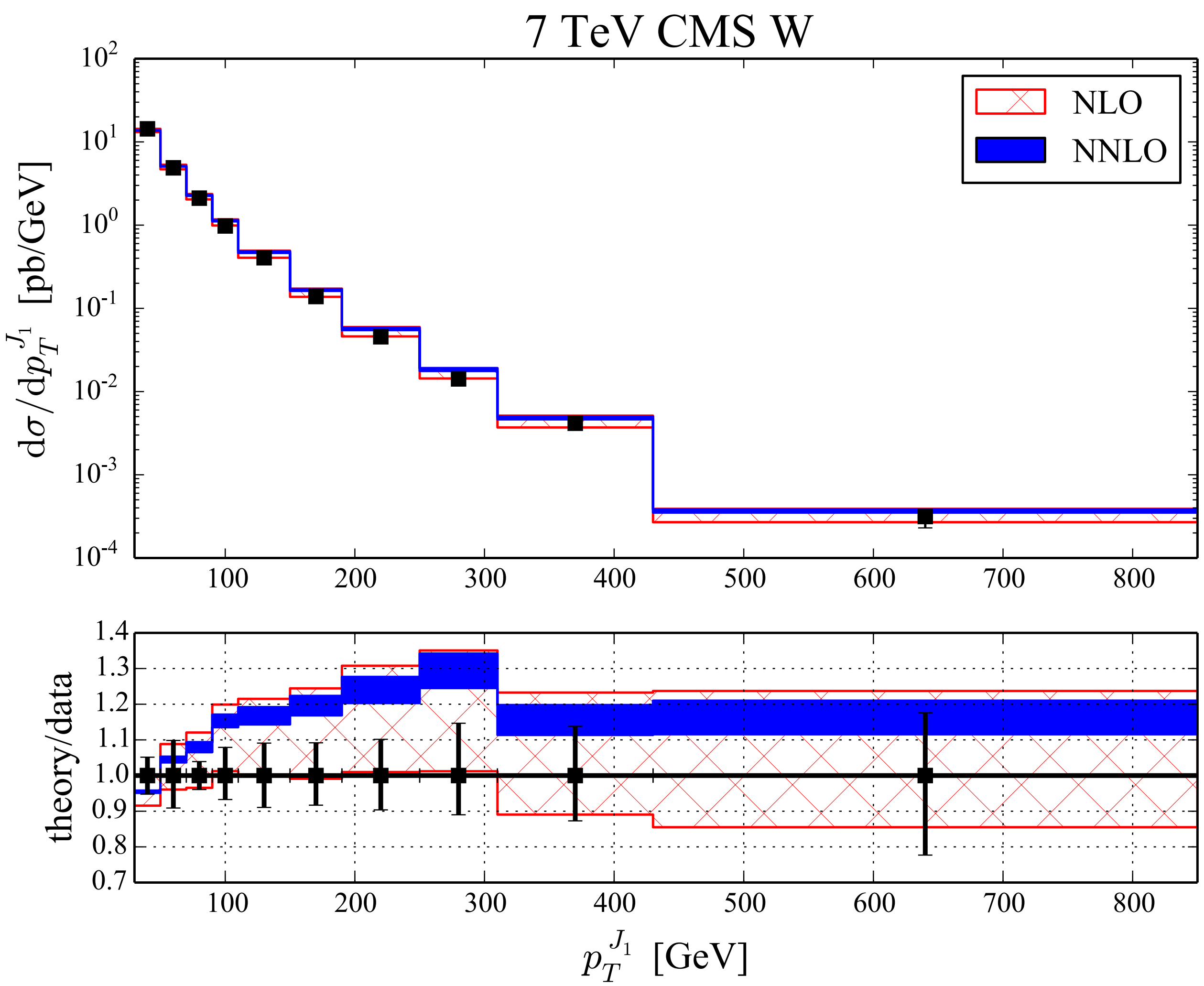
RB, Liu, Petriello 1602.05612

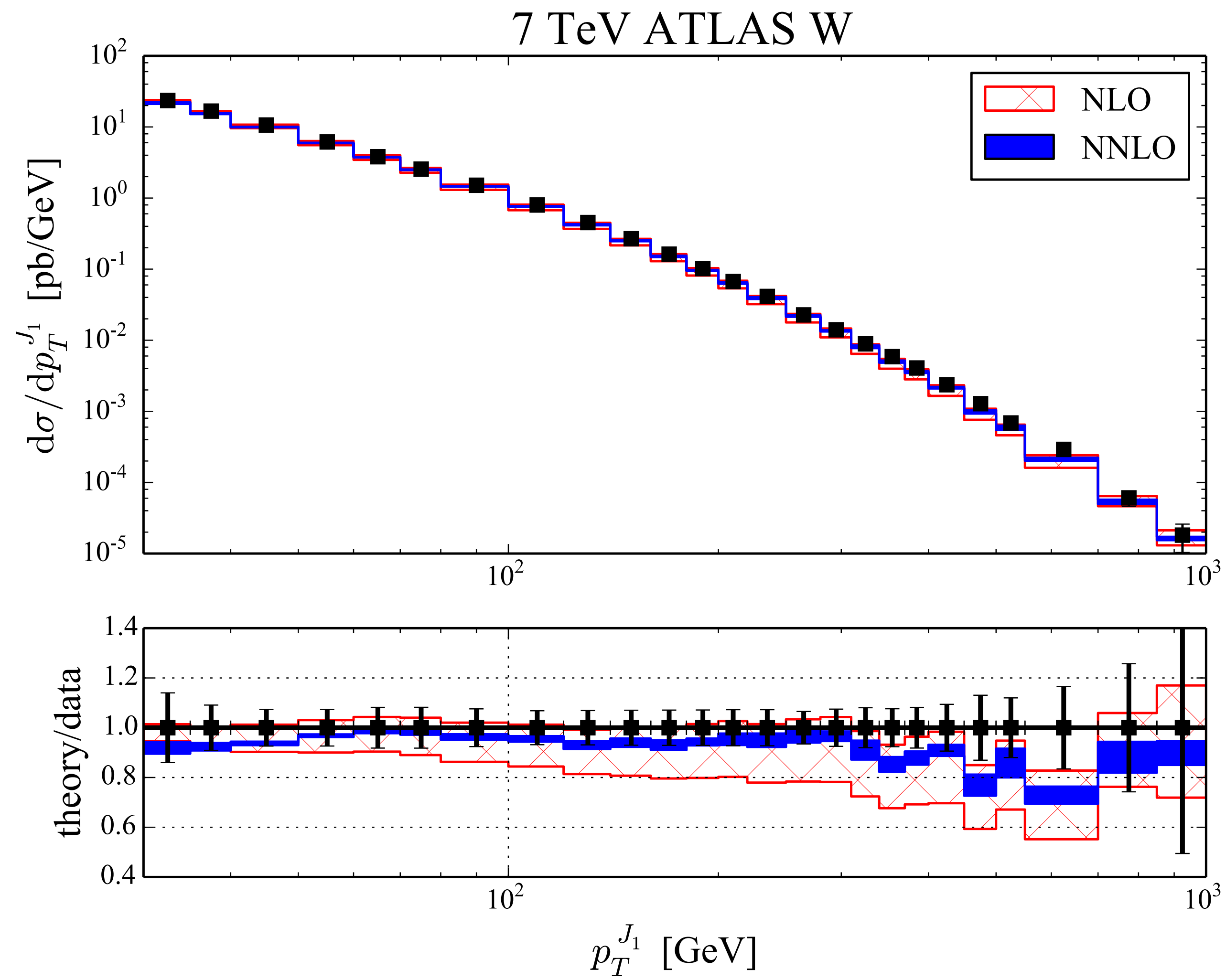


- While NLO QCD results undershoot the ATLAS and CMS data for most of the H_T/S_T range, NNLO QCD corrections lead to a much better description of data over the entire range.

- NNLO correction in the 1-jet bin plays an important role in describing H_T.

Leading Jet Transverse Momentum

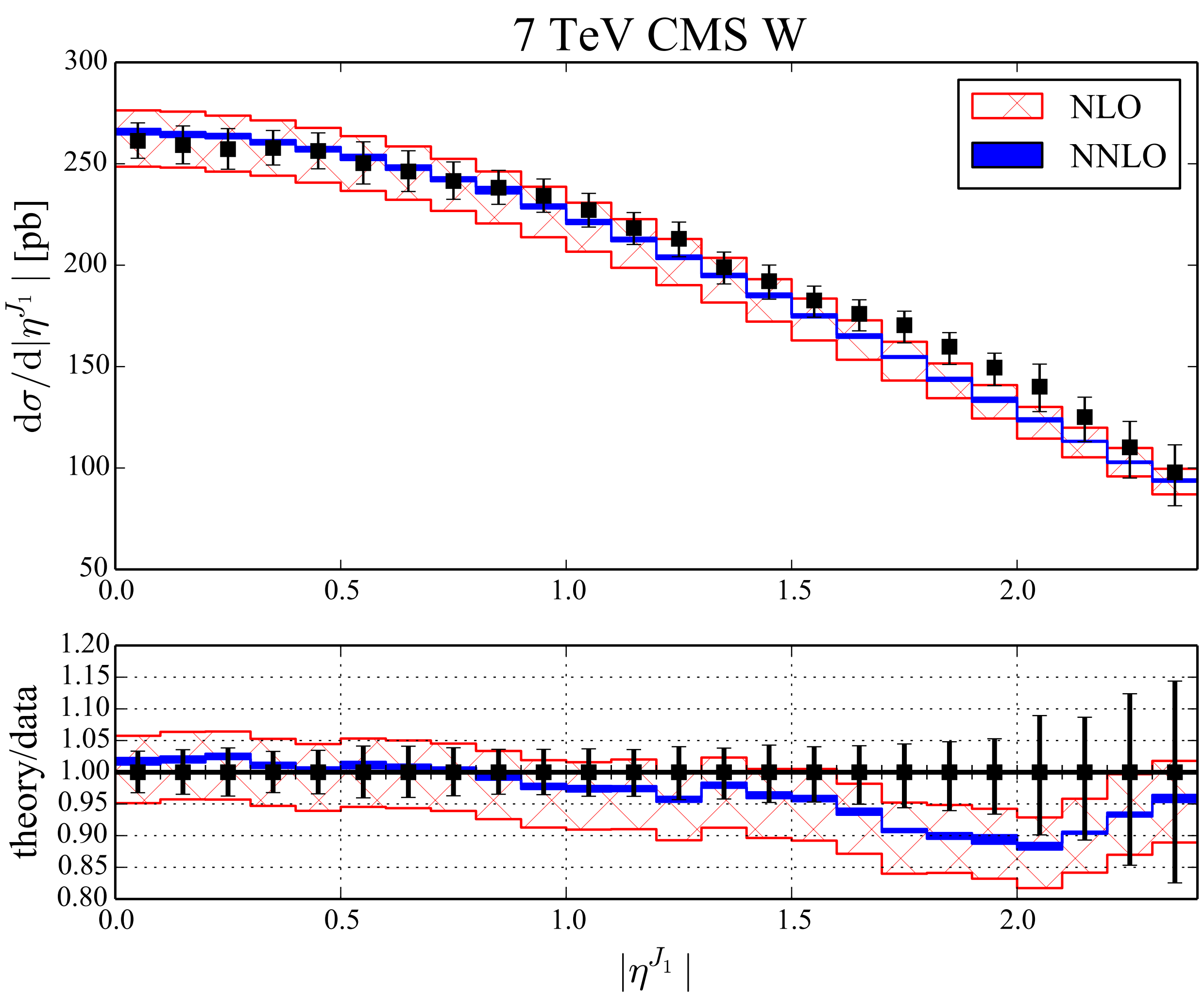


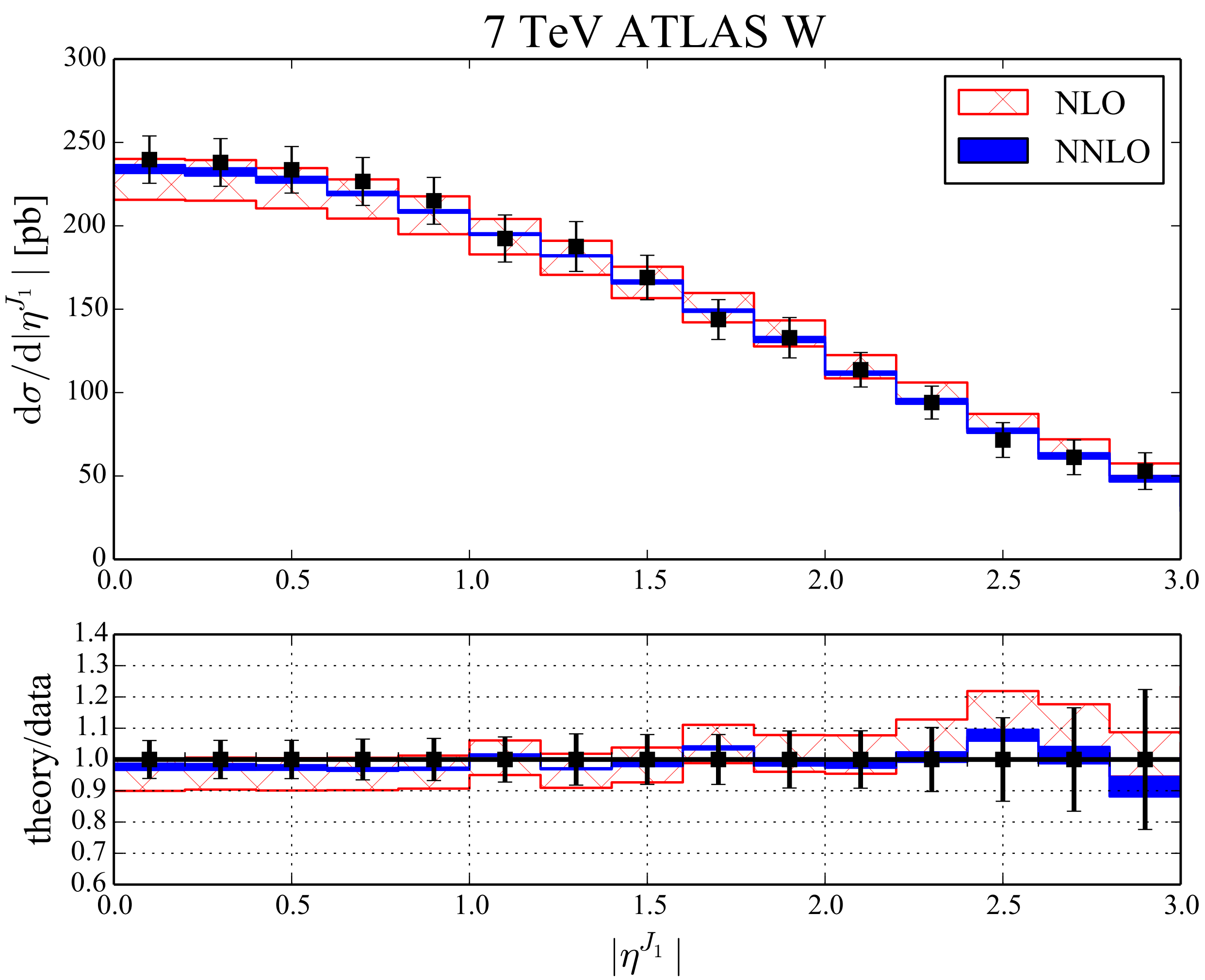


- Good agreement between theory and ATLAS data, with theory slightly undershooting the data. Scale variation error is smaller than the experimental errors throughout the entire studied range.

- Both NLO and NNLO corrections are systematically higher than the CMS data. Similar discrepancies between merged leading-order plus parton-shower and CMS data were observed.

Leading Jet Rapidity Distributions





- Good agreement between the NNLO prediction and ATLAS data over the entire range.
- For CMS, theory predictions agree well with data at central rapidities, but differ slightly at high rapidities.

Fiducial Cross Sections For Inclusive Z+j

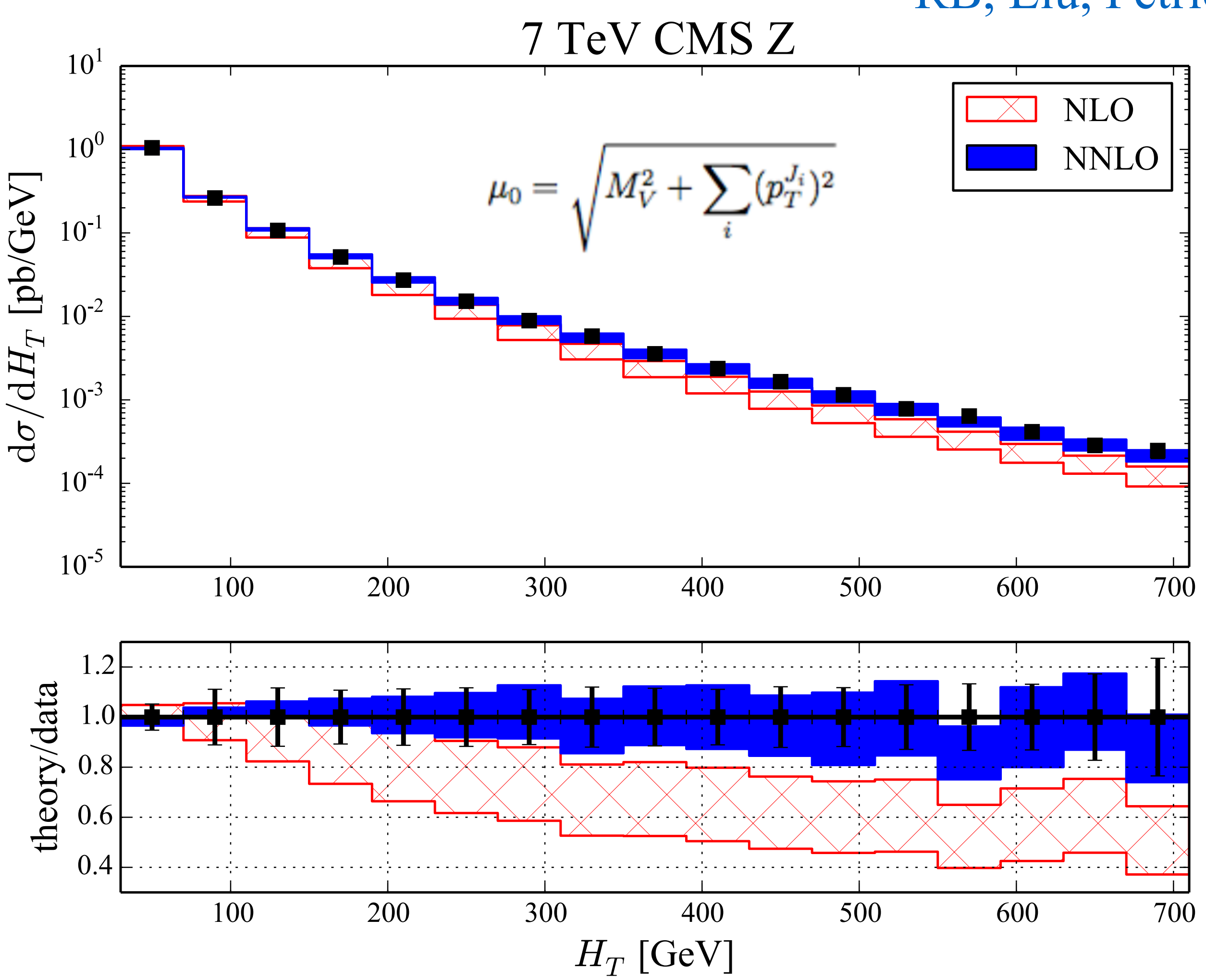
RB, Liu, Petriello 1602.05612

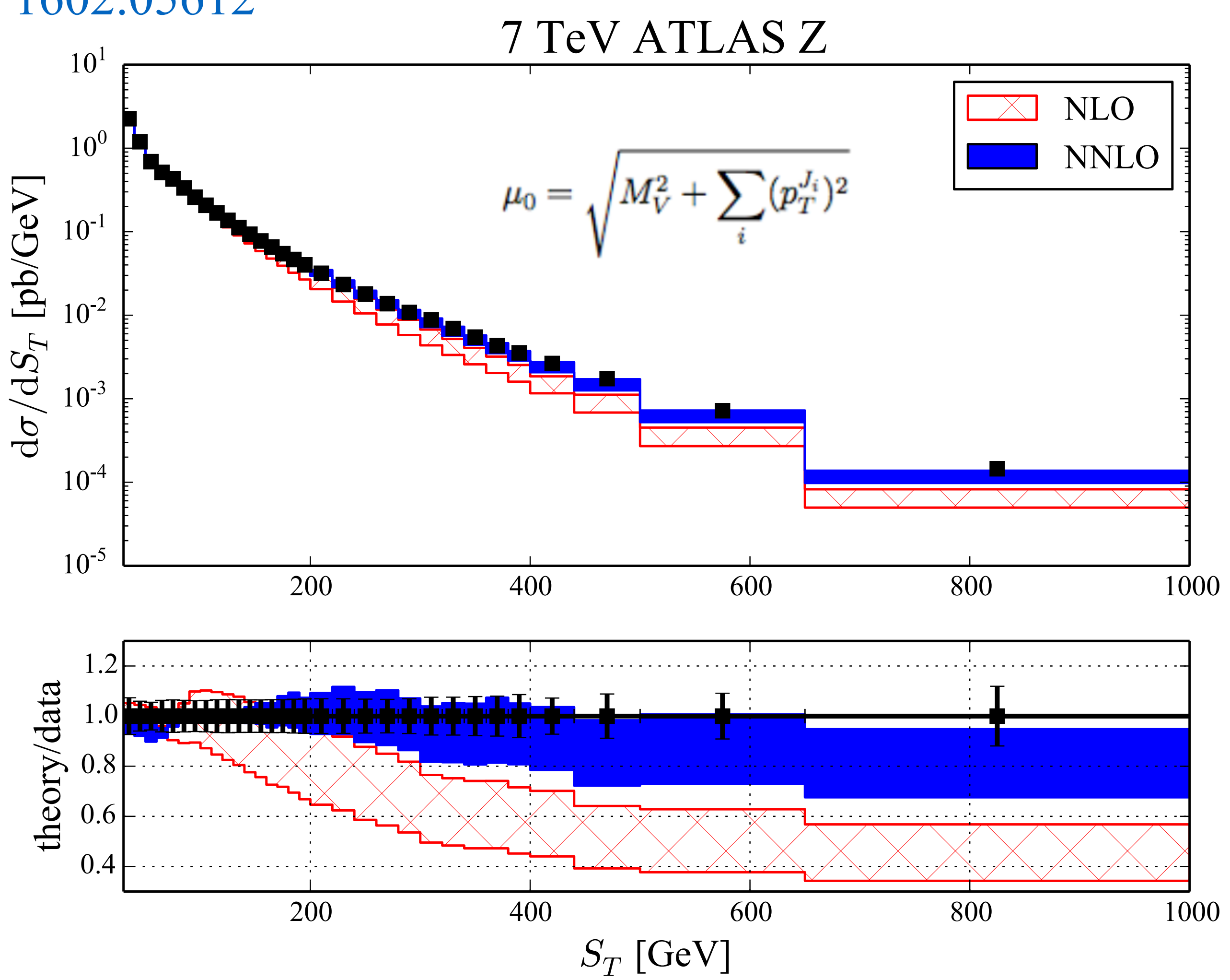
- NNLO theory predictions are in good agreement with both ATLAS and CMS fiducial cross sections, within the experimental errors.
- NNLO result decreases the residual scale dependence from ±5% at NLO to below ±1% at NNLO.

Z-boson cuts	ATLAS [12]	CMS [13]
lepton p_T	$p_T^l > 20$ GeV	$p_T^l > 20$ GeV
lepton η	$\lvert\eta^l\rvert < 2.5$	$\lvert\eta^l\rvert < 2.4$
lepton separation	$\Delta R_{ll} > 0.2$	–
lepton invariant mass	$66\,\text{GeV} < m_{ll} < 116\,\text{GeV}$	$71\,\text{GeV} < m_{ll} < 111\,\text{GeV}$
jet p_T	$p_T^J > 30$ GeV	$p_T^J > 30$ GeV
jet η	$\lvert\eta^J\rvert < 4.4$	$\lvert\eta^J\rvert < 2.4$
anti-k_T radius	$R = 0.4$	$R = 0.5$

The H_T Distribution

RB, Liu, Petriello 1602.05612

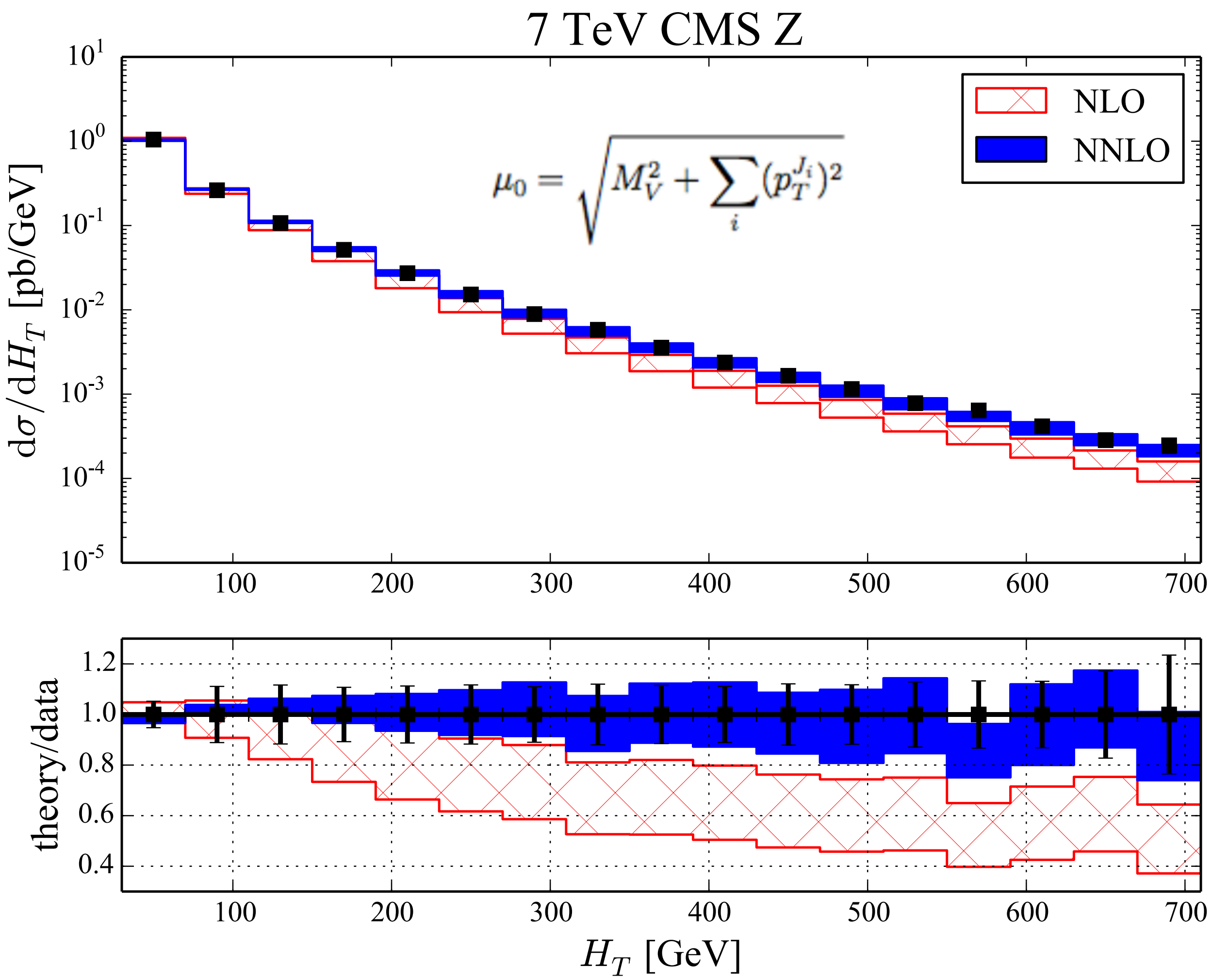


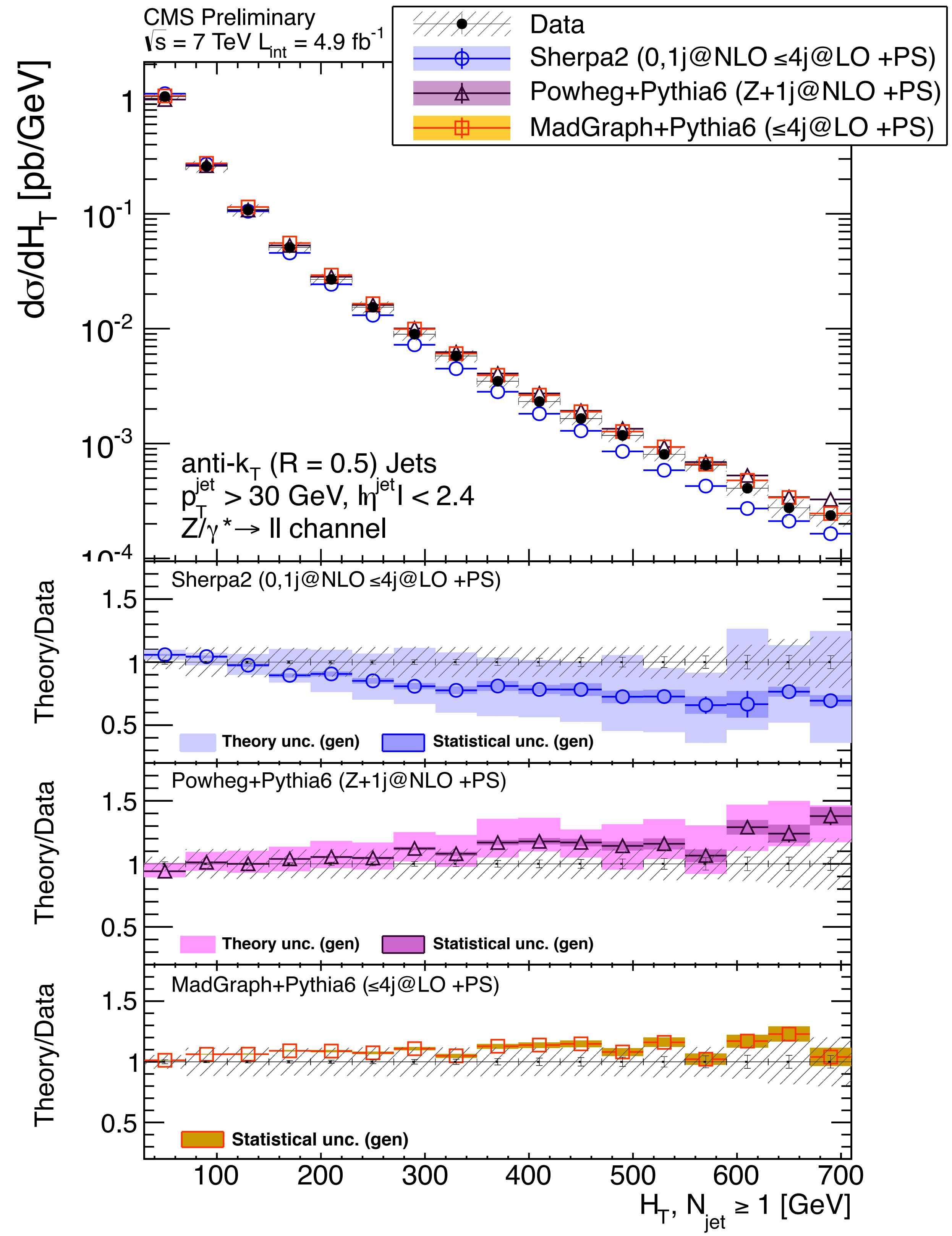


- While NLO QCD results significantly underestimate the cross section at intermediate and high HT, the ATLAS and CMS data for the entire H_T/S_T range are well described with the NNLO QCD corrections.

The H_T Distribution

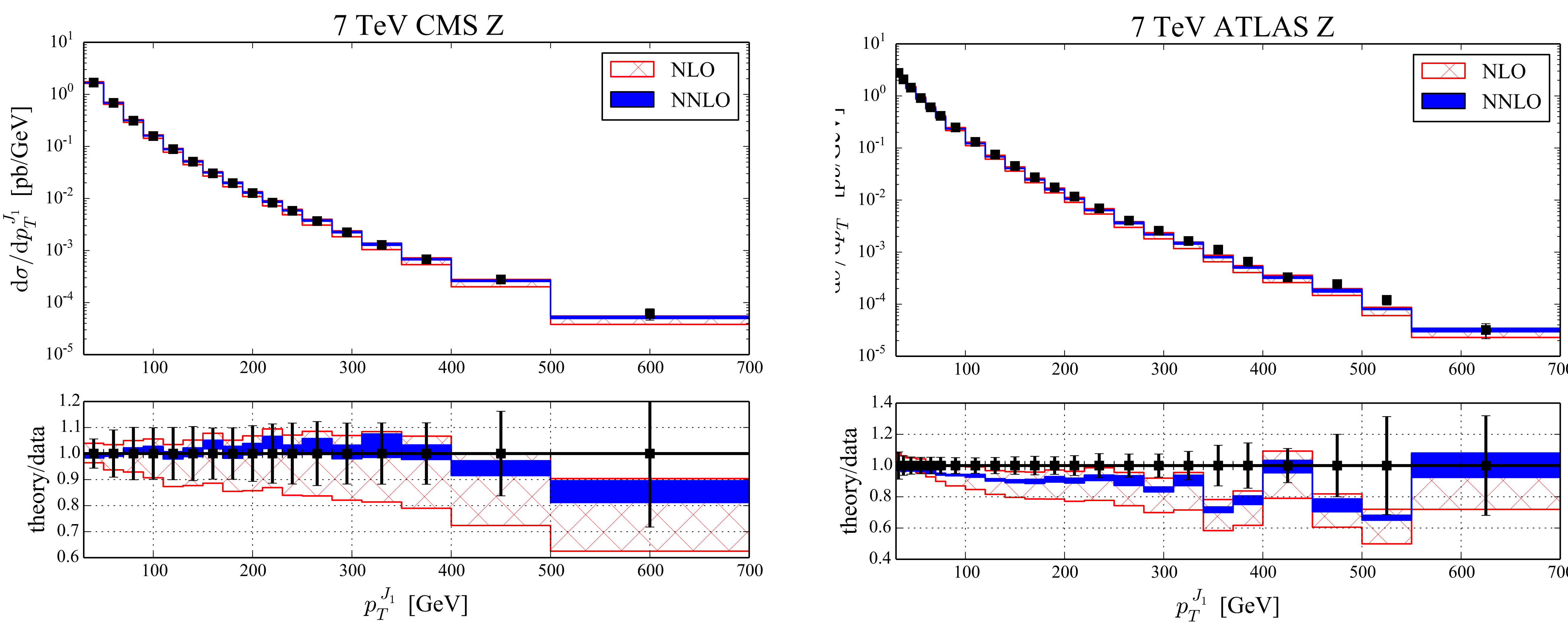
RB, Liu, Petriello 1602.05612





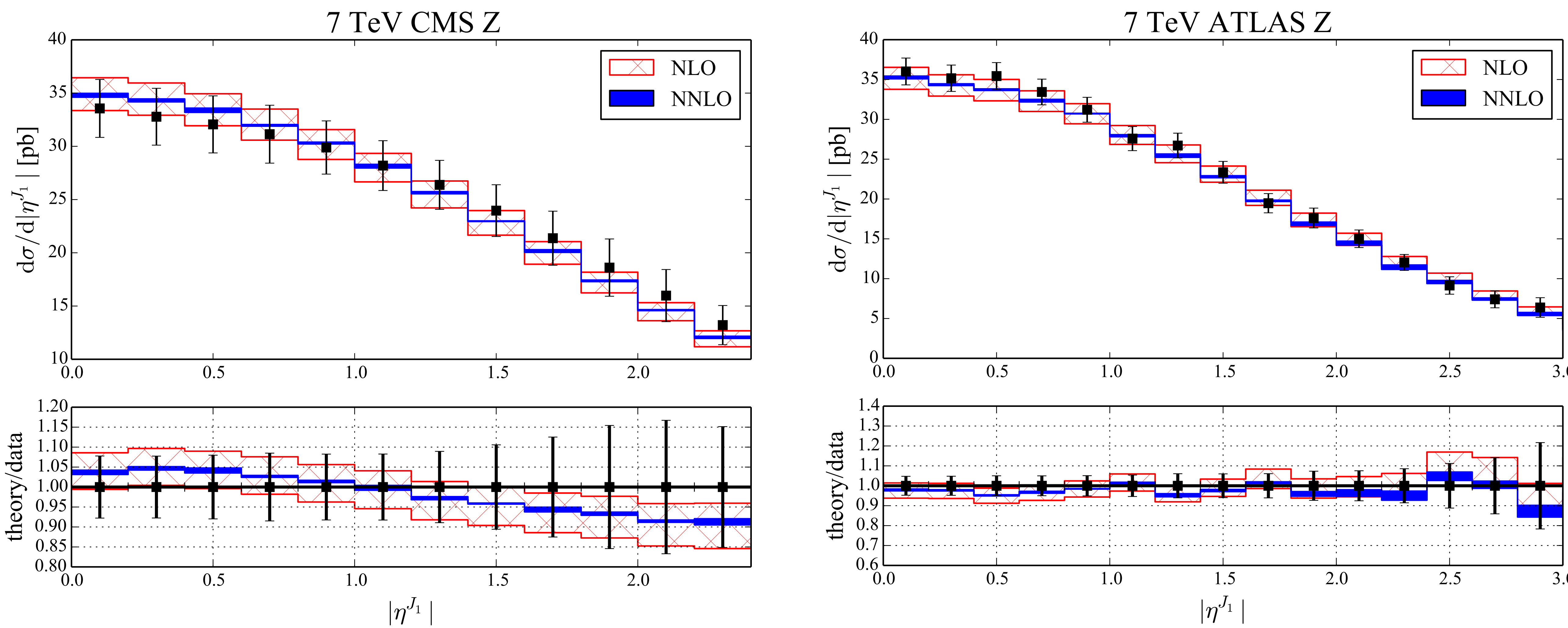
NNLO does a better job in describing the shape and the normalization of this distribution

Leading Jet Transverse Momentum



- Excellent agreement of NNLO results with CMS data over the entire P_{Tj1} range.
- The NNLO prediction is systematically slightly lower than the ATLAS data, lying right outside the experimental 1σ error bars.

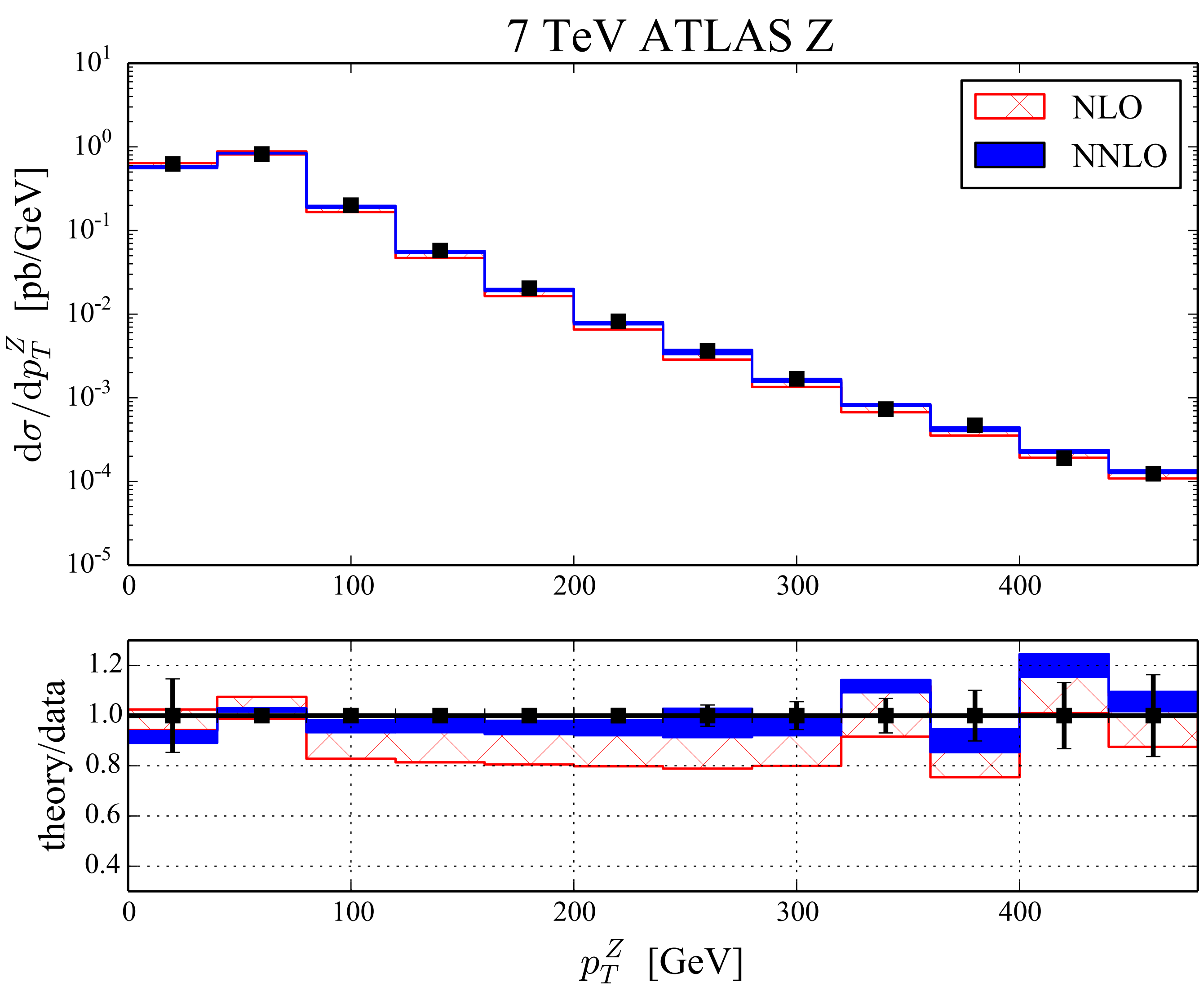
Leading Jet Rapidity Distributions



- Good agreement between the NNLO prediction and ATLAS data over the entire range, with a slight undershoot consistent with the behavior seen in the fiducial cross section.
- Theory prediction is consistent with CMS data within the 1σ experimental errors, where both NLO and NNLO results show a slight shape difference. Similar small discrepancies are seen when comparing CMS data to POWHEG and MADGRAPH.

The P_T of the Reconstructed Z

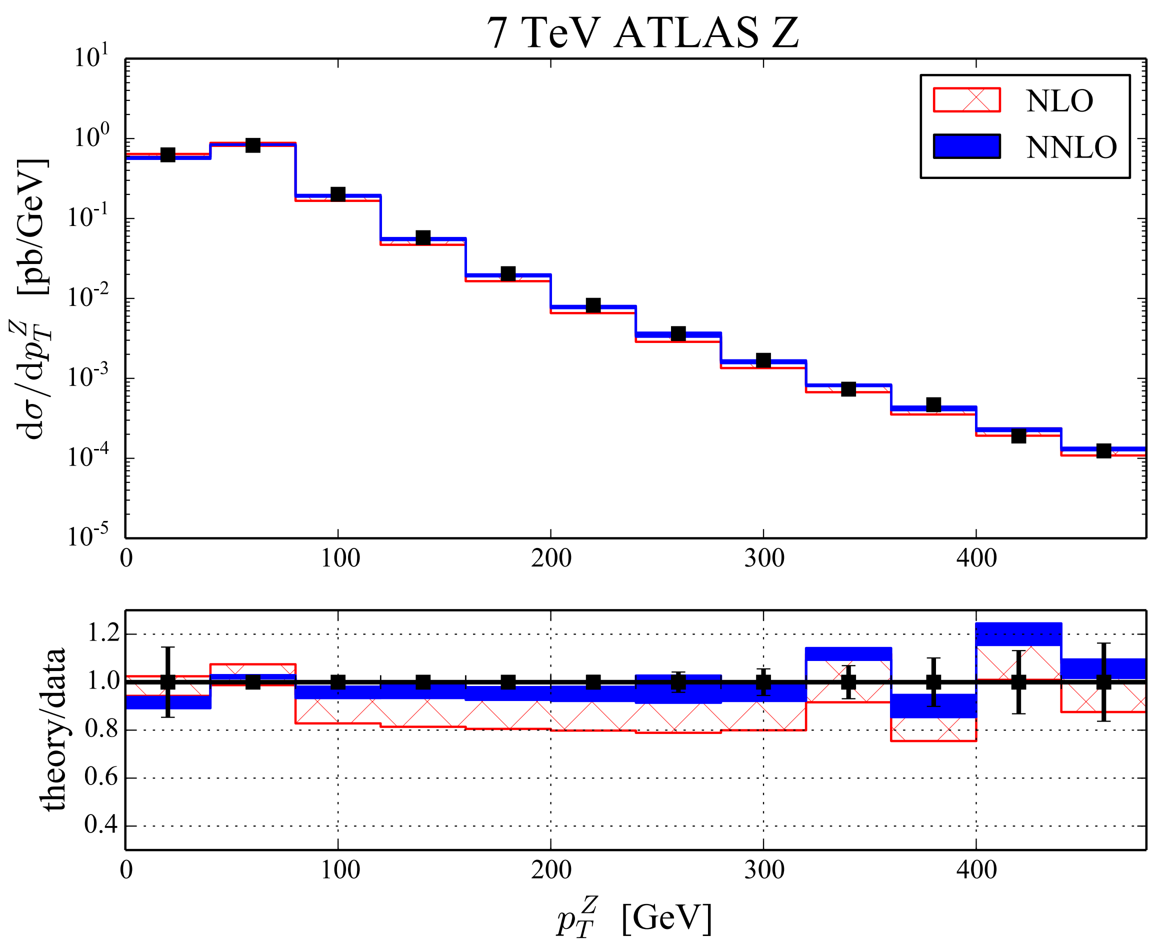
RB, Liu, Petriello 1602.05612

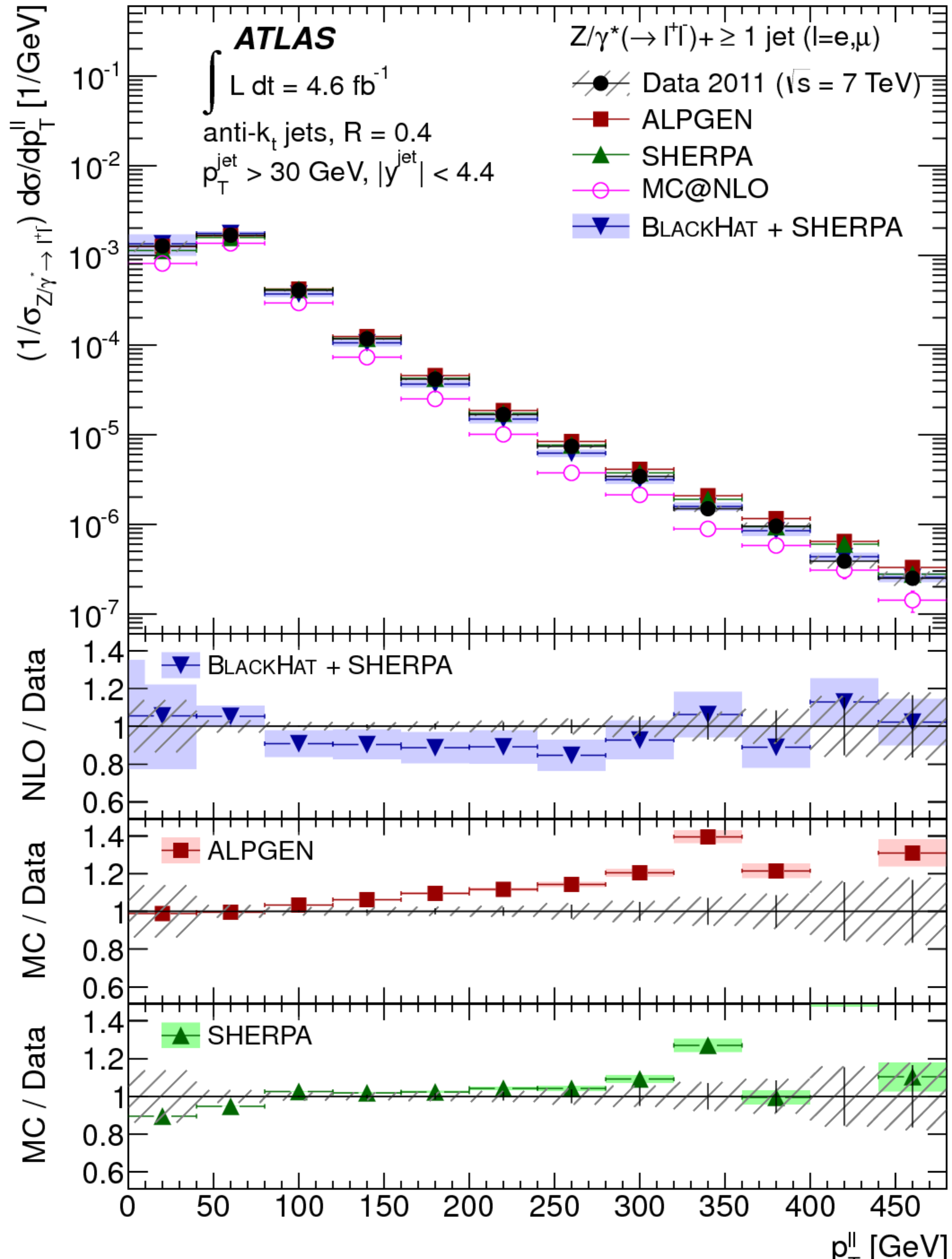


- Good agreement between the measured p_{TZ} by ATLAS and the NNLO QCD predictions over the entire range, with a slight undershoot consistent with the offset observed in the fiducial cross section.

The P_T of the Reconstructed Z

RB, Liu, Petriello 1602.05612

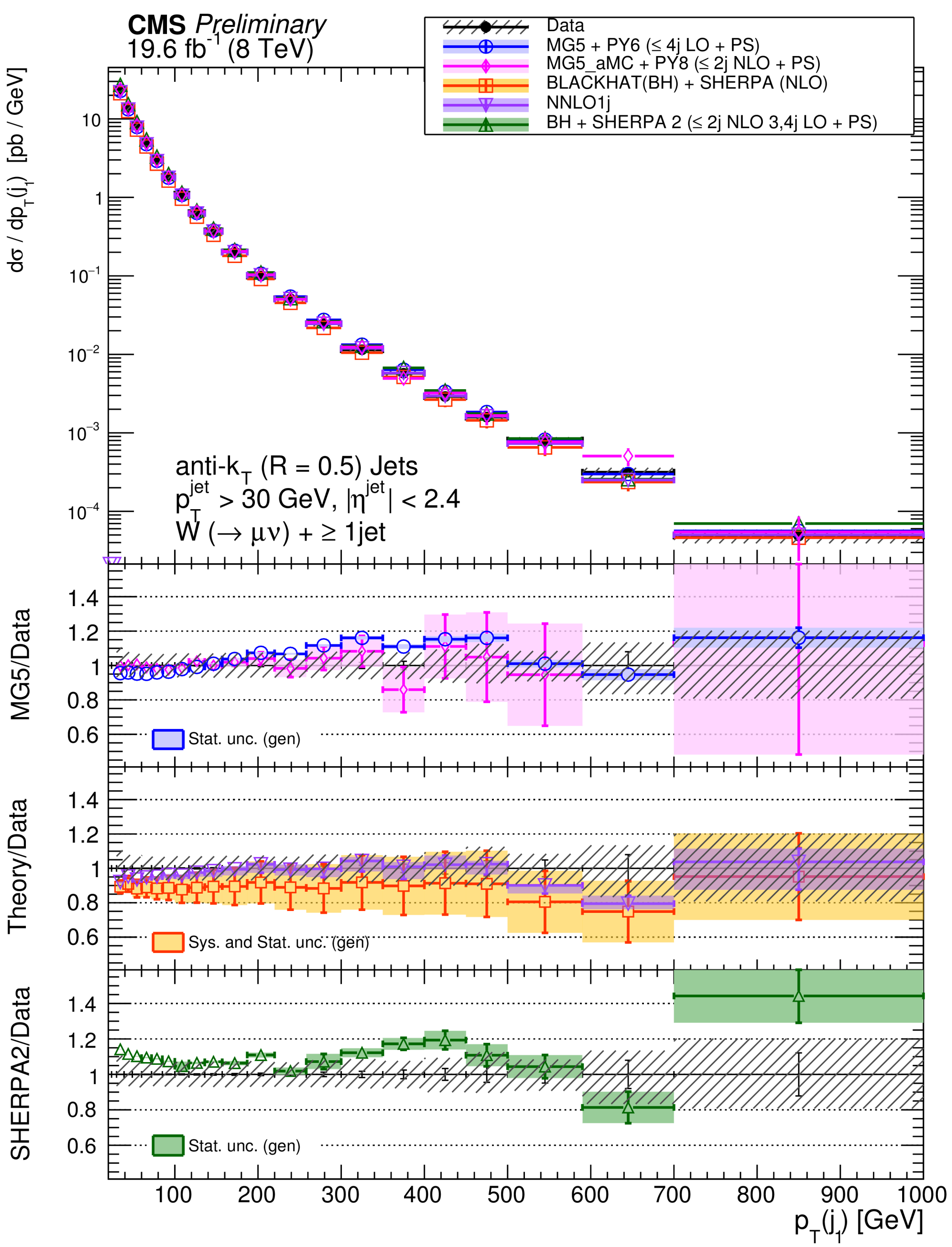


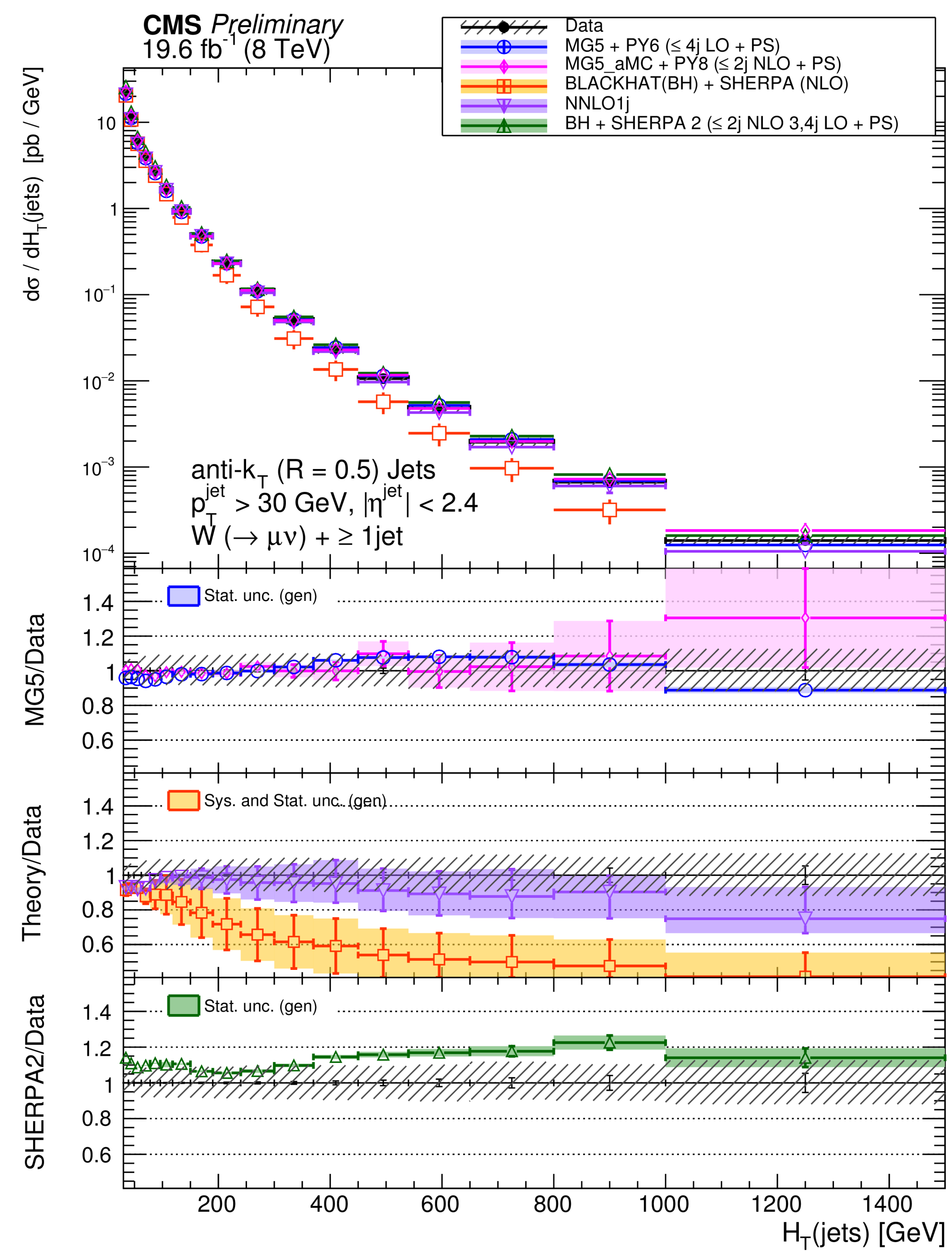


NNLO has smaller uncertainty than NLO and does a better job in describing the shape than some other tools.

NNLO predictions provide a significant improvement over NLO results in describing the W/Z+jet data. Good agreement with almost all the distributions.

W+1j: CMS 13 TeV comparison





- Both NNLO and MG5_aMC+PY8/MG5+PY6 describe data within uncertainties
- Uncertainties associated with merging and shower prescriptions lead to differences between merged predictions. NNLO does not have these ambiguities.

Z+1j: CMS 13 TeV comparison

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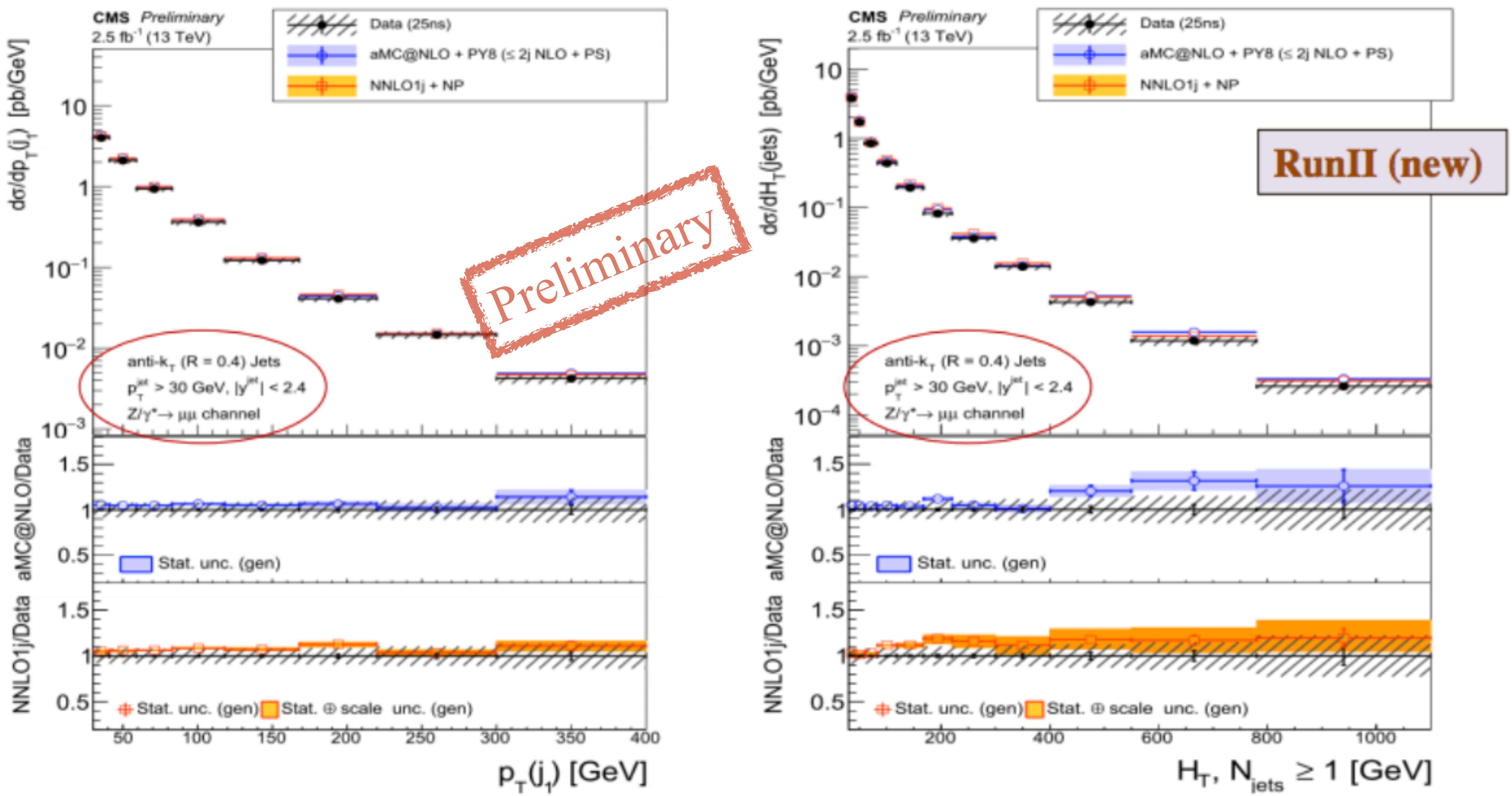

- Good agreement with multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

NNLO predictions provide as good (or better) agreement as merged + matched parton shower predictions

Conclusions

- We have entered the era of percent-level jet phenomenology
- The N-jettiness subtraction scheme is a powerful method in predicting NNLO cross sections for jet production processes
- NNLO QCD corrections to V+jet are at the percent level; comparing these results with 7 and 13 TeV LHC data shows an overall good agreement over several orders of magnitude in cross section and energy. Electroweak corrections should also be accounted for in the future.
- For some observables, such as the H_T distribution, the NNLO QCD corrections are essential for resolving existing discrepancies between various theory predictions and data.