NNLO phenomenology using jettiness subtraction

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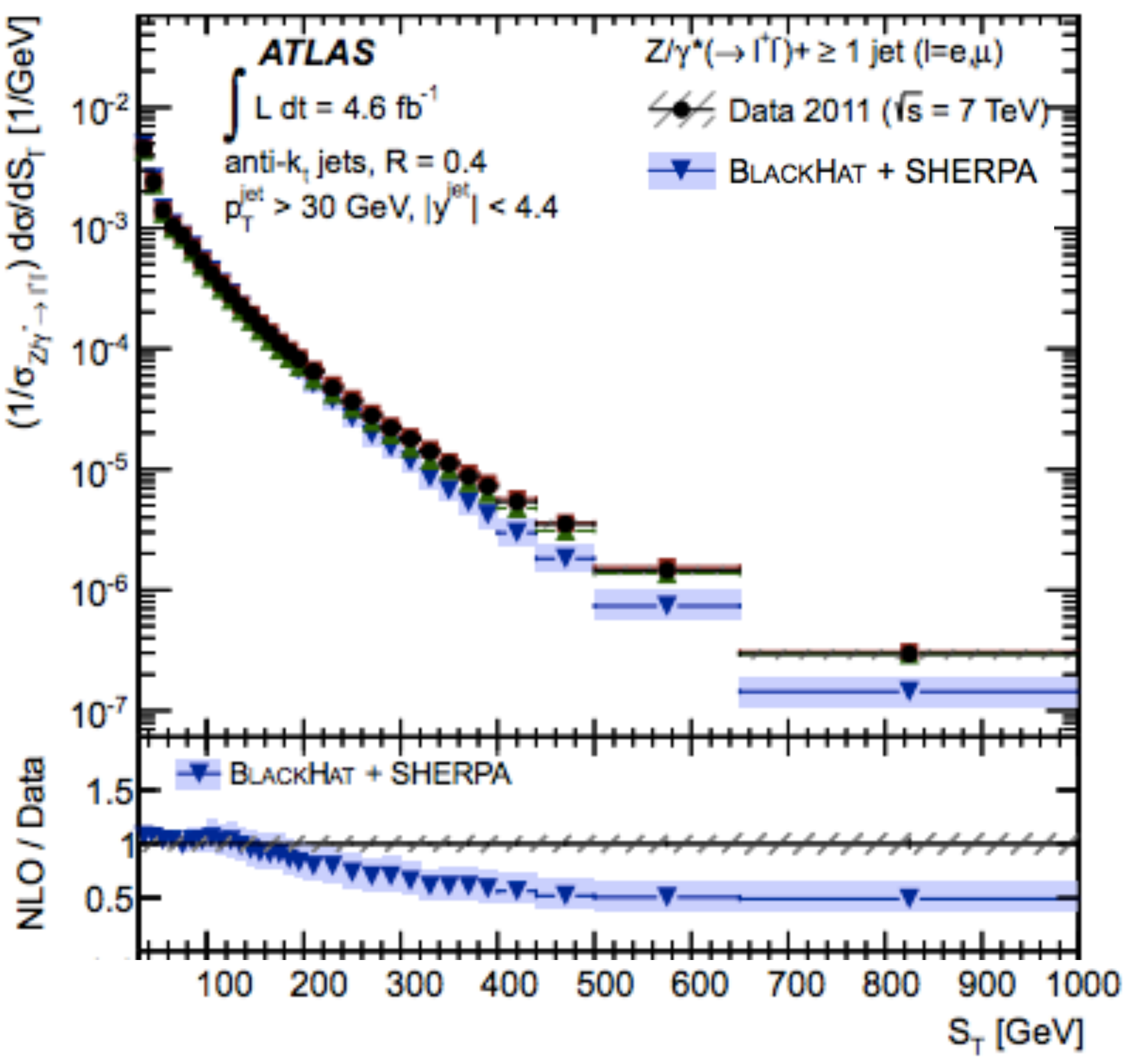
LoopFest XV @ Buffalo, 2016

Why NNLO



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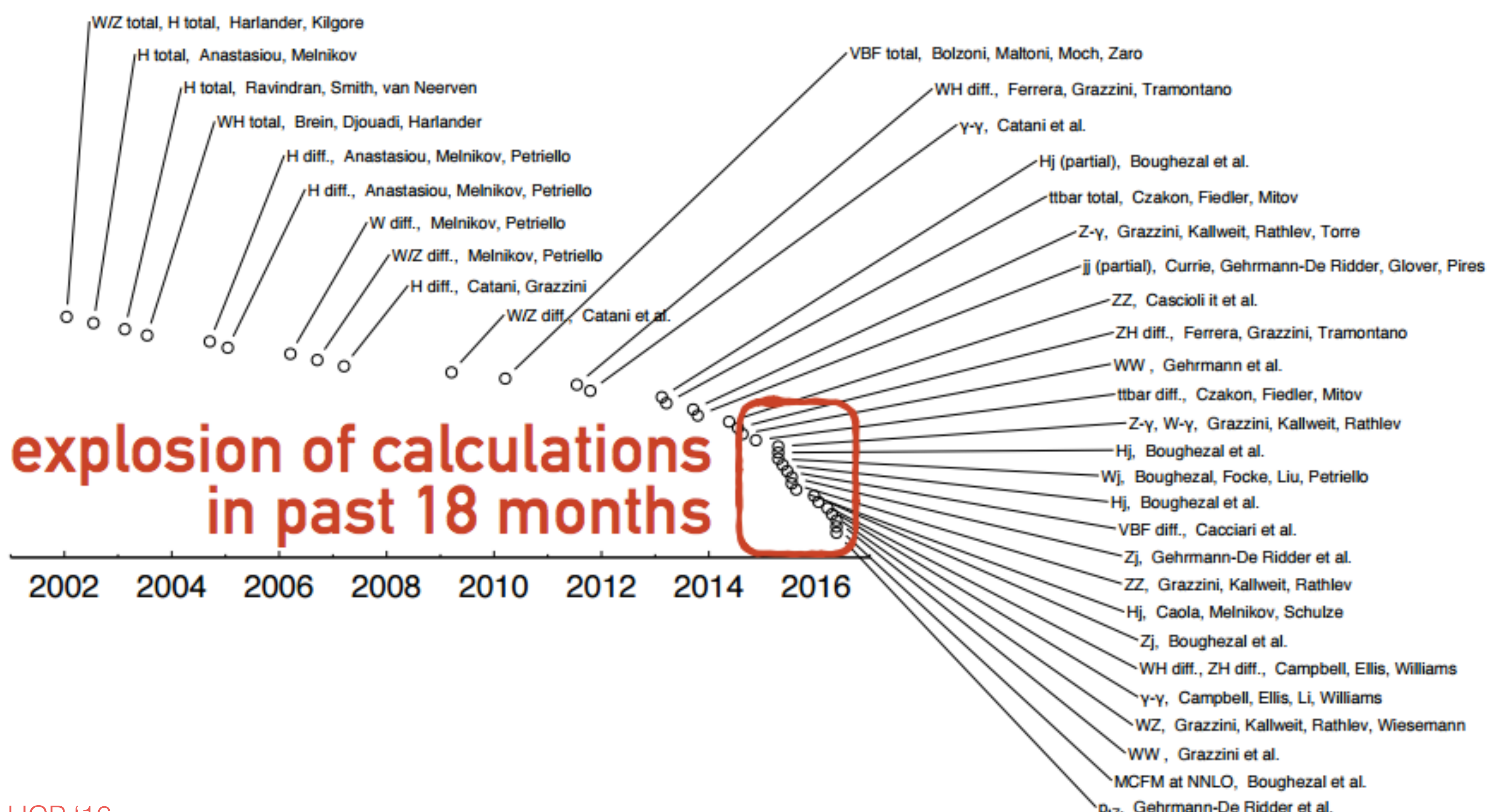
- many reasons
  - ……
  - discrepancy between NLO and data
  - …… .

Theory Setups

- **Real corrections**



Salam, LHCP ‘16

Theory Setups

- **Real corrections**

$$\int \mathrm{d}z \frac{f(z)}{z^{1+a\epsilon}}$$

Local Subtraction

$$\int \mathrm{d}z \frac{f(z)-f(0)}{z} + \int \mathrm{d}z z^{-1-a\epsilon} f(0)$$

- **sector decomposition, sector improved residue** Binoth, Heinrich; Anastasiou, Melnikov, Petriello Czakon; Boughezal, Melinkov, Petriello
- **antenna subtraction** Kosower Gehrmann-De Ridder, Gehrmann, Glover
- **projection to Born** Cacciari, Dreyer, Karlberg, Salam, Zanderighi
- **Colorful NNLO** Del Duca, Somogyi and Trócsányi Del Duca, Duhr, Kardos, Somogyi and Trócsányi

Non-local Subtraction

$$\int \frac{f(z)}{z}\theta(z > z_0) - f(0)\frac{z_0^{-a\epsilon}}{a\epsilon} + \ldots$$

- **qT subtraction, N-jettiness subtraction**

Catani, Grazzini Gao, Li and Zhu Boughezal, Focke, XL, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

Theory Setups

- **N-Jettiness subtraction**

  Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

  - **N-jettiness observable**

    Stewart,Tackmann,Waalewijn,'10

$$\mathcal{T}_N = \sum_k \min\{w_a\, n_a \cdot q_k\,,\, w_b\, n_b \cdot q_k\,,\, w_i\, n_i \cdot q_k\,,\, \ldots\,,\, w_N\, n_N \cdot q_k\}$$

N	**the minimum number of jets required**
n_i	**light-like vectors along beam or jet axes**
q_k	**final state partons' 4-momenta**
w_k	**arbitrary positive weight**

Theory Setups

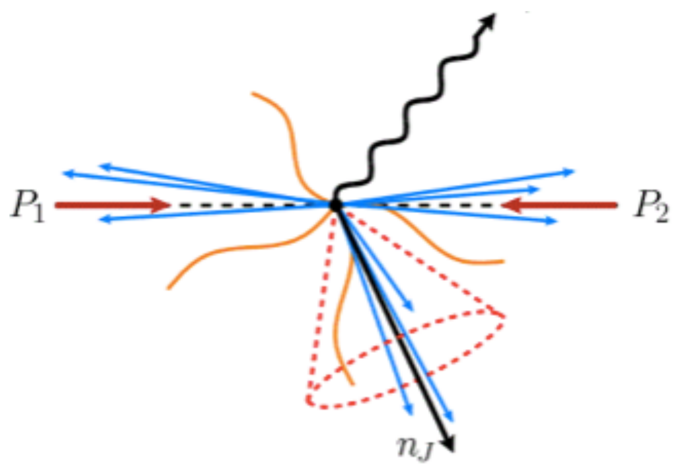
- **N-Jettiness subtraction**

Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

$$\mathcal{T}_N = \sum_k \min\{w_a\, n_a \cdot q_k\,, w_b\, n_b \cdot q_k\,, w_i\, n_i \cdot q_k\,, \ldots\,, w_N\, n_N \cdot q_k\}$$

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

- **Contribution only from 2-loop, soft+collinear radiations**



$$\mathrm{Tr}[H \cdot S_N] \otimes B_a \otimes B_b \otimes J_i + \ldots$$

jet: Becher and Neubert, '06, Becher and Bell, '10

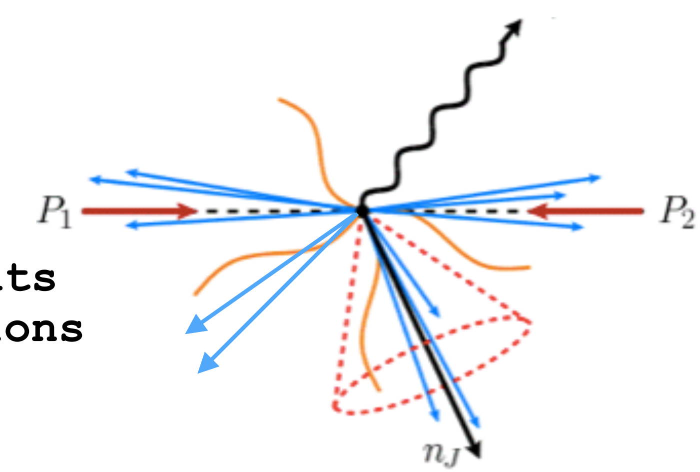
beam: Gaunt, Stahlhofen, Tackmann, '14

soft: Boughezal, XL and Petriello, '15

small $\mathcal{T}_N^{\rm cut}$

smaller than any experimental cuts
small to suppress power corrections
final result independent of $\mathcal{T}_N^{\rm cut}$

- **At least N+1 hard radiations**



- **NLO N+1 jet calculation**
- **Simply recycle known NLO results/tools**

Theory Setups

- **N-Jettiness subtraction**

  Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

  - **New results for processes with a jet**
    - **H/W/Z/DIS+1j**

      Boughezal, Focke, XL, Petriello,'15,
      Boughezal, Focke, Giele, XL, Petriello, '15
      Boughezal, Campbell, Ellis, Focke, Giele, XL, Petriello,'15,
      Ablof, Boughezal, XL, Petriello,'16,
  - **Confirm existing results**
    - **H/W/Z production**   Gaunt, Stahlhofen, Tackmann, Walsh, '15
    - **VH/Di-photon production**

      Campbell, Ellis, Williams, '16   Campbell, Ellis, Li, Williams, '16

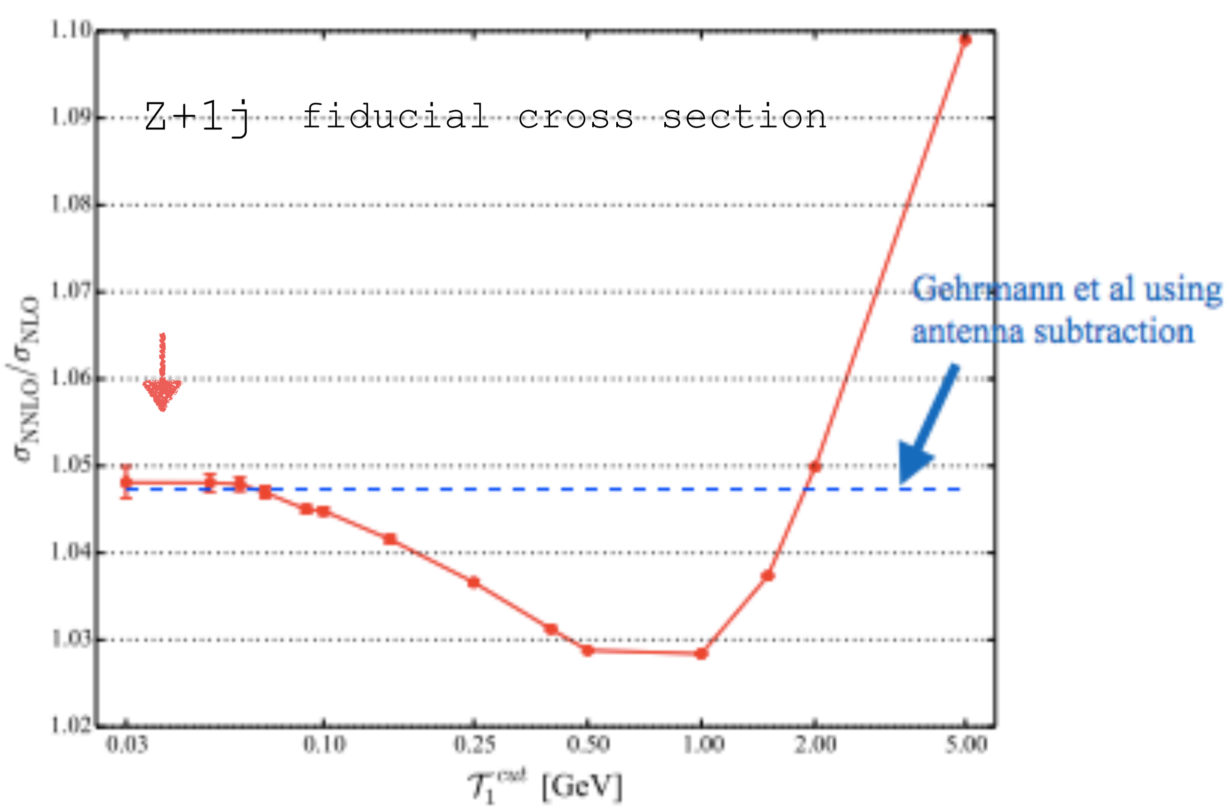
Validation and Improvements

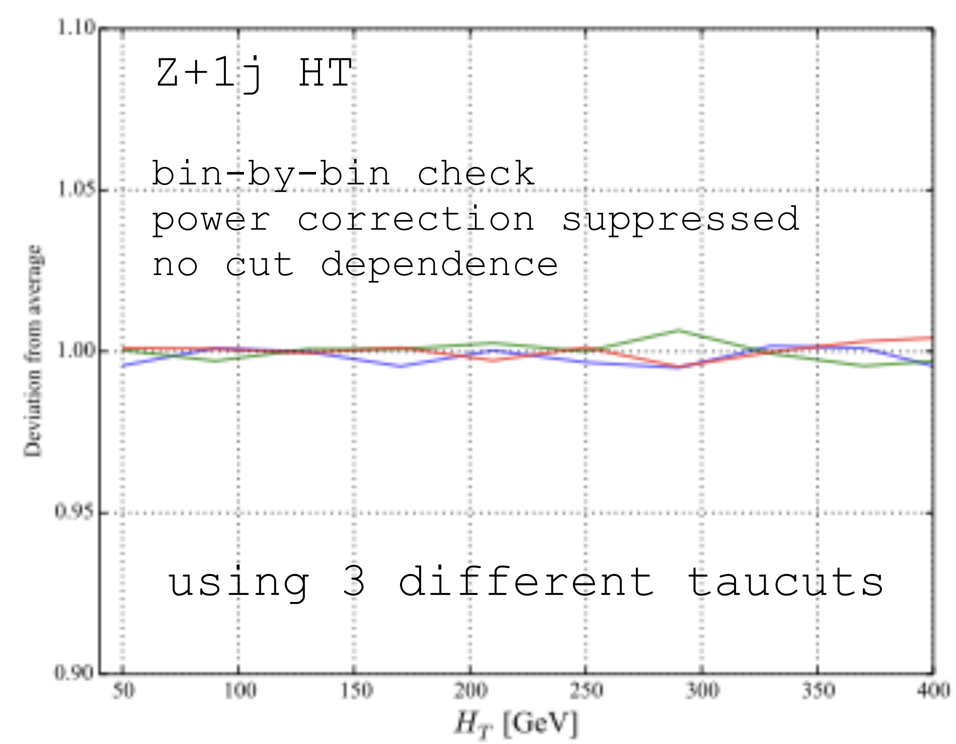
- **N-Jettiness subtraction**

Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

Validations

- **taucut-independence check in all calculations**





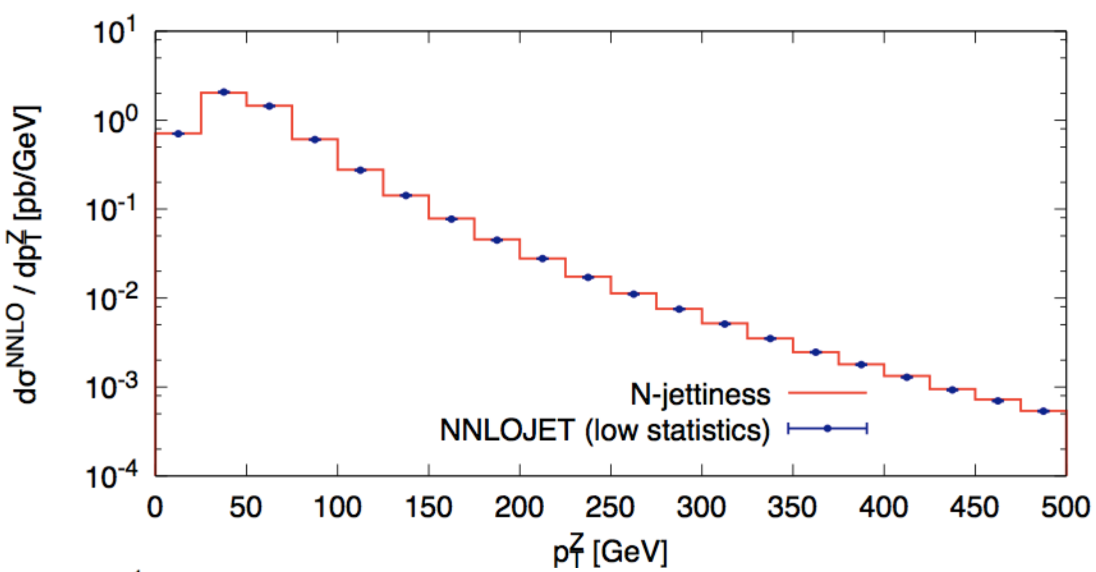
Validation and Improvements

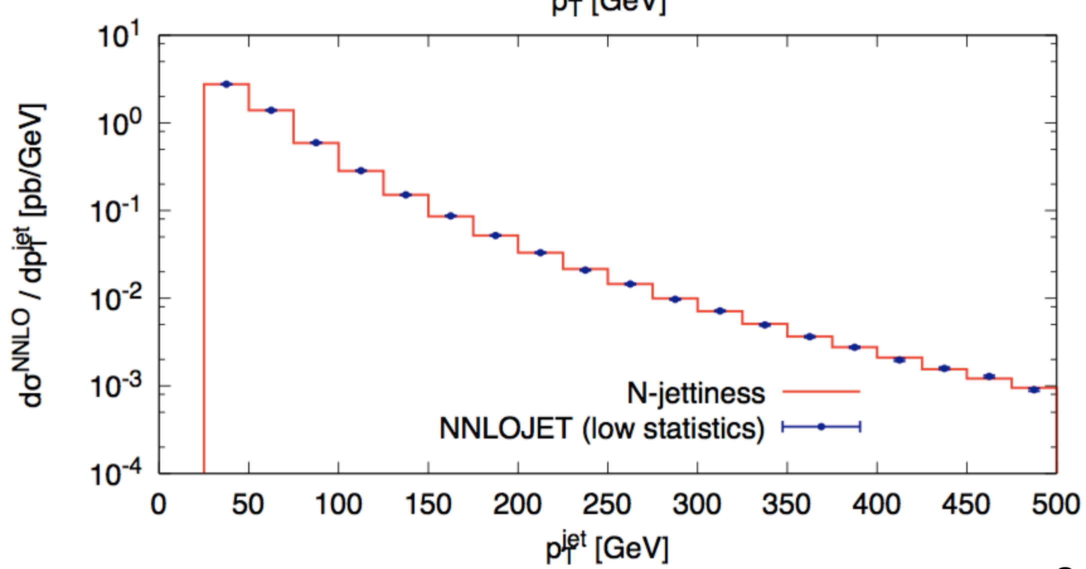
- **N-Jettiness subtraction**

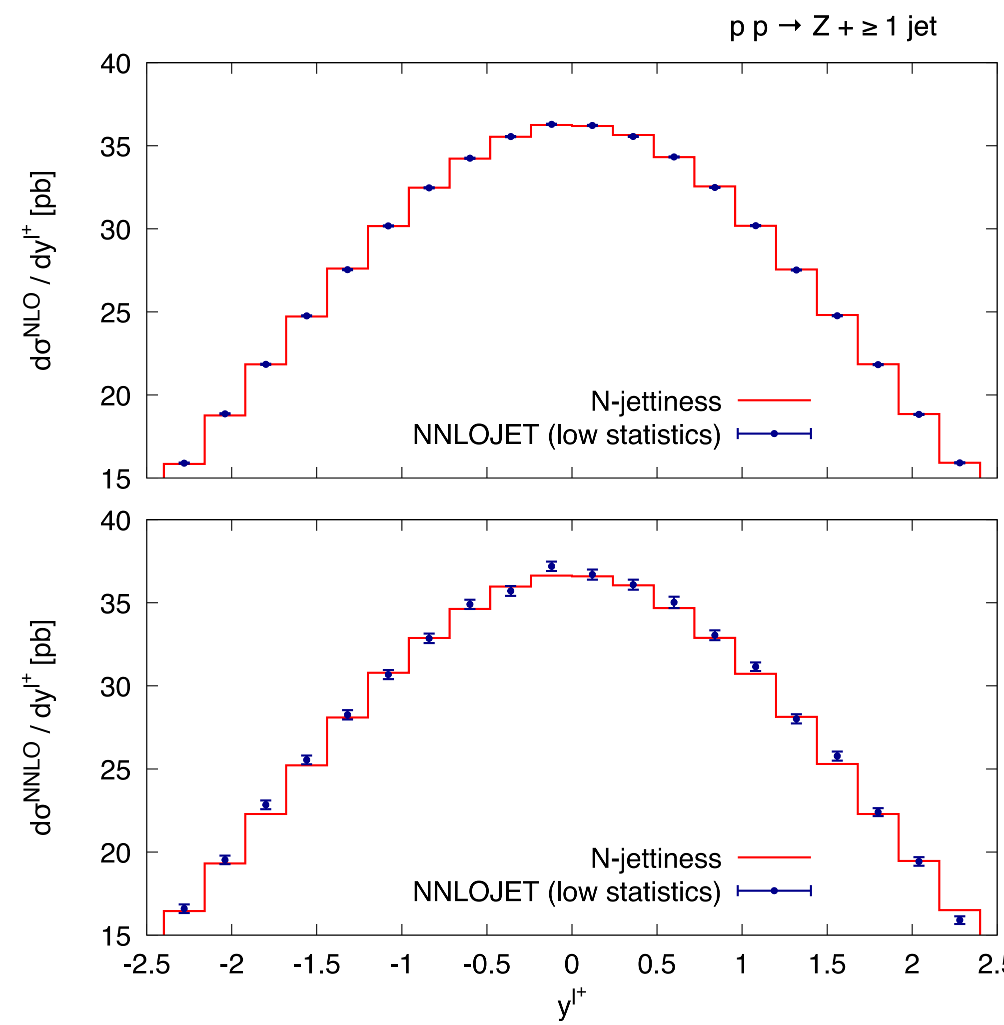
Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

Validations

- more comparisons







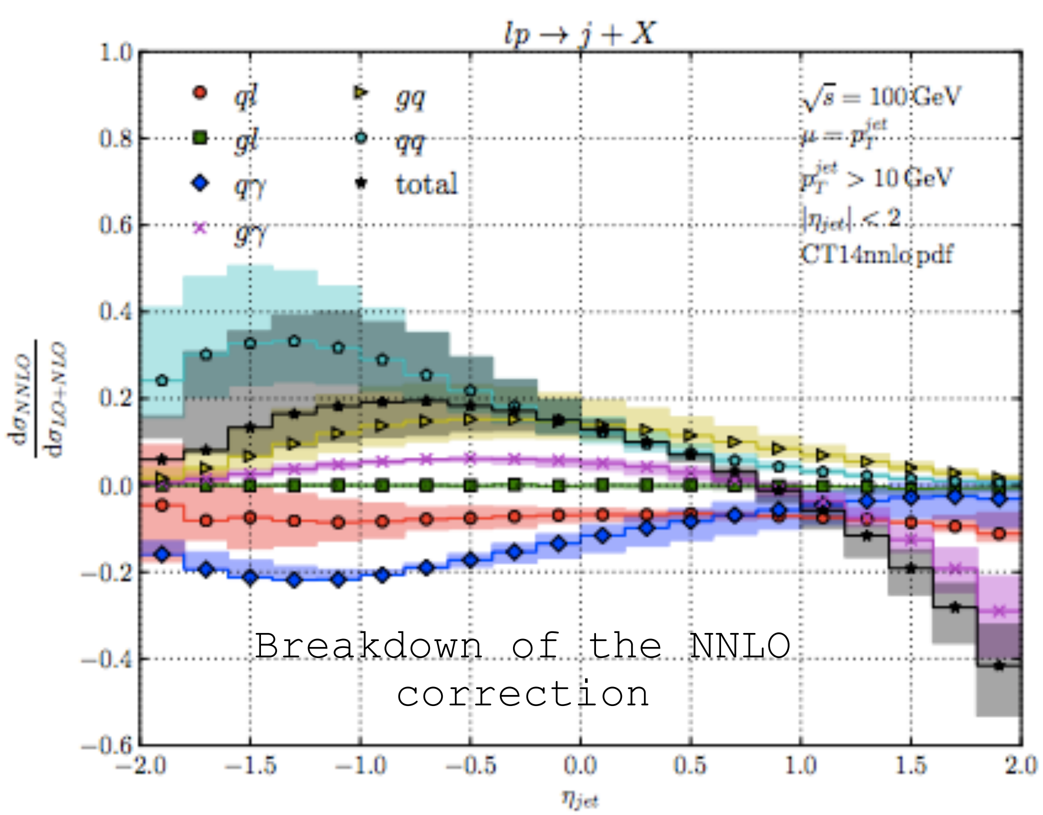
Validation and Improvements

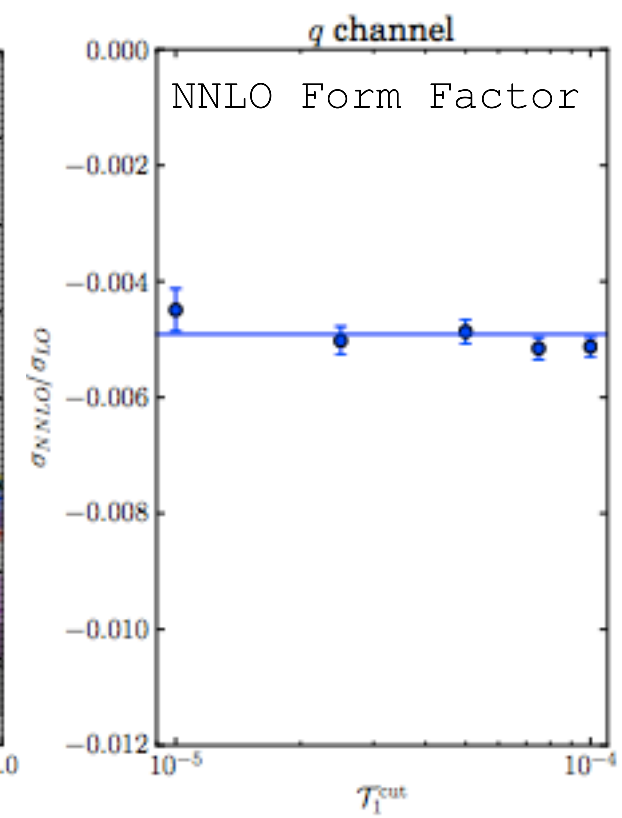
- **N-Jettiness subtraction**

Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

Validations

- **DIS form factor**





Abelof, Boughezal, XL, Petriello, '16

- **NNLO Single jet production**
  - **new channels with large correction**
- **integrate over the phase space to reproduce the NNLO form factor**
- **interesting for EIC phenomenology**

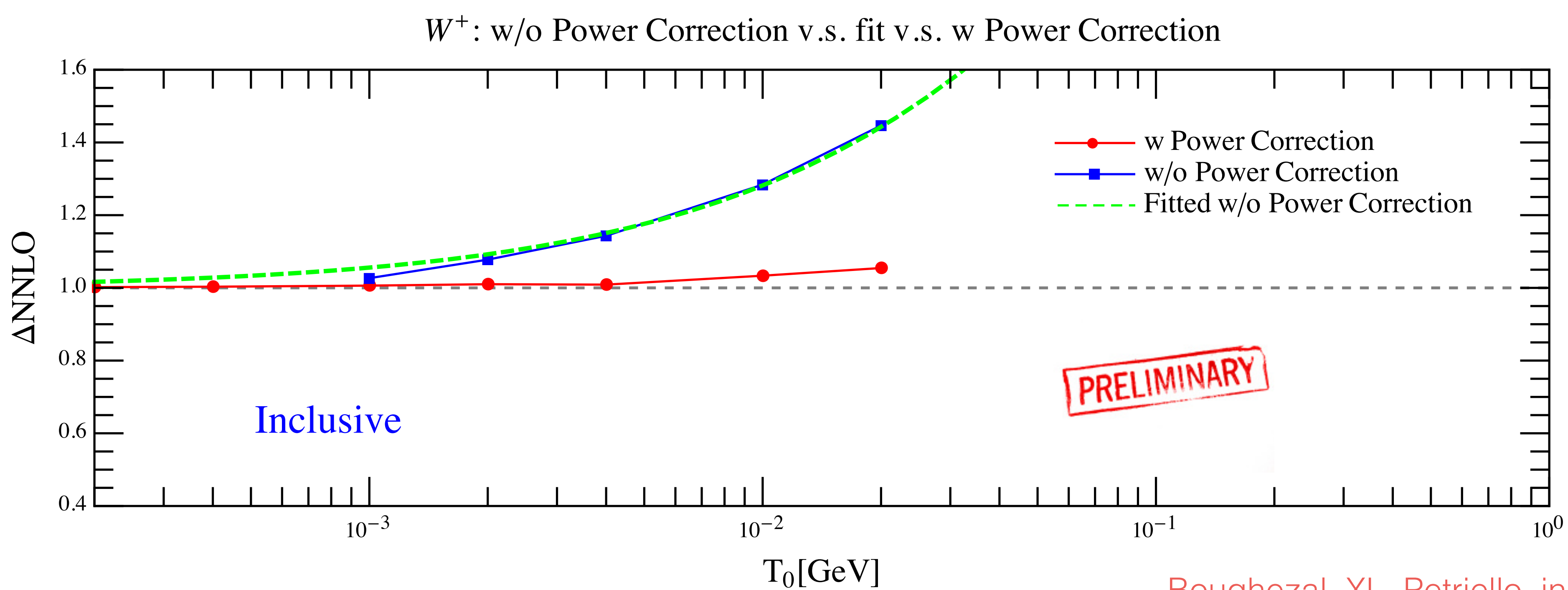
Validation and Improvements

- **N-Jettiness subtraction**

Boughezal, Focke, XL, Petriello, '15 Gaunt, Stahlhofen, Tackmann, Walsh, '15

power corrections

- **logarithmic nature of dominant power corrections** $\alpha_s^n \, C_n \, \mathcal{T}_N^{\rm cut} \, L^{2n-1}$
- **can be calculated in an easy way and higher order power corrections can be predicted from lower order calculations**
- **including power corrections can improve the convergence**



Boughezal, XL, Petriello, in preparation

Validation and Improvements

- **N-Jettiness subtraction**

Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

power corrections

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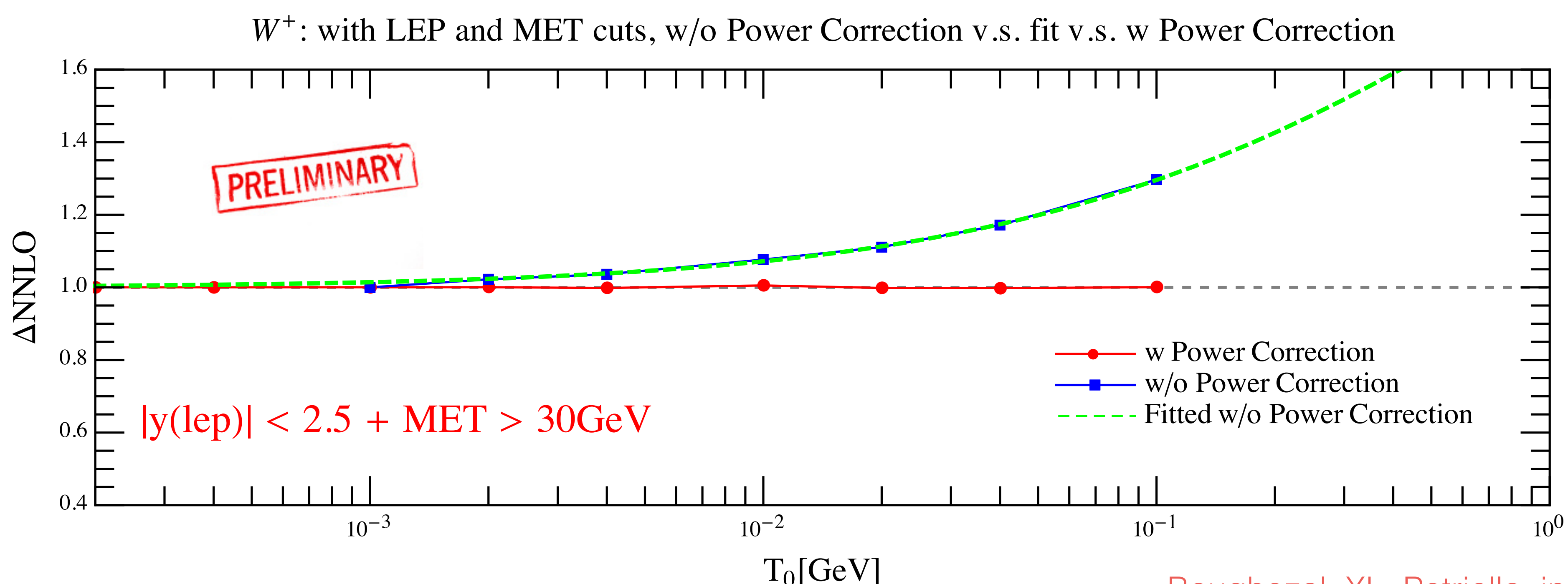

Boughezal, XL, Petriello, in preparation

Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16
  - **W+1j**

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	$R = 0.4$	$R = 0.5$

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CERN-PH-EP-2014-134

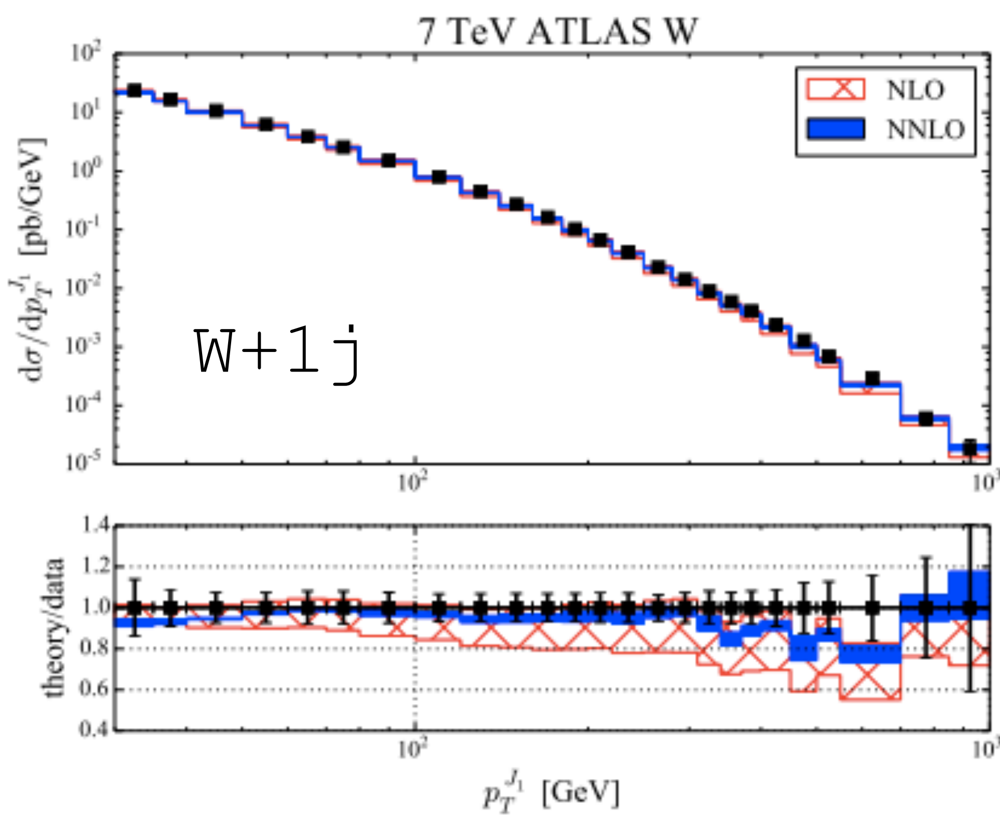
$$\mu_0 = \sqrt{M_V^2 + \sum_i (p_T^{J_i})^2}$$

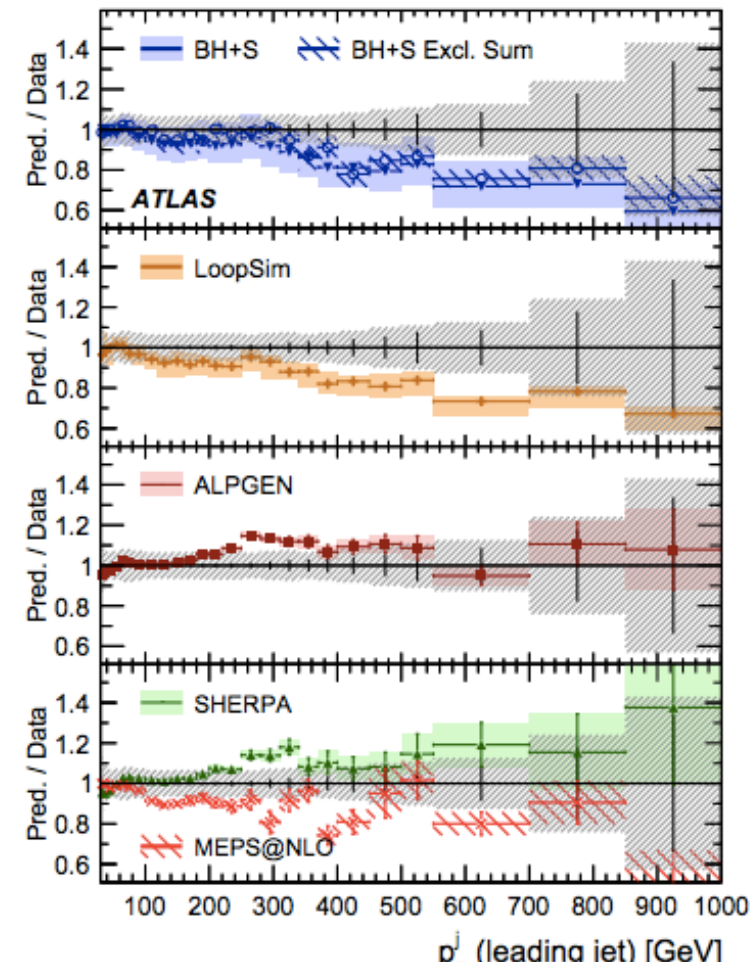
- **CT14NNLO PDFs for NNLO results, CT14NLO for NLO results**
- **Vary muF and muR independently**
- **non-perturbative corrections included for ATLAS pTJ and yJ**
- **QED FSR factors included for ATLAS pTJ and yJ**

Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, ‘16

pTJ1:





- **Merged tree-level amplitudes combined with a parton shower describe the measurements: higher than but within experimental errors**
- **NLO QCD, LoopSim and MEPS@NLO predictions are all lower than the data.**
- **NNLO QCD corrections increase the NLO prediction, leading to a better agreement with ATLAS data. Scale uncertainty is reduced**

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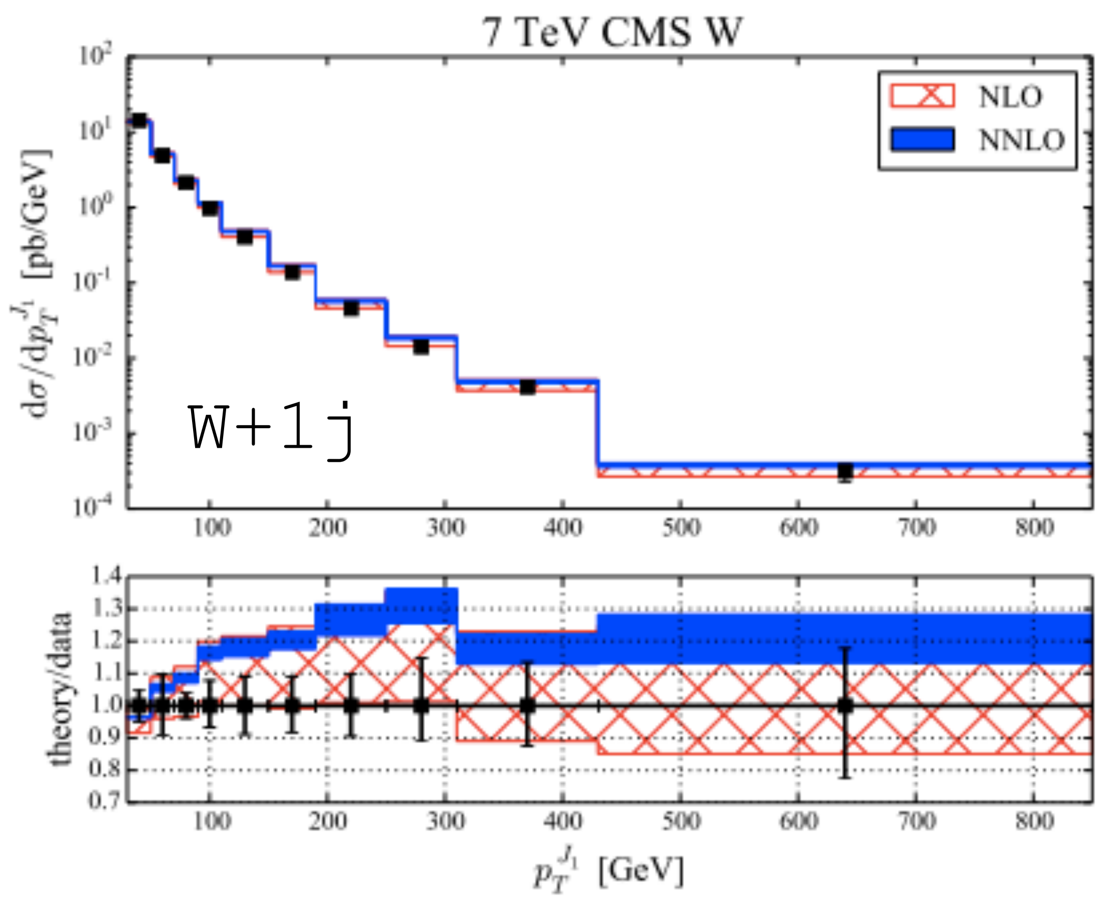
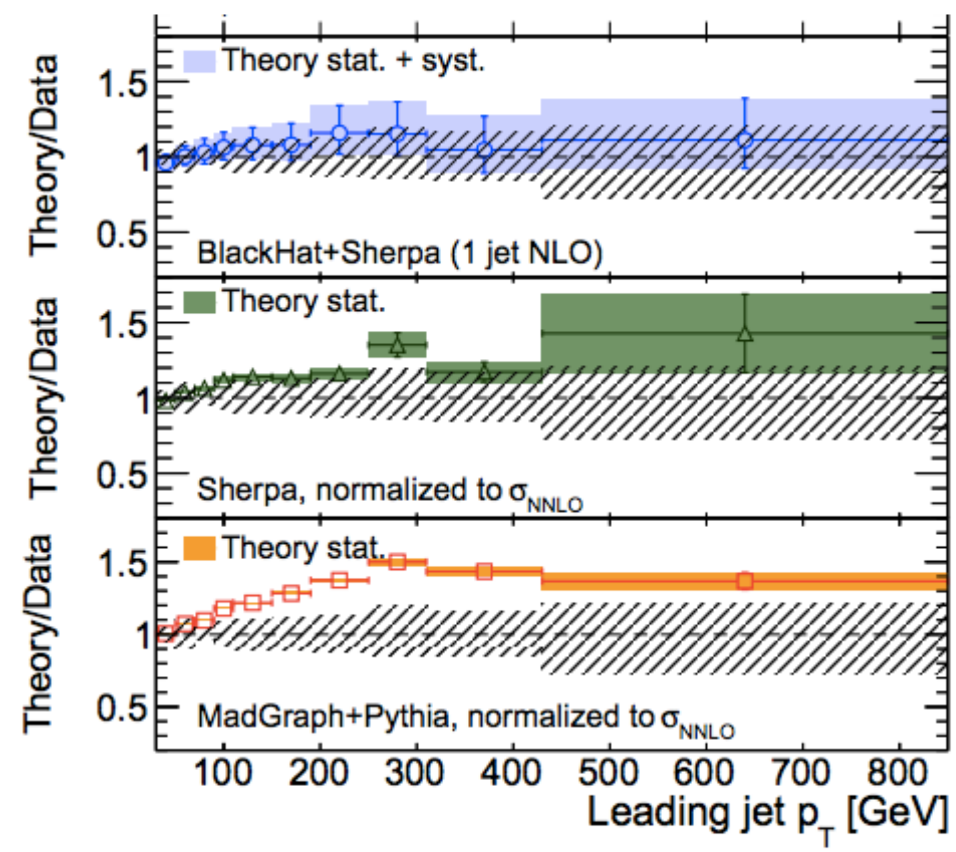
Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16

pTJ1:





- **All predictions compared are systematically higher than the CMS data**
- **NNLO QCD corrections reduce the NLO scale uncertainty to make it clear**

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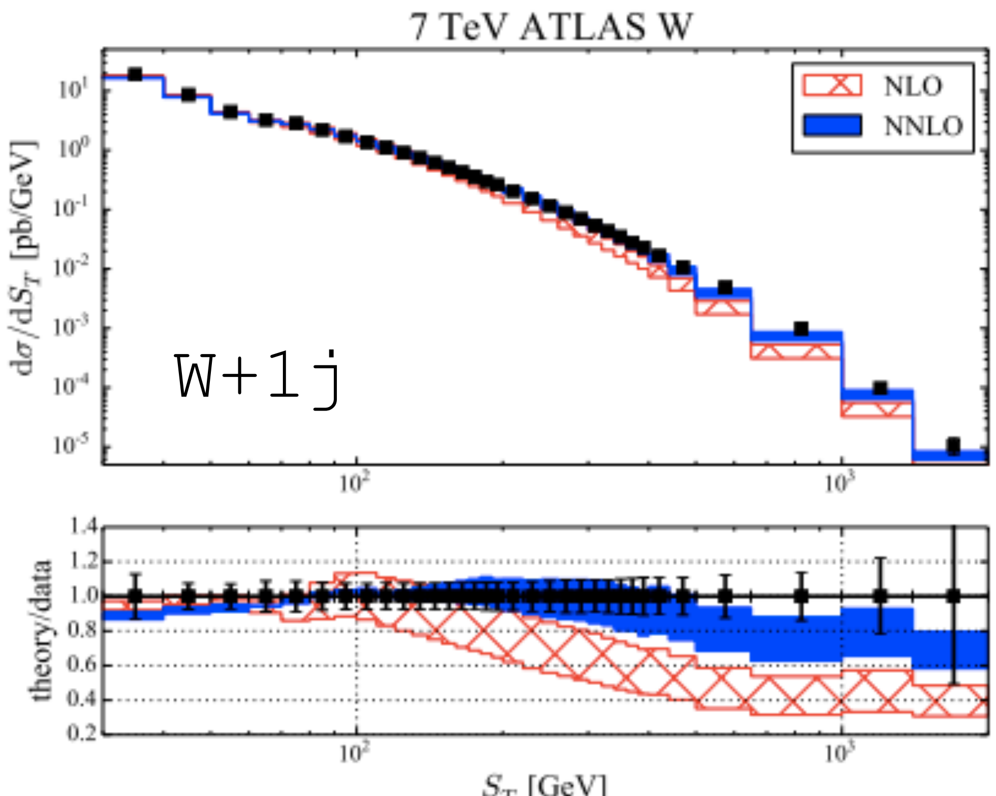
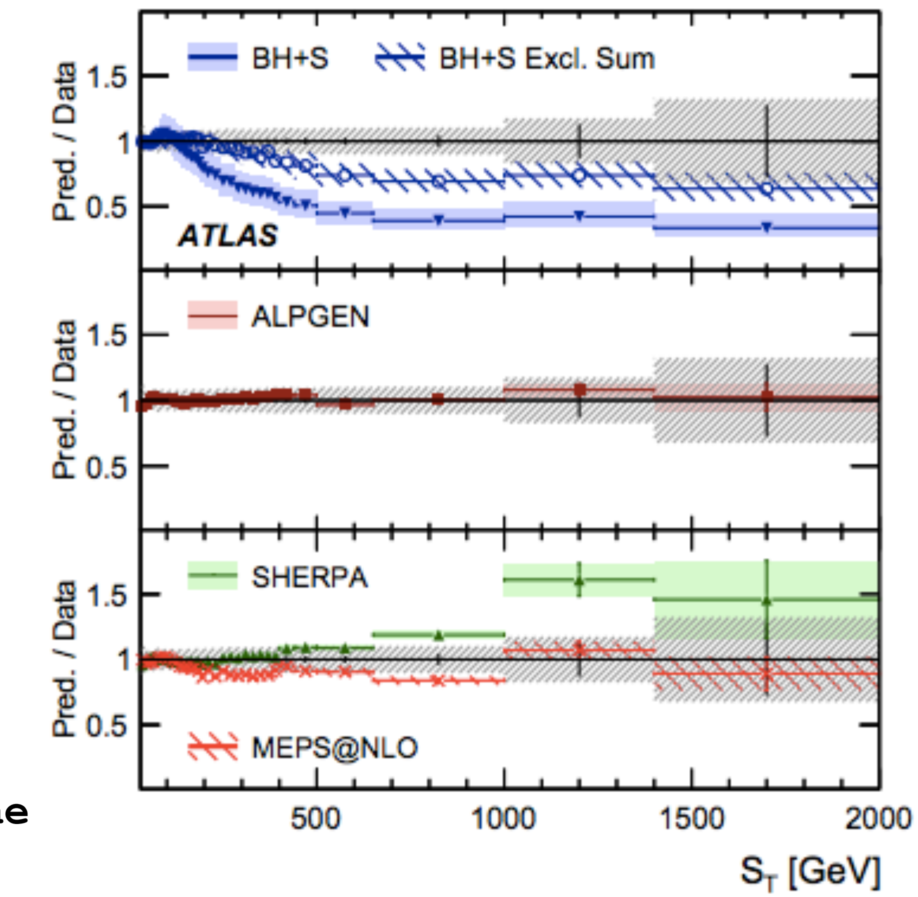
Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16

$H_T(S_T)$:





- **ALPGEN agrees with data while SHERPA overshoots the measurements**
- **The NLO predictions far undershoot the data while MEPS@NLO does a good job**
- **The NNLO corrections bring theory into good agreement with experiment, with a slight undershoot at very high ST**

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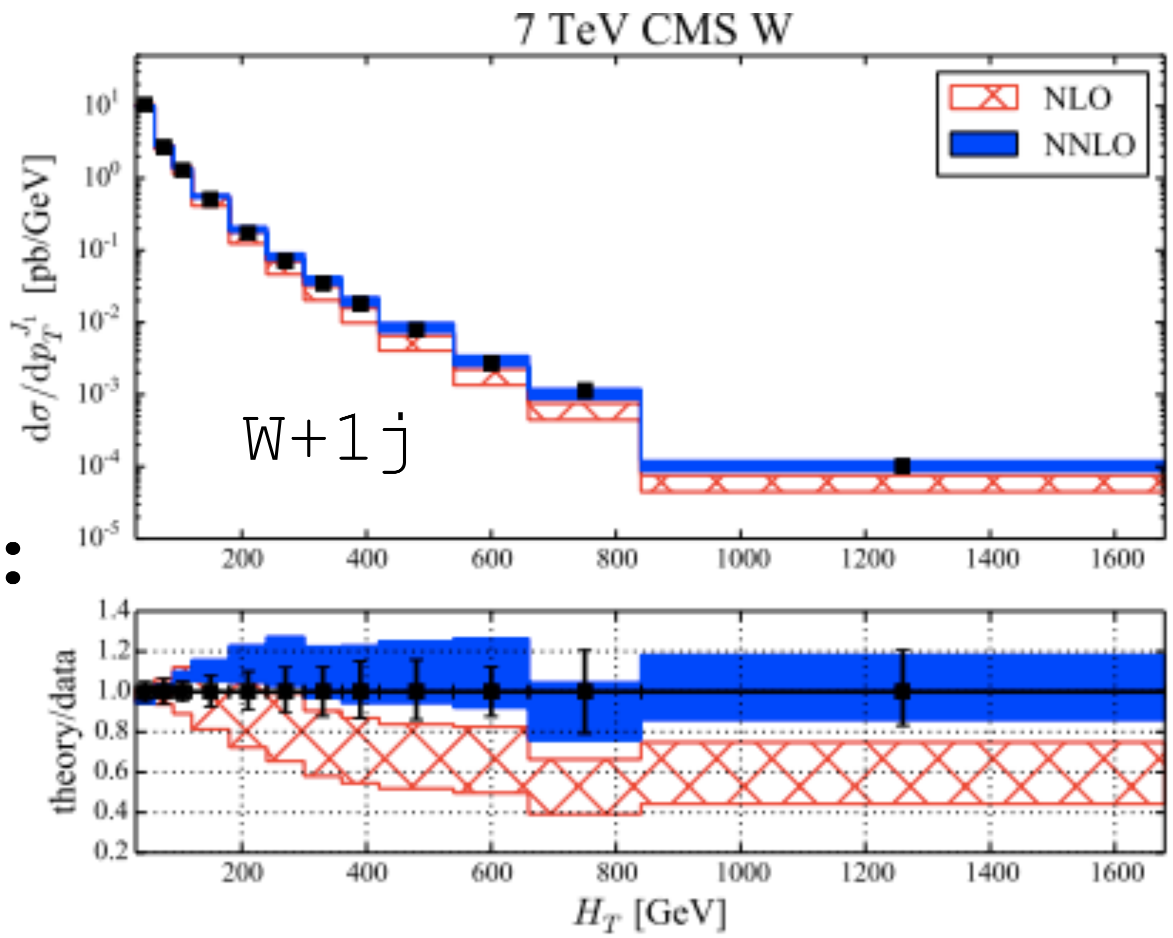
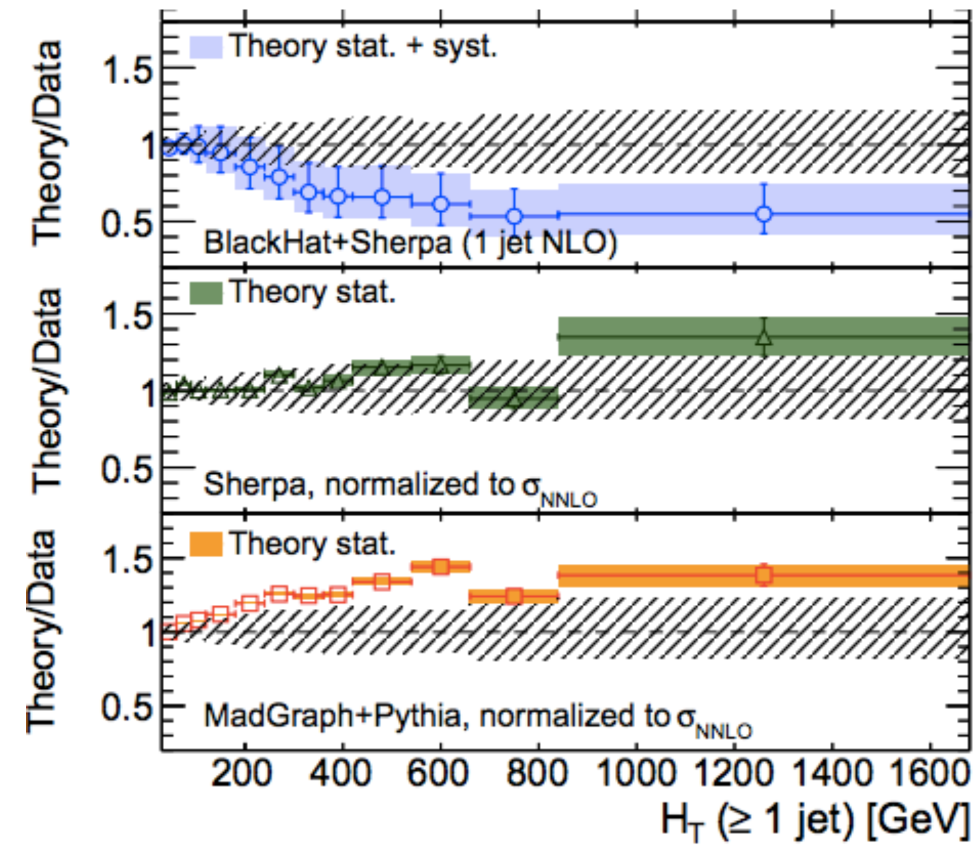
Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16

$H_T(S_T)$:





- Merged tree-level amplitudes combined with a parton shower are higher than the measurements.
- NLO QCD corrections lower than the data.
- NNLO can predict this distribution well.

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Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16
  - **Z+1j**

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	$R = 0.4$	$R = 0.5$

CERN-PH-EP-2013-023

CERN-PH-EP-2014-205

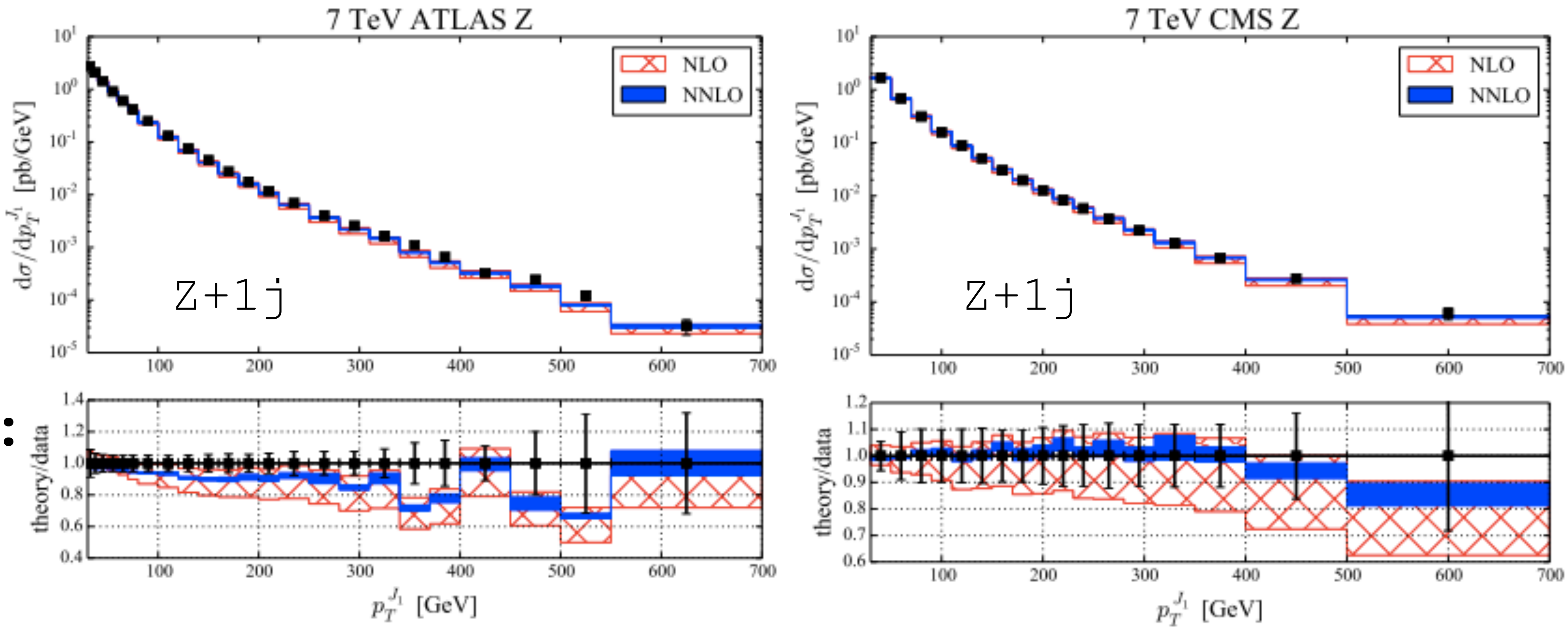
$$\mu_0 = \sqrt{M_V^2 + \sum_i (p_T^{J_i})^2}$$

- **CT14NNLO PDFs for NNLO results, CT14NLO for NLO results**
- **Vary muF and muR independently**
- **non-perturbative corrections included for ATLAS pTJ and yJ**
- **QED FSR factors included for ATLAS pTJ and yJ**

Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16

pTJ1:



- **The NLO prediction agrees with the data within errors.**
- **The NNLO QCD prediction is in better agreement with the CMS data over the entire pTJ1 range.**
- **The NNLO QCD prediction increases NLO but still undershoots the ATLAS data.**

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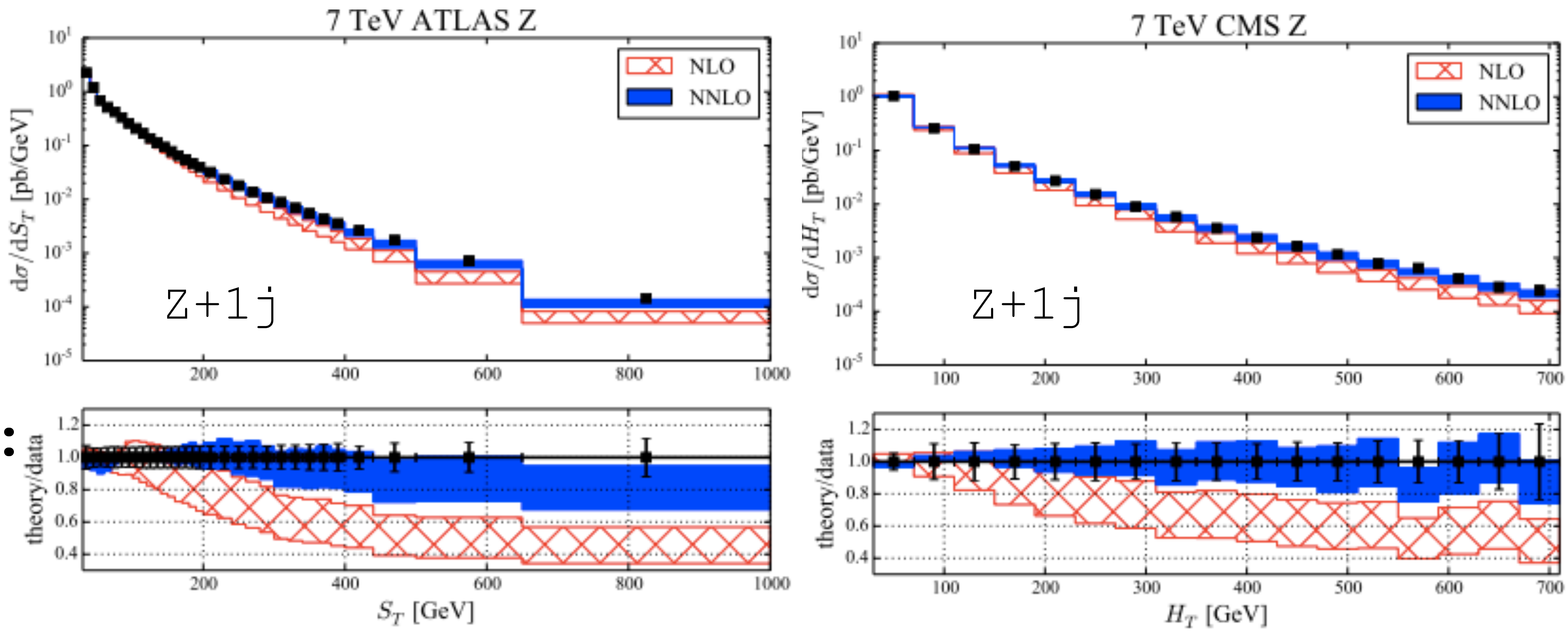
Phenomenology

- **Comparison with 7TeV data** Boughezal, XL, Petriello, '16

H_T (S_T) :



- **The NLO prediction below the data.**
- **The NNLO QCD prediction is in good agreement with both experiments over the entire range.**

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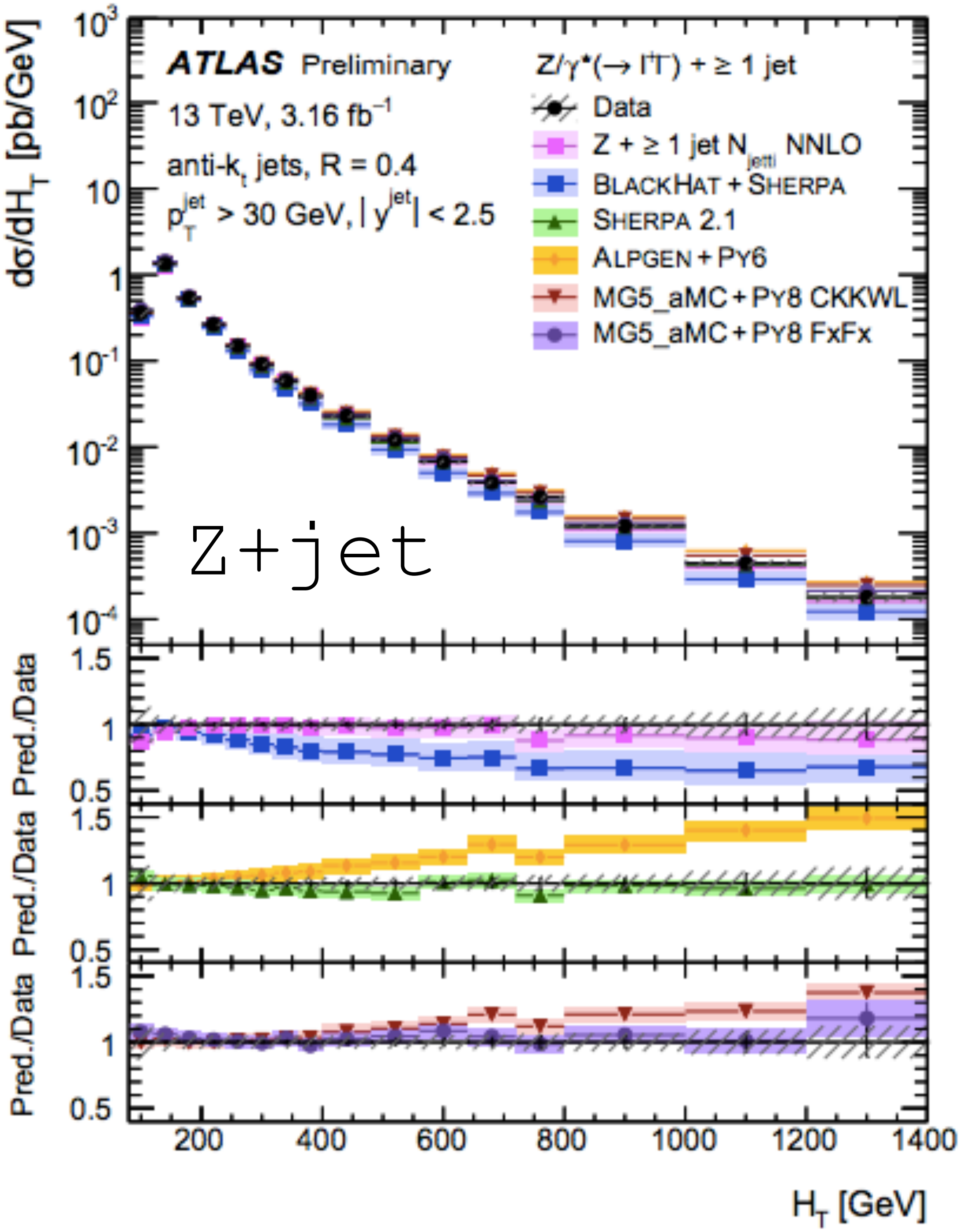
Phenomenology

- **Comparison with 13TeV data** Boughezal, XL, Petriello, '16



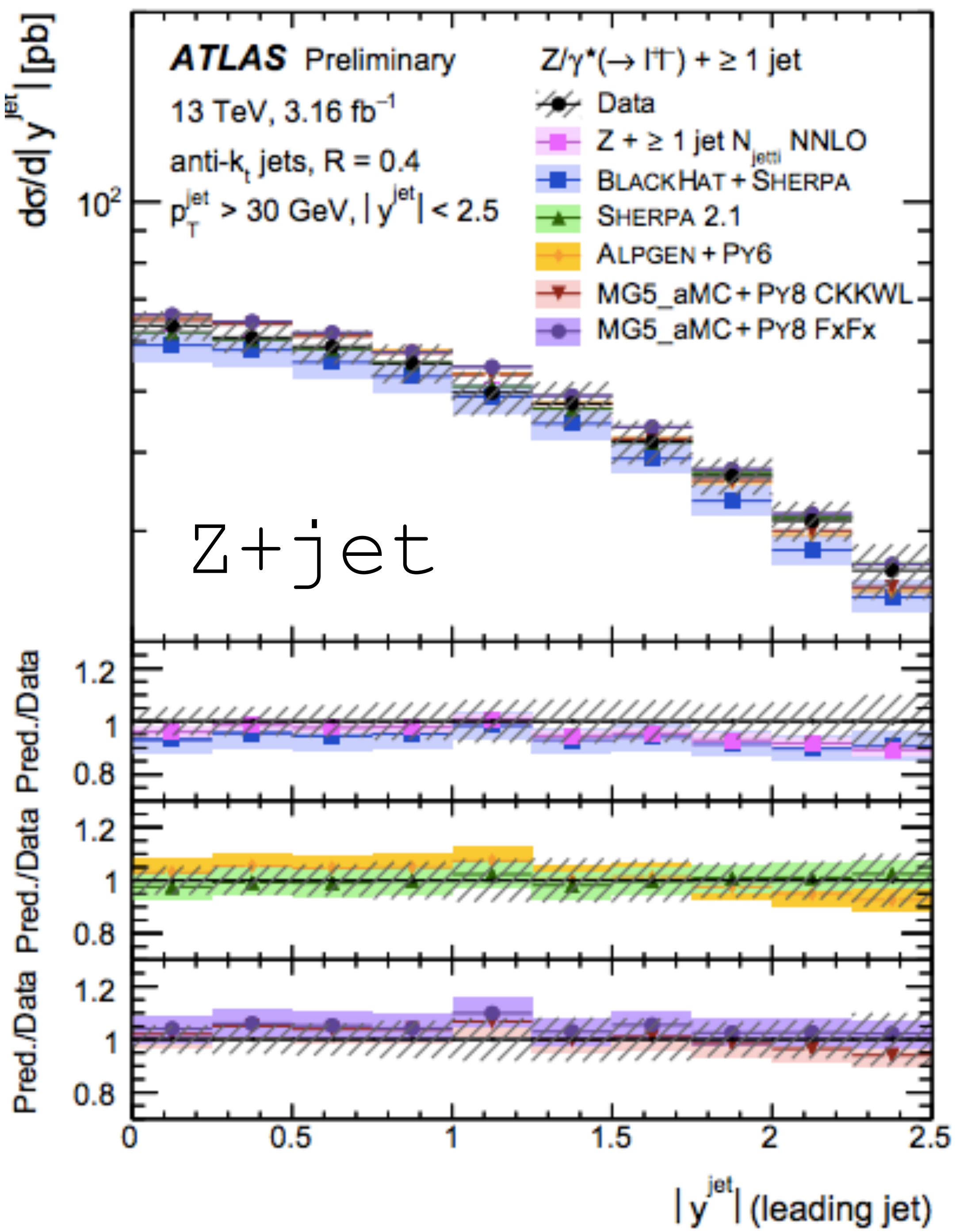
Non-perturbative (hadronisation and underlying event) and FSR corrections included

- SHERPA AND MG5_aMC+PY8 FxFx describes well the data
- ALPGEN+PY6 AND MG5_aMC+PY8 CKKWL overshoot at large H_T
- BlackHat+SHERPA under-estimates the cross section for large values of H_T > 300 GeV
- The agreement is recovered by adding NNLO corrections in perturbative QCD

ATLAS-CONF-2016-046

Phenomenology

- **Comparison with 13TeV data** Boughezal, XL, Petriello, '16



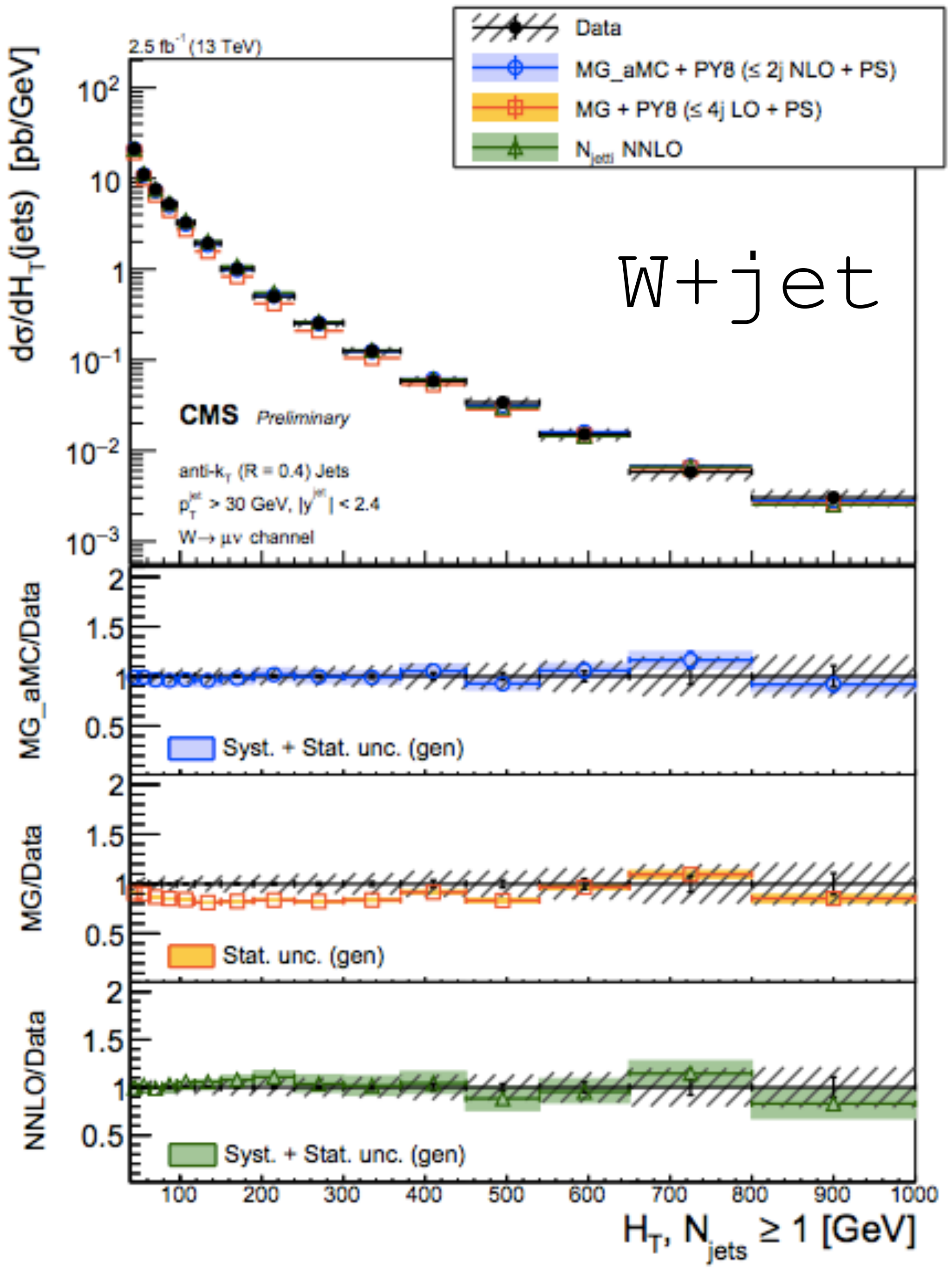
Non-perturbative (hadronisation and underlying event) and FSR corrections included

- all predictions show a good agreement with the measured data within the uncertainties

ATLAS-CONF-2016-046

Phenomenology

- **Comparison with 13TeV data** Boughezal, XL, Petriello, '16



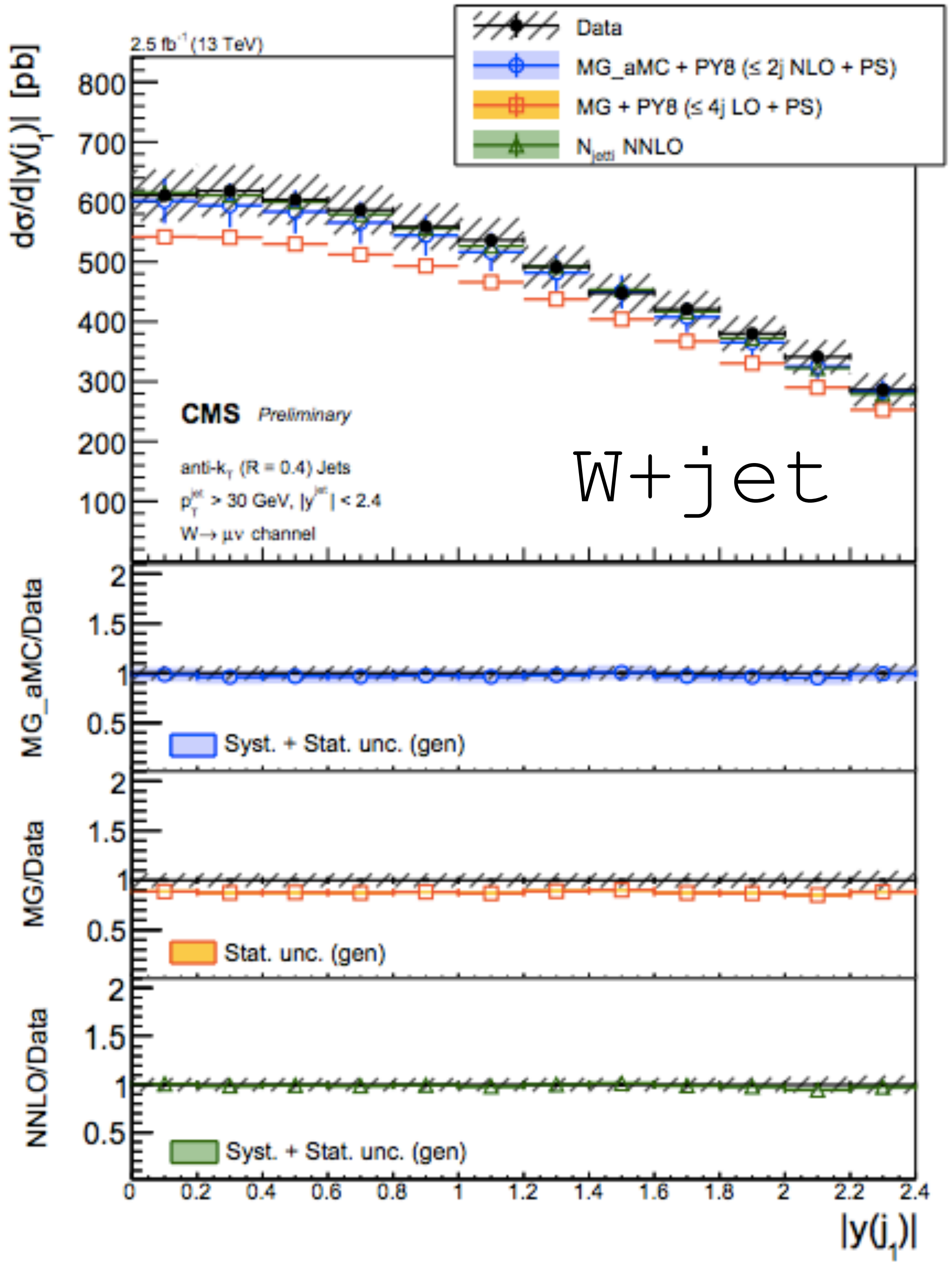
Non-perturbative (hadronisation and MPI) and FSR corrections included

- **the merged NLO generator for all inclusive jet multiplicities describes the data well**
- **LO MG+PY8 is slightly lower than the data in the small H_T region**
- **the NNLO calculation for one inclusive jet multiplicity describes the data well**

CMS PAS SMP-16-005

Phenomenology

- **Comparison with 13TeV data** Boughezal, XL, Petriello, '16



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CMS PAS SMP-16-005

Conclusions

- **N-jettiness subtraction**
  - **a subtraction scheme for jet production**
  - **confirm the known V/H inclusive, VH and di-photon productions**
  - **used for H/V/DIS+1J**

Thanks