NNLO results for V+j at the LHC using N-jettiness

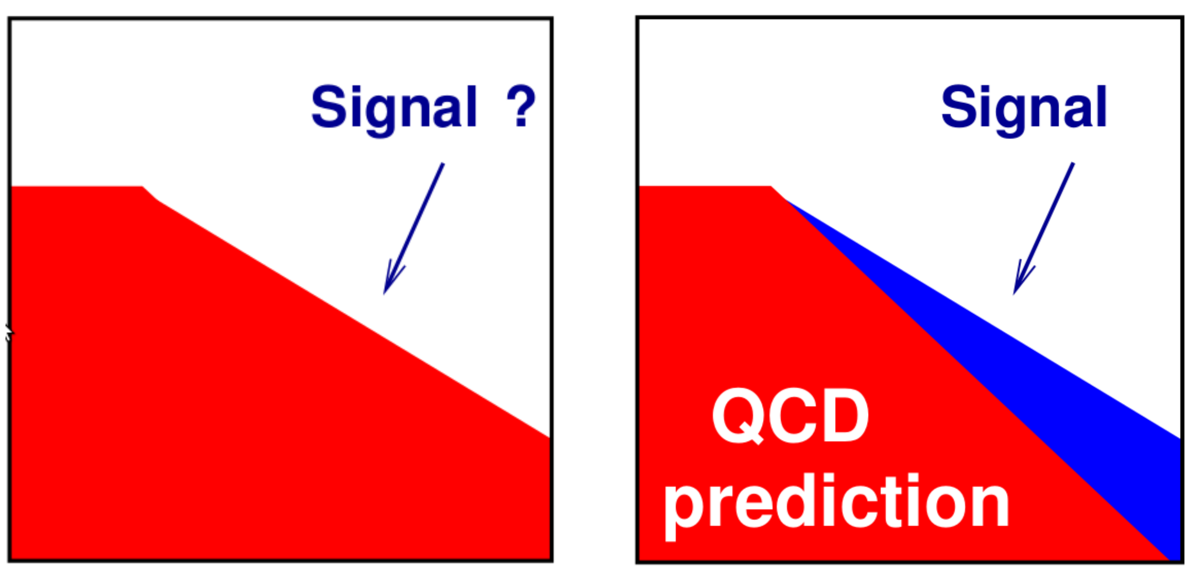
Xiaohui Liu

KITP, 2016

Why V+1j

- SUSY, dark matter mono jet search Background

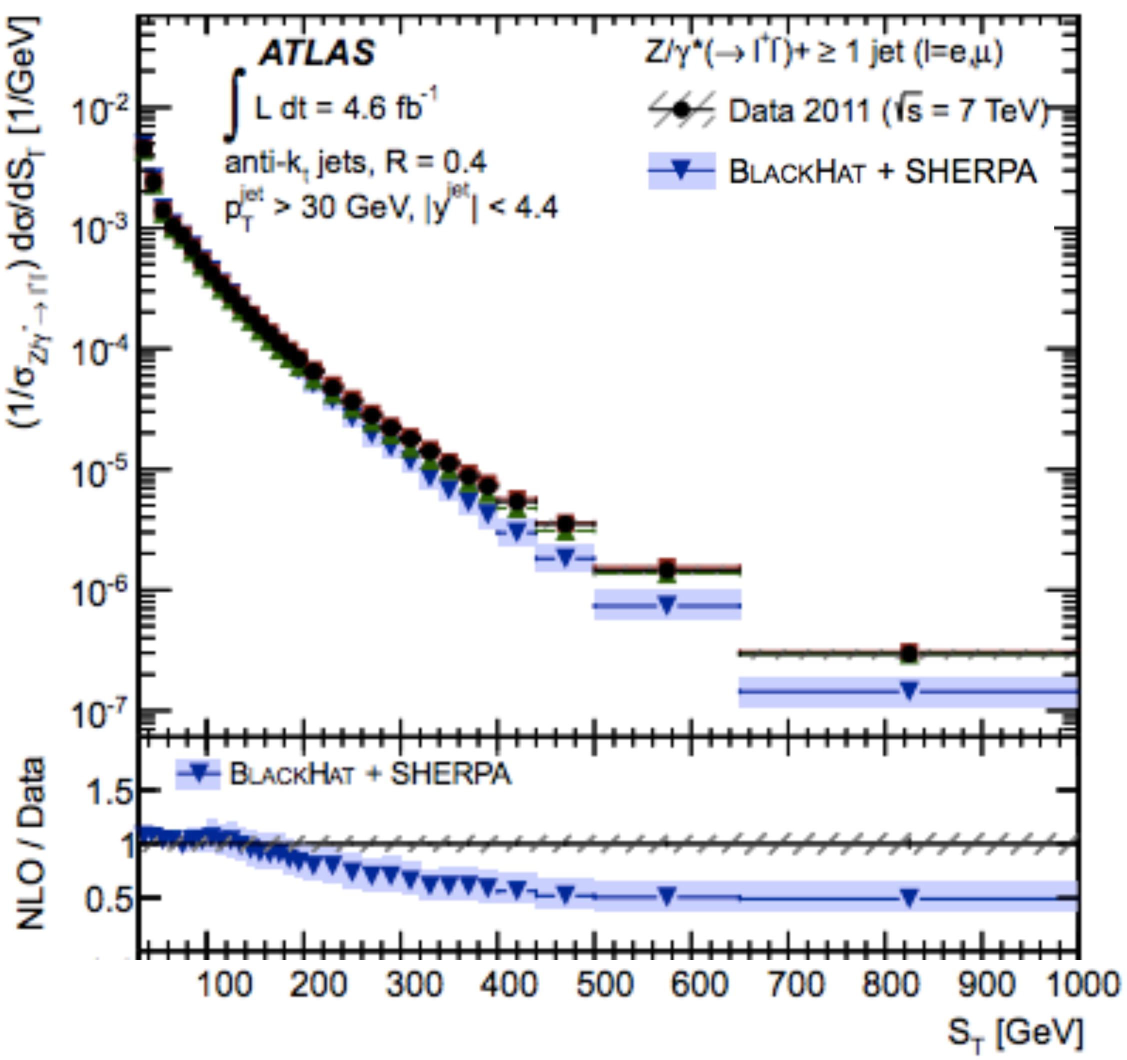
Background process	Method
$Z(\rightarrow \nu\bar{\nu})$+jets	MC and control samples in data
$W(\rightarrow e\nu)$+jets	MC and control samples in data
$W(\rightarrow \tau\nu)$+jets	MC and control samples in data
$W(\rightarrow \mu\nu)$+jets	MC and control samples in data
$Z/\gamma^*(\rightarrow \ell^+\ell^-)$+jets ($\ell = e, \mu, \tau$)	MC-only
$t\bar{t}$, single top	MC-only
Diboson	MC-only
Multijets	data-driven
Non-collision	data-driven



- No resonance, only see excess in the data
- Predicting the shape correctly is crucial

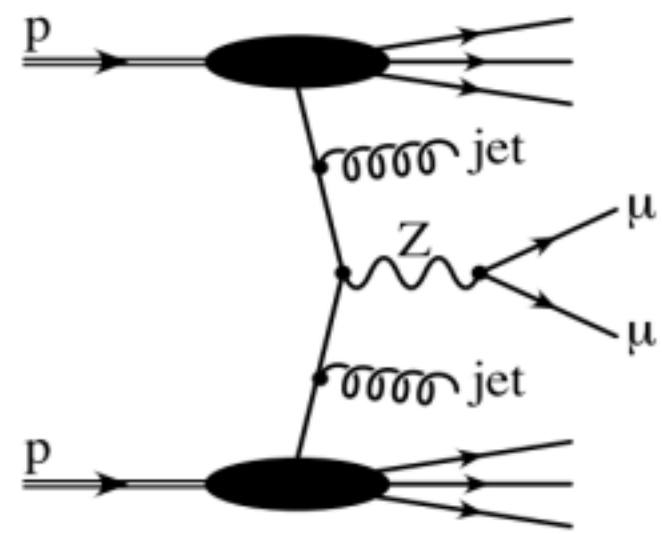
Why V+1j

- Precise experimental measurements



CERN-PH-EP-2013-023

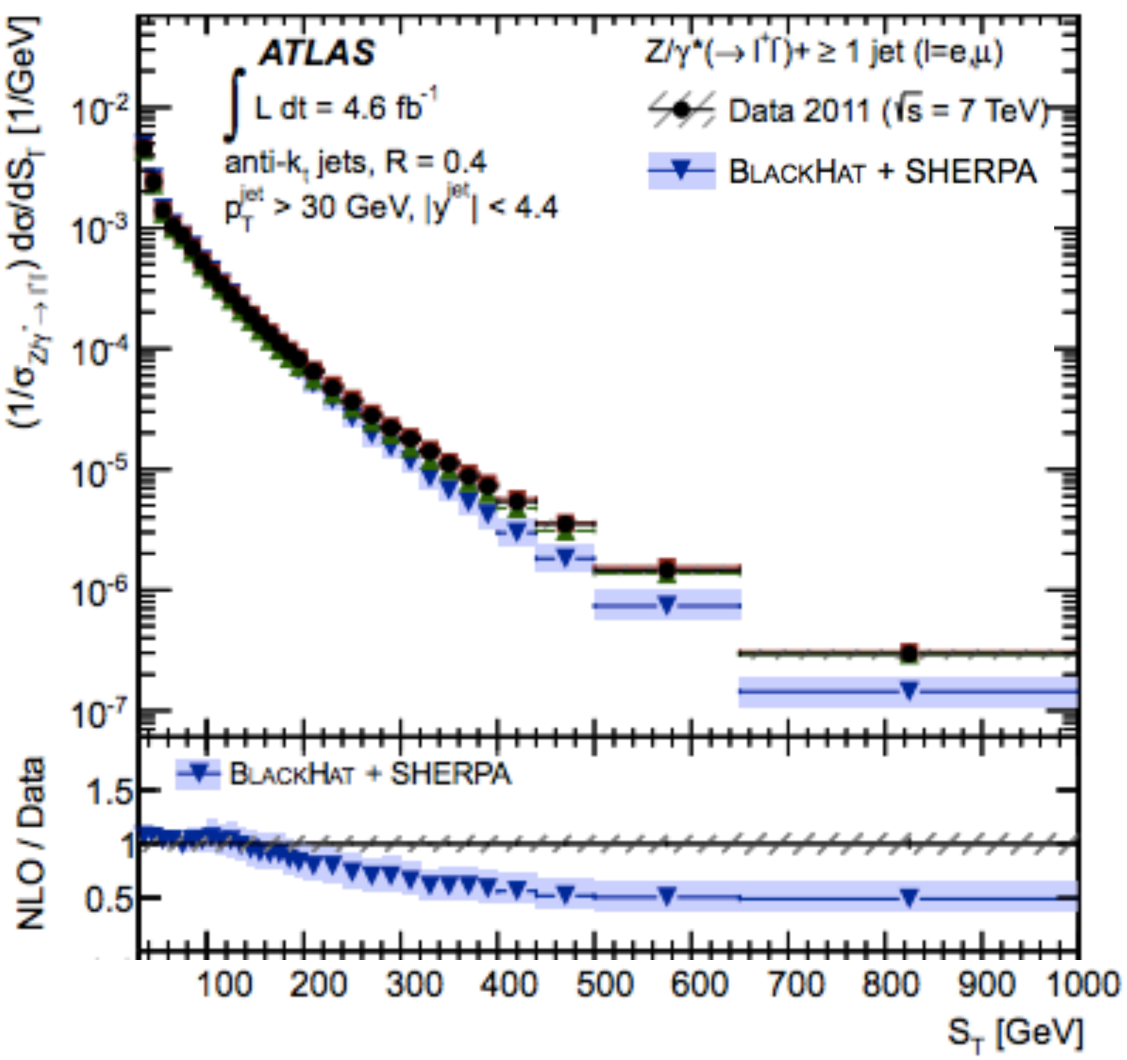
clean signature



- Uncertainty ~ +/- 10% up to TeV scale

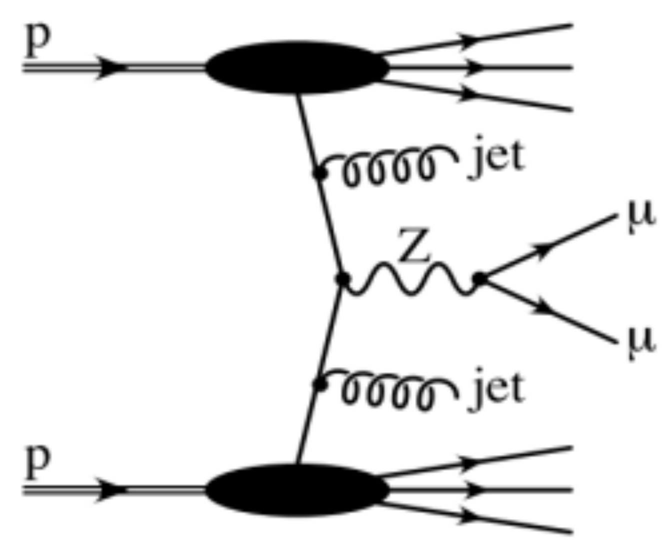
Why V+1j

- Precise experimental measurements



CERN-PH-EP-2013-023

clean signature

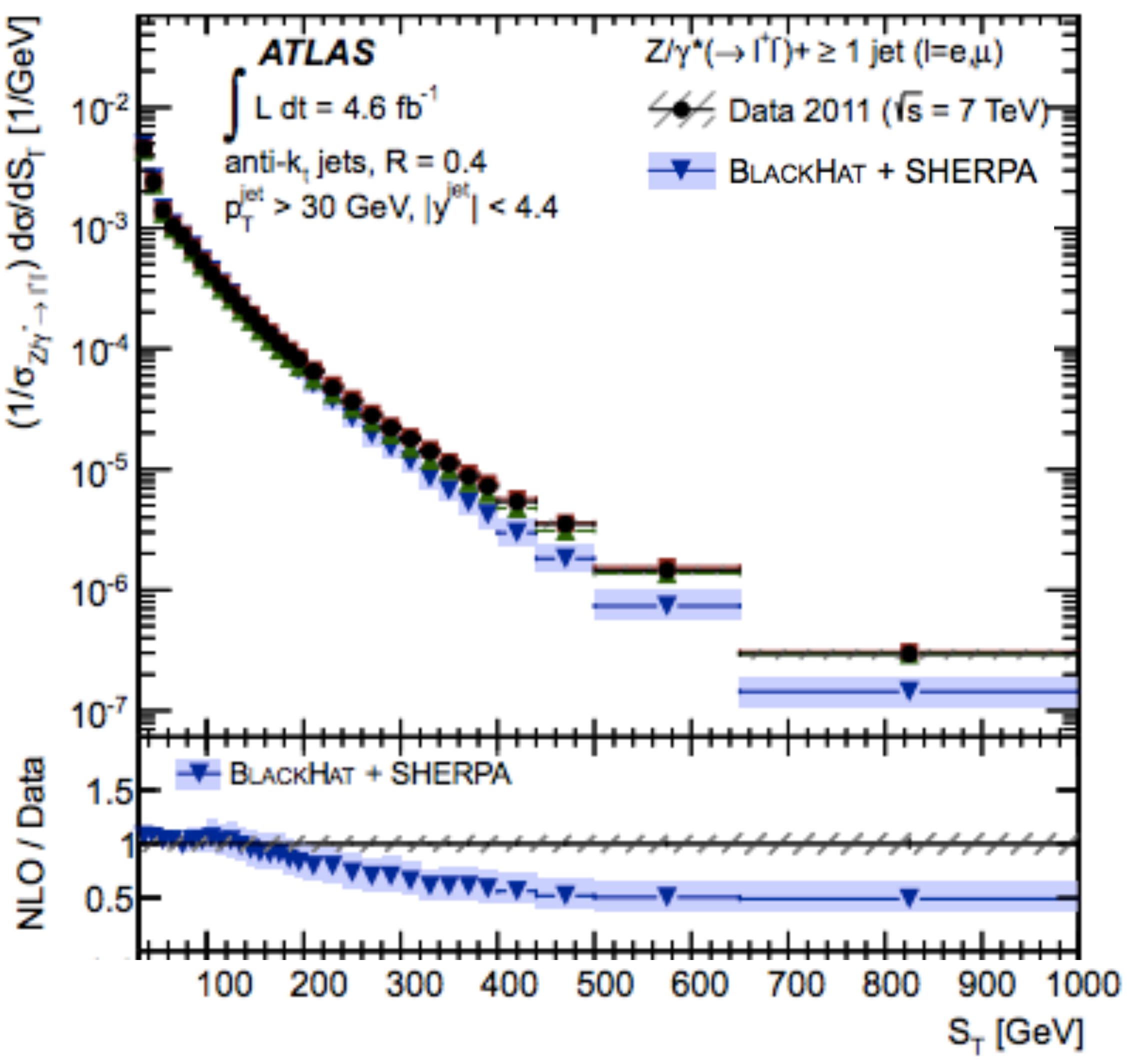


- Uncertainty ~ +/- 10% up to TeV scale
- Standard candle at the LHC
  - Jet energy scale calibration CERN-PH-EP-2013-222
- Precision test/measurements of QCD
  - constrain PDFs

require high-precision predictions!

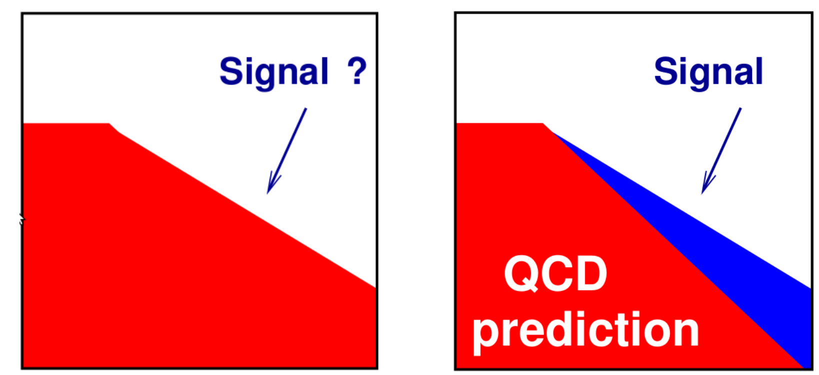
Theory Status

- NLO prediction



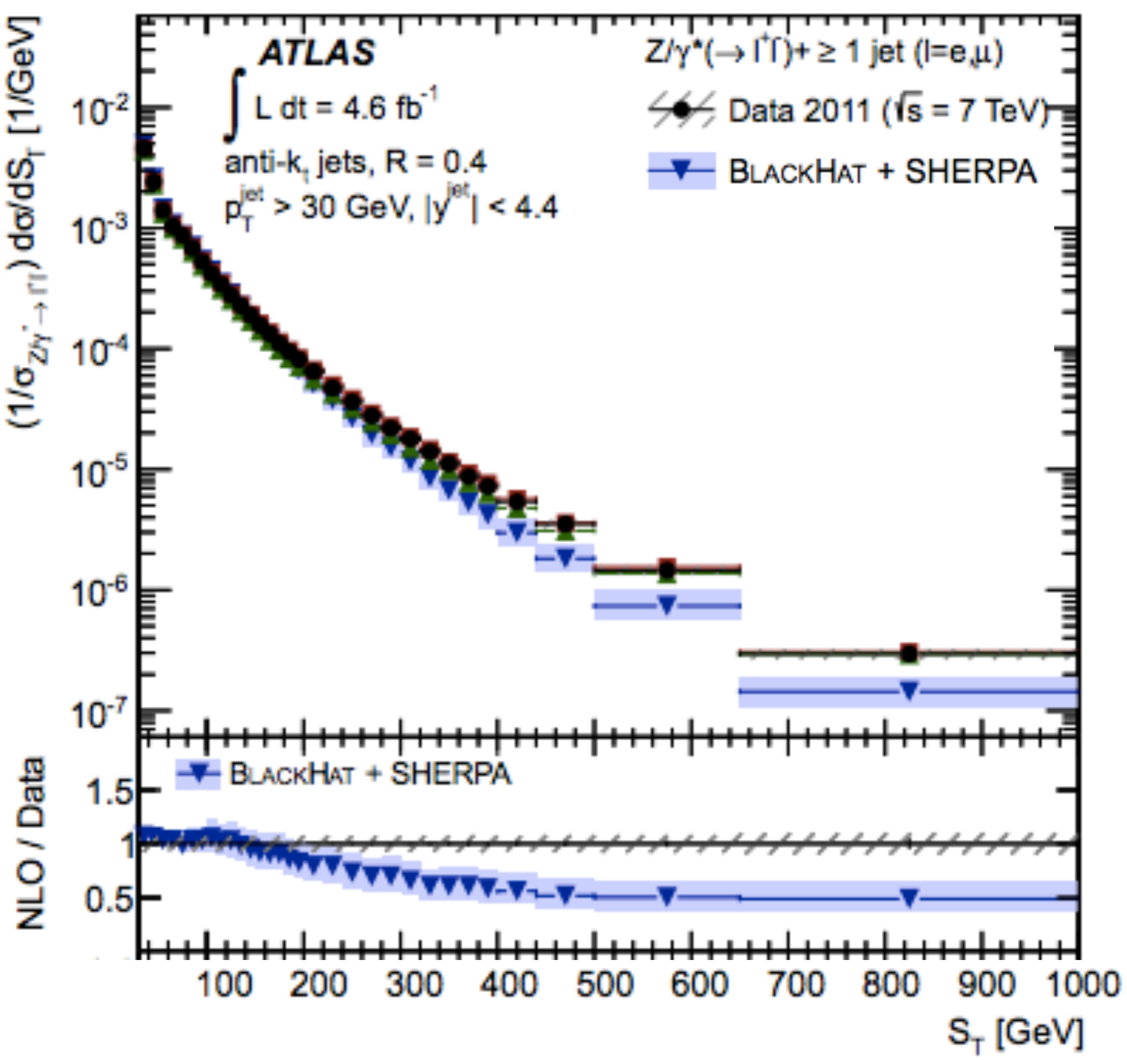
CERN-PH-EP-2013-023

- QCD NLO underestimates the data by 50% at large ST



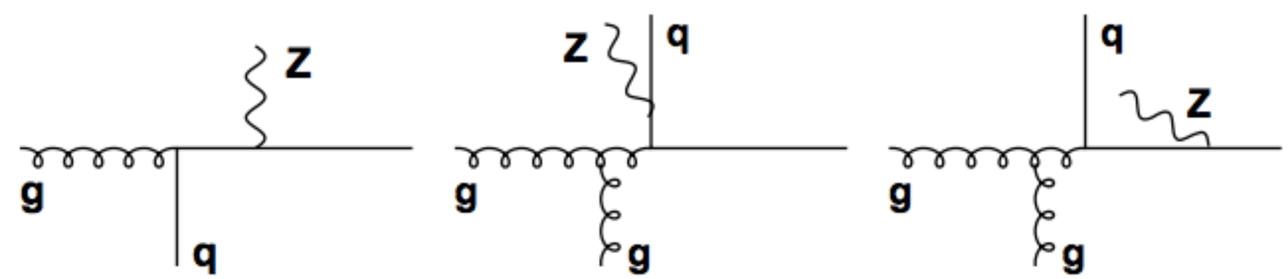
Theory Status

- NLO prediction

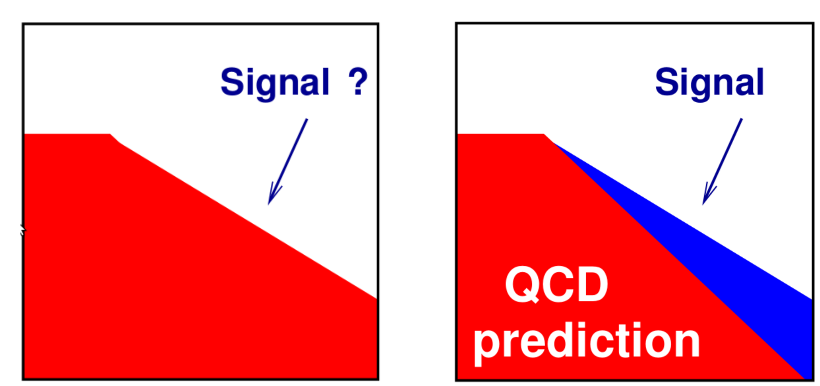


CERN-PH-EP-2013-023

- QCD NLO underestimates the data by 50% at large ST



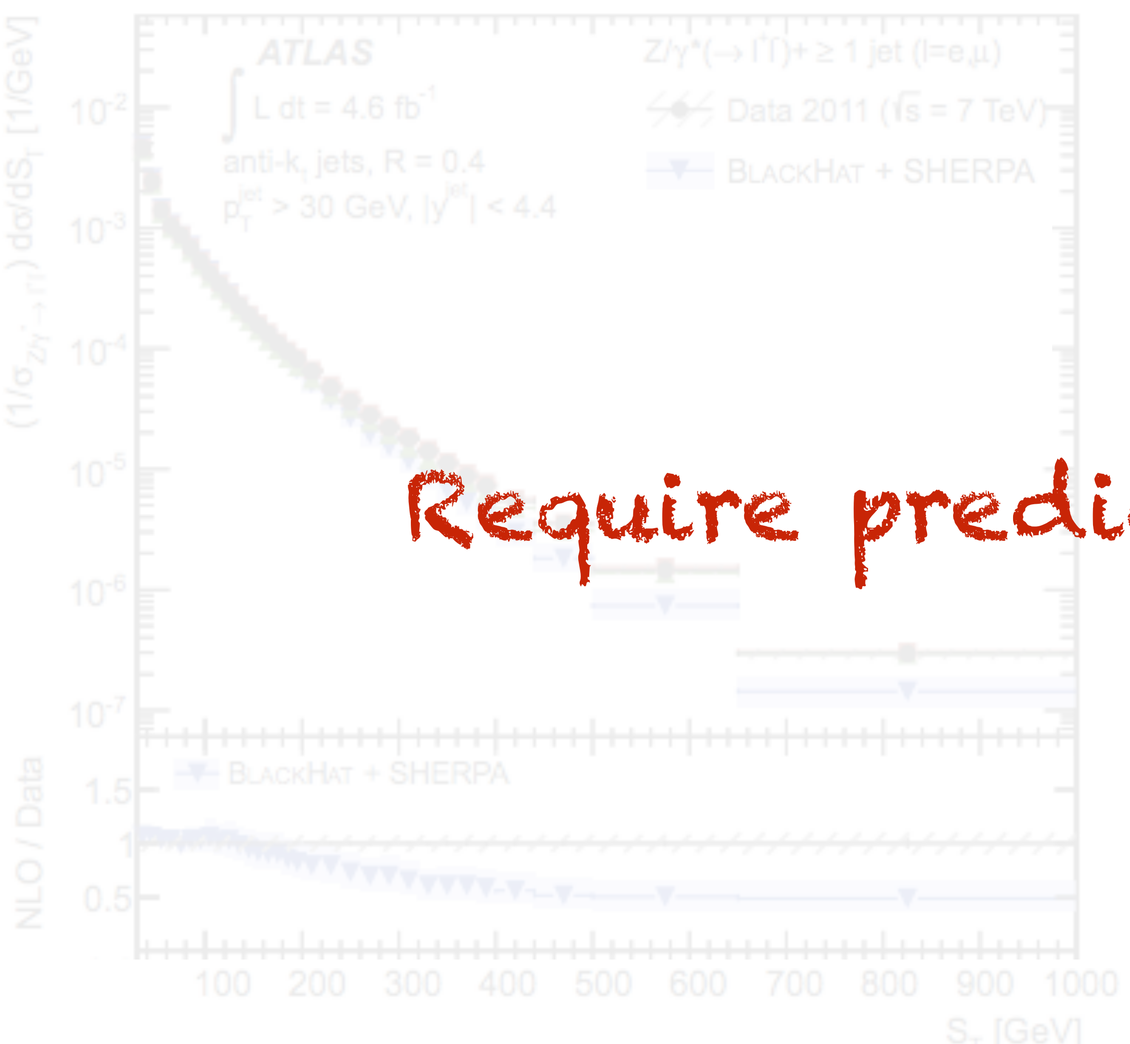
New channels open up at higher orders allow for a soft/collinear Z



Rubin, Salam, Sapeta, ‘10

Theory Status

- NLO prediction



CERN-PH-EP-2013-023

- QCD NLO underestimates the data by 50% at large ST

Require predictions from the NNLO

New channels open up at higher orders allow for a soft/collinear Z

Rubin, Salam, Sapeta '16

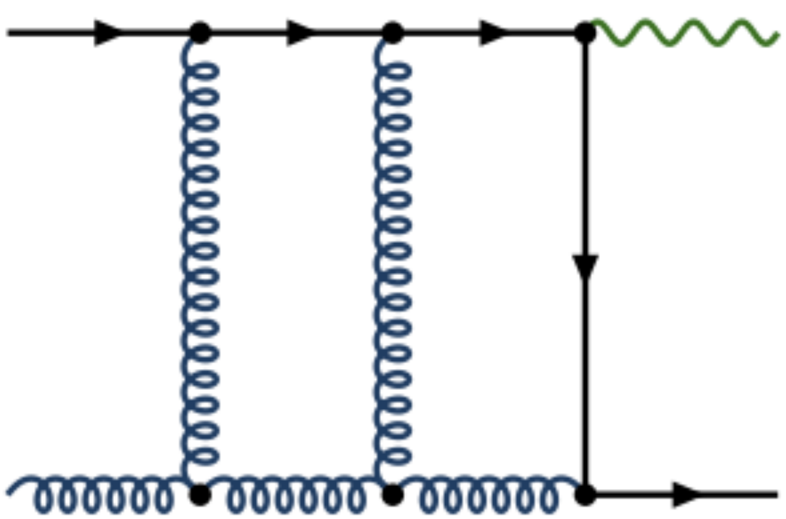
Outline

- Theory Setups
  - N-jettiness subtraction
- NNLO V + 1jet at the LHC
- Conclusion

Theory Setups

- Virtual corrections
  - Explicit IR poles
  - Known to 2-loop analytically

Moch, Uwer, Weinzierl, '02; Garland, Gehrmann, Glover, Koukoutsakis, Remiddi, '02; Gehrmann, Tancredi, '12

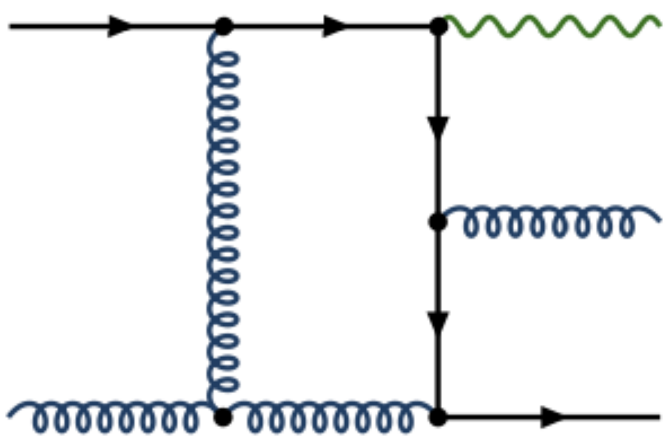


$$\int \mathrm{d}\Phi_2 \sum_{i=0}^{4} \frac{vv_i}{\epsilon^i}$$

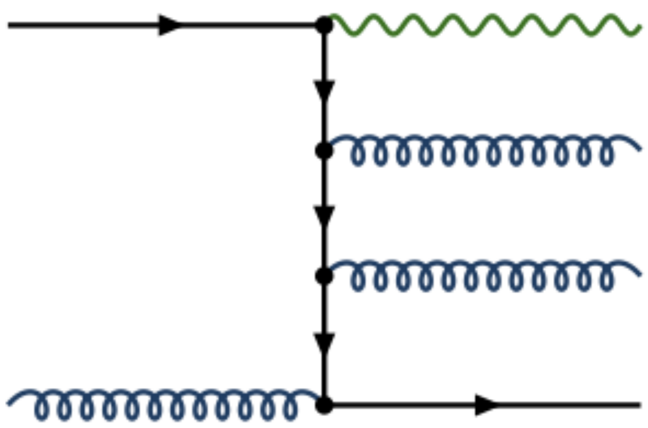
Theory Setups

- Real corrections

  - Implicit IR poles



$$\int \mathrm{d}\Phi_3 \sum_{i=0}^{2} \frac{vr_i}{\epsilon^i}$$



$$\int \mathrm{d}\Phi_4 \, rr$$

IR poles fully show up only after integrating over phase space for degenerate (soft/collinear) states

Theory Setups

- Real corrections
  - Various methods proposed to extract implicit IR poles
    - Sector decomposition, Sector-improved residues
      Binoth, Heinrich; Anastasiou, Melnikov, Petriello   Czakon; Boughezal, Melinkov, Petriello
    - Antenna subtraction Kosower Gehrmann-De Ridder, Gehrmann, Glover
    - qT subtraction, N-Jettiness subtraction
      Catani, Grazzini   Boughezal, Focke, XL, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh
    - Projection to Born process Cacciari, Dreyer, Karlberg, Salam, Zanderighi
    - CoLorFul NNLO Del Duca, Somogyi and Trócsányi Del Duca, Duhr, Kardos, Somogyi and Trócsányi

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

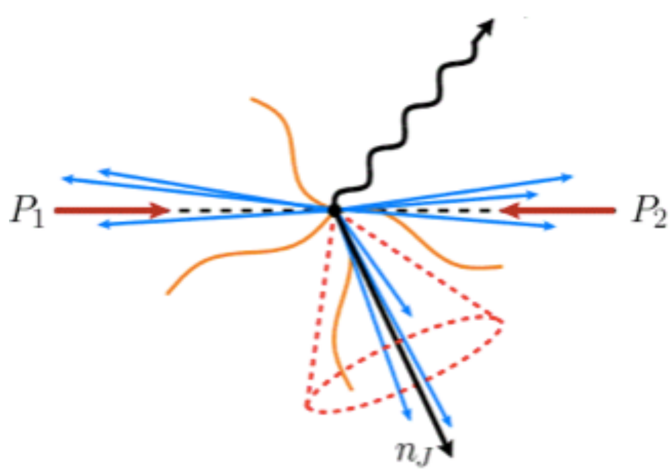
- N-Jettiness subtraction

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

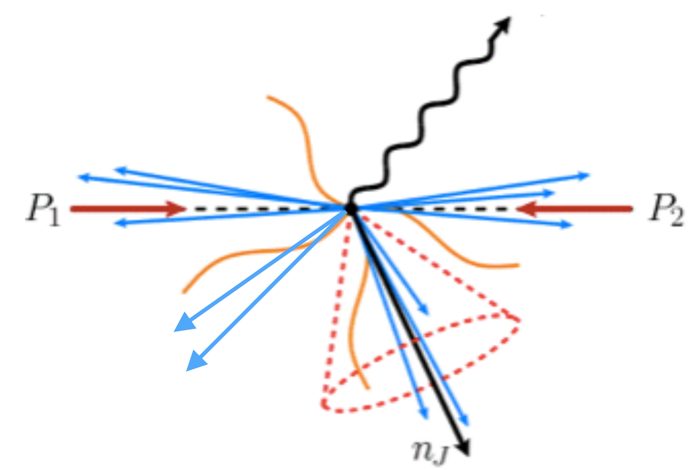
$$\mathcal{T}_N = \sum_k \min\left\{w_a\, n_a \cdot q_k\,, w_b\, n_b \cdot q_k\,, w_i\, n_i \cdot q_k\,, \ldots\,, w_N\, n_N \cdot q_k\right\}$$

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

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



- At least N+1 hard radiations



Theory Setups

- N-Jettiness subtraction

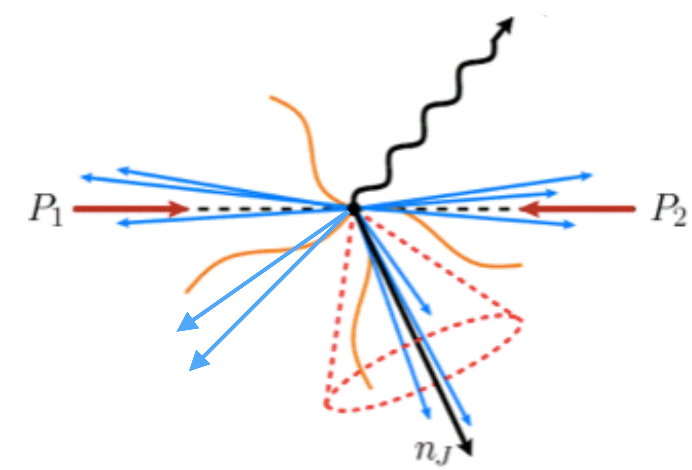
Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15

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

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

- 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

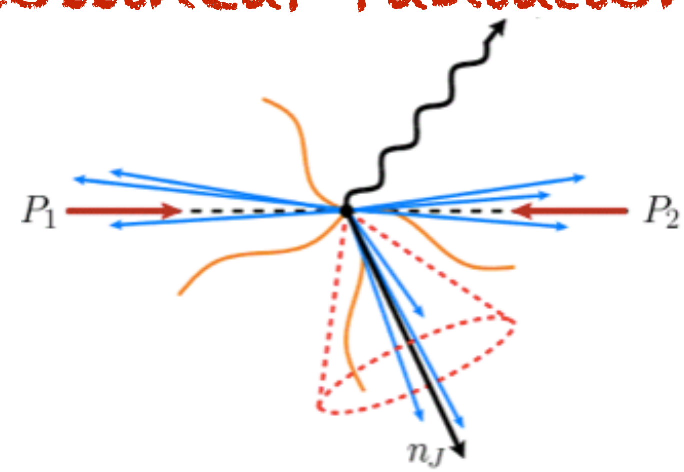
$$\mathcal{T}_N = \sum_k \min\{w_a\, n_a \cdot q_k\,, w_b\, n_b \cdot q_k\,, w_i\, n_i \cdot q_k\,, \ldots\,, w_N\, n_N \cdot q_k\}$$

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

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

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

Stewart,Tackmann, Waalewijn, '10



- simple calculation based on factorization theorem
- all components known to 2-loop
- most of them are universal, re-usable for other process
- power corrections vanish as $\mathcal{T}_N \to 0$

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

beam: Gaunt, Stahlhofen, Tackmann, '14

soft: Boughezal, XL and Petriello, '15

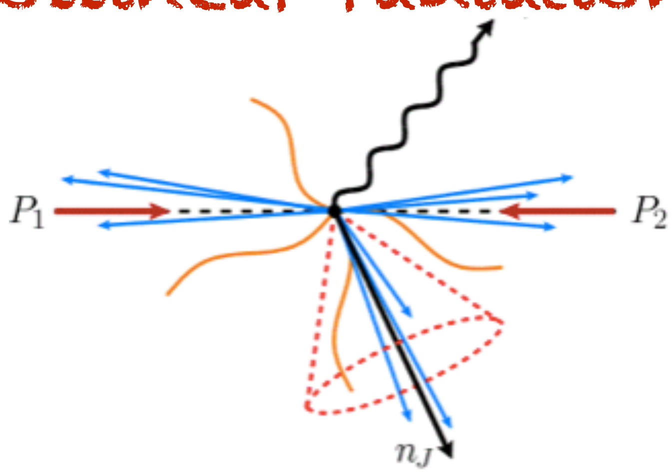
Theory Setups

- 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

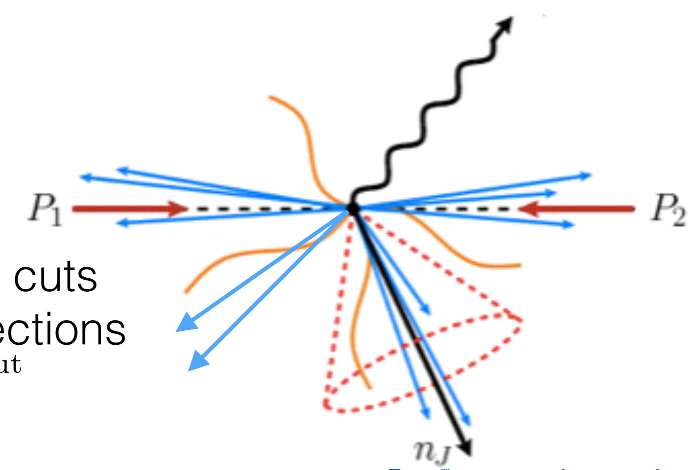


$$\mathrm{Tr}[H \cdot S_N] \otimes B_a \otimes B_b \otimes J_i + \ldots$$

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

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

- 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
  - Successfully used to provide new results for processes with a jet
    - H/W/Z+1j   Boughezal, Focke, XL, Petriello,'15, Boughezal, Focke, Giele, XL, Petriello, '15 Boughezal, Campbell, Ellis, Focke, Giele, XL, Petriello,'15,
  - Successfully used to confirm (and correct) 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 power correction

- N-Jettiness subtraction Boughezal, Focke, XL, Petriello, '15 Gaunt, Stahlhofen, Tackmann, Walsh, '15
  - Successfully used to provide new results for processes with a jet
  - Successfully used to confirm (and correct) existing results

Validations

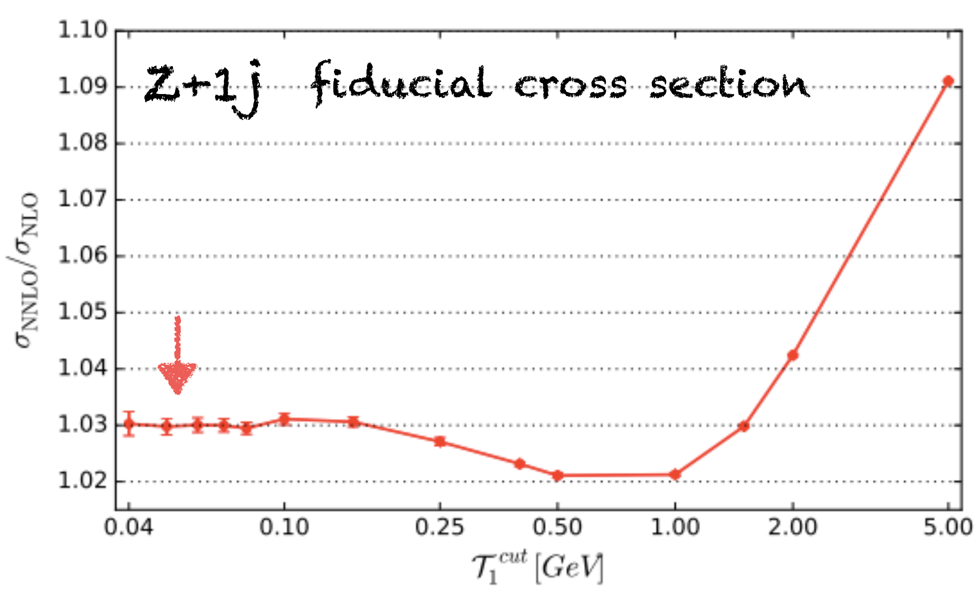
- H+1j agrees with the one using Sector-improved residues method Boughezal, Caola, Melnikov, Petriello, Schulze, '13 '15
- Reproduced existing results (VH by Campbell, et al, '16 inclusive H/W/Z by Gaunt, et al, '15)
- di-photon production using jettiness-subtraction [Campbell, et al, '16] corrected existing results by qT-subtraction for di-photon production [Catani, et al, '11]

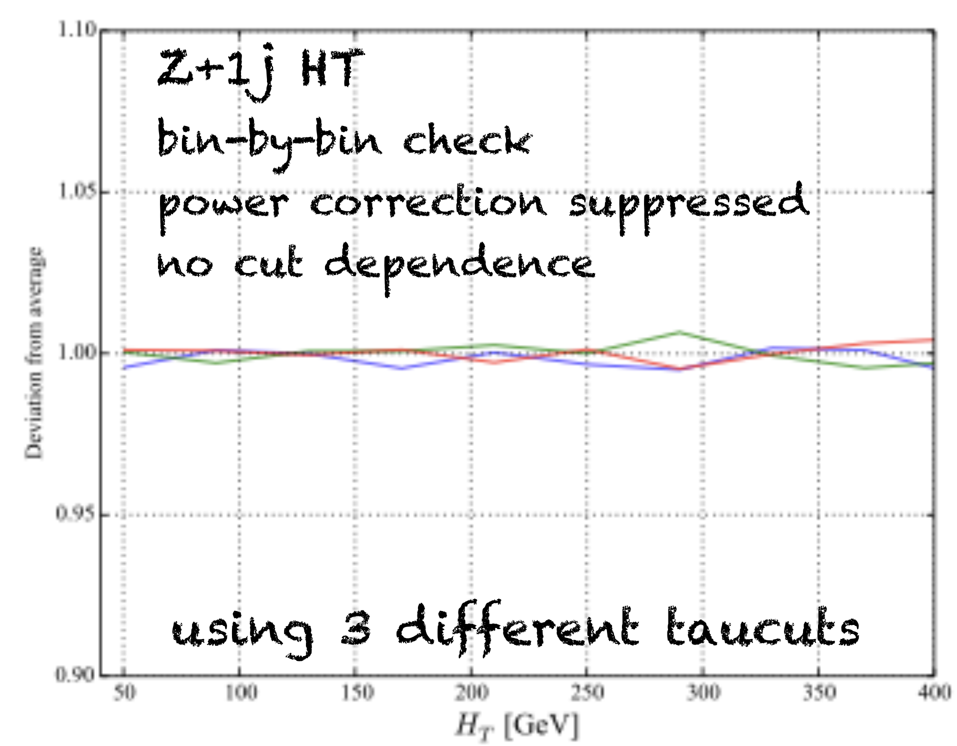
Validation and power correction

- N-Jettiness subtraction   Boughezal, Focke, XL, Petriello, '15   Gaunt, Stahlhofen, Tackmann, Walsh, '15
  - Successfully used to provide new results for processes with a jet
  - Successfully used to confirm (and correct) existing results

Validations

- taucut-independence check in all calculations





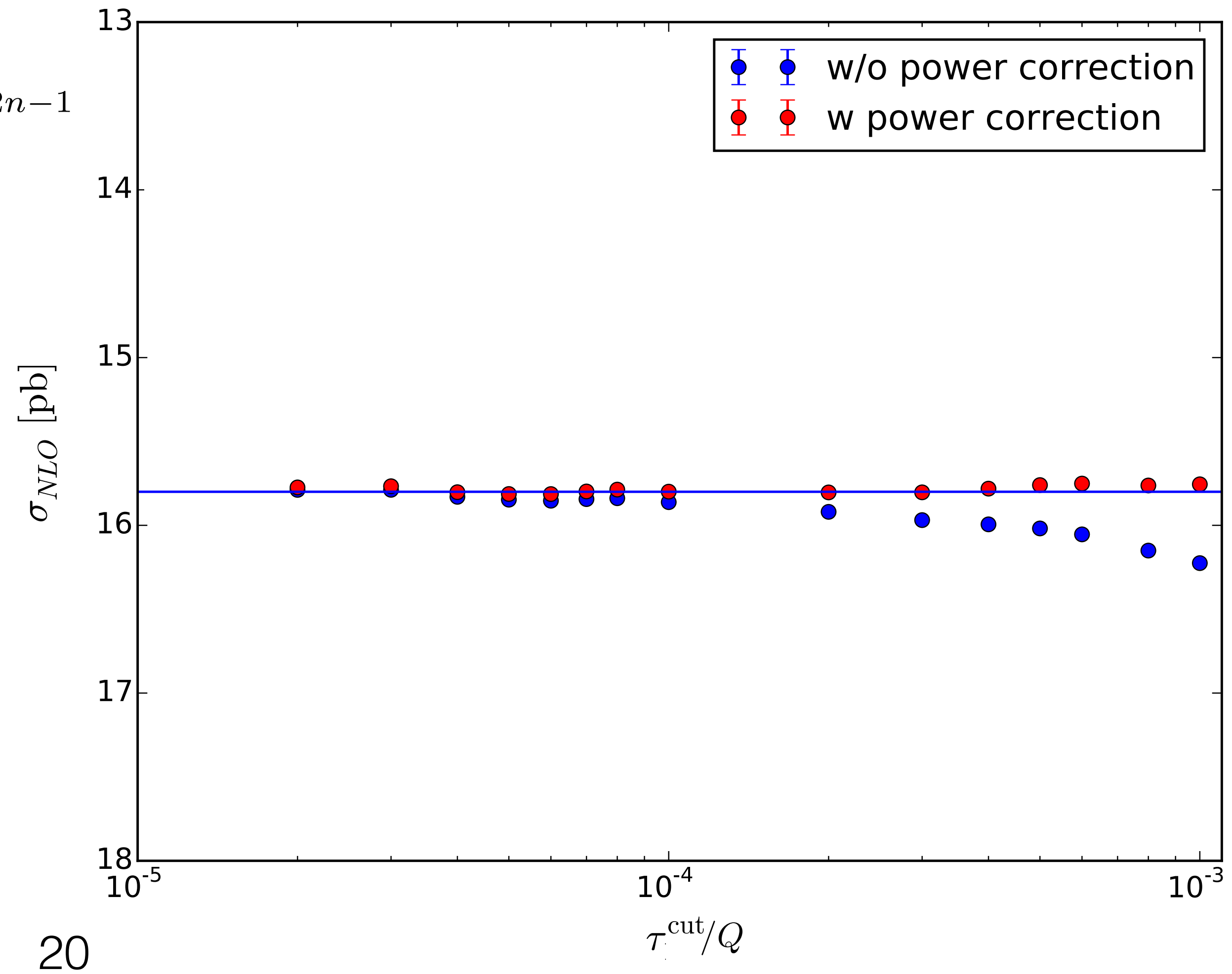
Validation and power correction

- N-Jettiness subtraction Boughezal, Focke, XL, Petriello, '15 Gaunt, Stahlhofen, Tackmann, Walsh, '15
  - Successfully used to provide new results for processes with a jet
  - Successfully used to confirm (and correct) existing results

power corrections

- logarithmic nature of dominant power corrections
- 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

$\alpha_s^n\, C_n\, \mathcal{T}_N^{\rm cut}\, L^{2n-1}$



V+1j at the LHC

- 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	$\lvert\eta^l\rvert < 2.5$	$\lvert\eta^l\rvert < 2.1$
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	$\lvert\eta^J\rvert < 4.4$	$\lvert\eta^J\rvert < 2.4$
anti-k_T radius	$R = 0.4$	$R = 0.5$

CERN-PH-EP-2014-199

CERN-PH-EP-2014-134

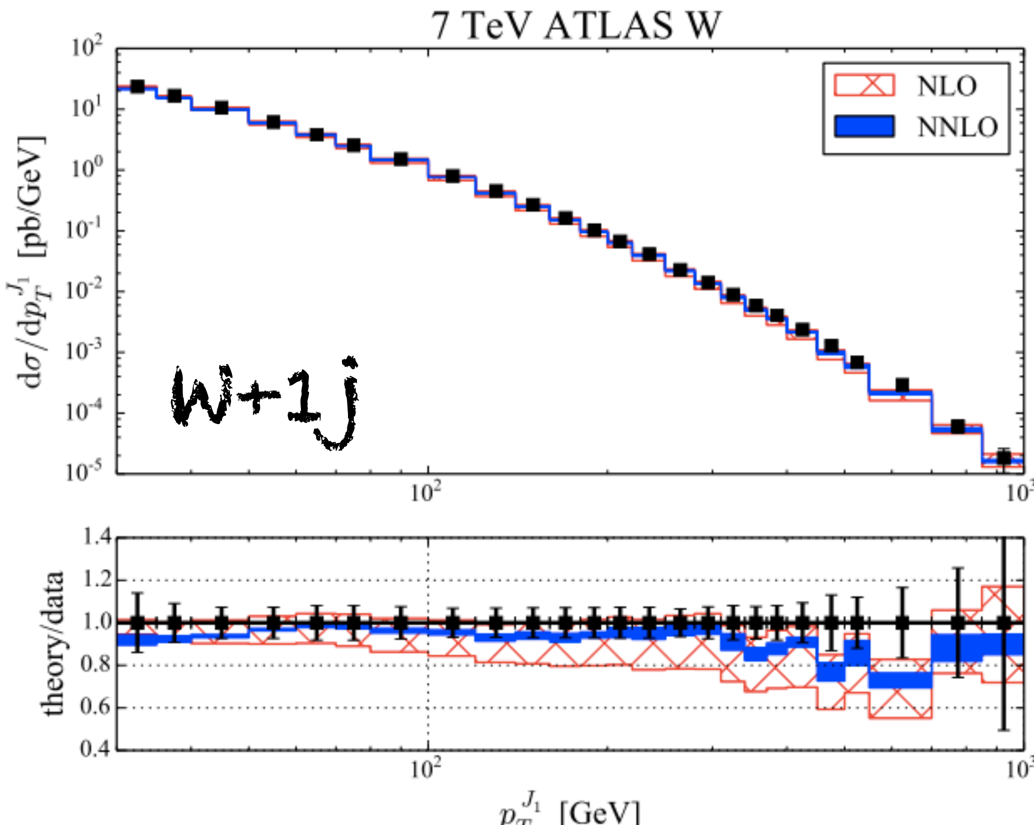
$$\mu_0 = \sqrt{M_V^2 + \sum_i (p_T^{J_i})^2}$$

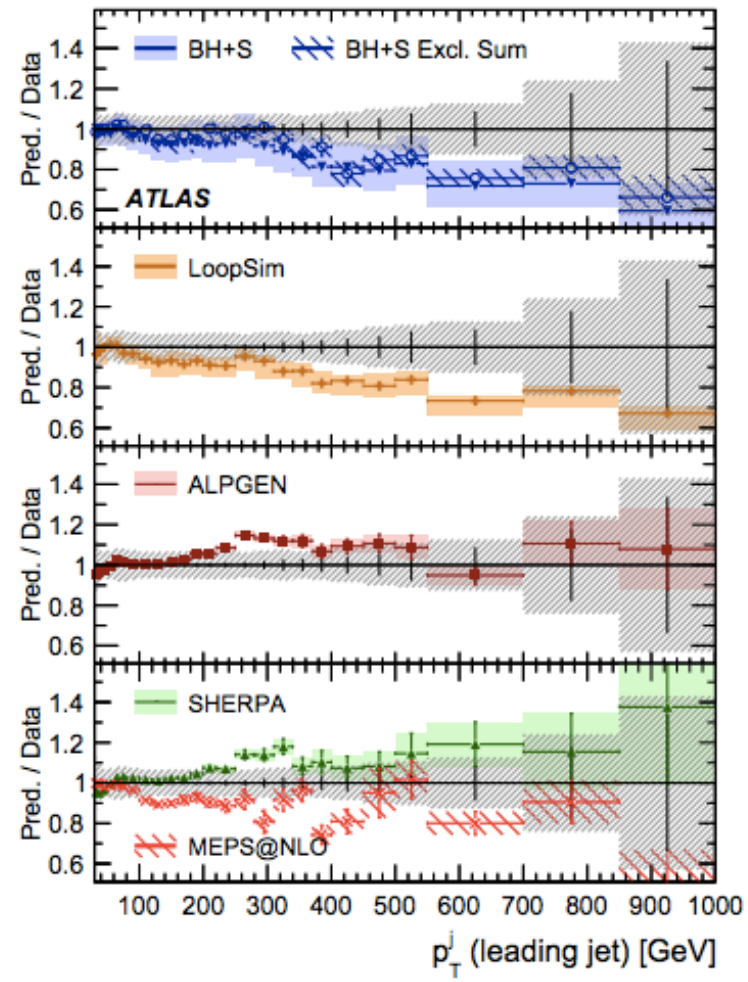
- CT14NNLO PDFs for NNLO results, CT14NLO for NLO results
- Vary muF and muR independently
- non-perturbative corrections included for ATLAS pTJ and yJ
- QED FSR factors included for ATLAS pTJ and yJ

V+1j at the LHC

- 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

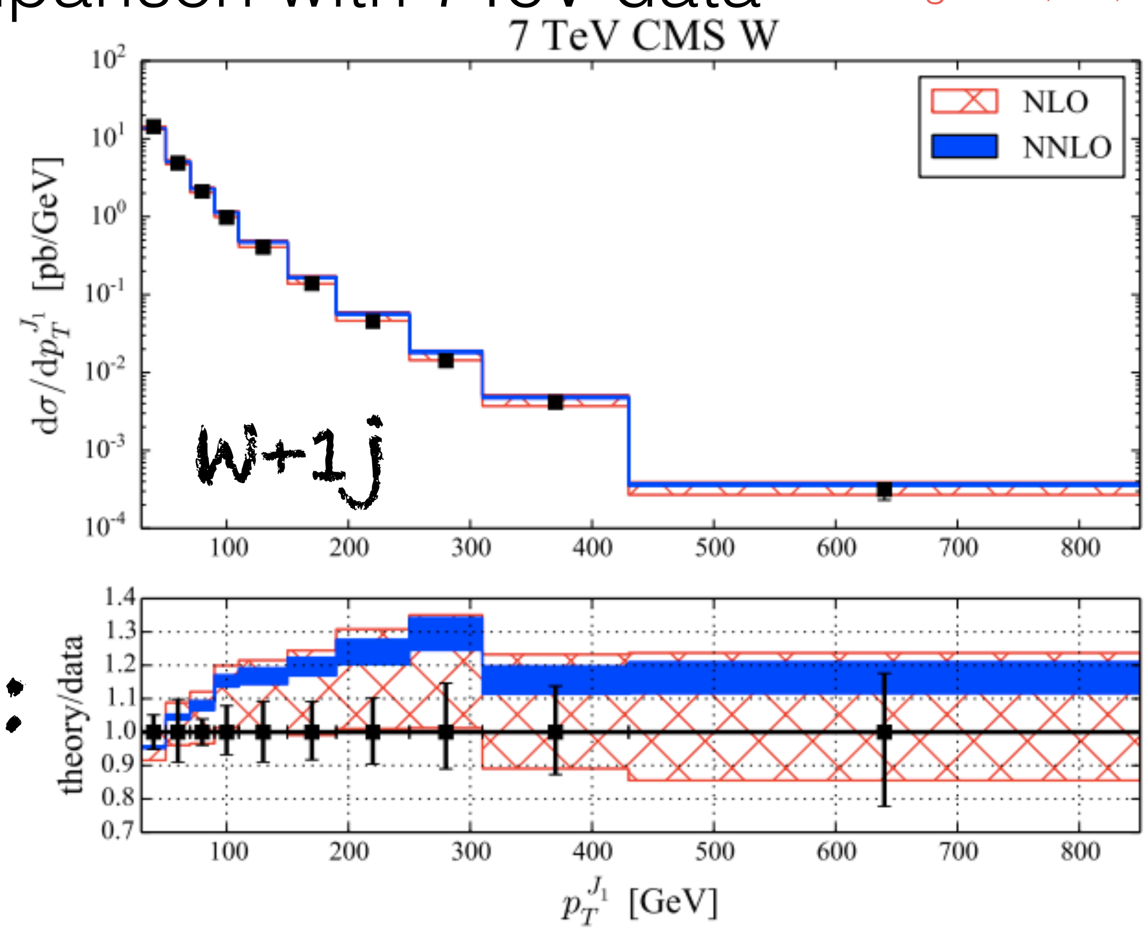
CERN-PH-EP-2014-199

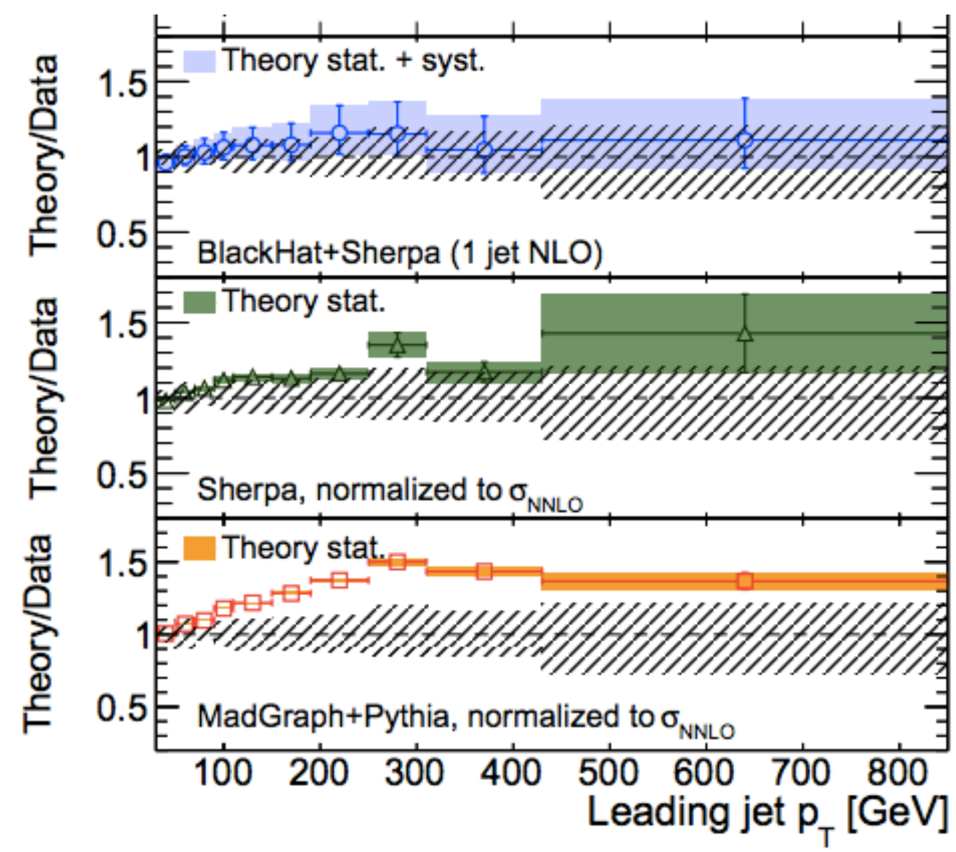
V+1j at the LHC

- 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

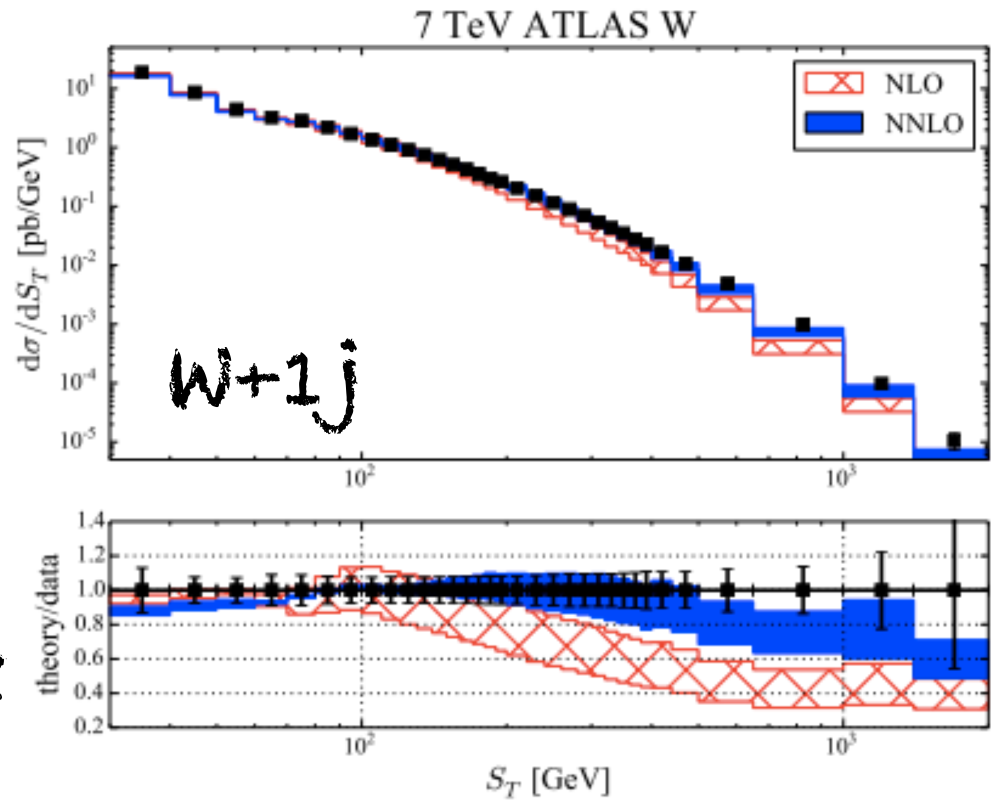
CERN-PH-EP-2014-134

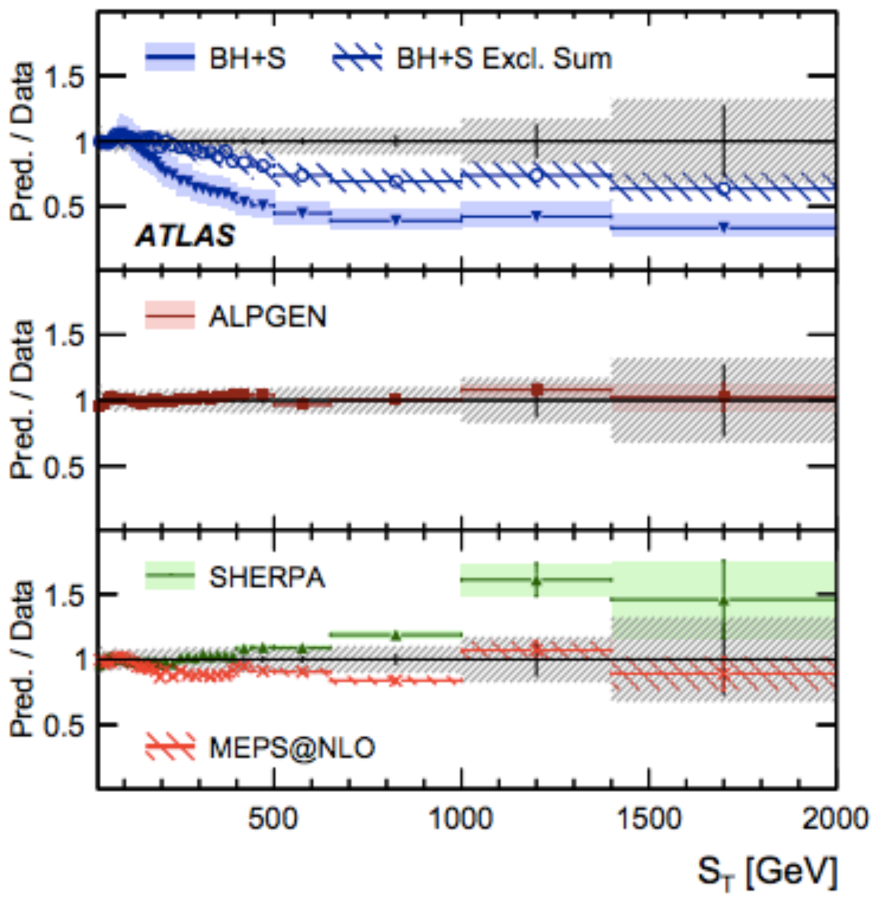
V+1j at the LHC

- Comparison with 7TeV data

Boughezal, XL, Petriello, '16

$H_T(S_T)$:





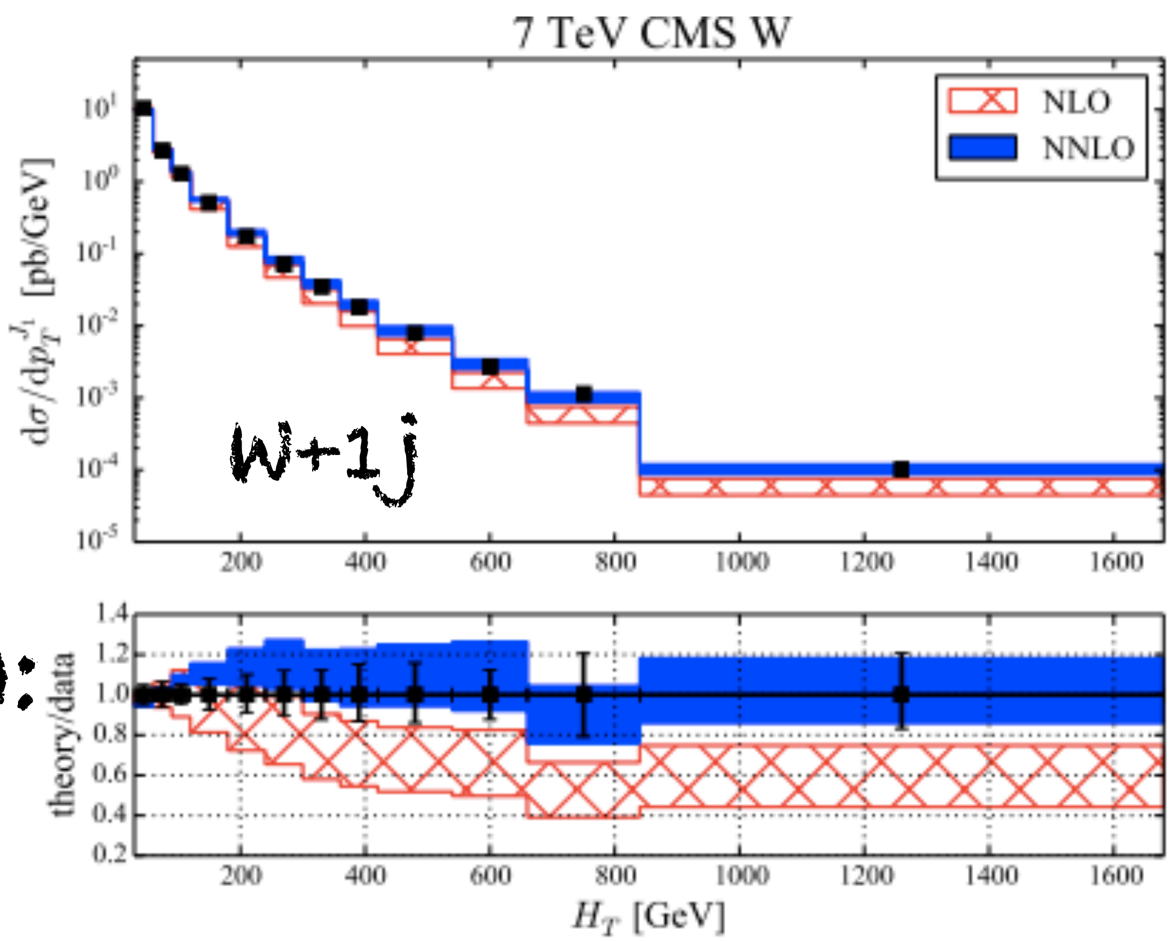
- ALPGEN agrees with data while SHERPA overshoots th measurements
- The NLO predictions far undershoot the data while MEPS@NLO does a good job
- The NNLO corrections bring theory into good agreement with experiment, with a slight undershoot at very high ST

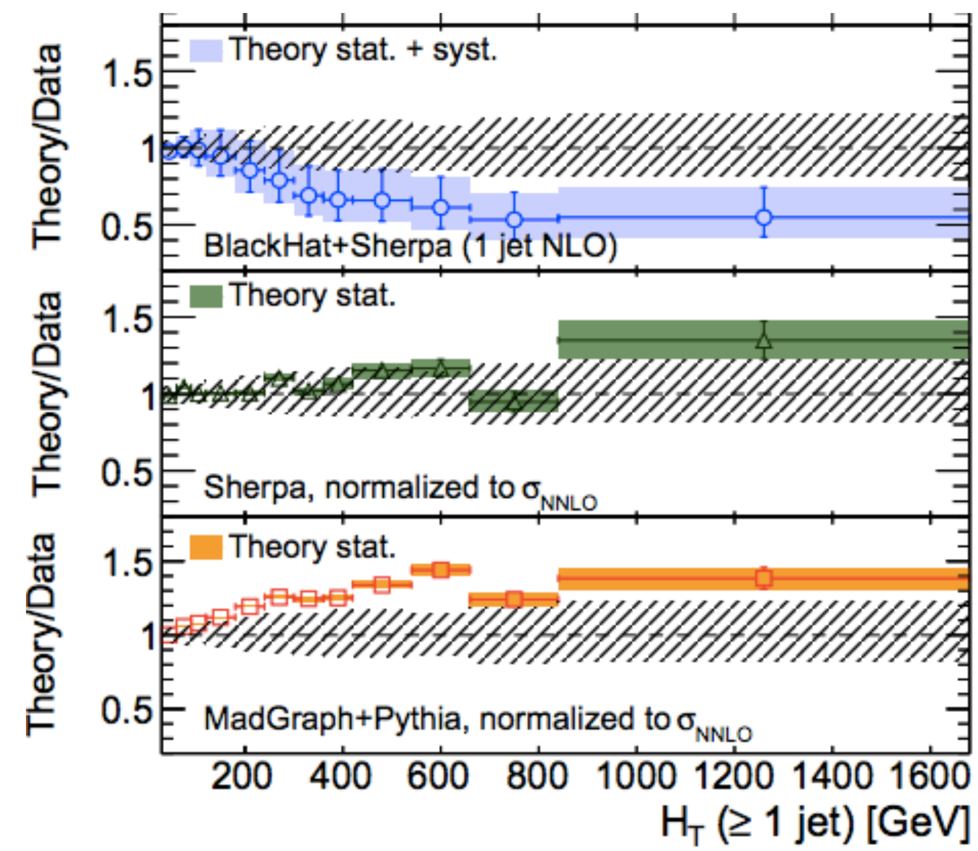
CERN-PH-EP-2014-199

V+1j at the LHC

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

$H_T(S_T)$:





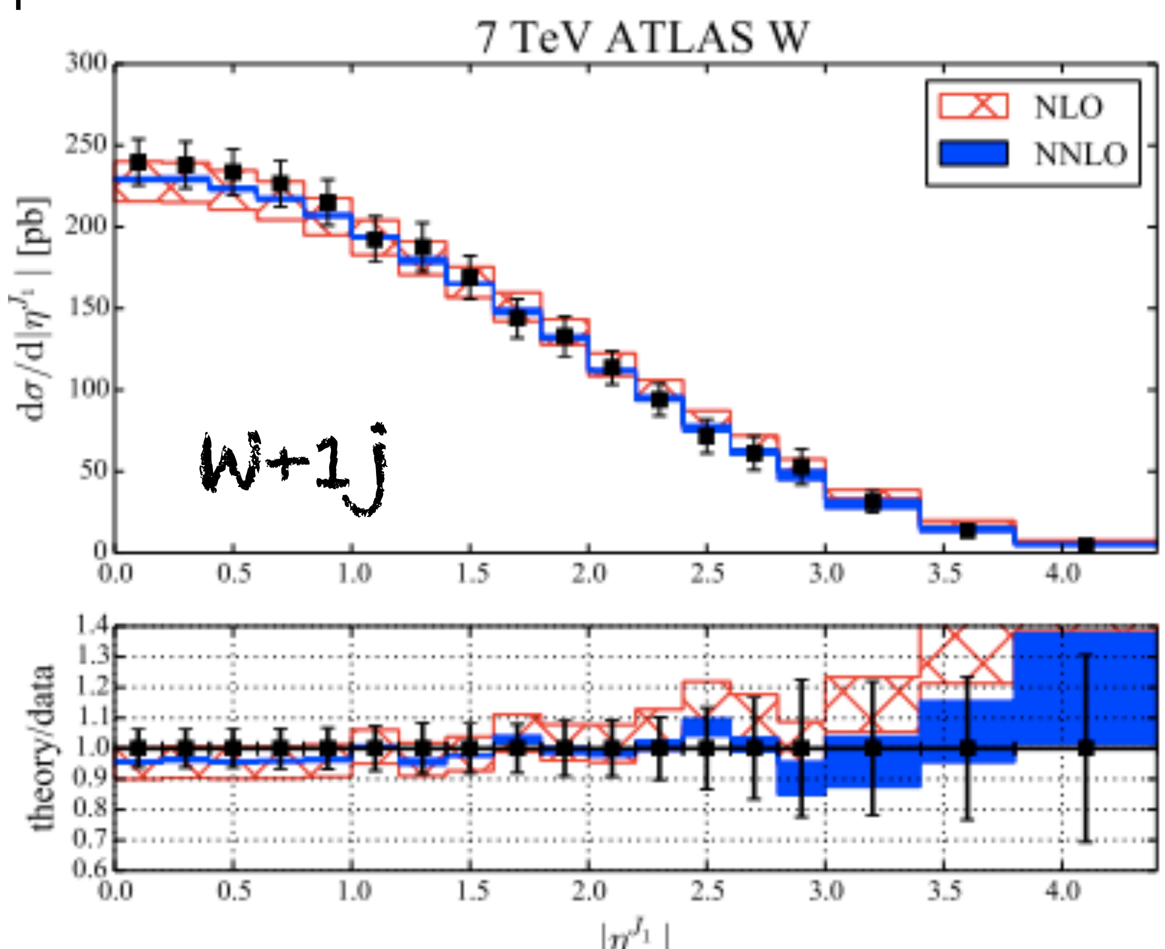
- Merged tree-level amplitudes combined with a parton shower are higher than the measurements.
- NLO QCD corrections lower than the data.
- NNLO can predict this distribution well.

CERN-PH-EP-2014-134

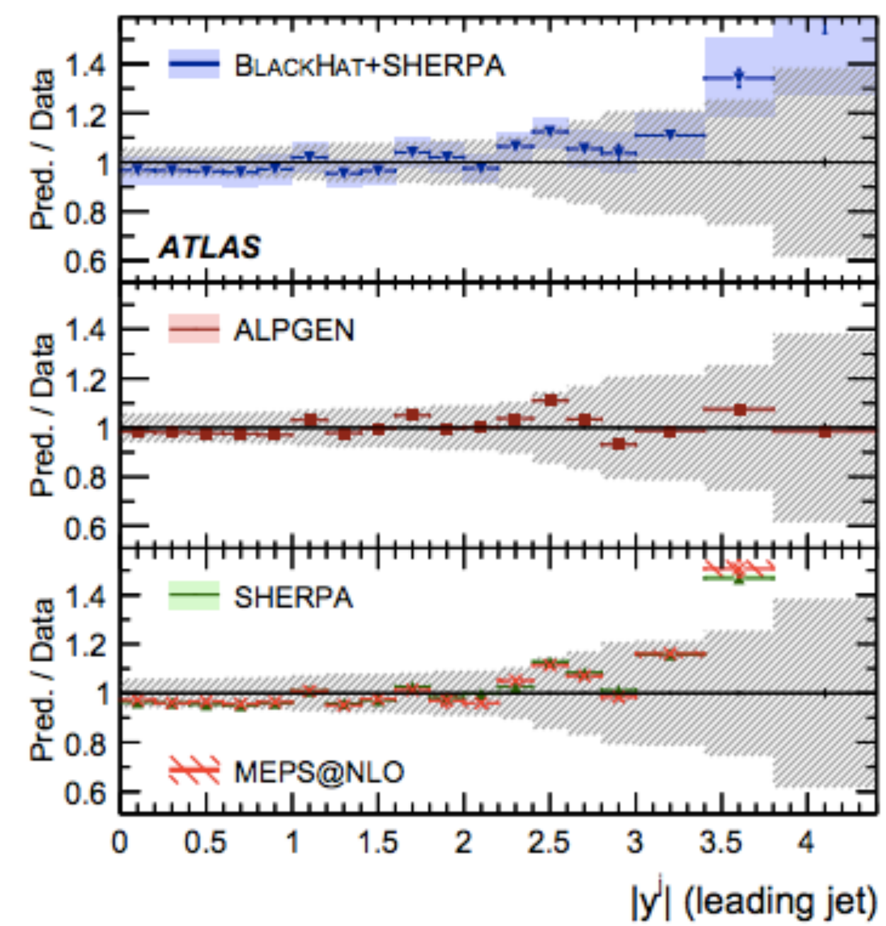
V+1j at the LHC

- Comparison with 7TeV data

Boughezal, XL, Petriello, '16



yJ:



- All predictions are good in the central region
- The NLO predictions far above the data in the forward region
- The NNLO corrections bring theory into good agreement with experiment

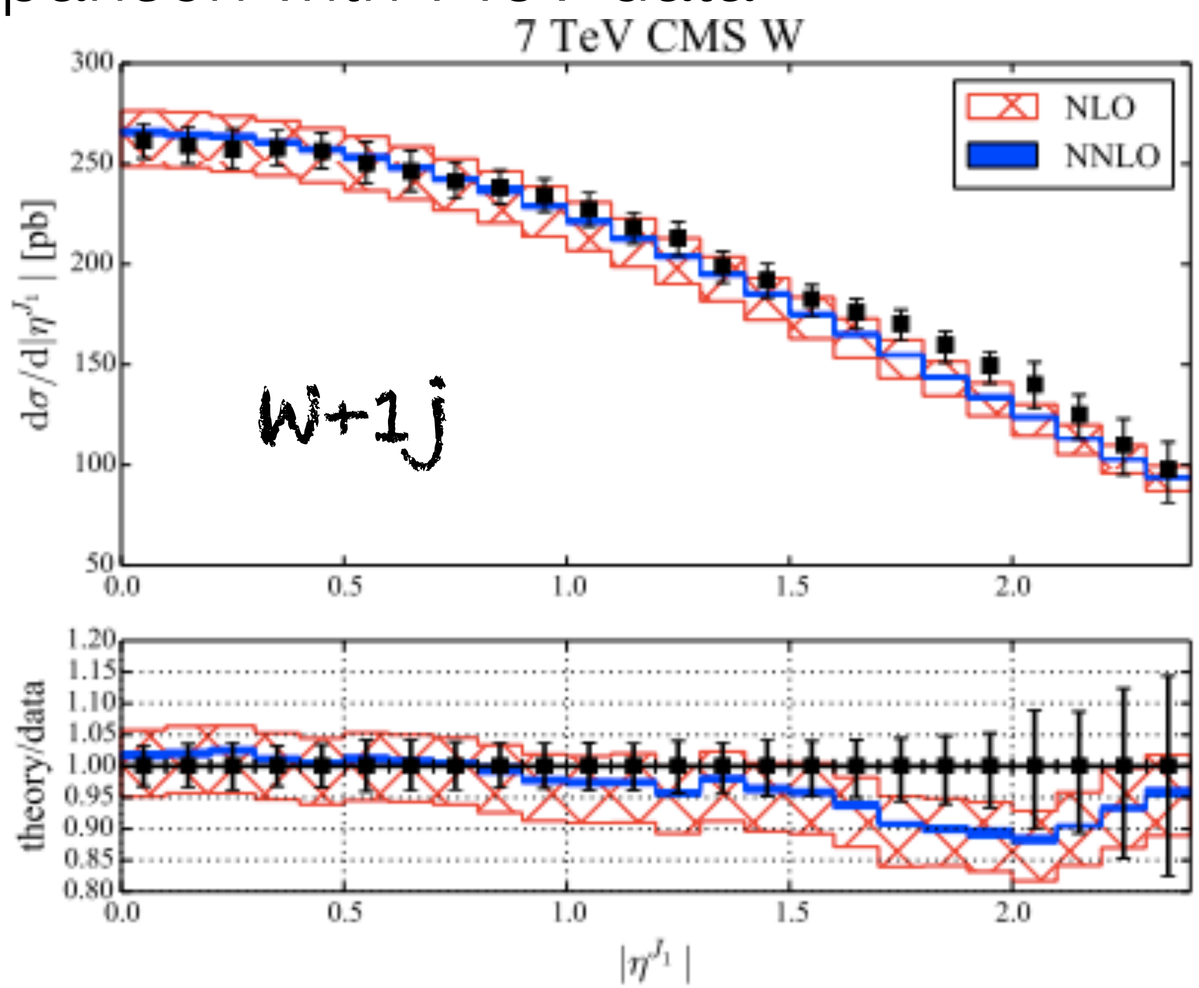
CERN-PH-EP-2014-199

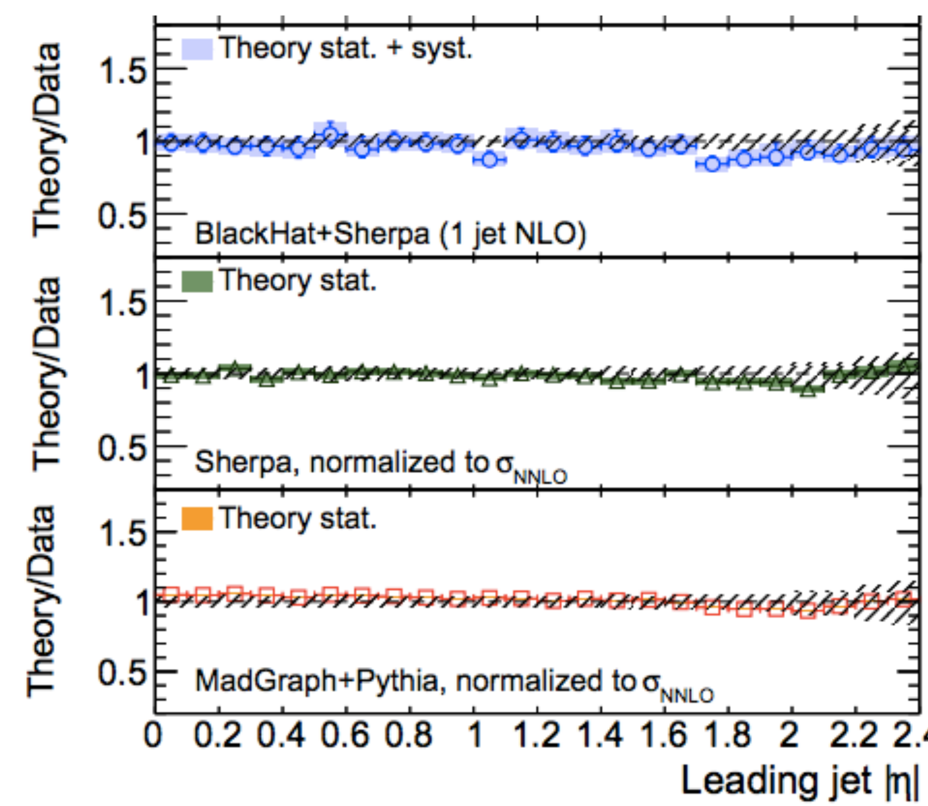
V+1j at the LHC

- Comparison with 7TeV data

Boughezal, XL, Petriello, '16

Yj:





CERN-PH-EP-2014-134

- The various tree-level plus parton shower do slightly better in the high rapidity region.
- Slight discrepancy is seen in both NLO and NNLO with data in the high rapidity region.
- NNLO reduces the scale uncertainty dramatically.

V+1j at the LHC

- 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	$\|\eta^l\| < 2.5$	$\|\eta^l\| < 2.4$
lepton separation	$\Delta R_{ll} > 0.2$	–
lepton invariant mass	$66\,\mathrm{GeV} < m_{ll} < 116\,\mathrm{GeV}$	$71\,\mathrm{GeV} < m_{ll} < 111\,\mathrm{GeV}$
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	$R = 0.4$	$R = 0.5$

CERN-PH-EP-2013-023

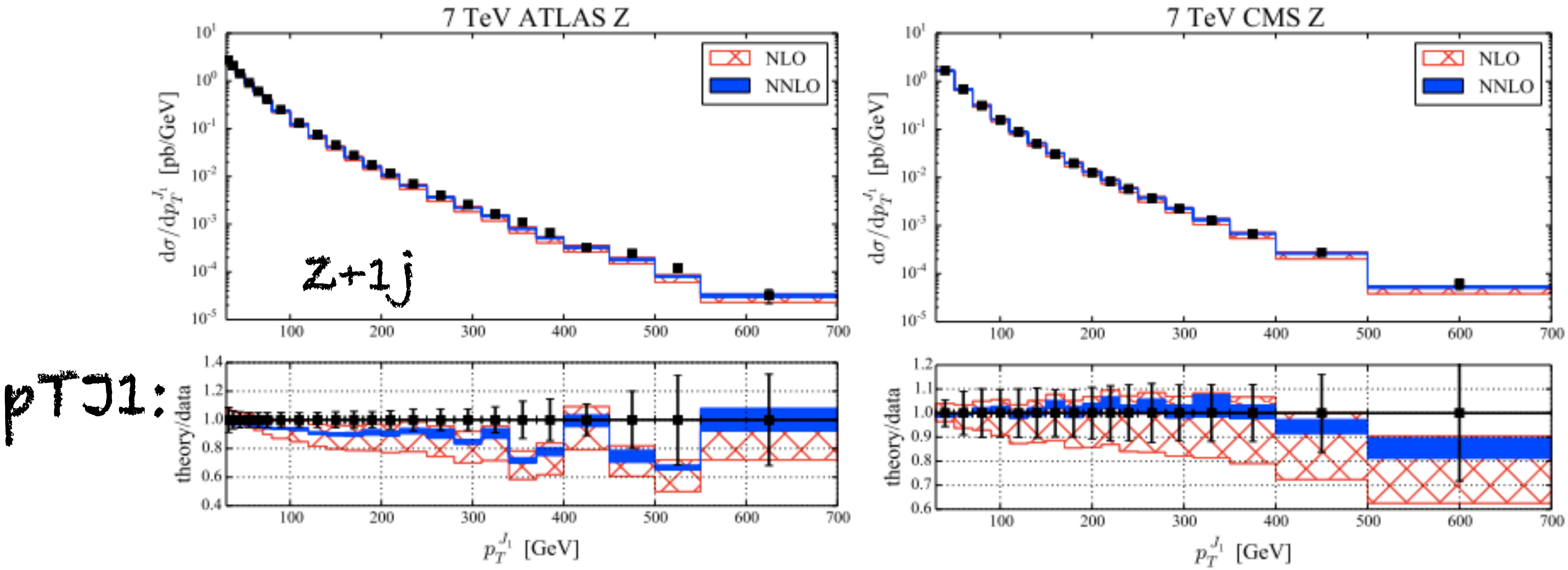
CERN-PH-EP-2014-205

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

- 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

V+1j at the LHC

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



- 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.

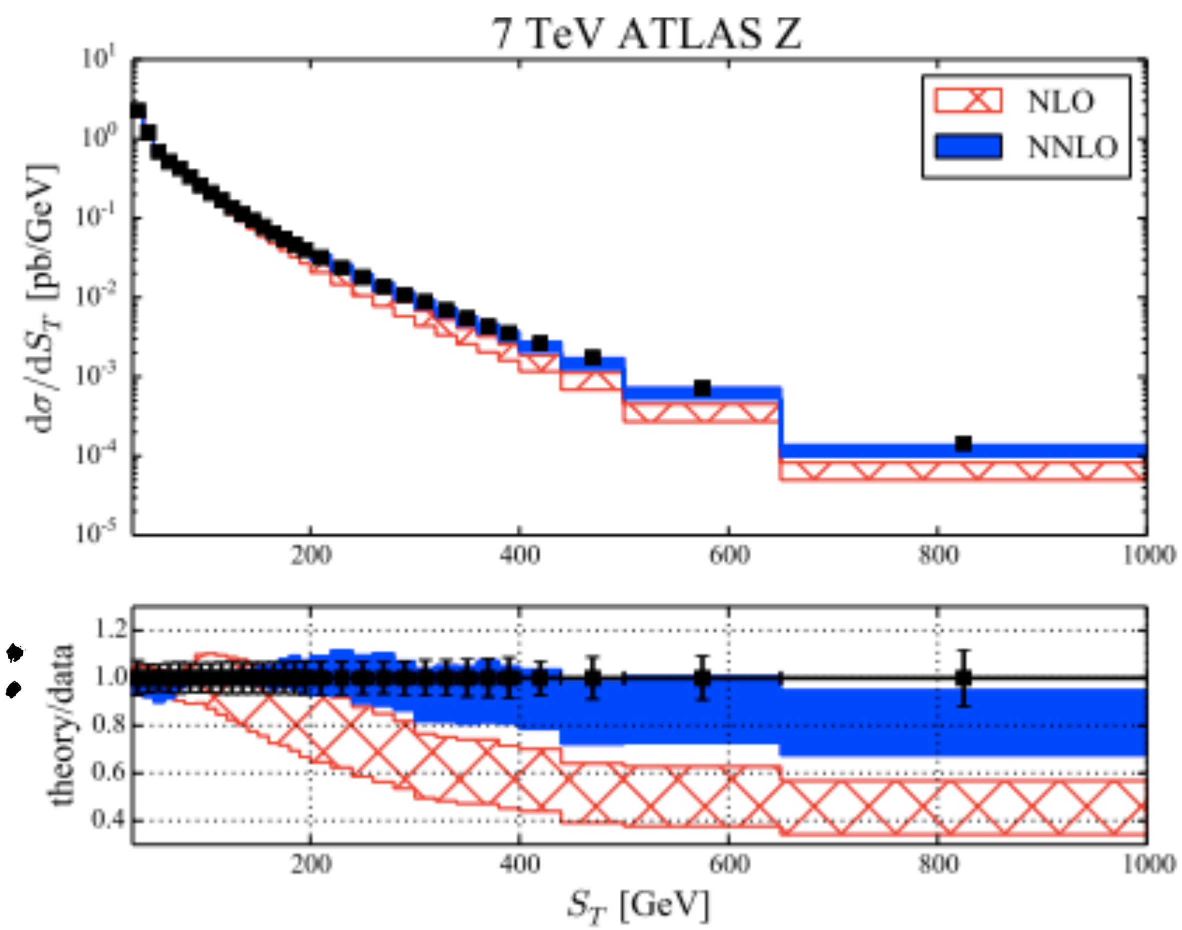
CERN-PH-EP-2013-023

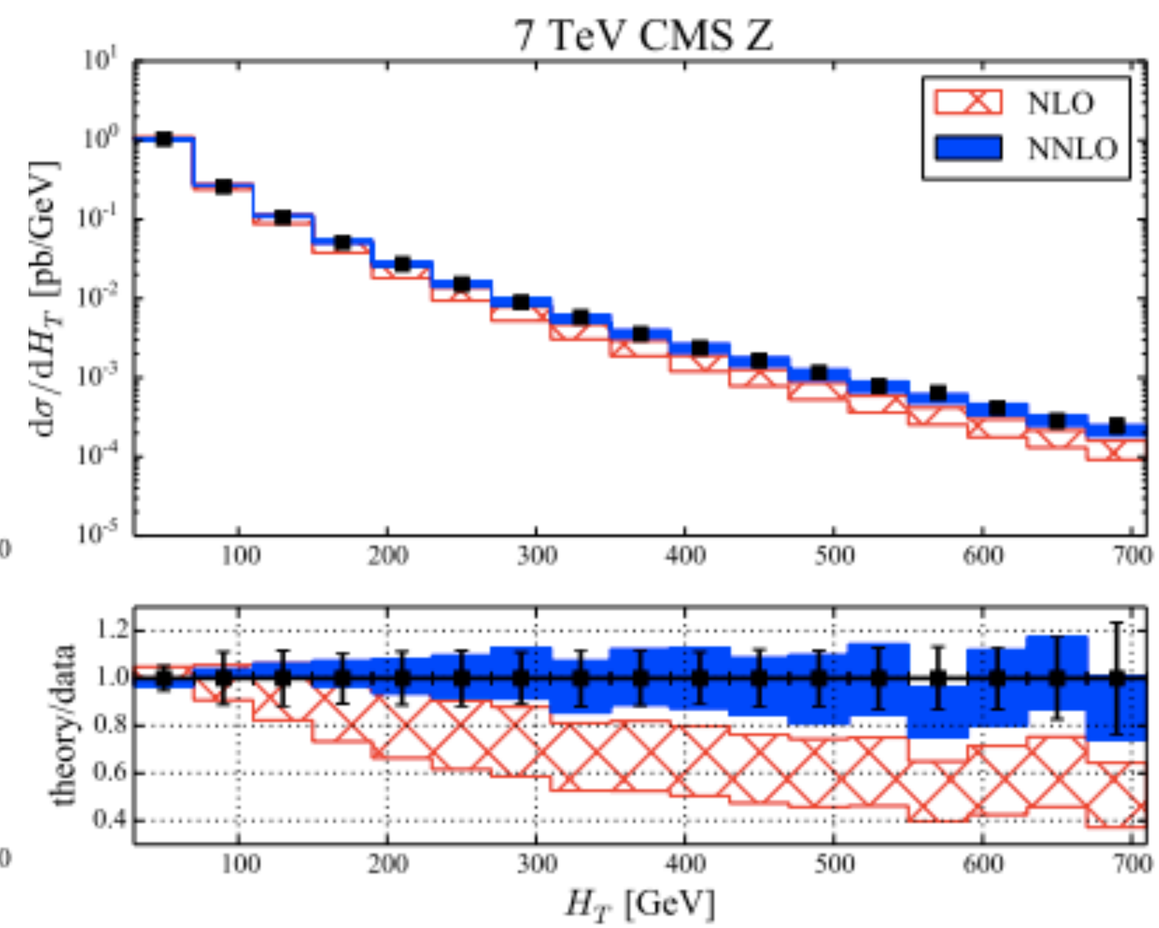
CERN-PH-EP-2014-205

V+1j at the LHC

- 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.

CERN-PH-EP-2013-023

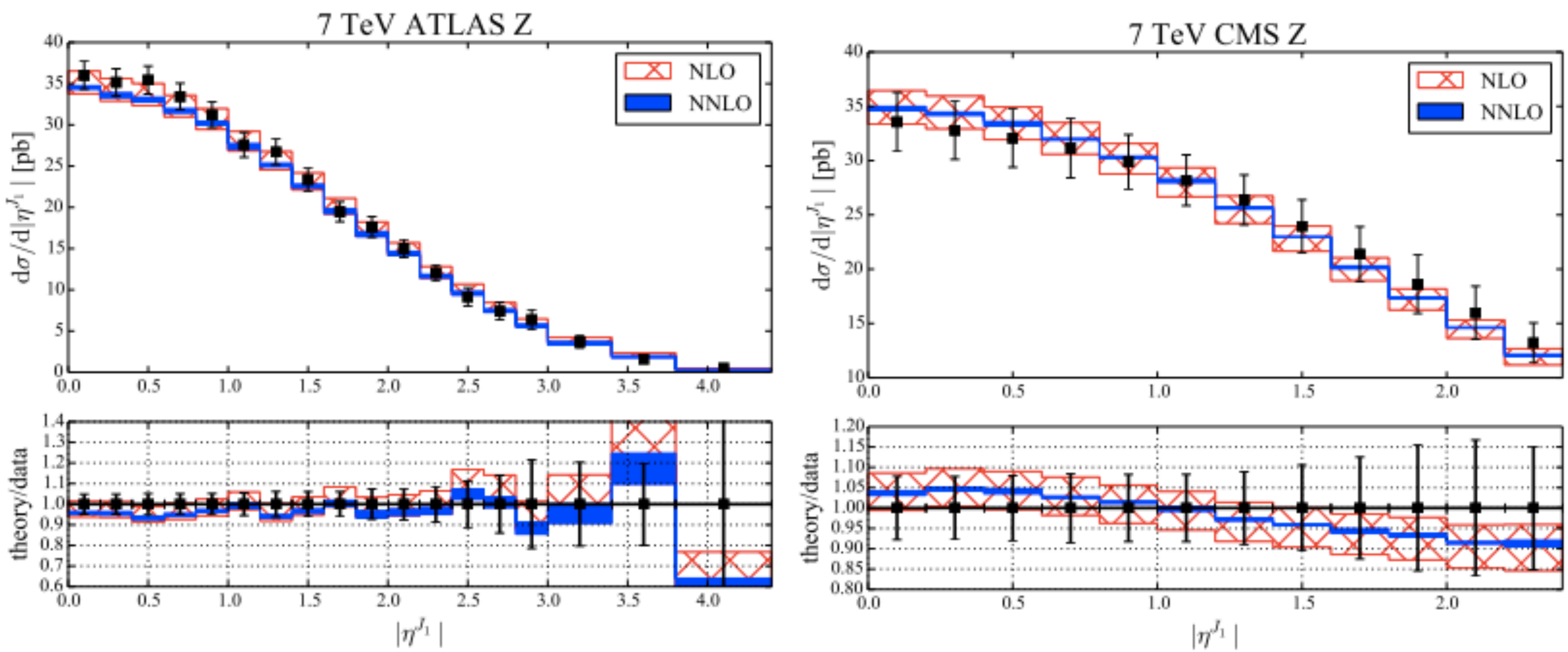
CERN-PH-EP-2014-205

V+1j at the LHC

- Comparison with 7TeV data

Boughezal, XL, Petriello, ‘16

Yj:



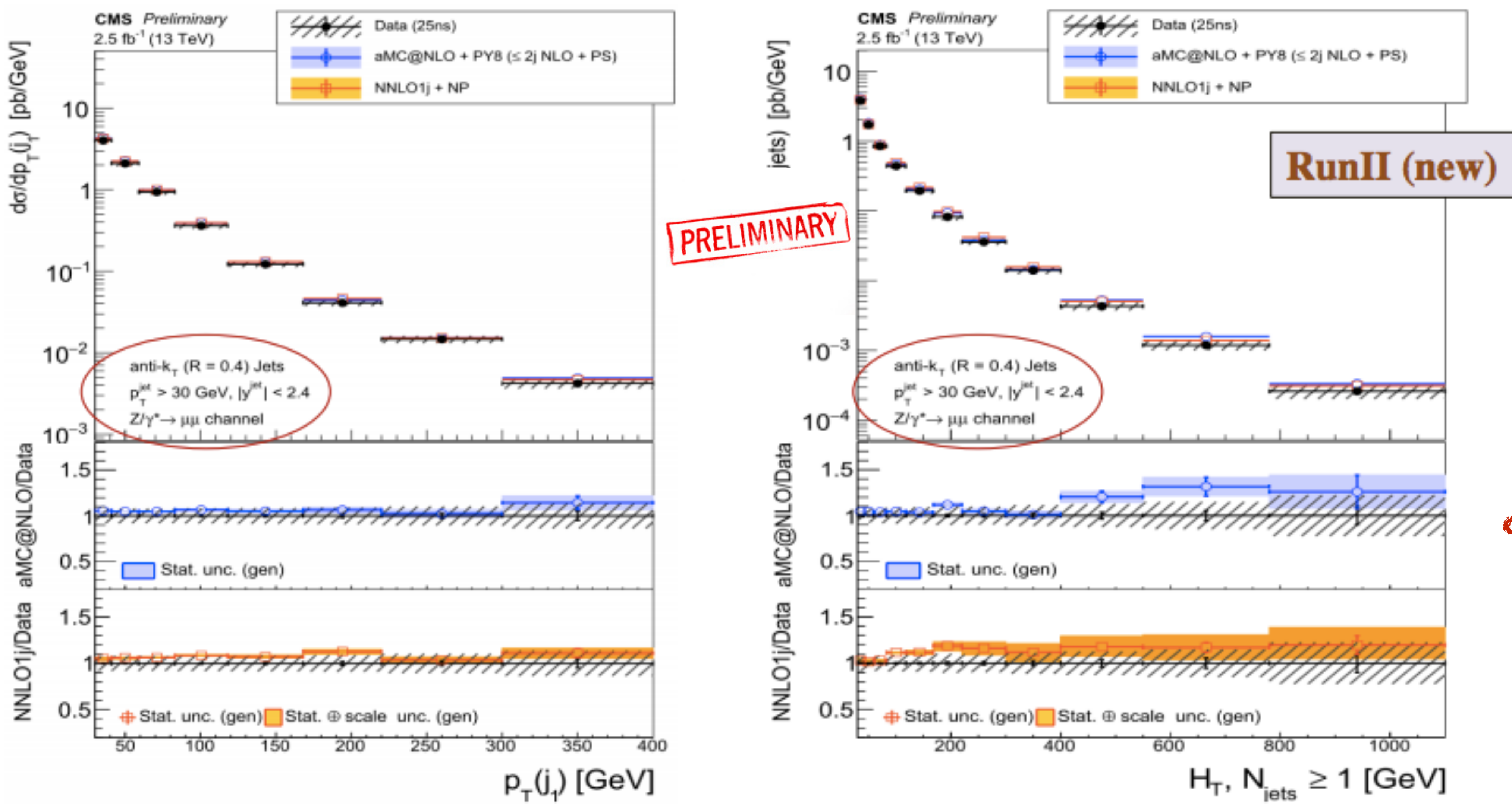
- The NNLO QCD prediction is in good agreement with data.
- Both NLO and NNLO QCD show a slight shape difference with respect to the CMS data. Similar small discrepancies are seen by CMS when they compare to POWHEG and MADGRAPH predictions.

CERN-PH-EP-2013-023

CERN-PH-EP-2014-205

V+1j at the LHC

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



EW correction is not included

➢ 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

Fengwangdong Zhang @ DIS16

Conclusions

- N-jettiness subtraction
    - a new subtraction scheme for jet production
    - has been applied to get new results for H/V+1J and confirm the existing V/H inclusive, VH and di-photon productions
- NNLO V + 1jet at the LHC
    - detailed comparisons with data; in better agreement with data
    - reduces scale uncertainty dramatically

Thanks