Vector Boson Production in association with Jets @CMS

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on behalf of CMS collaboration

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Outline

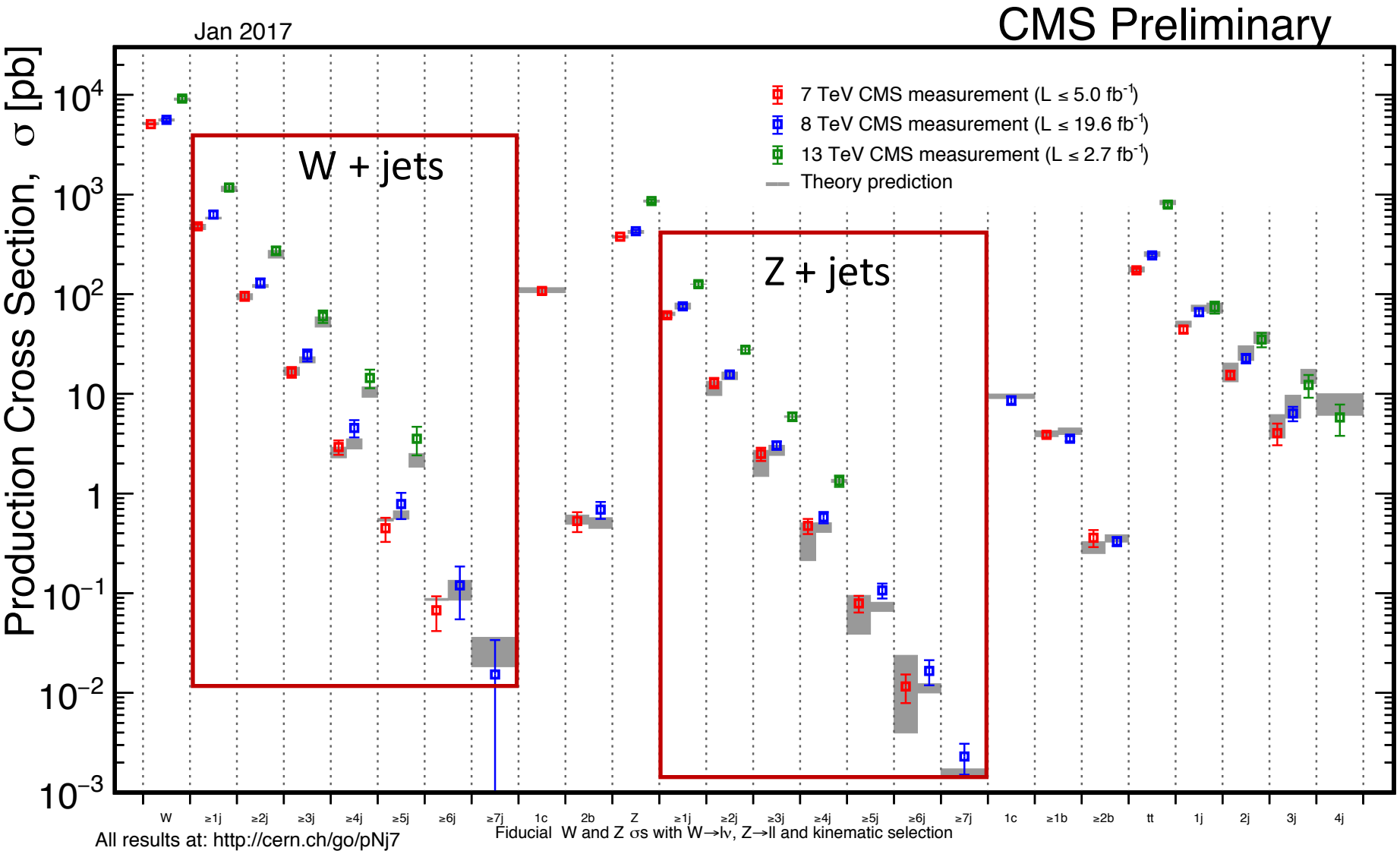
Many experimental results on V + jets processes.

- 8 TeV (Lumi = 19.6 fb^{-1})
  - W boson + jets (arXiv: 1610.04222, Accepted by PRD)
  - Z boson + jets (arXiv: 1611.03844, Accepted by JHEP)
- 13 TeV (Lumi = 2.5 fb^{-1})
  - W boson + jets (CMS-PAS-SMP-16-005)
  - Z boson + jets (CMS-PAS-SMP-15-010)

- Standard Model Public Results from CMS:

http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Outline



- Measurement up to large jet multiplicity cross sections.
- Cover six orders of magnitude of cross sections.

Motivations on V + jets physics

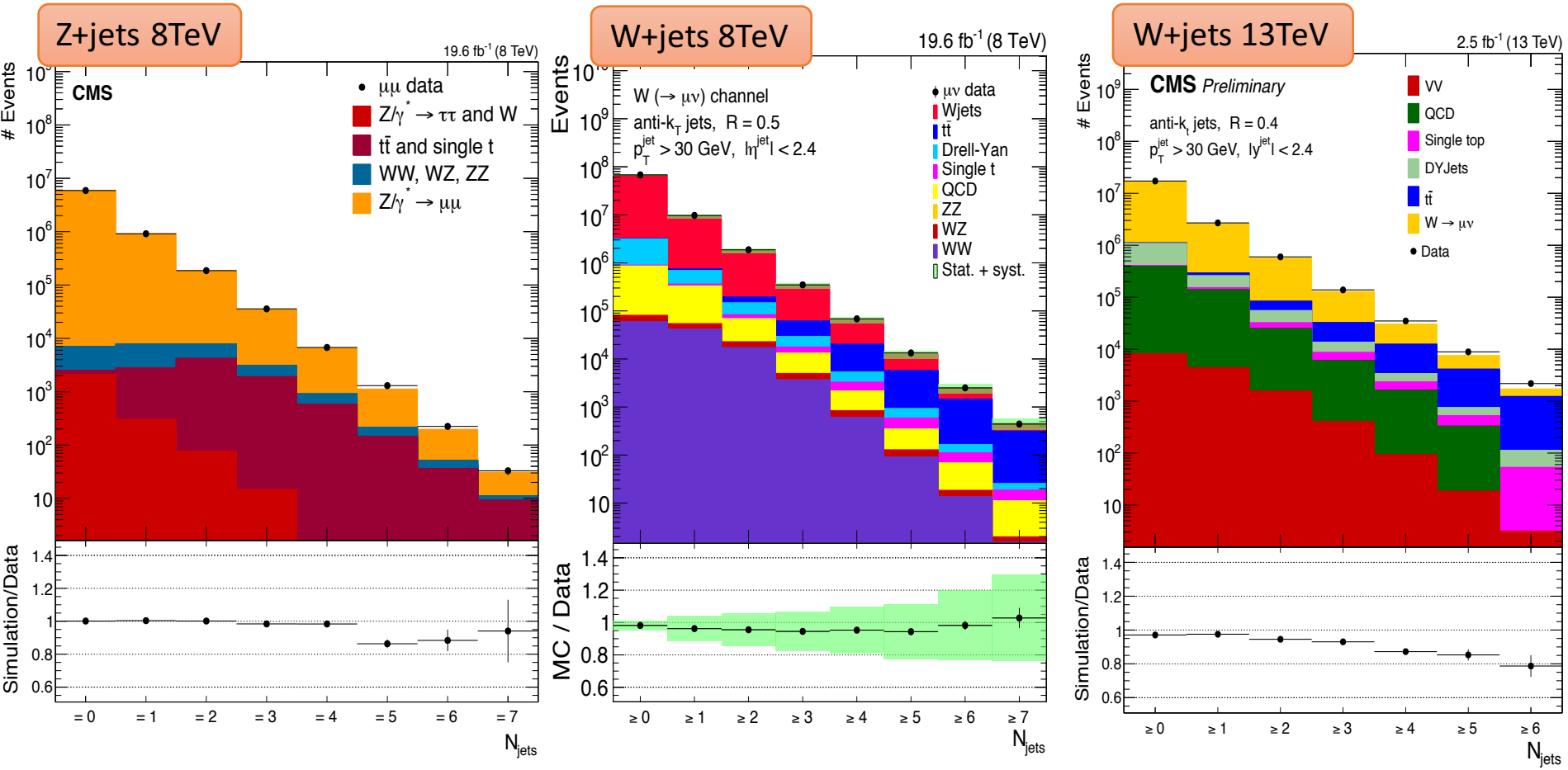
- V + jets process can probe different aspects of QCD effects.

- Precision measurement is crucial for deep understanding and modelling of QCD interactions
  - W/Z + jets is a standard candle at LHC: high cross section; almost background free.
  - Important for modelling of the production mechanism involved in the Higgs boson and new physics searches (e.g. Supersymmetry, dark matter)
  - A dominant background for:
    - Top quark measurements
    - Precision measurement of Higgs production –VH (H->bb)

- Compare latest fixed order calculations, latest MC based event generators

Measurement of V + jets cross section at 8/13 TeV

- Data: 2012 (8 TeV) and 2015 (13 TeV)
- Measured differential cross section as a function of several observables



Precision measurement up to large jet multiplicity.

Theoretical predictions for W/Z + jets at 8 TeV

- **MADGRAPH5 + PYTHIA6**
- LO matrix element up to 4 partons
- k_T–MLM merging
- CTEQ6L1 PDF

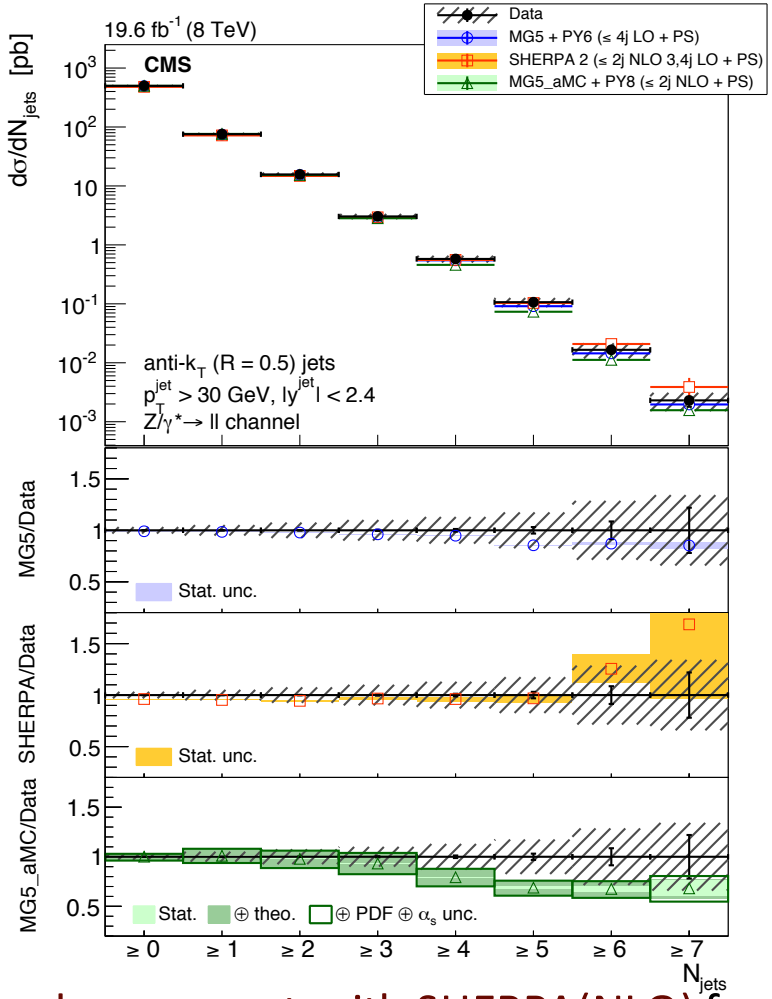
- **MADGRAPH5_AMC@NLO + PYTHIA8**
- NLO matrix element up to 2 partons (LO accuracy for 3 partons)
- FxFx PS merging
- NNPDF2.3 PDF

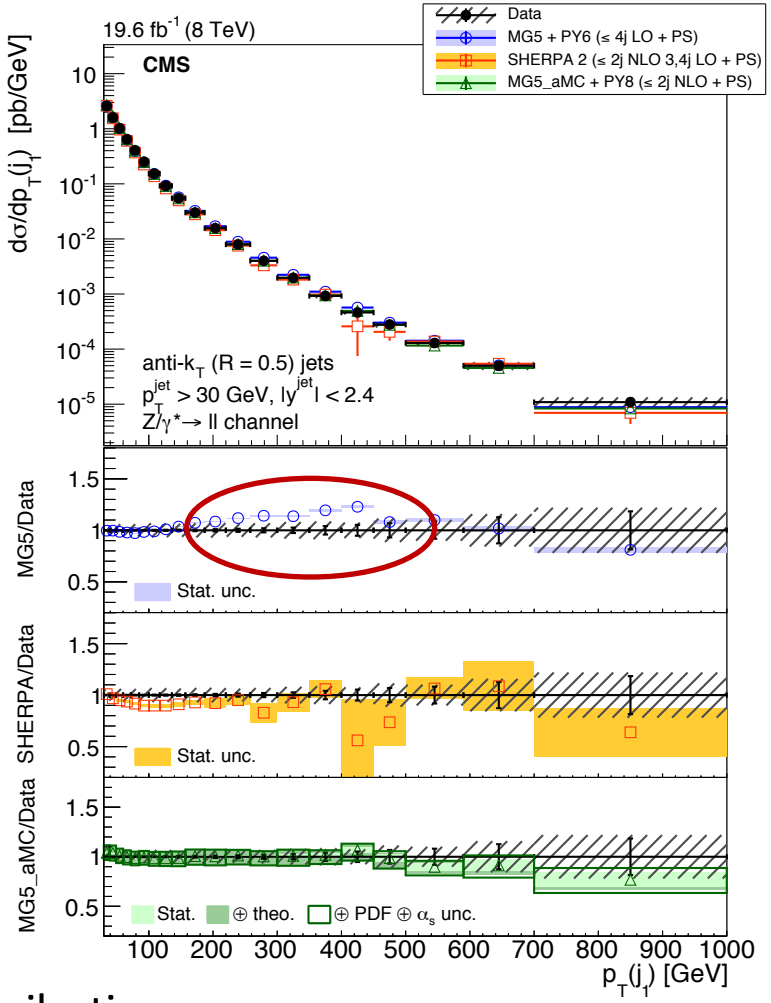
- **SHERPA 2 + BLACKHAT**
- Matrix element with NLO accuracy up to 2 partons, LO for 3-4 partons
- MEPS@NLO method of merging
- CT10 PDF

- **BLACKHAT + SHERPA** Nucl.Phys.Proc.Suppl. 205-206(2010)92-97
- Fixed-order NLO predictions for W + n jets (n = 1-4)
- CT10 PDF

- **N-jettiness NNLO (W/Z+1jet NNLO fixed order)** Phys. Rev. Lett. 115(2015), 062002, Phys. Rev. D 94, 113009 (2016)
- Correction for hadronization and multiple parton interaction computed with MADGRAPH5_AMC@NLO + PYTHIA8
- CT14 PDF

Z + jets differential cross section at 8 TeV





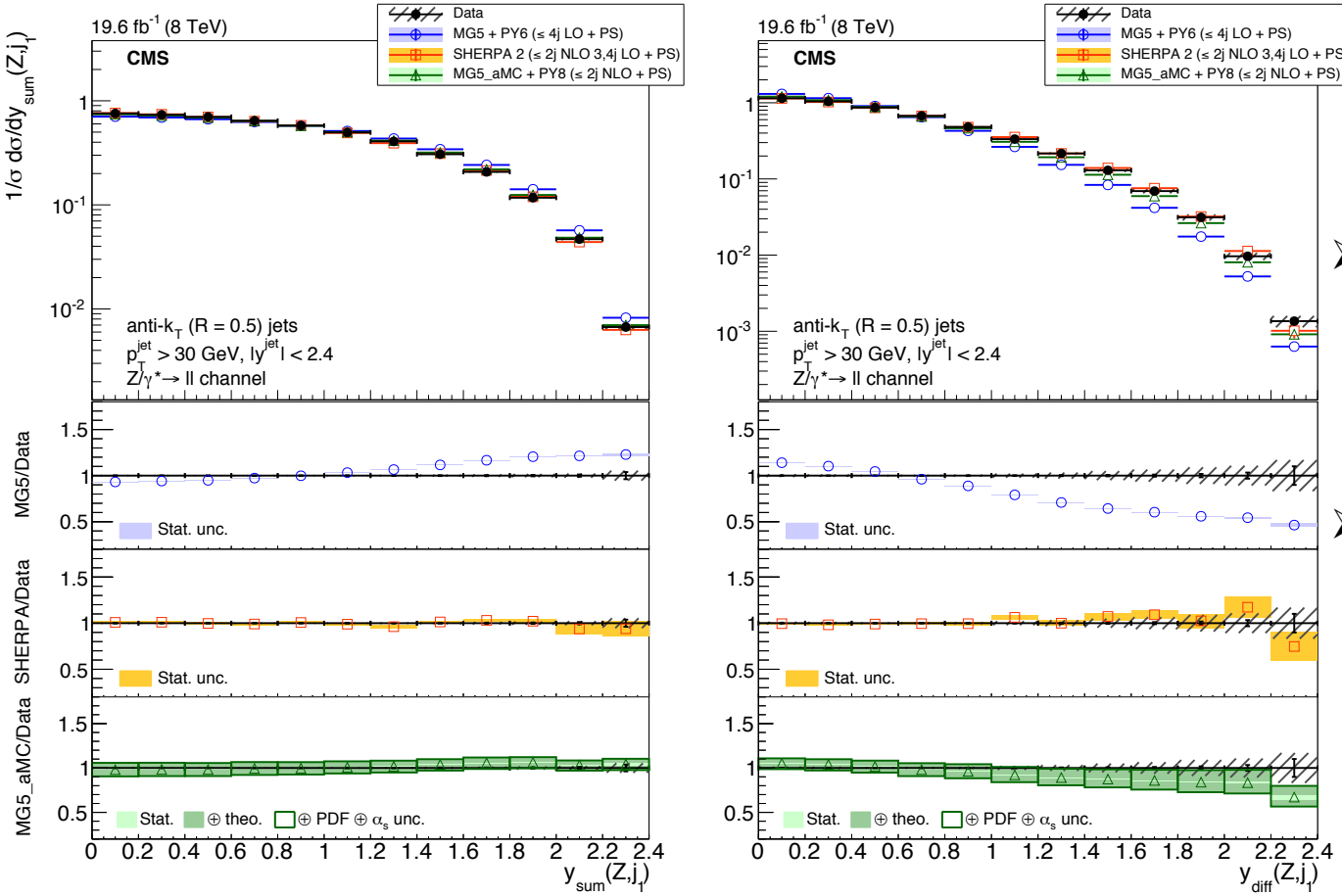
- Good agreement with SHERPA(NLO) for both distributions.
- Jet multiplicities N_{jets}: MG5_aMC+PY8 differs at large N_{jets} due to limited number of partons in matrix element calculation (only relying on parton shower).
- Leading jet p_T : discrepancy with MG5+PY6(LO) computation not in NLO calculation.

Rapidity correlation measurement of Z + jets

- The measurement of jet angular correlation of Z+Jets can help to understand QCD process much more accurately.

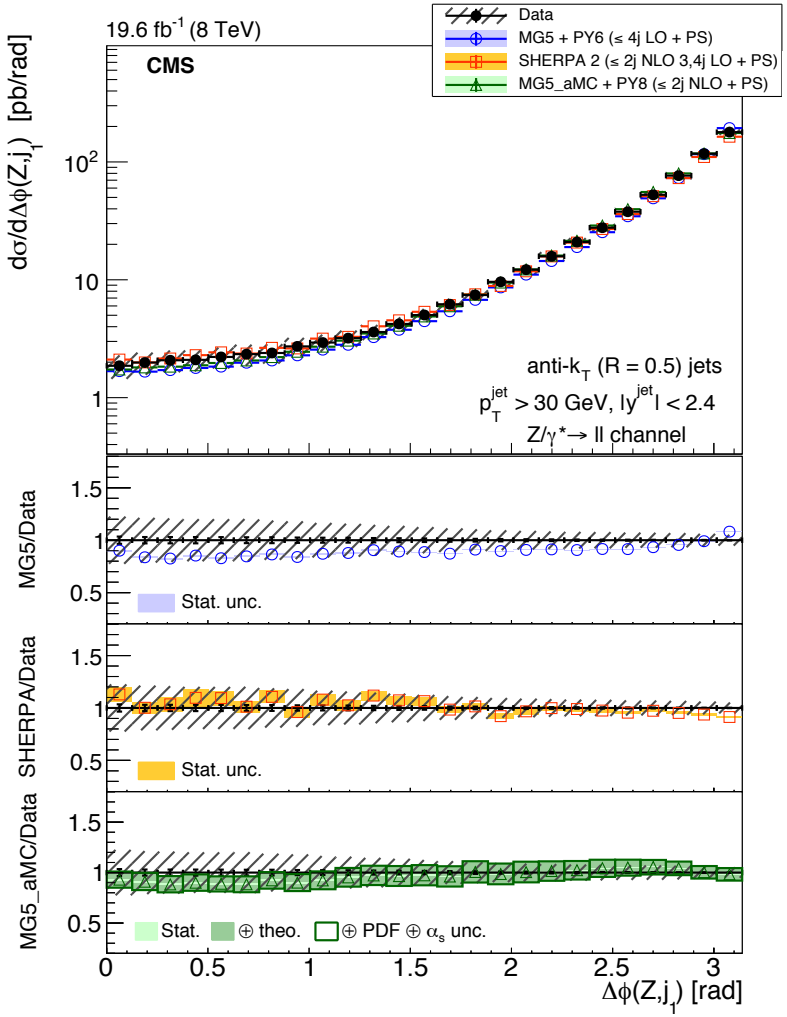
$$y_{sum} = \frac{|y_Z + y_{jet}|}{2}$$ -->Depends mainly on parton density functions.

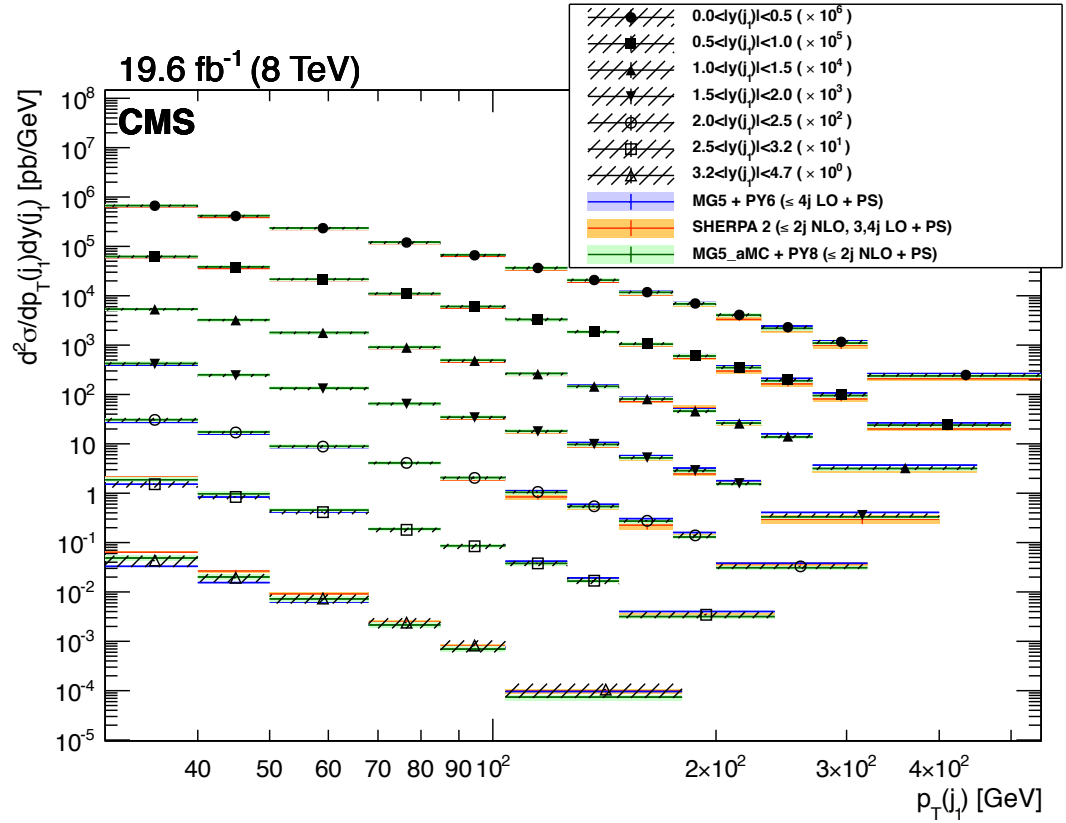
$$y_{diff} = \frac{|y_Z - y_{jet}|}{2}$$ -->Reflects the leading order partonic differential cross section.



- LO calculation fails to describe the shape, confirms the observation at 7 TeV: (PhysRevD.88.112009(2013))
- Discrepancy with LO computation has disappeared with NLO accuracy!

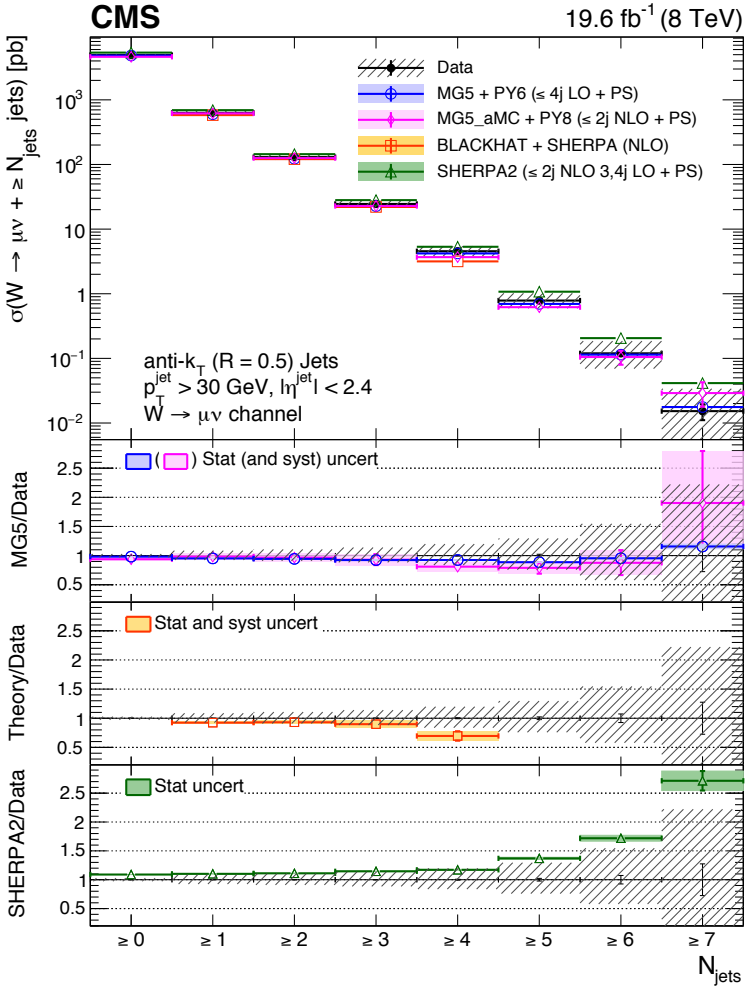
Azimuthal correlation & 2D measurement of Z + jets

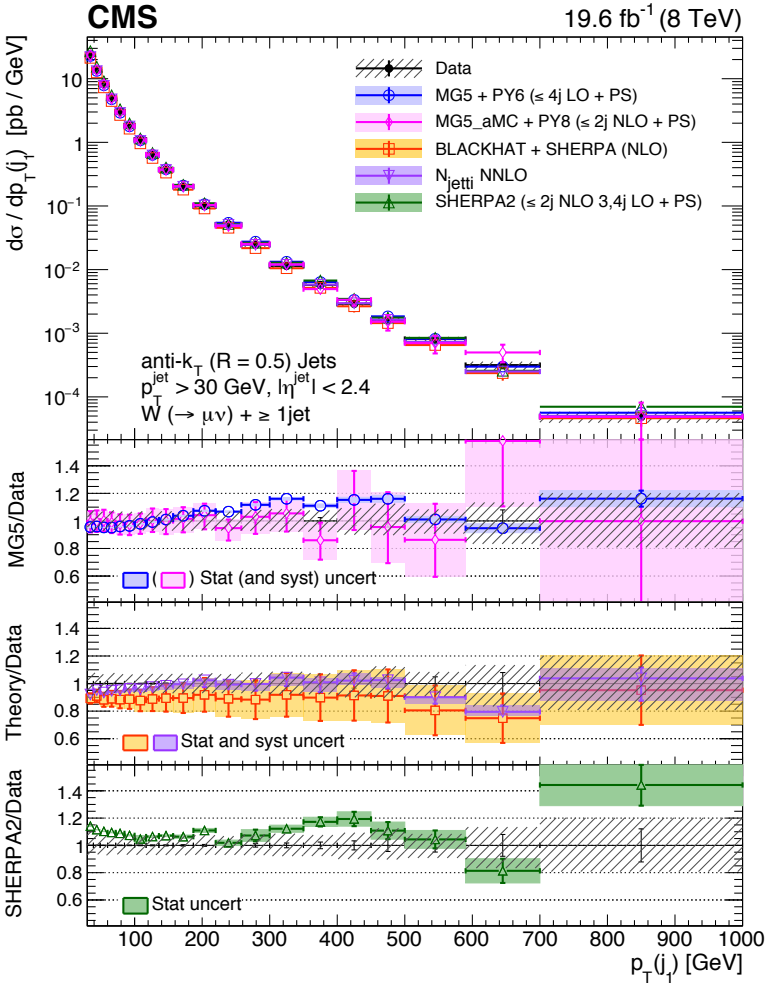




- No apparent discrepancy with LO and NLO predictions for the azimuthal correlation observables
- The 2D differential cross section with respect to jet pT and rapidity (up to 4.7) is measured precisely, good agreement with predictions.

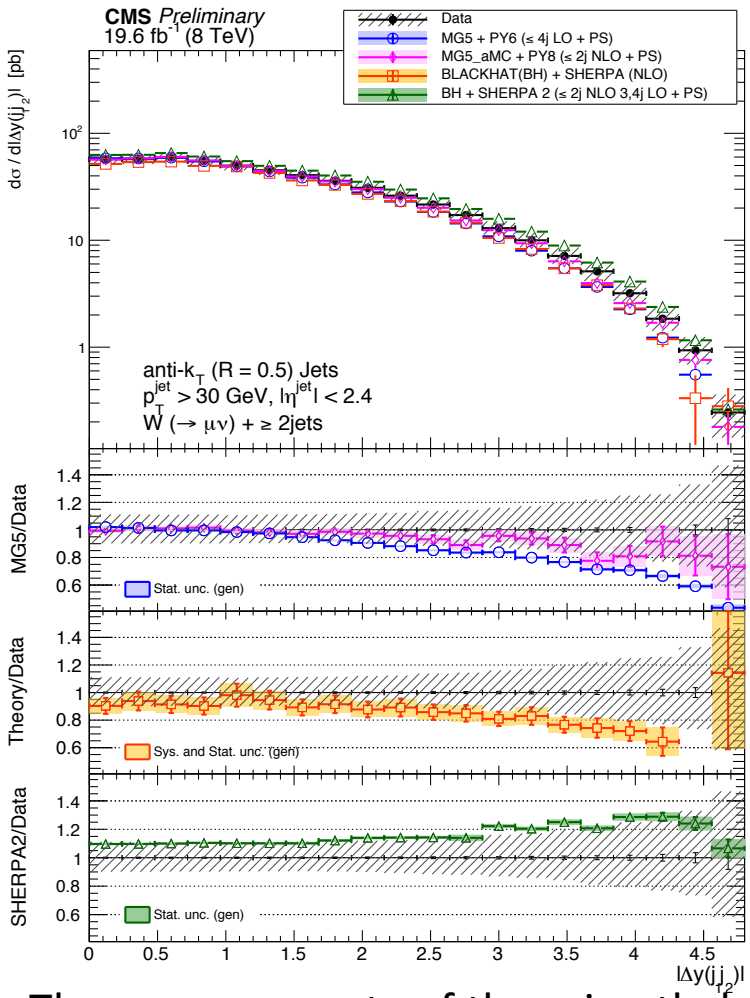
W + jets differential cross section at 8 TeV

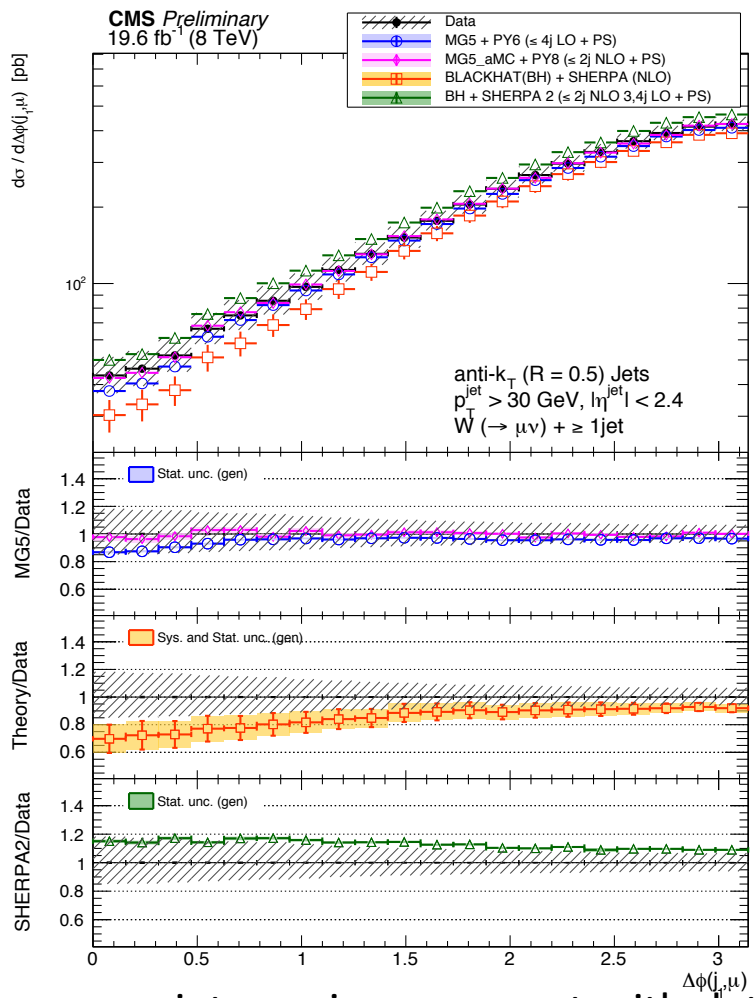




- The measured inclusive jet multiplicity distribution is in agreement with the predictions of MG5+PY6, MG5_aMC+PY8, and BLACKHAT.
- SHERPA 2 deviate from the measurement distribution for multiplicities covered by PS only.
- The jet p_t is sensitive to the effects of higher order corrections.

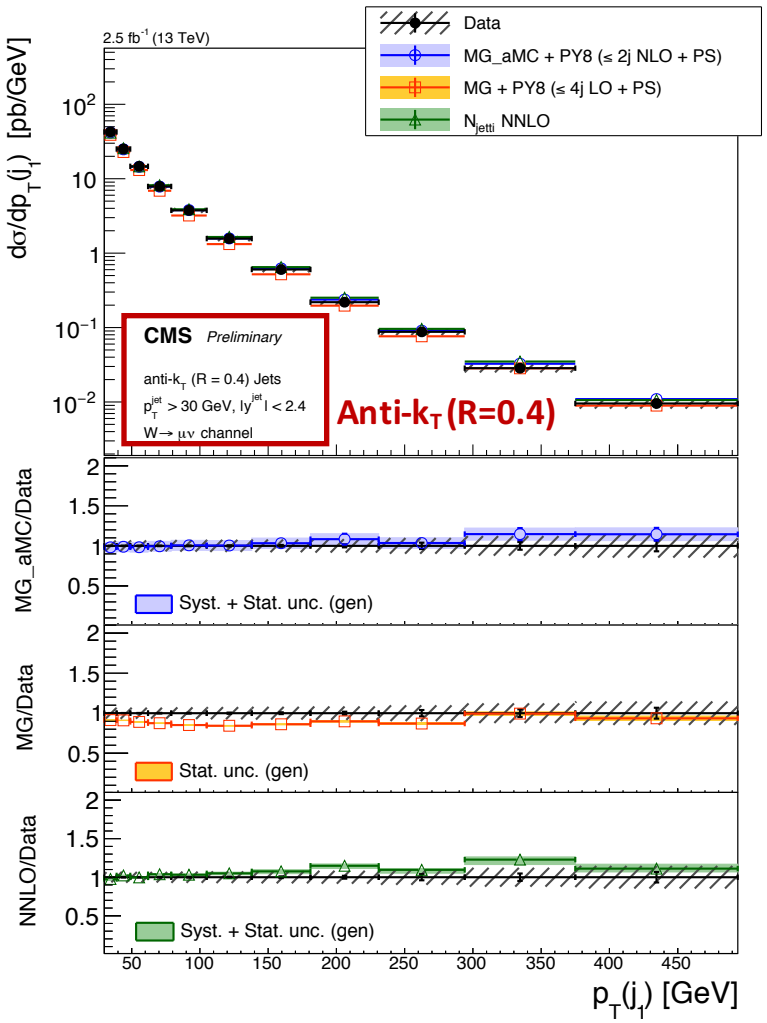
Angular correlation measurement of W + jets

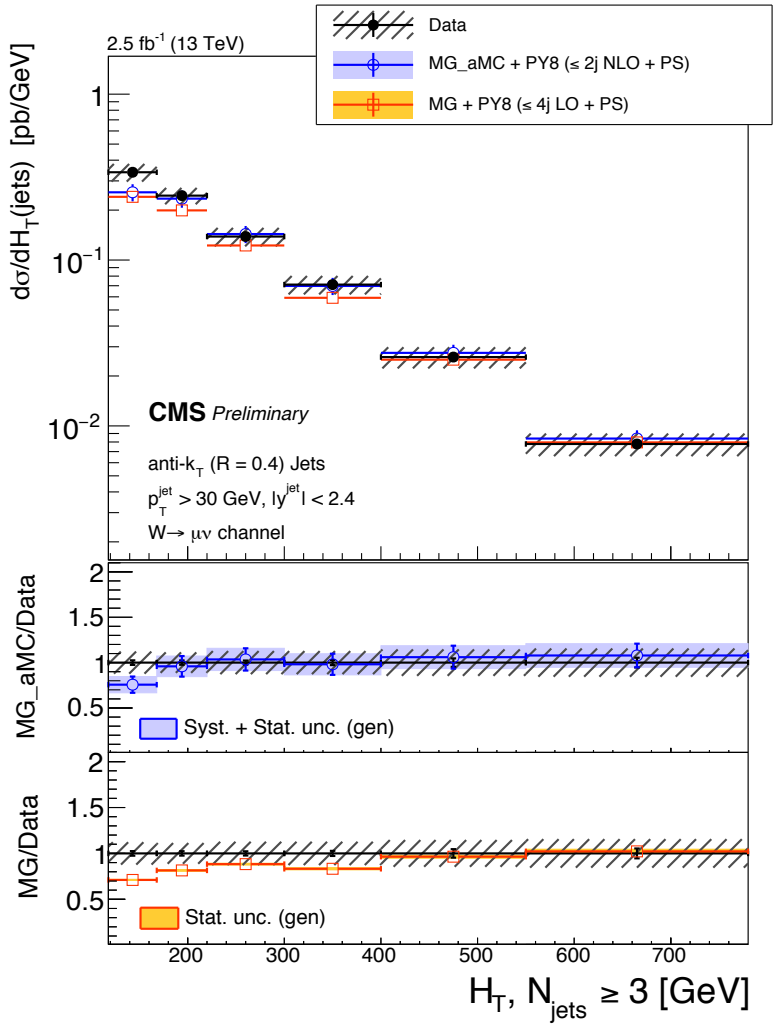




- The measurements of the azimuthal difference among jets are in agreement with data for all predictions.
- The measurements of the azimuthal difference between the muon and leading-jet are in agreement with predictions except for BLACKHAT, which disagrees with measurements at low values of the azimuthal angle difference.

W + jets differential cross section at 13 TeV





- The predictions are in good agreement with data within uncertainties on both jet p_T spectra and jet H_T spectra for inclusive jet multiplicity of 3.
- MG+PY8 exhibits slightly lower in estimating data.

Conclusion

- The measurements of vector boson plus jets processes are quite important:
  - Deepen our understanding on QCD dynamics
  - Improve the modelling of the production mechanism involved in Higgs boson measurement and new physics searches

- Significant improvements are in theoretical predictions and experimental measurements:
  - Better described by higher order (NLO) calculation than LO in general
  - Reach high precision of measurements

- The first results of W + jets differential cross section measurements at 13 TeV are in good agreement with predictions.

Backup

W/Z +jets measurement

Phase space for Z(μμ)+jets(8TeV):

- Lepton selection:
  - $p_T > 20$ GeV
  - $|\eta| < 2.4$
  - $M_{ll} \in (71, 111)$GeV
- Jet selection:
  - $p_T \geq 30$ GeV
  - $|\eta| < 2.4$

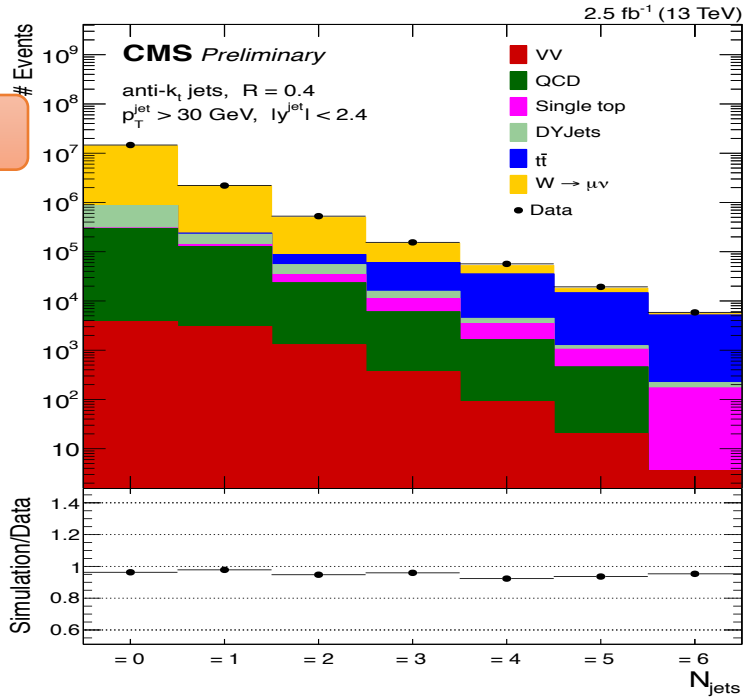
Phase space for W(μ)+jets (8TeV):

- Lepton selection:
  - $p_T > 25$ GeV
  - $|\eta| < 2.1$
  - $M_T > 50$ GeV
- Jet selection:
  - $p_T \geq 30$ GeV
  - $|\eta| < 2.4$

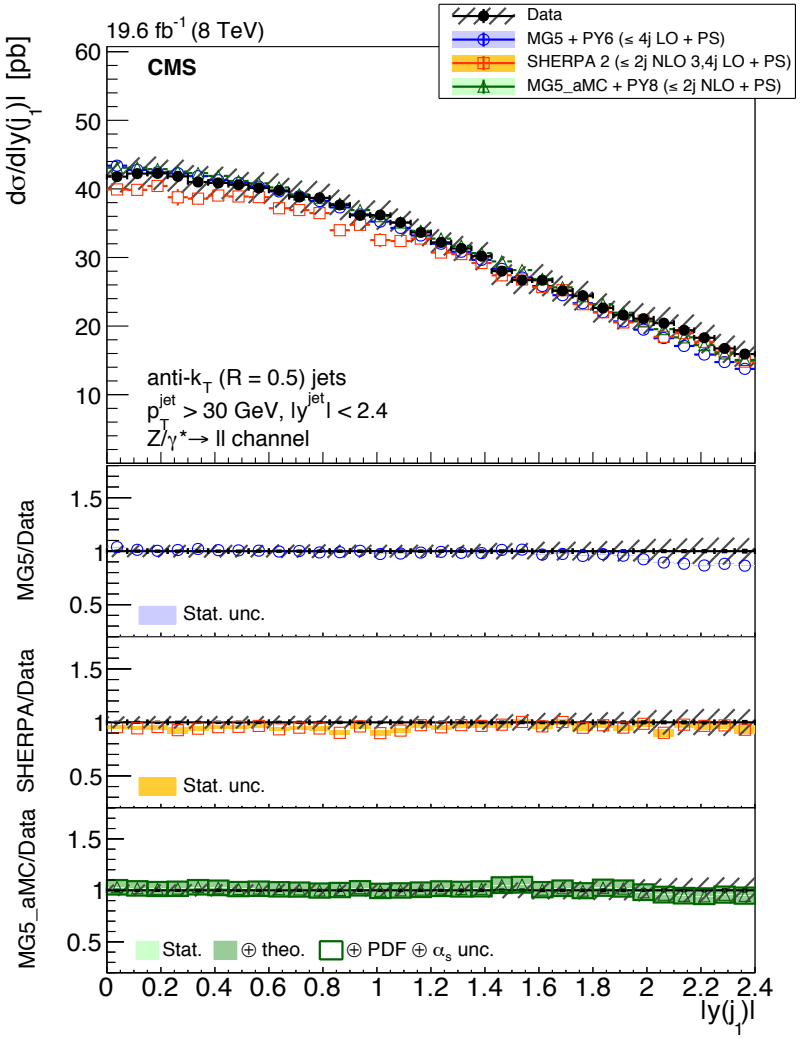
Phase space for W(μ)+jets(13TeV):

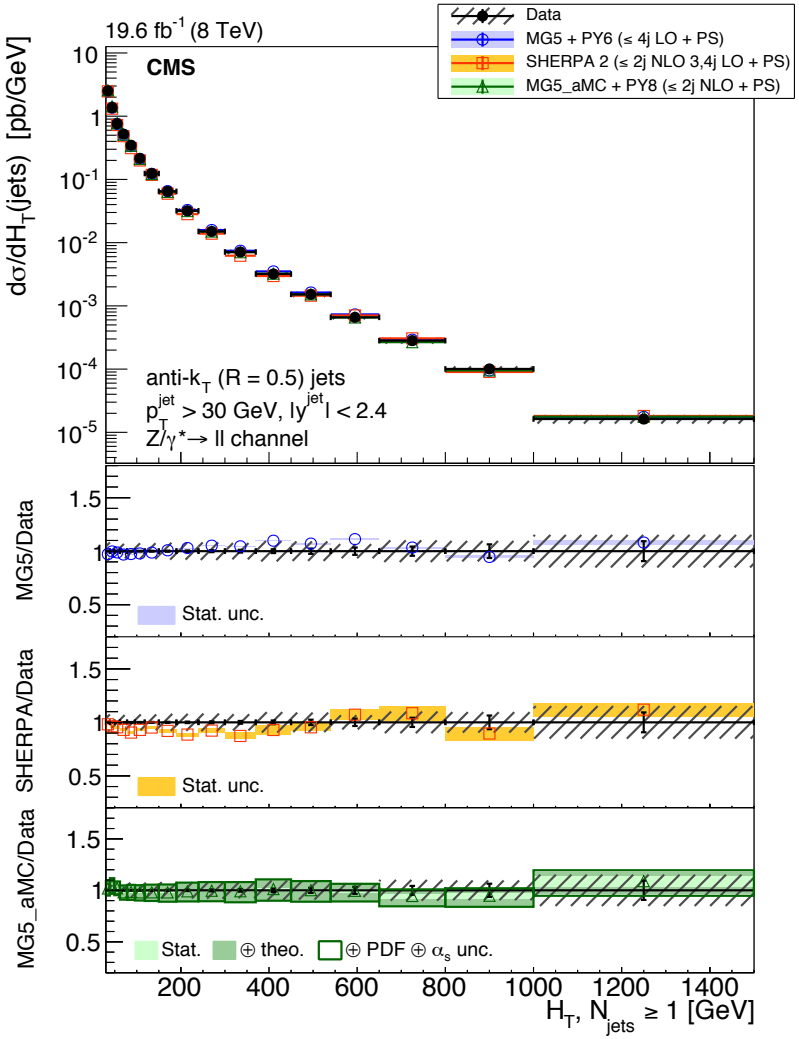
- Lepton selection:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - $M_T > 50$ GeV
- Jet selection:
  - $p_T \geq 30$ GeV
  - $|\eta| < 2.4$

W+jets



Z + jets differential cross section at 8 TeV

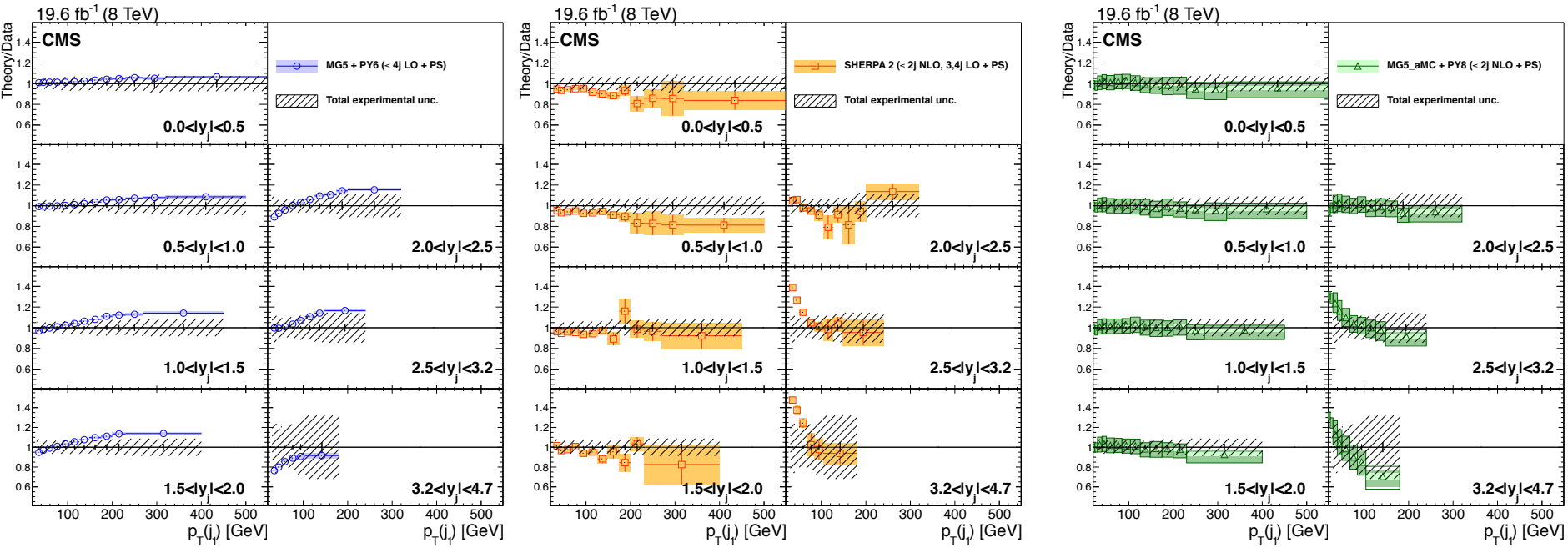




- Good agreement in general for all the predictions.
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 5 jets have also been measured.

2D-differential cross section W+jets

8 TeV



[PAS] Figure: Ratio to the measurement of the differential cross section $d^2\sigma/dp_T(j1)dy(j1)$ obtained with MadGraph 5+PYTHIA 6(left), sherpa(middle), MG_aMC(right).

Theoretical predictions for W + jets at 13 TeV

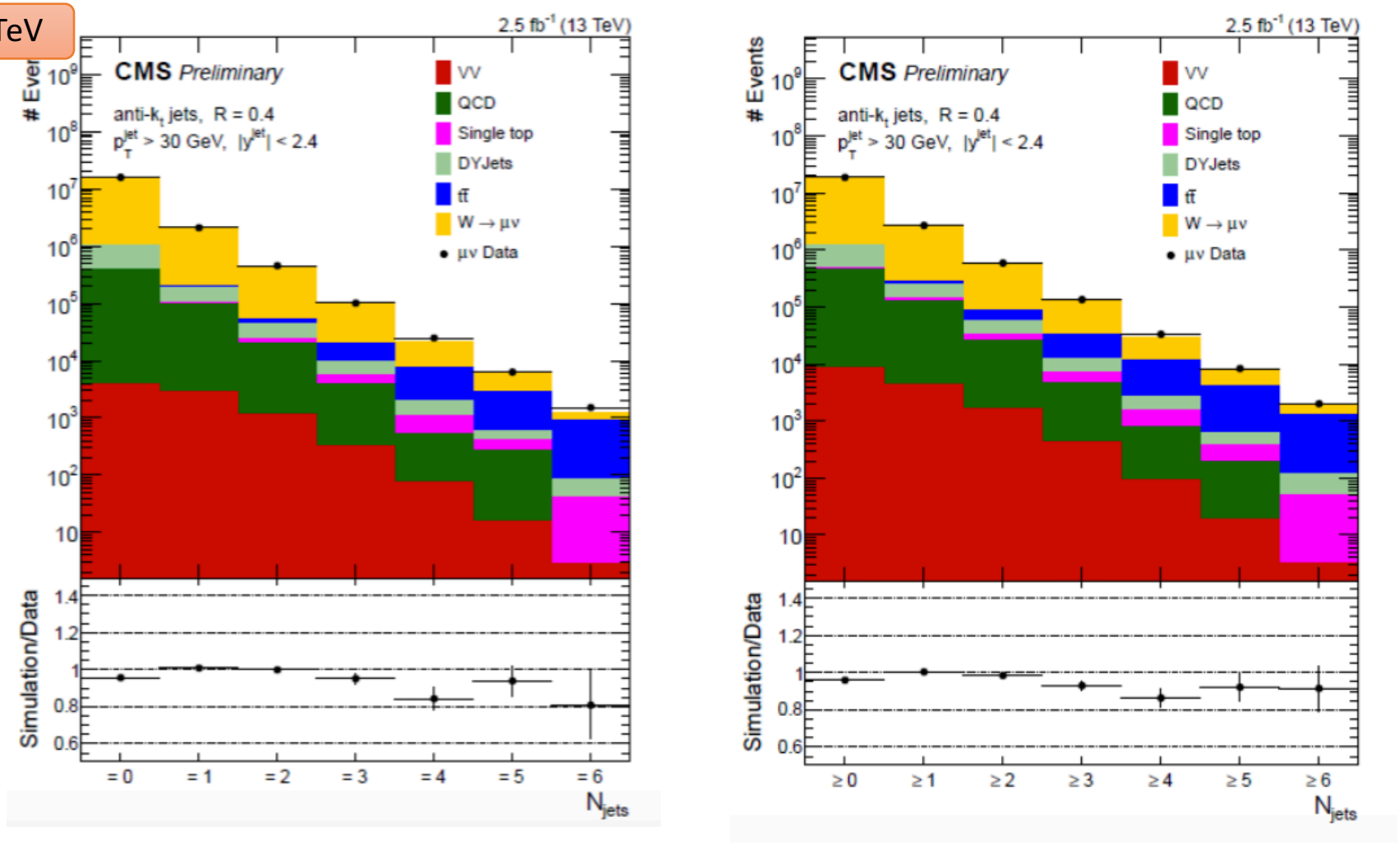
- **MADGRAPH5_AMC@NLO + PYTHIA8**
- NLO matrix element up to 2 partons, LO accuracy for 3-4 partons
- Both kT-MLM and FxFx jet merging scheme
- NNPDF 3.0 NLO PDF
- CUETP8M1 PYTHIA8 tune
- normalised to NNLO cross section obtained with FEWZ

- **MADGRAPH5 + PYTHIA8**
- Matrix element with LO accuracy up to 4 partons
- kT-MLM merging
- CTEQ6L1 PDF

- **NNLO**
- NNLO Z+1jet with fixed order
- Correction for hadronization and multiple parton interaction computed with MADGRAPH5_AMC@NLO + PYTHIA8
- CT14 PDF set
- References:
  - Phys. Rev. Lett. 115, 062002 (arXiv: 1602.06965)

W + jets data vs simulation comparison: jet multiplicity

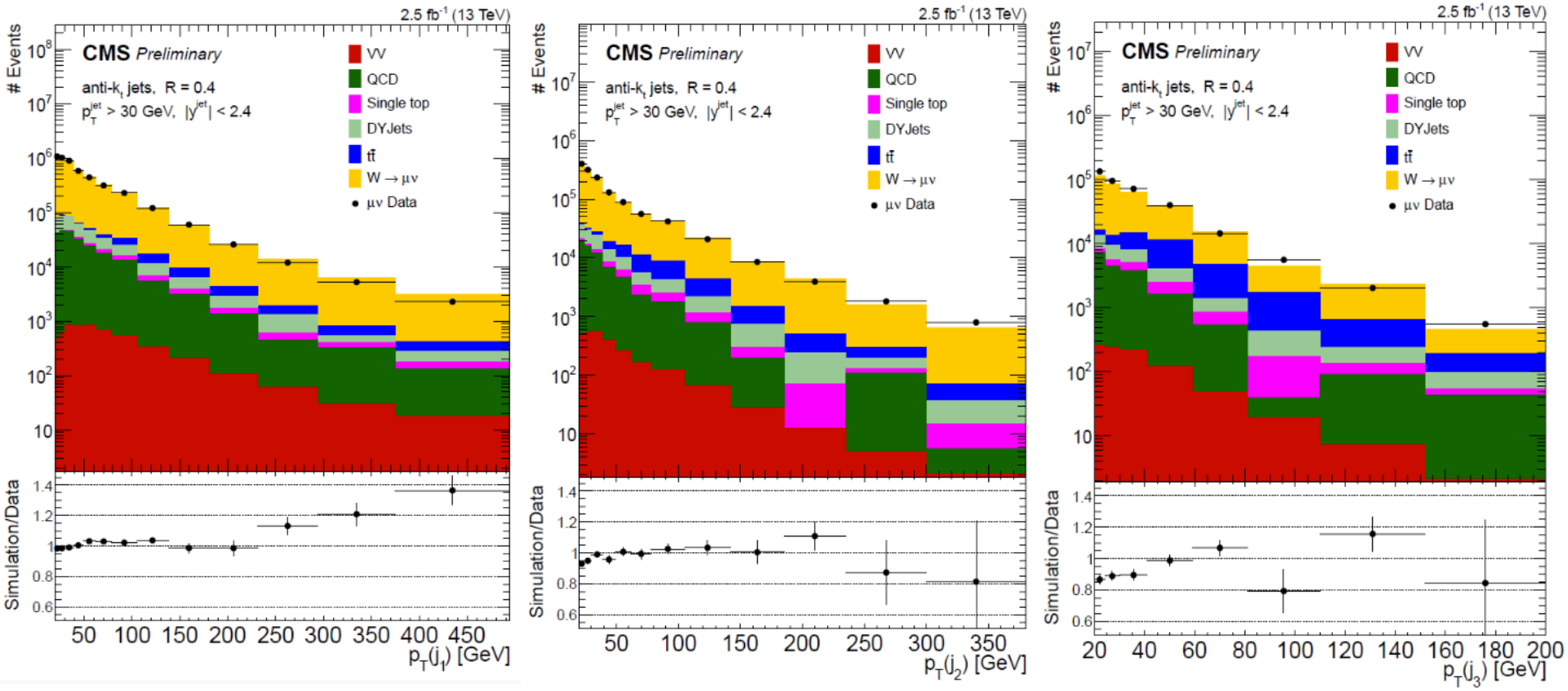
13TeV



[PAS] Figure: Data to simulation comparison of exclusive (left) and inclusive (right) jet multiplicity

Data vs simulation comparison: jet p_T

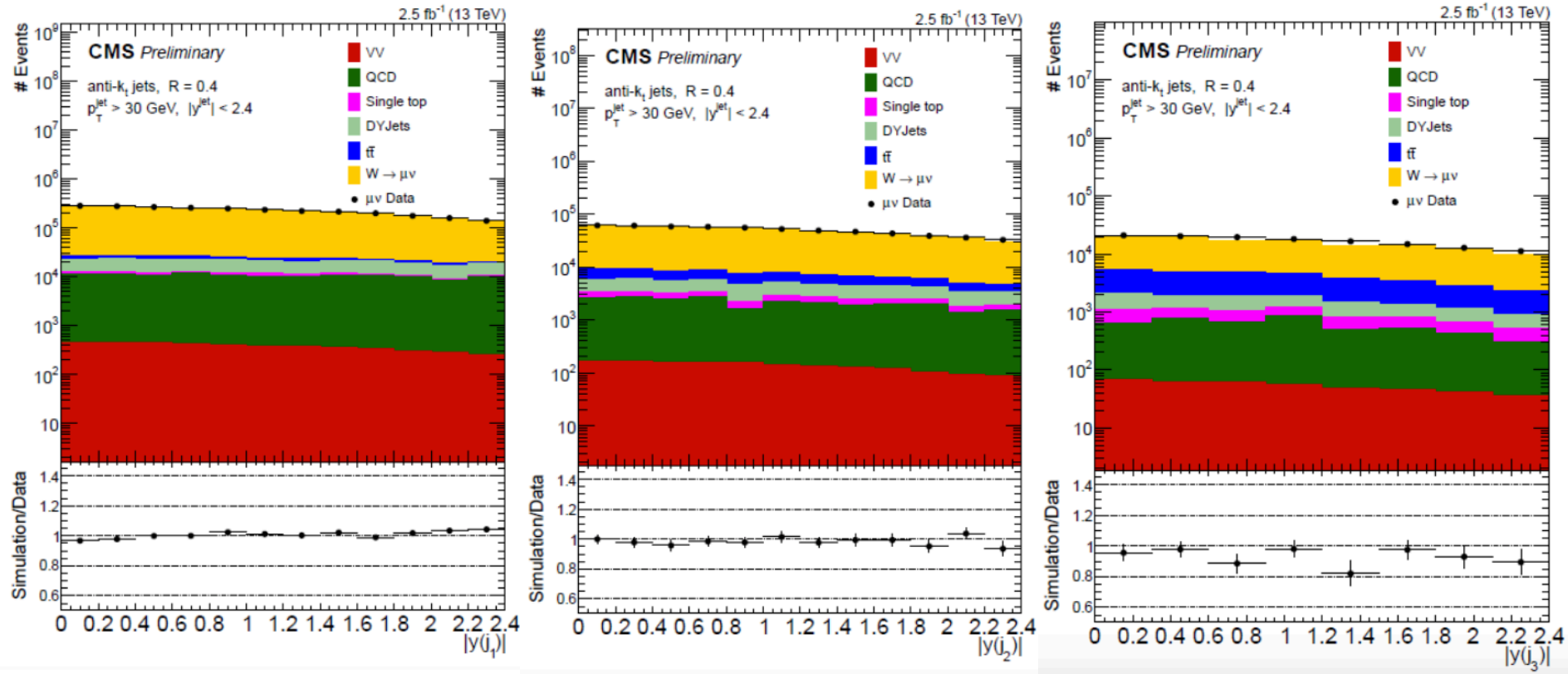
13TeV



[PAS] Figure: Data to simulation comparison of 1st jet p_T for $N_{jets} \geq 1$ (left), 2nd jet p_T for $N_{jets} \geq 2$ (middle), and 3rd jet p_T for $N_{jets} \geq 3$ (right)
Similar behavior like Z+jets.

Data vs simulation comparison: jet |y|

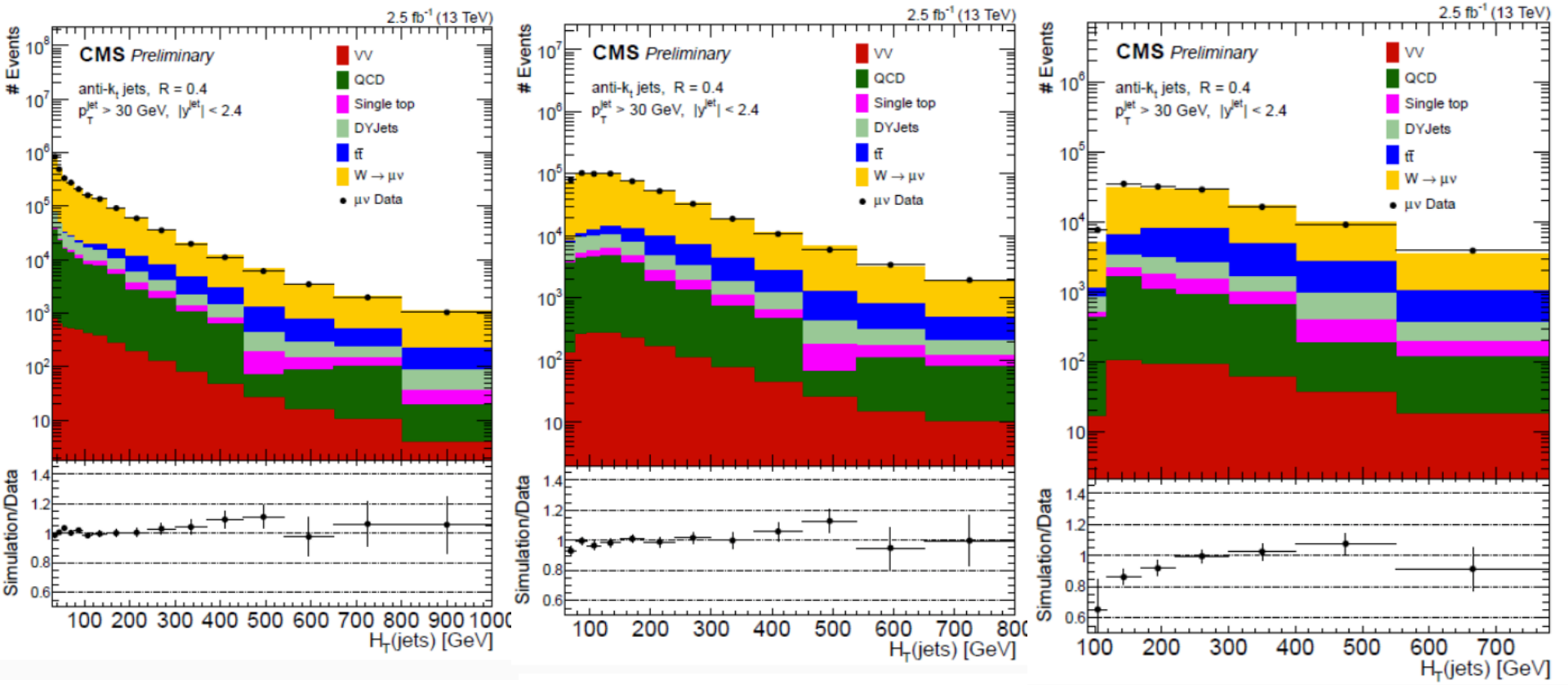
13TeV



[PAS] Figure: Data to simulation comparison of 1st jet |y| for $N_{jets} \geq 1$ (left), 2nd jet |y| for $N_{jets} \geq 2$ (middle), and 3rd jet |y| for $N_{jets} \geq 3$ (right)

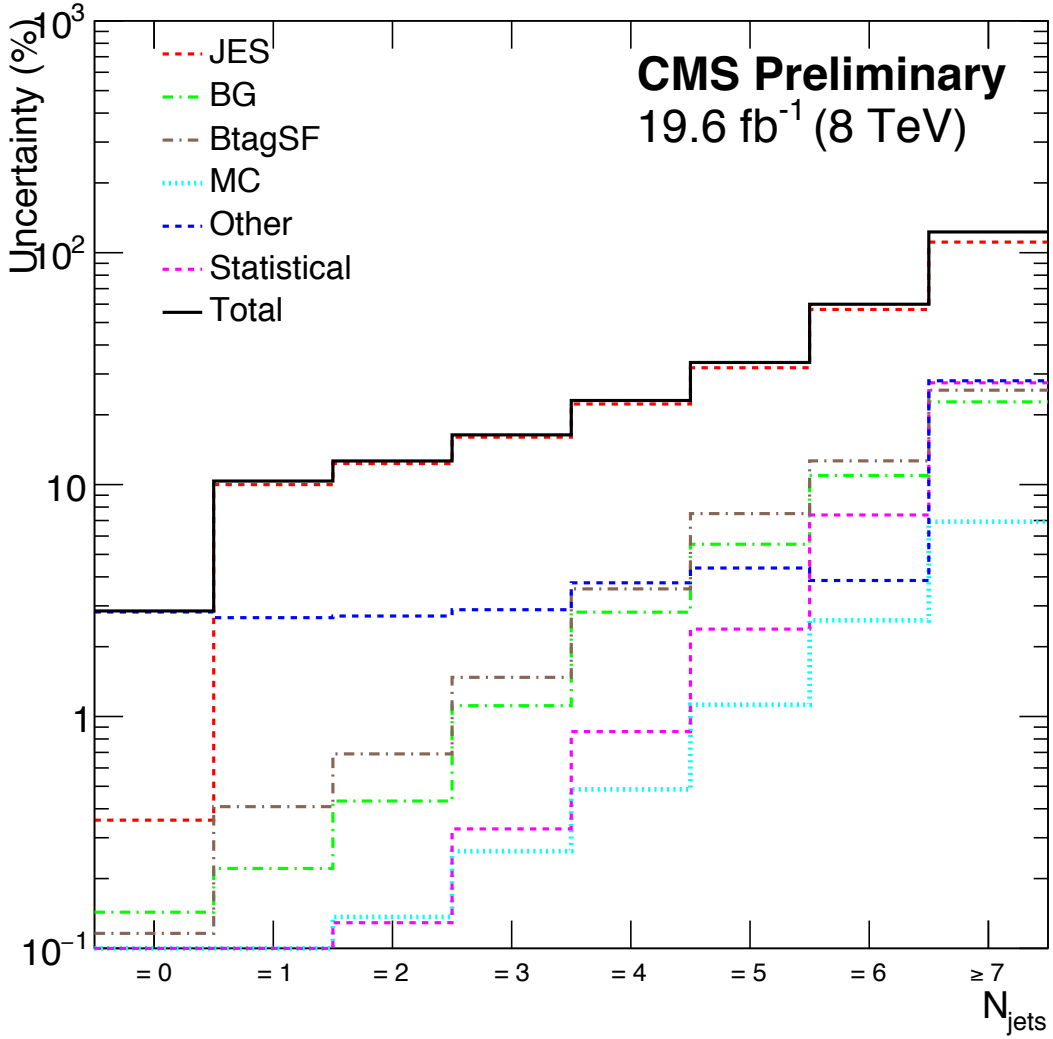
Data vs simulation comparison: jet H_T

13TeV



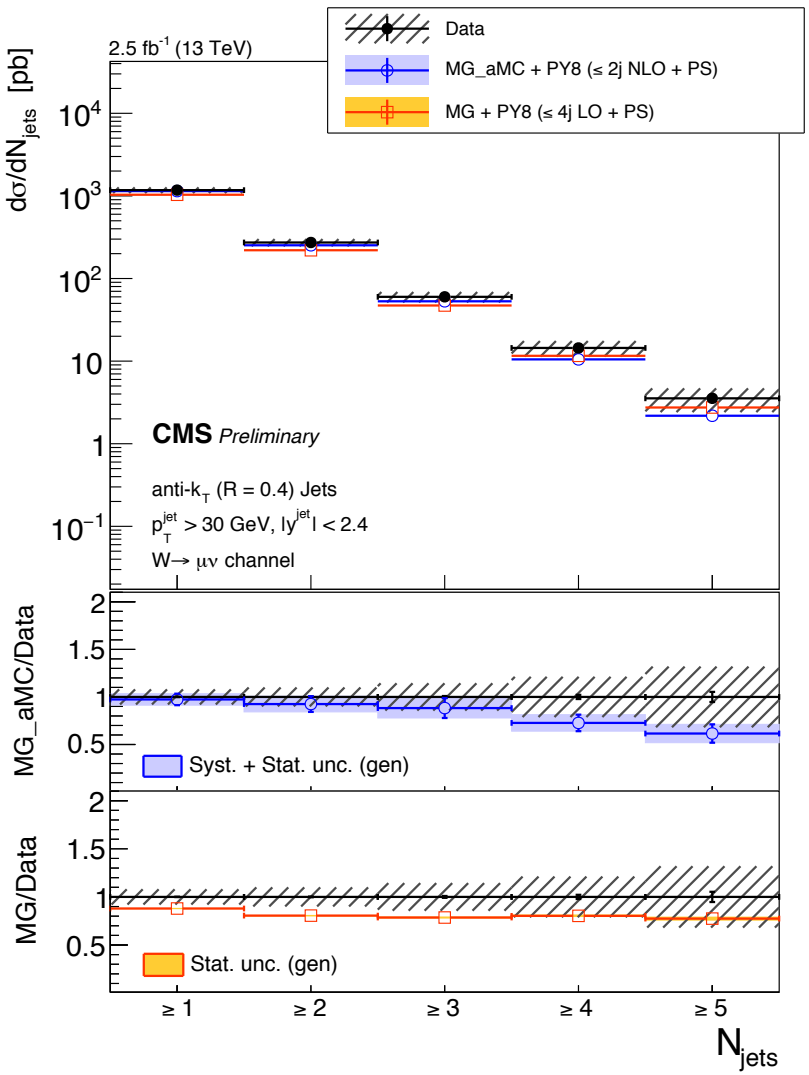
[PAS] Figure: Data to simulation comparison of jets HT for $N_{jets} \geq 1$ (left), $N_{jets} \geq 2$ (middle), and $N_{jets} \geq 3$ (right)

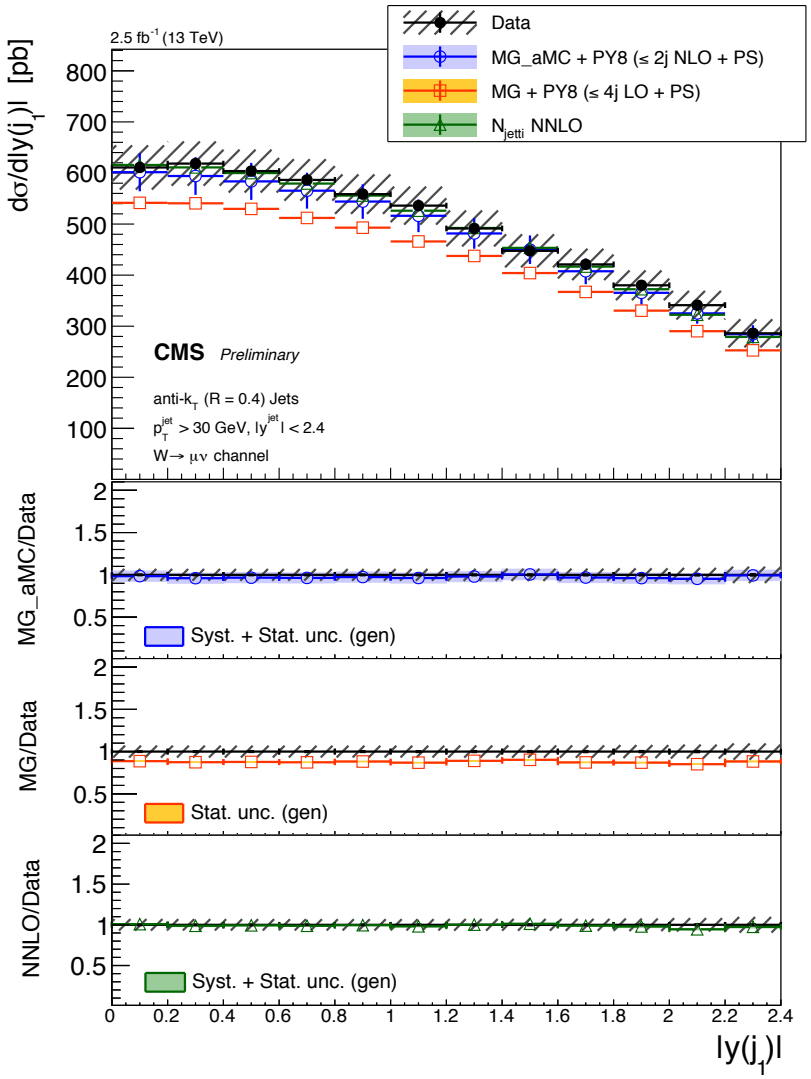
W + jets differential cross section uncertainty



The dominant uncertainty comes from the jet energy scale variations

W + jets differential cross section at 13 TeV

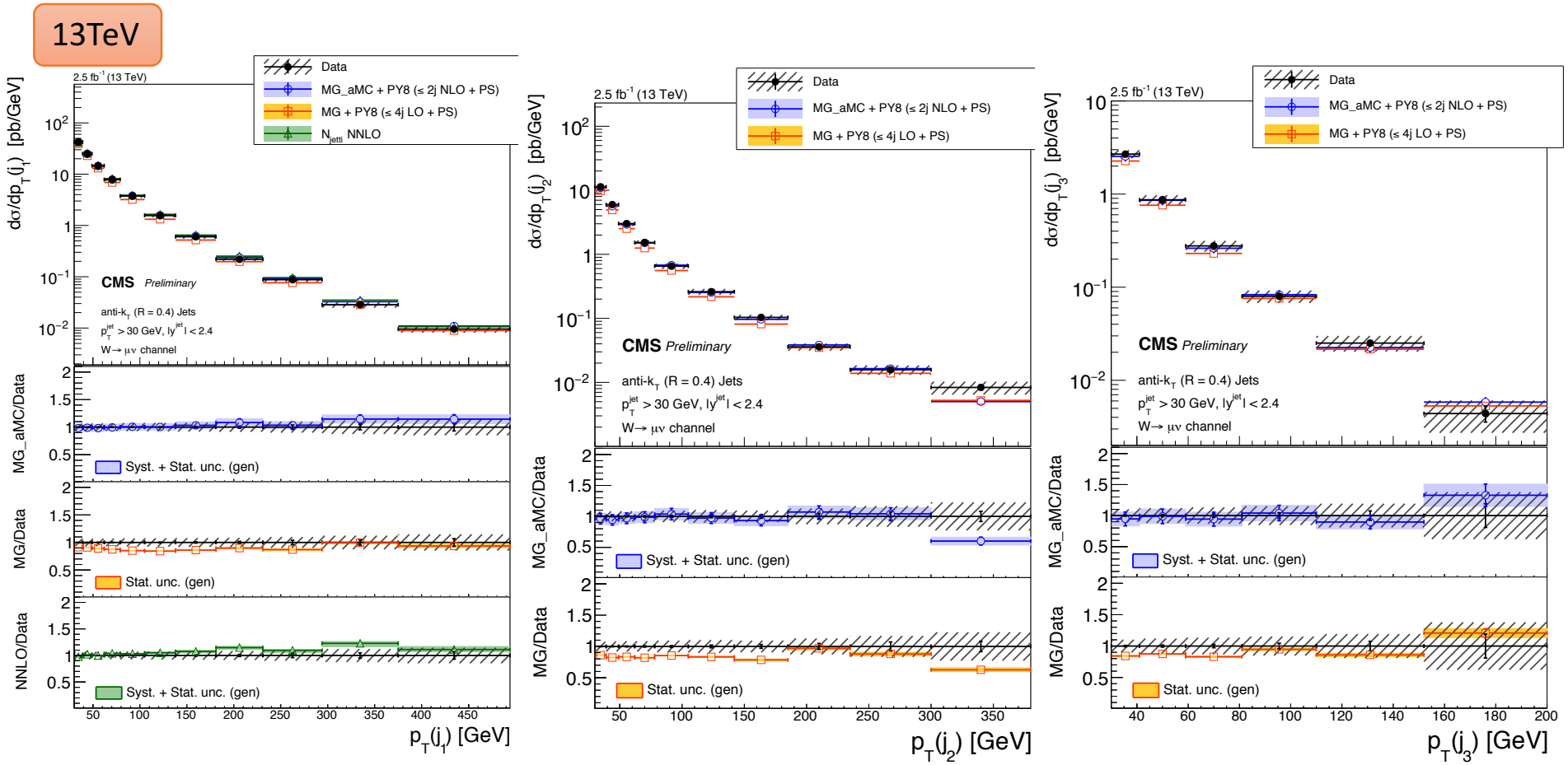




Good agreement between reconstructed data and simulation is observed up to five jets multiplicity for W+jets.

All the predictions are in good agreement in the rapidity distribution.

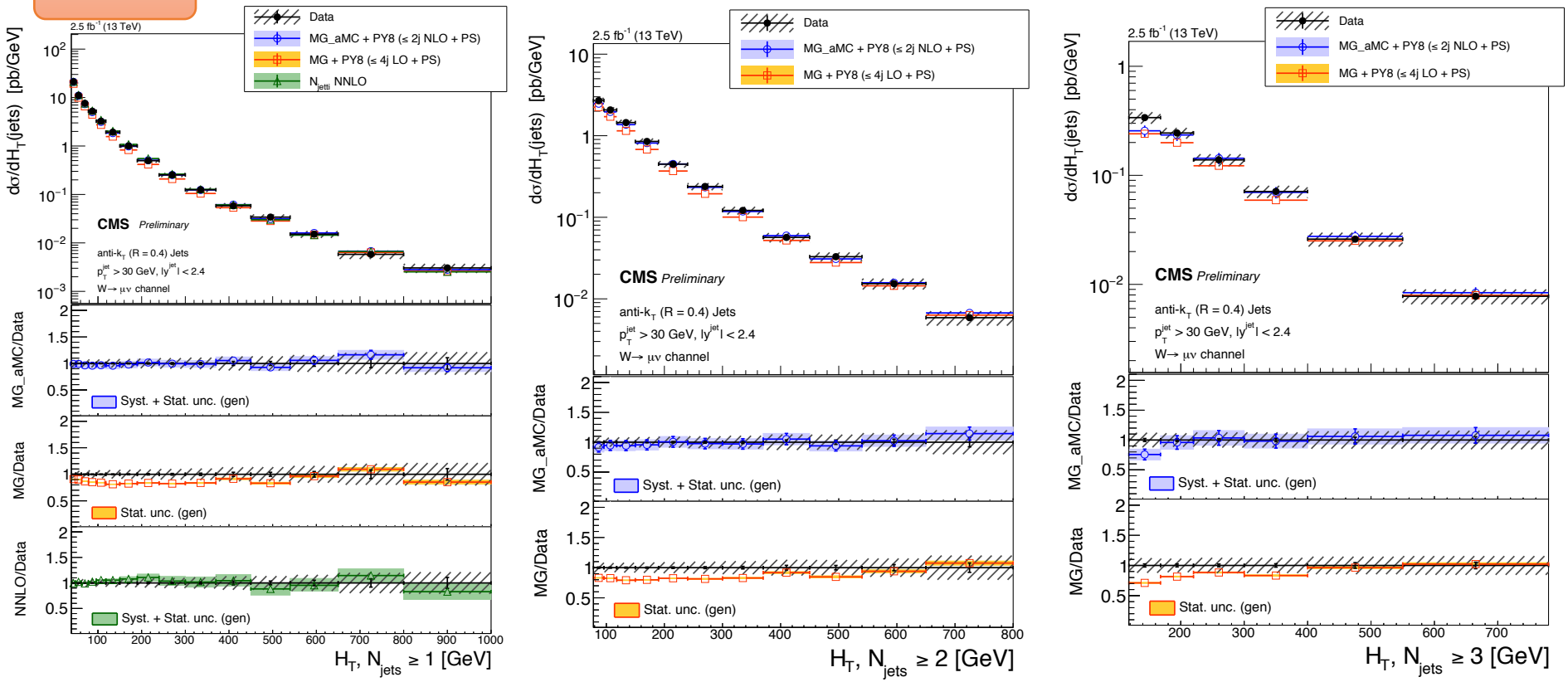
W + jets differential cross section: jet p_T



[PAS] Figure: The differential cross section measurement for the leading three jets' transverse momenta, compared to the predictions including the NNLO for first jet pT. Good agreement is to be expected up to three jets since the MG5 AMC@NLO sample was generated for two partons in the final state at NLO.

W + jets differential cross section: jets scalar sum of transverse momenta

13TeV



[PAS] Figure: The differential cross section measurement for HT for inclusive jet multiplicities 1-3, compared to the predictions including the NNLO for HT for one inclusive jet.

Data distributions are in agreement with the simulation.