Measurement of differential cross section of V boson in association with jets @13TeV

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Analysis Overview

- Objectives:
  - Jet multiplicity (up to 5 jets for W+jets, up to 4 for Z+jets)
  - p_T, $|y|$, H_T of the jets (W/Z + n jets, n $\geq$1, 2, 3)

- Motivations:
  - This process is a standard candle at LHC: high cross section; almost background free
  - It is an ideal laboratory for jet production study
  - Fundamental precision tests for perturbative QCD computations
  - Testing MC based event generators
  - Important background to SM processes and BSM searches:
    - Higgs production – VH ($H \rightarrow b\bar{b}$), single top, ttbar, VBF, ...
    - SUSY, dark matter, extra dimensions, ...

PAS: SMP-15-010, AN: AN-2015/219--- Z+jets

PAS: SMP-16-005, AN: AN-2015/247--- W+jets

Datasets(W/Z+jets)

- Data:

  Data collected during 2015 with 25 ns bunch crossing with integral lumi 2.5fb^{-1}. Processed with CMSSW_7_4_X, based on MINIAOD v2

- Signal:
  - Signal modeled with MG5_aMC FxFx (0,1,2 jets at NLO)+PYTHIA8
  - Using the FxFx pattern on jet merging scheme
  - The matrix elements include V+ 0,1,2 partons at NLO accuracy; V+ 3 partons with LO approximation
  - Total cross section normalized to native cross section of the sample

- Background

Name	σ (pb)
Background	
TT_TuneCUETP8M1_13TeV-powheg-pythia8	831.76
ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6
ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.6
ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	10.32
WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	61526.7
WWTo2L2Nu_13TeV-powheg	12.21
WZJets_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	4.4
ZZ_TuneCUETP8M1_13TeV-pythia8	15.4

W/Z +jets measurement

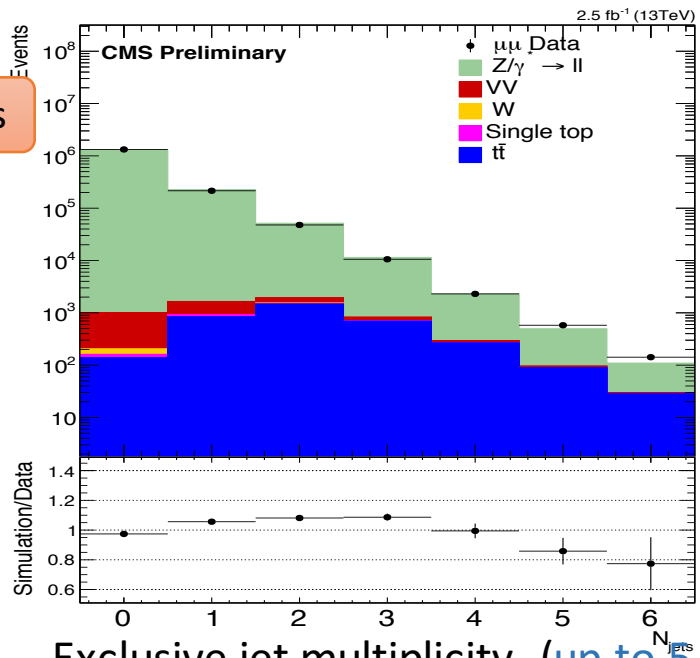
Phase space for Z(μμ)+jets:

- Lepton selection:
  - $p_T > 20$ GeV
  - $|\eta| < 2.4$
  - $M_{ll} \in (71, 111)$GeV
- Jet selection:
  - $p_T \geq 30$ GeV
  - $|\eta| < 2.4$
  - $\Delta R(j, l) > 0.4$

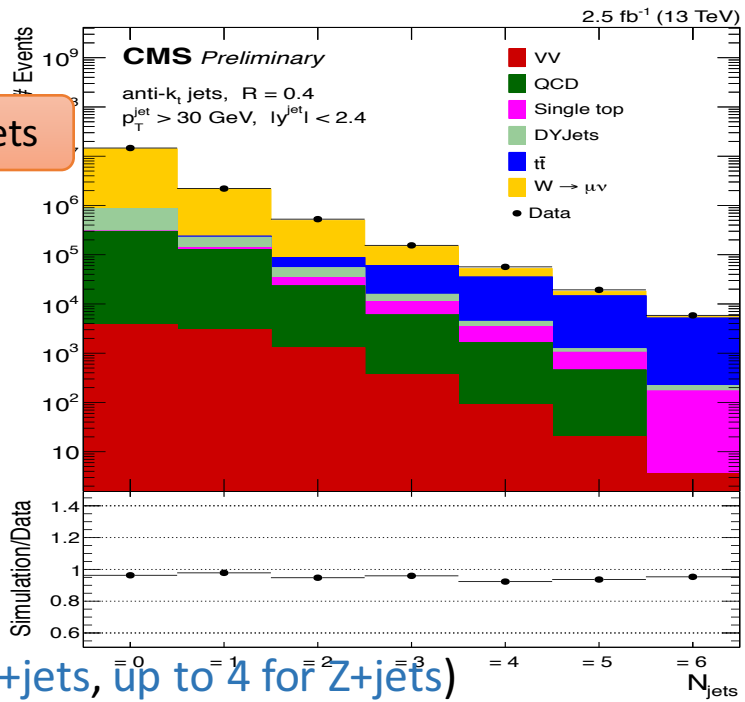
Phase space for W(μ)+jets:

- Lepton selection:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - $M_T > 50$ GeV
- Jet selection:
  - $p_T \geq 30$ GeV
  - $|\eta| < 2.4$
  - $\Delta R(j, l) > 0.4$

Z+jets



W+jets

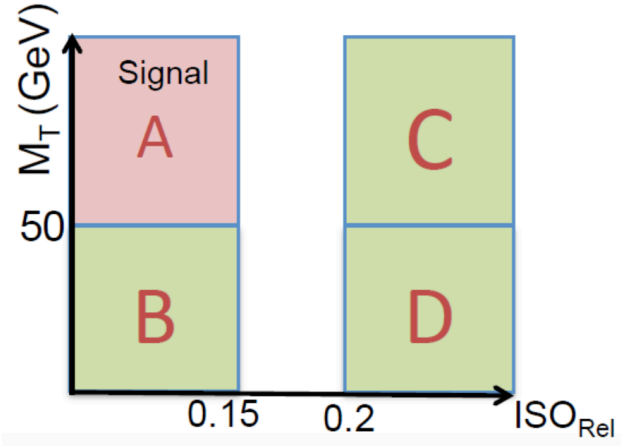


Exclusive jet multiplicity (up to 5 jets for W+jets, up to 4 for Z+jets)

Data-Estimated QCD Multijets Background (W+jets)

- Signal and background processes are simulated by event generators
- Estimate the QCD multijets background by data-driven method
- Choose two uncorrelated variables, MT and ISORel, and divide the 2-D phase space into four regions
- The scaling factor ($f_{B/D}$) is calculated for each distribution (and for each bin for the jet multiplicity distribution)

$$f_{B/D} = \frac{N^{B}_{Data} - N^{B}_{MC}}{N^{D}_{Data} - N^{D}_{MC}}$$



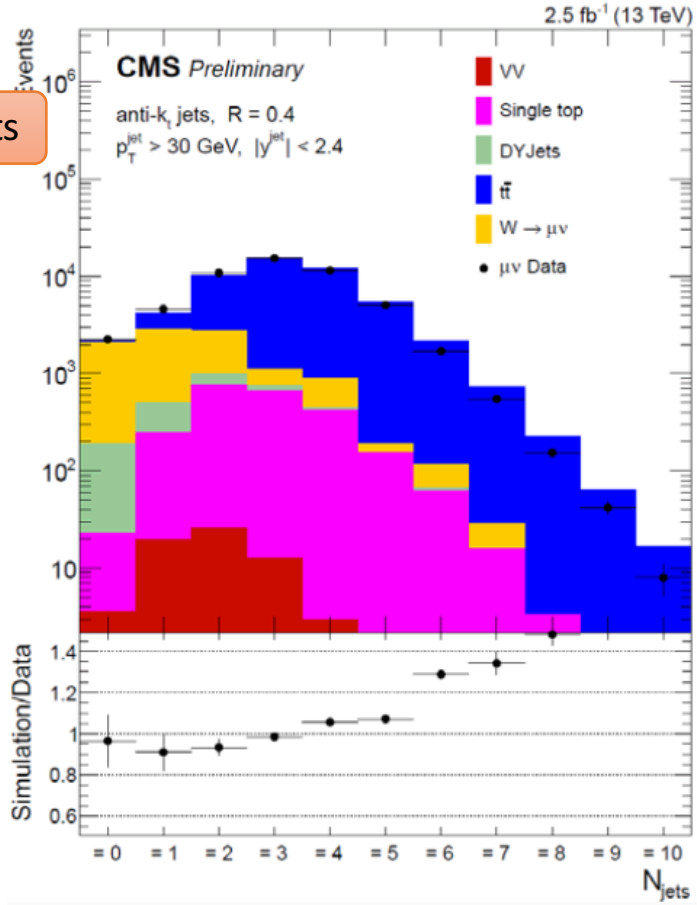
- Assuming that the shape of QCD in signal region A is the same as in region C, the QCD histogram in region A can be found by

$$QCD^{A}_{i} = f_{B/D} \times (Data^{C}_{i} - MC^{C}_{i})$$

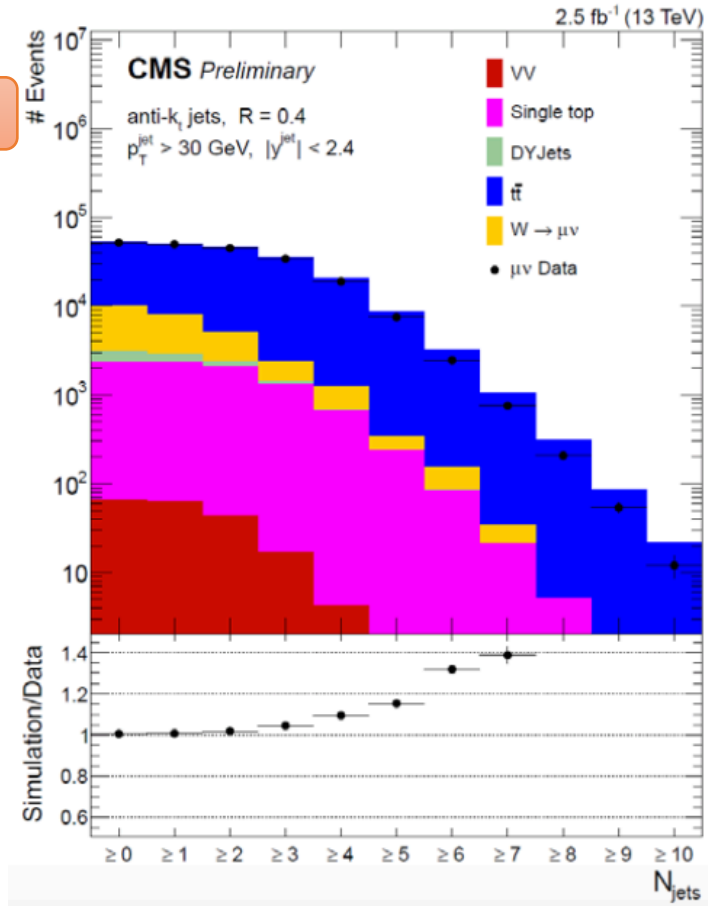
- W+jets MC is normalized to data in region A. Since the QCD normalization affects the W normalization and vice-versa, this is done iteratively to achieve a stable result.

Data vs simulation comparison: TTbar bkg. study

Z+jets



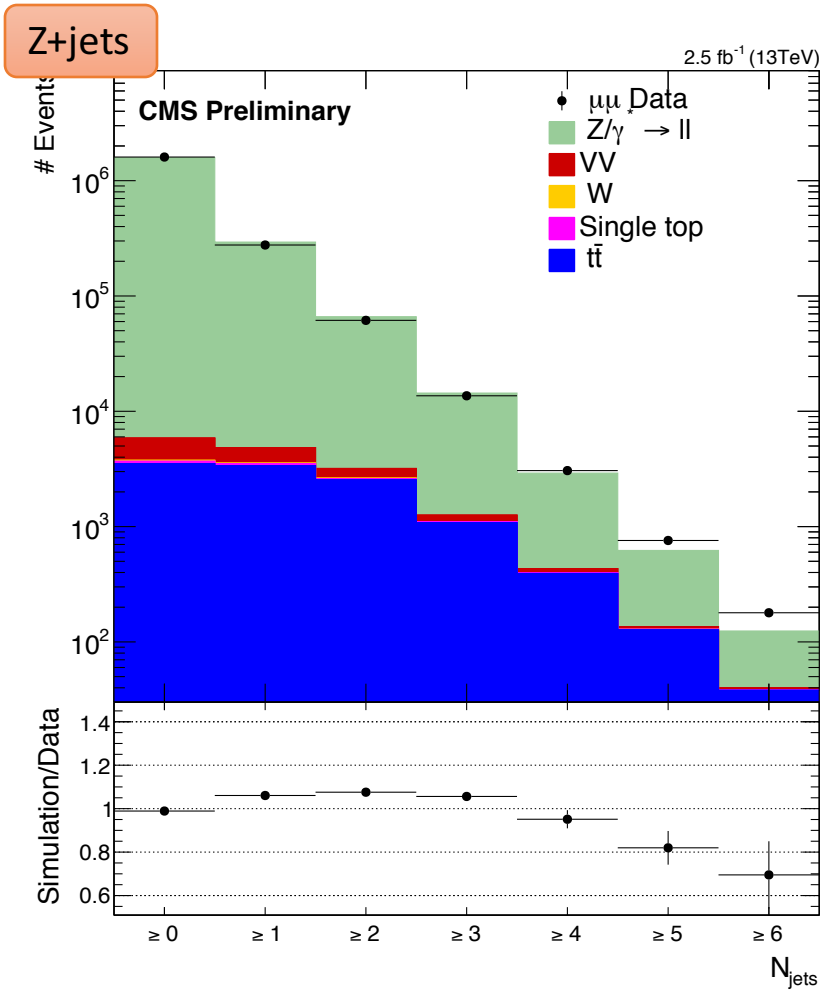
W+jets

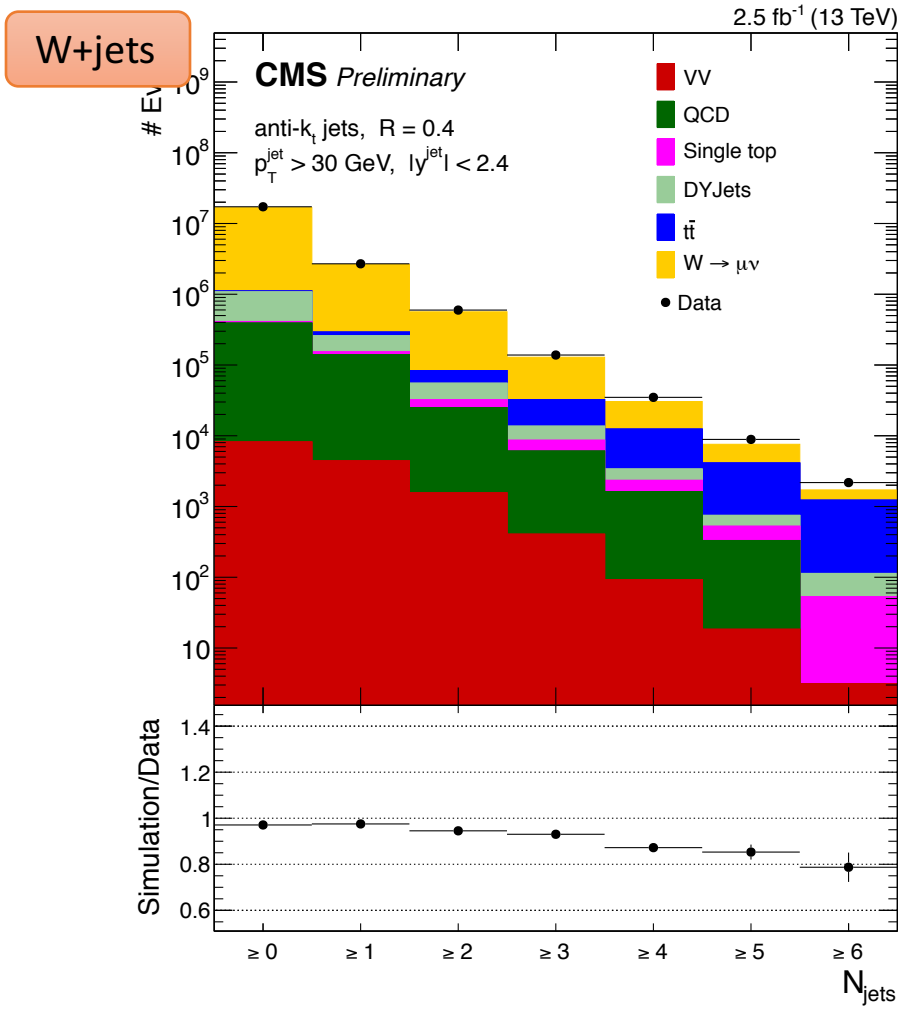


The data-simulation agreement is within 10% up to exclusive jet multiplicity of 5 therefore we use the systematic uncertainty of 10% assigned to the ttbar cross section covers the mis-modeling observed here

[PAS] Figure: Data to simulation comparison of exclusive (left) and inclusive (right) jet multiplicity in the ttbar-enriched control sample

Data vs simulation comparison: inclusive multiplicity



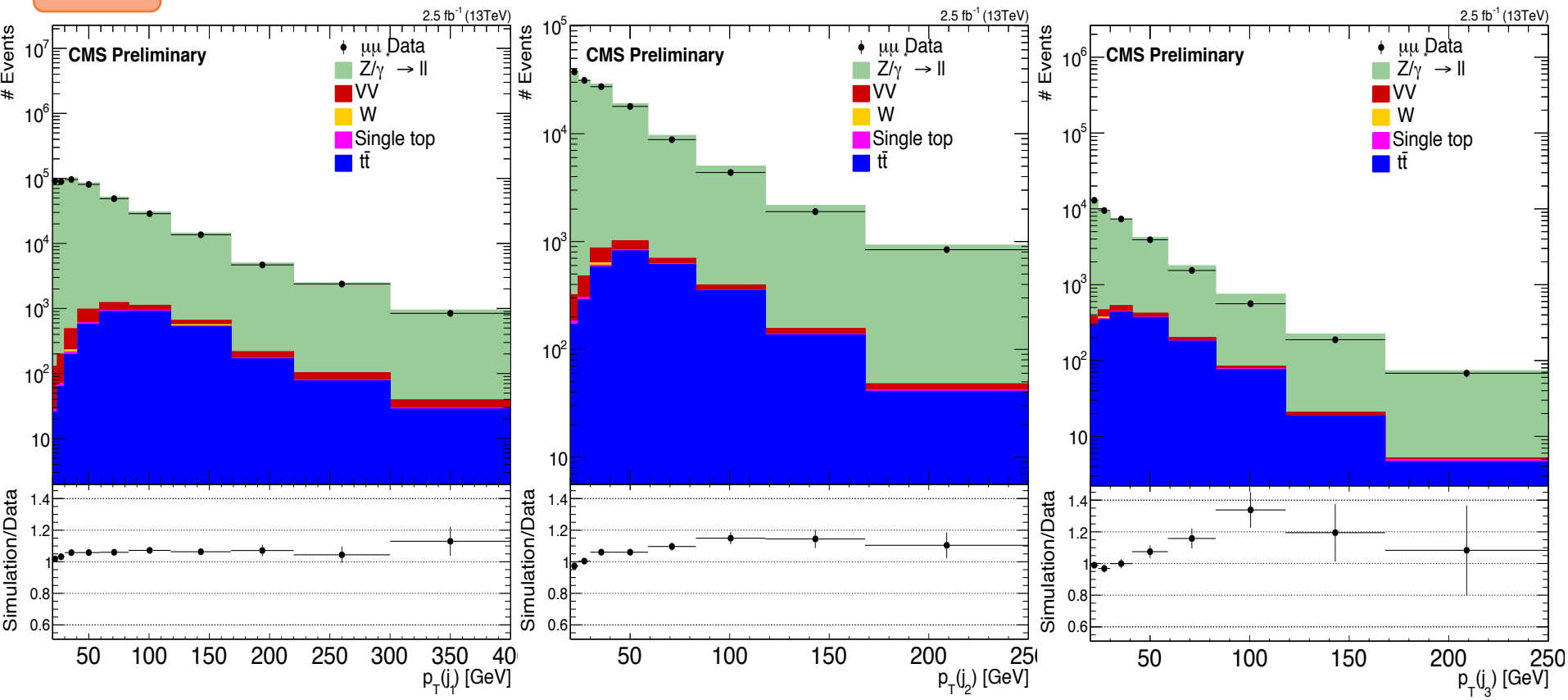


[PAS] Figure: Data to simulation comparison of inclusive jet multiplicity for Z+jets (left) and W+jets(right).

Data and simulations are in good agreement for Z+jets (up to 4 jets) and W+jets (up to 5 jets).

Data vs simulation comparison: jet p_T

Z+jets



[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)

Simulations are consistent with data for 1st jet and 2nd jet pt distributions. The 3rd jet pt is not so good because of the limited statistics.

Unfolding Procedure

- The background-subtracted measured data distributions are corrected back to the hadron level by using an unfolding procedure
  - migration of events between close bins due to finite detector resolution
  - lepton reconstruction, identification and isolation inefficiencies
- Iterative D'Agostini method is used.
- Response matrices are obtained from the V+jets simulation sample by matching the objects before and after detector simulation MG5_aMC FxFx + PYTHIA8
- Fraction of fake events, passing the Reco level selection but are absent from Gen level, are estimated using the MG5_aMC FxFx + PYTHIA8 sample
- Number of iterations is chosen so that folding the unfolded distribution leads to a compatible distribution with the original one (with a minimum of 4 iterations to avoid bias to simulation distribution)

Systematic uncertainties

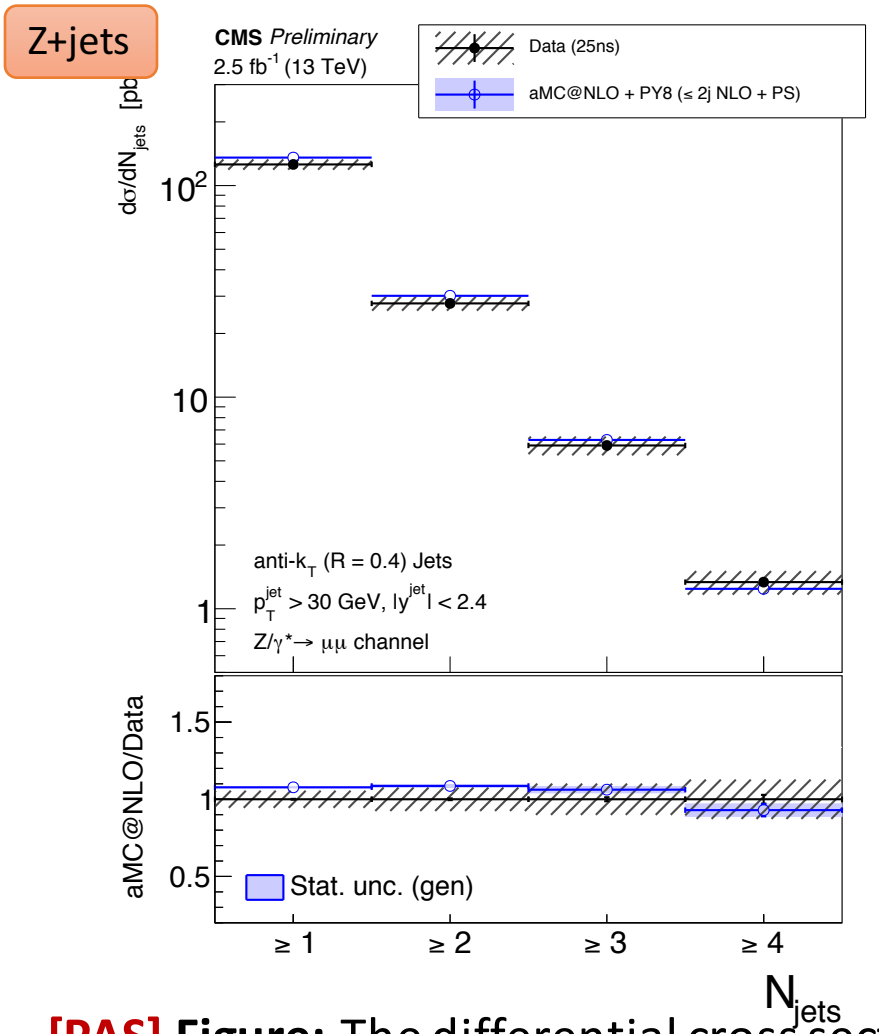
- Jet energy scale (JES) uncertainty (N_{jet} from 0 to 5: 0.15% to 21%)
- Jet energy resolution (JER) uncertainty (below 1%)
- Pileup (PU): Varying the bias cross section by ±5%
- Background cross section (XSEC): The values range from 4% to 10%
- Muon identification, isolation, and HLT trigger scale factors (Eff): 1.2%
- B tagging scale factor (BtagSF), N_{jet} from 0 to 5: 0.40-11% (W+jets)
- Finite number of simulated events in the unfolding response matrix (Sim. stat.)
- Unfolding using reweighted response matrix (Unf)
- Integrated luminosity (Lumi): Uncertainty of 4.6%

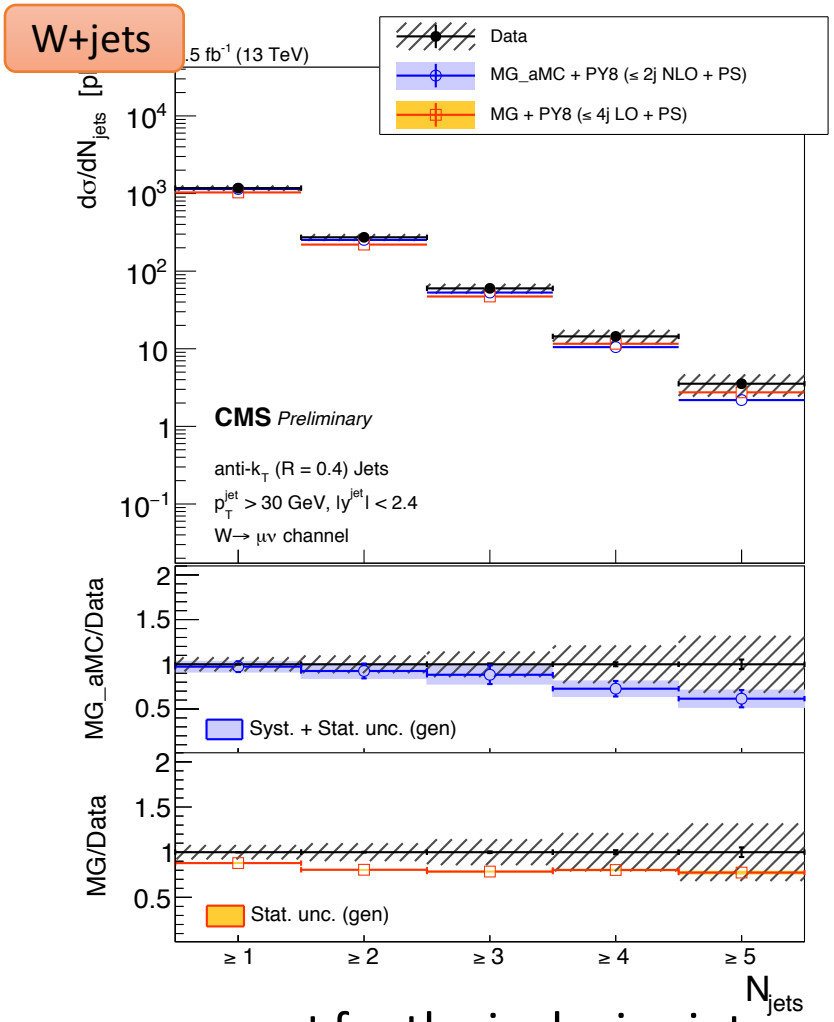
Exclusive jet multiplicity

N_{jets}	$\frac{d\sigma}{dN_{jets}}$ [pb]	Tot. Unc [%]	stat [%]	Simulation stat [%]	JES [%]	JER [%]	PU [%]	XSEC [%]	Lumi [%]	BtagSF [%]	Eff [%]
= 0	7.43e+03	5.3	0.064	0.15	0.15	0.092	1.7	0.17	4.9	0.40	0.53
= 1	867.	5.6	0.28	0.69	1.4	0.43	1.3	0.25	5.2	0.82	0.56
= 2	197.	8.8	0.76	1.8	6.4	0.31	1.5	0.58	5.3	1.7	0.57
= 3	44.8	13.	1.9	4.2	8.7	0.74	3.3	1.9	5.9	2.8	0.64
= 4	12.8	18.	4.3	9.4	11.	0.42	0.12	4.9	7.2	5.1	0.78
= 5	1.76	41.	14.	27.	21.	0.12	2.1	11.	11.	11.	1.1

Z+jets has the similar systematic uncertainties, expect the BtagSF uncertainty, details in backup.

Differential cross section: jet multiplicity



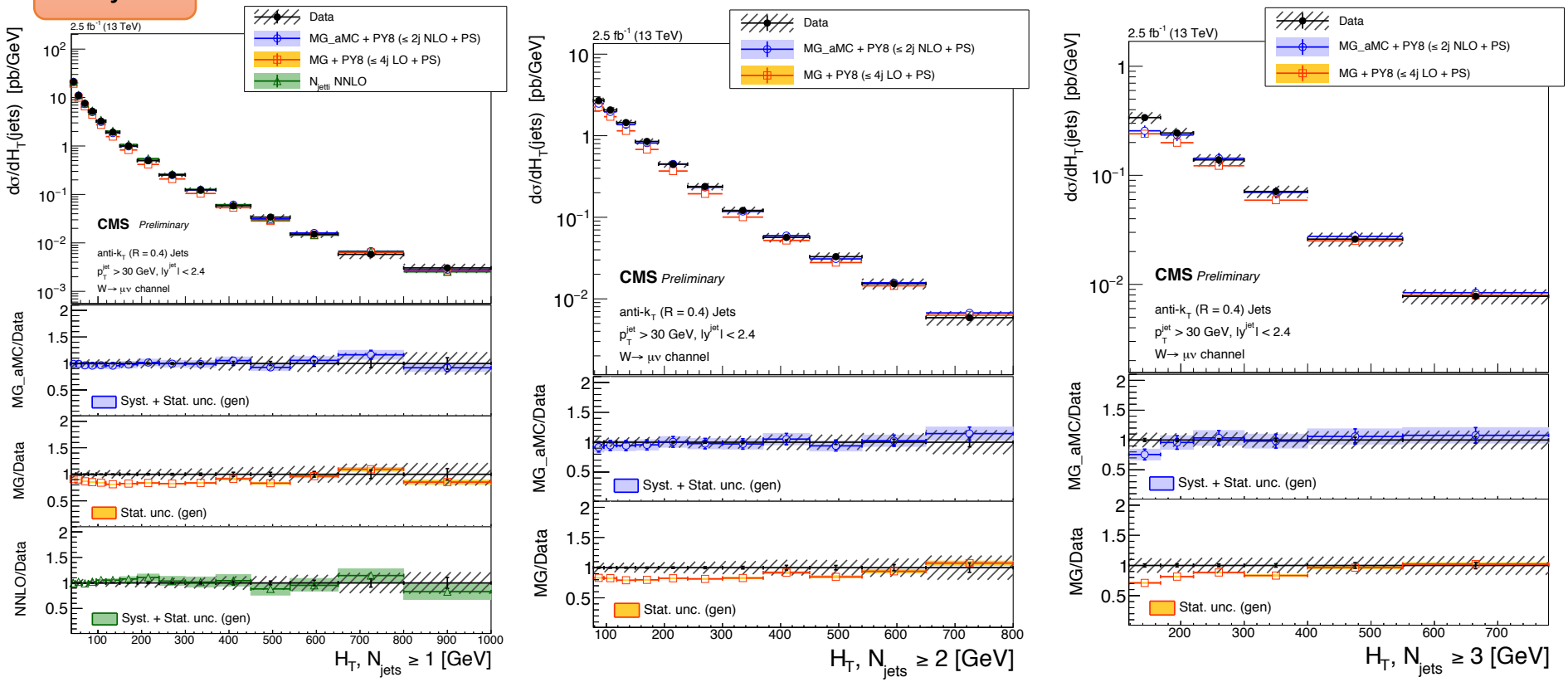


[PAS] Figure: The differential cross section measurement for the inclusive jet multiplicities for the Z+jets(left) and W+jets(right).

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

Differential cross section:
jets scalar sum of transverse momenta

W+jets

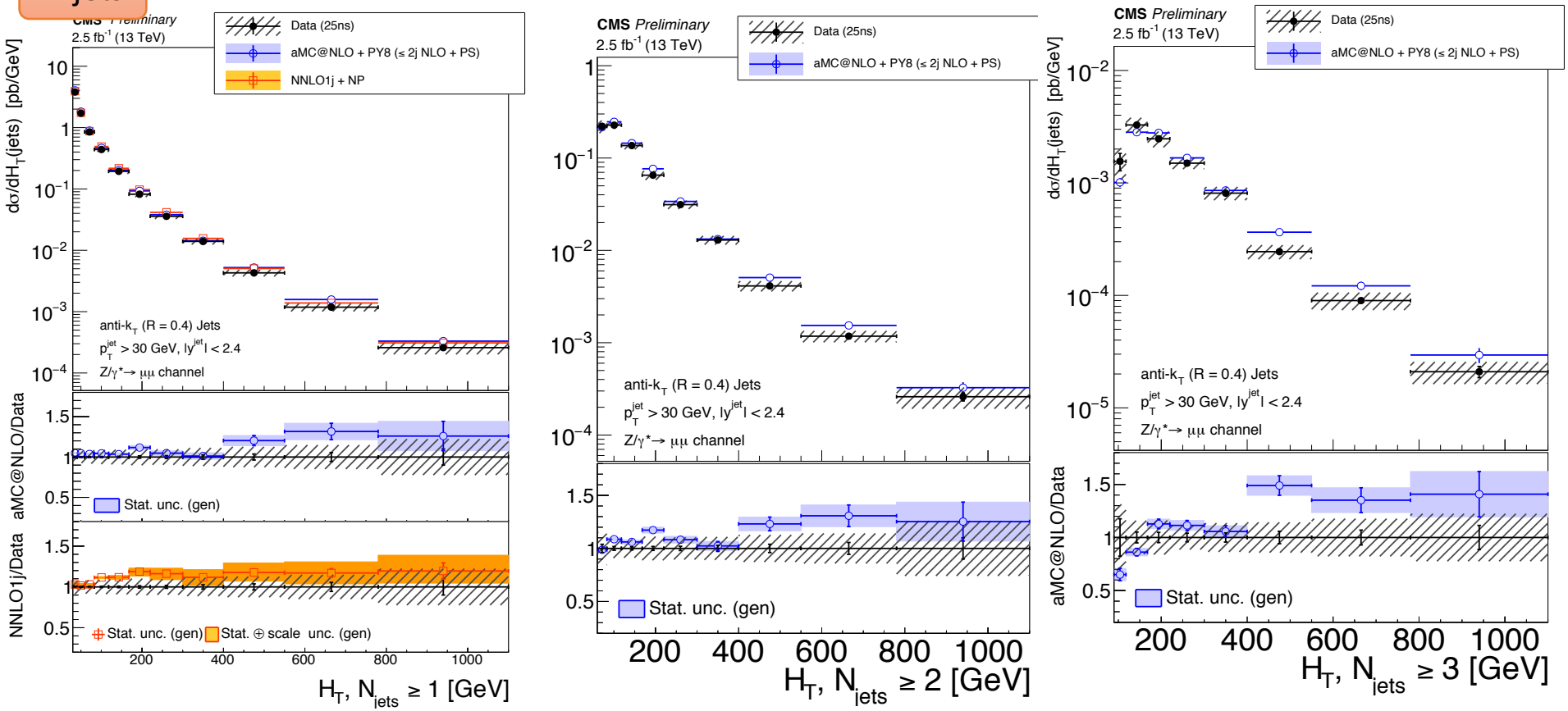


[PAS] Figure: The differential cross section measurement for HT for inclusive jet multiplicities 1-3, compared to the predictions including the NNLO for HT for one inclusive jet.

Data distributions are well reproduced by the simulation.

Differential cross section: jets scalar sum of transverse momenta

Z+jets



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

Conclusion

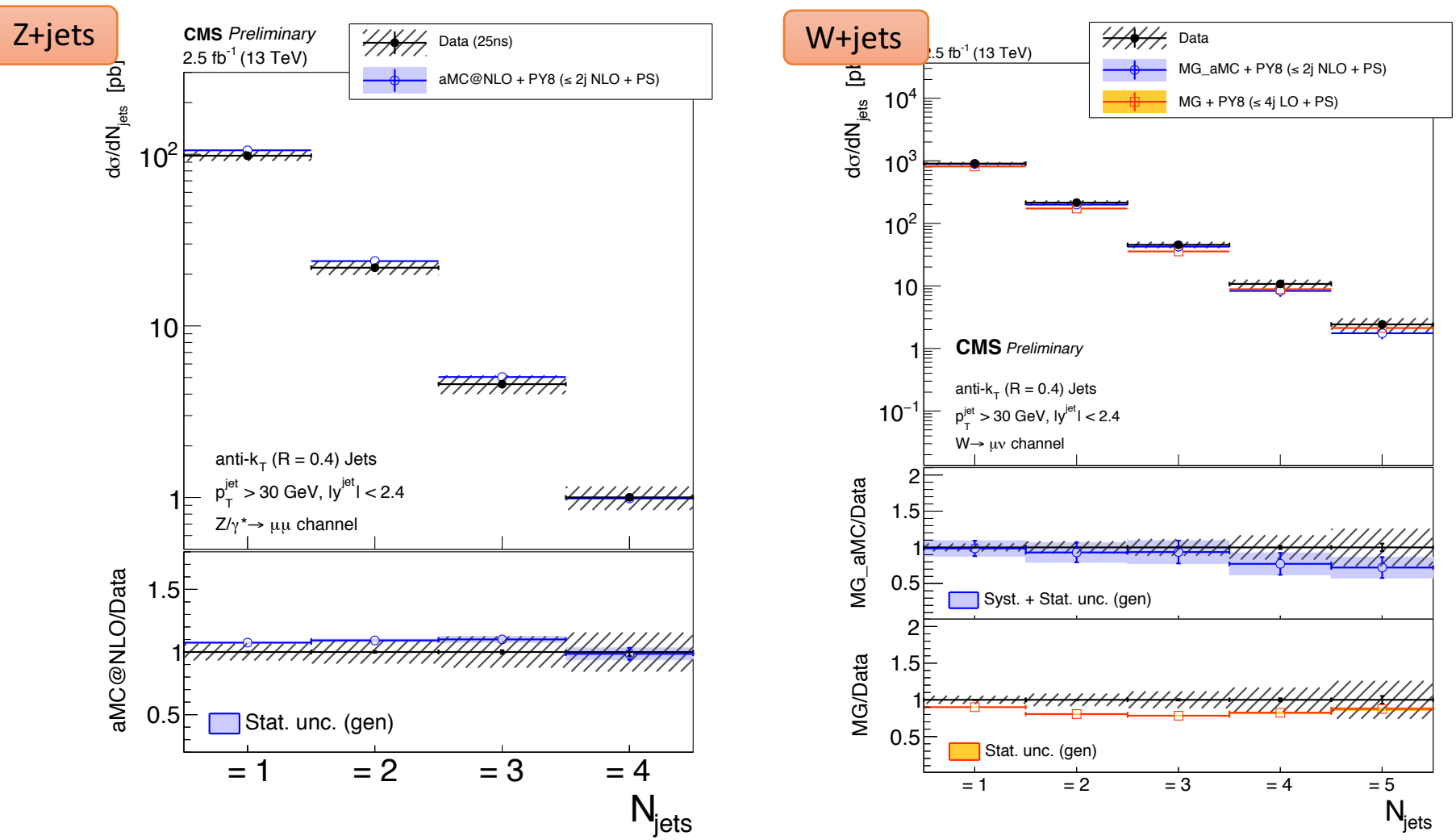
- Using early 13 TeV pp collision data corresponding to an integrated luminosity of 2.5 fb-1
- We have measured differential cross sections for W(-> μv)/ Z(-> μμ) boson production in association with jets as a function of jet multiplicity up to five jets/ four jets and kinematic variables up to three inclusive jets
- For W+jets, we provide complete data descriptions by MC and theoretical predictions at multileg LO and NLO, and W+1j NNLO
- The measurements are compared to multi-legs NLO theoretical prediction, and they are consistent within systematical and statistical uncertainties.

Backup

Systematic uncertainties(Z+jets)

- Jet energy correction (JEC) uncertainty
  Varying the JEC by plus and minus by the values provided by JETMET POG
- Background estimation (Bgnd)
  Estimated using simulated events by varying the cross section of 10% for $t\bar{t}$. The cross section uncertainties of other backgrounds are negligible.
- Pile-up (PU)
  Varying the minimum bias cross section by ±5% only for top up.
- Unfolding
  Estimated by reweighting MC with ratio data/simulation of fine binning reco-level histogram: introduced difference on unfolding results taken as uncertainties
- Luminosity (Lumi)
  Total integrated luminosity uncertainty of 12% is considered. 4.6% for top up.

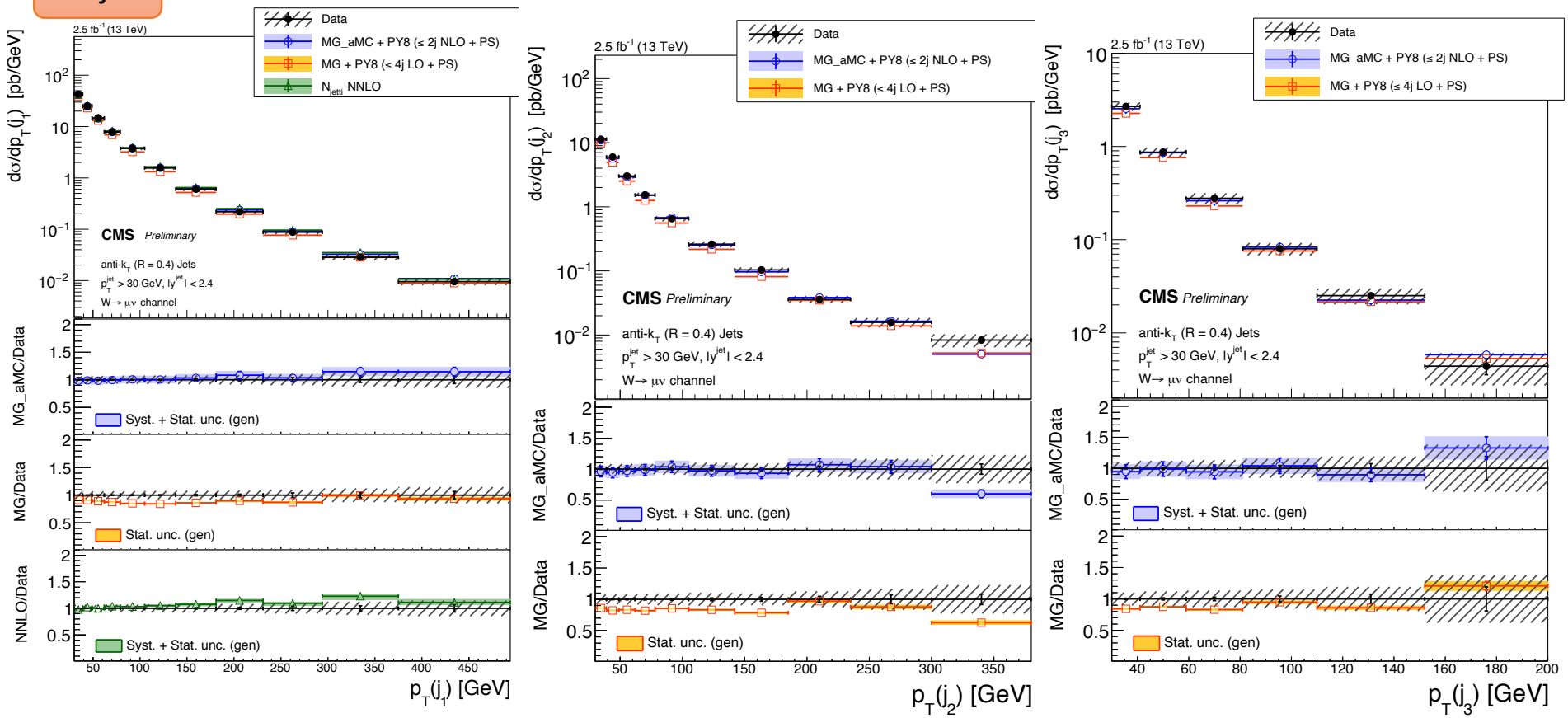
Differential cross section: jet multiplicity



[PAS] Figure: The differential cross section measurement for the exclusive jet multiplicities for the Z+jets(left) and W+jets(right), compared to the predictions of MG5_aMC FxFx and MG5_aMC tree level

Differential cross section: jet p_T

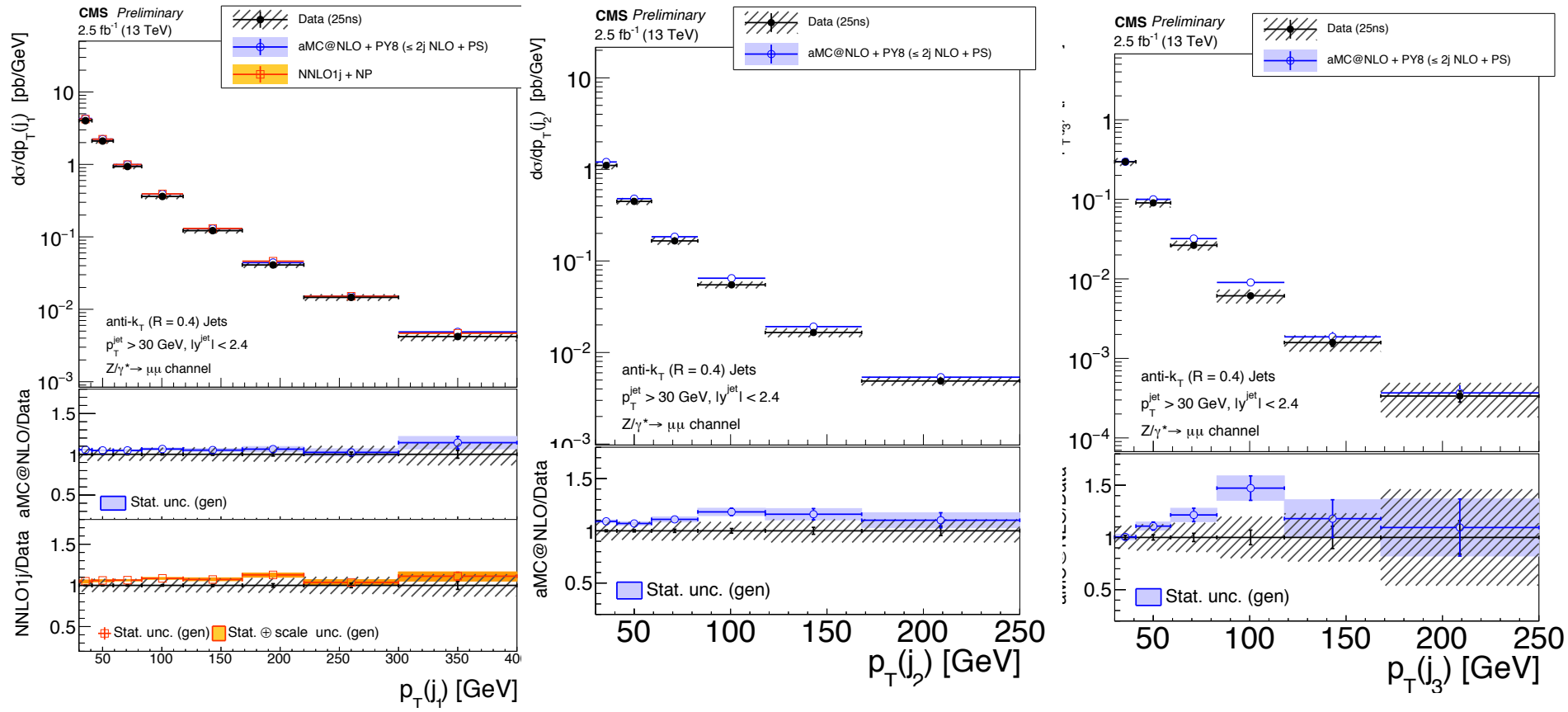
W+jes



[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.

Differential cross section: jet p_T

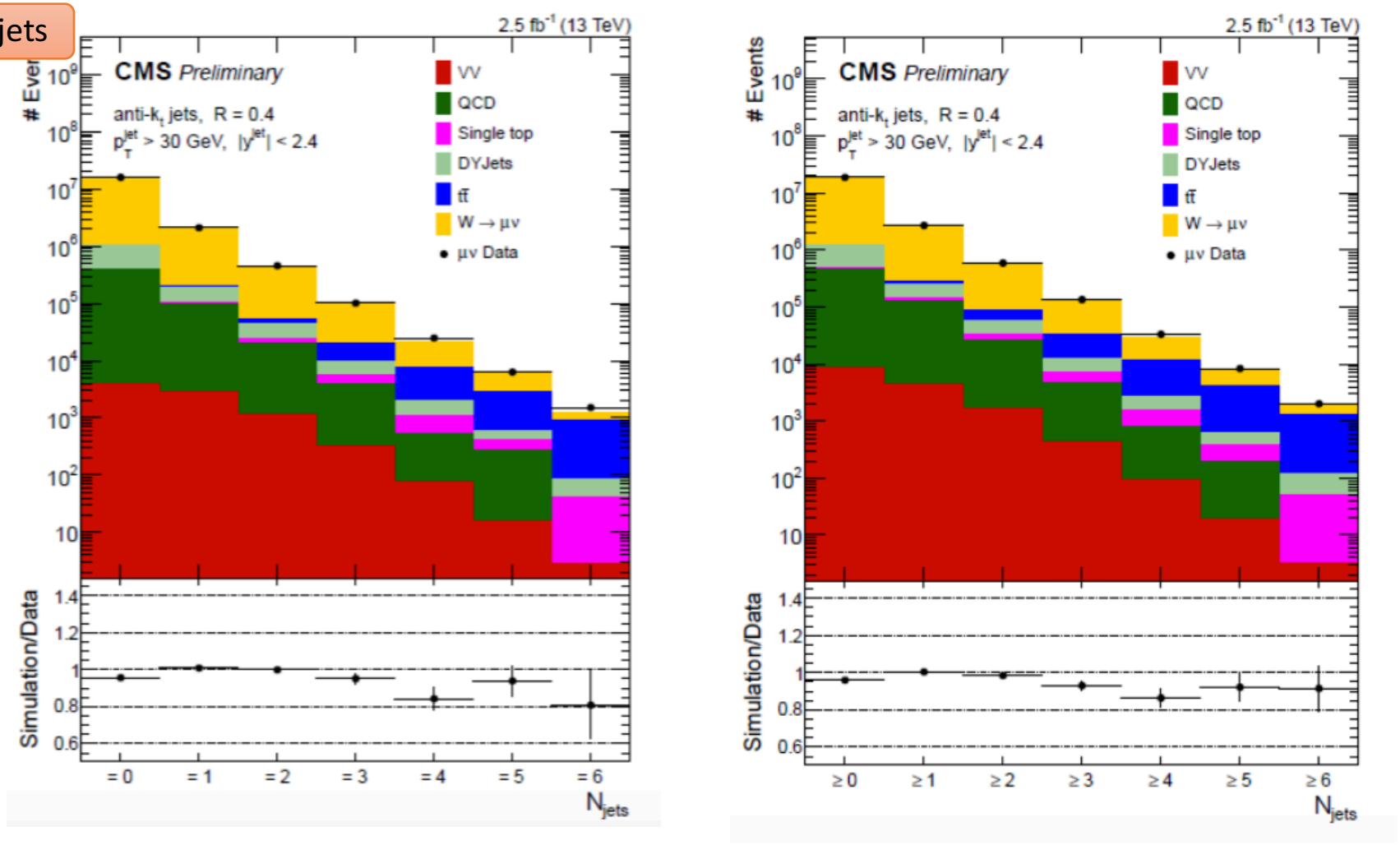
Z+jets



[PAS] Figure: The differential cross section measurement for the leading three jets' transverse momenta

Data vs simulation comparison: jet multiplicity

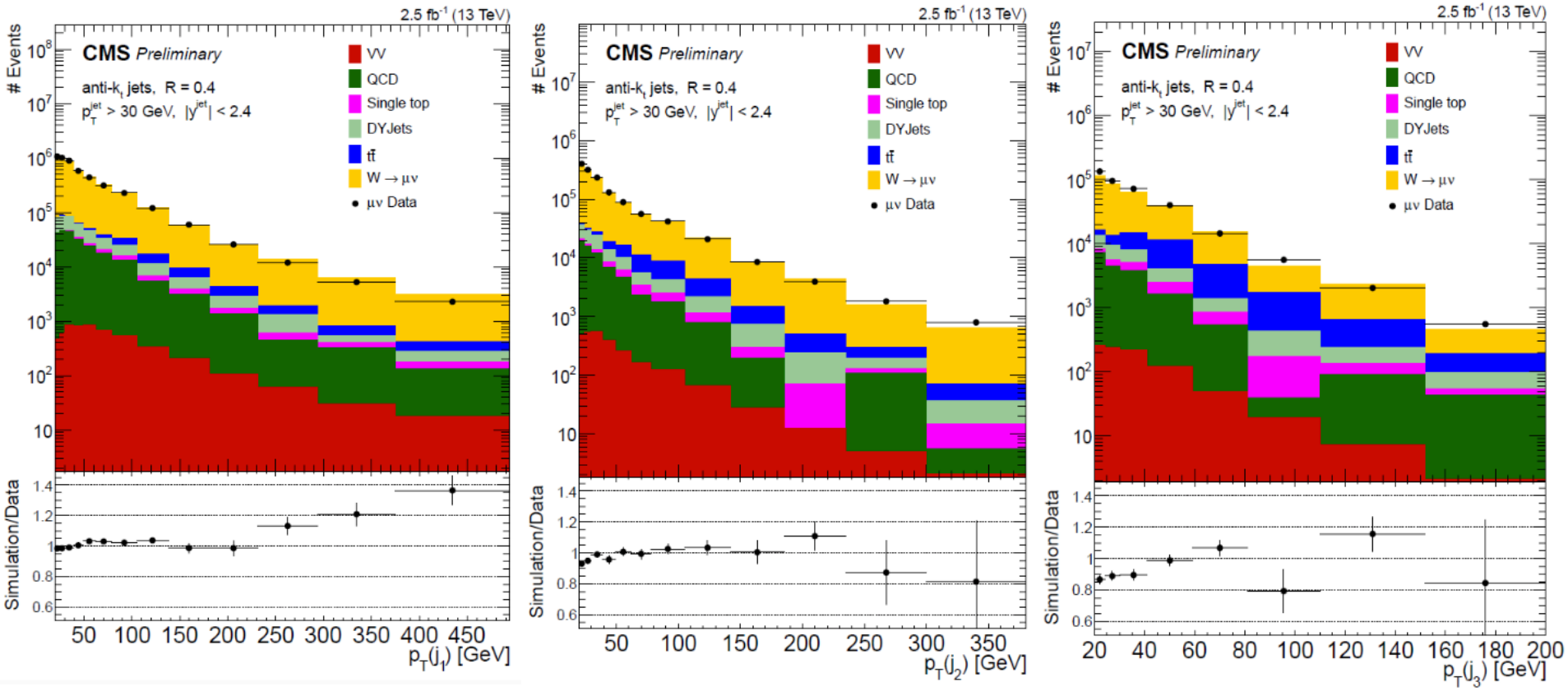
W+jets



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

Data vs simulation comparison: jet p_T

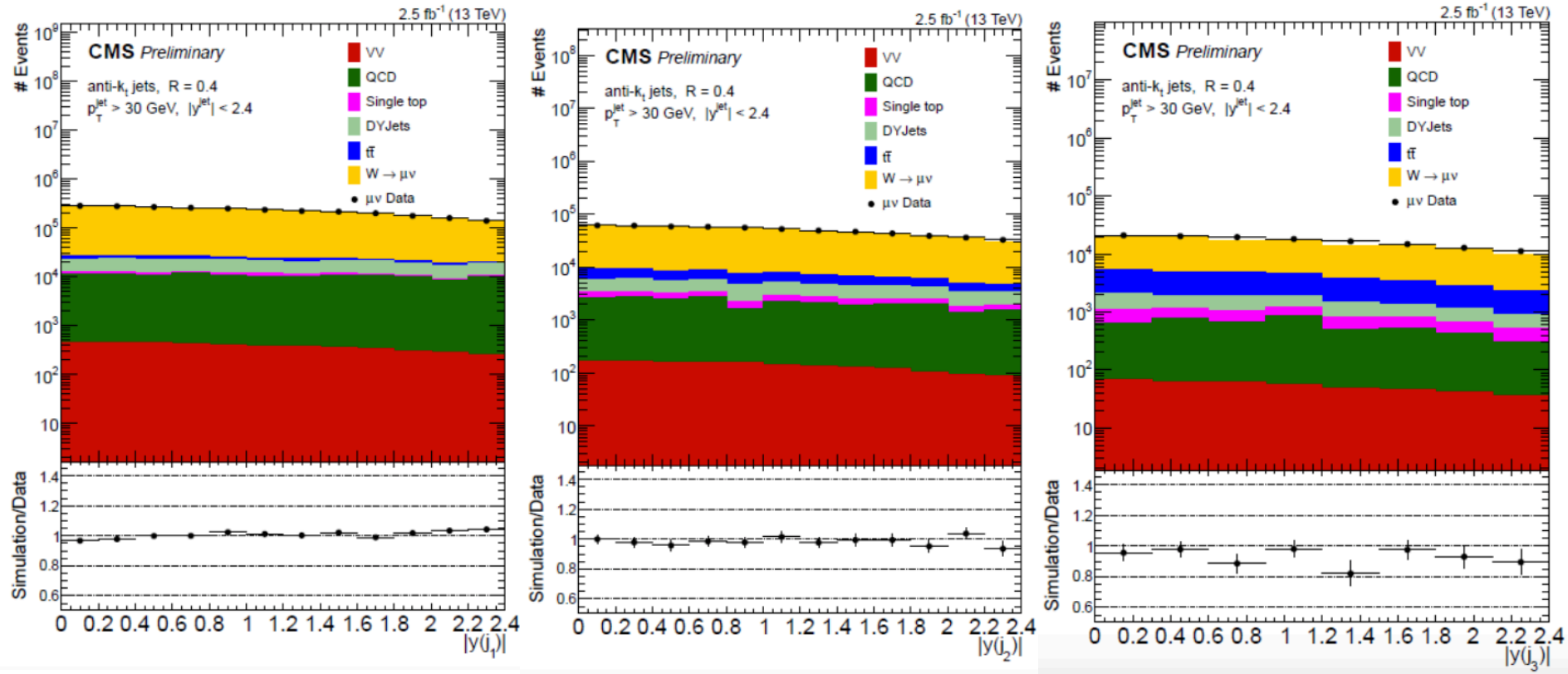
W+jets



[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|

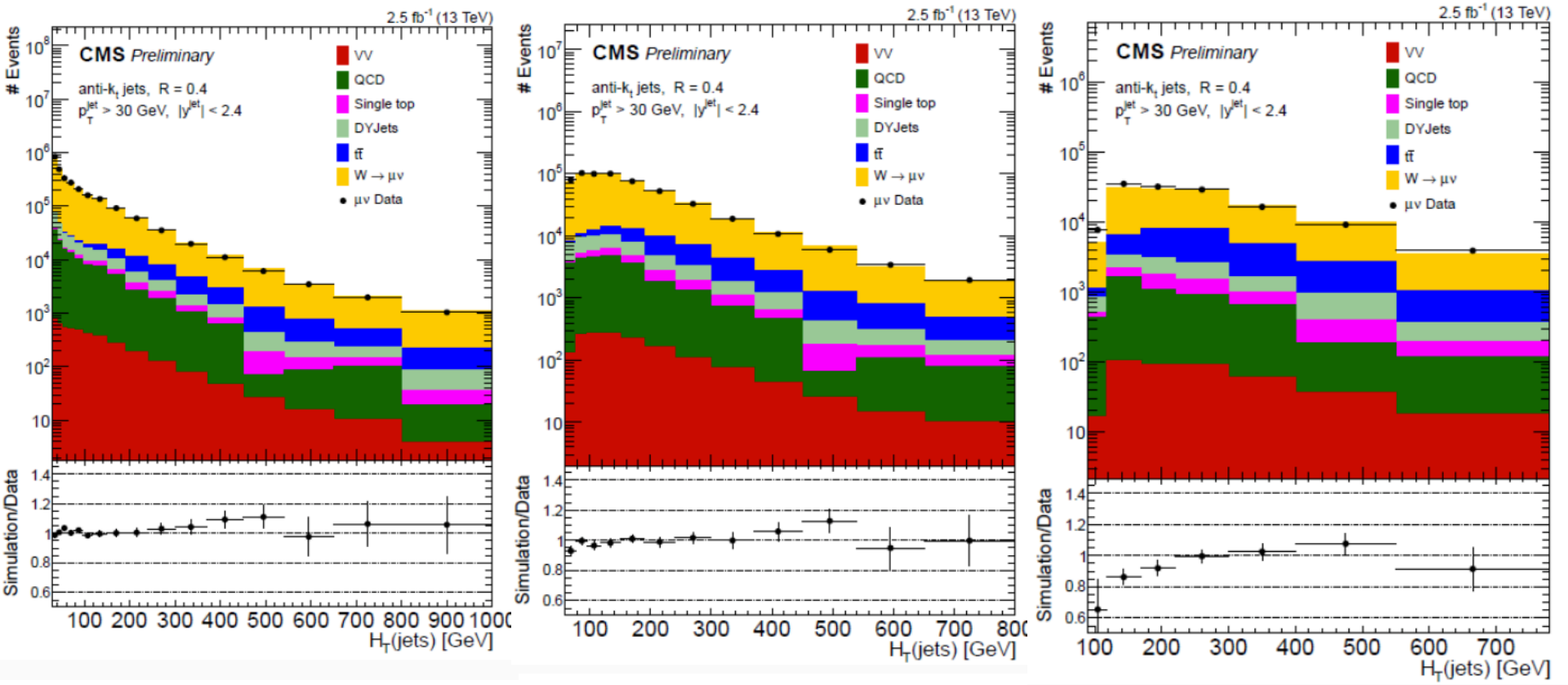
W+jets



[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

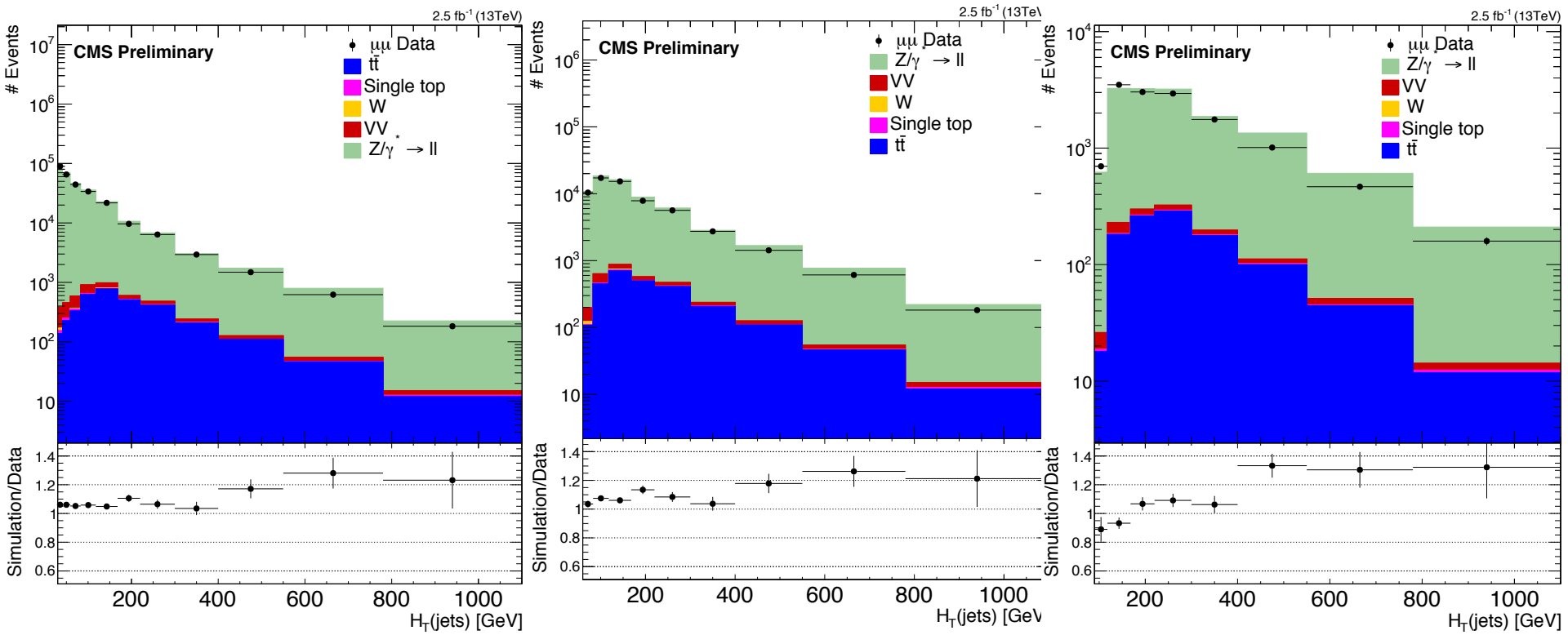
W+jets



[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)

Data vs simulation comparison: jet H_T

Z+jets



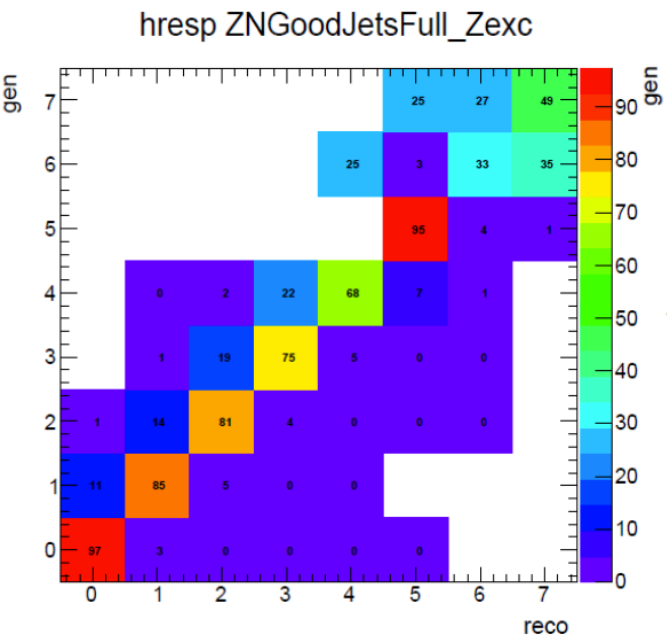
[PAS] Figure: Data to simulation comparison of jets HT for $N_{jets} \geq 1$ (left), $N_{jets} \geq 2$ (middle), and $N_{jets} \geq 3$ (right)

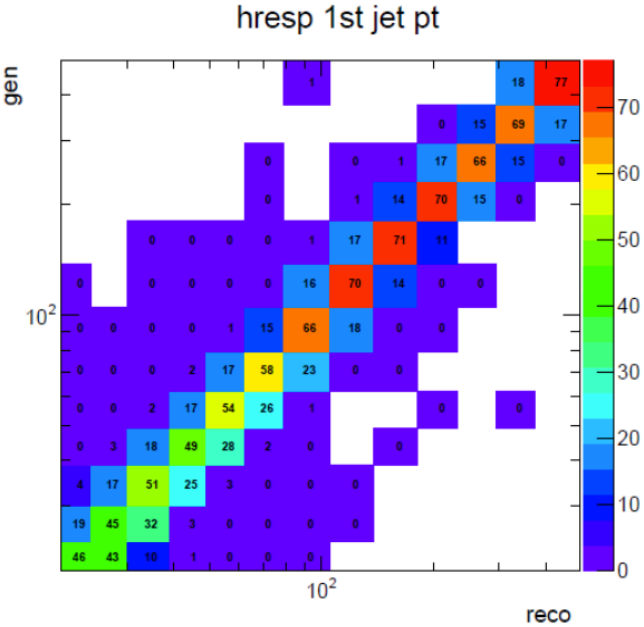
Generator level selection

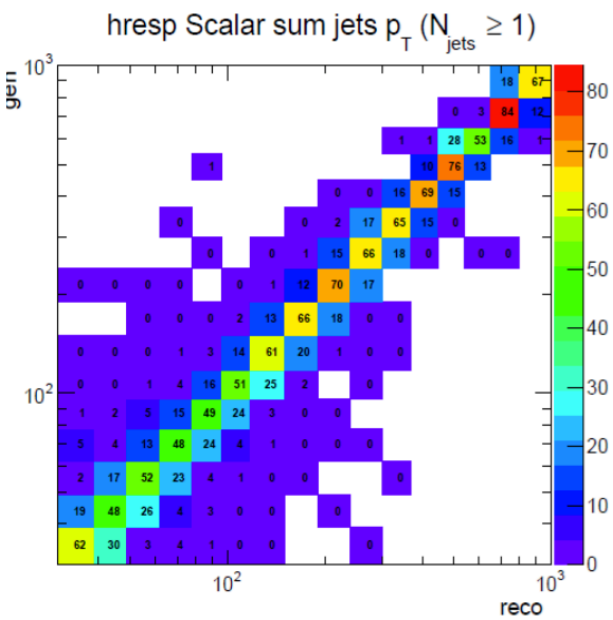
- Muon (Dressed)
  - 'Dressed' muon is defined as the status-1 muon, added with all the status-1 photons in a cone of 0.1 around the muon direction
  - Muon must have $p_T > 25$ GeV and $|\eta| < 2.4$
- Jets
  - Jets must be separated from the muon by $\Delta R(\text{jet}, \mu) > 0.4$
  - Jets must have $p_T > 30$ GeV and $|y| < 2.4$
- MT
  - MT is calculated from the neutrino (the one from W decay)
- Phase Space
  - The event must have the muon and at least one jet, with MT $(\mu, \nu) > 50$ GeV

Response Matrices

- Response matrices (here for exclusive Njets, first jet pT, and HT for Njets ≥ 1) used to obtain unfolded distributions in this analysis
- Percentage of the fraction of events in gen bin *i* to be reconstructed in bin *j*

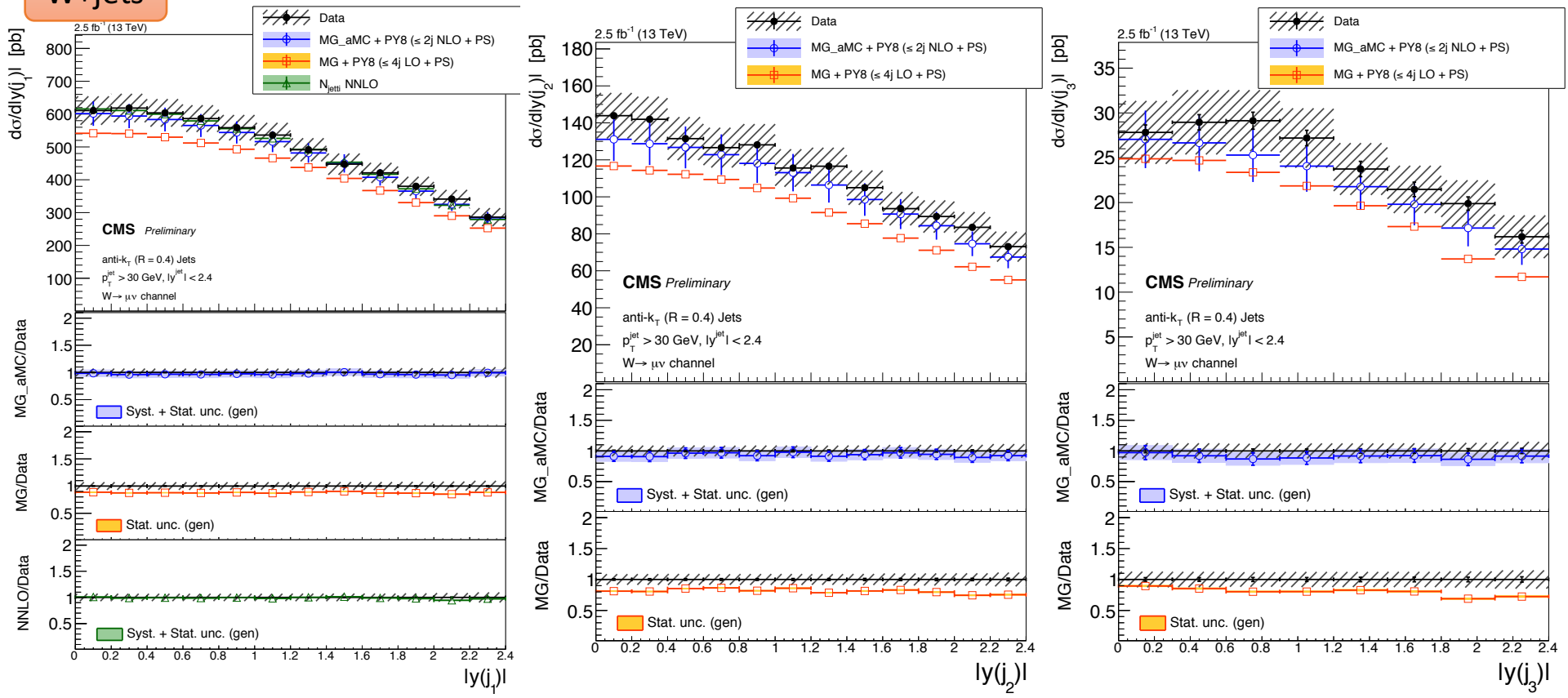






Differential cross section: jet |y|

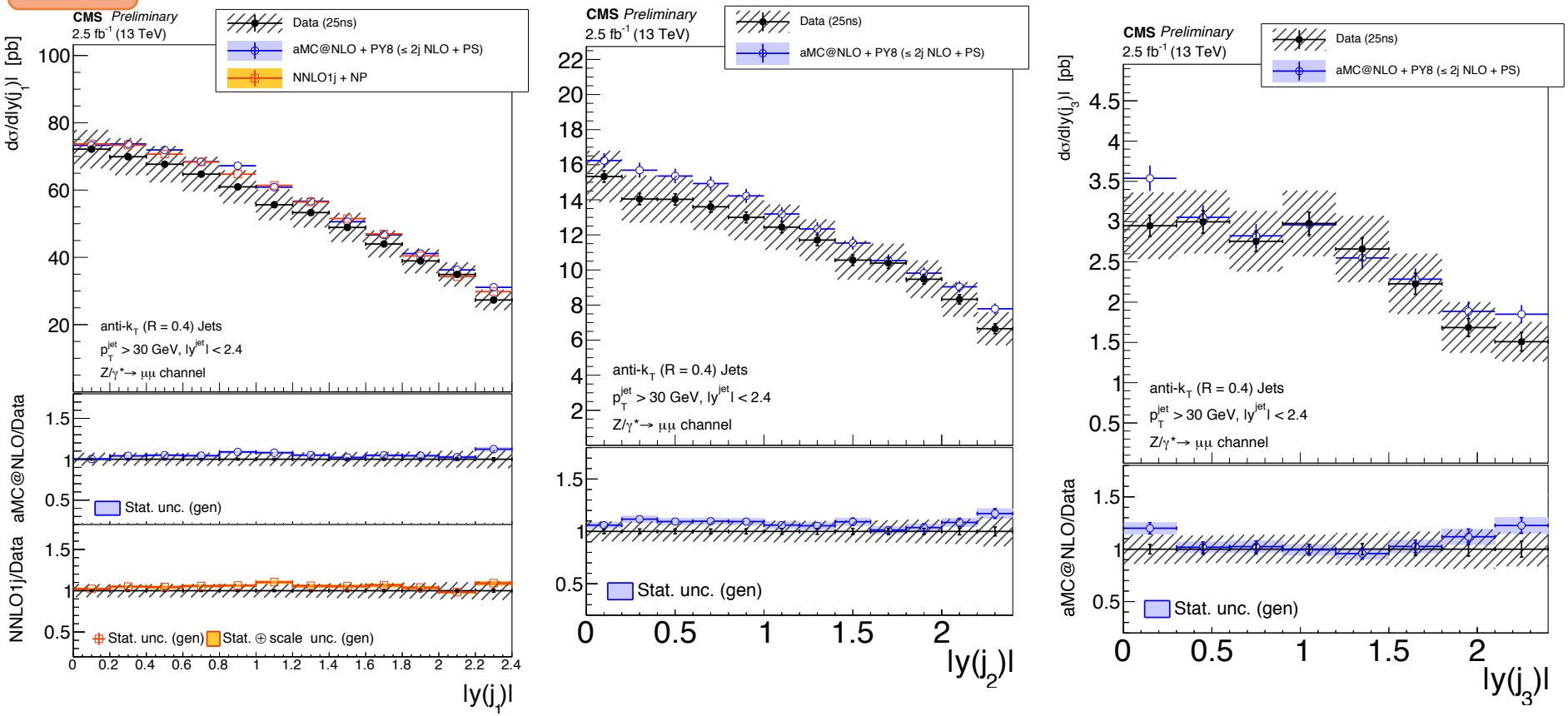
W+jets



[PAS] Figure: The differential cross section measurement for the leading three jets' absolute rapidities, compared to the predictions including the NNLO for first jet |y|

Differential cross section: jet |y|

Z+jets



[PAS] Figure: The differential cross section measurement for the leading three jets' absolute rapidities

Theoretical predictions, MG5_aMC FxFx

- Interfaced with PYTHIA8 providing up to three final state partons with a ME computation up to two jets at NLO accuracy
- Using FxFx jet merging scheme
- The NNPDF 3.0 NLO PDF is used for the ME calculation while the NNPDF 2.3 LO
- PDF is used for the parton showering and hadronization
- Normalized to the native cross section
- The predictions are given with statistical and systematic uncertainties added in quadrature
- Systematic uncertainty is due to choice of scale factors
  - varying the central scale factors by a factor of 2 up and down for inclusive processes
  - combining inclusive uncertainties for exclusive jet multiplicity distribution using the method described in arXiv:1107.2117

Theoretical predictions, MG5_aMC kT-MLM

- Interfaced with PYTHIA8 providing up to three final state partons with a ME computation up to two jets at NLO accuracy
- Tree level generator interfaced with PYTHIA8 for parton showering and hadronization
- The ME calculation has been matched to the parton showering using the kT- MLM scheme
- The PDF set CTEQ6L1 is used
- Total cross section is normalized to the NNLO calculation by FEWZ
- The predictions are displayed with statistical uncertainties only

Theoretical predictions, NNLO fixed-order

- NNLO predictions for W + 1 inclusive jet production
- The NNLO PDF set CT14 is used
- Corrected for non-perturbative (NP) effects, correction is computed with MG5_aMC tree level interfaced with PYTHIA8. The value of this correction applied to the NNLO is within the range of 0.95-1.10
- The effect of final state radiation (FSR) from the muon on the NNLO prediction is estimated to be within 1%
- The predictions are associated with statistical and systematic uncertainties summed in quadrature
  - Statistical uncertainty associated with NP correction
  - Systematic uncertainty is obtained by varying the central scale factors by a factor of 2 up and down
- NNLO W + 1 jet references:
- Phys. Rev. Lett. 115, 062002
- arXiv: 1602.06965