The University of Kansas

V+ jets production in CMS

Low X 2023, Greece

Sorina Popescu for CMS

Motivation for V+jets analysis

The production of electroweak (EW) vector bosons in association with jets →important in the LHC physics

Inclusive and differential measurements of vector-boson plus MultiJet cross sections offers good analysis for various clean final states that arise from the leptonic decays of W and Z bosons.

This offers unique opportunities to test the Standard Model

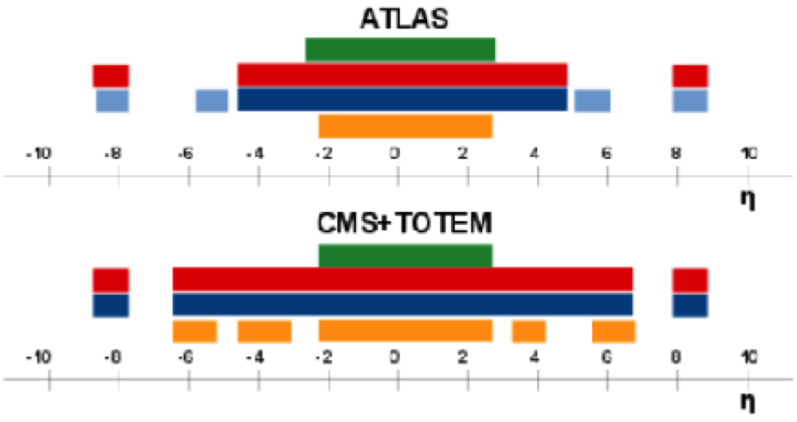
V (V = W, Z) + multijet production represents an important contribution to analyses based on signatures with leptons, missing energy and jets.

In particular, searches for physics beyond the Standard Model (BSM) at the TeV scale. In this context, the availability of precise theoretical predictions for V + multijet production can play a critical role for the sensitivity to new phenomena and for the interpretation of possible discoveries.

Predictions for V+multijet production at next-to-leading order (NLO) in QCD are widely available, and the precision of higher-order QCD calculations has already reached the next- to-next-to-leading order (NNLO) for $pp \rightarrow V + 1$ jet

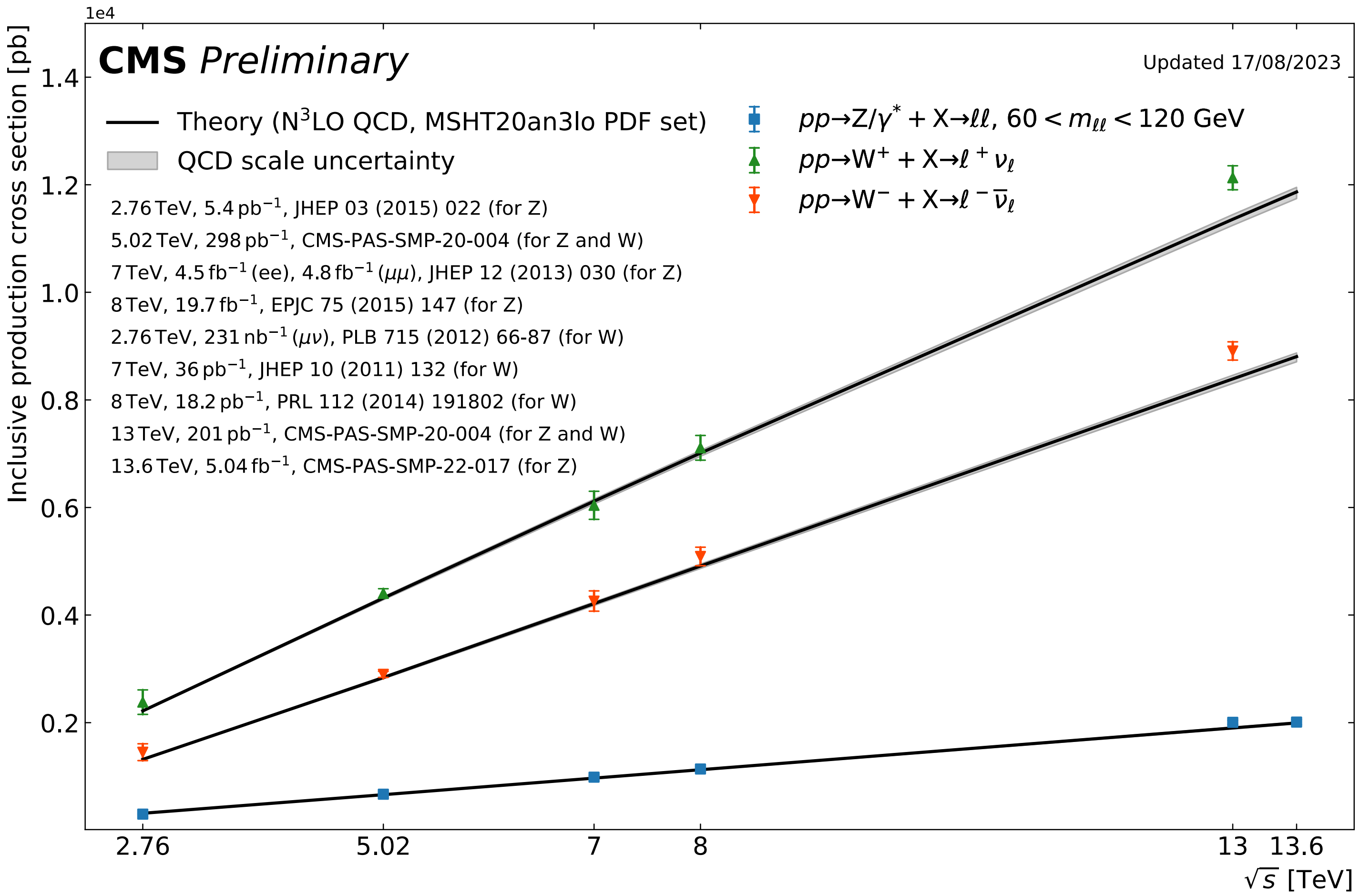
THEORY

- In the current version of understanding the Standard Model , we have the V+ jet productions as beeing the ones produced by the W and Z decaying into leptons and photons jets.
- In CMS we have measurements from the two regions of rapidity namely:
  - $|\eta| < 1.5$
  - $1.5<|\eta|< 2.5$



CMS current W and Z cross-section measurements as a function of center-of-mass energy

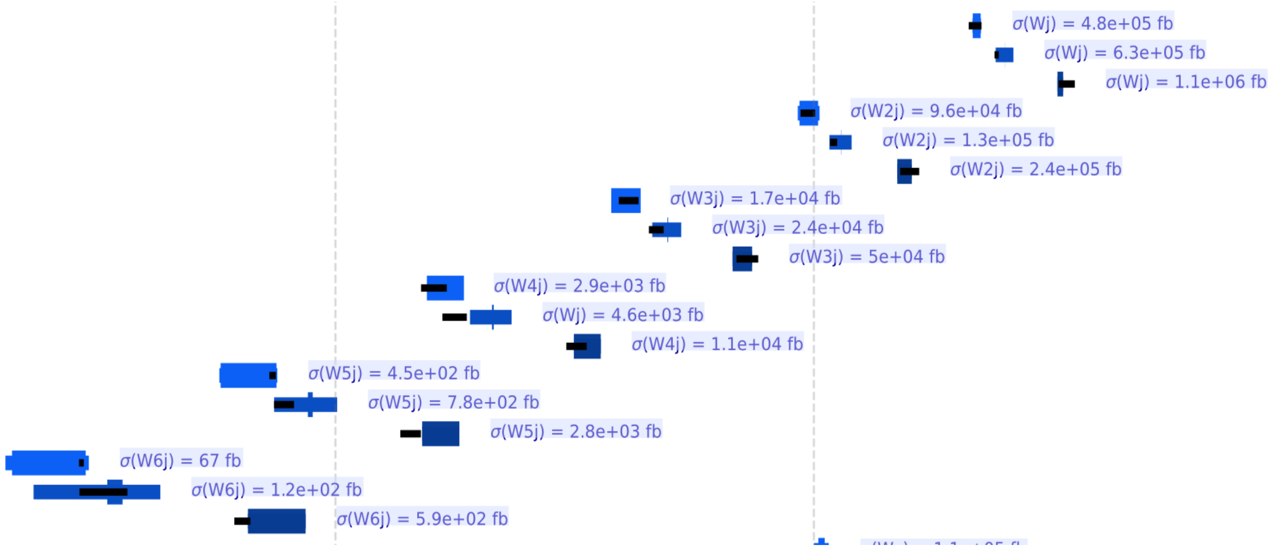
- This is what we have now
- W and Z boson inclusive cross-section measurements, compared with N3LO predictions
- Good agreement between the data and the model
- The LO , NLO, NNLO and NNNLO progress reported in
- https://arxiv.org/pdf/2209.06138.pdf

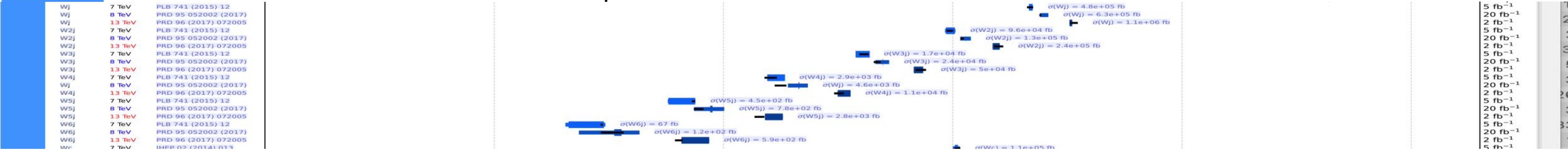


CMS X+Jets cross section results → *WJ*

$3\ \mu b^{-1}$ - $138\ fb^{-1}$ (2.76,5.02,7,8,13,13.6 TeV)

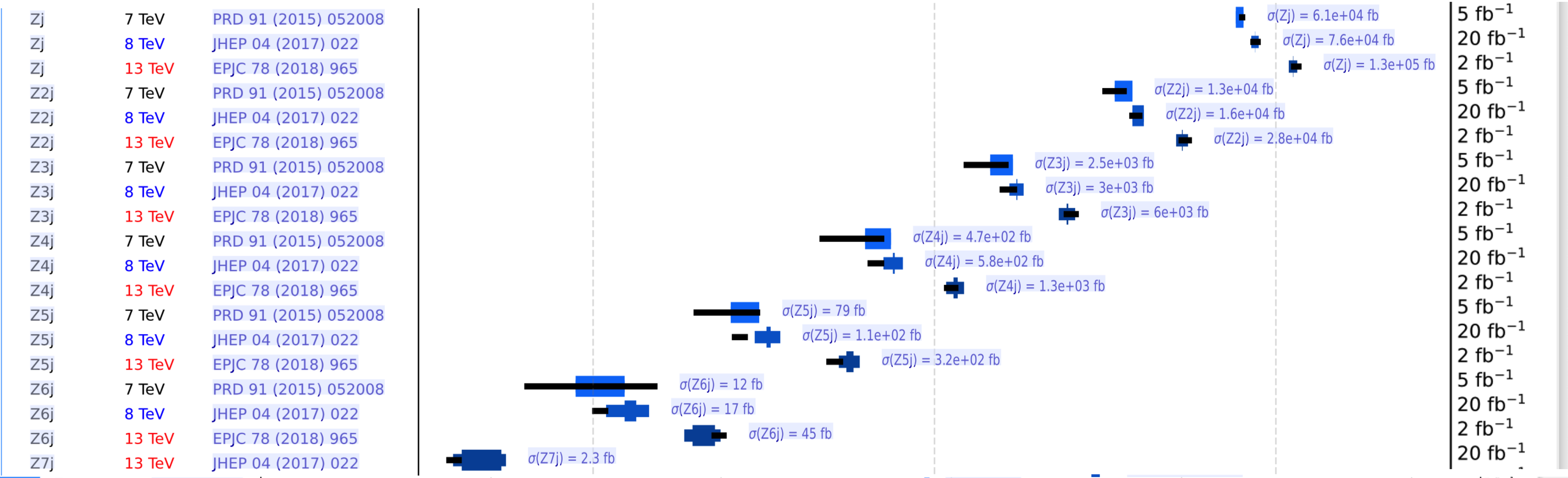
Wj	7 TeV	PLB 741 (2015) 12	$5\ fb^{-1}$
Wj	8 TeV	PRD 95 052002 (2017)	$20\ fb^{-1}$
Wj	13 TeV	PRD 96 (2017) 072005	$2\ fb^{-1}$
W2j	7 TeV	PLB 741 (2015) 12	$5\ fb^{-1}$
W2j	8 TeV	PRD 95 052002 (2017)	$20\ fb^{-1}$
W2j	13 TeV	PRD 96 (2017) 072005	$2\ fb^{-1}$
W3j	7 TeV	PLB 741 (2015) 12	$5\ fb^{-1}$
W3j	8 TeV	PRD 95 052002 (2017)	$20\ fb^{-1}$
W3j	13 TeV	PRD 96 (2017) 072005	$2\ fb^{-1}$
W4j	7 TeV	PLB 741 (2015) 12	$5\ fb^{-1}$
Wj	8 TeV	PRD 95 052002 (2017)	$20\ fb^{-1}$
W4j	13 TeV	PRD 96 (2017) 072005	$2\ fb^{-1}$
W5j	7 TeV	PLB 741 (2015) 12	$5\ fb^{-1}$
W5j	8 TeV	PRD 95 052002 (2017)	$20\ fb^{-1}$
W5j	13 TeV	PRD 96 (2017) 072005	$2\ fb^{-1}$
W6j	7 TeV	PLB 741 (2015) 12	$5\ fb^{-1}$
W6j	8 TeV	PRD 95 052002 (2017)	$20\ fb^{-1}$
W6j	13 TeV	PRD 96 (2017) 072005	$2\ fb^{-1}$

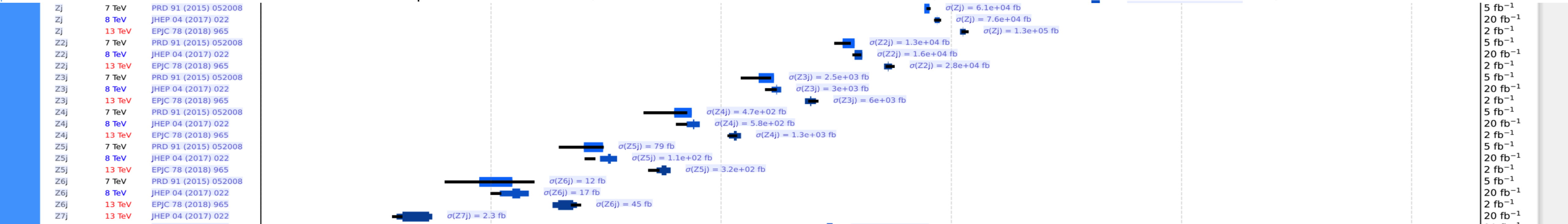




CMS X+Jets cross section results → *ZJ*

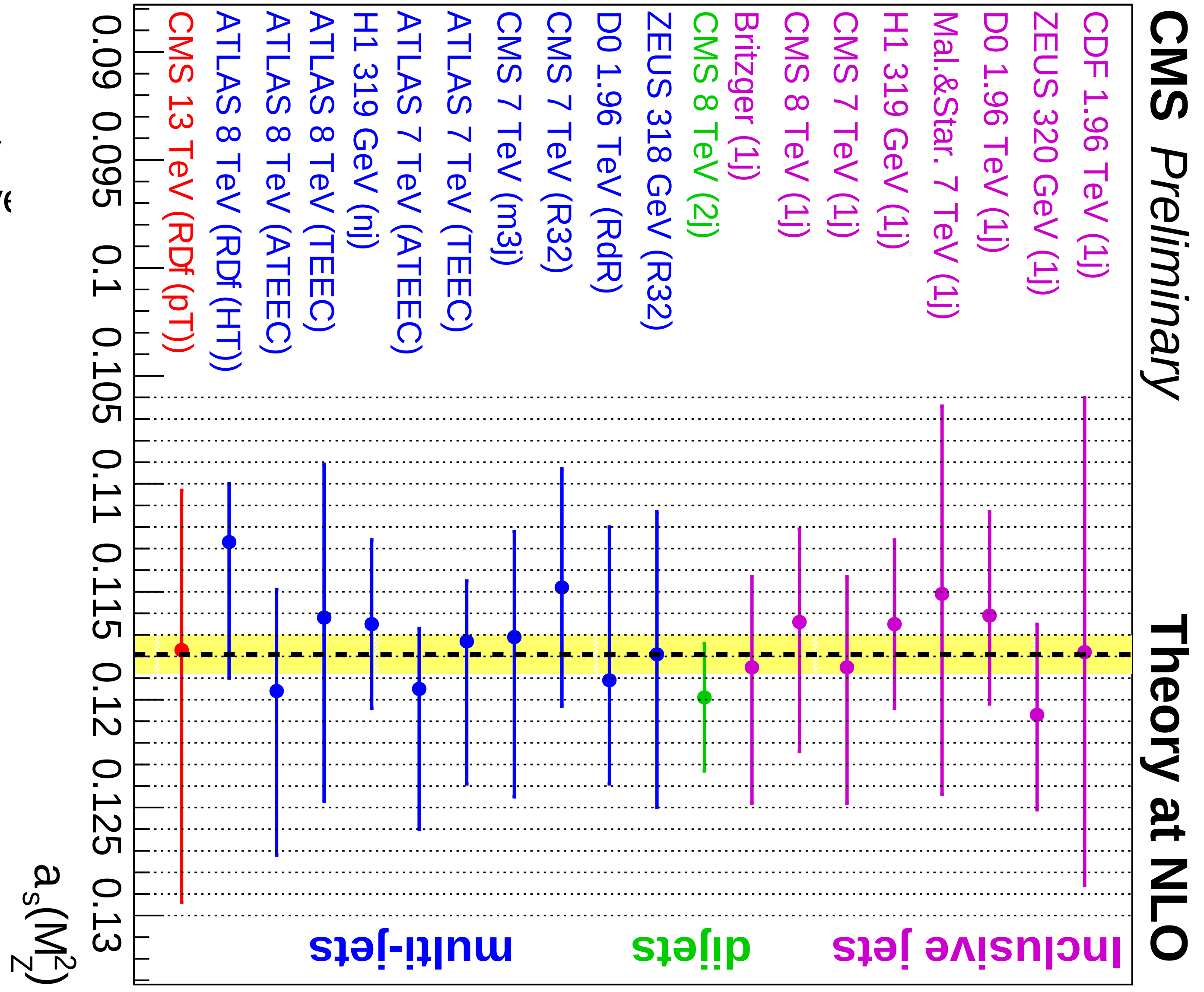
$3\ \mu b^{-1}$ - $138\ fb^{-1}$ (2.76,5.02,7,8,13,13.6 TeV)



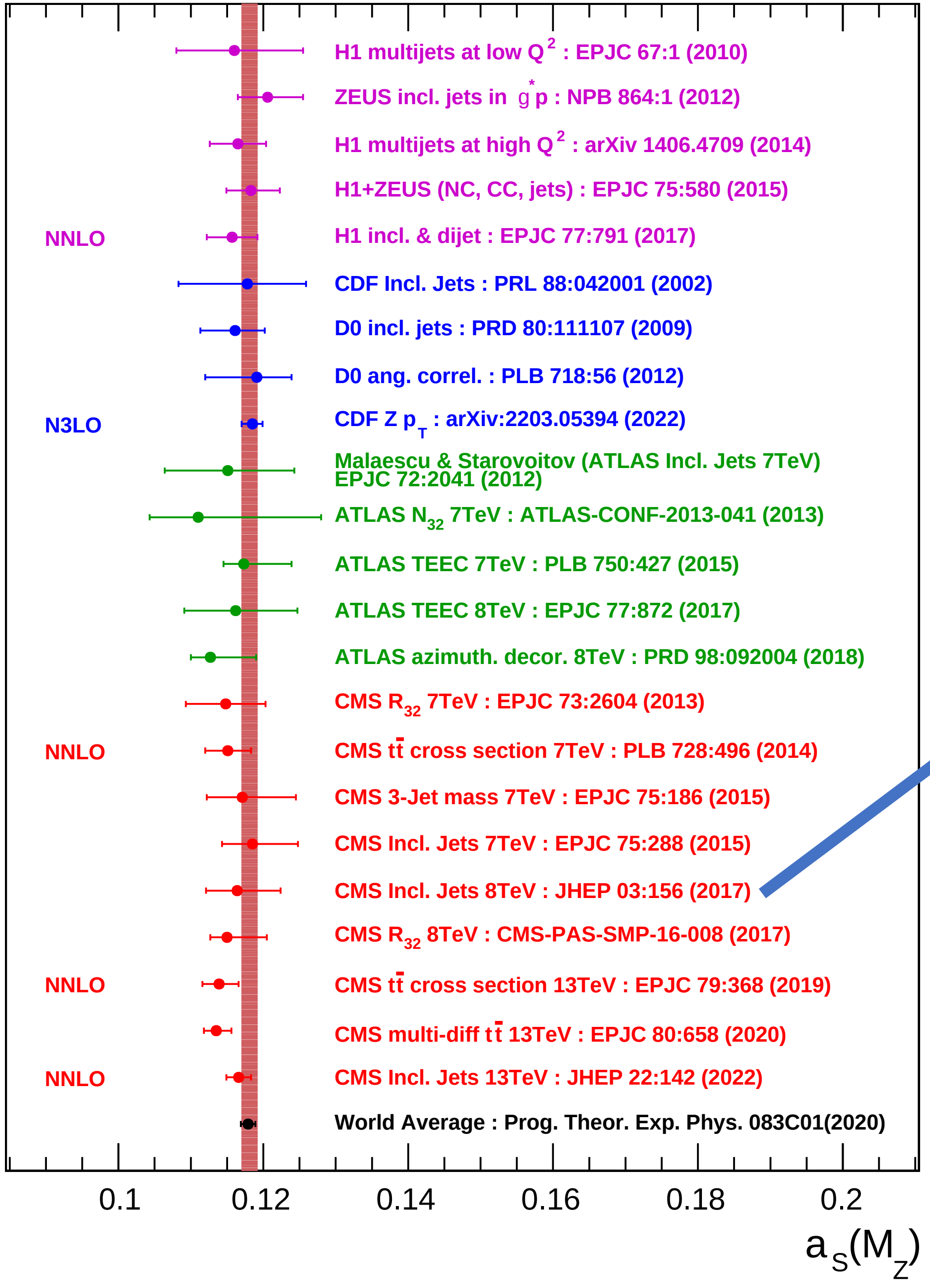


Measurements of alphaS at NLO

The world-average α_SS (MZ) value is represented by vertical dashed black line and its uncertainty by the ye band.



Measurements of alphaS at NNLO



$\lvert y \rvert$ bin	Fitted $\alpha_S(M_Z)$	PDF unc.	scale unc.	NP unc.	exp unc.	$\chi^2_{\min}/N_{\text{Bins}}$
0.0–0.5	0.1155	$^{+0.0027}_{-0.0027}$	$^{+0.0070}_{-0.0026}$	$^{+0.0003}_{-0.0003}$	$^{+0.0025}_{-0.0025}$	48.6/37
0.5–1.0	0.1156	$^{+0.0025}_{-0.0026}$	$^{+0.0069}_{-0.0026}$	$^{+0.0003}_{-0.0003}$	$^{+0.0026}_{-0.0025}$	28.4/37
1.0–1.5	0.1177	$^{+0.0024}_{-0.0026}$	$^{+0.0062}_{-0.0027}$	$^{+0.0002}_{-0.0002}$	$^{+0.0024}_{-0.0026}$	19.3/36
1.5–2.0	0.1163	$^{+0.0025}_{-0.0029}$	$^{+0.0040}_{-0.0019}$	$^{+0.0002}_{-0.0002}$	$^{+0.0023}_{-0.0027}$	65.6/32
2.0–2.5	0.1164	$^{+0.0020}_{-0.0022}$	$^{+0.0046}_{-0.0024}$	$^{+0.0002}_{-0.0002}$	$^{+0.0019}_{-0.0022}$	38.3/25
2.5–3.0	0.1158	$^{+0.0029}_{-0.0030}$	$^{+0.0049}_{-0.0025}$	$^{+0.0006}_{-0.0006}$	$^{+0.0036}_{-0.0038}$	14.3/18
Combined	0.1164	$^{+0.0025}_{-0.0029}$	$^{+0.0053}_{-0.0028}$	$^{+0.0001}_{-0.0001}$	$^{+0.0014}_{-0.0015}$	186.5/185

Table 4. Results for $\alpha_S(M_Z)$ extracted using the CT10 NLO PDF set. The fitted value for each $\lvert y \rvert$ bin; the corresponding uncertainty components due to PDF, scale, and nonperturbative corrections; and the total experimental uncertainty is shown. The last row of the table shows the results of combined fitting of all the $\lvert y \rvert$ bins simultaneously.

http://link.springer.com/article/10.1007%2FJHEP03%282017%29156

Precision QED and Electroweak measurements as a preparation for new physics

- This talk is based on CMS paper

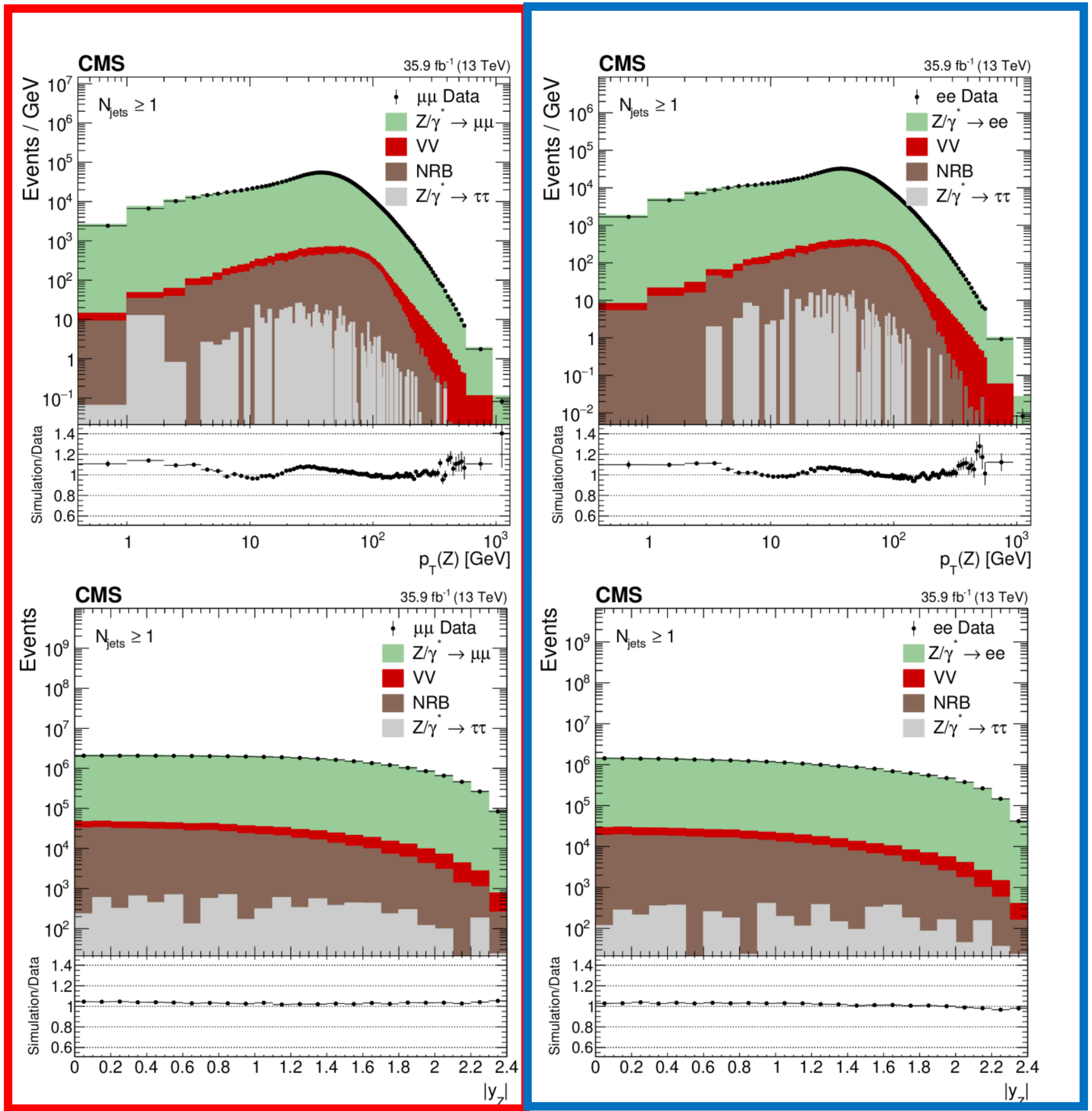
Measurement of differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at =13 TeV
CMS Collaboration , May 5-th 2022

Accepted for publication in Phys. Rev. D
https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-19-009/index.html

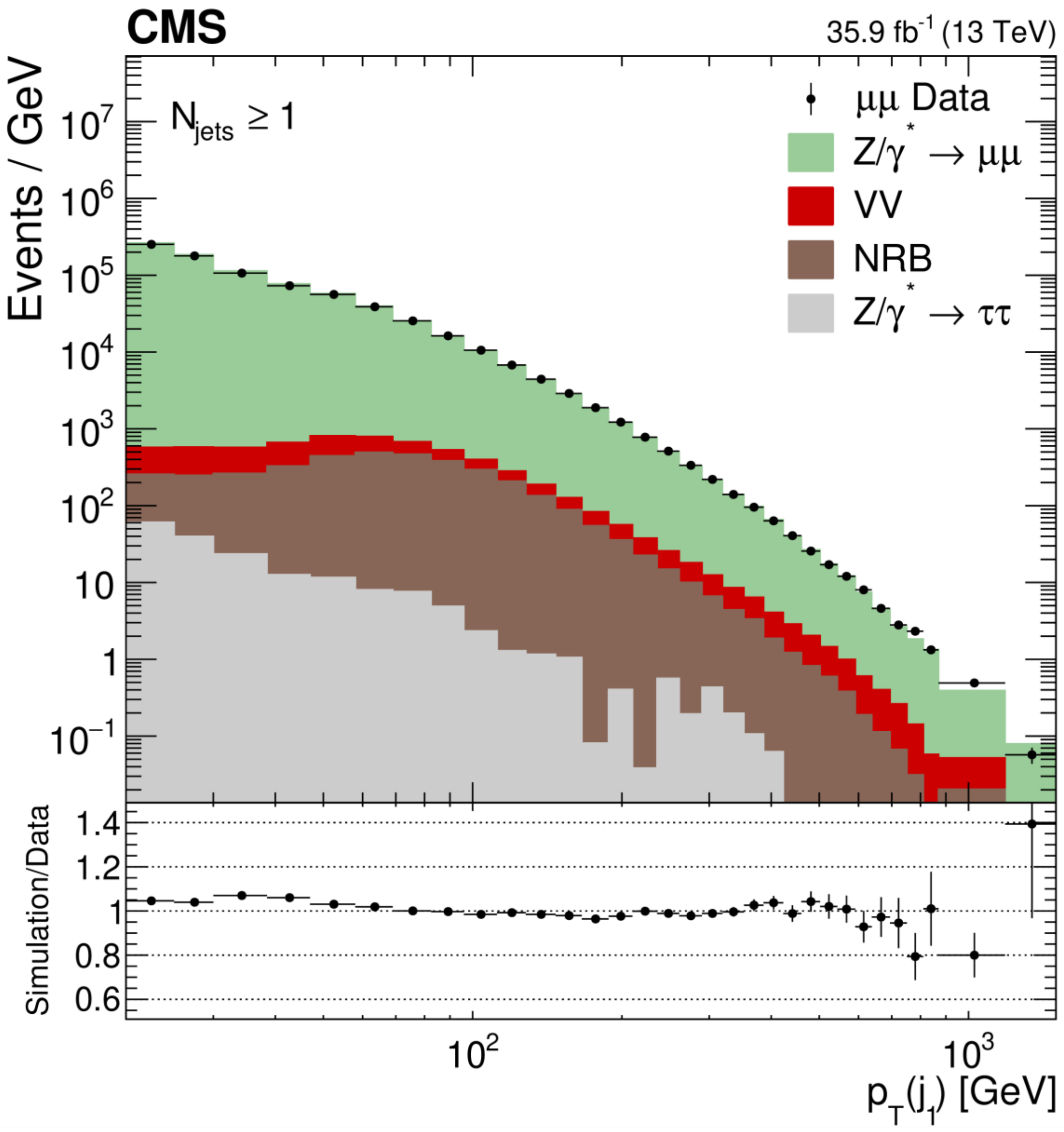
Previous overview presentations/analysis on V+Jets , done by E. Gallo DIS2022

The kinematics of Z and leading jet, measurements, and simulation results are shown.
VV→ di-boson EW production background samples
NRB → Non resonant background samples
Z/γ → τ τ → **considered background and estimated with MG5.aMC**

The Pt and rapidity spectra of Z candidates are very similar for the muon and electron channels

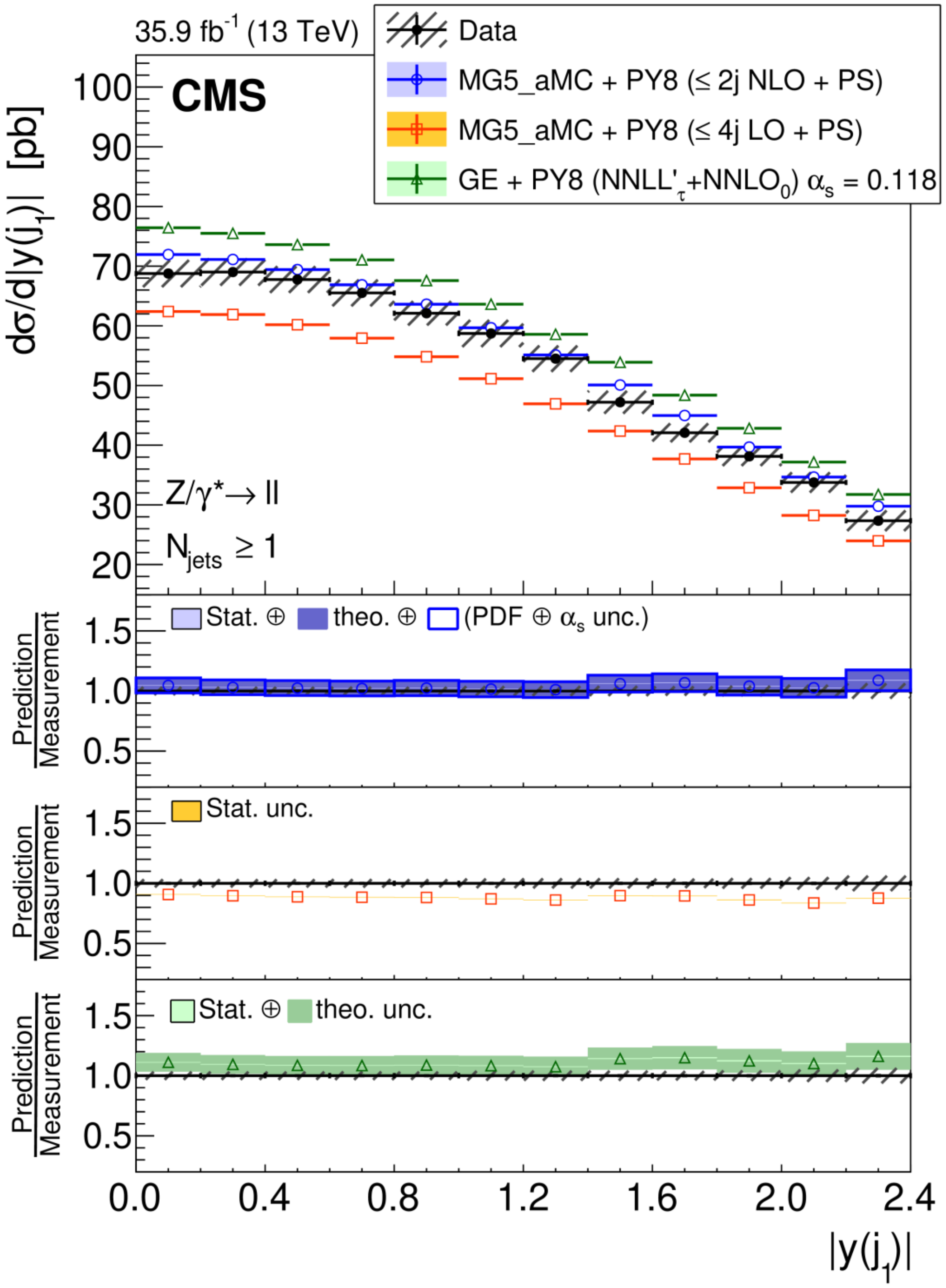


The jet P_t distribution is dominated by the Z signal.



Differential cross section vs rapidity of first jet

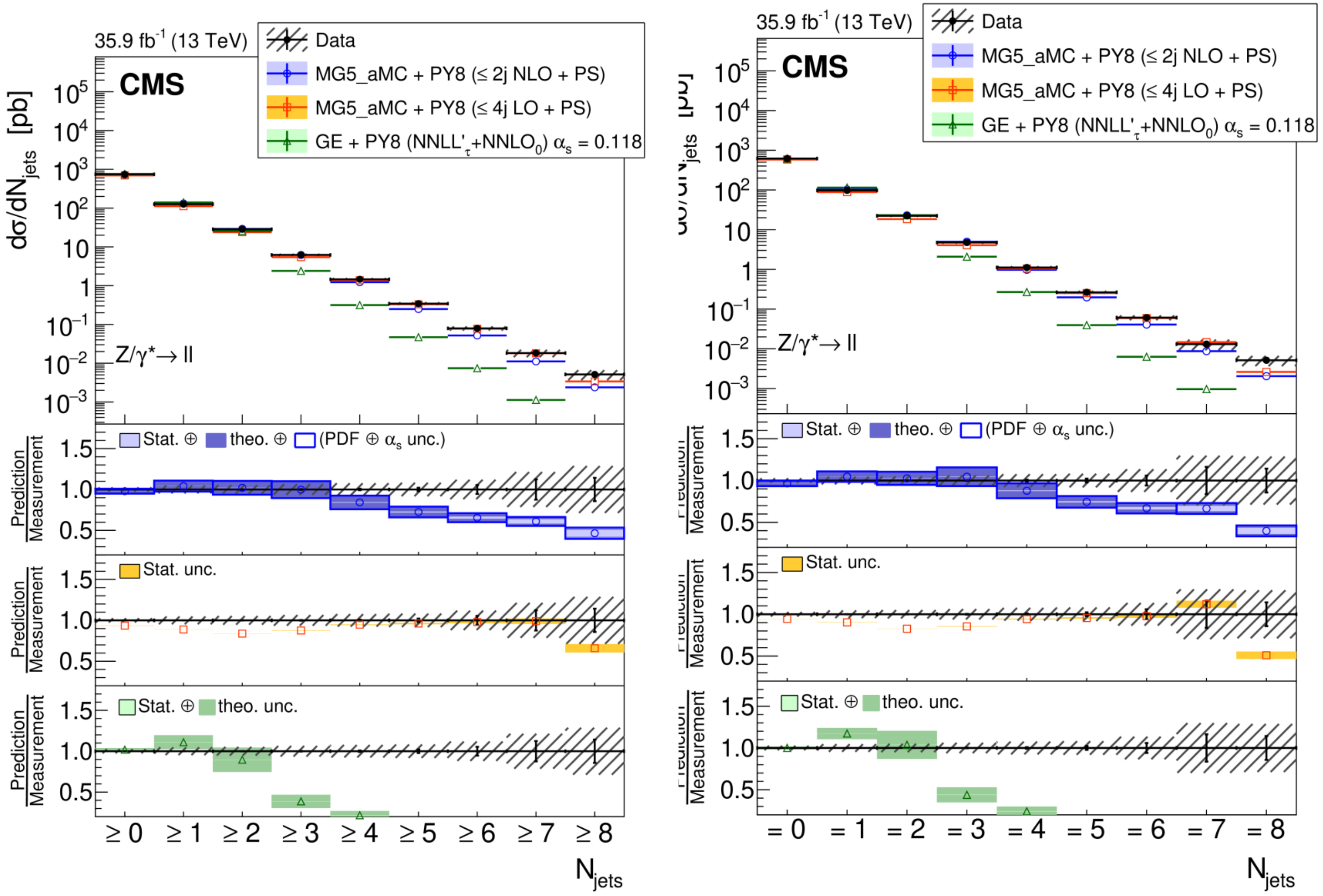
Next to leading order Madgraph5_AMC does better than the leading order calculation or the Geneva model



Z yield vs number of jets for data and MCs

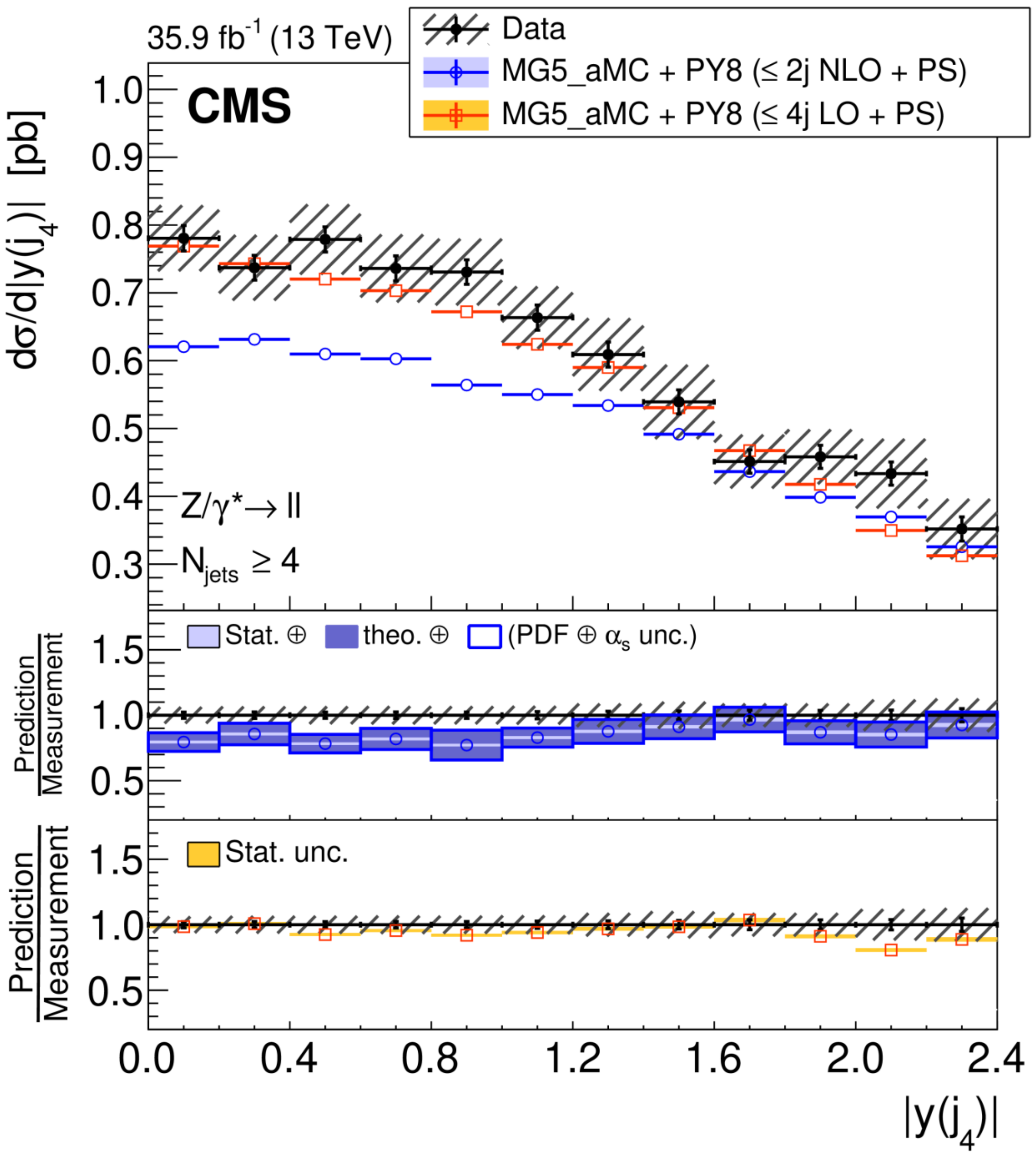
Measured cross sections vs nr of jet (up to 8)
The trend of jet multiplicity is good for exclusive distributions but…

Geneva generator unable to predict multijet cross section because due to lack of hard jets at ME level beyond 2 jets

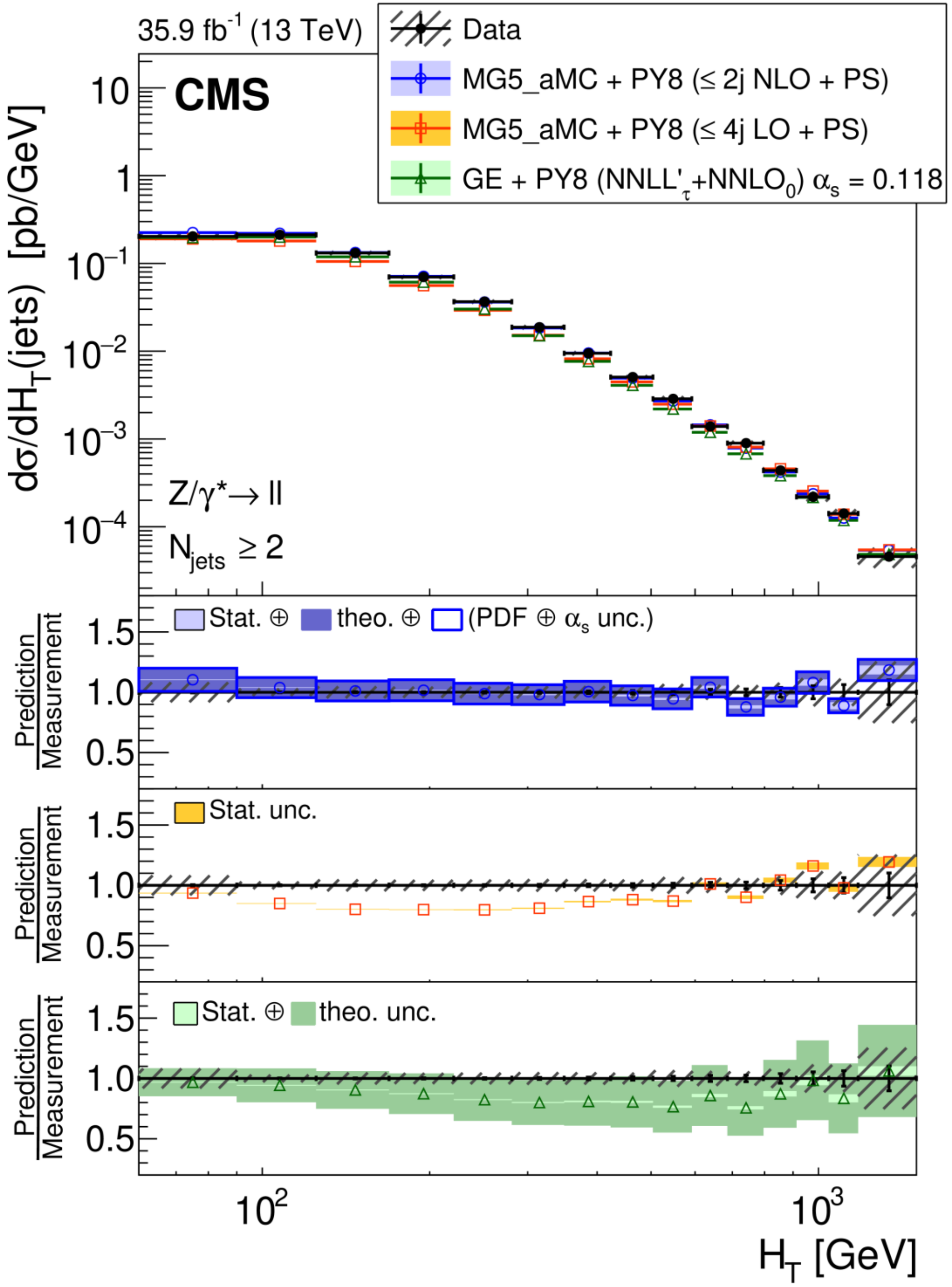


Differential cross section vs rapidity of 4th jet

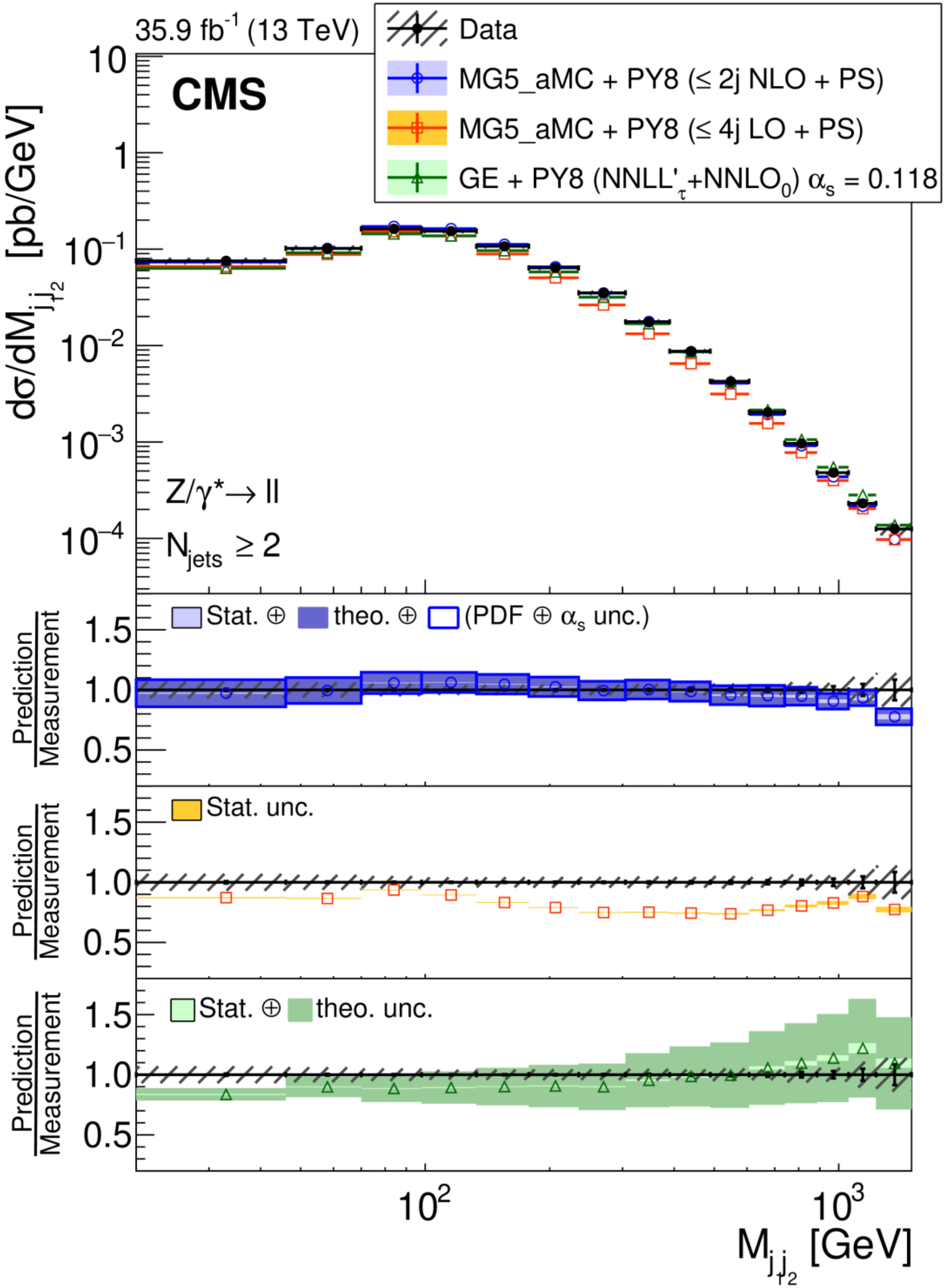
For 4 jets NLO calculation is off.



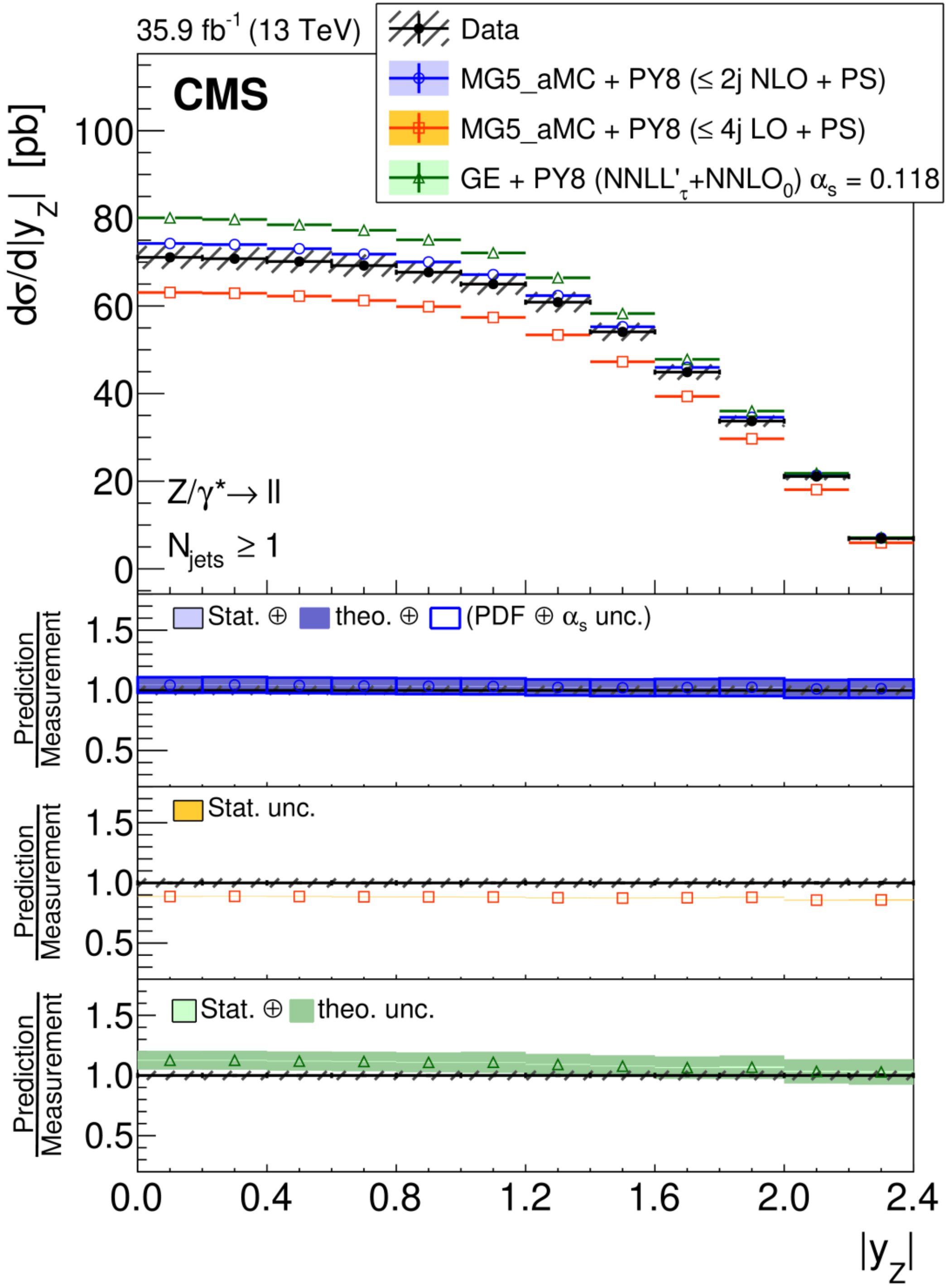
Generators can describe cross section as a function of the H_T ie the scaler sum of the jet P_{T}.



Models also describe dependence upon dijet mass

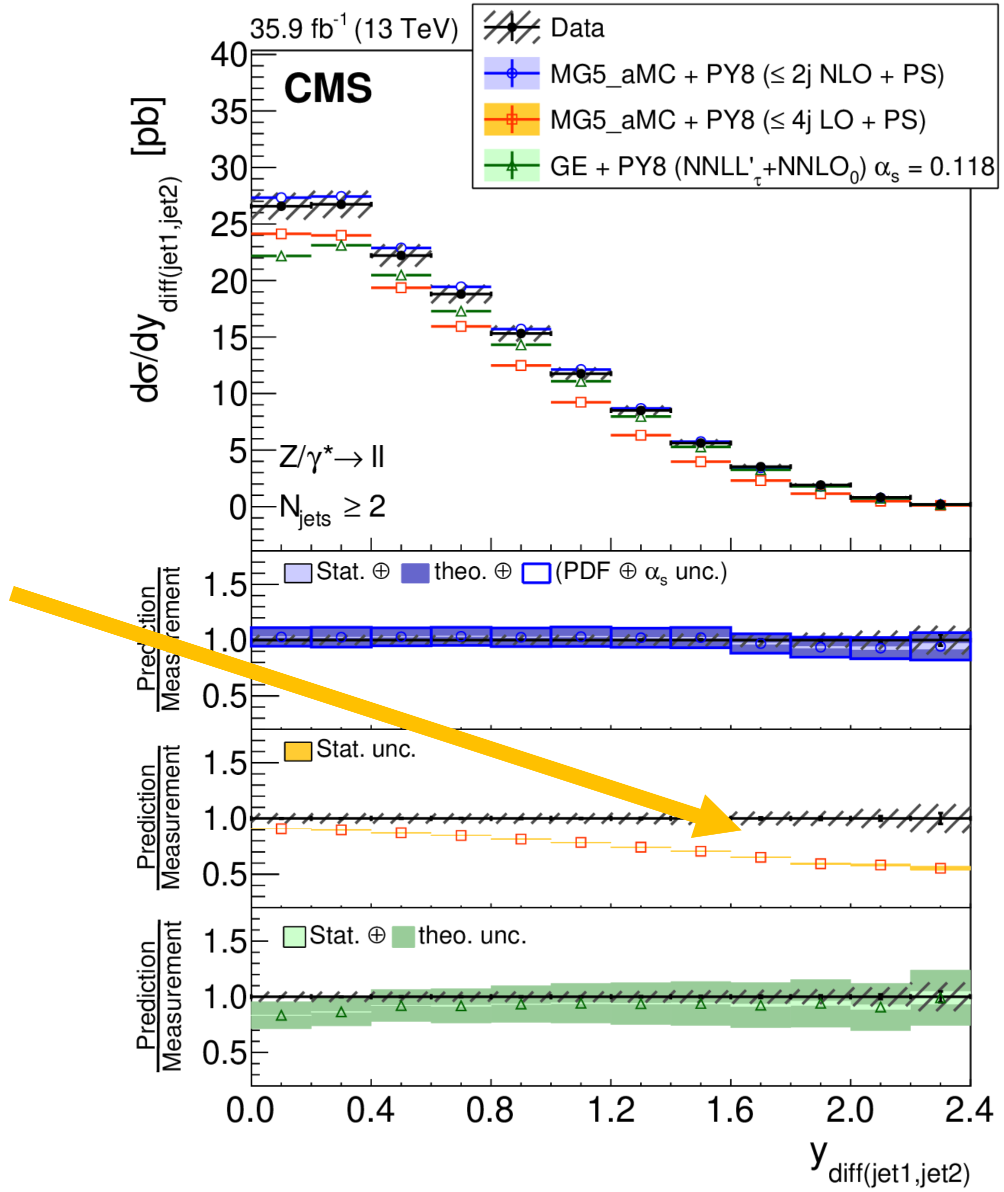


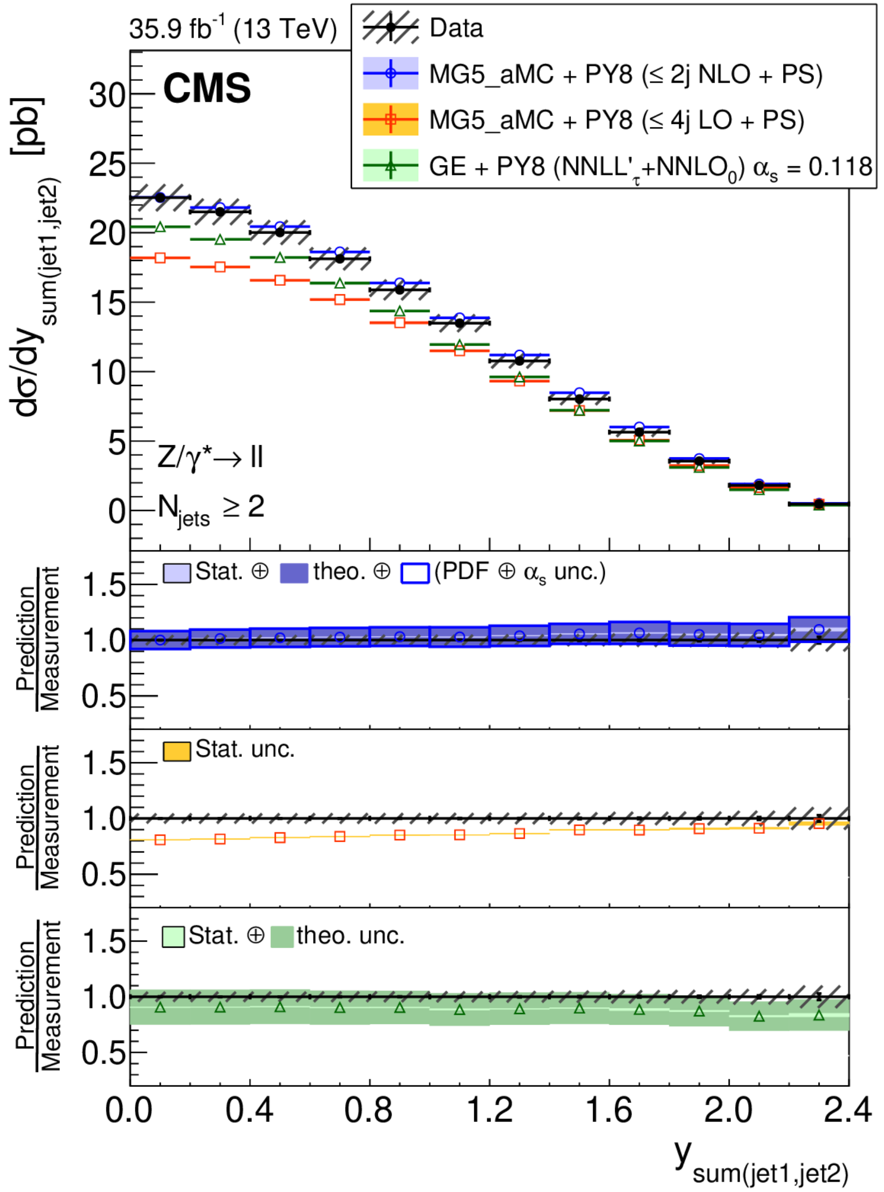
Agreement with rapidity of Z is excellent.



NNLO describes di-jet rapidity difference and sum

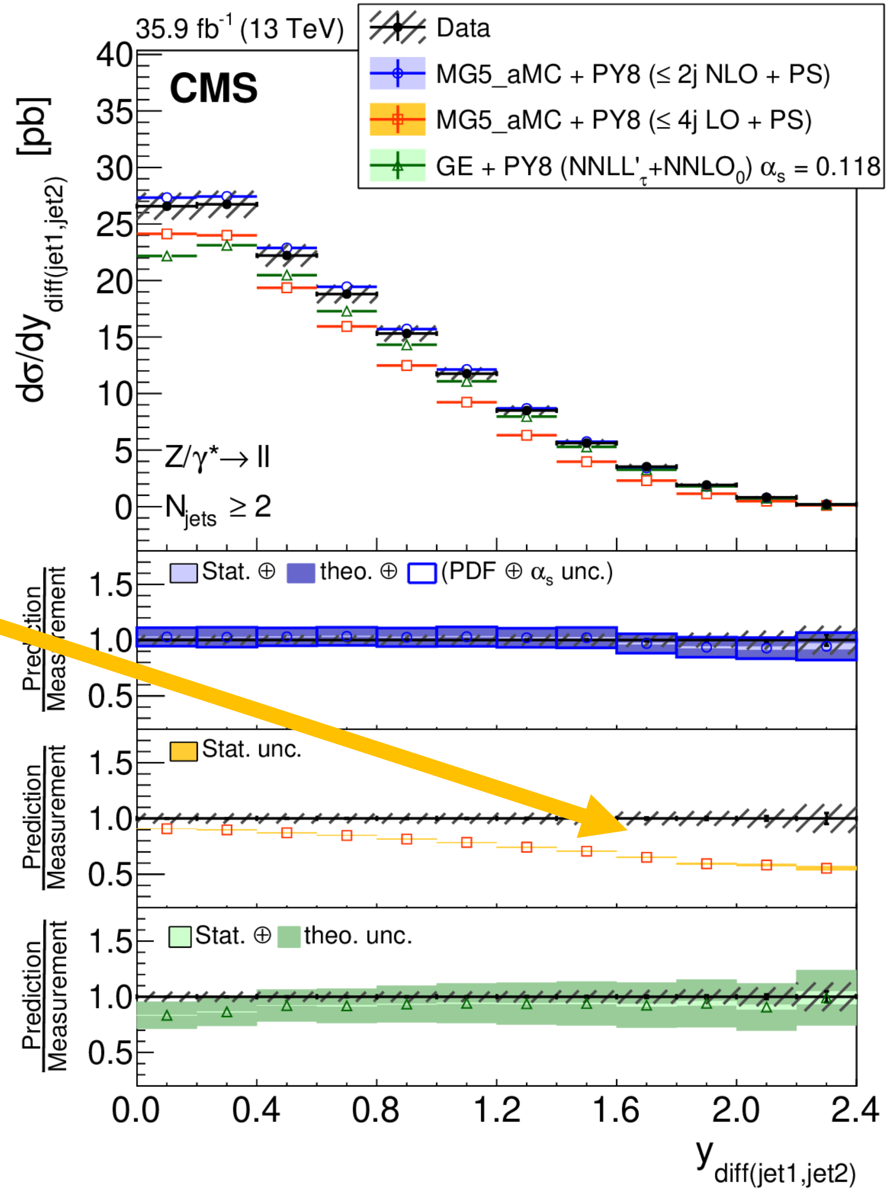
NLO has problems

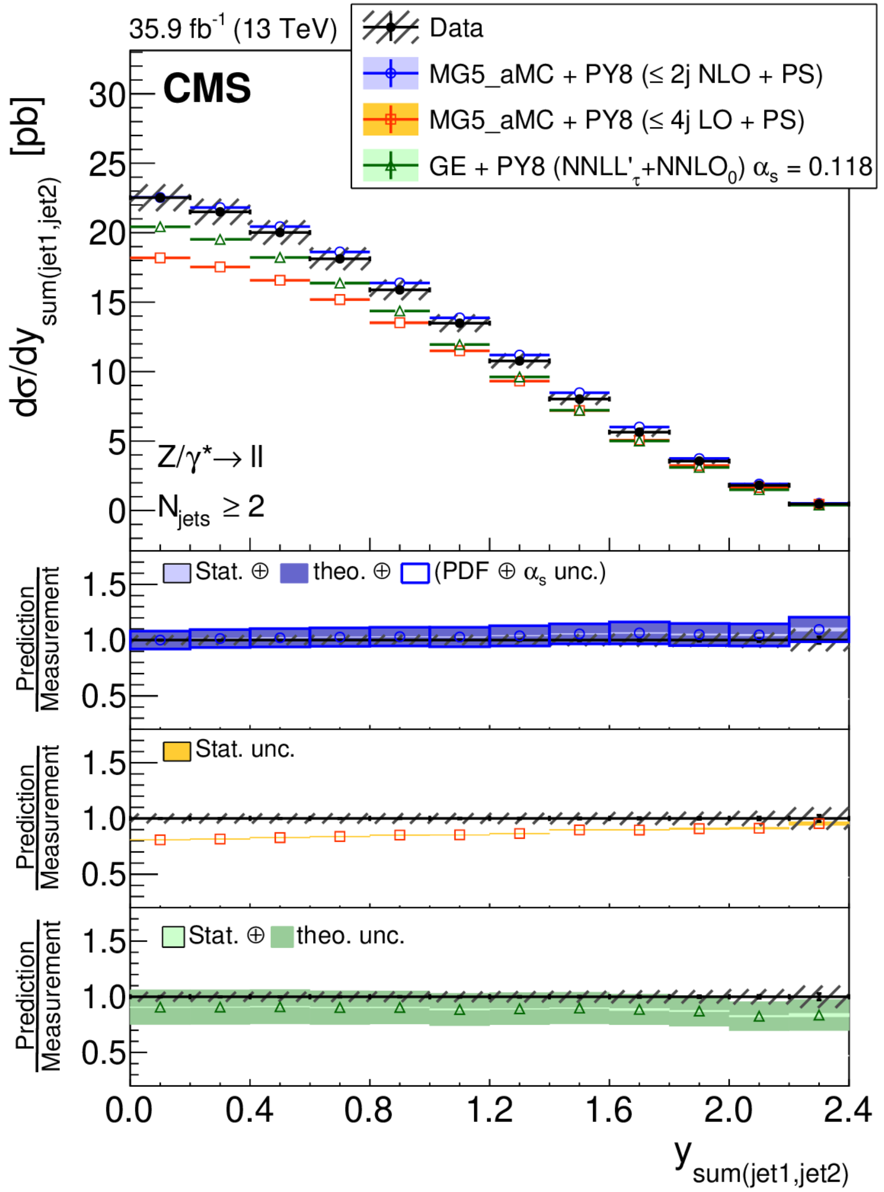




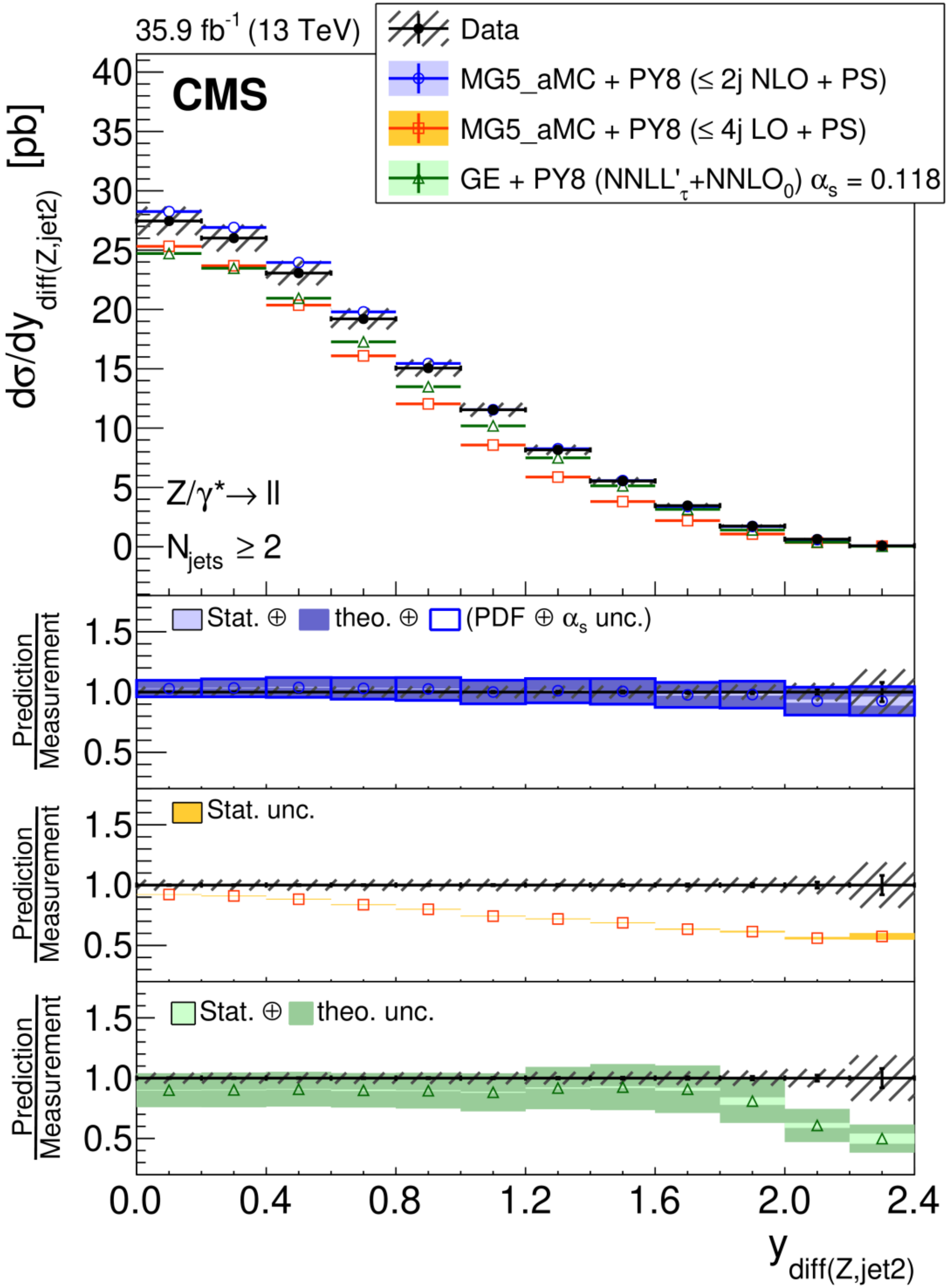
Difference and sum of rapidities of Z and leading jet.

NLO has problems

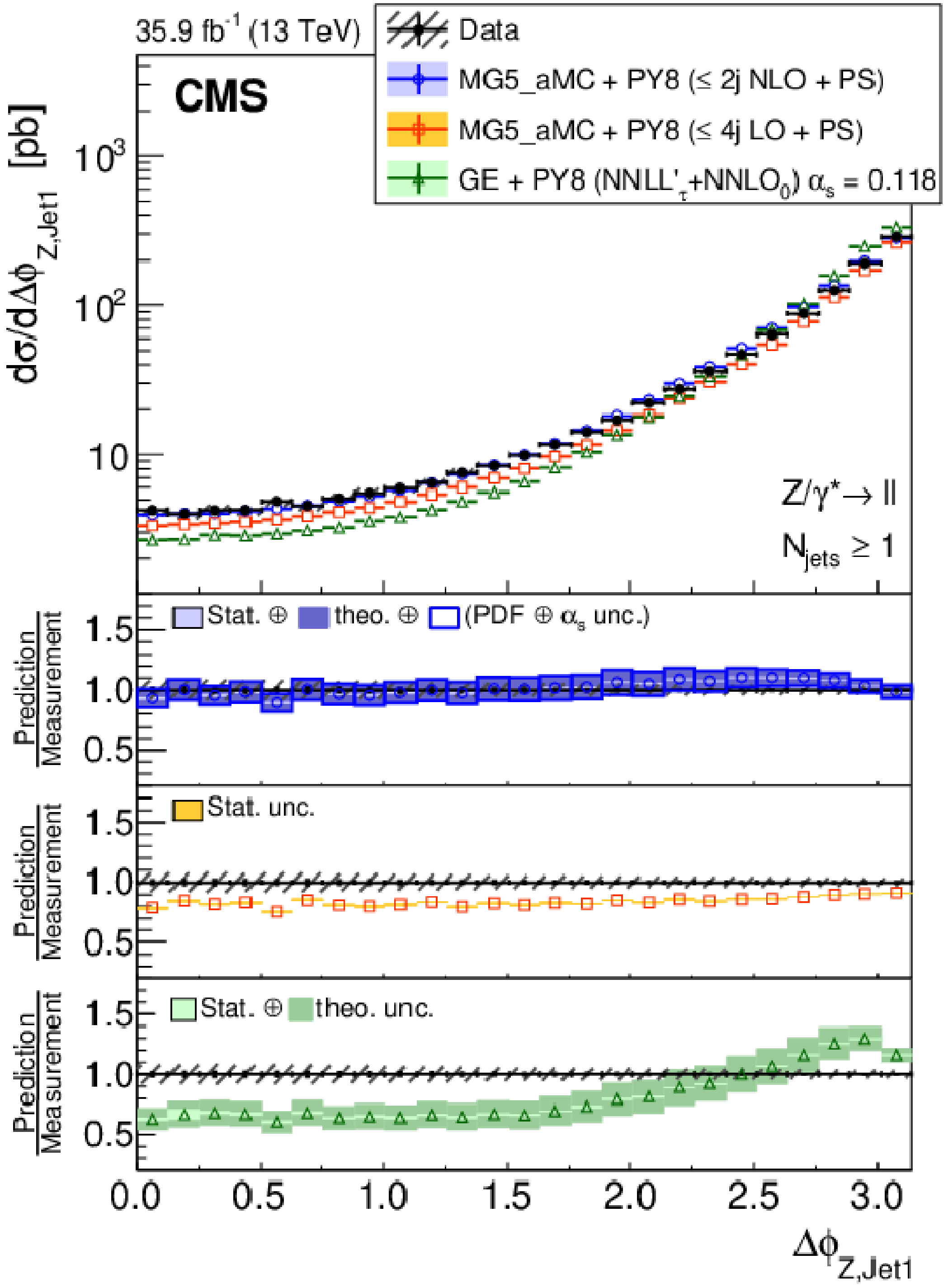




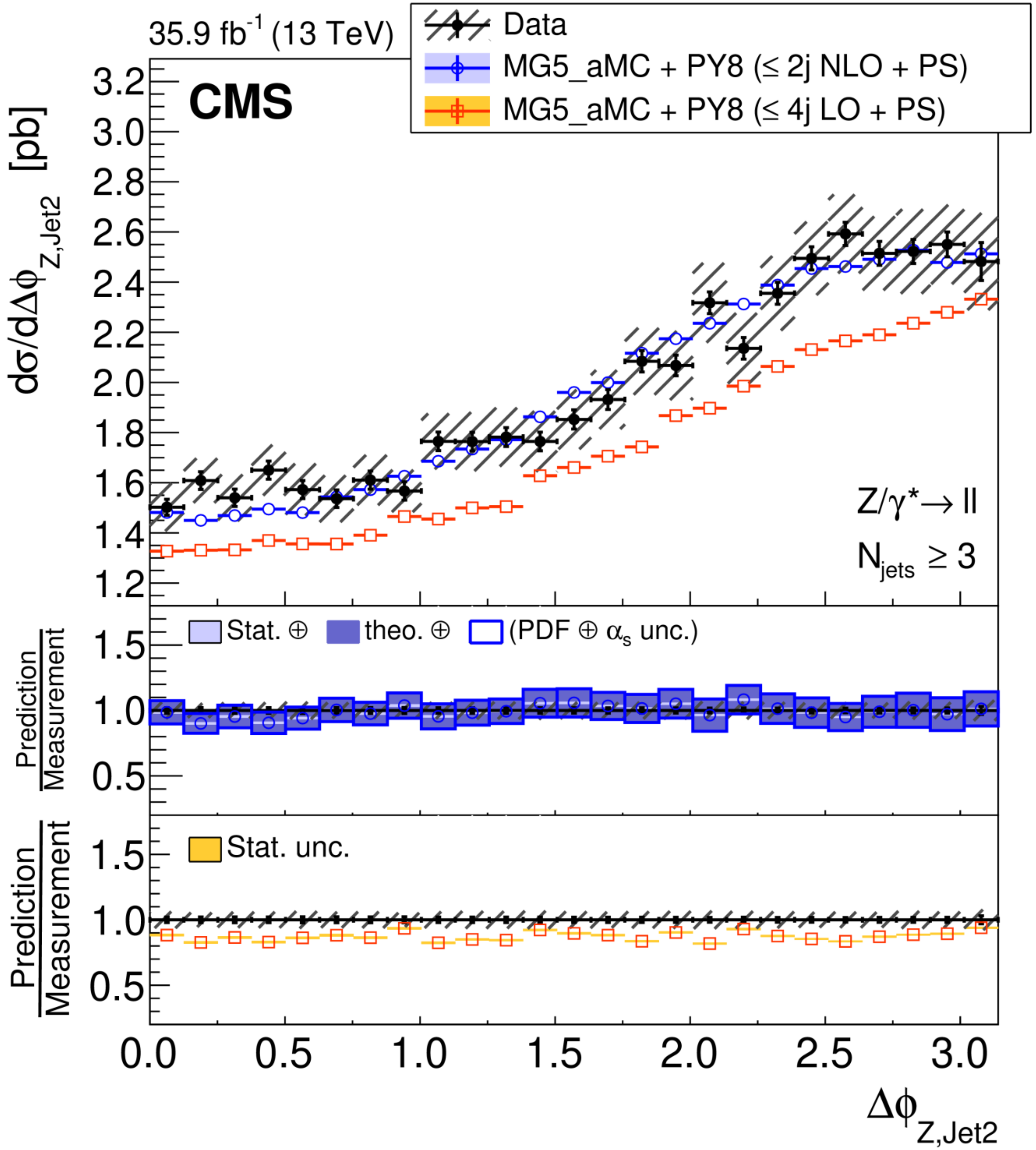
We see a similar level of agreement with the rapidity difference between the Z and the sub-leading jet.



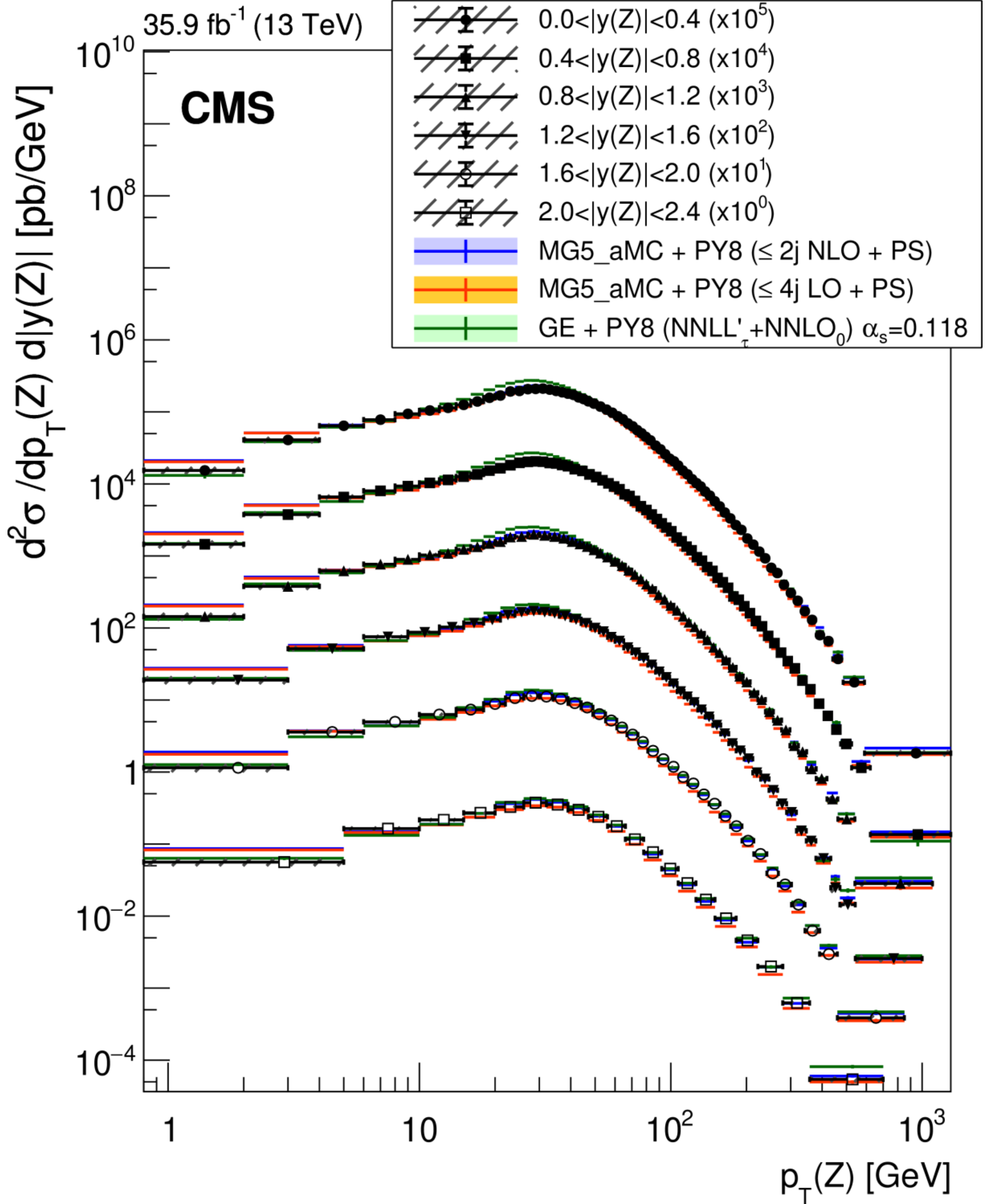
For events with Njet>1 we have a good description of the azimuthal angle between the Z and leading jet.



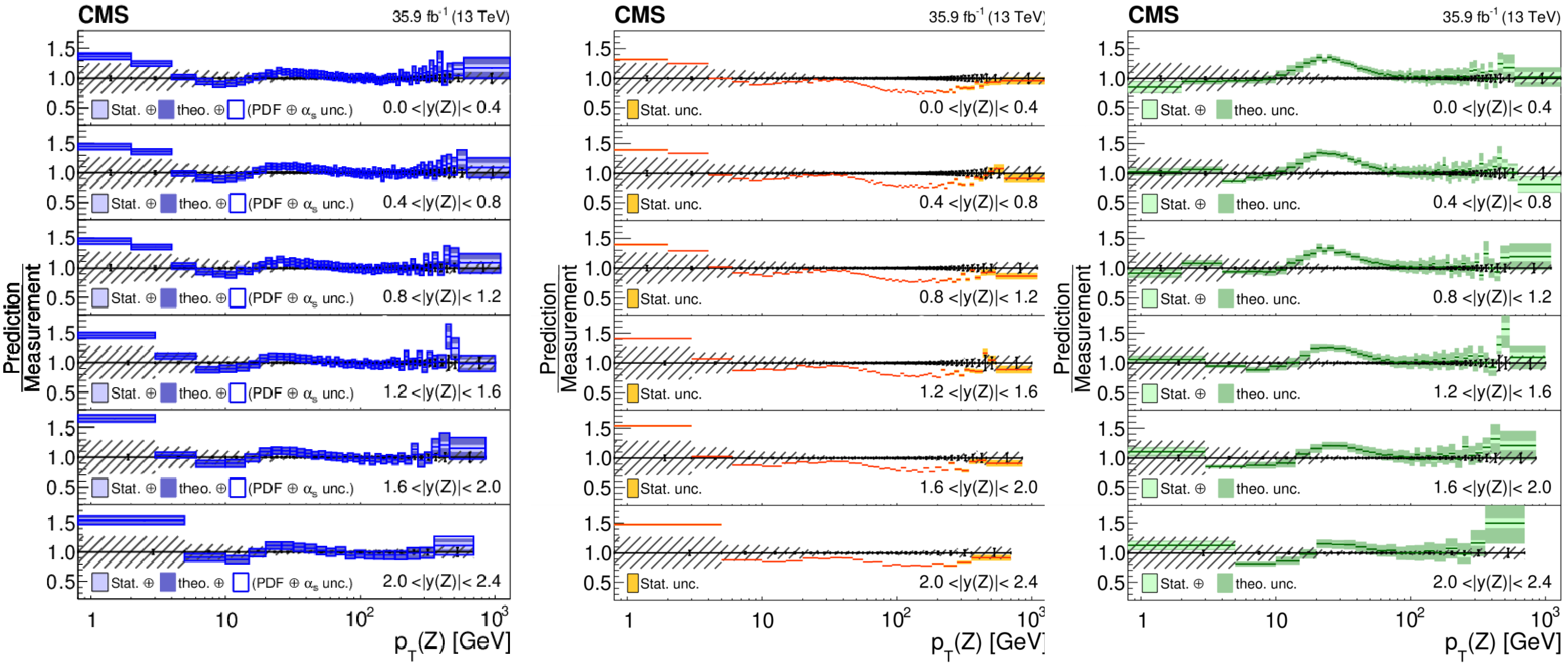
We see some discrepancies when we look at the angle between the Z and the subleading jet for events when we have more than 3 jets.



Double differential cross section vs p_T and rapidity of the Z



Generators general do a good job



Summary

CMS has measured differential cross sections for Z + Njets

NLO calculations generally accurately estimate the Z + jets contributions to new physics searches at the LHC.

Some deviations are observed for Njets > 3.

Such discrepancies offer the possibility of using these data to further improve the modeling

Back up

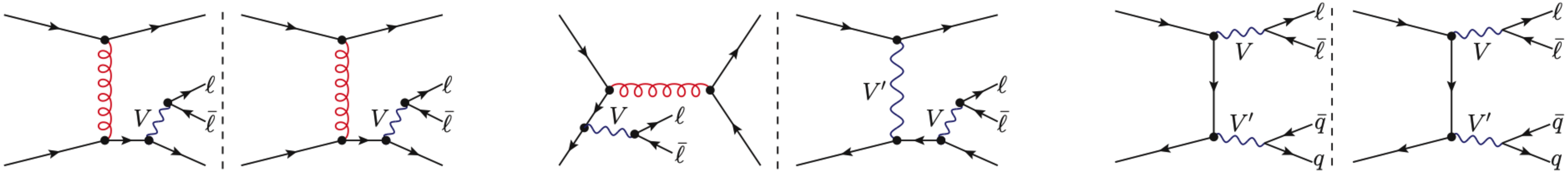
Simulations using Madgraph and Geneva

- We generated at next-to-leading order (NLO) with MADGRAPH5 aMC@NLO versions 2.2.2 and 2.3.2 (denoted MG5 aMC) using the FxFx merging scheme [24, 25].
- Parton showering and hadronization are simulated with PYTHIA 8 (using the CUETP8M1 tune [27].
- The matrix element includes Z boson production with up to two additional jets generated at NLO with MG5 aMC, effectively yielding leading order (LO) accuracy for Z+3 jets.
- GENEVA does a NNLO calculation for Drell–Yan production combined with higher-order
- resummation. Logs of the 0-jettiness resolution variable are resumed to including part of the next-to-NNLL corrections. The accuracy refers to the t dependence of the
- cross section and is denoted as NNLL0 t.

Not necessary – just as reminder

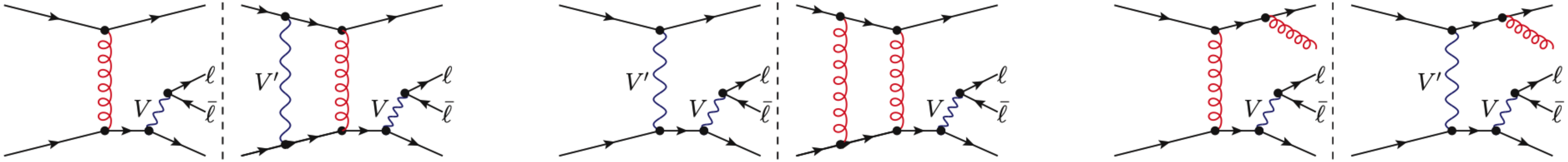
- EW corrections are especially relevant at the TeV scale, where large logarithms of Sudakov type can lead to NLO EW effects of tens of percent. While NLO predictions for electroweak-boson production in association with a single jet have been available for a while, thanks to the recent progress in NLO automation also V + multijet calculations at NLO EW became feasible.
- Various algorithms for the automated generation of one-loop scattering amplitudes have proven to possess the degree of flexibility that is required in order to address NLO EW calculations
- Predictions for vector-boson plus multijet production at NLO EW are motivated by the large impact of EW Sudakov effects on BSM signatures with multiple jets and, more generally, by the abundance of multijet emissions in pp → V + jets at high energy. First NLO EW predictions for vector-boson production in association with more than one jet have been presented for pp → l+l−jj and for on-shell W+-boson production with up to three associated jets at NLO QCD+EW . Independent NLO EW results for pp → W + 2 jets have been reported in.
- Independent NLO EW results for pp → W + 2 jets have been reported.
- Predictions can be obtained within the NLO QCD+EW framework , using the OpenLoops generator in combination with the Munich and Sherpa Monte Carlo programs.
- Off-shell effects in vector-boson decays can be fullyanalysed with the general implementation of the complex-mass scheme at NLO QCD+EW in Open- Loops.
- This is applicable to any process that involves the production and decay of intermediate electroweak vector bosons, top quarks and Higgs bosons.

reminder



(a) $\mathcal{O}(\alpha_S^2\alpha^2)$ LO (b) $\mathcal{O}(\alpha_S\alpha^3)$ LO mix (c) $\mathcal{O}(\alpha^4)$ LO EW

Figure 3. Representative LO, LO mix and LO EW contributions to $V + 2\,$jet production.



(a) Virtual $\mathcal{O}(\alpha_S^2\alpha^3)$ correction (b) Virtual $\mathcal{O}(\alpha_S^2\alpha^3)$ correction (c) Real $\mathcal{O}(\alpha_S^2\alpha^3)$ correction

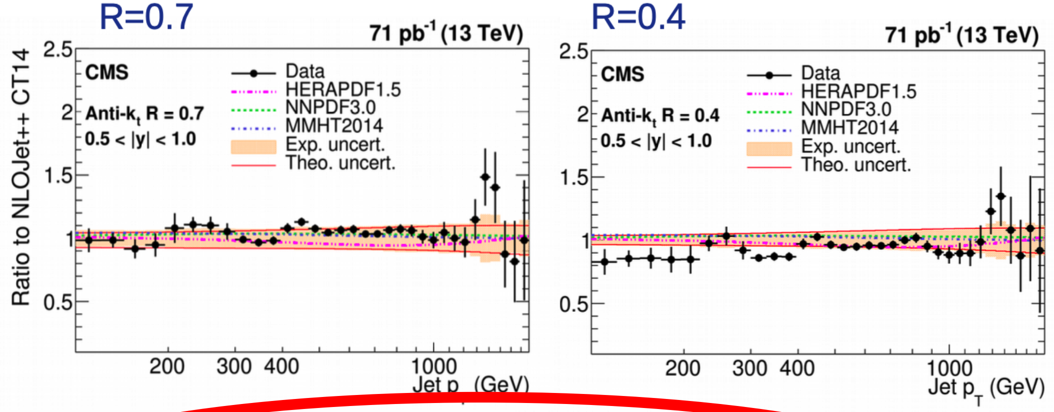
Figure 4. Representative virtual and real NLO EW contributions to $V + 2\,$jet production.

Example of analysis + simulation

p_T(jet)>114 GeV, anti-k_T R=0.4 and R=0.7 $\frac{d^2\sigma}{dp_T\,dy}$

NLO predictions (NLOJet++)

R=0.7 R=0.4

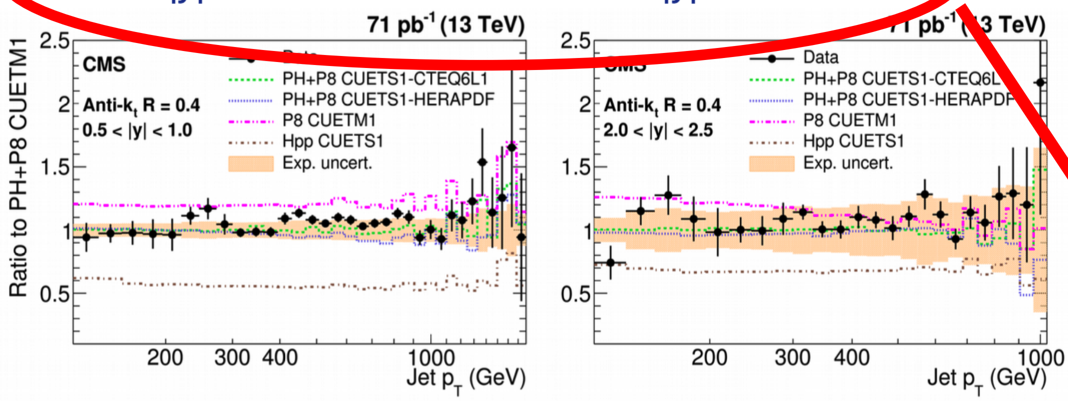


- R = 0.4 x-section overestimatec by about 5–10%
- R=0.7: better description

→ PS and soft-gluon resummation contributions, which are missing in fixed-order calculations are more relevant fo smaller jet cone sizes

comparison to MC generators

0.5<|y|<1.0 2.0<|y|<2.5



POWHEG+Pythia
good agreement
HERWIG++:
good in shape, poor in scale
Pythia 8
does describe shape for y<2.0

Confinement 2018, Maynooth, August 5, 2018 Katharina Müller

We will look in the same region
Curently we have data in

https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/CMSCrossSectionXJetsSummaryBarChart.pdf