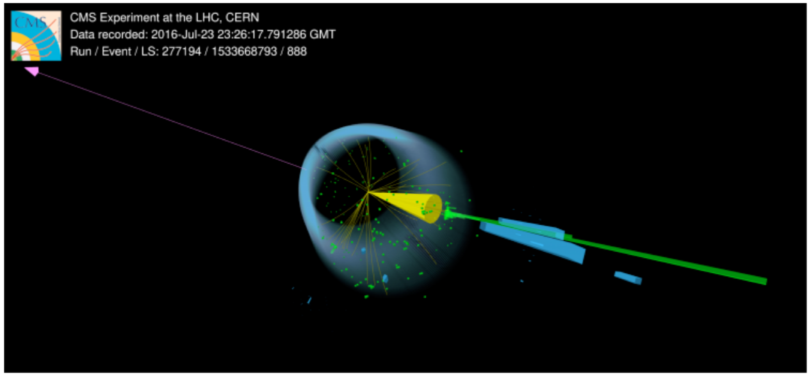
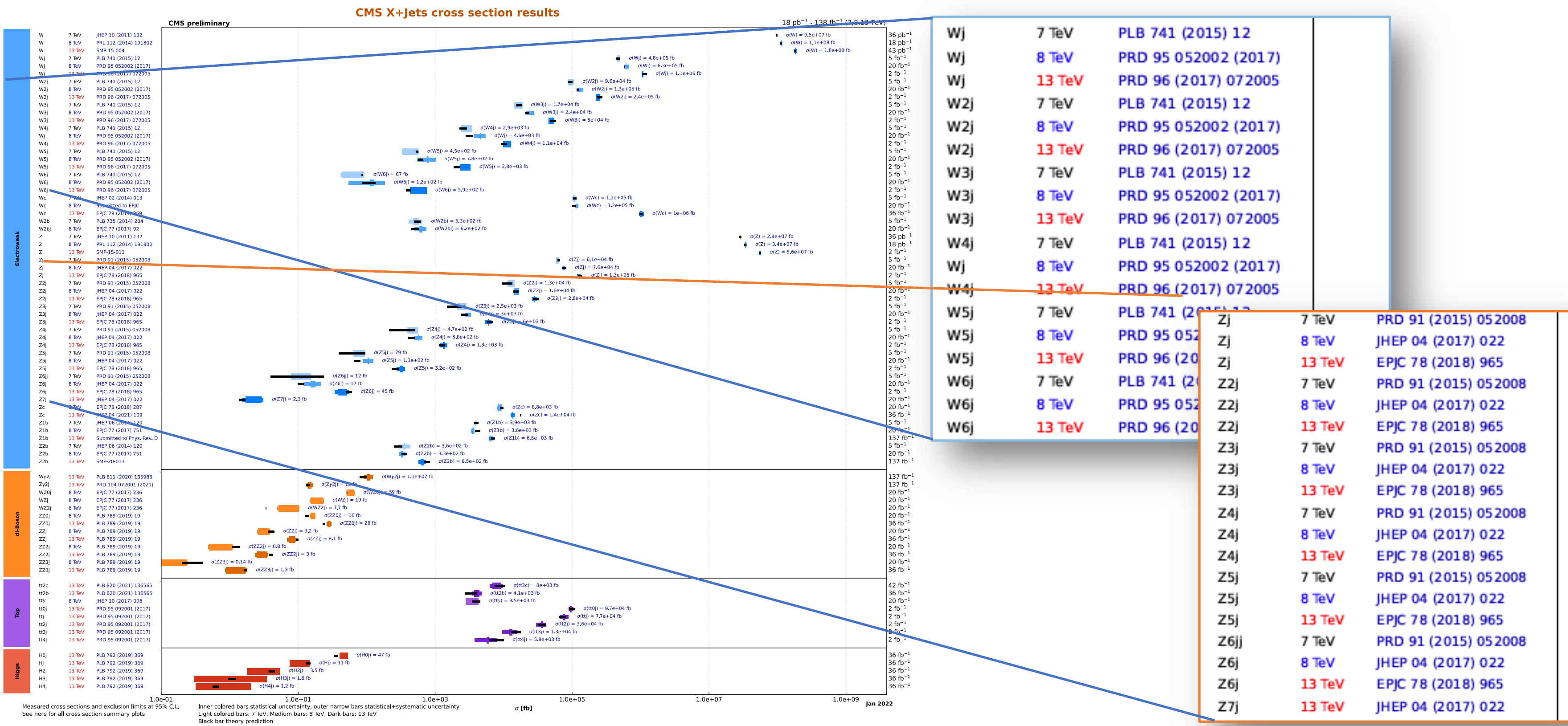
QCD aspects of V+jets in CMS

Elisabetta Gallo (DESY and UHH)
On behalf of the CMS Collaboration



V+jets at CMS

New compilation of SM cross sections for processes with jets

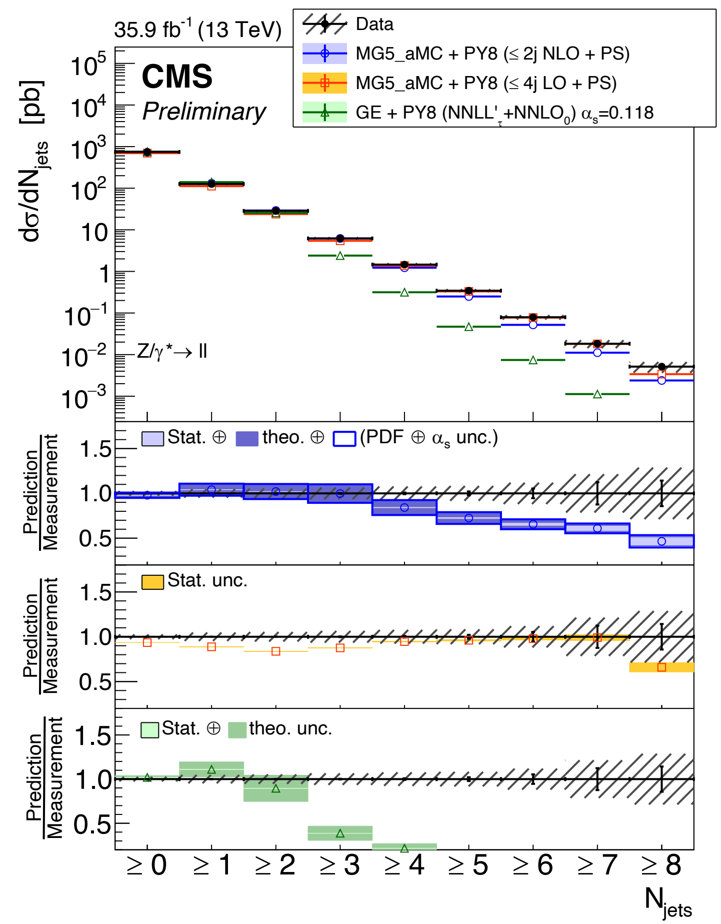


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

V+jets at CMS

Motivation for precise studies of V+jets at the LHC:

- Important input to MC and pQCD calculations
- Process for JEC calibration and background for many processes (i.e. Higgs associated W, Z production, SUSY and dark matter searches,..)
- Important input for PDF (especially V+heavy flavour, separate talk)
- Selection of newest results from the last year shown in the following slides, mainly based on 2016 data
- Z, W, γ+jets all measured at $\sqrt{s} = 13$ TeV, up to 8 jets for Z



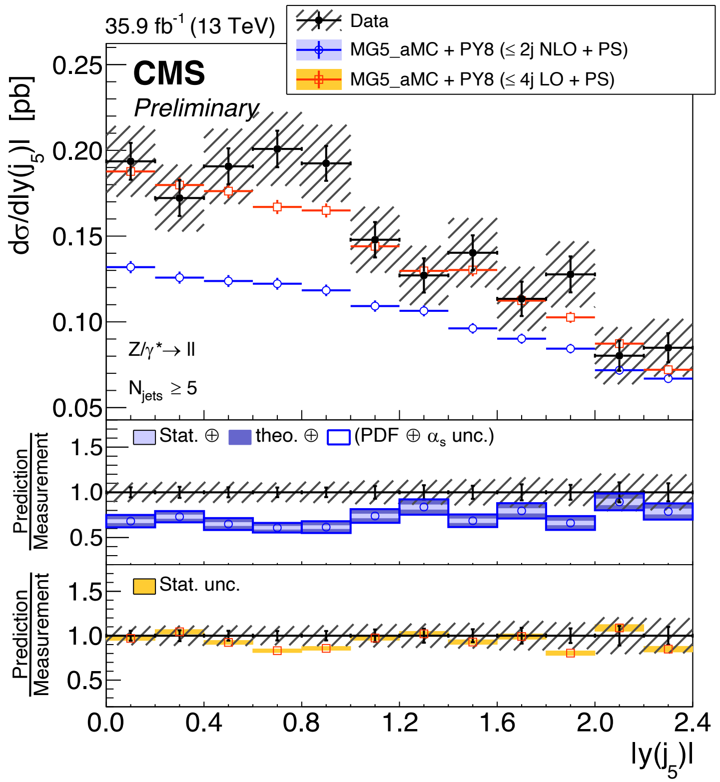
[CMS-PAS-SMP-19-009](CMS-PAS-SMP-19-009)

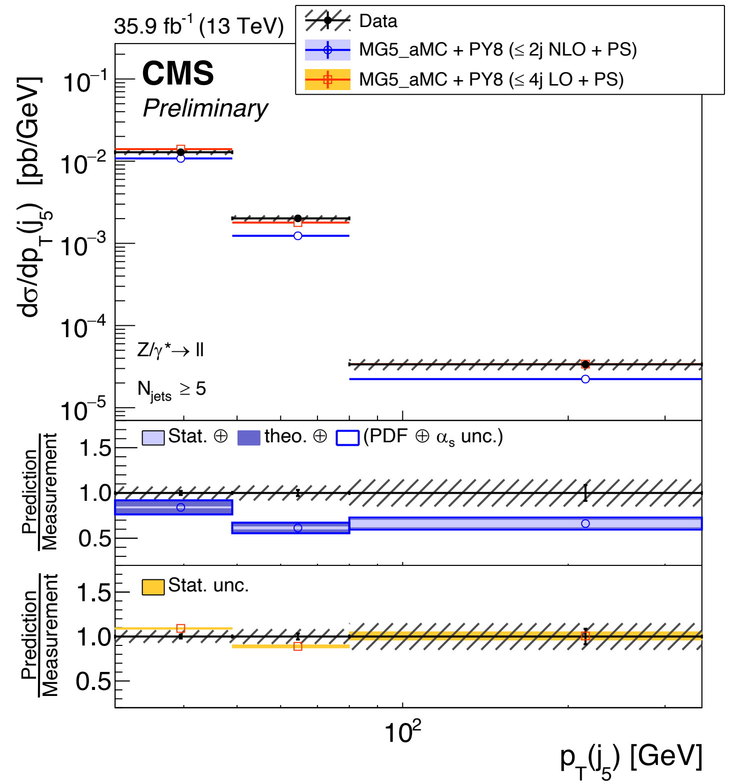
Z+jets differential cross sections

CMS-PAS-SMP-19-009

Madgraph5_aMC (Madgraph5_amc @NLO) + PS , NLO up to 2 jets

Madgraph5_aMC + PS, LO up to 4 jets





- Cross sections unfolded to particle level
- Comprehensive series of differential cross sections measured in Z+jets with 2016 data, up to the 5th jet

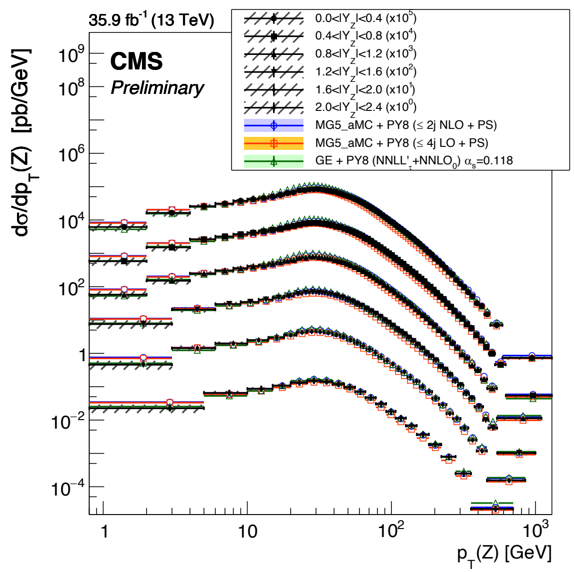
Z+jets differential cross sections

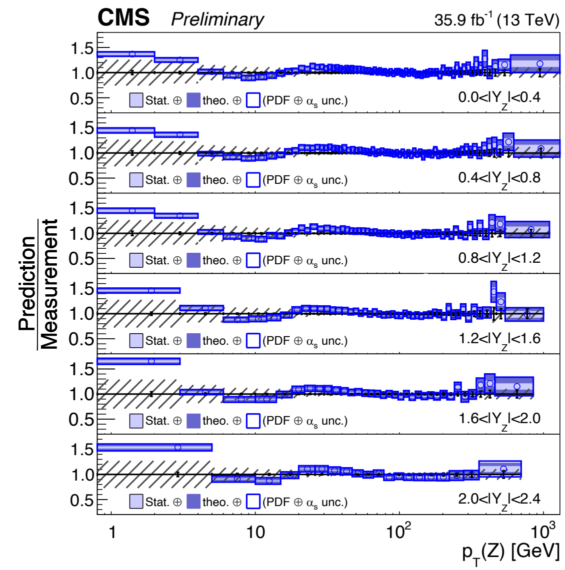
CMS-PAS-SMP-19-009

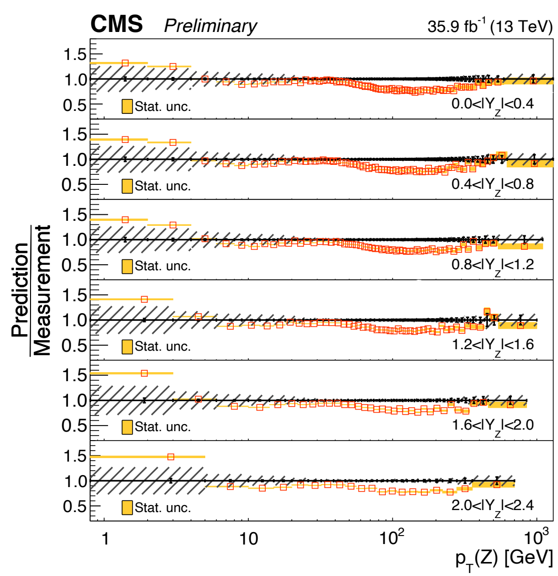
Madgraph5_aMC + PS
NLO up to 2 jets

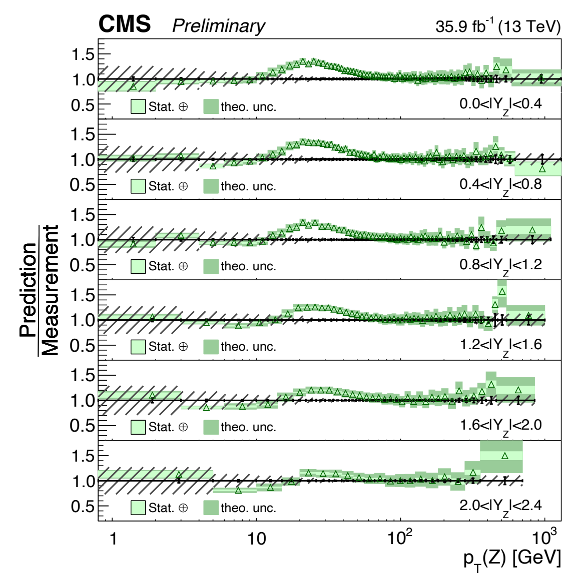
Madgraph5_aMC + PS
LO up to 4 jets

GENEVA NNLO+NNLL





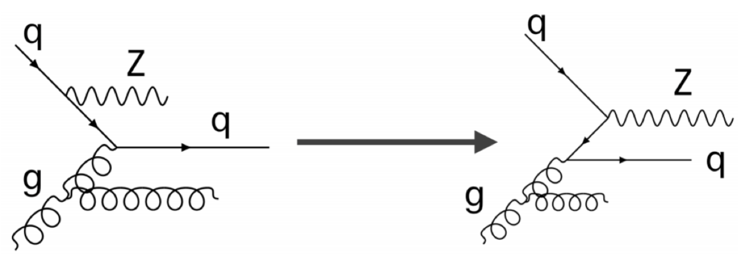




- Double differential cross section in p_T, y of Z for at least 1 jet
- p_T sensitive to pQCD, y to PDFs
- In general good agreement with MG5_aMC NLO, especially at p_T >~30 GeV where jets at NLO are well-modeled, and up to the ~ 1 TeV scale

Azimuthal correlation in Z+jets events

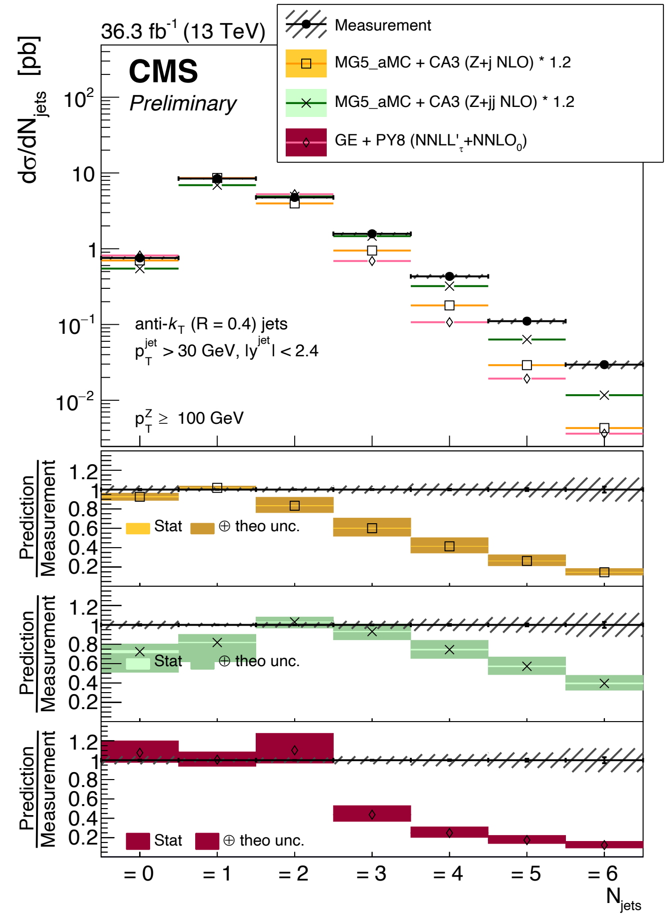
CMS-PAS- SMP-21-003



Low p_T Z

High p_T Z

- Three different intervals in p_T (Z) studied, looking at azimuthal correlations between the Z and the leading jet
- At low $p_{T,}$ sensitive to EW correction as well as soft-gluon resummation and non-perturbative effects
- At high p_T sensitive to higher order QCD corrections



At high p_T most of the events have at least one jet, with Z+ 1 non-collinear hard jet as main process

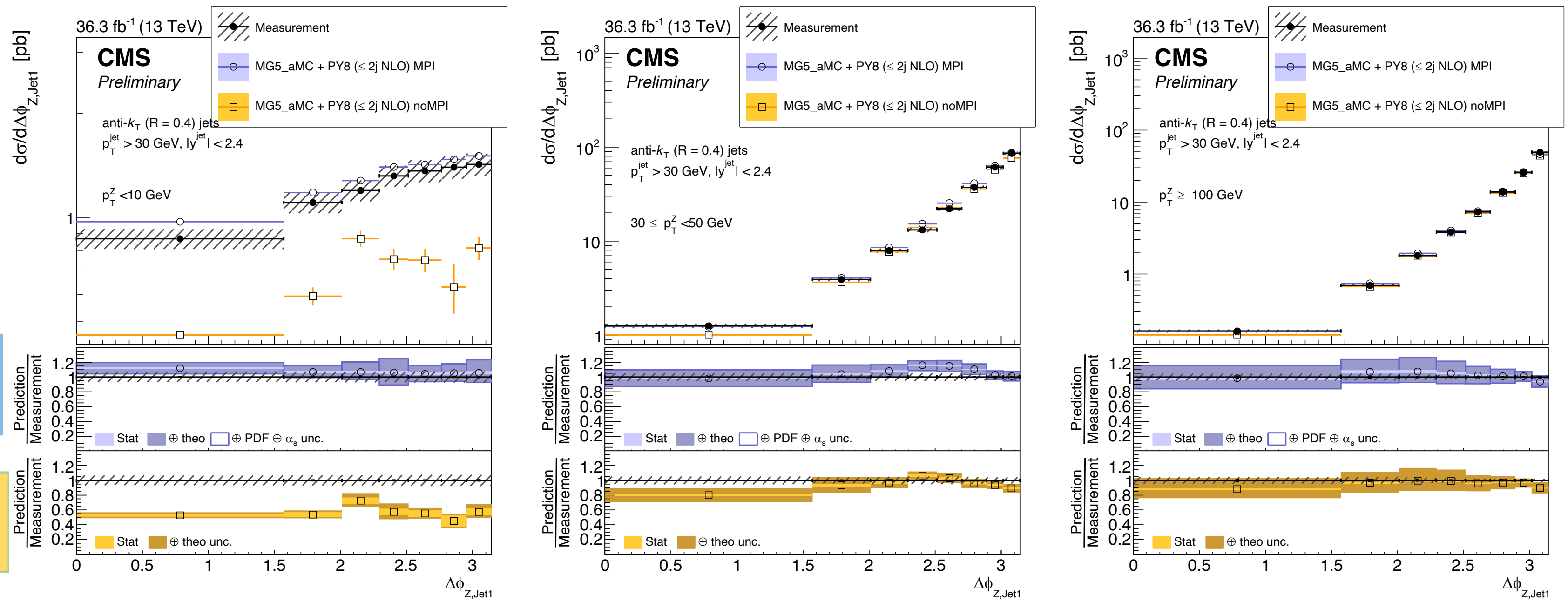
Azimuthal correlation in Z+jets events

CMS-PAS- SMP-21-003

Low p_T Z (<10 GeV) | Middle p_T Z (30:50 GeV) | High p_T Z (>100 GeV)

MG5_aMC MPI

MG5_aMC no MPI



- At low p_T Z not very correlated to jet
- At middle-high p_T Z back-to-back to leading jet, cross section peaking at high $\Delta\varphi$
- MG5_aMC + PY8 (for PS and UE) – NLO up to 2 jets - describes data well
- Large effect of MPI (up to 40%) at low p_T

Azimuthal correlation in Z+jets events

CMS-PAS- SMP-21-003

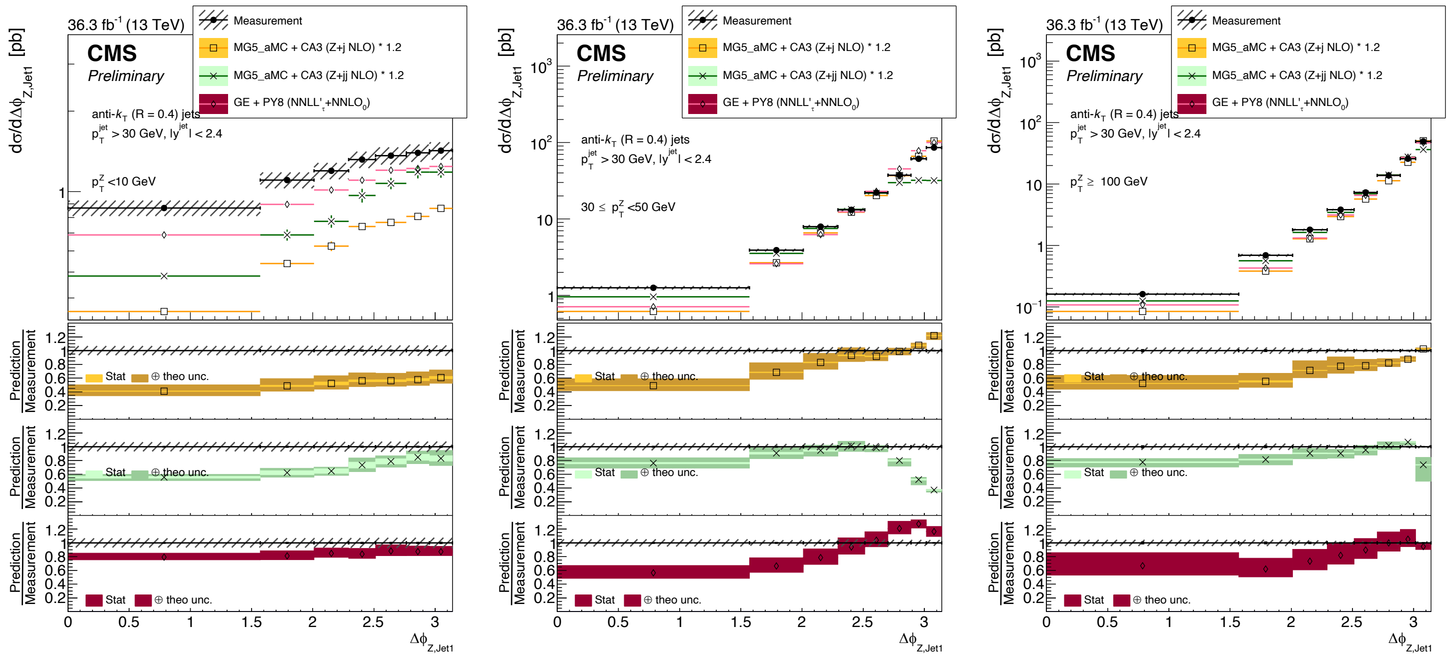
MG5_aMC-CA3* (Z+1 jet at NLO)

MG5_aMC-CA3* (Z+2 jet at NLO)

Geneva NNLO+ NNLL′ resummation

* With TMDs and PS implemented with the Parton-Branching method in CASCADE 3

Low p_T Z (<10 GeV) | Middle p_T Z (30:50 GeV) | High p_T Z (>100 GeV)



- MG5_aMC+CA3 NLO calculation for Z+1,2 jets, with transverse momentum dependence in the parton shower, come close to the data but effect of no MPI seen
- Higher-order corrections become important at high Z p_T, better agreement with NLO+2 jets
- GENEVA is in most regions close to the measurements

Double parton scattering in Z+jets

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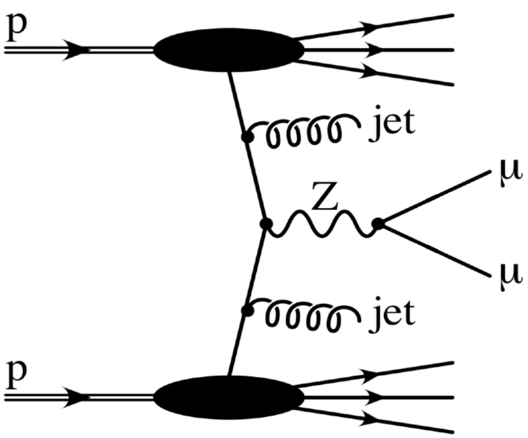
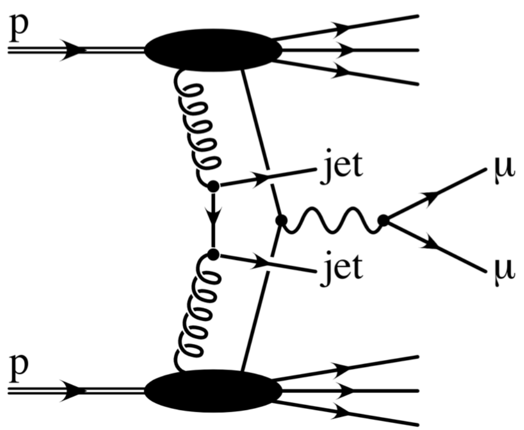
- DPS in Z + >= 1, 2 jets process sensitive to hadronization and MPI
- Jets measured from $p_T > 20$ GeV and $|\eta| < 2.4$. Potential jets at low p_T due to pileup removed by Pileup jet ID

- Z and jets are uncorrelated in DPS and in 2-jet events jets are back to back
- In Single Parton Scattering (SPS) Z and jets are correlated

- Differential cross sections measured for the azimuthal correlations and differences in p_T among the Z and jets
- Both absolute and normalized distributions





Double parton scattering in Z+jets

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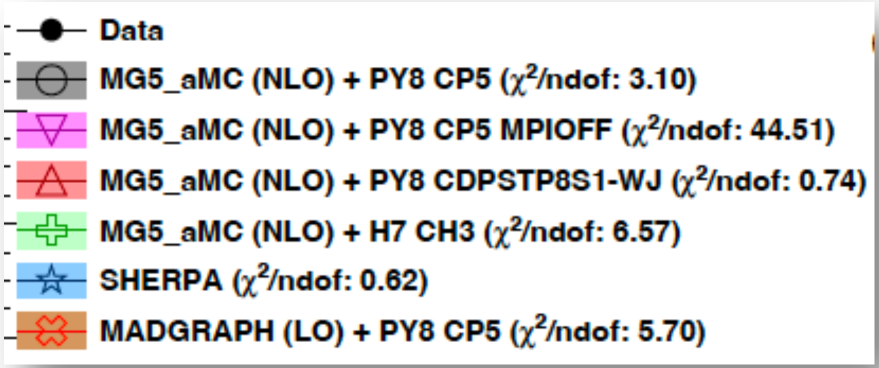

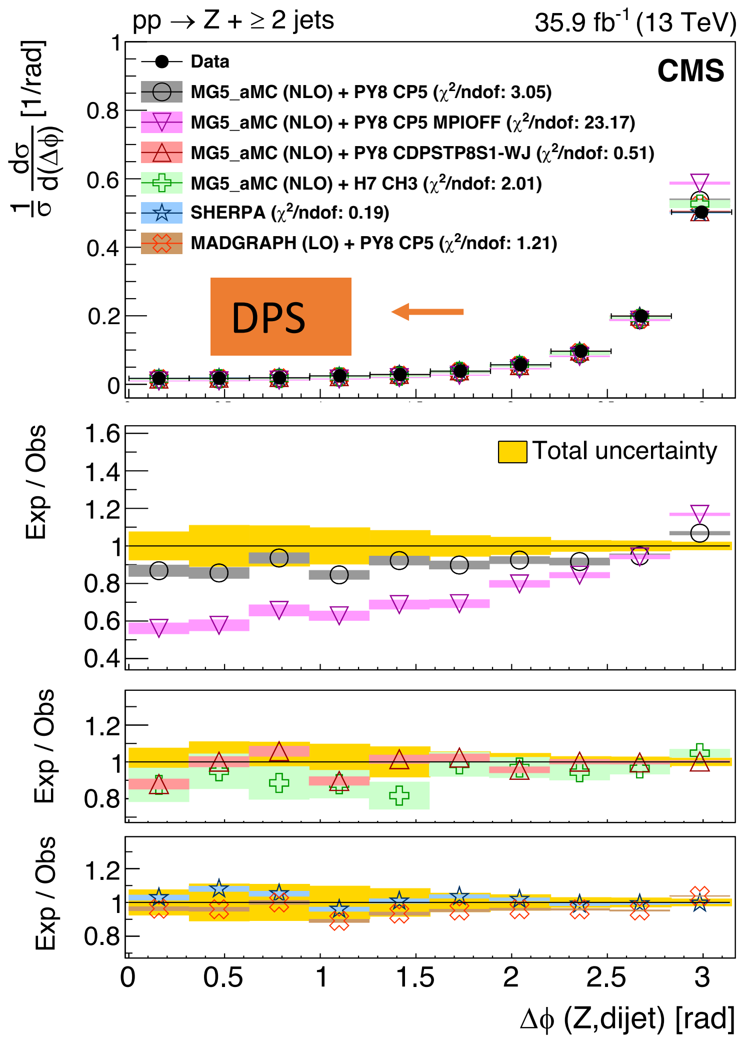

- Area normalized azimuthal correlation between Z and the dijet system
- Effect of MPI clearly seen in region where Z and dijet are uncorrelated
- All models with MPI and SHERPA reproduce distributions well

Double parton scattering in Z+jets

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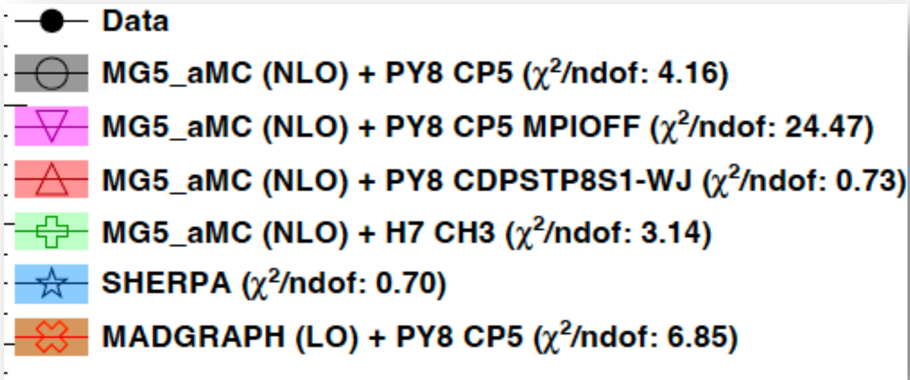
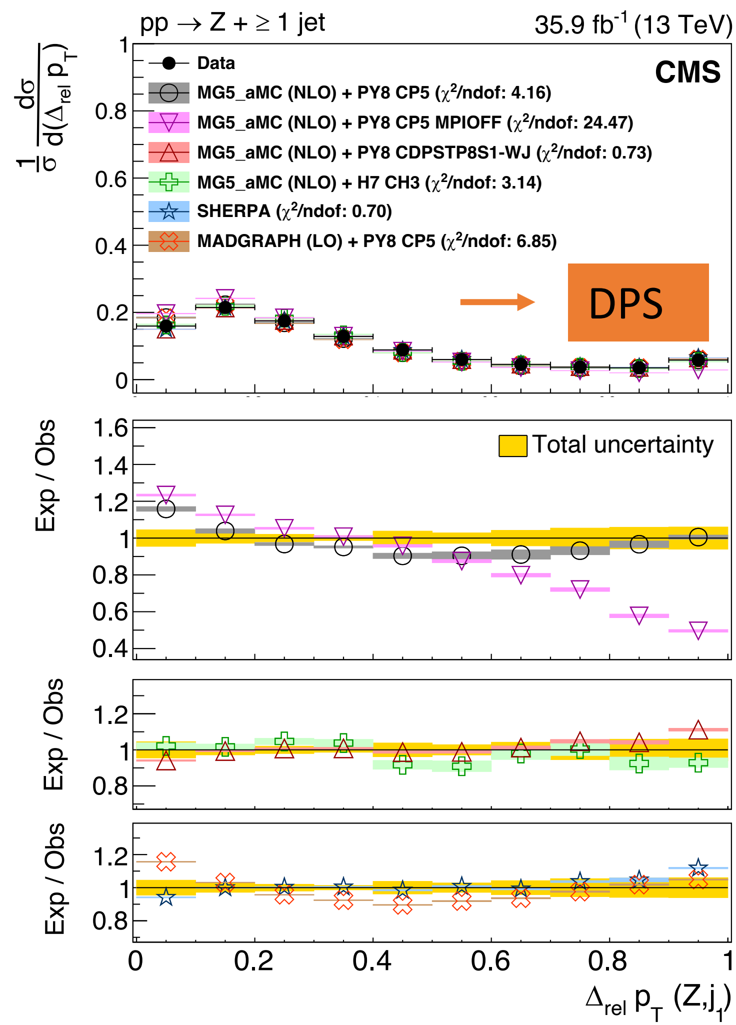


$$\Delta^{\mathrm{rel}}_{p_{\mathrm{T}}}(Z, j_1) = \frac{|\vec{p_{\mathrm{T}}}(Z) + \vec{p_{\mathrm{T}}}(j_1)|}{|\vec{p_{\mathrm{T}}}(Z)| + |\vec{p_{\mathrm{T}}}(j_1)|}$$

- Normalized relative p_T distribution measured in Z + >= 1 jet events
- Some differences in tunes seen at low values of the relative p_T , i.e. for MG5_aMC+PYTHIA8 CP5 (standard CMS tune in 2017, 2018 MC)



Double parton scattering in Z+jets

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Integrated cross section measured in fiducial region for particle-level jets:

Object	Selections
Muons (dressed)	$p_T > 27\,\text{GeV}, \lvert\eta\rvert < 2.4$
Z boson	$70 < m_{\mu^+\mu^-} < 110\,\text{GeV}$
At least 1 jet	$p_T > 20\,\text{GeV}, \lvert\eta\rvert < 2.4$

Cross section (pb)		$Z+\geq 1$ Jets	$Z+\geq 2$ Jets
Measured in data		158.5 ± 0.3 (stat)	44.8 ± 0.4 (stat)
		± 7.0 (syst)	± 3.7 (syst)
		± 1.2 (theo)	± 0.5 (theo)
		± 4.0 (lumi) pb	± 1.1 (lumi) pb
Predicted by MC			
MG5_aMC (NLO)	PYTHIA8, CP5 tune	167.4 ± 9.7	47.0 ± 3.9
	PYTHIA8, CP5 tune MPIOFF	143.8 ± 0.3	37.7 ± 0.2
	PYTHIA8, CDPSTP8S1-WJ tune	178.4 ± 0.3	50.5 ± 0.2
	HERWIG7, CH3 tune	158.3 ± 1.1	44.4 ± 0.6
MG5_aMC (LO) + PYTHIA8, CP5 tune		161.2 ± 0.1	45.3 ± 0.1
SHERPA (NLO+LO)		149.8 ± 0.2	41.6 ± 0.1

- Predictions with MPI in general in good agreement with measured cross sections
- DPS specific tune CDPSTP8S1-WJ describes shape but about 10% higher in cross section than data
- MG5_aMC + PYTHIA8 and CP5 tune compatible in cross section value

Measurement of the Z invisible spectrum

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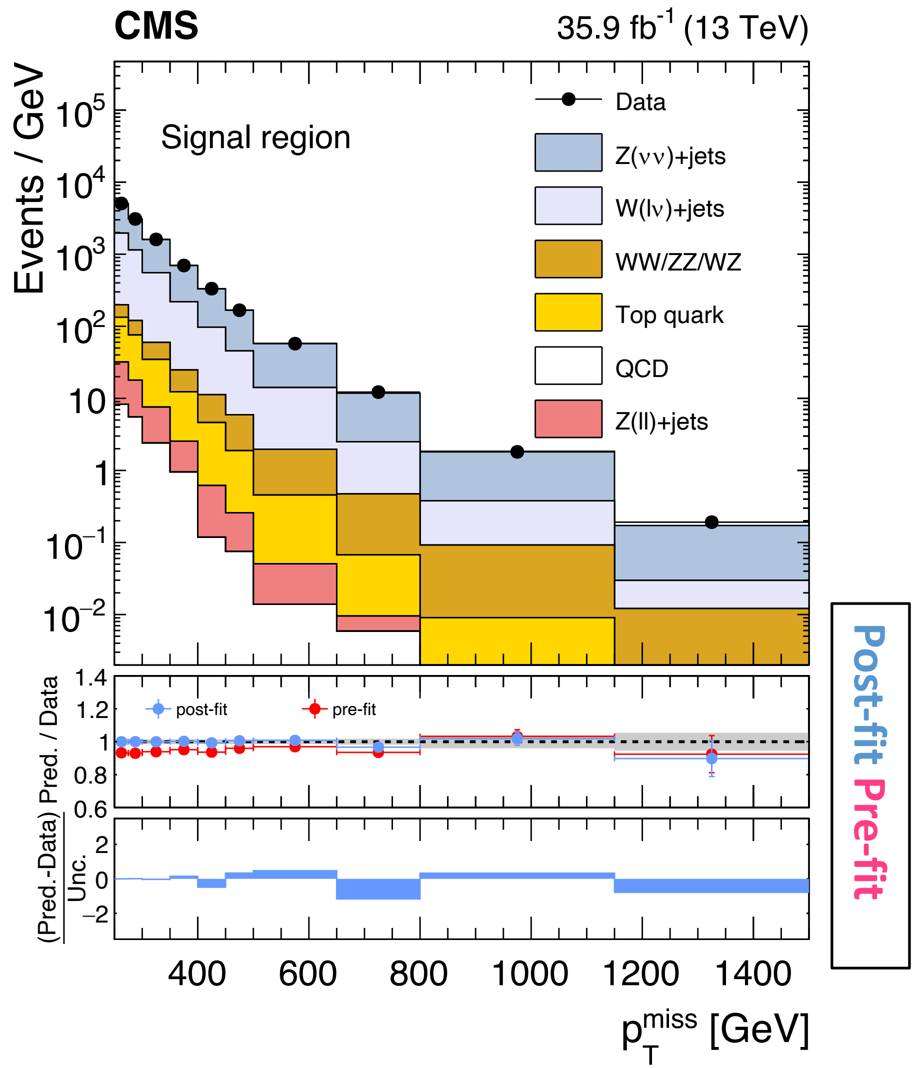
- Measurement of the total and differential cross section of $Z \rightarrow \nu\nu$
- Events are selected with $p_T^{miss} > 250$ GeV and jets $p_T > 100$ GeV, and a lepton veto
- Control regions (CR) with single leptons to constrain the W background (largest background ~ 85%)
- Combined fit of signal region (SR) and CRs in 10 bins of p_T^{miss}
- Total fiducial cross section measured:

$$\sigma(observed) = 3000^{+180}_{-170} \text{ fb}$$

with main systematics due to luminosity (2.5%) and jet/ p_T^{miss} energy scale (4%)



Measurement of the Z invisible cross sections

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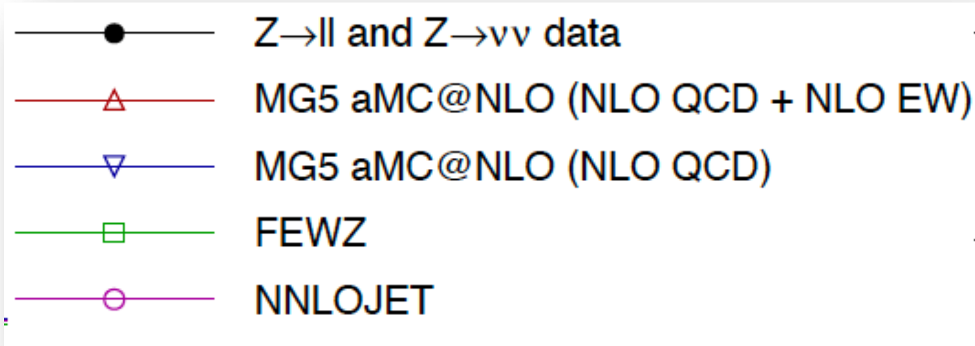
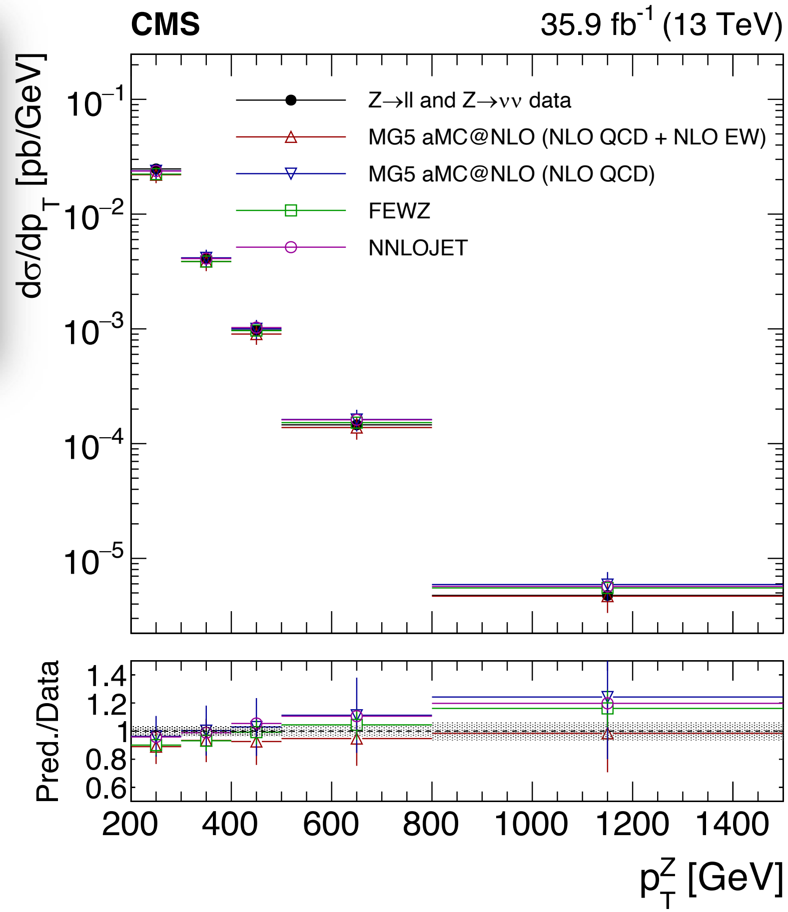


- Differential cross section for $Z \to \nu\nu$ measured in 5 bins and combined with $Z \to ll$ [JHEP 12 (2019) 061]
- Compared to MC predictions and QCD calculations
- $Z \to \nu\nu, ll$ at high p_T important background for many searches, most precise measurement here
- Agreement with models and EW corrections important in the highest two p_T^Z bins (0.9 and 0.8 corrections)



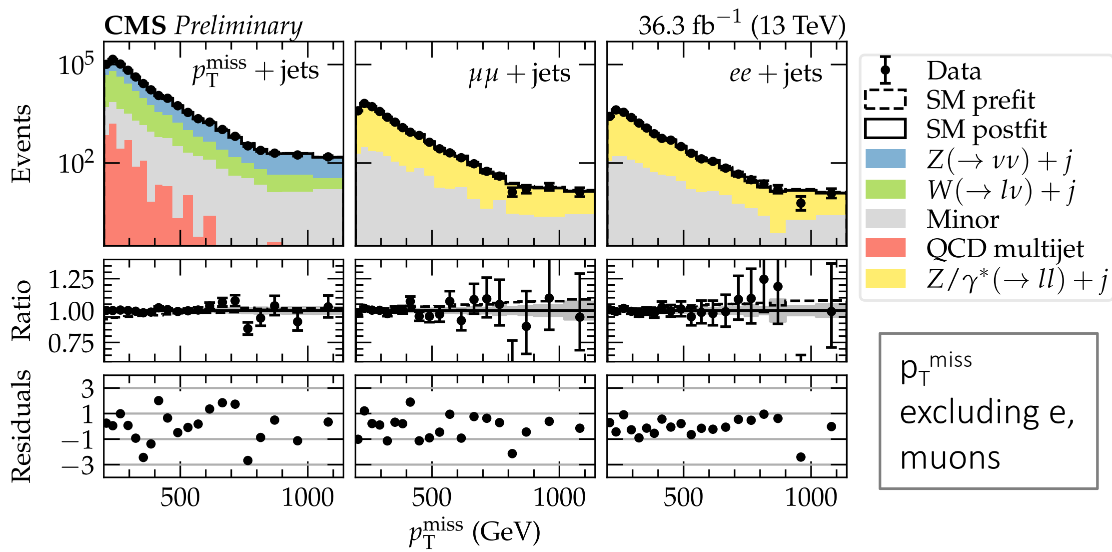
Combination is systematically limited and dominated by $Z \to ll$ at low p_T. It is driven by $Z \to \nu\nu$ at high p_T

Measurement of Z invisible width

CMS-PAS-SMP-18-014

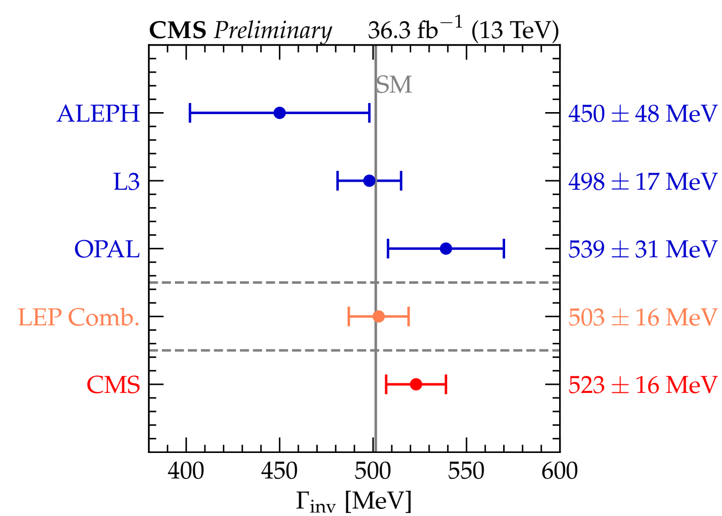
- Process also used to measure the Z invisible width
- Combined fit of invisible and lepton Z decays, and CRs for W+jets

- Γ_{inv}= 523 +/- 3 (stat.) +/- 16 (syst) MeV
- Main systematics: lepton efficiency (1.5-2.0%) and jet energy scale (1.8%)



p_T^{miss} excluding e, muons

$$\Gamma(Z \rightarrow \nu\bar{\nu}) = \frac{\sigma(Z+jets)\mathcal{B}(Z\rightarrow\nu\bar{\nu})}{\sigma(Z+jets)\mathcal{B}(Z\rightarrow l\bar{l})}\Gamma(Z \rightarrow l\bar{l})$$



Summary

- Measurement of differential cross section for Z+jets up to 5 jets
- Azimuthal correlations measured in different regions of Z p_T , sensitive to different processes. Z + leading jet distributions show the importance of MPI at low p_T (Z) and of higher order matrix element at high p_T (Z)
- Comprehensive study of distributions sensitive to DPS in Z + >=1, 2 jets
- Measurement of Z invisible p_T spectra up to ~ 1.5 TeV, combined with Z in lepton measurement, most precise to-date. In agreement with calculations, EW corrections important at high p_T
- Measurement of Z invisible width at a hadron collider, Γ_{inv}= 523 +/- 3 (stat.) +/- 16 (syst) MeV, very competitive with LEP direct result, most precise measurement in a single experiment
- HepData available for published results

Backup

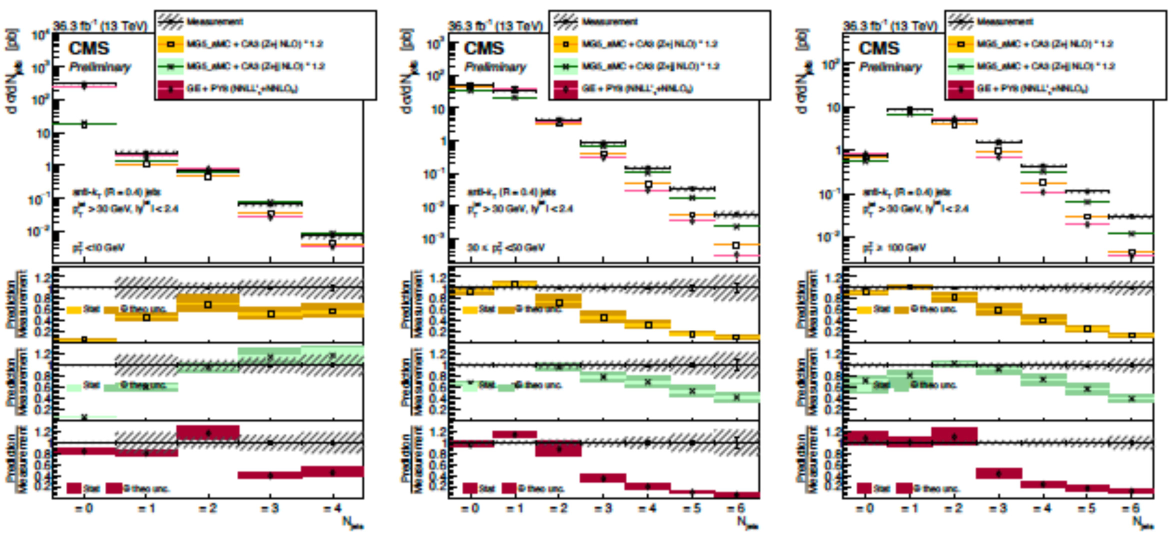
- Available MC models and calculations in differential Z+jets distributions:
  - MADGRAPH5_aMC at LO +PYTHIA8, Z+N jets (N=0,..4,) at LO, MLM matching, NNPDF 3.0
  - MADGRAPH5_AMC@NLO 2.2.2 and 2.3.2 with FxFx merging scheme using PYTHIA8 for PS and CUETP8M1 tune for 2016, CP5 tune for 2017,2018. Z+ up to 2 jets at NLO, LO for Z+3 jets
  - GENEVA 1.0RC3, NNLO+resummation at NNLL$'$ accuracy, PDF NNPDF 3.1+PYTHIA8 for PS. NLO for Z+1 jet, effectively LO at Z+2 jets.
  - Uncertainties in renormalization and factorization scales as recommended by the authors. PDF uncertainties in MG5_AMC from the replicas of NNPDF 3.0 NLO PDF.

Samples	0j	1j	2j	3j	4j	>4j
MG5_aMC LO	LO	LO	LO	LO	LO	PS
MG5_aMC NLO	NLO	NLO	NLO	LO	PS	PS
Geneva	NLO	NLO	LO	PS	PS	PS

Backup

CMS-PAS- SMP-21-003

- MADGRAPH5_aMC@NLO, with PB-TMDs as in CASCADE3, with collinear parton density PB-NLO-HERAI+II-2018-set2. The inclusion of the corresponding TMD is done via CASCADE3. The PB parton density and PB initial PS follow angular ordering and the PS parameters are fixed by the PB. The calculation is at NLO for Z+1 or Z+2 partons. No free parameter for the PS and no MPI included. The predictions need a scaling factor of 1.2.



Backup

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- SHERPA 2.2 NLO up to 2 additional partons, or LO up to 4 additional partons.
- CUETP8M1: uses NNPDF 2.3 LO
- CP5 tune: uses NNPDF 3.1 at NNLO and is obtained fitting a large number of 1.96, 7 and 13 TeV measurements sensitive to soft and semihard multiparton interactions [CMS paper]
- MG5_AMC@NLO also interfaced with Herwig7 with CH3 tune
- SHERPA and MG5_aMC+PY8 CUETP8M1 used for model uncertainties in the unfolding

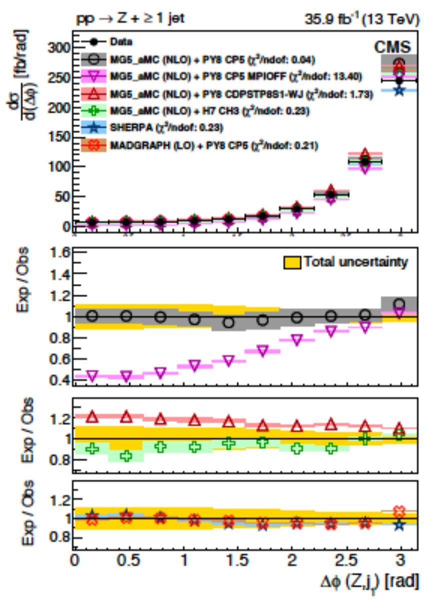

Table 3: Uncertainty sources and their effect on the differential cross section distributions.

Observable/Uncertainty	$\Delta\phi(Z, j_1)$	$\Delta_{rel} p_T(Z, j_1)$	$\Delta\phi$(Z, dijet)	$\Delta_{rel} p_T$(Z, dijet)	$\Delta_{rel} p_T(j_1, j_2)$
JES	2.7–7.5%	2.4–7.4%	4.9–7.9%	4.5–8.4%	4.4–7.3%
JER	0.9–6.6%	1.4–5.8%	1.2–7.2%	2.1–5.1%	1.1–4.2%
Pileup jet identification	1.3–1.7%	0.9–1.6%	1.7–2.1%	1.6–2.1%	1.7–2.3%
Integrated luminosity	2.5%	2.5%	2.5%	2.5%	2.5%
Pileup modelling	0.1–0.7%	0.2–1.0%	0.2–1.4%	0.4–1.4%	0.8–1.4%
Closure uncertainty	0.6–4.0%	0.8–5.1%	2.7–6.1%	2.2–8.7%	2.2–8.7%
Muon selection	<1.0%	<1.0%	<1.0%	<1.0%	<1.0%
Background modelling	<0.2%	<0.2%	<0.6%	<0.6%	<0.4%
Total	4–11%	4–10%	8–14%	8–14%	7–11%

Backup

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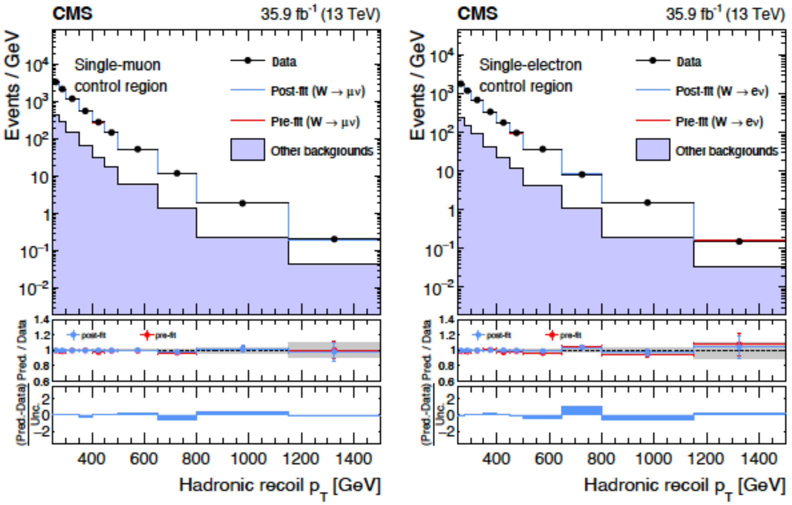
Table 1: Summary of the signal region definition.

Variable	Selection	To suppress background from
Electron veto	$p_T > 10\,\text{GeV}, \|\eta\| < 2.5$	$Z \to \ell\ell + \text{jets}, W(\ell\nu) + \text{jets}$
Muon veto	$p_T > 10\,\text{GeV}, \|\eta\| < 2.4$	$Z \to \ell\ell + \text{jets}, W(\ell\nu) + \text{jets}$
τ veto	$p_T > 18\,\text{GeV}, \|\eta\| < 2.3$	$Z \to \ell\ell + \text{jets}, W(\ell\nu) + \text{jets}$
Photon veto	$p_T > 15\,\text{GeV}, \|\eta\| < 2.5$	$\gamma + \text{jets}$
b jet veto	CSVv2 <0.8484, $p_T > 20\,\text{GeV}$, $\|\eta\| < 2.4$	Top quark
p_T^{miss}	>250 GeV	QCD multijet, top quark, $Z \to \ell\ell + \text{jets}$
$\Delta\phi(\vec{p}_T^{jet}, \vec{p}_T^{miss})$	>0.5 radians	QCD multijet
Leading jet	$p_T > 100\,\text{GeV}, \|\eta\| < 2.4$	All



p_T^Z (GeV)	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$	$Z \to \ell\ell$	$Z \to \nu\nu$	$Z \to \ell\ell + \nu\nu$	Theory
200–300	2500^{+140}_{-110}	2400^{+120}_{-120}	2500^{+100}_{-100}	2500^{+150}_{-150}	2500^{+82}_{-100}	2200 ± 350
300–400	390^{+22}_{-18}	400^{+22}_{-21}	400^{+17}_{-16}	420^{+24}_{-23}	410^{+14}_{-17}	390 ± 69
400–500	$99^{+5.7}_{-4.9}$	$97^{+6.4}_{-6.1}$	$100^{+4.4}_{-4.2}$	$97^{+5.6}_{-5.4}$	$97^{+3.3}_{-4.0}$	90 ± 18
500–800	$47^{+3.0}_{-2.5}$	$41^{+4.0}_{-3.7}$	$45^{+2.3}_{-2.2}$	$44^{+2.7}_{-2.6}$	$44^{+1.6}_{-1.9}$	41 ± 9.0
800–1500	$3.9^{+0.6}_{-0.5}$	$3.2^{+0.7}_{-0.6}$	$3.7^{+0.4}_{-0.4}$	$3.2^{+0.3}_{-0.3}$	$3.3^{+0.2}_{-0.2}$	3.3 ± 0.9
200–1500	3000^{+160}_{-130}	3000^{+150}_{-140}	3000^{+120}_{-110}	3000^{+180}_{-170}	3000^{+100}_{-120}	2700 ± 440