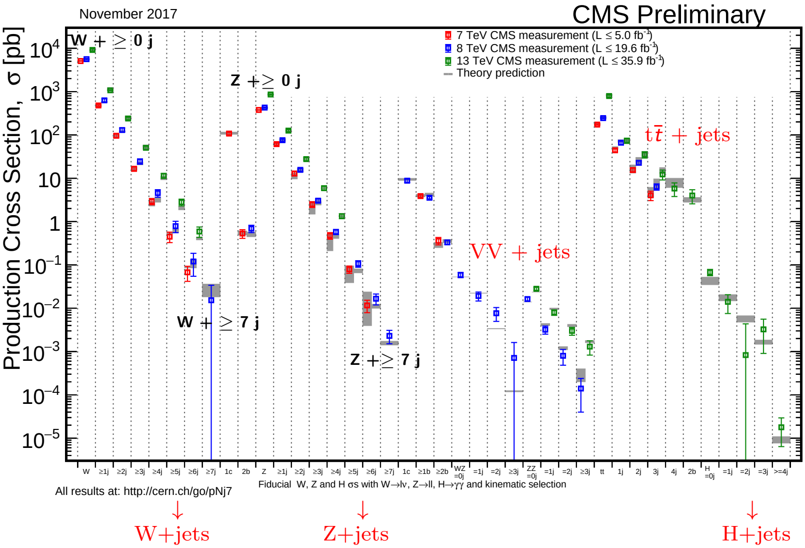
REF2018, Krakow

Differential cross sections for Z boson production in association with jets at CMS

Anastasia Grebenyuk on behalf of the CMS collaboration

21 November 2018

Standard Model Production Cross Section Measurements:

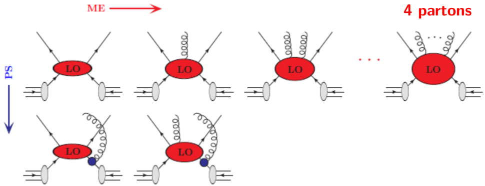


Motivation

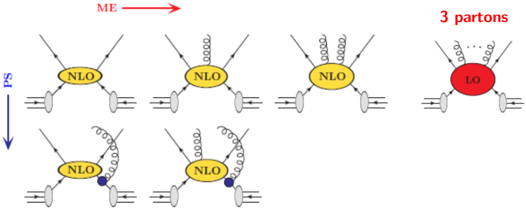
- With Z+jets we can probe different aspects of QCD calculations
- Z+jets precision measurement is crucial for deep understanding and modeling of QCD interactions
- Z+jets is dominant background for:
  - top quark measurements
  - Higgs physics -VH ($H \rightarrow bb$)
  - searches of new particles
- Comparisons of data with predictions allows further Monte Carlo generator development and determination of systematic uncertainties.

Theoretical prediction for cross section for Z+jets

- MADGRAPH5_AMC@NLO + PYTHIA8 (denoted as LO MG5_aMC)
  - LO matrix element up to 4 partons
  - k_T -MLM merging between matrix element and parton shower
  - NNPDF3.0 LO PDF, CUETP8M1 PYTHIA8 tune



- MADGRAPH5_AMC@NLO + PYTHIA8 (denoted as NLO MG5_aMC)
  - NLO matrix element up to 2 partons (LO accuracy for 3 partons)
  - FxFx jet merging between matrix element and parton shower
  - NNPDF3.0 NLO PDF, CUETP8M1 PYTHIA8 tune



- Z+1 jet fixed order NNLO
  (Phys. Rev. D 94 (2016) 074015, Phys. Rev. Lett. 116 (2016) 152001)
  - Correction for hadronization and multiple parton interaction computed with NLO MG5_aMC+ PYTHIA8 as differential scaling factors
  - CT14 PDF
- GENEVA 1.0-RC2 + PYTHIA8
  - NNLO+NNLL'
  - Use n-jettiness to separate N-jet and inclusive (N+1)-jet region, here τ_0 and τ_1
  - τ_0 ($\equiv$ beam-thrust) dependence resummed at NNLL'
  - $d\sigma_{\geq 0j}$ at NNLO, $d\sigma_{\geq 1j}$ at NLO, $d\sigma_{\geq 2j}$ at LO
  - PDF4LHC15 NNLO, CUETP8M1 PYTHIA8 tune

Samples	0j	1j	2j	3j	4j	>4j	Used cross section [pb]
LO MG5_aMC	LO	LO	LO	LO	LO	PS	5787 (FEWZ NNLO)
NLO MG5_aMC	NLO	NLO	NLO	LO	PS	PS	5931 (native)
GENEVA	NNLO	NLO	LO	PS	PS	PS	5940 (native)
Z+1 jet at NNLO	-	NNLO	(NLO)	(LO)	-	-	

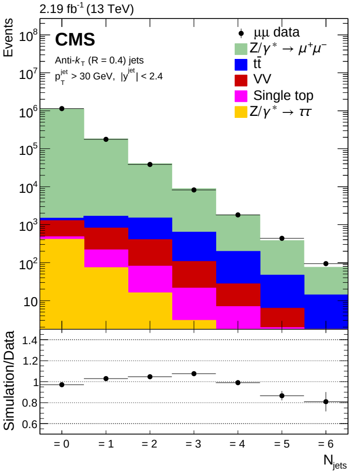
$Z\ (\rightarrow \ell^+\ell^-)$+jets at 13 TeV (arXiv:1804.05252)

- Integrated luminosity of 2.19 fb^{-1}

Phase Space at Generator Level:

- $p_T(\ell) \geq 20$ GeV, $|\eta(\ell)| \leq 2.4$ and $71 \leq m_{\ell^+\ell^-} \leq 111$ GeV
- $p_T(j) \geq 30$ GeV, $|y(j)| \leq 2.4$, $\Delta R(j,\ell) > 0.4$

Bin-to-bin migration due to limited detector resolution corrected using unfolding method



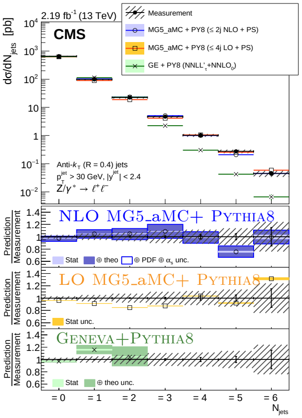
Signal: NLO MG5_aMC

Transverse momentum of the Z boson for $N_{\text{jets}} \geq 0$

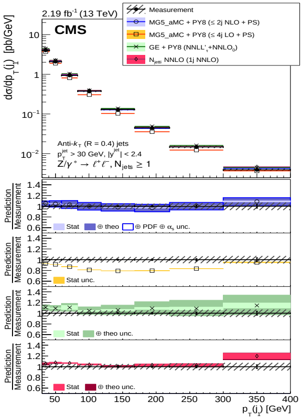
Q.Wang, *"Measurement of the differential cross section of Z boson production in association with jets at the LHC"*, PhD thesis, Université Libre de Bruxelles and Peking University, 2018

`http://web.iihe.ac.be/publications/doctoralThesis_QunWANG.pdf`
(Figure 5.37)

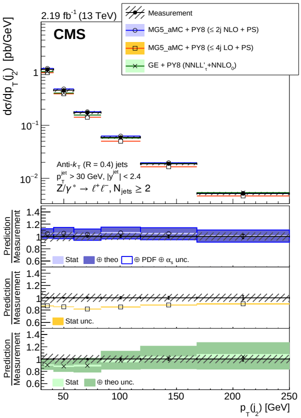
N_{jets}



Leading jet p_T:



Subleading jet p_T:



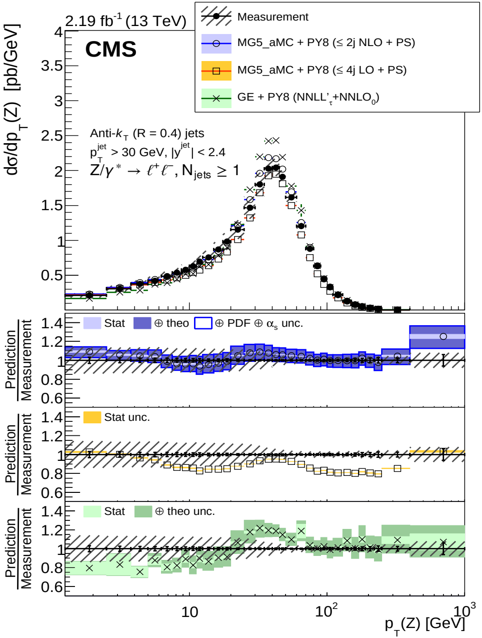
- NLO correction is needed to describe the measurements (jet p_T shape)

GENEVA (NNLL'+NNLO) describes the data up to N_{jets}=2 but but fails to describe the data for higher jet multiplicities

Z+1 jet fixed order NNLO and NLO MG5_aMC describe data; improved precision for NNLO calculation

LO MG5_aMC+ PYTHIA8 predicted distribution differs from the measurement

Transverse momentum of the Z boson for $N_{jets} \geq 1$



At least one jet requirement shifts the peak toward the higher value → possibility of studying multiple gluon emissions away from the non-perturbative region

Small p_T (below the peak):

- all samples are interfaced with PYTHIA8 with CUETP8M1 tune
- NLO MG5_aMC is best in describing the data
- GENEVA is below the data but bescribes the shape of the distribution below 10 GeV. GENEVA is LO below the jet cut (30 GeV)

High p_T:

- GENEVA and NLO MG5_aMC describe the data
- LO MG5_aMC shows different shape from data

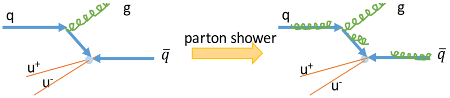
Correlation observables

- p_T balance between the Z boson and the vector sum of the jets:

  $p_T^{bal} = |\vec{p_T}(Z) + \sum_{jets} \vec{p_T}(j_i)|$, for $N_{jets} \geq 1,2,3$

  The imbalance is caused by:

  - hadronic activity outside the jet acceptance ($p_T > 30$ GeV, $|y| < 2.4$ which is dominant contribution)
  - gluon radiation in the central region, not clustered in a jet

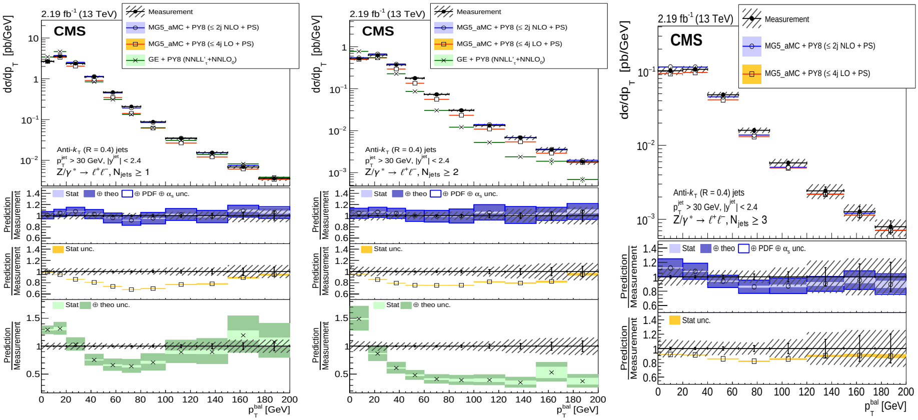


- Jets-Z balance (JZB): JZB $= |\sum_{jets} \vec{p_T}(j_i)| - |\vec{p_T}(Z)|$

  for $p_T(Z) \leq 50$ GeV and $p_T(Z) \geq 50$ GeV

  - the same source of imbalance as for p_T^{bal}
  - it allows the distinction of the two configurations, where non-accounted hadronic activity is in the Z hemisphere and where it is in the opposite one

$N_{\text{jets}} \geq 1$ $N_{\text{jets}} \geq 2$ $N_{\text{jets}} \geq 3$



Imbalance (large $p_{\mathrm{T}}^{\mathrm{bal}}$) from two jets in the final state with one of them out of the acceptance - NLO accuracy for NLO MG5_aMC sample and LO accuracy for other samples

Large $p_{\mathrm{T}}^{\mathrm{bal}}$: at least 2 jets in the acceptance and one is out GENEVA: 3rd jet is from PS

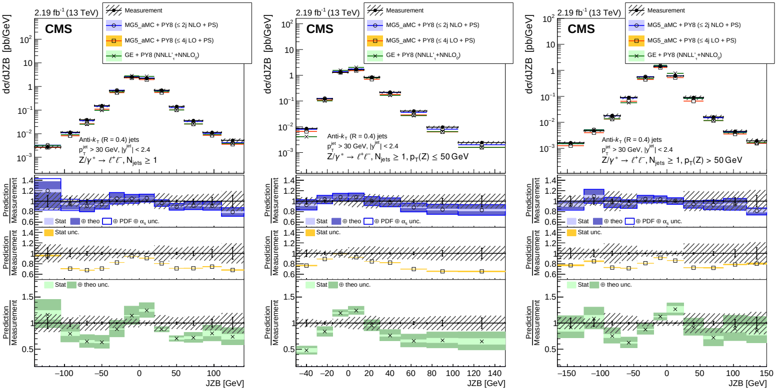
LO MG5_aMC and NLO MG5_aMC provide reasonable description of the data

→ NLO correction is important for the description of hadronic activity beyond the jet acceptance used in this analysis

Correlation observable: $\mathrm{JZB} = |\sum_{\mathrm{jets}} \vec{p_T}(j_i)| - |\vec{p_T}(Z)|$

JZB< 0: unaccounted hadronic activity in the Z hemisphere
JZB> 0: unaccounted hadronic activity in the opposite hemisphere
$N_{\mathrm{jets}} \geq 1$ is required

full phase space: $p_{\mathrm{T}}(\mathrm{Z}) \leq 50$ GeV: $p_{\mathrm{T}}(\mathrm{Z}) \geq 50$ GeV:

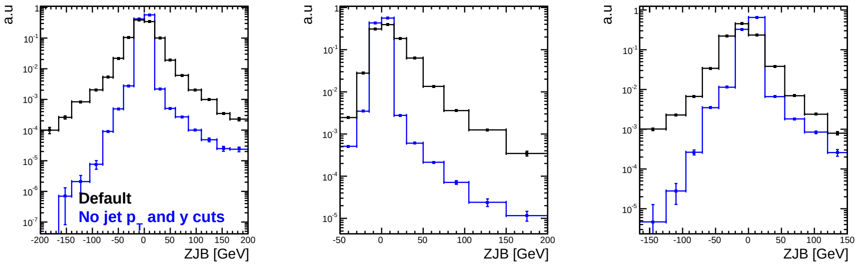


- NLO MG5_aMC prediction provides a better description of the JZB distribution than GENEVA and LO MG5_aMC

Correlation observable: $\mathrm{JZB} = |\sum_{\mathrm{jets}} \vec{p_T}(j_i)| - |\vec{p_T}(Z)|$

Effect on the imbalance of the hadronic activity beyond the jet acceptance ($p_T > 30$ GeV, $|y| < 2.4$) in Monte Carlo:

full phase space: $p_T(Z) \leq 50$ GeV: $p_T(Z) \geq 50$ GeV:



Dominant contribution is hadronic activity in the forward region ($|y| > 2.4$)

Outlook

The measurements of Z boson plus jets processes are important:

- deepen our knowledge of QCD
- improve the modeling of the production mechanism involved in Higgs boson measurement and new physics searches

- high experimental precision (5% total uncertainty for the cross section in the exclusive jet multiplicity of one) exposes data-predictions discrepancies
- NLO is essential to describe jet multiplicity, transverse momentum of the leading jet and Z boson
- NNLO ME models are available with significantly reduced theory uncertainties
  - current precision of the measurement do not allow to conclude on gain in using NNLO vs multipaton NLO ME calculations

→ Results suggest using multiparton NLO predictions for the estimation of the Z + jets contribution at the LHC in measurements and searches, and its associated uncertainty

Back up slides

Z ($\rightarrow \ell^+\ell^-$)+jets at 13 TeV (arXiv:1804.05252)

Cross section in exclusive jet multiplicity for the combination of both decay channels and breakdown of the uncertainties:

N_{jets}	$\frac{d\sigma}{N_{\text{jets}}}$ [pb]	Tot. unc [%]	Stat [%]	JES [%]	JER [%]	Eff [%]	Lumi [%]	Bkg [%]	Pileup [%]	Unf model [%]	Unf stat [%]
$= 0$	652.	3.0	0.090	1.1	0.046	1.5	2.3	$<$0.01	0.22	–	0.026
$= 1$	98.0	5.1	0.27	4.3	0.18	1.5	2.3	0.012	0.30	–	0.10
$= 2$	22.3	7.3	0.62	6.7	0.20	1.6	2.3	0.026	0.43	–	0.26
$= 3$	4.68	10.	1.3	9.8	0.39	1.7	2.3	0.13	0.29	–	0.54
$= 4$	1.01	11.	3.4	10.	0.24	1.7	2.3	0.42	0.56	–	1.4
$= 5$	0.274	14.	5.0	12.	0.076	2.0	2.3	1.2	0.30	–	2.2
$= 6$	0.045	24.	15.	17.	0.35	1.8	2.4	3.5	1.7	–	6.6