

Vector boson production in association with jets

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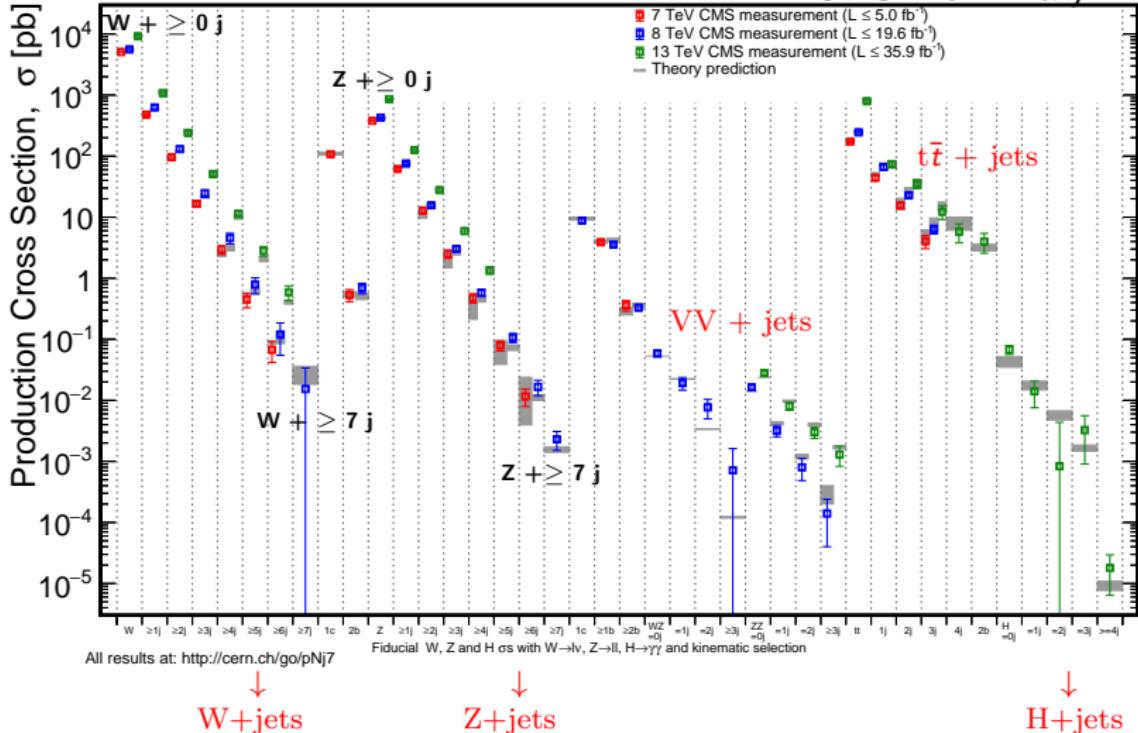
18 April 2018



Standard Model Production Cross Section Measurements:

November 2017

CMS Preliminary



In today's talk:

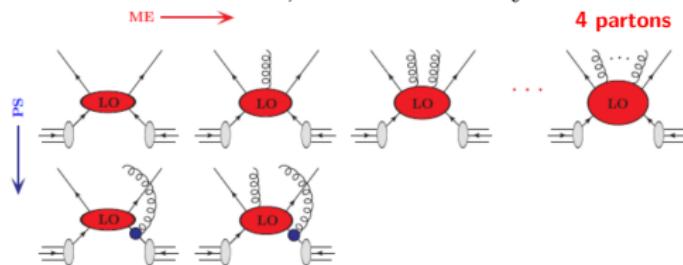
- Z+jets and W+jets at 13 TeV
- EWK Z + 2 jets at 13 TeV

Motivation

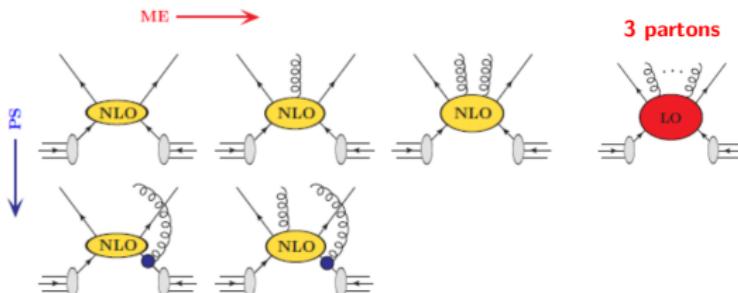
- ▶ With V+jets we can probe different aspects of QCD calculations
- ▶ V+jets precision measurement is crucial for deep understanding and modeling of QCD interactions
- ▶ V+jets is dominant background for:
 - ▶ top quark measurements
 - ▶ Higgs physics -VH ($H \rightarrow bb$)
 - ▶ searches of new particles
- ▶ Understanding differences between QCD and EWK production
- ▶ 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 differentioal 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)	-	-	

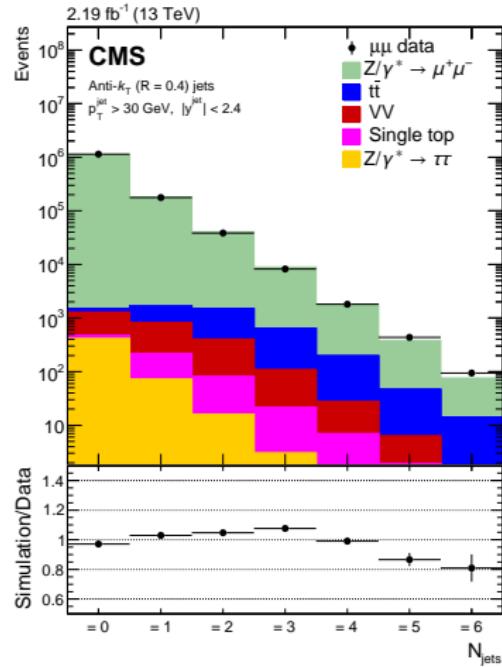
$Z \rightarrow \ell^+ \ell^-$ +jets at 13 TeV (arXiv:1804.05252)

- ▶ Integrated luminosity of 2.19 fb^{-1}

Phase Space at Generator Level:

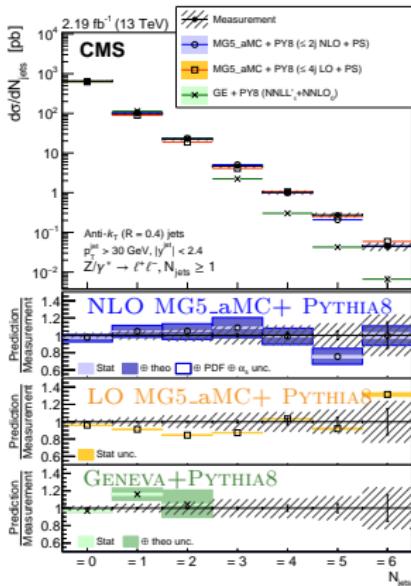
- ▶ $p_T(\ell) \geq 20 \text{ GeV}, |\eta(\ell)| \leq 2.4$ and $71 \leq m_{\ell^+ \ell^-} \leq 111 \text{ GeV}$
- ▶ $p_T(j) \geq 30 \text{ GeV}, |y(j)| \leq 2.4, \Delta R(j, \ell) > 0.4$

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

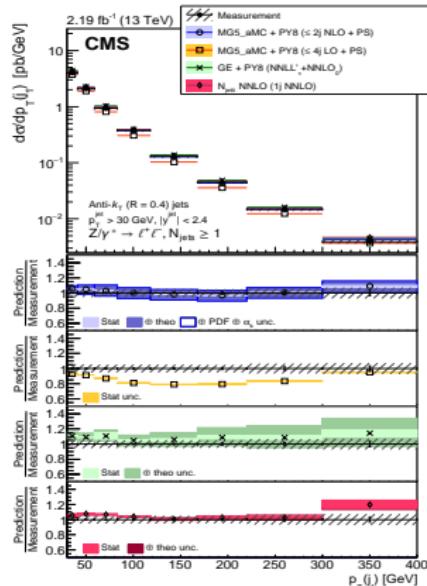


Signal: NLO MG5_aMC

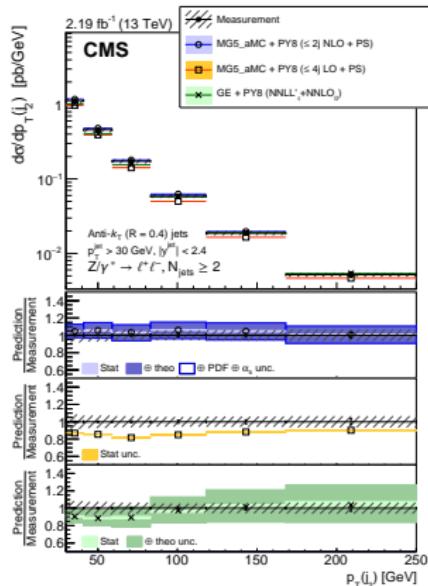
N_{jets}



Leading jet p_T :



Subleading jet p_T :



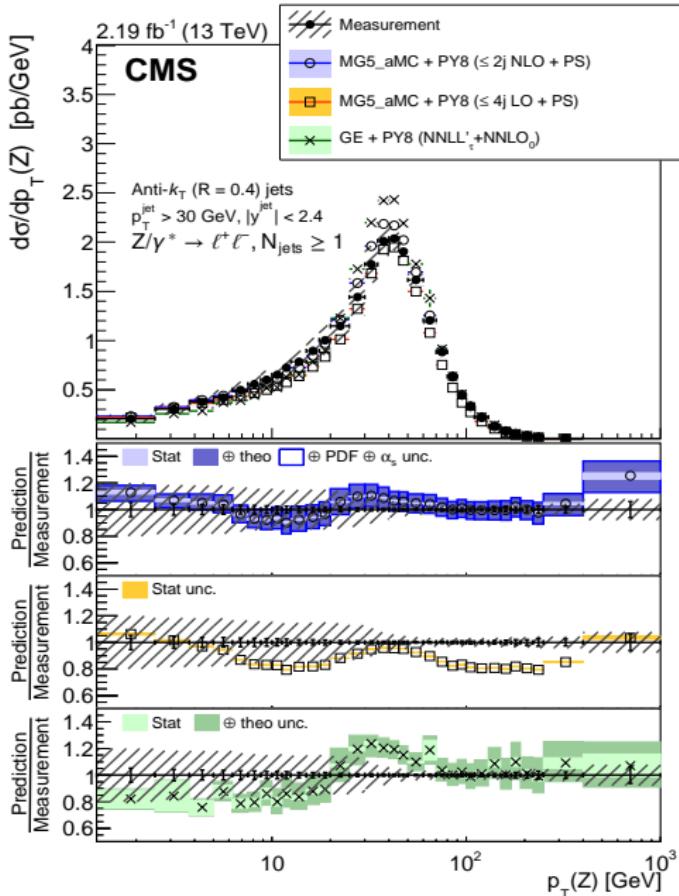
- NLO correction is needed to describe the measurements (jet p_T shape)

GENEVA (NNLL'+NNLO) describes the data up to $N_{\text{jets}}=2$ 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 $N_{\text{jets}} \geq 1$



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 :

- all samples are interfaced with PYTHIA8 with CUETP8M1 tune
- NLO MG5_aMC is best in describing the data
- GENEVA is below the data but describes 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

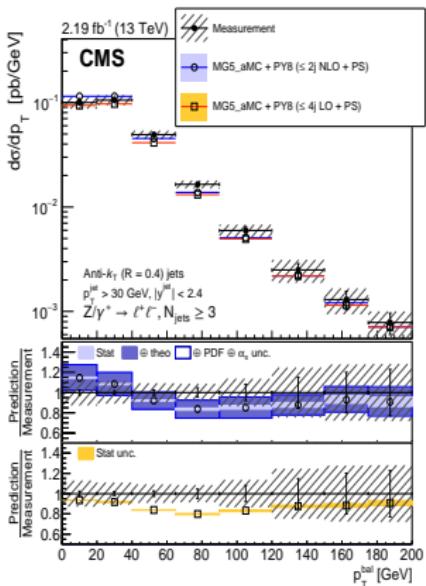
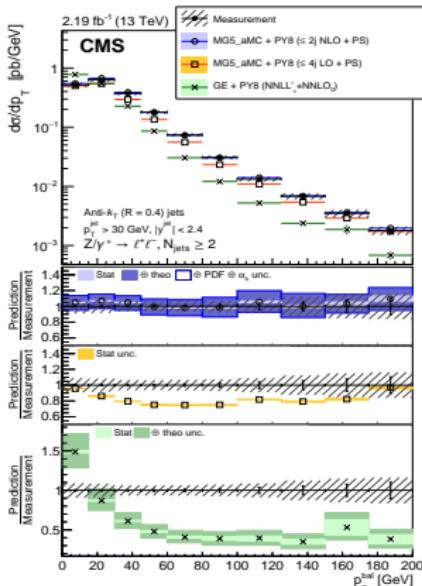
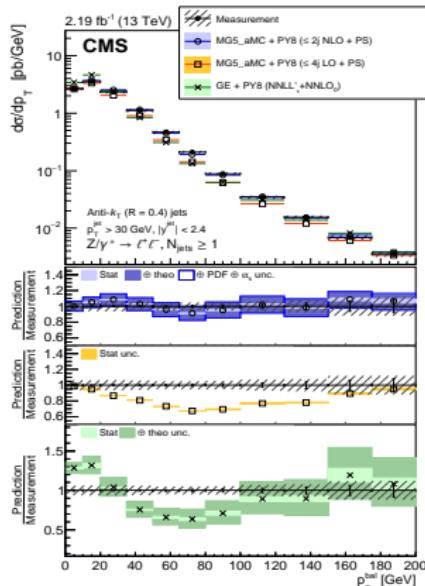
- ▶ p_T balance between the Z boson and the vector sum of the jets:

$$p_T^{\text{bal}} = |\vec{p}_T(\text{Z}) + \sum_{\text{jets}} \vec{p}_T(\text{j}_i)|, \text{ for } N_{\text{jets}} \geq 1, 2, 3$$

The imbalance is caused by:

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



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

Imbalance (large p_T^{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_T^{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

$W(\rightarrow \mu\nu) + \text{jets}$ at 13 TeV (Phys.Rev.D 96 (2017) 072005)

- ▶ Integrated luminosity of 2.2 fb^{-1}

Phase Space at Generator Level:

- ▶ $p_T(\mu) \geq 25 \text{ GeV}, |\eta(\mu)| \leq 2.4$ and $M_T(W) > 50 \text{ GeV}$
- ▶ $p_T(j) \geq 30 \text{ GeV}, |y(j)| \leq 2.4, \Delta R(j, \mu) > 0.4$

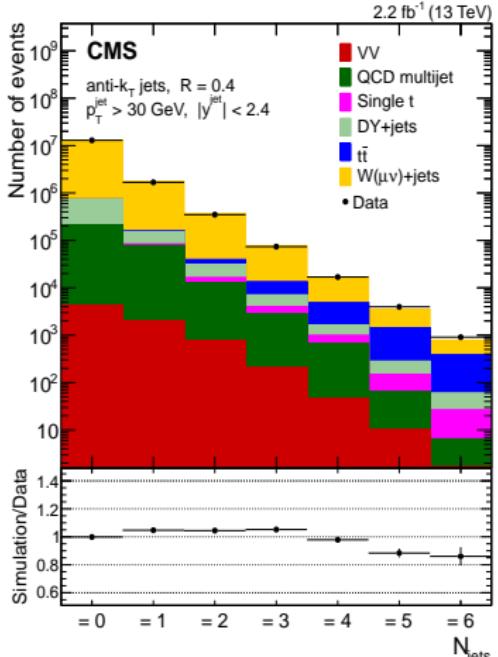
Bin-to-bin migration due to limited detector resolution corrected using unfolding method

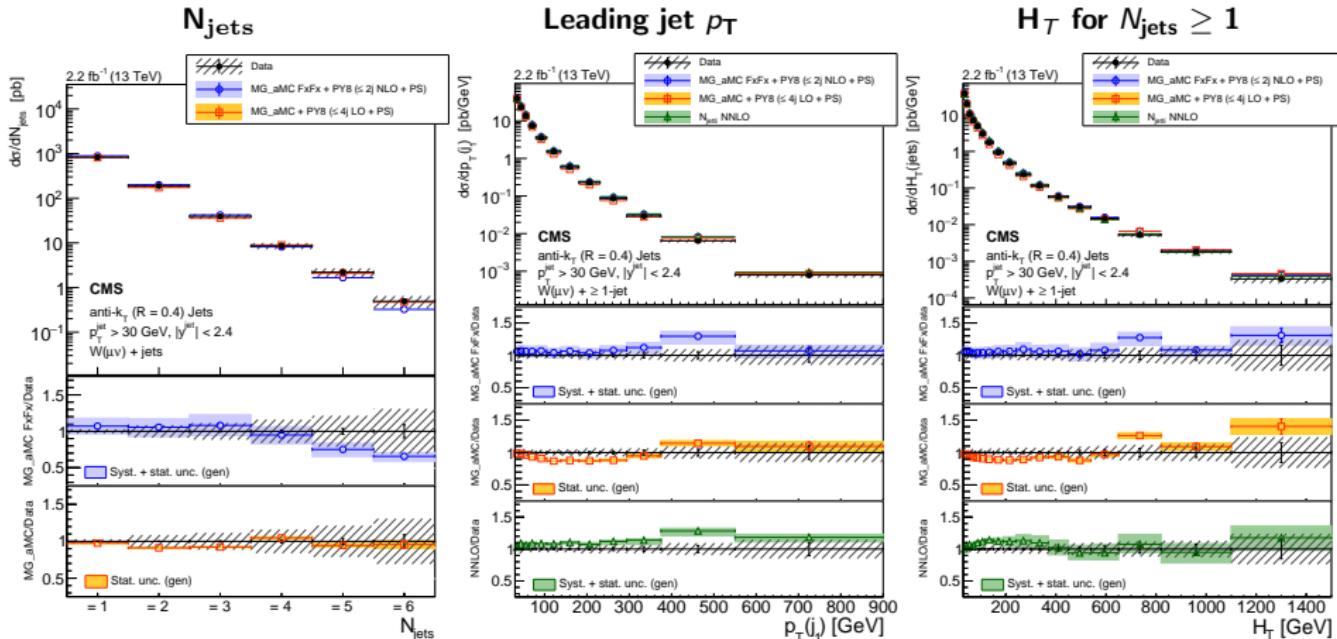
Theoretical prediction for cross section:

- ▶ LO MG5_aMC+ PYTHIA8
- ▶ NLO MG5_aMC+ PYTHIA8
- ▶ W+1 jet fixed order NNLO

Phys. Rev. D 94 (2016) 113009, Phys. Rev. Lett. 115 (2015)

- ▶ Correction for hadronization and multiple parton interaction computed with NLO MG5_aMC+ PYTHIA8 as differential scaling factors
- ▶ NNPDF 3.0 NNLO PDF



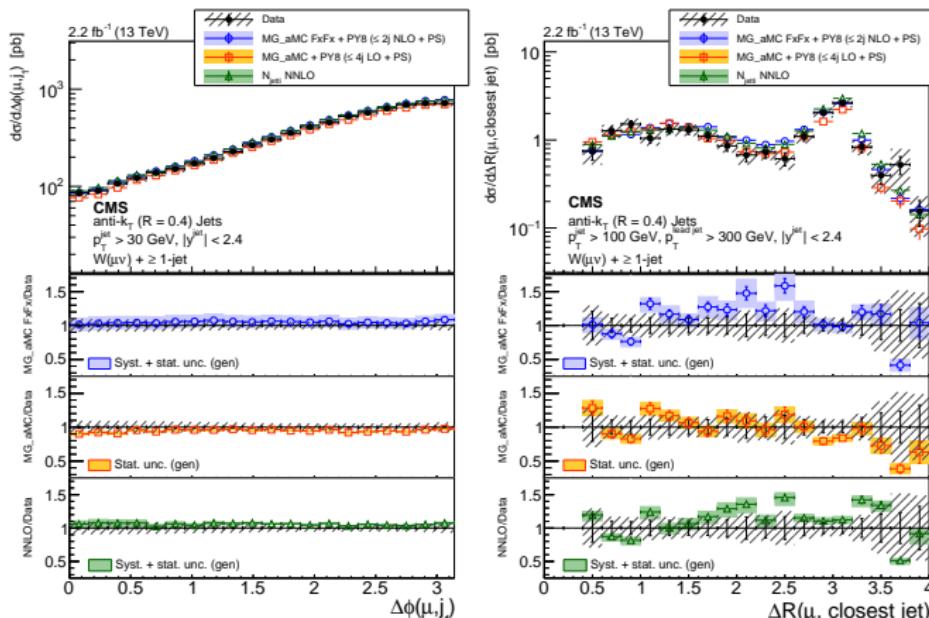


NLO MG5_aMC+Pythia8
 LO MG5_aMC+Pythia8
 W+1 jet fixed order NNLO

- ▶ LO MG5_aMC underestimates data at low and moderate p_T of leading jet and H_T
- ▶ NLO MG5_aMC and W+1 jet fixed order NNLO perform better for leading jet p_T and H_T

Angular variables: $\Delta\phi(\mu, \text{jet})$ and $\Delta R(\mu, \text{closest jet})$

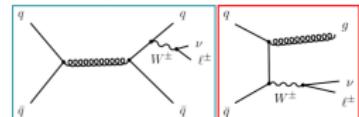
- ▶ $\Delta\phi(\mu, \text{jet})$ is sensitive to the implementation of particle emissions and other (non)perturbative effects modeled by PS algorithms in event generators
- ▶ $\Delta R(\mu, \text{closest jet})$ probes contribution of electroweak radiative processes to W+jets



$$p_T(j) > 100 \text{ GeV}$$

$$p_T(j_1) > 300 \text{ GeV}$$

small ΔR : collinear W emission



large ΔR : W balanced by a hadronic recoil

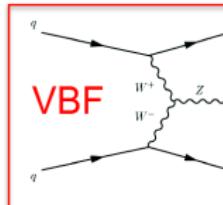


- ▶ $\Delta\phi(\mu, \text{jet})$: all predictions accurately describe the data
- ▶ $\Delta R(\mu, \text{closest jet})$: predictions are in fairly good agreement with data within the uncertainties

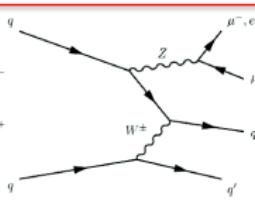
EWK Z + 2 jets 13 TeV (arXiv:1712.09814)

- ▶ Pure EW Z ($\rightarrow \ell^+ \ell^-$) + 2-jets final state

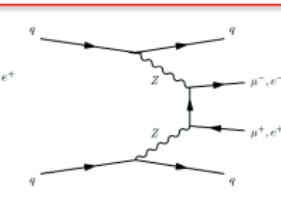
Vector boson fusion:



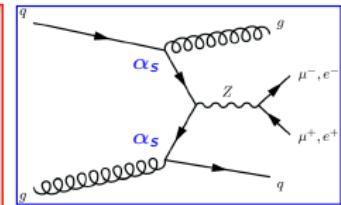
Bremsstrahlung-like:



Multiperipheral production:



Electroweak production

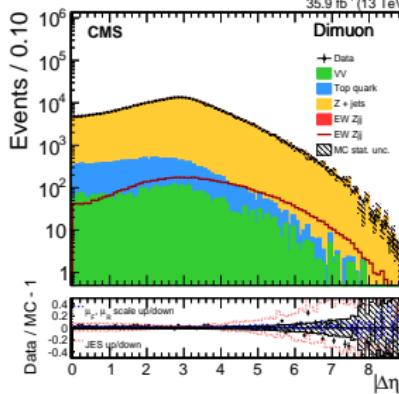
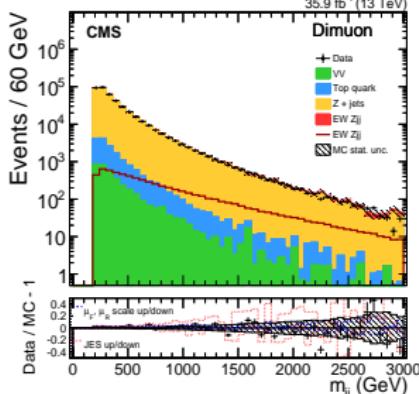
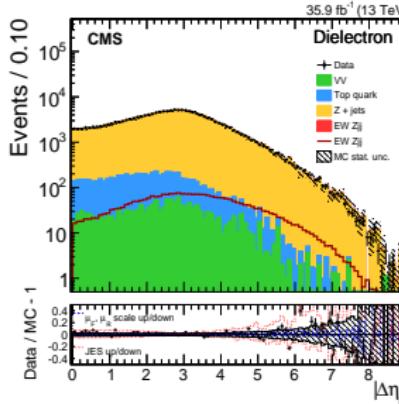
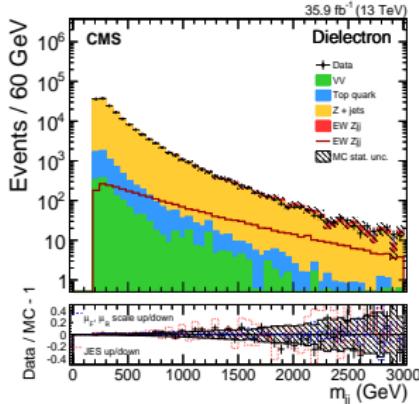


Strong production

- ▶ Properties of EW Zjj signal events:
 - ▶ well-separated jets in rapidity with large m_{jj} , and a central decay of a Z boson
 - ▶ suppressed color flow in the region between the two jets (low hadronic activity in the rapidity interval)
- ▶ Integrated luminosity of 35.9 fb^{-1}
- ▶ The first observation for this process at 13 TeV
- ▶ Cross section measured in the kinematic region defined as:
 $p_T(j) > 25 \text{ GeV}$, $m_{jj} > 120 \text{ GeV}$, $m_{\ell^+\ell^-} > 50 \text{ GeV}$

BDT variables

Several discriminating variables used to achieve the best separation between DY Z+2jet and EW Z+2jet signal.



Discriminating variables:

m_{jj} , $\Delta\eta_{jj}$, $R(p_T^{\text{hard}})$, $z^*(Z)$,
 p_{Tjj} , quark/gluon likelihood
(QGL) of the two tagging jets

$$R(p_T^{\text{hard}}) = \frac{|\vec{p}_{Tj_1} + \vec{p}_{Tj_2} + \vec{p}_{TZ}|}{|\vec{p}_{Tj_1}| + |\vec{p}_{Tj_2}| + |\vec{p}_{TZ}|}$$

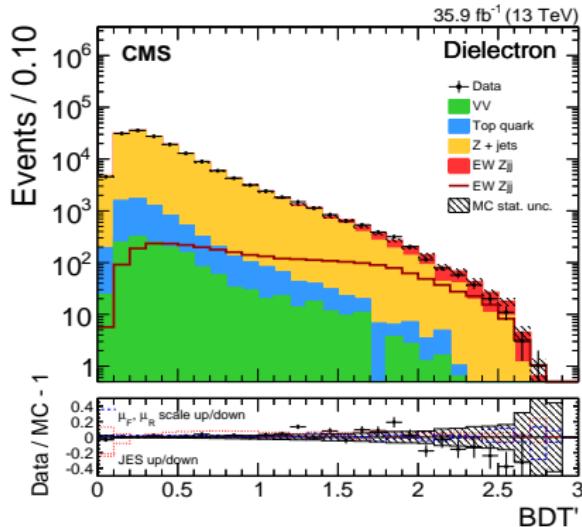
$$y^* = yz - \frac{1}{2}(y_{j1} + y_{j2})$$

$$z^* = \frac{y^*}{\Delta\eta_{jj}}$$

MG5_aMC+ Pythia8:

EW Zjj (LO MG5_aMC)
DY Zjj (NLO MG5_aMC)
DY Zjj (LO MG5_aMC)

Good agreement between
data and MC predictions



$\text{BDT} > 0.92 \Rightarrow$ region with 50% EW Zjj

- ▶ $\sigma(\text{EW } \ell\ell jj) = 552 \pm 19(\text{stat}) \pm 55(\text{syst}) \text{ fb}$
in agreement with SM LO prediction by
MG5_aMC+PYTHIA8

Gap veto efficiency: fraction of events with a measured gap activity below a given threshold.

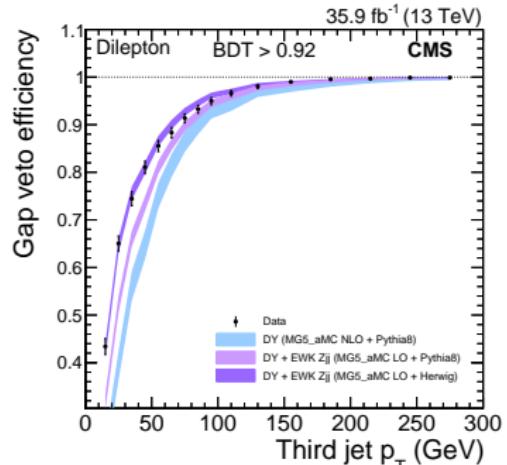
Data disfavour bgd only predictions;
Bkg+Signal model with [HERWIG](#) do better at low
gap activity values
[HERWIG](#) and [PYTHIA8](#) describe larger gap activity

Signal extraction:

Distribution of BDT discriminant used to extract cross-section.

Shown envelopes for dominant uncertainties:
JES and QCD scales.

Simultaneous fit of EW and QCD component in the signal (high BDT) and control (low BDT) regions.



Outlook

The measurements of vector boson plus jets processes are quite important:

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

Z/W+jets

- ▶ 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 multiparton 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

EWK Z + 2 jets

- ▶ first observation of the EW Zjj production at 13 TeV
- ▶ measured cross section is in agreement with SM prediction with $\sim 10\%$ precision

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}	$\frac{d\sigma}{dN_{\text{jets}}}$ [pb]	Tot. unc [%]	Stat [%]	JES [%]	JER [%]	Eff [%]	Lumi [%]	Bkg [%]	Pileup [%]	Unf model [%]
=0	652	3.0	0.091	1.1	0.046	1.5	2.3	<0.01	0.22	—
=1	97.9	5.1	0.27	4.3	0.18	1.5	2.3	0.012	0.30	—
=2	22.2	7.3	0.63	6.7	0.20	1.6	2.3	0.026	0.43	—
=3	4.68	10	1.4	9.9	0.39	1.7	2.3	0.13	0.29	—
=4	1.01	11	3.5	10	0.24	1.7	2.3	0.43	0.56	—
=5	0.275	14	5.0	12	0.081	2.0	2.3	1.2	0.29	—
=6	0.045	24	15	17	0.36	1.8	2.4	3.5	1.7	—