Electroweak Boson Production With Jets at CMS

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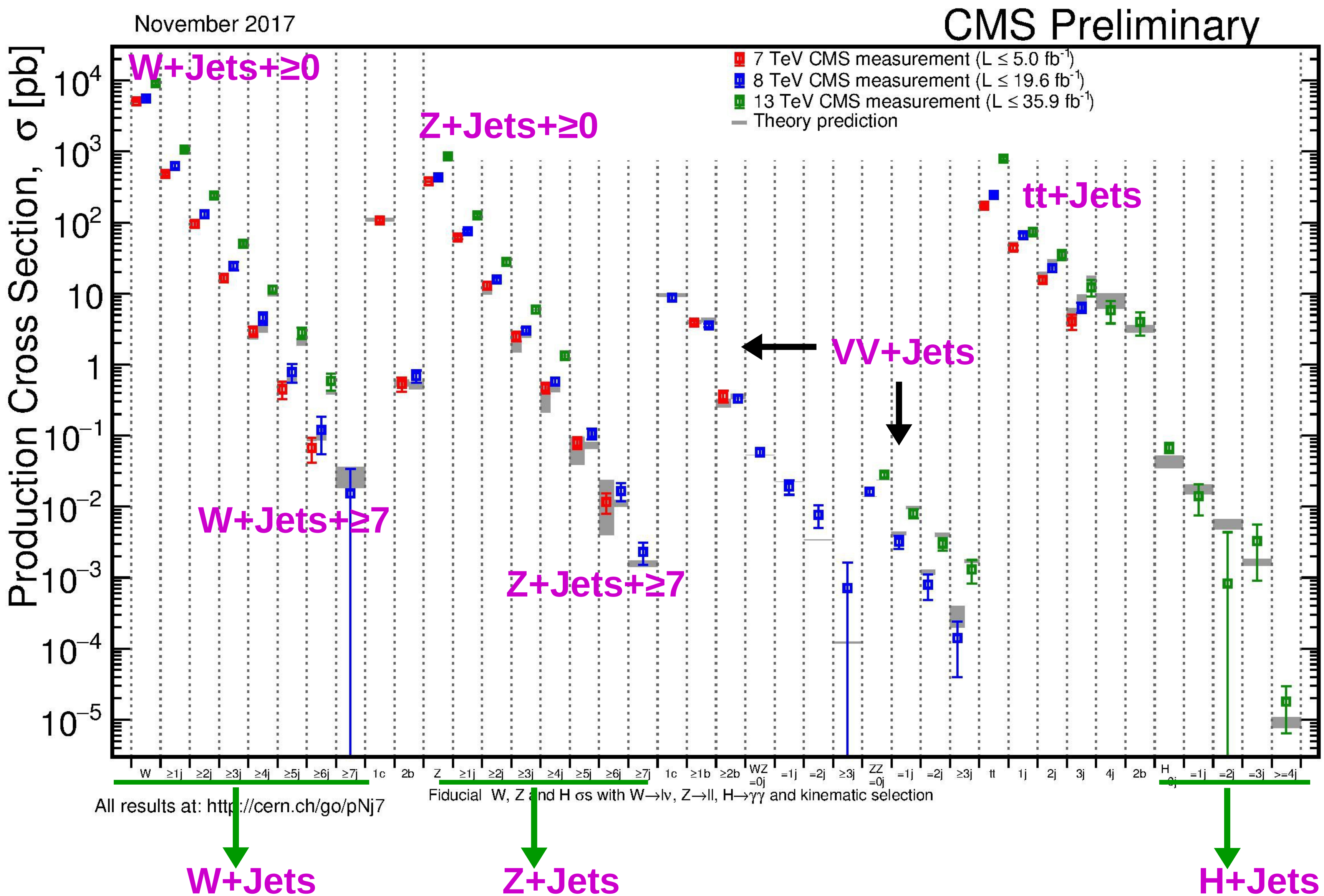
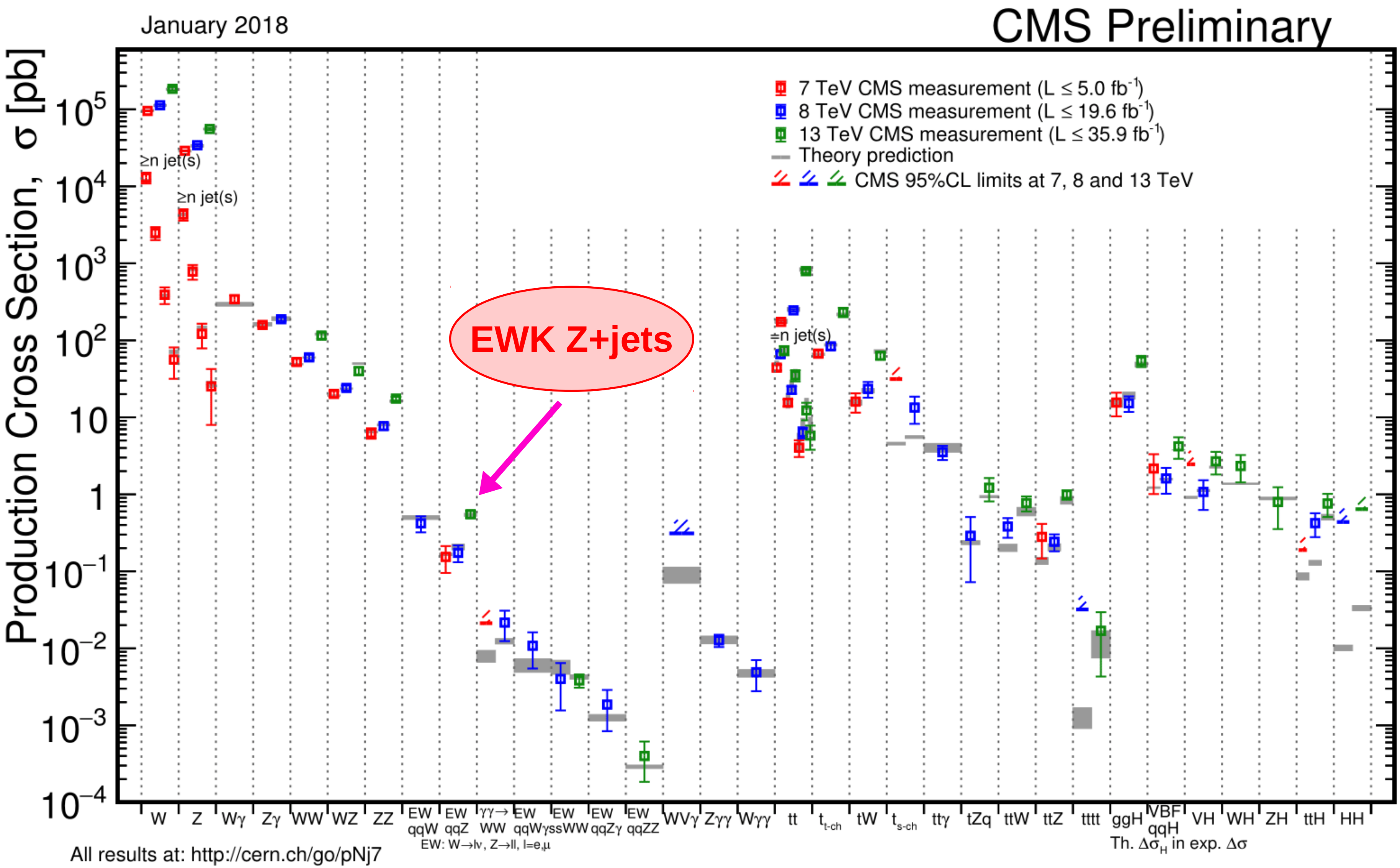
30th Rencontres de Blois-Particle Physics and Cosmology
3-8 June 2018, Blois (France)

Standard Model Production Cross Section Measurements



Today's talk
- Z+jets and W+jets at 13 TeV **(pp collisions 2015)**
- EWK Z+2jets at 13 TeV **(pp collisions 2016)**

Standard Model Production Cross Section Measurements



Today's talk
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- EWK Z+2jets at 13 TeV **(pp collisions 2016)**

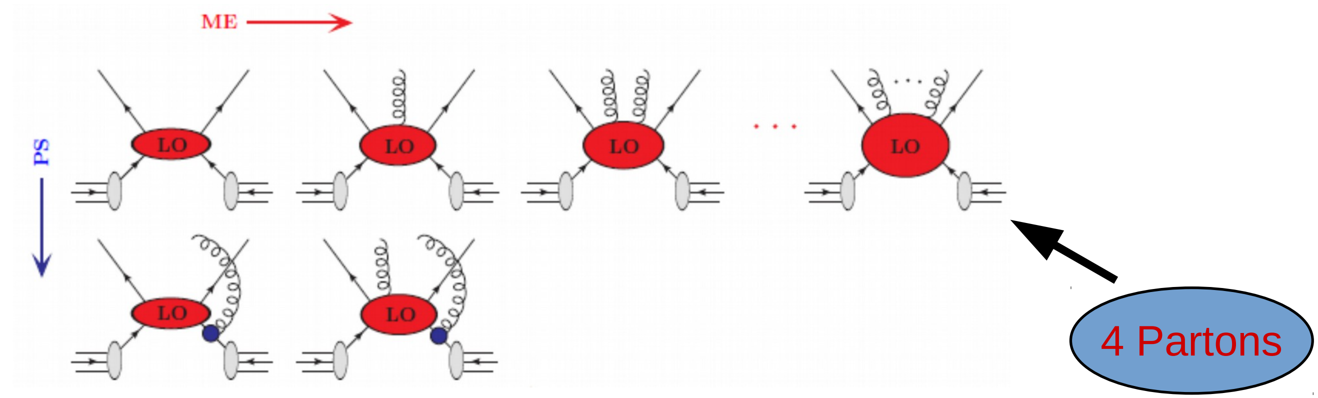
Motivation

- 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 ($H \to bb$)
  - Searches of new particles
- To understand differences between QCD and EWK production.
- Comparison of data with predictions allows further Monte Carlo generator development and reduction of systematic uncertainties.

Theoretical prediction for Z+jets cross section

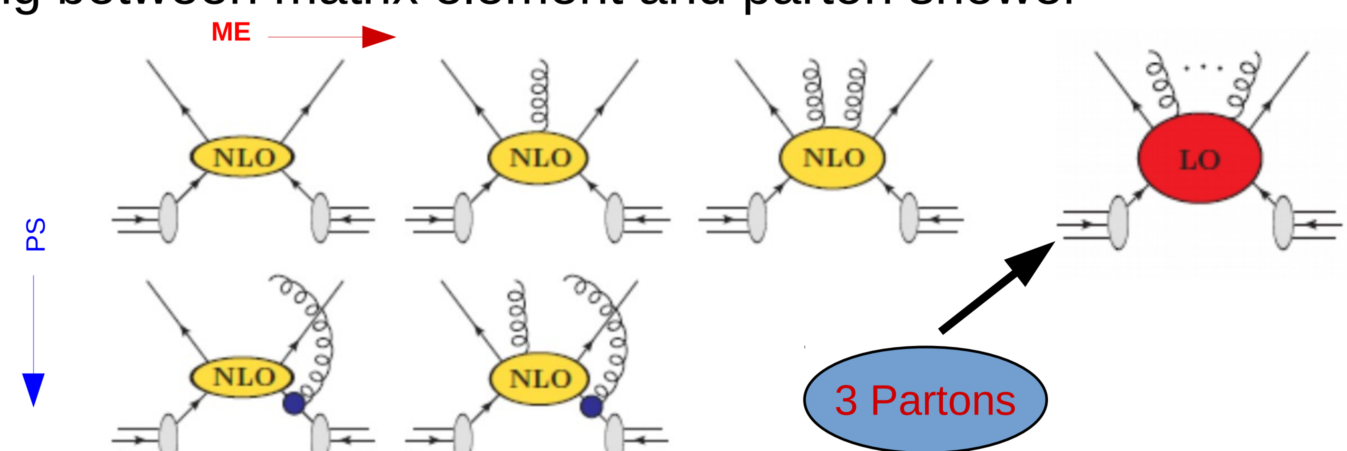
- MADGRAPH5_AMC@NLO + Pythia8 (denoted as LO MG5_aMC)
  - LO matrix element up to 4 partons
  - k_T-MLM merging between matrix element and parton shower

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



Theoretical prediction for Z+jets cross section

Phys. Rev. D 94 (2016) 074015,
Phys. Rev. Lett. 116 (2016) 152001)

Z+1jet fixed order NNLO

- 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 (≡ beam-thrust) dependence resummed at NNLL'
- $d\sigma_{\geq 0j}$ at NNLO, $d\sigma_{\geq 1j}$ at NLO, $d\sigma_{\geq 2j}$ at LO

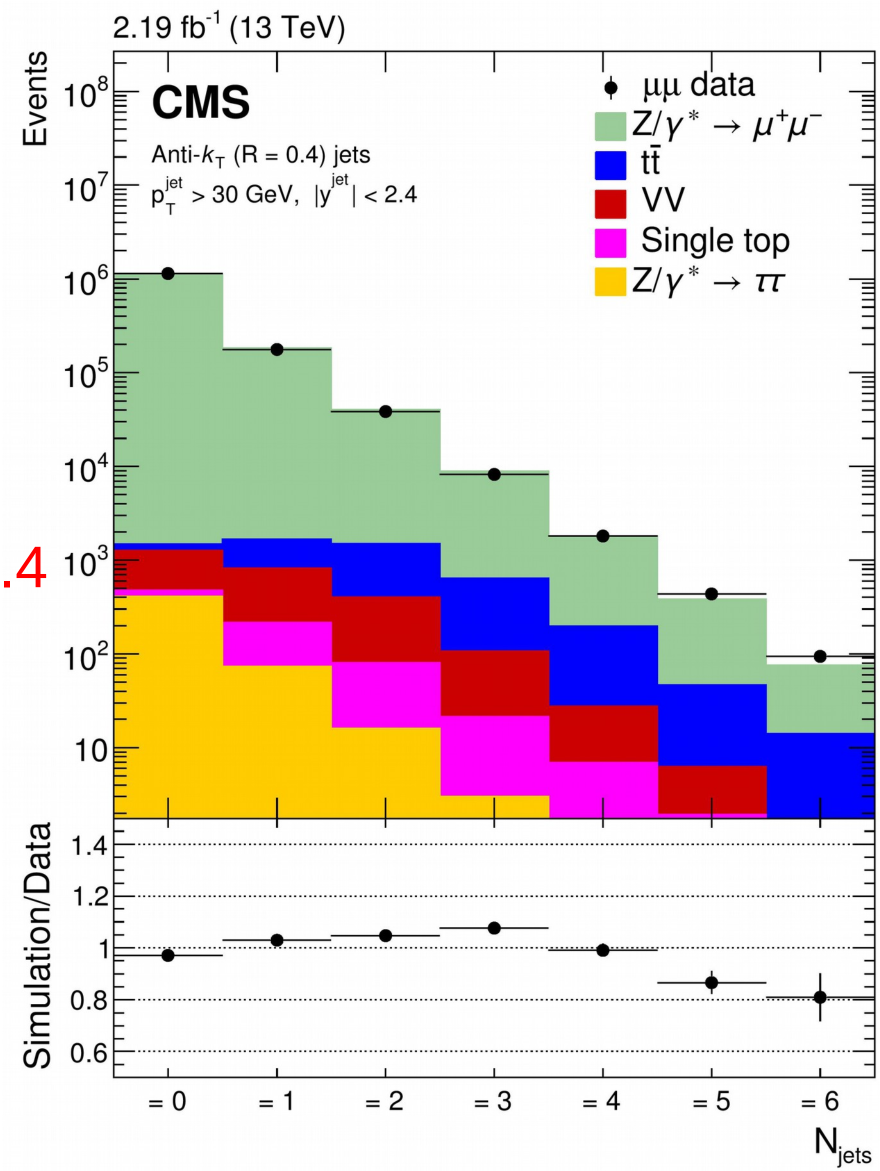
PDF4LHC15 NNLO
CUETP8M1 Pythia8 tune

Samples	0j	1j	2j	3j	4j	>4j	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	NLO	NLO	LO	PS	PS	PS	5940 (native)
Z+1 jet at NNLO	-	NNLO	NLO	LO	-	-	134.6 (native)

arXiv:1804.05252

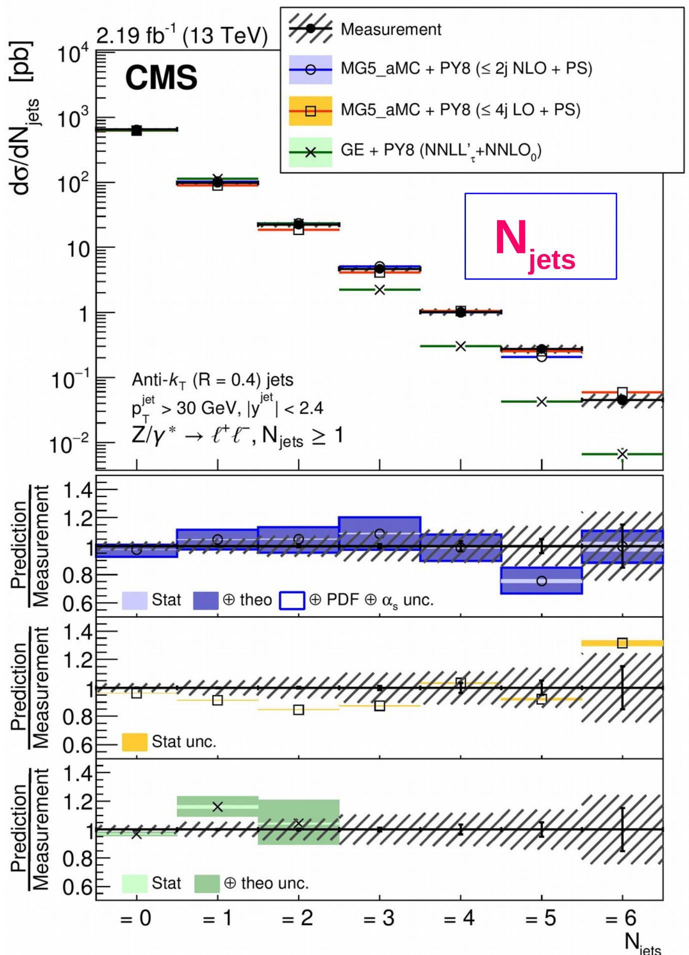
pp collisions 2015

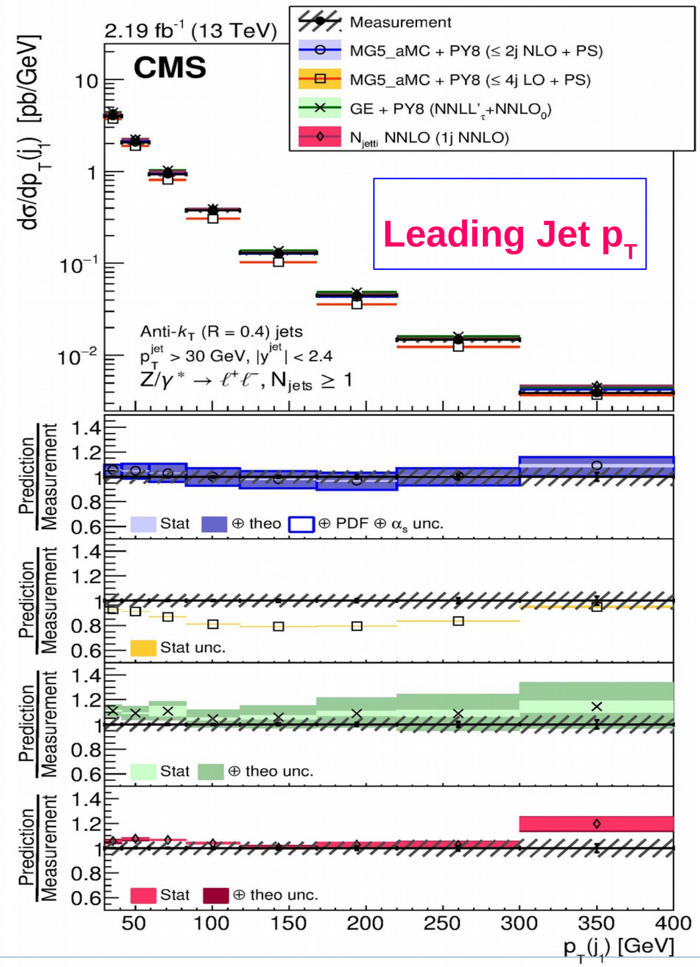
- Data Sample:
  - Integrated luminosity 2.19 fb^{-1}
- Phase Space at Generator Level:
  - $p_T(\ell) \geq 30$ GeV, $|\eta(\ell)| \leq 2.4$
  - $71 \leq m(\ell^+\ell^-) \leq 111$ GeV
  - $p_T(j) \geq 30$ GeV, $|y(j)| \leq 2.4$, $\Delta R(j,\ell) > 0.4$
- Bin-to-bin migration due to limited detector resolution → corrected using detector unfolding method

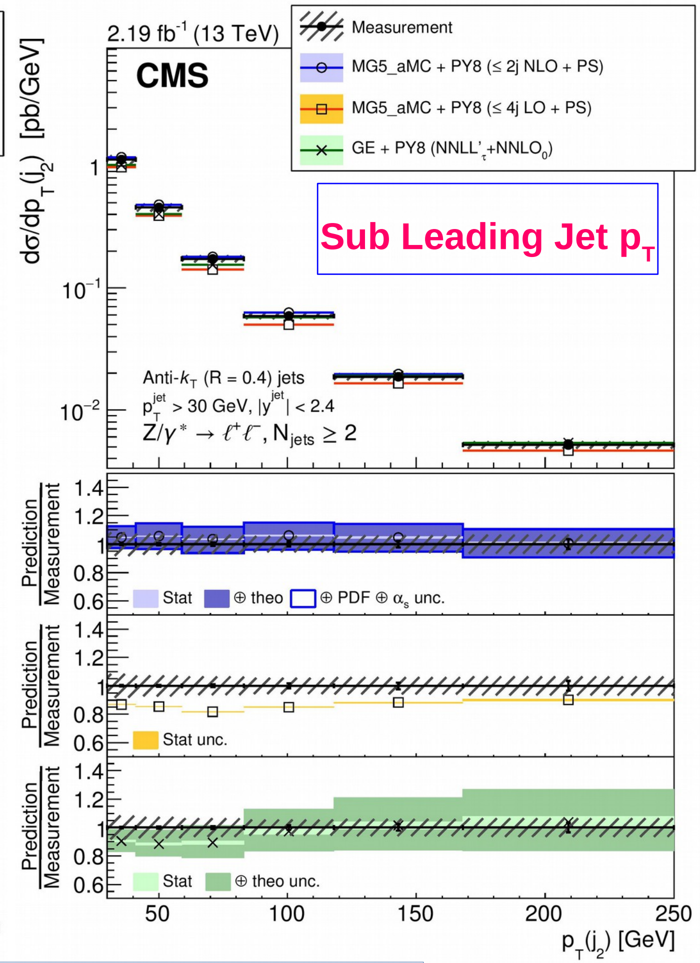


Differential Cross Sections of $Z(\rightarrow \ell^+ \ell^-)$+Jets

arXiv:1804.05252







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

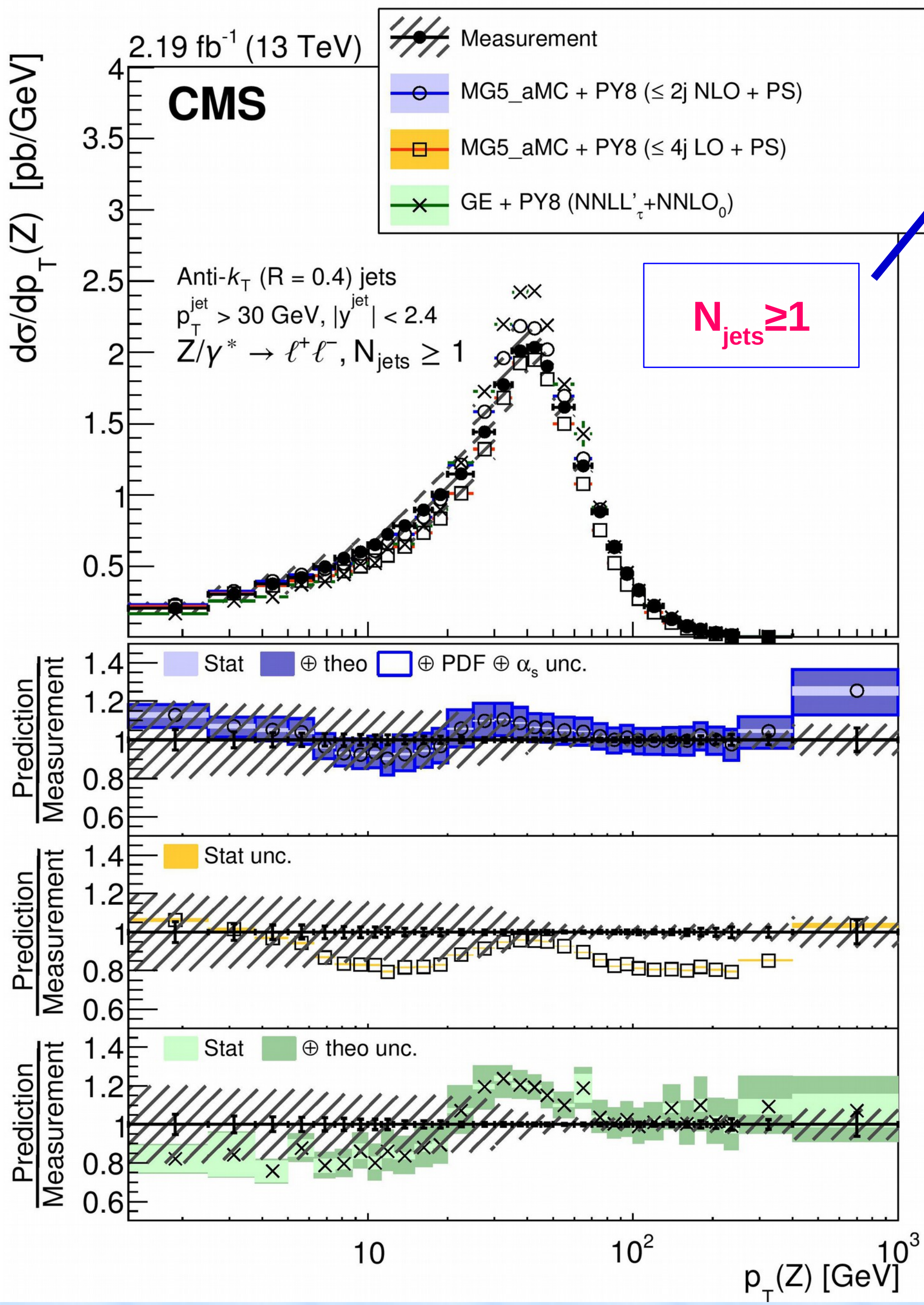
Geneva (NNLL'+NNLO) describes the data up to N jets =2 but but fails to describe the data for higher jet multiplicities

Z+1jet 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

arXiv:1804.05252



Shifts the peak toward the higher values → possibility of studying multiple gluon emissions away from the non-perturbative region

- **At low p_T:**
  - NLO MG5_aMC is best in describing the data
  - Geneva is below the data but describes the shape of the distribution < 10 GeV.
  - Geneva is LO below the jet cut (30 GeV)
- **At high p_T:**
  - Geneva and NLO MG5_aMC describe the data
  - LO MG5_aMC shows different shape from data

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

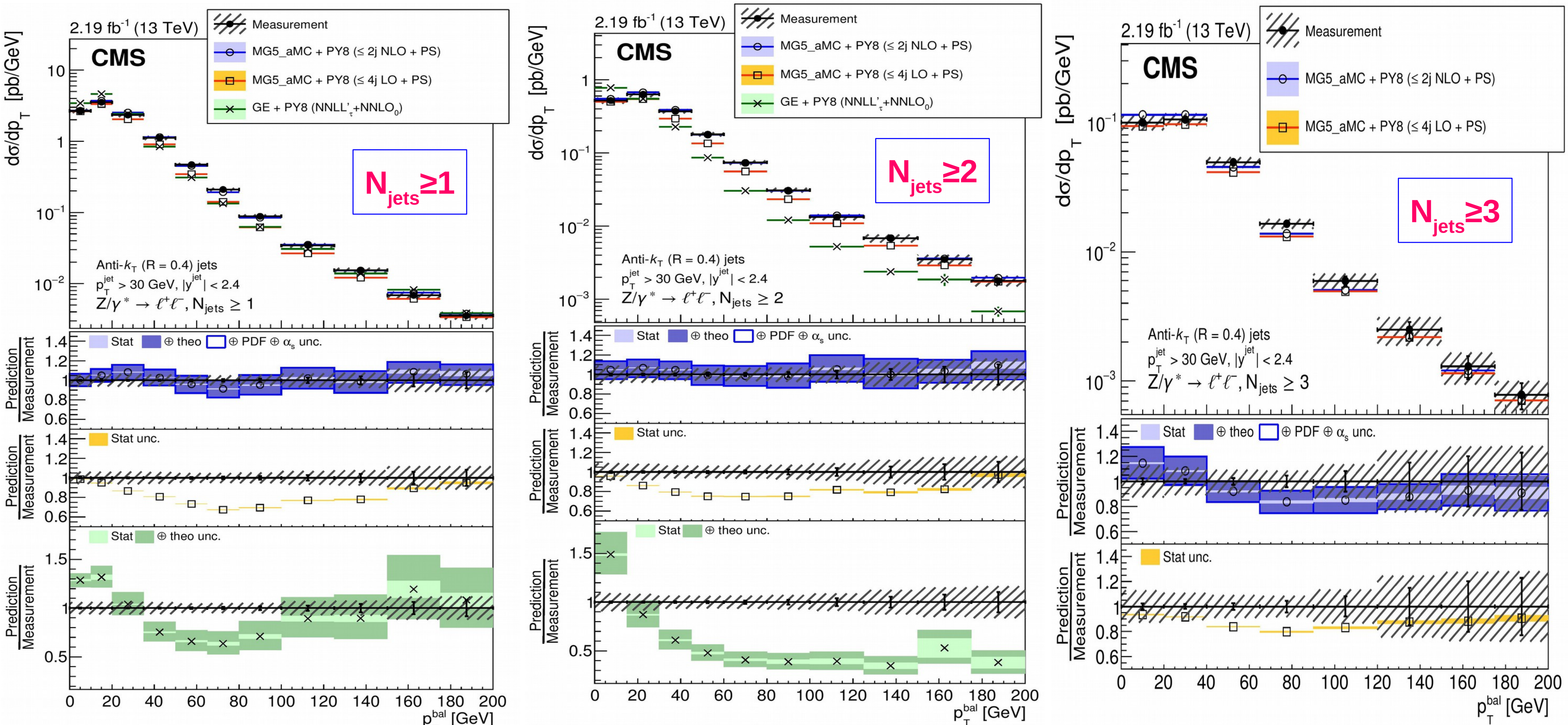
$$\vec{p}_T^{\,bal} = |\, \vec{p}_T(Z) + \Sigma_{jets} \vec{p}_T(j_i)\, |$$

for $N_{jets} \geq 1,2,3$

- The imbalance is caused by:
  - Hadronic activity outside the jet acceptance:
    - $p_T \geq 30$ GeV, $|y| \leq 2.4$
  - This is dominant contribution
  - Gluon radiation in the central region, not clustered in a jet

Differential Cross Sections of $Z(\rightarrow \ell^+ \ell^-)$+Jets

arXiv:1804.05252



Imbalance (large p_T^{bal}) from two jets in the final state with one of them out of acceptance- NLO accuracy for **NLO MG5_aMC** sample and LO accuracy for others

Large p_T^{bal} : at least 2 jets in the acceptance and one is out
Geneva : 3rd jet is from PS improved precision for NNLO calculation

LO MG5_aMC and NLO MG5_aMC provide reasonable description of data

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

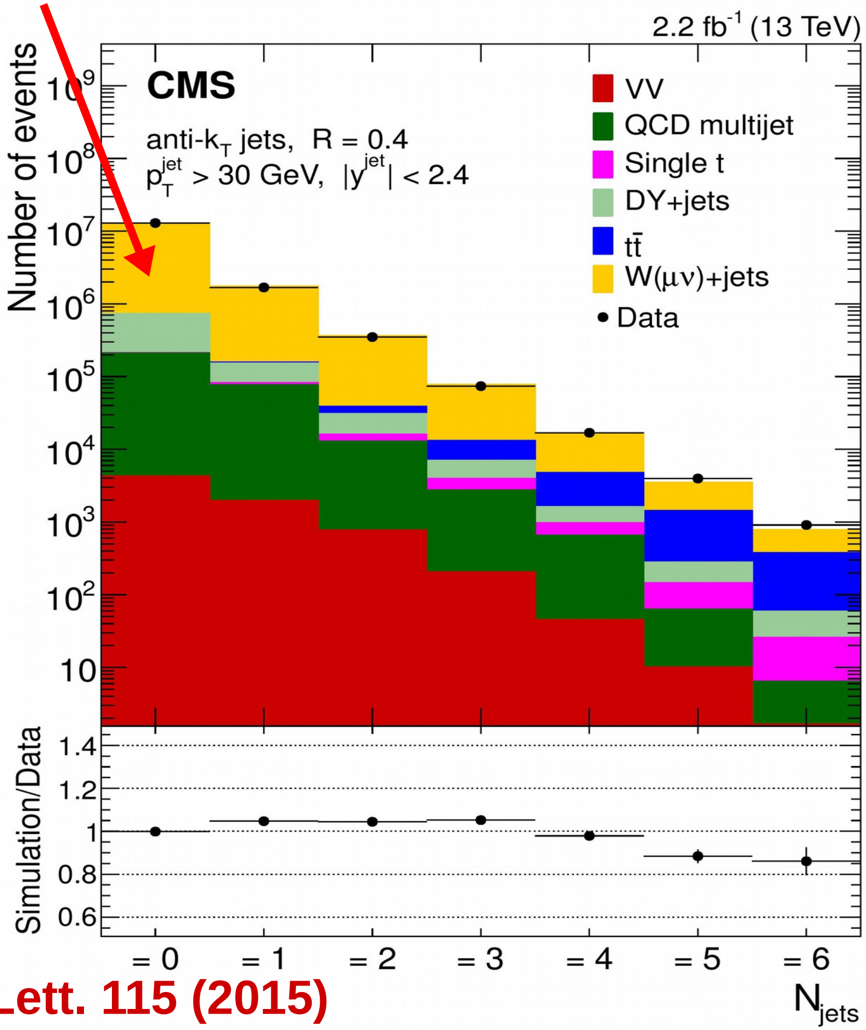
$W(\rightarrow \mu\nu)$+Jets at 13 TeV

Phys.Rev.D 96 (2017) 072005

pp collisions 2015

- Data Sample:
  - Integrated luminosity 2.2 fb^{-1}
- Phase Space at Generator Level:
  - $p_T(\mu) \geq 30$ GeV, $|\eta(\mu)| \leq 2.4$, $M_T > 50$GeV
  - $p_T(j) \geq 30$ GeV, $|y(j)| \leq 2.4$, $\Delta R(j,l) > 0.4$
- 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

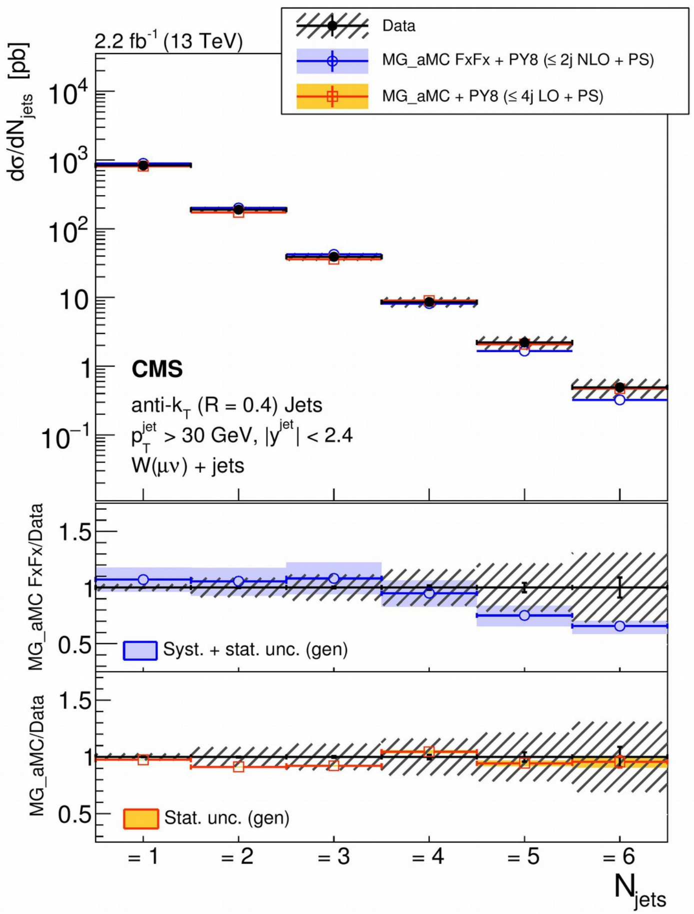
NLO MG5_aMC



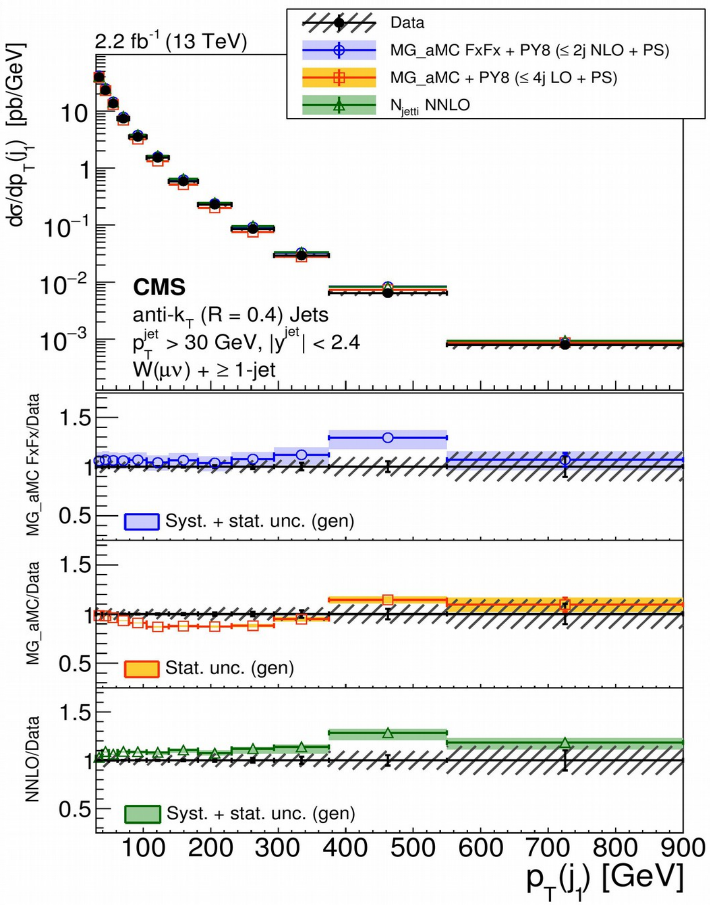
Differential Cross Sections of $W(\rightarrow \mu\nu)$+Jets

Phys.Rev.D 96 (2017) 072005

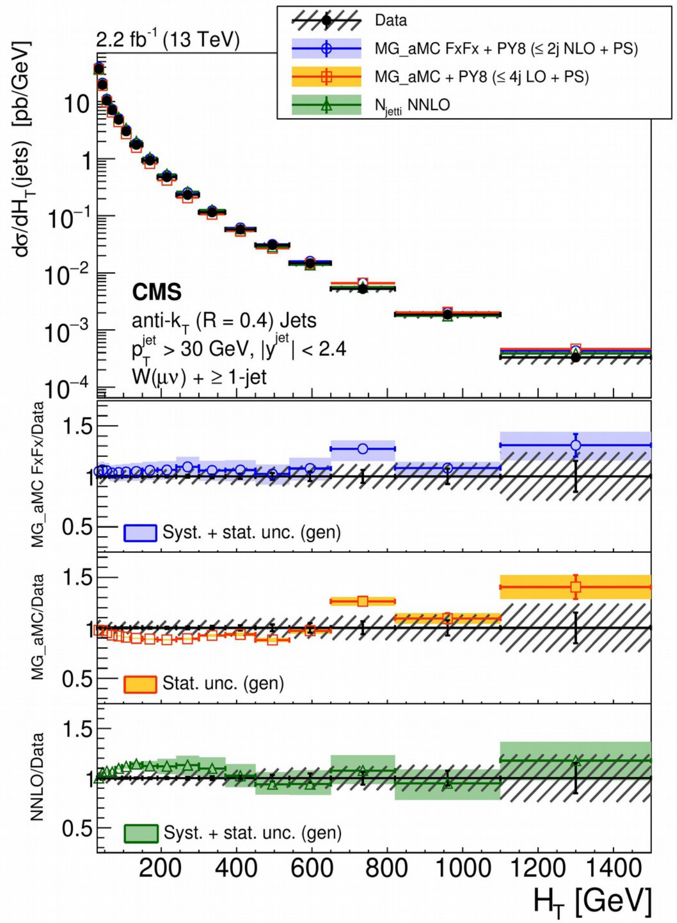
$N_{jets} \geq 1$



Leading jet p_T



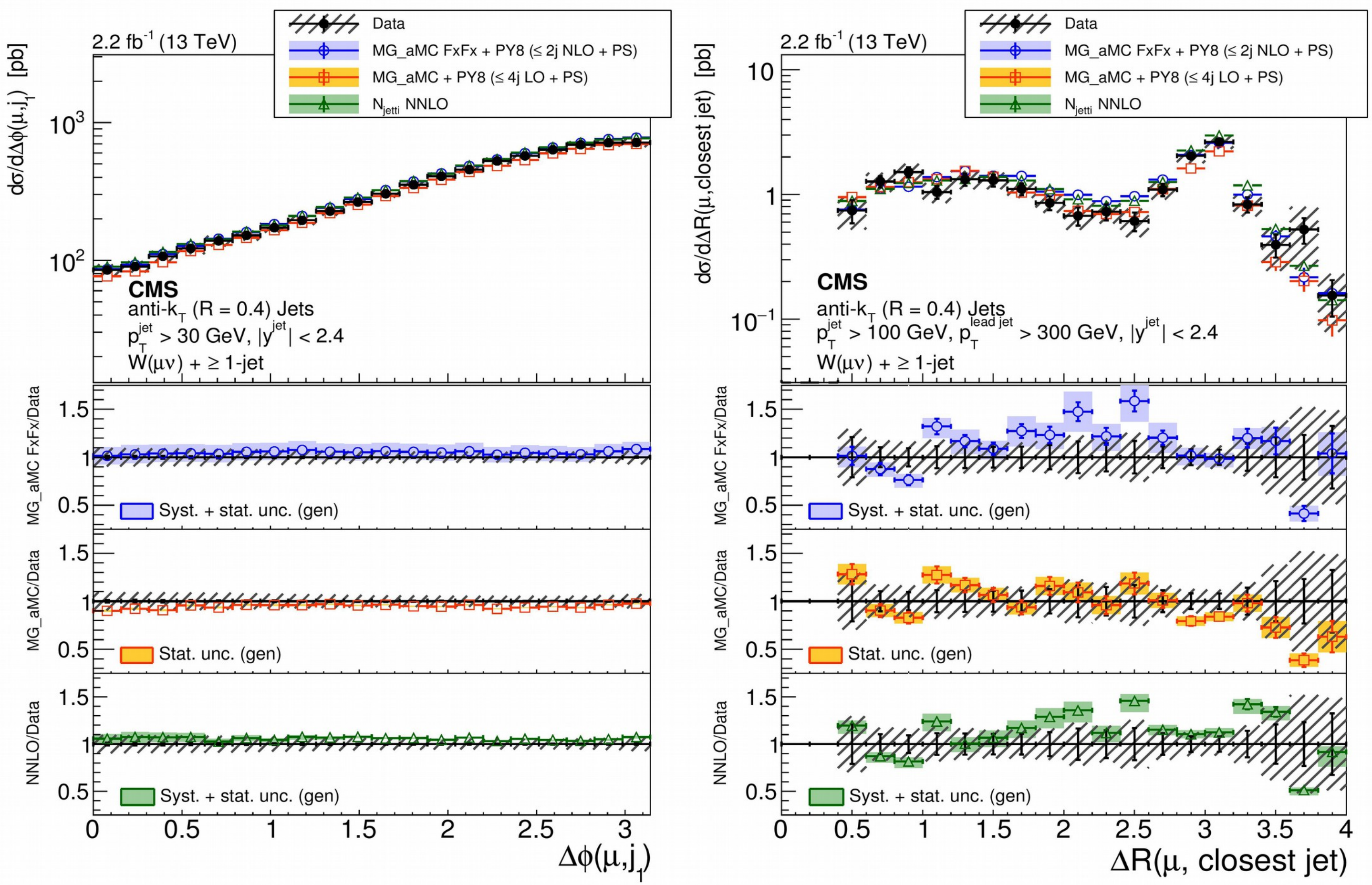
H_T for $N_{jets} \geq 3$



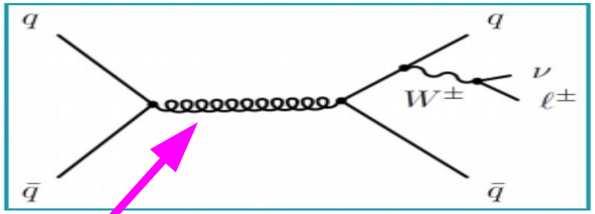
- **LO MG5_aMC** underestimates data at low and moderate p_T of leading jet and H_T
- **NLO MG5_aMC** and W+1 jet fixed order **NNLO** perform better for leading jet p_T and H_T

Phys.Rev.D 96 (2017) 072005

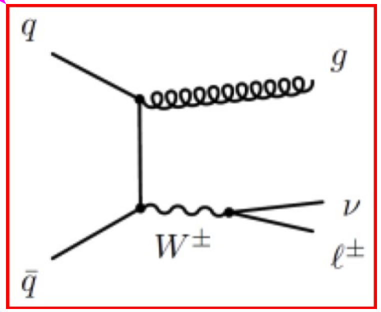
- **Δφ (μ, jet)** is sensitive to the implementation of particle emissions and other (non) perturbative effects modeled by PS algorithms in event generators
- **ΔR_{min} (μ, jet)** probes contribution of electroweak radiative processes to W+jets



$p_T(j)$ > 100 GeV
$p_T(j_1)$ > 100 GeV



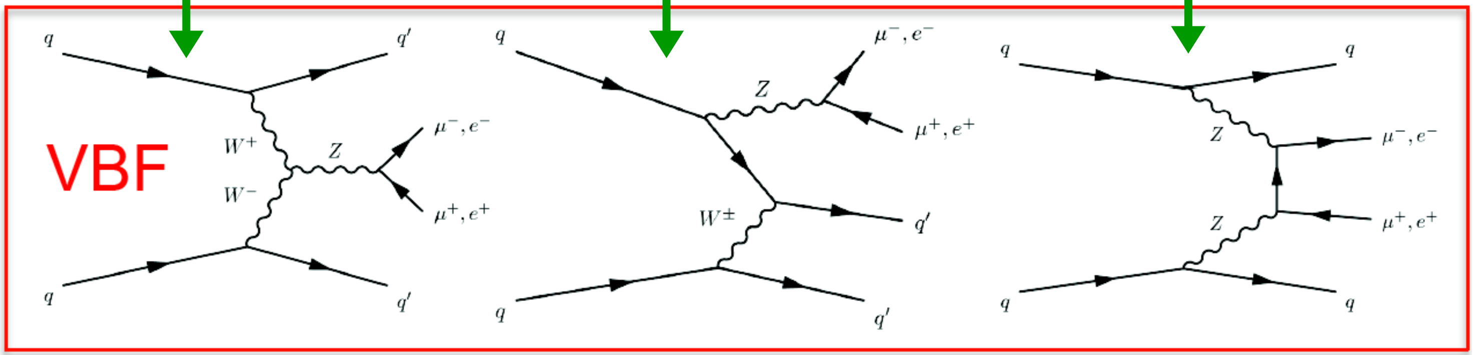
Small ΔR: collinear W emission
Large ΔR: W balanced by hadronic recoil



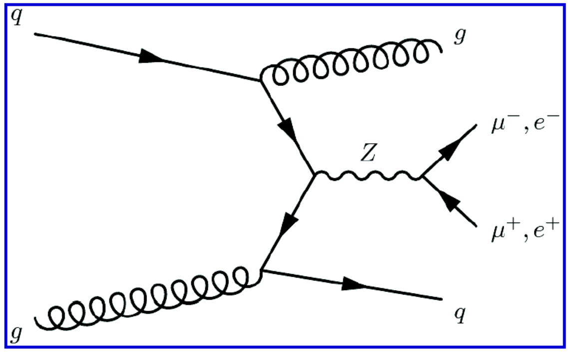
- Δφ(μ, jet): All predictions accurately describe the data
- ΔR_{min}(μ, jet): predictions are in fairly good agreement with data within the uncertainties

Pure EWK Z(→$\ell^+\ell^-$)+2Jets Final State

Vector boson fusion | Bremsstrahlung-like | Multiperipheral production



Electroweak production



Strong production

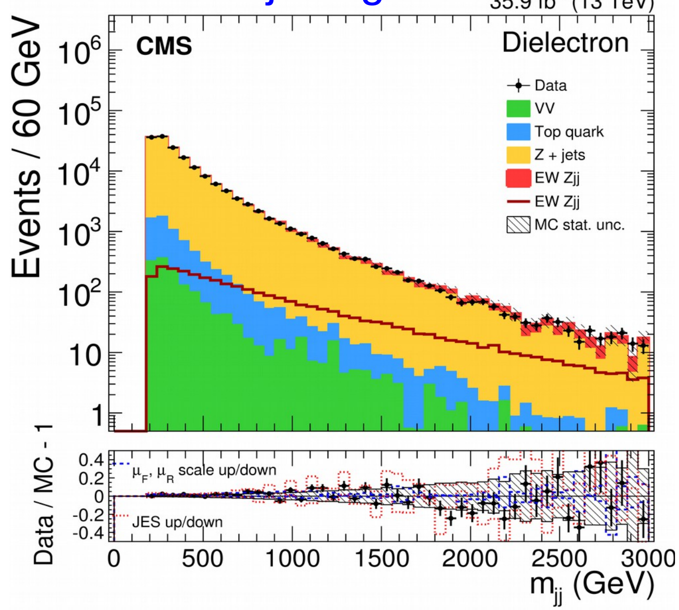
- **EW Zjj signal events are:**
  - Well-separated jets in rapidity with large m_{jj} and a central decay of a Z boson
  - Suppressed color flow in the region between the two jets (low hadronic activity in the rapidity interval)
- The first observation for this process at 13 TeV
- Integrated luminosity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

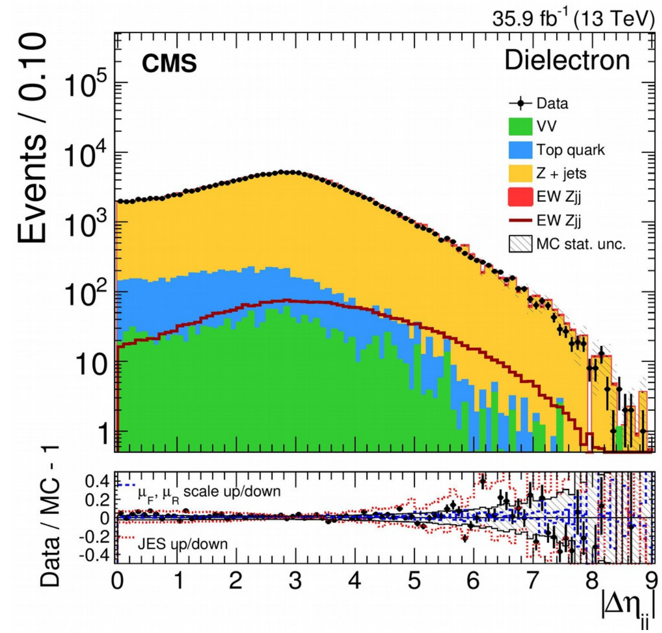
pp collisions 2016

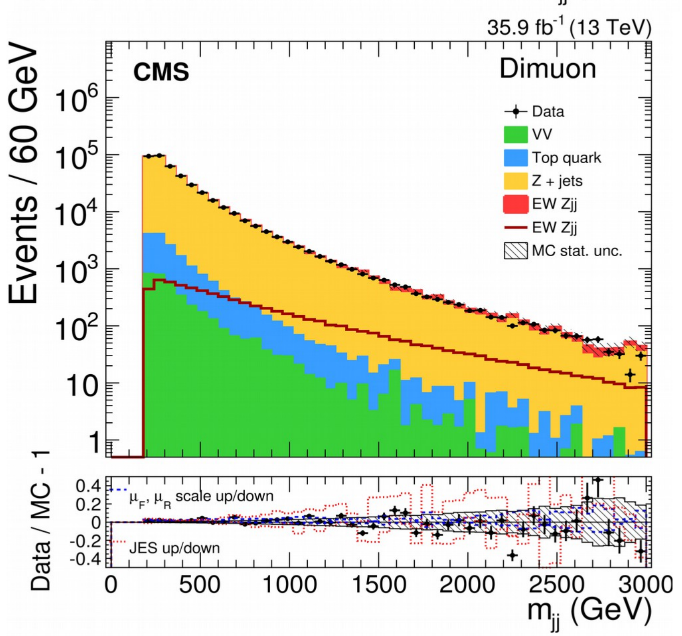
BDT Variables

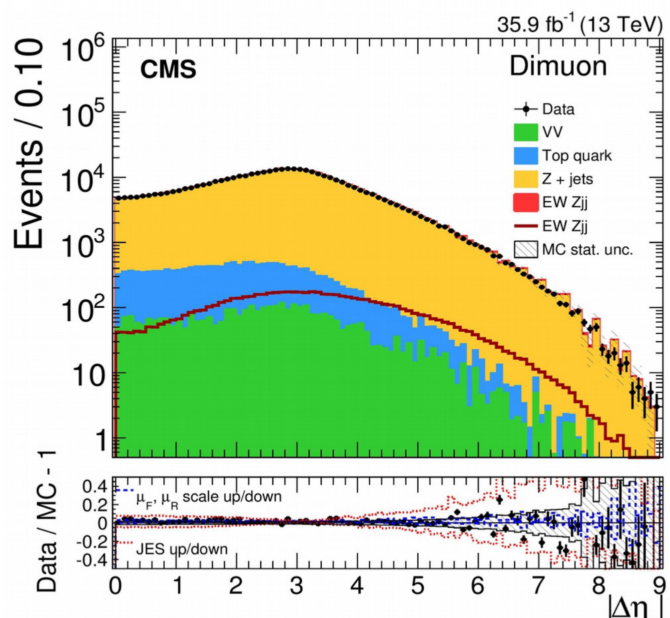
arXiv:1712.09814

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









Discriminating variables:

m_{jj} , $\Delta\eta_{jj}$, $R(p_T^{hard})$, $z^*(Z)$

p_{Tjj} , quark/gluon likelihood (QGL) of the two tagging jets

$$R(p_T^{hard}) = \frac{|\vec{p}_{Tj1}+\vec{p}_{Tj2}+\vec{p}_{TZ}|}{|p_{Tj1}|+|p_{Tj2}|+|p_{TZ}|}$$

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

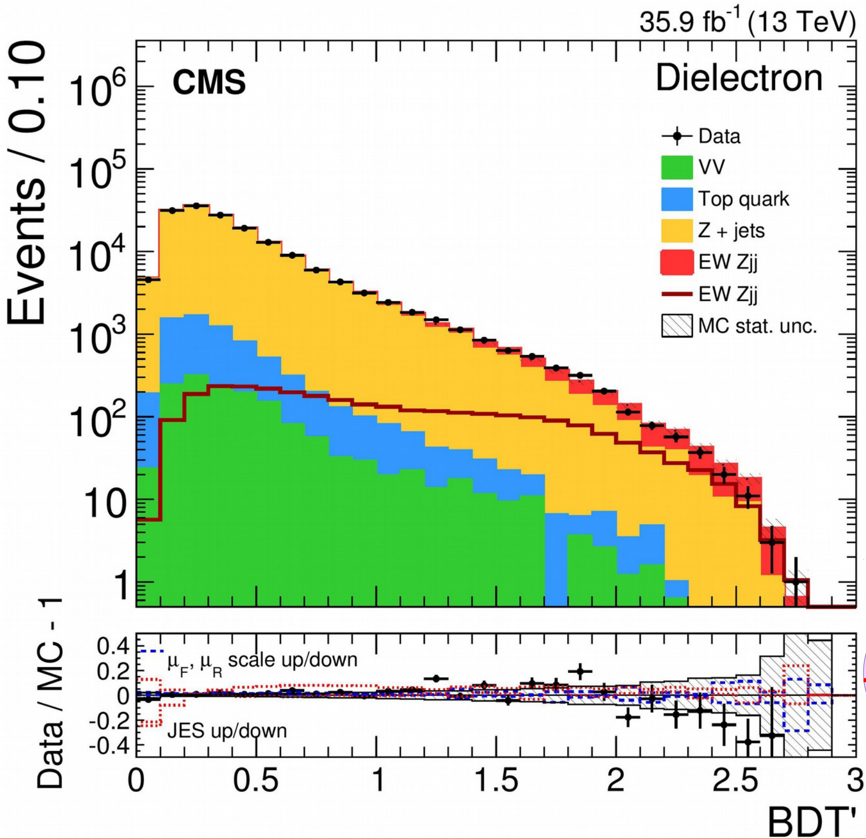
$$Z^* = y^*/\Delta y_{jj}$$

MG5 aMC+ Pythia8:

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

BDT Variables

arXiv:1712.09814



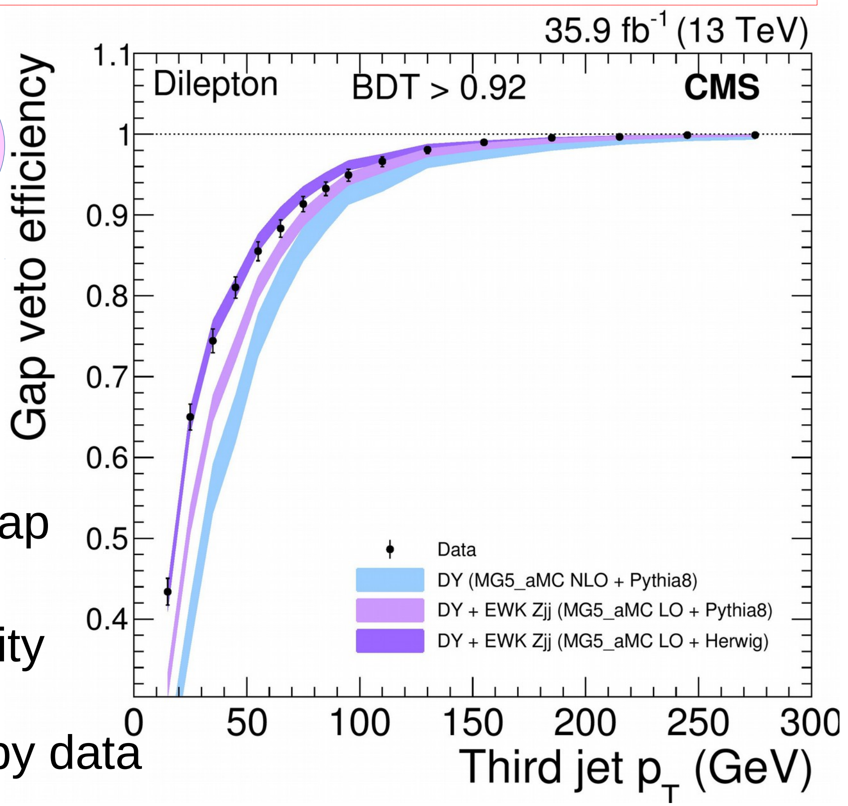
Signal extraction:

- 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 (lowBDT) regions

BDT > 0.92 → Region with 50% EW Zjj

$\sigma(\text{EW } \ell\ell_{jj})$ = 552 ± 19(stat) ± 55(syst) 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.

- Bkg+Signal model with Herwig do better at low gap activity values.
- Pythia8 describes larger gap activity and is disfavoured by data

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

W/Z+jets: *pp collisions 2015*

- 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

EWK Z+2jets: *pp collisions 2016*

- First observation of the EW Zjj production at 13 TeV
- Measured cross section is in agreement with SM prediction with ∼ 10% precision

Thank You !!!