Measurement of Z bosons produced in association with jets via vector boson fusion at 13 TeV with the ATLAS detector

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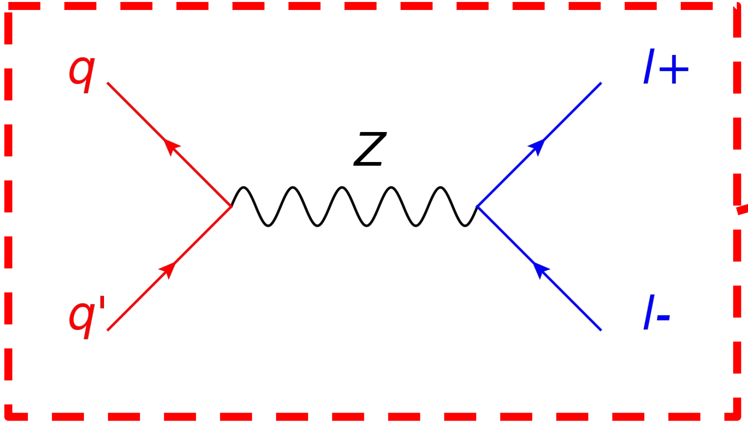
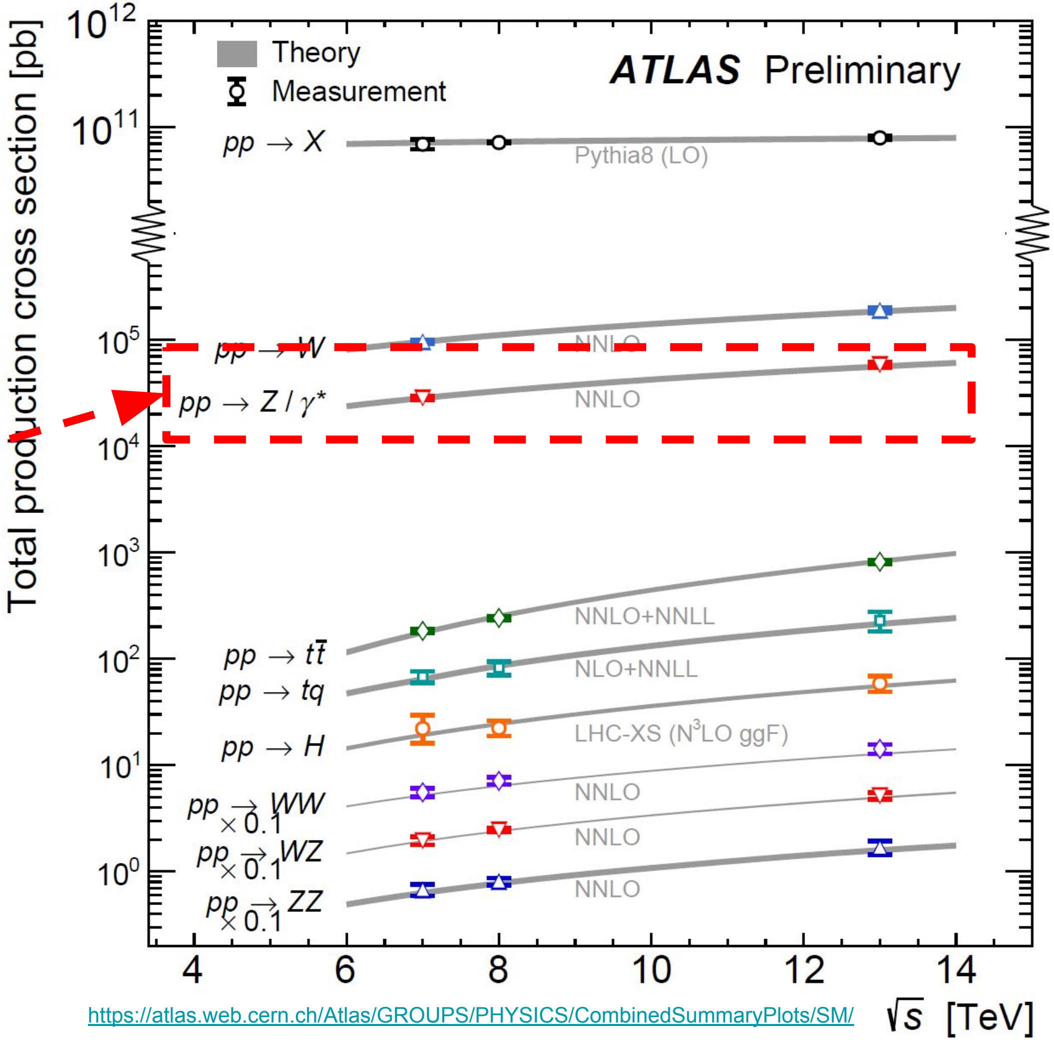
Canadian Association of Physicists
Association canadienne des physiciens et physiciennes

Motivation

Drell-Yan Z production





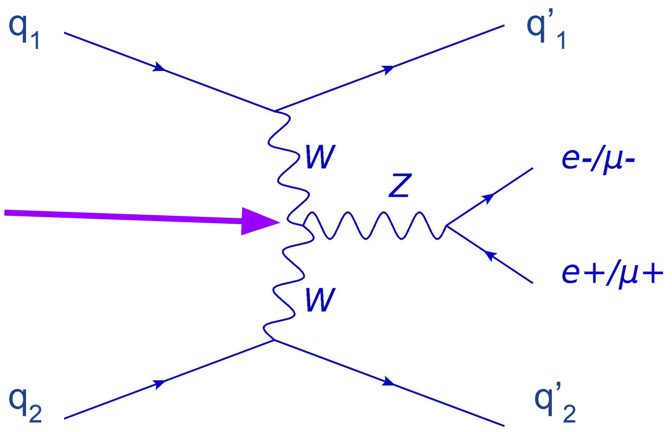
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

- Well measured leptonic final states with large statistics
- Background for many precision measurements (Higgs, top, diboson) and new physics searches

Signal: Electroweak Z + dijets

EW Z+dijets includes all processes where there is a **t-channel** exchange of a **W/Z boson** and a **l^+l^-jj** final state

Triple gauge coupling

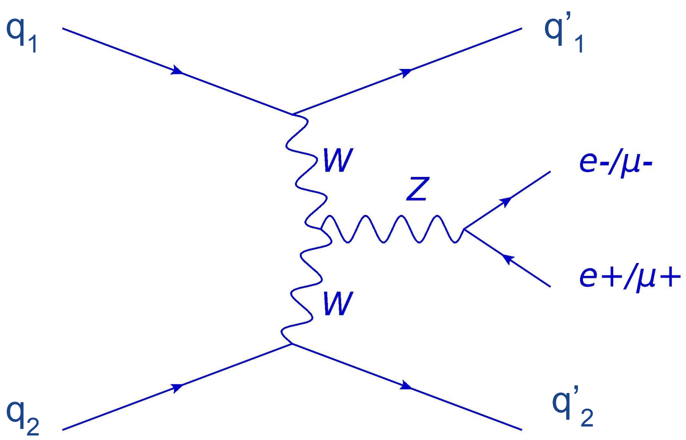


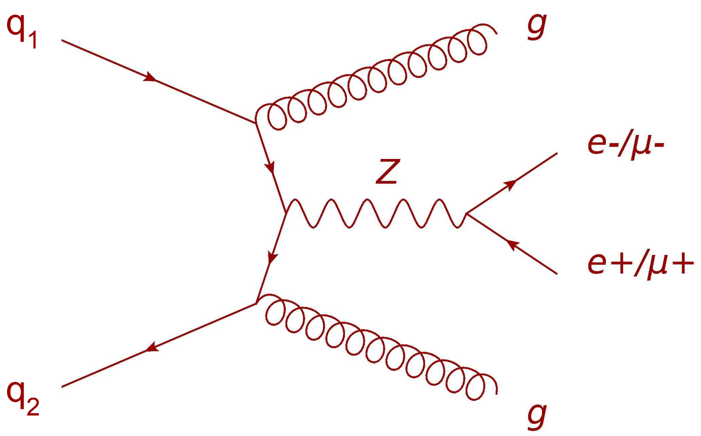
Vector boson fusion (VBF)

- Drell-Yan Z+dijets is produced frequently in pp collisions compared to EW Z+dijets (Large Background!)
- VBF Z is a probe for new physics via higher order corrections to the WWZ vertex (the triple gauge coupling)

Z+dijets production

EW Zjj has a **much smaller cross section** compared to the Drell-Yan process





SM Prediction: Powheg+Pythia

$\sigma_{fid} = 125.2 \pm 3.4$ fb

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SM Prediction: CT14nnlo PDF

$\sigma_{fid} = 0.74 \pm 0.03(\text{PDF}) \pm 0.01(\text{scale}) \pm 0.01(\text{other})$ nb

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*A factor of **6000** larger*

Extracting the EW signal from the dominant Drell-Yan background is challenging

Modeling of the background is crucial

Measurement: Cross section

SR = Signal Region

EW Z+dijets cross section of bin *i*

Drell-Yan Zjj prediction ~99% of total bkg

ttbar, dibosons ... ~1% of total bkg

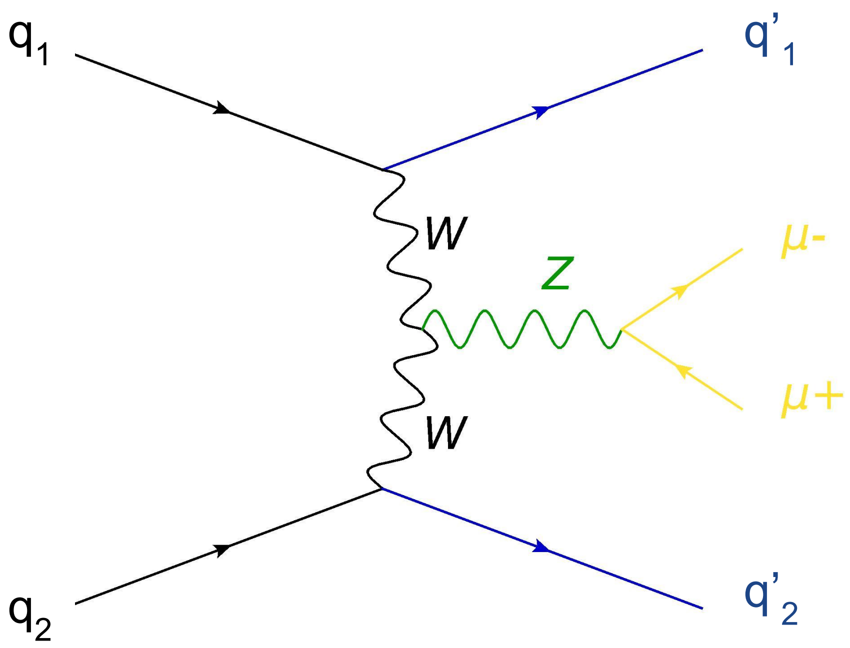
$$\sigma_{\mathrm{fid},i} = \frac{N^{\mathrm{data}}_{\mathrm{SR},i} - N^{\mathrm{strong}}_{\mathrm{SR},i} - N^{\mathrm{non}\text{-}Z}_{\mathrm{SR},i}}{C_i\,\mathcal{L}}$$

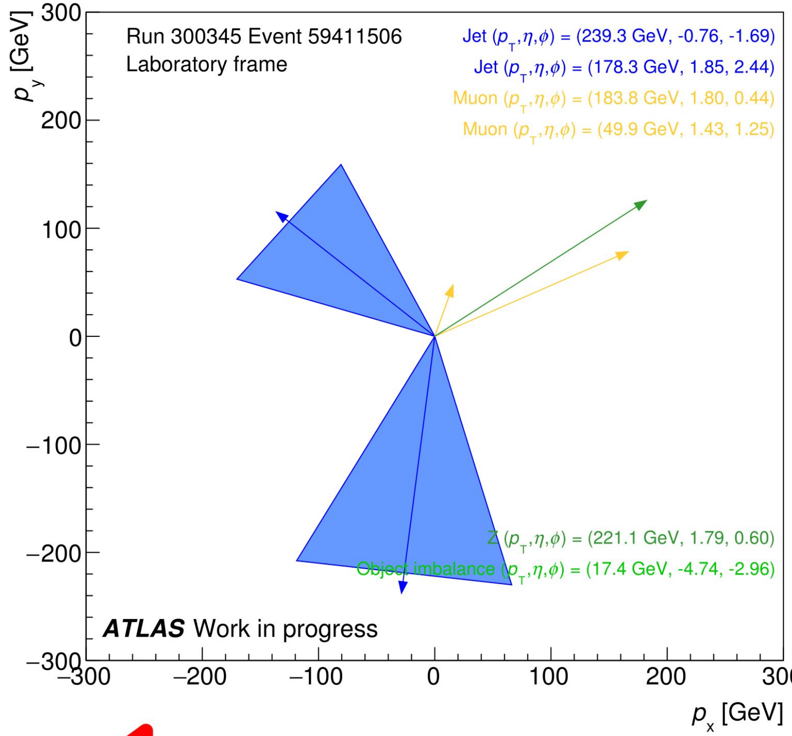
Bin-by-bin correction factor for reconstruction inefficiency

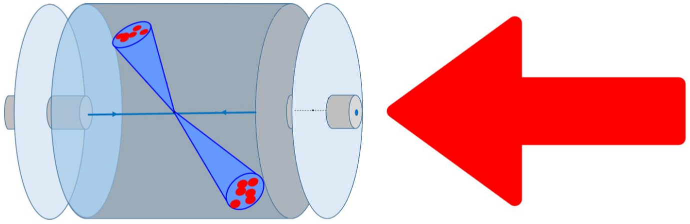
Integrated Luminosity

- The Drell-Yan Z+dijets accounts for the vast majority of events
- Crucial to understand this process to extract the EW Z+dijets signal

EW Z+dijets: What we see with the ATLAS detector

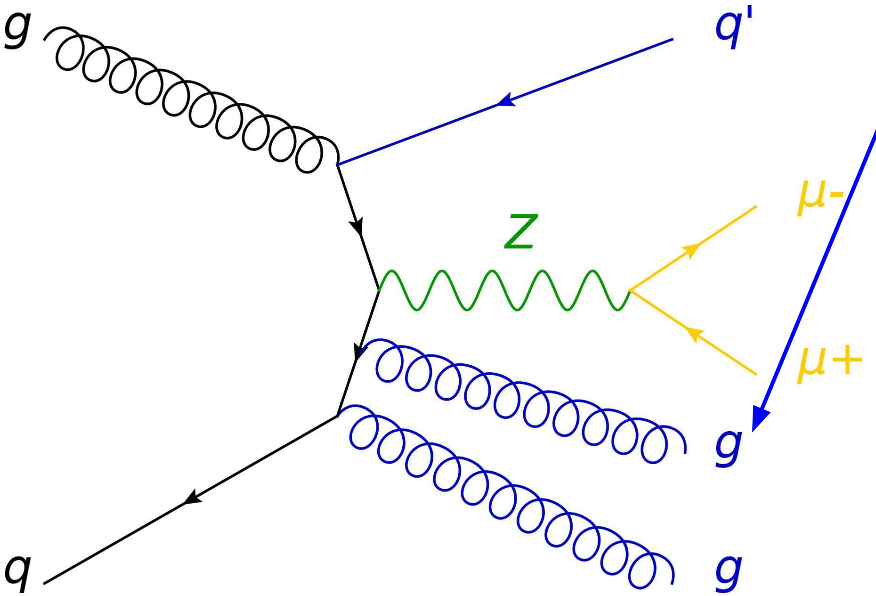


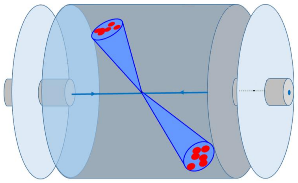


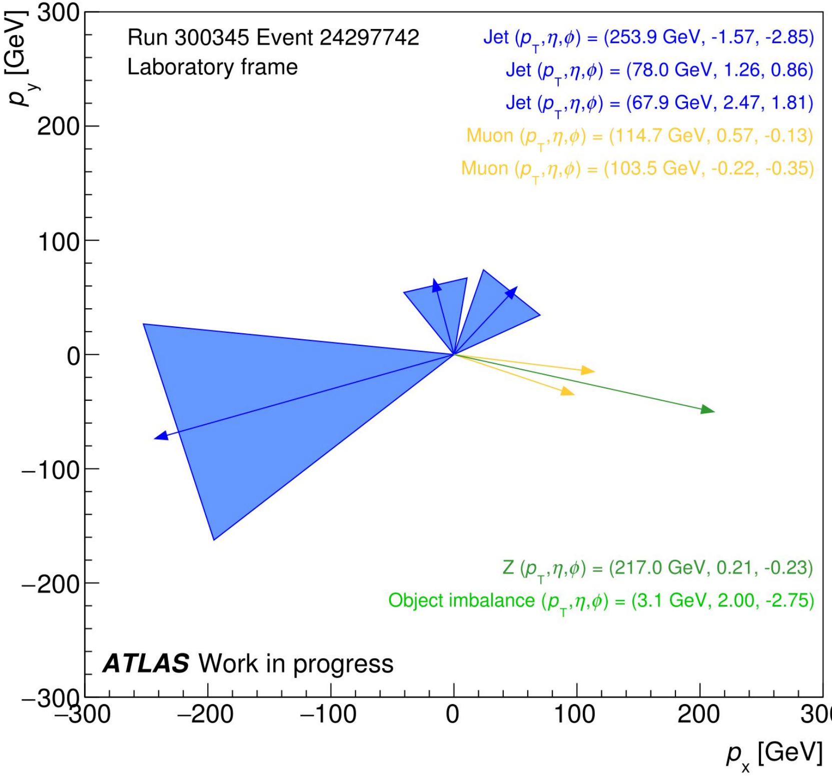


DY Z+dijets: What we see with the ATLAS detector

The Drell-Yan process is more likely to have additional hadronic activity between the two leading jets than the EW process. This is observed as so-called **gap jets**



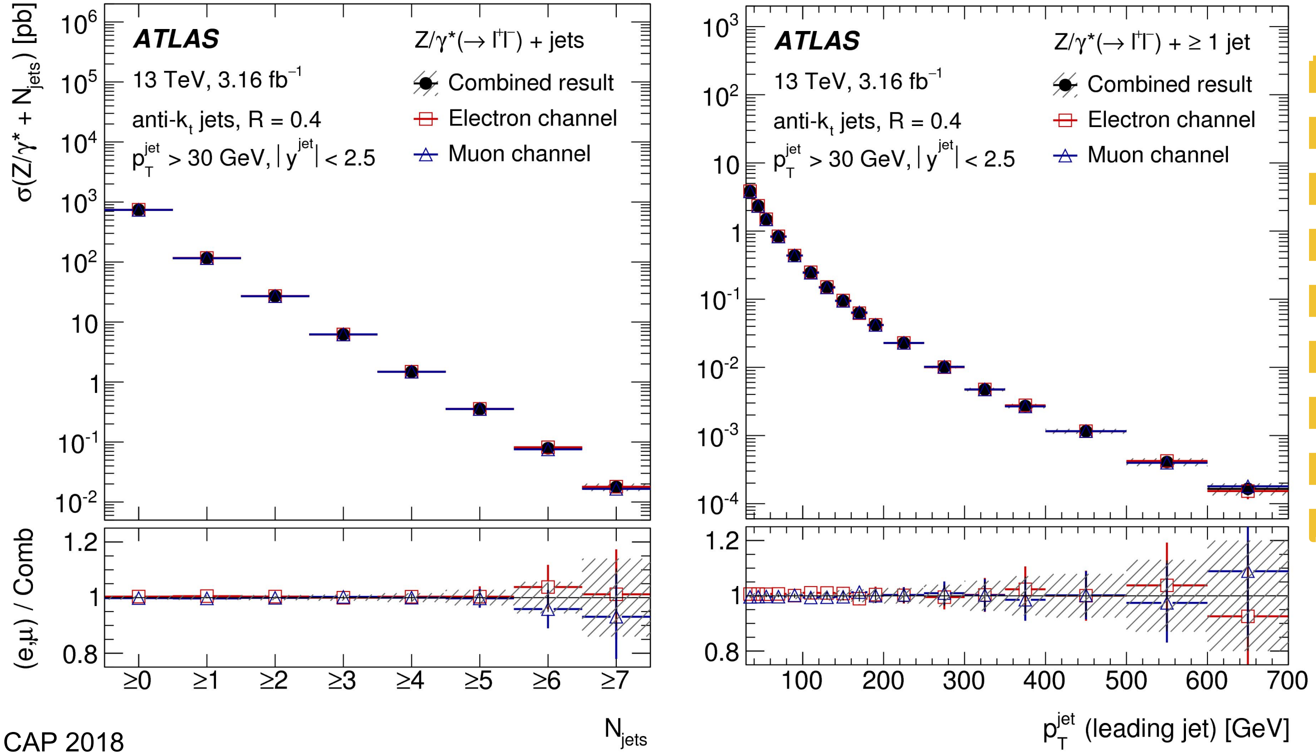




Z+jets @ 13 TeV

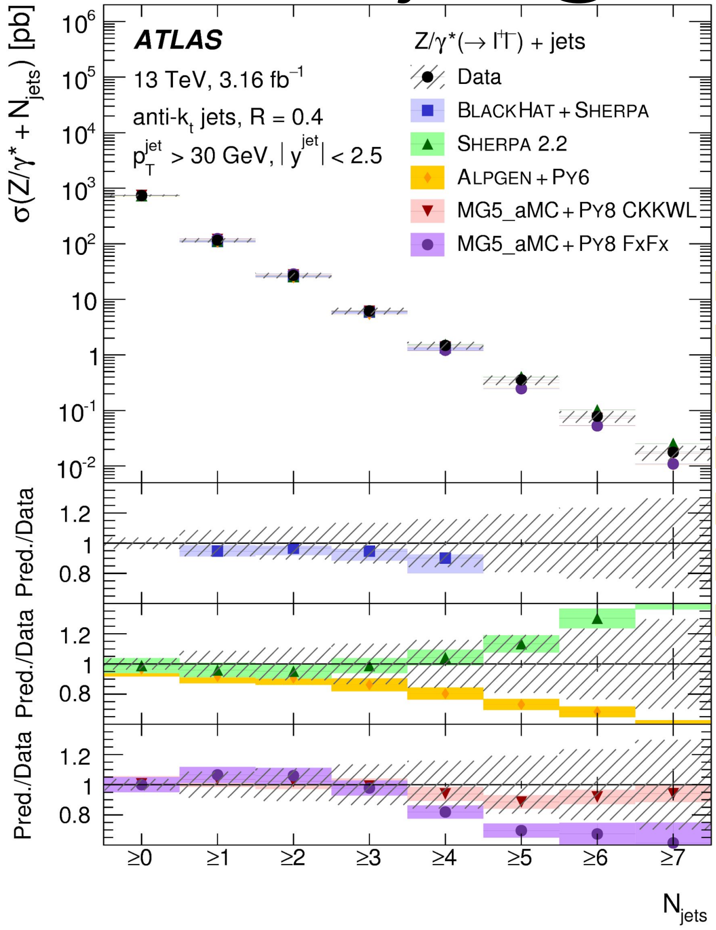
Z+jets @ 13 TeV Eur. Phys. J. C 77 (2017) 361

- Using the 2015 dataset, 3.16 fb^{-1}
- Cross section measured differentially as a function of **characteristic variables**
    - N_{jets} , jet p_T (shown) + others



- e^+e^- and $\mu^+\mu^-$ measurements are compatible
- Combination improves stat. uncertainty by ~30% for N_{jets}≥4 or greater

Z+jets @ 13 TeV Eur. Phys. J. C 77 (2017) 361



This differential measurement can be used to test various **theory predictions** provided by different **MC generators**

Cross section at high jet multiplicity provides sensitivity to differences in **MC generators**

Differential cross section as a function of jet multiplicity

- BlackHat+Sherpa is a fixed order NLO calculation of Z with ≤4 partons
- Sherpa 2.2 is NLO for ≤2 partons + LO for ≤4 partons+PS
- Alpgen+Py6 is LO for ≤5 partons+PS
- MG5_aMC+Py8CKKWL is LO for ≤4 partons+PS
- MG5_aMC+Py8FxFX is NL0 for ≤2 partons+PS

Observe that predictions vary substantially once the **number of jets** exceeds the number of **partons** included in the matrix element calculation

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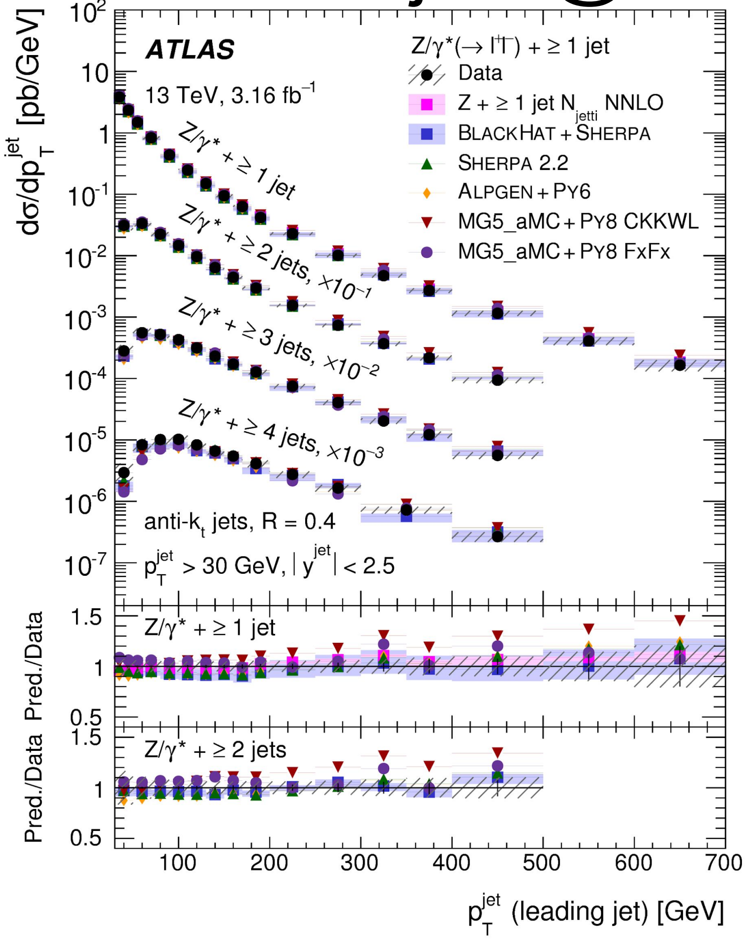


Differential cross section as a function of jet p_T

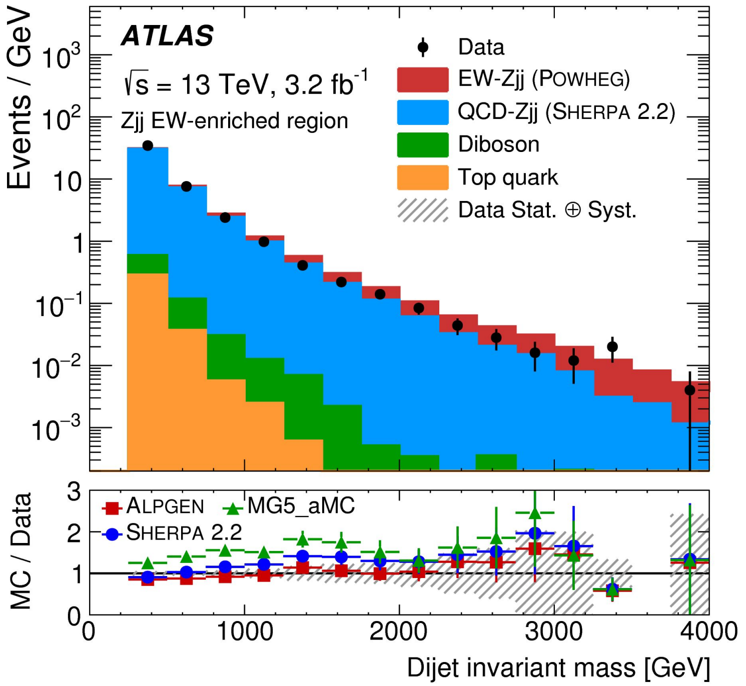
- Additional generator **Z+≥1 jet N$_{jetti}$ NNLO** is a fixed order **NNLO** prediction
  - Precise agreement with data for Z+≥1 jet
- Jet p_T is a fundamental observable and a probe for perturbative QCD over a wide range of scales
- The kinematics of jets in events with Z bosons is essential to model the backgrounds of other SM processes and BSM searches
- Observe that the LO generator **MG5_aMC+Py8CKKWL** models a too hard p_T spectrum
- The other NLO generators and fixed order predictions model the spectrum well over the full range of p_T

Electroweak Z+dijets @ 13 TeV

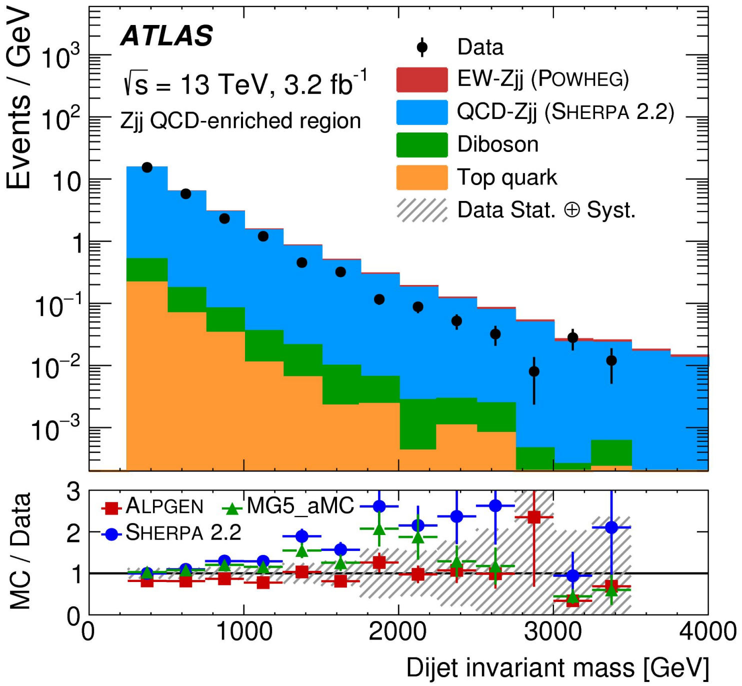
Electroweak Z+dijets @ 13 TeV Phys. Lett. B 775 (2017) 206

Define **two regions** to model background and extract signal:

EW enhanced: $N_{\text{gap jets}} = 0$



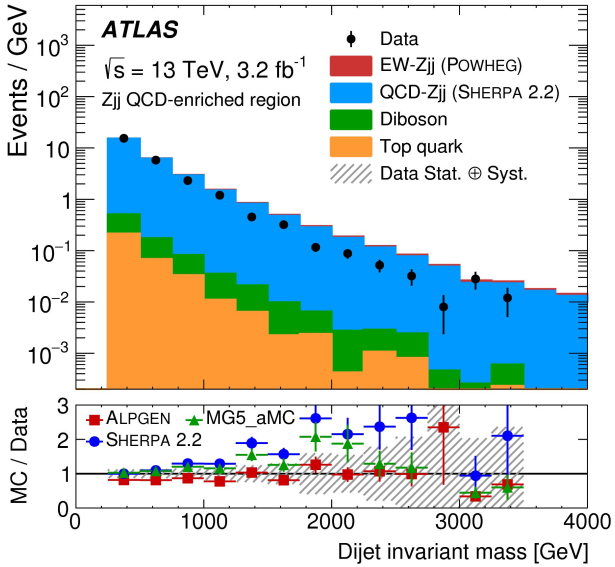
DY enhanced: $N_{\text{gap jets}} \geq 1$



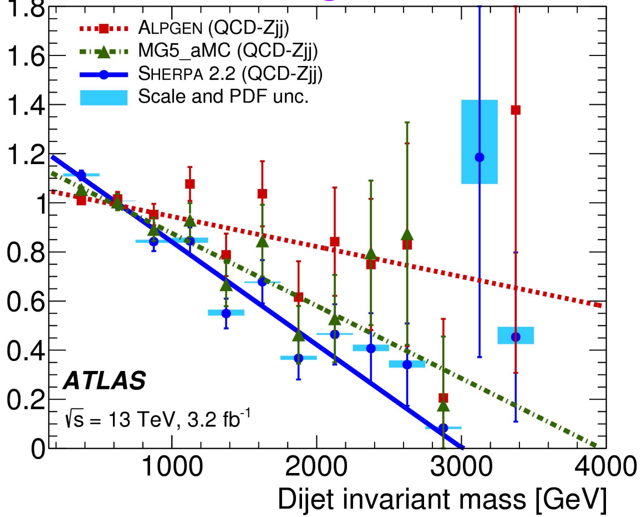
- All 3 Drell-Yan MC generators tested **mismodel** Zjj cross section at very high $\mathbf{m_{jj}}$
- Differential $\mathbf{m_{jj}}$ prediction constrained using data-driven approach

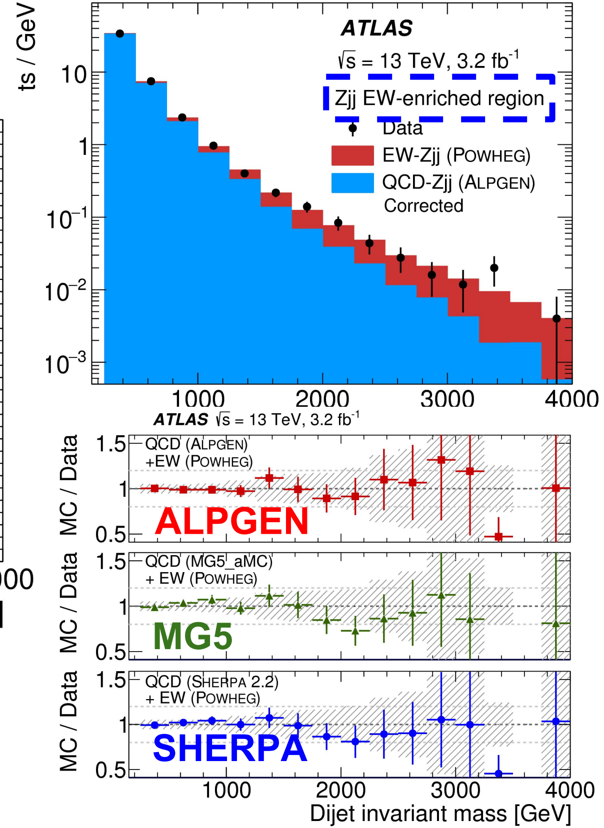
Electroweak Z+dijets @ 13 TeV Phys. Lett. B 775 (2017) 206

- Derive **constraining function** for each MC generator by constraining Drell-Yan Zjj to the data in the **QCD-enhanced** region
- Apply the **constraining function** in the **EW-enhanced** region to correctly model the DY background
- Subtract the DY background to extract the EW signal



constraining function



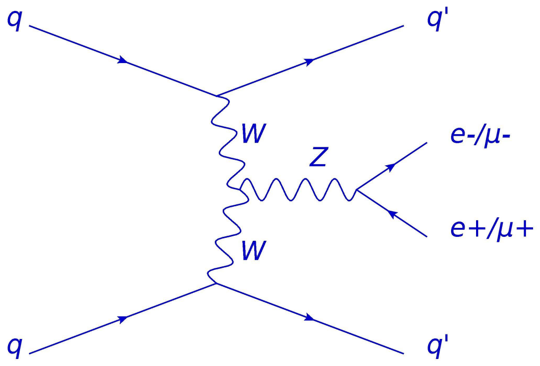


Cross section extracted in EW-enhanced region:

σ_{fid} = 119±16(stat)±20(syst)±2(lumi) fb

Summary

- Differential cross section of Z bosons produced in association with jets
    - Comparing different MC generators at **high jet multiplicity** to observe differences in theory predictions
- Electroweak Z+jets measurement at 13 TeV
    - Extract EW signal from QCD background by applying **data-driven constraint**
    - With more statistics it will be possible to extract a differential EW cross section and search for new physics in the **WWZ** vertex (anomalous triple gauge coupling)

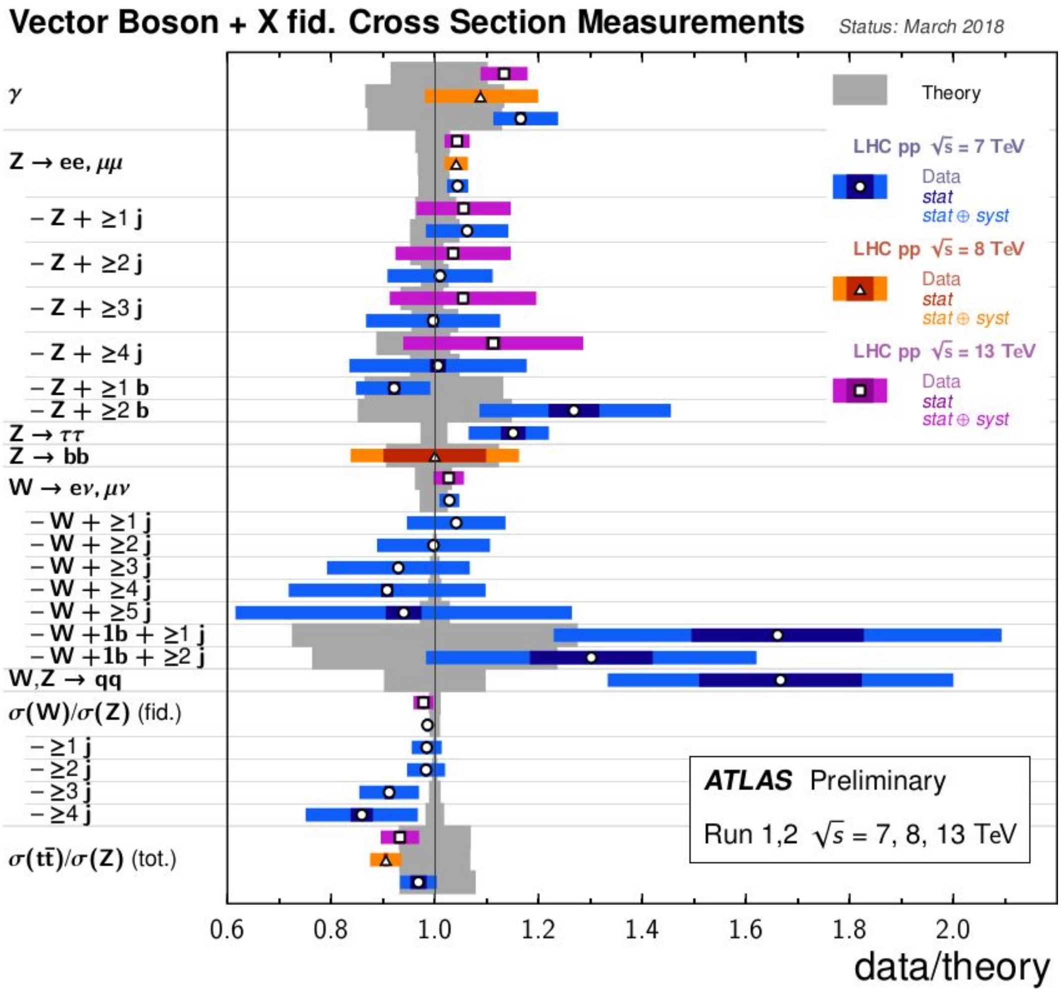


Future Outlook:

- Work is in progress to measure the EW Z+dijets cross section differentially
- Will study the full Run 2 dataset (2015-2018)

$$\mathcal{L} \sim 150\ \mathrm{fb}^{-1}$$

BACKUP


Vector Boson + X fid. Cross Section Measurements
Status: March 2018
γ
$Z \to ee, \mu\mu$
$- Z + \geq 1$ j
$- Z + \geq 2$ j
$- Z + \geq 3$ j
$- Z + \geq 4$ j
$- Z + \geq 1$ b
$- Z + \geq 2$ b
$Z \to \tau\tau$
$Z \to bb$
$W \to e\nu, \mu\nu$
$- W + \geq 1$ j
$- W + \geq 2$ j
$- W + \geq 3$ j
$- W + \geq 4$ j
$- W + \geq 5$ j
$- W + 1b + \geq 1$ j
$- W + 1b + \geq 2$ j
$W,Z \to qq$
$\sigma(W)/\sigma(Z)$ (fid.)
$- \geq 1$ j
$- \geq 2$ j
$- \geq 3$ j
$- \geq 4$ j
$\sigma(t\bar{t})/\sigma(Z)$ (tot.)
Theory
LHC pp $\sqrt{s}$ = 7 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 8 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 7, 8, 13 TeV
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
data/theory

The effective Lagrangian, $\mathcal{L}$, for aTGCs can be written as

$$\frac{\mathcal{L}}{g_{WWZ}} = i\left[g_{1,Z}\left(W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{\dagger\mu}Z^{\nu}\right) + \kappa_Z W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}\right] \quad (8.2)$$

if only those terms that conserve charge conjugation and parity are retained from the general expression [68]. Here, $g_{WWZ} = -e\cot\theta_{\mathrm{W}}$, e is the electric charge, θ_W is the weak mixing angle, W^{μ} and Z^{μ} are the W-boson and Z-boson fields, $X_{\mu\nu} = \partial_{\mu}X_{\nu} - \partial_{\nu}X_{\mu}$ for $X = W$ or Z, and $g_{1,Z}$, κ_Z and λ_Z are dimensionless couplings. The SM values of these dimensionless couplings are $g_{1,Z}^{SM} = 1$, $\kappa_Z^{SM} = 1$ and $\lambda_Z^{SM} = 0$.

The tree-level S-matrix for this effective Lagrangian violates unitarity at large energy scales. Unitarity is restored in the full theory by propagator (form factor) effects. A typical approach is to modify the couplings by a dipole form factor

$$a(\hat{s}) = \frac{a_0}{(1+\hat{s}/\Lambda^2)^2} \quad (8.3)$$

Table 7. The 95% confidence intervals obtained on the aTGC parameters from counting the number of events with $m_{jj} > 1$ TeV in the *search* region. Observed and expected intervals, labelled 'obs' and 'exp' respectively, are presented for unitarisation scales of $\Lambda = 6$ TeV and $\Lambda = \infty$. The parameter $\Delta g_{1,Z}$ refers to the deviation of $g_{1,Z}$ from the SM value.

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

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