Measurements of Vector Boson Fusion with the ATLAS detector

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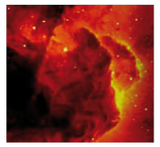
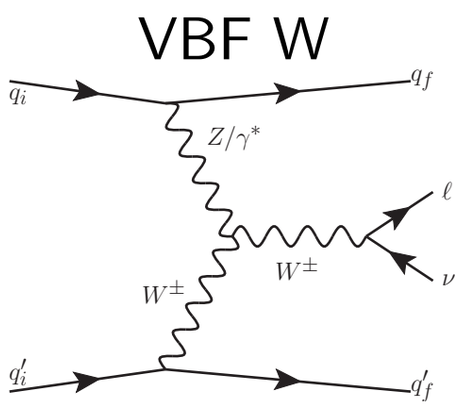
On Behalf of the ATLAS Collaboration

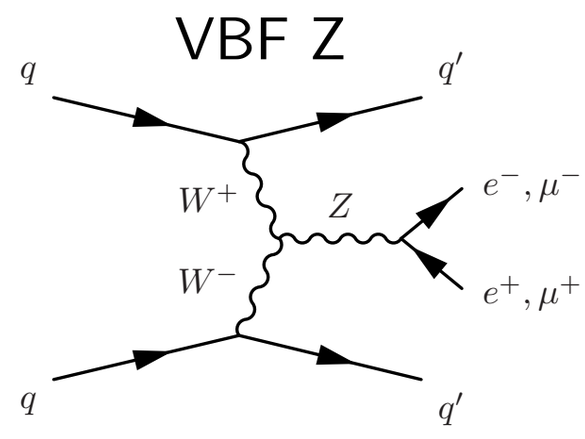
EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676



Overview



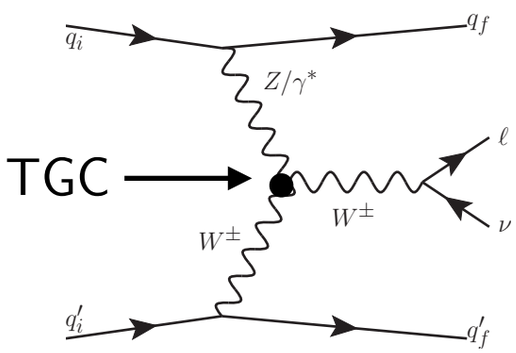


- Electroweak ("EW") *Wjj* production measurement at 7 and 8 TeV
  - Submitted to EPJC – available on arXiv
  - Observation of electroweak *W*-boson production in the VBF topology
  - Fiducial and (for the first time) differential measurements
    - Focus on variables sensitive to kinematic differences of QCD and EW *Wjj* production
  - TGC vertex is a probe for new physics beyond the Standard Model
    - Limits on anomalous TGC are set using an aTGC or EFT framework

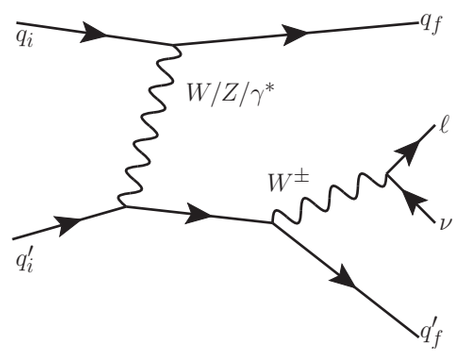
- EW *Zjj* production measurement at 13 TeV (3.2 fb^{-1}, 2015 data)
  - Available on arXiv imminently
  - Fiducial cross sections measured in regions enriched with EW *Zjj*
  - Inclusive cross section measured in six fiducial regions with varying contributions from QCD and EW production

Wjj – Motivation

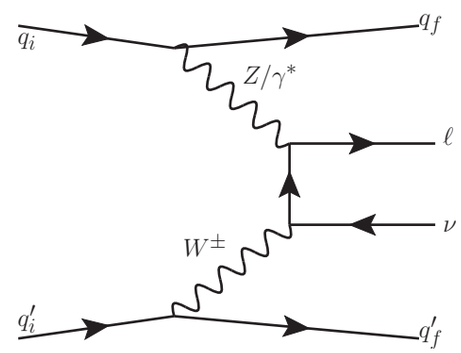
Electroweak *Wjj* production (Signal)



Vector boson fusion

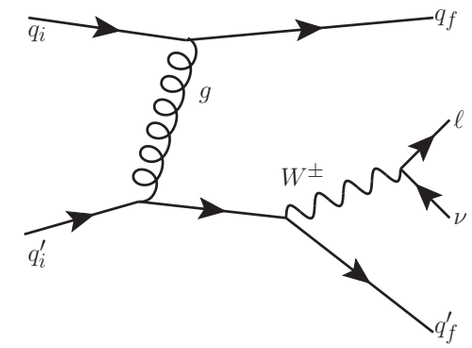


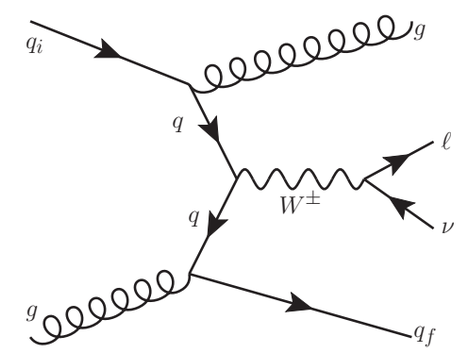
Bremsstrahlung-like



non-resonant

Strong (QCD) *Wjj* production (Background)





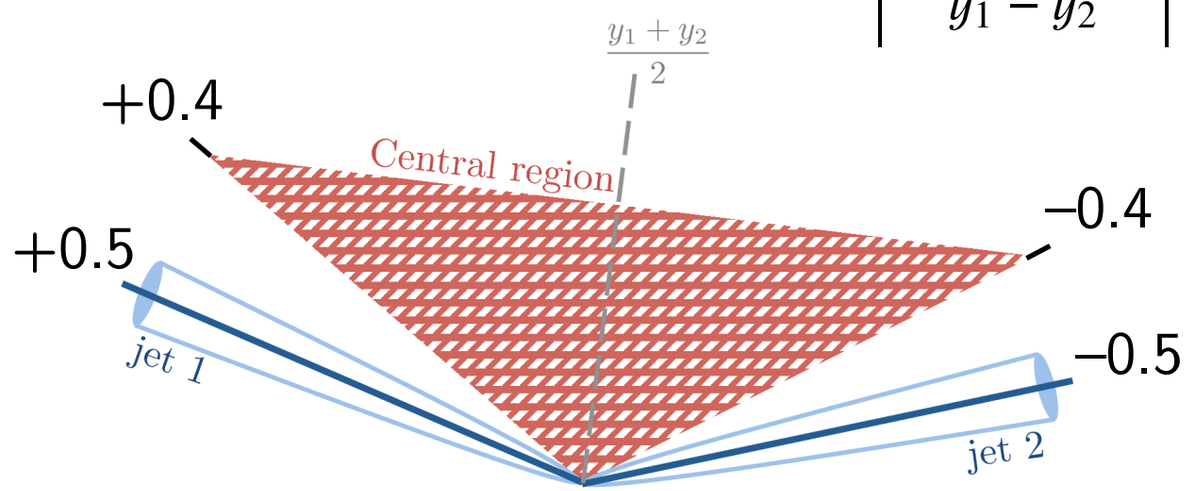
- W: Lepton and $E_{T\,miss}$ from neutrino
- Two high-p_T jets with large invariant mass M_{JJ}
- EW production:
  - W boson inside the rapidity range of two jets
  - No additional jets in the rapidity range between jets (absence of color connection between incoming partons)
- QCD "background":
  - M_{JJ} typically lower than in EW production
  - W boson can be outside the rapidity "gap" of leading jets
  - Additional jet radiation allowed inside rapidity gap between leading jets

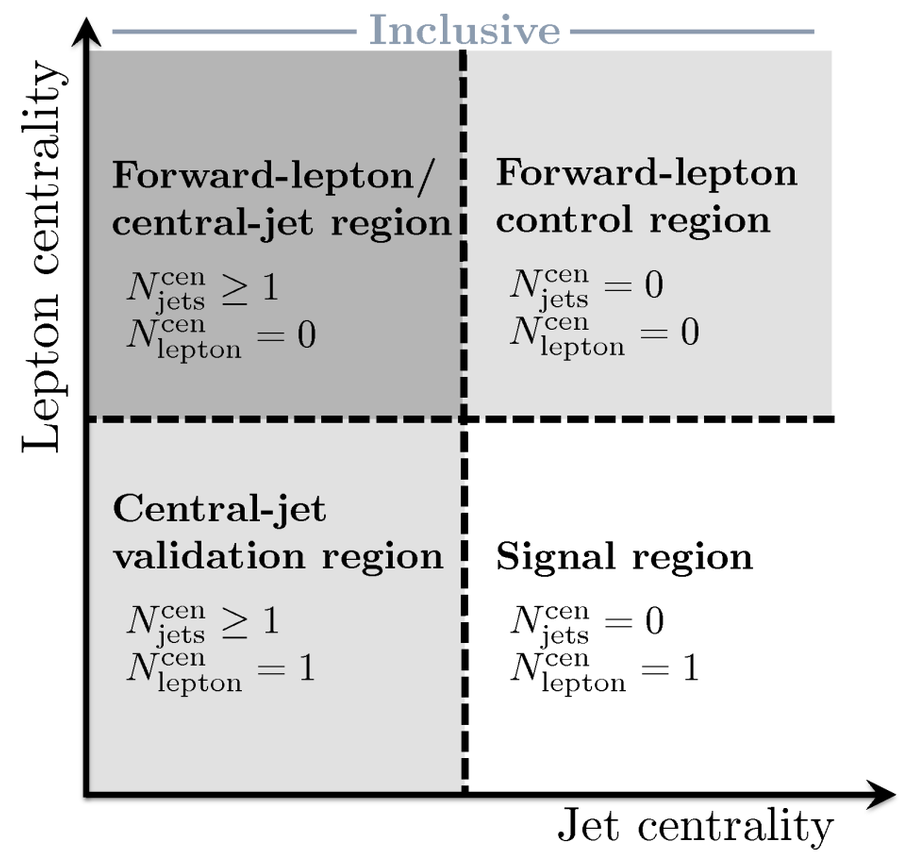
Wjj Event Selection, Definition of Fiducial Regions

- Basic *Wjj* ($W \to \ell\nu$) selection:
  - 1 triggered lepton ($p_T > 25$ GeV)
  - $E_{T\,miss} > 20$ GeV, $M_T(\ell, E_{T\,miss}) > 40$ GeV
  - 2 high-p_T jets with $M_{JJ} > 500$ GeV
- Discriminate EW from QCD *Wjj* using <u>Jet and Lepton centrality</u>:
  - 1 lepton inside the *dijet rapidity gap*
  - No additional jets inside the rapidity gap
- Control / validation regions defined using lepton and jet centrality
  - Constrain QCD *Wjj* using **forward lepton control** region (0 central leptons or jets)
  - Validation region with ≥1 central jet, 1 central lepton

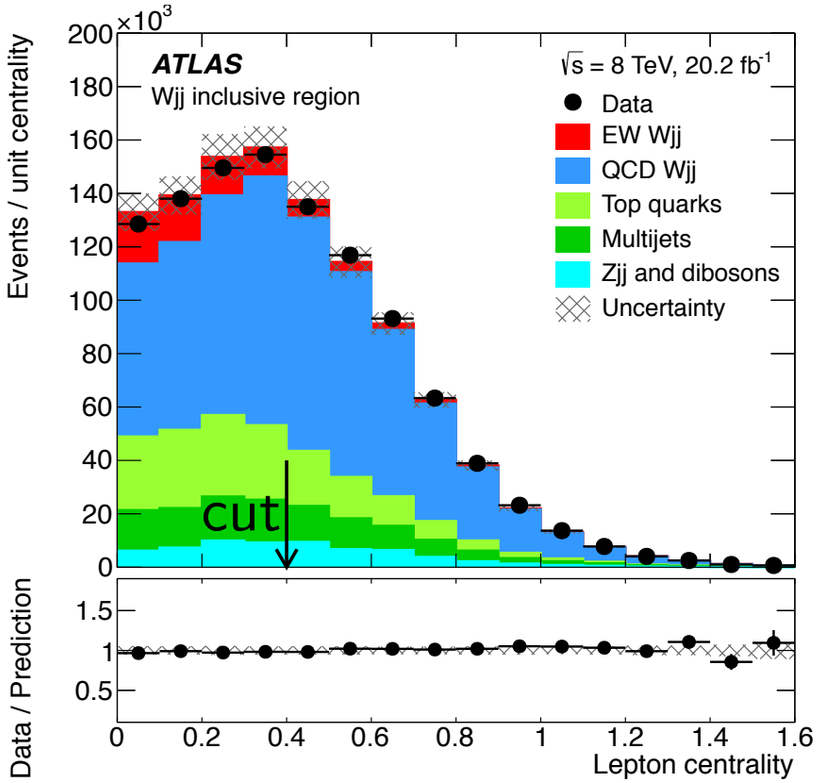
Centrality:

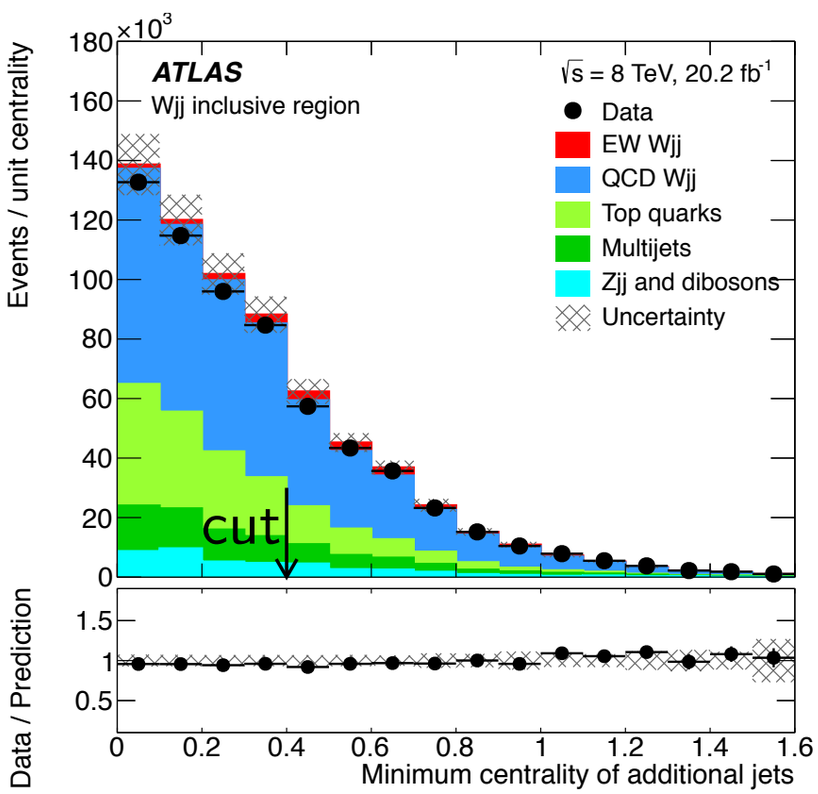
$$C_{\ell\,(j)} \equiv \left| \frac{y_{\ell\,(j)} - \frac{y_1+y_2}{2}}{y_1 - y_2} \right|$$

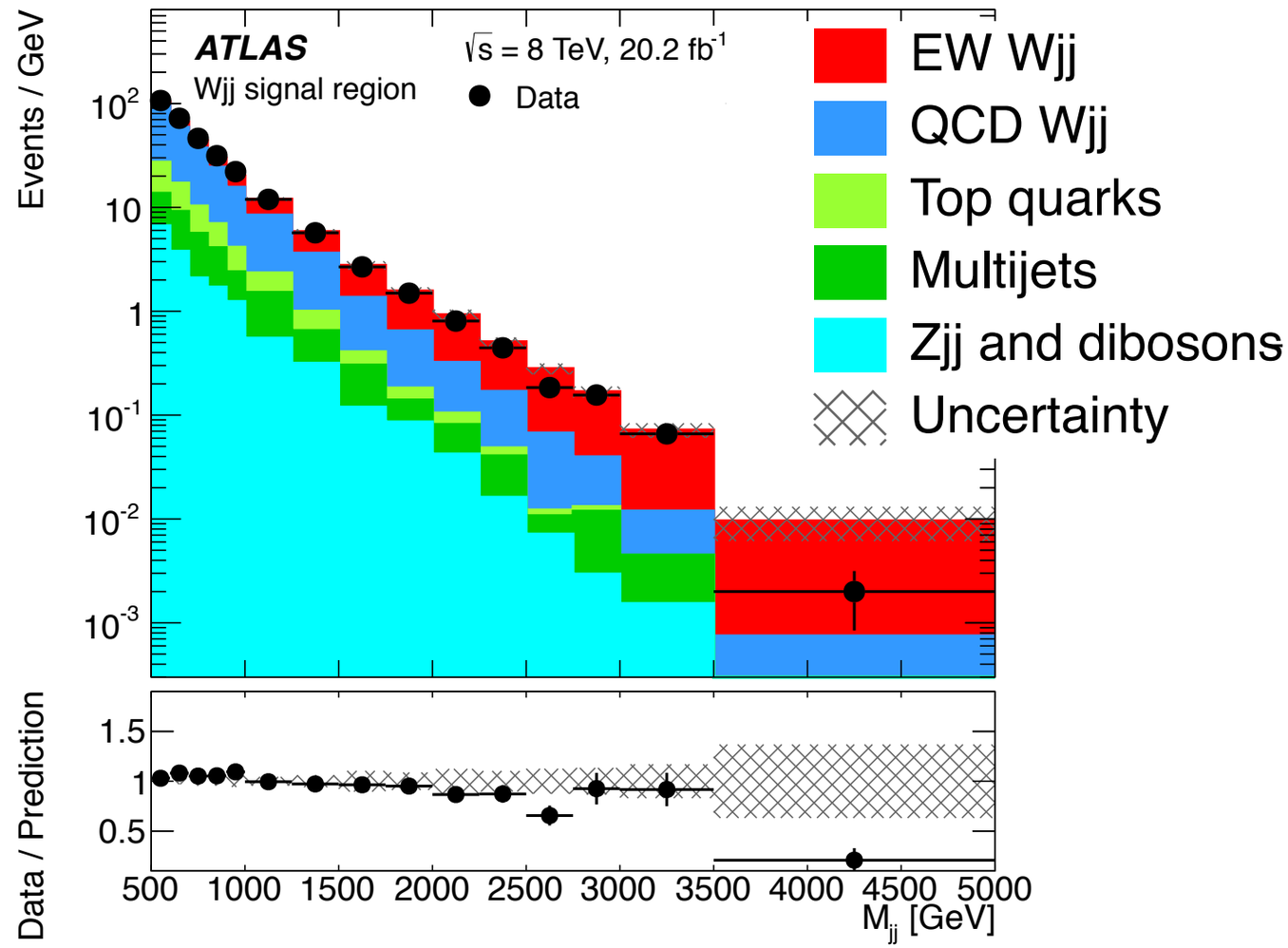




EW *Wjj* Measurement Method







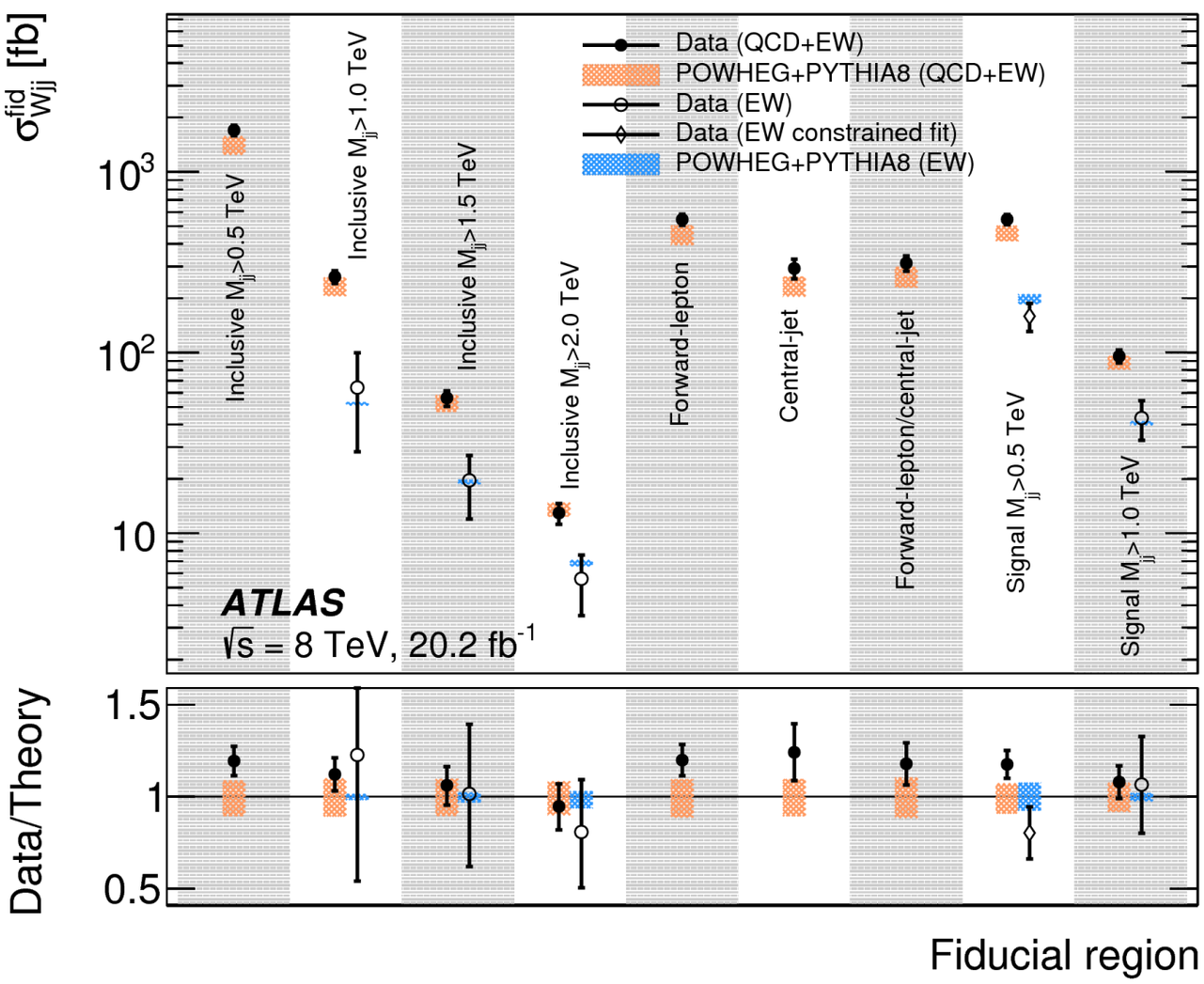
- QCD- and EW-*Wjj* fractions are obtained using fit to the M_{JJ} spectrum with MC
  - QCD MC suffers from mismodeling in M_{JJ} spectrum; constrained using forward lepton control region
- Other backgrounds:
  - Multijet production, constrained using data-driven techniques
  - Top quarks, *Zjj*, dibosons (modeled using MC)

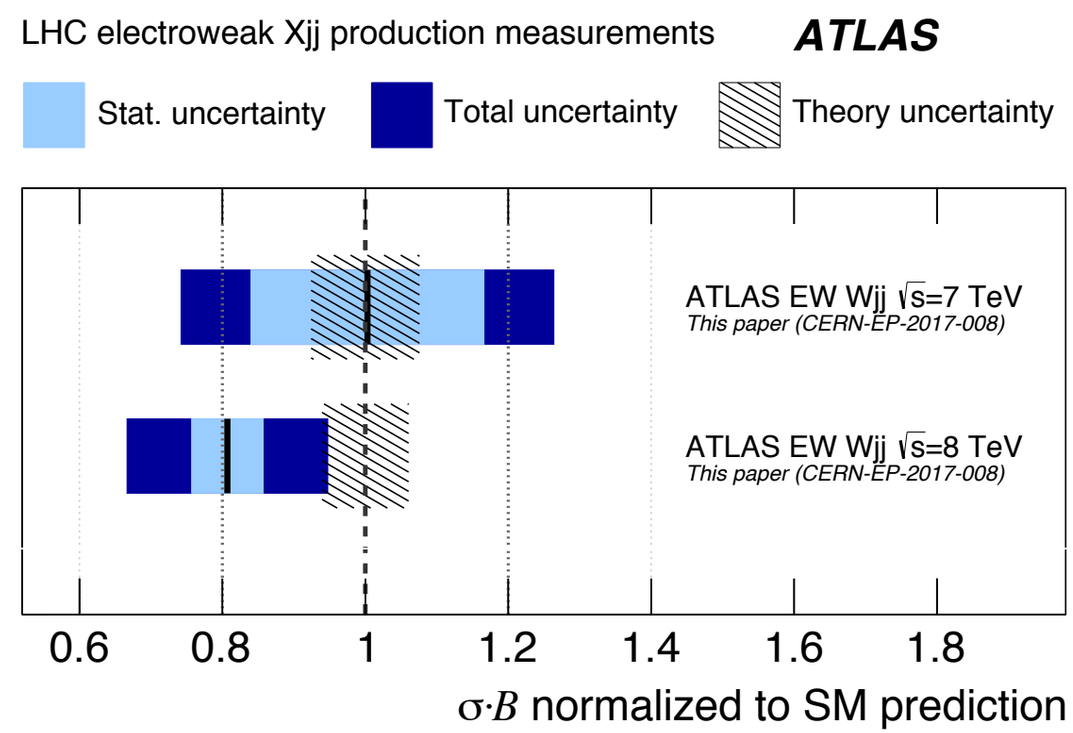
Fiducial Measurement Results

Measured EW *Wjj* production (M_{JJ}>0.5 TeV)

$\sqrt{s}$	$\sigma^{\text{fid}}_{\text{meas}}$ [fb]	$\sigma^{\text{fid}}_{\text{SM}}$ [fb]
7 TeV	144 ± 23 (stat) ± 23 (exp) ± 13 (th)	144 ± 11
8 TeV	159 ± 10 (stat) ± 17 (exp) ± 20 (th)	198 ± 12

Powheg+Pythia8 Prediction



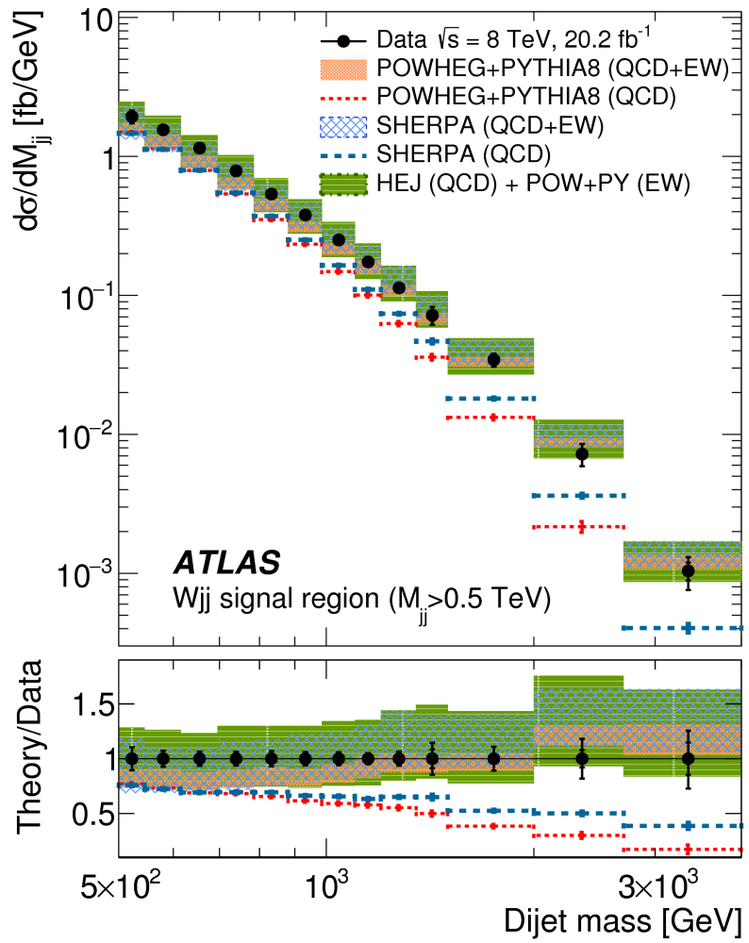


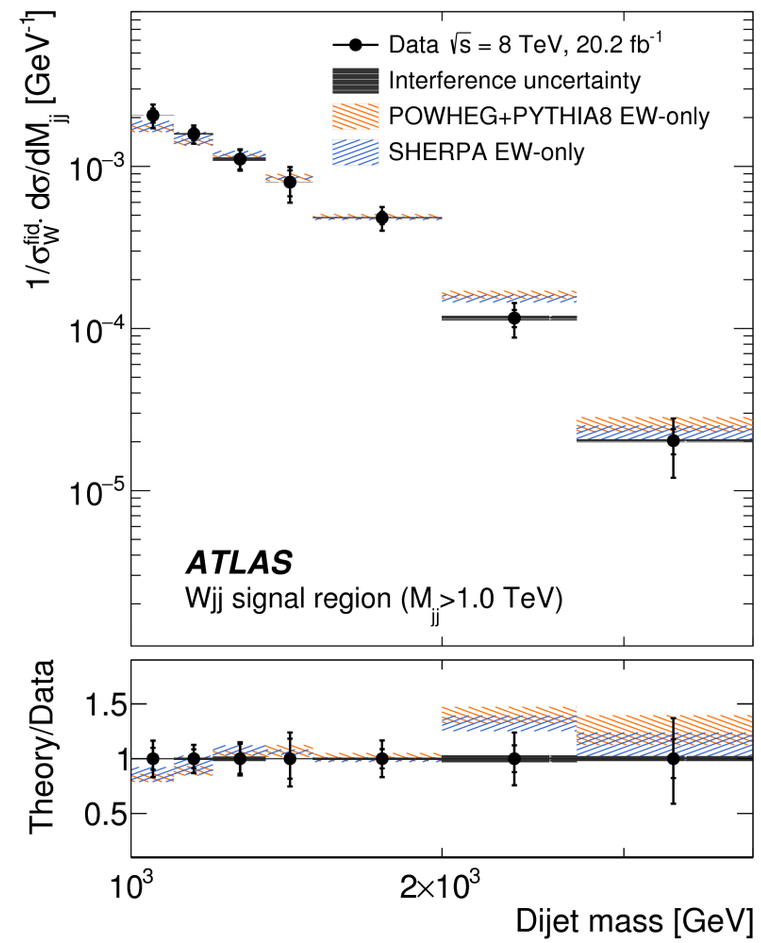
- EW *Wjj* production measured at 7 and 8 TeV in the signal region (M_{JJ}>0.5 TeV)
  - 24% uncertainty in 7 TeV measurement
  - 18% uncertainty in 8 TeV measurement
- QCD+EW *Wjj* measured in inclusive regions (no C_j or C_ℓ requirements) and control regions

Differential Cross Section Measurements

M_{JJ}>0.5 TeV
QCD+EW

QCD-only predictions for comparison





M_{JJ}>1.0 TeV
EW-Only

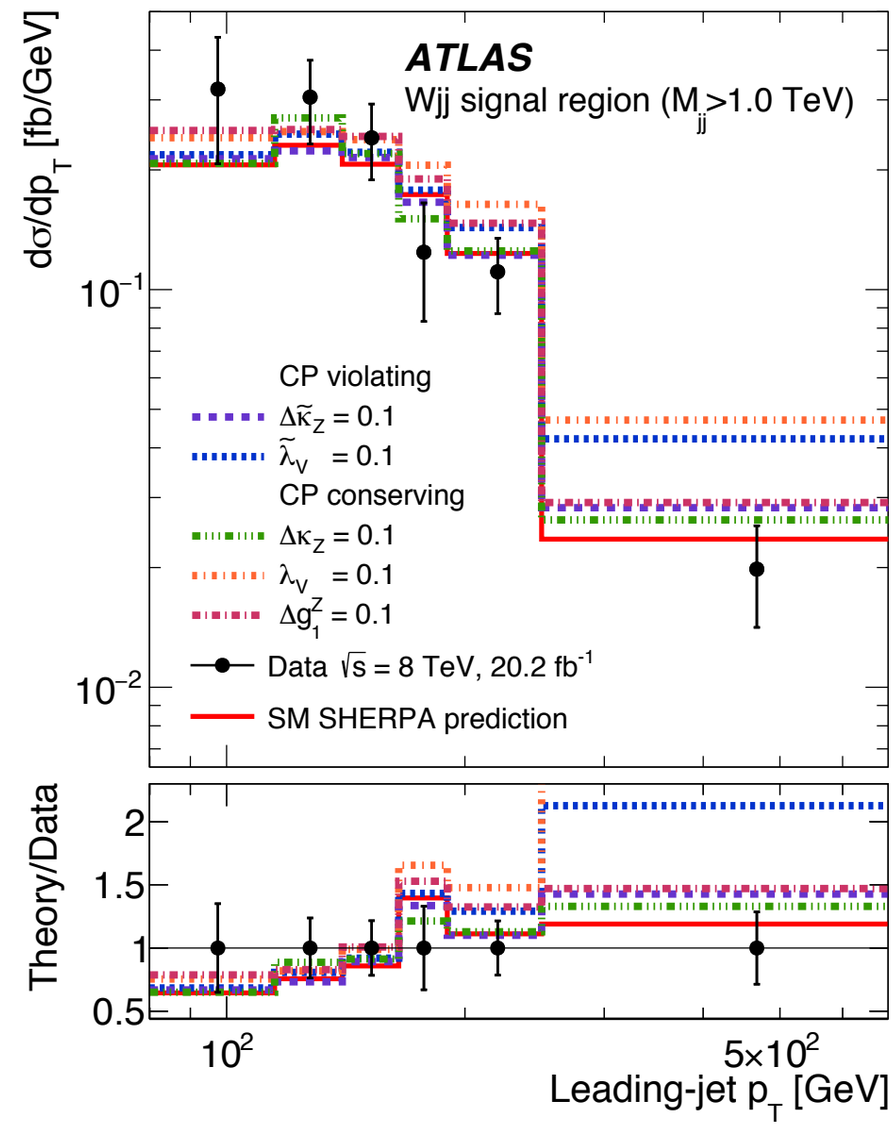
- Differential measurements are made for <u>QCD+EW *Wjj*</u> (in inclusive signal regions) as well as <u>EW-only *Wjj*</u> in high-M_{JJ} regions
  - For EW-only differential definitions, QCD normalization factor measured earlier
- Focus on differential distributions that discriminate between QCD and EW *Wjj* production
  - M_{JJ}, C_J, C_ℓ, $\Delta y(j_1,j_2)$, $N_{j,gap}$
- Also differential distributions with sensitivity to anomalous TGCs
  - p_{Tj1}, p_{Tjj}, $\Delta\varphi(j_1,j_2)$

Limits on aTGC

	$\Lambda = 4$ TeV		$\Lambda = \infty$	
	Expected	Observed	Expected	Observed
Δg_1^Z	$[-0.39, 0.35]$	$[-0.32, 0.28]$	$[-0.16, 0.15]$	$[-0.13, 0.12]$
$\Delta\kappa_Z$	$[-0.38, 0.51]$	$[-0.29, 0.42]$	$[-0.19, 0.19]$	$[-0.15, 0.16]$
λ_V	$[-0.16, 0.12]$	$[-0.13, 0.090]$	$[-0.064, 0.054]$	$[-0.053, 0.042]$
$\tilde{\kappa}_Z$	$[-1.7, 1.8]$	$[-1.4, 1.4]$	$[-0.70, 0.70]$	$[-0.56, 0.56]$
$\tilde{\lambda}_V$	$[-0.13, 0.15]$	$[-0.10, 0.12]$	$[-0.058, 0.057]$	$[-0.047, 0.046]$

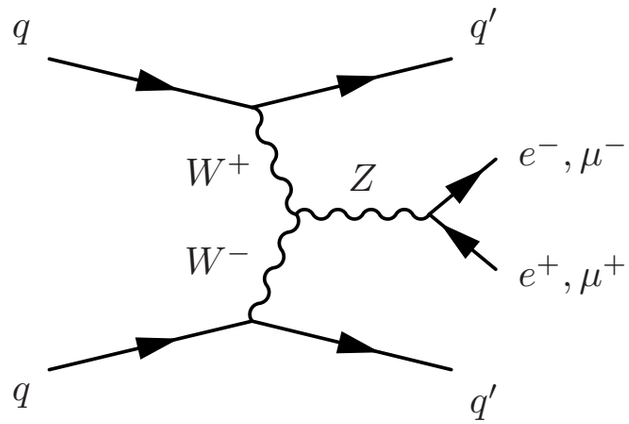
CP-Violating

- Anomalous coupling measurements performed in high-q^2 region
  - $M_{JJ} > 1$ TeV, $p_{T,j1} > 600$ GeV
- Sensitive differential variables:
  - p_{Tj1}, p_{Tjj}, $\Delta\varphi(j_1,j_2)$ (CP-violating couplings)
- Limits placed on aTGC effective Lagrangian couplings, as well as on EFT parameters

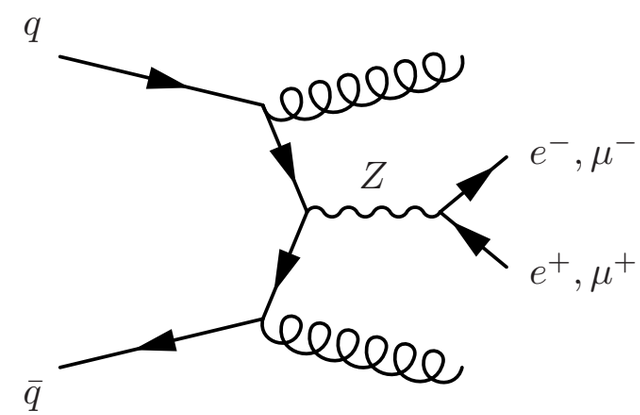


Theoretical predictions with aTGC parameters set to +10% from SM predictions

Zjj @ 13 TeV: Event Selection



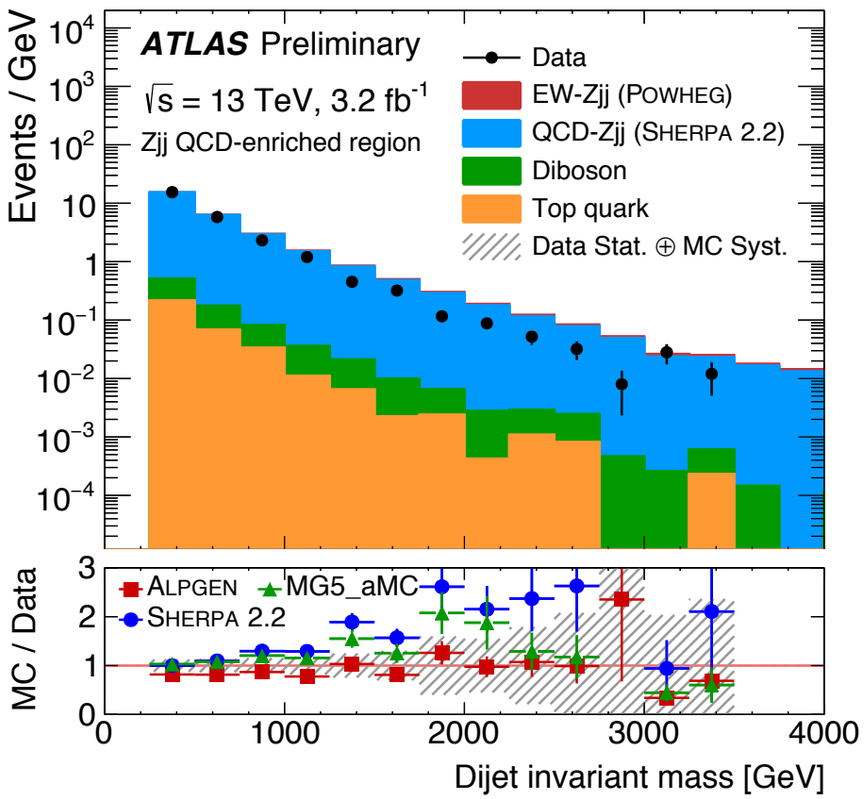
Electroweak *Zjj* production (Signal)



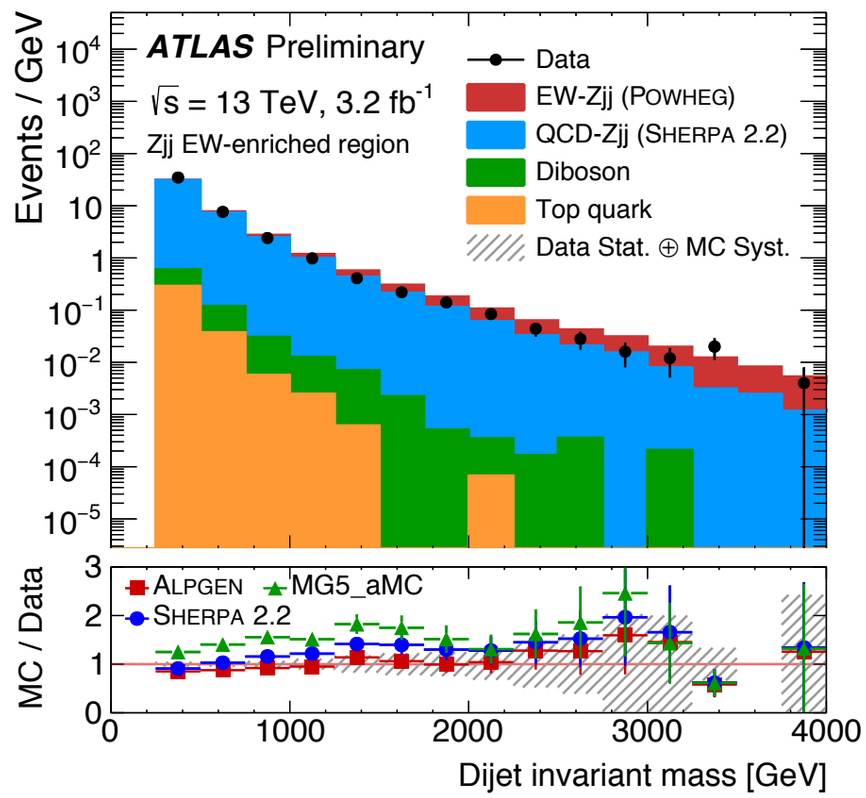
Strong (QCD) *Zjj* production (Background)

- Measurement at 13 TeV using 3.2 fb^{-1} of data collected in 2015
- QCD+EW Zjj production measured in 4 fiducial regions
- EW-only Zjj production measured in 2 regions designed to enhance EW signal:
  - High dijet M_{JJ} (either $M_{JJ} > 250$ GeV or $M_{JJ} > 1$ TeV)
  - A central jet veto to suppress QCD production
- EW-only measurement: Fit EW and QCD Zjj components in the M_{JJ} distribution

Signal Selection



QCD-enriched



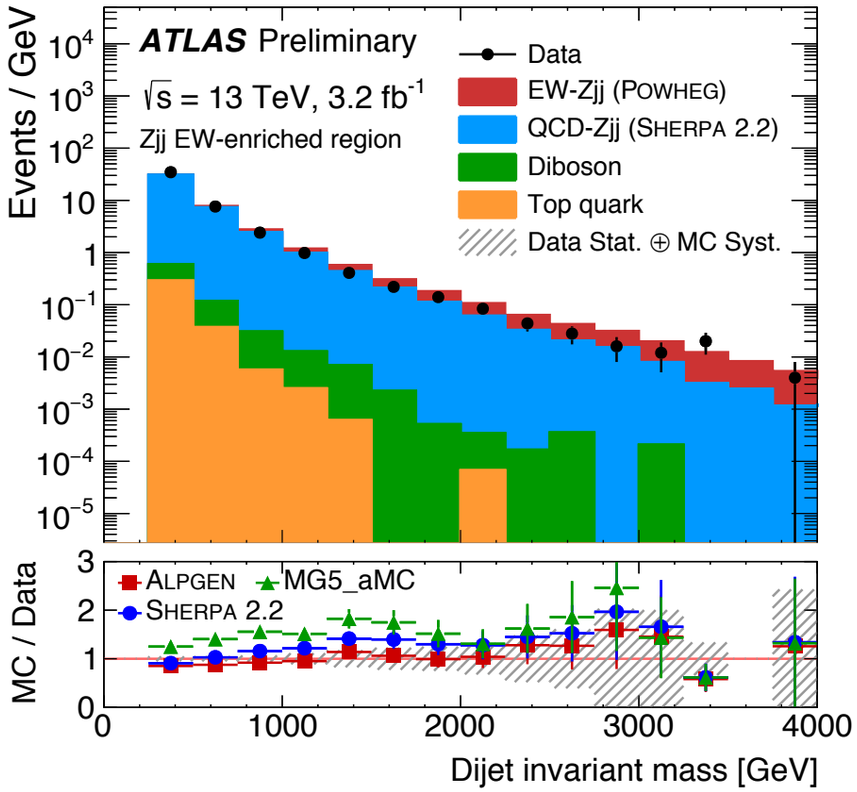
EW-enriched

p_T Balance:

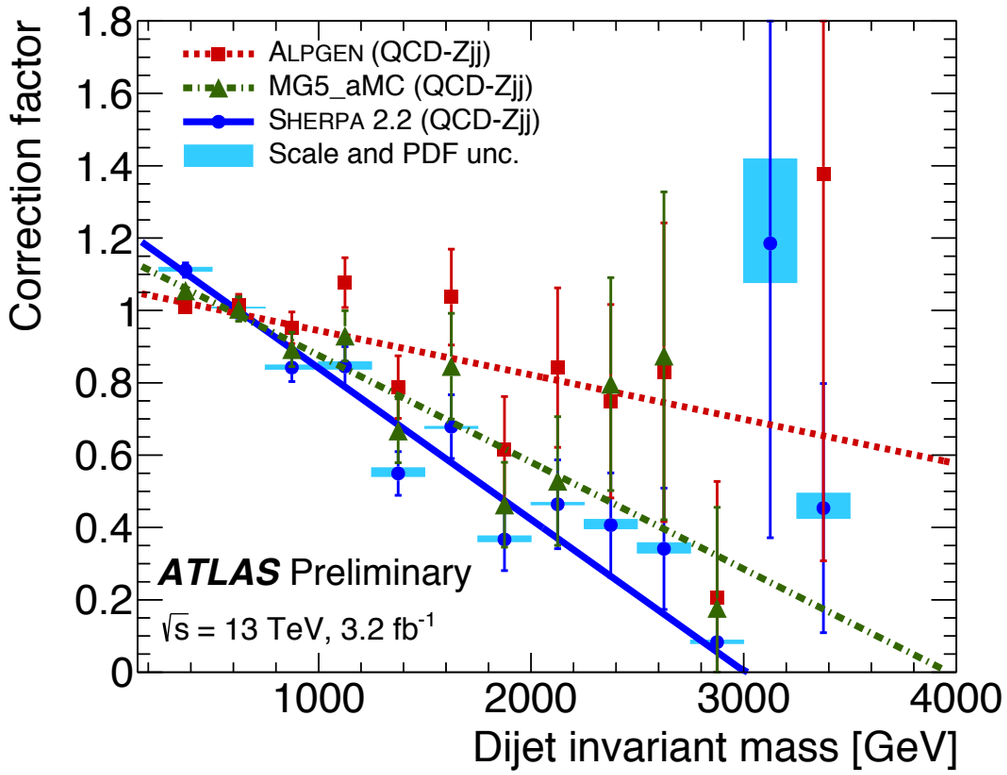
$$p_T^{\text{balance}} = \frac{\left|\vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}\right|}{\left|\vec{p}_T^{\,\ell_1}\right| + \left|\vec{p}_T^{\,\ell_2}\right| + \left|\vec{p}_T^{\,j_1}\right| + \left|\vec{p}_T^{\,j_2}\right|}$$

- 2 same-flavor leptons; $m_{\ell\ell}$ required to be within 10 GeV of PDG Z mass
- "Baseline jets" require $|y| < 4.4$, $p_{Tj1} > 55$ GeV, $p_{Tj2} > 45$ GeV
  - Other fiducial regions have higher p_T thresholds
- Balance of object momenta: $p_{T,\text{balance}} < 0.15$
  - Reduces backgrounds with jets from pile-up or multiple interactions
- EW *Zjj* regions: Central Jet Veto
  - No jet (p_T>25 GeV) in the rapidity region bounded by 2 leading jets
  - A QCD-enriched region requiring ≥1 jet in this region is used to correct the QCD component

Constraining QCD with a data-driven approach



QCD Mismodeling
in EW-enriched region

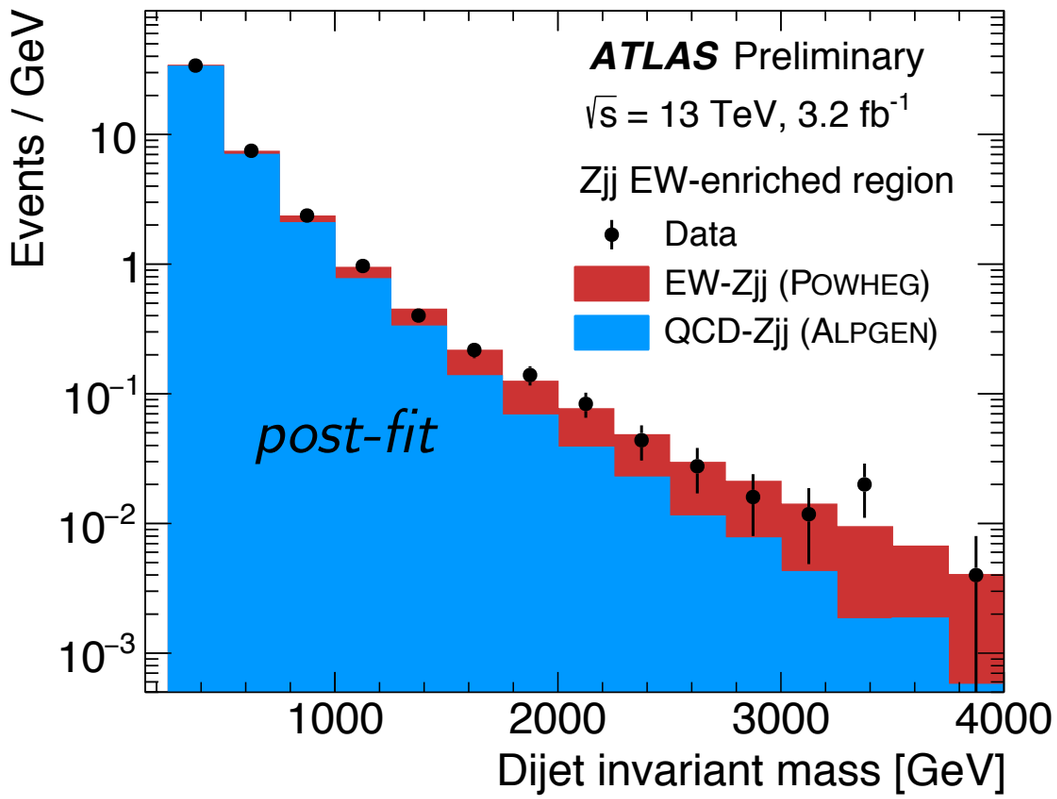


Correction in QCD-enriched
control region

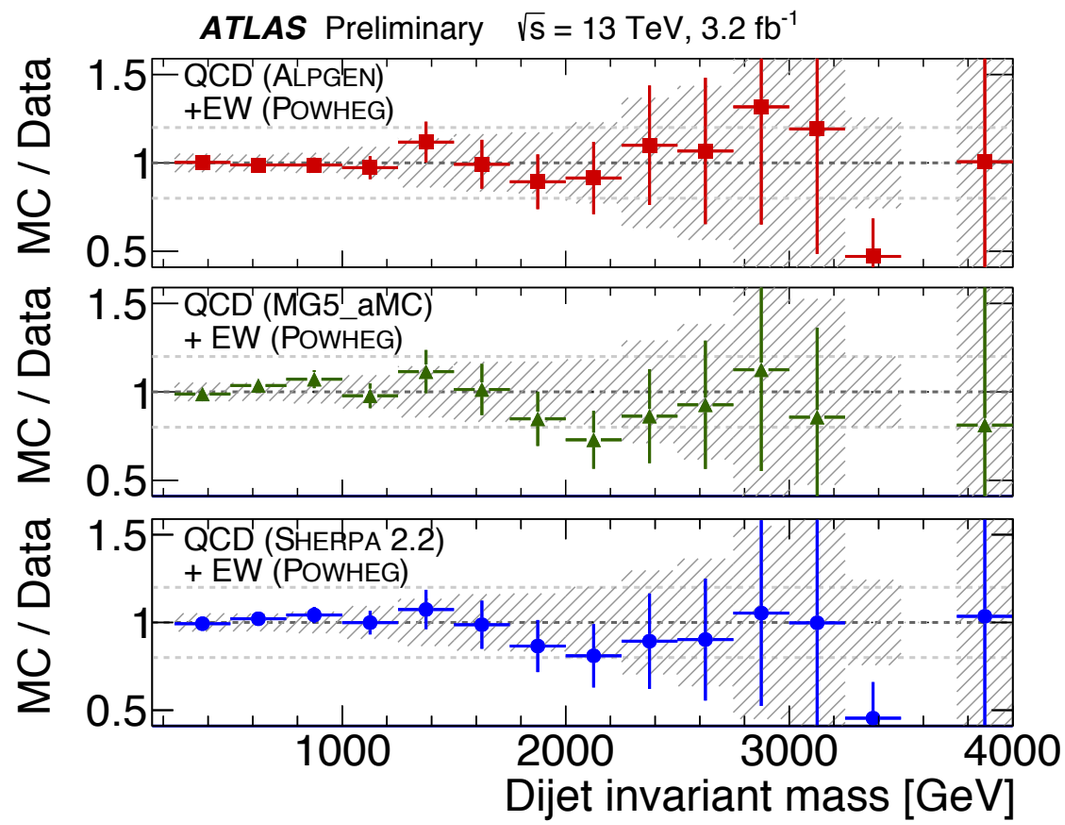
- QCD modeling of M_{JJ} is imperfect in EW-enriched region and QCD-enriched control region
- Use QCD-enriched control region to derive a linear data-MC M_{JJ} correction factor
- Resulting corrected QCD M_{JJ} distribution is used in fit to determine EW Zjj

Extraction of EW *Zjj* Fiducial Cross Section

QCD+EW Zjj fit in signal region



QCD+EW comparison with MC (post-fit)

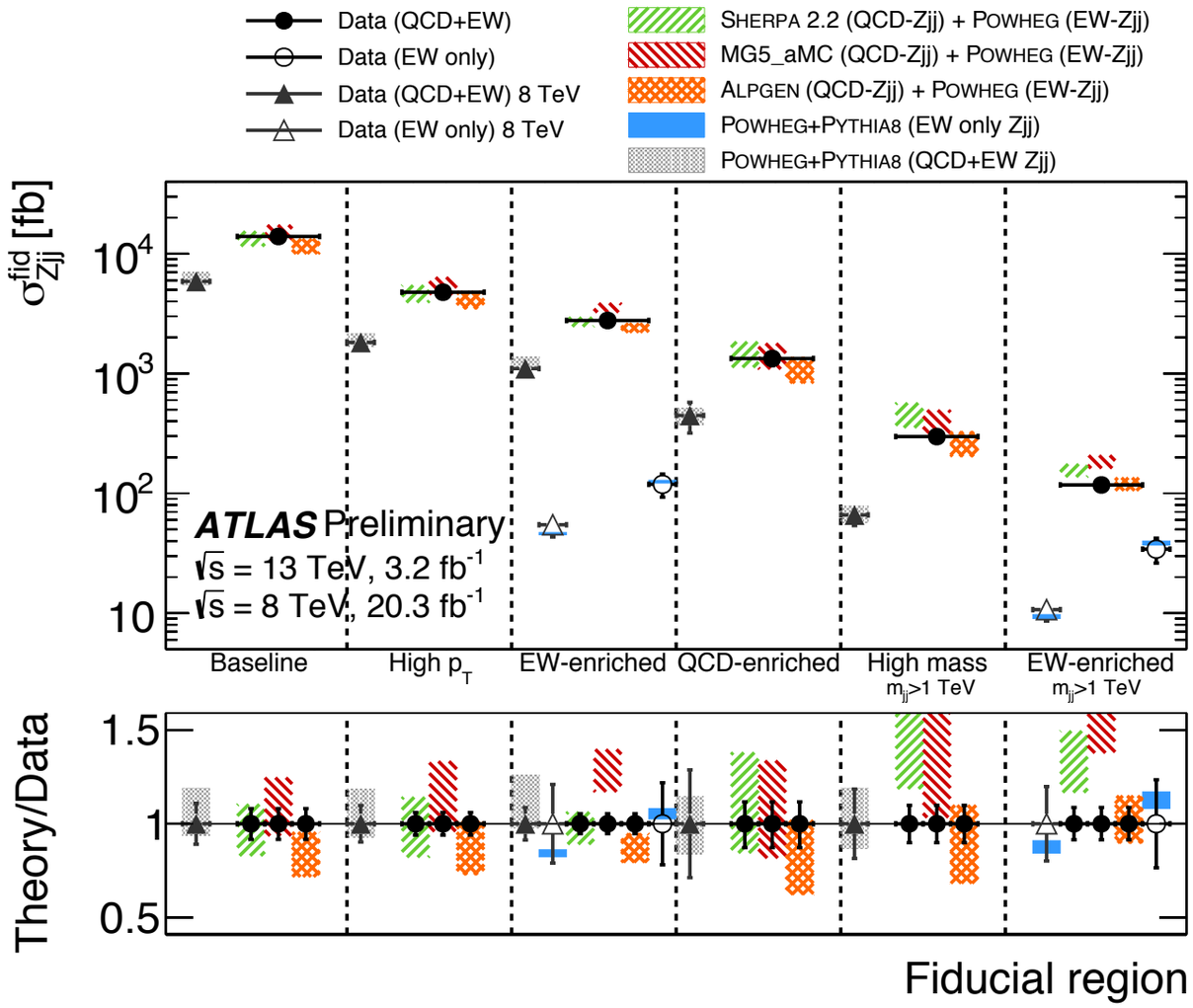


- Corrected QCD *Zjj* distribution is normalized via a log-likelihood fit of QCD and EW *Zjj* simulation in the M_{JJ} distribution
- EW Zjj fiducial cross section is calculated using:

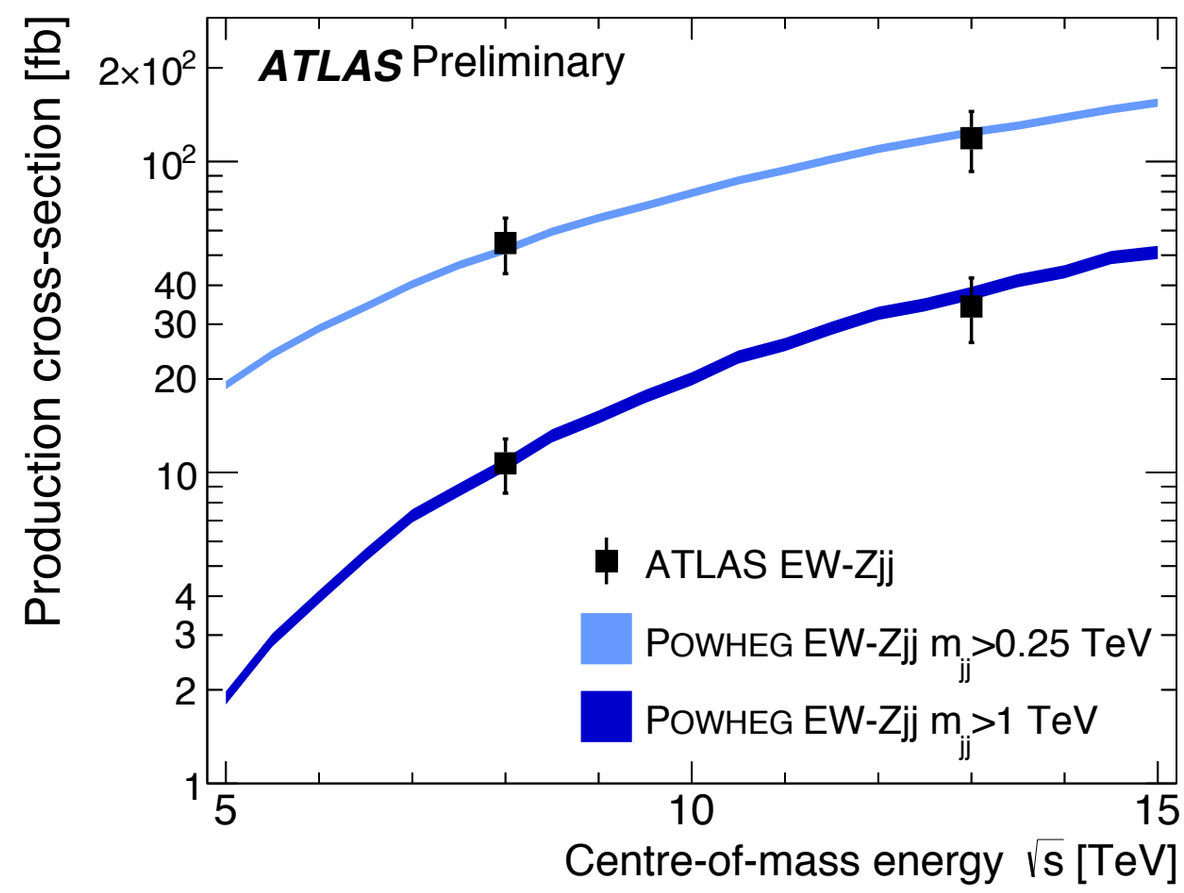
$$\sigma^f_{\mathrm{EW}} = \frac{N^f_{\mathrm{obs}} - N^f_{\mathrm{QCD}-Zjj} - N^f_{\mathrm{bkg}}}{L \cdot C^f_{\mathrm{EW}}}$$

- ...with other backgrounds subtracted using simulation predictions, and a correction factor $C^f{}_{EW}$ to correct for detector-level efficiency and resolution effects (L is luminosity)

Results – *Zjj*

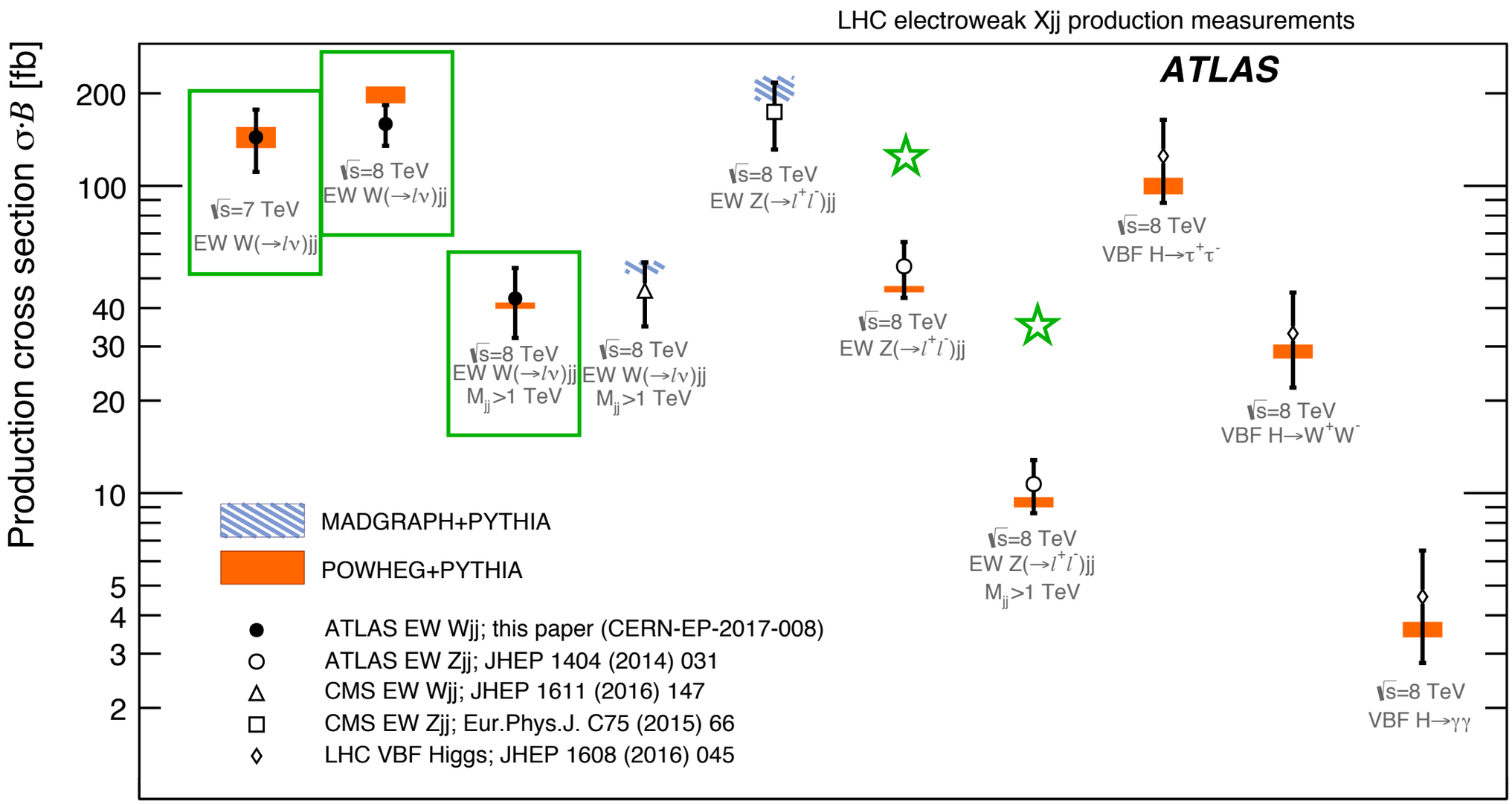


EW-enriched Fiducial Region	EW-*Zjj* cross-sections [fb]	
	Measured	POWHEG+PYTHIA
m_{jj} > 250 GeV	119 ± 16 ± 20 ± 2	125.2 ± 3.4
m_{jj} > 1 TeV	34.2 ± 5.8 ± 5.5 ± 0.7	38.5 ± 1.5



- Results of QCD+EW Zjj fiducial measurements compared to leading MC predictions in all 6 fiducial regions
- EW-only Zjj cross sections measured in 2 enriched fiducial regions
  - Compatible with SM predictions
- EW production increase vs c.o.m. energy well-predicted by MC

Summary and Conclusions



☆ Preliminary *Zjj* 13 TeV ATLAS results

- *Wjj* results at 7 and 8 TeV with small relative uncertainties
  - First differential cross section measurements of EW *Wjj* production
- Preliminary *Zjj* result begins the process of extending Electroweak production physics to higher-energy regimes

BACKUP

Zjj Fiducial Region Descriptions

	Fiducial region					
Object	Baseline	High-mass	High-p_{T}	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_{\mathrm{T}} > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_{\mathrm{T}}^{j_1} > 55$ GeV		$p_{\mathrm{T}}^{j_1} > 85$ GeV	$p_{\mathrm{T}}^{j_1} > 55$ GeV		
	$p_{\mathrm{T}}^{j_2} > 45$ GeV		$p_{\mathrm{T}}^{j_2} > 75$ GeV	$p_{\mathrm{T}}^{j_2} > 45$ GeV		
Dijet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N_{\mathrm{jet}\ (p_{\mathrm{T}}>25\ \mathrm{GeV})}^{\mathrm{interval}} = 0$		$N_{\mathrm{jet}\ (p_{\mathrm{T}}>25\ \mathrm{GeV})}^{\mathrm{interval}} \geq 1$
Zjj system	—			$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$		$p_{\mathrm{T}}^{\mathrm{balance},3} < 0.15$

Zjj Expected Composition in fiducial regions

	Composition [%]					
Process	Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
QCD-Zjj	94.2 ± 0.4	86.8 ± 1.6	92.3 ± 0.4	93.4 ± 0.9	72.9 ± 2.1	95.4 ± 0.8
EW-Zjj	1.5 ± <0.1	10.6 ± 0.2	2.6 ± <0.1	4.8 ± <0.1	26.1 ± 0.5	1.6 ± <0.1
Diboson	1.6 ± <0.1	1.5 ± 0.1	2.0 ± <0.1	1.0 ± <0.1	0.8 ± 0.1	1.8 ± <0.1
$t\bar{t}$	2.6 ± <0.1	1.1 ± 0.1	3.1 ± 0.1	0.7 ± <0.1	0.1 ± 0.1	1.2 ± 0.1
Single-t	<0.2	<0.2	<0.2	<0.1	<0.1	<0.1
W+jets	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Multijet	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Total expected	64800 ± 130 ± 5220	2220 ± 20 ± 200	21900 ± 40 ± 1210	11100 ± 50 ± 520	640 ± 10 ± 40	7120 ± 30 ± 880
Total observed	67472	1471	22461	11630	490	6453