VBF production of single gauge bosons at the LHC

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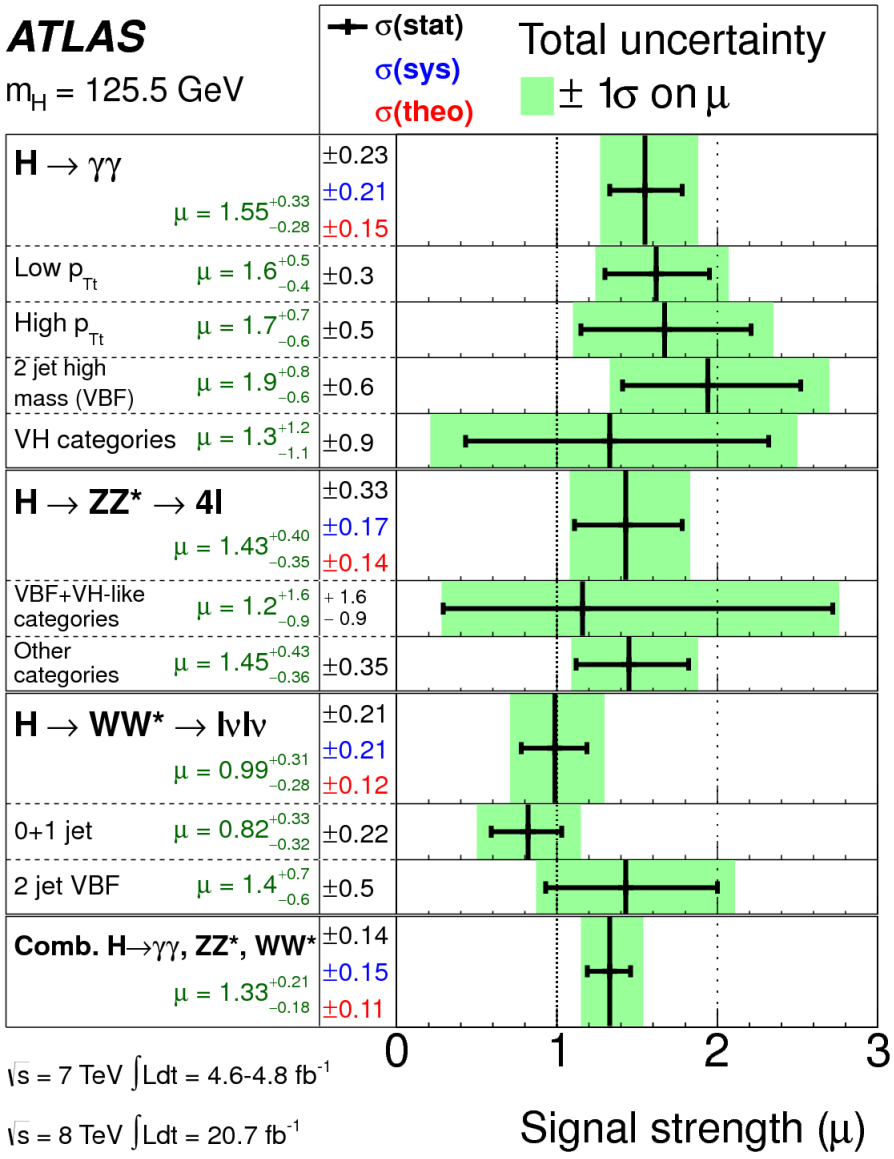
On behalf of ATLAS and CMS

Presented at SM@LHC 2014

THE UNIVERSITY OF WARWICK

Why VBF?

- Vector boson fusion was an unmeasured process.
- Important production mode for the Higgs discovery.
- Another opportunity to probe anomalous couplings.
- Provides a test bed for future weak boson fusion/scattering measurements.



[Phys. Lett. B 726 (2013), pp. 88-119]

Public results

Current public results : -

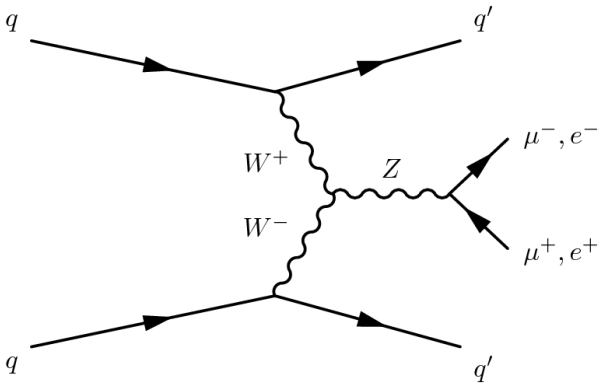
Measurement of the hadronic activity in events with a Z and two jets and extraction of the cross section for the electroweak production of a **Z** with two jets in pp collisions at $\sqrt{s}$ = 7 TeV. **J. High Energy Phys. 10 (2013) 062**

Measurement of pure electroweak production of a **Z** boson in association with two forward/backward jets in proton-proton collisions at 8 TeV. **CMS-PAS-FSQ-12-035**

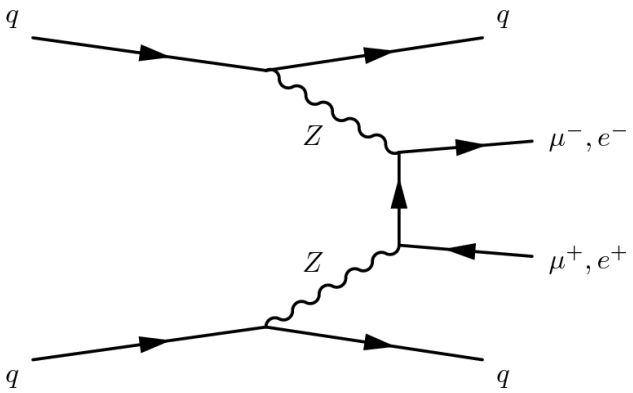
Measurement of the electroweak production of dijets in association with a **Z**-boson and distributions sensitive to vector boson fusion in proton-proton collisions at $\sqrt{s}$ = 8 TeV using the ATLAS detector. **arXiv:1401.7610 [hep-ex]**

Event categorization

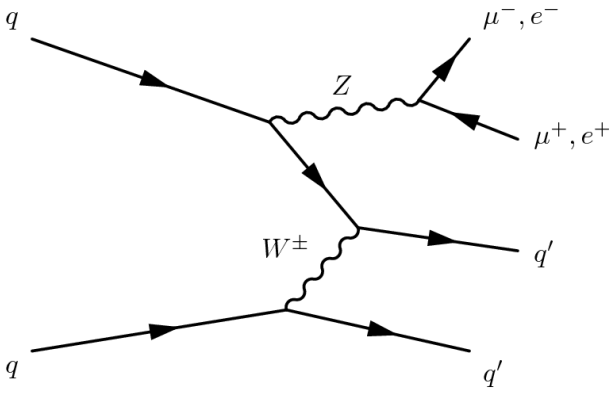
Signal



VBF

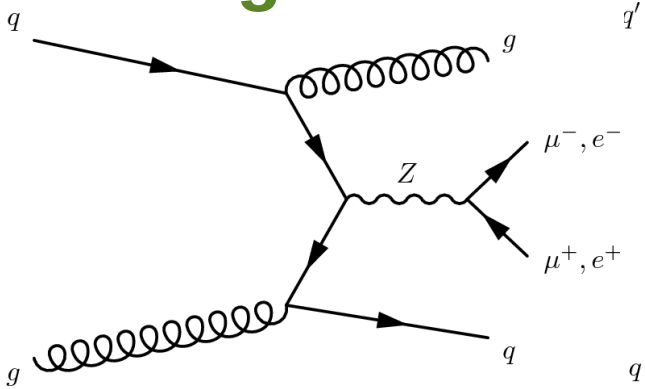


Non-resonant

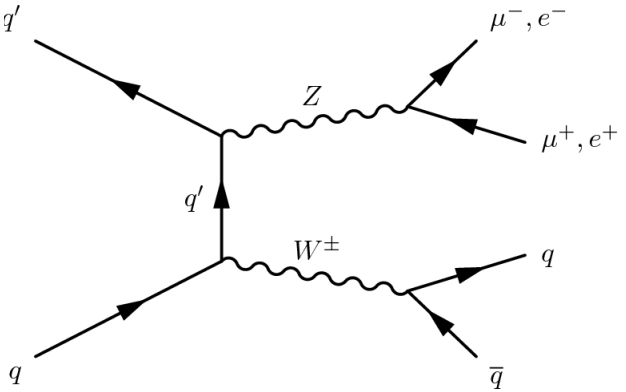


Z bremsstrahlung

Background



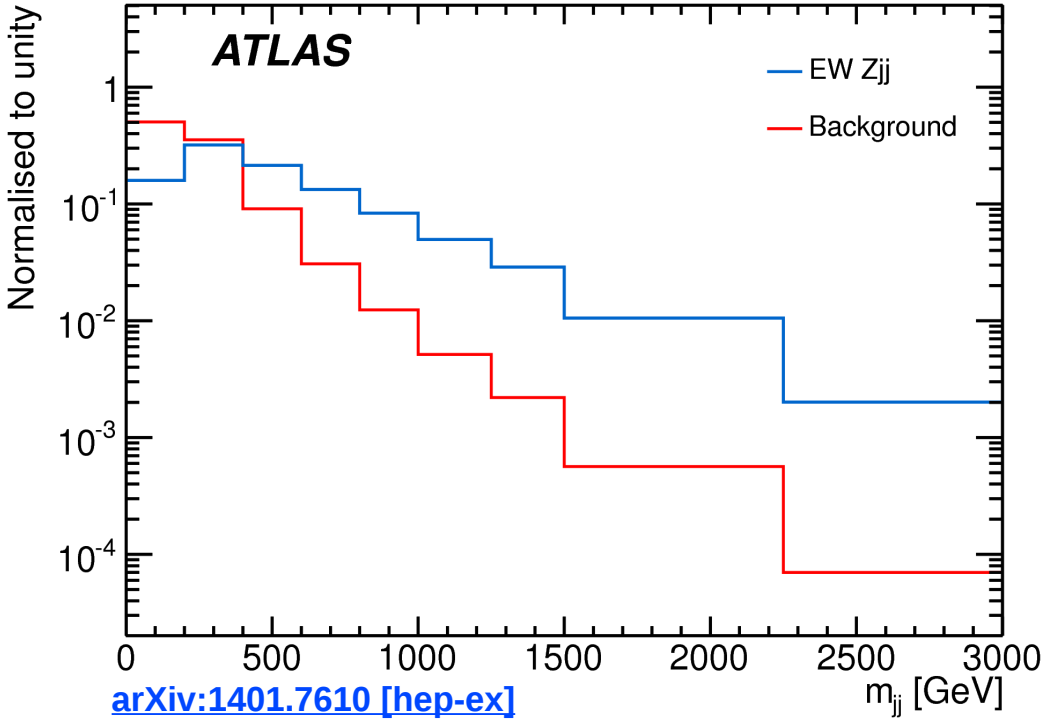
Strong Zjj

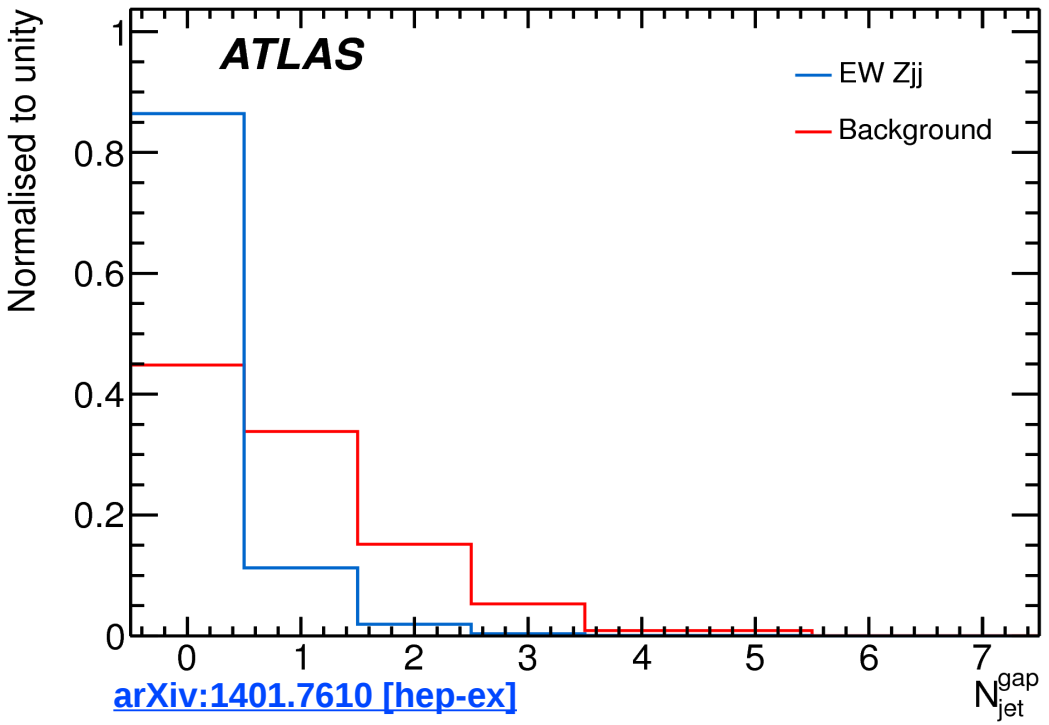


Diboson

+ $t\bar{t}$
Single top
Multi-jet
W+jets

Sensitive variables



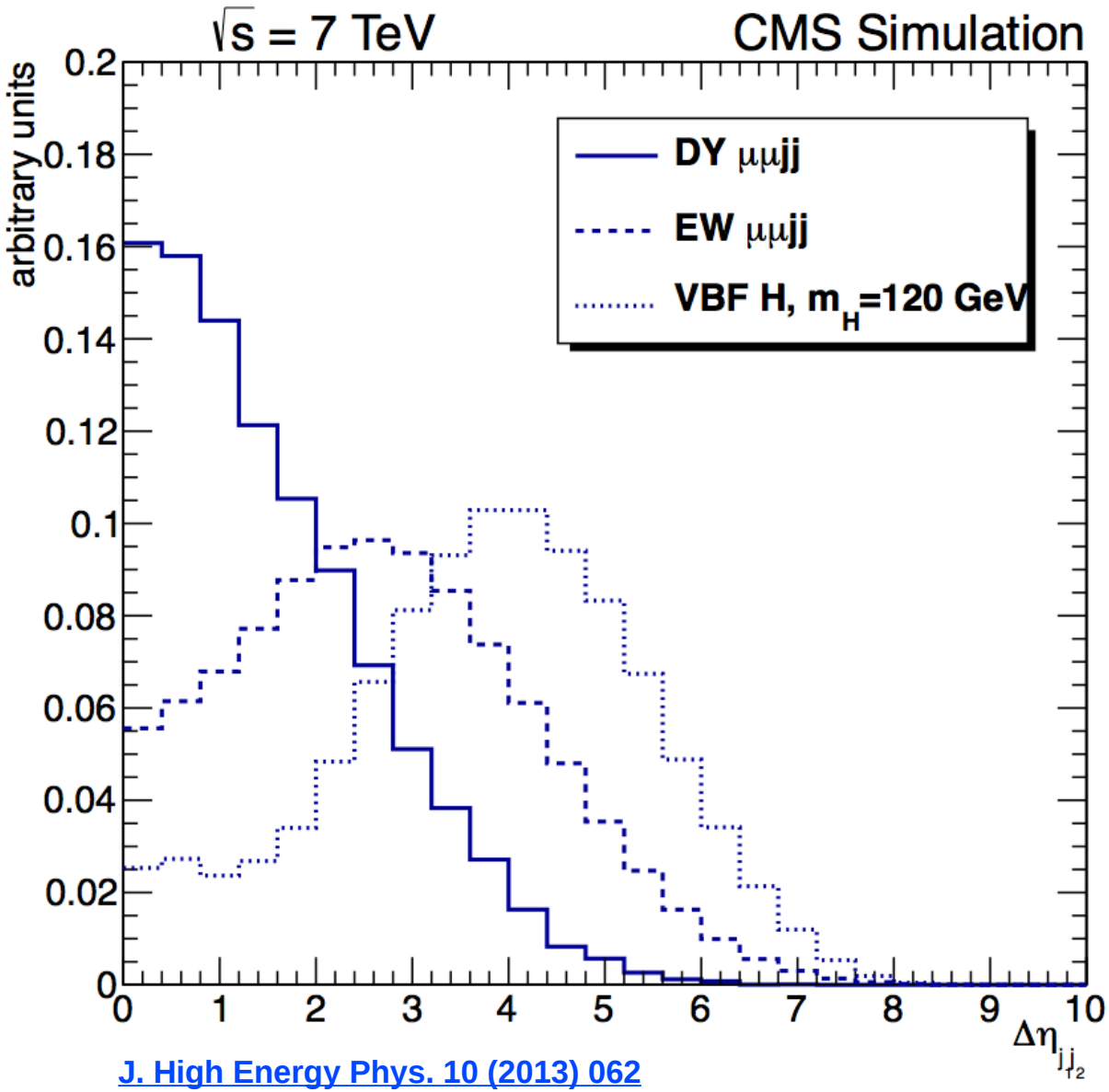


- **The dijet mass provides significant discrimination between the signal and background.**

- **Other variables of interest include lepton centrality, azimuthal separation between the jets (and leptons) and central hadronic activity.**

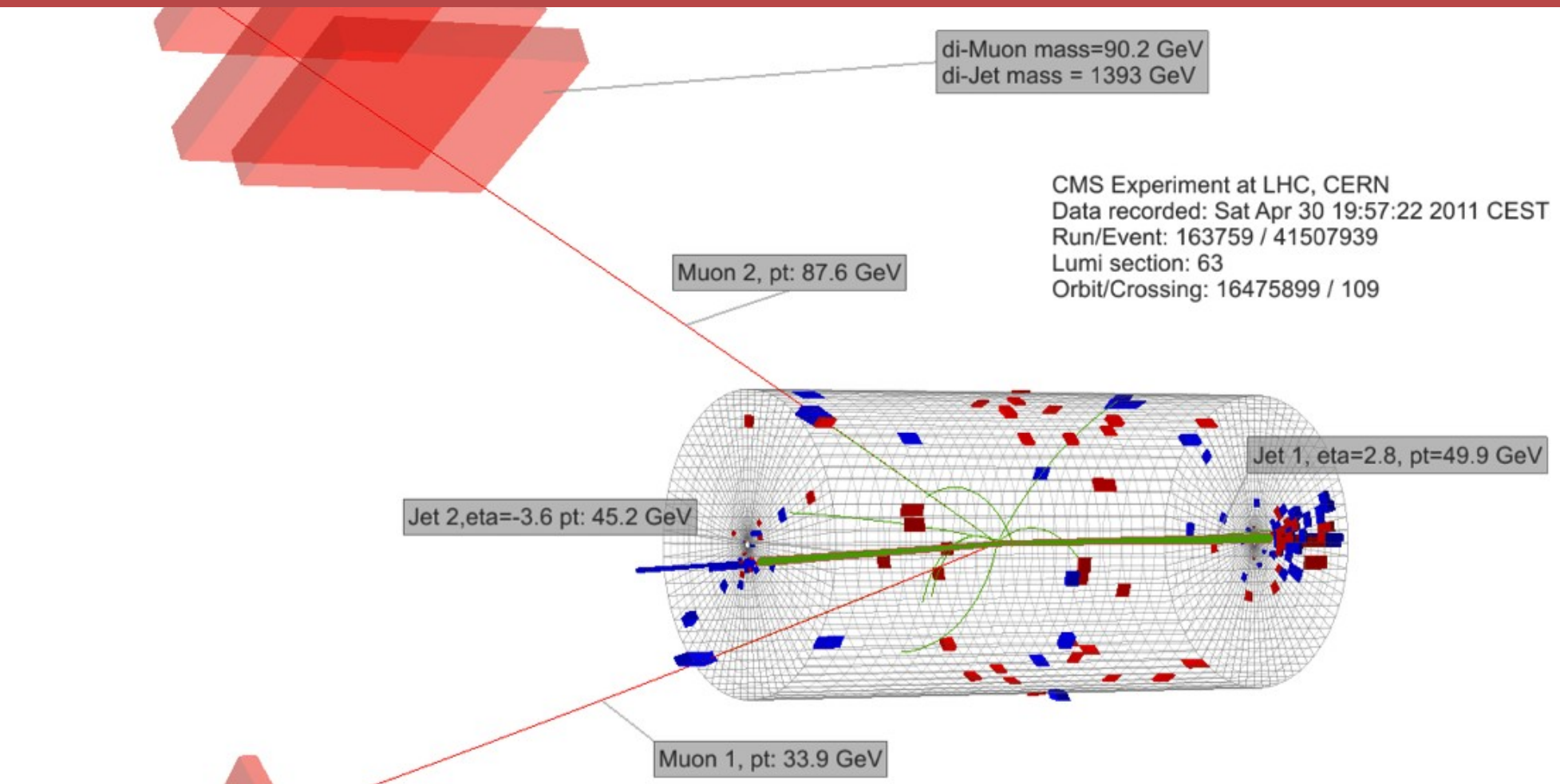
Sensitive variables

- The optimal selection for discrimination differs from the VBF Higgs case.
- Additional signal processes and interference effects are the cause of the differences.



J. High Energy Phys. 10 (2013) 062

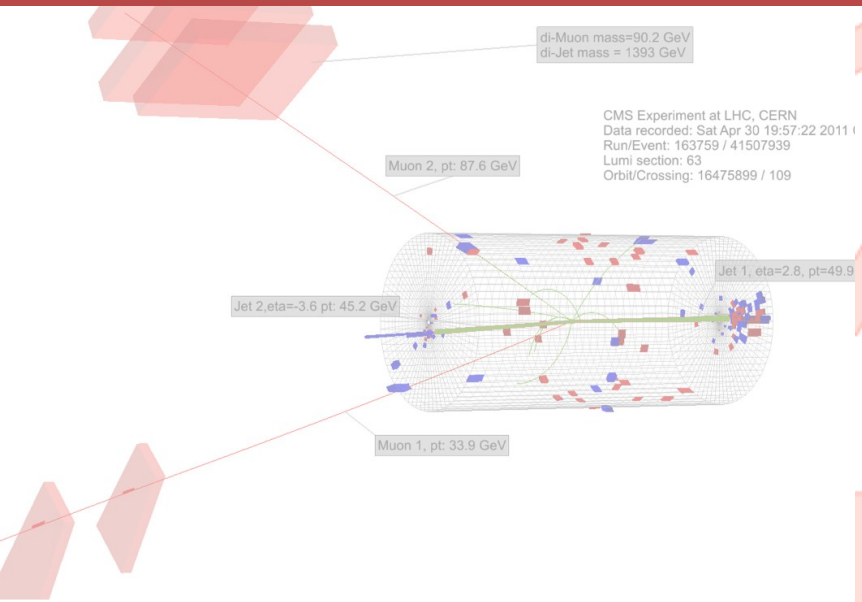
A candidate event

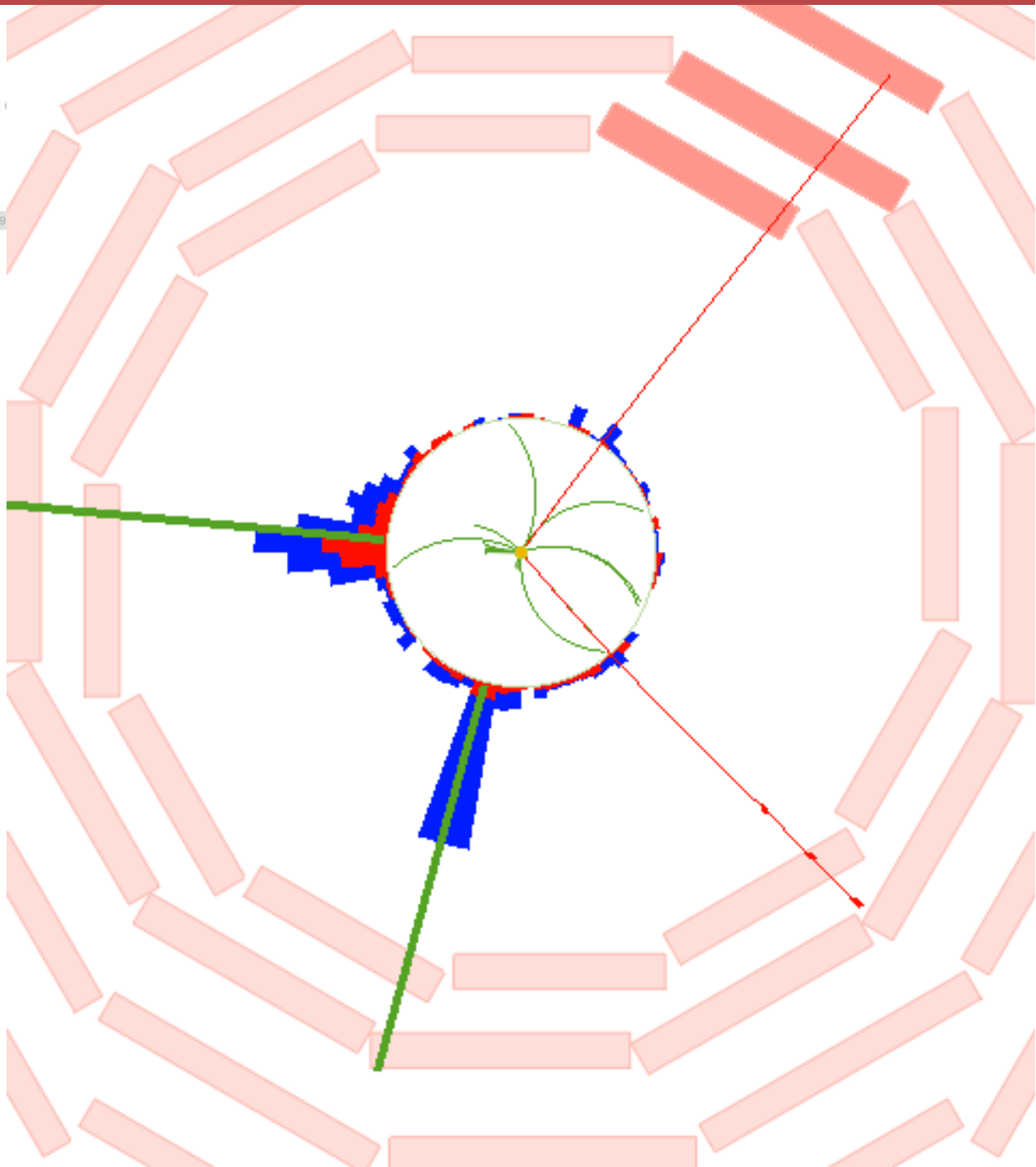


Events with the characteristic properties of an EW produced Z-boson are observed in data.

The importance of calorimetric instrumentation in the forward region is evident.

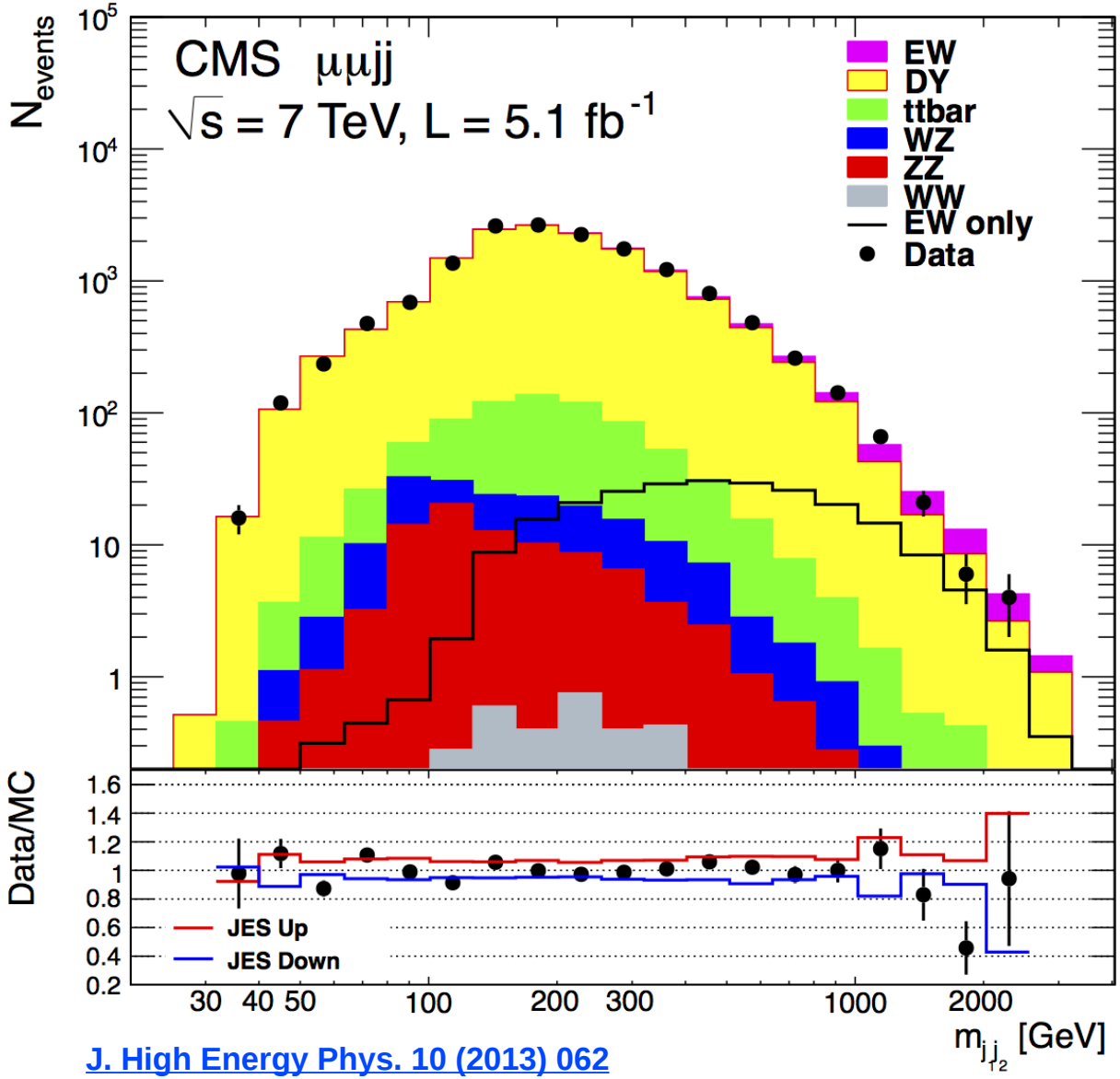
A candidate event





In the r-φ plane the transverse momentum balance of the two lepton and two jet system can be seen.

Extraction method : MC template

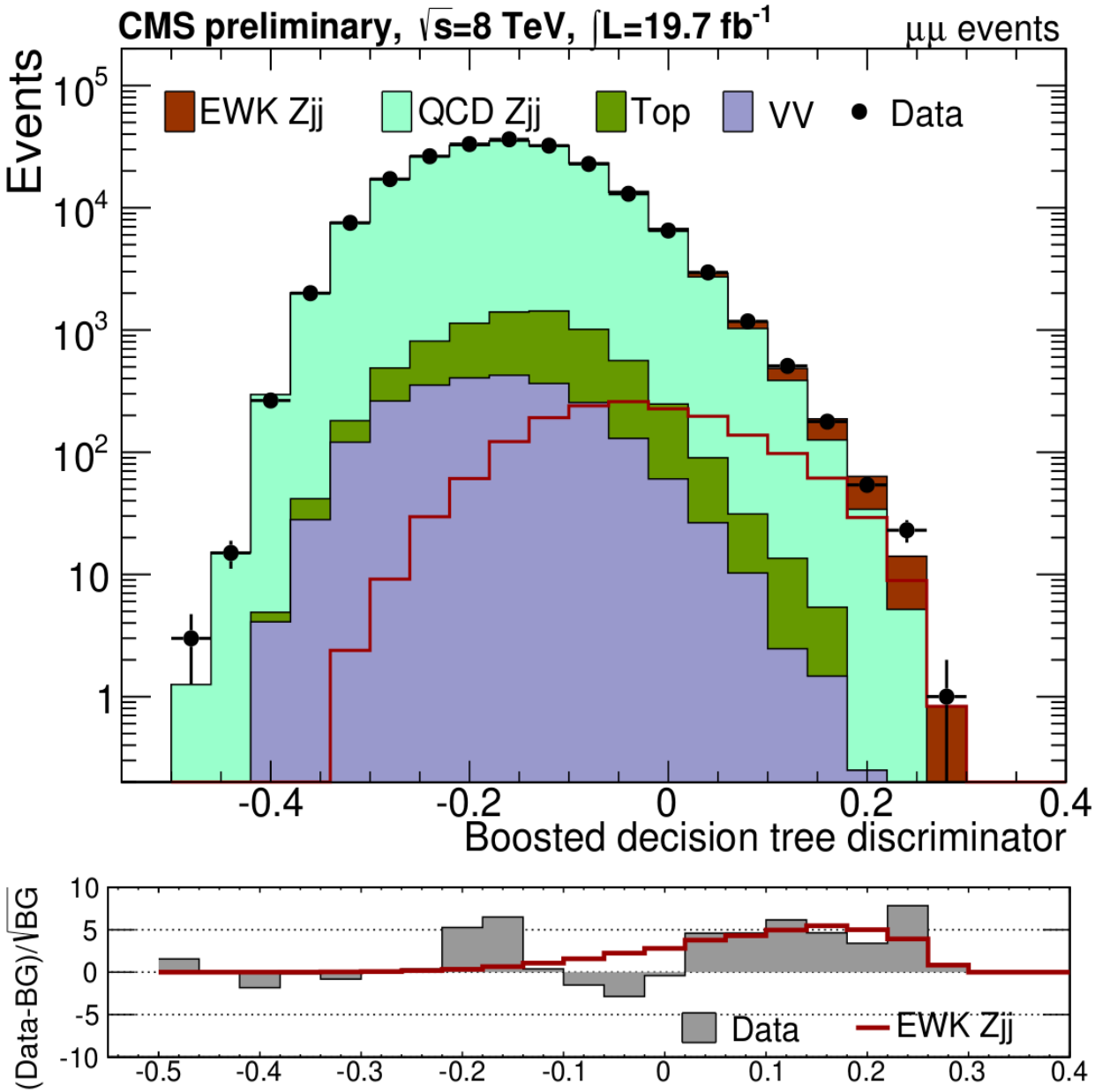


J. High Energy Phys. 10 (2013) 062

In the CMS 7 TeV cross section measurement.

- MC simulation used to provide templates for both signal and background.
- Signal extraction performed using fits to m_{jj} (just μμ) and also a BDT (both μμ and ee).

Extraction method : MC template

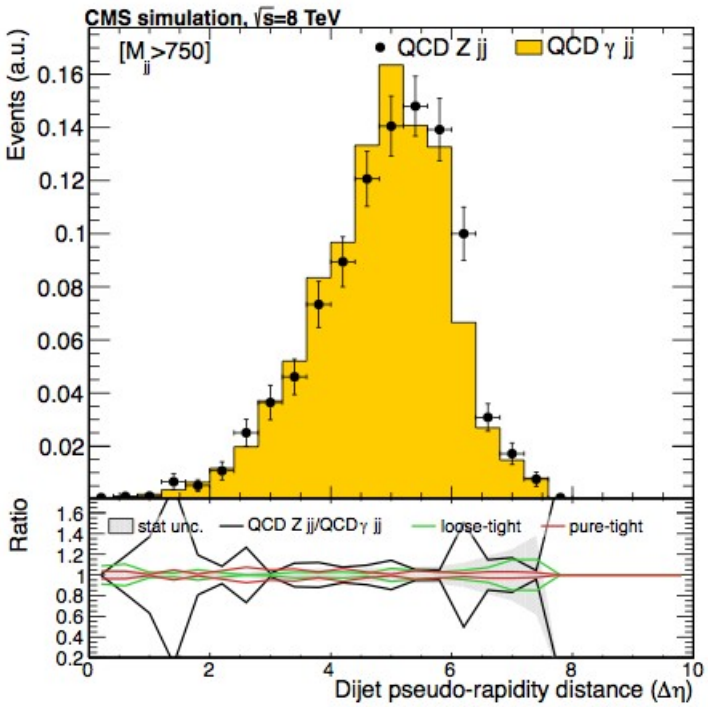


CMS-PAS-FSQ-12-035

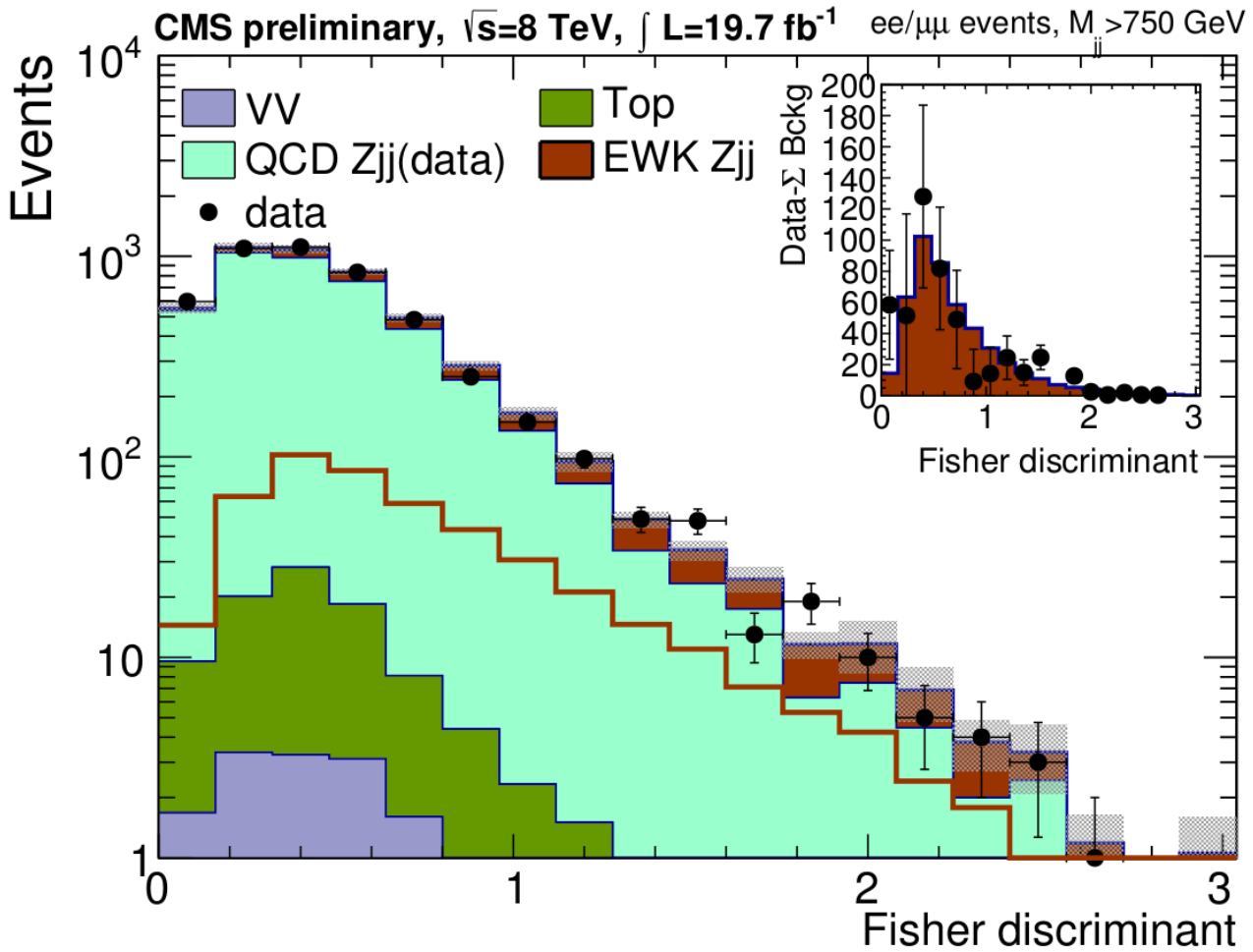
At 8 TeV CMS considered two methods for signal extraction.
In the first method : -

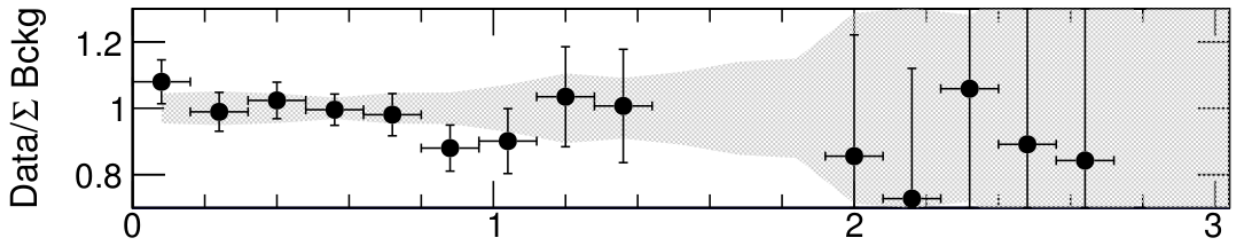
- A multivariate analysis variable is fitted.
- MC simulation was used for the signal and background templates.
- Improvement in the modelling of the background was achieved by re-weighting MC to NLO.

Extraction method : Data driven



CMS-PAS-FSQ-12-035



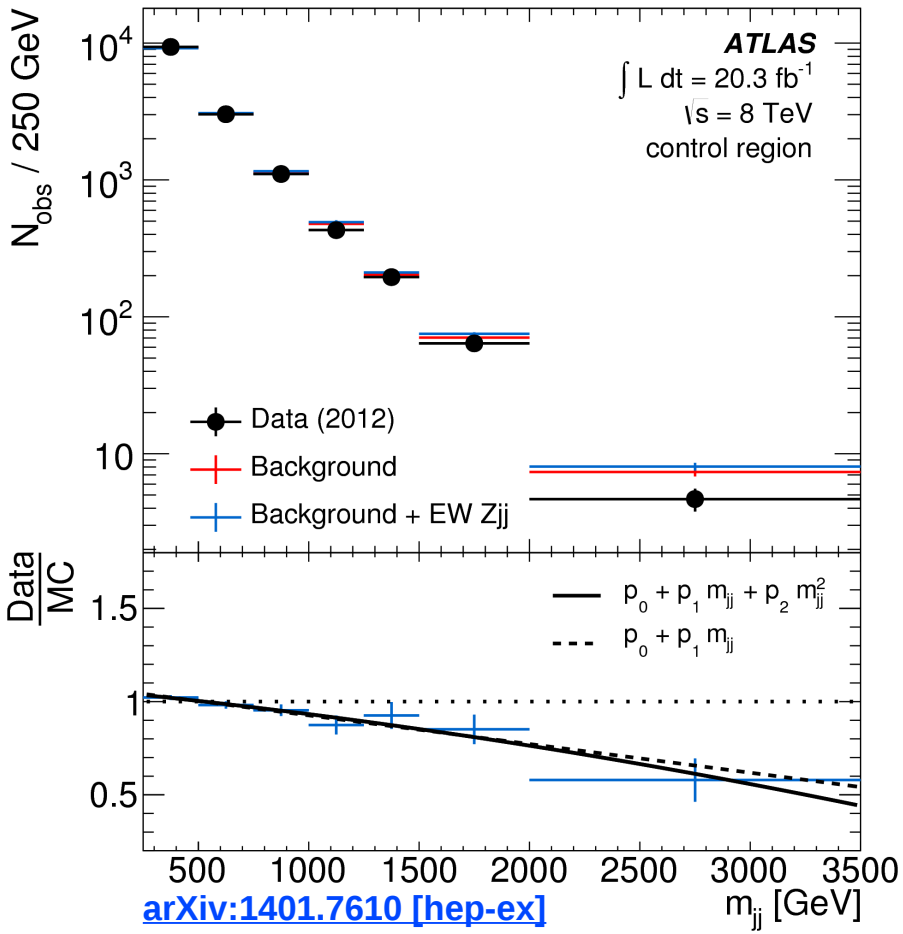


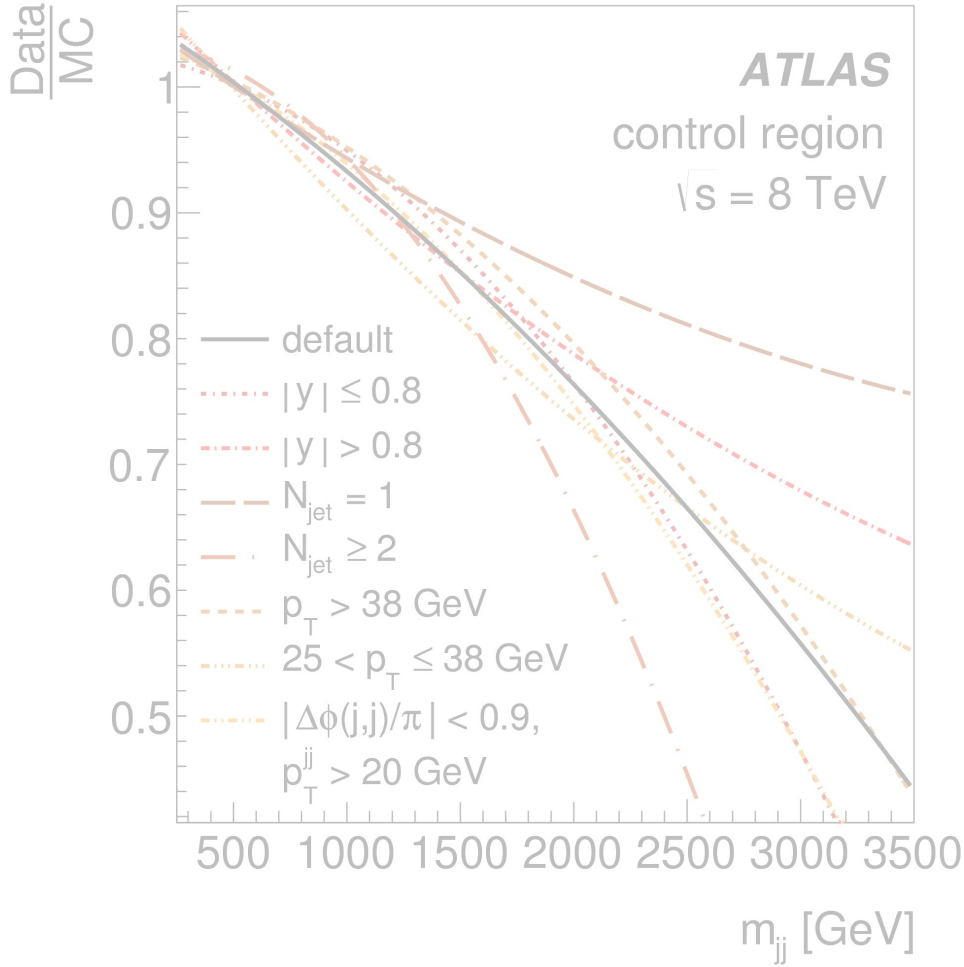
CMS-PAS-FSQ-12-035

In the second method : -

- **A measurement of photon + two jets was used to estimate the Z + two jets background.**
- **The EW photon + two jet component was subtracted using MC simulation.**

Extraction method : Data driven

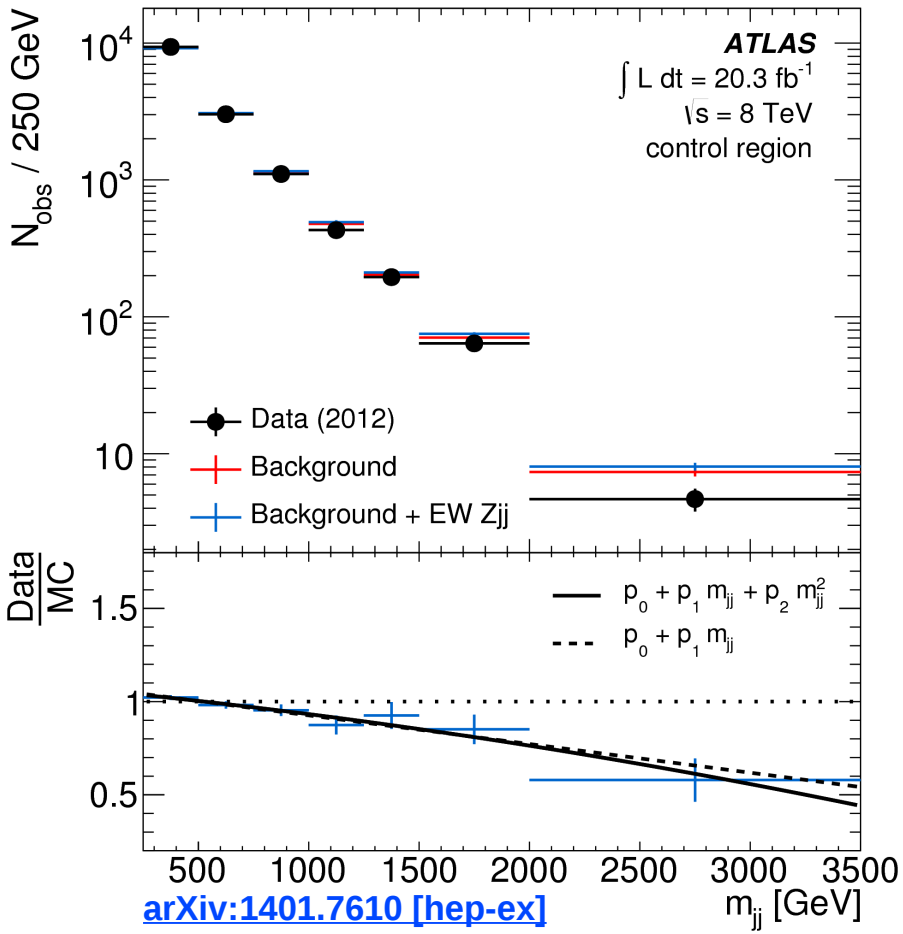




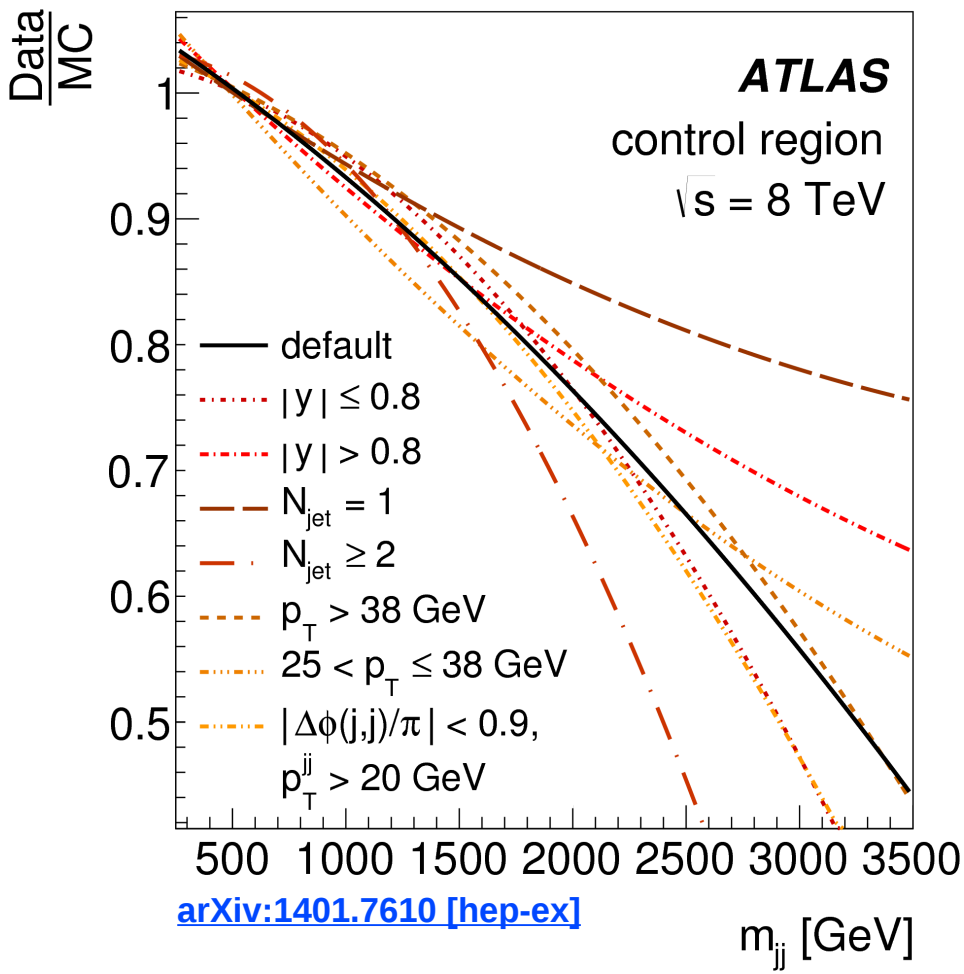
ATLAS used a fit to the dijet mass spectrum to extract the signal cross section.

Control region used to re-weight the MC simulation of the main background process.

Extraction method : Data driven



arXiv:1401.7610 [hep-ex]

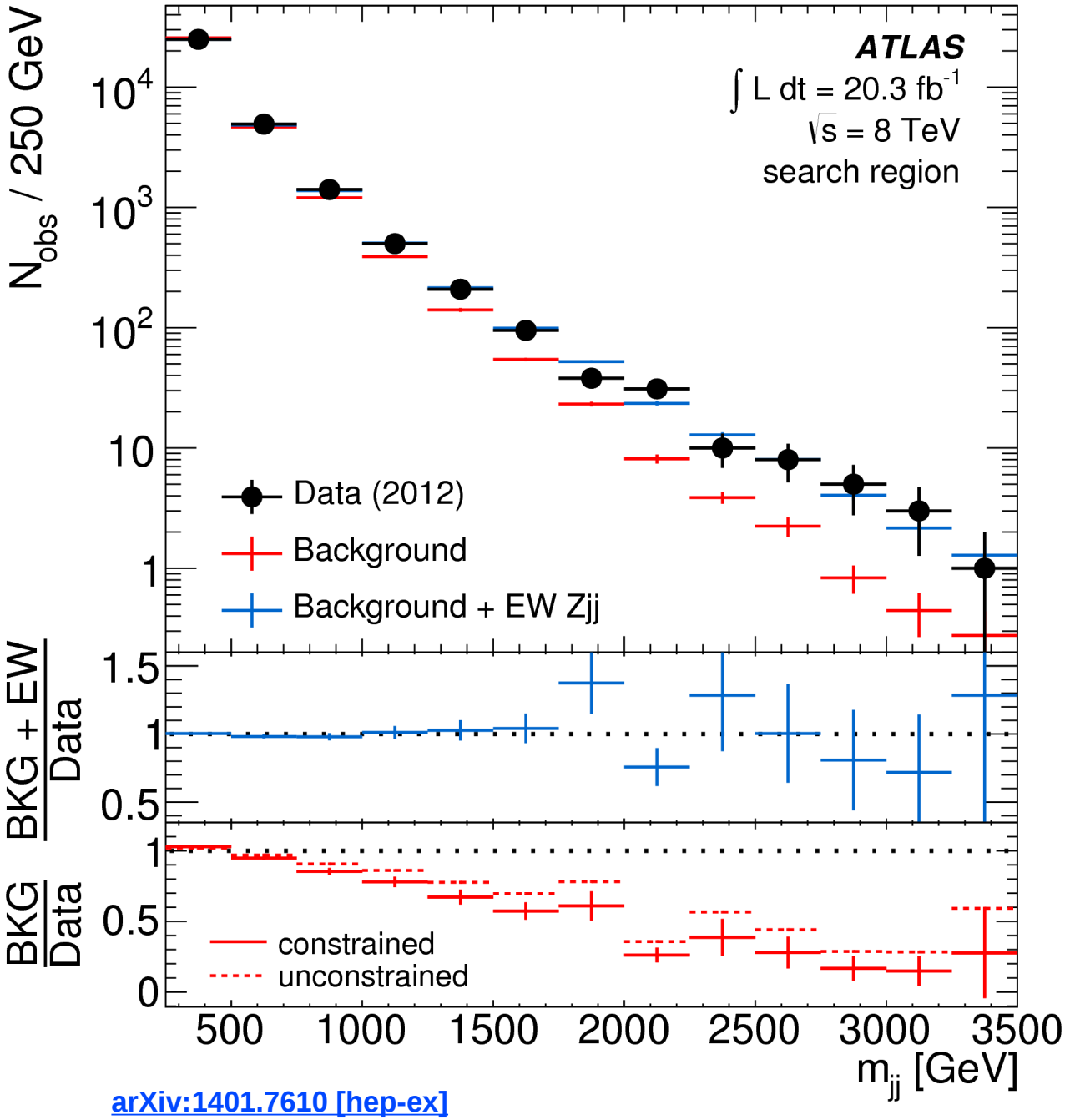


arXiv:1401.7610 [hep-ex]

Many control region definitions tested.

Generator choice checked by re-weighting to POWHEG prediction (0.8% change in signal yield).

Extraction method : Data driven



arXiv:1401.7610 [hep-ex]

Systematics

Define fiducial cross section to be

$$\sigma_{\mathrm{EW}} = \frac{N_{\mathrm{EW}}}{\int L\mathrm{d}t \cdot C_{EW}}$$

Where N_{EW} is the number of signal events from the fit and C_{EW} is correction from reconstruction to the particle level.

Source	ΔN_{EW}		ΔC_{EW}	
	Electrons	Muons	Electrons	Muons
Lepton systematics	—	—	±3.2 %	±2.5%
Control region statistics	±8.9 %	±11.2 %	—	—
JES	±5.6 %		$^{+2.7}_{-3.4}$ %	
JER	±0.4 %		±0.8 %	
Pileup jet modelling	±0.3 %		±0.3 %	
JVF	±1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	±8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	±7.5 %		—	
Signal/background interference	±6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		±0.1 %	

Main systematic uncertainties originate from the modelling of the signal and background.

Measured cross sections

7 TeV

$$\sigma_{\mathrm{EW}}^{\mathrm{CMS}} = 154 \pm 24(stat) \pm 46(syst_{exp}) \pm 27(syst_{theory}) \pm 3(lumi)\mathrm{fb}$$

$$\sigma_{\mathrm{EW}}^{\mathrm{VBFNLO}} = 166\mathrm{fb}$$

8 TeV

$$\sigma_{\mathrm{EW}}^{\mathrm{CMS}} = 226 \pm 26(stat) \pm 35(syst)\mathrm{fb}$$

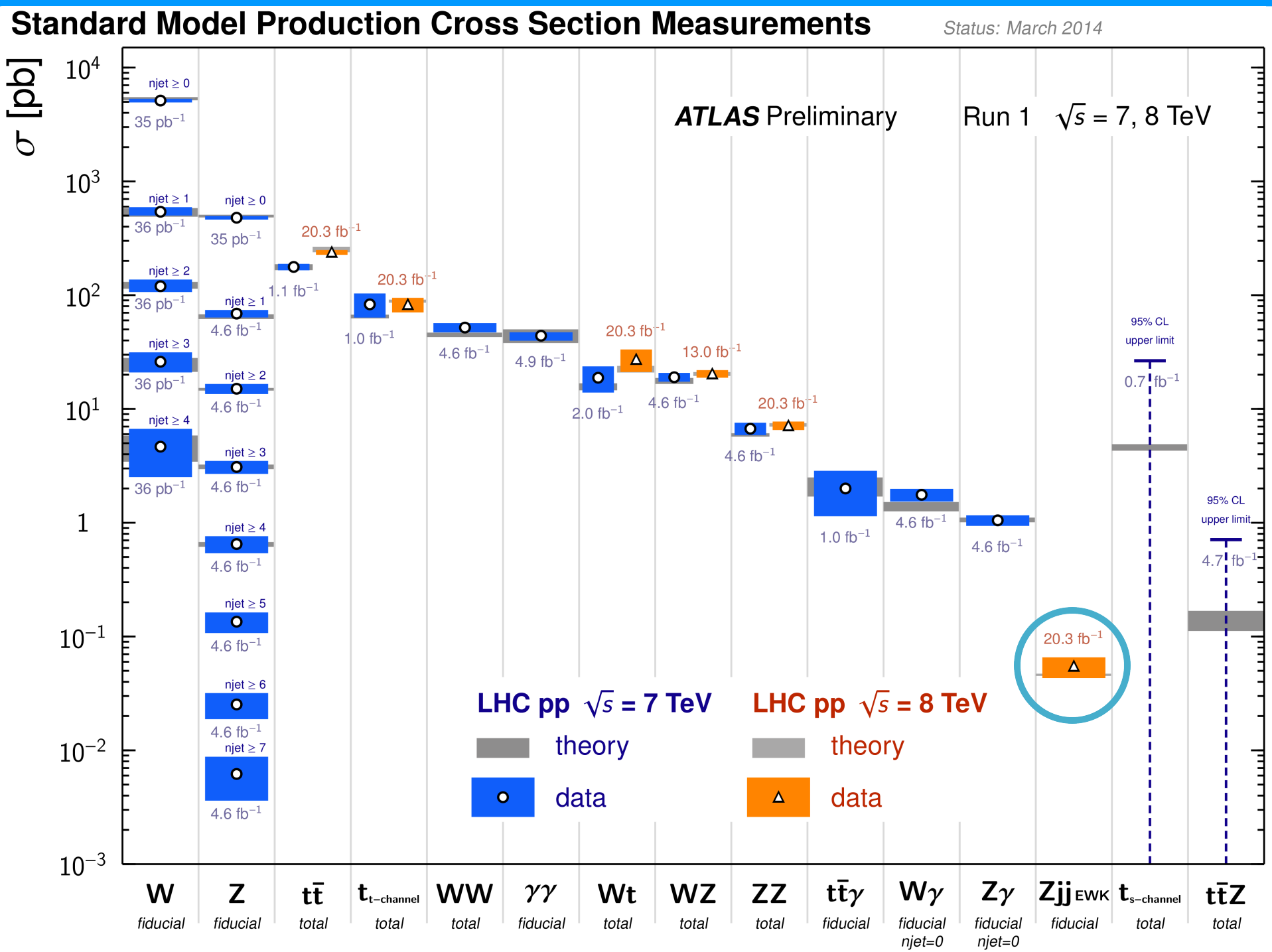
$$\sigma_{\mathrm{EW}}^{\mathrm{VBFNLO}} = 239\mathrm{fb}$$

$$\sigma_{\mathrm{EW}}^{\mathrm{ATLAS}} = 54.7 \pm 4.6(stat)^{+9.8}_{-10.4}(syst) \pm 1.5(lumi)\mathrm{fb}$$

$$\sigma_{\mathrm{EW}}^{\mathrm{POWHEG}} = 46.1 \pm 0.2(stat)^{+0.3}_{-0.2}(scale) \pm 0.8(pdf) \pm 0.5(model)\mathrm{fb}$$

All measured cross sections agree with their respective theory predictions.

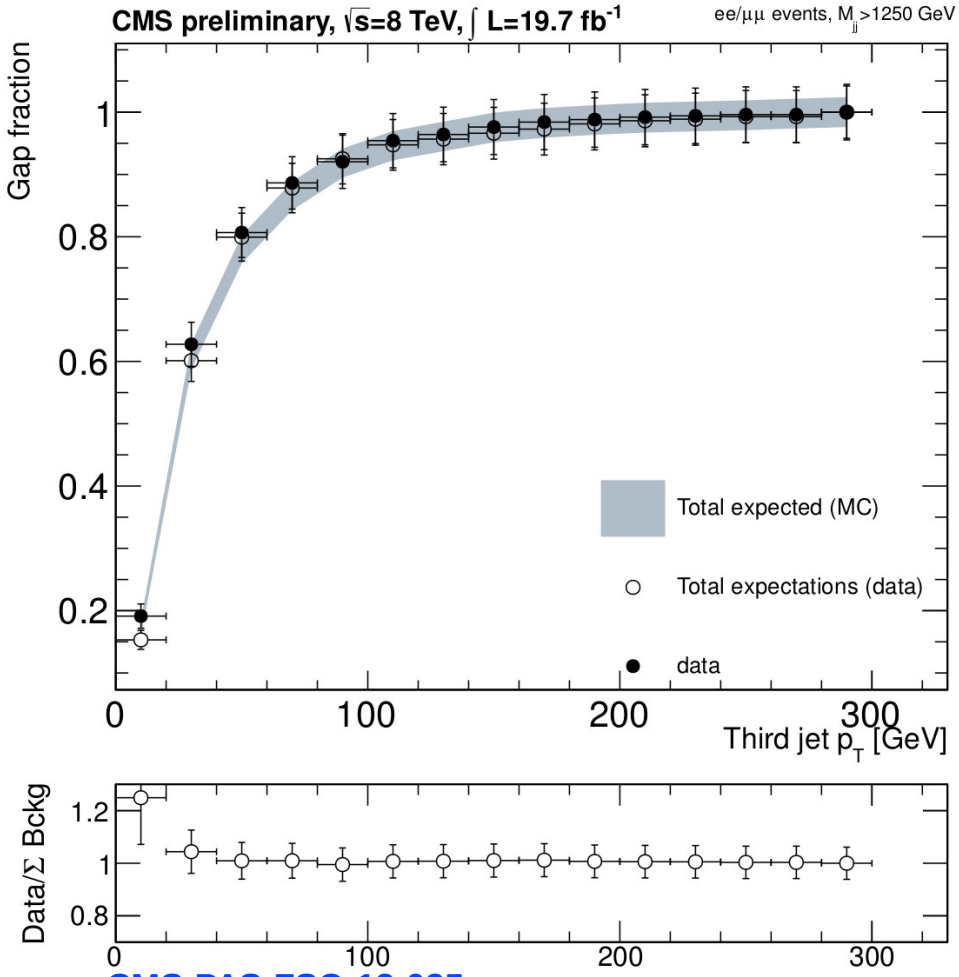
Measurement in context



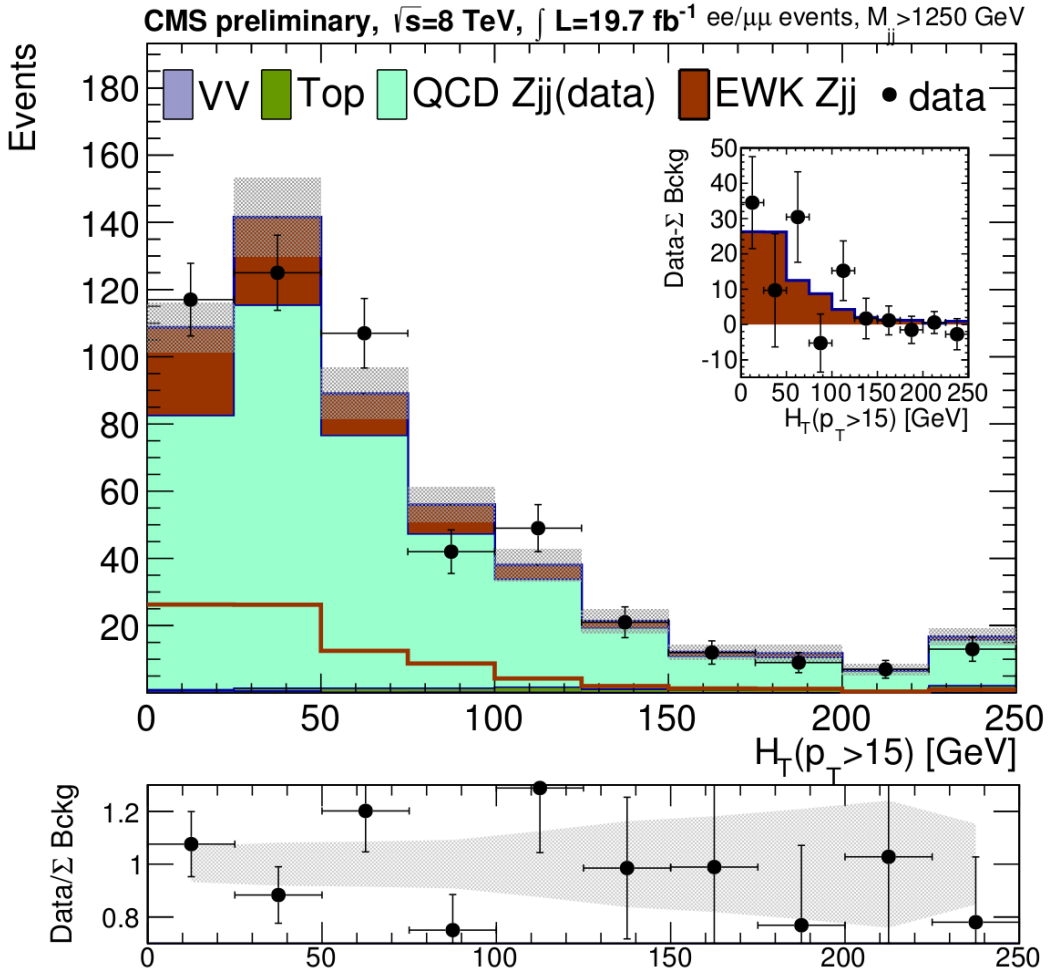
Hadronic activity

With strong evidence of the presence of EW Z boson production the properties of these events were analysed.

Investigations were made into radiation patterns, charged hadronic activity and production of extra jets in a high purity region.

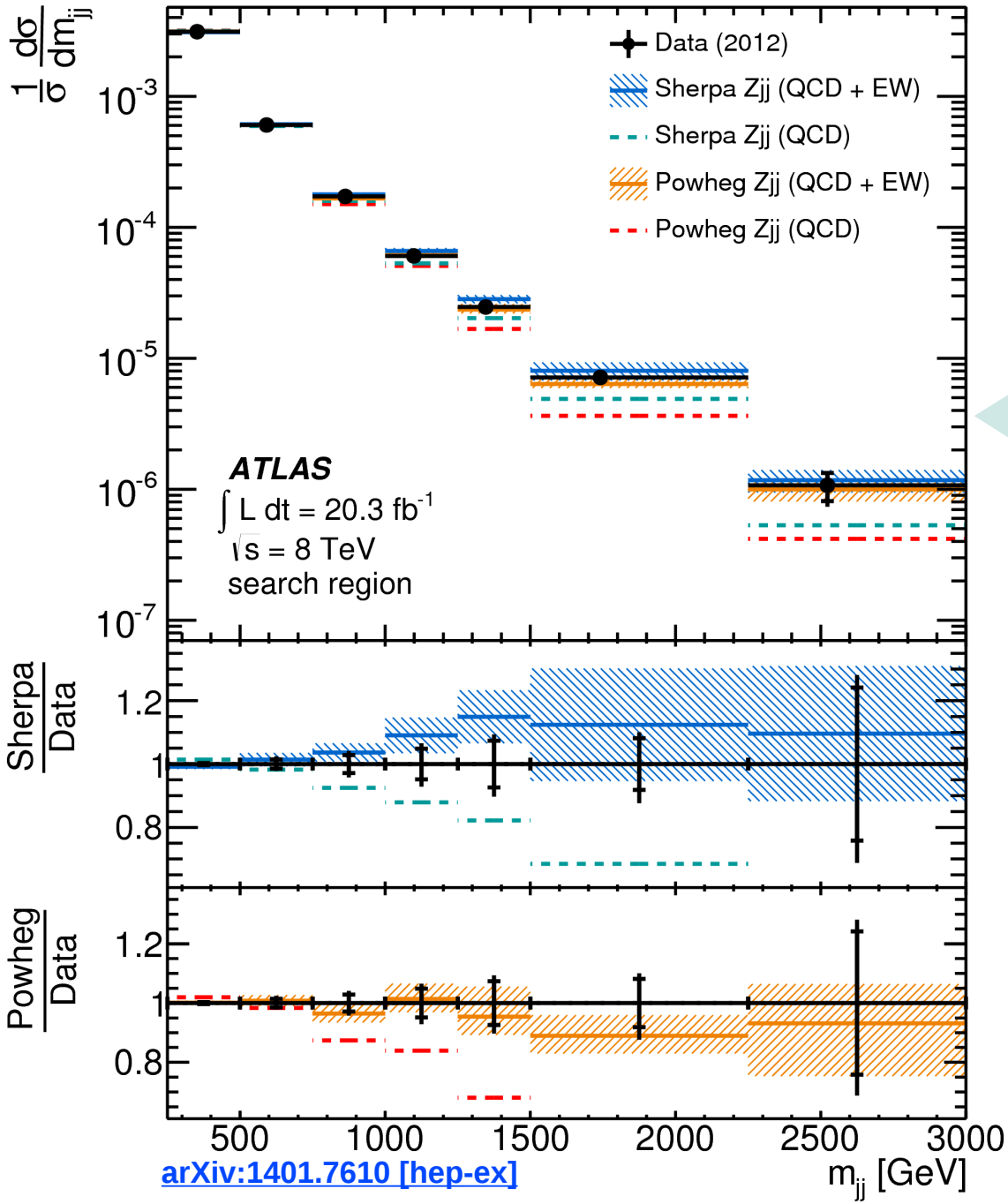


CMS-PAS-FSQ-12-035



CMS-PAS-FSQ-12-035

Unfolded distributions



- A number of differential distributions have been corrected to the particle-level.
- Comparisons have been made to Sherpa and POWHEG.
- At high dijet mass the signal component is clearly visible.
- These distributions will be available from HEPDATA in the near future.

Anomalous couplings

The measurement of the electroweak cross section for Z production offers a complimentary test of anomalous triple gauge couplings.

Given an effective Lagrangian

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

and a dipole form factor

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

the following limits are set using a search region with m_{jj}>1TeV.

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	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Summary

- Measurements of EW Z-boson production have been made at the LHC.
  - Different techniques give consistent results.
  - Data driven methods help to constrain systematic uncertainties.
  - Consistent with the NLO theory predictions.
- A variety of differential distributions have been measured.
  - Varying levels of agreement with theory.
  - Many have been unfolded and will be available from HEPDATA.
- Limits have been set on anomalous couplings.

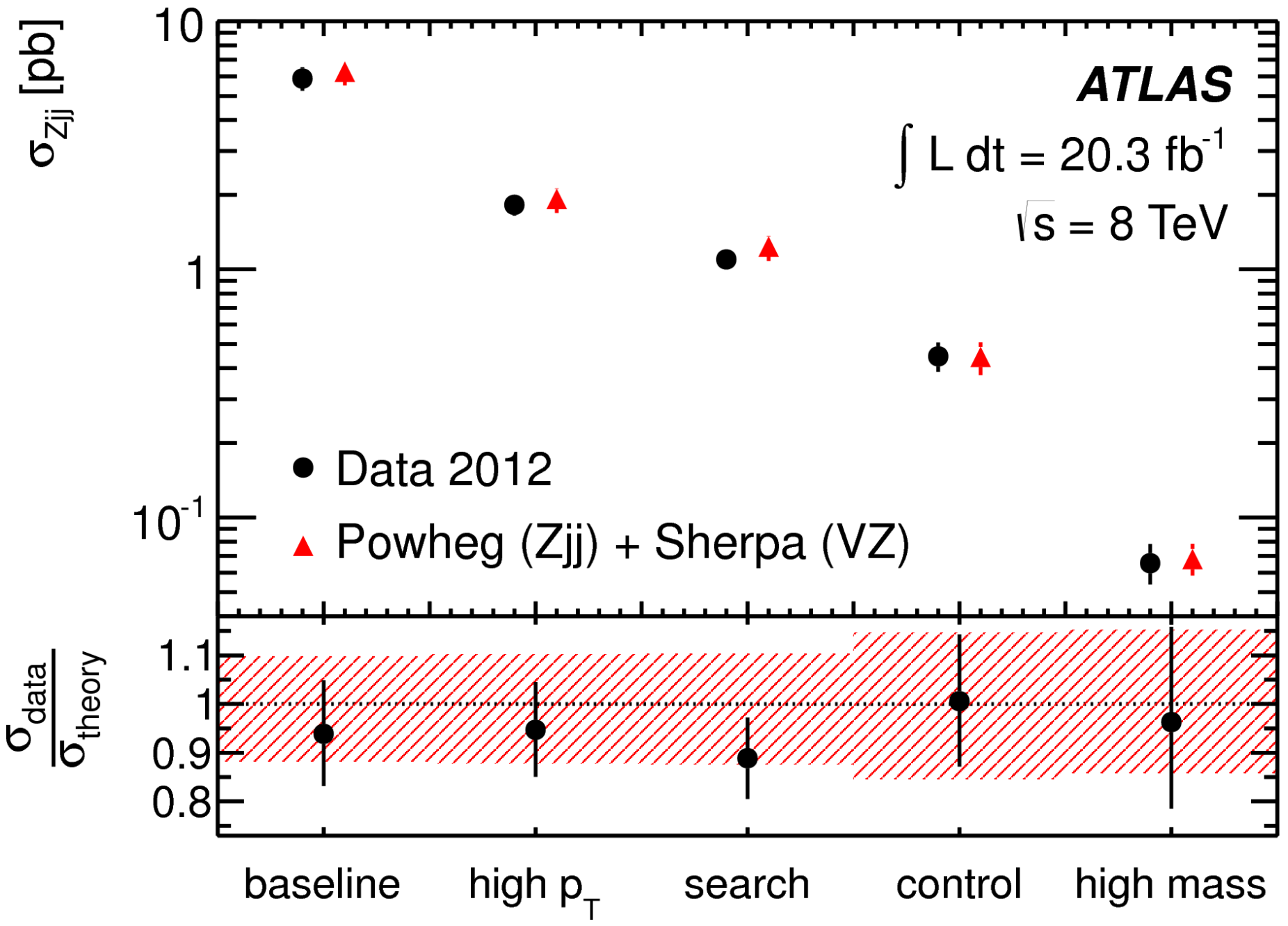
Backup

ATLAS Region defintions

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_{T}*
Leptons	$\lvert\eta^{\ell}\rvert < 2.47$, $p_{\mathrm{T}}^{\ell} > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^{j}\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_{\mathrm{T}}^{j1} > 55$ GeV				$p_{\mathrm{T}}^{j1} > 85$ GeV
	$p_{\mathrm{T}}^{j2} > 45$ GeV				$p_{\mathrm{T}}^{j2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} \geq 1$	—
Zjj system	—		$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$	$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$	—

$$p_{\mathrm{T}}^{\mathrm{balance}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\ell_1} + \vec{p}_{\mathrm{T}}^{\ell_2} + \vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{j_2}\right|}$$

Inclusive cross sections

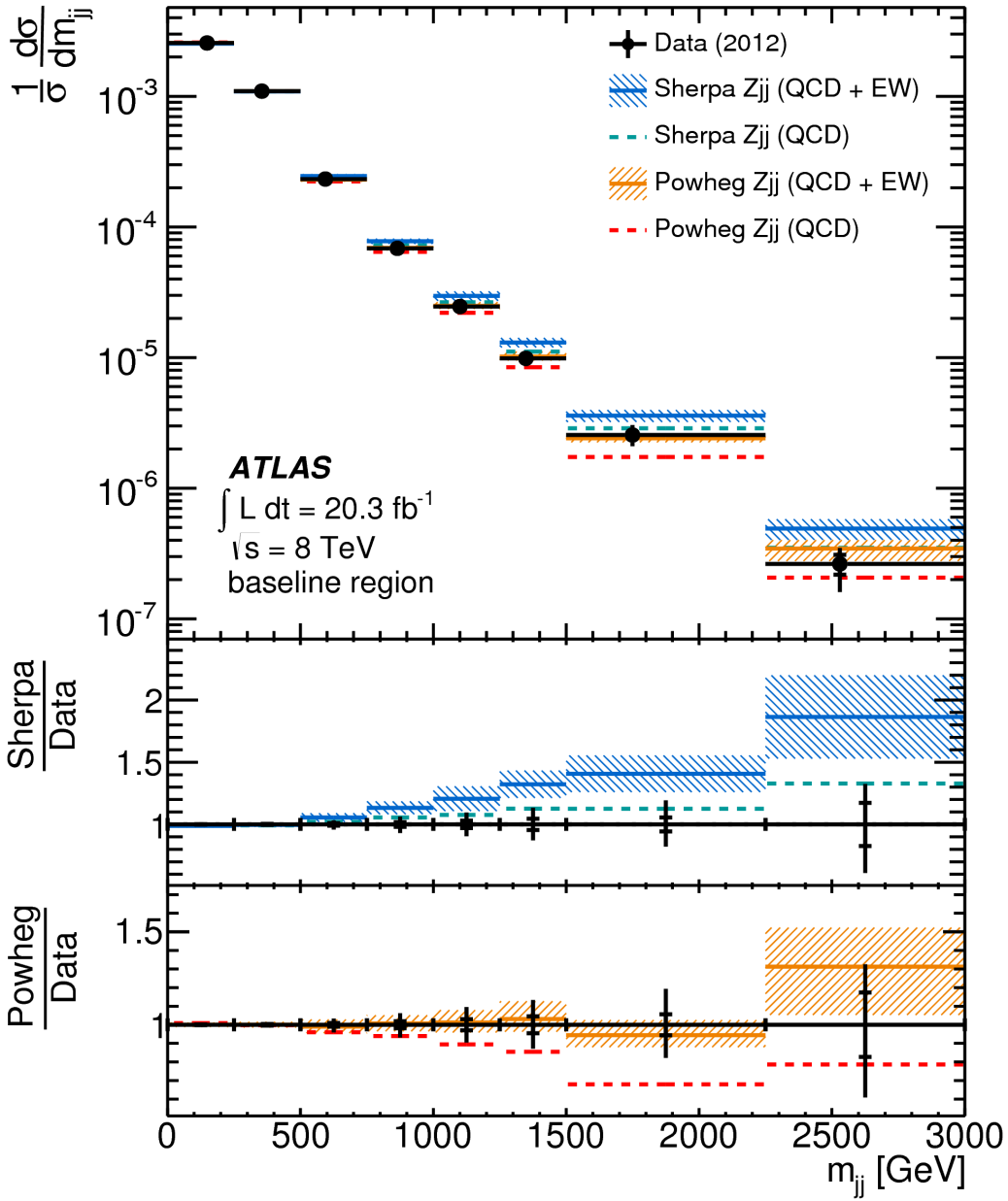


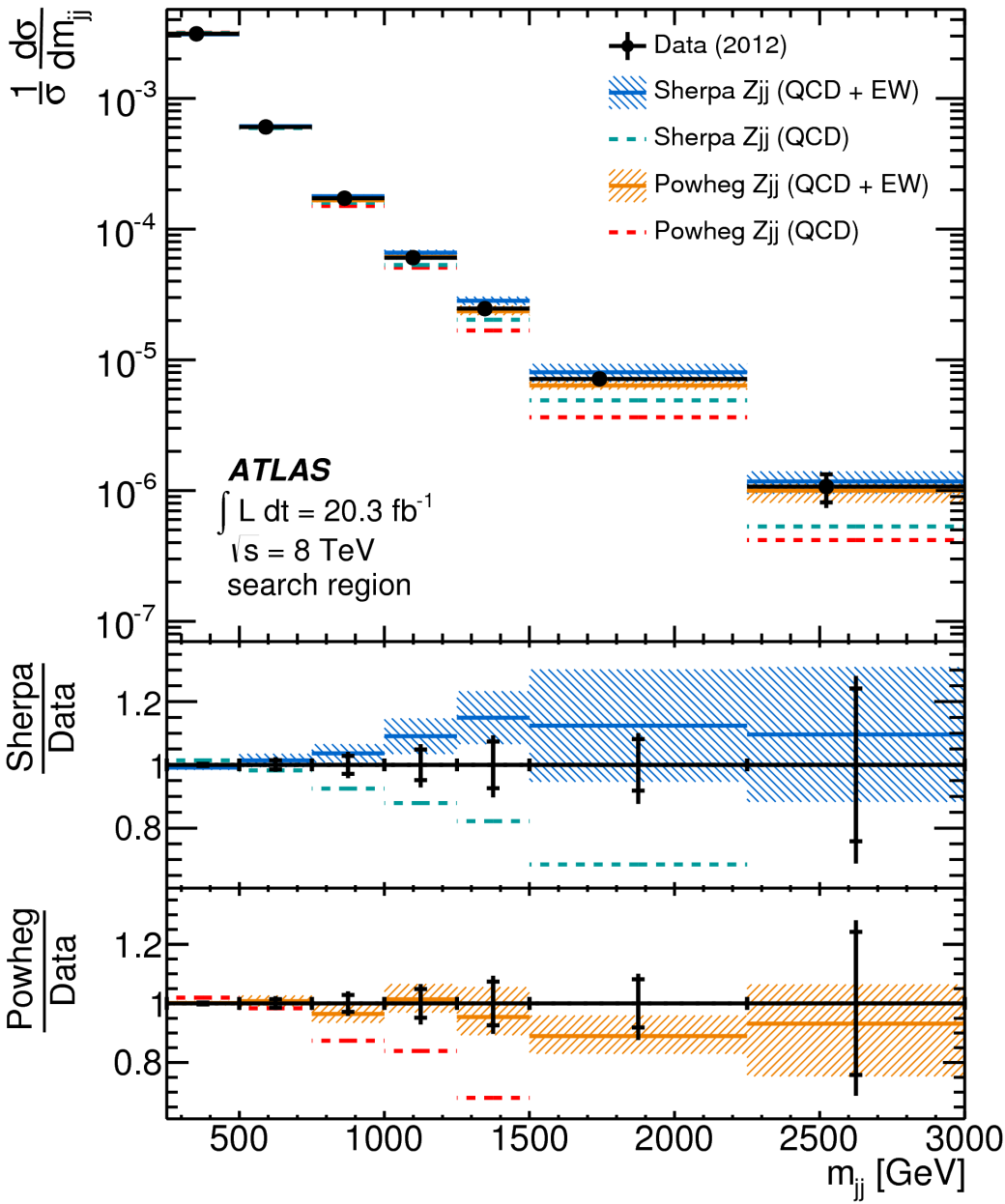
Event composition

	Composition (%)				
Process	*baseline*	*high-p_{T}*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

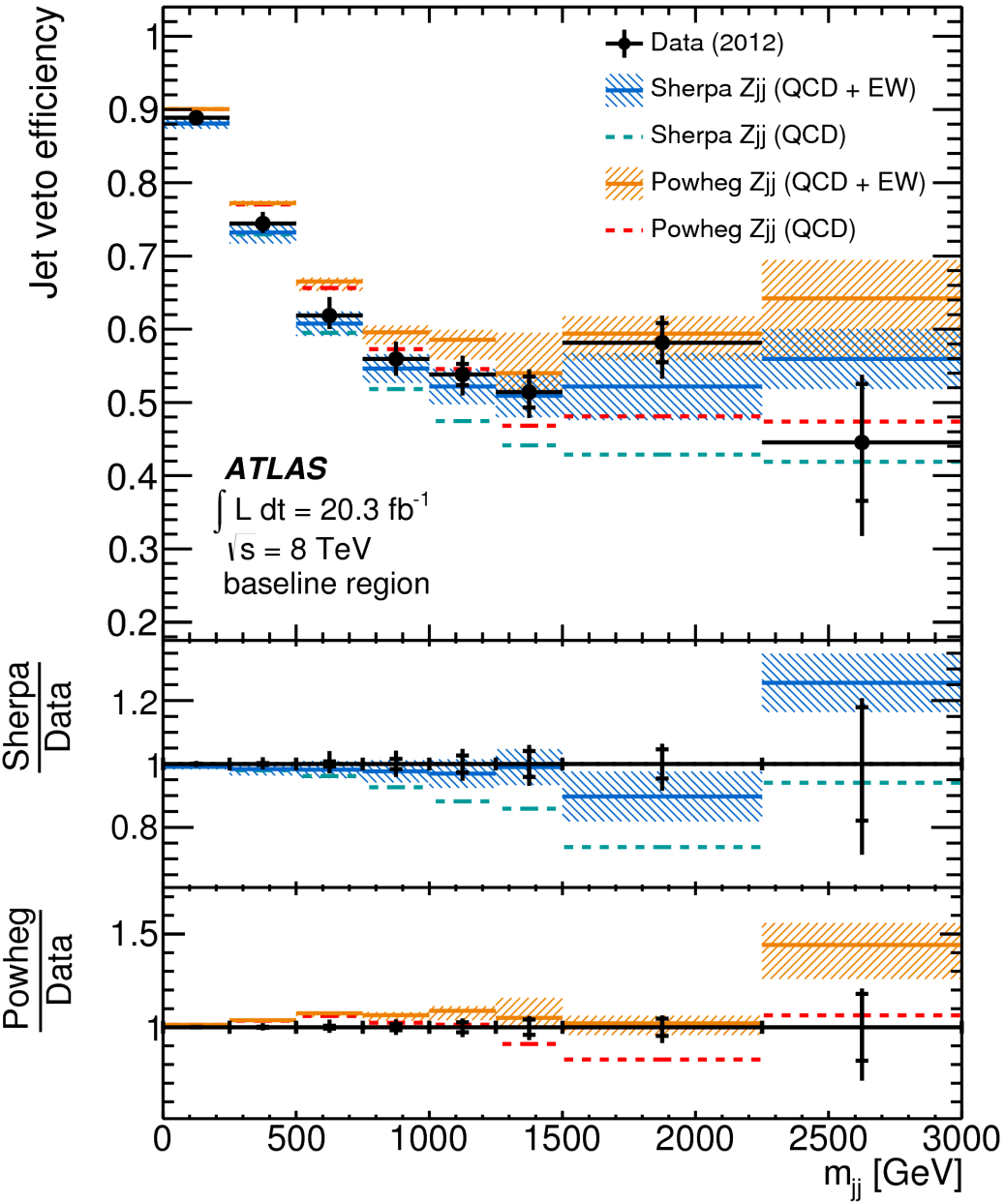
The Mulit-jets are the only process not evaluated using simulation, relying upon a data driven estimate instead.

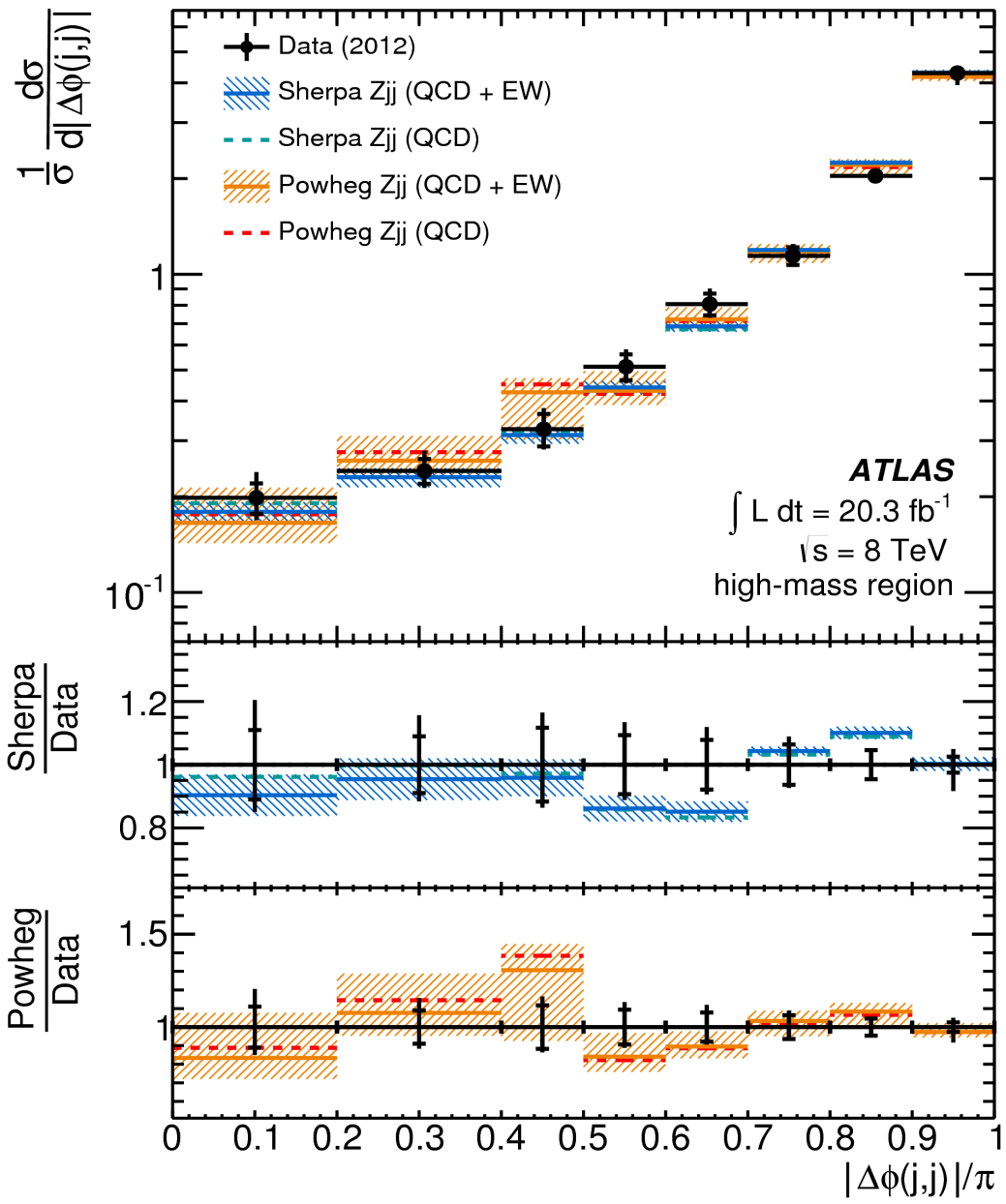
Unfolded distributions





Unfolded distributions





Fiducial regions

The CMS measurements are made within the fiducial regions

$$m_{ll} > 50\text{GeV}, m_{jj} > 120\text{GeV}, p_T^j > 25\text{GeV}, |\eta^j| < 4.0$$

for 7 TeV and

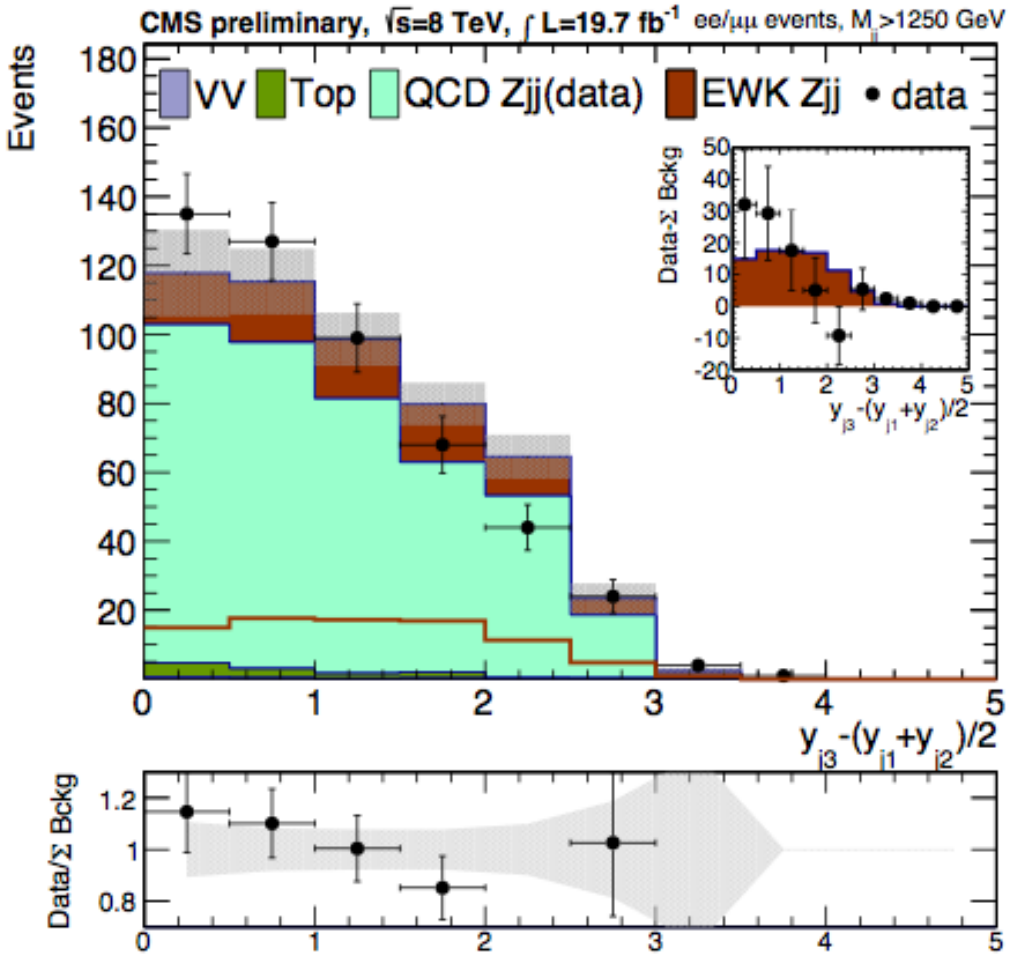
$$m_{ll} > 50\text{GeV}, m_{jj} > 120\text{GeV}, p_T^j > 25\text{GeV}, |\eta^j| < 5.0$$

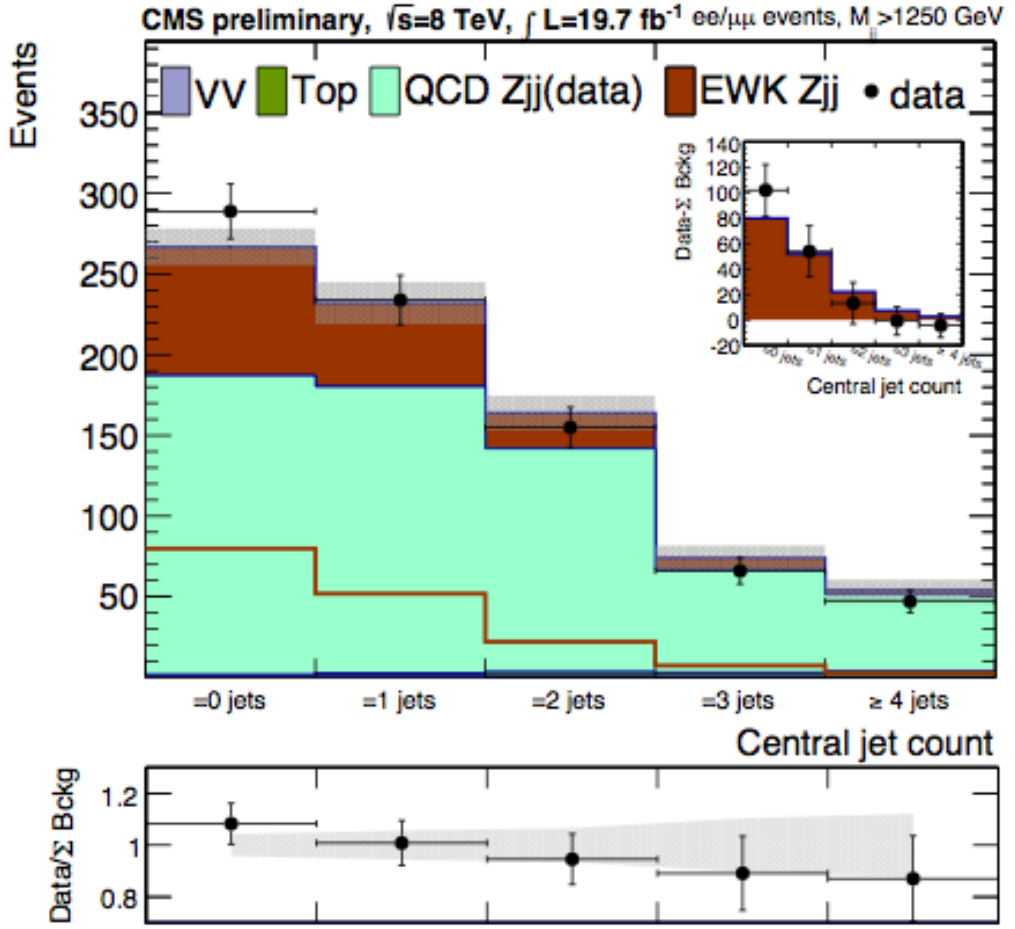
for 8 TeV.

Systematics (8 TeV)

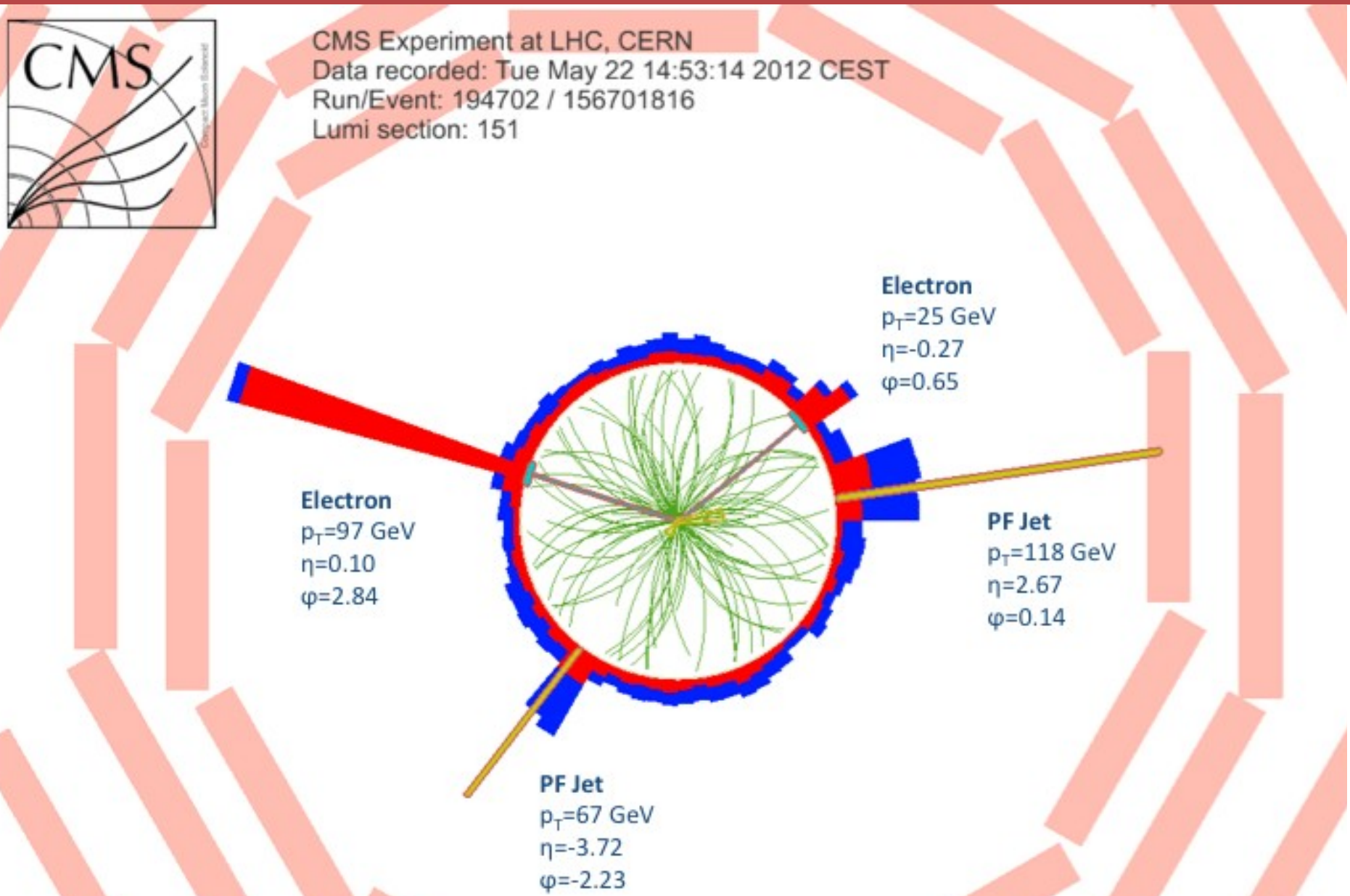
	Analysis			
	Method I	Method II		
	$\mu\mu$	ee	$\mu\mu$	Combination
$\mu = \sigma/\sigma_{\text{th}}$	0.80 ± 0.20	0.82 ± 0.37	1.30 ± 0.30	1.27 ± 0.27
Statistical uncertainty	0.12	0.23	0.16	0.12
Systematic uncertainty	0.16	0.28	0.25	0.24
Luminosity	0.03	0.03	0.03	0.03
Trigger/lepton selection	0.01	0.03	0.03	0.02
JES+residual response	0.05	0.05	0.04	0.04
JER	0.02	0.02	0.02	0.02
Pileup	0.06	0.03	0.03	0.02
QCD Zjj	0.13	0.26	0.23	0.22
Top, dibosons	0.01	0.04	0.03	0.02
Signal	0.05	0.08	0.07	0.06

Hadronic activity

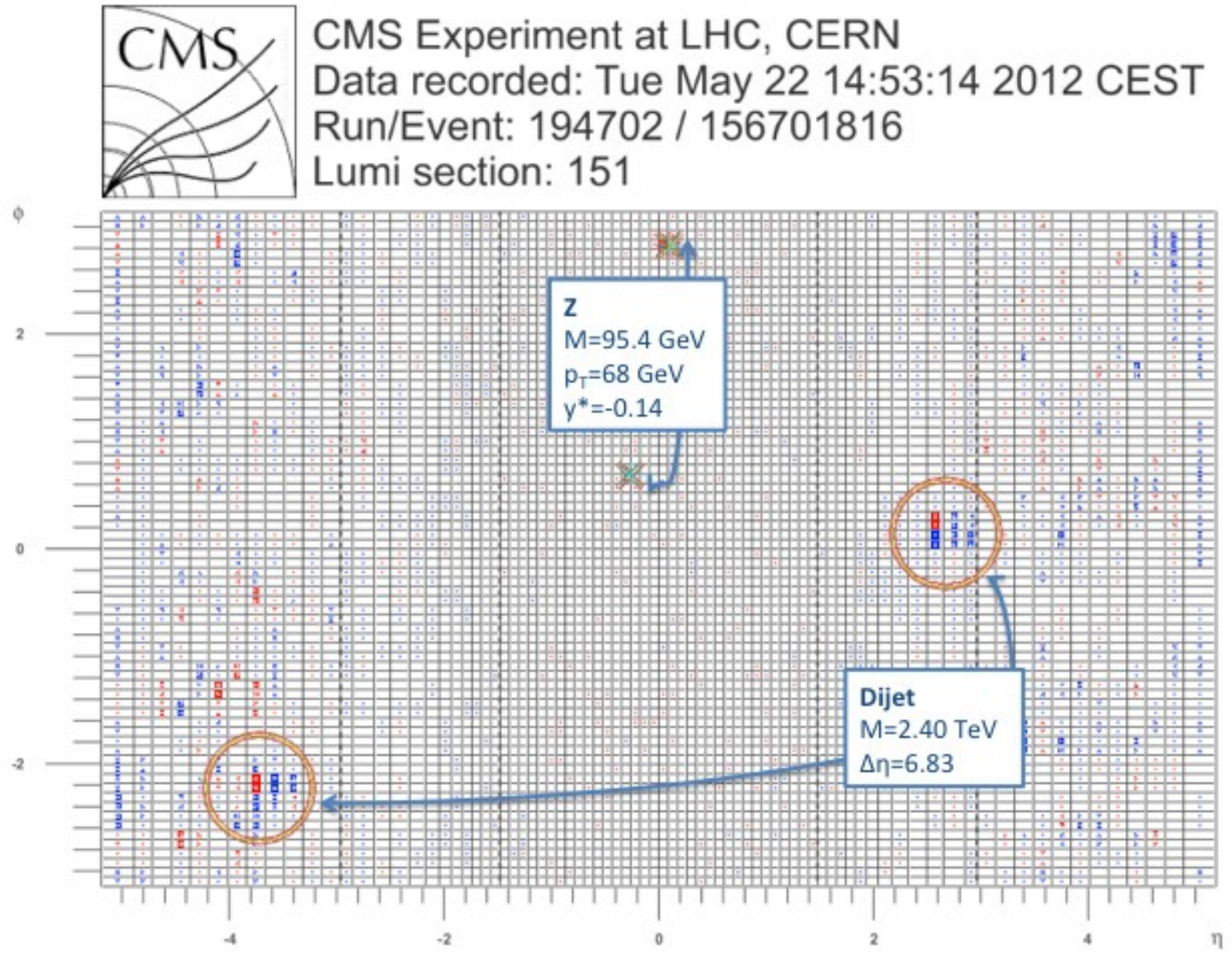




Events


CMS Experiment at LHC, CERN
Data recorded: Tue May 22 14:53:14 2012 CEST
Run/Event: 194702 / 156701816
Lumi section: 151
Electron
p_T=25 GeV
η=-0.27
φ=0.65
Electron
p_T=97 GeV
η=0.10
φ=2.84
PF Jet
p_T=118 GeV
η=2.67
φ=0.14
PF Jet
p_T=67 GeV
η=-3.72
φ=-2.23

Events


CMS Experiment at LHC, CERN
Data recorded: Tue May 22 14:53:14 2012 CEST
Run/Event: 194702 / 156701816
Lumi section: 151
Z
M=95.4 GeV
p_T=68 GeV
y*=-0.14
Dijet
M=2.40 TeV
Δη=6.83
ϕ
2
0
-2
-4
-2
0
2
4
η