Recent Electroweak Results from ATLAS

- Electroweak Zjj
- VBS $W^{\pm}W^{\pm}jj$
- $Z \rightarrow 4l$
- Diboson Measurements
- Summary

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On behalf of the ATLAS Collaboration

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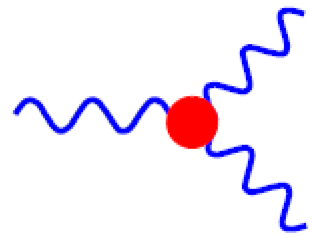
Electroweak Physics

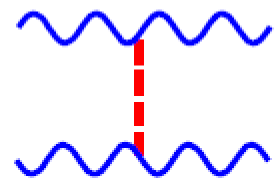
σ (pb)	
10^4	Single W, Z Measurements A_{FB} in Z → ll
50--1	Diboson Measurements Wγ, Zγ, WW, WZ, ZZ
10^{-1}	Single Z production Z → 4l (ZZ*/Zγ*)
10^{-2}	Vector Boson Fusion (VBF) Zjj
10^{-3}	Vector Boson Scattering (VBS) WWjj

Precision EW

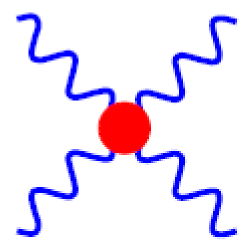
$\sin^2\theta_W$, (m_W)



TGC



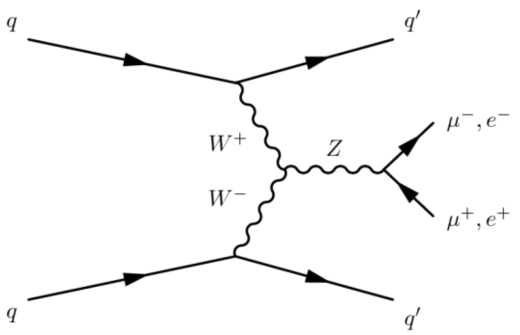
EWSB

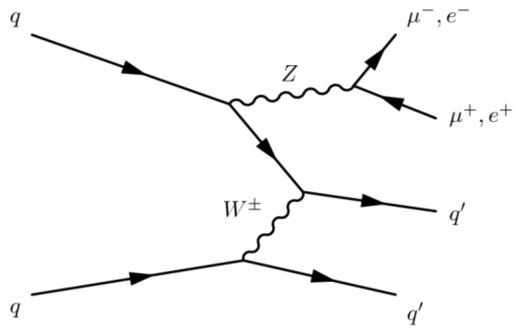


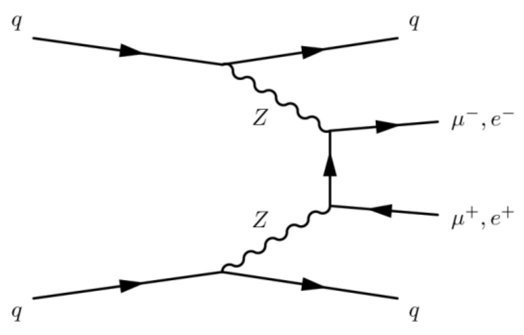
QGC

Electroweak Zjj : VBF

8TeV, JHEP 04 (2014) 031





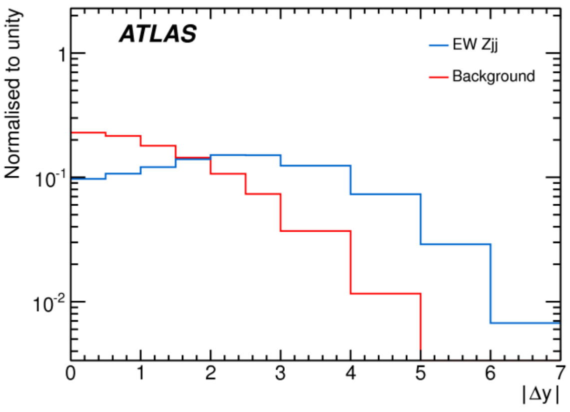


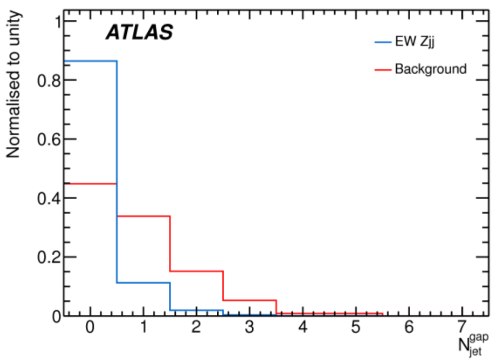
VBF : sensitive aTGC;
Similar VBF Higgs production

Z-Bremsstrahlung

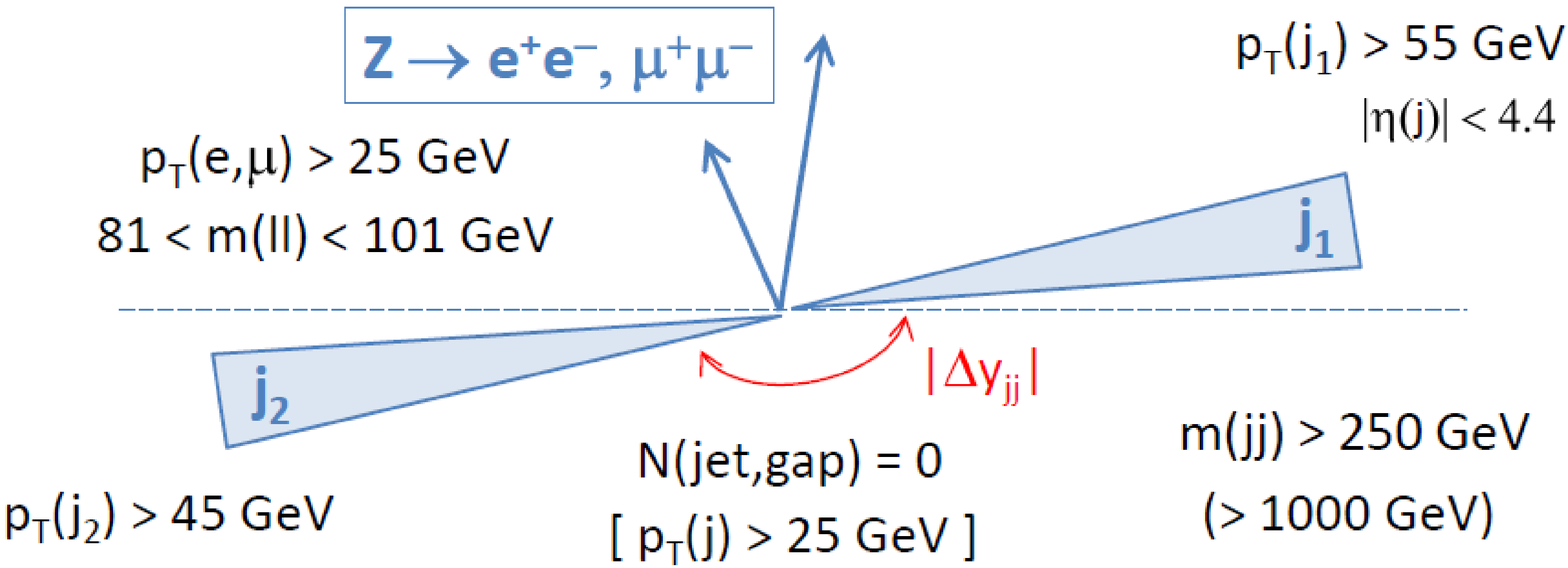
Non-resonant

- **Electroweak Zjj has high mass, large separation tagging jets and less hadronic activity**





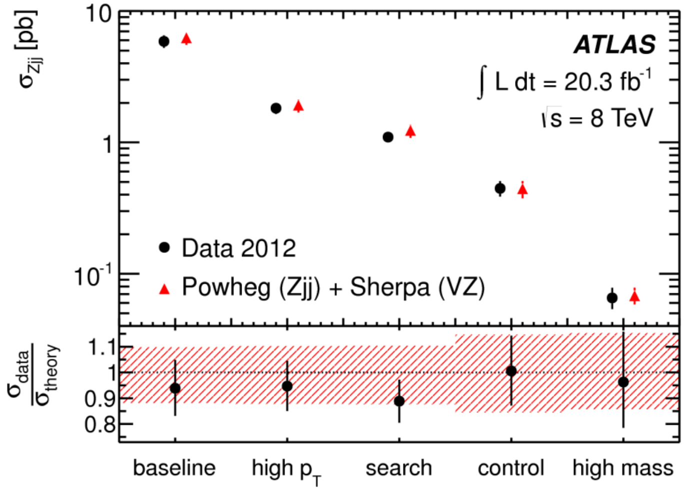
Electroweak Zjj : Event selection

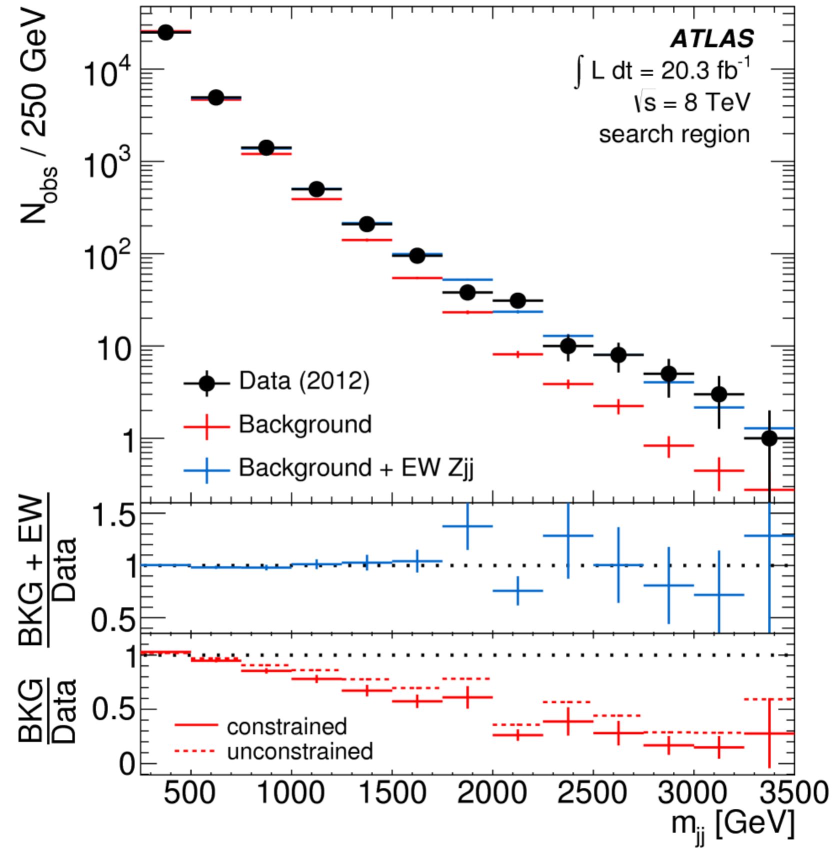


Fid region	N(jet,gap)	m(jj)	Zjj-QCD	Zjj-EW	WZ,ZZ	Top
"search"	= 0	> 250 GeV	94.7%	4.0%	0.7%	0.6%
"high mass"	≥ 0	> 1 TeV	85%	12%	1%	2%

- **POWHEG/Sherpa to model production**
- **Multijet background from data, others from MC**
- **Baseline, control and hight-pT regions to check Zjj and Zjj QCD modeling**

Electroweak Zjj : Results





EW component measured in search region with m_{jj} > 1 TeV :

$$\sigma_{\text{fid}}(\text{Zjj - EW}) = 10.7 \pm 0.9(\text{stat}) \pm 1.9(\text{syst}) \pm 0.3(\text{lumi})\ \text{fb}$$

$$\sigma_{\text{SM}} = 9.38 \pm 0.05(\text{stat})^{+0.15}_{-0.24}(\text{scale}) \pm 0.24(\text{PDF}) \pm 0.09(\text{model})\ \text{fb}$$

- **Background only hypothesis excluded over 5σ**

Complementary test of aTGCs on WWZ at 95% CL from search region

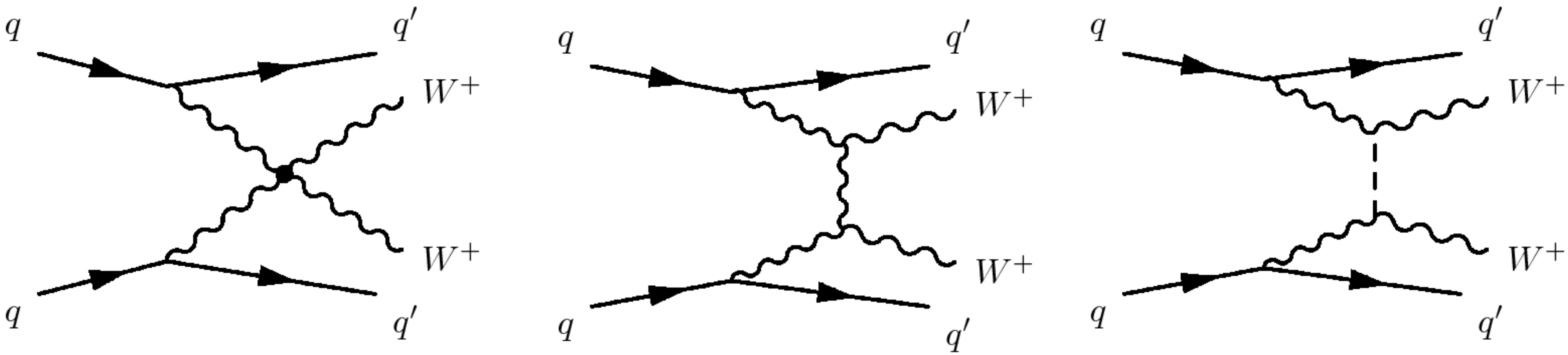
aTGC	Δg_1^Z
$\Lambda = 6$ TeV (obs)	$[-0.65, 0.33]$
$\Lambda = 6$ TeV (exp)	$[-0.58, 0.27]$
$\Lambda = \infty$ (obs)	$[-0.50, 0.26]$
$\Lambda = \infty$ (exp)	$[-0.45, 0.22]$

aTGC	λ_Z
$\Lambda = 6$ TeV (obs)	$[-0.22, 0.19]$
$\Lambda = 6$ TeV (exp)	$[-0.19, 0.16]$
$\Lambda = \infty$ (obs)	$[-0.15, 0.13]$
$\Lambda = \infty$ (exp)	$[-0.14, 0.11]$

VBS $W^{\pm}W^{\pm}jj$: Introduction

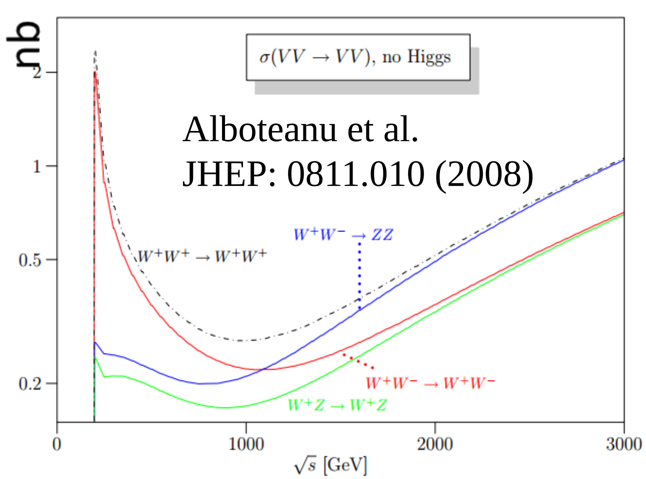
8TeV, arXiv:1405.6241

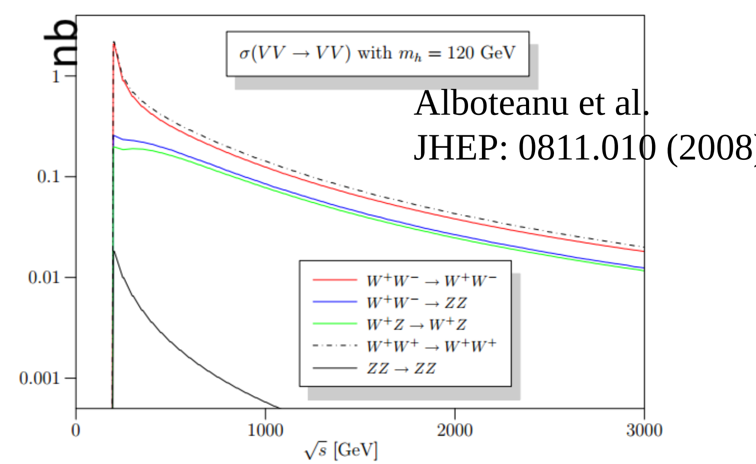
VBS topology : two high momentum, forward jets



Sensitive to quartic gauge couplings (QGCs)

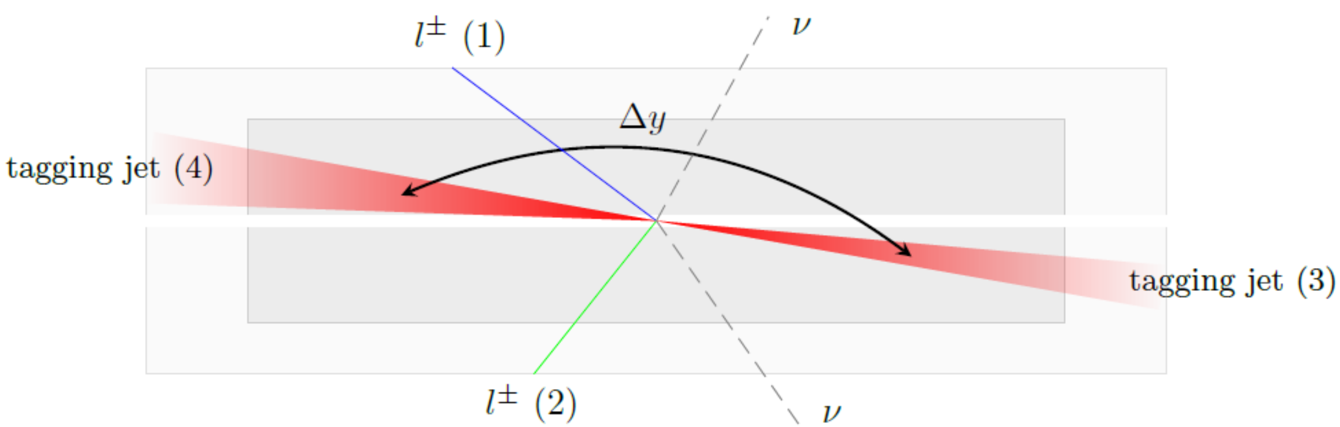
Violate unitarity without a SM Higgs



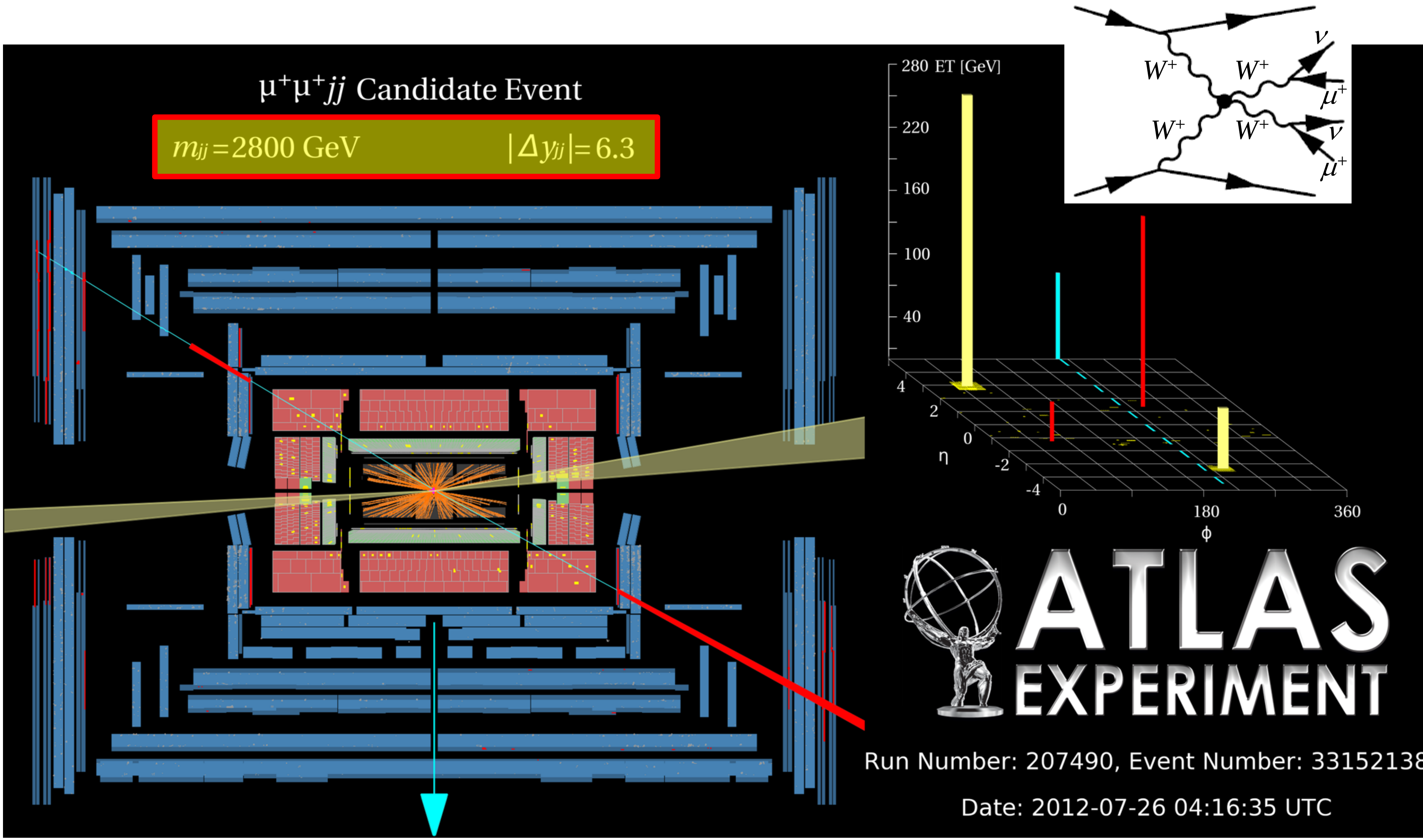


VBS $W^{\pm}W^{\pm}jj$: Event Selection

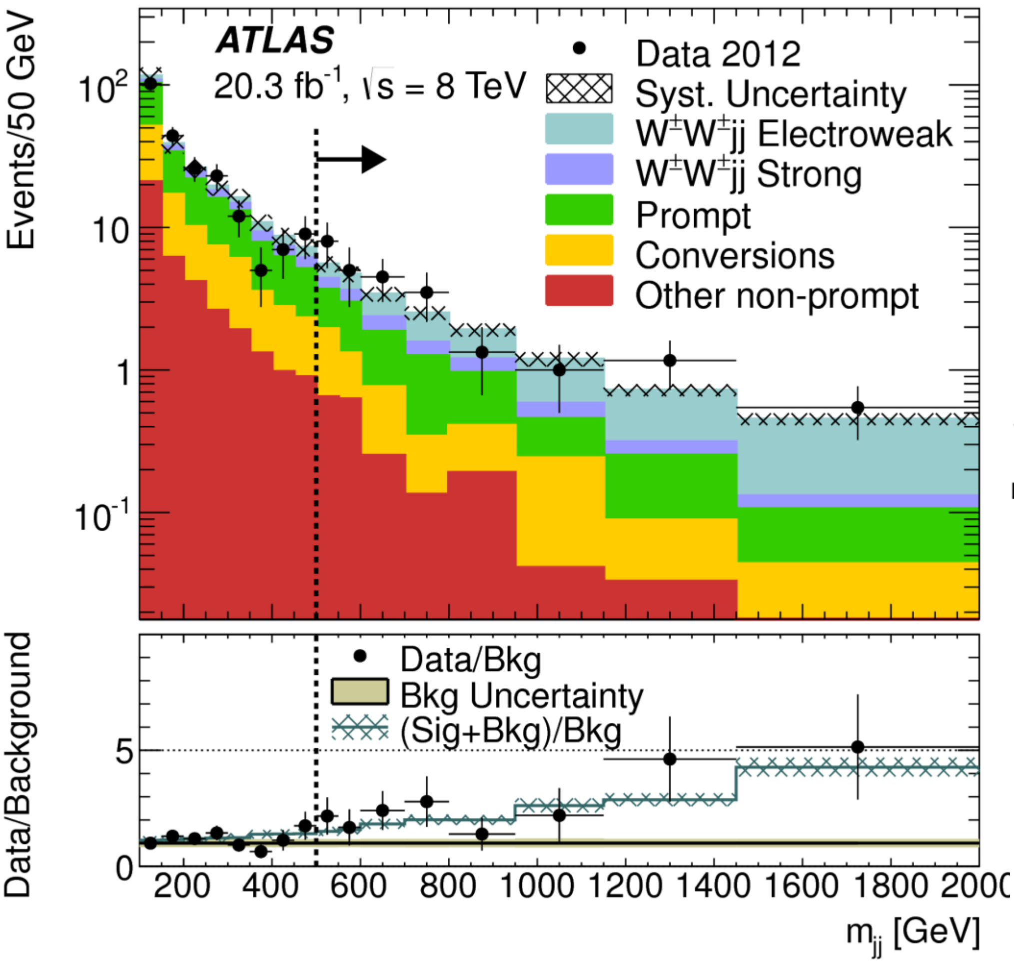
- **Exactly two SS isolated leptons with p_T>25 GeV and |η|<2.5**
- **MET > 40 GeV**
- **At least two jets with p_T>30 GeV and |η|<4.5**
- **WZ veto: veto a third lepton with lower p_T and looser quality requirements**
- **Z veto: $|m_{ee} - m_Z|$ > 10 GeV to suppress the Z→ee contribution with the charge of one electron misidentified**
- **ttbar veto: no b-tagged jets in each event**
- **Inclusive region: m_{jj} > 500 GeV**
- **VBS region: m_{jj} > 500 GeV and $|\Delta y_{jj}|$ > 2.4 → enhance the contribution from electroweak production**



VBS $W^{\pm}W^{\pm}jj$: Event Display

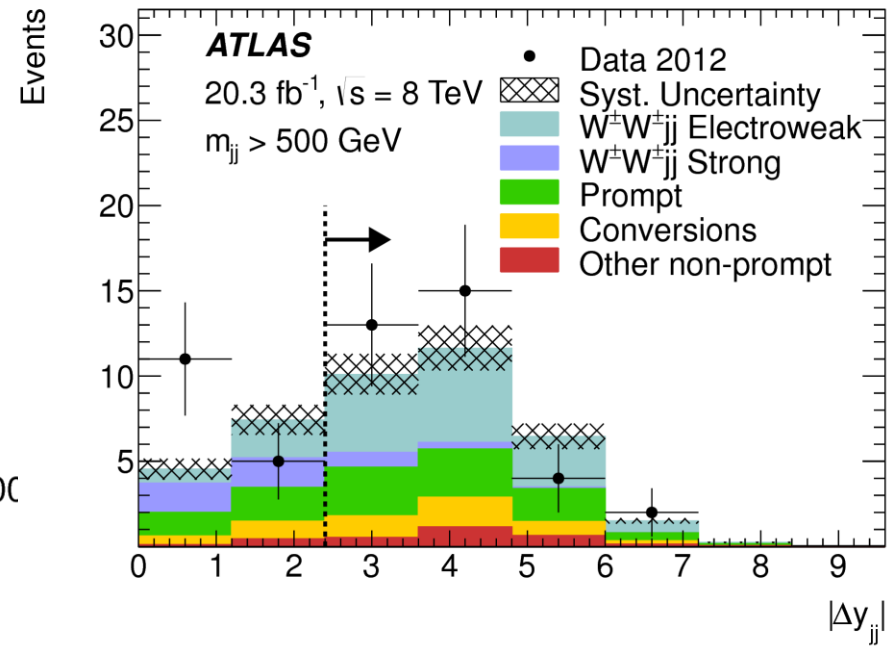


VBS $W^{\pm}W^{\pm}jj$: Compare with MC



WWjj signal MC :

- SHERPA (LO, up to 3 jets)
- Normalised to POWHEG
- Cross-checked with VBFNLO



Enhance VBS contribution

VBS $W^{\pm}W^{\pm}jj$: Selected Events

Inclusive Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5
$W^{\pm}W^{\pm}$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8
$WZ/\gamma^*,ZZ,t\bar{t}+W/Z$	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5
$W+\gamma$	1.1 ± 0.6	1.6 ± 0.8	–	2.7 ± 1.2
OS prompt leptons	2.1 ± 0.4	0.77 ± 0.27	–	2.8 ± 0.6
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	2.9 ± 0.8
Total Predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	42 ± 5
Data	12	26	12	50

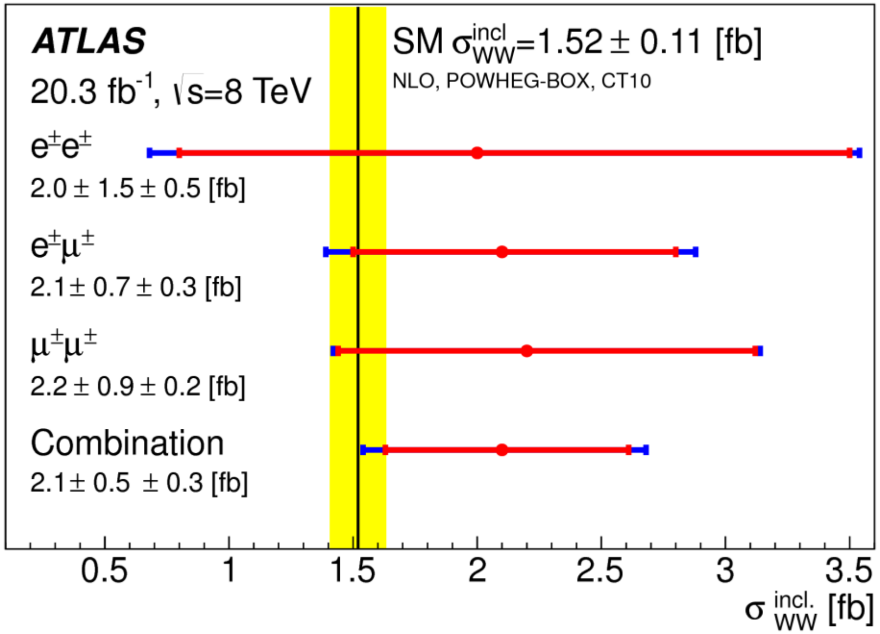
VBS Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*,ZZ,t\bar{t}+W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W+\gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

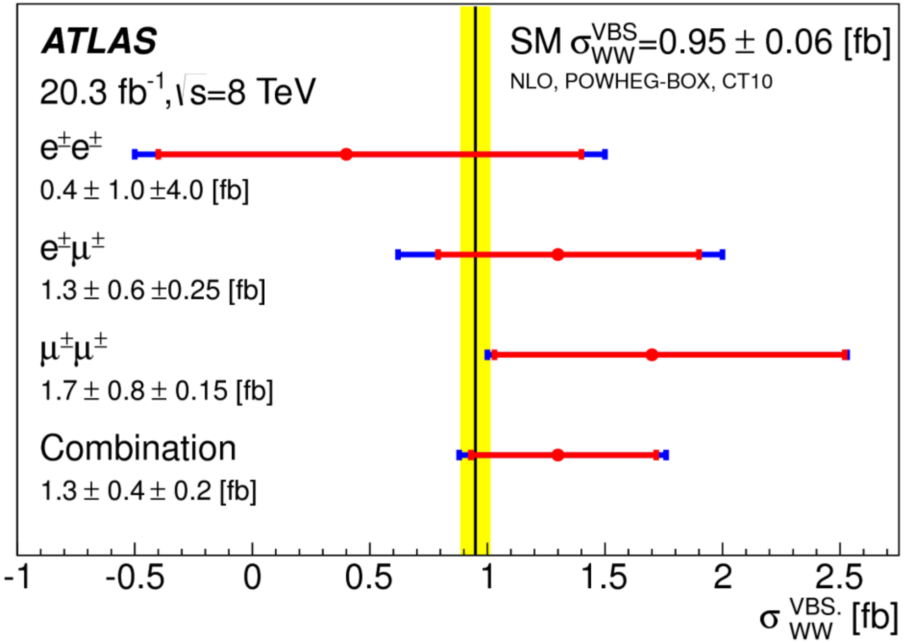
VBS $W^{\pm}W^{\pm}jj$: Cross-section Measurement

- Profile likelihood ratio method used to extract the final cross sections from all three channels taken into account correlated systematics

$$L(\sigma_{W^{\pm}W^{\pm}jj}, \mathcal{L}, \alpha_j) = \mathrm{Gaus}(\mathcal{L}_0|\mathcal{L}, \sigma_{\mathcal{L}}) \prod_{i\in\{ee,\mu\mu,e\mu\}} \mathrm{Pois}(N_i^{\mathrm{obs}}|N_{i,\mathrm{tot}}^{\mathrm{exp}}) \prod_{j\in\mathrm{syst}} \mathrm{Gaus}(\alpha_j^0|\alpha_j, 1)$$

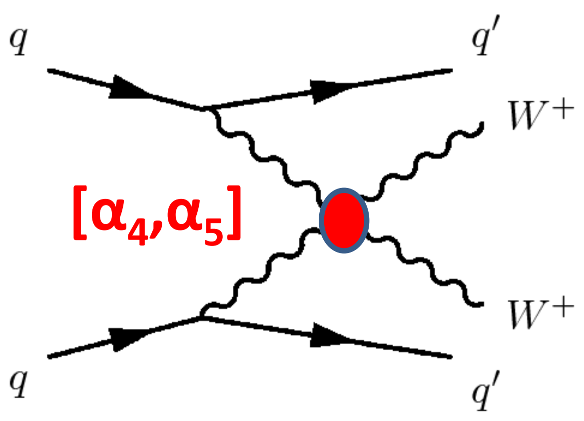
  - Inclusive SR: σ = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb, 4.5σ obs. (3.4σ exp.)
  - VBS SR: σ = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb, 3.6σ obs. (2.8σ exp.)
- **First ever evidence for EWK VV → VV scattering at the LHC**





VBS $W^\pm W^\pm jj$: QGC Limits

Use measured "VBS" cross section to limit aQGCs:

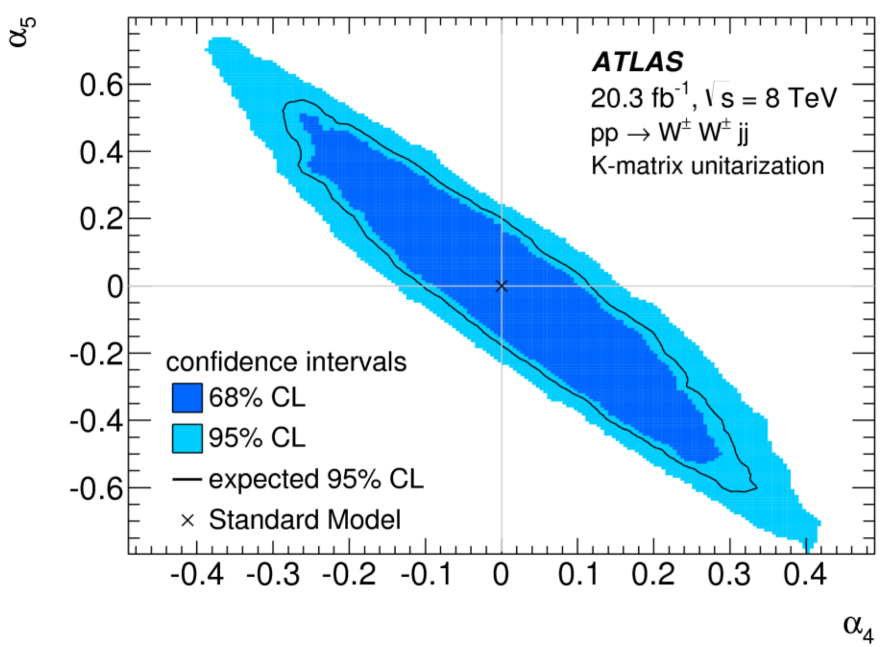


$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- **WWVV aQGCs are α_4 and α_5**
- **Lowest dimension (8) operators**

Theoretical cross-section from WHIZARD+PYTHIA8 with K-matrix unitarisation

→ First limitation on α_4,α_5

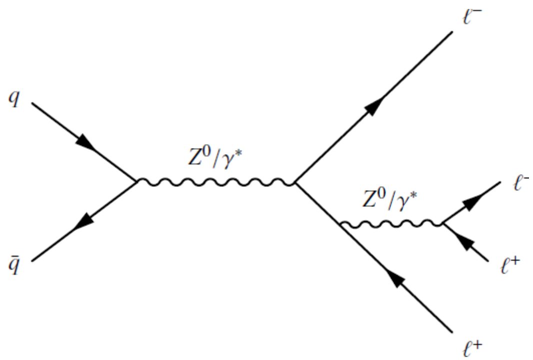


$\alpha_4 \propto [-0.139, 0.157]$ obs. $[-0.104, 0.116]$ exp.

$\alpha_5 \propto [-0.229, 0.244]$ obs. $[-0.180, 0.199]$ exp.

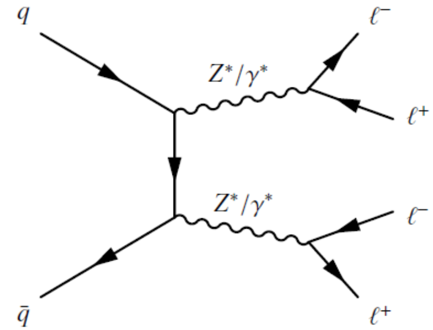
Z→4l : Introduction

arXiv:1403.5657

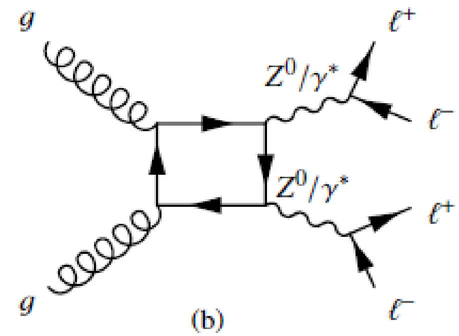


s-channel,~96%*

* Phase space m4l=[80,100]GeV, m2l>5GeV



t-channel < 4%



gg fusion ~0.1%

Physics Motivations

- A SM test from a rare decay process
- A complementary test of the detector response for H→ 4l
- Calibration for new physics discovery

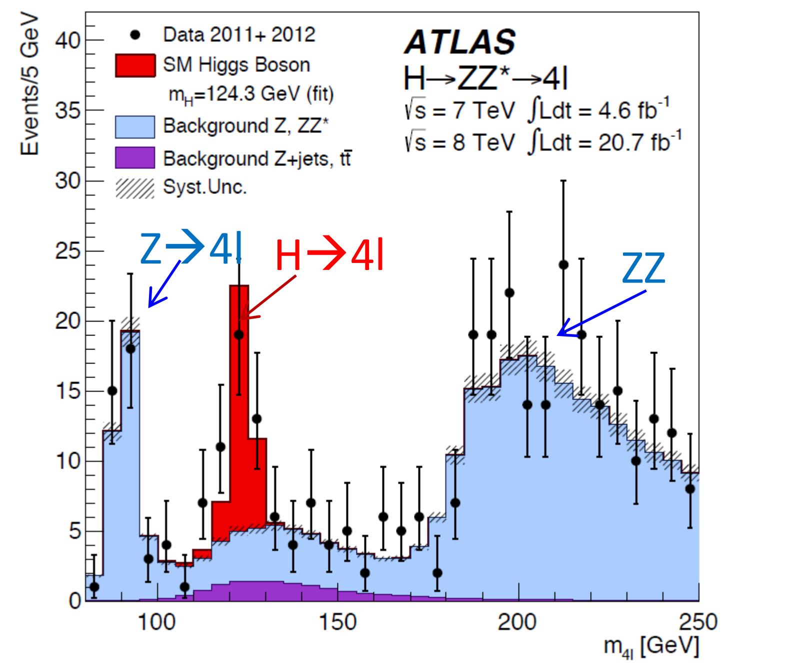
Event Selections

e : p_T > 20, 15, 10, 7 GeV, $|\eta|$ <2.5

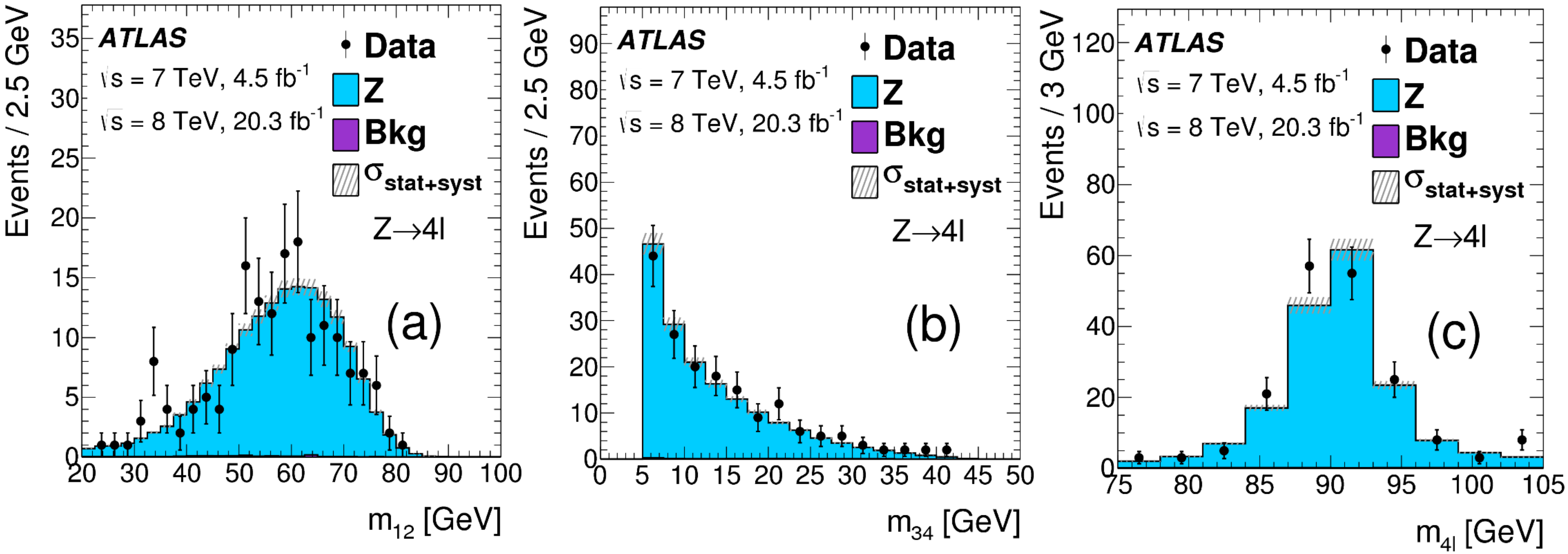
μ : p_T > 20, 15, 8, 4 GeV, $|\eta|$ <2.7

m_{12} ($\ell^+\ell^-$)> **20** GeV, m_{34} ($\ell^+\ell^-$)> **5** GeV

80 GeV < m_{4l} < 100 GeV



Z→4l : Mass and Cross-section



ATLAS	Phase-space cross section (m_{2l} > 5 GeV, 80 < m_{4l} < 100 GeV)
7 TeV measured	76±18 (stat.) ±4 (syst.) ±1.4 (lumi.) fb
7 TeV NLO SM prediction	90.0±2.1 fb
8 TeV measured	107±9 (stat.) ±4 (syst.) ±3.0 (lumi.) fb
8 TeV NLO SM prediction	104.8±2.5 fb

Good agreement with prediction, and measurement error still dominated by statistic

Z→4l : Branching Ratio

- s-channel only
- Normalized to high statistic Z→2μ cross section
- Cancels luminosity uncertainty and theoretical uncertainty of σ(pp→Z）
- Derive the BR(Z→4l) as:

$$\mathrm{BR}(Z \to 4\ell) = \mathrm{BR}(Z \to 2\mu)(1-f_t)\frac{\left(N_{\mathrm{obs.}} - N_{\mathrm{bkg.}}\right)^{4\ell}(C \times A)^{2\mu}}{\left(N_{\mathrm{obs.}} - N_{\mathrm{bkg.}}\right)^{2\mu}(C \times A)^{4\ell}}$$

Uncertainty on $\mathrm{BR}(Z \to 2\mu)$ is small. f_t = fraction of t-channel in phase-space.

f_t = (3.35 ± 0.02)% for 4e, 4μ ; f_t = (3.90 ± 0.02)% for 2e2μ

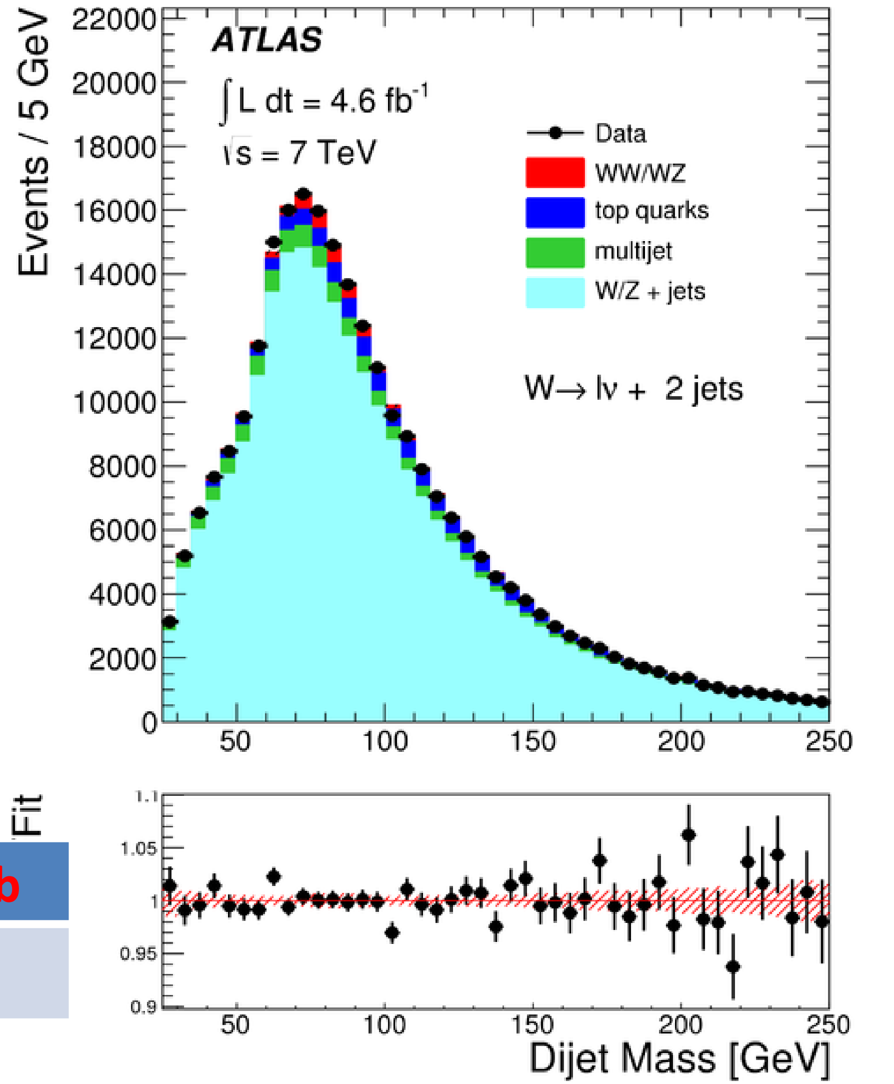
Quantity	$\sqrt{s}$	Value
Measured	7 TeV	$(2.67 \pm 0.62\,(\mathrm{stat}) \pm 0.14\,(\mathrm{syst})) \times 10^{-6}$
	8 TeV	$(3.33 \pm 0.27\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})) \times 10^{-6}$
	Combined	$(3.20 \pm 0.25\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst})) \times 10^{-6}$
Expected		$(3.33 \pm 0.01) \times 10^{-6}$

7TeV WW+WZ : Cross-section

arXiv:1410.7238

Final state : WW+WZ → lν qq (e/μ E_T^{miss} two jets)

Signal processes	e	μ
WW	1435 ± 70	1603 ± 79
WZ	334 ± 23	370 ± 26
Background processes		
$W+$ jets	$(107 \pm 21) \times 10^3$	$(116 \pm 23) \times 10^3$
$Z+$ jets	$(55 \pm 11)\times10^2$	$(46.3 \pm 9.3)\times10^2$
$t\bar{t}$	$(47.2 \pm 7.1)\times10^2$	$(47.2 \pm 7.1)\times10^2$
Single-top	$(20.2 \pm 3.0)\times10^2$	$(20.5 \pm 3.1)\times10^2$
Multijet	$(67 \pm 10)\times10^2$	$(50.5 \pm 7.6)\times10^2$
ZZ	19.2 ± 3.8	21.1 ± 4.2
Total SM prediction	$(128 \pm 17)\times10^3$	$(135 \pm 19)\times10^3$
Total Data	127 650	134 846



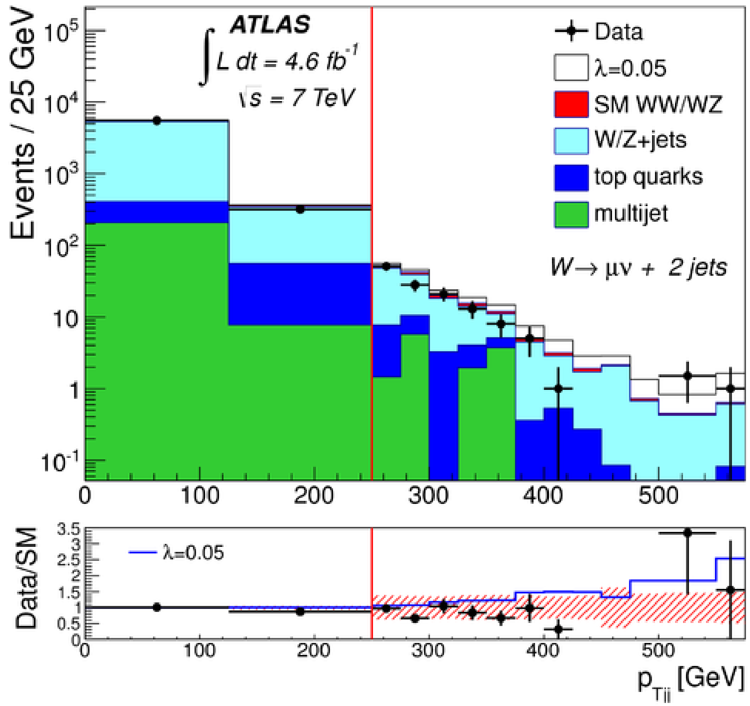
Template fit used to extract cross section
Measured σ Consistent with SM prediction
~ 30% systematic uncertainty

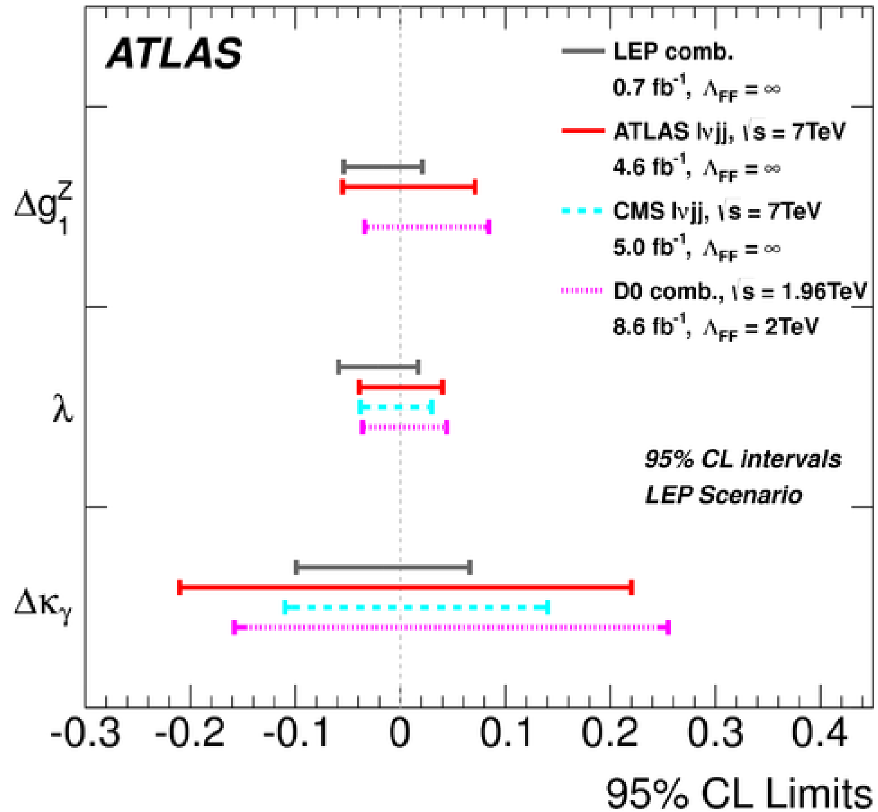
Measured	68±7(stat.) ±19(syst.)pb
NLO SM	61.1±2.2pb

7TeV WW+WZ : aTGC (LEP Scenario)

arXiv:1410.7238

Transverse momentum of the two jets





An alternative approach from the SM in terms of an effective-field-theory (EFT),

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}\Delta g_1^Z ,$$

$$\frac{c_B}{\Lambda^2} = \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z ,$$

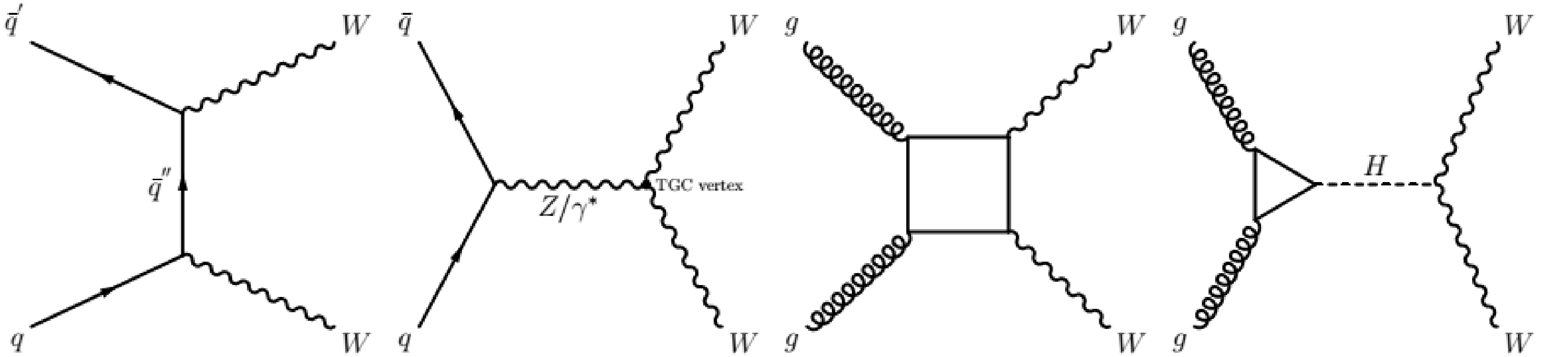
$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda ,$$

1D Limits at 95% CL

Parameter	Observed Limit	Expected Limit
c_{WWW}/Λ^2	$[-9.5,\ 9.6]$ TeV^{-2}	$[-11.6,\ 11.5]$ TeV^{-2}
c_B/Λ^2	$[-64,\ 69]$ TeV^{-2}	$[-73,\ 79]$ TeV^{-2}
c_W/Λ^2	$[-13,\ 18]$ TeV^{-2}	$[-17,\ 21]$ TeV^{-2}

W^+W^- Cross-section : Overview

WW signal: qq→WW, gg→(H)→WW σ_{tot} = 58.7± 3.0 pb **at 8TeV**



53.2±2.5 pb (MCFM, NLO) 1.4±0.3 pb (MCFM, LO) 4.1±0.5 pb (NNLO+NNLL, NLO EWK)

arXiv:1307.1347

Previous LHC results show higher cross section than prediction

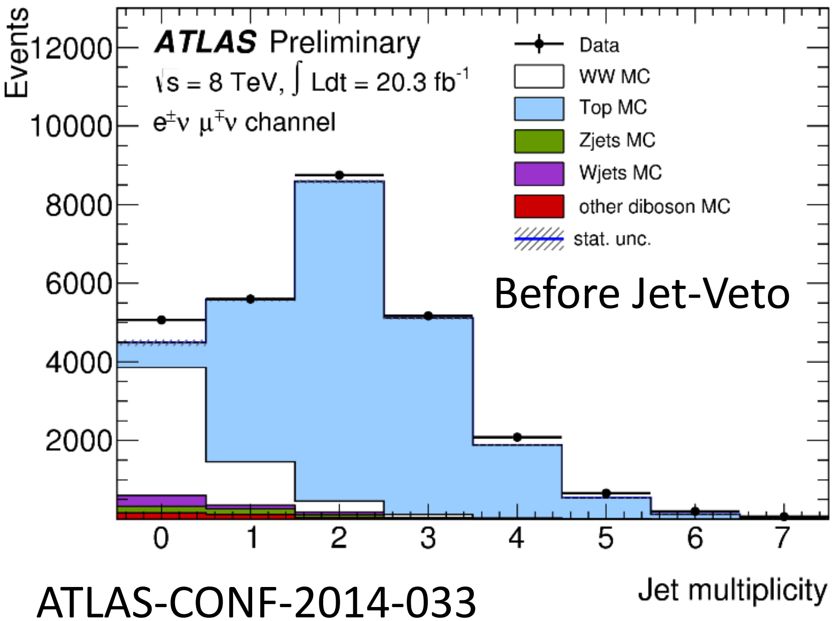
	$\int L$ (fb^{-1})	$\sigma(pp \to WW) \times B$ (pb)	SM NLO*
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat.) \pm 3.9(syst.) \pm 2.0(\text{lumi.})$	44.7±2.0
CMS 7TeV	4.9	$52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2(\text{lumi.})$	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1(\text{lumi.})$	54.6±2.5

Phys. Rev. D 87, 112001 (2013); CMS PAS SMP-12-005, CMS PAS SMP-12-013

* Higgs contribution not included

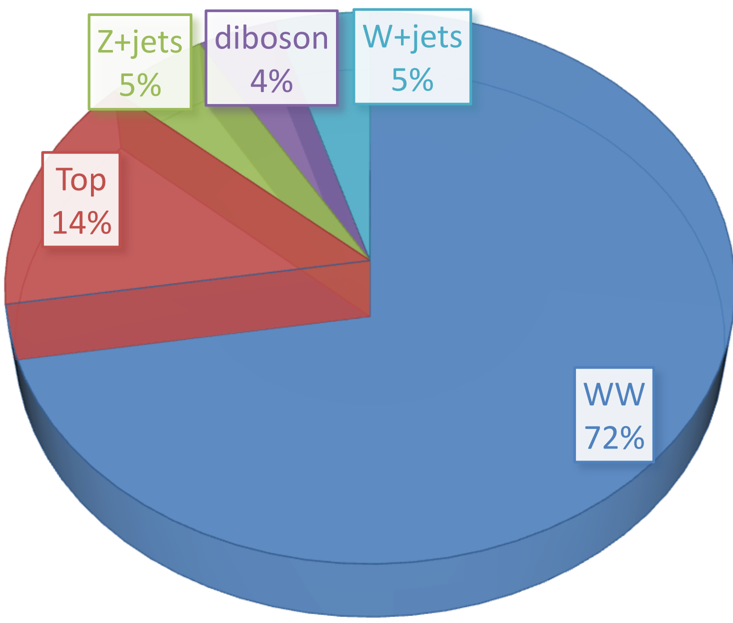
W^+W^- : Selected Event Composition

- Signature: two high-pt leptons and large MET (ee, μμ, eμ)
- Backgrounds
  - Top (ttbar, Wt), Z+jets, Other Diboson, W+jets
- Selection
  - Two leptons: Pt>25, 20 GeV
  - Remove Z peak in same flavor channel
  - Cut on relative E_T^{miss}, track-based p_T^{miss}, $\Delta\phi(E_T^{miss}, p_T^{miss})$ to reduce Z+jets
  - Require zero jets (25GeV) to reduce Top



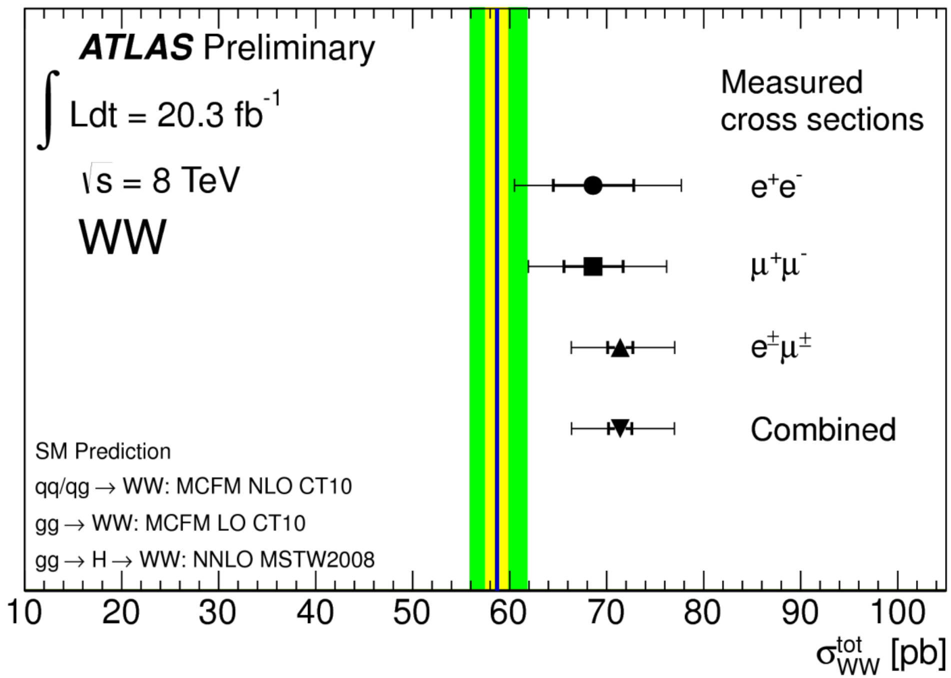
ATLAS-CONF-2014-033

At final selection
S/B~2.5
Data ~ 6600



W⁺W⁻ Cross-section at 8TeV

$$\sigma_{WW}^{tot} = 71.4\,^{+1.2}_{-1.2}(\text{stat})\,^{+5.0}_{-4.4}(\text{syst})\,^{+2.2}_{-2.1}(\text{lumi})\text{ pb}$$



<2% statistical uncertainty
~8% systematic uncertainty
About 2 σ higher than SM prediction

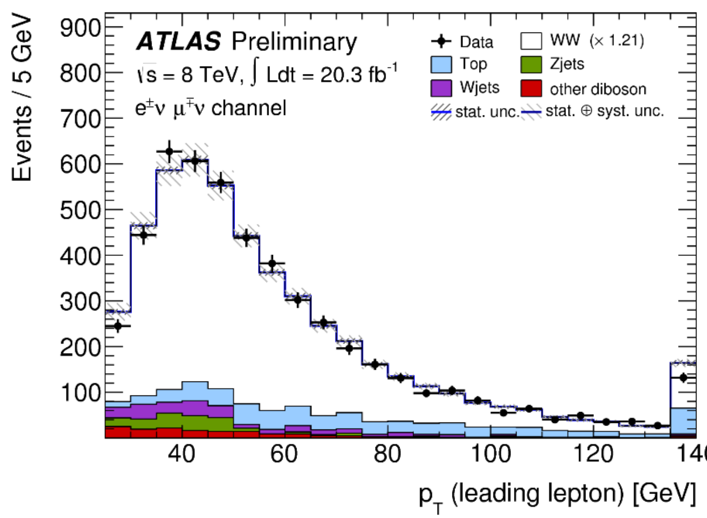
Systematic Uncertainties

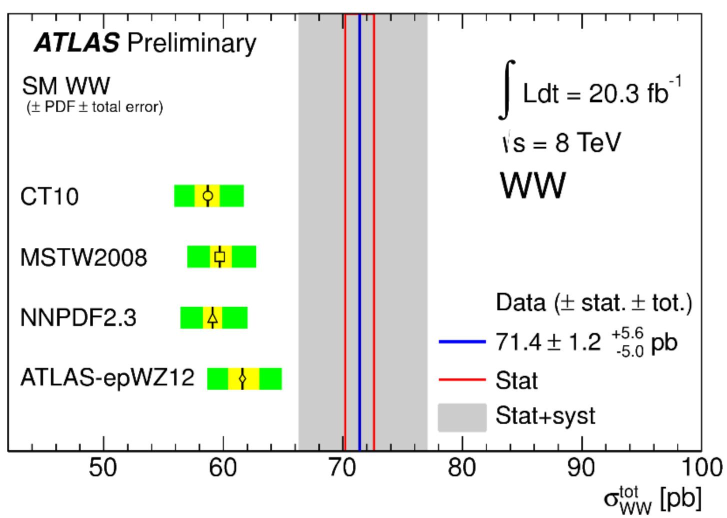
Sources	$e^{\pm}\mu^{\mp}$	e^+e^-	$\mu^+\mu^-$
C_{WW} experimental uncertainties			
Pileup	1.3%	1.9%	2.0%
e trigger efficiency	0.3%	2.5%	–
μ trigger efficiency	0.3%	–	2.8%
Muon MS resolution	0.0%	–	0.1%
Muon ID resolution	0.5%	–	1.5%
Muon scale	0.1%	–	0.4%
Muon efficiency	0.4%	–	0.8%
Muon isolation/IP	0.6%	–	1.1%
Electron resolution	0.0%	0.2%	–
Electron energy scale	0.4%	1.4%	–
Electron efficiency	0.9%	2.0%	–
:	:	:	:
E_T^{miss} soft term scale	2.3%	4.2%	3.8%
p_T^{miss} soft term resolution	0.1%	0.0%	0.2%
p_T^{miss} soft term scale	0.3%	0.6%	0.5%
Total experimental uncertainties	3.7%	6.3%	6.3%
$A_{WW} \times C_{WW}$ theoretical uncertainties			
Jet-veto requirement (theory)	3.3%	3.3%	3.3%
PDF	1.3%	1.6%	0.8%
Scale	1.5%	2.0%	1.8%
Total theoretical uncertainties	3.9%	4.2%	3.8%
Total (exp.+theo.)	5.4%	7.6%	7.4%

W^+W^- Cross-section : Comments

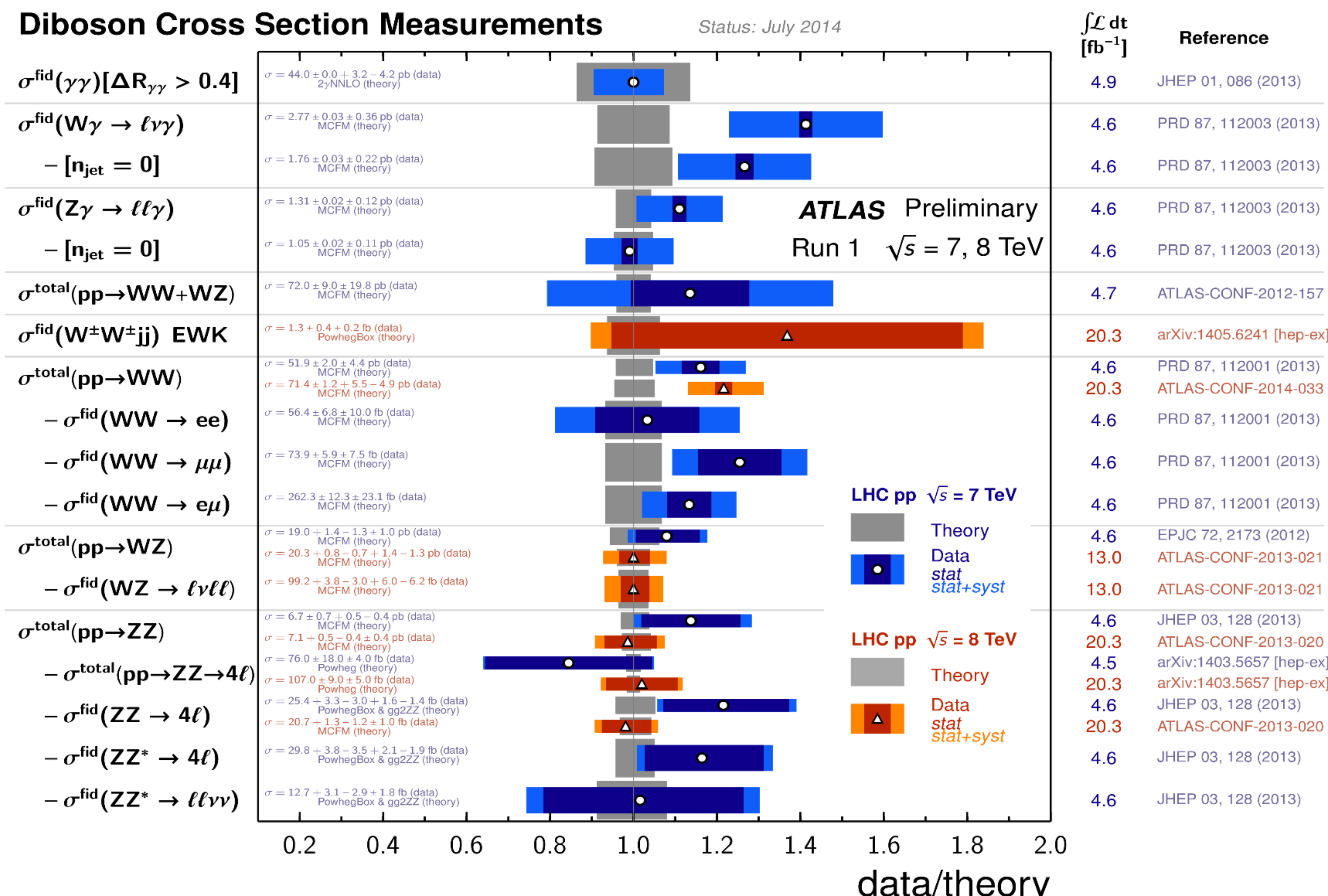
Comments of observed excess (20% difference v.s. 10% uncertainty)

- **Full NNLO QCD qq calculation could increase the inclusive NLO qq σ**
  - +5%, arXiv:1408.5243v1
- **Sizable effect possible due to PDFs**
  - +5% with ATLAS PDF, Phys.Rev.Lett. 109 (2012) 012001
- **NNLO/LO k-factor for gg->WW non resonant contribution**
  - If assume same k-factor as gg->H->WW, will see +5% increase on total σ
- **Modelling on the gluon resummation**
  - A few percent to O(10%) effect on fiducial cross section
  - arXiv:1407.4481v1, arXiv:1407.4537v1
- **Other possible effects at or smaller than O(1%) level to total cross section**
  - NLO electroweak correction, γγ->WW, vector boson scattering, double parton interaction





Diboson Cross-section Results Compare with MC



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Summary

Electroweak Zjj

- First observation over 5σ
- Cross-section measured in multi-phase spaces
- Complementary constrain on aTGC

Vector Boson Scattering $W^{\pm}W^{\pm}jj$

- First evidence of VBS
- Cross-section measured with 30% precision

Z→4l

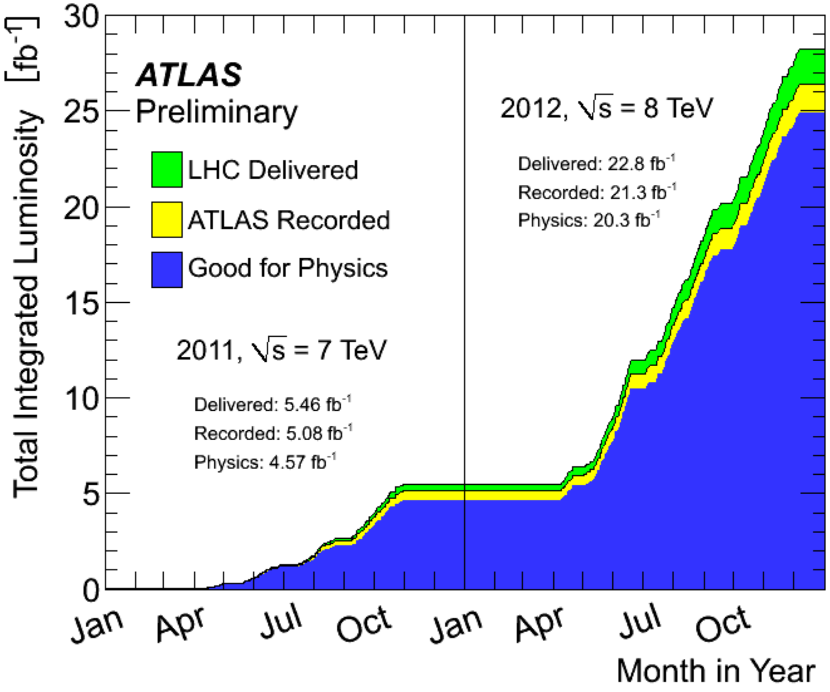
- Rare Z decay process cross-section measured to ±10%
- s-channel branching ratio measured as SM prediction

Diboson

- Most measured cross-sections agree with SM predictions except $W^{+}W^{-}$ with 2.1σ over expectation
- Explored aTGC

Backup

Data collected at ATLAS



Integrated luminosity for physics analysis

4.6 fb^{-1} at 7 TeV

20.3 fb^{-1} at 8 TeV

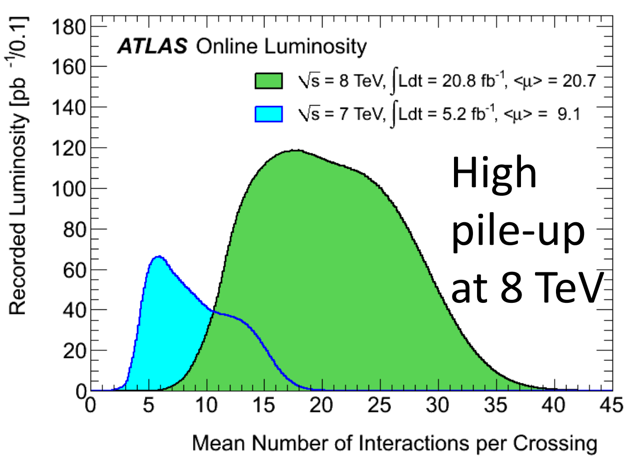
Data taking efficiency

~ 94%

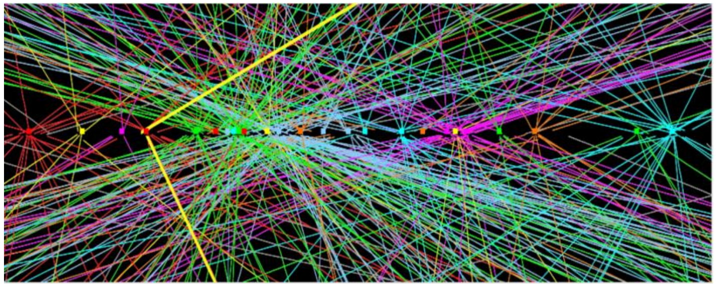
Detector operation fraction

> 97%

Very stable detector performance



High pile-up at 8 TeV

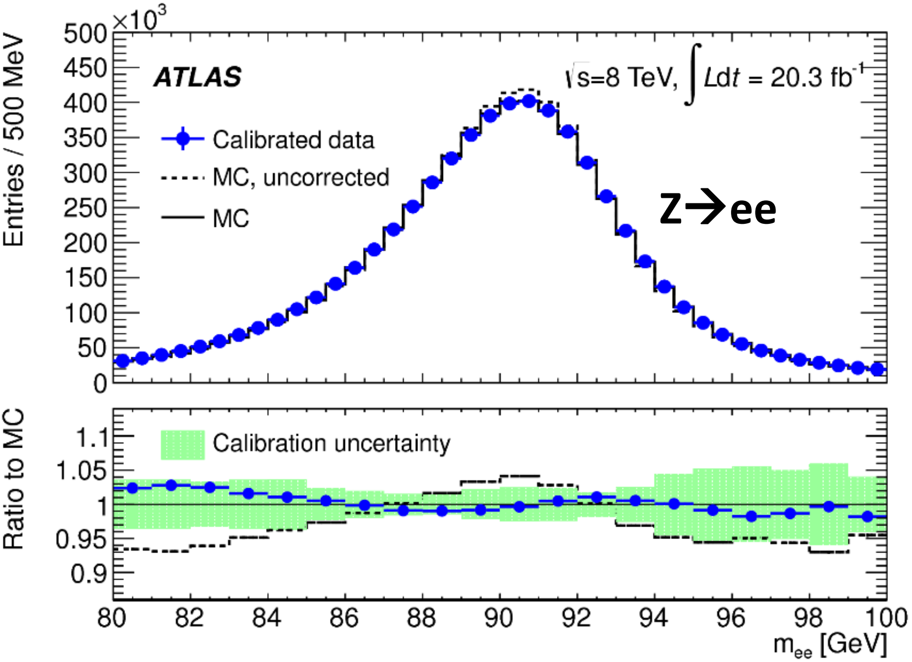


Demonstration of an event with O(25) vertices

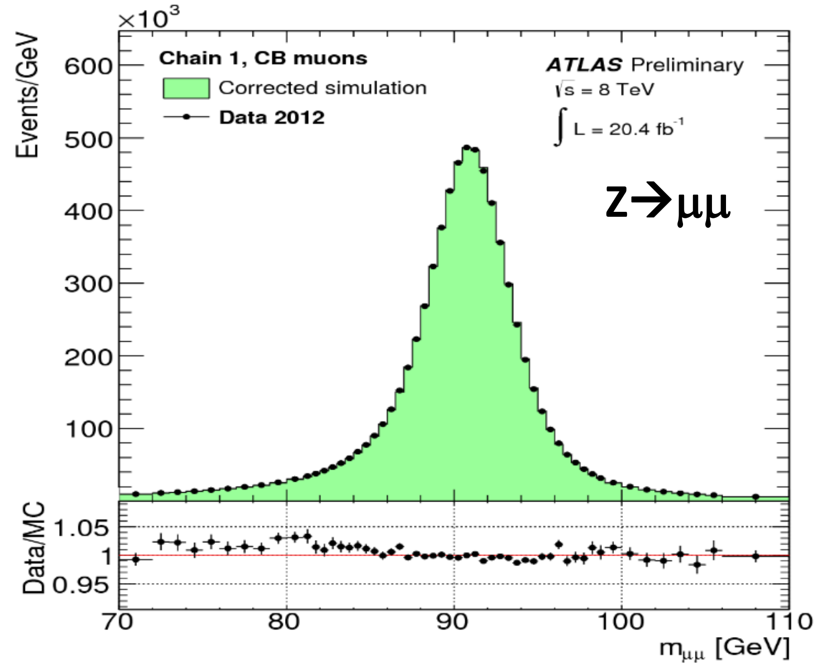
Crucial to correct for the pile-up effects in momentum and energy measurements

Reconstruction Performance e, μ

arXiv:1407.5063



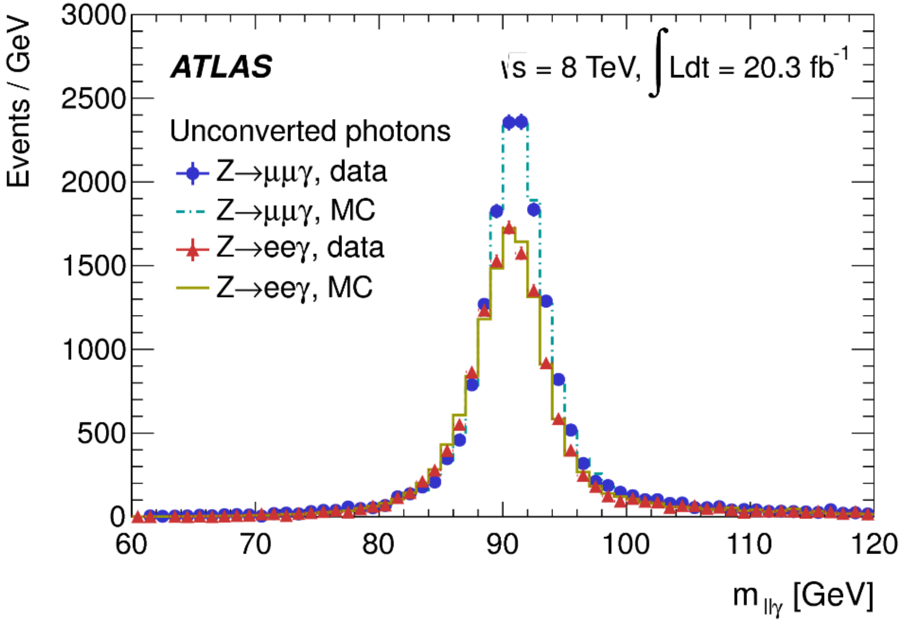
ATLAS-CONF-2013-088



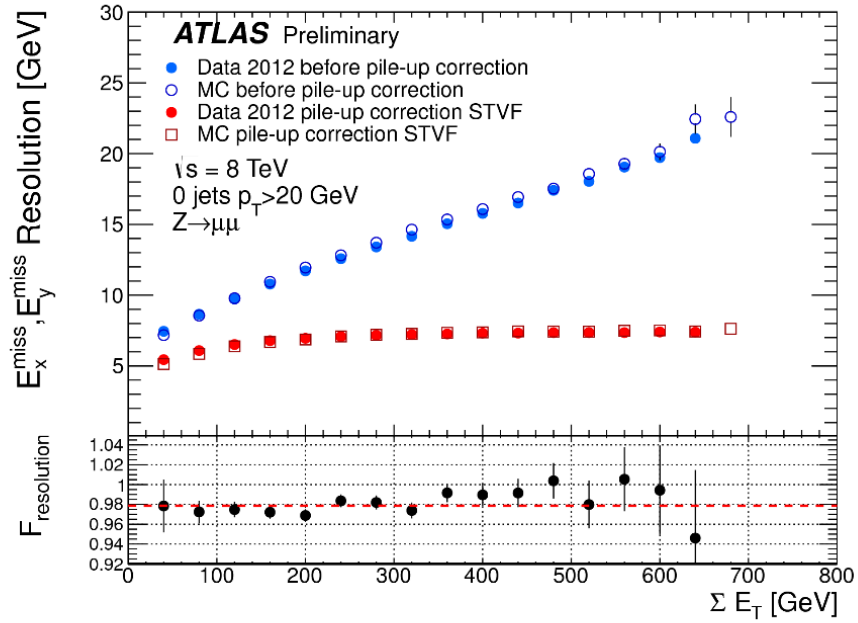
Precise calibration of energy scale and resolution for e/μ and Good modelling in MC

Reconstruction Performance γ, E_T^{miss}

arXiv:1407.5063



ATLAS-CONF-2014-019



Precise energy scale / resolution determination for photon

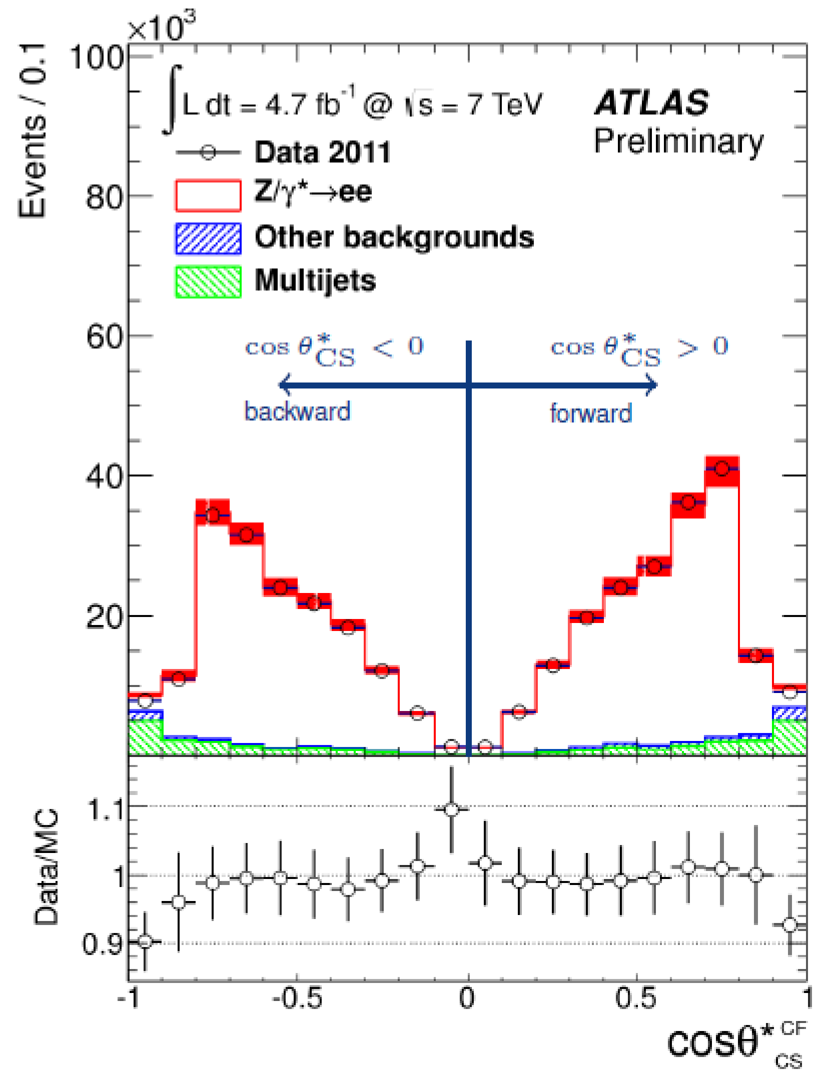
Good modelling of pileup effects for E_T^{miss}

Good detector calibration and Well simulated MC are essential for precision measurement

Weak Mixing Angle : Data Events

ATLAS-CONF-2013-043

- 4.8fb^{-1} (4.7fb^{-1}) of data recorded at $7\ \text{TeV}$ in ee ($\mu\mu$) channel
- sample selection:
  - opposite charge is required for muons or two central electrons (CC)
  - only central electrons with tight quality are paired with forward electrons (CF)
  - dilepton mass $66\ \text{GeV} < m_{\ell\ell} < 1\ \text{TeV}$ (or $< 250\ \text{GeV}$ for CF)
- background composition:
  - data-driven: multijet three (four) orders of magnitude less than ee ($\mu\mu$) signal
  - Monte Carlo: diboson, $Z \to \tau\tau$, $t\bar{t}$



angles defined in Collins-Soper frame, i.e. Z boson rest frame

Weak Mixing Angle : Measurement Results

ATLAS-CONF-2013-043

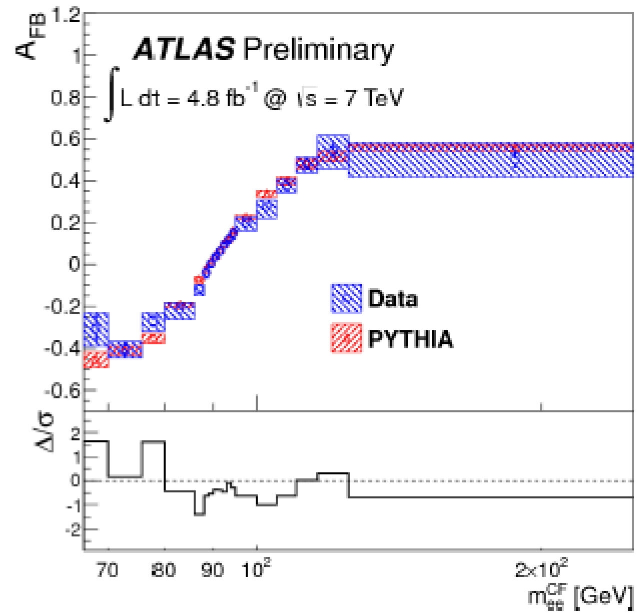
- measurement of forward-backward-asymmetry

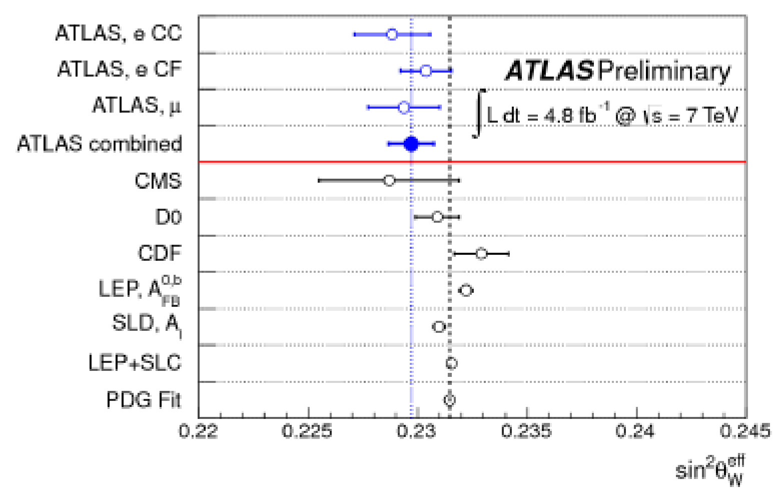
$$A_{\rm FB} = \frac{\sigma_{\rm forward} - \sigma_{\rm backward}}{\sigma_{\rm total}}$$

- dominant systematics: PDF uncertainty followed by MC statistics
- determination of leptonic effective weak mixing angle $\sin^2\theta_W^{\rm eff}$:
  - extracted with templates and χ^2 fit to data for $m_{\ell\ell} = 70 - 250$ GeV
  - combined result:

$$\sin^2\theta_W^{\rm eff} = 0.2297 \pm 0.0004({\rm stat}) \pm 0.0009({\rm syst})$$
$$= 0.2297 \pm 0.0010({\rm tot})$$

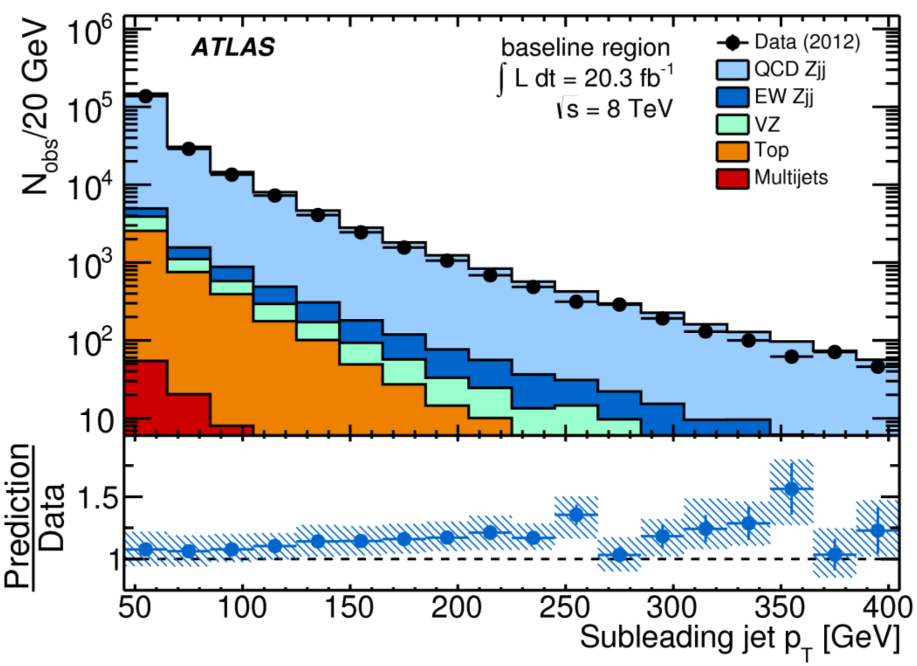
  - 1.8 standard deviations with respect to PDG best fit value
  - first measurement from hadron collider combining electron/muon final state to determine $\sin^2\theta_W^{\rm eff}$ at Z pole



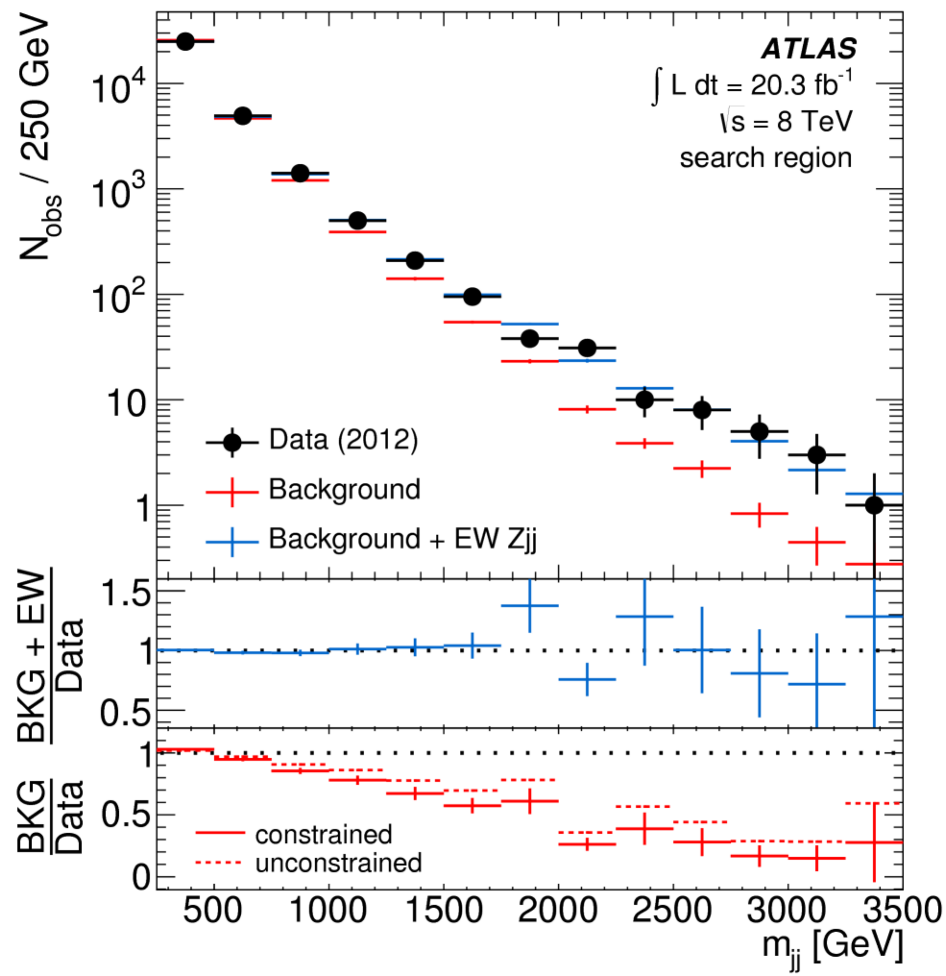


Electroweak Zjj : Data and MC Comparision

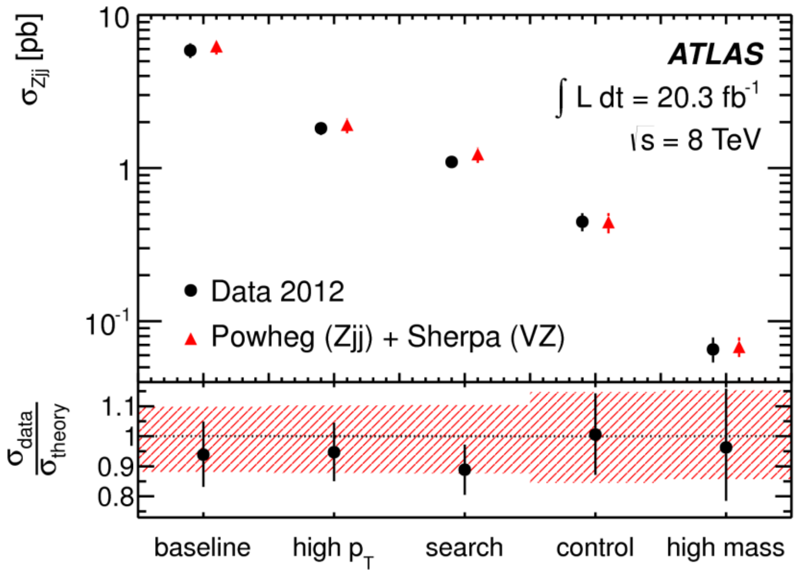
Baseline Region



Search Region



Electroweak Zjj : Results



EW component measured in search region with m_{jj} > 1 TeV :

$$\sigma_{fid}(Zjj\text{ - }EW) = 10.7 \pm 0.9(stat) \pm 1.9(syst) \pm 0.3(lumi)\ \ fb$$

$$\sigma_{SM} = 9.38 \pm 0.05(stat)^{+0.15}_{-0.24}(scale) \pm 0.24(PDF) \pm 0.09(model)\ \ fb$$

Background only hypothesis excluded over 5σ

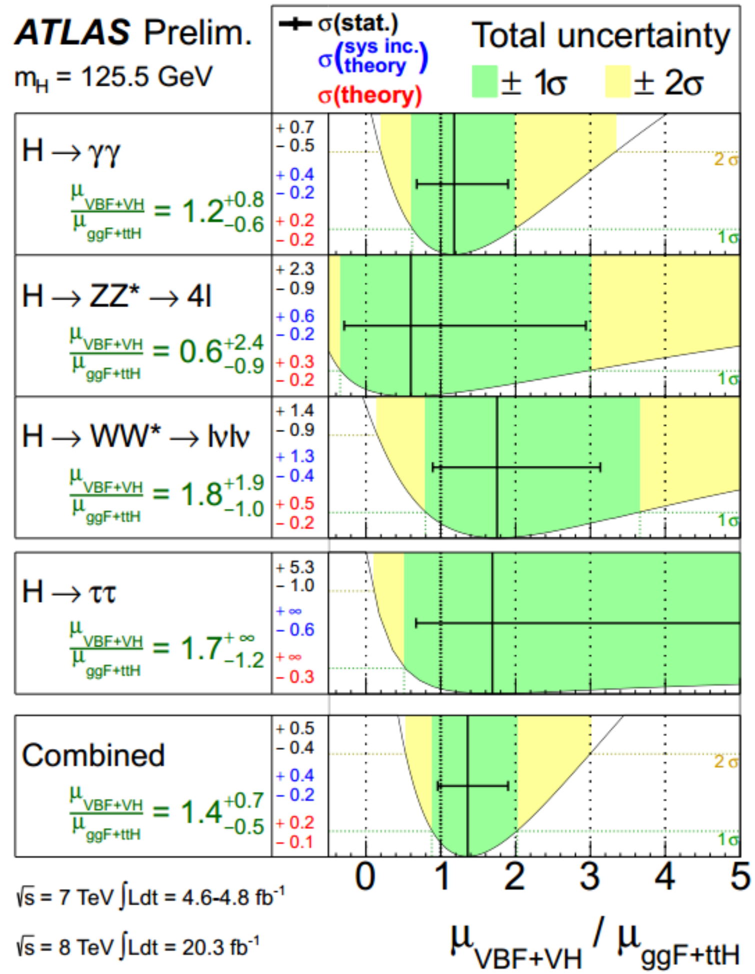
Search region is used for a complementary test of aTGCs on WWZ at 95% CL

aTGC	Δg_1^Z
$\Lambda = 6$ TeV (obs)	$[-0.65, 0.33]$
$\Lambda = 6$ TeV (exp)	$[-0.58, 0.27]$
$\Lambda = \infty$ (obs)	$[-0.50, 0.26]$
$\Lambda = \infty$ (exp)	$[-0.45, 0.22]$

aTGC	λ_Z
$\Lambda = 6$ TeV (obs)	$[-0.22, 0.19]$
$\Lambda = 6$ TeV (exp)	$[-0.19, 0.16]$
$\Lambda = \infty$ (obs)	$[-0.15, 0.13]$
$\Lambda = \infty$ (exp)	$[-0.14, 0.11]$

VBF Higgs Search at ATLAS

- Searched for $H \rightarrow \gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, bb production in VBF modes
- No 3σ evidence observed in each individual channel yet



Anomalous QGCs

- Anomalous quartic couplings modify the expected cross sections
- We would like to set limits on possible new physics using the measured cross sections in a model-independent way
  - Use the effective Lagrangian:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

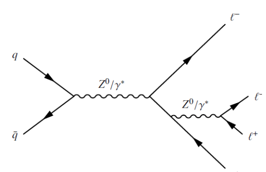
  - Can introduce unphysical predictions at high energies
  - Requires unitarization scheme
- Consider the chiral Lagrangian approach as implemented in WHIZARD (JHEP 11(2008) 010):
  - The terms that affect WWVV QGCs are α_4 and α_5
- Indirect constraints from electroweak precision data (Eboli et al, PRD 74, 073005 (2006), 99% CL bounds):

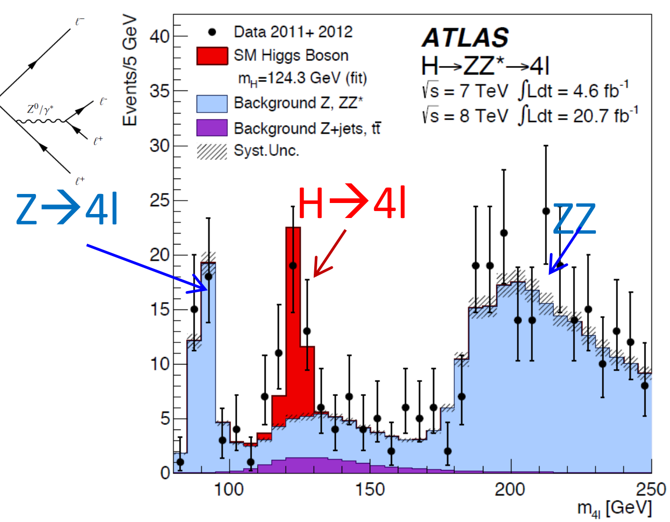
$$-0.35 < \alpha_4 < 0.06 \text{ and } -0.87 < \alpha_5 < 0.15$$

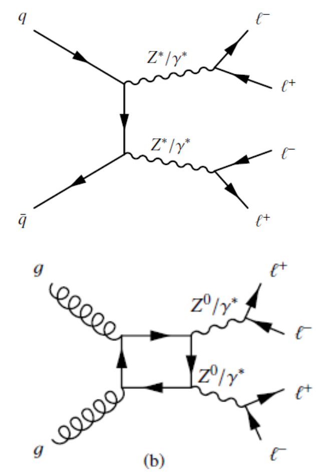
Z→4l : Introduction

arXiv:1403.5657

- Rare decay of Z→4ℓ production was first observed at the LHC by both ATLAS and CMS experiments along with the Higgs boson discovery in the 4ℓ decay channel
- Cross section measurement of the Z→4ℓ production provides
  - A SM test for a rare decay process (measurements of σ(4ℓ) and BR(Z→4ℓ))
  - A complementary test of the detector response for H→4ℓ detection



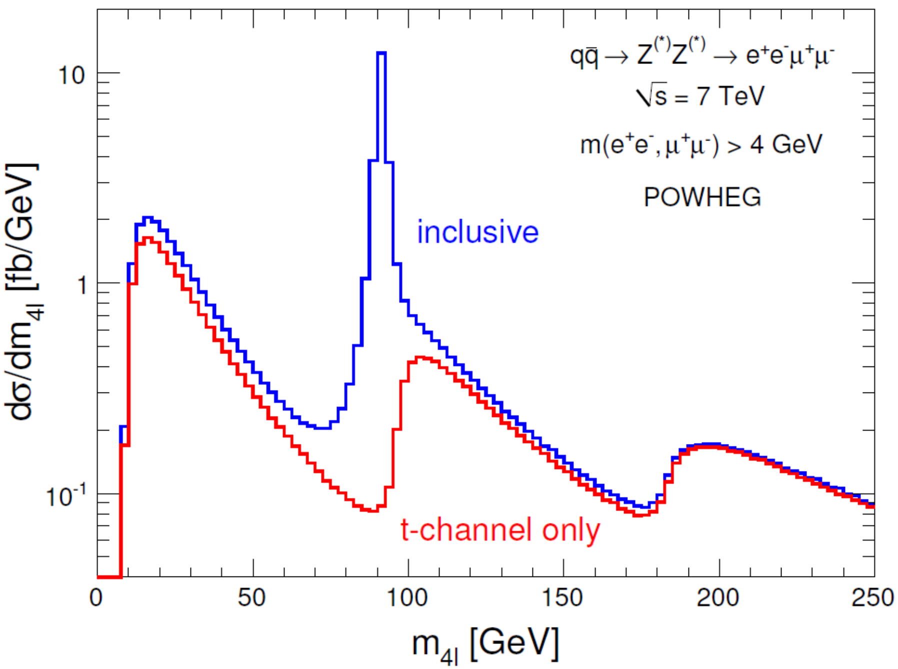


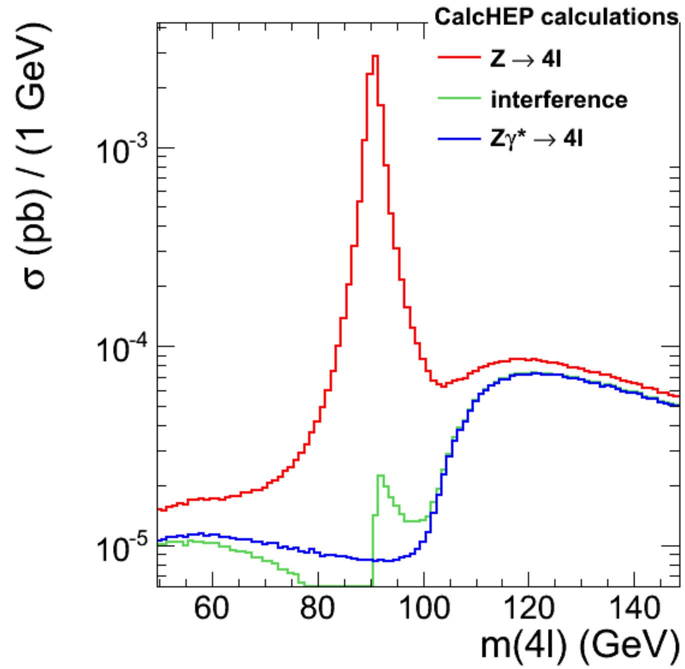


Non Z→4ℓ production

- Z→4l standard candle in calibration 4l analysis, such as Higgs

Z→4l : Modeling





qq → Z/Z*Z* → 4ℓ modeled by Powheg MC for

- Cross section calculations (NLO QCD)
- Event generations (interfaced to PYTHIA)

gg → ZZ →4ℓ modeled by GG2ZZ MC for

- Cross section calculations (LO QCD)
- Event generations (interfaced to Herwig/Jimmy)

MCFM MC used to cross check cross sections

CalcHEP MC (LO QCD) used to calculate the magnitude of interference between the s-channel and the t-channel 4ℓ production processes

- ~0.2% in the 4ℓ phase space

  $80 < m_{4l} < 100$ GeV, $m_{2l} > 5$ GeV

- treat it as systematic uncertainty when determine the Z→4l branching fraction

Z→4l : Detection Challenge

- The Z→4ℓ process is dominant by low mass m_{34} and low pT leptons (the pT-ordered 4^{th} leptons)
- **Need to detect low pT leptons**

ATLAS Z→4ℓ selection:

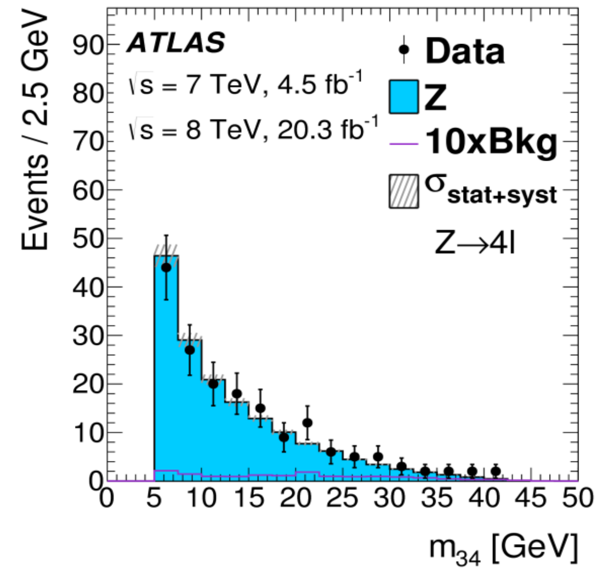
e : p_T > 20, 15, 10, 7 GeV, |η| <2.5

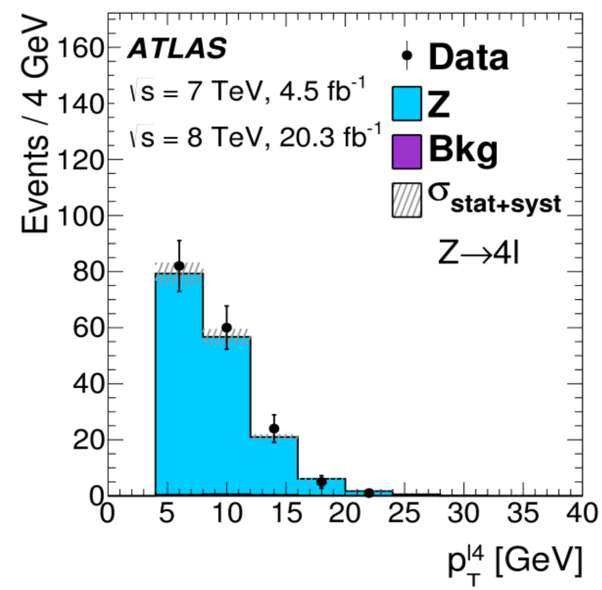
μ : p_T > 20, 15, 8, 4 GeV, |η| <2.7

m_{12} ($\ell^+\ell^-$)> **20** GeV, m_{34} ($\ell^+\ell^-$)> **5** GeV

80 GeV < m_{4l} < 100 GeV

- **< 1% backgrounds expected from:**
  - **Z+Jets and ttbar from data-driven method**
  - **WZ, gg ! ZZ and decays from Z from MC**





Z→4l : Cross-section Results

ATLAS measurement in final phase space

$80 < m_{4l} < 100$ GeV and $m_{\ell+\ell-} > 5$ GeV

$$\sigma^{total}_{Z\rightarrow 4\ell} = \frac{\sigma^{fiducial}_{Z\rightarrow 4\ell}}{A_{Z\rightarrow 4\ell}}$$

- **The 4e and 4μ channels, and The 2e2μ and 2μ2e channels are combined with 2x2 covariance error matrices for σ measurement**
- **The 4l $\sigma^{total} = \sigma(4e+4\mu) + \sigma(2e2\mu)$, uncertainties are determined by 4x4 error matrices**
- **Good agreement with prediction, and measurement error still dominated by statistic**

ATLAS	Phase-space cross section ($m_{2l} > 5$ GeV, $80 < m_{4l} < 100$ GeV)
7 TeV measured	76±18 (stat.) ±4 (syst.) ±1.4 (lumi.) fb
7 TeV NLO SM prediction	90.0±2.1 fb
8 TeV measured	107±9 (stat.) ±4 (syst.) ±3.0 (lumi.) fb
8 TeV NLO SM prediction	104.8±2.5 fb

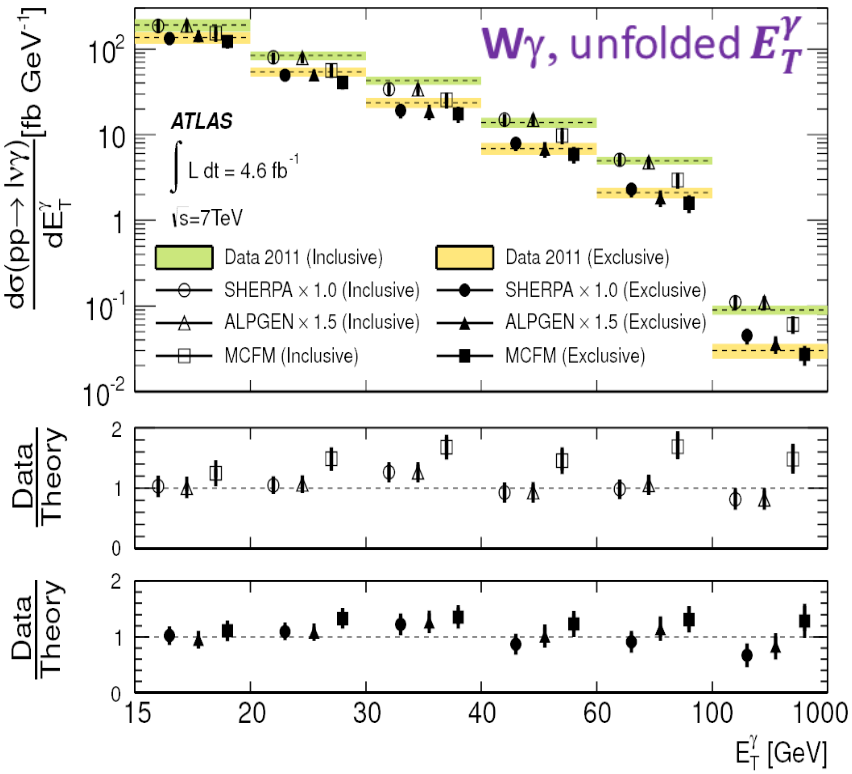
7TeV Wγ, Zγ Cross-sections

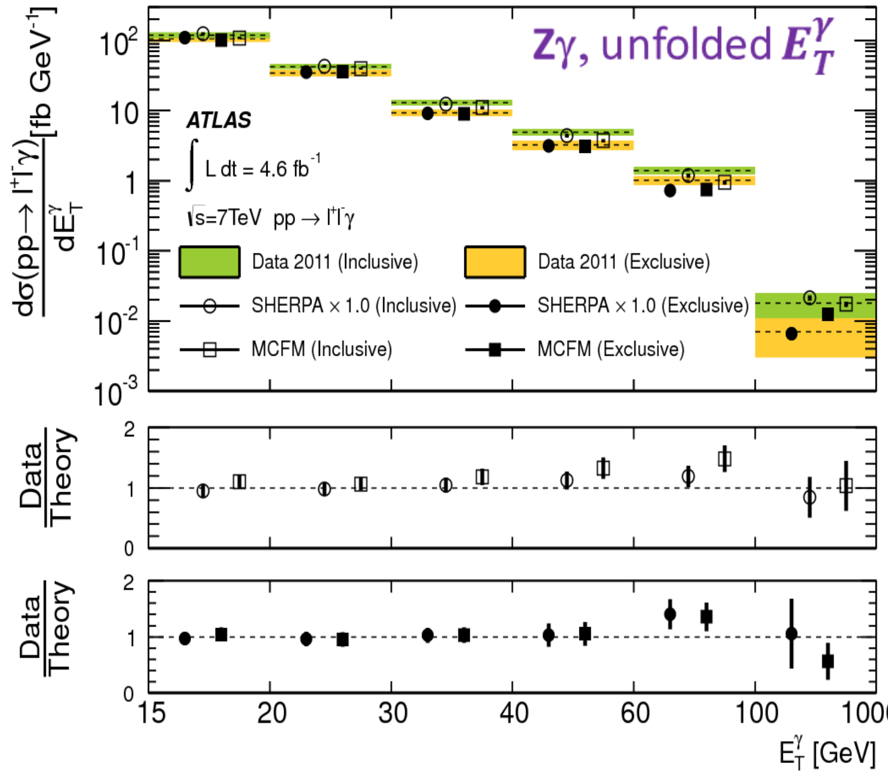
Final state: Wγ -> lν γ
+ signature: e/μ, E_T^{miss}, γ, $\Delta R(l,\gamma) > 0.7$
+ backgrounds: Z+jets, γ+jets, ttbar, τ decays
+ S/B ~ 1.5

Final state: Zγ -> ll γ or Zγ -> νν γ
+ signature: ee/μμ or E_T^{miss}, γ ,$\Delta R(l,\gamma) > 0.7$
+ backgrounds: Z+jets, W+X, τ decays
+ S/B > 5

Typical uncertainty at 5 – 10%, dominated by photon ID systematics
Exclusive region defined with zero jet (30GeV)

Phys. Rev. D 87, 112003 (2013)





8TeV WZ Cross-section

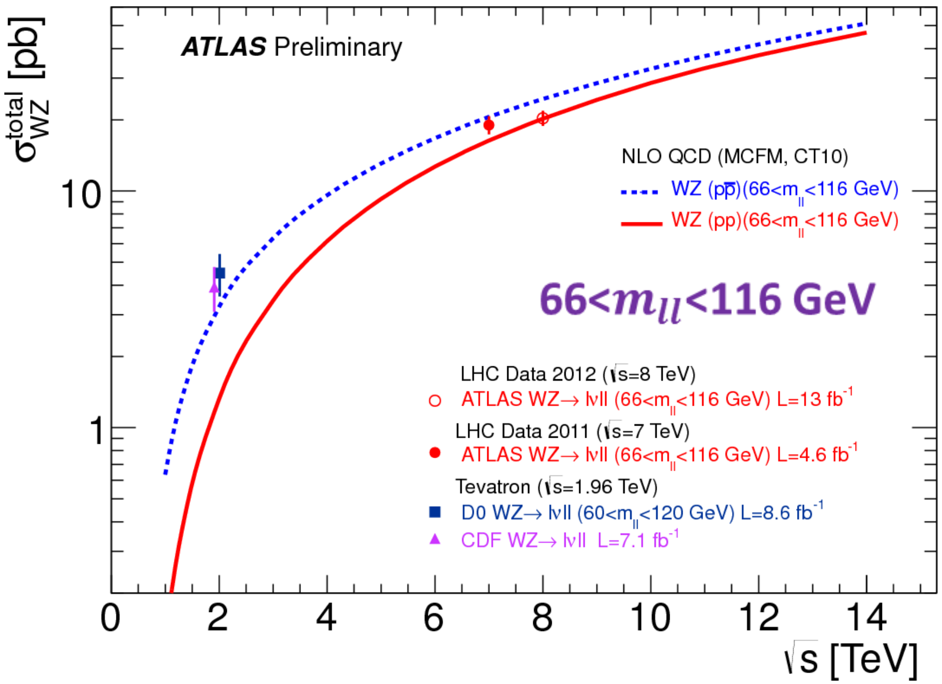
Event selection (WZ->3l+ν):

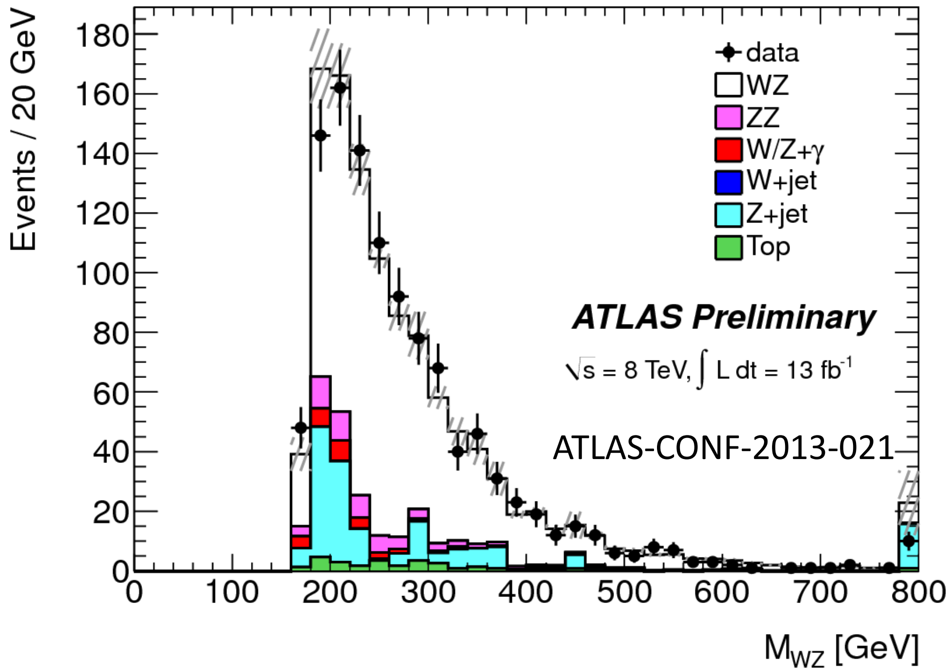
- Three isolated leptons (p_T>15GeV)
- m_{ll} consistent with Z mass within 10GeV, pair of leptons with min|m_{ll}-m_Z| to form a Z
- Third lepton (W lepton) p_T>25GeV
- E_T^{miss}> 25 GeV, m_T^W>20GeV

Backgrounds and Uncertainties:

- Z+jets, Top: data-driven
- ZZ, W/Z+γ: MC
- ~1000 candidates, S/B ~ 3
- Uncertainties on measured σ
  - about 4% stat. error
  - 7% syst. Uncertainty (bkg., lepton, lumi.)

With 13 fb^{-1} pp collision data at 8 TeV





Consistent with NLO prediction

8TeV ZZ Cross-section

Event selection (ZZ->4l):

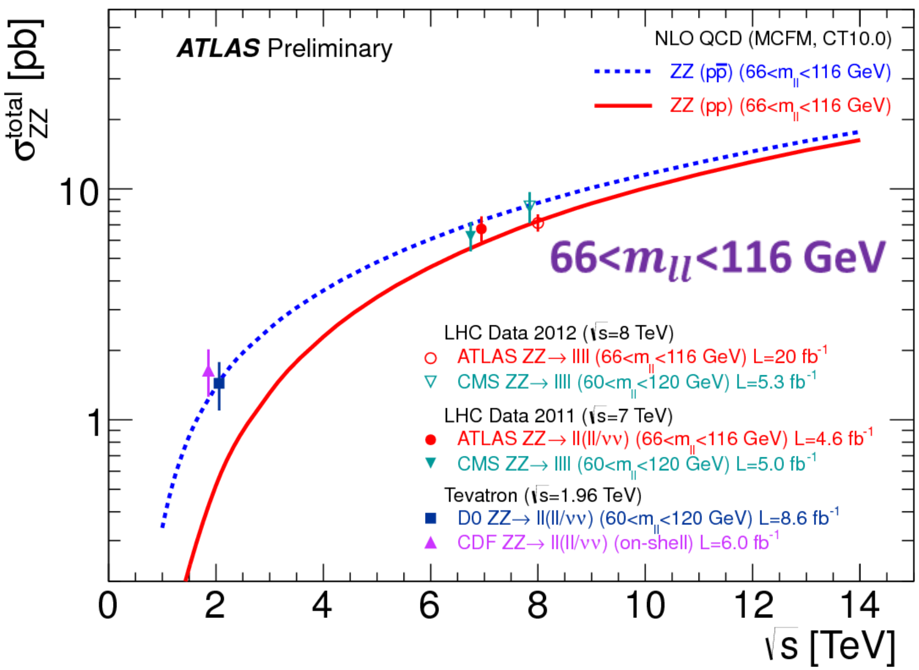
- Four isolated leptons (p_T>7GeV), at least one lepton with p_T>25GeV

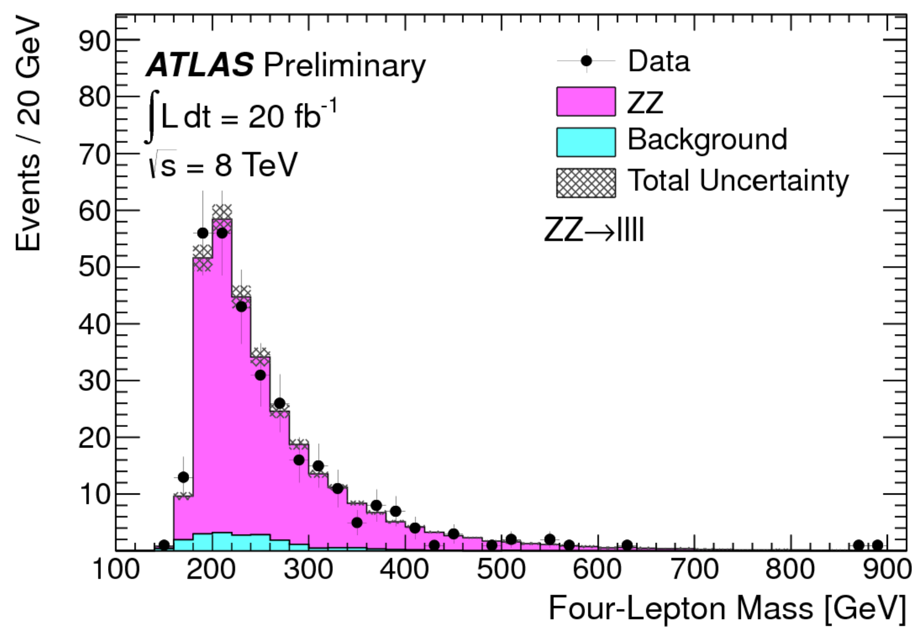
Backgrounds and Uncertainties:

- Background: 2l+X, 3l+X → data driven
- ~300 candidates, S/B ~ 10 (**Clean!**)
- Uncertainties on measured σ
  - about 7% stat. error
  - 5% syst. (lepton, lumi.)

With 20 fb^{-1} pp collision data at 8 TeV

ATLAS-CONF-2013-020

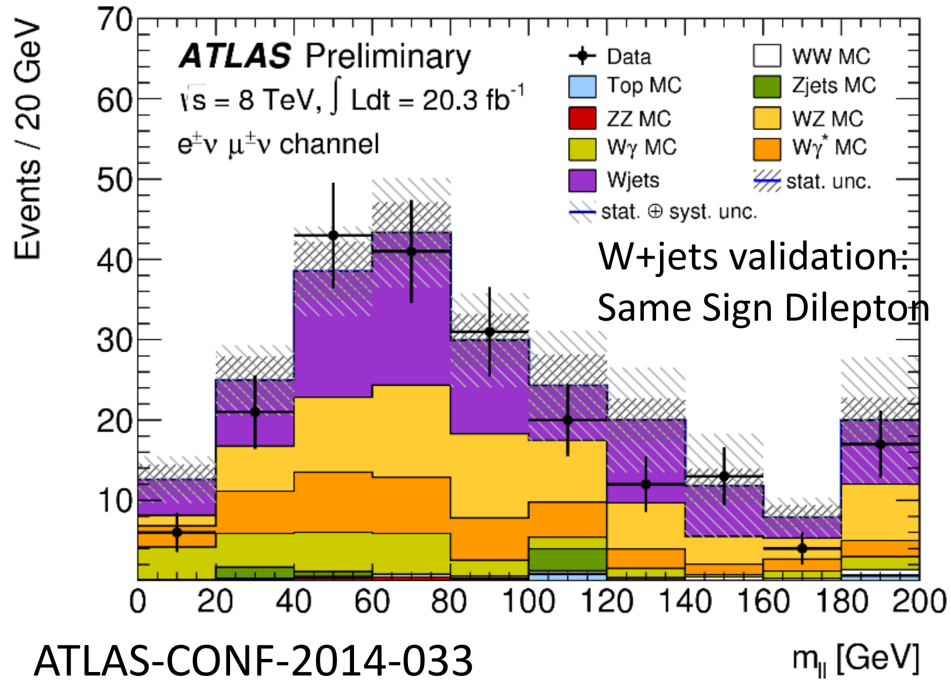




W^+W^- : Background Estimation

Data-driven Background estimation (relative uncertainty in bracket)

- Top: ttbar + single top (10%)
  - jet veto efficiency measured from data in b-tagged control region. Apply this efficiency on data events with inclusive jet bins to extract to signal region
- Z+jets (20%)
  - Likelihood fit on both Z+jets dominated control region and signal region with only free parameters of signal and Z+jets normalization, systematics considered as nuisance parameter, and other backgrounds fixed as their data-driven yields.
- W+jets (50%)
  - Rely on the measured jet faking lepton probability from dijet events (f) and the real lepton selection efficiency (r) to determine the true origin of reconstructed events
  - $Truth \times Matrix(f,r) = Reco$
    $Truth = Reco \times Matrix^{-1}(f,r)$
  - Major systematics: jet flavor composition



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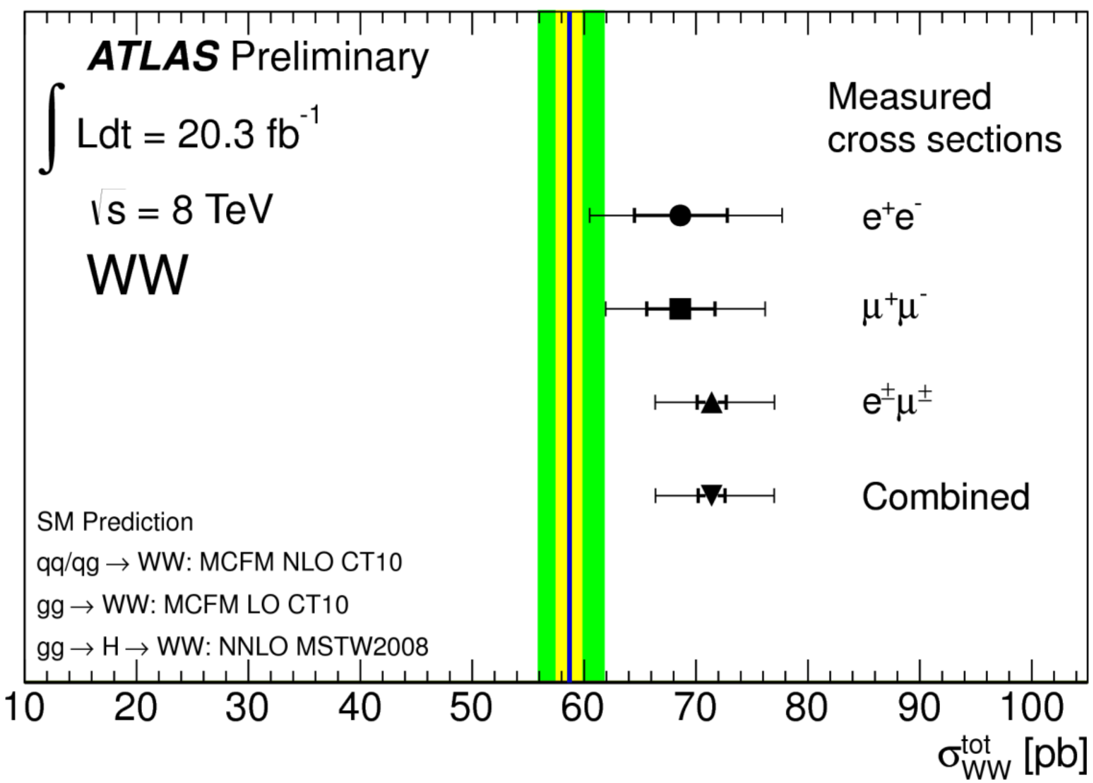
W^+W^- Cross-section at 8TeV

Signal acceptance and uncertainty (PowHeg + Pythia 8)

Channels	C_{WW}	$A_{WW} \times C_{WW}$
$e\nu\mu\nu$	0.511 ± 0.025	0.116 ± 0.007
$e\nu e\nu$	0.291 ± 0.021	0.025 ± 0.002
$\mu\nu\mu\nu$	0.471 ± 0.033	0.044 ± 0.004

Overall efficiency ~ 10%
uncertainty ~ 6% (Lepton, Jet, MET, JVSF*)

* Use Z events in data to constrain MC jet-veto efficiency: SF = $\frac{\varepsilon_Z^{data}}{\varepsilon_Z^{MC}} \sim 1$



<2% statistical uncertainty
~8% systematic uncertainty
About 2 σ higher than SM prediction