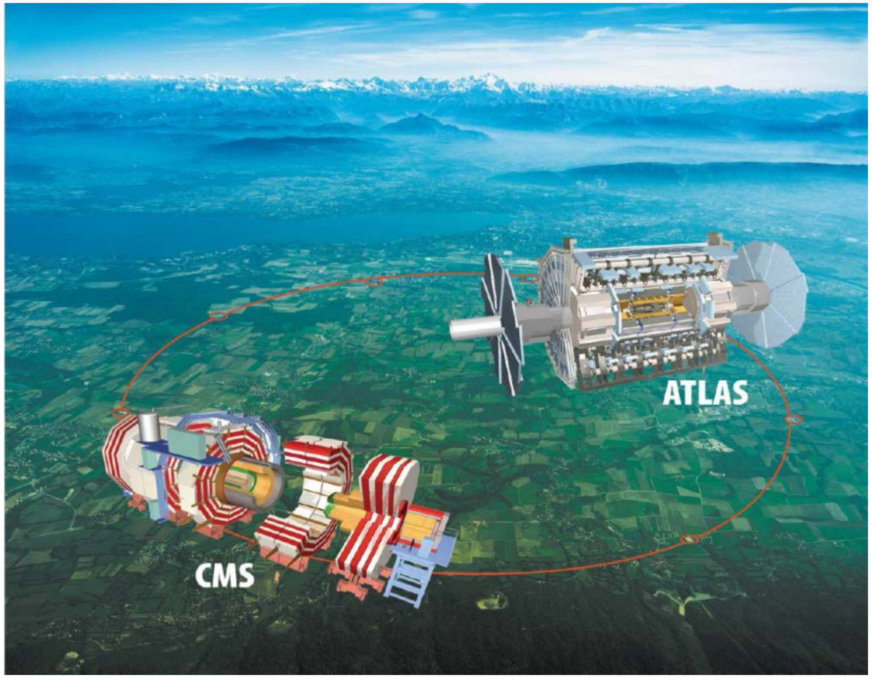
Measurements of the 7 and 8 TeV cross sections for Z→4l in pp collisions with ATLAS and CMS



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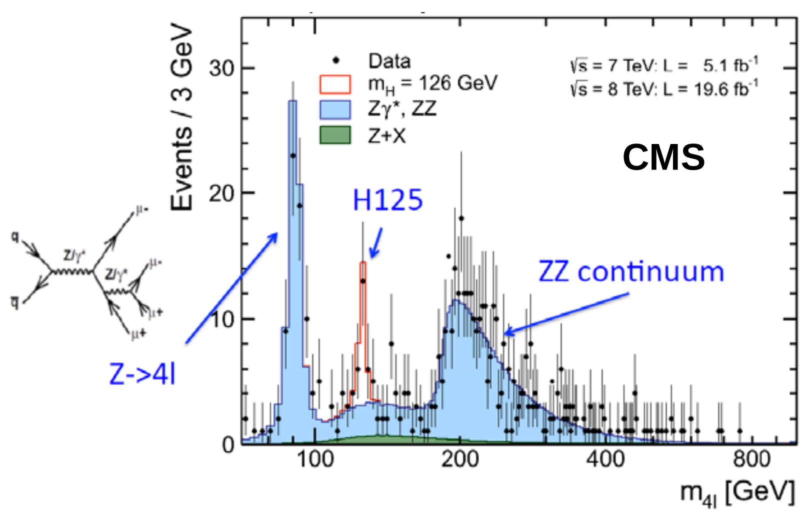
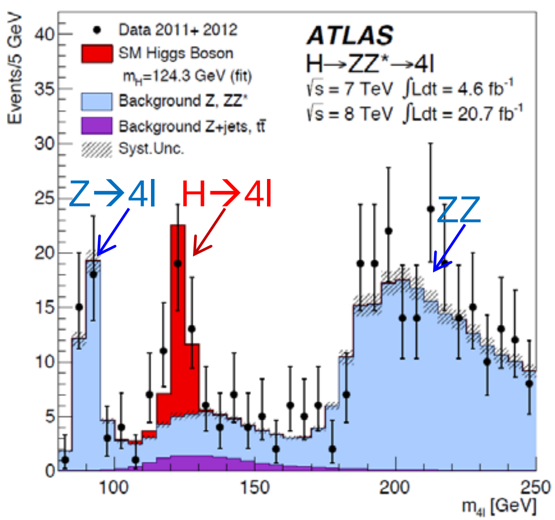
Introduction

- The $Z\rightarrow 4\ell$ 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 $Z\rightarrow 4\ell$ production provides
  - A SM test for a rare decay process (measurements of $\sigma(4\ell)$ and $BR(Z\rightarrow 4\ell)$)
  - A complementary test of the detector response for $H\rightarrow 4\ell$ detection

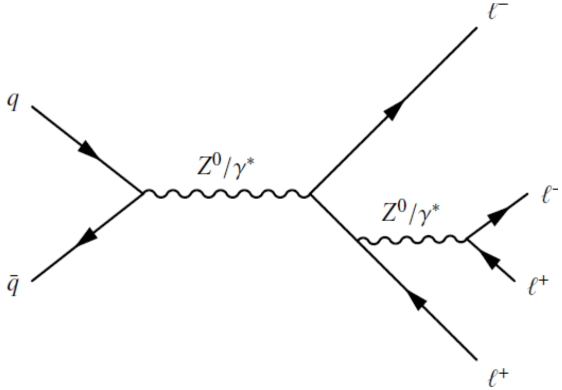




- References:
  - **ATLAS**: arXiv:1403.5657 [hep-ex]; ATLAS-CONF-2013-055
  - **CMS:** JHEP 12 (2012) 034, arXiv:1210.3844 [hep-ex]; CMS PAS SMP-12-009

4ℓ Production at Z Resonance

❖Four lepton final states: 4e, 4μ and 2e2μ



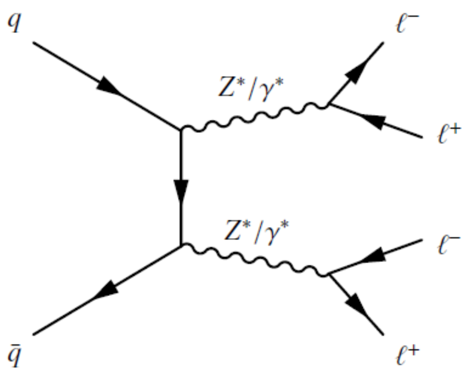
❖ **Resonant 4ℓ production** via an s-channel

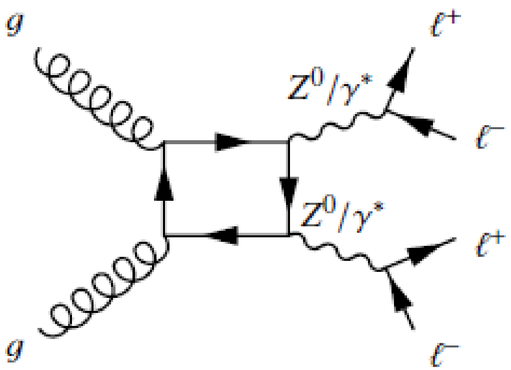
-- $Z \rightarrow \ell^+\ell^-$ include an additional $\ell^+\ell^-$ from internal conversion of Z^*/γ^*

-- s-channel is dominant (>96% for $80 < m_{4\ell} < 100$ GeV, $m_{2\ell} > 5$ GeV)

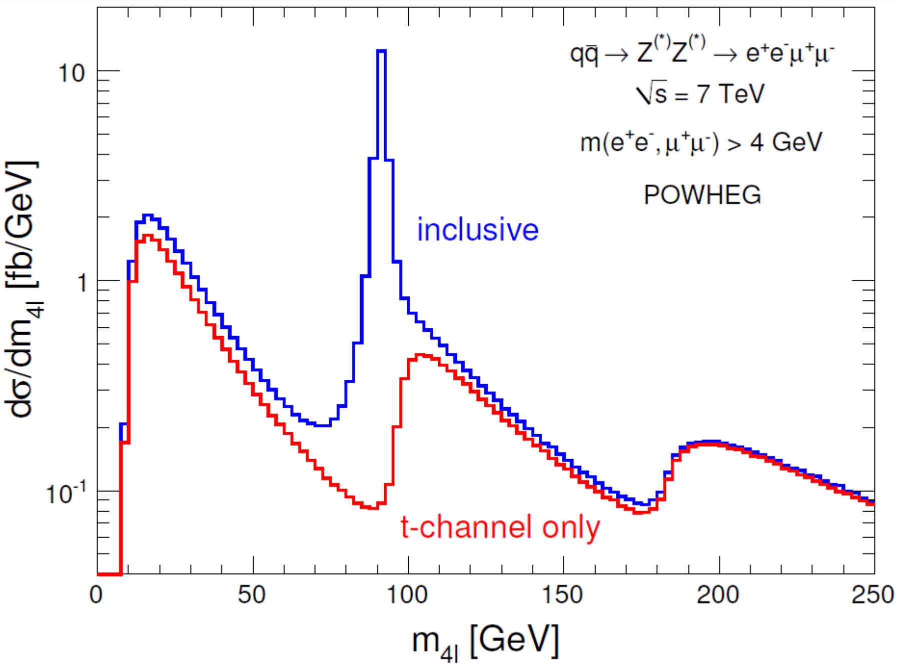
❖ **Non-resonant 4ℓ production**

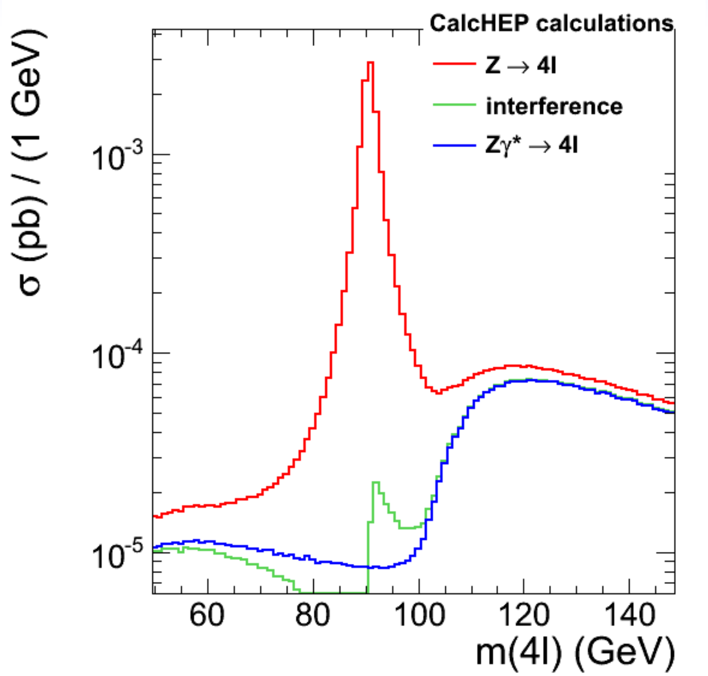
- via t-channel: $qq \rightarrow Z^*/\gamma^* + Z^*/\gamma^* \rightarrow 4\ell$ including the Z production with ISR internal conversion (< 4% 4ℓ event rate at the Z resonance)
- via $gg \rightarrow ZZ \rightarrow 4\ell$ (~0.1% 4ℓ event rate at the Z resonance)





4ℓ Production Modeling





$qq \to Z/Z^*Z^* \to 4\ell$ modeled by Powheg MC for

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

$gg \to ZZ \to 4\ell$ 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 $Z \to 4l$ branching fraction

Z→4l Is A Rare Decay

- **No measurement before the LHC**
- NLO Calculation by Powheg MC (PDF: CT10, Scales: $m_{4\ell}$) in a phase space: $80 < m_{4\ell} < 100$ GeV and $m_{\ell+\ell-} > 5$ GeV

Expected quantity	7 TeV	8 TeV
Total inclusive cross-section of $pp \to Z$	26.0 ± 0.6 nb	30.3 ± 0.8 nb
Total cross-section of $pp \to Z/ZZ^* \to 4\ell(e,\mu)$	89.97 ± 2.06 fb	104.84 ± 2.50 fb
Cross-section of $pp \to Z/ZZ^* \to 4e, 4\mu$	45.78 ± 1.10 fb	53.35 ± 1.24 fb
Cross-section of $pp \to Z/ZZ^* \to 2e2\mu$	44.19 ± 1.04 fb	51.49 ± 1.26 fb
Total t-ch. cross-section of $pp \to ZZ^* \to 4\ell(e,\mu)$)	3.28 ± 0.08 fb	3.80 ± 0.09 fb
t-ch. cross-section of $pp \to ZZ^* \to 4e, 4\mu$	1.55 ± 0.04 fb	1.79 ± 0.04 fb
t-ch. cross-section of $pp \to ZZ^* \to 2e2\mu$	1.73 ± 0.04 fb	2.01 ± 0.05 fb
Branching ratio of $Z \to 4\ell(e,\mu)$	$(3.33 \pm 0.01) \times 10^{-6}$	

- For a larger phase space $80 < m_{4\ell} < 100$ GeV, $m_{\ell+\ell-} > 4$ GeV, the inclusive 4ℓ cross section is 35% higher

Measurement Approaches

- **ATLAS (with data collected at 7 and 8 TeV)**
  - Measure ***inclusive 4ℓ*** production cross-section at the Z resonance, i.e. the non-resonance 4l events are treated as *signal* → cross section measurement will be less depending on theory interpretation; measured both ***fiducial*** and **final phase space** cross sections.
  - In determination of Z→4ℓ decay branching fraction, the non-resonance 4l contribution is subtracted and the resonance 4l event yield is normalized by the Z→μμ with the same dataset
- **CMS (with data collected at 7 TeV)**
  - Measure the resonance Z→4ℓ production cross section, and treat the t-channel 4ℓ events as background
  - Using the Z→μμ events to normalize the Z→4ℓ events to determine the BR(Z→4l)
- Phase space for measurements
  - **ATLAS:** $80 < m_{4l} < 100$ GeV and $m_{\ell^+\ell^-} > 5$ GeV;
    also measured BR in a larger phase space: $m_{\ell^+\ell^-} > 4$ GeV
  - **CMS:** $80 < m_{4l} < 100$ GeV, $m_{\ell\ell} > 4$ GeV (for any pairs of leptons)

Data Sets for Z→4l Analysis

- ATLAS
  - 4.6 fb^{-1} at 7 TeV (collected in 2011);
  - 20.3fb^{-1} at 8 TeV (collected in 2012)
  - In detection fiducial volume, trigger efficiencies for 4ℓ event detection: 95 - 99% (2011); 94 – 98% (2012)
- CMS
  - 5.0 fb^{-1} at 7 TeV (collected in 2010 and 2011)
  - In detection fiducial volume, trigger efficiencies: 96 – 99%

Experimental Challenge to Detect Z→4ℓ

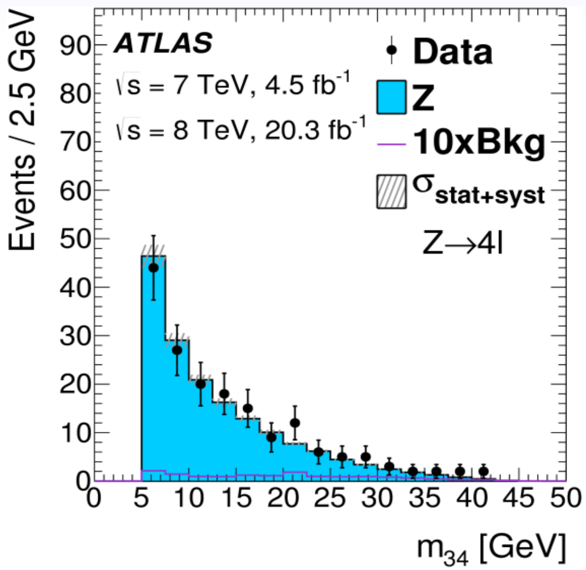
- The Z→4ℓ process is dominant by low mass m_{34} and low pT leptons (the pT-ordered 4[th] leptons)
- **Need to detect low pT leptons**

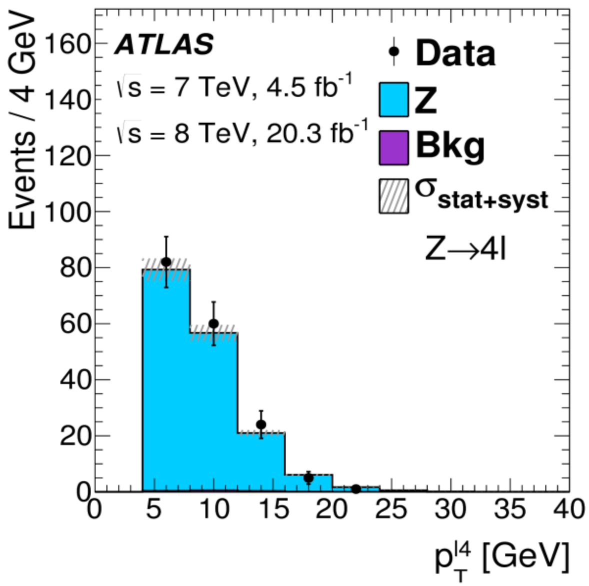
ATLAS Z→4ℓ selection:

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

CMS Z→4ℓ selection:

e: p_T > 20, 10, 7, 7 GeV, |η| <2.5
μ : p_T > 20, 10, 5, 5 GeV, |η| <2.4
$m_{\ell\ell}$ > **4** GeV
80 GeV < m_{4l} < 100 GeV





Event Display of Z→4μ

CMS
Run: 180076
Event : 456795917

pT_1 : 43.76 GeV
pT_2 : 24.20 GeV
pT_3 : 10.51 GeV
pT_4 : 7.39 GeV

M_{Z1} : 62.58 GeV
M_{Z2} : 17.27 GeV
M_{4L} : (91.30 ± 0.61) GeV

Min(mass2l) : 12.22 GeV
Max(mass2l) : 62.58 GeV

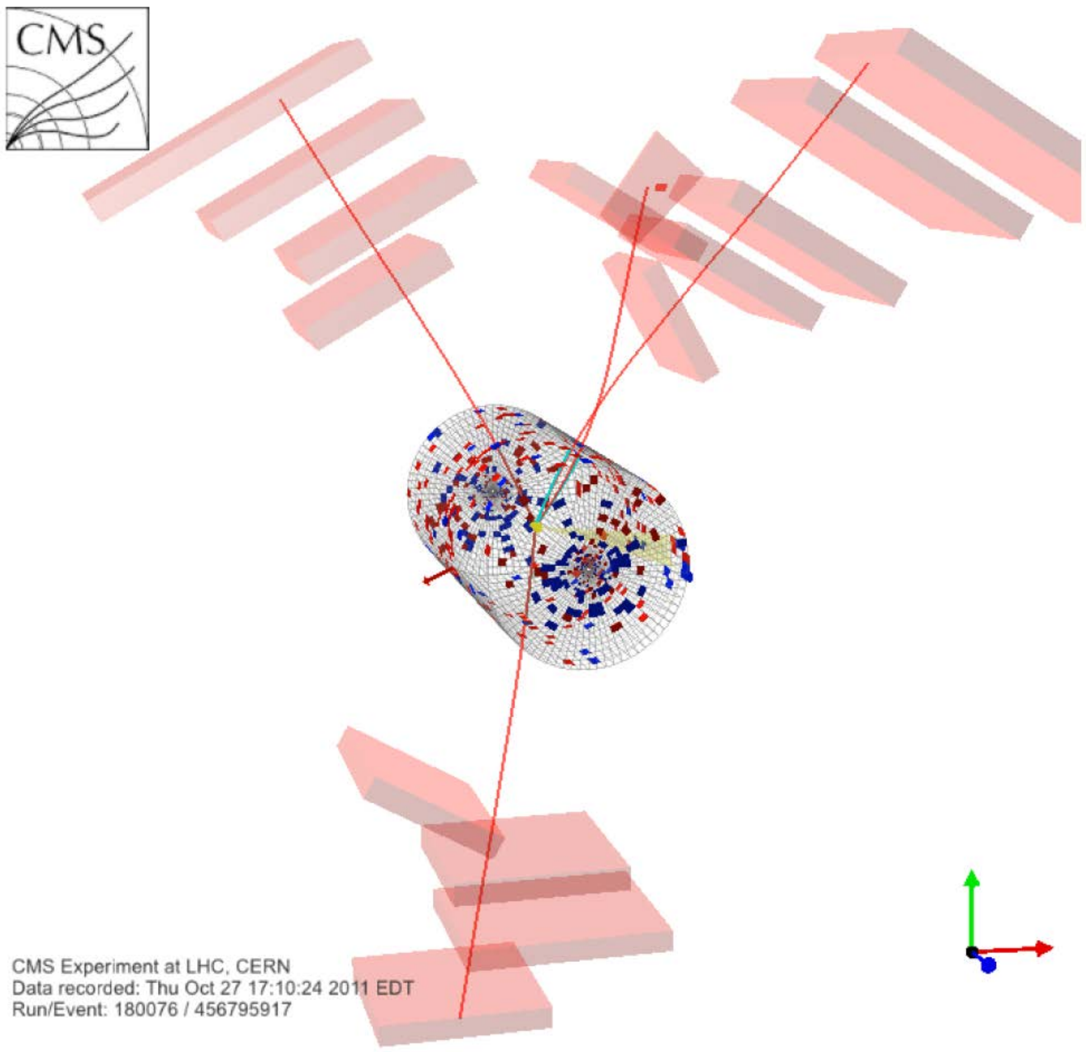


Figure 5: Event display of a typical event from the peak at the Z boson mass.

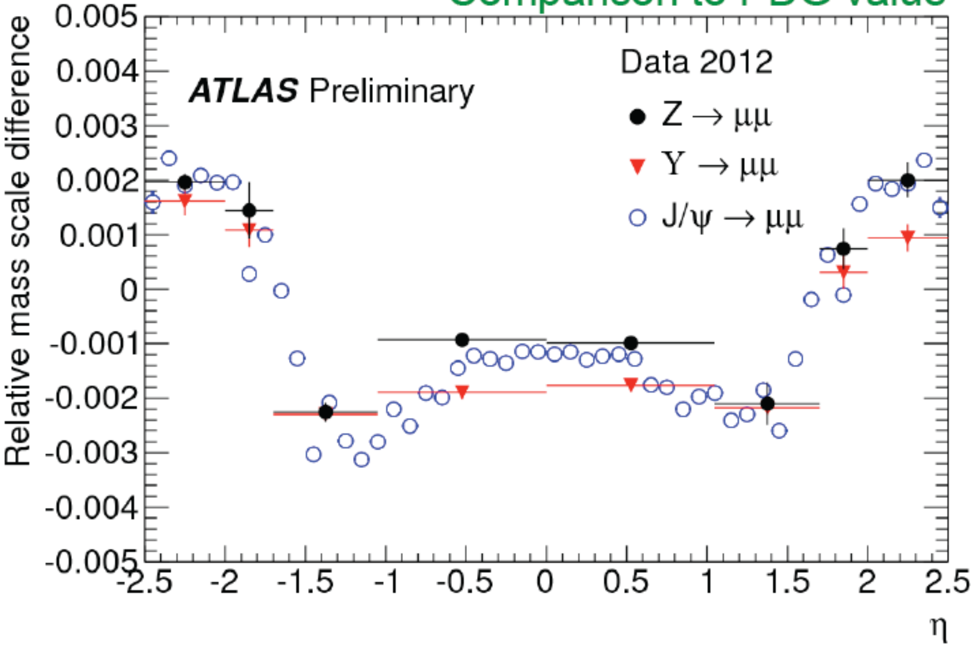
Muon Momentum Scale and Resolution

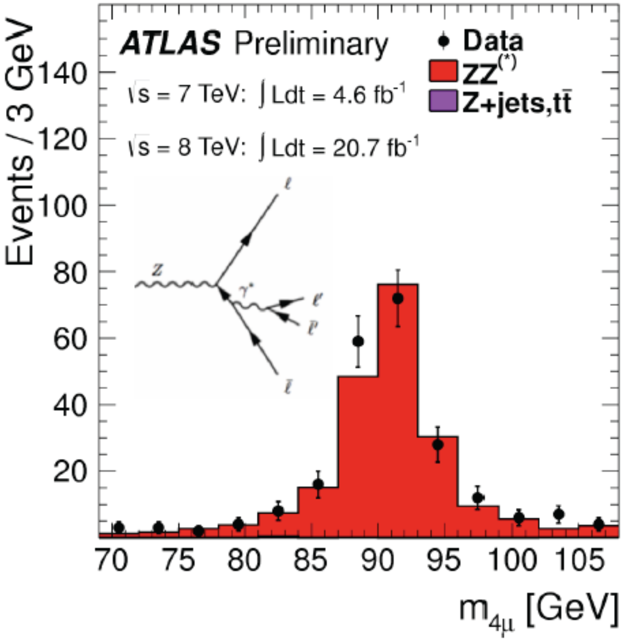
ATLAS

Muon energy scale and resolution corrections and systematic uncertainties determined from large Z, J/ψ and Y samples

- Resolution correction (0.2-1.3%), scale correction (< 0.1%)
- Independent measurements from Muon Spectrometer and inner tracker
- Probe global and local scale biases, overall uncertainty on 4μ scale 0.2%
- Calibration using Z→ 4μ mass peak (with m_{2l} > 1 GeV)

Comparison to PDG value





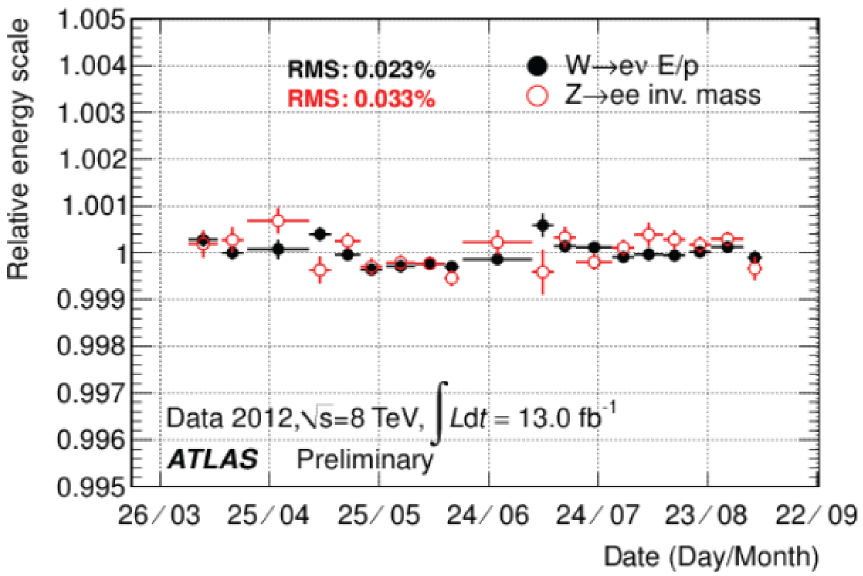
EM Calorimeter Calibration

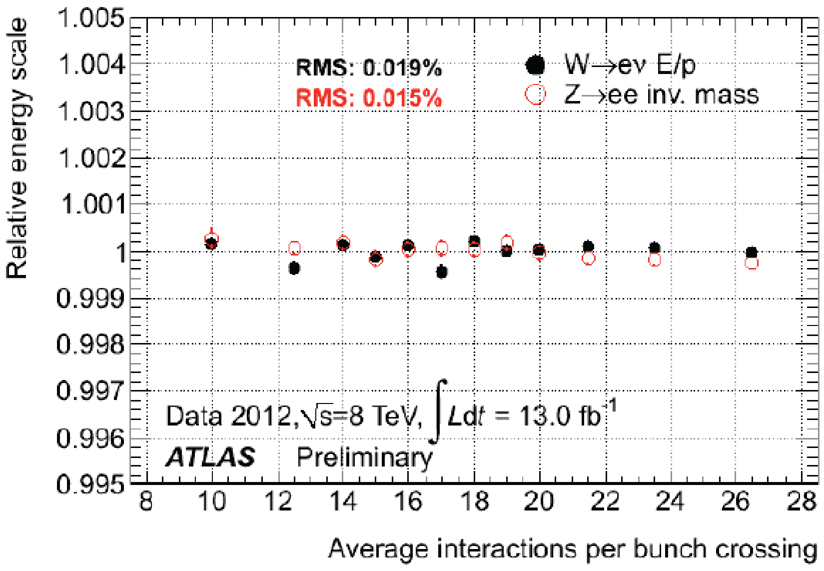
ATLAS

- In-situ energy calibration results and their stability checked with different methods (E/P with W→ eν, Z→ee, and J/ψ → ee)

- Uncertainty on the diphoton mass scale 0.6%, largely contributions
  - Material effects (separately for volumes for |η| < 1.8, and |η| > 1.8)
  - Uncertainty on the in-situ calibration method

Stability of EM calorimeter response vs time/pile-up better than 0.1%





Acceptance A_{4l}, Correction Factor C_{4l}, σ^{fid} and σ^{total}

Fiducial volume definition

ATLAS

$p_T^{\ell 1} > 20$ GeV; $p_T^{\ell 2} > 15$ GeV;
$p_T^{\ell 3} > 10$ GeV (if electron), > 8 GeV (if muon);
$p_T^{\ell 4} > 7$ GeV (if electron), > 4 GeV (if muon);
$|\eta^{\mu}| < 2.7$ for all muons; $|\eta^{e}| < 2.5$ for all electrons;
$\Delta R(\ell, \ell') > 0.1$ for all same flavor parings and > 0.2 for different flavor pairings;
$M_{\ell^+\ell^-} > 20$ GeV for at least one SFOS lepton pair;
$M_{\ell^+\ell^-} > 5$ GeV for all SFOS lepton pair;
$80 < M_{4\ell} < 100$ GeV.

Acceptance factors:

$C_{4l} = N_{4l}$ (pass full selection)/N_{4l} (in F. V.)

$A_{4l} = N_{4l}$ (in F.V.)/N_{4l} (in P.S.)

$\sigma^{fiducial}$ and σ^{total} :

$$\sigma^{fiducial}_{Z\to 4\ell} = \frac{N_{obs} - N_{bkg}}{\mathcal{L} C_{Z\to 4\ell}}$$

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

Signal Acceptance A_{4l} and C_{4l}

ATLAS

The acceptance and correction factors are determined by using Powheg MC signal samples

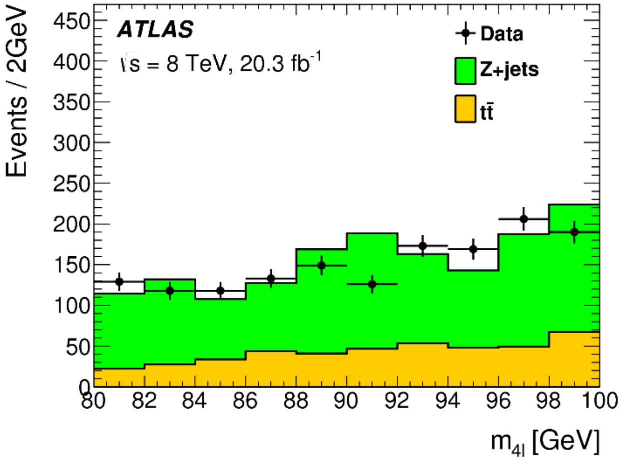
7 TeV	**eeee**	**eeμμ**	**μμee**	**μμμμ**
A_{4l}	7.47%	15.83%	8.79%	18.26%
C_{4l}	21.5%	49.0%	36.3%	59.2%
8 TeV				
A_{4l}	7.30%	14.8%	7.91%	17.79%
C_{4l}	36.06%	55.54%	46.24%	71.13%

- The uncertainties on A_{4l} are theoretical due to scales and PDF (1.3 - 1.7%)
- The uncertainties on C_{4l} are mainly experimental: lepton reconstruction and identification efficiencies and energy/momentum scales and resolution; **$\Delta C_{4l}/C_{4l}$: 2.7%, 3.7%, 6.2% and 9.4%** for 4m, eeμμ, μμee and 4e channel, respectively (at 8 TeV).
- Larger C_{4l} values at 8 TeV due to lepton recon. And ID improvements
- Currently statistical uncertainties are larger than the systematic uncertainties

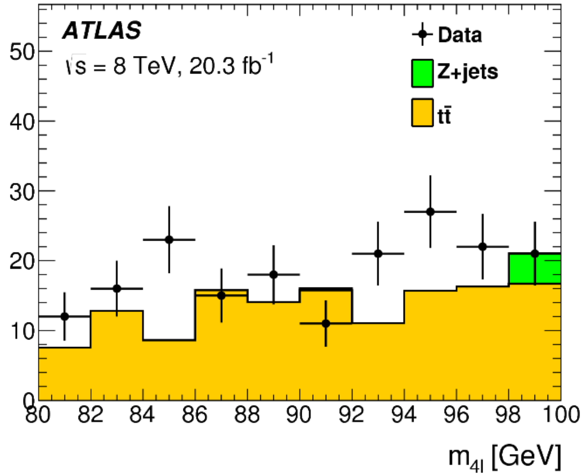
Data Driven Top and Z+jet Background Estimation

ATLAS

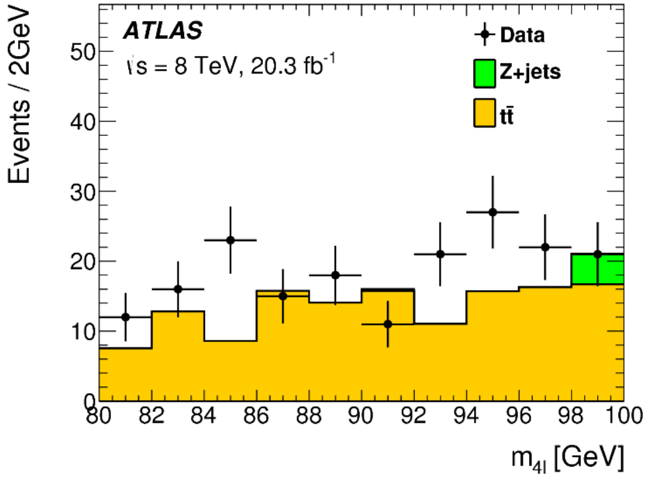
- Select the $\ell\ell + j_\ell j_\ell$ background control samples, where $j_\ell j_\ell$ are two lepton-like jets (selected with invert lepton selection cuts)



Two electron-like jets



One electron-like jet
One muon-like jet



Two muon-like jets

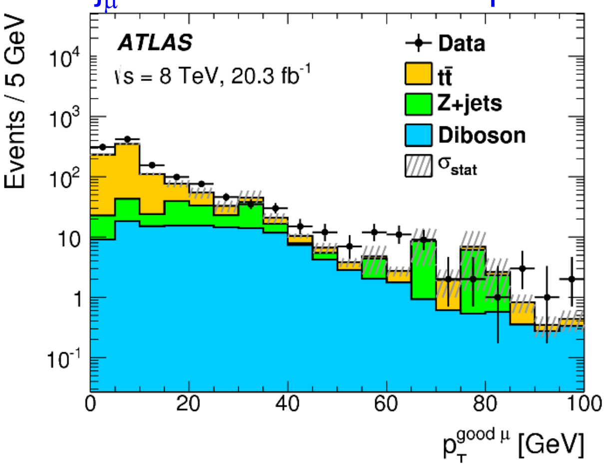
- MC background control samples indicate the jet compositions
- Each event in the control samples is scaled by a fake-factor product $f_1 x f_2$ to estimate the background in the signal region
- f is determined using jet enriched ttbar and Z+jet samples

Determination of Fake-Factor f

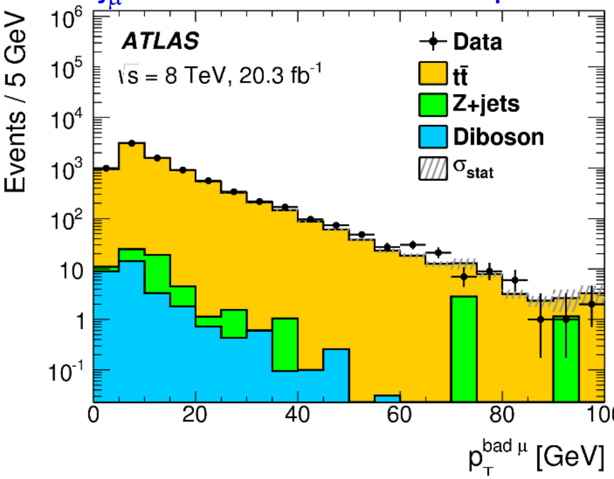
ATLAS

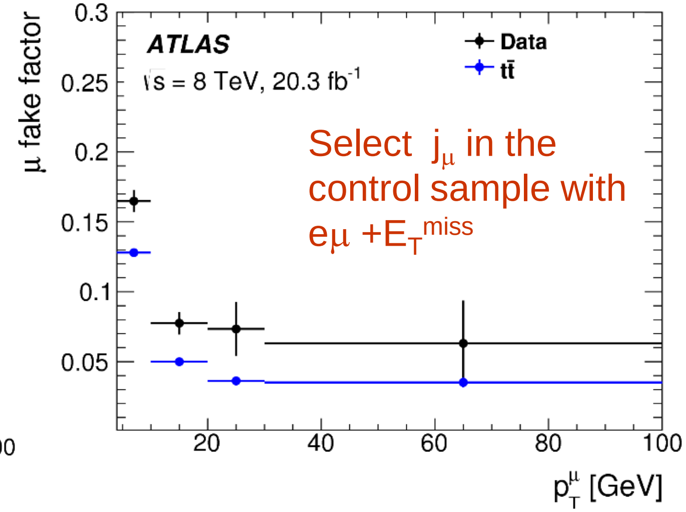
f = N_j (pass full lepton selection) / N_j (fail full lepton selection)

j_μ from ttbar control sample



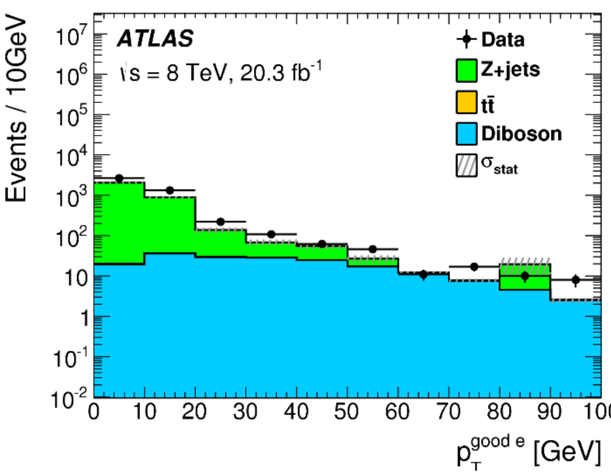
j_μ from ttbar control sample



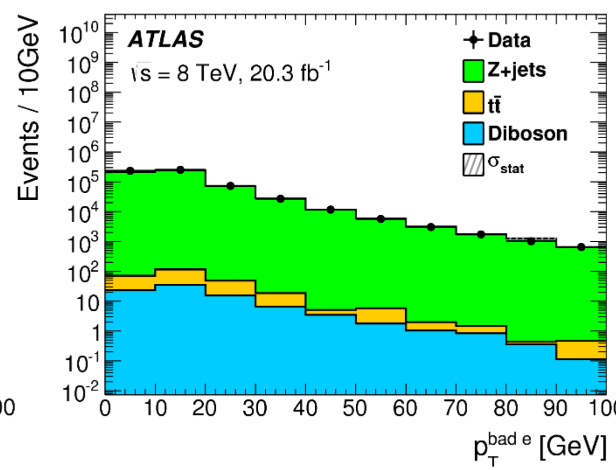


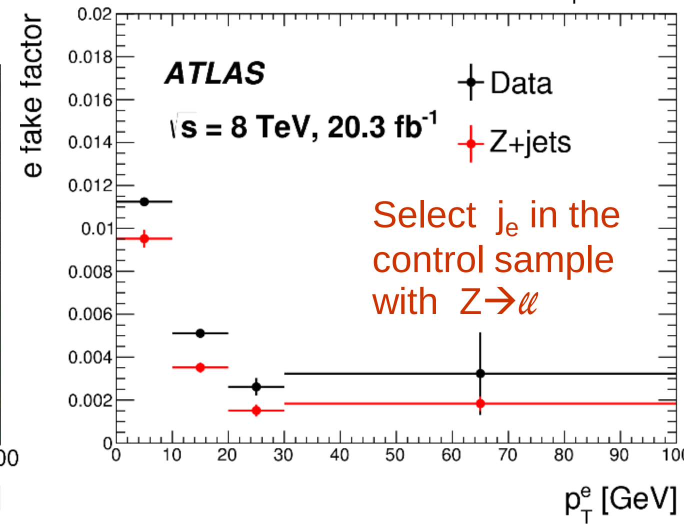
Select j_μ in the control sample with $e\mu + E_T^{miss}$

j_e from Z+jet control sample



j_e from Z+jet control sample





Select j_e in the control sample with $Z \rightarrow \ell\ell$

Summary of Estimated Background

ATLAS

Dibosons (including τ final states and gg production) estimated with MC, $t\bar{t}$ and $Z+X$ estimated with data and fake factor as before.

Year	Channel	diboson from MC	Z+jet and $t\bar{t}$ from data-driven	total
2011	$4e$	0.010 ± 0.002	0.11 ± 0.05	0.12 ± 0.04
	$2e2\mu$	0.024 ± 0.002	0.16 ± 0.09	0.18 ± 0.09
	$2\mu2e$	0.015 ± 0.002	0.06 ± 0.03	0.08 ± 0.04
	4μ	0.038 ± 0.003	0.05 ± 0.04	0.09 ± 0.04
2012	$4e$	0.064 ± 0.009	0.10 ± 0.01	0.16 ± 0.03
	$2e2\mu$	0.156 ± 0.019	0.20 ± 0.05	0.36 ± 0.05
	$2\mu2e$	0.132 ± 0.017	0.08 ± 0.02	0.21 ± 0.04
	4μ	0.301 ± 0.026	0.11 ± 0.05	0.41 ± 0.05

Remark:

- **Overall background contribution to selected 4l sample is < 1%**
- **Likelihood e-ID significantly reduce the fake electron rate in 2012 data analysis**

Selected Candidates Observation vs Predictions

ATLAS

	Channel	Data	Total expected	MC signal ($Z/ZZ \to 4\ell$)	Backgrounds
7 TeV	$eeee$	1	1.8 ± 0.3	1.7 ± 0.3	0.12 ± 0.04
	$ee\mu\mu$	7	8.0 ± 0.4	7.7 ± 0.4	0.18 ± 0.09
	$\mu\mu ee$	5	3.3 ± 0.3	3.2 ± 0.3	0.08 ± 0.04
	$\mu\mu\mu\mu$	8	11.3 ± 0.5	11.2 ± 0.3	0.09 ± 0.04
	Combined	21	24.4 ± 1.2	23.8 ± 1.2	0.47 ± 0.11
8 TeV	$eeee$	16	14.4 ± 1.2	14.3 ± 1.2	0.16 ± 0.03
	$ee\mu\mu$	48	43.2 ± 2.3	42.9 ± 2.2	0.36 ± 0.05
	$\mu\mu ee$	16	19.3 ± 1.2	19.1 ± 1.2	0.21 ± 0.04
	$\mu\mu\mu\mu$	71	68.8 ± 3.0	68.4 ± 2.9	0.41 ± 0.05
	Combined	151	145.7 ± 7.7	145 ± 7	1.14 ± 0.13

CMS (7 TeV)

Final state channels	4e	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \to Z\gamma^* \to 4\ell$)	0.07	0.25	0.14	0.46 ± 0.05
Other (reducible) backgrounds	0.01	0.01	0.05	0.07 ± 0.1
Expected signal ($pp \to Z \to 4\ell$)	3.8	13.6	12.0	29.4 ± 2.6
Total expected (simulation)	3.9	13.9	12.2	30.0 ± 2.6
Observed events	2	14	12	28
Yield from fit to the observed mass distribution	-	13.6 ± 3.8	11.5 ± 3.1	27.3 ± 5.4

CMS 4l Spectrum at 7 TeV

arXiv:1210.3844

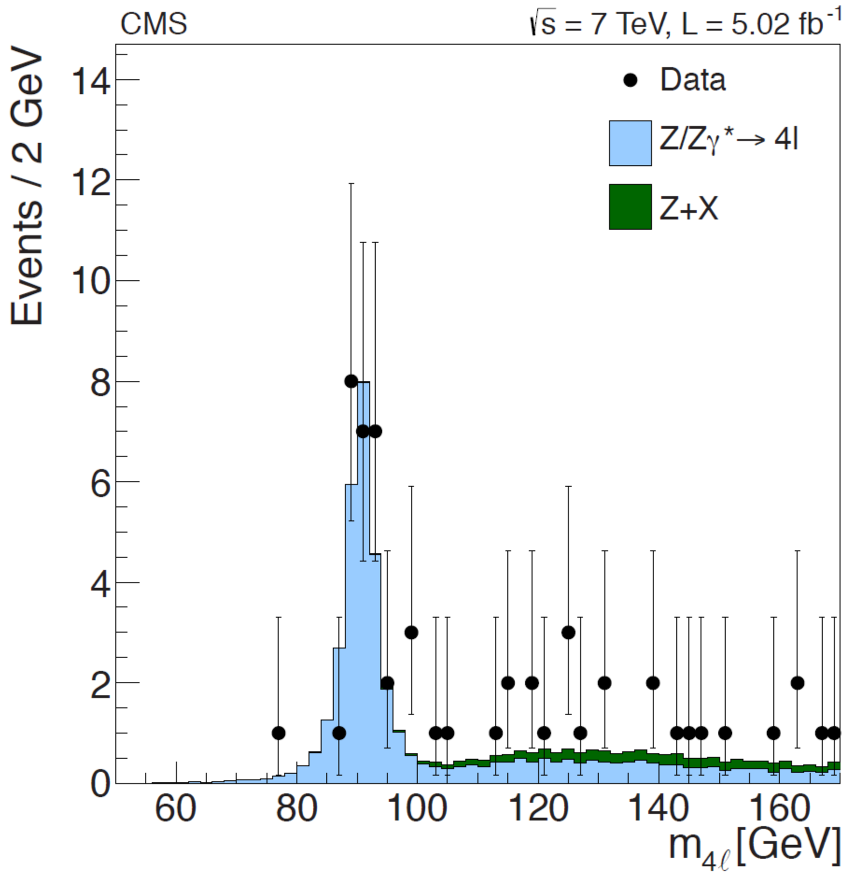


Figure 2: Four-lepton invariant mass distribution for events passing all selection requirements except that on $m_{4\ell}$. The data are shown by points. The filled histograms represent standard model expectations for pp $\rightarrow Z/Z\gamma^* \rightarrow 4\ell$ and for reducible backgrounds. The three final states, 4e, 4μ, and $2e2\mu$, are combined.

ATLAS 4l Mass Distributions

arXiv:1403.5657

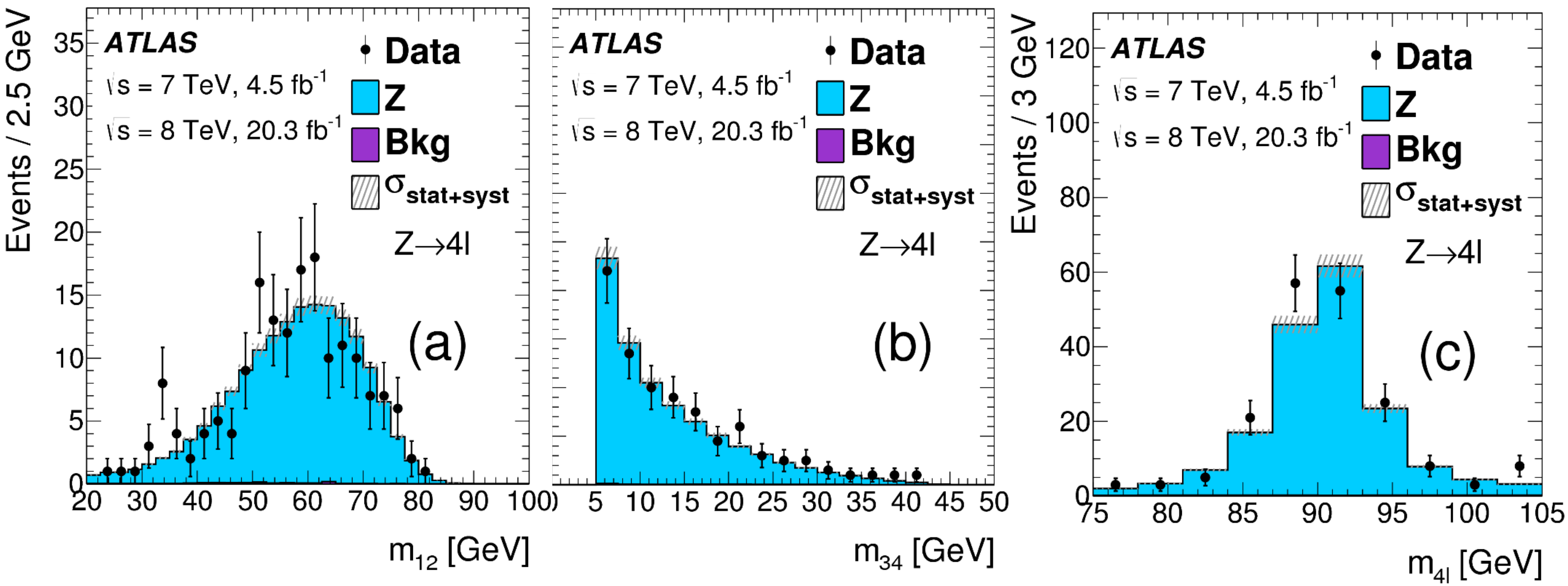
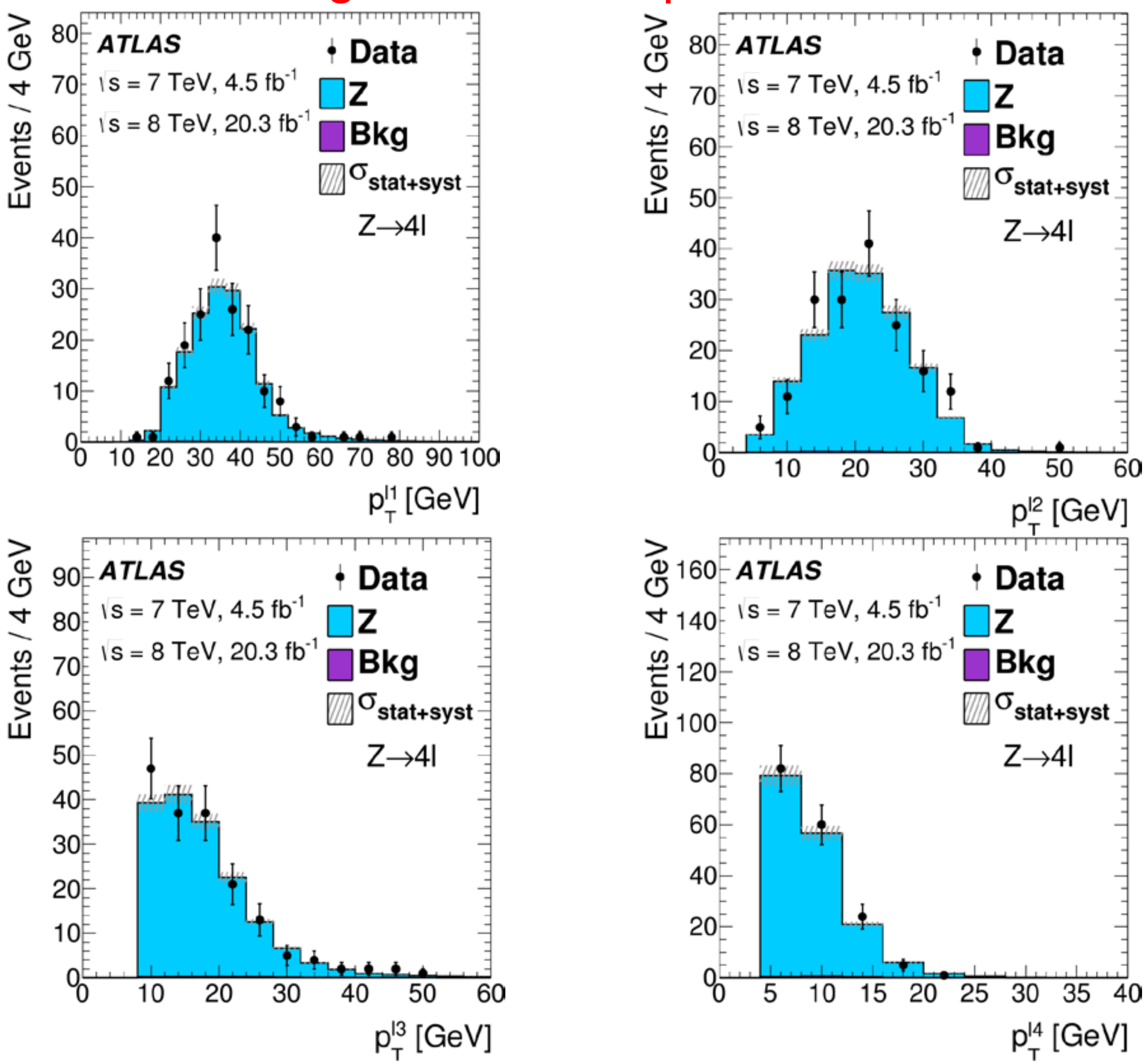


FIG. 2. Invariant mass distributions of (a) the leading lepton pair, m_{12}, (b) the subleading lepton pair, m_{34} , and (c) the four-lepton system, $m_{4\ell}$. The MC simulation expectation for a combination of all channels is compared to $\sqrt{s} = 7$ and 8 TeV data. All selections are applied except in (c) there is no $m_{4\ell}$ requirement. The background contributes $< 1\%$ of the total expected signal (invisible in the plots).

pT of Leptons

arXiv:1403.5657

Good data and MC agreement in lepton kinematic distributions



Measured Fiducial Cross Sections

$$\sigma^{fiducial}_{Z\to 4\ell} = \frac{N_{obs} - N_{bkg}}{\mathcal{L} C_{Z\to 4\ell}}$$

ATLAS

$\sqrt{s}$	Final state	$C_{4\ell}$	Measured σ^{Fid} fb
7 TeV	$eeee$	21.5%	$0.910^{+1.39}_{-0.72}$ (stat) $\pm$ 0.14 (syst) $\pm$ 0.02 (lumi) fb
	$\mu\mu\mu\mu$	59.2%	$2.970^{+1.18}_{-0.94}$ (stat) $\pm$ 0.07 (syst) $\pm$ 0.05 (lumi) fb
	$ee\mu\mu$	49.0%	$3.091^{+1.35}_{-1.05}$ (stat) $\pm$ 0.16 (syst) $\pm$ 0.05 (lumi) fb
	$\mu\mu ee$	36.3%	$3.015^{+1.57}_{-1.17}$ (stat) $\pm$ 0.30 (syst) $\pm$ 0.06 (lumi) fb
8 TeV	$eeee$	36.06%	$2.16^{+0.59}_{-0.50}$ (stat) $\pm$ 0.16 (syst) $\pm$ 0.06 (lumi) fb
	$\mu\mu\mu\mu$	71.13%	$4.89^{+0.66}_{-0.56}$ (stat) $\pm$ 0.13 (syst) $\pm$ 0.14 (lumi) fb
	$ee\mu\mu$	55.54%	$4.23^{+0.65}_{-0.59}$ (stat) $\pm$ 0.15 (syst) $\pm$ 0.12 (lumi) fb
	$\mu\mu ee$	46.24%	$1.68^{+0.46}_{-0.39}$ (stat) $\pm$ 0.07 (syst) $\pm$ 0.04 (lumi) fb

σ_{4l} measurement in final phase-space

ATLAS measurement in final phase space
80 < m_{4l} < 100 GeV and $m_{\ell^+\ell^-}$ > 5 GeV

$$\sigma^{total}_{Z\to4\ell} = \frac{\sigma^{fiducial}_{Z\to4\ell}}{A_{Z\to4\ell}}$$

❖The 4e and 4μ channels, and The 2e2μ and 2μ2e channels are combined with 2x2 covariance error matrices for σ measurement

❖The 4l σ^{total} = σ(4e+4μ) + σ(2e2μ), uncertainties are determined by 4x4 error matrices

$\sqrt{s}$	4ℓ state	$N^{obs}_{4\ell}$	$N^{exp}_{4\ell}$	$N^{bkg}_{4\ell}$	$C_{4\ell}$	$\sigma^{fid}_{Z4\ell}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	21.5%	$0.9^{+1.4}_{-0.7}\pm0.14\pm0.02$	7.5%	$4e, 4\mu$	$32\pm11\pm1.0\pm0.6$
	$\mu\mu+\mu\mu$	8	11.3 ± 0.5	0.08 ± 0.04	59.2%	$3.0^{+1.2}_{-0.9}\pm0.07\pm0.05$	18.3%		
	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	49.0%	$3.1^{+1.4}_{-1.1}\pm0.16\pm0.05$	15.8%	$2e2\mu$	$44\pm14\pm3.3\pm0.9$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	36.3%	$3.0^{+1.6}_{-1.2}\pm0.30\pm0.06$	8.8%		
	combined	21	24.2 ± 1.2	0.44 ± 0.14					$76\pm18\pm4\pm1.4$
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5}\pm0.20\pm0.06$	7.3%	$4e, 4\mu$	$56\pm6\pm1.8\pm1.6$
	$\mu\mu+\mu\mu$	71	68.8 ± 2.7	0.34 ± 0.05	71.1%	$4.9^{+0.7}_{-0.6}\pm0.13\pm0.14$	17.8%		
	$ee+\mu\mu$	48	43.2 ± 2.1	0.32 ± 0.05	55.5%	$4.2^{+0.7}_{-0.6}\pm0.16\pm0.12$	14.8%	$2e2\mu$	$52\pm7\pm2.4\pm1.5$
	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	46.2%	$1.7^{+0.5}_{-0.4}\pm0.10\pm0.04$	7.9%		
	combined	151	146 ± 7	1.0 ± 0.11					$107\pm9\pm4\pm3.0$

Measured σ^{total} vs Predicted σ^{total}

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

CMS	Phase-space cross section (m_{2l} > 4 GeV, 80 < m_{4l} < 100 GeV)
7 TeV measured	112^{+23}_{-20} (stat.) $^{+7}_{-5}$ (syst.) $^{+3}_{-2}$ (lumi.) fb
7 TeV NLO SM prediction	120 ± 2.1 fb

Determination of BR(Z→4l)

ATLAS

- ❑ Measure the Z→2μ cross section and take the known Br(Z→2μ) to get inclusive cross section of Z from pp collisions
- ❑ Cancels luminosity uncertainty and theoretical uncertainty of σ(pp→Z)
- ❑ Derive the BR（Z→4l) as below

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

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

- **Cancel luminosity uncertainty: 2.8% （8 TeV）**
- **Cancel NLO σ(Z) calculation uncertainties (Scales, PDF, NNLO correction): 4%**

Branching Fraction of $Z \rightarrow 4\ell$

Branching fraction results uses an error weighted combination of 7 and 8 TeV results. For phase space **$m_{2\ell}$ > 5 GeV**, 80 < $m_{4\ell}$ < 100 GeV

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

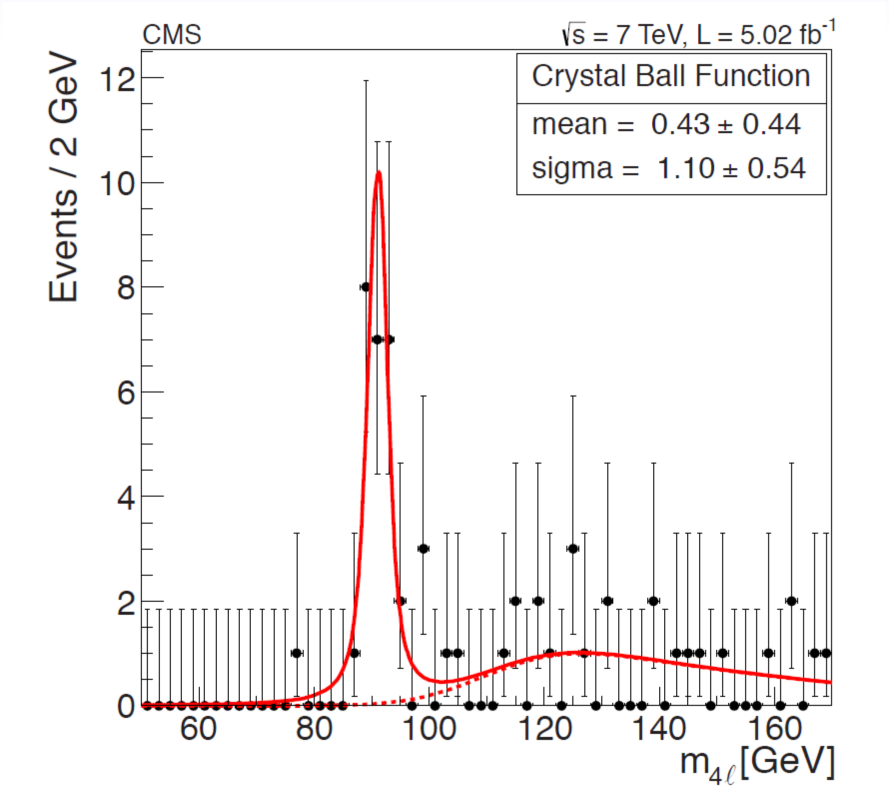
For phase space **$m_{2\ell}$ > 4 GeV**, 80 < $m_{4\ell}$ < 100 GeV

	BR (measured)	**BR (predicted)**
ATLAS	$(4.31 \pm 0.34 \pm 0.17)\text{x}10^{-6}$	$(4.50 \pm 0.01)\text{x}10^{-6}$
CMS	$(4.2^{+0.9}_{-0.8} \pm 0.2)\text{x}10^{-6}$	$4.45\ \text{x}10^{-6}$

Cross Check the Mass Scale for H→4l Mass Measurement

CMS PAS SMP-12-009

CMS
4l mass scale

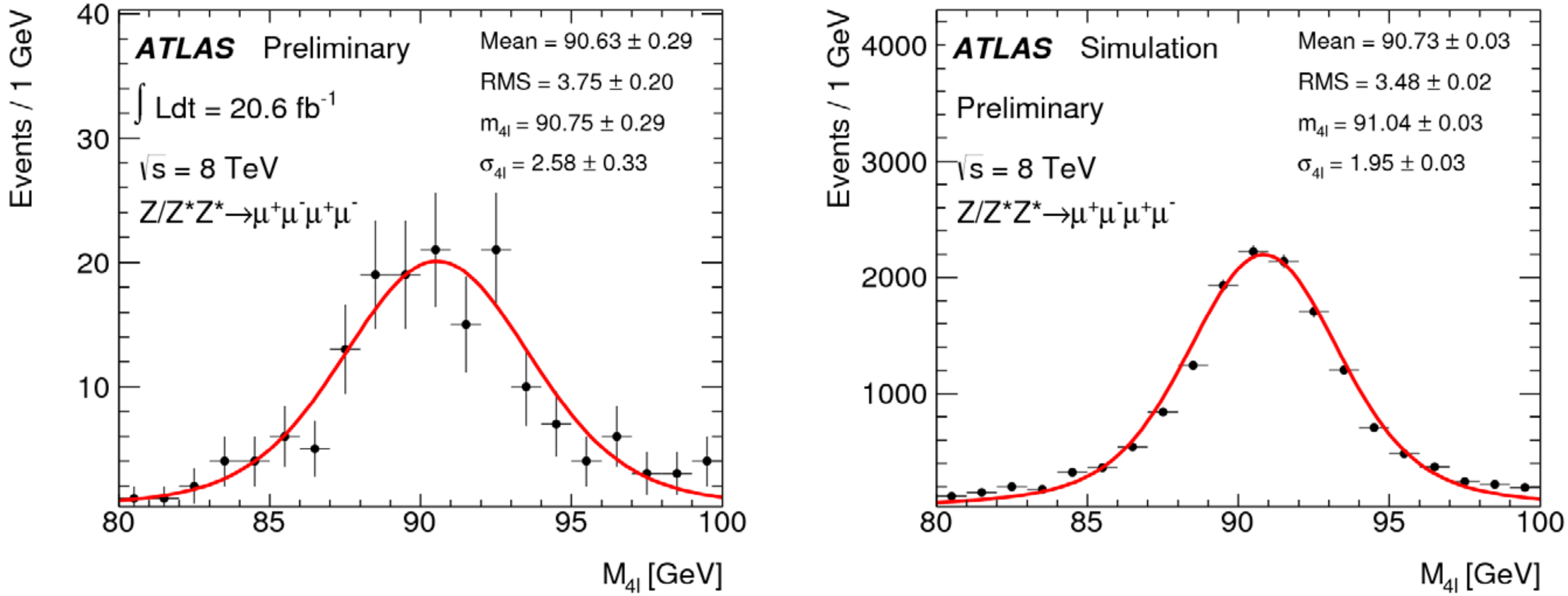


From the fit results, as shown in Fig. above, one can see that the offset of the peak is $0.4 \pm 0.4\,\text{GeV}$ (to the right) (the "mean" value of the Crystal Ball function represents an offset with respect to the fixed Breit–Wigner function peak position), or, in relative units, $0.4 \pm 0.4\%$. These numbers can be used to constrain the possible systematic uncertainty of the four-lepton mass scale. With the current data there is no evidence for a statistically significant bias.

ATLAS 4ℓ Mass Scale

ATLAS-CONF-2013-055

4l mass fitted with the convolution of a Breit-Wigner and a Gaussian distribution for four 4l channels shown good consistence with MC predictions. Example of 4μ mass fit for data and MC



Invariant mass distributions of 4μ, fitted with the convolution of a Breit-Wigner and a Gaussian distribution, for the reconstructed events within the Z-mass window of 80 to 100 GeV using (a) 4μ data, (b) simulated Z→4μ. All for 8 TeV datasets using relaxed dilepton mass requirement in event selection, m_{2l} > 1 GeV. The parameter m_{4l} is the fit mean and σ_{4l} is the standard deviation of the Gaussian component of the fit.

Summary

- The 4ℓ production at the Z resonance has been observed at the LHC by both ATLAS and CMS experiments
- The 4ℓ production cross sections are measured by ATLAS (at 7 and 8 TeV) and by CMS (at 7 TeV). Results are consistent with the SM predictions calculated to NLO (QCD) (Powheg/MCFM)
- The rare decay branching fraction of $Z \to 4\ell$ is determined from the cross section measurements by normalizing the 4ℓ events to the $Z \to \mu\mu$ events. Results are consistent within uncertainties from both experiments

	Phase Space	BR (measured)	BR (predicted)
ATLAS	$80 < m_{4l} < 100$ GeV and $m_{\ell+\ell-} > 5$ GeV	$(3.20 \pm 0.25 \pm 0.13) \times 10^{-6}$	$(3.33 \pm 0.01) \times 10^{-6}$
	$80 < m_{4l} < 100$ GeV and $m_{\ell+\ell-} > 4$ GeV	$(4.31 \pm 0.34 \pm 0.17) \times 10^{-6}$	$(4.50 \pm 0.01) \times 10^{-6}$
CMS	$80 < m_{4l} < 100$ GeV and $m_{\ell\ell} > 4$ GeV	$(4.2^{+0.9}_{-0.8} \pm 0.2) \times 10^{-6}$	4.45×10^{-6}

- The 4ℓ mass scales and resolutions between data and MC simulations are consistent for both ATLAS and CMS, which provide a good cross-check on the Higgs $\to 4\ell$ mass measurement.

Backup slides

ATLAS 4l Event Selection

Red indicates differences from $H \to ZZ^* \to 4\ell$

Electrons	GSF electrons selected with Loose++ from the H4l2011 menu (2011) or Loose from the Likelihood menu (2012) with $E_T > 7$ GeV and $\|\eta\| < 2.47$
Muons	Combined, segment-tagged, calo-tagged ($p_T > 15$ GeV), and stand-alone Staco muons with $p_T > 4$ GeV and $\|\eta\| < 2.7$
Event Selection	
Quadraplet selection	Two pairs of same-flavour opposite-charge leptons. The three leading leptons in the quadruplet have $p_T > 20, 15$, and 10 GeV. If the third lepton is a muon it may have $p_T > 8$ GeV Pick the pair that has M_{Z1} nearest the Z-mass, and then a second pair with M_{Z2} greatest.
Kinematic selection	Leading di-lepton pair must have inv. mass $M_{Z1} > 20$ GeV Sub-leading di-lepton pair must have inv. mass $M_{Z2} > 5$ GeV No same-flavor opposite-charge di-lepton giving $M_{\ell^+\ell^-} < 5$ GeV (J/ψ veto) $\Delta R(\ell, \ell') > 0.1$ (0.2) for all same-flavor (opposite-flavor) leptons in the quadruplet.
Isolation	Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T / p_T < 0.15$ Lepton calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T / E_T < 0.30$ except < 0.15 for stand-alone muons and in 2012 < 0.20 for electrons,
Impact parameter significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $d_0 / \sigma_{d_0} < 6.5$ For muons : $d_0 / \sigma_{d_0} < 3.5$
Four-body mass	$80 < m_{4\ell} < 100$ GeV