Diboson Measurements at ATLAS

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Outline

Introduction

Data and object reconstruction performance

Cross section measurements

aTGCs limit setting

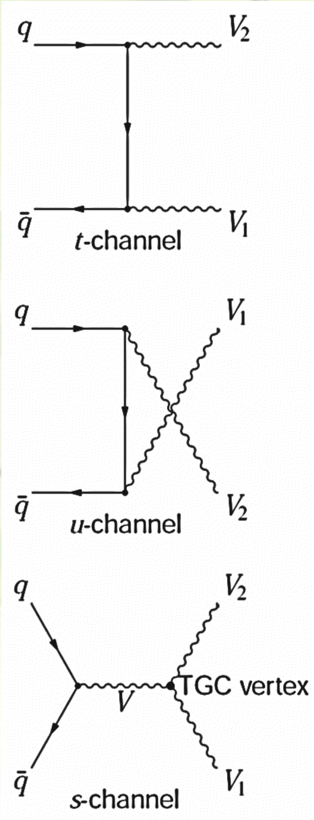
The precision

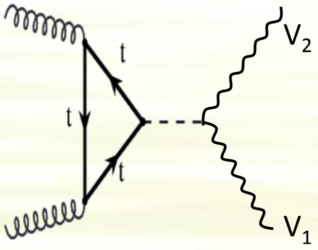
Summary

Introduction

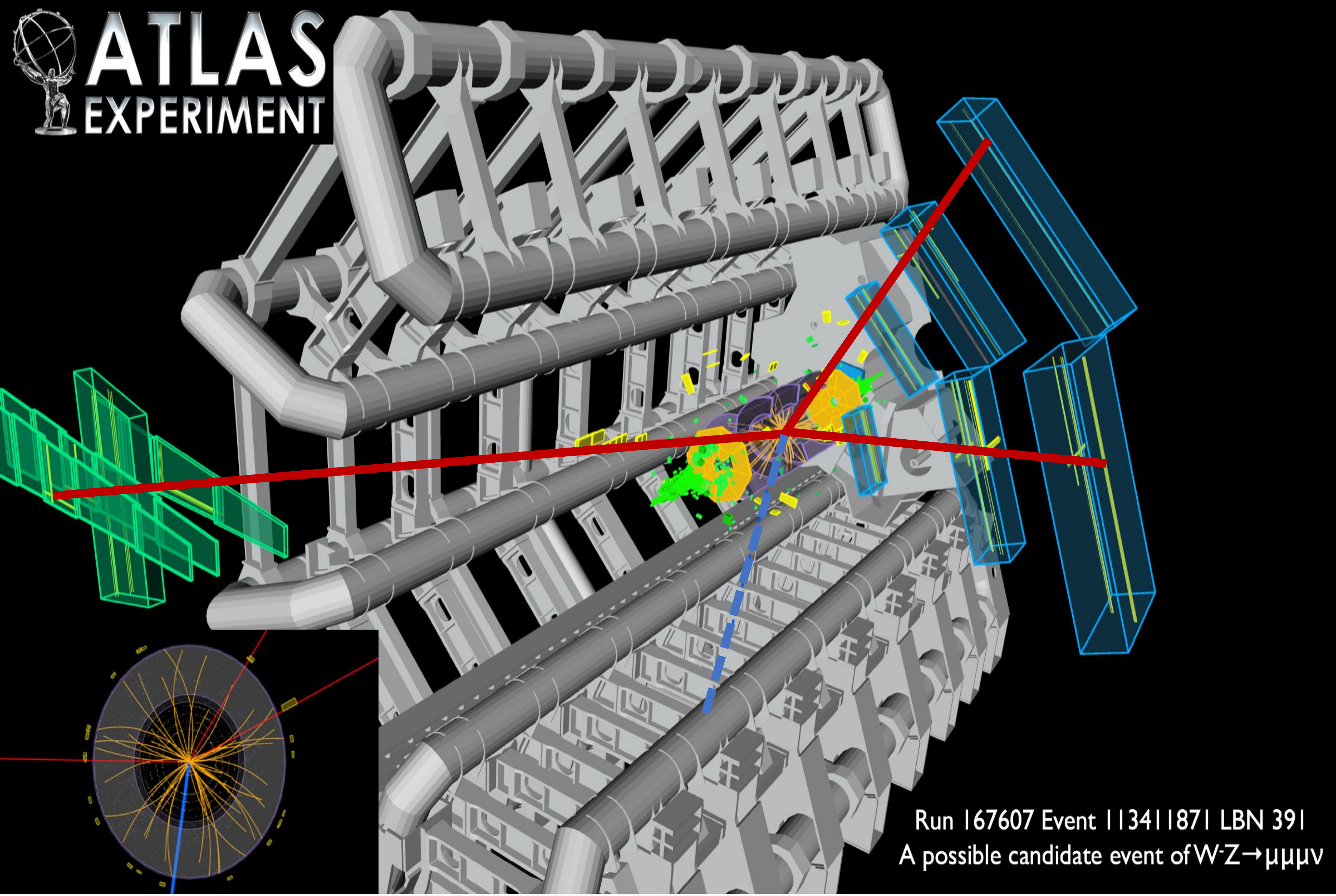
❑ Diboson production at ATLAS

- The considered processes in this talk
  - ❖ pp → Wγ, Zγ, WW, WZ, ZZ
- Large statistics and clean signature
  - ❖ Large production rate at high $\sqrt{s}$
  - ❖ Clean signature with leptontic decays of heavy bosons
  - ❖ High pt (isolated) leptons/photons, E_T^{miss} from boson decays
- Sensitive to theoretical calculations
  - ❖ Large NLO/LO QCD k-factor at high $\sqrt{s}$
  - ❖ Non-negligible NNLO QCD and NLO electroweak corrections
  - ❖ Gluon resummation effect on exclusive measurement (e.g. in jet bins)
- Sensitive to new physics
  - ❖ Search for new particles decaying to vector boson pairs (W', Z', gravitons, …)
  - ❖ Probe anomalous triple-gauge-boson-couplings (aTGCs)
  - ❖ Probe anomalies in vector boson scattering
- Irreducible background to Higgs measurement (Zγ, WW, ZZ)

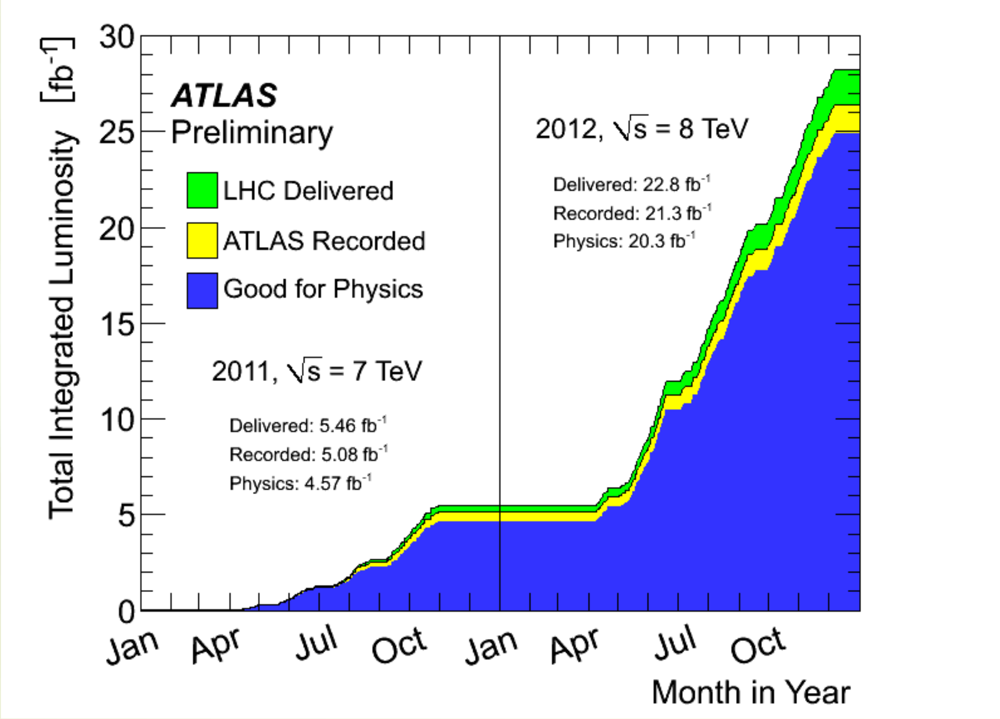




Event display of a WZ candidate event (WZ→μμμν)



Data collected at ATLAS



Integrated luminosity for physics analysis

4.6 fb^{-1} at 7 TeV

20.3 fb^{-1} at 8 TeV

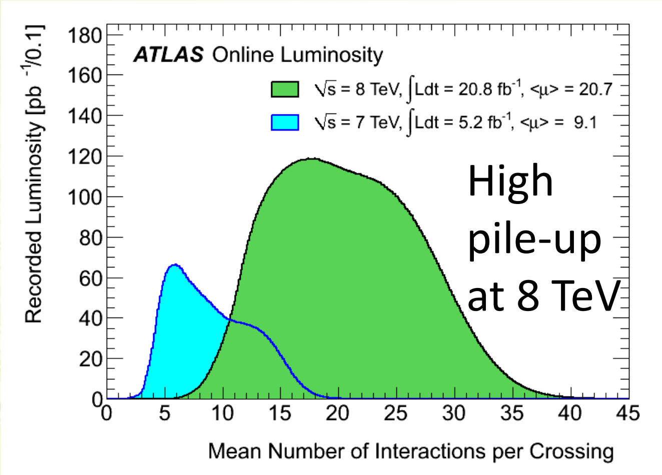
Data taking efficiency

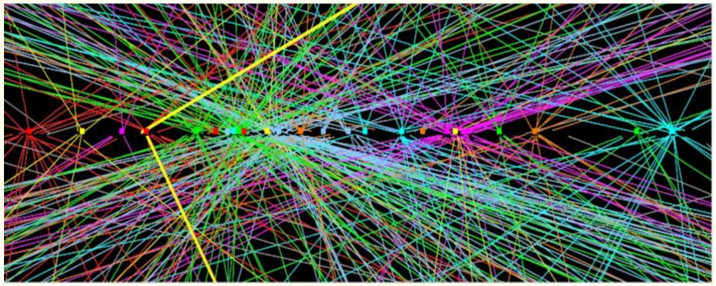
~ 94%

Detector operation fraction

> 97%

Very stable detector performance



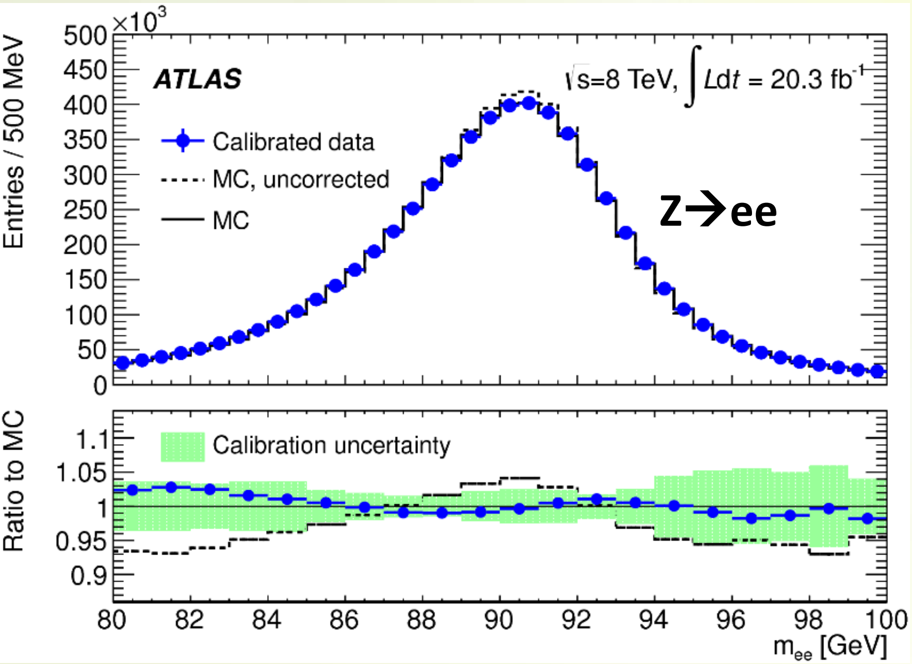


Demonstration of an event with O(25) vertices

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

Reconstruction Performance e, μ

arXiv:1407.5063



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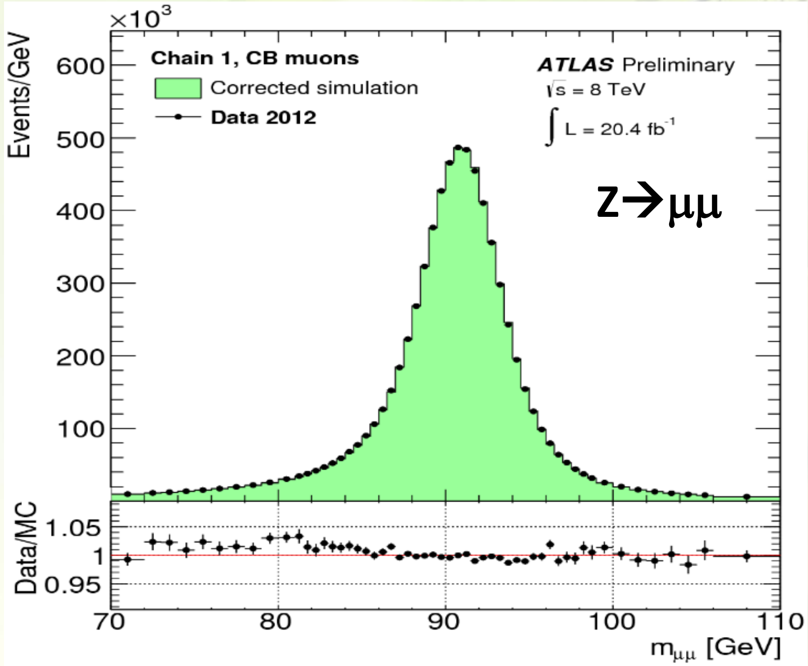
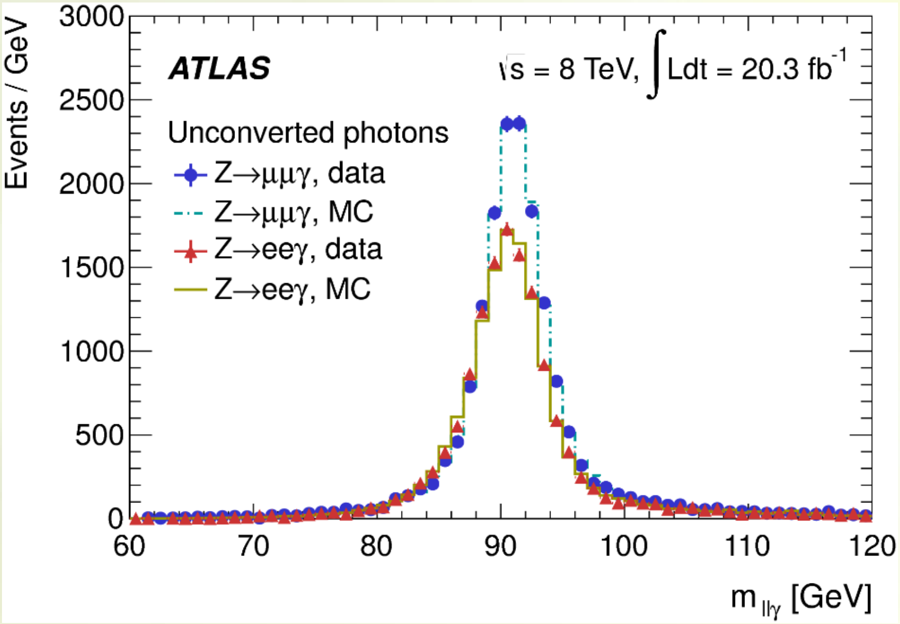


Precise calibration of energy scale and resolution for e/μ and Good modelling in MC

Reconstruction Performance γ, E_T^{miss}

arXiv:1407.5063



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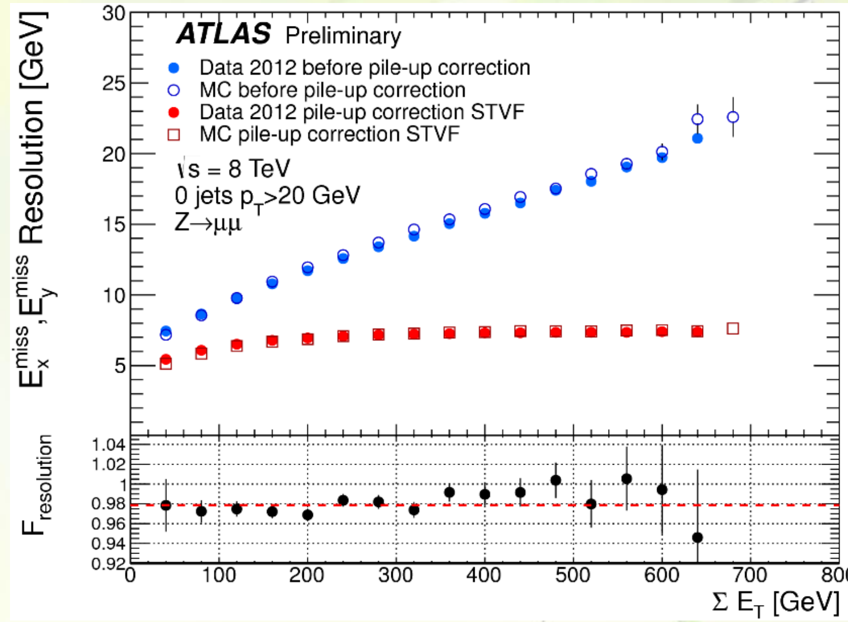
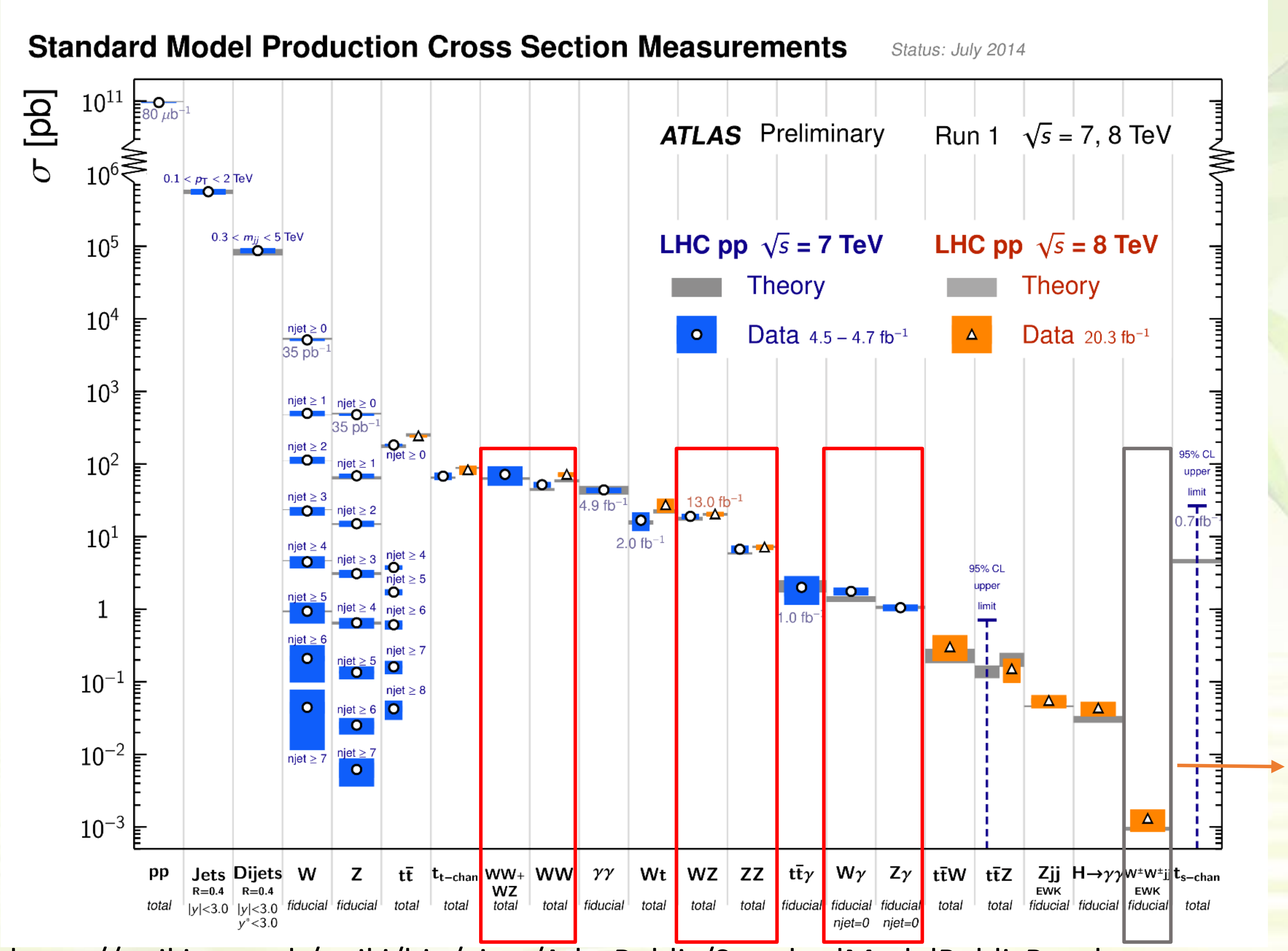


Precise energy scale / resolution determination for photon
Good modelling of pileup effects for E_T^{miss}

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

Cross section Overview

Measured cross sections comparable with SM predictions at NLO precision



Will be covered by L. Liu in the VBS talk

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

❑ Cross section measurements

– Definition of fiducial and total cross sections

- $\sigma_{fid} = \frac{N_{obs}-N_{bkg}}{C\cdot\mathcal{L}}$, $\sigma_{tot} = \frac{N_{obs}-N_{bkg}}{A\cdot C\cdot\mathcal{L}\cdot Br}$
- A: kinematic and geometric acceptance from total phase space to fiducial region
- C: efficiency correction in the fiducial region due to reconstruction effects

– Extraction/Combination of cross sections from decay channels

- Maximize extended Log-likelihood functions based Poisson statistics

$$-\ln L(\sigma,\{x_k\}) = \sum_{i=1} -\ln\left(\frac{e^{-(N_s^i(\sigma,\{x_k\})+N_b^i(\{x_k\}))} \times (N_s^i(\sigma,\{x_k\})+N_b^i(\{x_k\}))^{N_{\rm obs}^i}}{(N_{\rm obs}^i)!}\right) + \sum_{k=1}^{n}\frac{x_k^2}{2}$$

- Least Square with covariance matrices

– Comparison of data and prediction in fiducial region

- Unfold data distributions by correcting for detector effects
  - direct comparison with MC
- Methods being used: iterative Bayesian method, etc.

  Nucl. Instrum. Methods Phys. Res., Sect. A 362, 487 (1995)

Cross section Contents

❑ Included in this talk

– Brief summary of 7TeV results (4.6 fb^{-1})

❖ Wγ, Zγ, WW, WZ, ZZ

❖ WW+WZ*, WW→$e\nu\mu\nu$ (Simultaneous Fit)

– The 8TeV results (13-20fb^{-1})

❖ WZ, ZZ

❖ More focus on the recent results

- Z->4l (extension of 4l mass spectrum to Z pole)
- WW

* Final state with semi-leptonic decays of heavy vector bosons, it means fully leptonic decay if no "*"

Cross section

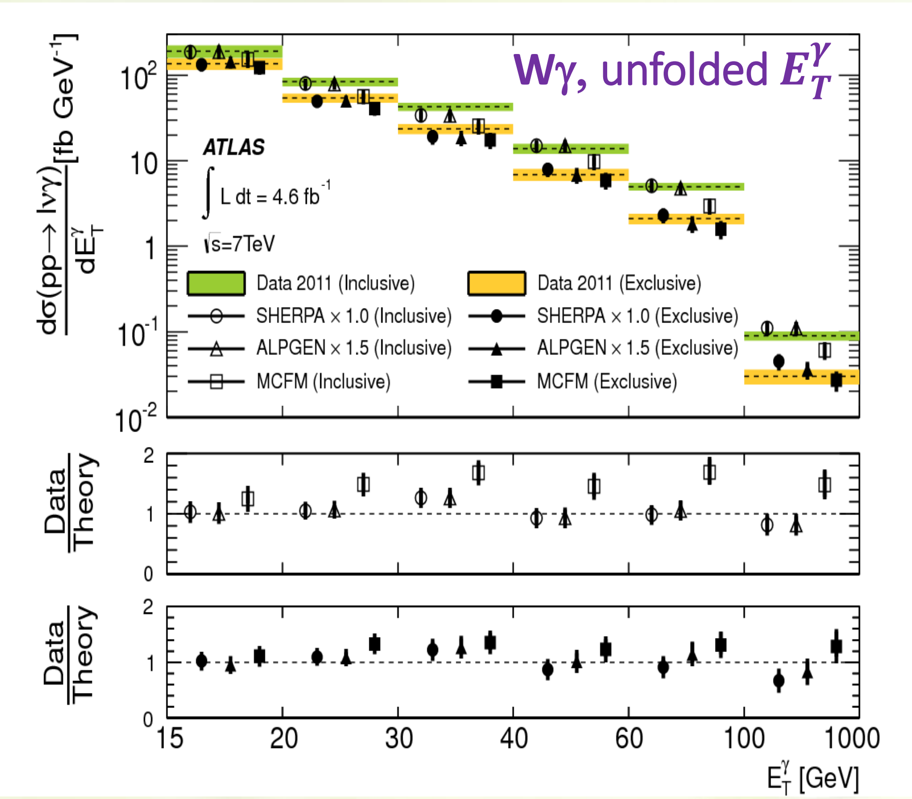
7TeV: Wγ, Zγ

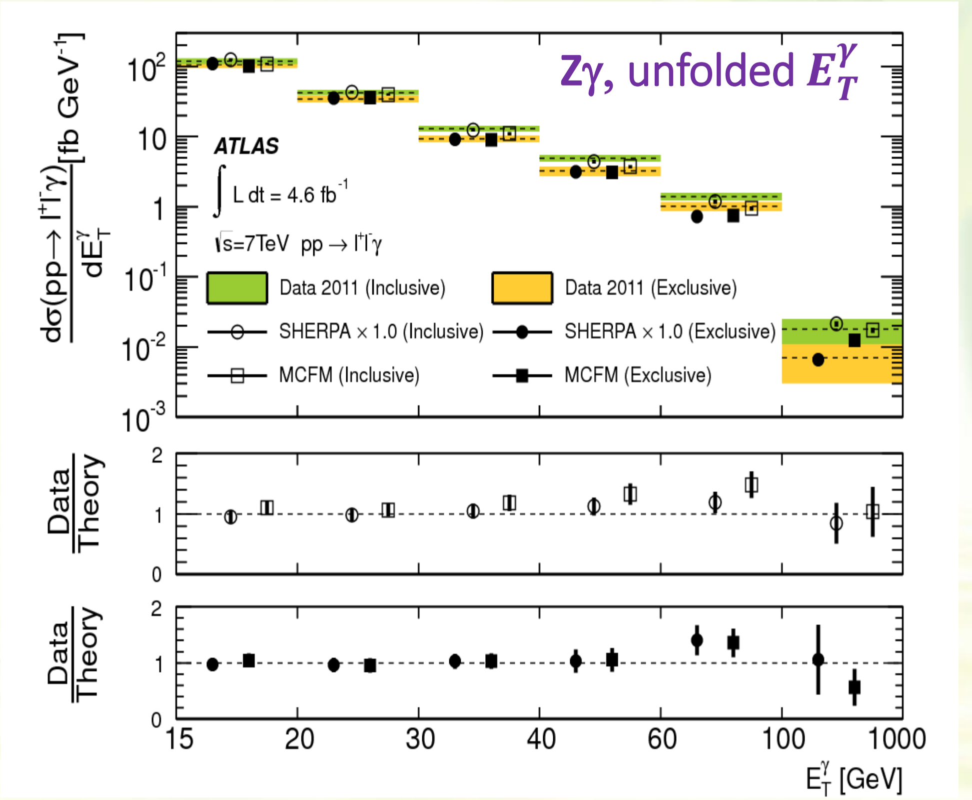
Final state: Wγ -> lν γ
+ signature: e/μ, E_T^{miss}, γ, $\Delta R(l,\gamma) > 0.7$
+ backgrounds: Z+jets, γ+jets, ttbar, τ decays
+ S/B ~ 1.5

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)





Cross section 7TeV: WW

Final state: WW->$l^+\nu l^-\nu$ (τ decays included)

+ e, μ, E_T^{miss}
+ backgrounds: Z+jets, Top, W+jets, other diboson
+ require 0 jet (25GeV)
+ cut on relative E_T^{miss}* and p_T^{ll} to reduce Z+jets
+ S/B ~ 2
+ about 4% stat. error and 8% syst. error

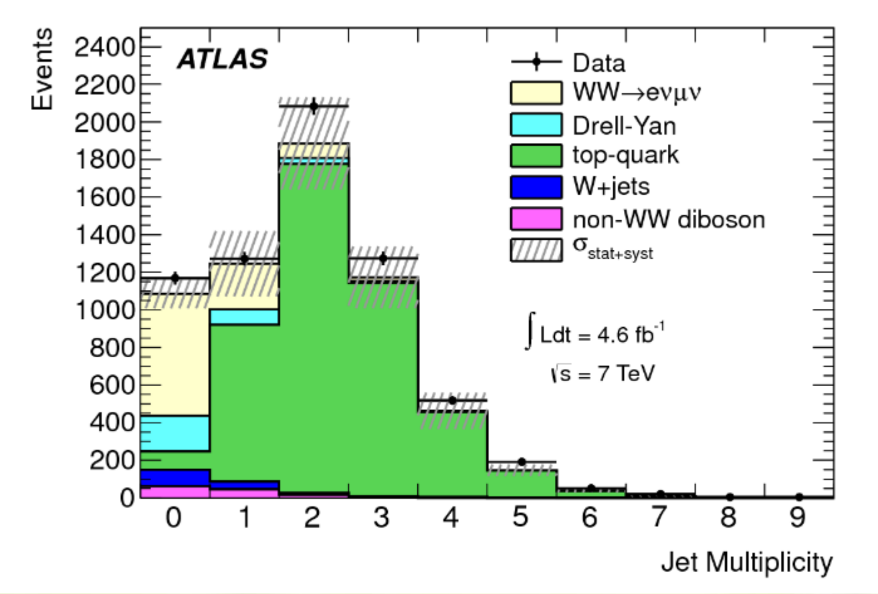
$$* \quad E_{\mathrm{T,\ Rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \times \sin(\Delta\phi) & \text{if } \Delta\phi < \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

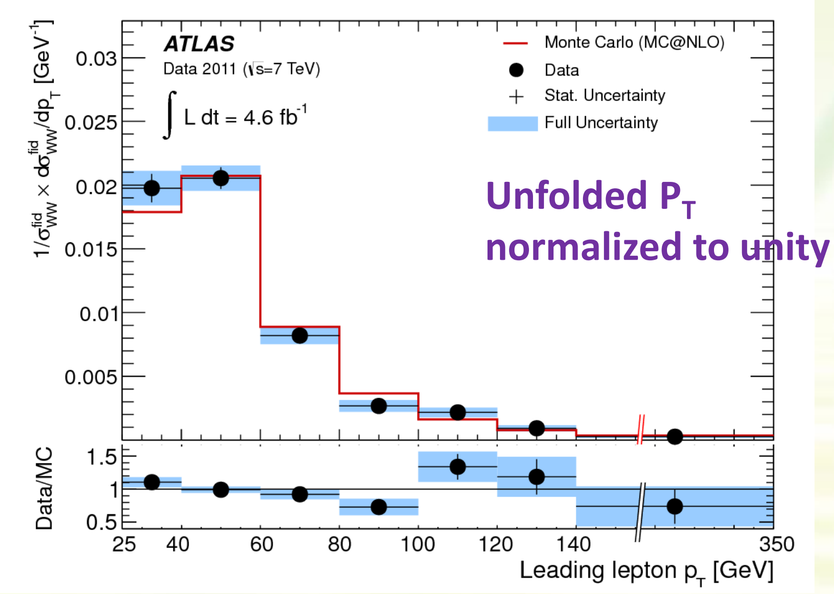
$\Delta\phi$ is the smallest azimuthal angle difference between lepton and E_T^{miss}

$\sigma_{tot}^{NLO} = 44.7 \pm 2.0$ pb

$\sigma_{tot}^{Measured} = 51.9 \pm 2.0\,(stat.) \pm 3.9(syst.) \pm 2.0(lumi.)$ pb

Phys. Rev. D 87, 112001 (2013)





Unfolded P_T normalized to unity

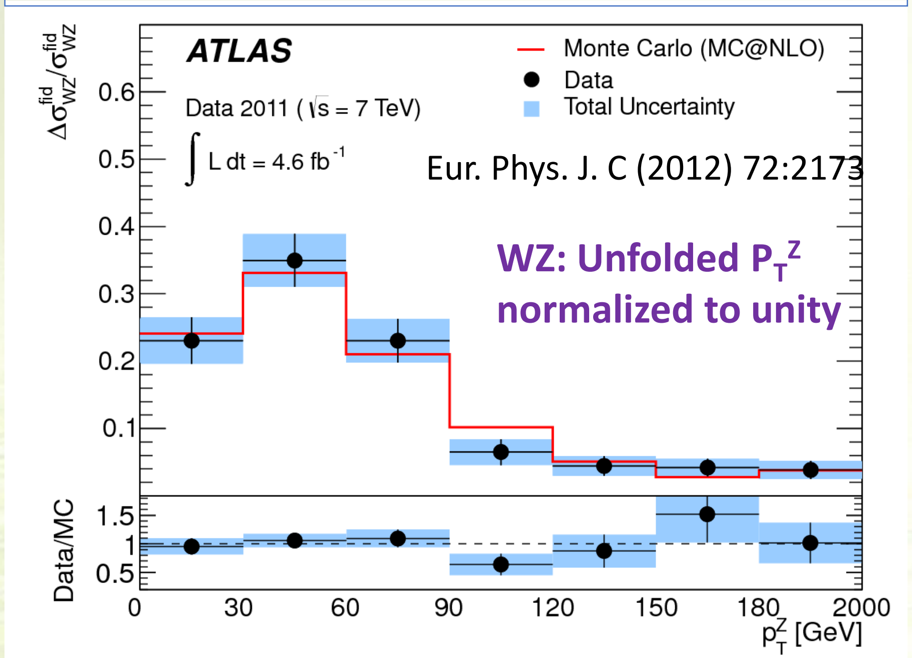
Cross section

7TeV: WZ, ZZ

Final state: WZ→ lν ll (τ excluded in fid. region)
+ three leptons (e/μ), E_T^{miss}
+ backgrounds: Z+jets, ZZ
+ S/B ~ 3.5
+ Inclusively ~7% stat. and ~5% syst. error

$\sigma_{tot}^{NLO} = 17.6 \pm 1.1$ pb, 66<m_{ll}<116 GeV

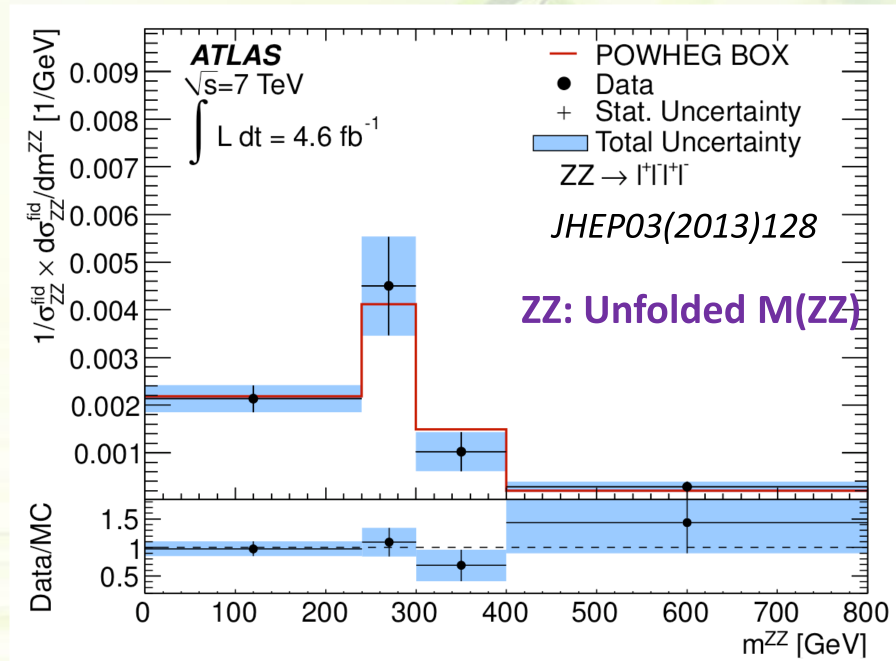
$\sigma_{tot}^{Measured} = 19.0 \pm 1.4(stat.) \pm 0.9(syst.) \pm 0.4(lumi.)$ pb



Final state: ZZ(*)→ 4l or 2l2ν (τ excluded in fid.)
+ four leptons (e/μ) or two leptons + E_T^{miss}
+ backgrounds: Z+jets, Top, WZ, WW
+ S/B > 5 (4l), ~1 (2l2ν)
+ Inclusively ~10% stat. and ~6% syst. error

$\sigma_{tot}^{NLO} = 5.9 \pm 0.2$ pb

$\sigma_{tot}^{Measured} = 6.7 \pm 0.7(stat.) \pm 0.4(syst.) \pm 0.3(lumi.)$ pb

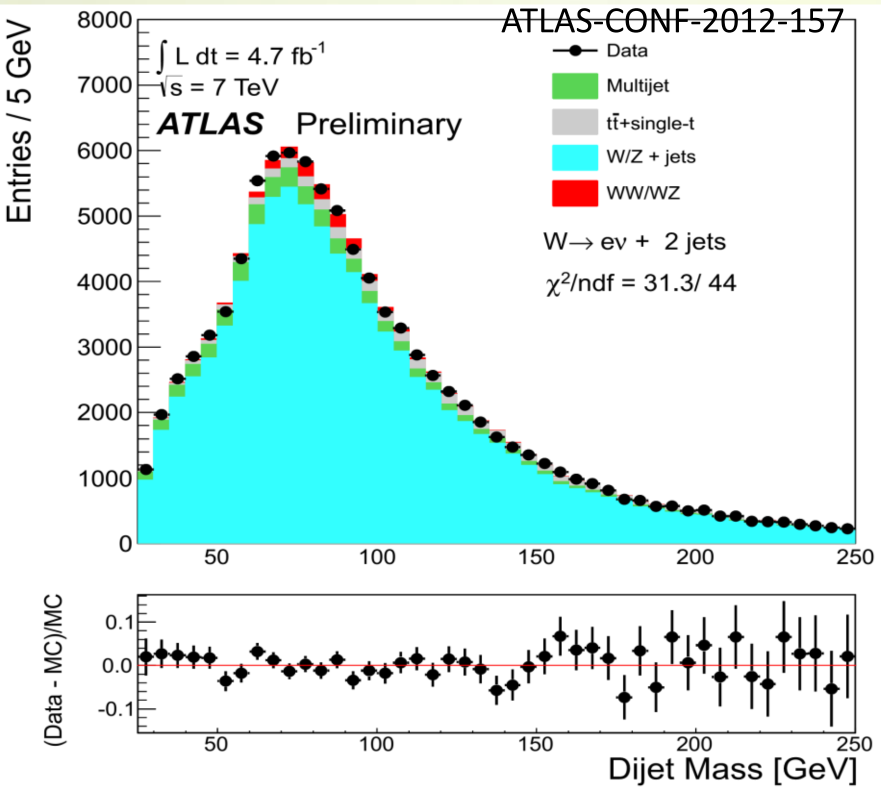


Cross section

7TeV: others

Final state: WW+WZ → lν qq

+ e/μ, E_T^{miss}, two jets



Template fit used to extract cross section

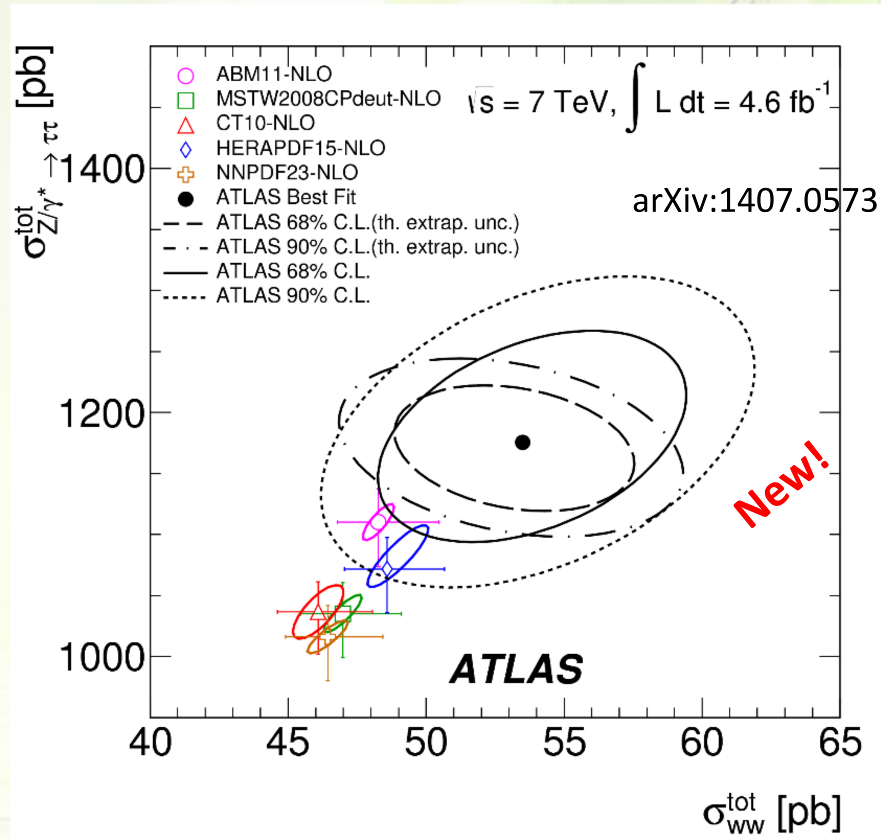
Measured σ Consistent with SM prediction

~ 30% systematic uncertainty

Will be discussed in details by B. Lindquist

Final state: WW → eνμν

+ Likelihood fit to simultaneously determine the cross-sections for Z→ττ, ttbar and WW processes



Consistent with dedicated WW analysis

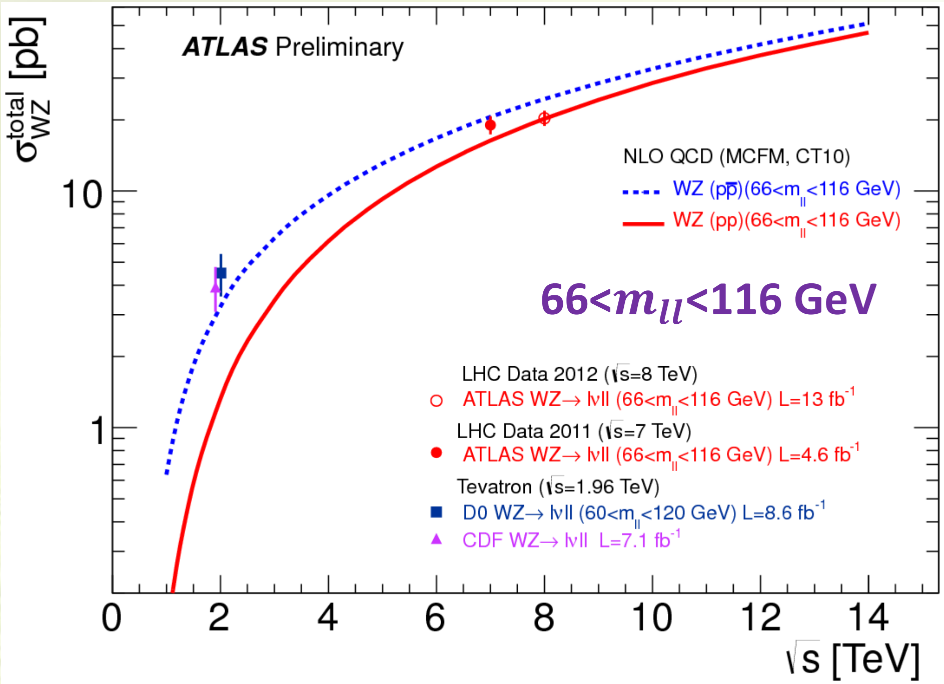
~15% systematic uncertainty

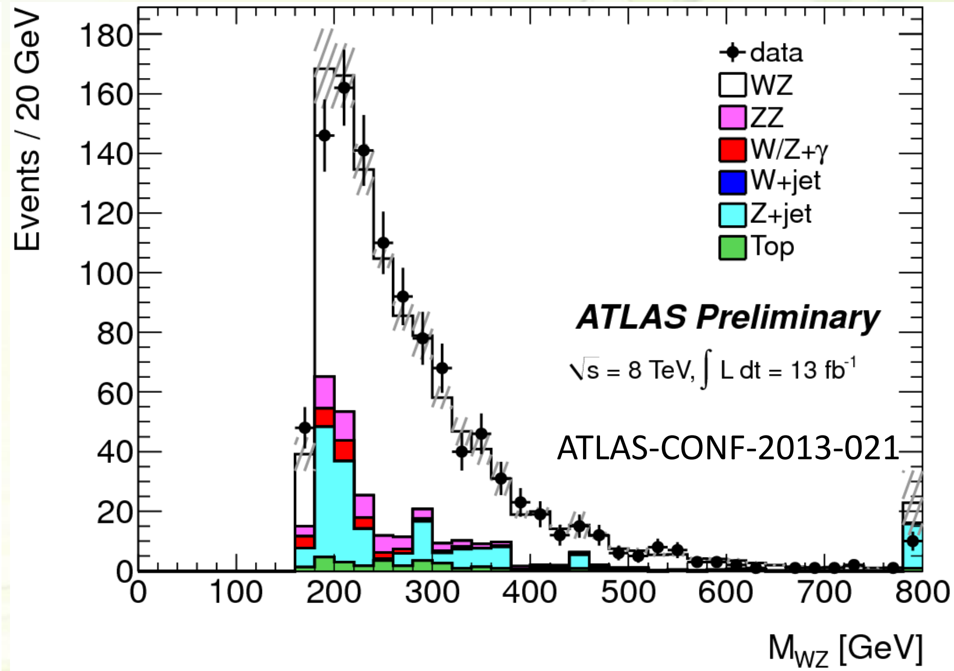
Cross section 8TeV: WZ

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

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

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.)





Consistent with NLO prediction

Cross section 8TeV: ZZ

Event selection (ZZ->4l):

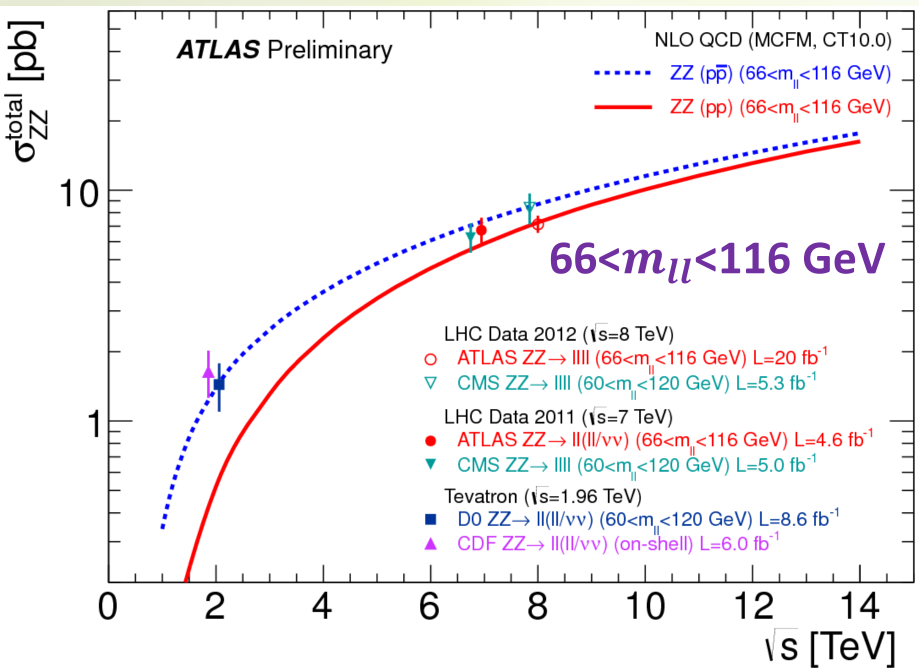
- Four isolated leptons (p_T>7GeV), at least one lepton with p_T>25GeV

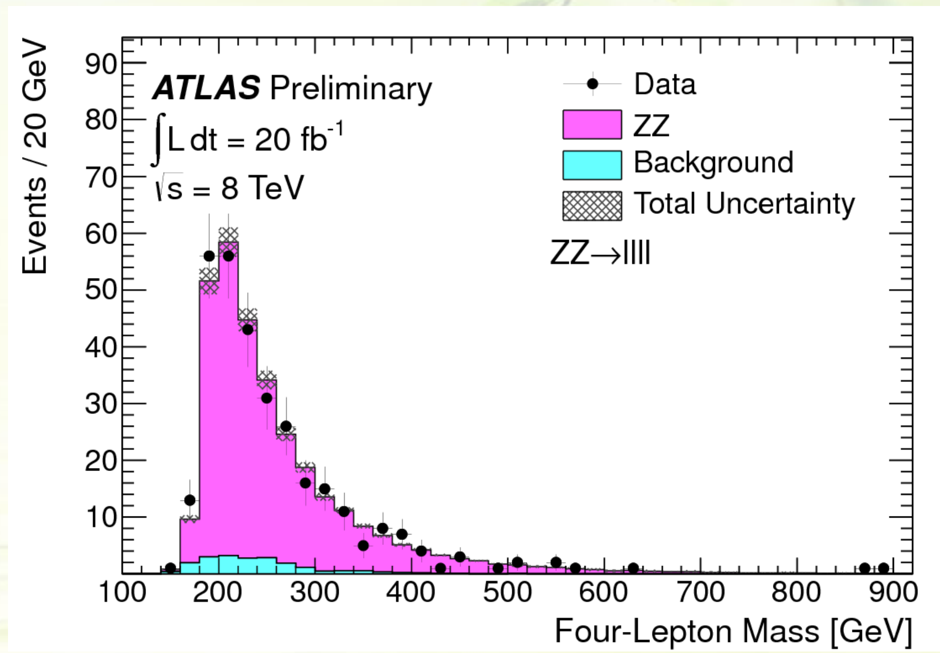
Backgrounds and Uncertainties:

- 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

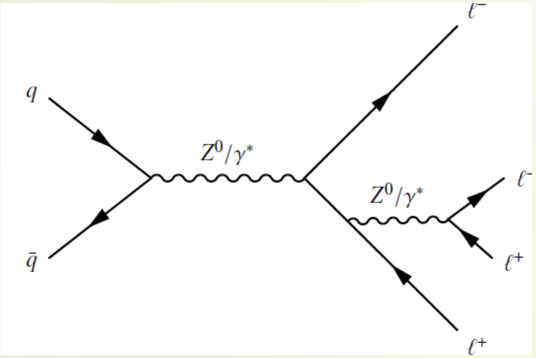
ATLAS-CONF-2013-020



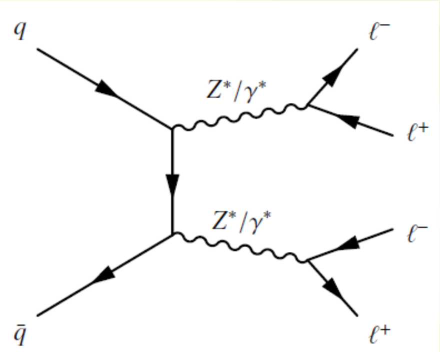


8TeV: Z→4l New!

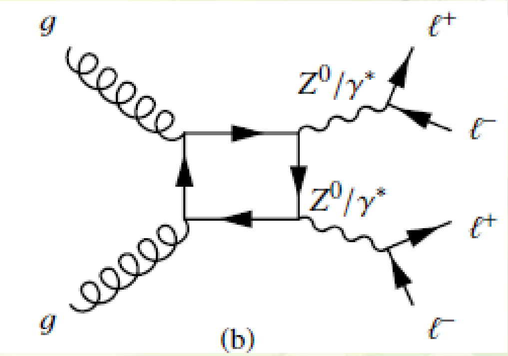
❑ 4*l* production at Z resonance (Z→4*l*) at the LHC



S channel, ~96%*



T channel, <4%



gg fusion, ~0.1%

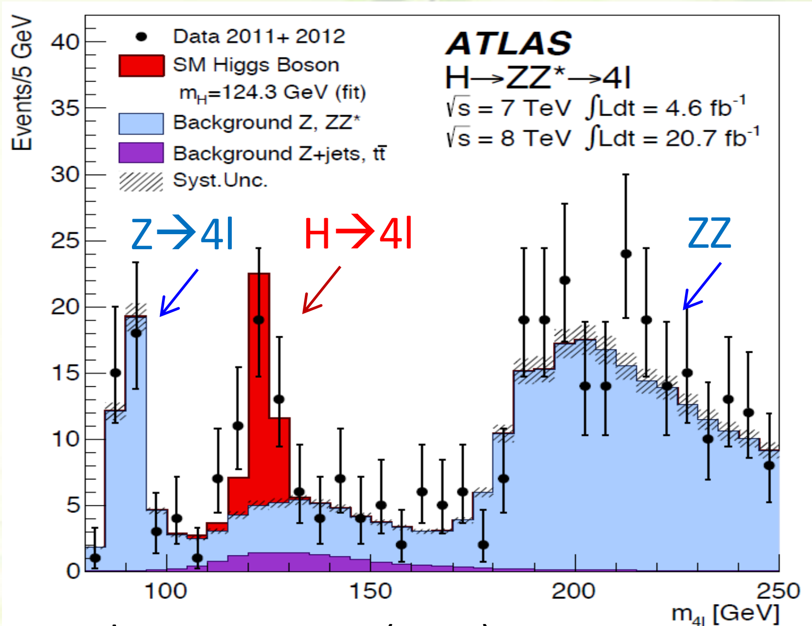
*Phase space: $m_{4\ell} \in [80, 100]$ GeV, $m_{2\ell}$>5 GeV

❑ Physics motivation

- Building block of complete 4l mass spectrum
- Test of detector response at low E,p

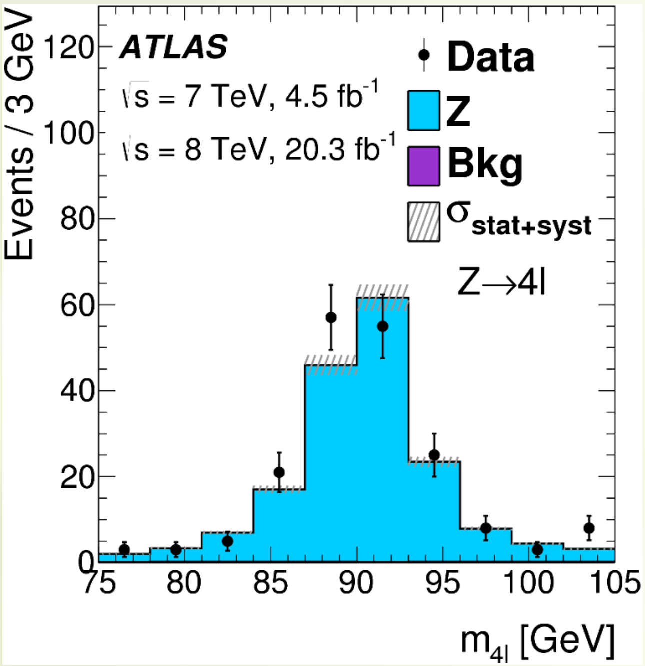
❑ Data and selection

- Both 7 and 8 TeV data are used
- At least four leptons
  - ❖ e: p_T > 20, 15, 10, 7 GeV
  - ❖ μ: p_T > 20, 15, 8, 4 GeV
- m_{2l}^{lead}>20, $m_{2l}^{sub-lead}$>5 GeV
- 80 GeV < m_{4l} < 100 GeV



Phys. Lett. B 726 (2013) 88

Cross section 8TeV: Z→4l **New!**



Phys. Rev. Lett. 112, 231806 (2014)

	$\sigma_{tot}^{Measured}$ **(fb) ***	σ_{tot}^{NLO} **(fb)**
$\sqrt{s}$= 7 TeV	76±18±4±1.4	90.0±2.1
$\sqrt{s}$= 8 TeV	107±9±4±3.0	104.8±2.5

* in phase space, uncertainties: ±stats. ±syst. ± lumi.

Consistent with SM prediction

S/B = 100 / 1 !

In total observed 172 candidate events, 170 expected

~10% statistical uncertainty and 5% systematics

- Extraction of the Z→4l branching fraction

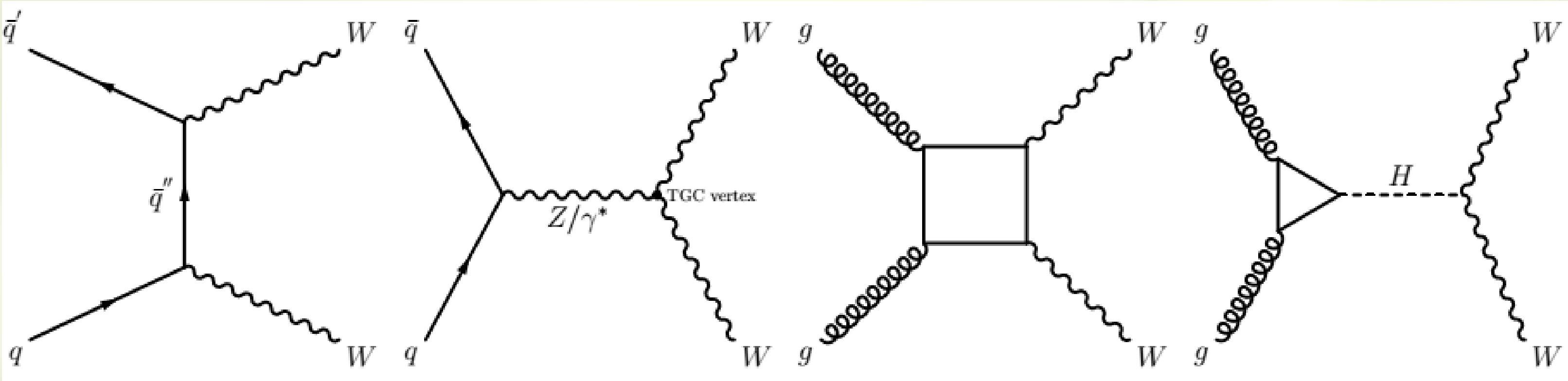
$$\frac{\Gamma_{Z\to 4\ell}}{\Gamma_Z} = \left(\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_Z}\right) \frac{\left(N_{4\ell}^{\text{obs}} - N_{4\ell}^{\text{bkg}}\right)(1 - f_{\text{nr}})\, C_{2\mu} \cdot A_{2\mu}}{\left(N_{2\mu}^{\text{obs}} - N_{2\mu}^{\text{bkg}}\right) C_{4\ell} \cdot A_{4\ell}}$$

  - Reduced theory uncert. with $Z \to \mu\mu$ events
  - $Br_{Z\to\mu\mu}$ from PDG, $1 - f_{nr}$: subtract non-resonance contribution

	Combined	$(3.20 \pm 0.25\ (\text{stat}) \pm 0.12\ (\text{syst})) \times 10^{-6}$
Expected		$(3.33 \pm 0.01) \times 10^{-6}$

Cross section 8TeV: WW New!

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



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

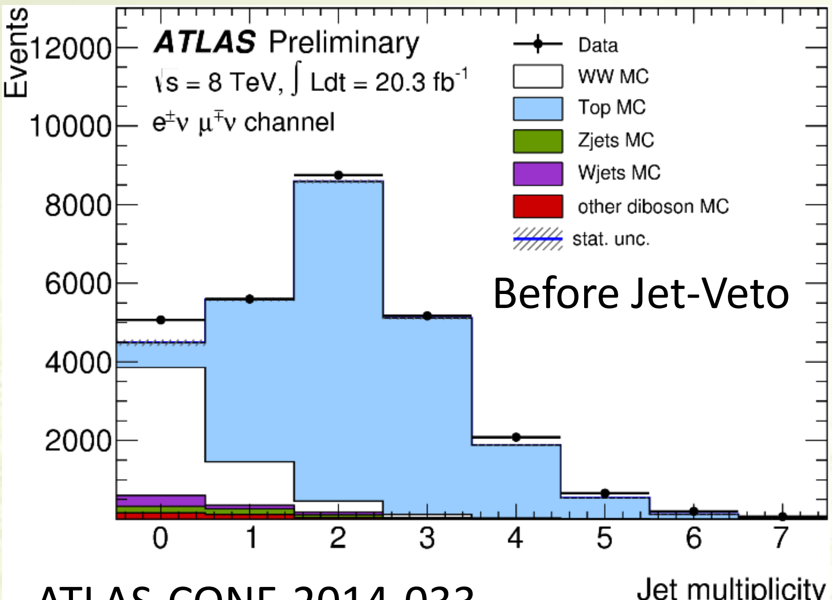
	$\int L$ (fb^{-1})	$\sigma(pp \to WW) \times B$ (pb)	SM NLO*
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat.) \pm 3.9(syst.) \pm 2.0$(lumi.)	44.7±2.0
CMS 7TeV	4.9	$52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2$(lumi.)	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1$(lumi.)	54.6±2.5

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

* Higgs contribution not included

Cross section 8TeV: WW New!

- **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



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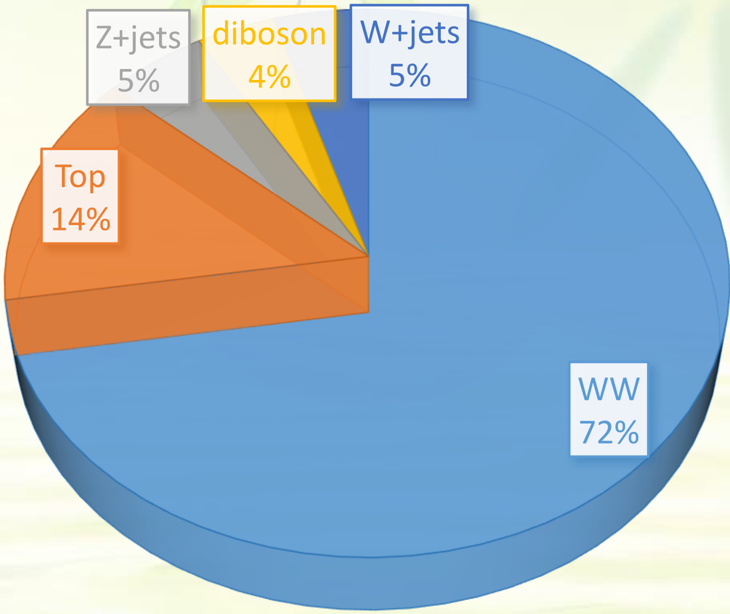
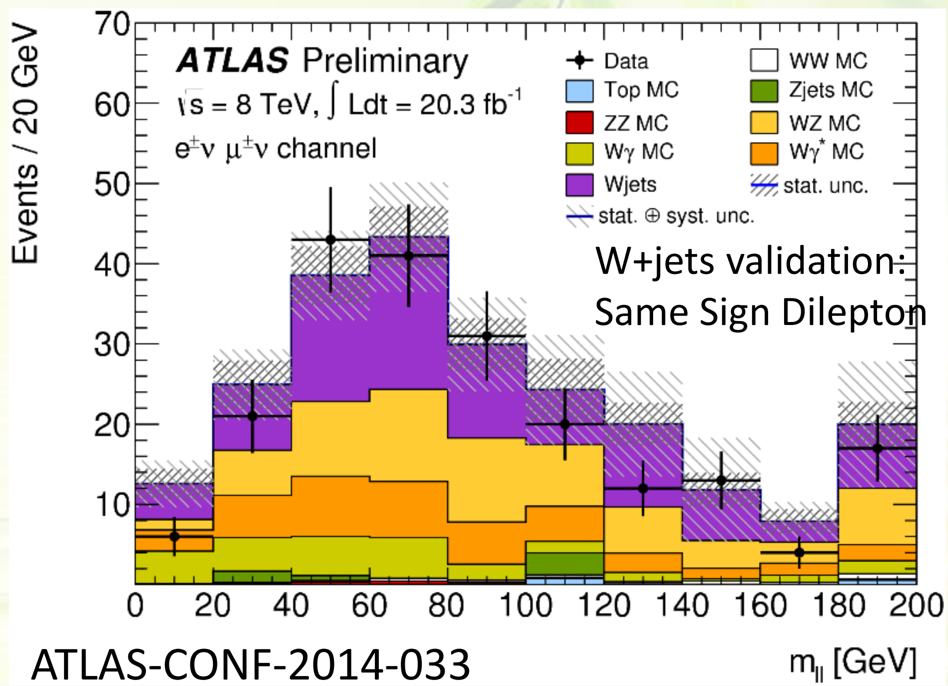
At final selection
S/B~2.5
Data ~ 6600



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



ATLAS-CONF-2014-033

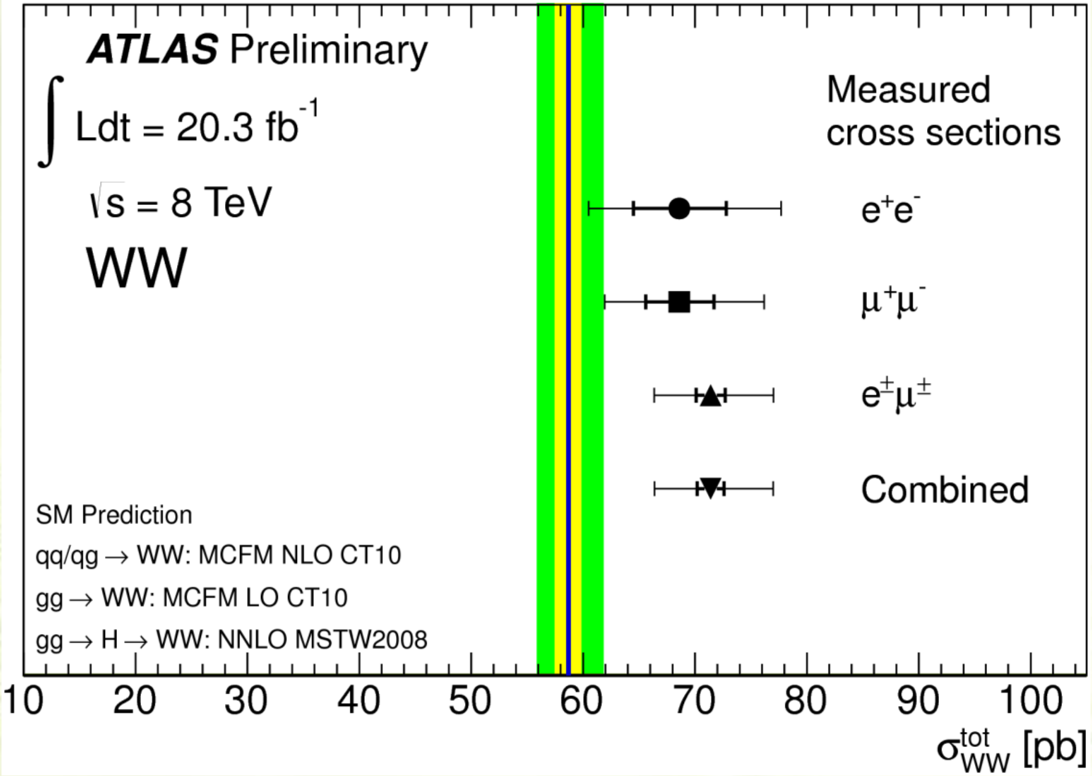
Cross section 8TeV: WW New!

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 = $\frac{\varepsilon_Z^{data}}{\varepsilon_Z^{MC}} \sim 1$

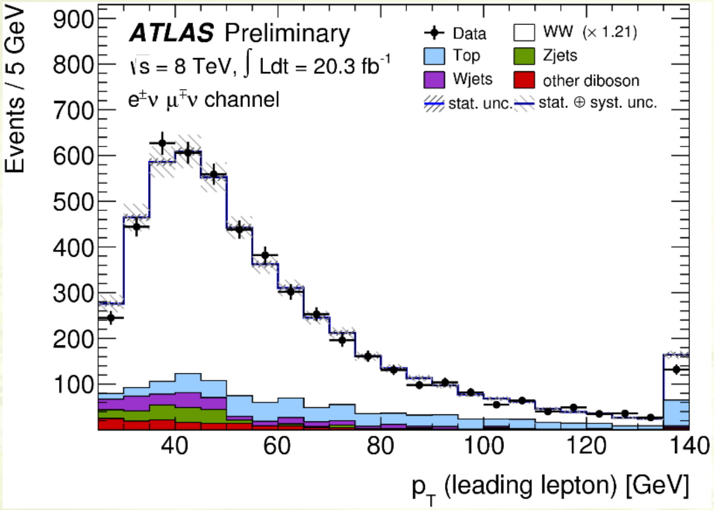


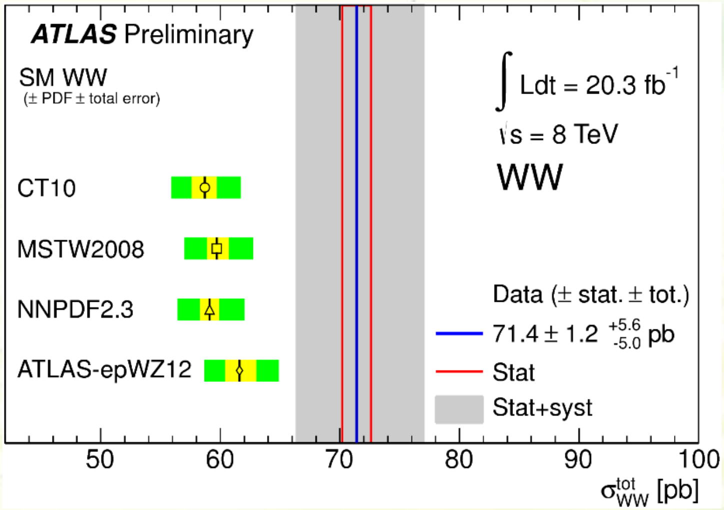
<2% statistical uncertainty
~8% systematic uncertainty
About 2 σ higher than SM prediction

Cross section 8TeV: WW New!

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





aTGCs parameters

❑ Indirect search for new physics with aTGCs

– Effective Lagrangian with anomalous couplings (Used in 7TeV results)

WWV vertices (V=Z,γ) WW/WZ/Wγ processes	ZZV vertices ZZ process	ZγV vertices Zγ process
$\Delta g_1^Z, \Delta\kappa_Z, \Delta\kappa_\gamma, \lambda_Z, \lambda_\gamma$	$f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma$	$h_3^Z, h_3^\gamma, h_4^Z, h_4^\gamma$

- ❖ aTGCs all zero in SM, neutral vertices not existing in LO
- ❖ Charged aTGCs: C and P conservation
- ❖ h_3^V, h_4^V, f_5^V: conserve CP, f_4^V: violate CP conservation
- ❖ Need a form factor (Λ) to preserve unitarity $\boldsymbol{\alpha}(\hat{\boldsymbol{s}}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^n}$

– Effective field theory approach with new physics scale of Λ

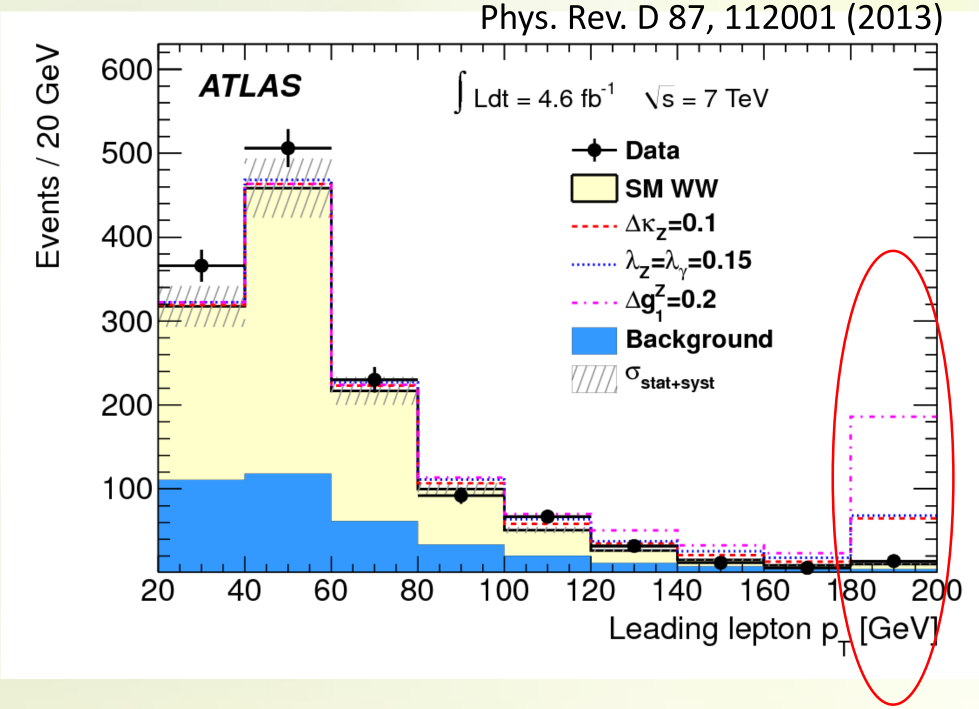
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{\text{dimension } d} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Without the need of form factor

– Two set of parameters are interconvertible

Limits on aTGCs Approaches

Phys. Rev. D 87, 112001 (2013)



+ Sensitive to $\sqrt{\hat{s}}$

p_T^l, p_T^V, invariant mass, etc.

Proper binning to optimize sensitivity

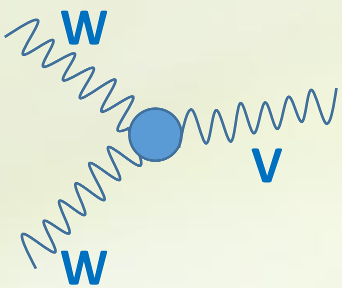
+ General workflow

1) Obtain distributions with aTGCs
2) Construct likelihood function and incorporating systematics
3) 95% C.L. Limit from Δlog-likelihood, Bayesian, Frequentist methods

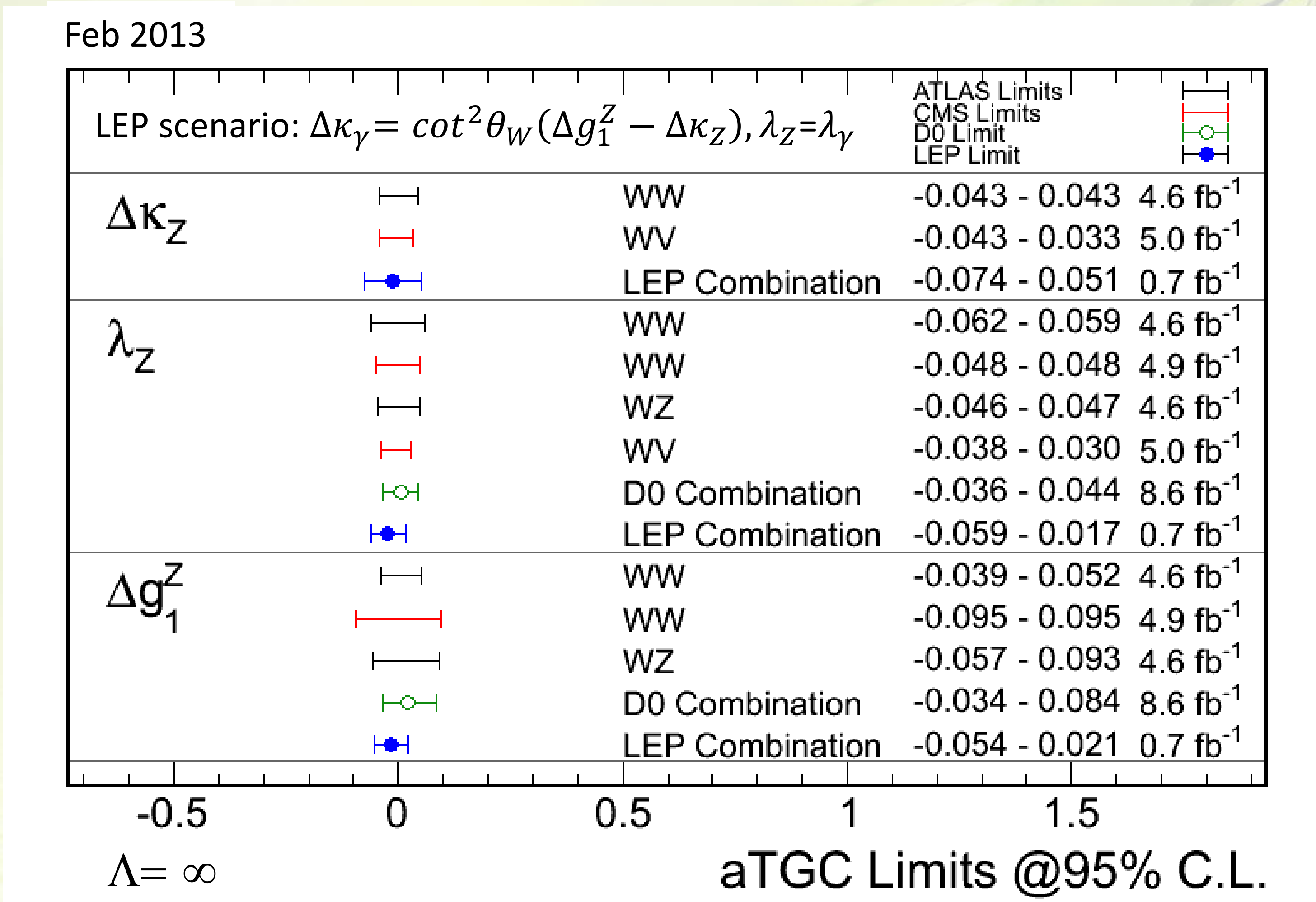
❑ Approaches to obtain distributions with aTGCs

- Event-by-event reweighting on MC@NLO MC events (WZ)
- Use 3D bin-by-bin parameterization derived from BHO generator and apply on MC events (WW)
- MC@NLO MC events with Matrix-element reweighting to BHO (ZZ)
- Fiducial distributions from MCFM (Wγ/Zγ)

Limits on aTGCs 7TeV results



V = Z, γ

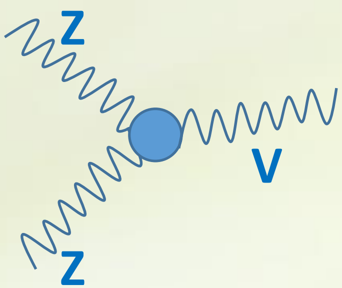


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Data consistent with SM prediction, limits comparable to LEP/Tevatron

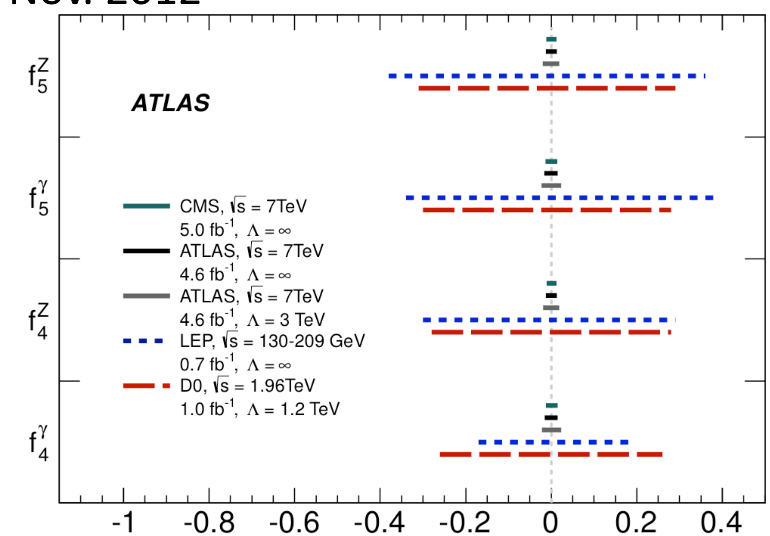
Limits on aTGCs

7TeV results



V = Z, γ

Nov. 2012



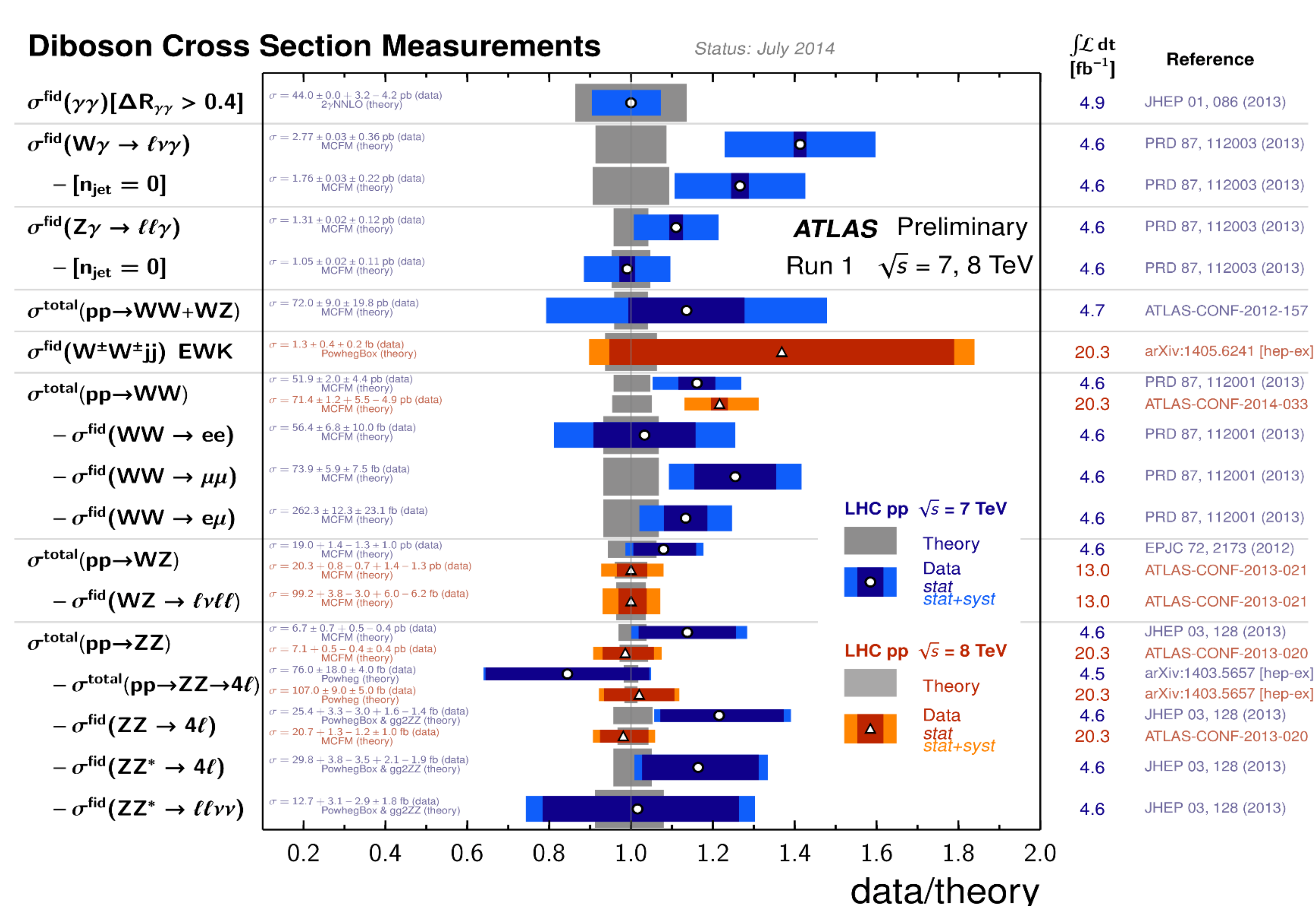
JHEP03(2013)128

Data consistent with SM prediction, stringent limits set for neutral aTGCs

	ATLAS	CMS	Final State
f_γ^4	[-0.015, 0.015]	[-0.013, 0.015]	ZZ
f_Z^4	[-0.013, 0.013]	[-0.011, 0.012]	ZZ
f_γ^5	[-0.016, 0.015]	[-0.014, 0.015]	ZZ
f_Z^5	[-0.013, 0.013]	[-0.014, 0.014]	ZZ
h_γ^3	[-0.015,0.016]	[-0.0032, 0.0032]	$Z\gamma$
h_Z^3	[-0.013,0.015]	[-0.0032, 0.0032]	$Z\gamma$
h_γ^4	[-0.000094,0.000092]	[-0.000016, 0.000016]	$Z\gamma$
h_Z^4	[-0.000087,0.000087]	[-0.000014, 0.000014]	$Z\gamma$

Table from arXiv:1406.7731v2 $\Lambda = \infty$

The Precision



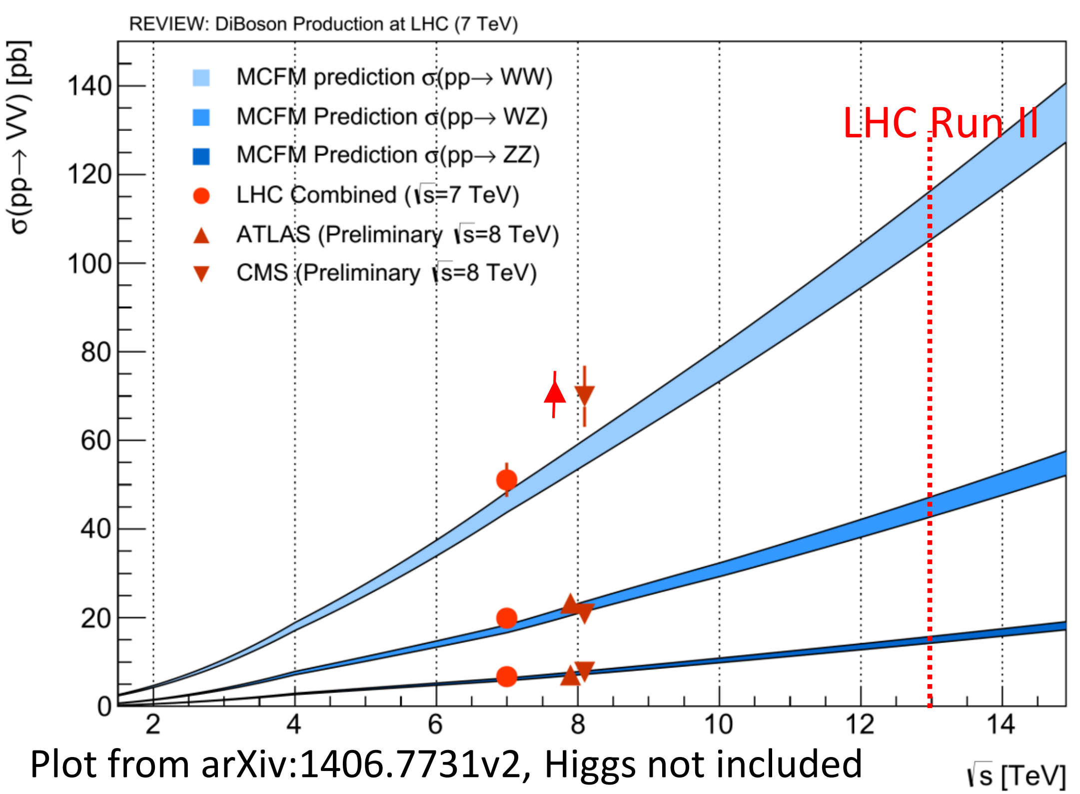
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

The Precision

Fractional uncertainty for inclusive measurement (stat. / syst.)

	W+γ	Z+γ	WW	WZ	ZZ
7 TeV, 4.6 fb^{-1}	1% / 13%	1.5% / 9%	4% / 8.5%	7.5% / 5%	10.5% / 7.5%
8 TeV, 13-20 fb^{-1}	-	-	1.7% / 7.7%	4% / 7%	7% / 5.5%

About 10% precision: systematic uncertainty dominates (leptons/photons, bkg., lumi.)



Plot from arXiv:1406.7731v2, Higgs not included

8 TeV ATLAS WW result added by hand

$$\frac{\sigma^{VV}(\sqrt{s} = 13\ TeV)}{\sigma^{VV}(\sqrt{s} = 8\ TeV)} \sim 2$$

Better precision at Run II?

- Comparable statistics in 2015
- Systematic uncertainty
- MC modelling
  - Essential for acceptance calculation
  - NLO MC in use: POWHEG, MC@NLO

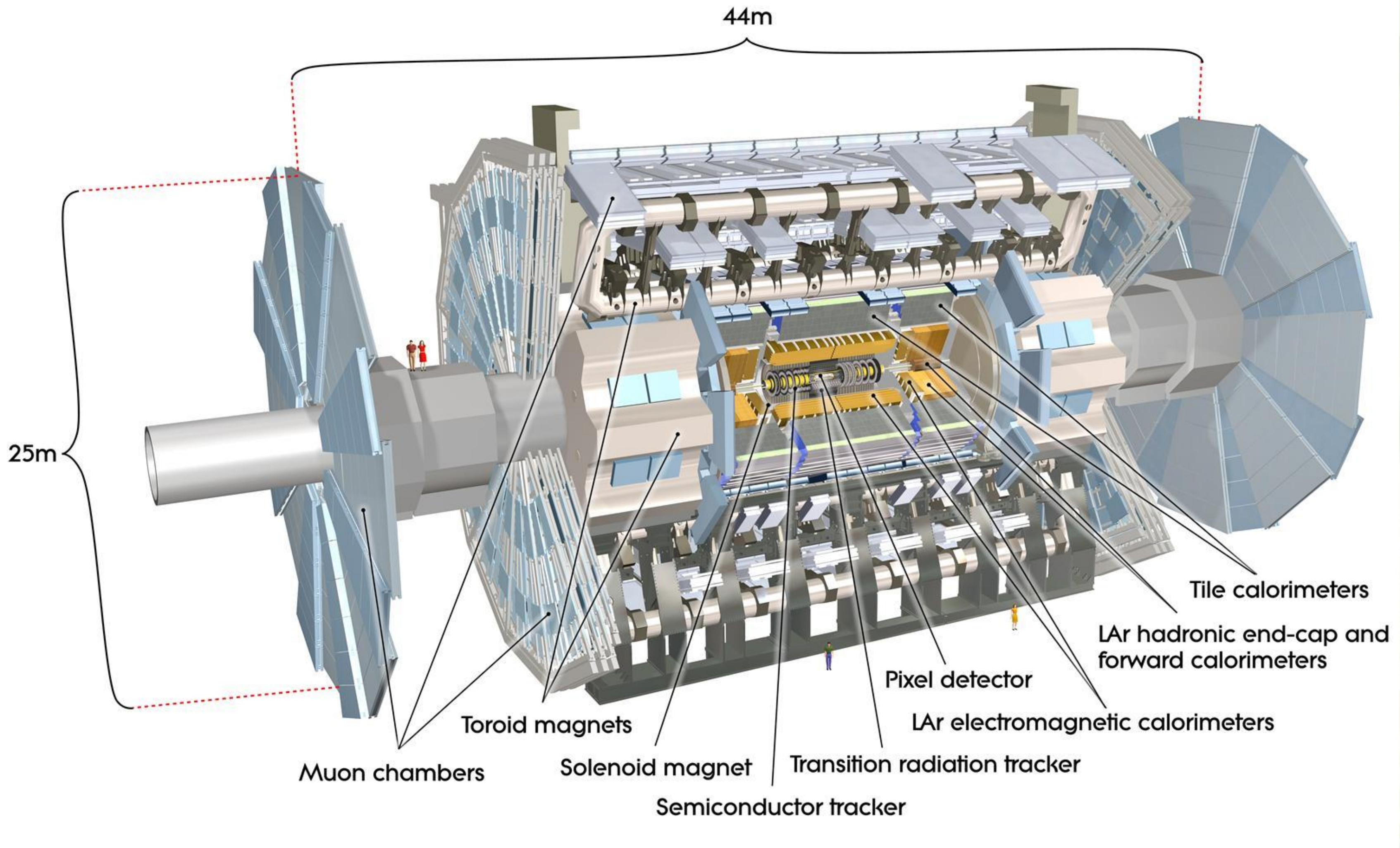
Summary

- **Diboson measurements with 7, 8 TeV pp collision data**
  - Precise measurement with full data
    - Smooth data-taking and detector operation in 2011/2012
    - Precise detector calibration and stable reconstruction performance
  - Total and fiducial cross sections for pp$\rightarrow$Wγ, Zγ, WW, WZ, ZZ
    - Comparable with NLO prediction
    - Sensitive to higher order corrections/contributions
  - aTGCs limits with 7 TeV data
  - Recent 8TeV results:
    - Z->4l phase space cross section and branching fraction
    - WW total/fiducial cross section
  - Stay tuned for more results with full 8 TeV data
    - Final papers for WW/WZ/ZZ, etc.
  - Looking forward to Run II !

Backup

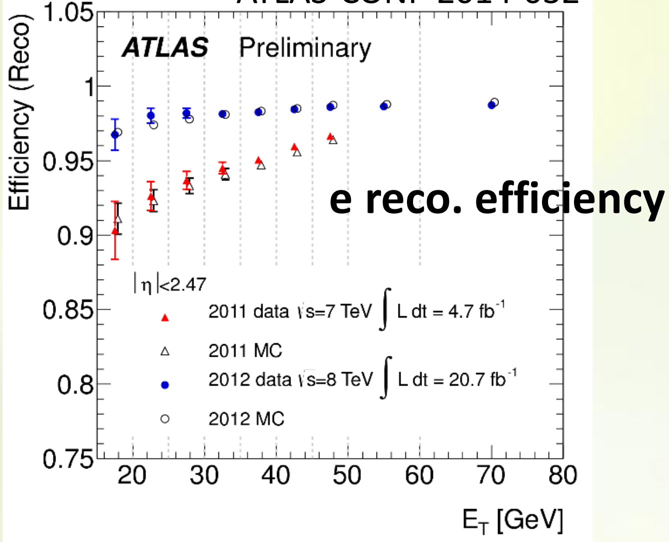
ATLAS Detector

ATLAS (A Toroidal LHC ApparatuS): 44×25m, 7000t
Inner tracking $|\eta|<2.5$, EM calo $|\eta|<3.2$, Hadronic calo $|\eta|<4.9$, Muon system $|\eta|<2.7$
ATLAS collaboration 3k physicists from 38 countries

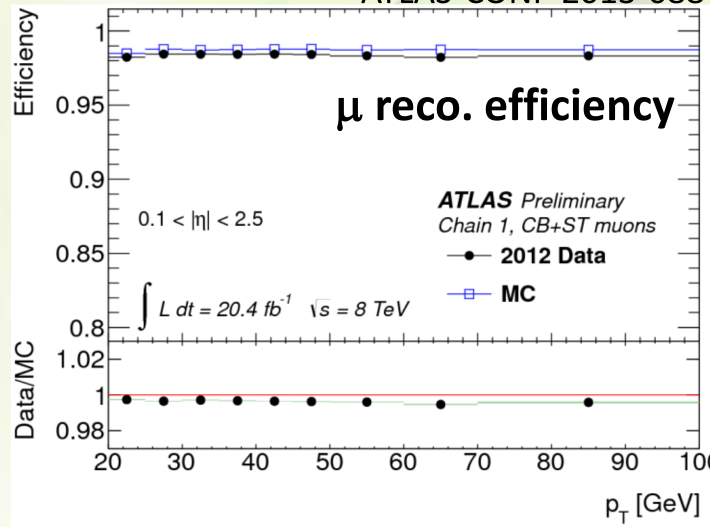


Reconstruction Performance e, μ

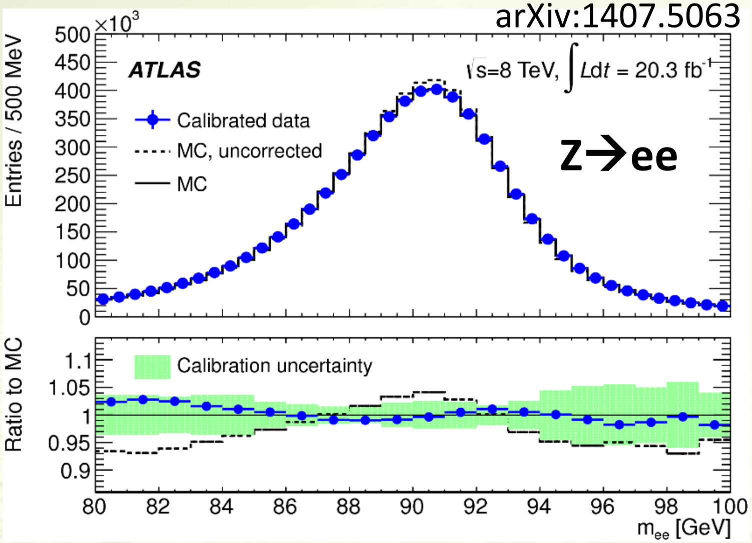
ATLAS-CONF-2014-032

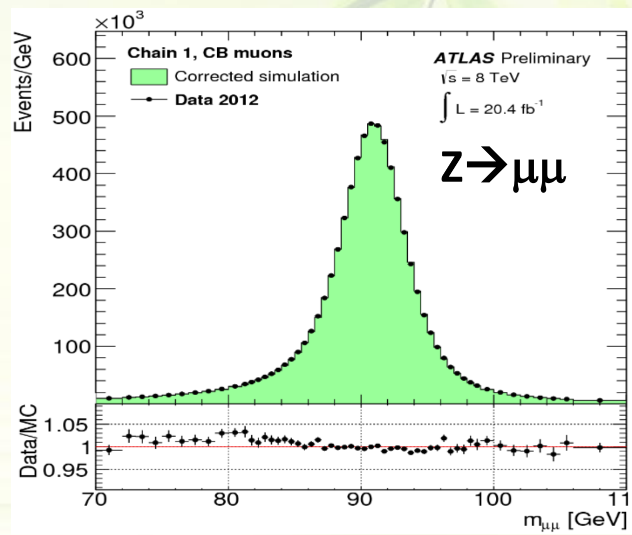


ATLAS-CONF-2013-088



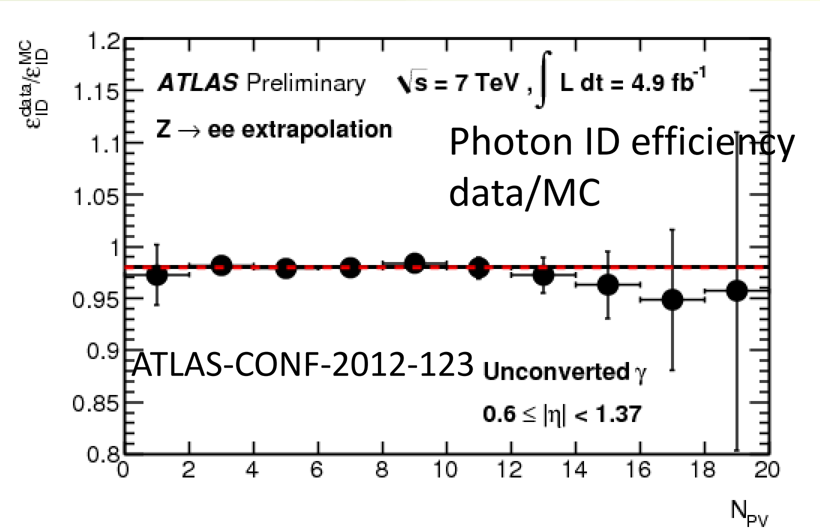
arXiv:1407.5063





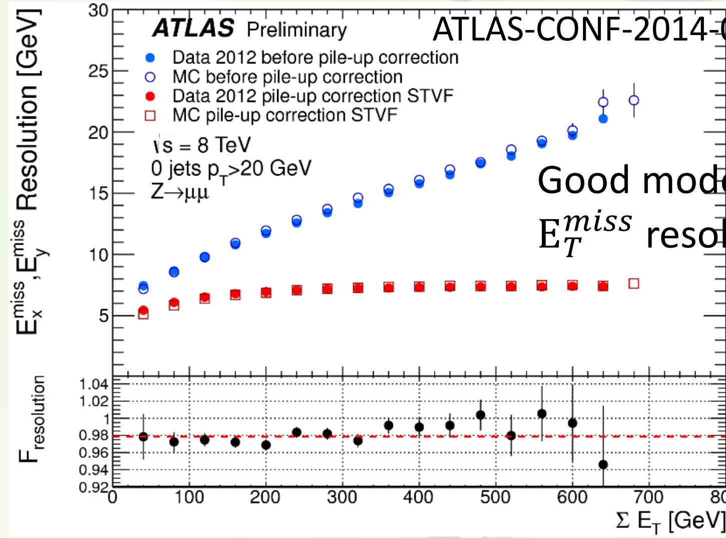
Stable performance of electron and muon reconstruction and good modelling in MC

Reconstruction Performance γ, jet, E_T^{miss}



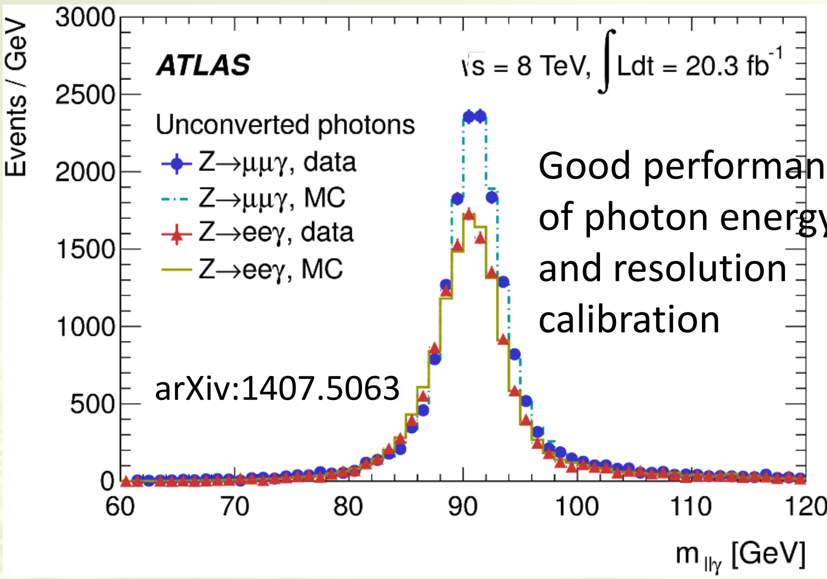
Photon ID efficiency data/MC

ATLAS-CONF-2012-123



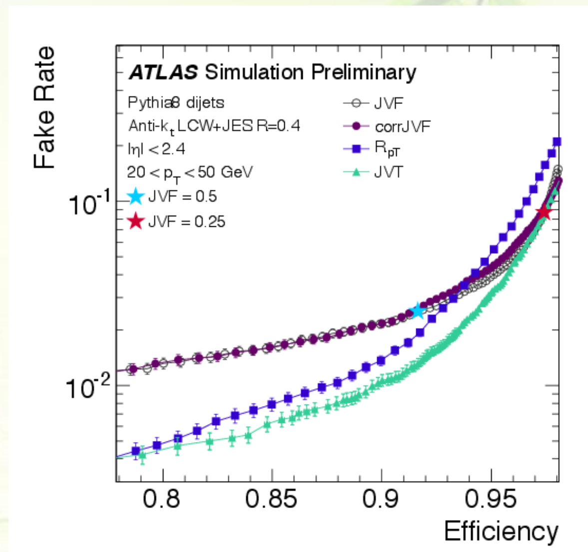
ATLAS-CONF-2014-019

Good modelling of E_T^{miss} resolution



Good performance of photon energy and resolution calibration

arXiv:1407.5063



Suppress of Pileup jets with vertex information

Good handle on pileup effects and well simulated MC are essential for precision measurement

More details on 8 TeV Z->4l measurement

$\sqrt{s}$	4ℓ state	$N_{4\ell}^{\text{obs}}$	$N_{4\ell}^{\text{exp}}$	$N_{4\ell}^{\text{bkg}}$	$C_{4\ell}$	$\sigma_{Z4\ell}^{\text{fid}}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	21.5%	$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$	7.5%	} $4e, 4\mu$	$32 \pm 11 \pm 1.0 \pm 0.6$
	$\mu\mu+\mu\mu$	8	11.3 ± 0.5	0.08 ± 0.04	59.2%	$3.0^{+1.2}_{-0.9} \pm 0.07 \pm 0.05$	18.3%		
	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	49.0%	$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$	15.8%	} $2e2\mu$	$44 \pm 14 \pm 3.3 \pm 0.9$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	36.3%	$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$	8.8%		
	combined	21	24.2 ± 1.2	0.44 ± 0.14					$76 \pm 18 \pm 4 \pm 1.4$
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$	7.3%	} $4e, 4\mu$	$56 \pm 6 \pm 1.8 \pm 1.6$
	$\mu\mu+\mu\mu$	71	68.8 ± 2.7	0.34 ± 0.05	71.1%	$4.9^{+0.7}_{-0.6} \pm 0.13 \pm 0.14$	17.8%		
	$ee+\mu\mu$	48	43.2 ± 2.1	0.32 ± 0.05	55.5%	$4.2^{+0.7}_{-0.6} \pm 0.16 \pm 0.12$	14.8%	} $2e2\mu$	$52 \pm 7 \pm 2.4 \pm 1.5$
	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	46.2%	$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$	7.9%		
	combined	151	146 ± 7	1.0 ± 0.11					$107 \pm 9 \pm 4 \pm 3.0$

Phys. Rev. Lett. 112, 231806 (2014)

More details on 8 TeV WW measurement

$$\begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix}^{-1} \times \begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix}$$

W+jets (N_{RF}, N_{FR})

QCD (N_{FF})

F-fake, R-real

r-signal lepton efficiency, f-fake rate

T-tight lepton, L-loose lepton

Matrix method

→ **Loose lepton definition**

No IP/Isolation requirements

For electrons, further loose eID to MediumLLH

→ **Fake rate**

measured from dijet events with supporting triggers

trigger dependent fake-rate applied

→ **Systematics:**

sample dependence, lepton efficiency

On W+jets

More details on 8 TeV WW measurement

- **Data-driven method based on probability of jet to pass jet-veto cut**
  - **1st data control region**: events with full event selection without jet-veto cut, further apply Ht* to reduce the WW signal contamination. The MC jet-veto efficiency is P_1^{MC}

    * Ht is scalar sum of pt for leptons and jets

  - **2nd data control region:** a subset of 1st CR with a b-jet identified in the events.
    - ❖ The probability is calculated from 2nd CR, as $P_{2(Btag)}^{Data}$ or $P_{2(Btag)}^{MC}$
  - **Formula**

$$P_1^{DATA} = P_1^{MC} \times \left(\frac{P_{2(Btag)}^{DATA}}{P_{2(Btag)}^{MC}} \right)^2$$

$$N_{Top}^{DATA}(0\,jet) = N_{Top}^{DATA}(all) \times P_1^{DATA} / \varepsilon_{Ht}$$

- ❖ Uncertainty ~ 10%

JES/JER/b-tagging, MC generator/Parton Shower

On Top

More details on 8 TeV WW measurement

Channel	$e^{\pm}\mu^{\mp}$	$e^{+}e^{-}$	$\mu^{+}\mu^{-}$
Observed Events	5067	594	975
Total expected events	$4376 \pm 26 \pm 280$	$536 \pm 10 \pm 42$	$873 \pm 12 \pm 63$
MC WW signal	$3224 \pm 10 \pm 248$	$346 \pm 3 \pm 32$	$610 \pm 5 \pm 56$
Top(data-driven)	$609 \pm 18 \pm 52$	$92 \pm 7 \pm 8$	$127 \pm 9 \pm 11$
W+jets(data-driven)	$220 \pm 15 \pm 112$	$14 \pm 5 \pm 9$	$3 \pm 5 \pm 6$
Z+jets (data-driven)	$166 \pm 3 \pm 26$	$55 \pm 1 \pm 23$	$96 \pm 2 \pm 27$
Other dibosons (MC)	$157 \pm 4 \pm 31$	$30 \pm 2 \pm 5$	$39 \pm 1 \pm 5$
Total background	$1152 \pm 24 \pm 130$	$190 \pm 9 \pm 26$	$264 \pm 11 \pm 30$