Recent electroweak measurements at ATLAS

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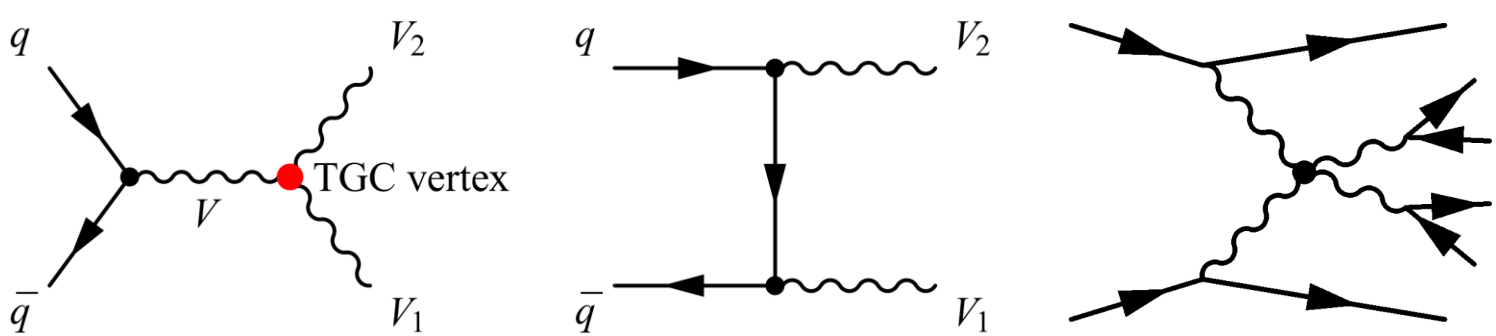
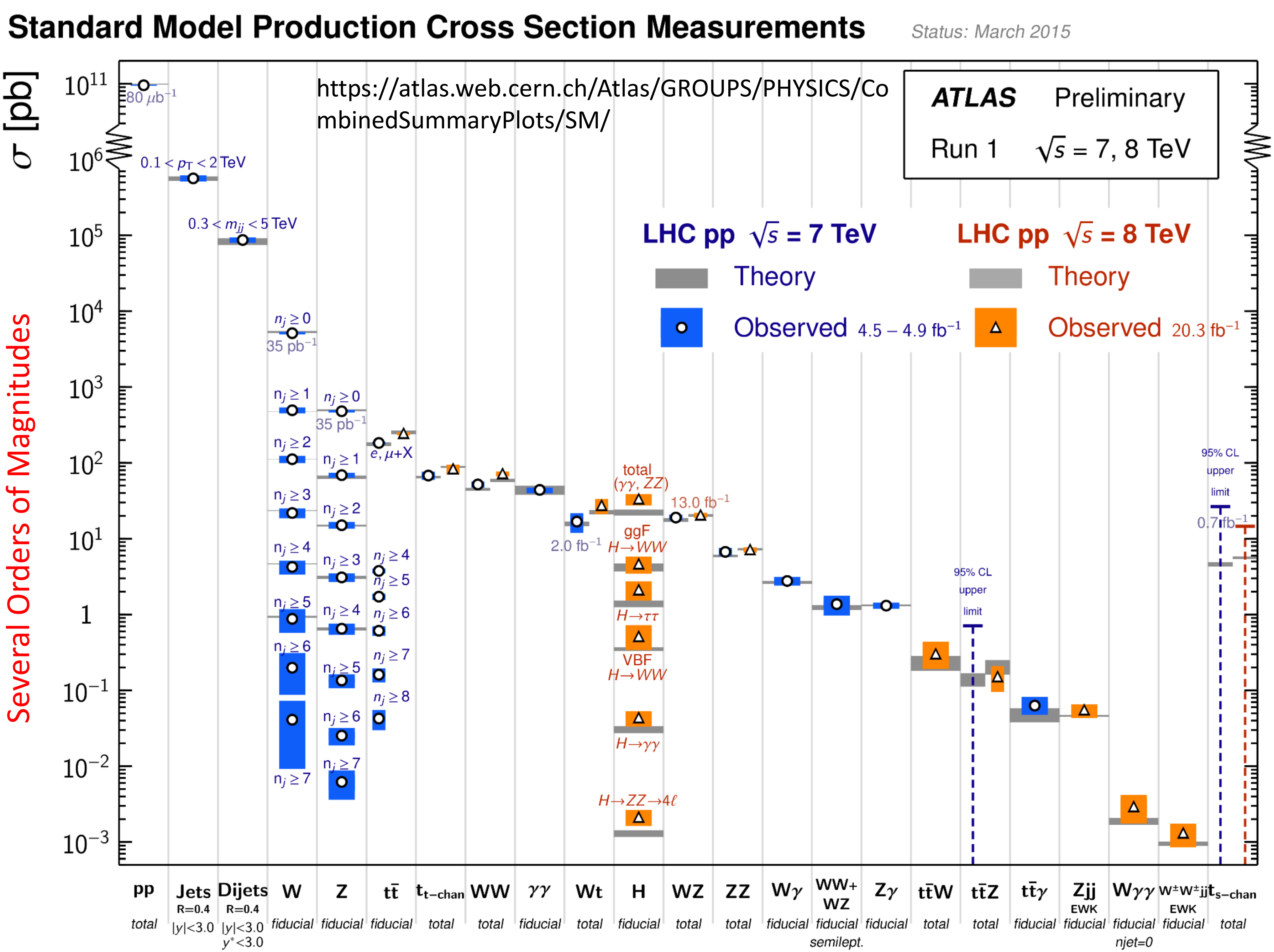
Introduction

❑ Electroweak studies

- ❖ Precision measurements
  - o Single boson, diboson productions
  - o Tight constrain on SM parameters, QCD and EWK corrections
- ❖ Exploration of less constrained or new production channels
  - o Higgs, vector boson fusion/scattering, three boson productions
  - o Understanding of EWSB and production of rare processes
- ❖ Search for discrepancies that are sensitive to new physics
  - o Anomalous boson self couplings



Example diagrams



Standard Model Production Cross Section Measurements
Status: March 2015
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Observed 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Theory
Observed 20.3 fb⁻¹
σ [pb]
Several Orders of Magnitudes
80 μb⁻¹
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
35 pb⁻¹
e, μ+X
total (γγ, ZZ)
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
13.0 fb⁻¹
2.0 fb⁻¹
95% CL upper limit
0.7 fb⁻¹
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ fiducial
tt-chan total
WW total
γγ fiducial
Wt total
H fiducial
WZ total
ZZ total
Wγ fiducial
WW+WZ fiducial semilept.
Zγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial
ts-chan total

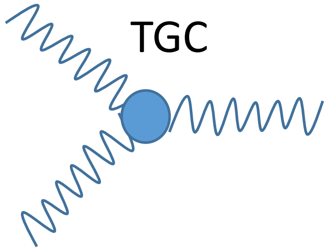
Cross Section Measurement

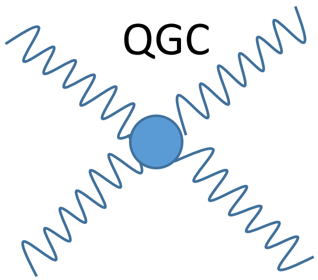
$$\sigma_{PS} = \frac{N_{data} - N_{bkg}}{lumi \times A \times C} \quad \sigma_{FV} = \frac{N_{data} - N_{bkg}}{lumi \times C}$$

- Often measured in both fiducial volume and total phase space
  - A – signal acceptance in fiducial volume
  - C – efficiency correction due to reconstruction
  - σ_{FV} less affected by theoretical uncertainty
- Differential measurements
  - "Unfolded" to FV by removing the detector effects
  - Properly binned according to statistics and migration effects
- Comparison with theory
  - Overall good agreement
  - Some discrepancies (e.g. in WW, Wγ, Zγ) were reduced by inclusion of high order corrections in the predictions

Anomalous Gauge Boson Couplings (aGCs)

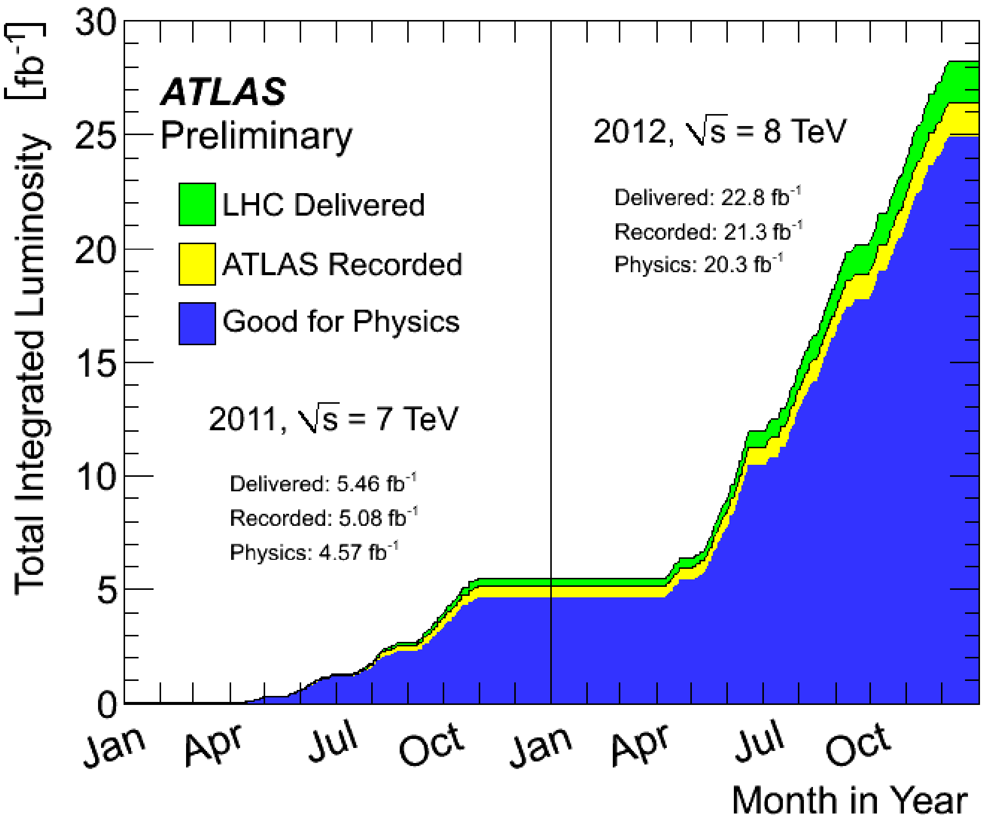
- ❑ Trilinear and Quartic boson couplings (TGC, QGC)
  - ❖ Precisely determined by SU(2) x U(1) gauge symmetry
    - o Only charged couplings allowed
    - o TGCs in VBF, VV; QGCs in VBS, VVV
  - ❖ Can be used to constrain new physics that modify bosonic self couplings
    - o Anomaly can result in large derivation in production σ or in differential distributions
    - o aGCs Sensitive to $\sqrt{s}$



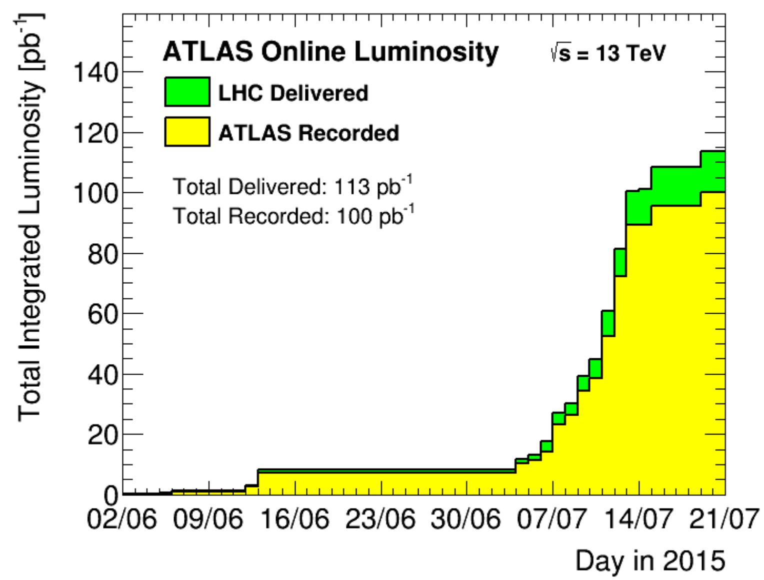


No deviation from SM prediction is observed with Run I data
➔ Stringent limits are set
- o aGCs parameters based on effective Lagrangian or EFT
- o Tighter or comparable to Tevatron/LEP results

Recorded data with ATLAS



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



~25 fb^{-1} recorded in LHC Run I

LHC Run II, 100pb^{-1} already!!!

High data-taking efficiency and detector operation rate, thanks to the teams that operate LHC and ATLAS

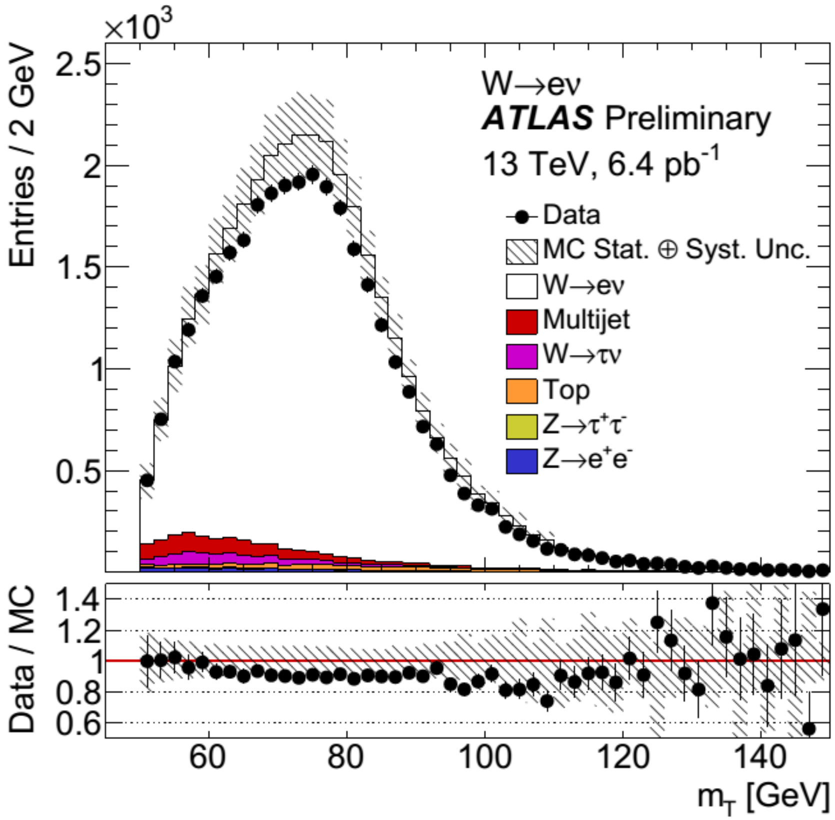
Recent electroweak measurements

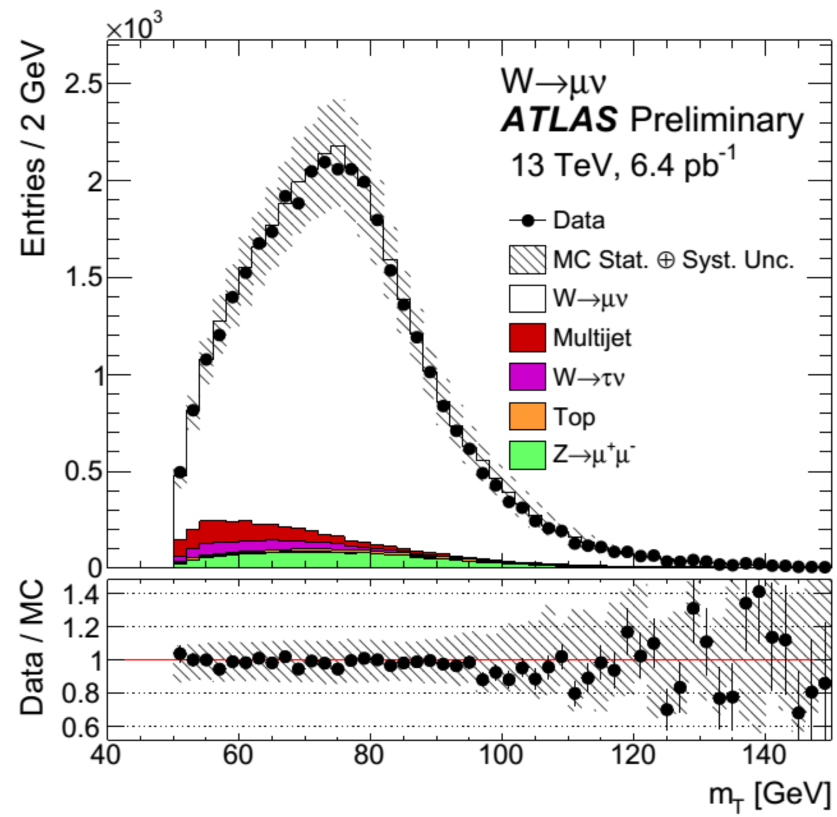
- Measurements covered in this talk
  - Based on 13 TeV data
    - Public plots for W, Z and ZZ productions, ATL-PHYS-PUB-2015-021
  - Based on 8 TeV data
    - Four lepton differential measurement, ATLAS-CONF-2015-031
    - Evidence of Wγγ production, Phys. Rev. Lett. 115, 031802 (2015)
    - WW cross section measurement, ATLAS-CONF-2014-033
  - Based on 7 TeV data
    - Z Forward-backward asymmetry and extraction of θ_W, arXiv:1503.03709
    - Combined WW+WZ measurement in lνjj final state, JHEP01(2015)049

13 TeV W plots

ATL-PHYS-PUB-2015-021

Very early Run II data, reasonable agreement with MC





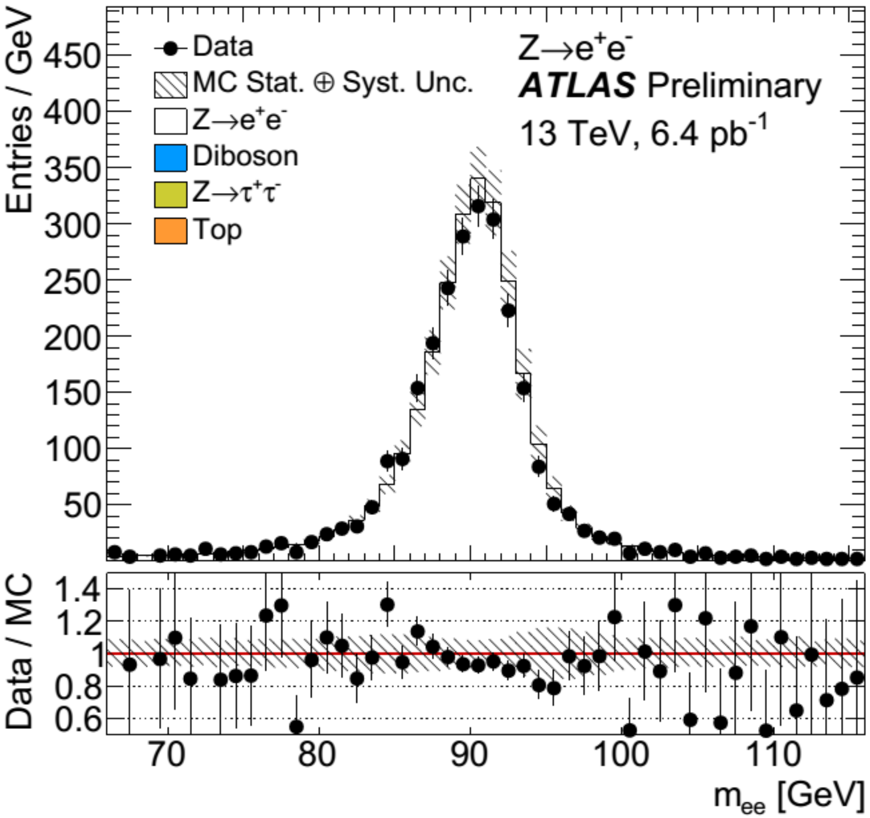
W candidates: lepton pt > 25 GeV, Etmiss > 20 GeV, M_T > 50 GeV

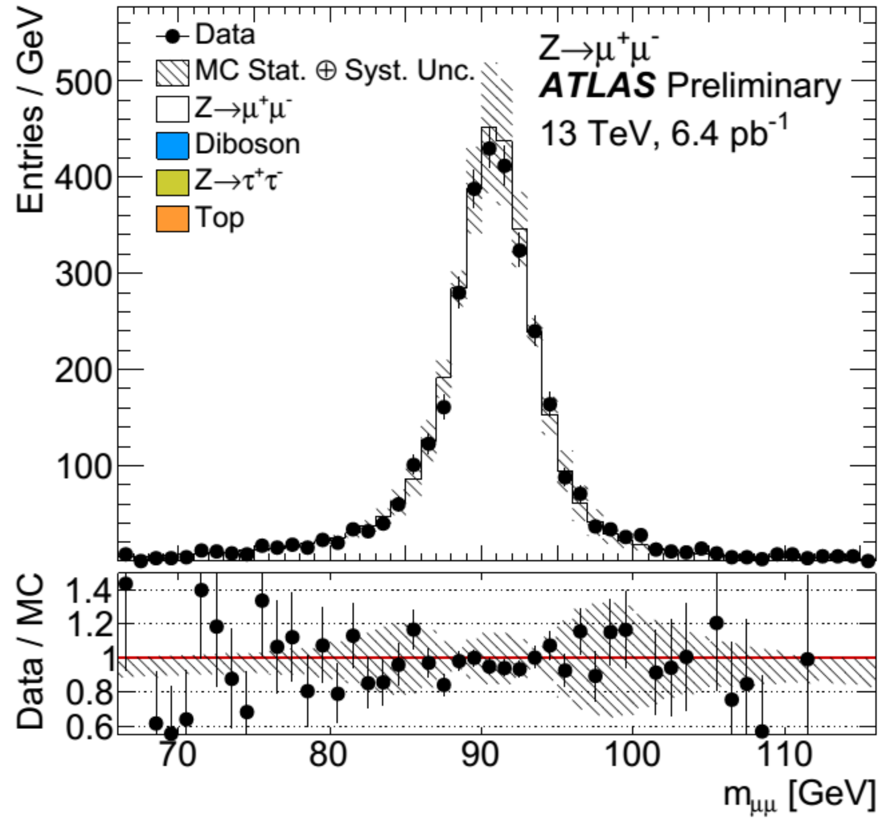
$|\eta_\mu|$<2.4, $|\eta_e|$<2.47 excluding [1.37, 1.52]

13 TeV Z plots

ATL-PHYS-PUB-2015-021

Very early Run II data, reasonable agreement with MC

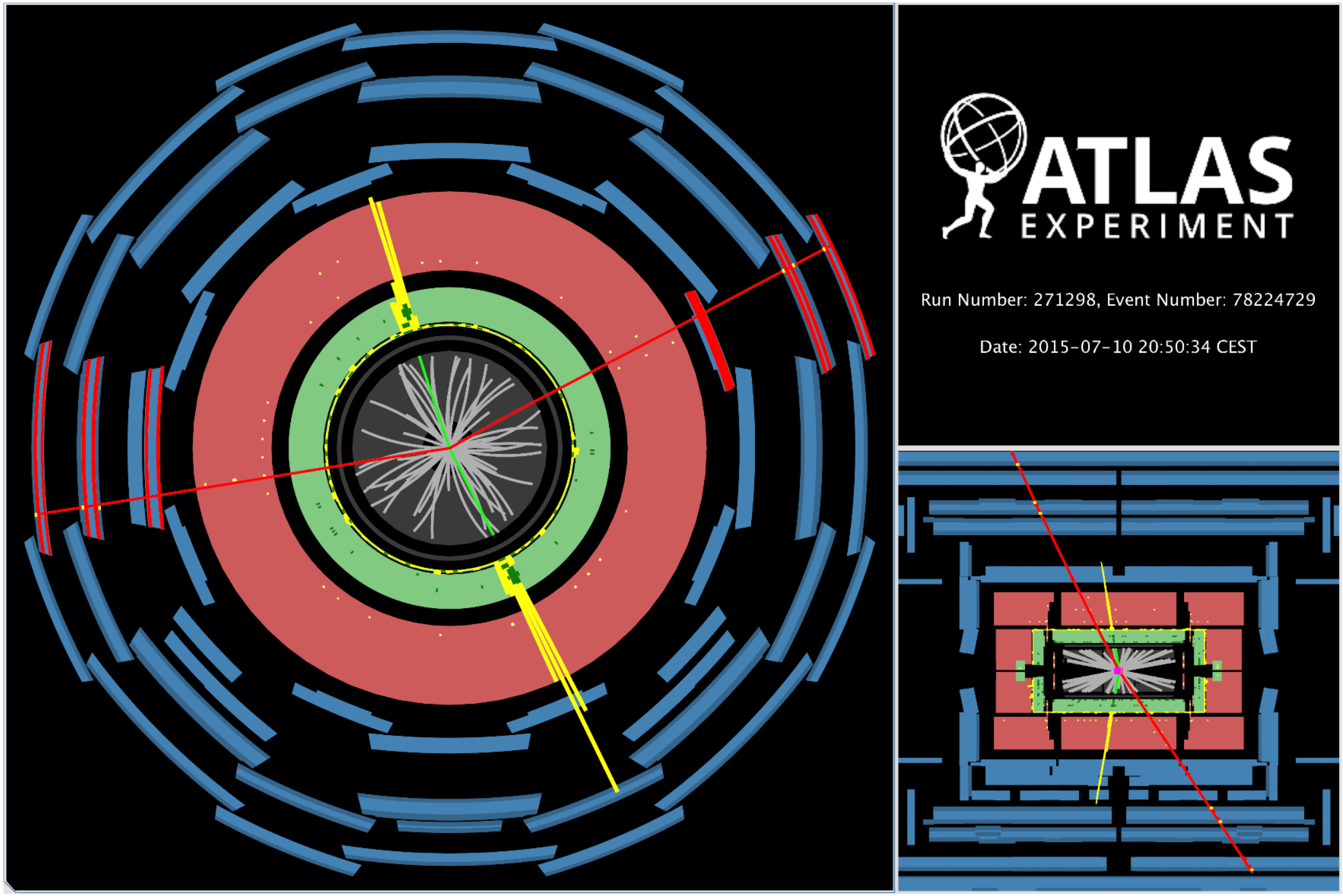




Z candidates: two leptons with pt > 25 GeV, 66<M(ll)<116 GeV

$|\eta_\mu|$<2.4, $|\eta_e|$<2.47 excluding [1.37, 1.52]

13 TeV ZZ candidate

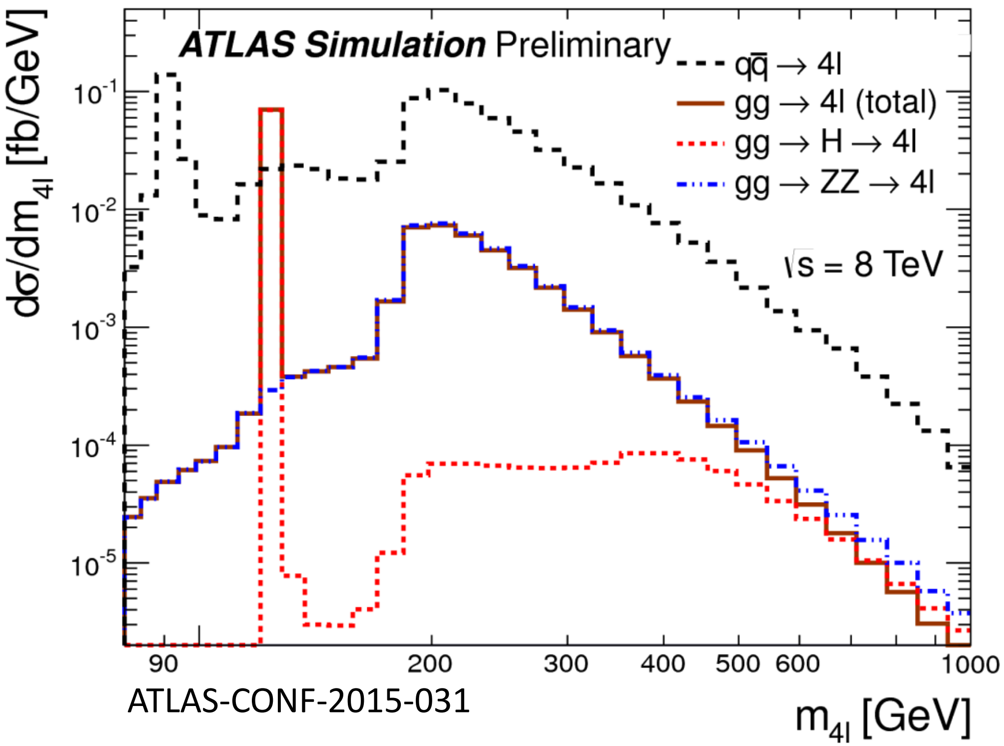


Inv. Masses of two Z candidates: 94 GeV, 86 GeV

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions

8 TeV: 4l differential measurement

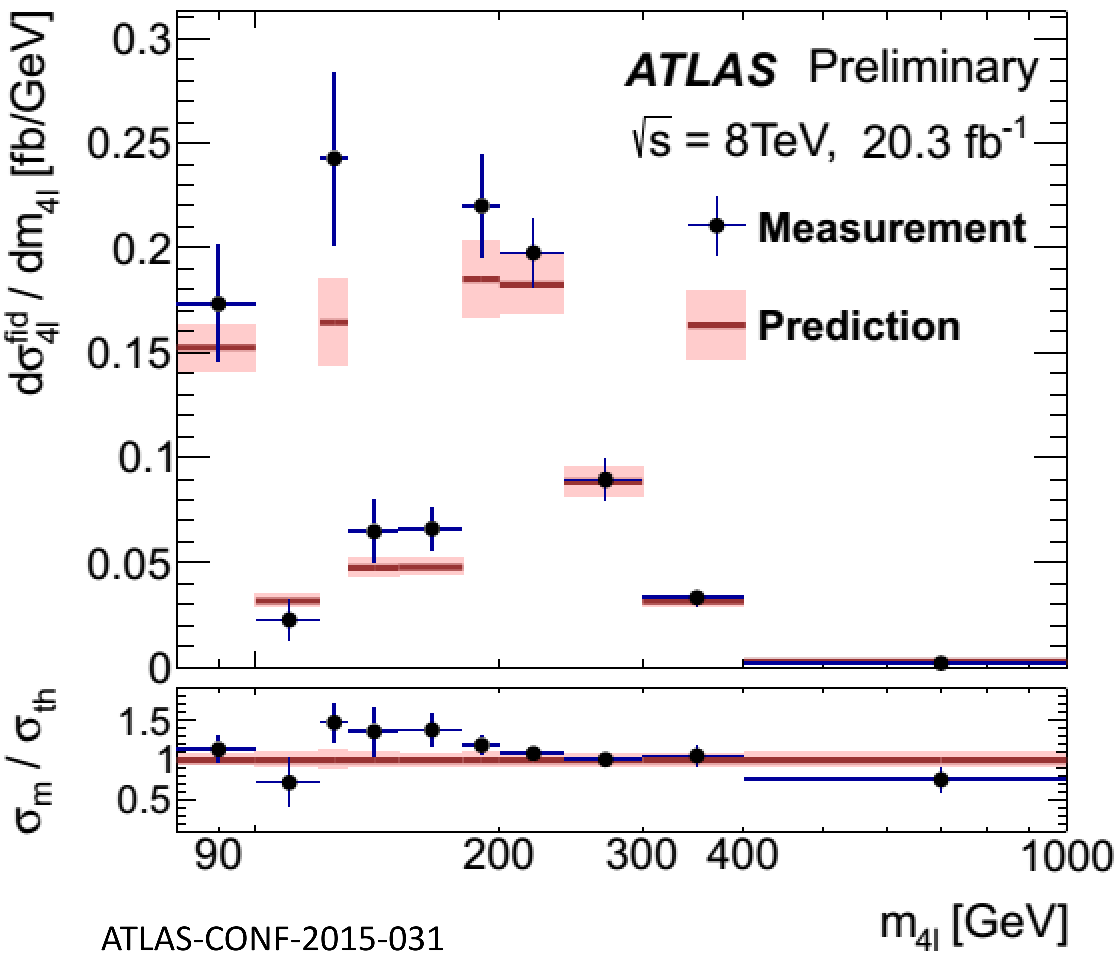
- **Measure differential σ in M(4l) and Pt(4l) for inclusive 4l production**
  - Explore multiple production modes at once, constrain higher order effects in a wide range (80<M(4l)<1000 GeV)
  - First try to constrain gg->4l contribution from data: gg induced production is only predicted at LO so far in on-shell ZZ region



ATLAS-CONF-2015-031

About 500 candidates, expect ~5% from backgrounds

8 TeV: 4l differential measurement



ATLAS-CONF-2015-031

Unfolded to fiducial region:

Four selected leptons

80<M(4l)<1000 GeV

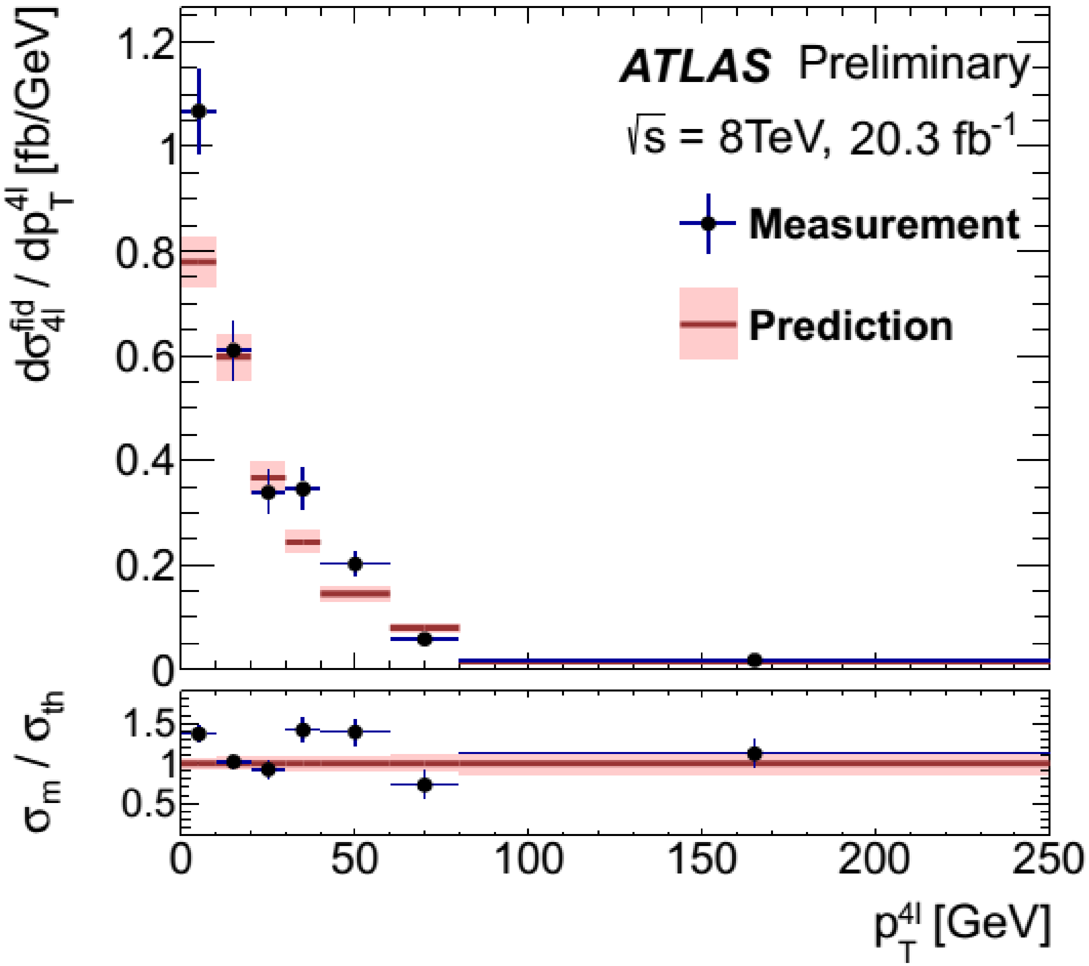
SM prediction:

- qq->4l at NLO QCD, non resonant gg->4l at LO
- H->4l and on-shell qq->4l corrected to NNLO QCD + NLO EWK

Comparison:

- Consistent with Higgs signal strength in dedicated paper: arXiv:1408.5191
- Possibly missing k-factor for off-shell ZZ* production
- Slight tension in on-shell ZZ region relates to missing k-factor in gg->4l

8 TeV: 4l differential measurement



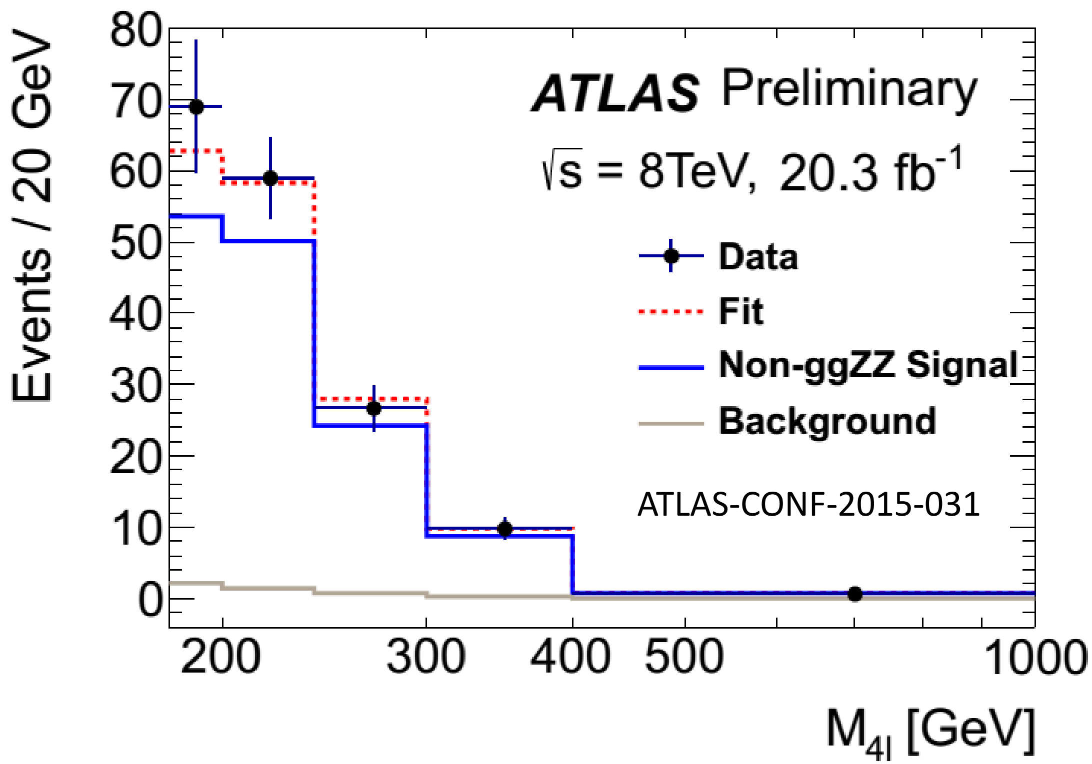
ATLAS-CONF-2015-031

Unfolded to fiducial region:
Four selected leptons
80<M(4l)<1000 GeV

SM prediction:
- qq->4l at NLO QCD, no resonant gg->4l at LO
- H->4l corrected to NNLO QCD + NLO EWK

Comparison:
- Missing higher order corrections in Pt spectrum
- Modelling issue in low Pt due to gluon resummation

8 TeV: 4l differential measurement



Inclusive gg component is extracted from data in m(4l)>180GeV region, where qq contribution is precisely predicted at NNLO QCD + NLO EWK

At on-shell ZZ region, inclusive gg->4l contribution includes:
Off-shell Higgs, Non-resonant gg, and the interference

The derived signal strength w.r.t. current LO prediction

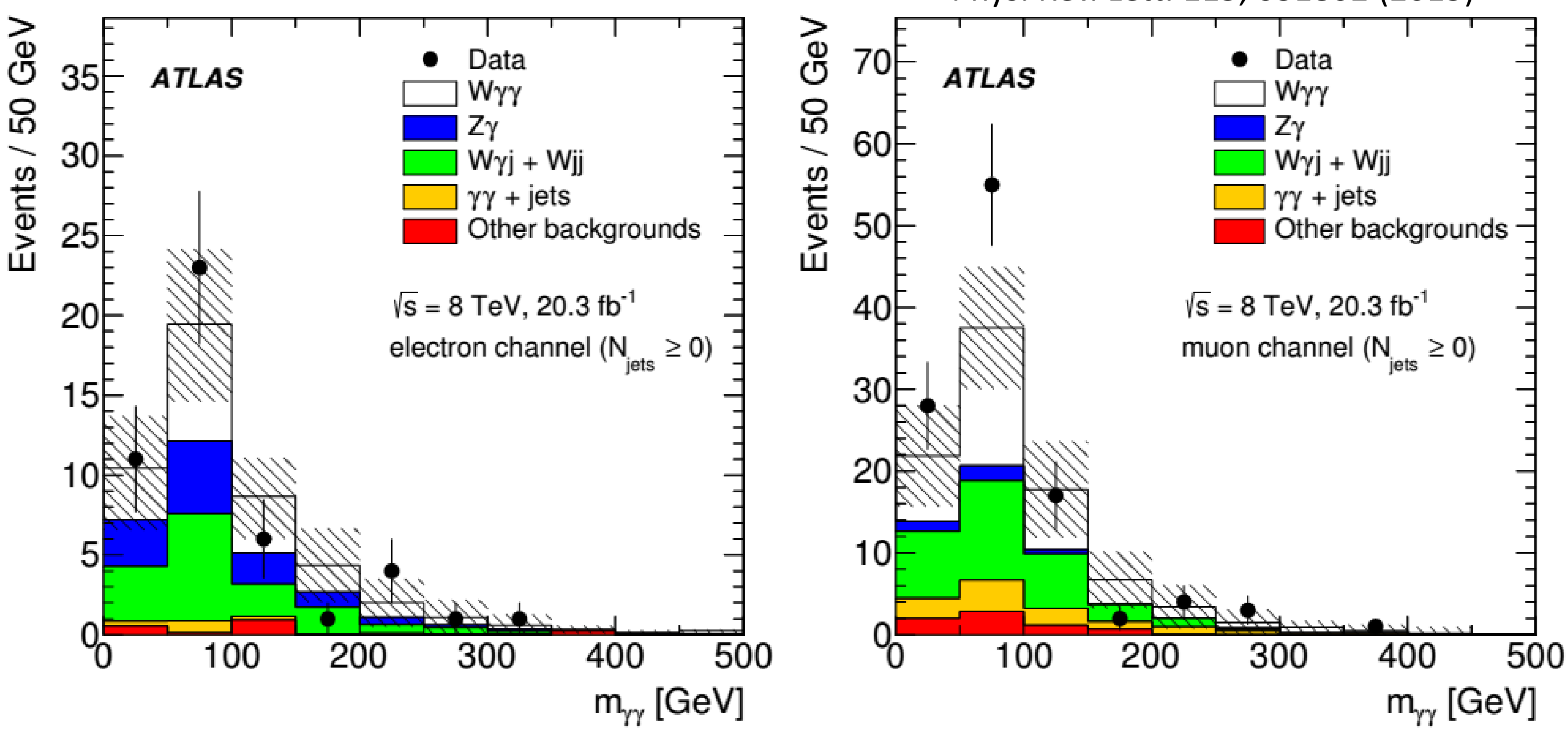
$$\mu_{gg} = 2.4 \pm 1.0(stat.) \pm 0.5(syst.) \pm 0.8(theory)$$

Consistent with the predicted k-factor for of-shell Higgs and interference, yet to be calculated for the full process

8 TeV: Evidence of Wγγ production

- Tri-boson production with relative large cross section
  - Final state: lepton + Etmiss + two photons
  - Significant fake backgrounds : jet->γ, jet->lepton, estimated from data
  - Sensitive to the WWγγ aQGC

Phys. Rev. Lett. 115, 031802 (2015)



8 TeV: Evidence of Wγγ production

Phys. Rev. Lett. 115, 031802 (2015)

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

First time have 3σ evidence of Wγγ production

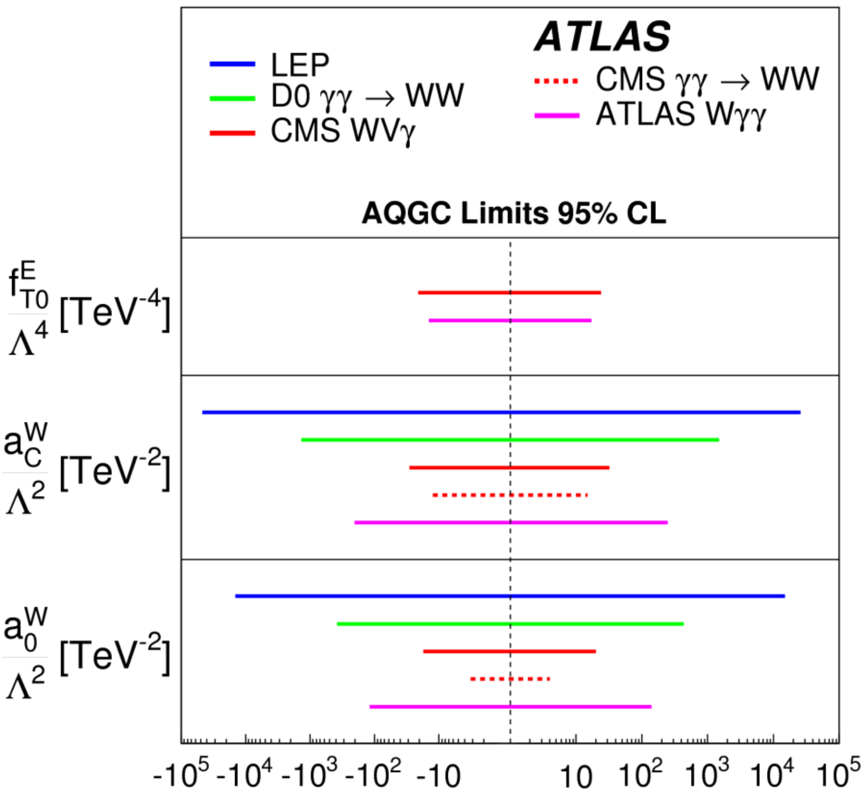
- Measured inclusive cross section about 2σ higher than NLO prediction
- Better agreement in zero jet case

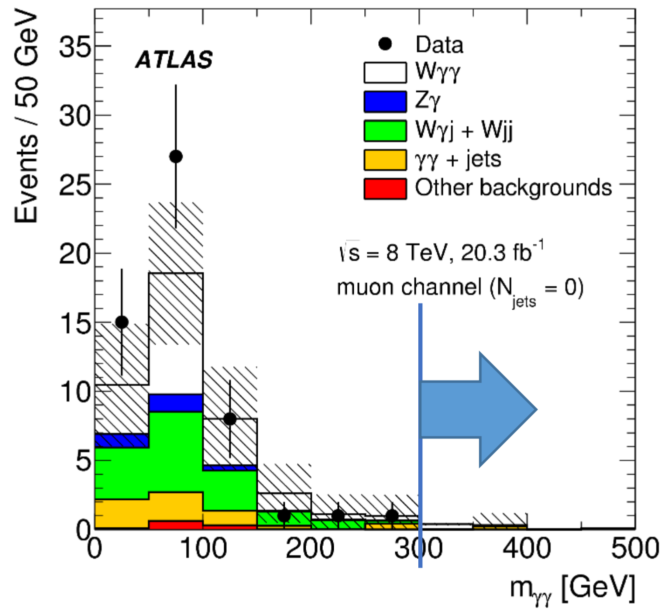
➔ Likely due to missing higher order correction

8 TeV: Evidence of Wγγ production

- **WWγγ aQGCs are explored in high m(γγ)>300 GeV and exclusive region**
  - No data events observed
  - Limits are set on dimension eight operators

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2013-05/

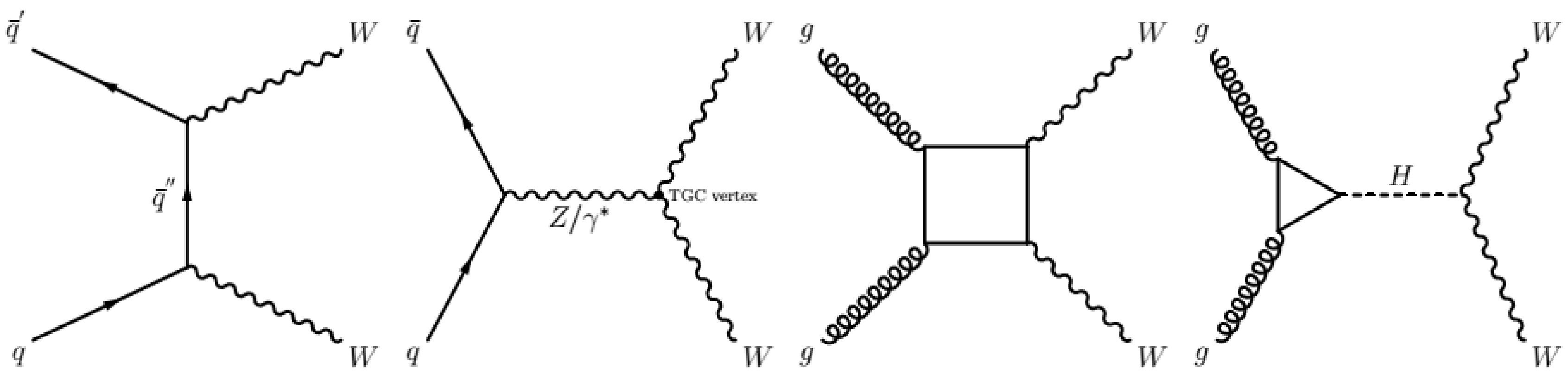




Comparable limits to CMS
More sensitive to f_{T0}

8 TeV: WW Cross Section

- Large WW cross section and Search for aTGCs with WWV vertices
- Previous LHC measurements indicated higher cross section than NLO prediction
    - at 1.5 σ level from both ATLAS and CMS



Inclusive WW cross section prediction at 8TeV:

NLO qq + LO gg + NNLO ggH ~ 58.7 ± 3.0 pb

NNLO qq + LO gg + NNLO ggH ~ 63.2 ± 2.0 pb

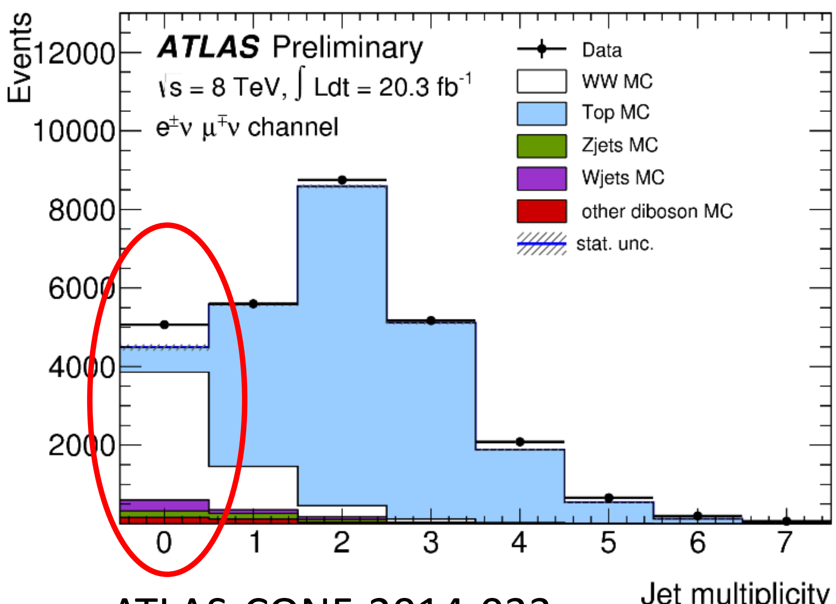
Phys. Rev. Lett. 113, 212001 (2014)

Sizable NNLO correction ~ 8%

Important to test the consistency with NNLO predictions using full Run I data

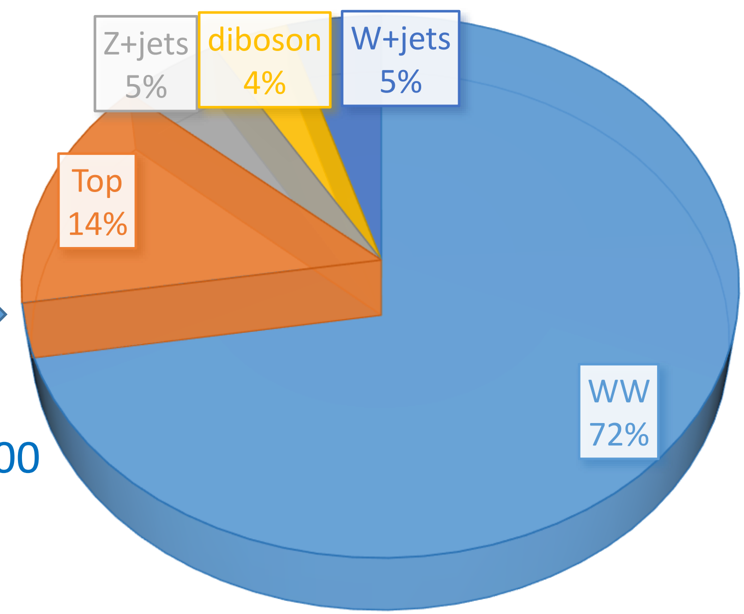
8 TeV: WW Cross Section

- **Signature: two high-pt leptons and large MET (ee, μμ, eμ)**
- **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



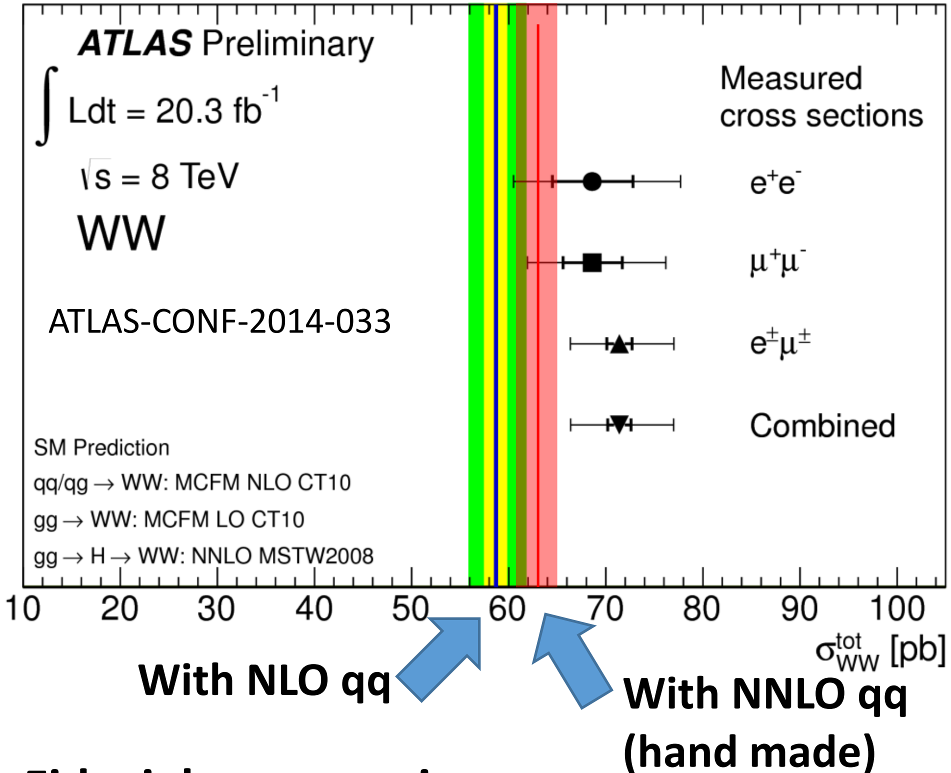
ATLAS-CONF-2014-033

S/B~2.5
Data ~ 6600



8 TeV: WW Cross Section

Cross Section at total phase space



Fiducial cross sections:

$$\sigma^{fid}_{e\mu}\ 377.8^{+6.9}_{-6.8}\ (\text{stat})\ ^{+25.1}_{-22.2}\ (\text{syst})\ ^{+11.4}_{-10.7}\ (\text{lumi})\ \text{fb}$$

Compatible with approximate NNLO+NNLL calculation

$$357.9 \pm 14.4\ \text{fb}$$

arXiv:1410.4745

Measured total cross section

- 10% precision, mainly systematic unc.
- Compatible with full NNLO prediction at about 1 σ

Remaining difference may due to

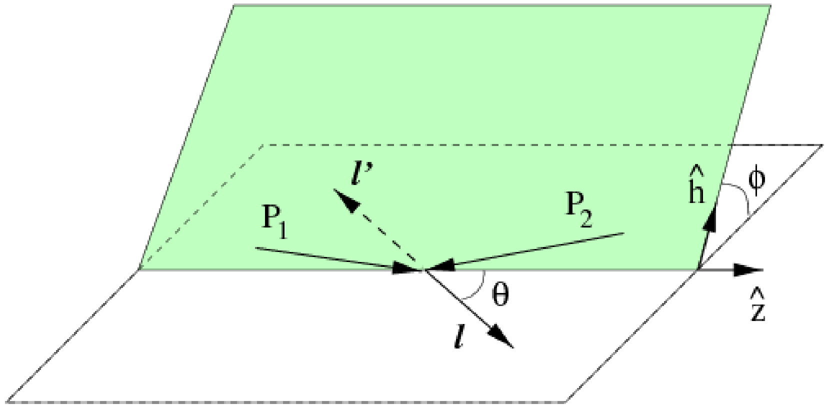
- Missing k-factor for gg->WW
- Modelling on gluon resummation (effect on Jet-Veto)

New result from CMS

- arXiv:1507.03268
- Measured total σ agree well with NNLO prediction
- Applied resummation correction to the acceptance

7 TeV: Z Forward-Backward Asymmetry

- Forward-Backward Asymmetry (A_{FB}) in Z decays
  - Predicted by V-A structure of weak interaction
  - Can be used to determine weak mixing angle
    - Both relates to the coupling ratio of vector and axial vector parts
  - Related to $\cos\theta$, where θ is angle between lepton and quark in di-lepton rest frame

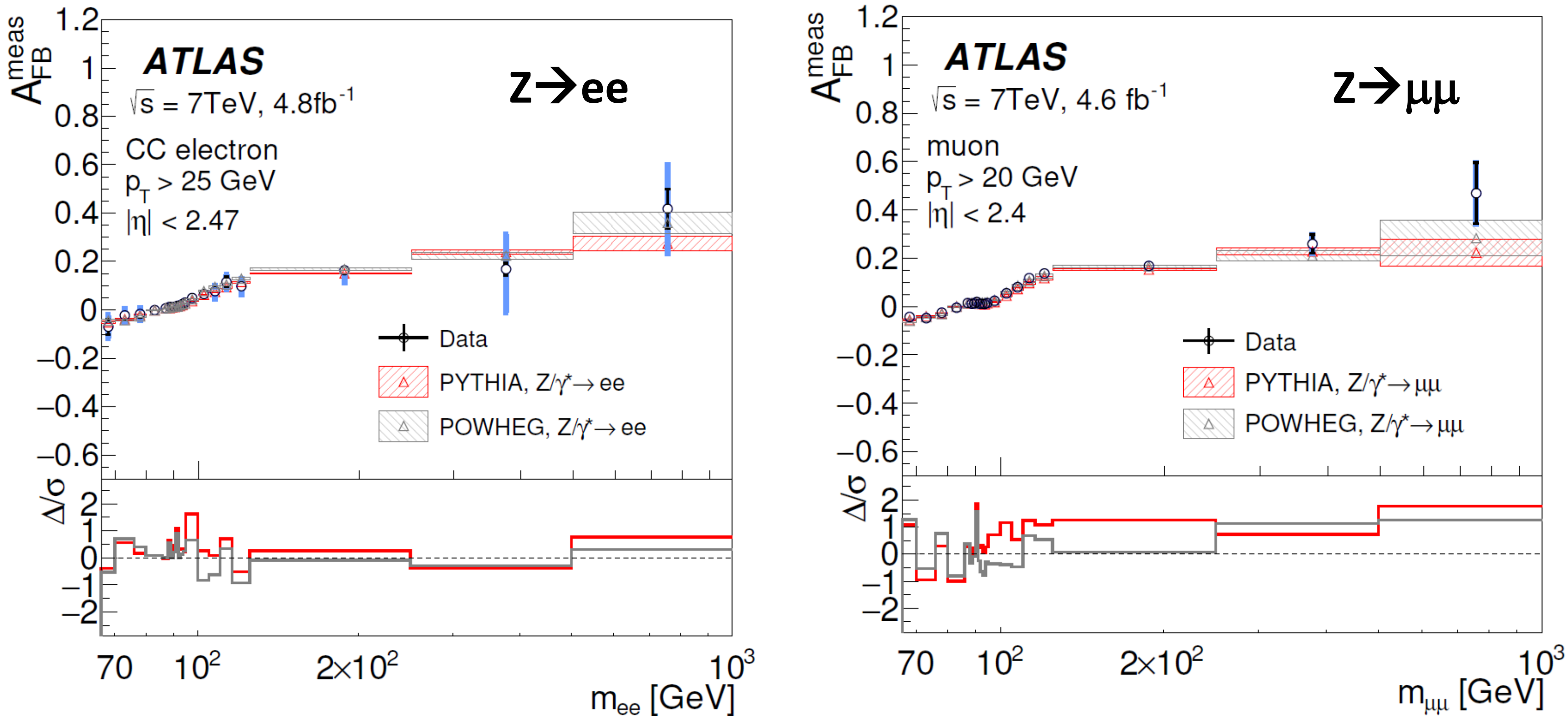


$$A_{\mathrm{FB}} = \frac{N_{\cos\theta^*_{\mathrm{CS}}\geq 0} - N_{\cos\theta^*_{\mathrm{CS}}<0}}{N_{\cos\theta^*_{\mathrm{CS}}\geq 0} + N_{\cos\theta^*_{\mathrm{CS}}<0}}$$

Collin-Soper Frame is used to minimize the ambiguity due to transverse momentum of incoming quark: θ^*_{CS}

7 TeV: Z Forward-Backward Asymmetry

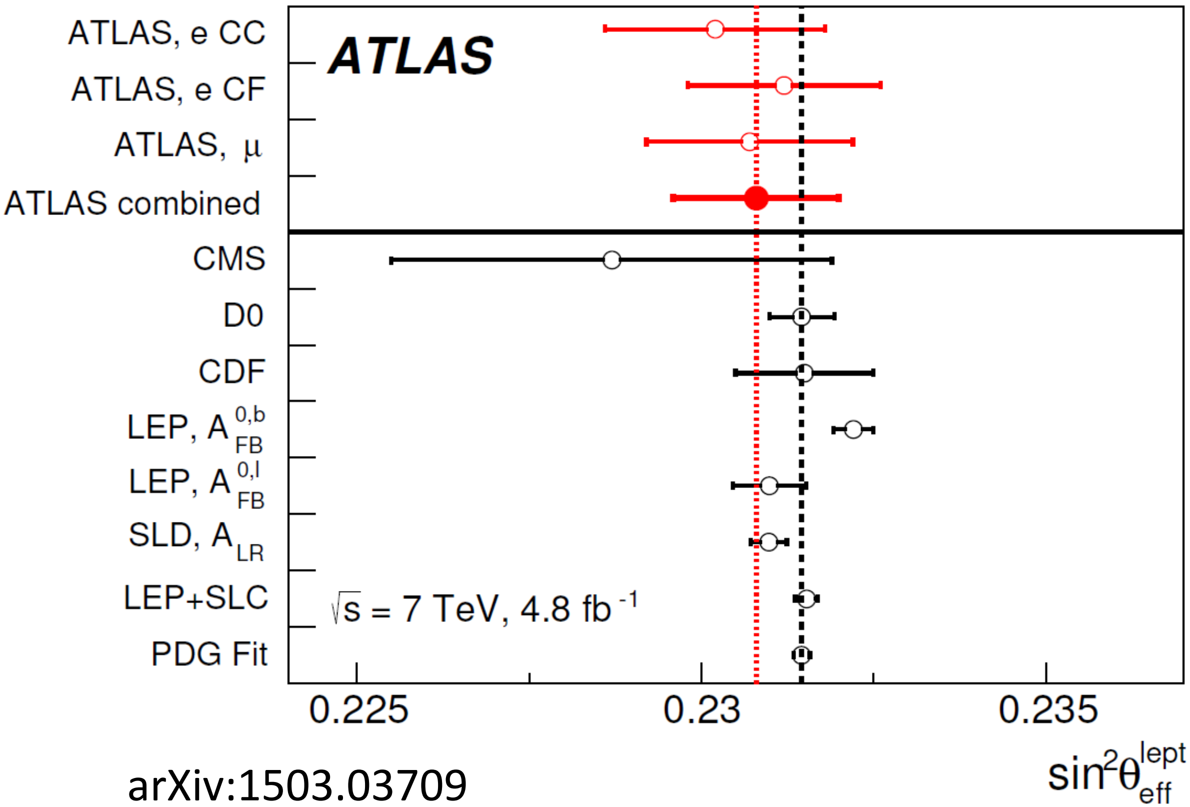
arXiv:1503.03709



A_{FB} only occur in the Z production, expect different A_{FB} in different mass range due to mixing of γ^* and Z production modes.

In general, nice agreement between data and prediction

7 TeV: Z Forward-Backward Asymmetry



arXiv:1503.03709

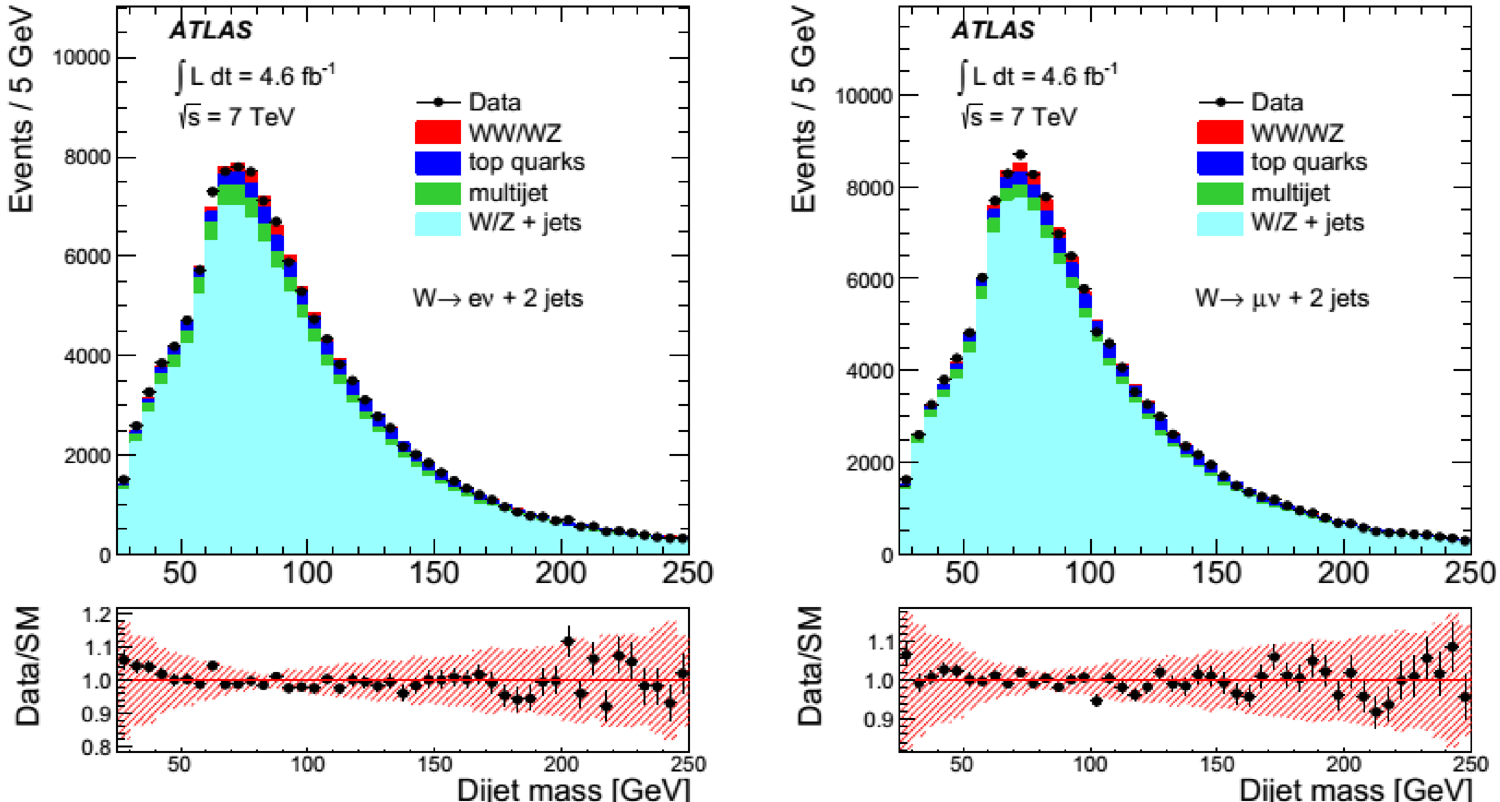
Template fit used to extract the most probable mixing angle w.r.t. measured A_{FB}

Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012$

- Large PDF uncertainty. Consistent with previous results
- Most precise record from LEP and SLC, Complementary test from ATLAS and CMS

7 TeV: WW+WZ measured in lνjj final state

- WW/WZ Semi-leptonic decay final state
  - lepton + Etmiss + two jets with inv. mass consistent with W/Z
  - Large irreducible background from W/Z+jets
  - Complementary sensitivity to aTGCs



JHEP01(2015)049

7 TeV: WW+WZ measured in lνjj final state

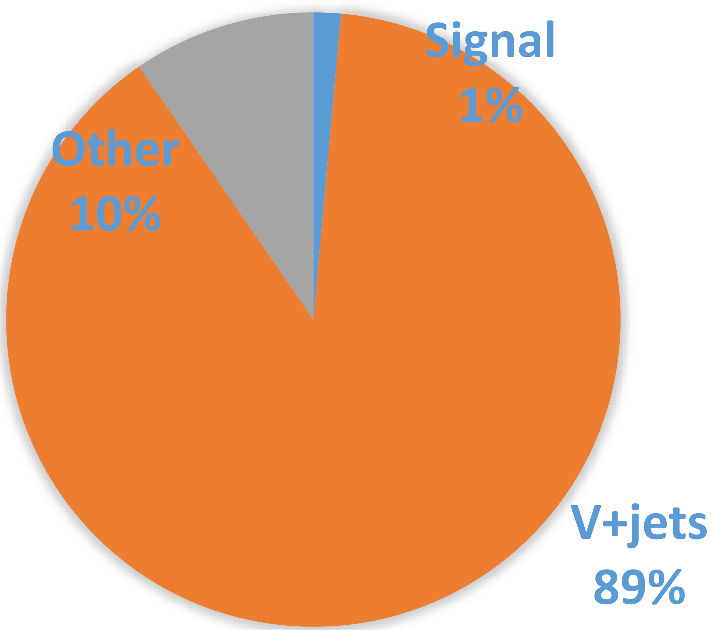
JHEP01(2015)049

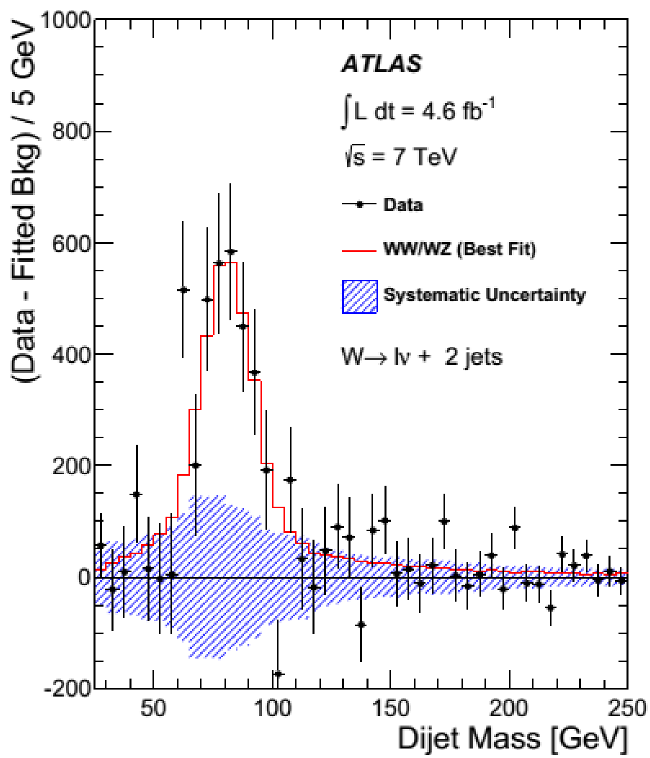
- **W/Z+jets background estimation**
  - MC shape
  - Relax Etmiss requirement and fit MC to data to derive scale factor, close to one

- **Cross Section Extraction** $\sigma_{\text{tot}} = 68 \pm 7\ (\text{stat.}) \pm 19\ (\text{syst.})\ \text{pb}$

Compatible with NLO prediction of 61.1±2.2 pb

Total data: $2.62\text{x}10^5$

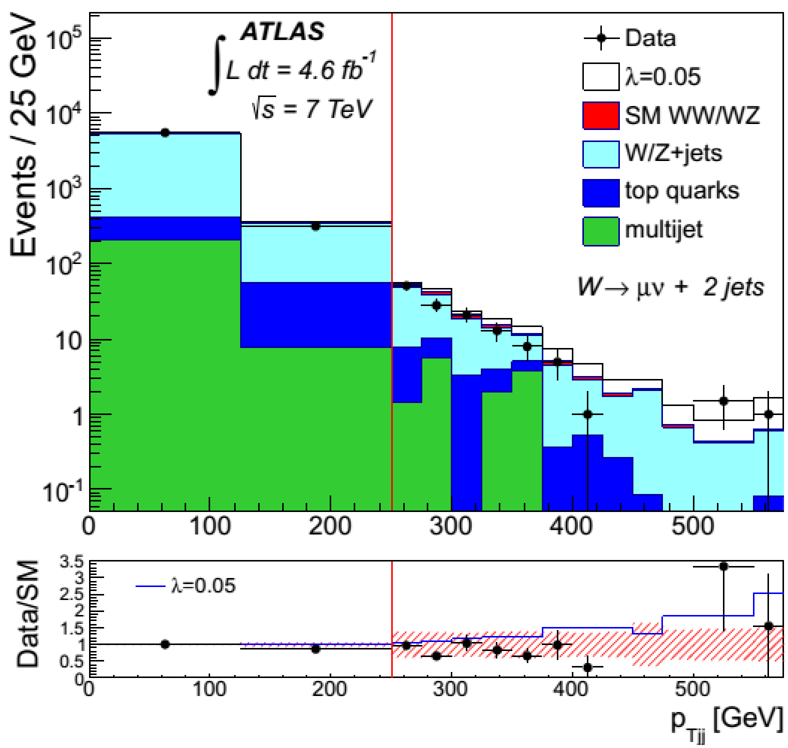


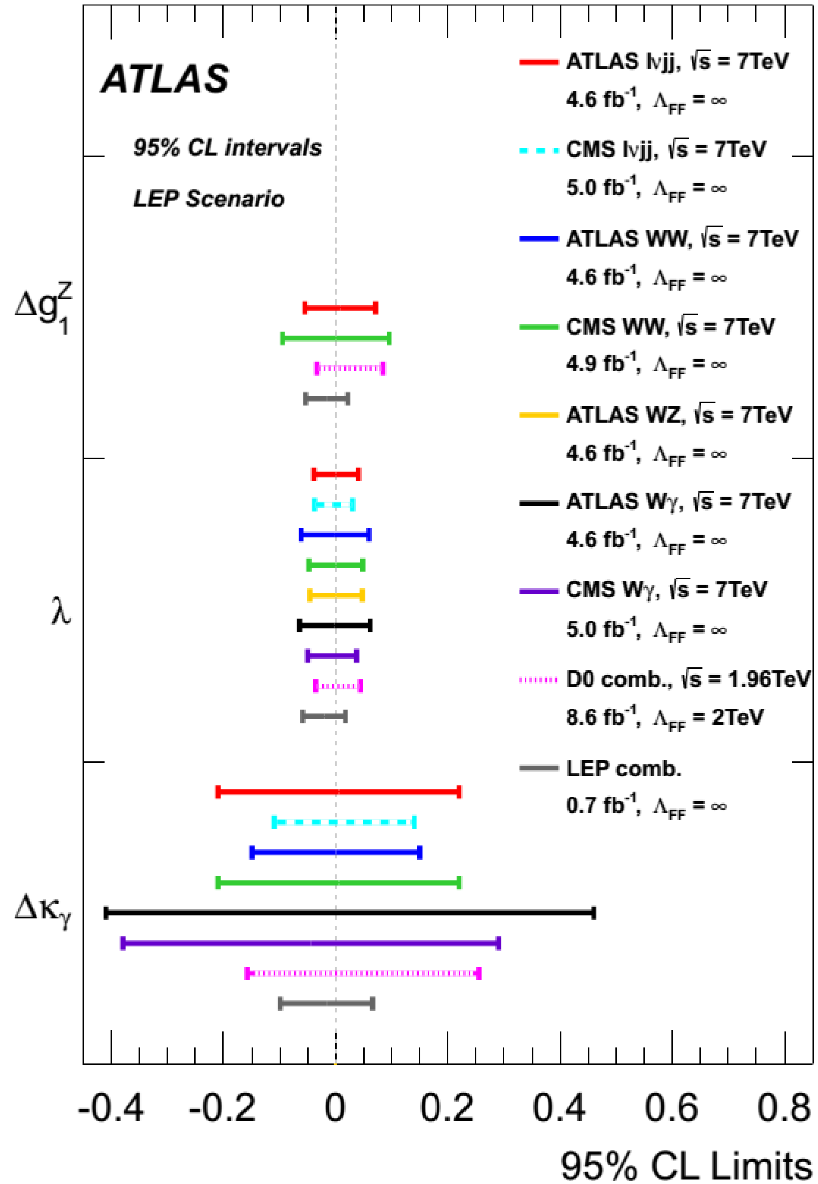


7 TeV: WW+WZ measured in lνjj final state

JHEP01(2015)049

- aTGCs explored by fitting Pt(jj) with 75<m(jj)<95 GeV
  - Stringent limits set on aTGCs parameters or EFT dimension six parameters





Summary

- Recent electroweak measurements been summarized
  - Overall consistency with SM prediction
  - Several discrepancies can be reduced by adding higher order corrections
    - Start to be sensitive to NNLO corrections
  - Stringent limits placed on anomalous boson couplings
  - Open channels inaccessible in the past, e.g. Tri-boson

- Prospects
  - A few final Run I papers are coming
  - Stay tuned for more 13 TeV results!

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