Recent Electroweak Results from ATLAS

QCD@LHC
1st - 5th September 2015

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On behalf of the ATLAS Collaboration

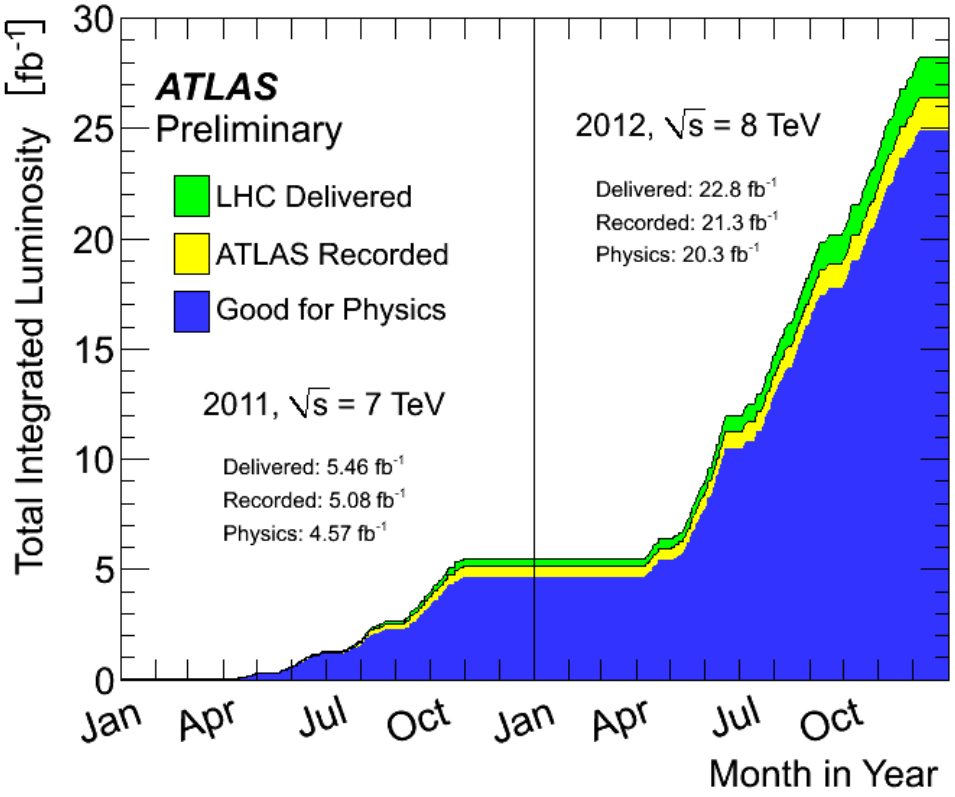
JDK

Electroweak Measurements

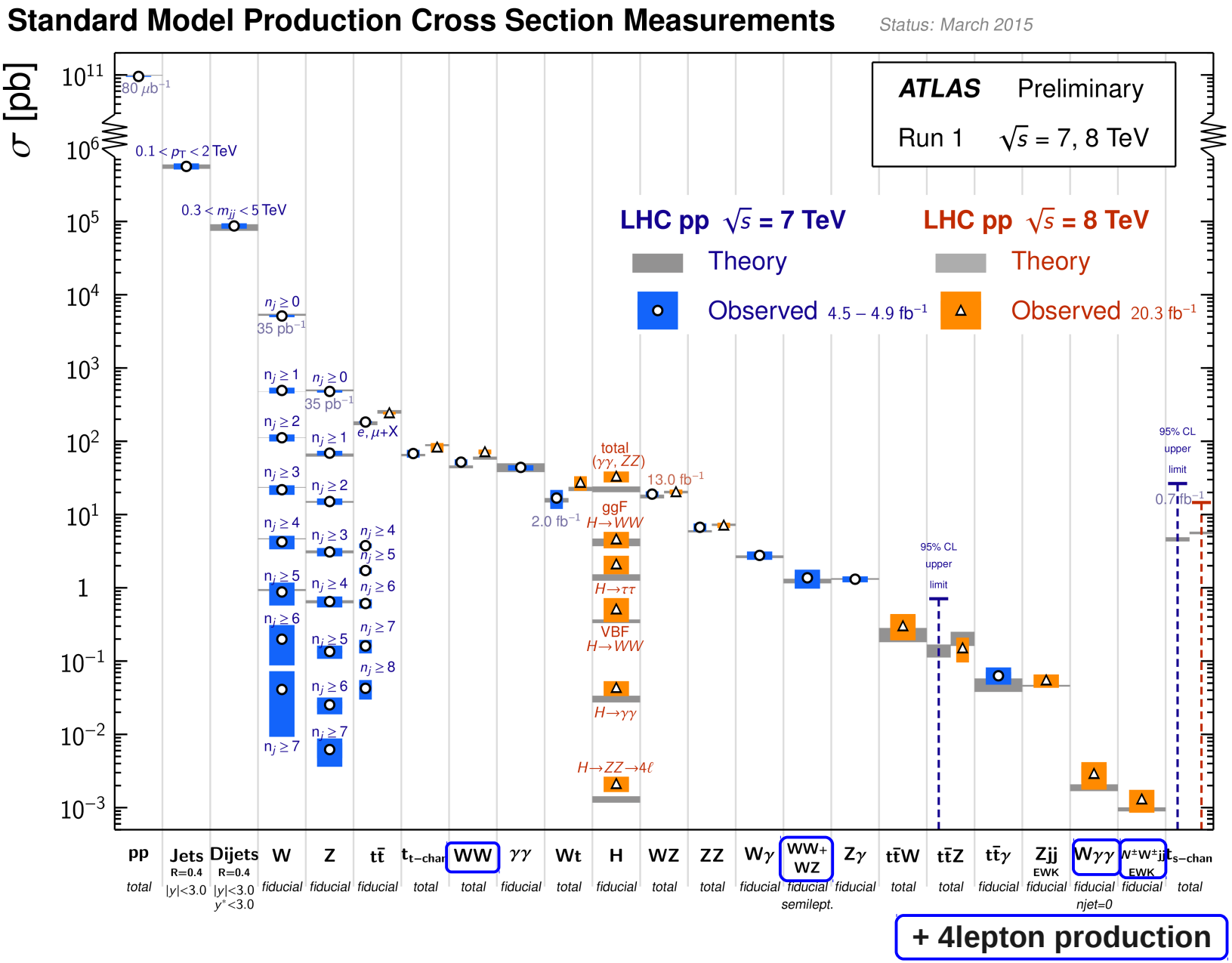
Goals for electroweak measurements:

- validate Standard Model up to TeV scale
  (e.g.: cross section measurements of rare processes)
- improve accuracy of SM parameters (e.g.: $\sin^2 \Theta_{eff}^{lep}$)
- model independent search for new physics via anomalous triple/quartic gauge couplings (aTGC/aQGC)
- comparison with and better understanding of higher order QCD and EW effects

Talk will discuss 7TeV and 8TeV studies



SM Cross Section Measurements



WW Production - Motivation

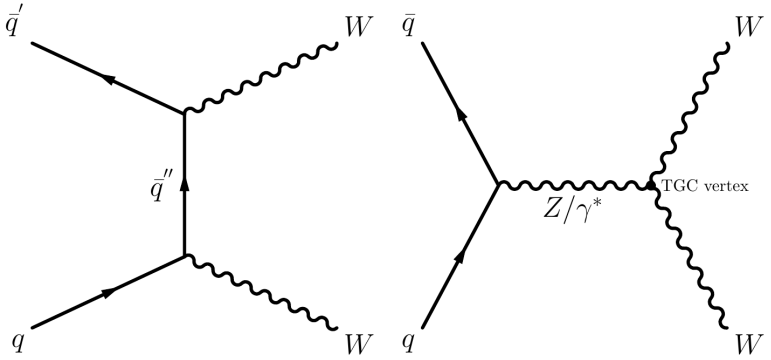
$\sqrt{s}$ = 8TeV, $\int \mathcal{L}$ = 20.3 fb^{-1}

ATLAS-CONF-2014-33

Goals:

- test of the non-abelian structure of SM
- sensitive to new physics via aTGC
- non-resonant WW production is irreducible background to Higgs boson studies

possible production processes

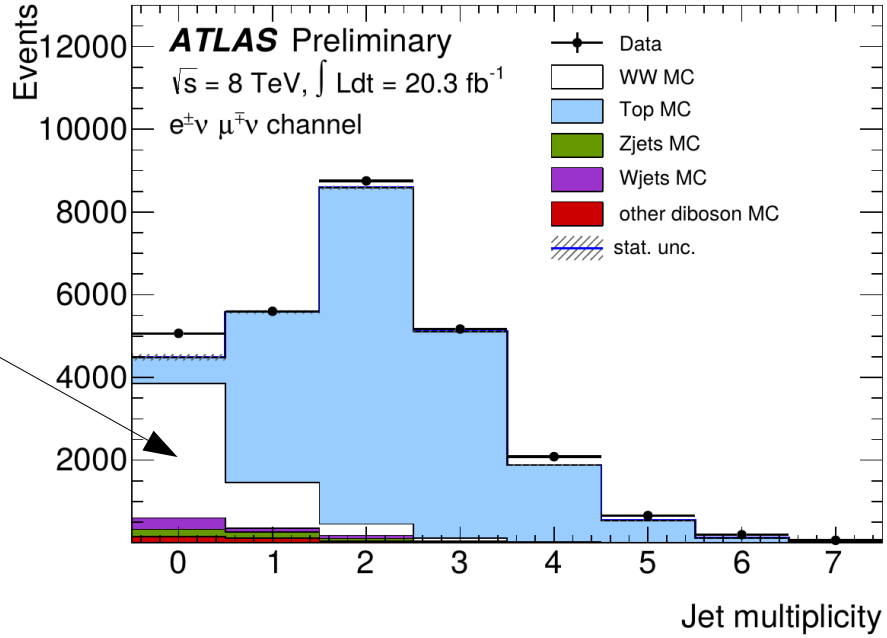


Signature:

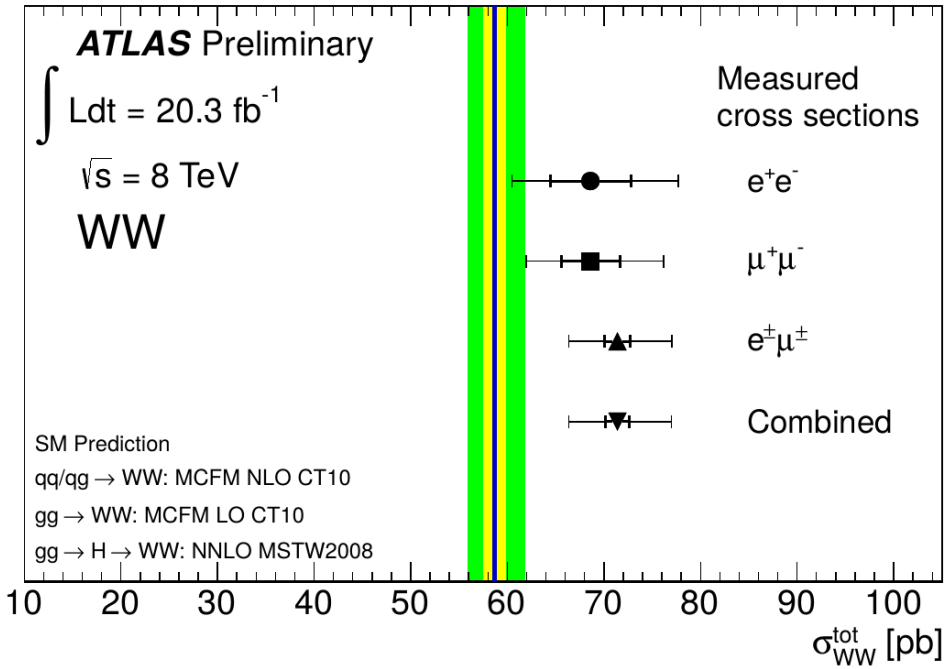
- 2 W decayed into leptons and neutrinos
  (2 isolated leptons and high missing energy)
- jet veto (reduce top background)

Backgrounds:

- $t\bar{t}$, Wt, W+jets, Z+jets (data driven)
- diboson (MC)



WW Production - Cross Section



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

- Agreement within channels
- SM prediction: NLO qq → WW
  NNLO gg → H → WW
  LO non-resonant gg → WW

Latest update:

- arXiv:1410.4745: fiducial cross section measurements compatible with estimated NNLO+NNLL effects (agreement within ~1σ)
- arXiV:1408.5243:
  NNLO SM prediction
  → difference reduces to 1.1σ

With: NNLO qq → WW
NNLO gg → H → WW

➡ 2.1σ difference to SM prediction
(using CT10 PDF and standard PDF and scale uncertainties)

Semileptonic WW+WZ - Cross Section

JHEP 01 (2015) 049

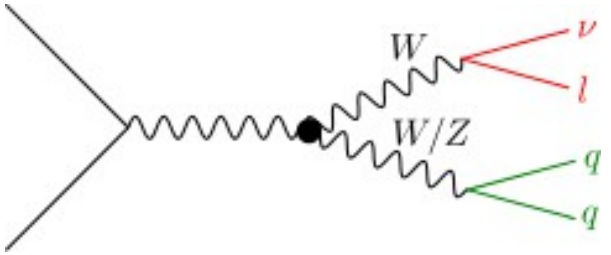
- $\sqrt{s}$ = 7TeV, $\int \mathcal{L}$ = 4.6 fb^{-1}

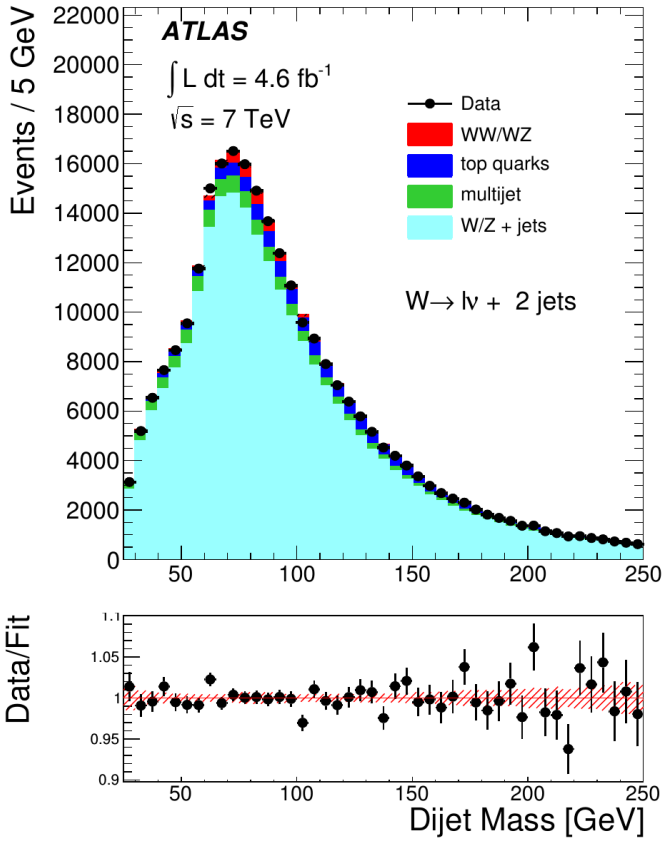
Goals:

  - measure cross section σ(WW/WZ → lνjj), with l = e,μ
  - sensitive to new physics via aTGC

Signal:

  - one W decayed into lepton and neutrino (one isolated lepton and high missing energy)
  - one W or Z decayed into jets (exactly two jets)





- Significance of signal: 3.4σ
- Template fit used to extract cross section:

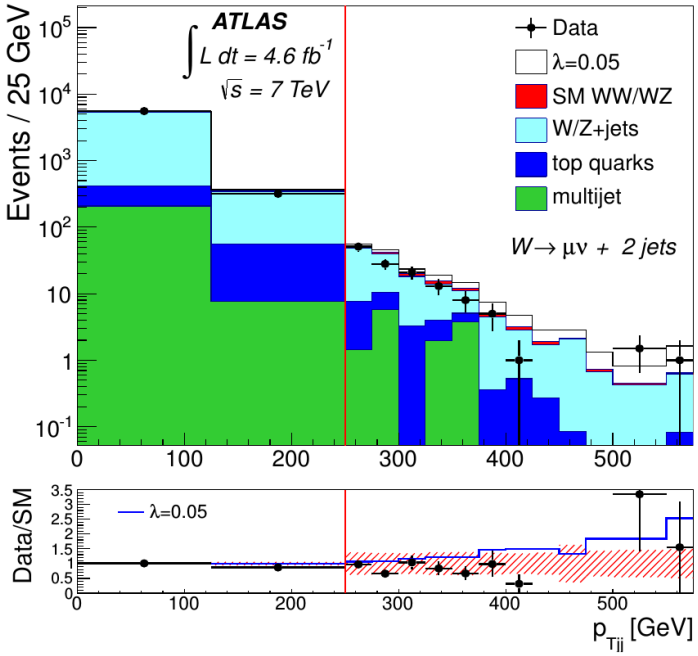
$$\sigma_{tot} = 68 \pm 7\,(stat.) \pm 19\,(syst.)\,pb$$

with NLO SM prediction:

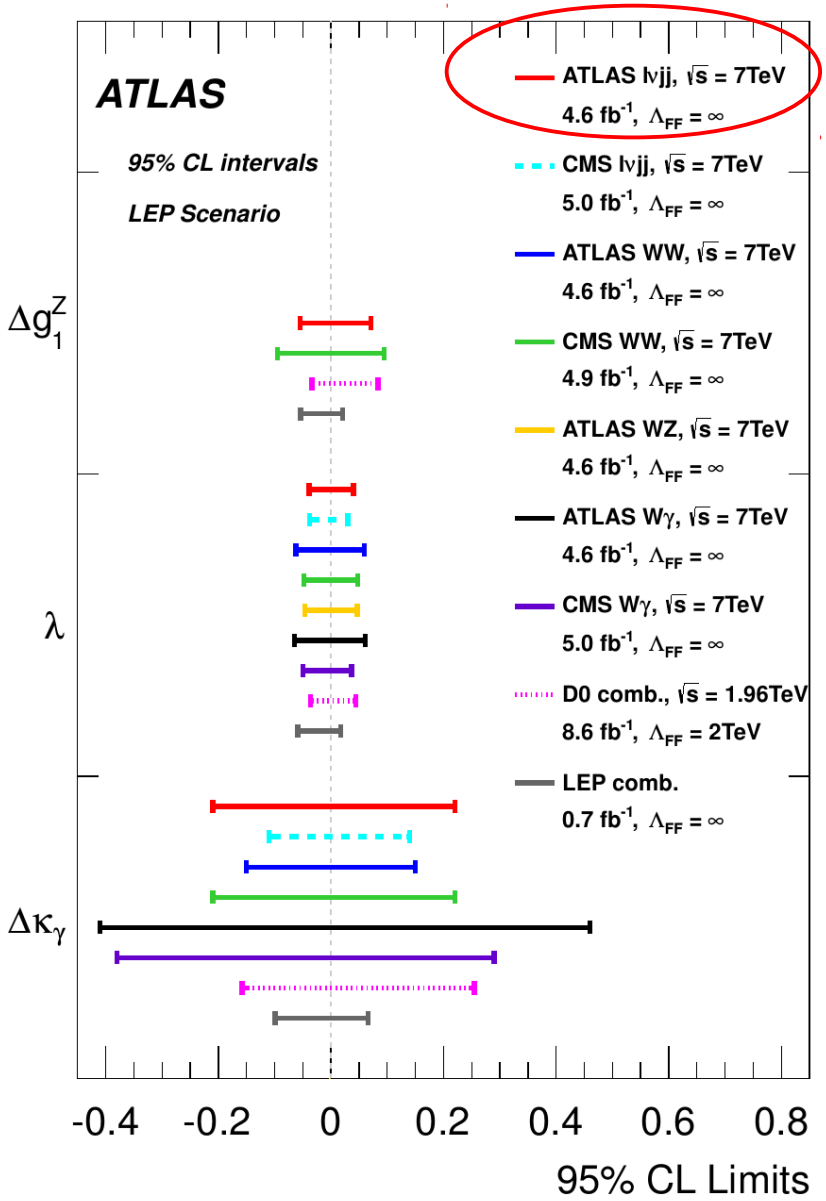
$$\sigma_{tot}^{theo} = 61.1 \pm 2.2\,pb$$

Semileptonic WW+WZ - aTGC

- Used LEP convention: three free parameters:
  λ , $\Delta\kappa_\gamma$ and Δg_1^Z
- Limits set for 75 GeV <m_{jj} < 95 GeV by fitting $p_{T,jj}$



Competitive results to other diboson analyses



results also available in effective field theory approach

Wγγ - Motivation

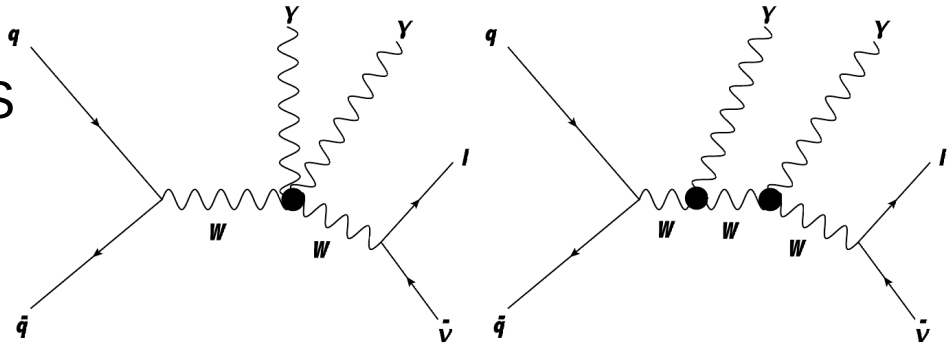
√s = 8TeV, ∫ℒ = 20.3 fb^{-1}

Phys. Rev. Lett. 115, 031802

Goal:

- measure first triboson process in ATLAS
- measure cross section of rare process
- sensitive to new physics via aQGC

possible production processes

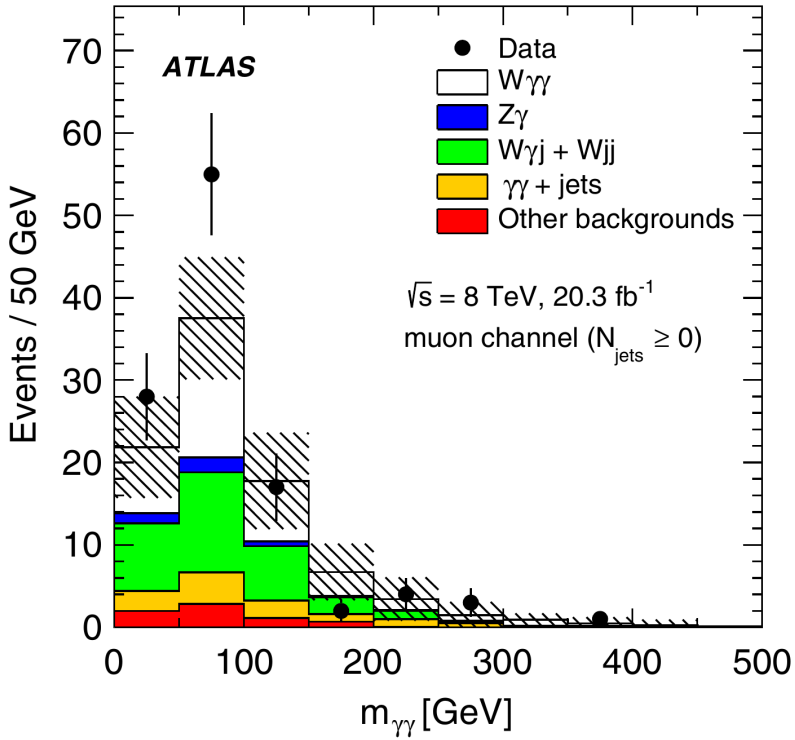


Signal:

- one W decayed into lepton and neutrino
  (one isolated lepton and high missing energy)
- two isolated photons

Backgrounds:

- largest contribution: jets faking photons and leptons (data driven method)



Wγγ - Cross Section

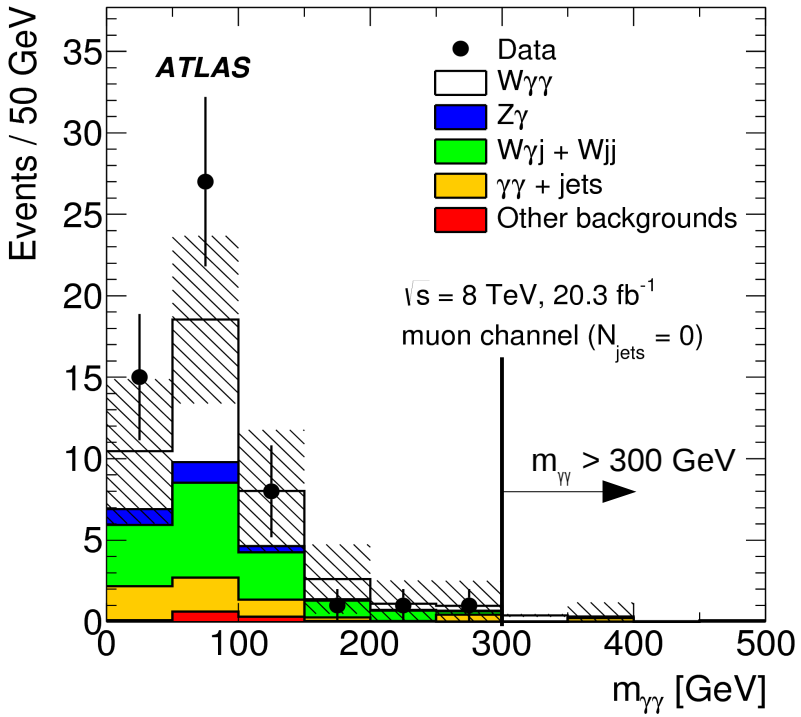
- Cross section obtained from maxiumum-likelihood fit
- Largest uncertainty: data-driven background estimate
- Measured cross sections are higher than NLO SM predictions by 1.9σ
- Above 3σ evidence for the Wγγ process for the first time

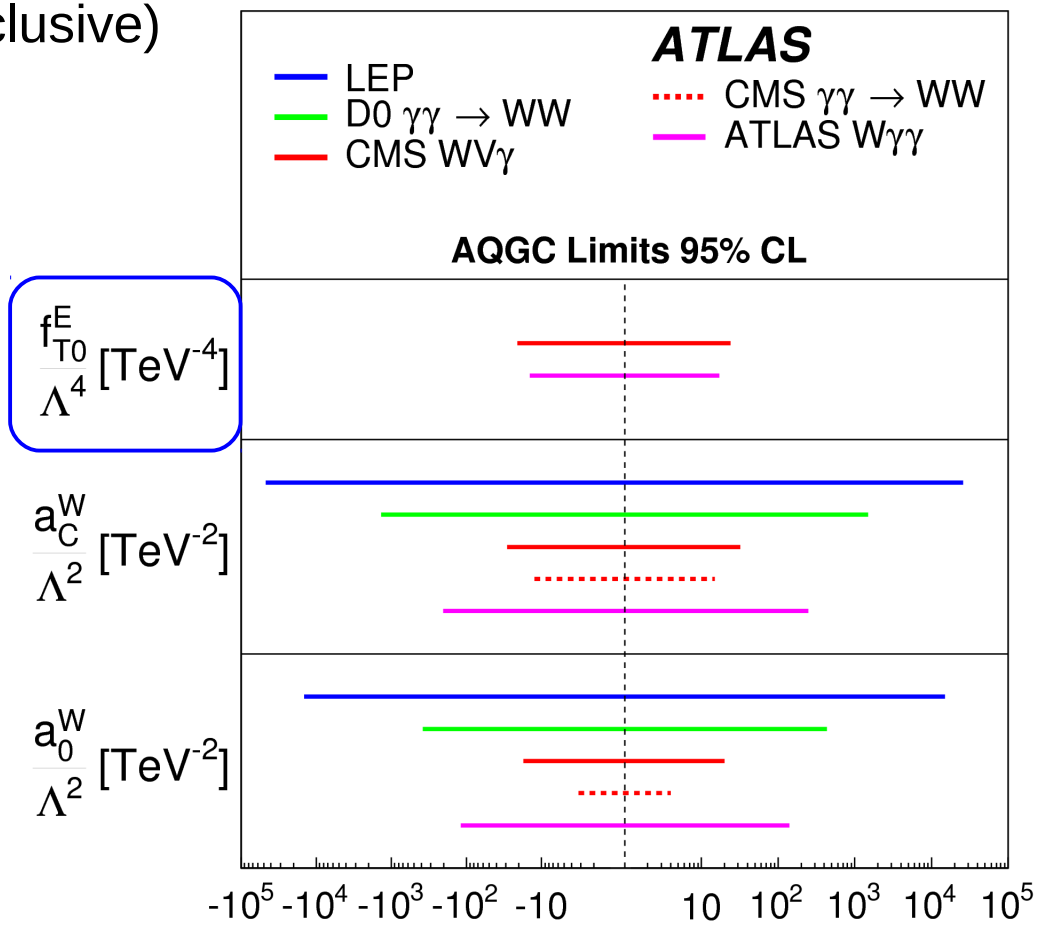
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (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 triboson process measured in ATLAS

Wγγ - aQGC

- Limits set
  - for dim-8 operators (effective field theory approach, Phys. Rev. D. 91, 012006)
  - for $m_{\gamma\gamma}$ > 300 GeV and N_{jets} = 0 (exclusive)
- Improved limits to LEP / Tevatron and similar limits to CMS (different channels)



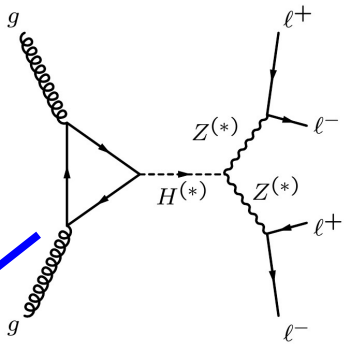


Limit on f_{T0} / Λ^4 improved

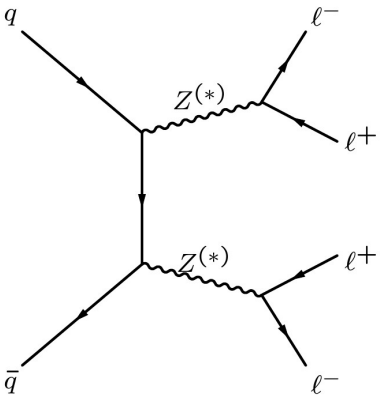
4-Lepton - Motivation

Goals:
- differential cross section

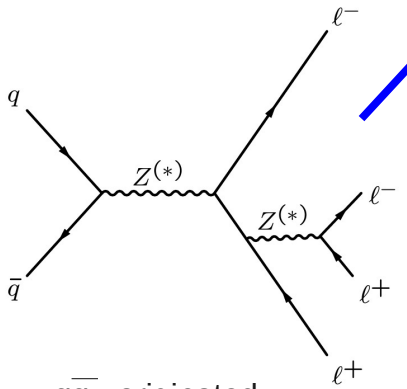
ATLAS-CONF-2015-031



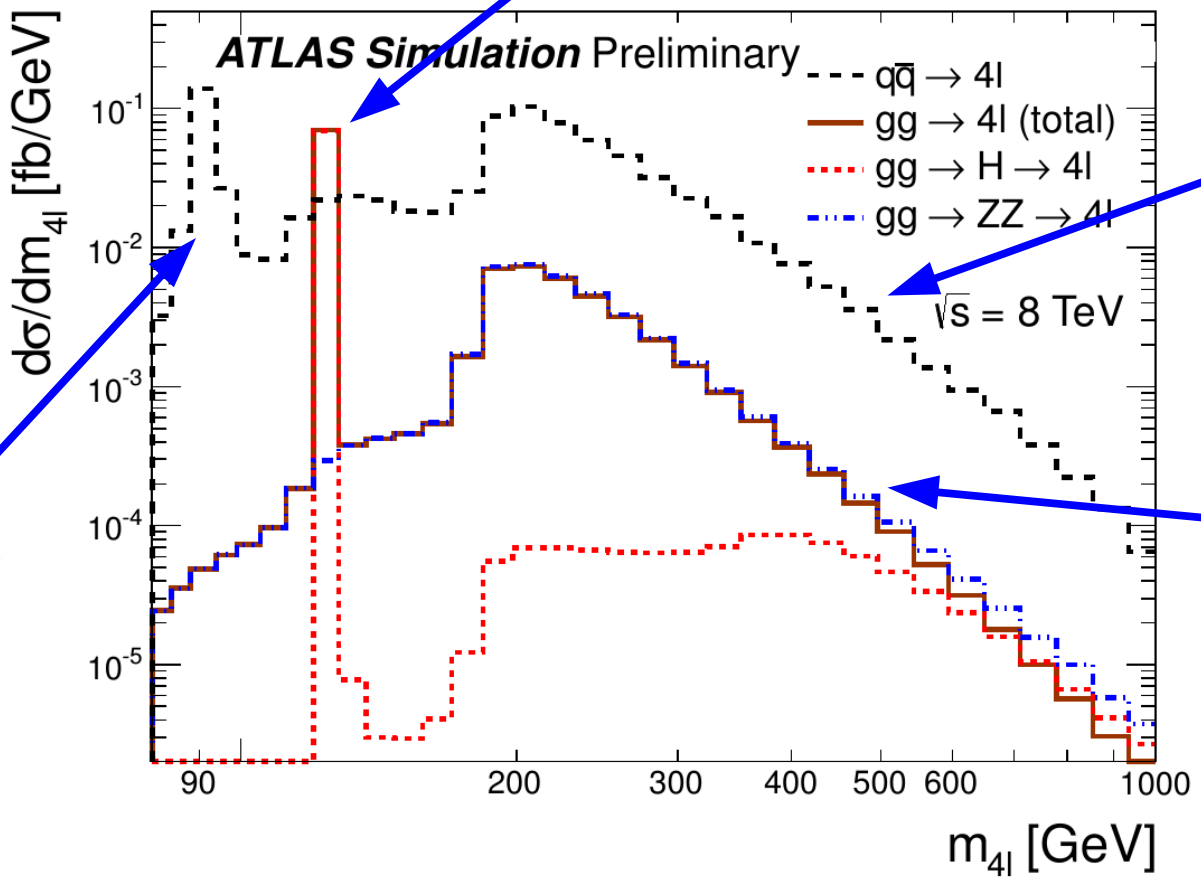
4l from Higgs decay

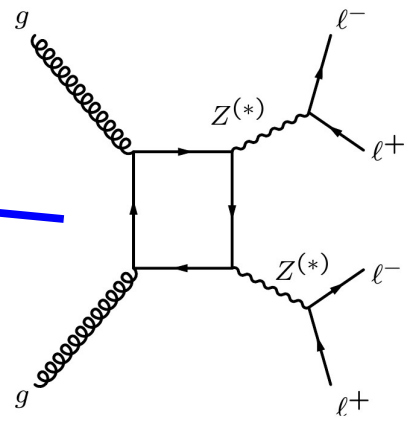


$q\bar{q}$ - originated
t-channel



$q\bar{q}$ - originated
s-channel

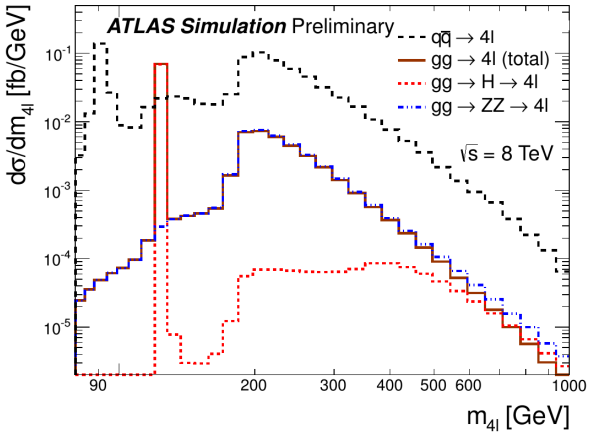




non-resonant ZZ→4l
e.g.: via ggF

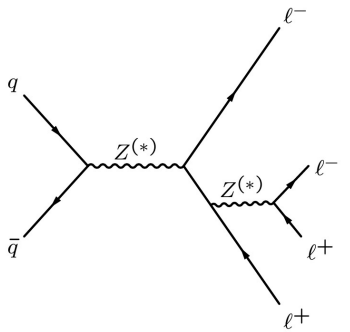
4-Lepton - Motivation

$\sqrt{s}$ = 8TeV, $\int \mathcal{L} = 20.3\ fb^{-1}$



Goals:

- differential cross section
- measure gg → 4-lepton signal strength w.r.t. its LO prediction
- test of SM through interplay of QCD and EW effects for different production mechanisms

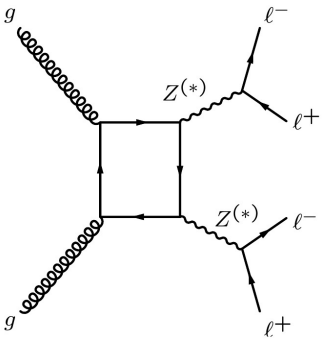


Signal:

- 2 pairs of opposite charged isolated leptons (3 channels: 4μ, 2e2μ, 4e)

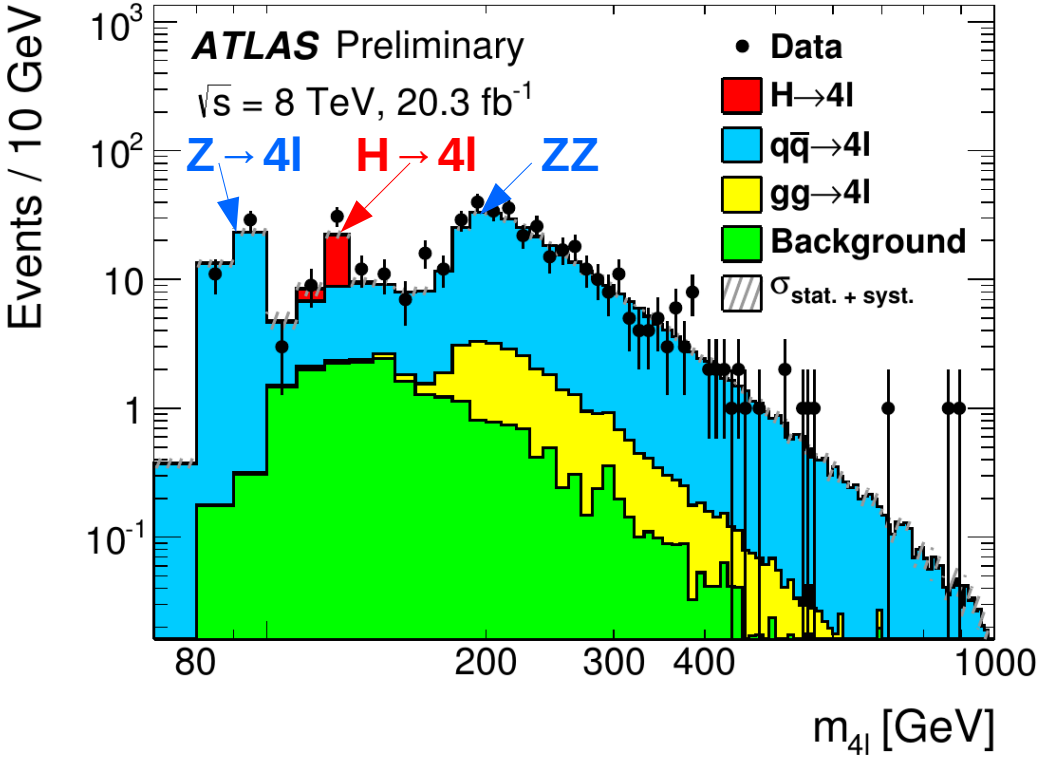
Backgrounds:

- Z+jets and $t\bar{t}$ (data driven)
- ZW, Zγ, Z+top, VVV, ZH and double Drell Yan (MC)

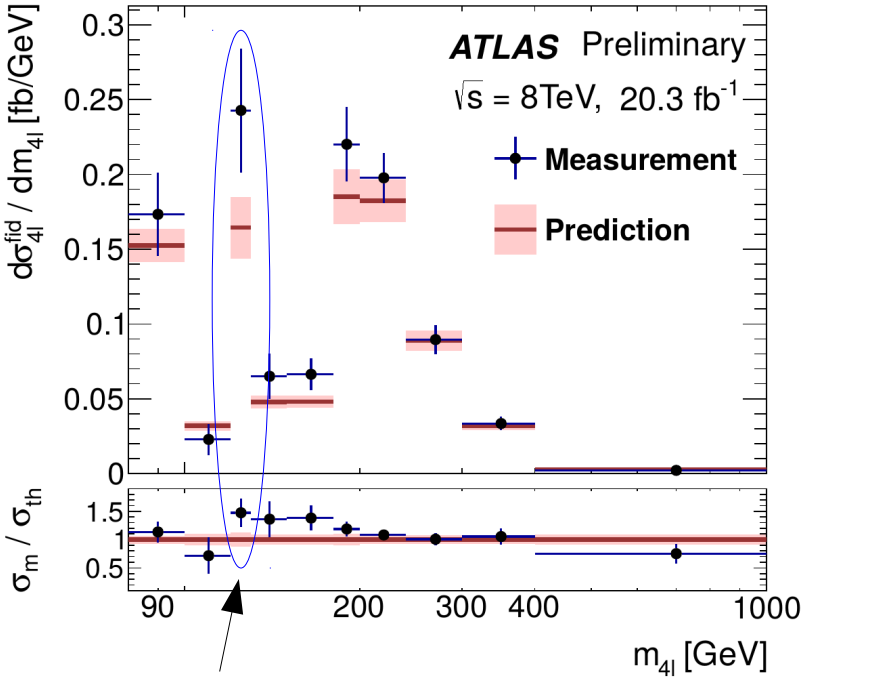


4-Lepton - Cross Section

476 4-lepton candidate events and **26.2 ± 3.6** expected background events



differential cross section



ratio of data/MC compatible with ATLAS H → ZZ
Phys.Rev.D 91, 012006

cross section in extended phase space
(same geometric and kinematic acceptance for leptons)

$\sigma_{ext} = 73 \pm 4(\text{stat}) \pm 4(\text{sys}) \pm 2(\text{lumi})$ fb

$\sigma_{theo} = 65 \pm 4$ fb

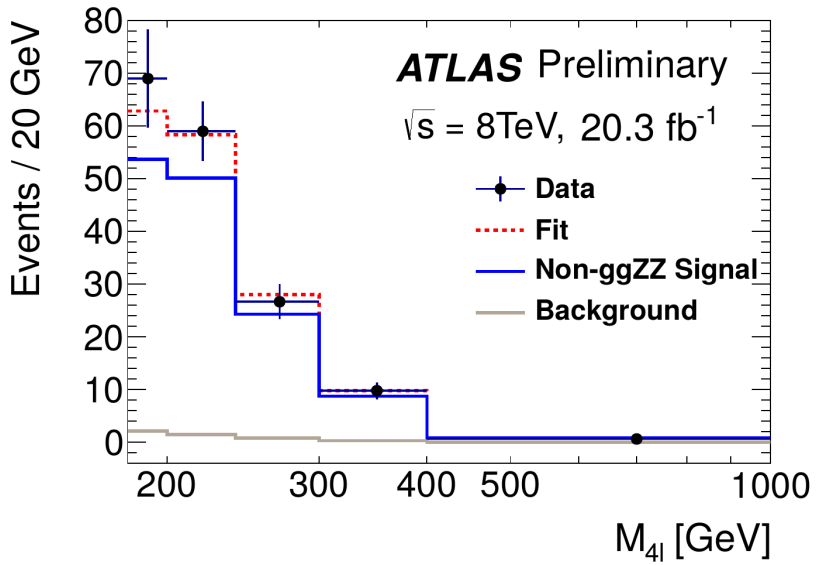
generally good agreement

4-Lepton - μ_{gg} Signal Strength

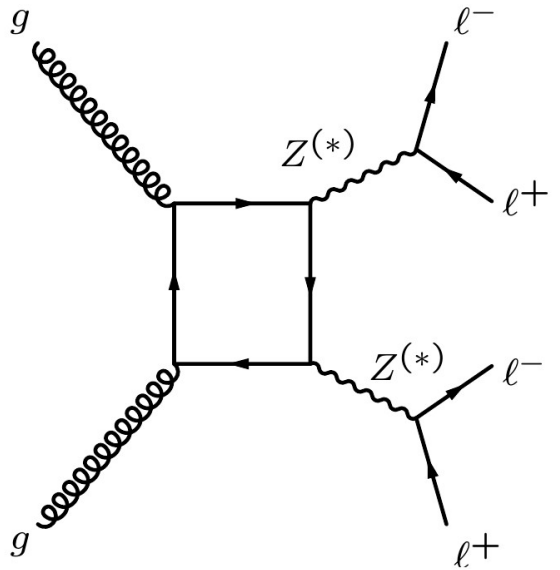
- Determine signal strength for non-resonant gg→4-lepton production:

$$\mu_{gg} = \frac{\sigma(data)}{\sigma_{gg}(LO)}$$

- Require: M_{4l} > 180 GeV (gg→4l is dominated by continuum gg → ZZ)
- μ_{gg} extracted from M_{4l} distribution via likelihood fit
- $q\bar{q}$ → ZZ constrained in fit (QCD NNLO and EW NLO)



non resonant ZZ→4l production via ggF



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

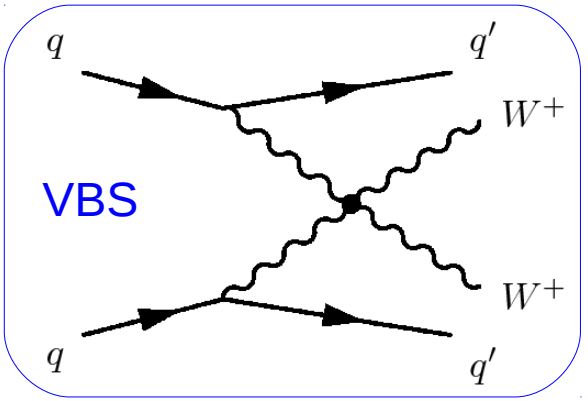
$W^{\pm}W^{\pm}jj$ - Motivation

Phys.Rev.Lett 113, 141803

$\sqrt{s}$ = 8TeV, $\int \mathcal{L}$ = 20.3 fb^{-1}

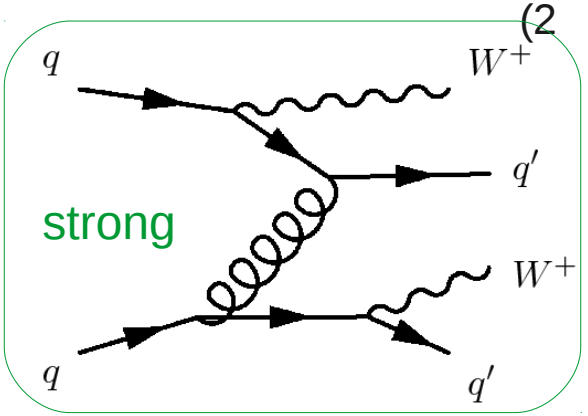
Goals:

- first observation of VBS WW production
- probe nature of electroweak symmetry breaking
- sensitive to new physics via aQGC



Signal:

- 2 W decayed into leptons and neutrinos (2
  (same sign isolated leptons and missing energy)
- at least 2 jets



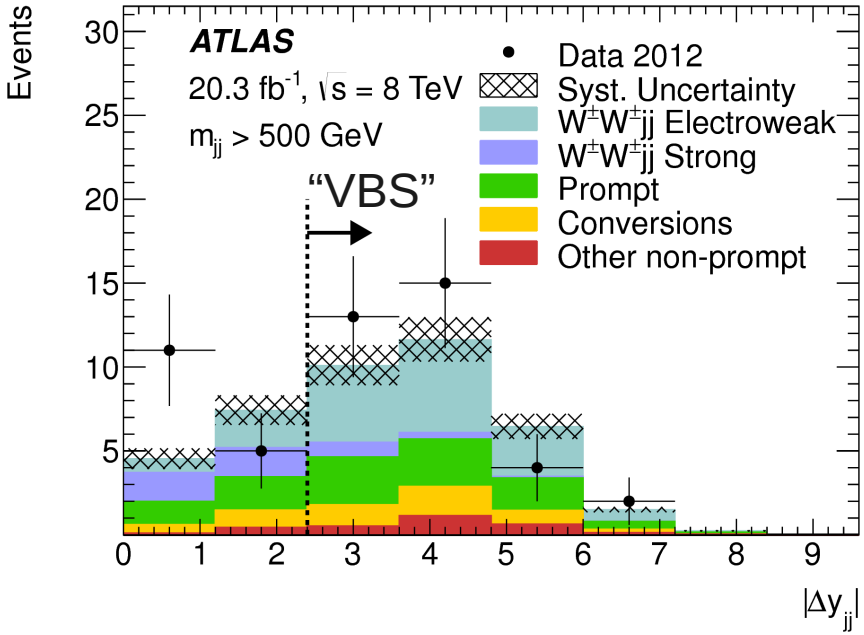
Backgrounds:

- prompt leptons (e.g. WZ/γ*, ZZ+jets,...) (MC)
- conversions (e.g. Wγ,...) (MC)
- other non-prompt (e.g. W+jets, $t\bar{t}$, single top,...) (MC and data)

$W^{\pm}W^{\pm}jj$ - Cross Section

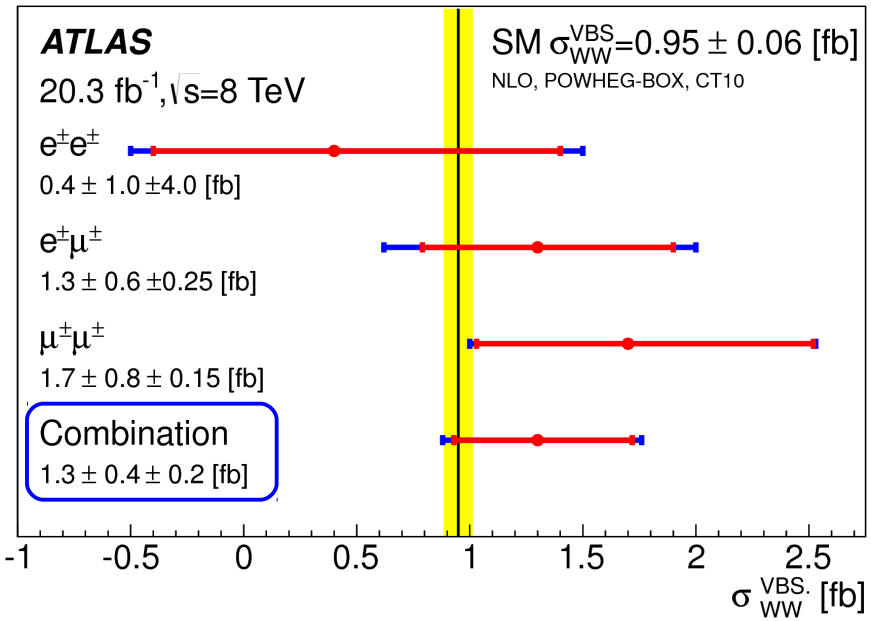
Two signal regions:

- **"inclusive"**
  - study combination of EW and strong mechanisms
- **"VBS"**
  - enhance purity of EW production



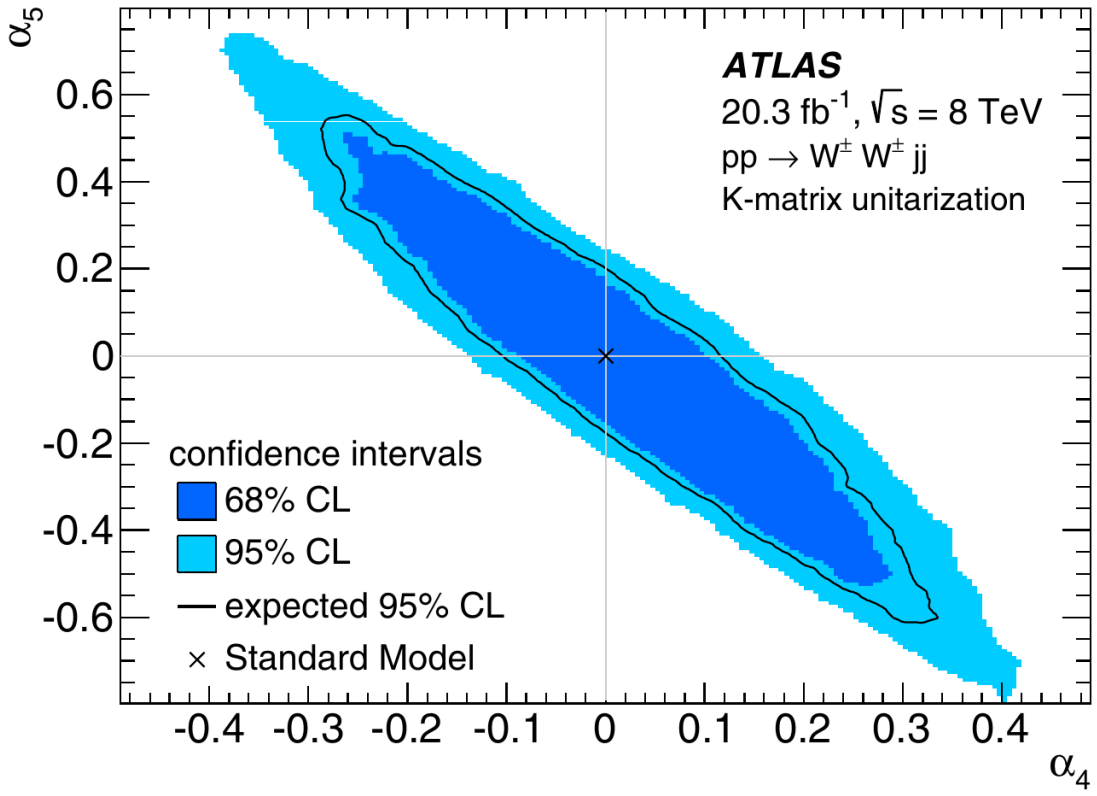
- Signal significance 3.6σ
- First ever evidence for EWK VV → VV scattering at LHC with
- Profile likelihood used to extract cross sections
- SM expected cross section :

$$\sigma_{fid}^{theo} = 0.95 \pm 0.06\, fb$$



$W^{\pm}W^{\pm}jj$ - aQGC Limits

- "VBS" region results used
- Theoretical cross sections from Whizard+Pythia8 with k-matrix unitarization
- Limits on dim-8 operators, using parametrization from JHEP11 (2008) 010 and Phys.Rev.D 22, 1166
- First limits on $\alpha_{4,5}$ set



Summary

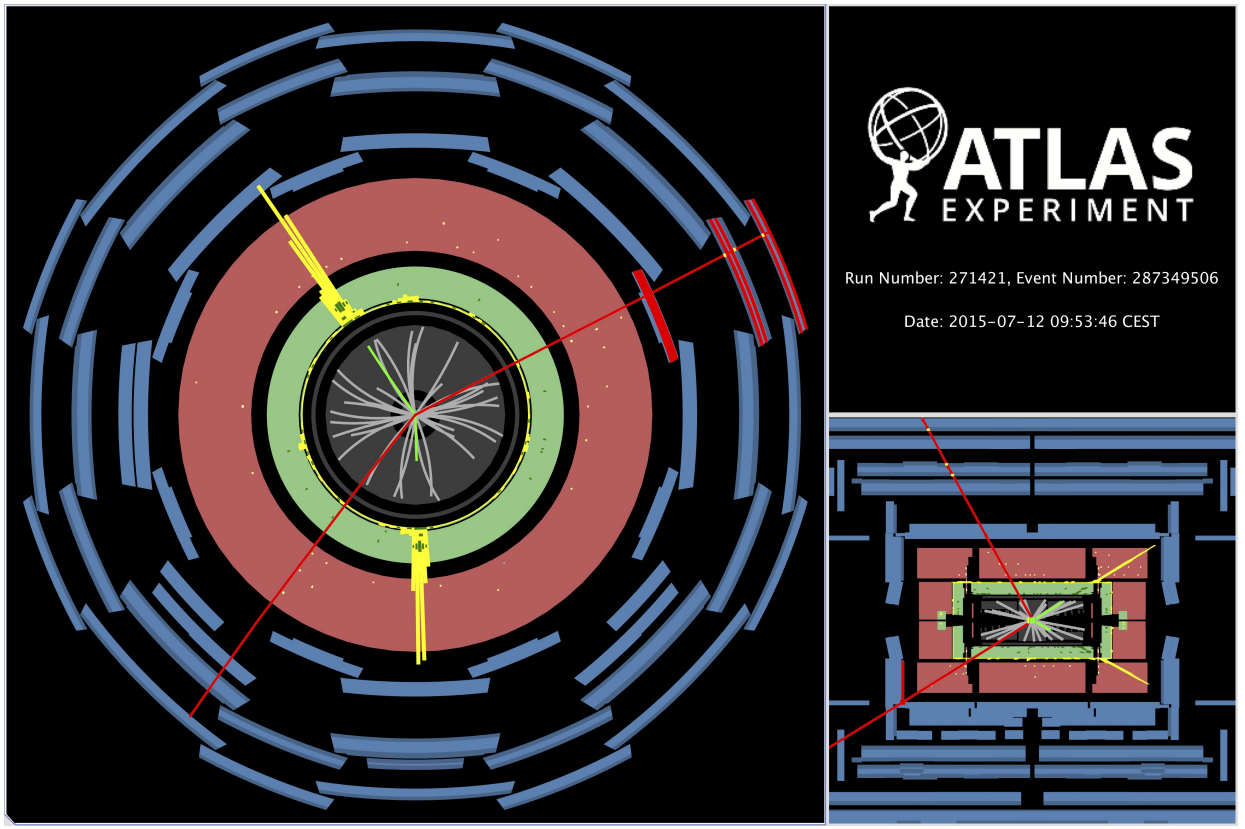
- Many analyses performed by the ATLAS electroweak working group, but only few presented:
  - Measurements of **WW production**
  - Measurement of **semileptonic WW/WZ production** and **limits on aTGS**
  - First **evidence of Wγγ,** first measurement of triboson production in ATLAS and **limits on aQGS**
  - **4 lepton production** and strength of the **gluon-gluon fusion component**
  - Evidence for the electroweak production of **$W^{\pm}W^{\pm}jj$** and **limits on aQGS**

- Overall good agreement with the SM expectations!

ATLAS public results are available at:

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

Thank you and stay tuned - more results soon!



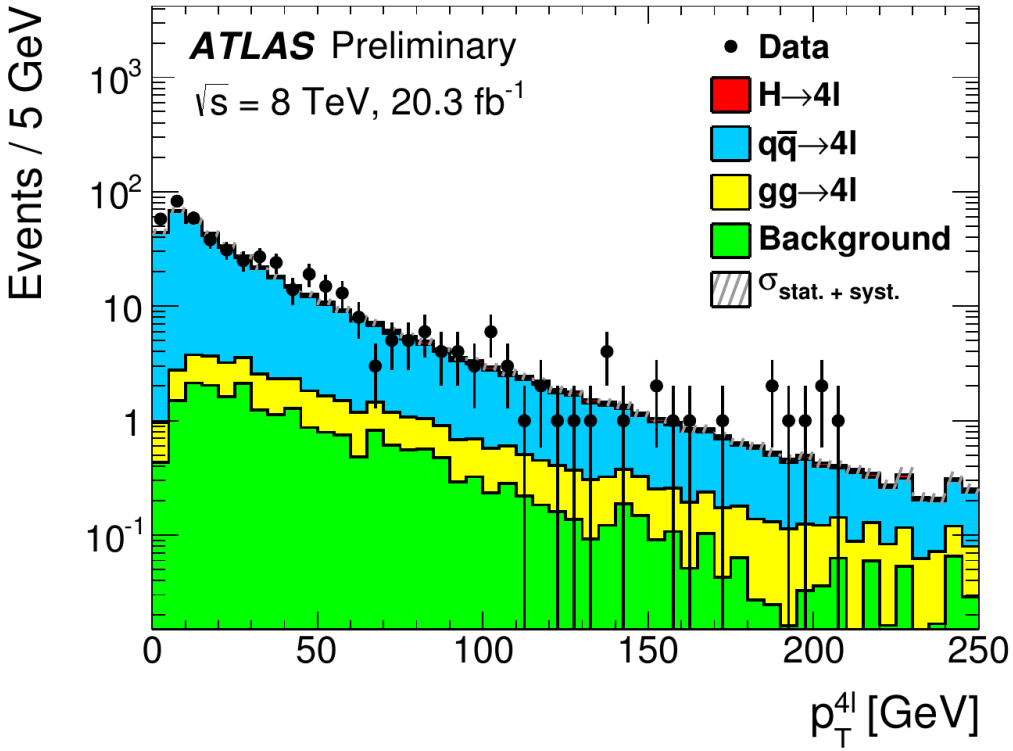
pp → ZZ → e^+e^- $\mu^+\mu^-$ candidate event, √s = 13TeV

Backup

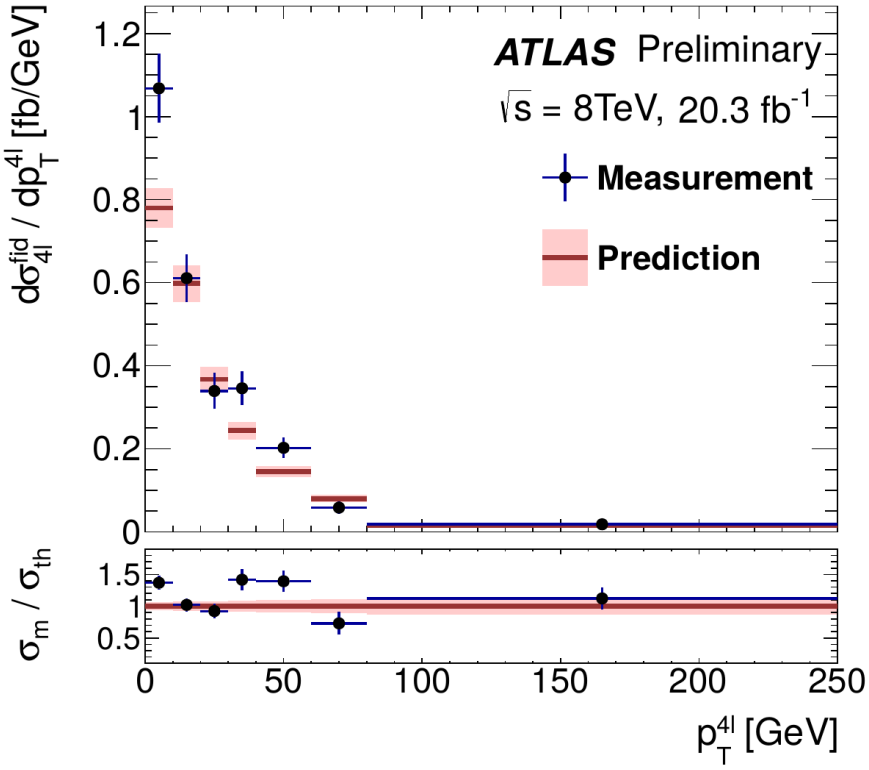
4-Lepton Production - Results III

Results as a function of the p_T^{4l}

data and MC prediction comparison

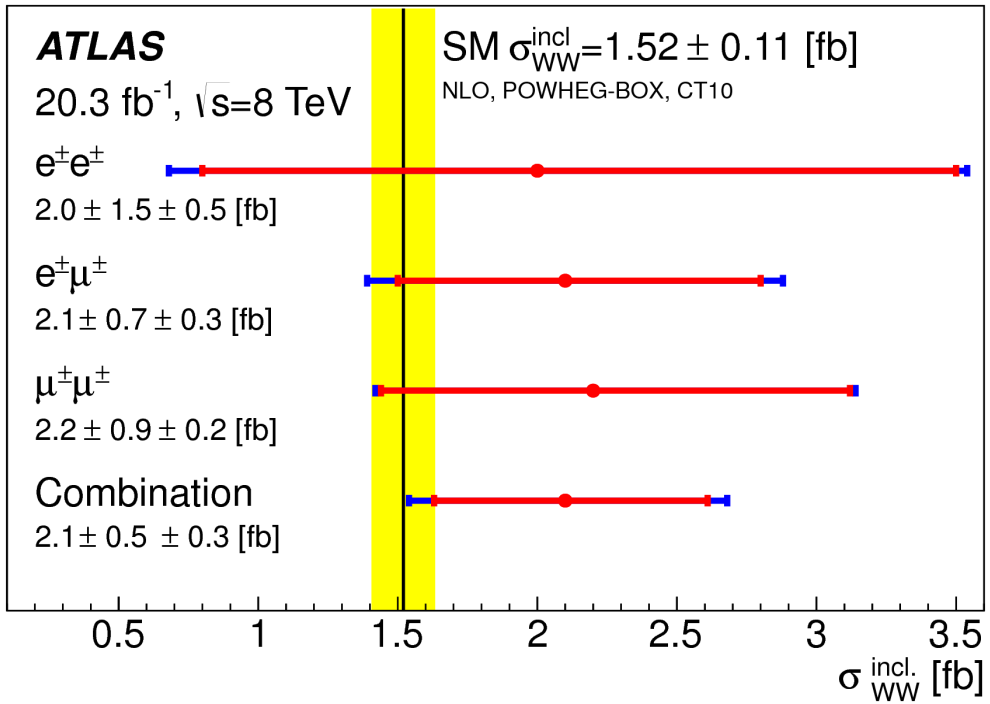


measured differential cross section



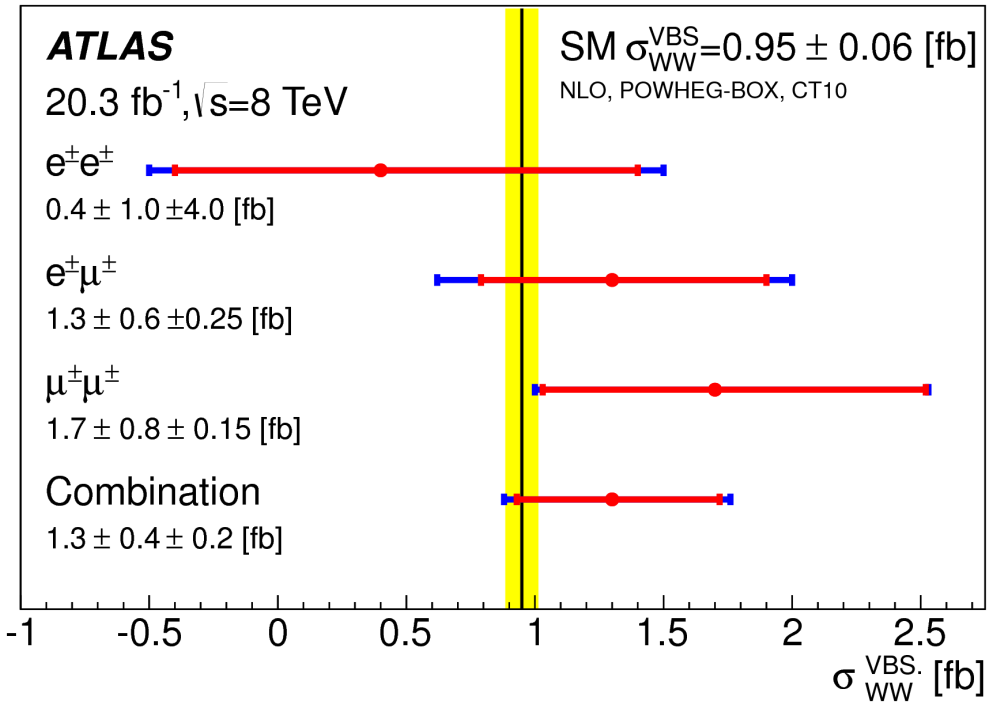
$W^{\pm}W^{\pm}jj$ - Results

"inclusive"



$$\sigma_{fid}^{theo} = 1.52 \pm 0.11\, fb$$

"VBS"



$$\sigma_{fid}^{theo} = 0.95 \pm 0.06\, fb$$

Z/γ* Forward-Backward Asymmetry

arXiv: 1503.03709v1

- $\sqrt{s}$ = 7TeV, $\int \mathcal{L}$ = 4.6 fb^{-1}
- Asymmetry due to V-A nature of EW interaction

Goals:

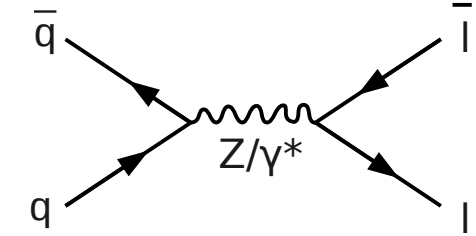
- measure $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$
- extract weak mixing angle: $\sin^2 \Theta_{eff}^{lep}$

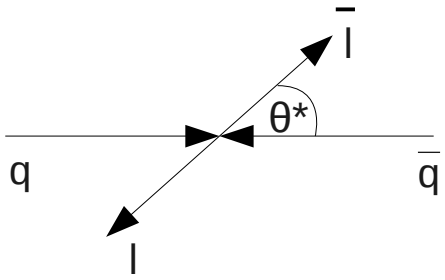
Signal:

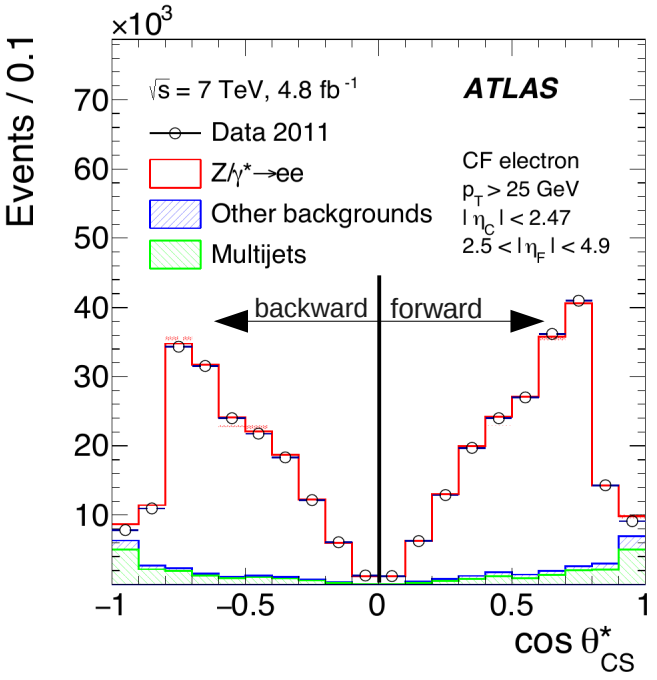
- Drell-Yan Z events: $q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+ l^-$
- two leptons
  (muons $|\eta| < 2.4$, electrons $|\eta| < 2.5$ (C) and $2.5 < |\eta| < 4.9$ (F))
- three channels: muon and 2 electron channels
  central-central (CC) and central-forward (CF)

Backgrounds:

- multijet (data driven)
- diboson, $Z \rightarrow \tau\tau$, $t\bar{t}$ (MC)





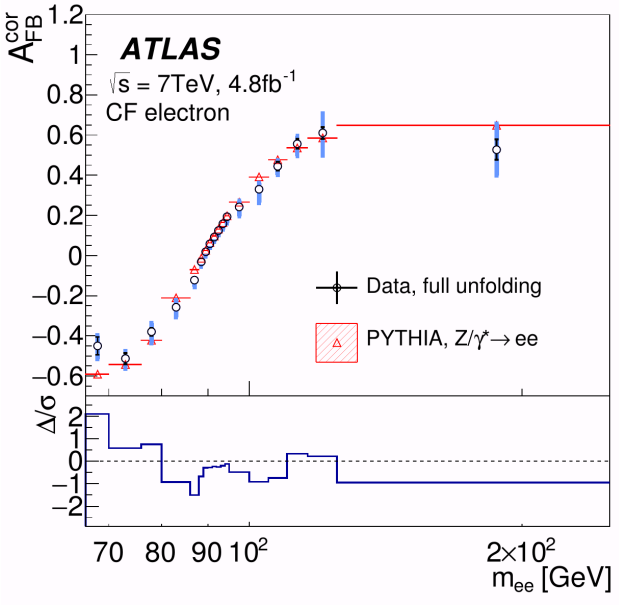


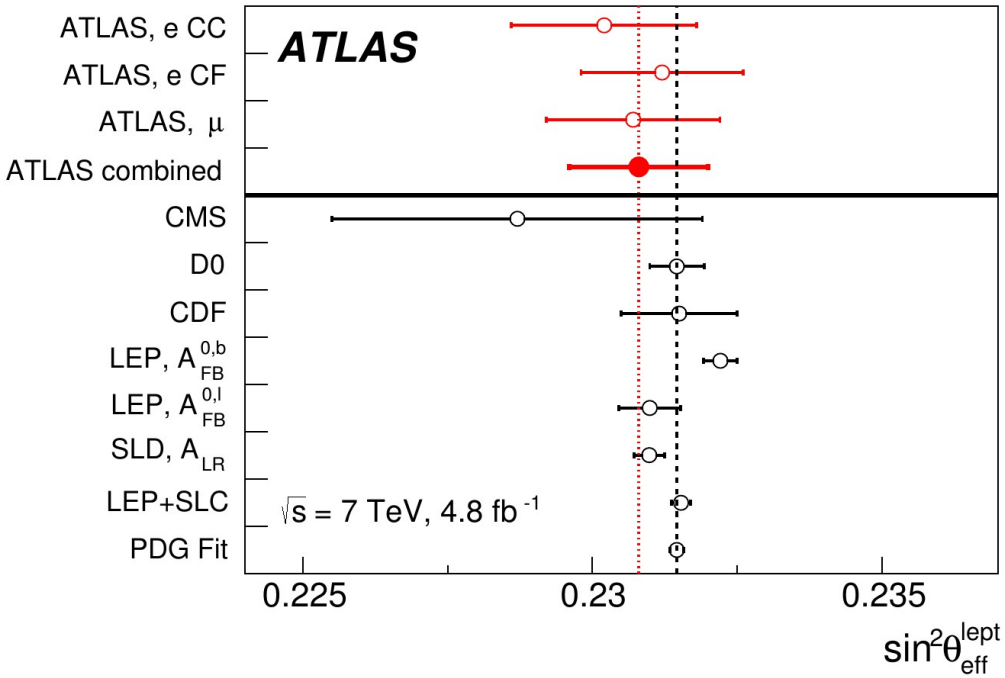
Z/γ* Forward-Backward Asymmetry

- Measure A_{FB} as function of dilepton mass
  - dominant uncertainty from PDF
- Extract $\sin^2\Theta_{eff}^{lep}$ from A_{FB} measurement

$$\sin^2\Theta_{eff}^{lep} = 0.2308 \pm 0.0005\,(stat.) \pm 0.0006\,(sys.) \pm 0.0009\,(PDF)$$

A_{FB} after correcting for detector effects





- agreement with PDG best fit value
- precision comparable to TEVATRON

WZ Production

- $\sqrt{s}$ = 8TeV, $\int \mathcal{L}$ = 13 fb^{-1}

Goal:

- measure cross section

Signal:

- one W bosons decayed into a lepton and missing energy
- one Z bosons decayed into two leptons (opposite charge)

Backgrounds:

- Z+jets, top (data driven)
- ZZ, W/Z+γ (MC)

Results:

$$\sigma_{WZ}^{tot} = 20.3^{+0.8}_{-0.7}(\text{stat.})\ ^{+1.2}_{-1.1}(\text{syst.})\ ^{+0.7}_{-0.6}(\text{lumi.})\ \text{pb}$$

theory expectation:

$$\sigma_{WZ}^{theo} = 20.3 \pm 0.8\ pb$$

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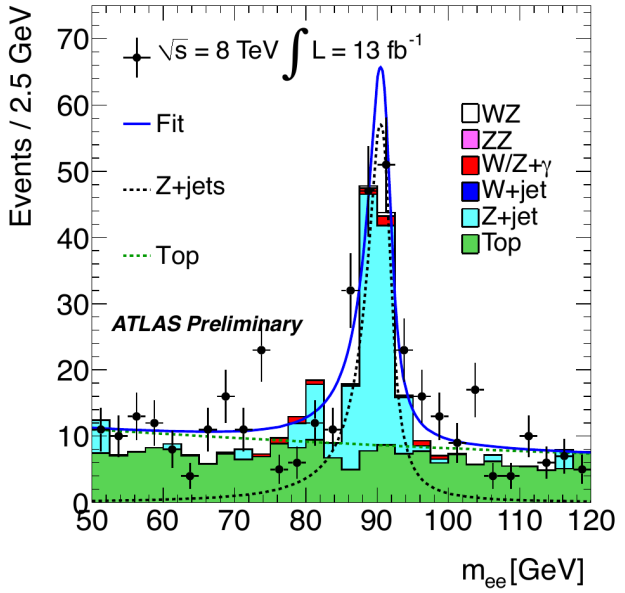

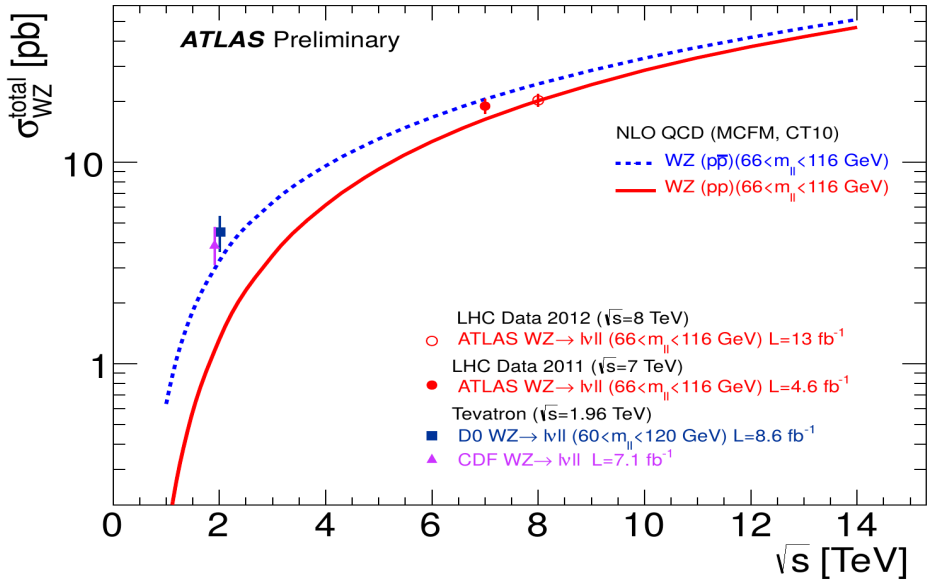

ZZ Production

- $\sqrt{s}$ = 8TeV, $\int \mathcal{L}$ = 20.3 fb^{-1}

Goal:

  - measure cross section

Signal:

  - two Z bosons decayed into 4 leptons
    (2 pairs of opposite charge)

Backgrounds:

  - 2l+X, 3l+X (data driven)
  - $t\bar{t}$, single top, diboson

Results:

$$\sigma_{ZZ}^{tot} = 7.1^{+0.5}_{-0.4}(stat.) \pm 0.3(syst.) \pm 0.2(lumi.)\ pb$$

theory expectation:

$$\sigma_{ZZ}^{theo} = 7.2^{+0.3}_{-0.2}\ pb$$

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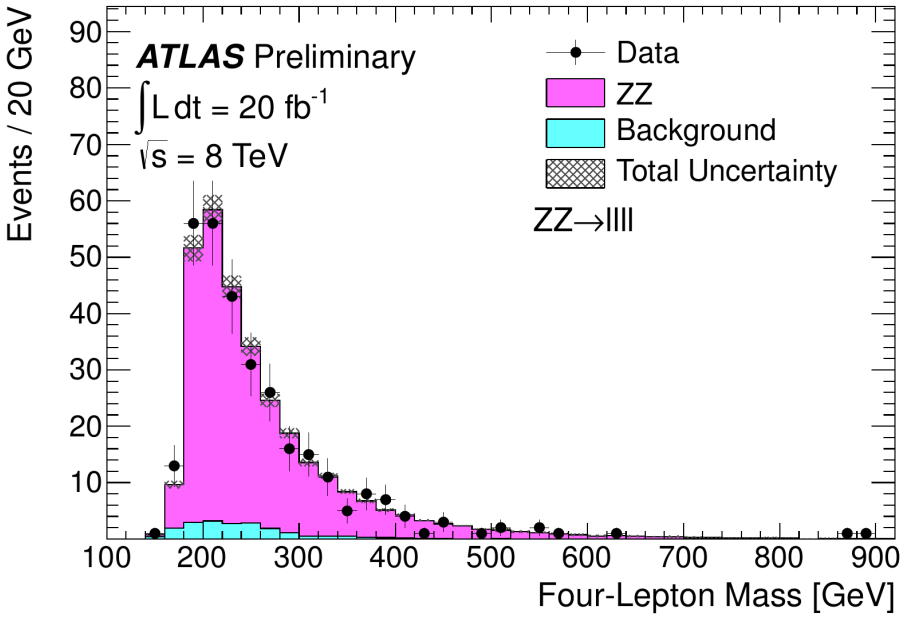
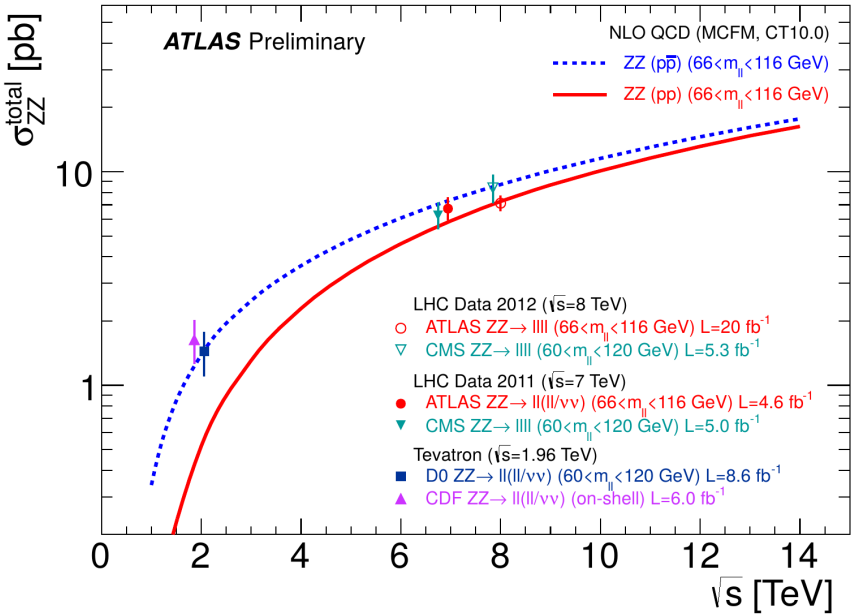
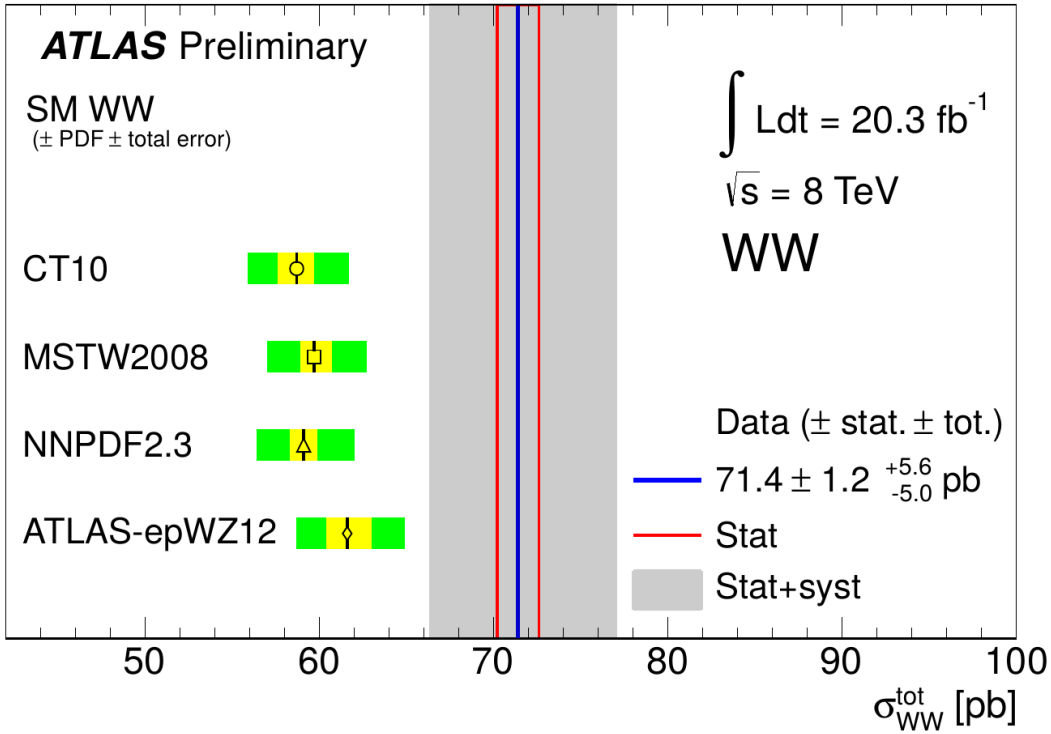




WW Production - Comments

Different PDFs for SM prediction



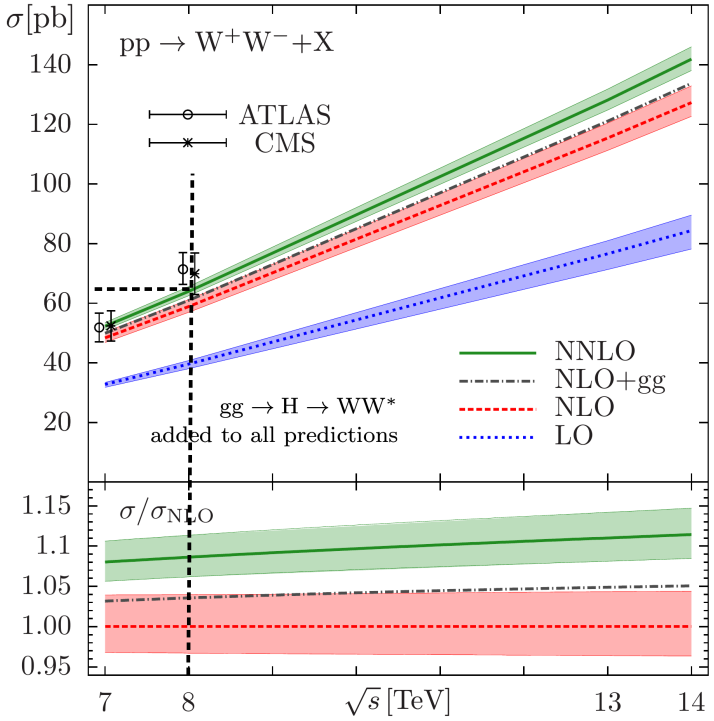
Sizable effect possible due to PDF
+5% with ATLAS PDF

WW Production - Comments II

- Fiducial cross section measurement compatible with estimated NNLO+NNLL effects

decay mode	$\sigma_{\text{fid.}}^{\text{exp.}}$ [fb]	$\sigma_{\text{fid.}}^{\text{th.}}$ [fb]
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$75.1^{+3.0}_{-3.0}$

from arXiv:1410.4745



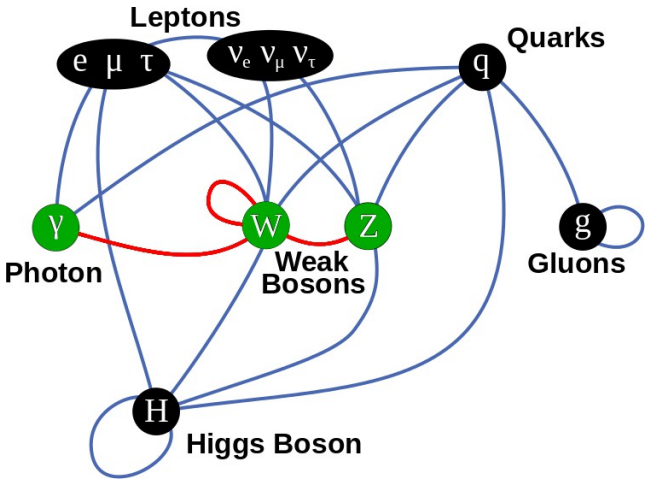
from arXiV:1408.5243

→ Difference reduces to 1.1σ

FIG. 1. The on-shell W^+W^- cross section in the 4FNS at LO (dots), NLO (dashes), NLO+gg (dot dashes) and NNLO (solid) combined with $gg \to H \to WW^*$ is compared to recent ATLAS and CMS measurements [5–8]. In the lower panel NNLO and NLO+gg results are normalized to NLO predictions. The bands describe scale variations.

Electroweak Sector and aTGC/aQGC

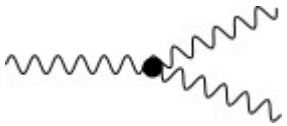
- Based on $SU(2)_L$ x $U(1)_\gamma$ gauge group (non-Abelian)
- predicts: EW gauge boson self coupling through 3- and 4- point interaction
- coupling fixed in SM → deviations hint to **new physic**



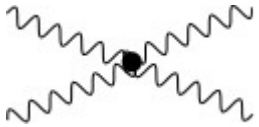
- gauge coupling not as expected in SM → anomalous triple / quartic gauge coupling (**aTGC/aQGC**)
- often introduced via effective Lagrangian
  (respecting $U(1)_\gamma$ x $SU(2)_L$ and CP invariance)

  → advantage: model independent

trilinear coupling



quartic coupling



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{aTGC/aQGC}$$

$$= \mathcal{L}_{SM} + \sum_i \frac{c_i^6}{\Lambda_i^2} * O_i^6 + \sum_i \frac{c_i^8}{\Lambda_i^4} * O_i^8 + \ ...$$

LEP Convention

- WWZ and WWγ vertices described with 5 dimensionless parameters:

  $\lambda_\gamma, \lambda_Z, \kappa_\gamma, \kappa_Z$ and g_1^Z (Nucl. Phys. B 282 (1987) 253)

- LEP scenario: additional constraints from SU(2)xU(1) gauge invariance

  $\lambda_\gamma = \lambda_Z \equiv \lambda$

  $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\Theta_W$

  with

  $\Delta\kappa_\gamma \equiv \kappa_\gamma - 1$, $\Delta\kappa_Z \equiv \kappa_Z - 1$ and $\Delta g_1^Z \equiv g_1^Z - 1$

⇒ three free parameters: $\lambda, \Delta\kappa_\gamma$ and Δg_1^Z