Diboson and Electroweak Physics at ATLAS

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on behalf of the ATLAS collaboration

"Les Rencontres de Physique de la Vallée d'Aoste 2014"
La Thuile, Aosta Valley, Italy

February 26, 2014

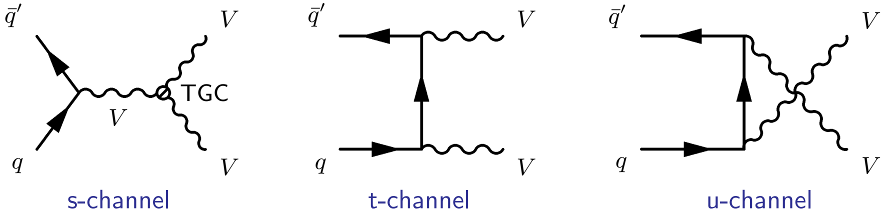
TECHNISCHE UNIVERSITÄT DRESDEN

Outline

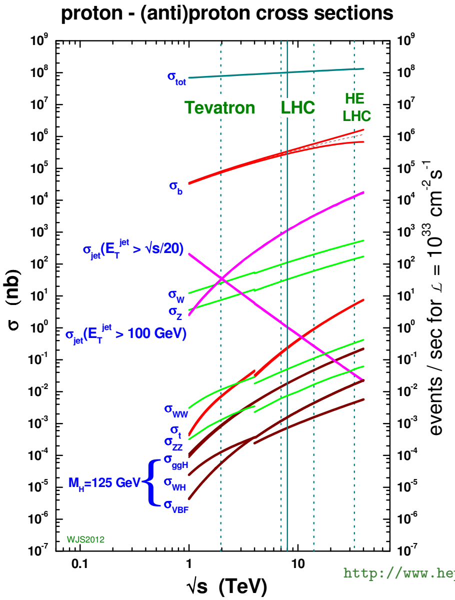
1. Introduction
2. Diboson and electroweak physics
   - total/fiducial cross section measurements
   - limits on anomalous triple gauge couplings
3. Prospects for vector boson scattering and triboson production
4. Summary and outlook

Diboson and electroweak physics at the LHC

- diboson and electroweak (EW) physics:
  - test of the electroweak sector of the SM at the TeV scale
  - sensitive to anomalous (= non-SM) gauge couplings
    $\rightarrow$ new physics in EW sector
  - important/irreducible background to Higgs and beyond-SM searches
    $\rightarrow$ precise knowledge of cross sections and kinematic distributions needed
  - evident prerequisite for vector boson scattering measurements
- leading order diagrams for electroweak diboson production:



Electroweak diboson production at the LHC



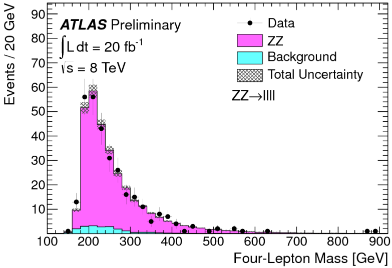
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/crosssections2012_v5.pdf

- small cross sections
  - → profit from high energy and high luminosity
- cross sections at $\sqrt{s} = 7/8$ TeV presented in this talk calculated to NLO
  - → using MCFM with PDF set CT10
  - → gluon-gluon enters at NNLO, $<10\%$ of the total cross section

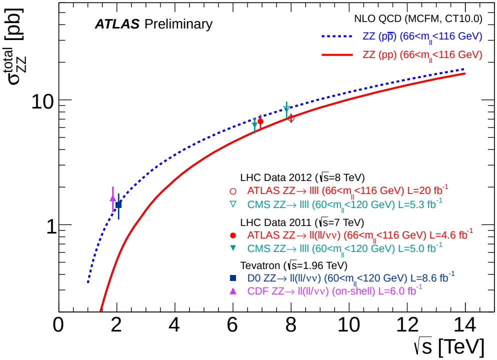
$ZZ^{(*)} \to llll$ and $ll\nu\nu$

JHEP03 (2013) 128, ATLAS-CONF-2013-020

- two $(l^+l^-l^+l^-)$ or one $(l^+l^-\nu\nu)$ opposite-sign same-flavor high p_T, isolated lepton pair(s), within 66 GeV $< m_Z <$ 116 GeV $(l^+l^-l^+l^-)$ or 76 GeV $< m_Z <$ 106 GeV $(l^+l^-\nu\nu)$



total cross sections

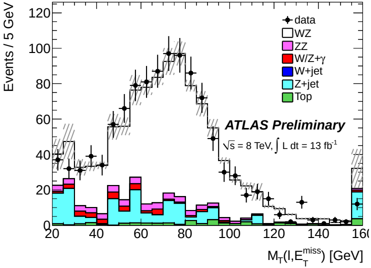


$\sqrt{s}$	$\int \mathrm{L\,dt}$	measured total cross section (pb)	theory (pb)
7 TeV	4.6 fb^{-1}	6.7 $\pm$ 0.7(stat) $^{+0.4}_{-0.3}$(syst) $\pm$ 0.3(lumi)	$5.89^{+0.22}_{-0.18}$
8 TeV	20 fb^{-1}	7.1 $^{+0.5}_{-0.4}$(stat) $\pm$ 0.3(syst) $\pm$ 0.2(lumi)	$7.2^{+0.3}_{-0.2}$

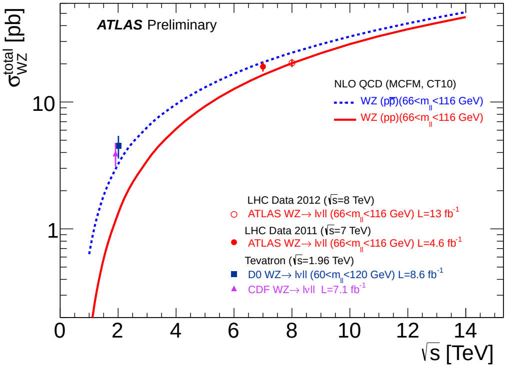
$WZ \rightarrow l\nu ll$

EPJC 72 (2012) 2173, ATLAS-CONF-2013-021

- 3 high p_T, isolated leptons
- 1 opposite-sign lepton pair forming Z within 81 GeV $< m_Z <$ 101 GeV
- residual lepton + E_T^{miss} forming W



total cross sections

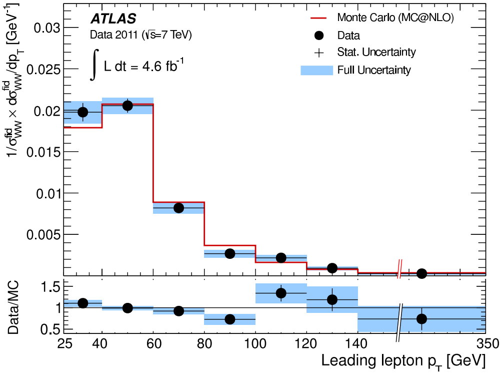


$\sqrt{s}$	$\int \mathrm{L\,dt}$	measured total cross section (pb)	theory (pb)
7 TeV	4.6 fb^{-1}	19.0 $^{+1.4}_{-1.3}$(stat) $\pm$ 0.9(syst) $\pm$ 0.4(lumi)	17.6 $^{+1.1}_{-1.0}$
8 TeV	13 fb^{-1}	20.3 $^{+0.8}_{-0.7}$(stat) $^{+1.2}_{-1.1}$(syst) $^{+0.7}_{-0.6}$(lumi)	20.3 $\pm$ 0.8

$WW \to l\nu l\nu$

Phys.Rev. D87, 112001 (2013)

- tight event selection needed against background:
  - two opposite-sign high p_T isolated leptons
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ (against Z+jets)
  - jet veto (against $t\bar{t}$)



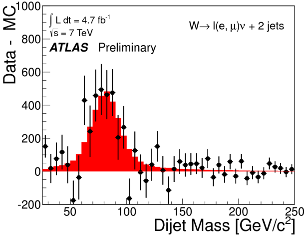
- measured cross section slightly larger than the SM prediction

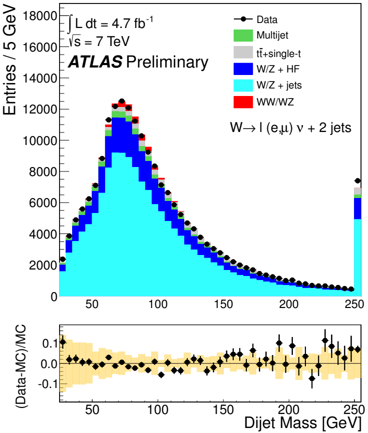
$\sqrt{s}$	$\int \mathrm{L}\,\mathrm{dt}$	measured total cross section (pb)	theory (pb)
7 TeV	4.6 fb^{-1}	51.9 $\pm$ 2.0(stat) $\pm$ 3.9(sys) $\pm$ 2.0(lumi)	$44.7^{+2.1}_{-1.9}$

$WW/WZ \rightarrow l\nu jj$

- $WW/WZ \rightarrow l\nu jj$ signal also established
  - one high p_T isolated lepton
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
  - exactly two jets with $p_T > 25/30$ GeV
- W/Z resonance observed with 3.3 σ

background subtracted di-jet invariant mass of reconstructed $W/Z \rightarrow jj$ candidates:



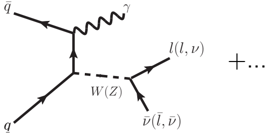


$\sqrt{s}$	$\int$ L dt	measured cross section (pb)	theory (pb)
7 TeV	4.7 fb^{-1}	72 $\pm$ 9(stat) $\pm$ 15(syst) $\pm$ 13(MC stat)	63.4 $\pm$ 2.6

$W\gamma, Z\gamma$

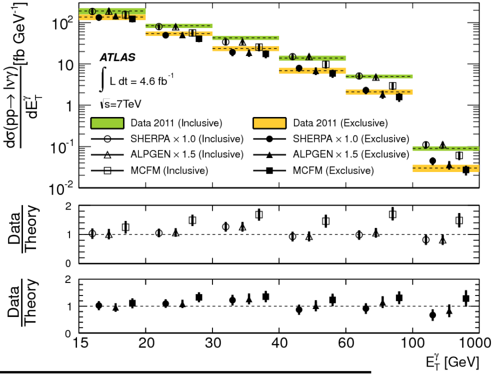
Phys. Rev. D 87, 112003 (2013)

- final states: $l\nu\gamma$, $l^+l^-\gamma$ and $\nu\nu\gamma$



- one high E_T isolated photon
- isolated high p_T lepton(s)
- $\Delta R(\gamma, l) > 0.7$ to suppress FSR photons
- $E_{\mathrm{T}}^{\mathrm{miss}} > 35/90$ GeV ($l\nu\gamma/\nu\nu\gamma$)

example: $W\gamma \to l\nu\gamma$:



7 TeV, 4.6 fb^{-1}

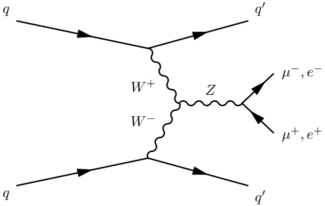
jet multiplicity	channel	measured cross section (pb)	theory (pb)
inclusive ($N_{\mathrm{jet}} \geq 0$)	$l\nu\gamma$	2.77 ± 0.03(stat) ± 0.33(syst) ± 0.14(lumi)	1.96 ± 0.17
inclusive ($N_{\mathrm{jet}} \geq 0$)	$l^+l^-\gamma$	1.31 ± 0.02(stat) ± 0.11(syst) ± 0.05(lumi)	1.18 ± 0.05
inclusive ($N_{\mathrm{jet}} \geq 0$)	$\nu\bar{\nu}\gamma$	0.133 ± 0.013(stat) ± 0.20(syst) ± 0.005(lumi)	0.156 ± 0.012
exclusive ($N_{\mathrm{jet}} = 0$)	$l\nu\gamma$	1.76 ± 0.04(stat) ± 0.24(syst) ± 0.08(lumi)	1.39 ± 0.13
exclusive ($N_{\mathrm{jet}} = 0$)	$l^+l^-\gamma$	1.05 ± 0.02(stat) ± 0.10(syst) ± 0.04(lumi)	1.06 ± 0.05
exclusive ($N_{\mathrm{jet}} = 0$)	$\nu\bar{\nu}\gamma$	0.116 ± 0.010(stat) ± 0.13(syst) ± 0.004(lumi)	0.115 ± 0.009

Electroweak Zjj production **new!**

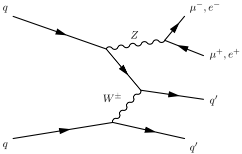
arXiv:1401.7610

- EW Zjj production, $\sqrt{s} = 8$ TeV, $\int \mathrm{L}\,\mathrm{dt} = 20.3$ fb^{-1}

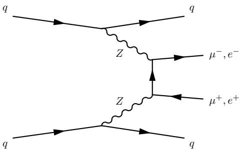
vector boson fusion (VBF):
similar to VBF Higgs production
sensitive to aTGC



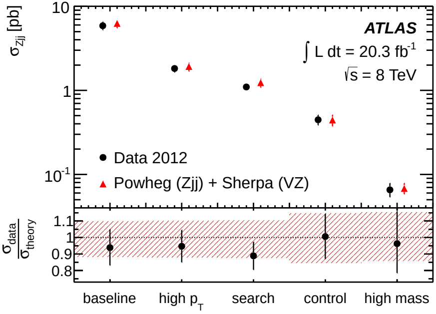
Z bremsstrahlung:



non-resonant l^+l^-jj production:



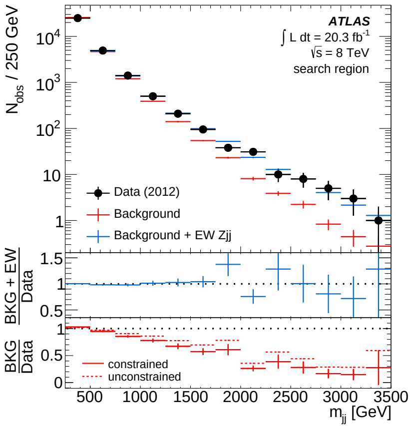
- opposite-sign same-flavor lepton pair within $81\ \mathrm{GeV} < m_Z < 101\ \mathrm{GeV}$
- ≥ 2 high p_T jets
- inclusive Zjj production: measurement of fiducial cross sections in 5 phase space regions with different sensitivity to the EW component
- search regions: $m_{jj} > 250$ GeV & 1 TeV and jet veto on additional jets in the rapidity interval between the two tag jets



Electroweak Zjj production new!

arXiv:1401.7610

- EW Zjj component extracted using a 2-component template fit to the m_{jj} spectrum, signal template by SHERPA EW Zjj Monte Carlo
- background-only hypothesis rejected with significance above the 5σ level
- Bayesian unfolding to particle level: normalized differential cross sections
- fiducial cross sections in search regions (theory prediction from POWHEG):



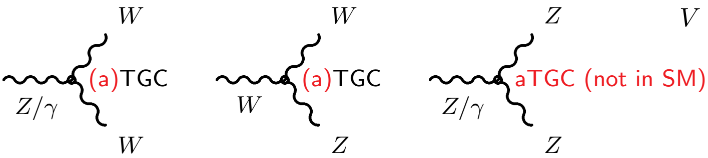
$$\sigma_{\mathrm{EW,measured}}(m_{jj} > 250\ \mathrm{GeV}) = 54.7 \pm 4.6(\mathrm{stat})\ ^{+9.8}_{-10.4}(\mathrm{syst}) \pm 1.5(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma_{\mathrm{theory}}(m_{jj} > 250\ \mathrm{GeV}) = 46.1 \pm 0.2(\mathrm{stat})\ ^{+0.3}_{-0.2}(\mathrm{scale}) \pm 0.8(\mathrm{PDF}) \pm 0.5(\mathrm{model})\ \mathrm{fb}$$

$$\sigma_{\mathrm{EW,measured}}(m_{jj} > 1\ \mathrm{TeV}) = 10.7 \pm 0.9(\mathrm{stat}) \pm 1.9(\mathrm{syst}) \pm 0.3(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma_{\mathrm{theory}}(m_{jj} > 1\ \mathrm{TeV}) = 9.38 \pm 0.05(\mathrm{stat})\ ^{+0.15}_{-0.24}(\mathrm{scale}) \pm 0.24(\mathrm{PDF}) \pm 0.09(\mathrm{model})\ \mathrm{fb}$$

Anomalous triple gauge couplings (aTGC)



$V = Z, \gamma$

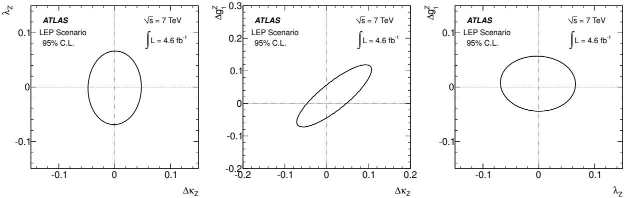
- beyond SM physics modeled by effective Lagrangian with anomalous TGC (aTGC) parameters (in red) which are zero in the SM
- charged aTGC: WWV
  - from WW, WZ, $W\gamma$, and EW Zjj (new!) measurements
  - $\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V (W^+_{\mu\nu} W^\mu V^\nu - W^+_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^+_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^+_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$
  - 5 parameters: Δg_1^Z $(= g_1^Z - 1)$, $\Delta\kappa_Z$ $(= \kappa_Z - 1)$, $\Delta\kappa_\gamma$ $(= \kappa_\gamma - 1)$, λ_Z, λ_γ
- neutral aTGC: ZZV (not in SM)
  - from ZZ and $Z\gamma$ measurements
  - $\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2} \left(f_4^V (\partial_4^V V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta \right)$
  - 8 parameters: h_3^V, h_4^V, f_4^V, f_5^V
- avoiding unitarity violation via dipole form factors $\mathcal{F}(s) = \frac{1}{(1 + \hat{s}/\Lambda^2)^n}$

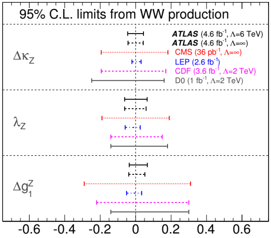
(Λ: scale above which unitarity is violated)

aTGC results

One- and two-dimensional 95% confidence intervals for aTGC:

- example: limits from WW
  Phys.Rev. D87, 112001 (2013)





- **new**: first ever limits at a hadron collider from VBF Z (from $m_{jj} > 1$ TeV):
  arXiv:1401.7610

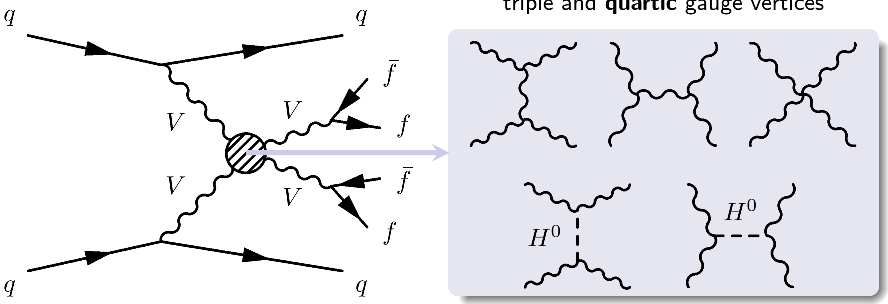
aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
Δg_1^Z	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

$\rightarrow$ **TGC consistent with the SM**

Vector boson scattering (VBS)

- vector boson scattering at the LHC at high energy (14 TeV) is the key process to experimentally probe the SM nature of EWSB

triple and **quartic** gauge vertices



Higgs exchange and Higgs production via vector boson fusion (VBF)

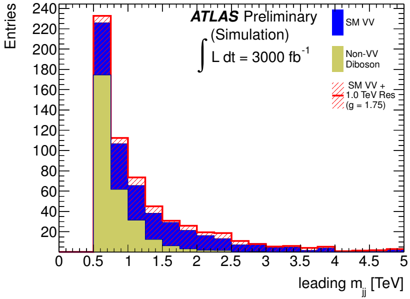
- final state: diboson + $\geq$ 2 jets ($VVjj$)
- sensitive to anomalous quartic gauge couplings (aQGC)

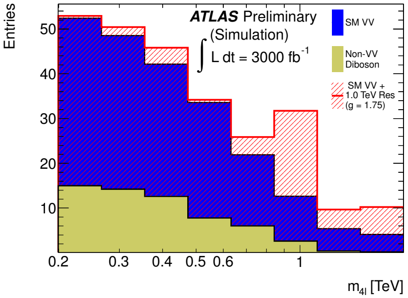
Prospects for VBS at $\sqrt{s} = 14$ TeV

ATLAS-PHYS-PUB-2012-005

- $\sqrt{s} = 14$ TeV$\rightarrow$ VBS centre-of-mass energy of $\sim 1 - 2$ TeV
- signal: anomalous VBS ZZ tensor singlet resonance f^0
  - $\rightarrow$ 2 opposite sign, same flavor lepton pairs, at least two jets with $m_{jj} > 1$ TeV
  - $\rightarrow$ signal chosen is a hard benchmark, sensitivity higher for other resonances

$m_{\text{resonance}}$	coupling	width	300 fb^{-1}	3000 fb^{-1}
500 GeV	$g = 1$	$\Gamma = 2$ GeV	2.4σ	7.5σ
1 TeV	$g = 1.75$	$\Gamma = 50$ GeV	1.7σ	5.5σ
1 TeV	$g = 2.5$	$\Gamma = 100$ GeV	3.0σ	9.4σ





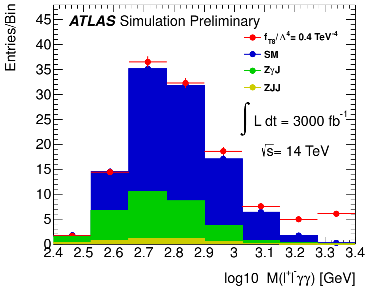
Triboson production at $\sqrt{s} = 14$ TeV: $Z\gamma\gamma$

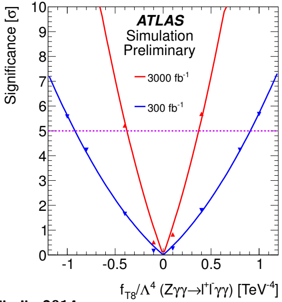
ATL-PHYS-PUB-2013-006

- 2 opposite charge, same-flavor high p_T leptons in Z window
- 2 photons, well separated
- one lepton and one γ with $p_T > 160$ GeV (improves aQGC sensitivity)

- $\frac{f_{T8,9}}{\Lambda^4}$: anomalous quartic gauge coupling parameters
- expected sensitivity to anomalous Z$\gamma\gamma$ production at $\sqrt{s} = 14$ TeV, quoted in 5σ-significance discovery values:

	300 fb^{-1}	3000 fb^{-1}
f_{T8}/Λ^4	0.9 TeV^{-4}	0.4 TeV^{-4}
f_{T9}/Λ^4	2.0 TeV^{-4}	0.7 TeV^{-4}





Summary and outlook

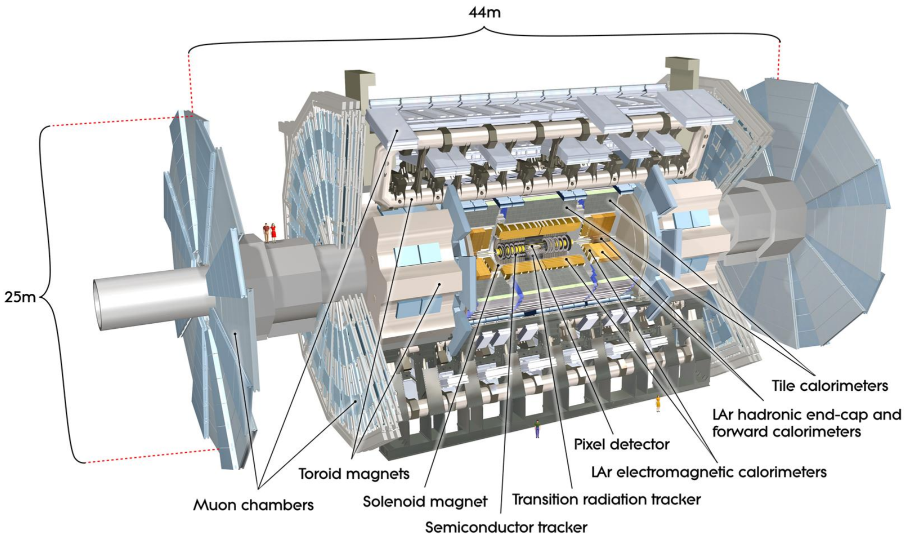
- electroweak diboson measurements continue to improve
  - cross sections measurements: no significant deviations from the SM
    - → measurement of fiducial and total (ZZ, WZ, WW) cross sections
    - → unfolded differential cross sections for all fully leptonic results at 7 TeV
  - TGC consistent with the SM ↔ limits on aTGC
    - → sensitivity for aTGC limits expected to increase with increased centre-of-mass energy and integrated luminosity
  - more results on full 8 TeV dataset to come
- **new**: EW Zjj production measurement, including VBF
  - cross sections measurements and limits on aTGC
- prospects for VBS and triboson production at $\sqrt{s} = 14$ TeV:
  - access to quartic gauge couplings
  - increase of significances for anomalous resonances or couplings with high luminosity

Backup

References

Analysis	Dataset	Reference
EW Zjj	20.3 fb^{-1}, 8 TeV	arXiv:1401.7610
$ZZ \to llll$	20.3 fb^{-1}, 8 TeV	ATLAS-CONF-2013-020
$WZ \to l\nu ll$	13 fb^{-1}, 8 TeV	ATLAS-CONF-2013-021
$WW/WZ \to l\nu jj$	4.7 fb^{-1}, 7 TeV	ATLAS-CONF-2012-157
$ZZ \to llll, ll\nu\nu$	4.6 fb^{-1}, 7 TeV	JHEP03 (2013) 128
$WW \to l\nu l\nu$	4.6 fb^{-1}, 7 TeV	Phys. Rev. D 87, 112001 (2013)
$WZ \to l\nu ll$	4.6 fb^{-1}, 7 TeV	EPJC 72 (2012) 2173
$W\gamma, Z\gamma$	4.6 fb^{-1}, 7 TeV	Phys. Rev. D 87, 112003 (2013)
vector boson scattering	300...3000 fb^{-1}, 14 TeV	ATLAS-PHYS-PUB-2012-005
vector boson scattering	300...3000 fb^{-1}, 14 TeV	ATLAS-PHYS-PUB-2013-006

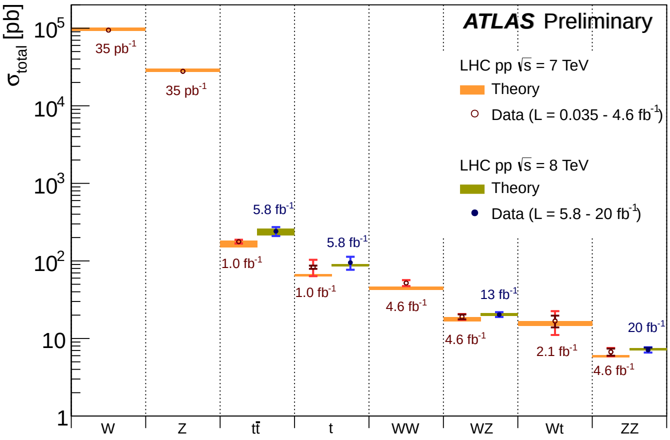
The ATLAS detector



ATLAS Experiment © 2013 CERN

Summary of (diboson) cross sections

SM total production cross sections corrected for leptonic branching fractions, compared to theoretical expectations:

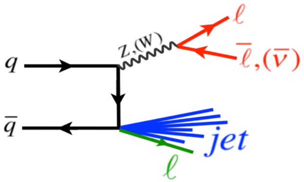


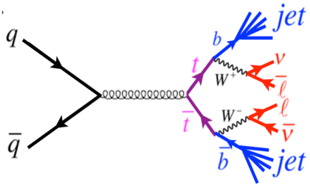
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/SM_SummaryPlot/SM_SummaryPlot.png

→ no significant deviation from the SM observed

Analysis strategy

- Common characteristics:
  - small cross sections
  - high p_T isolated leptons (electrons or muons)
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ due to neutrinos from W or $Z \to \nu\nu$ decays
  - two forward jets for VBF Z process
- Common backgrounds:
  - W+jets/Z+jets: data driven methods to estimate backgrounds from jets mis-reconstructed as charged leptons or $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $t\bar{t}$ and single top: estimated using data driven backgrounds





  - (massive) diboson production: estimated from MC

Analysis strategy

- Cross section measurements
  - fiducial phase space: event yields at final selection, correct for efficiency
  - extrapolation to total phase space: additionally correct for acceptance

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \cdot \mathcal{L}}, \quad \sigma_{\text{tot}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{A \cdot C \cdot \mathcal{L} \cdot BR}, \quad C = \frac{N_{\text{passed}}}{N_{\text{generated fid}}}, \quad A = \frac{N_{\text{generated fid}}}{N_{\text{generated all}}}$$

- N_{obs}: number of observed events passing the selection
- N_{bkg}: number of estimated background events
- $\mathcal{L}$: integrated luminosity
- C: efficiency correction factor in the fiducial volume
- A: kinematic and geometric acceptance from the total phase space to the fiducial phase space
- BR: branching ratio of bosons decaying to leptons

- Extraction of exclusion limits:
  - we can use the impact of anomalous couplings on both production rate and event kinematics to set limits
  - various scenarios assumed:
    - aTGC: equal couplings scenario, LEP scenario, HISZ scenario
    - aQGC: electroweak chiral Lagrangian / effective field theory approach
    - unitarization method

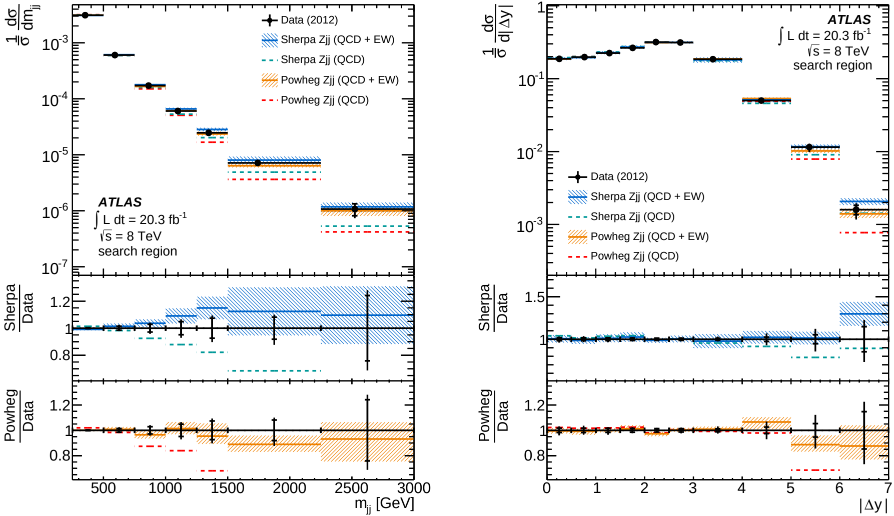
Electroweak Zjj production new!

arXiv:1401.7610

Unfolded normalized differential cross section distributions in the **search regions**:

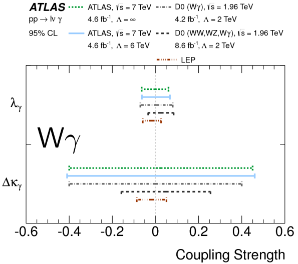
dijet invariant mass

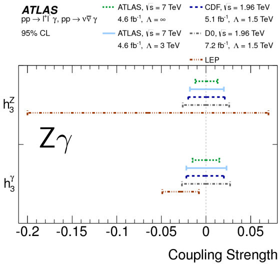
rapidity separation between the leading jets

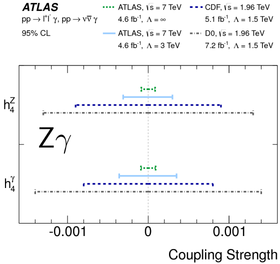


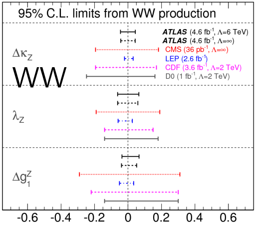
aTGC results overview

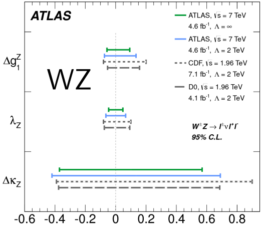
One-dimensional 95% confidence intervals for aTGC:

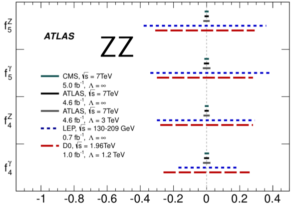








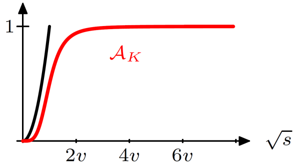




TGC consistent with the SM

Unitarization

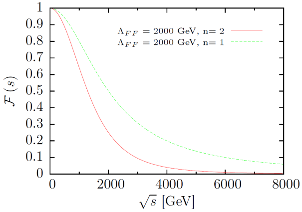
- Unitarization with the **k-matrix method** (e.g. WHIZARD arXiv:0806.4145)
  - unitarization by infinitely heavy and wide resonance
    k-matrix amplitude: $|\mathcal{A}_K(s)|^2 \xrightarrow{s\to\infty} 1$
  - allows arbitrary number of resonances with free couplings g and free widths Γ



- Unitarization via **form factors** (e.g. VBFNLO arXiv:1205.4231)
  - regime where unitarity is violated depends on the operators and their coupling strengths
  - energy-dependent form factors

$$\mathcal{F}(s) = \frac{1}{(1 + \hat{s}/\Lambda^2)^n}$$

Λ: scale above which unitarity is violated



Shape of $\mathcal{F}(s)$ with $\Lambda_{\rm FF} = 2$ TeV