Electroweak measurements with the ATLAS detector

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on behalf of the ATLAS collaboration

LHC Seminar, 24 June 2014

TECHNISCHE UNIVERSITÄT DRESDEN

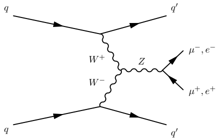
GEFÖRDERT VOM

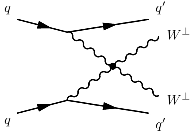
Bundesministerium für Bildung und Forschung

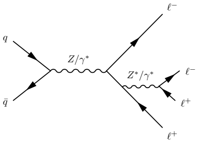
FSP 101 ATLAS

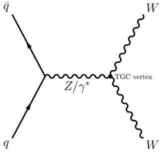
Outline

1. Introduction & motivation
2. Electroweak measurements with the ATLAS detector
   - Diboson production
   - Electroweak Zjj production
   - Electroweak $W^{\pm}W^{\pm}jj$ production
   - Inclusive $Z \rightarrow 4\ell$ production
   - $W^{+}W^{-}$ production (new results from $\sqrt{s} = 8$ TeV)
3. Summary



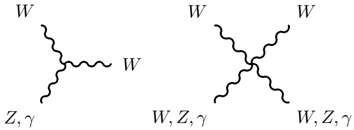






Motivation – electroweak measurements

- important test of the electroweak (EW) sector of the SM at the TeV scale
  - $\rightarrow$ probe triple and quartic gauge boson self-interactions as predicted by the EW theory



  - $\rightarrow$ probe their unitarization by HVV contribution in VV scattering $(V = W, Z)$

- probe QCD $\rightarrow$ NNLO calculations improve data-MC agreement
- irreducible background to Higgs and beyond-SM searches

Electroweak measurements with the ATLAS detector

- measurement of (multi)-boson production processes
  - involving combinations of W, Z and isolated γ
  - common characteristics:
    - $\rightarrow$ small cross sections
    - $\rightarrow$ high p_T isolated e or μ and/or photons,
    - $\rightarrow$ $E_{\mathrm{T}}^{\mathrm{miss}}$ from W or $Z \rightarrow \nu\bar{\nu}$ decays
    - $\rightarrow$ (high p_T jets)
- extraction of (differential) fiducial and total cross sections

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

C: efficiency correction factor in the fiducial phase space
A: kinematic and geometric acceptance from the total to the fiducial phase space

Look at physics beyond the SM

- the SM may be considered as a low-energy effective theory of a more complete but unknown theory
- model independent approach, complementary to direct searches:
  - → low energy effects from beyond SM physics can be parametrized by an effective Lagrangian (SM + higher-dimension operators):

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

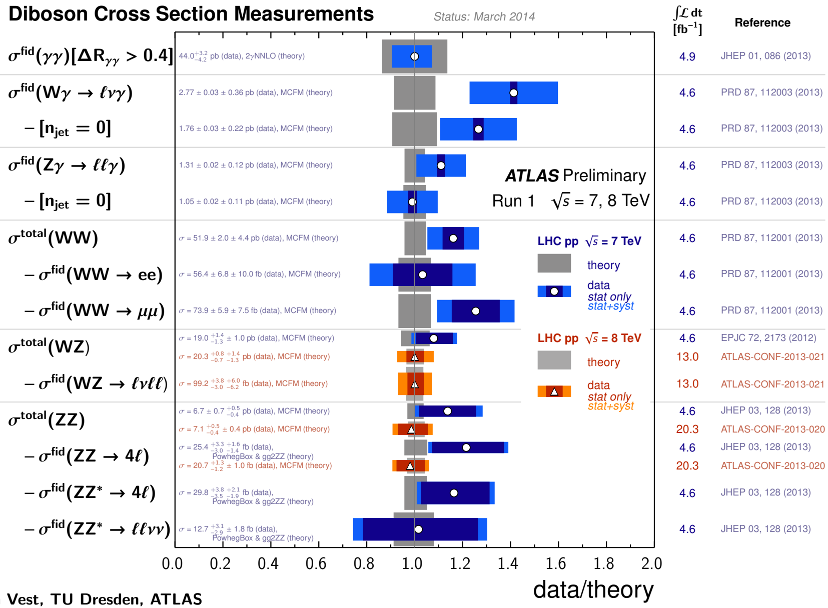
Λ: scale of new physics

  - → new physics in EW sector modify gauge boson self-interactions
  - → anomalous coupling approach: effective Lagrangian with anomalous triple or quartic gauge couplings (aTGC, aQGC)
  - → unitarization scheme introduces model dependence

Diboson production

($\sqrt{s} = 7$ & 8 TeV)

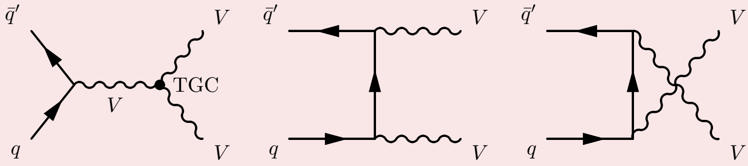
Diboson measurements with the ATLAS detector



Diboson measurements with the ATLAS detector

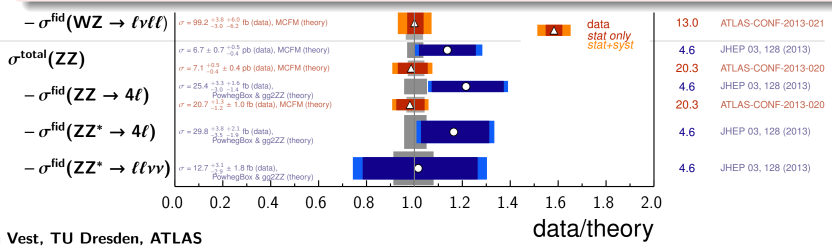
Diboson Cross Section Measurements *Status: March 2014* $\int\mathcal{L}\,dt$ [fb^{-1}] **Reference**

- LO diagrams of EW diboson production:



s-channel t-channel u-channel

- SM theory prediction for cross sections from MCFM (NLO, PDF set CT10)



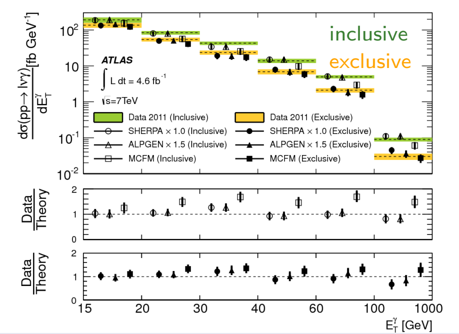
$W\gamma$ and $Z\gamma$ production (7 TeV)

Phys. Rev. D 87, 112003 (2013)
(CMS: Phys. Lett. B 701 (2011) 535555)

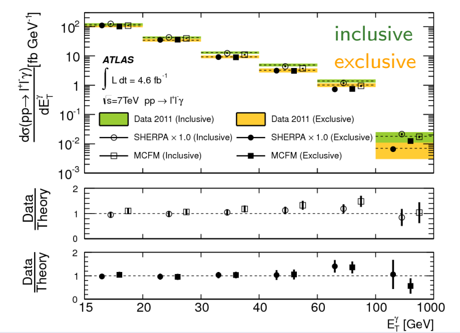
$W\gamma \to \ell\nu\gamma$ and $Z\gamma \to \ell\ell\gamma$ & $\nu\nu\gamma$

- leptons and/or large E_T^{miss} ($\ell\nu\gamma$ & $\nu\nu\gamma$)
- 1 high E_T isolated γ with $\Delta R(\gamma, \ell) > 0.7$ to suppress photons from final state radiation
- fiducial cross sections in inclusive ($N_{\text{jet}} \geq 0$) and exclusive ($N_{\text{jet}} = 0$) phase space

$W\gamma \to \ell\nu\gamma$:



$Z\gamma \to \ell\ell\gamma$:

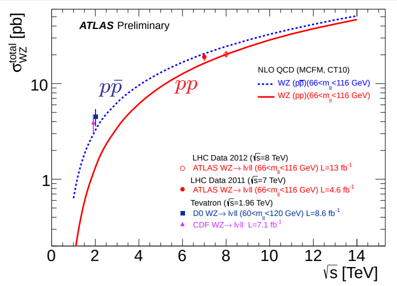


WZ and ZZ production (7 & 8 TeV)

$WZ \to \ell\nu\ell\ell$

EPJC 72 (2012) 2173, ATLAS-CONF-2013-021
(CMS: CMS-PAS-SMP-12-006)

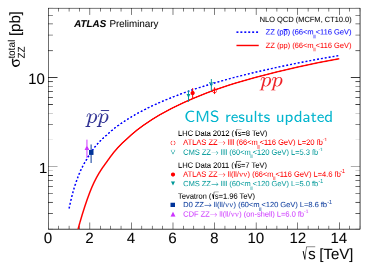
- 3 high p_T, isolated leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$
- 1 opposite-sign same-flavor lepton pair within 66 GeV $< m_{\ell\ell} <$ 116 GeV
- residual lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ forming W



$ZZ \to \ell\ell\ell\ell$ (& $\ell\ell\nu\nu$)

JHEP03 (2013) 128, ATLAS-CONF-2013-020
(CMS: CMS-PAS-SMP-13-005, CMS-PAS-SMP-12-016, J. High Energy Phys. 01 (2013) 063)

- $ZZ \to \ell\ell\ell\ell$:
  2 opposite-sign same-flavor lepton pairs within 66 GeV $< m_{\ell\ell} <$ 116 GeV
- $ZZ \to \ell\ell\nu\nu$ (7 TeV only):
  1 opposite-sign same-flavor lepton pair within 76 GeV $< m_{\ell\ell} <$ 106 GeV



Combined WW and WZ production

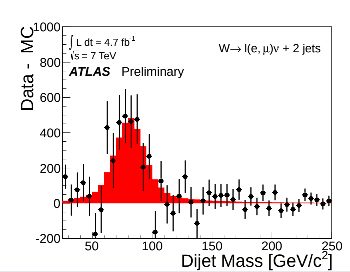
ATLAS-CONF-2012-157
(CMS: Eur.Phys.J. C73 (2013) 2283)

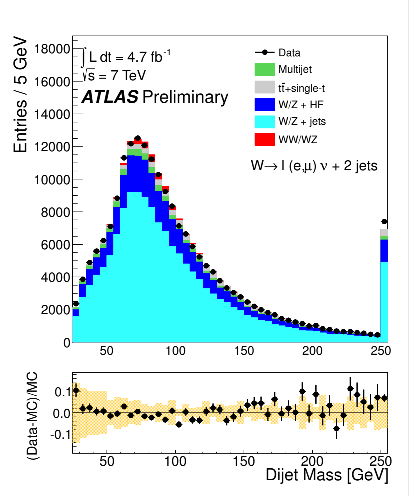
$WW/Z \to \ell\nu jj$ single lepton final state

$\sigma^{\text{tot}} = 72 \ \pm 9(\text{stat}) \ \pm 15(\text{syst}) \ \pm 13(\text{MCstat})$ pb

- 1 lepton + $E_{\text{T}}^{\text{miss}}$ from W
- exactly 2 jets from W/Z decay
  - $\rightarrow$ larger statistics
- $W/Z \to jj$ resonance observed with 3.3σ

background subtracted m_{jj}
of reconstructed $W/Z \to jj$ candidates





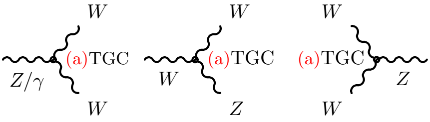
Constraints on anomalous triple gauge couplings

$V = Z, \gamma$

- effective parametrizations for anomalous couplings:

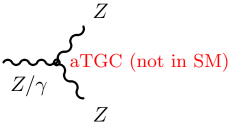
  - WWV vertex: Δg_1^Z, $\Delta\kappa_Z$, $\Delta\kappa_\gamma$, λ_Z, λ_γ

  $\rightarrow$ constraints from WW, WZ, $W\gamma$, and EW Zjj measurements



  - ZZV vertex (not in SM): h_3^V, h_4^V, f_4^V, f_5^V

  $\rightarrow$ constraints from ZZ and $Z\gamma$ measurements

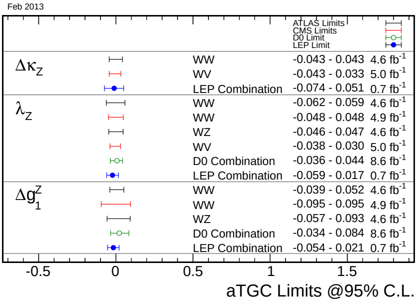


- 1- and 2-dimensional 95% confidence intervals for aTGC from 7 TeV data, e.g.

  $\rightarrow$ without and with form factors to avoid unitarity violation

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

(Λ_{FF}: form factor scale)



Electroweak Zjj production

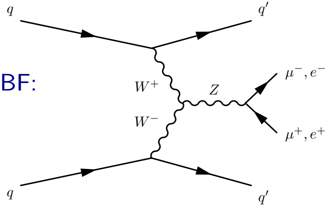
($\sqrt{s} = 8$ TeV)

Electroweak Zjj production

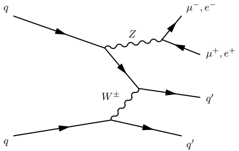
JHEP 04 (2014) 031
(CMS, 7 TeV: JHEP 10 (2013) 101)

- electroweak Zjj production: rare, $\sim$ 1% of inclusive Zjj cross section

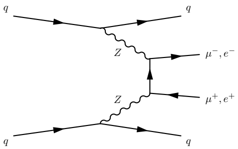
VBF:



Z bremsstrahlung:



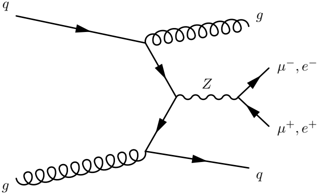
non-resonant $\ell^+\ell^- jj$:

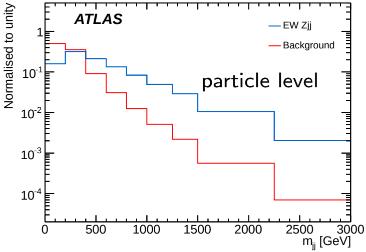


$\rightarrow$ VBF: "tagging" jets well separated in y with large m_{jj}

$\rightarrow$ colorless exchange region between the two quarks $\rightarrow$ low jet activity in rapidity interval

- strong Zjj production dominates:





Zjj production: event selection

JHEP 04 (2014) 031

- 5 phase space regions with different sensitivity to the EW Zjj production:

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^\ell\rvert < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \le m_{\ell\ell} \le 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^j\rvert < 4.4$, $\Delta R_{j,\ell} \ge 0.3$				
	$p_T^{j_1} > 55$ GeV				$p_T^{j_1} > 85$ GeV
	$p_T^{j_2} > 45$ GeV				$p_T^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\text{jet}}^{\text{gap}} = 0$	$N_{\text{jet}}^{\text{gap}} \ge 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance,3}} < 0.15$	—

→ Z boson selection, baseline jet selection

→ search region for extraction of EW component

→ control region for modelling of strong Zjj production

→ probe impact of EW Zjj production at high m_{jj}, high p_T

Inclusive Zjj production

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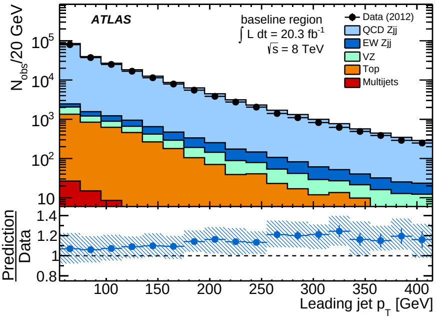
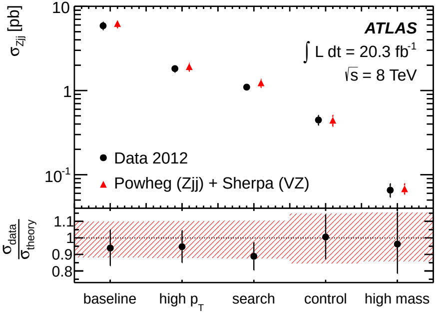
leading jet p_T in *baseline* region



- strong and EW Zjj production: SHERPA, normalized with POWHEG
- WZ and ZZ SHERPA
- $t\bar{t}$ and single top MC@NLO+HERWIG/JIMMY
- multijets: data-driven

- fiducial cross section measurements for inclusive Zjj production (EW+strong):



$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\int L\,\text{d}t \cdot \mathcal{C}}$$

Inclusive Zjj production: unfolded distributions

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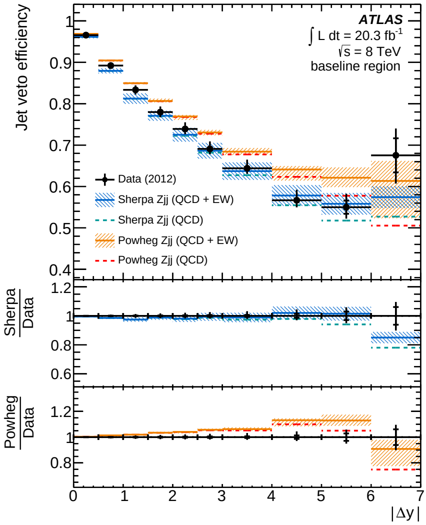
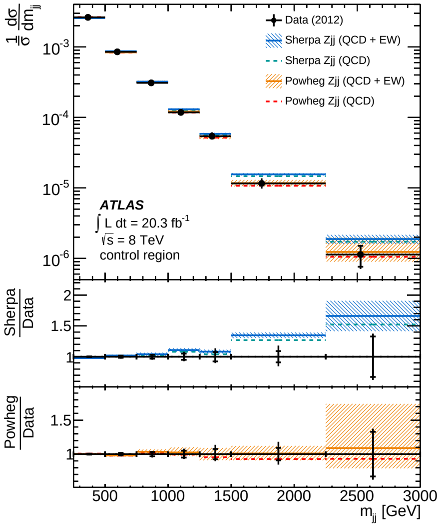
unfolded jet veto efficiency as a function of $|\Delta y|$ (**baseline region**)



normalized differential cross section as a function of m_{jj} (**control region**)



Electroweak Zjj production extraction

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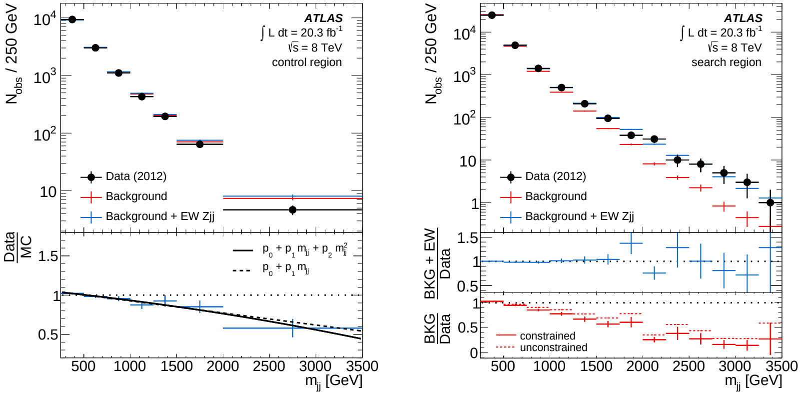
- EW Zjj component extracted by a fit to the m_{jj} spectrum
- strong Zjj production constrained from events with $\geq$ 1 jet within tag jets
  - → idea: correct simulation in search region using data/MC ratio in control region
  - → improves the modelling by SHERPA and limits systematic uncertainties



→ background-only hypothesis excluded with significance above 5σ !

Electroweak Zjj production cross sections

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- extracted cross sections in **search fiducial regions**:

$m_{jj} > 250$ GeV:

$$\sigma_{\mathrm{EW,measured}} = 54.7 \pm 4.6(\mathrm{stat})\,^{+9.8}_{-10.4}(\mathrm{syst}) \pm 1.5(\mathrm{lumi})\,\mathrm{fb}$$
$$\sigma_{\mathrm{theory}} = 46.1 \pm 0.2(\mathrm{stat})\,^{+0.3}_{-0.2}(\mathrm{scale}) \pm 0.8(\mathrm{PDF}) \pm 0.5(\mathrm{model})\,\mathrm{fb}$$

$m_{jj} > 1$ TeV (most sensitive to EW Zjj component):

$$\sigma_{\mathrm{EW,measured}} = 10.7 \pm 0.9(\mathrm{stat}) \pm 1.9(\mathrm{syst}) \pm 0.3(\mathrm{lumi})\,\mathrm{fb}$$
$$\sigma_{\mathrm{theory}} = 9.38 \pm 0.05(\mathrm{stat})\,^{+0.15}_{-0.24}(\mathrm{scale}) \pm 0.24(\mathrm{PDF}) \pm 0.09(\mathrm{model})\,\mathrm{fb}$$

- theory prediction from POWHEGBOX

Constraints on aTGC from Zjj

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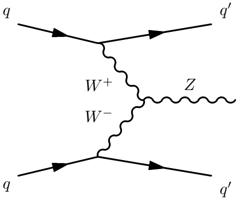
- two of the gauge bosons entering the WWZ vertex have space-like four-momentum transfer

  → electroweak Zjj production offers a complementary test of aTGCs



- 95% confidence intervals on aTGC parameters Δg_1^Z and λ_Z from counting the number of events in search region with $m_{jj} > 1$ TeV

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	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

$\Lambda = \Lambda_{\mathrm{FF}}$

→ limits not as stringent as those from WZ production (e.g. $\sim 3\times$ smaller for λ_Z)

Electroweak $W^{\pm}W^{\pm}jj$ production

($\sqrt{s}$ = 8 TeV)

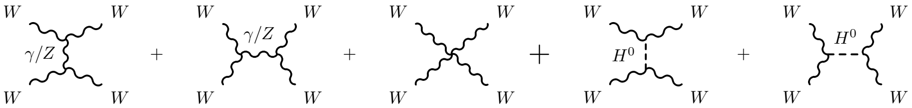
Vector boson scattering and EWSB

$V = W, Z$

- the mechanism responsible for EWSB must regulate $\sigma(V_L V_L \to V_L V_L)$ to restore unitarity above $\sim 1-2$ TeV

  $\rightarrow$ a light SM Higgs boson exactly cancels increase for large s (for HWW coupling)

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s - t + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2}\right]$$



- unitarity preservation only visible in VV scattering

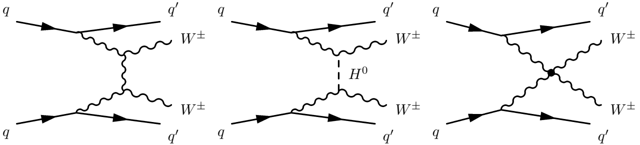
  $\Rightarrow$ VV scattering is a key process to probe the SM nature of EWSB!

- at the LHC: measure $VVjj$ final states $\rightarrow$ same-sign $W^\pm W^\pm jj$ most promising

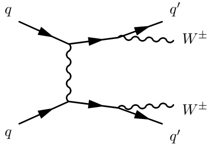
Same-sign $W^\pm W^\pm jj$ production at the LHC

- electroweak $W^\pm W^\pm jj$ production:

  $W^\pm W^\pm jj$-EW VBS: no s-channel diagrams

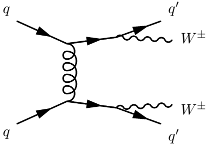
  non-VBS diagrams, e.g.

  → lowest order: $W^\pm W^\pm + 2$ jets, there is no SM inclusive $W^\pm W^\pm$ production!

  → VBS: "tagging" jets well separated in y with large m_{jj} (similar to EW Zjj production)

- strong $W^\pm W^\pm jj$ production:

  → no LO gg or qg initial state → strong $W^\pm W^\pm jj$ contributions comparably small

$W^{\pm}W^{\pm}jj$ event selection

arXiv:1405.6241, submitted to PRL

- event topology:
  - exactly 2 same-sign leptons, $p_T^{\ell} > 25$ GeV ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$ final states)
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
  - ≥ 2 jets with $p_T^{\mathrm{jet}} > 30$ GeV
- suppress backgrounds:
  - prompt background $\rightarrow$ 3 or more prompt leptons

    WZ/γ^* and ZZ +jets (Sherpa), $t\bar{t} + W/Z$ (Madgraph+Pythia8), tZj (Sherpa)

    $\Rightarrow$ veto events with any additional $e(\mu)$ with $p_T > 7(6)$ GeV
  - conversions

    $\rightarrow$ prompt photon conversion: $W\gamma$ (Alpgen+Herwig/Jimmy, Sherpa)

    $\rightarrow$ charge mis-ID due to bremsstrahlung with conversion (data driven):

    Z/γ^*+jets, di-leptonic $t\bar{t}$ decays, $W^{\pm}W^{\mp}$

    $\Rightarrow$ Z-veto in ee channel: $|m_{ee} - m_Z| > 10$ GeV
  - other non-prompt background: (data driven)

    $\rightarrow$ leptons from hadron decays in jets: W+jets, semi-leptonic $t\bar{t}$ decays, dijet events
  - veto events containing b-jets (reduces $t\bar{t}$)

$W^{\pm}W^{\pm}jj$ production

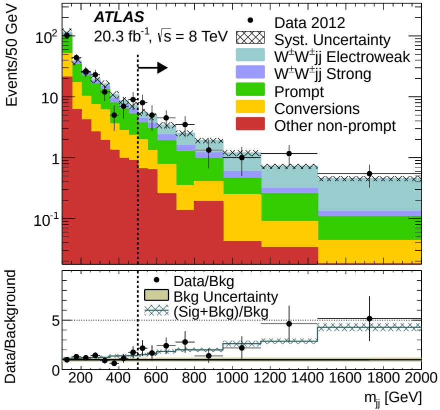
arXiv:1405.6241

for EW+strong measurement

("inclusive signal region")

$\rightarrow$ $m_{jj} > 500$ GeV (jets with largest p_T)

invariant mass of the 2 tagging jets

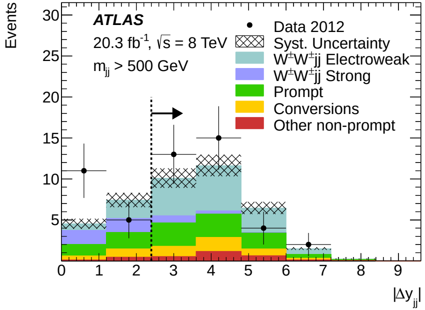


for EW measurement

("VBS signal region")

$\rightarrow$ additional cut on $|\Delta y_{jj}| > 2.4$

$|\Delta y_{jj}|$ between the 2 tagging jets

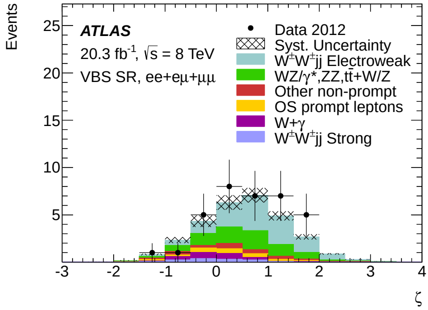


EW and strong $W^{\pm}W^{\pm}jj$ from SHERPA, normalized with POWHEG

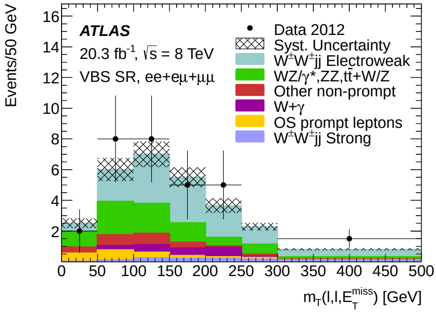
$W^{\pm}W^{\pm}$ system in the VBS signal region

arXiv:1405.6241

lepton centrality ζ



transverse mass of $W^{\pm}W^{\pm}$ system



lepton centrality:

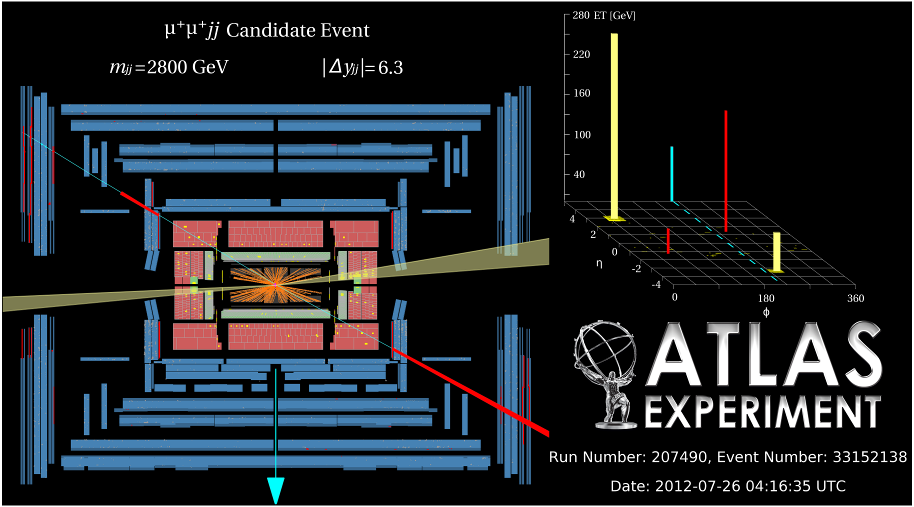
$$\zeta = \min\left[\min(\eta_{\ell 1}, \eta_{\ell 2}) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_{\ell 1}, \eta_{\ell 2})\right]$$

→ both leptons between tagging jets (in η): $\zeta > 0$

→ one or both leptons with larger η than closest jet: $\zeta < 0$

$W^{\pm}W^{\pm}jj$ candidate event

arXiv:1405.6241, submitted to PRL



jets: $p_T^{j1} = 271$ GeV, $p_T^{j2} = 54$ GeV, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$ $\quad E_{\mathrm{T}}^{\mathrm{miss}} = 75$ GeV

muons: $p_T^{\mu 1} = 180$ GeV, $p_T^{\mu 2} = 38$ GeV, $\eta^{\mu 1} = 1.4$, $\eta^{\mu 2} = -1.3$

$W^\pm W^\pm jj$ production cross sections

arXiv:1405.6241, submitted to PRL

- cross sections in inclusive and VBS fiducial regions
  (different sensitivities to EW and strong $W^\pm W^\pm jj$ production)

  → extracted by fitting a likelihood function to the observed data

	measurement	theory prediction POWHEGBOX+PYTHIA8
inclusive signal region (EW+strong $W^\pm W^\pm jj$ production)		
cross section [fb]	2.1 ± 0.5(stat) ± 0.3(syst)	1.52 ± 0.11
significance	4.5 σ	3.4 σ
VBS signal region (EW $W^\pm W^\pm jj$ production)		
cross section [fb]	1.3 ± 0.4(stat) ± 0.2(syst)	0.95 ± 0.06
significance	3.6 σ	2.8 σ

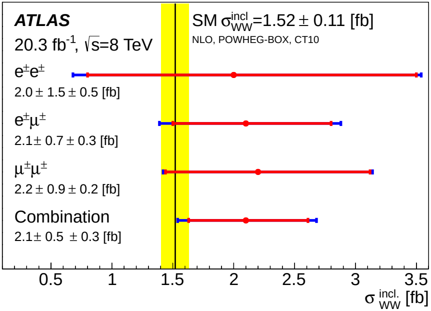
  → interference between EW and strong $W^\pm W^\pm jj$ production: $\sim 7 \pm 4$ %
  (LO, evaluated with SHERPA), included in EW signal

- **first evidence of a process containing VBS and a quartic gauge vertex!**

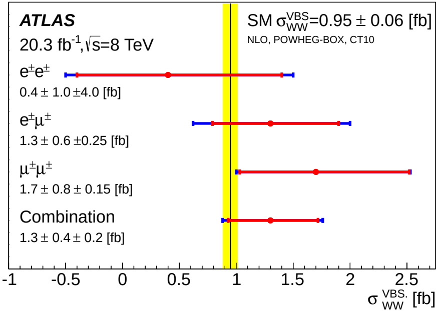
$W^{\pm}W^{\pm}jj$ production cross sections

arXiv:1405.6241, submitted to PRL

inclusive phase space



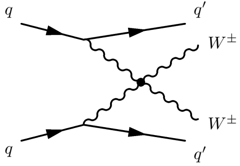
VBS phase space



Anomalous quartic gauge couplings

arXiv:0806.4145

- modeling of aQGC with electroweak chiral Lagrangian approach (non-linear representation of the gauge symmetry)

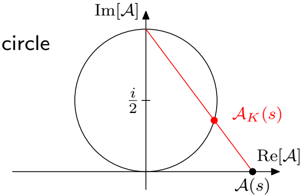


  $\rightarrow$ effective aQGC parametrization: α_4 and α_5

- with aQGC unitarity may be violated due to new physics

  $\Rightarrow$ unitarization with **K-matrix** method

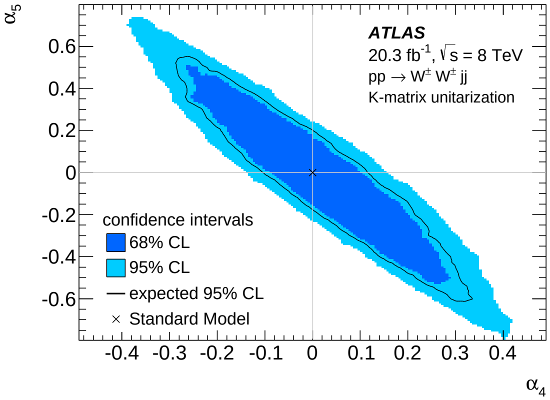
  - scattering amplitude $\mathcal{A}(s)$ projected on Argand circle $\rightarrow$ saturation of the amplitude
  - allows for probing the entire kinematic phase space without being unphysical



Constraints on aQGCs from $W^{\pm}W^{\pm}jj$

arXiv:1405.6241, submitted to PRL

- exclusion limits on α_4 and α_5 extracted from cross section in VBS phase space
  - aQGC samples from WHIZARD+PYTHIA8 with K-matrix unitarization
  - efficiency only weakly dependent on aQGC



1D 95% confidence intervals

expected:

$-0.10 < \alpha_4 < 0.12$

$-0.18 < \alpha_5 < 0.20$

observed:

$\mathbf{-0.14 < \alpha_4 < 0.16}$

$\mathbf{-0.23 < \alpha_5 < 0.24}$

(respective other $\alpha_i = 0$)

$\hat{=}$ scale of new physics: $\Lambda > 500 - 650$ GeV (rule of thumb: $\Lambda = v/\sqrt{\alpha_i}$ arXiv:1307.8170)

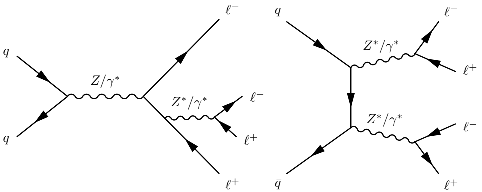
Inclusive $pp \to 4\ell$ production at the Z resonance

($\sqrt{s}$ = 7 & 8 TeV)

Inclusive $Z \to 4\ell$ production

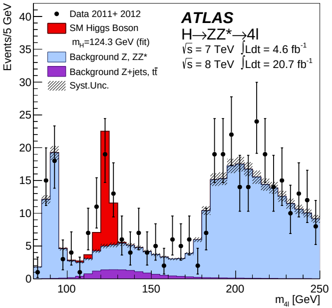
Phys. Rev. Lett. 112, 231806 (2014)
(CMS, 7 TeV: JHEP 12 (2012) 034)

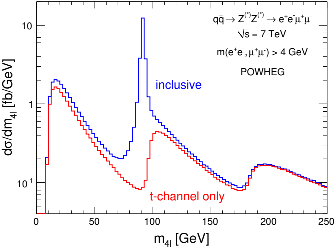
- peak around Z mass observed in $m_{4\ell}$ spectrum near $H \to 4\ell$ decay



~4% at the Z resonance

($gg \to Z^{(*)}Z^{(*)} \to 4\ell$ contributes with ≈ 0.1%)



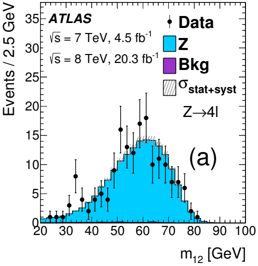


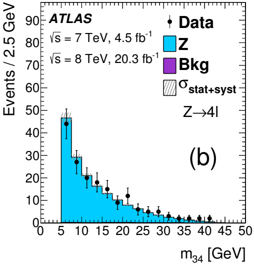
- measurement of inclusive 4ℓ production cross section and $Z \to 4\ell$ branching fraction (combining all 4ℓ final states)
  - → precision test of the Standard Model
  - → complementary test of the detector response to the 4ℓ final state from Higgs decays

Inclusive $Z \to 4\ell$ event selection

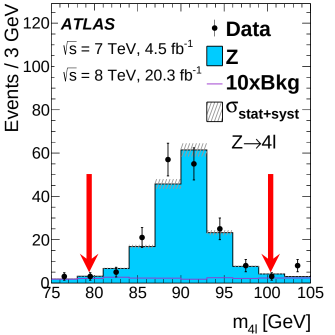
Phys. Rev. Lett. 112, 231806 (2014)

- 2 opposite-sign, same-flavor dilepton pairs with $p_{\mathrm{T}} > 20, 15, 10(8), 7(4)$ GeV, $e(\mu)$
- $m_{12} > 20$ GeV for leading lepton pair
  $m_{34} > 5$ GeV for sub-leading lepton pair
- in $4e$ and 4μ channels: $m_{\ell^+\ell^-} > 5$ GeV
  for all same-flavor, opposite-sign lepton pairs
  (reduces events with $J/\psi \to \ell^+\ell^-$ decays)
- 4ℓ invariant mass: 80 GeV $< m_{4\ell} <$ 100 GeV





before $m_{4\ell}$ requirement



- $21(151)$ $Z \to 4\ell$ candidate events at 7(8) TeV
- signal modeled by Powheg + Pythia6/8 and Photos; GG2ZZ+Herwig/Jimmy
- background below 1%

Inclusive $Z \to 4\ell$ cross sections

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

- inclusive 4ℓ cross sections in $4e, 4\mu$, $2e2\mu$ and combined final states in phase space
  - $m_{\ell^+\ell^-} > 5$ GeV for all same-flavor lepton pairs
  - 80 GeV $< m_{4\ell} <$ 100 GeV

$\sqrt{s}$	4ℓ state	$\sigma_{Z4\ell}$ [fb]	$\sigma_{Z4\ell}^{\text{theory}}$ [fb] (POWHEG)
7 TeV	$4e, 4\mu$	$32 \pm 11 \pm 1.0 \pm 0.6$	
	$2e2\mu$	$44 \pm 14 \pm 3.3 \pm 0.9$	
	combined	$76 \pm 18 \pm 4 \pm 1.4$	90.0 ± 2.1
8 TeV	$4e, 4\mu$	$56 \pm 6 \pm 1.8 \pm 1.6$	
	$2e2\mu$	$52 \pm 7 \pm 2.4 \pm 1.5$	
	combined	$107 \pm 9 \pm 4 \pm 3.0$	104.8 ± 2.5

$Z \to 4\ell$ branching fractions

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

- $Z \to 4\ell$ branching fraction determined by subtracting t-channel contributions ($f_{\rm nr}$) and normalizing with $Z \to \mu\mu$ events:

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

with $\Gamma_{Z\to\mu\mu}/\Gamma_Z = (3.366 \pm 0.007)\,\%$ (PDG)

→ cancels uncertainties on luminosity

→ partially cancels theoretical and μ experimental systematic uncertainties

- branching fractions (error weighted combination of 7 and 8 TeV results):

phase space		$\sqrt{s}$	$\Gamma_{Z\to 4\ell}/\Gamma_Z$
$m_{\ell^+\ell^-} > 5$ GeV	measured	7 TeV	$(2.67 \pm 0.62$ (stat) ± 0.14 (syst)$) \times 10^{-6}$
		8 TeV	$(3.33 \pm 0.27$ (stat) ± 0.13 (syst)$) \times 10^{-6}$
		combined	$(3.20 \pm 0.25$ (stat) ± 0.13 (syst)$) \times 10^{-6}$
	expected		$(3.33 \pm 0.01) \times 10^{-6}$

syst. includes interference between s- and t-channel, calculated with CalcHEP ($\sim$ 0.2%)

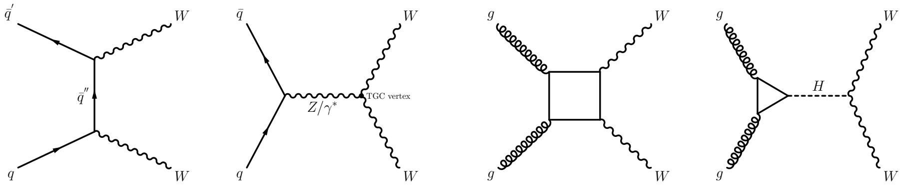
W^+W^- production

($\sqrt{s}$ = 7 & 8 TeV)

W^+W^- production

leading order processes:
t- and s-channel $q\bar{q} \rightarrow WW$

gluon fusion processes,
only considered in 8 TeV analysis,
$gg \rightarrow H \rightarrow WW$ contributes with $\sim$ 7%



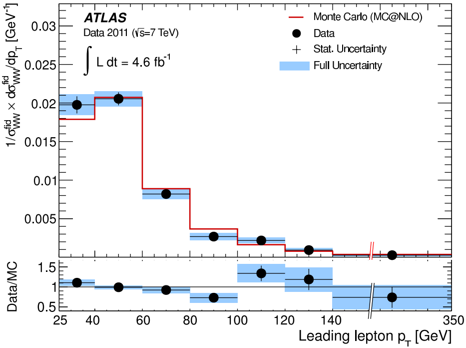
(WW production via VBS and double parton interactions neglected)

- important test of EW theory and of QCD
- irreducible background to Higgs property measurements in $H \rightarrow WW$
- signature: $\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ ($\ell = e$ or μ)
- EW pair production of charginos may result in the same final state, but different kinematics

W^+W^- production ($\sqrt{s} = 7$ TeV)

Phys.Rev. D87, 112001 (2013)
(CMS: Eur.Phys.J. C73 (2013) 2610)

- tight event selection against background:
  - → 2 opposite-sign high p_T isolated leptons
  - → $m_{\ell\ell}$, $E_T^{\rm miss}$ (against Z+jets)
  - → jet veto (against $t\bar{t}$)
- unfolded differential cross section



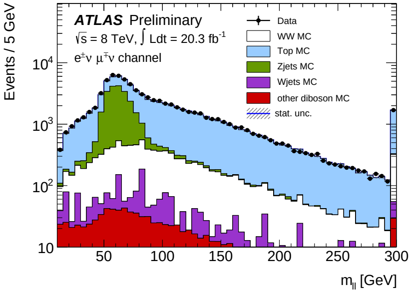
- total cross section:
  - measurement: $\sigma^{\rm tot} = 51.9 \ \pm 2.0({\rm stat}) \ \pm 4.4({\rm syst})$ pb
  - theory prediction: $\sigma^{\rm tot} = 44.7^{+2.1}_{-1.9}$ MCFM, PDF set CT10

W^+W^- production ($\sqrt{s} = 8$ TeV) new!

ATLAS-CONF-2014-033
(CMS: Phys. Lett. B 721 (2013) 190211)

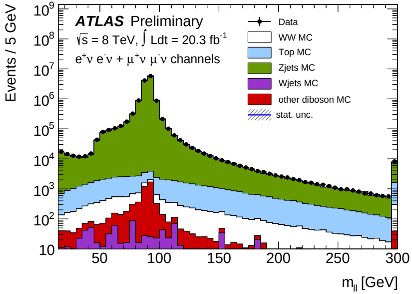
- select exactly 2 isolated, oppositely charged leptons with $p_T^{\ell 1/2} > 25/20$ GeV
- veto events with any additional leptons with $p_T > 7$ GeV
- main background: top ($e\mu$) and Z+jets (ee+$\mu\mu$) (ALPGEN+JIMMY or PYTHIA6)

$e\mu$ channel



$Z/\gamma^* \to \tau\tau$

$ee + \mu\mu$ channel



$Z/\gamma^* \to ee, \mu\mu$: $|m_{\ell\ell} - m_Z| > 15$ GeV

calorimeter and track-based E_T^{miss} requirements

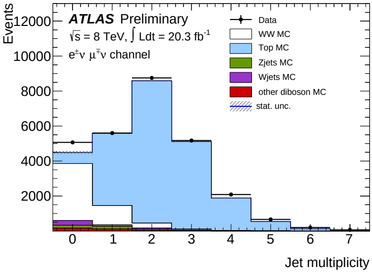
W^+W^- event selection

new!

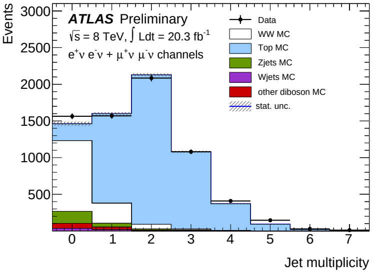
ATLAS-CONF-2014-033

- background from top ($t\bar{t}$ and single top) events with leptonically decaying Ws
  (MC@NLO+Herwig/Jimmy and AcerMC+Pythia6)
  - signature similar to WW signal, but additional jets
    $\Rightarrow$ veto events with any jets with $p_T^j > 25$ GeV
- jet multiplicities before jet-veto requirement:

$e\mu$ channel



$ee + \mu\mu$ channel



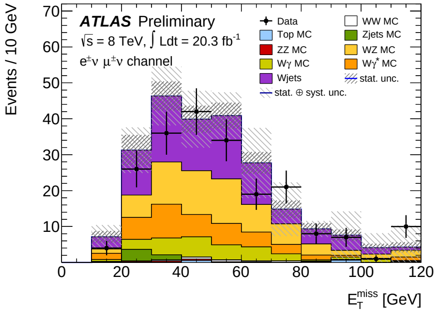
- residual top background from data-driven method
  (efficiency of the jet-veto requirement for top events corrected from data)

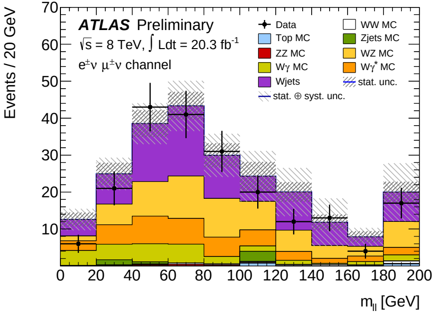
W^+W^-: further backgrounds

new!

- W+jets: data-driven estimation
- dibosons: WZ, ZZ (POWHEG+PYTHIA8), and $W\gamma/W\gamma^*$ (ALPGEN+HERWIG/JIMMY and SHERPA)
- check for normalization of backgrounds from diboson production

  → validation region in $e\mu$ channel where the leptons have same charge:



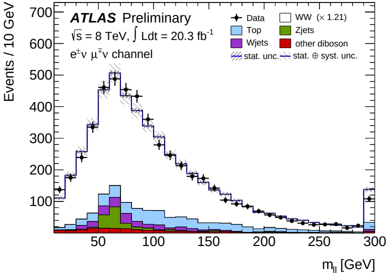


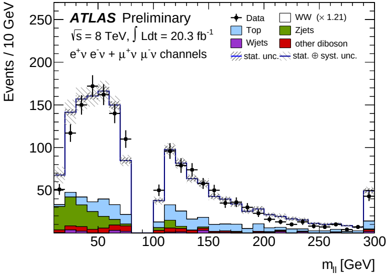
→ dominated by WZ and W+jets

W^+W^- total cross sections

new!

- 6636 WW candidate events observed after full selection (5067 $e\mu$, 594 ee, 975 $\mu\mu$)
- kinematic distributions in $e\mu$ channel (WW signal scaled by 21%):



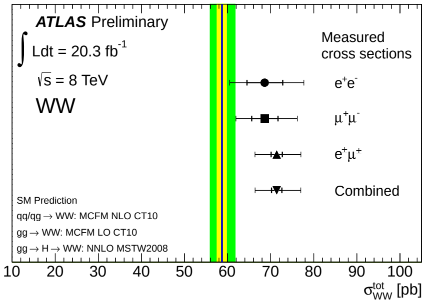


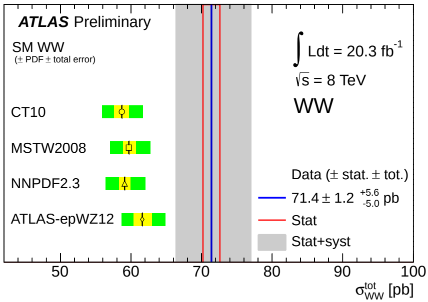
- measured total cross sections by fitting a likelihood function to the observed data:

Channel	$\sigma_{WW}^{\text{total}}$ [pb]
ee	$68.6^{+4.2}_{-4.1}$ (stat) $^{+7.8}_{-6.7}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$68.6^{+3.1}_{-3.0}$ (stat) $^{+6.6}_{-5.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$e\mu$	$71.4^{+1.3}_{-1.3}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
Combined	$71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)

W^+W^- total cross sections

new!





ATLAS-epWZ12 from HERAI data and ATLAS W/Z measurement (Phys.Rev.Lett. 109 (2012) 012001)

PDF set differences larger than the error on them

- measured total combined WW cross section:

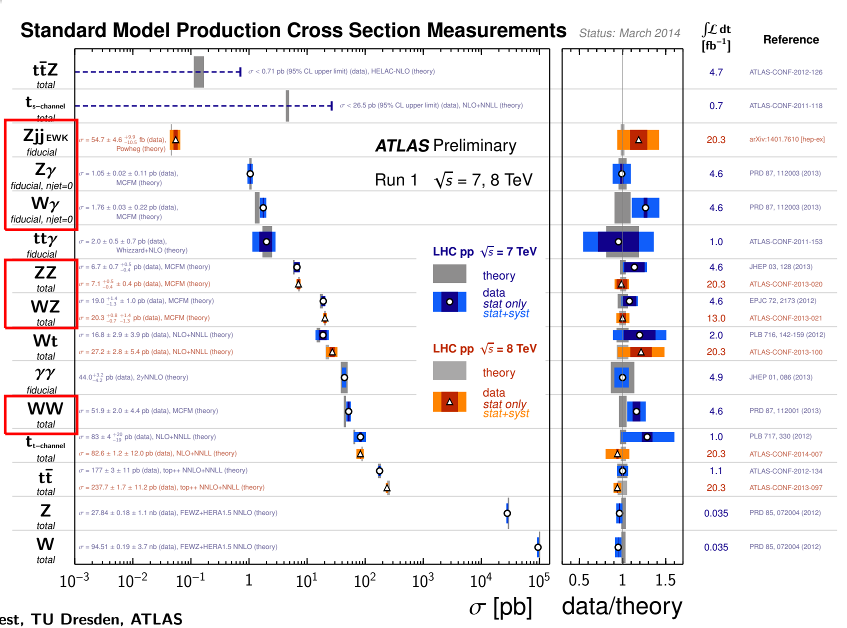
$$\sigma_{WW}^{\text{tot}} = 71.4\ ^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})\ \text{pb}$$

- SM theory prediction: $\sigma_{WW}^{\text{theory}} = 58.7^{+3.0}_{-2.7}$ pb
  - → $q\bar{q} \to WW$ and $qg/\bar{q}g \to WW$ (53.2 pb) at NLO from MCFM
  - → $gg \to WW$ (1.4 pb) at LO from MCFM, may have large corrections at higher orders
  - → $gg \to H \to WW$ (4.1 pb) at NNLO from LHC Higgs XS working group arXiv:1307.1347

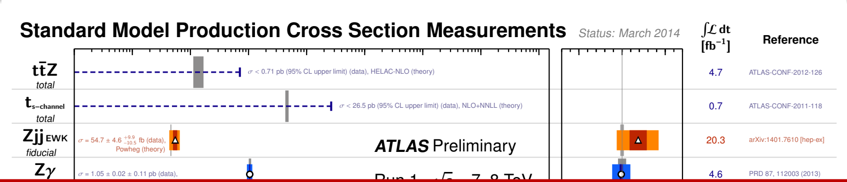
Summary

- electroweak measurements with the ATLAS detector
  - fiducial and total cross sections
  - unfolded differential cross sections for all fully leptonic diboson results at 7 TeV
  - gauge couplings consistent with the SM $\rightarrow$ limits on aTGC/aQGC
- new 8 TeV results:
  - electroweak Zjj production:
    first observation of a process containing VBF at a hadron collider
  - electroweak $W^{\pm}W^{\pm}jj$ production:
    first evidence ever for a process containing VBS and a quartic gauge vertex
  - $Z \rightarrow 4\ell$ production: precise branching fractions
  - $W^{+}W^{-}$ production
- more results on full 8 TeV dataset to come

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

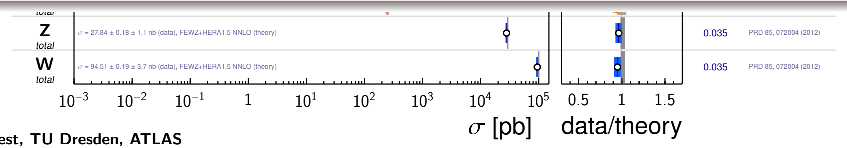


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults



new results:

process	measured cross section	theory prediction
$W^\pm W^\pm jj$ EW	$\sigma^{fid} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb	$\sigma^{fid} = 0.95 \pm 0.06$ fb
Zjj EW	$\sigma^{fid} = 54.7 \pm 4.6(\text{stat}) \pm 10.5(\text{syst})$ fb	$\sigma^{fid} = 46.1 \pm 1.2$ fb
$Z \rightarrow 4\ell$ (7 TeV)	$\sigma^{tot} = 76 \pm 18(\text{stat}) \pm 4(\text{syst})$ fb	$\sigma^{tot} = 90.0 \pm 2.1$fb
$Z \rightarrow 4\ell$	$\sigma^{tot} = 107 \pm 9(\text{stat}) \pm 5(\text{syst})$ fb	$\sigma^{tot} = 104.8 \pm 2.5$ fb
W^+W^-	$\sigma^{tot} = 71.4 \pm 1.2(\text{stat}) \pm 5.9(\text{syst})$ pb	$\sigma^{tot} = 58.7^{+3.0}_{-2.7}$ pb



Backup

W^+W^- event selection

new!

ATLAS-CONF-2014-033

cuts on $E_{\mathrm{T}}^{\mathrm{miss}}$:

$e\mu$ channel:

$E_{\mathrm{T,Rel}}^{\mathrm{miss}} > 15$ GeV
$p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.6$

$ee + \mu\mu$ channel:

$E_{\mathrm{T,Rel}}^{\mathrm{miss}} > 45$ GeV
$p_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.3$

$\rightarrow$ $E_{\mathrm{T,Rel}}^{\mathrm{miss}} = E_{\mathrm{T}}^{\mathrm{miss}} \times sin|\Delta\phi|$:
projection of $\vec{E}_{\mathrm{T,Rel}}^{\mathrm{miss}}$ on close-by ($\Delta\phi < \pi/2$) leptons or jets

$\rightarrow$ $p_{\mathrm{T}}^{\mathrm{miss}}$: track-based missing transverse momentum

W^+W^- event yields

new!

ATLAS-CONF-2014-033

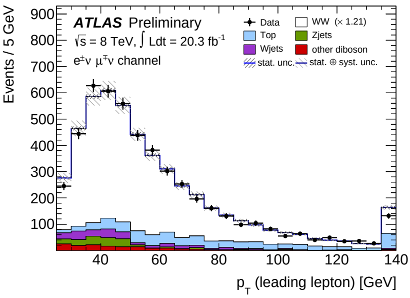
- summary of observed events and expected signal and background contributions:

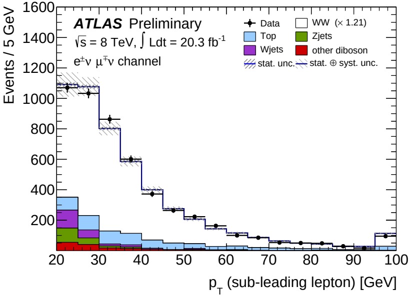
Channel	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Observed Events	594	975	5067
Total expected events	$536 \pm 10 \pm 42$	$873 \pm 12 \pm 63$	$4376 \pm 26 \pm 280$
MC W^+W^- signal	$346 \pm 3 \pm 32$	$610 \pm 5 \pm 56$	$3224 \pm 10 \pm 248$
Top(data-driven)	$92 \pm 7 \pm 8$	$127 \pm 9 \pm 11$	$609 \pm 18 \pm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

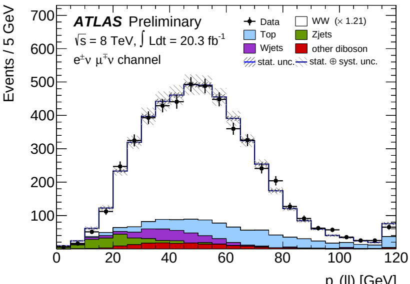
W^+W^- kinematic distributions

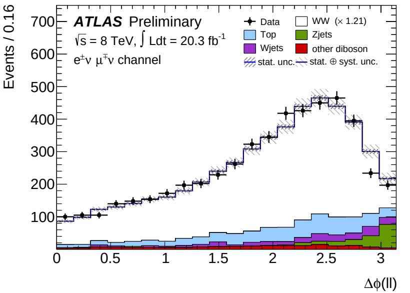
new!

ATLAS-CONF-2014-033





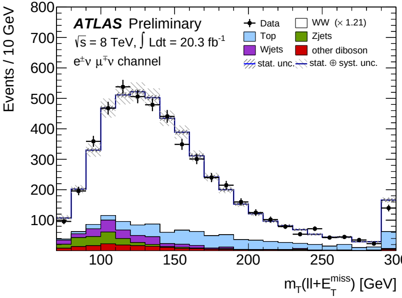


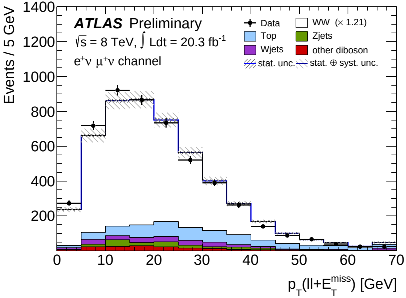


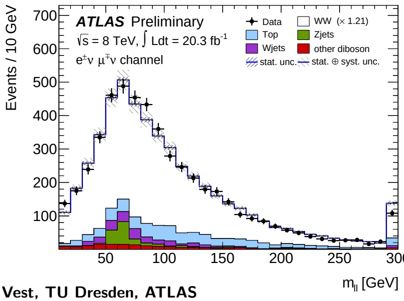
new!

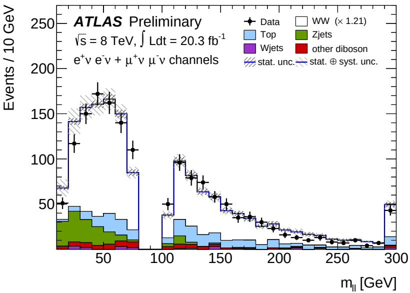
W^+W^- kinematic distributions

ATLAS-CONF-2014-033









W^+W^-: top background

new!

ATLAS-CONF-2014-033

- background from top ($t\bar{t}$ and single top) events with leptonically decaying Ws estimated from data-driven approach from 2 control regions:
  - CR1: same as signal region, but instead of jet-veto requirement: scalar sum p_T of leptons and jets, $H_\mathrm{t} > 130$ GeV

$$N_{top}^{DD} = (N_1^{\mathrm{data}} - N_1^{\mathrm{nonTop,MC}}) \times p_{\mathrm{CR1}}^{\mathrm{data}} / \epsilon_{H_\mathrm{t}}$$

    ϵ_{H_t}: efficiency of events with top quarks to pass the H_t requirement
  - CR2: sub-sample of CR1, with at least one b-jet (with 85% efficiency and $p_T > 25$ GeV)
- probability for $t\bar{t}$ and Wt event to pass the jet-veto requirement measured in CR2 and extrapolated to CR1:

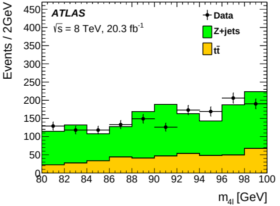
$$p_{\mathrm{CR1}}^{\mathrm{data}} = (p_{\mathrm{CR2}}^{\mathrm{data}})^2 \times \frac{p_{\mathrm{CR1}}^{\mathrm{MC}}}{(p_{\mathrm{CR2}}^{\mathrm{MC}})^2}$$

- data-to-MC correction factor for the efficiency of the jet-veto requirement: $\epsilon_{WW}^{\mathrm{data}} = \epsilon_{WW}^{\mathrm{MC}} \times f_Z$, with $f_Z = \epsilon_Z^{\mathrm{data}} / \epsilon_Z^{\mathrm{MC}} = 0.990 \pm 0.036$ (syst)

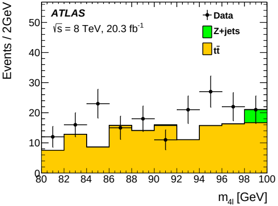
Inclusive $Z \to 4\ell$ background

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

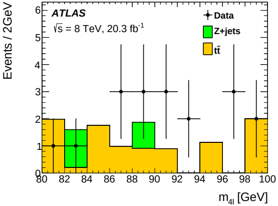
- background estimation (overall below 1%):
  - diboson processes:
    WZ and $Z\gamma$, and $Z^{(*)}Z^{(*)} \to 4\ell$ decays involving $\tau \to e/\mu + 2\nu$,
    modeled by POWHEG+PYTHIA6/8 and SHERPA
  - $t\bar{t}$ and Z+jets: data-driven
    (from $\ell\ell j_\ell j_\ell$ background control samples with inverted lepton selection,
    j_ℓ: lepton-like jet)



2 e-like jets



1 e-like, 1 μ-like jet



2 μ-like jets

MC control samples: MC@NLO and ALPGEN +HERWIG/JIMMY

Fiducial $Z \to 4\ell$ cross sections

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

- fiducial cross sections in $ee+ee$, $\mu\mu+\mu\mu$, $ee+\mu\mu$ and $\mu\mu+ee$ final states:

$\sqrt{s}$	4ℓ state	$N_{4\ell}^{\text{obs}}$	$N_{4\ell}^{\text{exp}}$	$N_{4\ell}^{\text{bkg}}$	$\sigma_{Z4\ell}^{\text{fid}}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$
	$\mu\mu+\mu\mu$	8	11.3 ± 0.5	0.08 ± 0.04	$3.0^{+1.2}_{-0.9} \pm 0.07 \pm 0.05$
	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$
	combined	21	24.2 ± 1.2	0.44 ± 0.14	
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$
	$\mu\mu+\mu\mu$	71	68.8 ± 2.7	0.34 ± 0.05	$4.9^{+0.7}_{-0.6} \pm 0.13 \pm 0.14$
	$ee+\mu\mu$	48	43.2 ± 2.1	0.32 ± 0.05	$4.2^{+0.7}_{-0.6} \pm 0.16 \pm 0.12$
	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$
	combined	151	146 ± 7	1.0 ± 0.11	

$Z \to 4\ell$ branching fractions

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

- branching fractions with $m_{\ell^+\ell^-} > 4$ GeV:

phase space		$\sqrt{s}$	$\Gamma_{Z\to 4\ell}/\Gamma_Z$
$m_{\ell^+\ell^-} > 4$ GeV	measured	combined	$(4.31 \pm 0.34$ (stat) ± 0.17 (syst)$) \times 10^{-6}$
	expected		$(4.50 \pm 0.01) \times 10^{-6}$

- CMS (JHEP 12 (2012) 034):
  - measurement: $(4.2^{+0.9}_{-0.8}(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-6}$
  - theory prediction 4.45×10^{-6}

Zjj production: sample composition

JHEP 04 (2014) 031

process composition for each fiducial region for the combined μ and e channels:

Process	Composition (%) *baseline*	*high-p_{T}*	*search*	*control*	*high-mass*
Strong Zjj (PowhegBox+Pythia6)	95.8	94.0	94.7	96.0	85
Electroweak Zjj (PowhegBox+Pythia6)	1.1	2.1	4.0	1.4	12
WZ and ZZ (Sherpa)	1.0	1.3	0.7	1.4	1
$t\bar{t}$ (MC@NLO+Herwig/Jimmy)	1.8	2.2	0.6	1.0	2
Single top (MC@NLO+Herwig/Jimmy)	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet (data driven)	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets (Sherpa)	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

$p_{\mathrm{T}}^{\mathrm{balance}}$ definition: $p_{\mathrm{T}}^{\mathrm{balance}} = \dfrac{\left|\vec{p}_{\mathrm{T}}^{\,\ell_1} + \vec{p}_{\mathrm{T}}^{\,\ell_2} + \vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\,\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\,\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{\,j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\,j_2}\right|}$

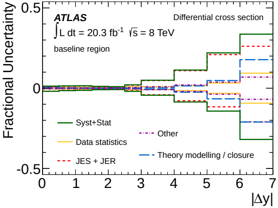
EW Zjj production: systematic uncertainties

JHEP 04 (2014) 031

Source	ΔN_{EW} Electrons	ΔN_{EW} Muons	$\Delta \mathcal{C}_{\mathrm{EW}}$ Electrons	$\Delta \mathcal{C}_{\mathrm{EW}}$ Muons
Lepton systematics	—	—	± 3.2 %	± 2.5%
Control region statistics	± 8.9 %	± 11.2 %	—	—
JES	± 5.6 %		$^{+2.7}_{-3.4}$ %	
JER	± 0.4 %		± 0.8 %	
Pileup jet modelling	± 0.3 %		± 0.3 %	
JVF	± 1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	± 8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	± 7.5 %		—	
Signal/background interference	± 6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		± 0.1 %	

- at large Δy_{jj} largest uncertainties from:
  - jet energy scale
  - theory modeling

$\rightarrow$ similar to electroweak $W^{\pm}W^{\pm}jj$ production . . .



VBS (heavy vector bosons only) at the LHC

- leading order cross sections (SHERPA) at $\sqrt{s} = 8$ TeV:

final state	$\sigma(VVjj\text{-EW})$	$\sigma(\text{strong } VVjj)$	$\sigma(\text{EW})/\sigma(\text{strong})$
$W^{\pm}W^{\pm}jj$	19.5 fb	18.8 fb	$\sim$ **1:1**
$W^{\pm}W^{\mp}jj + ZZjj$	93.7 fb	3192 fb	$\sim$ 1:35
$WZjj$	30.2 fb	687 fb	$\sim$ 1:20
$ZZjj$	1.5 fb	106 fb	$\sim$ 1:70*

* includes γ^*, would be also 1:20 – 1:30 with higher m_{ll} cut

(generator cuts: $m_{\ell\ell} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

$W^{\pm}W^{\pm}jj$ production

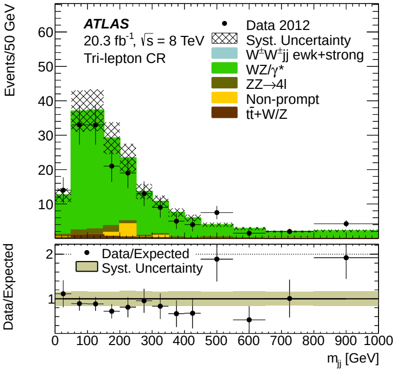
arXiv:1405.6241, submitted to PRL

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^{\pm}W^{\pm}jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

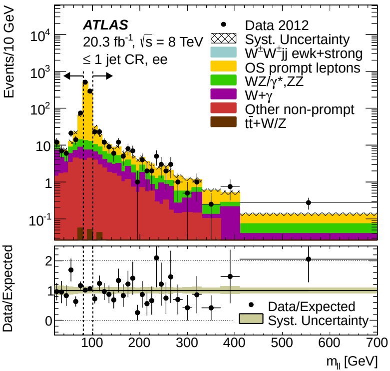
$W^{\pm}W^{\pm}jj$ production – control regions

arXiv:1405.6241, submitted to PRL

trilepton control region:
→ prompt



≤ 1 jet control region:
→ conversions (ee), prompt ($\mu\mu$)

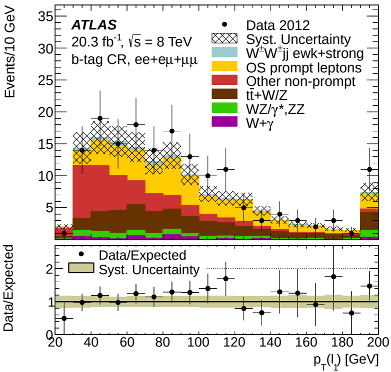


Control Region		Trilepton	$\leq$ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 $\pm$ 6	278 $\pm$ 28	40 $\pm$ 6	76 $\pm$ 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 $\pm$ 18	288 $\pm$ 42	75 $\pm$ 13	127 $\pm$ 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 $\pm$ 10	88 $\pm$ 14	25 $\pm$ 7	40 $\pm$ 6
	data	48	101	36	30

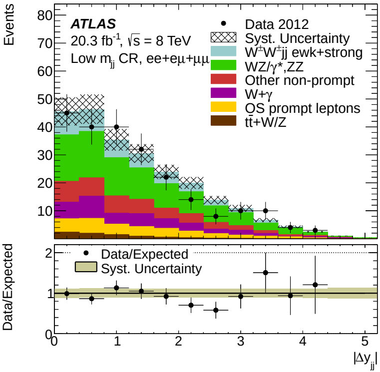
$W^\pm W^\pm jj$ production – control regions

arXiv:1405.6241, submitted to PRL

$t\bar{t}$/b-tag control region:
→ other non-prompt (b-decays)



$m_{jj} < 500$ GeV control region:
→ mix



Control Region		Trilepton	$\leq$ 1 jet	b-tagged	Low m_{jj}
$e^\pm e^\pm$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^\pm \mu^\pm$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^\pm \mu^\pm$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

Electroweak $W^{\pm}W^{\pm}jj$ production

arXiv:1405.6241, submitted to PRL

- expected numbers of events and measured data:

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

Modeling of anomalous quartic gauge couplings

EFT description can be translated in EW chiral Lagrangian approach for aTGC/aQGC and vice versa (switch of operator bases) arXiv:hep-ph/0606118

EW chiral Lagrangian approach (non-linear realization of the gauge symmetry)

- aQGC operators (dimension 4):

$$\mathscr{L}_4 = \alpha_4 (\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2 \qquad \mathscr{L}_5 = \alpha_5 (\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$

- $\mathbf{V}_\mu = \Sigma (D_\mu \Sigma)^\dagger$, $\Sigma = e^{-i\frac{\mathbf{w}}{v}}$, $\mathbf{w}$: goldstone scalar field triplett
- aQGC parametrizations: α_4 and α_5

EFT approach (linear realization of gauge symmetry)

- operators (dimension 8):

$$\mathscr{L}_{S,0} = \frac{f_{S,0}}{\Lambda^4} [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi]$$

$$\mathscr{L}_{S,1} = \frac{f_{S,1}}{\Lambda^4} [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]$$

- parametrizations: $\frac{f_{S,0}}{\Lambda^4}$ and $\frac{f_{S,1}}{\Lambda^4}$

Experimental tests of the EW theory at LEP

- SM confirmed at very high precision by the LEP experiments
- triple gauge boson couplings validated by $e^+e^- \rightarrow W^+W^-$ cross section measurements
- measured QGC processes at LEP:
  - e.g. $e^+e^- \rightarrow \nu\nu\gamma\gamma$ and $e^+e^- \rightarrow W^+W^-\gamma$
  - significant observation with small/negligible background
  - **but: consistent with ISR/FSR processes**, which can be gauge-invariantly distinguished from QGC processes
    - OPAL: http://arxiv.org/abs/hep-ex/0402021v1
    - L3: http://arxiv.org/pdf/hep-ex/0111029v1
    - OPAL: http://arxiv.org/abs/hep-ex/0309013
    - DELPHI: http://arxiv.org/pdf/hep-ex/0311004v1
- No "real" observation of any QGC process at LEP (nor at Tevatron)

arXiv:1302.3415