Measurements of Multi-boson production, Trilinear and Quartic Gauge Couplings with the ATLAS detector

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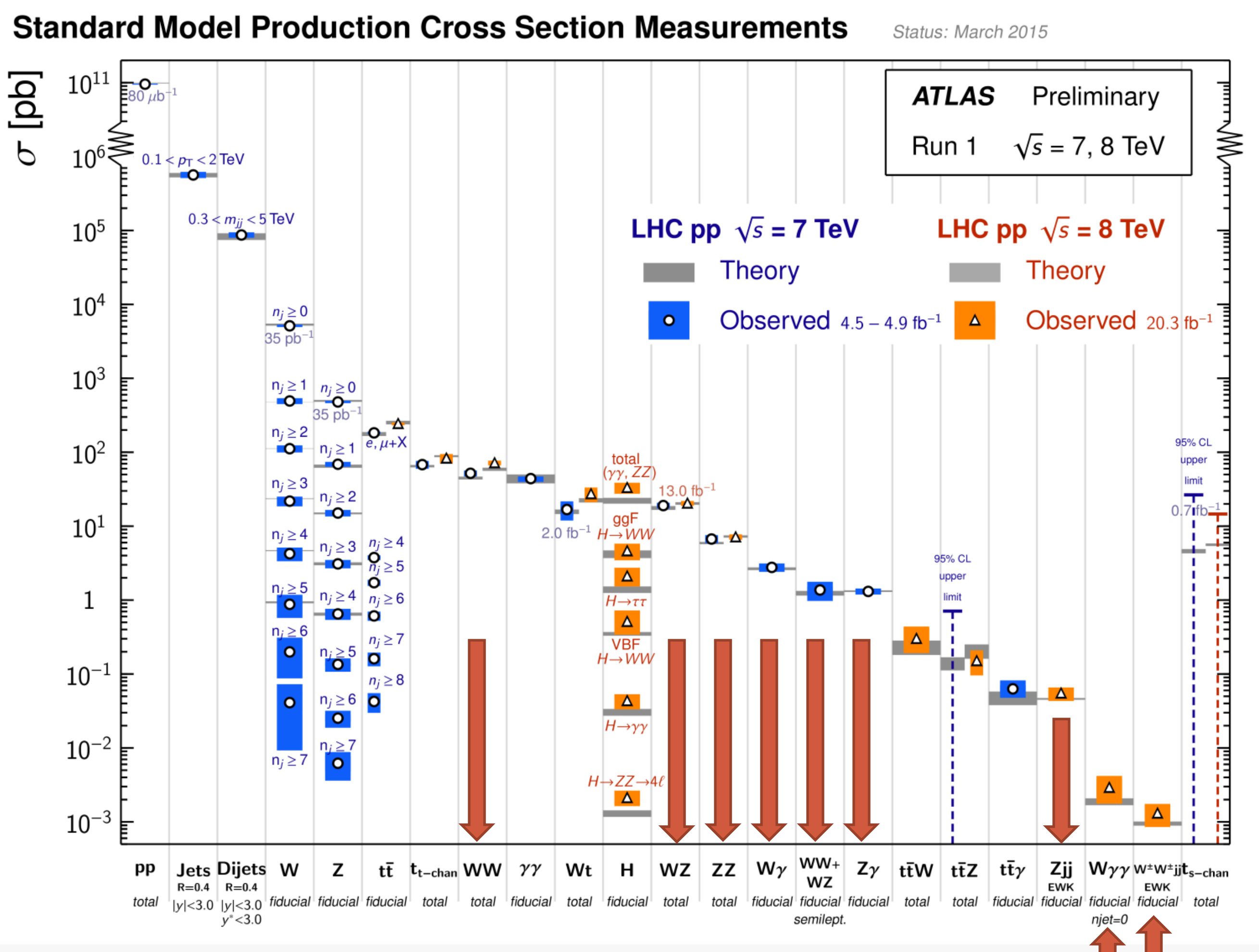
Why looking at EW processes?

- Measure EW cross section and compare it to (higher order) SM predictions

➢Possible to give constrains and input for theory predictions

- Important/irreducible background to many analyses (e.g. Higgs and searches for physics beyond SM)
- Possible to probe physics beyond SM (anomalous triple and quartic couplings)

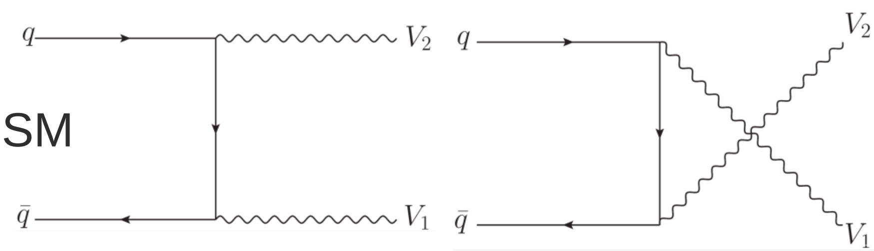


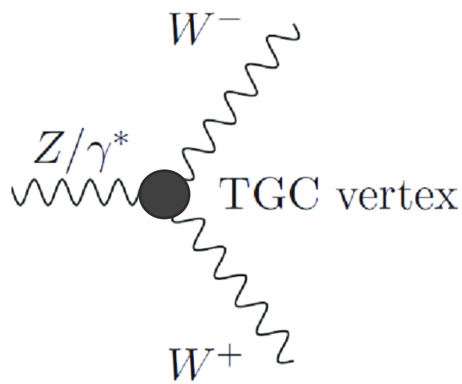
[1]

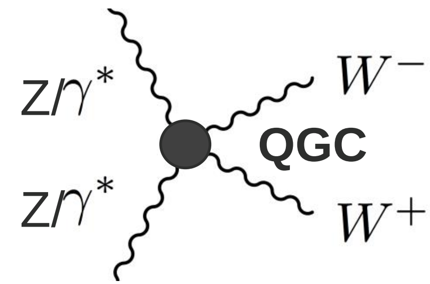
Multi-boson production at LHC

- Non abelian structure of $SU(2)_L \times U(1)_Y$ allows boson self-coupling

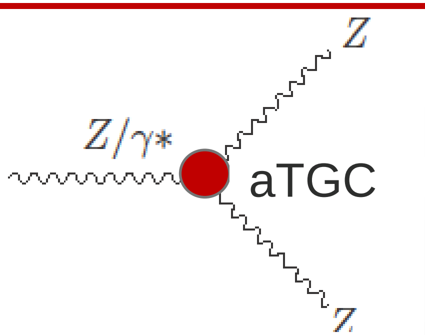
SM

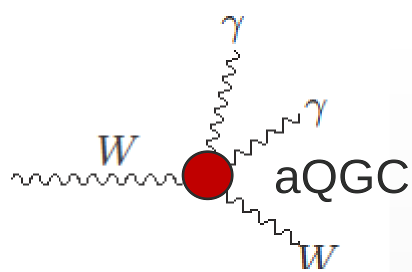






BSM





coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

Ref.: http://arxiv.org/abs/1305.3773

- Possible to introduce additional parameter in effective field theories that parametrize SM forbidden couplings

Cross section estimation

- Use decays to leptons to get a better background suppression
- Selecting high p_T leptons/jets
- Require high missing E_T if ν involved
- Apply selection based on process topology

- Irreducible backgrounds (estimated using simulation)
- Backgrounds including non prompt leptons using data-driven methods ($t\bar{t}$, V+ jets)

$$\sigma_{tot}^{fid} = \frac{N_{data} - N_{backg.}}{A * BR * C * \int Ldt}$$

- Extrapolation to full phase space via an acceptance factor (A) (and the branching ratio)

- Correction for detector inefficiencies

- Estimate systematic uncertainties from:
  - Experimental: energy-resolution/scale, reconstruction, ID, luminosity, …
  - Theoretical: PDFs, parton shower, renorm./fact. scale, …

Diboson production

Results shown in this presentation:

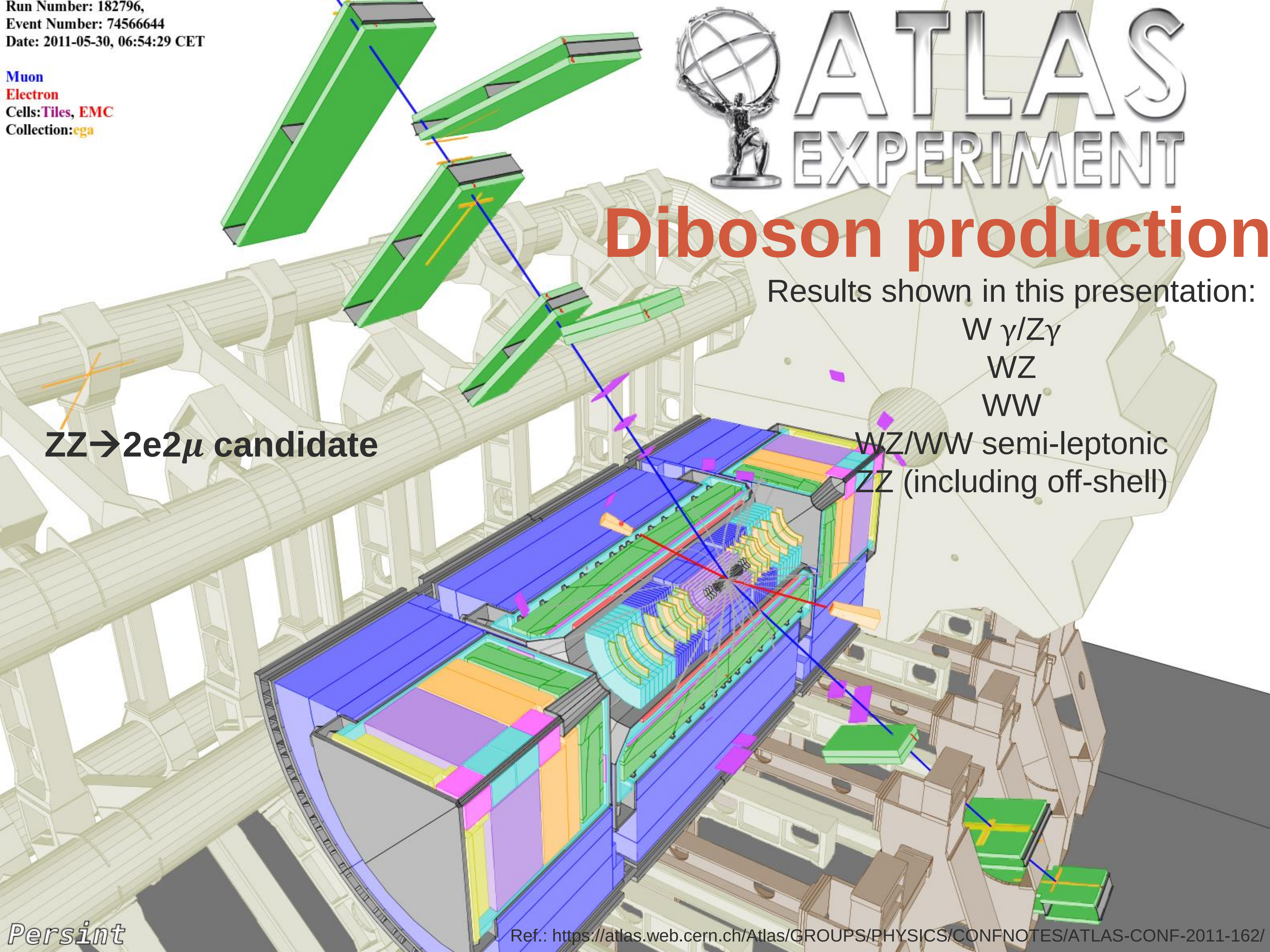
W γ/Zγ

WZ

WW

WZ/WW semi-leptonic

ZZ (including off-shell)



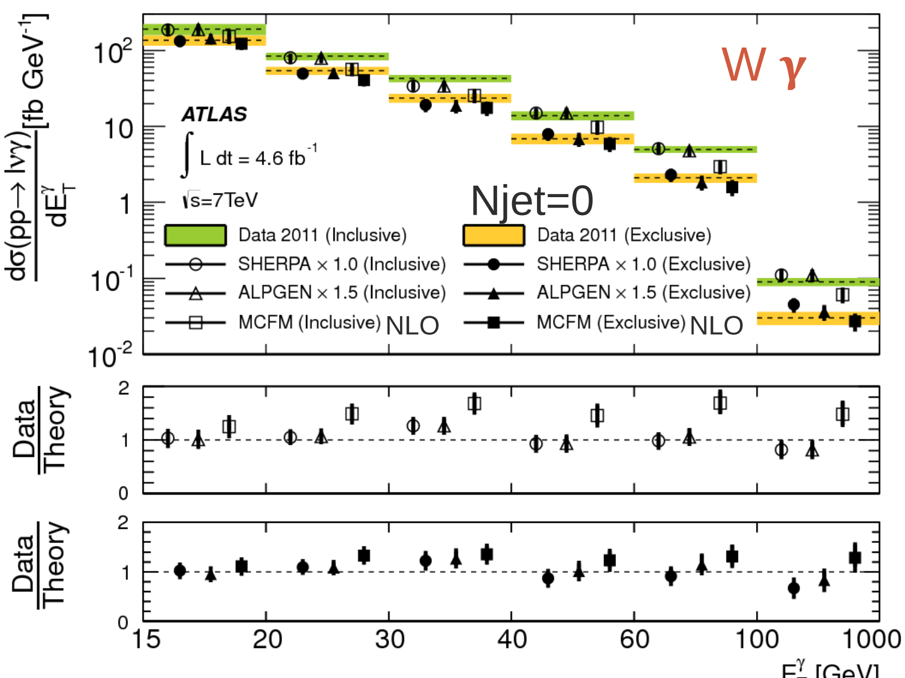
ZZ→2e2μ candidate

Ref.: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-162/

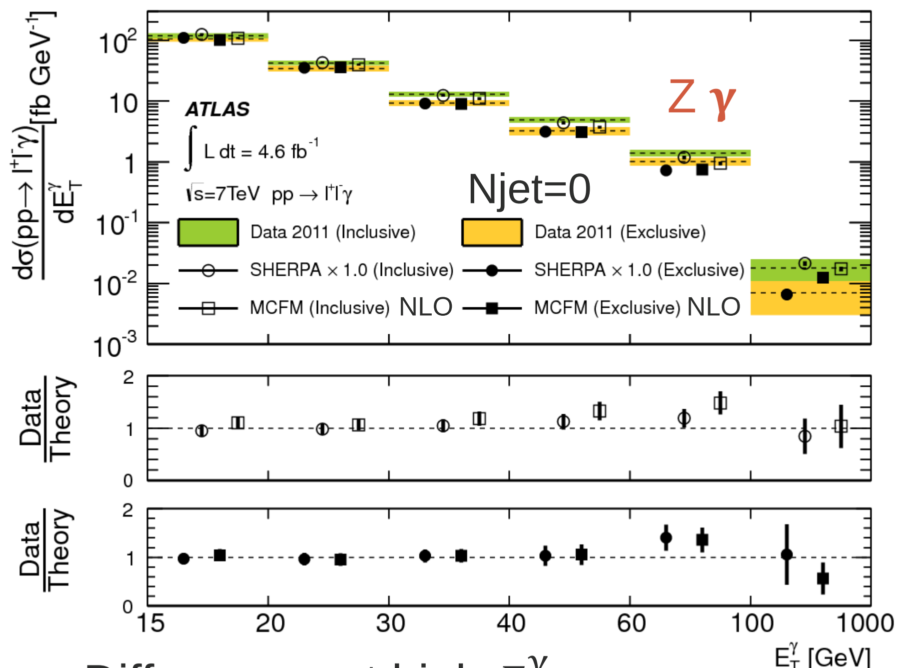
W γ & Z γ cross section at 7 TeV

Phys. Rev. D 87,112003

- Channel: W γ/Z γ → lνγ, llγ , ννγ
- Selection:
  - High p_T, isolated γ/leptons
  - High E_T^{miss} (when ν included)
  - l, γ well separated
- Exclusive (Njet=0) region more sensitive to aTGC



- Main Backgrounds:
  - W +jets: 15-25% (data-driven)
  - Z +jets: ~10% (data-driven)
  - γ+jets: 5-10% (data-driven)
  - t t̄: <5 % (simulation)



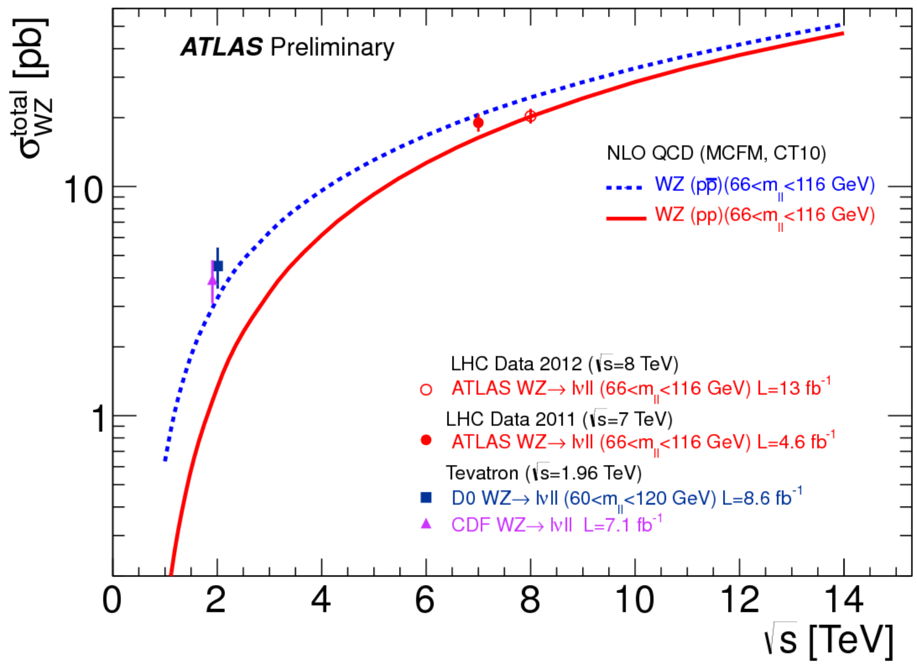
- Differences at high E_T^{γ}
- Improves with NNLO QCD corrections

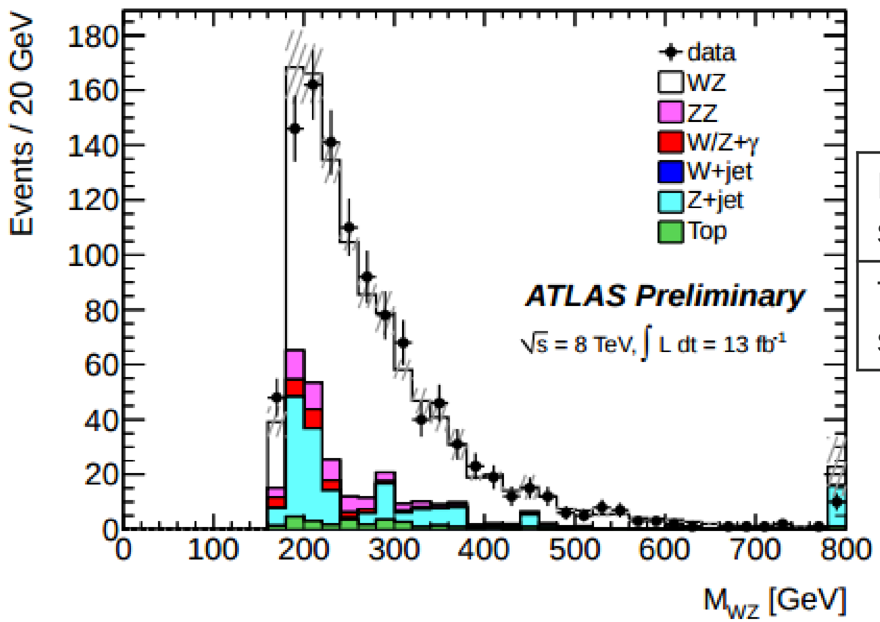
➢ New theoretical predictions

WZ→lllν cross section at 8 TeV

ATLAS-CONF-2013-021

- Selection:
  - Three high p_T, isolated leptons
  - E_T^{miss} >25 GeV
  - 66 GeV < M_{ll}< 116 GeV
- Main Backgrounds:
  - Z +jets: ~15 % (data-driven)
  - ZZ: ~5 % (simulation)
  - W/Z + γ: ~3 % (simulation)



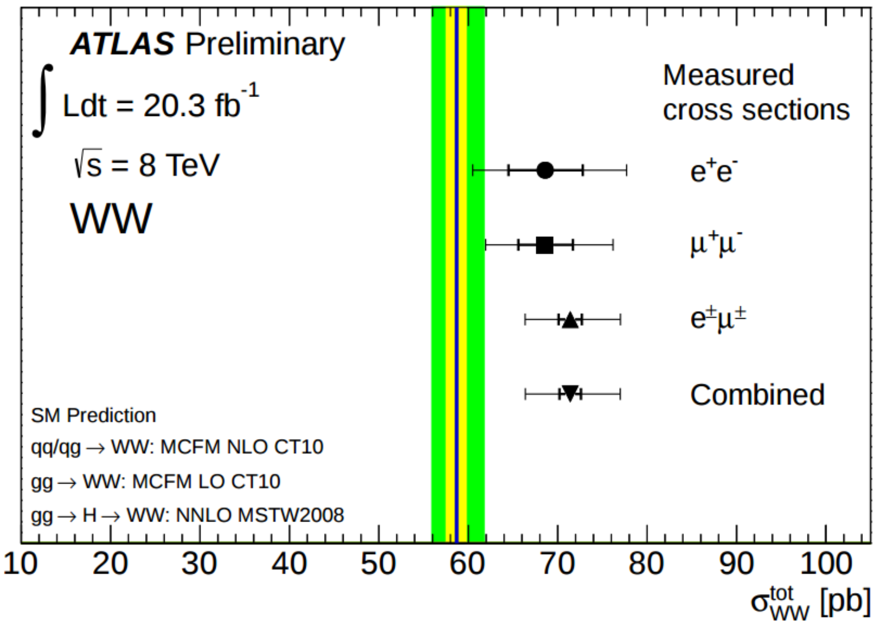


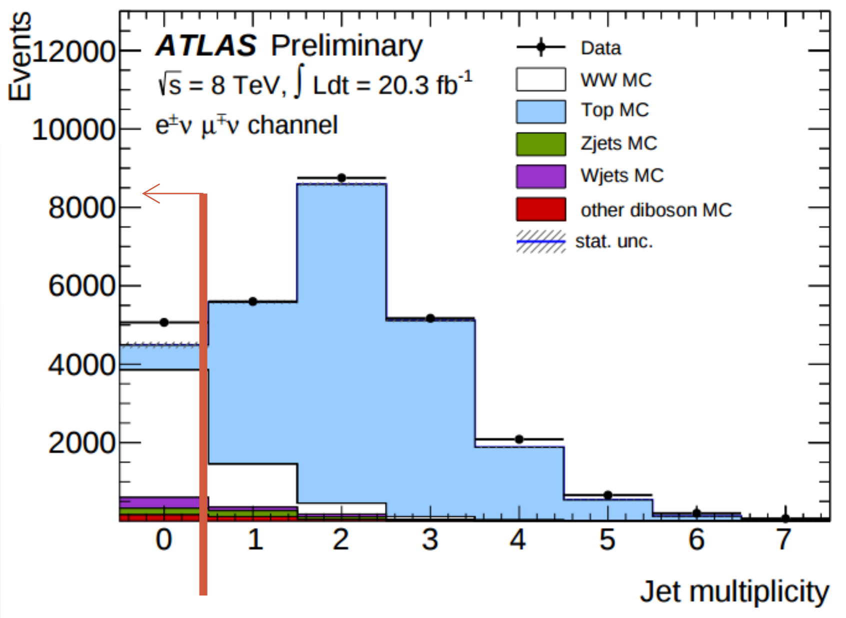
Meas. cross section [pb]	$20.3^{+0.8}_{-0.7}(\text{stat.})^{+1.2}_{-1.1}(\text{syst.})^{+0.7}_{-0.6}(\text{lumi.})$
Theory cross section (NLO) [pb]	20.8 ± 0.3

- Very precise diboson cross-section measurement
- Limits set on WWZ aTGC (done only with 7 TeV data so far)

WW→lνlν cross section at 8 TeV [ATLAS-CONF-2014-033]

- Selection:
  - 2 high p_T, isolated leptons (opp. Charge)
  - E_T^{miss} >45 (25) GeV for elec.(muon) channel
- Main Backgrounds:
  - Top: ~15% (data-driven)
  - W+jets: ~5% (data-driven)
  - Drell-Yan: ~5% (simulation)

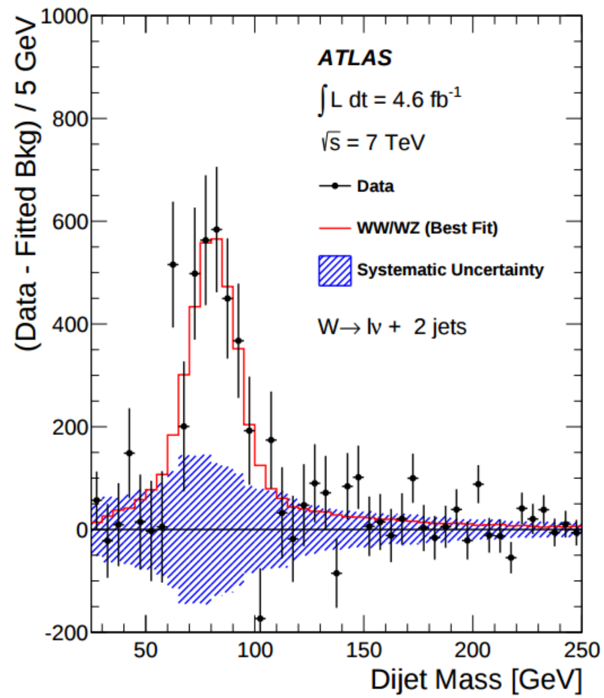


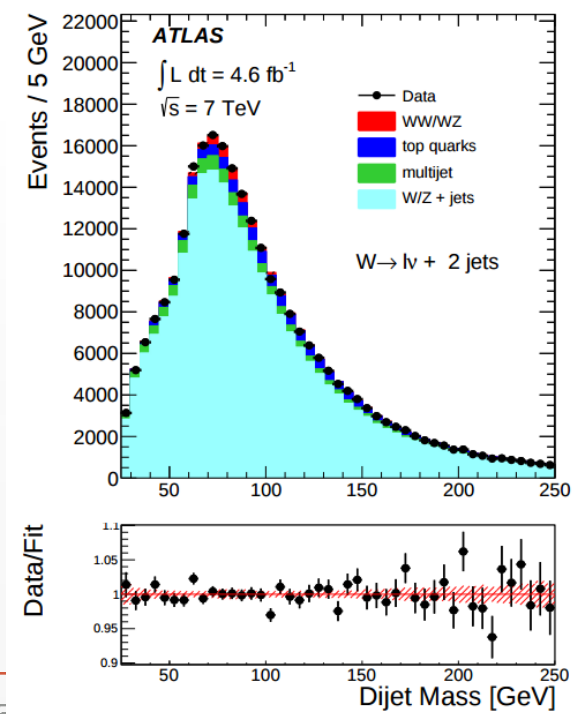


- Difference between theory and measured cross sec: 2.1 σ
  - NNLO theory corrections up to 10% (see: arXiv:1408.5243)
  - Possible explanations of the excess in terms re-summation due to Njet=0 requirement (see: arXiv:1407.4537)

WZ/WW→l ν qq cross section at 7 TeV [JHEP01(2015)049]

- Selection:
  - One high p_T, isolated lepton
  - E_T^{miss} >30 GeV, m_T>40 GeV
- Main Backgrounds:
  - W/Z+jets: ~89% (data driven)
  - multi-jets: ~5% (data driven)
  - Top: ~4% (simulation)
- Total background modeled by combined LH fit





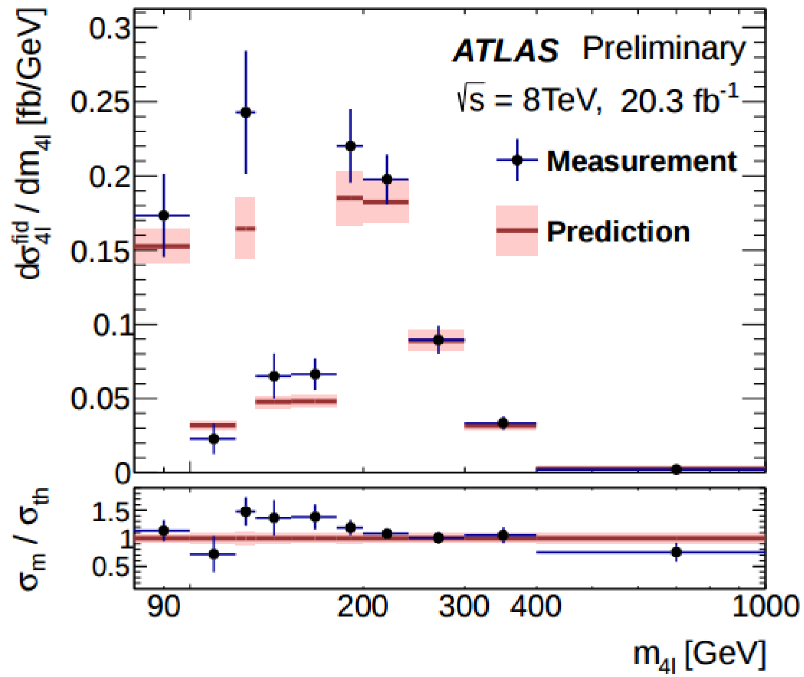
Measured (tot. comb.) [pb]	**68 ±7(stat.)±19(sys.)**
Theory pred. [pb]	**61.1±2.2**

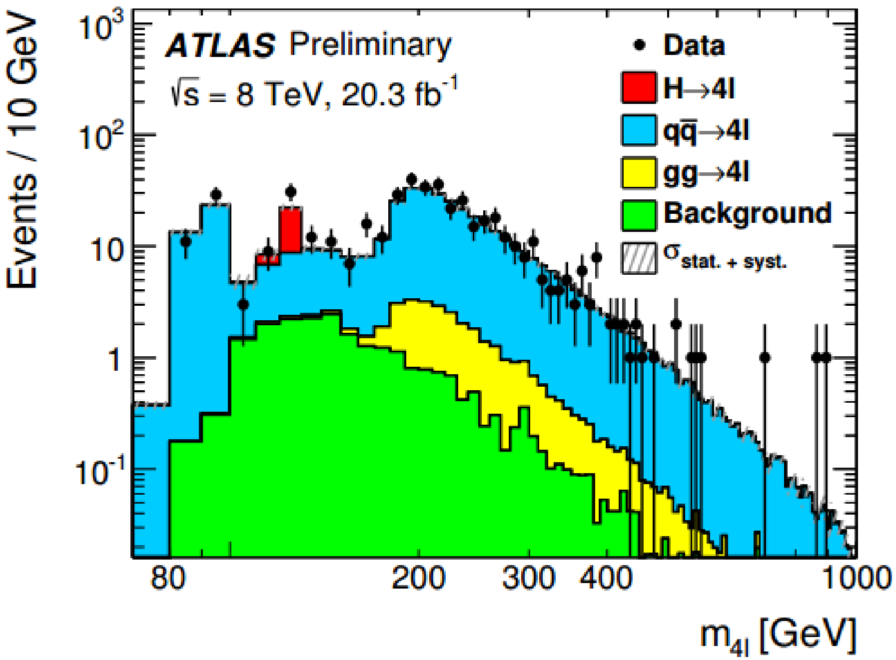
- Measured cross section in agreement with SM
- Limits set on anomalous WWZ, WWγ couplings

4l cross section at 8 TeV

ATLAS-CONF-2015-031

- Measurement in 4l mass range from 80-1000 GeV
- Good possibility to test SM predictions over a large kinematic range
- Background very small (~5%)
- Selection:
  - 4 high p_T isolated leptons
  - Build same flavor, opp. charge pairs
  - 50 GeV< m_{12}<120 GeV; 12GeV<m_{34} <120 GeV





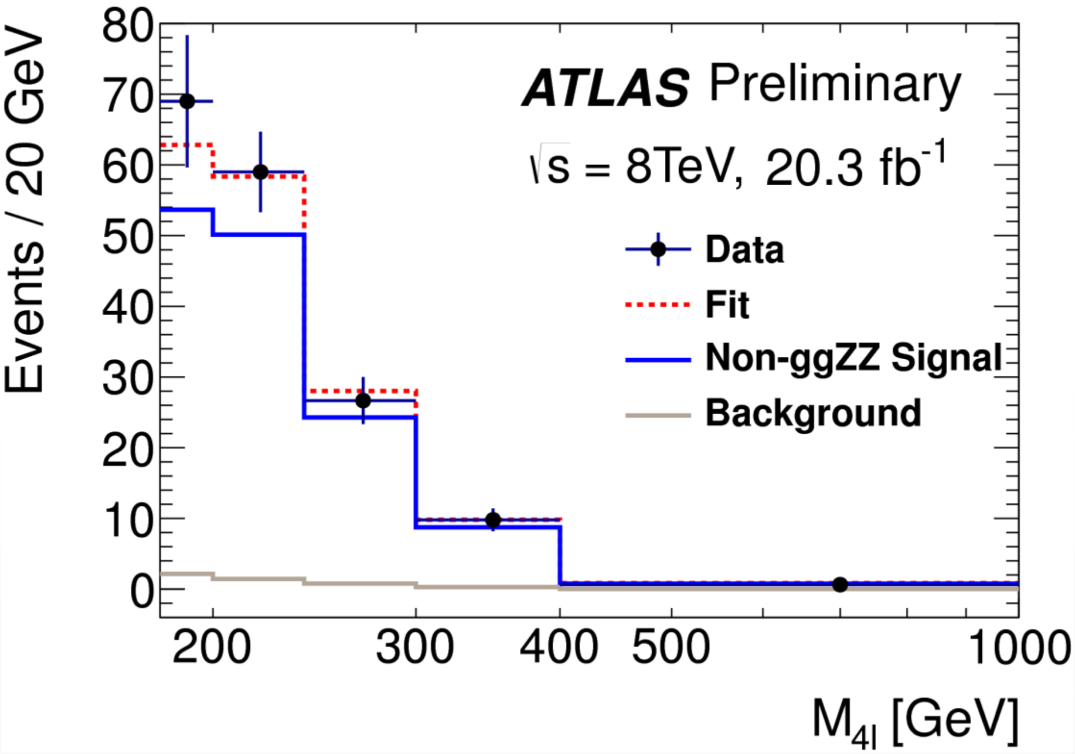
- Overall good agreement between theory prediction and measurement
- Predictions include NNLO QCD, NLO EW for $q\bar{q}$→4l and H→4l but only LO QCD gg→4l

➢ Measurement of NLO correction factor of gg→4l contribution

4l cross section at 8 TeV

ATLAS-CONF-2015-031

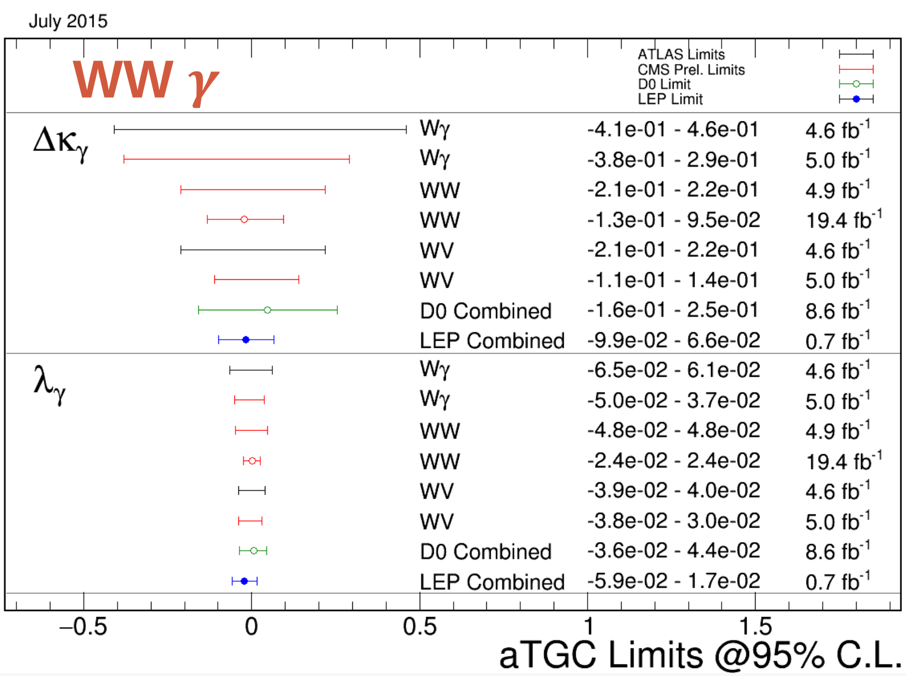
- Estiamtion of signal strength $\mu_{gg} = \sigma(\text{data})/\sigma(gg\rightarrow 4l\,;\text{LO})$ for m_{4l} > 180 GeV
- LH fit to data including non-ggZZ contribution to best knowledge and background

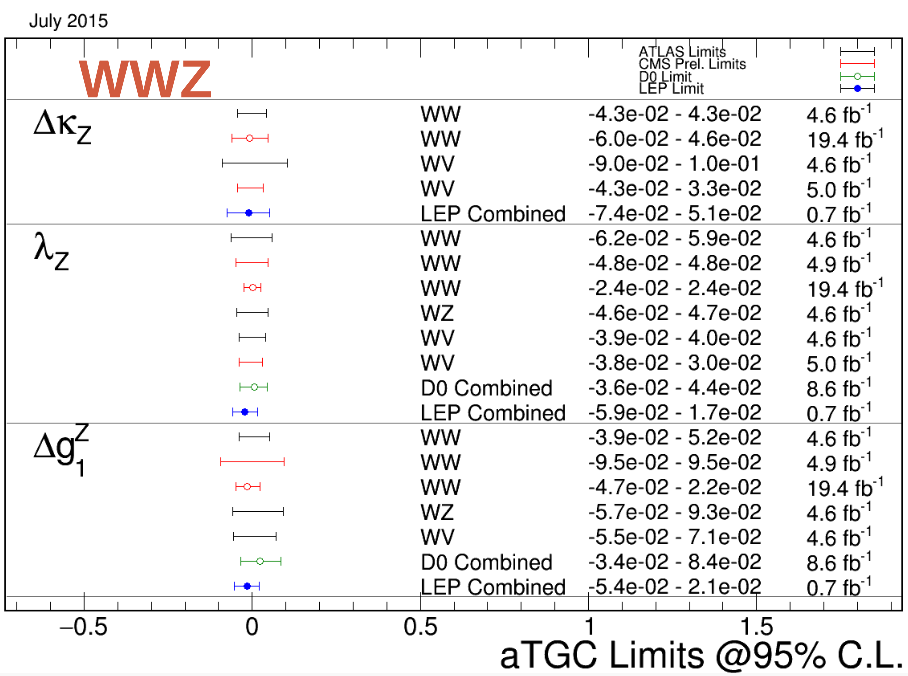


$$\mu_{gg} = 2.4 \pm 1.0(stat.) \pm 0.5(syst.) \pm 0.8(theory)$$

Limits on aTGCs

- Cross section would be higher for aTGC
- aTGC affect mostly high p_T regions
- Parametrization of aTGC in a perturbative, model independet way
- Parameters ($\Delta\kappa_\gamma, \lambda_\gamma, \ldots$) all 0 in SM
- No deviation to SM prediction found





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

Vector boson fusion/scattering (VBF/VBS)

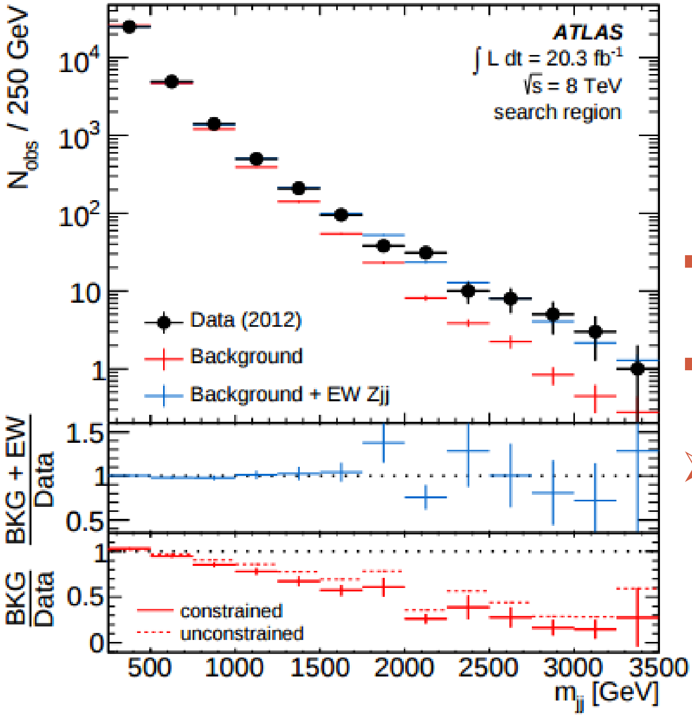
Z+2 jets (VBF) (JHEP 04(2014)031)

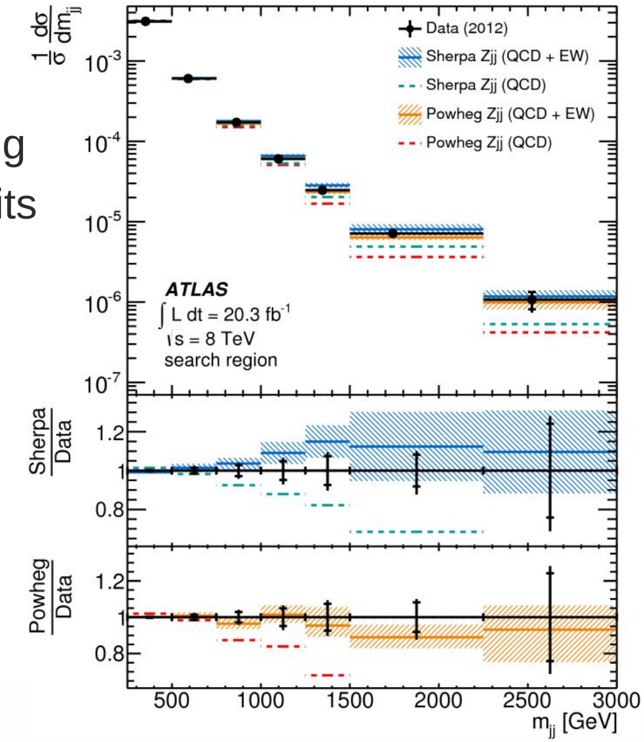
WW+2 jets (VBS) (Phys. Rev. Lett. 113, 141803 (2014))

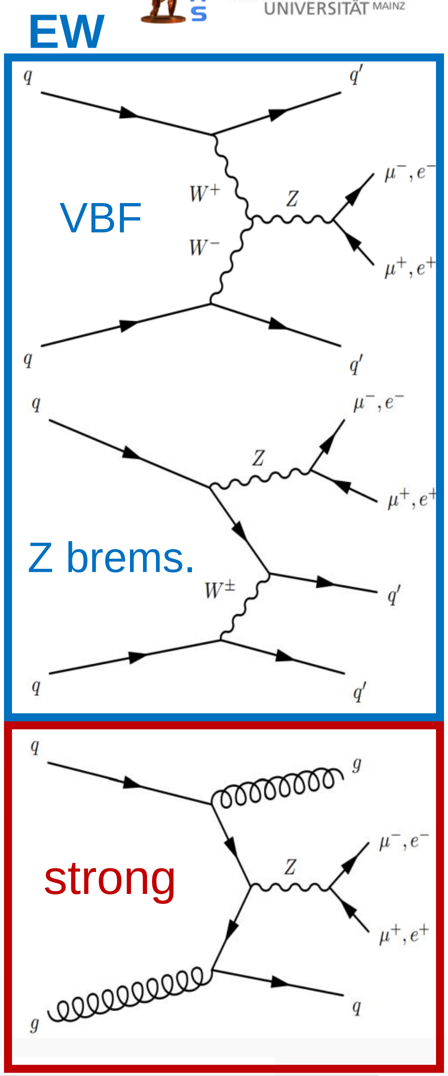
Z+2 jets at 8 TeV

JHEP 04(2014)031

- Two main goals:
  - Measure differential cross section →used to constrain theoretical modeling
  - Measure EW cross-section and set limits on aTGC
- Base selection:
  - 2 high p_T, isolated leptons in Z mass range
  - 2 jets with p_T >25 GeV







- Background only rejected with > 5 σ
- Both generators do not describe all distributions
- ➢ Constraints for theoretical modelling

$$\sigma_{EW} = 54.7 \pm 4.6\,(\text{stat})\,^{+9.8}_{-10.4}\,(\text{syst})\ \pm 1.5\,(\text{lumi})\,\text{fb}.$$

$$\sigma_{EW,Powheg} = 46.1 \pm 0.2\,(\text{stat}) \pm 0.8\,(\text{PDF}) \pm 0.5\,(\text{model})\text{fb}$$

WWjj VBS at 8 TeV

[Phys. Rev. Lett. 113, 141803 (2014)](#)

EW

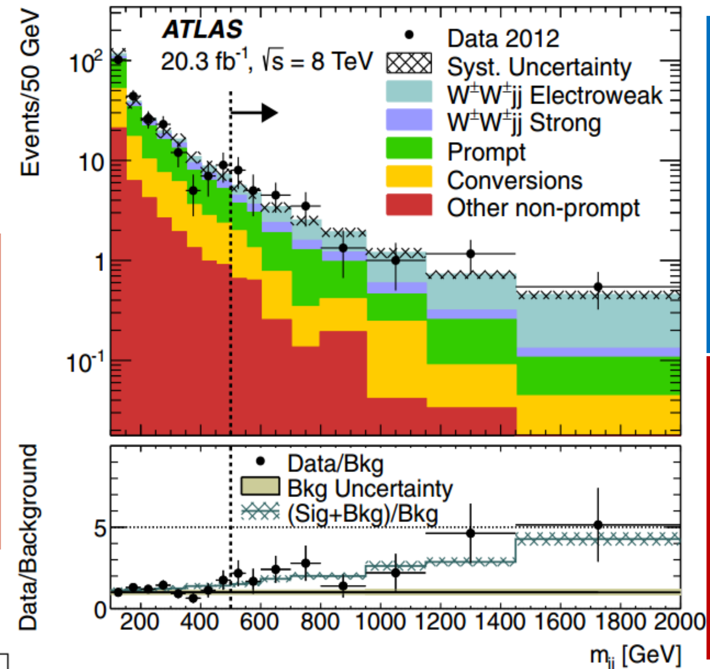
- Key process to probe EW symmetry breaking
- VBS amplitude increases with $\sqrt{s}$ → without Higgs this would violate unitarity at ~ 1 TeV

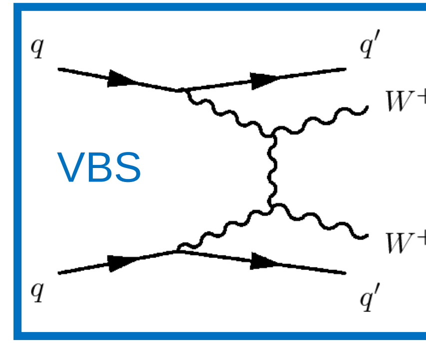
- 2 isolated **same sign** lepton $p_T >$ 25 GeV; $|\eta| < 2.47$ (2.5) (muons)
- $\geq$2 jets $p_T >$ 30 GeV; $|\eta| < 4.5$;
- $E_T^{miss} > 40$ GeV

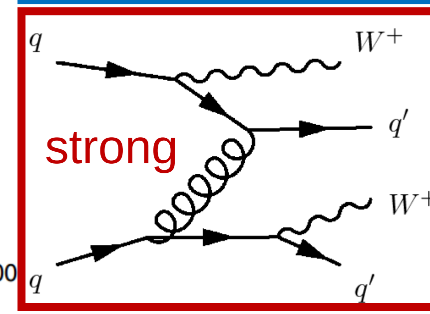
Inclusive

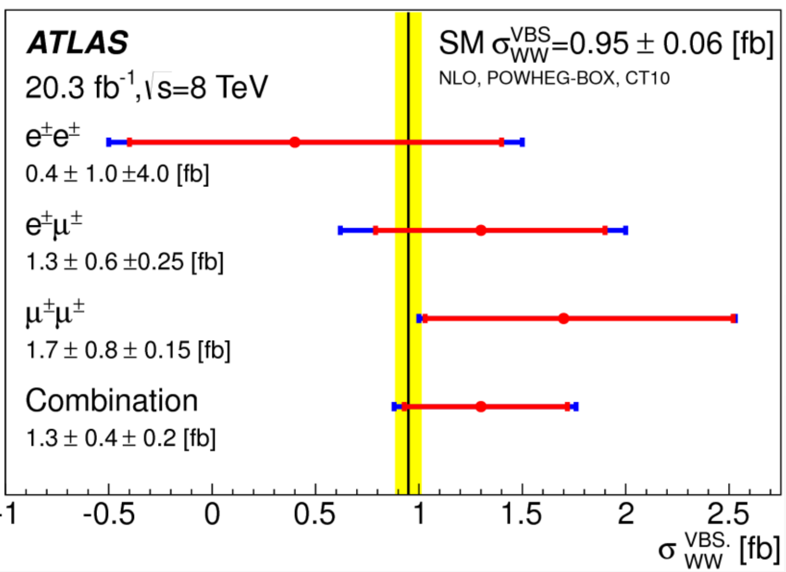
- $|\Delta y_{jj}| > 2.4$

VBS region









- Main background from t $\bar{t}$ (charge flip), WZ
- Main sys. uncertainty from background determination

➢ Combined signal over background only hypothesis
  - Inclusive (EW+ strong): 4.5σ (exp. 3.4σ)
  - VBS (EW only): 3.6σ (exp. 2.8σ)

Triboson production

$W\gamma\gamma$ (Phys. Rev. Lett .115, 031802)

Wγγ at 8 TeV

[Phys. Rev. Lett .115, 031802]

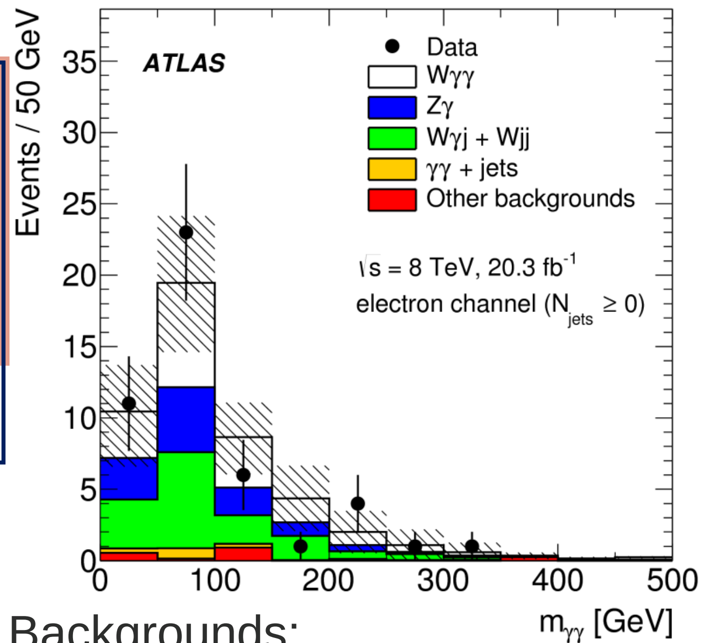
First evidence of triboson production

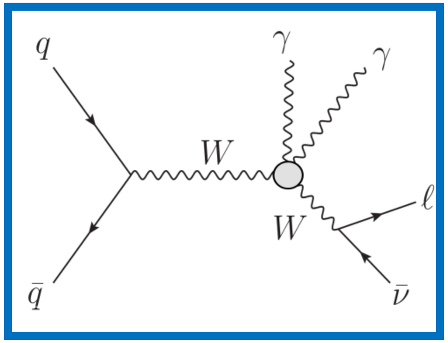
- 1 isolated lepton $p_T > 20$ GeV; $|\eta| < 2.47$ (2.4) (muons)
- p_T^{γ}>20 GeV; $|\eta_\gamma| < 2.37$
- $E_T^{miss} > 25$ GeV; $m_T > 40$ GeV

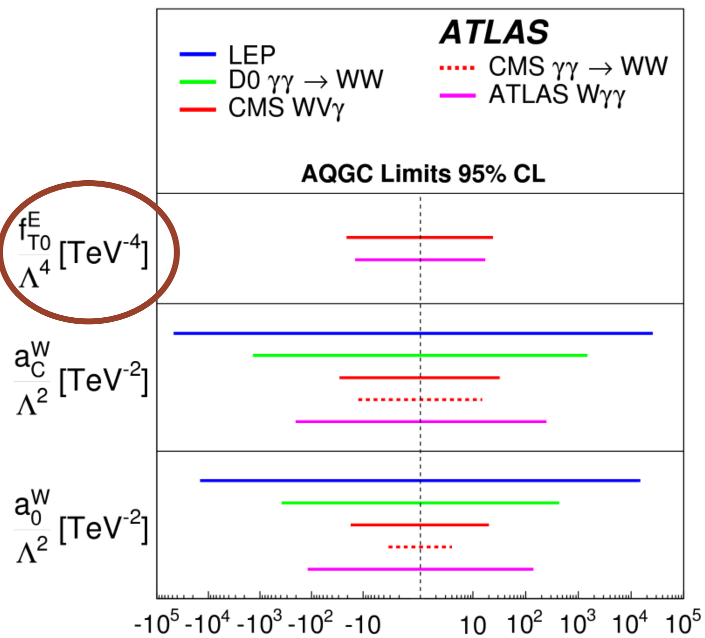
Inclusive

- $N_{jets} = 0$

Exclusive







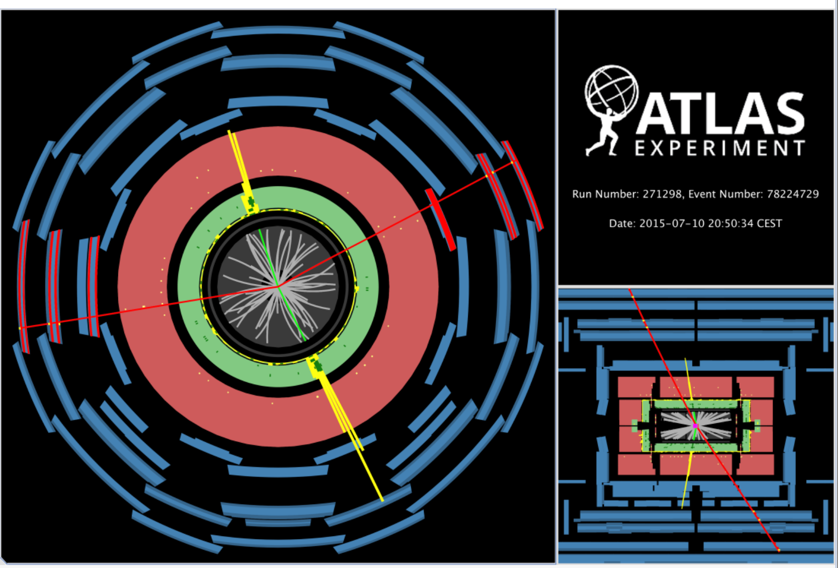
- Backgrounds:
  - Multijet background (data driven)
  - Prompt leptons e.g. $Z\gamma$ (simulation)

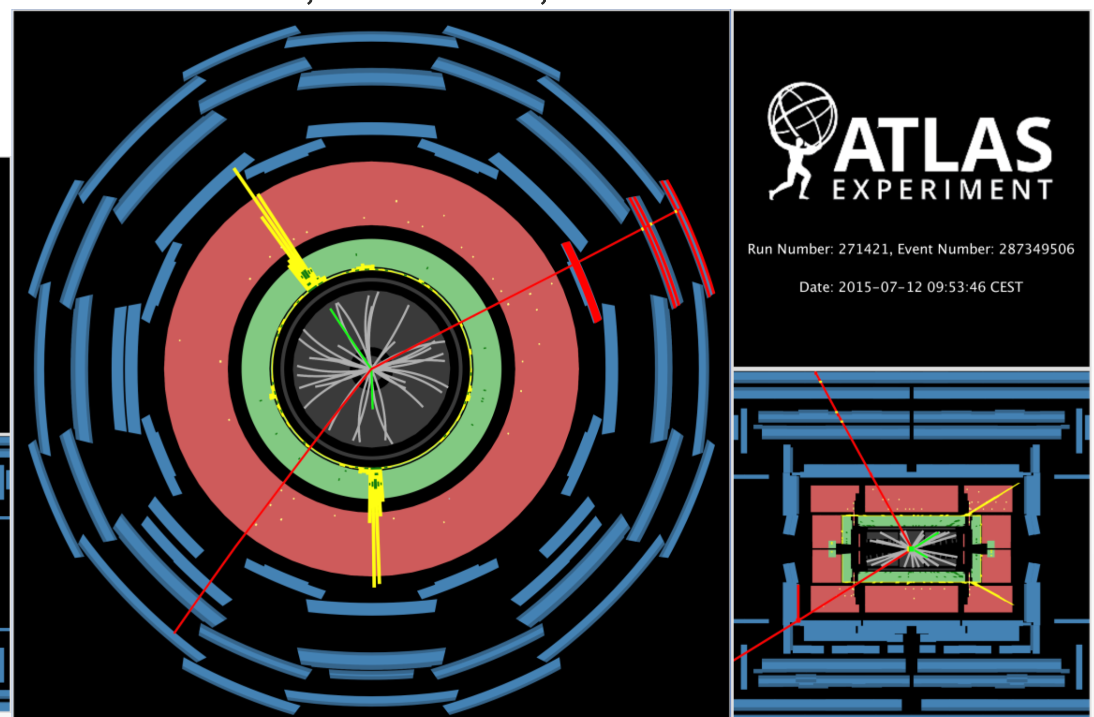
	σ^{fid}[fb]	σ^{MCFM} [fb]
Incl.	$6.1^{+1.1}_{-1.0}(\text{stat}) \pm 1.2(\text{syst}) \pm 0.2(\text{lumi})$	2.90 ± 0.16
Excl.	$2.9^{+0.8}_{-0.7}(\text{stat})^{+1.0}_{-0.9}(\text{syst}) \pm 0.1(\text{lumi})$	1.88 ± 0.20

- Combined significance over background only: 3.6 σ
- Consistent within SM → Limits set on aQCG

Conculsion/Outlook

- Many diboson processes and cross section measured
- VBF, VBS and first triboson production at LHC measured
- Measurements give input for more precise theory predictions
- No deviations between theory and experiment → Limits set on aTGC and aQGC
- More run 1 ATLAS results come soon: VBF W, VBS WZ, …
- Promising run 2 analysis started





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

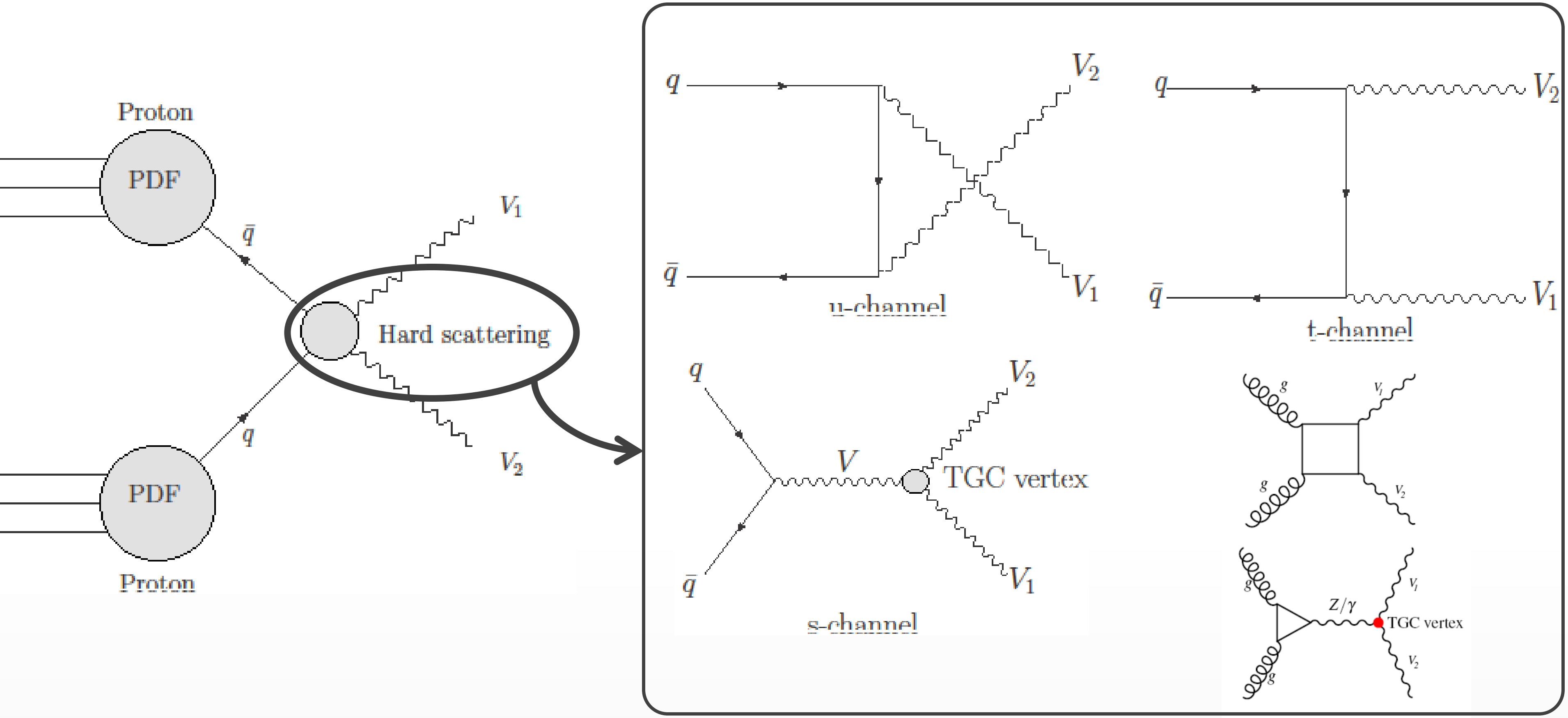
Thank you for your attention!

Backup

References

- [1]:https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/index.html#ATLAS_b_SMSummary_FiducialXsect

Diboson production at LHC

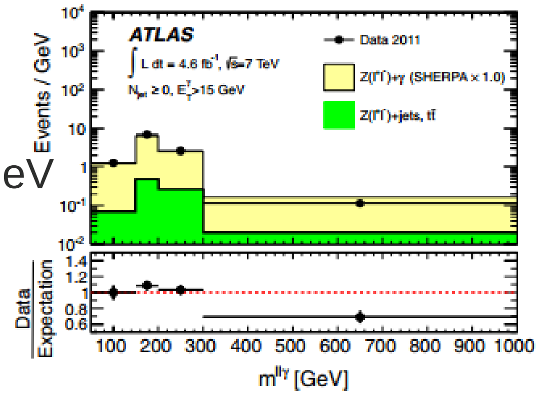


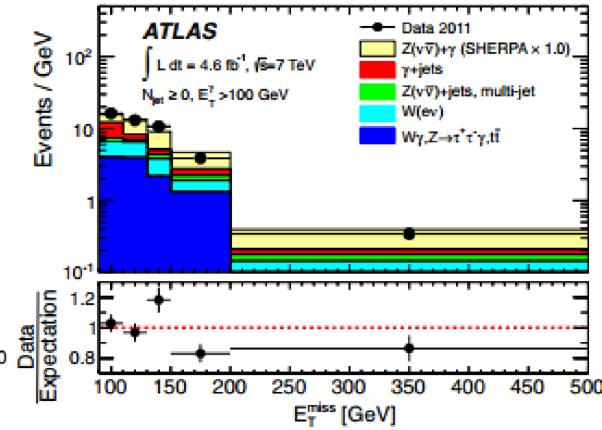
- Only WWγ or WWZ triple gauge coupling (TGC) vertex allowed in SM
- Possible to set limits on anomalous TGCs

W γ & Z γ at 7 TeV details

Phys. Rev. D 87,112003

- $l \nu \gamma$ selection:
  - One lepton with: p_T> 25 GeV
  - One isolated photon with: $E_T^\gamma > 35$ GeV
  - E_T^{miss}> 35 GeV; m_T> 40 GeV
  - Elec. chan.: Z-boson removal





- $ll \gamma$ selection:
  - Two opp. Charge same flavor lepton m_{ll}>25 GeV
  - One isolated photon with: $E_T^\gamma > 15$ GeV

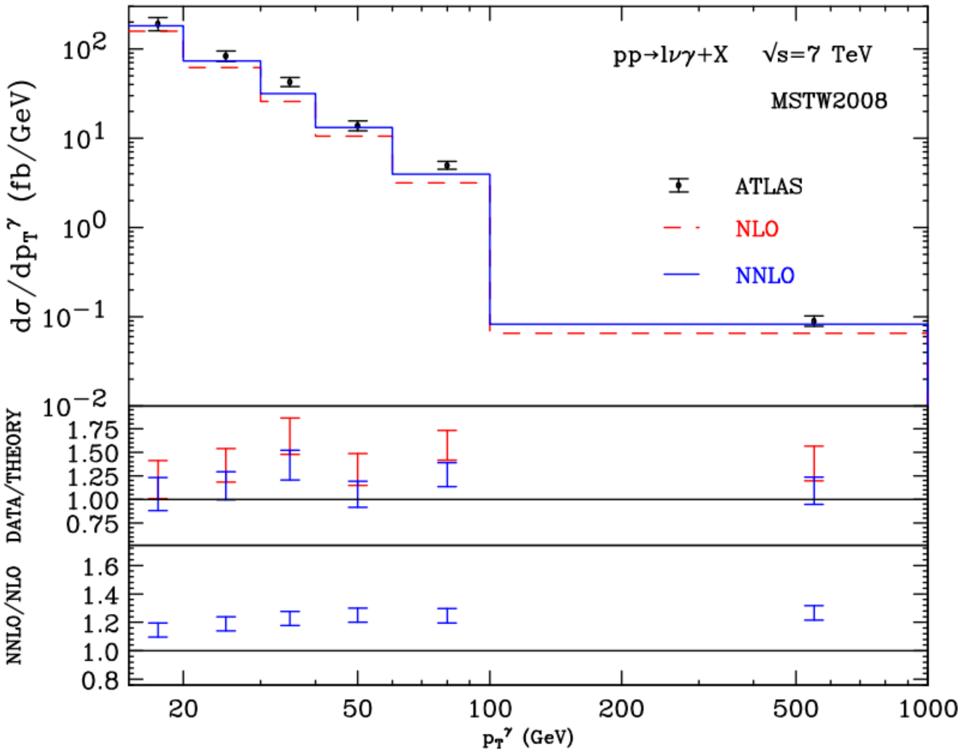
Cuts	$pp \to \ell\nu\gamma$	$pp \to \ell^+\ell^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Lepton	$p_T^\ell > 25$ GeV	$p_T^\ell > 25$ GeV	...
	$\lvert\eta_\ell\rvert < 2.47$	$\lvert\eta_\ell\rvert < 2.47$	...
	$N_\ell = 1$	$N_{\ell^+} = 1$, $N_{\ell^-} = 1$	$N_\ell = 0$
Neutrino	$p_T^\nu > 35$ GeV	...	...
Boson	...	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\bar{\nu}} > 90$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 100$ GeV
		$\lvert\eta^\gamma\rvert < 2.37$, $\Delta R(\ell,\gamma) > 0.7$	
		$\epsilon_h^p < 0.5$	
Jet		$E_T^{jet} > 30$ GeV, $\lvert\eta^{jet}\rvert < 4.4$	
		$\Delta R(e/\mu/\gamma, \text{jet}) > 0.3$	
		Inclusive: $N_{jet} \geq 0$, Exclusive: $N_{jet} = 0$	

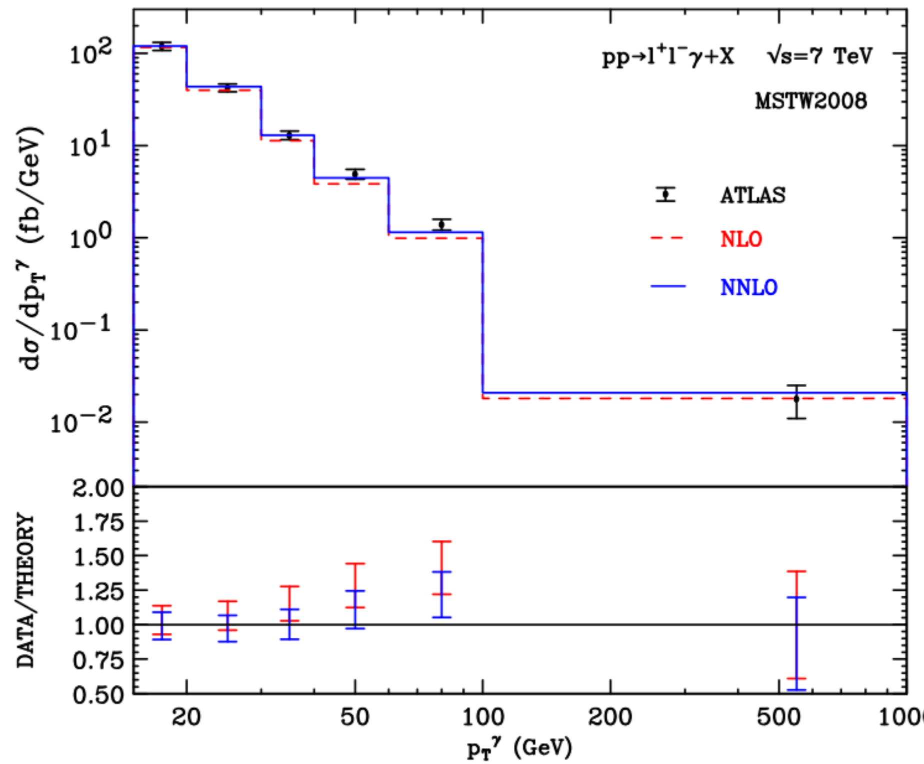
- $\nu \bar{\nu} \gamma$ selection:
  - E_T^{miss}> 90 GeV; m_T> 40 GeV
  - One isolated photon with: $E_T^\gamma > 100$ GeV
  - Photon, E_T^{miss}, jets (if found) separated
- DD background method (side-band)

channel	measured cross sec. [pb]	theory cross. Sec. [pb]
$\nu\bar{\nu}\gamma$	$0.116 \pm 0.010(\text{stat}) \pm 0.013(\text{syst}) \pm 0.004(\text{lumi})$	0.115 ± 0.009
$\ell\nu\gamma$	$1.76 \pm 0.03(\text{stat}) \pm 0.21(\text{syst}) \pm 0.08(\text{lumi})$	1.39 ± 0.13
$\ell^+\ell^-\gamma$	$1.05 \pm 0.02(\text{stat}) \pm 0.10(\text{syst}) \pm 0.04(\text{lumi})$	1.06 ± 0.05

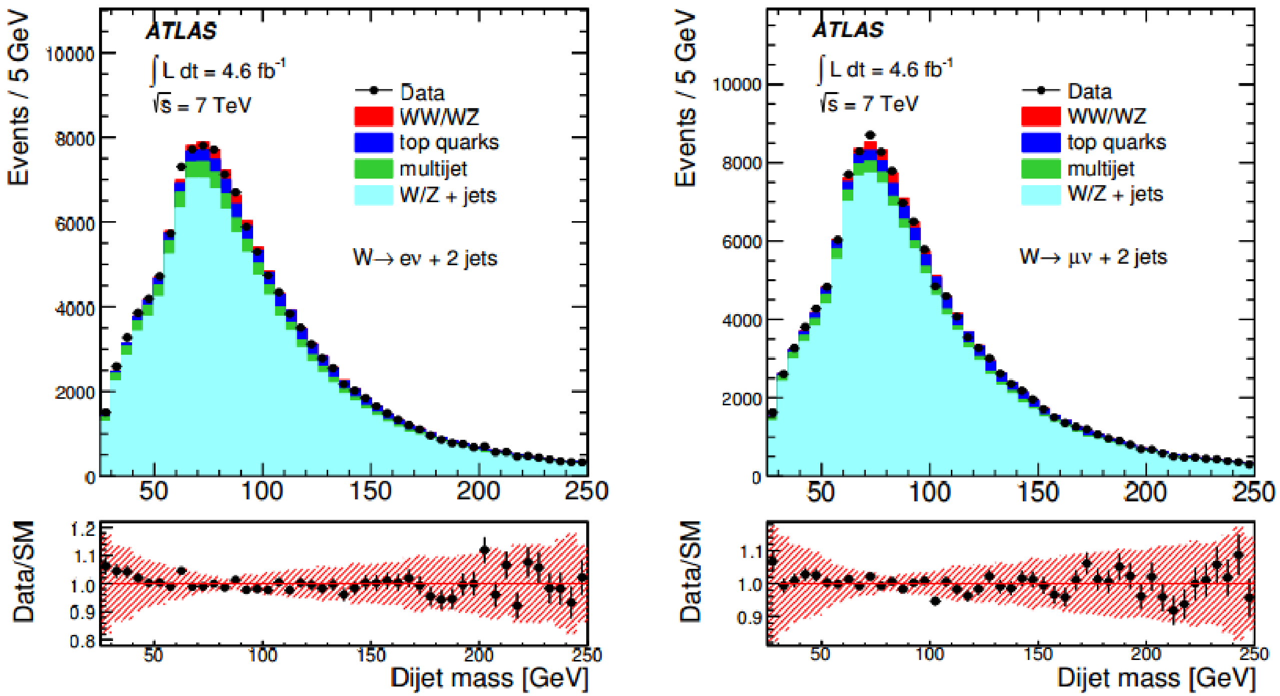
W γ & Z γ NNLO QCD corrections

- NNLO QCD corrections lead to better agreement (Grazzini et. al.)
- arXiv:1407.1618v1 [hep-ph] (W γ)
- arXiv:1309.7000 [hep-ph] (Z γ)





WZ/WW→llqq background and aTGC JHEP01(2015)049



- Background estimated via combined LH fit to both channels
- Systematics taken as nuisance parameter

Parameter	Observed Limit	Expected Limit
$\lambda_Z = \lambda_\gamma$	$[-0.039, 0.040]$	$[-0.048, 0.047]$
$\Delta\kappa_\gamma$	$[-0.21, 0.22]$	$[-0.23, 0.25]$
Δg_1^Z	$[-0.055, 0.071]$	$[-0.072, 0.085]$

Limits on aTGCs

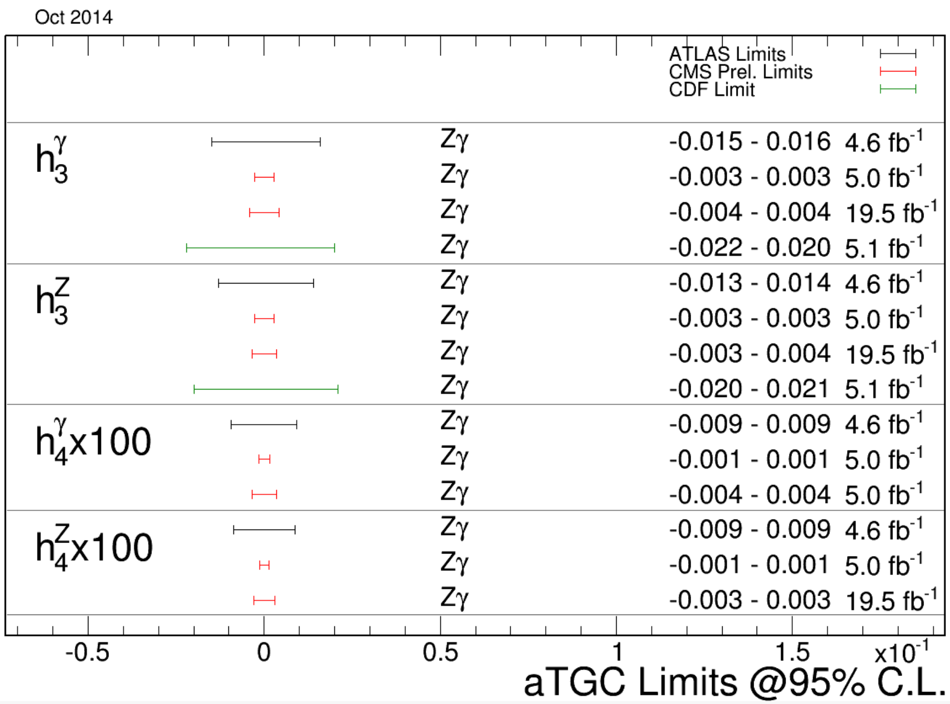
$$i\mathcal{L}_{eff}^{WWV} = g_{WWV}\Big[g_1^V V^\mu \left(W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}\right) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- + i g_5^V \varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right)V^\sigma + i g_4^V W_\mu^- W_\nu^+ (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\Big] , \quad (1)$$

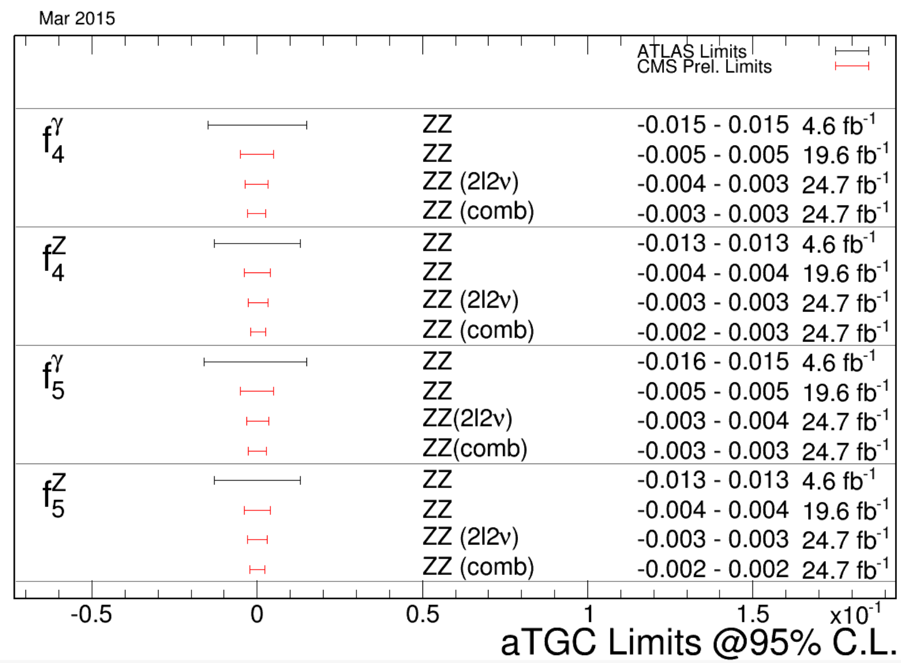
$$\Delta g_1^Z \equiv (g_1^Z - 1) \equiv \tan\theta_W \delta_Z , \quad \Delta\kappa_\gamma \equiv (\kappa_\gamma - 1) \equiv x_\gamma$$
$$\Delta\kappa_Z \equiv (\kappa_Z - 1) \equiv \tan\theta_W (x_Z + \delta_Z) ,$$
$$\lambda_\gamma \equiv y_\gamma , \quad \lambda_Z \equiv \tan\theta_W \, y_Z .$$

All 0 for SM

Ref.: http://arxiv.org/abs/hep-ph/9601233v1

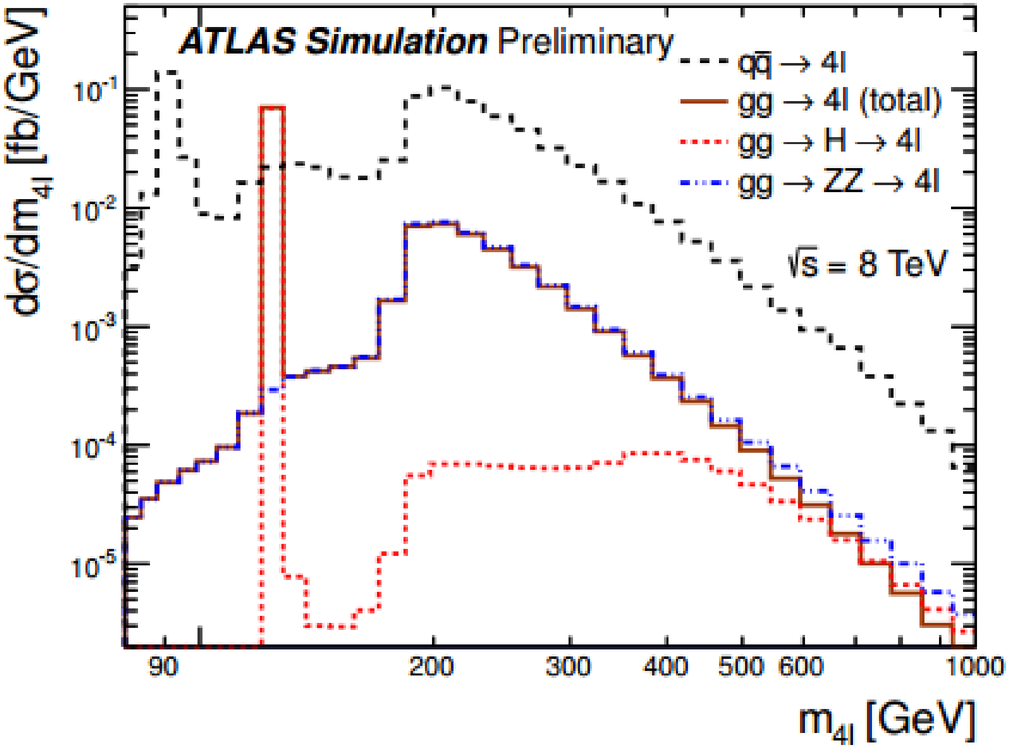
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

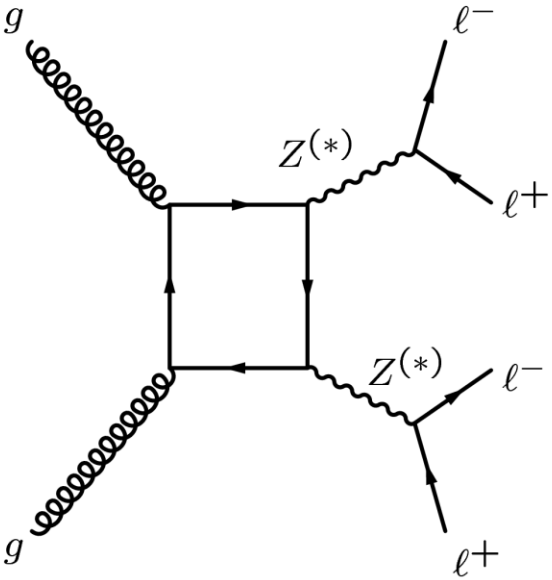


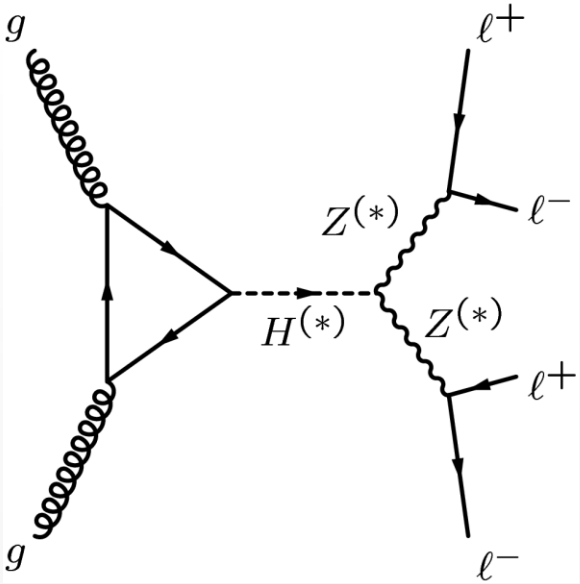


4l cross section at 8 TeV

ATLAS-CONF-2015-031



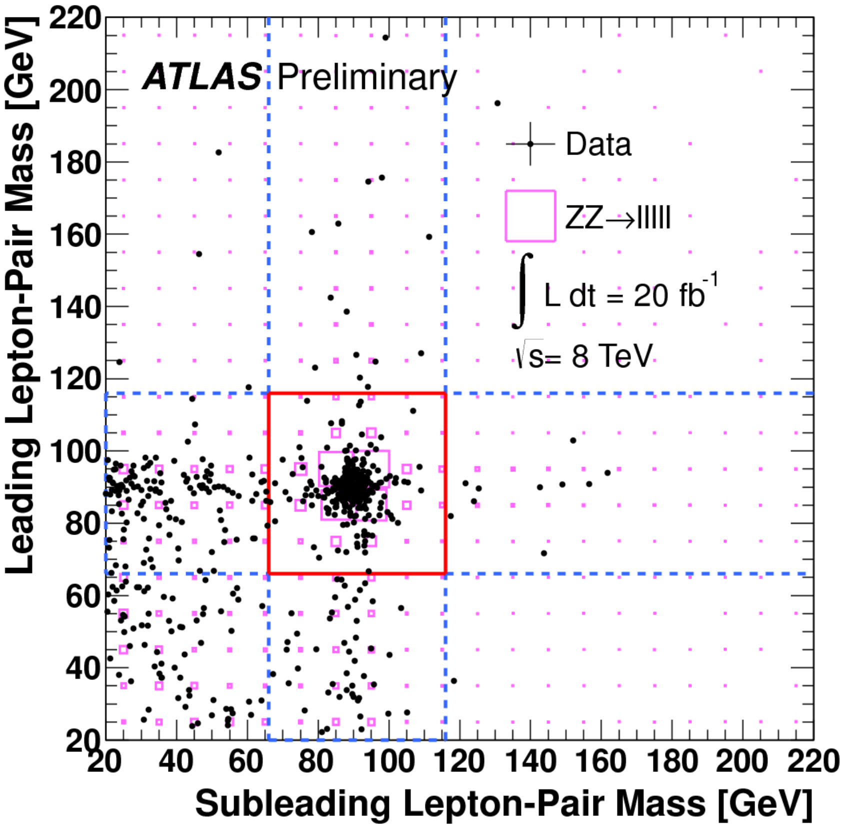


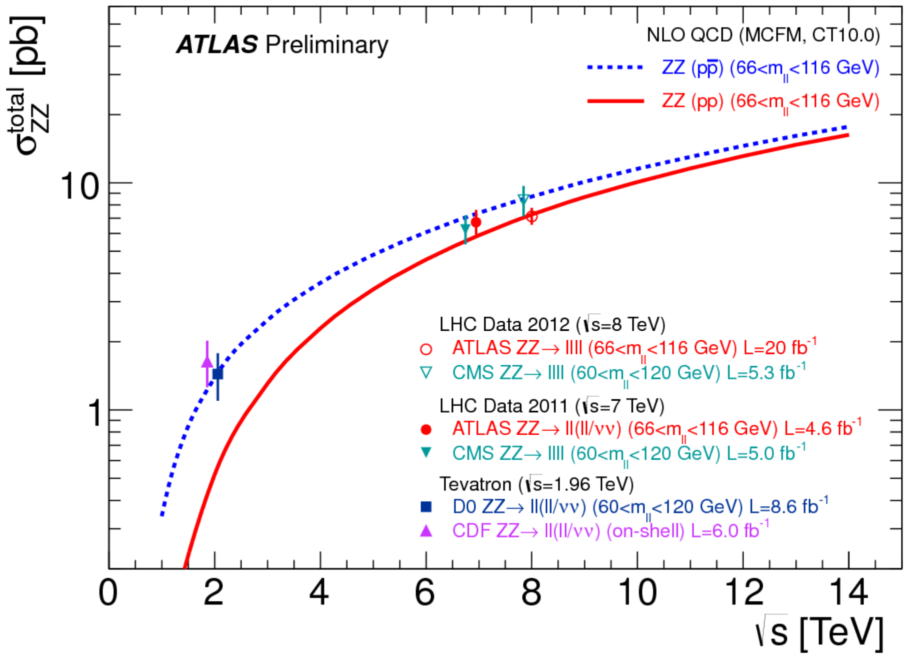


ZZ cross section at 8 TeV

ATLAS-CONF-2013-020

- Background very small
- Selection:
  - 4 high p_T isolated leptons
  - Build same flavor, opp. charge pairs
  - 66 GeV< m_{12}<116 GeV; 66GeV<m_{34} <116 GeV





- ZZ on-shell measurement also done

Meas. [pb]	$7.1^{+0.5}_{-0.4}$(stat.)±0.3(syst.)±0.2(lumi.)
Theory(NLO) [pb]	$7.2^{+0.3}_{-0.2}$

- Statistically dominated
- No deviation from SM
- Possible to set limits on ZZZ aTGC

Z +2 jets selection details

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- Muons:
  - p_T >25 GeV; |eta|<2.4
  - Track quality
  - Isolated $\sum p_T$ of dR<0.2 around the track < 10%* p_T
- Electrons:
  - Track←→ cluster matching
  - p_T >25 GeV; |eta|<2.47
  - Medium identification criteria (shower shape)
- Jets
  - Anti-Kt jet R=0.4
  - Energy corrected for pileup etc.
  - p_T >25 GeV |y|<4.4
  - Cuts to suppress jets from primary interaction (JVF)
  - Jets removed that overlap with lepton
- Cross section in 5 different fiducial volumes:

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^\ell\rvert < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^j\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j_1} > 55$ 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	—		$N_{\text{jet}}^{\text{gap}} = 0$	$N_{\text{jet}}^{\text{gap}} \geq 1$	—
Zjj system	—		$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance},3} < 0.15$	—

Z +2 jets analysis details and integrated cross section

- Backgrounds
  - $t\bar{t}$, WW , t+W, W+jets done with MC
  - Multijets with template method
- Systematic uncertainties:
  - 3% (2%) for electron (muon) reco., ID, iso. on cross section
  - 2.8% lumi. uncertainty

	Composition (%)				
Process	*baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

Fiducial region	σ_{theory} (pb)
baseline	6.26 ± 0.06 (stat) $^{+0.50}_{-0.60}$ (scale) $^{+0.29}_{-0.35}$ (PDF) $^{+0.19}_{-0.25}$ (model)
high-p_T	1.92 ± 0.02 (stat) $^{+0.17}_{-0.20}$ (scale) $^{+0.09}_{-0.10}$ (PDF) $^{+0.05}_{-0.07}$ (model)
high-mass	0.068 ± 0.001 (stat) $^{+0.009}_{-0.009}$ (scale) $^{+0.004}_{-0.003}$ (PDF) $^{+0.004}_{-0.002}$ (model)
search	1.23 ± 0.01 (stat) $^{+0.11}_{-0.13}$ (scale) $^{+0.06}_{-0.07}$ (PDF) $^{+0.03}_{-0.04}$ (model)
control	0.444 ± 0.005 (stat) $^{+0.051}_{-0.054}$ (scale) $^{+0.021}_{-0.025}$ (PDF) $^{+0.032}_{-0.034}$ (model)

Fiducial region	σ_{fid} (pb)
baseline	5.88 ± 0.01 (stat) ± 0.62 (syst) ± 0.17 (lumi)
high-p_T	1.82 ± 0.01 (stat) ± 0.17 (syst) ± 0.05 (lumi)
high-mass	0.066 ± 0.001 (stat) ± 0.012 (syst) ± 0.002 (lumi)
search	1.10 ± 0.01 (stat) ± 0.09 (syst) ± 0.03 (lumi)
control	0.447 ± 0.004 (stat) ± 0.059 (syst) ± 0.013 (lumi)

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Z +2 jets differential cross section and aTGC

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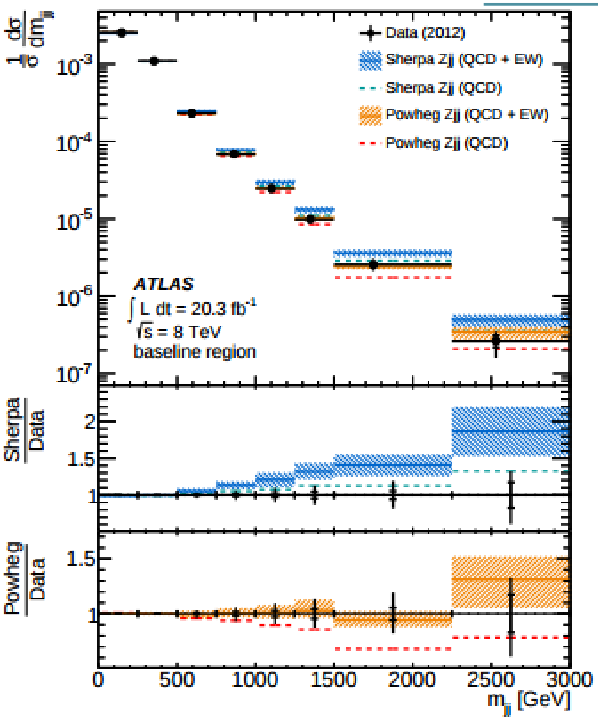
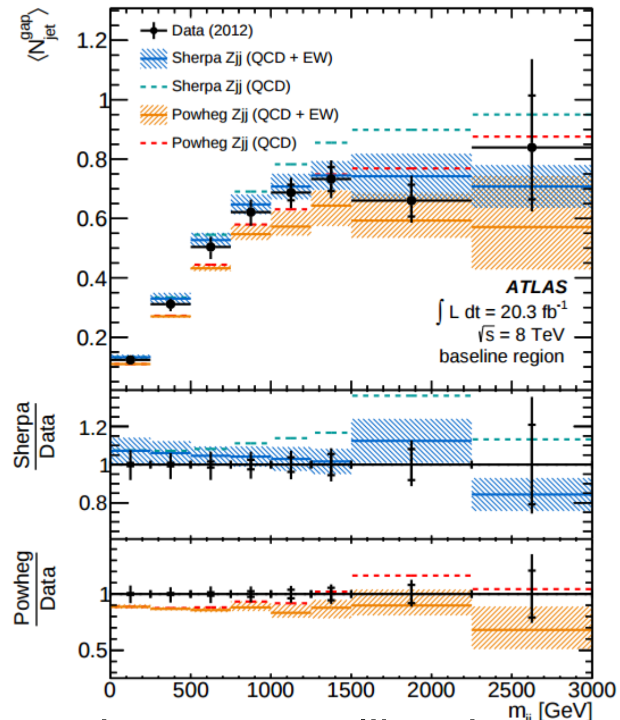




- Sherpa does not describe m_{jj} well
- New Sherpa version will fix this

- In VBF two of the three bosons have space like character in diboson-pair production all three time-like
- Complementary possibility to set limits

$$\frac{\mathcal{L}}{g_{WWZ}} = i\left[g_{1,Z}\left(W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{\dagger\mu}Z^{\nu}\right) + \kappa_Z W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}\right]$$

- $g_{1,Z}, \kappa_Z$ = 1 in SM λ_Z= 0
- Unitarity conservation obtained by introducing a dipole form factor that corrects the couplings in dependency of a unitarization scale (Λ)

WWjj selection details

Phys. Rev. Lett. 113, 141803 (2014)

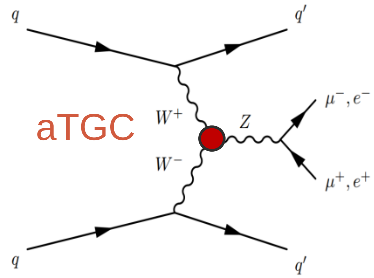
- Single μ trigger p_T >24 GeV +iso. or p_T >36 GeV
- Di-elec. trig p_T >12 GeV (both)
- From primary vertex
- Muons:
  - p_T >25 GeV; |eta|<2.4
  - Track quality
  - Isolated $\sum p_T$ of dR<0.2 around the track < 10%* p_T
- Electrons:
  - Track←→ cluster matching
  - p_T >25 GeV; |eta|<2.47
  - Medium identification criteria
- Jets
  - Anti-kt jet R=0.4
- Energy corrected for pileup etc.
- p_T >25 GeV |y|<4.4
- Cuts to suppress jets from primary interaction (JVF)
- Jets removed that overlap with lepton

Limits on aTGC/aQCGs from VBF/VBS

VBF

- Measured in search region $m_{jj} > 1$ TeV
- Coupling are modified by dipole form factor $g_{1,Z}$, λ_Z (0 and 1 in SM)
- Calculated for different unitarization scales Λ

aTGC



aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

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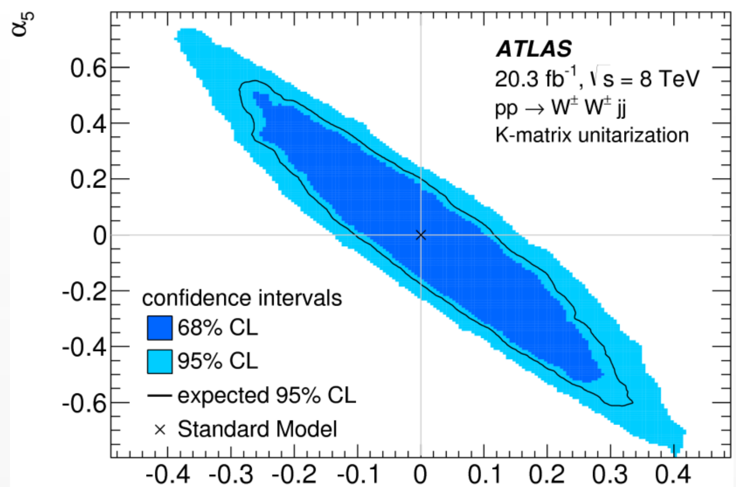
VBS

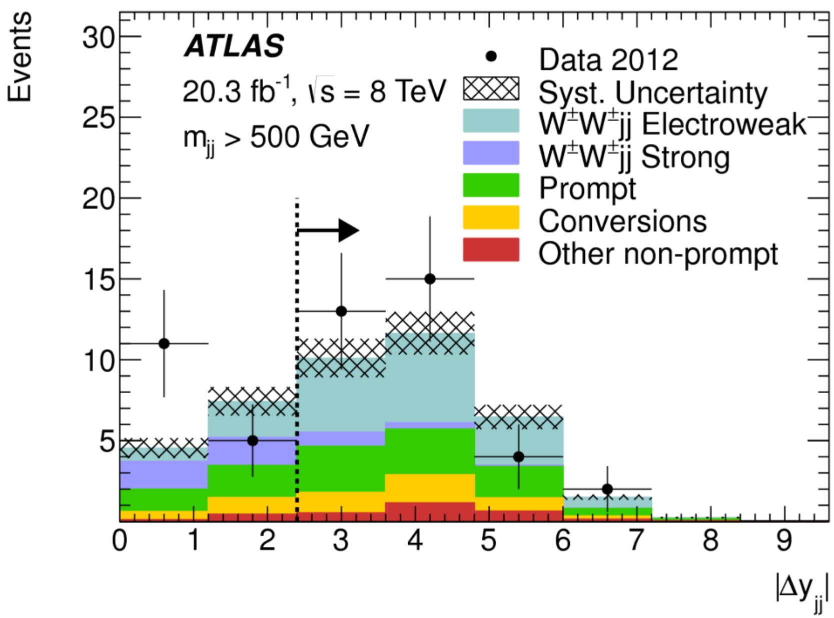
- Additional contribution to WWjj can be expressed in model-independent way using higher dim. operators
  - ➢ Anomalous quartic gauge couplings (aQGC)
- Deviation from SM parametrized in terms of (α_4, α_5) (both 0 in SM)



Phys. Rev. Lett. 113, 141803 (2014)

WWjj analysis details

Phys. Rev. Lett. 113, 141803 (2014)



- Irreducible (prompt) background:
  - WZ→l l ν ~ 90% (Simulation)
  - ZZ +jets (Simulation)
  - $t\bar{t}$ +W/Z (Simulation)
- Conversion background:
  - Wγ (simulation)
  - Background from lepton charge miss-identification e.g. Drell-Yan (data driven)
- Other non prompt background:
  - W+ jets, $t\bar{t}$, etc. jets faking leptons (data driven)

	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

Cross section compared to theory prediction