Di-Boson Production and Anomalous Couplings at the LHC

Rencontres de Blois 2012

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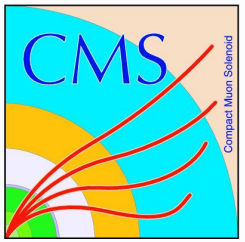
On behalf of the ATLAS and CMS collaborations



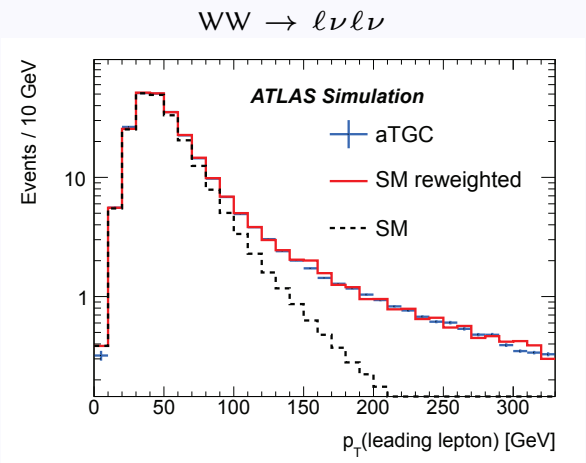
Introduction and motivations

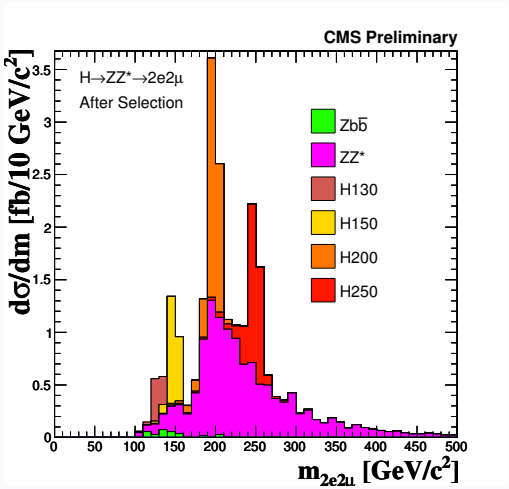
Test of the SM : vector-bosons self-interactions are constrained by SM

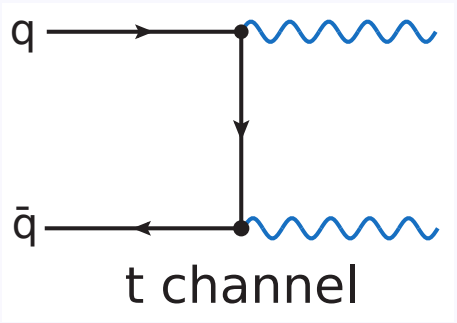
- WWγ and WWZ vertices predicted and experimentally observed
- ZZγ, ZγZ, Z$\gamma\gamma$ and ZZZ vertices forbidden

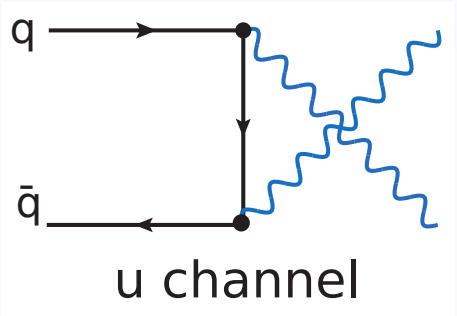
New Physics : could modify cross-sections, kinematic distributions, give anomalous triple gauge couplings (TGC)

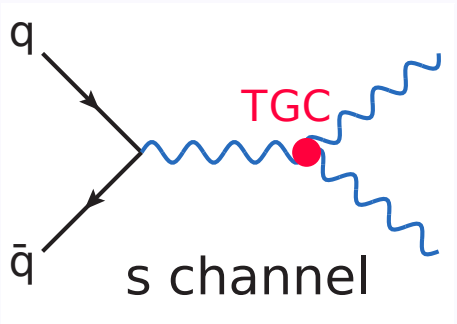
Background to : Higgs and new physics











Overview

Both experiments, ATLAS and CMS, analyzed dibosons events on 2010 and 2011 data :

Channel	ATLAS	CMS
$ZZ \to 4\ell$	1 fb^{-1}, 4.7 fb^{-1}	1.1 fb^{-1}
$ZZ \to 2\ell 2\nu$	4.7 fb^{-1}	–
$WZ \to \ell\nu\ell\ell$	1 fb^{-1}	1.1 fb^{-1}
$WW \to \ell\nu\ell\nu$	1 fb^{-1}, 4.7 fb^{-1}	36 pb^{-1}, 4.92 fb^{-1}
$W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell\ell\gamma$	1.02 fb^{-1}	36 pb^{-1}
$Z \to 4\ell$	–	4.7 fb^{-1}

cross-section and TGC available, cross section available

$\longrightarrow$ not dibosons but related

Fiducial cross-section can also be found for some of those analyses (depends on channel and experiment).

Leptonic channels (e, μ) chosen :

- clean signal, requiring high p_T isolated leptons
- but small event yields

Dominant backgrounds :

- W/Z+jets
- top
- other dibosons

mainly estimated by data driven methods on control regions when backgrounds produce fake leptons or photons, MC for the others (mainly dibosons)

$ZZ \to 4\ell$

ATLAS : 4.7 fb^{-1}, ATLAS-CONF-2012-026
CMS : 1.1 fb^{-1}, CMS-PAS-EWK-11-010

Selection

- 4 isolated leptons with $p_T > 7$ GeV (leading lepton $p_T > 20$ GeV or more [a])
- $66 < M_Z < 116$ GeV for ATLAS and $60 < M_Z < 120$ GeV for CMS
- CMS : also include $Z \to \tau\tau$, for the second Z

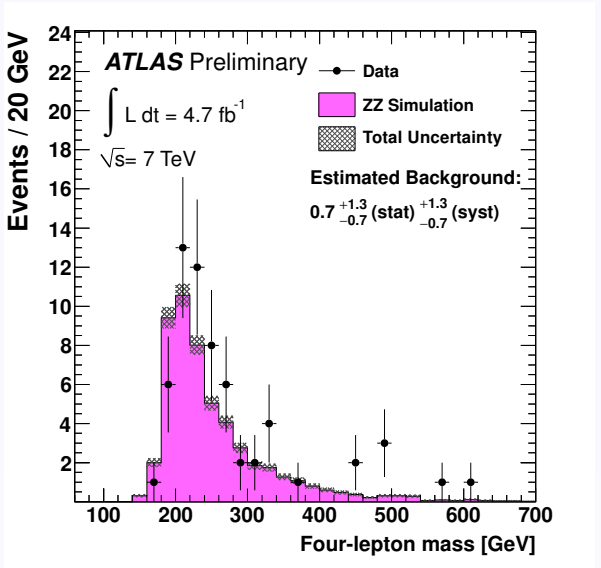
a. depending on experiment and lepton

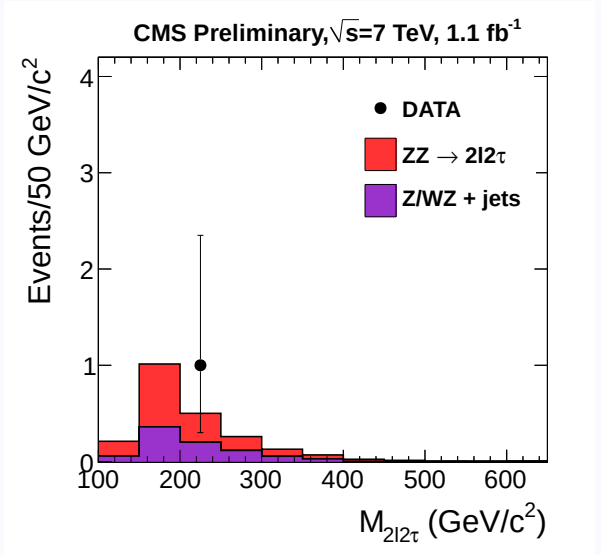
Observed events

ATLAS : $N_{obs} = 62$ (on 4.5 fb^{-1})
CMS : $N_{obs} = 8$ for $\ell = e,\mu$
$N_{obs} = 1$ for $ZZ \to 2\ell 2\tau$ (on 1.1 fb^{-1})

Measured cross sections

Expected : $\sigma^{SM} = 6.5^{+0.3}_{-0.2}$ pb (MCFM)
ATLAS : $\sigma^{tot} = 7.2^{+1.1}_{-0.9}$ (stat) $^{+0.4}_{-0.3}$ (syst) ± 0.3 (lumi) pb
CMS : $\sigma^{tot} = 3.8^{+1.5}_{-1.2}$ (stat) ± 0.2 (syst) ± 0.2 (lumi) pb



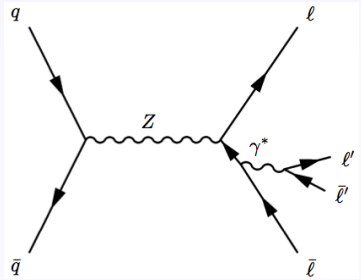


$Z \to 4\ell$

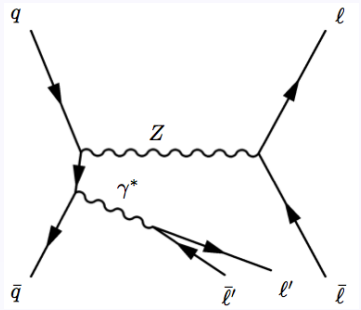
CMS : 4.7 fb^{-1}, CMS-PAS-SMP-12-009

Interest

- Background for Higgs, especially at low mass
- Same final state as $ZZ \to 4\ell$



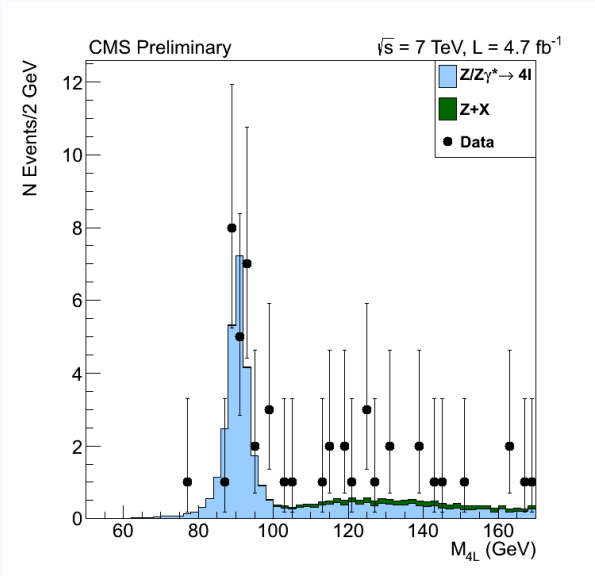
Signal



Irreductible background

Selection

- 4 isolated leptons, one with $p_T > 7$ GeV (+ trigger requirements)
- $m_{\ell\ell} > 4$ GeV (for 6 pairs)
- $80 < m_{4\ell} < 100$ GeV



Observed events

CMS : $N_{obs} = 26$, with $N_{exp\ sig} = 24.6 \pm 2.2$ and $N_{exp\ bkg} = 0.4 \pm 0.1$

Measured cross-section

Expected : $\sigma^{SM} \times BR(Z \to 4\ell) = 120 \pm 4.92$ fb

CMS : $\sigma \times BR(Z \to 4\ell) = 125^{+26}_{-23}(stat)\ ^{+9}_{-6}(syst)\ ^{+7}_{-5}(lumi)$ fb

$ZZ \to 2\ell 2\nu$

ATLAS : 4.7 fb^{-1}, ATLAS-CONF-2012-027

Selection

- 2 isolated leptons with $p_T > 20$ GeV with $|M_Z - M_{\ell^+\ell^-}| < 15$ GeV
- Axial-$E_T^{miss} = E_T^{miss} \cos\Delta\phi > 80$ GeV where $\Delta\phi = \Delta\phi(E_T^{miss}, p_T^{\ell\ell})$
- Jet veto : remove events with jets with $p_T > 25$ GeV
- $|E_T^{miss} - p_T^Z|/p_T^Z < 0.6$ (reduce WW)

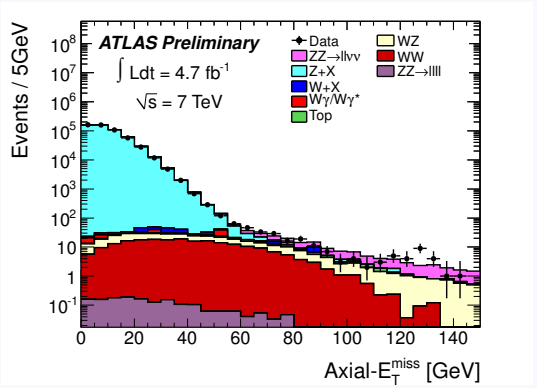
Observed events

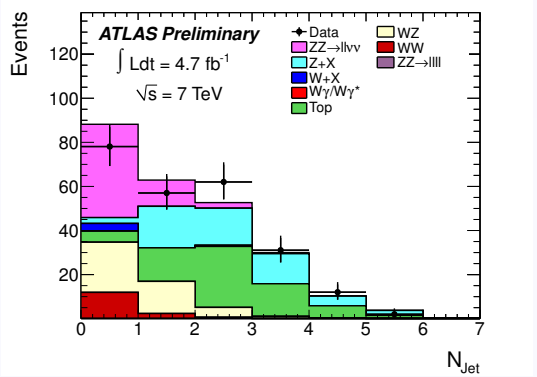
ATLAS : $N_{obs} = 78$ for $N_{exp\ bkg} = 40.7 \pm 5.6$

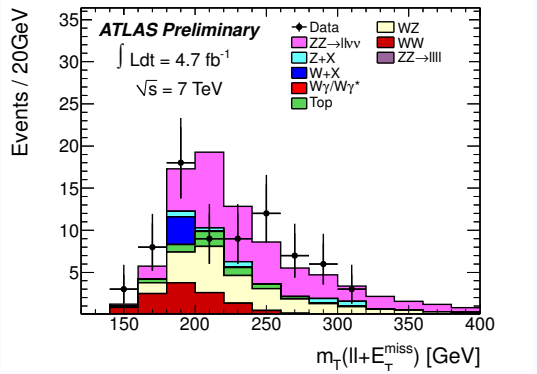
Measured cross sections

Expected : $\sigma^{SM} = 6.5^{+0.3}_{-0.2}$ pb (MCFM)

ATLAS : $\sigma^{tot} = 5.4^{+1.3}_{-1.2}$ (stat) $^{+1.4}_{-1.0}$ (syst) ± 0.2 (lumi) pb







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

ATLAS : 1.02 fb^{-1}, PLB 709 (2012) 341-357
CMS : 1.1 fb^{-1}, CMS-PAS-EWK-11-010

Selection

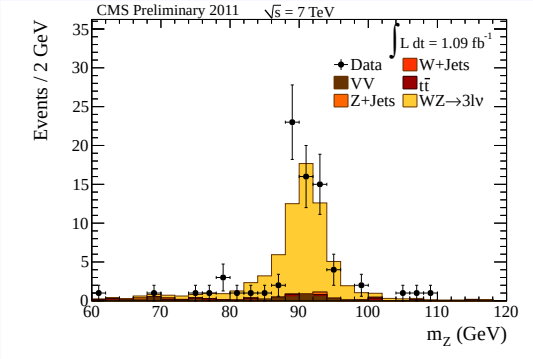
- Z boson : 2 isolated leptons with $p_T > 15$ GeV, $|M_{\ell\ell} - M_Z| < (10,30)$ GeV (ATLAS,CMS)
- 3rd lepton with $p_T > 20$GeV
- $E_T^{miss} > (25,30)$ GeV (ATLAS,CMS)
- W boson : reconstructed from the 3rd lepton and E_T^{miss}
- ATLAS : $M_T^W > 20$ GeV

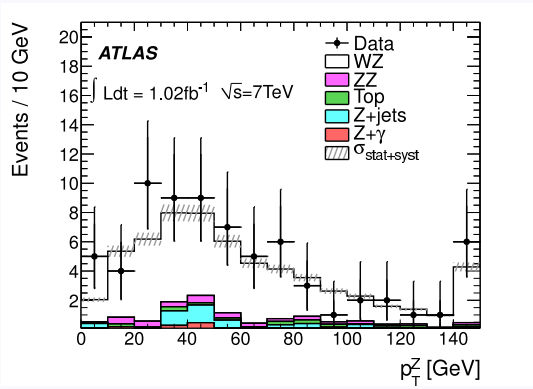
Observed events

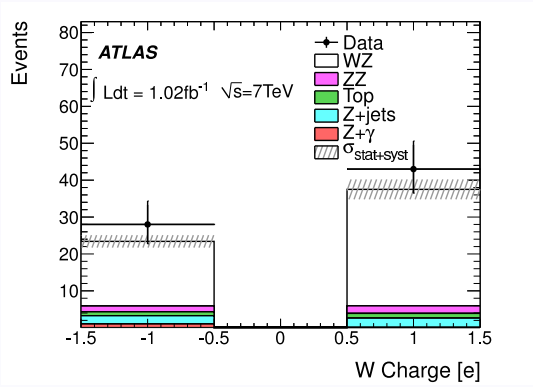
ATLAS : $N_{obs} = 71$ with $N_{exp\ bkg} = 12.1 \pm 1.4(stat)\ ^{+4.1}_{-2.0}(syst)$
CMS : $N_{obs} = 75$ with $N_{exp\ bkg} = 8.12$

Measured cross sections

Expected : $\sigma^{SM} \approx 17.4$ pb
ATLAS : $\sigma^{tot} = 20.5^{+3.1}_{-2.8}$ (stat) $^{+1.4}_{-1.3}$ (syst) $^{+0.9}_{-0.8}$ (lumi) pb
CMS : $\sigma^{tot} = 17.0 \pm 2.4$ (stat) ± 1.1 (syst) ± 1.0 (lumi) pb







WW $\to \ell\nu\ell\nu$

Selection

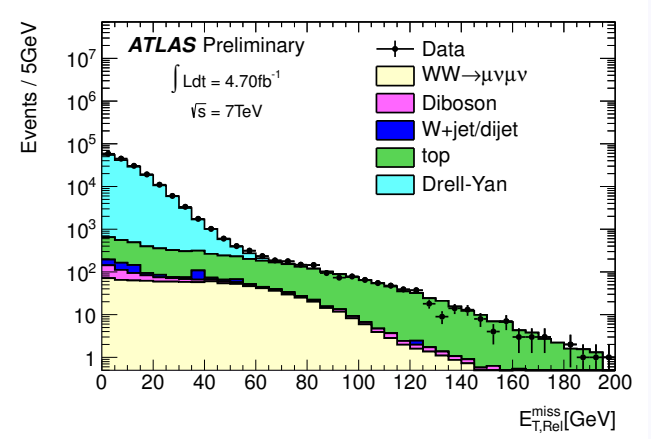
- Exactly 2 isolated leptons, $p_T > 20$ GeV
- Z/γ^* veto : $M_{\ell\ell} > 15$ (20) GeV, $M_{\ell\ell'} > 10$ (12) GeV
  $|M_{\ell\ell} - M_Z| > 15$ GeV (ee,$\mu\mu$)
- $E_{T,rel}^{miss} > 50$ (40) (ee), 55 (40) ($\mu\mu$) and 25 (20) GeV (eμ)
- Top veto : remove events containing jets with $p_T > 25$ (30) GeV or tagged jet with $p_T > 20$ GeV
- CMS : $p_T^{\ell\ell} > 45$ GeV

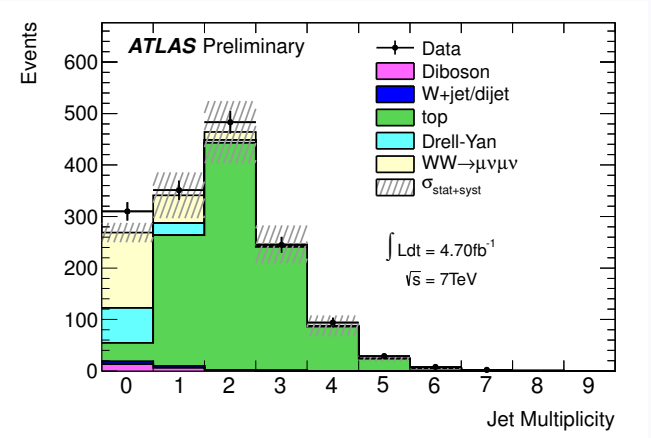
When 2 numbers : ATLAS (CMS)

Relative E_T^{miss} or projective E_T^{miss}

- To reduce impact of from mis-measured leptons or jets on E_T^{miss}
- $\Delta\phi = \Delta\phi(E_T^{miss}, p_T^{\text{nearest lepton or jet}})$
- $E_{T,rel}^{miss} = E_T^{miss} \sin\Delta\phi \quad \text{if } \Delta\phi < \pi/2$
  $E_{T,rel}^{miss} = E_T^{miss} \quad \text{if } \Delta\phi \geq \pi/2$

ATLAS : 4.7 fb^{-1}, ATLAS-CONF-2012-025
CMS : 4.92 fb^{-1}, CMS-PAS-SMP-12-005





$WW \to \ell\nu\ell\nu$

ATLAS : 4.7 fb^{-1}, ATLAS-CONF-2012-025
CMS : 4.92 fb^{-1}, CMS-PAS-SMP-12-005

Selection

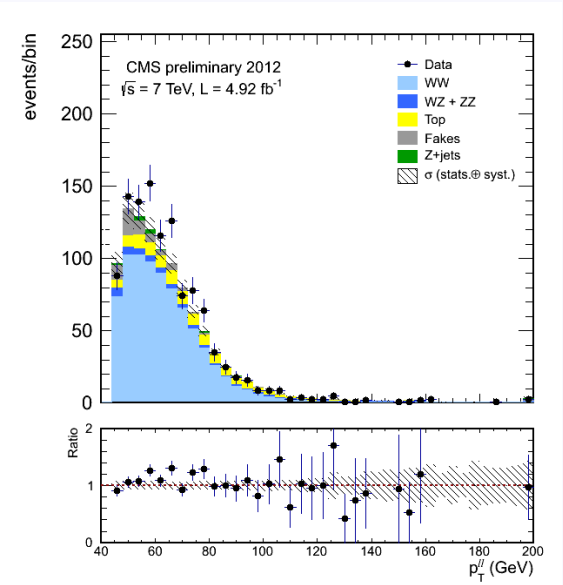
- Exactly 2 isolated leptons, $p_T > 20$ GeV
- Z/γ^* veto : $M_{\ell\ell} > 15$ (20) GeV, $M_{\ell\ell'} > 10$ (12) GeV
  $|M_{\ell\ell} - M_Z| > 15$ GeV (ee,$\mu\mu$)
- $E^{miss}_{T,rel} > 50$ (40) (ee), 55 (40) ($\mu\mu$) and 25 (20) GeV (eμ)
- Top veto : remove events containing jets with $p_T > 25$ (30) GeV or tagged jet with $p_T > 20$ GeV
- CMS : $p_T^{\ell\ell} > 45$ GeV

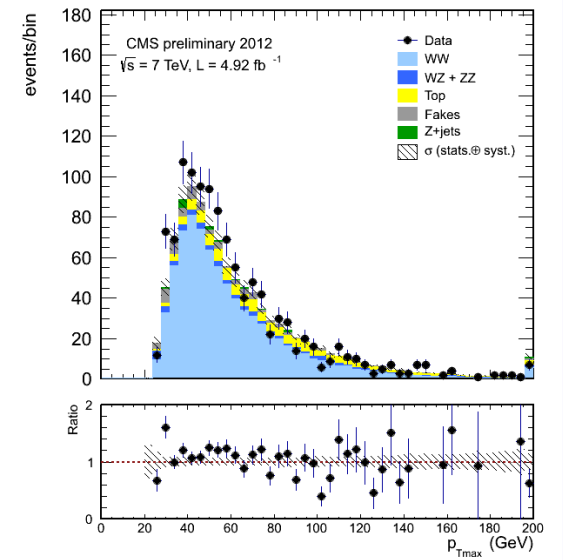
Observed events

ATLAS : $N_{obs} = 1524$ with $N_{exp\ bkg} = 531 \pm 51$
CMS : $N_{obs} = 1134$ with
$N_{exp\ bkg} = 247.1 \pm 14.6$ (stat) ± 29.5 (syst)

Measured cross sections

Expected : $\sigma^{SM} \approx 46$ pb
ATLAS : $\sigma^{tot} = 53.4 \pm 2.1$ (stat) ± 4.5 (syst) ± 2.1 (lumi) pb
CMS : $\sigma^{tot} = 52.4 \pm 2.0$ (stat) ± 4.15 (syst) ± 1.2 (lumi) pb





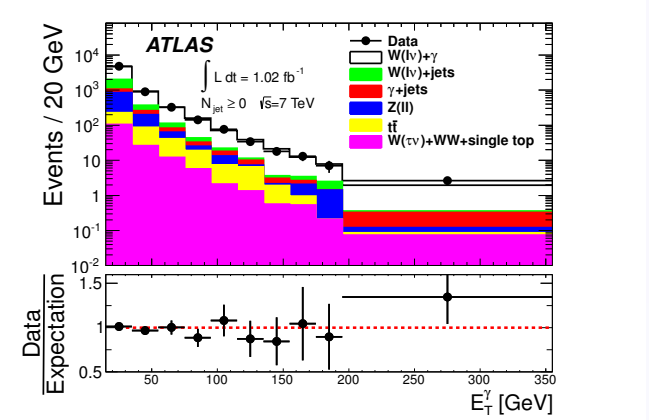
$W\gamma$ and $Z\gamma$: ATLAS analysis

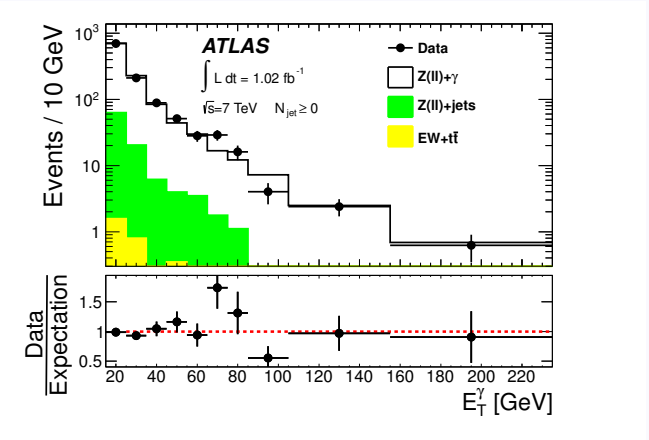
Selection

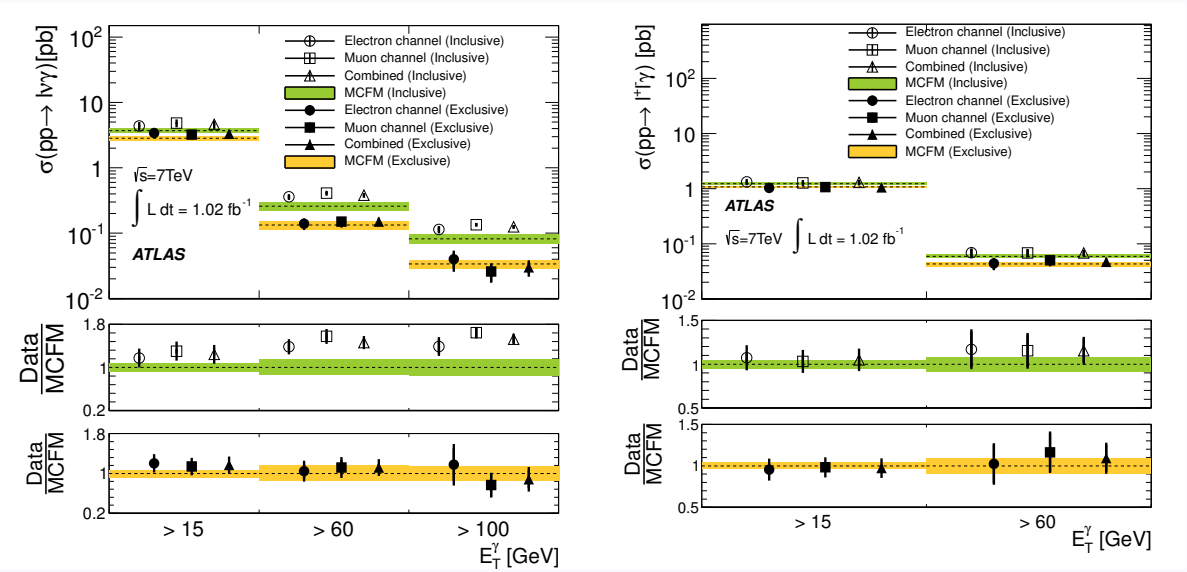
- W boson : 1 isolated lepton with $p_T > 25$ GeV, $E_T^{miss} > 25$ GeV, $M_T > 40$ GeV
- Z boson : 2 isolated leptons with $p_T > 25$ GeV, $M_{\ell\ell} > 40$ GeV
- γ : $E_T > 15$ GeV, isolated
- $\Delta R(\ell,\gamma) > 0.7$
- Exclusive measurement : veto of events containing jets with $p_T > 30$ GeV

ATLAS : 1.02 fb^{-1},
arXiv :1205.2531[hep-ex]

submitted to PLB







Wγ and Zγ : CMS analysis

CMS : 36 pb^{-1}, PLB 701 (2011) 535-555

Selection

- W boson : 1 lepton with $p_T > 20$ GeV, $E_T^{miss} > 25$ GeV
- Z boson : 2 leptons with $p_T > 20$ GeV, $M_{\ell\ell} > 50$ GeV
- γ : $E_T > 10$ GeV, isolated
- $\Delta R(\ell,\gamma) > 0.7$

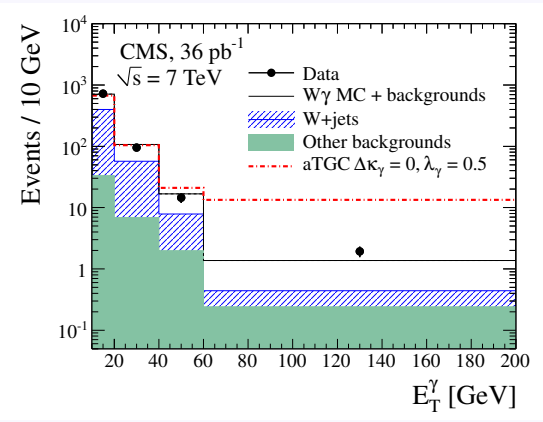
Measured cross-section

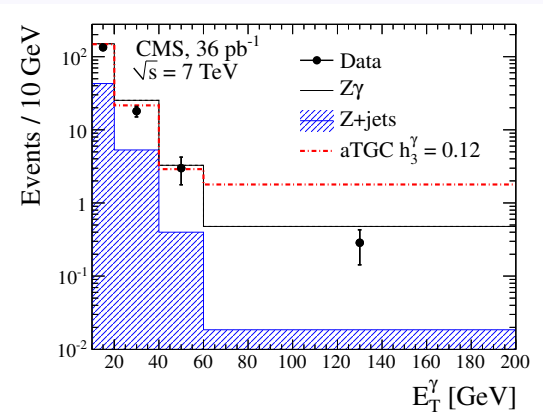
Wγ, considering $E_T^{\gamma} > 10$ GeV and $\Delta R > 0.7$:

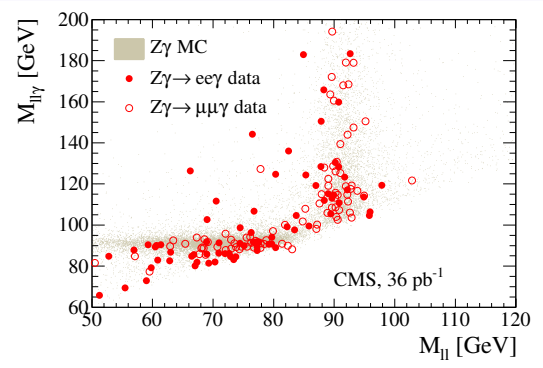
- $\sigma^{SM} = 49.4 \pm 3.8$ pb
- $\sigma \times BR(\ell\nu) = 56.3 \pm 5.0(stat) \pm 5.0(syst) \pm 2.3(lumi)$ pb

Zγ, considering $E_T^{\gamma} > 10$ GeV, $\Delta R > 0.7$ and $M_{\ell\ell} > 50$ GeV :

- $\sigma^{SM} = 9.6 \pm 0.4$ pb
- $\sigma \times BR(\ell\ell) = 9.4 \pm 1.0(stat) \pm 0.6(syst) \pm 0.4(lumi)$ pb







TGC evaluation

Accessible couplings

Assuming the CP conservation (except for f_{40}^{V}) :

Coupling	Parameters	Channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, Wγ
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	Zγ
$Z\gamma\gamma$	h_3^γ, h_4^γ	Zγ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ
$Z\gamma Z$	f_{40}^γ, f_{50}^γ	ZZ

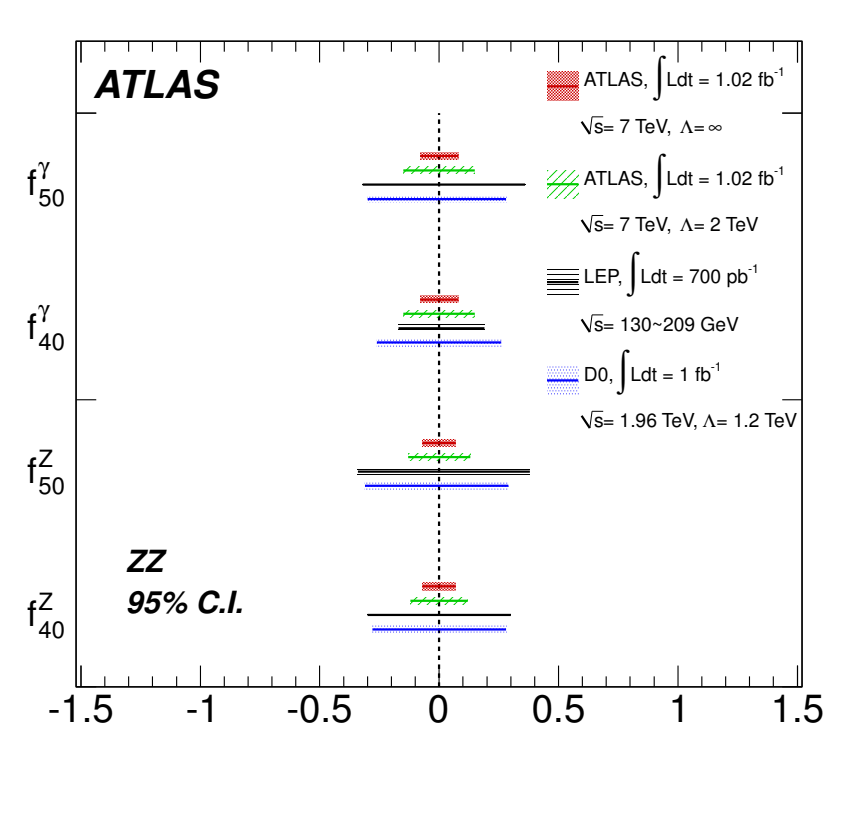
allowed by SM, forbidden by SM

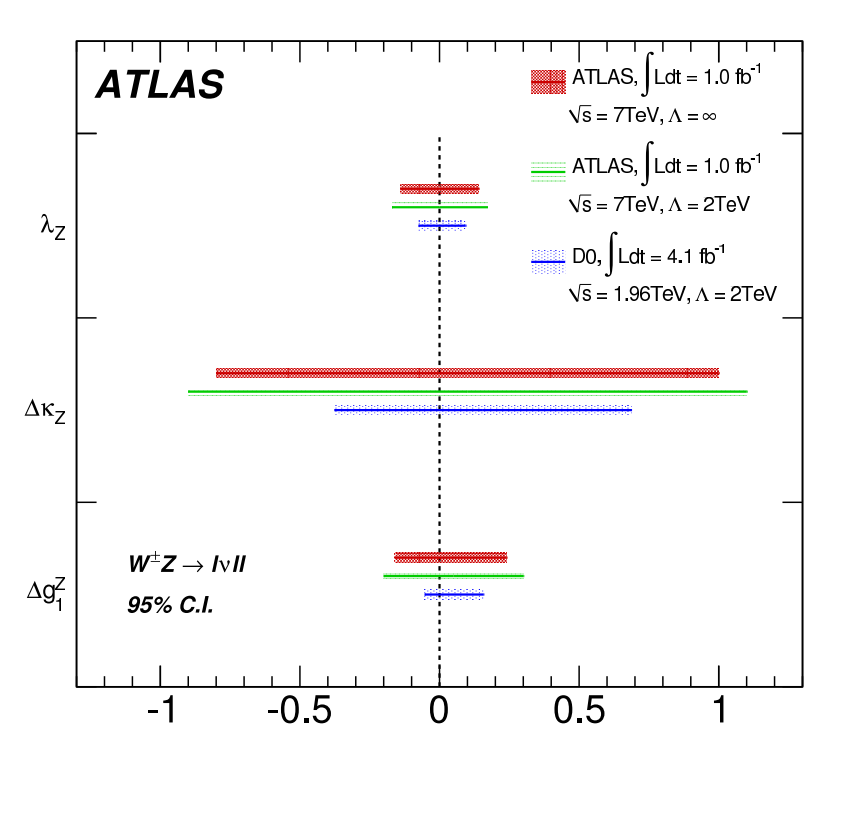
In the Standard Model : $g_1^V = \kappa_V = 1$, all the others are 0.
Hence, $g_1^V = 1 + \Delta g_1^V$ and $\kappa_V = 1 + \Delta\kappa_V$.

Method

- Use reconstruction-level data, possibly in a restricted phase-space (WW, Wγ and Zγ)
- Use likelihood 1D or 2D fit to determine the aTGCs

Anomalous couplings from ZZ and WZ

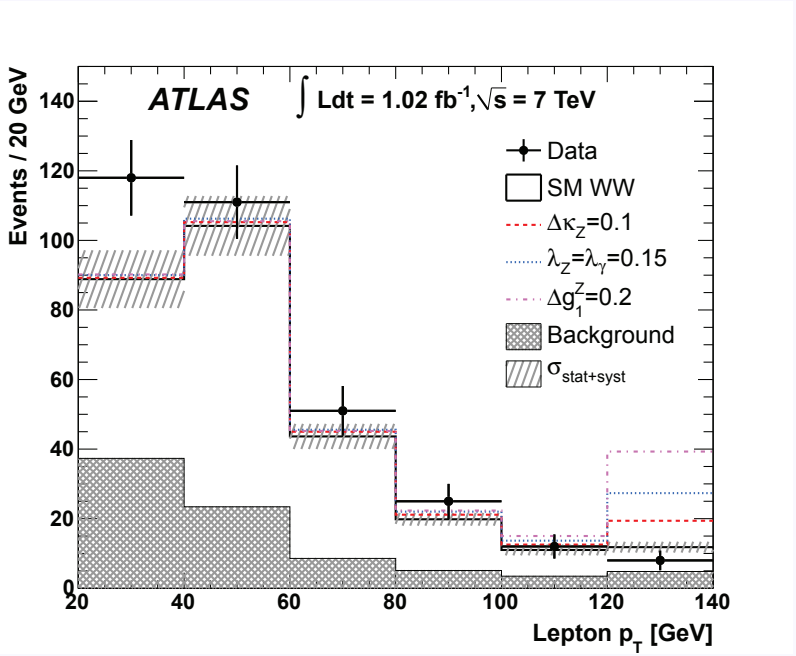


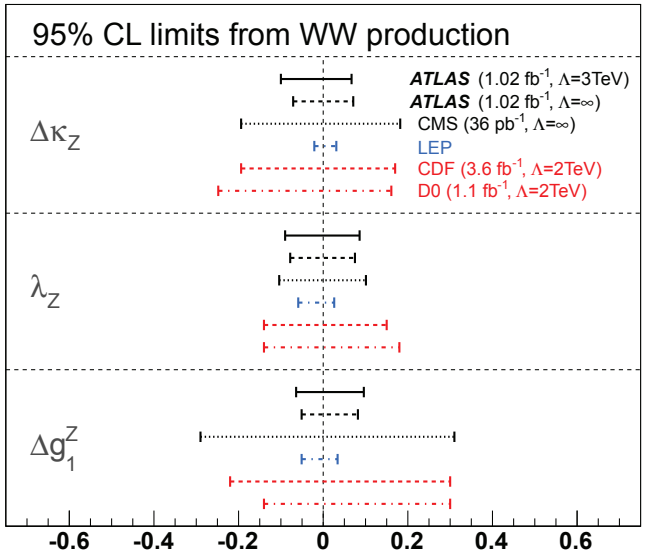


TGCs measured on $ZZ \rightarrow 4\ell$
by ATLAS at 1.02 fb^{-1}
Derived from the number of events.
PRL 108, 041804 (2012)

TGCs measured on $WZ \rightarrow \ell\nu\ell\ell$
by ATLAS at 1.02 fb^{-1}
Derived from the combined cross-section measurement.
PLB 709 (2012) 341-357

Anomalous couplings from WW





ATLAS and CMS results in black

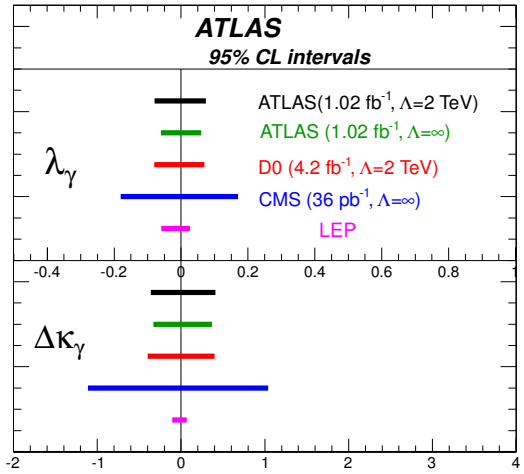
TGC measured on WW $\to \ell\nu\ell\nu$

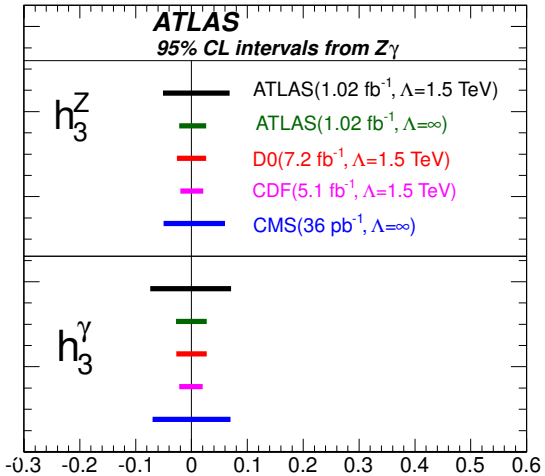
- by CMS, on 36 pb^{-1} (on 2010 data, PLB 699 (2011) 25-47)
- by ATLAS, on 1.02 fb^{-1} (on 2011 data, arXiv :1203.6232[hep-ex], submitted to PLB)

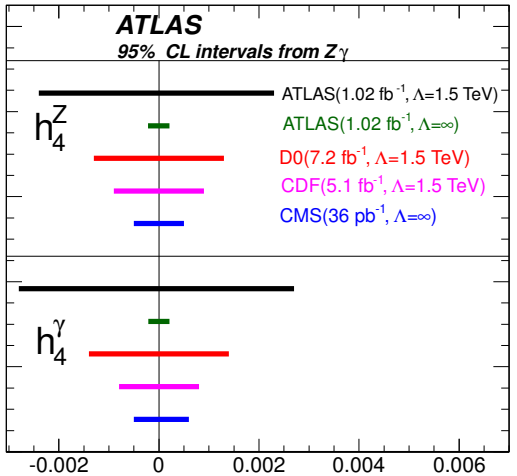
Some differences in details of the effective theory used.

1D or 2D fit on TGCs parameters taken in $(\Delta\kappa_Z, \lambda_Z, \Delta g_1^Z)$ for ATLAS and $(\Delta\kappa_\gamma, \lambda_Z, \Delta g_1^Z)$ for CMS.

Anomalous couplings from $W\gamma$ and $Z\gamma$







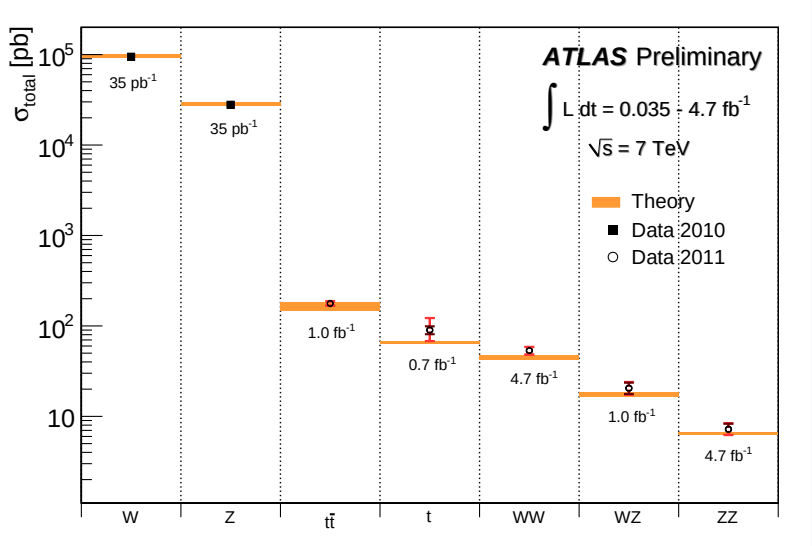
Comparison of ATLAS (green) and CMS (blue) results.

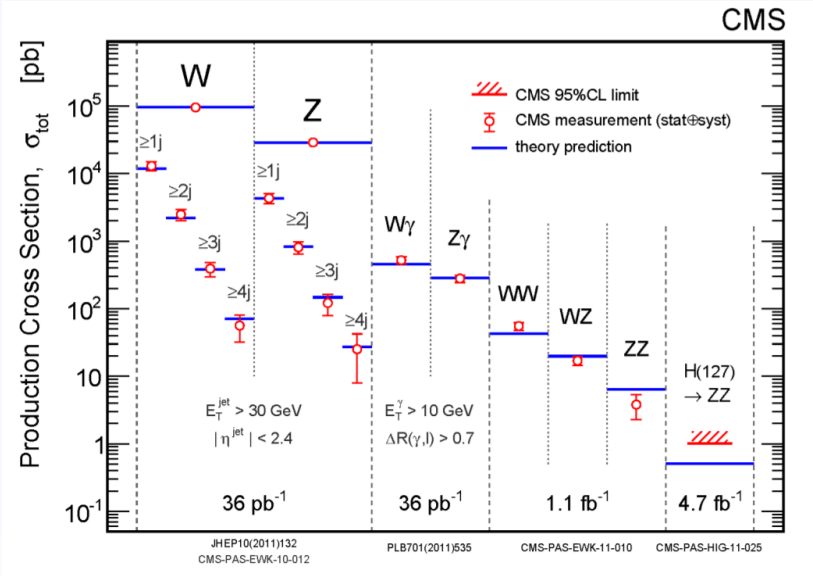
TGC measured on $W\gamma \to \ell\nu\gamma$ and $Z\gamma \to \ell\ell\gamma$

- by CMS, on 36 pb^{-1} (on 2010 data, PLB 701 (2011) 535-555)
- by ATLAS, on 1.02 fb^{-1} (on 2011 data, arXiv :1205.2531[hep-ex], sub. to PLB)

Both experiments used the exclusive measurement, in the highest bin in E_T^{γ}, 1D and 2D fits were done.

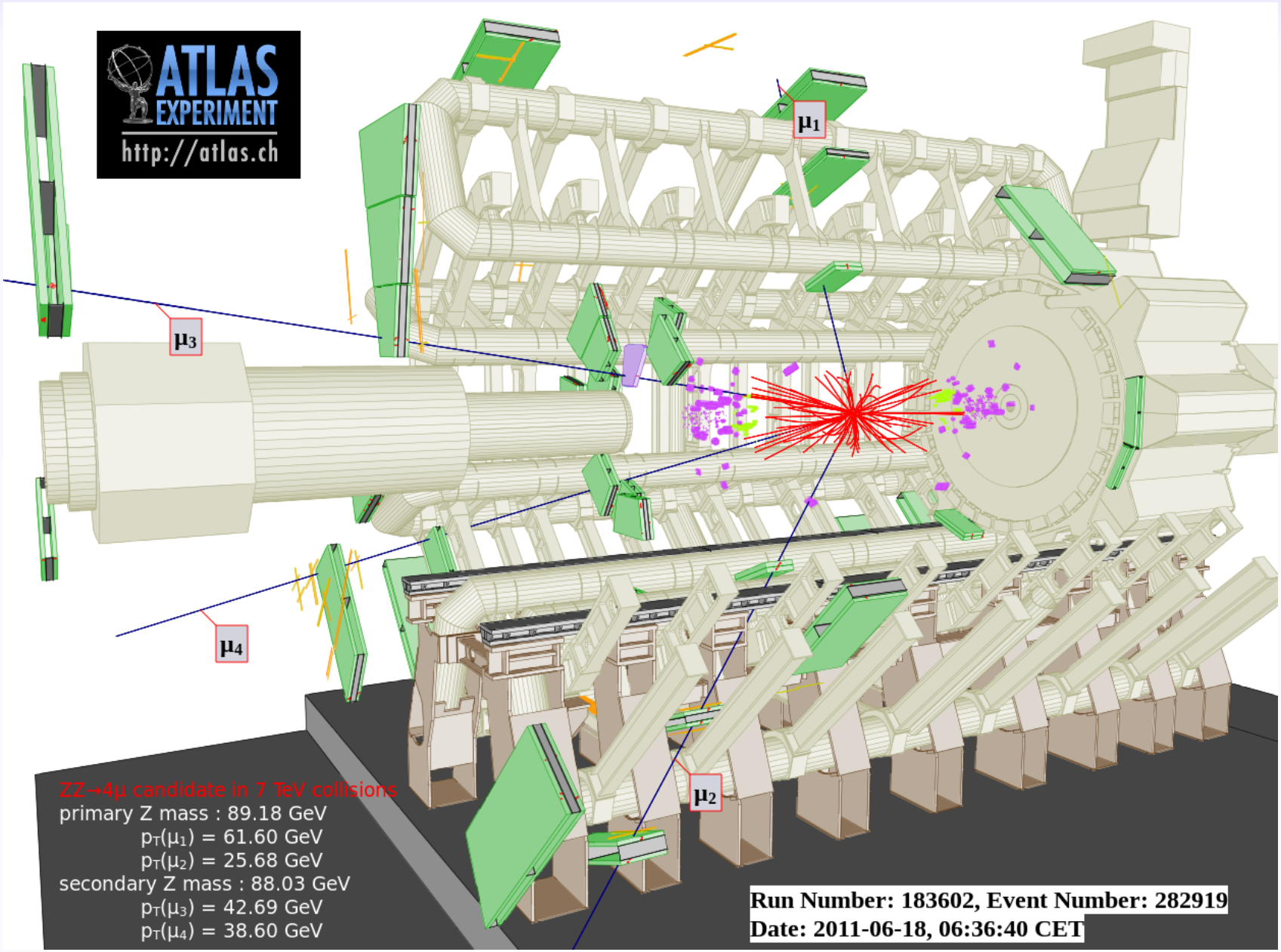
Conclusion





- Dibosons cross-sections and limits on TGCs have been measured by ATLAS and CMS
- Agreement with SM within uncertainties
- Already surpassing LEP and Tevatron in some channels
- New measurements and limits to come, on 2011 data (7 TeV) and 2012 data (8 TeV)

Event display : $ZZ \to 4\ell$



TGC details

Effective Lagrangian

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu) + i\kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^+_{\rho\mu} W^{-\mu}{}_\nu V^{\nu\rho}$$

$g_1^V = 1 + \Delta g_1^V$ and $\kappa_V = 1 + \Delta\kappa_V$,
g_1^γ fixed to 1 by electromagnetic gauge invariance LEP scenario :

$$\Delta\kappa_\gamma = -\frac{\cos^2\theta_W}{\sin^2\theta_W}(\Delta\kappa_Z - \Delta g_1^Z) \text{ and } \lambda_\gamma = \lambda_Z$$

HISZ scenario : $\Delta g_1^Z = \dfrac{\Delta\kappa_\gamma}{2\cos^2\theta_W}$

LEP scenario was used by ATLAS, D0 and LEP while HISZ scenario was used by CMS and CDF for the estimation of aTGCs from WW events

Form factor

To avoid divergent cross-section at high energy, a form factor depending on the scale Λ can be introduced :

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

with α the parameter considered, $\sqrt{\hat{s}}$ the invariant mass of the considered process and n depends on the coupling (2 for Δg_1^V, $\Delta\kappa_V$ and λ_V, 3 for h_3^V, f_4^V and f_5^V, and 4 for h_4^V).

ATLAS and CMS