DIS 2013

WW, WZ and ZZ production at ATLAS and limits on anomalous TGCs

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on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

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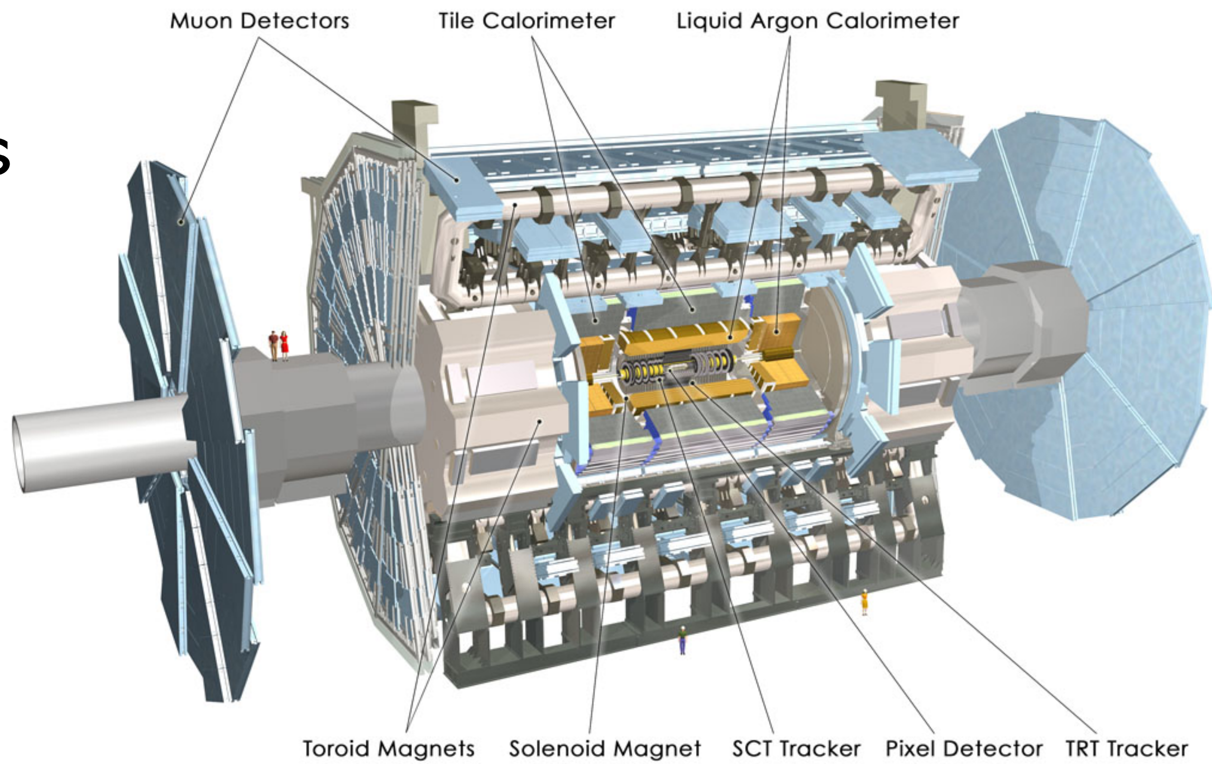
Presentation outline

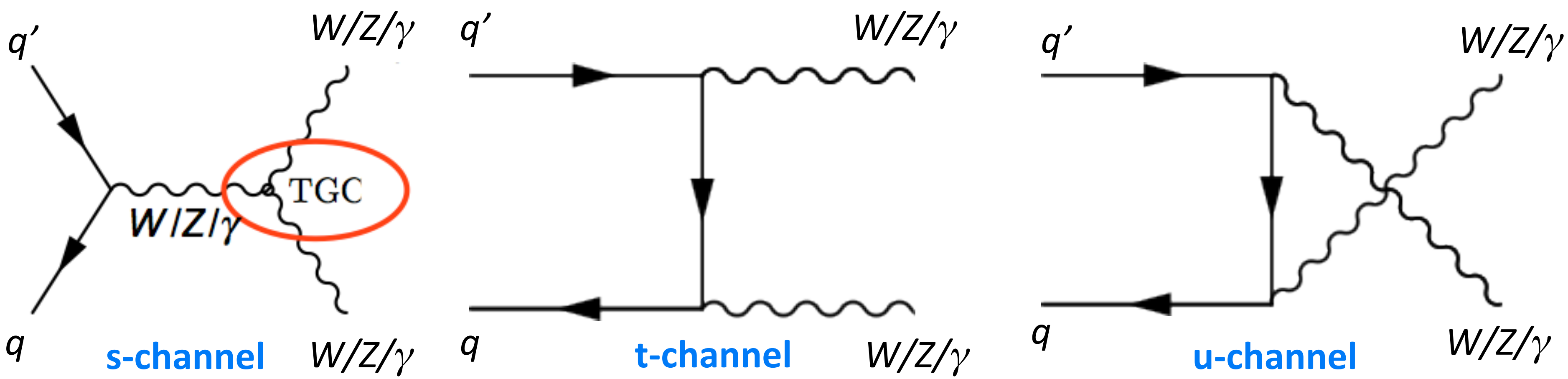
- Overview
  - Physics motivation
  - Common characteristics
  - Analysis strategy
- WW measurements
  - Cross-section results
  - aTGC results
- ZZ measurements
  - Cross-section results
  - aTGC results
- WZ measurements
  - Cross-section results
  - aTGC results
- Summary and conclusions



Physics motivation

- Electroweak boson pair measurements:
  - Test of the electroweak sector of the Standard Model at **TeV** scale
  - Sensitive to **anomalous triple gauge couplings (TGCs)**
    → new constraints on production cross-sections
  - Possible decay channel of new particles
  - Irreducible background of **Higgs** searches

- Di-boson production processes:



  - Standard model tree-level LO diagrams for **WW**, **WZ** and **ZZ** production
  - Cross-sections are calculated to NLO
  - Standard model forbids the neutral TGC vertex

Anomalous couplings

- The s-channel diagrams contain the triple gauge coupling vertex
  - Effect of aTGCs are modeled using an effective Lagrangian (depends on certain parameters)
  - Anomalous couplings enhance cross-sections at high W/Z boson p_T or M_T

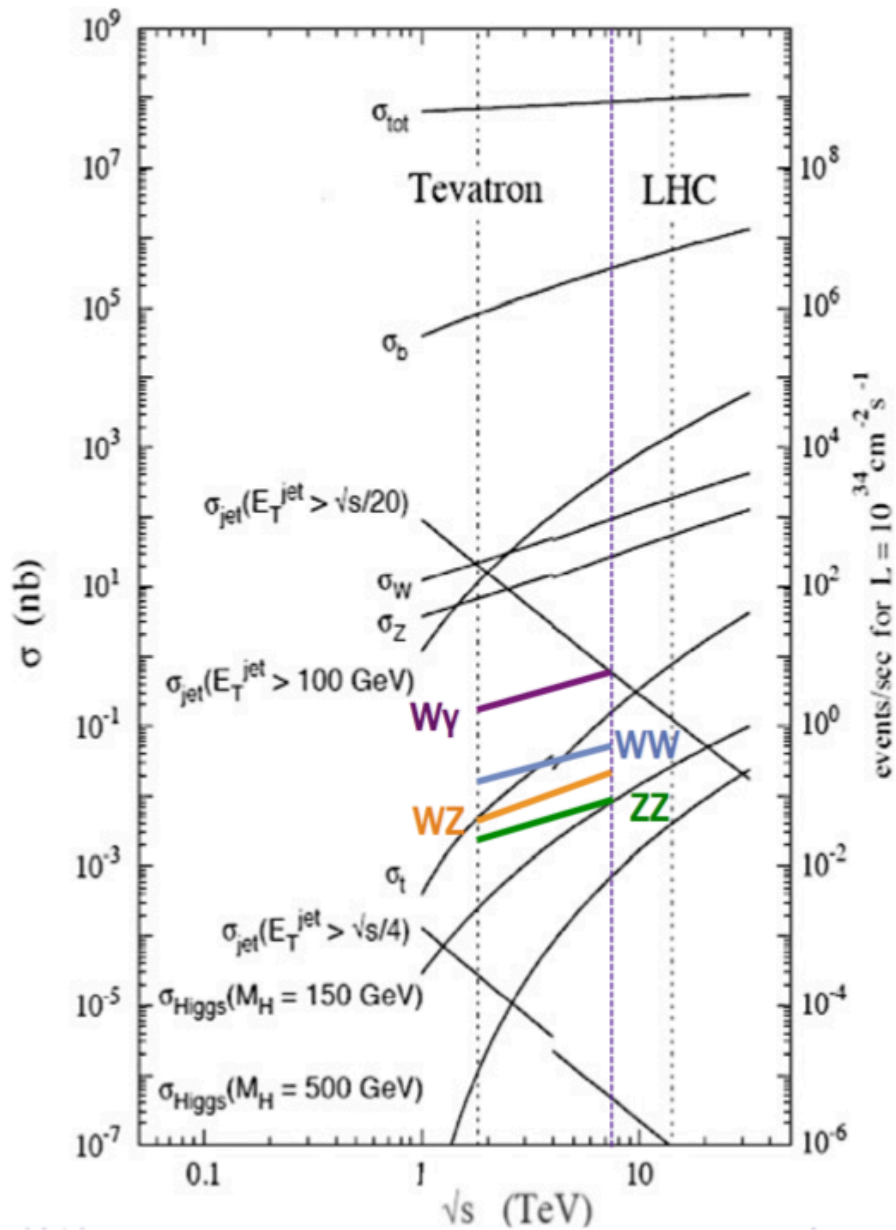
Coupling	Parameters	Channel
$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	WW, Wγ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	Zγ
$Z\gamma\gamma$	h_3^γ, h_4^γ	Zγ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ
$Z\gamma Z$	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

Neutral TGCs

- We set limits on couplings by measuring how much these parameters deviate the event yields from the SM
  - "Cut-off" form factor Λ is introduced to preserve the unitarity of the model
  - Neutral TGCs are not allowed in the Standard Model
- Multiple scenarios are assumed
  - **Equal couplings scenario** (WWZ and WWγ couplings are equal), **LEP scenario**, **HISZ scenario**, **no-relationship scenario**

Common characteristics

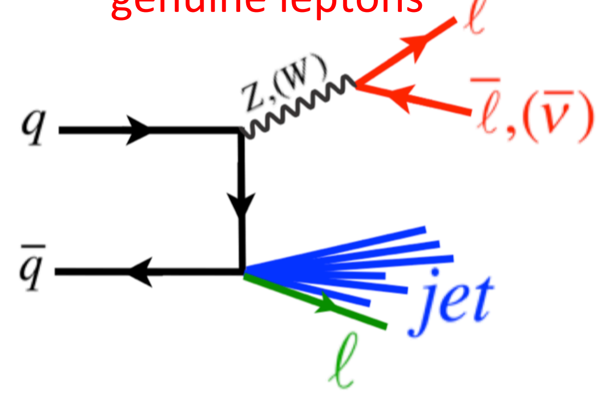
- Small cross-sections
  (1 to 100 pb)
- High p_T isolated leptons
  (electrons or muons)
  clean signal / low background
  - **Z decay:** opposite charge, same flavour lepton pairs.
  - **W decay:** includes E_T^{miss} coming from the neutrino
- Calorimeter isolation
- Track isolation
- Single lepton triggers



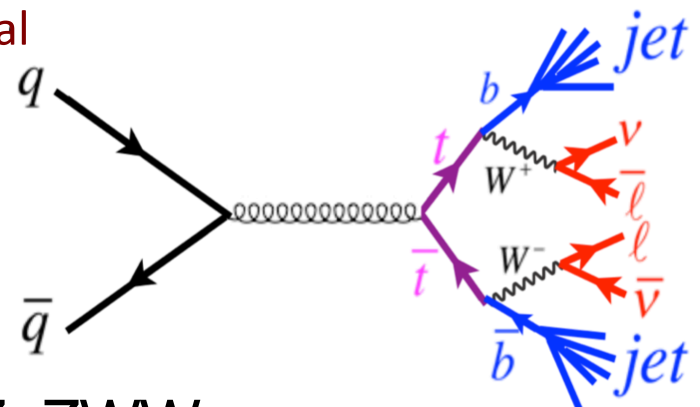
Common backgrounds

Standard model processes that mimic di-boson final states:

- **W+jets/Z+jets**
  - W/Z production in association with jets, where
    - jet is mis-identified as lepton
    - apparent E_T^{miss} arises from from pileup
  - These backgrounds are not well modeled by MC
    - data driven methods used to estimate fake leptons (pion, kaon, b-quark decay)



- **Top-antitop and single-top**
  - W boson from top cascade decays: mimics signal in events, where jets are not reconstructed
  - Estimated using data driven methods



- **Di-boson production**
  - Estimated from MC
- **Other minor backgrounds: Zγ, Wγ, ZZZ, ZWW**
  - Estimated from MC

Analysis strategy

Fiducial region:

- The efficiency correction is modeled by emulating the event selection at the truth level
  - N_{obs} … number of observed events passing selection
  - N_{bkg} … number of estimated background events
  - L … integrated luminosity
  - C … efficiency correction from MC (detector effects)

$$\sigma_{\mathrm{fid}}^{\mathrm{X}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{C_X \cdot \int L\,\mathrm{dt}}$$

$$C_X = \frac{N_{X,\,\mathrm{passed}}}{N_{X,\,\mathrm{generated}}}$$

Cross-section measurement:

1) Measure in detector fiducial region:
- Obtain event yields at final selection

2) Extrapolate to full phase space:
- Correct for acceptance and efficiency
  - A … acceptance (extrapolate to total phase space)
  - BR … Branching ratio of bosons decaying to leptons
- Acceptance defined to closely match the instrumented region of the detector
- Clear advantage of this approach is that fiducial cross-sections give overall smaller uncertainties

$$\sigma_{\mathrm{tot}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{A \cdot C \cdot \int L\,\mathrm{dt} \cdot BR}$$

ATLAS EXPERIMENT

WW → eνμν Candidate

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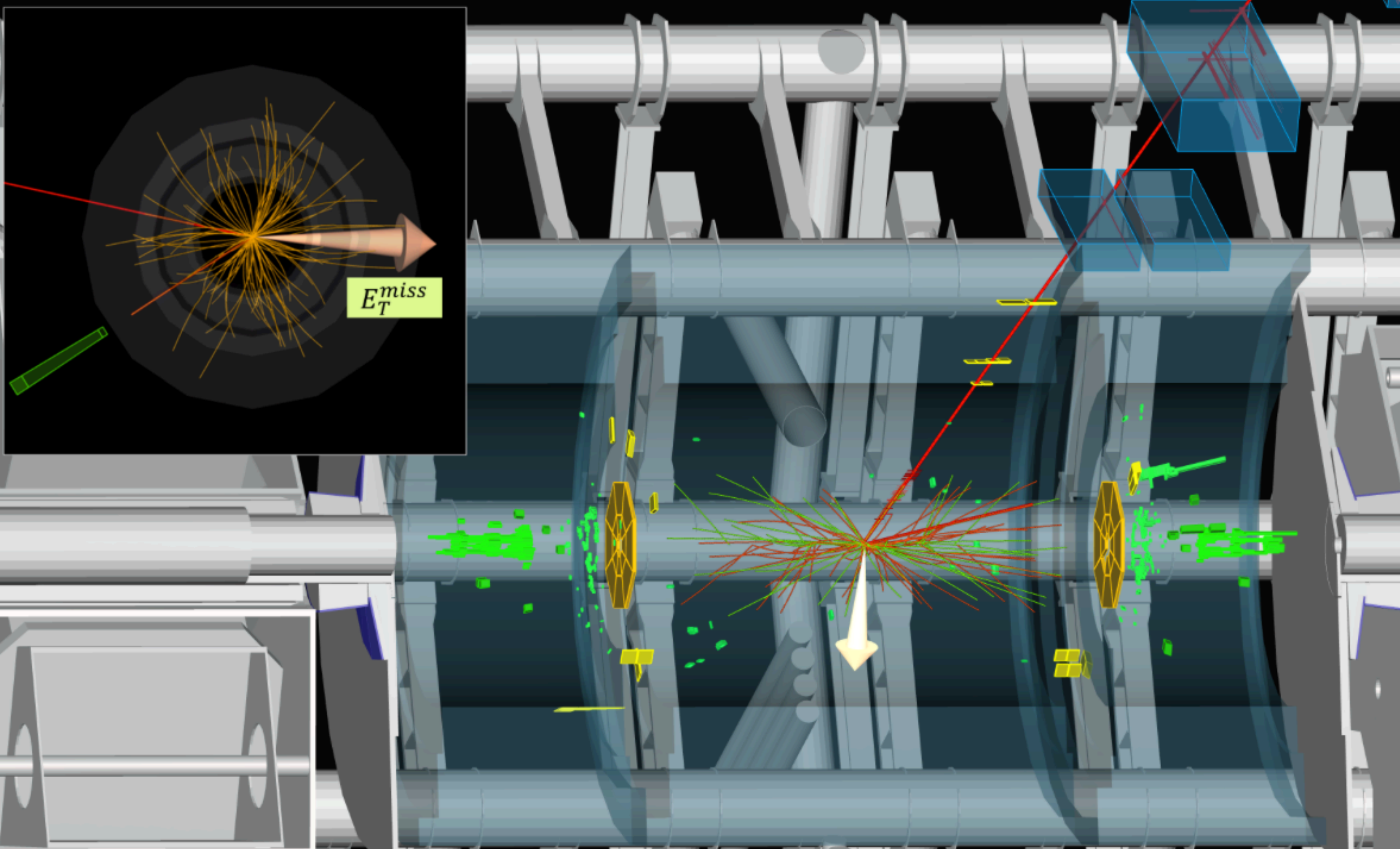
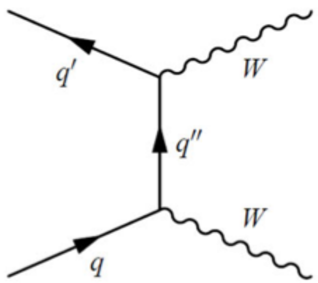


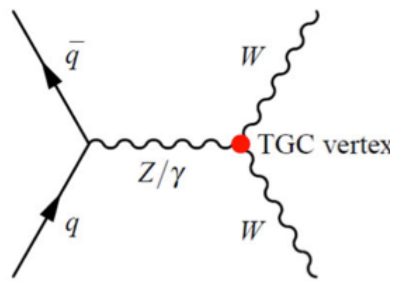
WW→2l2ν measurements

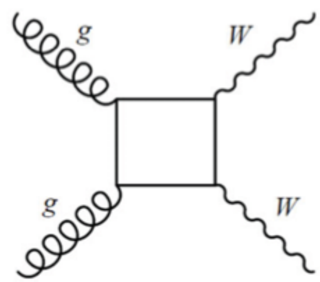
❖ Characteristics:

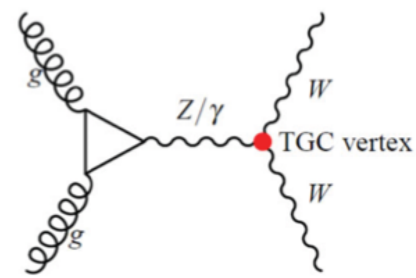
- ❑ Final states $e^+e^-E_T^{miss}$, $\mu^+\mu^-E_T^{miss}$ and $e^\pm\mu^\pm E_T^{miss}$
- ❑ Tau decay cascade $W \rightarrow \tau + X \rightarrow e/\mu + X$ is included
- ❑ Theoretical prediction from NLO: $\sigma_{NLO@7TeV} = 44.7 \pm 2.8$ pb

Latest publication:
4.6 fb^{-1}, 7 TeV
arXiv:1210.2979





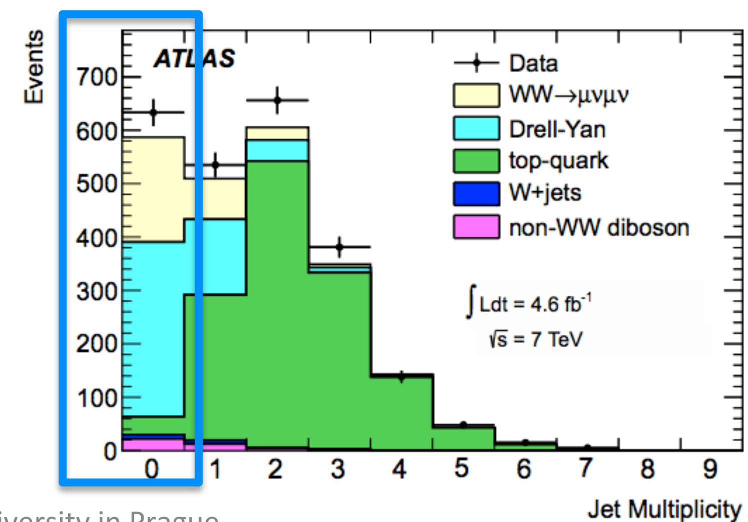




t-channel **s-channel** **Gluon fusion:** $gg \rightarrow WW$ contributes additional ~3%

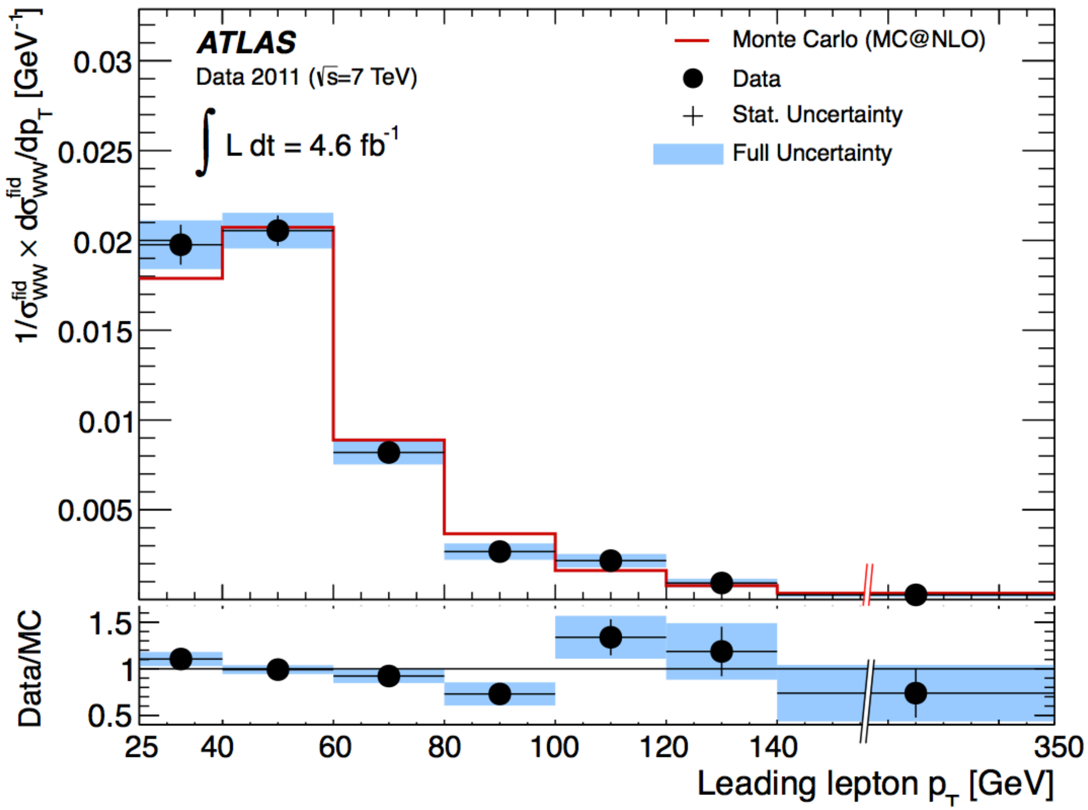
❖ Signal selection:

- $p_T(l) > 25\ (20)$ GeV for leading (trailing) lepton
- $m_{ll} > 15 / 15 / 10$ GeV in ee / μμ / eμ
- **Z veto:** $|m_{ll} - m_Z| > 15$ GeV in ee / μμ
- $E_{T,Rel}^{miss} > 45 / 45 / 25$ GeV in ee / μμ / eμ
- **Jet veto:** no jet with $p_T > 25$ GeV, $|\eta| < 4.5$
- $p_T(ll) > 30$ GeV in ee / μμ / eμ



WW→2l2ν cross-section results

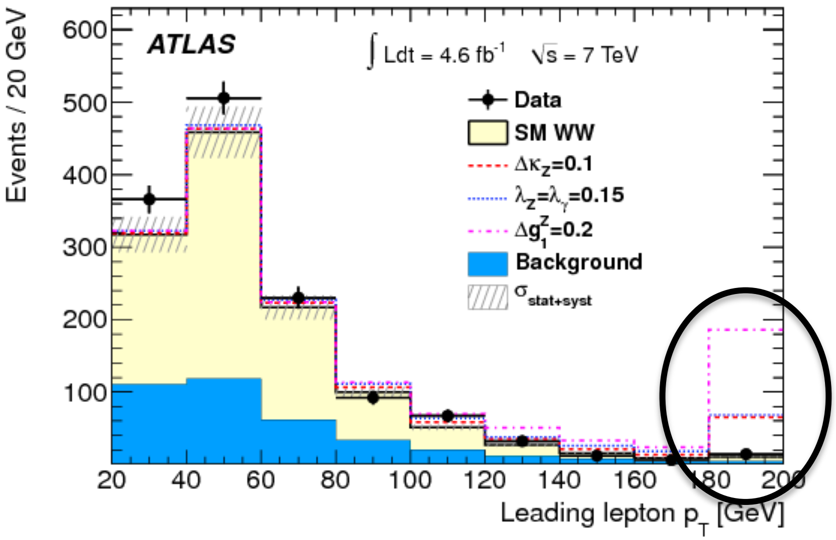
- Results compatible with the Standard model predictions:
  - Contributions from H→WW **not** included in signal (~3% increase for 126 GeV)
  - Unfolding performed to obtain normalized differential WW fiducial cross section as a function of the leading lepton p_T

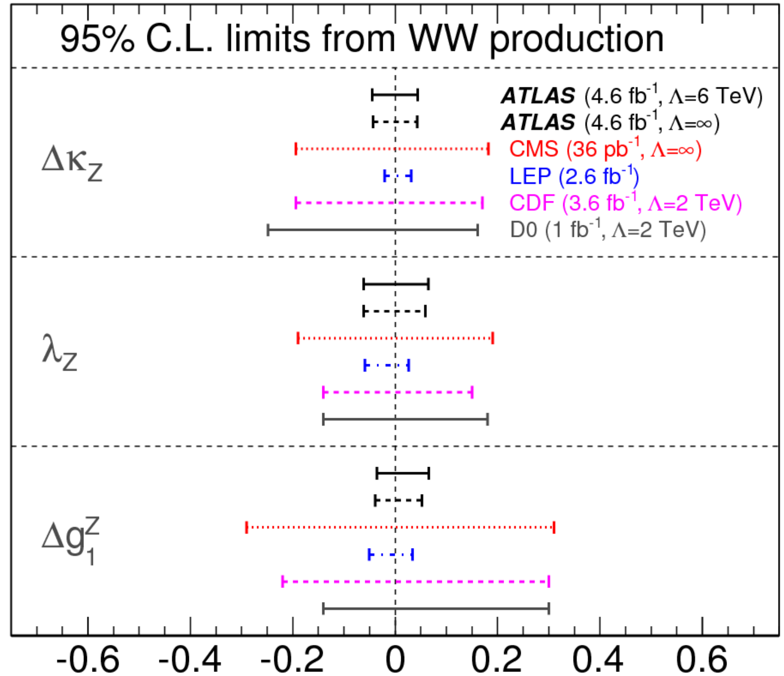


Energy	Int. lumi.	Theory	Experiment
7 TeV	34 pb^{-1}	$\sigma_{NLO@7TeV} = 44.7 \pm 2.8$ pb	$\sigma_{WW\to 2l2\nu} = 41.2 \pm 20(stat) \pm 5.0(syst) \pm 1.0(lumi)$ pb
7 TeV	1.02 fb^{-1}	$\sigma_{NLO@7TeV} = 44.7 \pm 2.8$ pb	$\sigma_{WW\to 2l2\nu} = 54.4 \pm 4.0(stat) \pm 3.9(syst) \pm 2.0(lumi)$ pb
7 TeV	4.6 fb^{-1}	$\sigma_{NLO@7TeV} = 44.7 \pm 2.8$ pb	$\sigma_{WW\to 2l2\nu} = 51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 2.0(lumi)$ pb

WW→2l2ν aTGC results

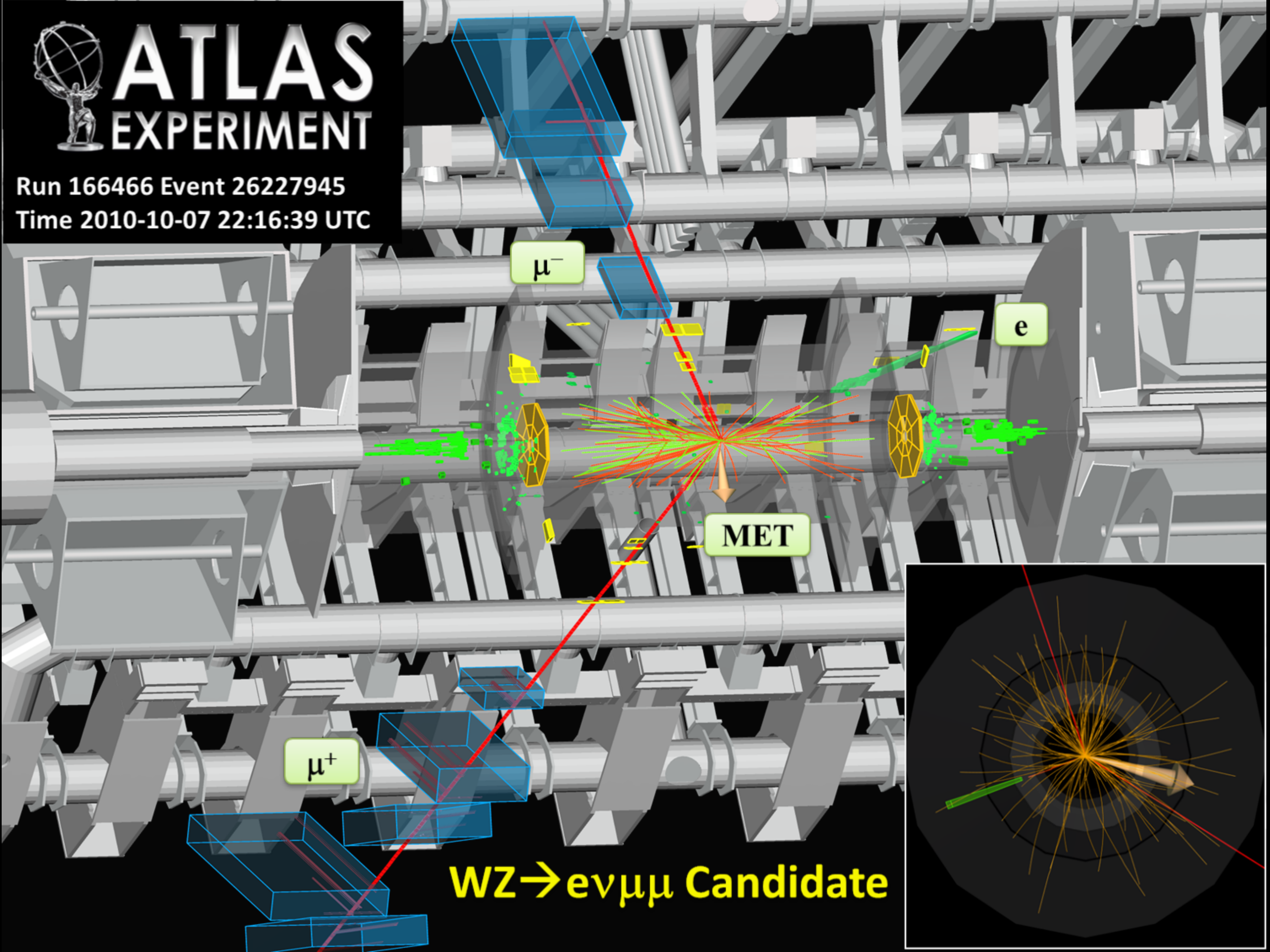
- Probed using p_T spectrum which is sensitive to aTGCs
  - Sensitive at p_T > 120 GeV





  - aTGCs considered in 3 scenarios:

Scenario	Parameter	Expected ($\Lambda = 6$ TeV)	Observed ($\Lambda = 6$ TeV)	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
LEP	$\Delta\kappa_Z$	$[-0.043, 0.040]$	$[-0.045, 0.044]$	$[-0.039, 0.039]$	$[-0.043, 0.043]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$
	Δg_1^Z	$[-0.034, 0.062]$	$[-0.036, 0.066]$	$[-0.038, 0.047]$	$[-0.039, 0.052]$
HISZ	$\Delta\kappa_Z$	$[-0.040, 0.054]$	$[-0.039, 0.057]$	$[-0.037, 0.054]$	$[-0.036, 0.057]$
	$\lambda_Z = \lambda_\gamma$	$[-0.064, 0.062]$	$[-0.066, 0.065]$	$[-0.061, 0.060]$	$[-0.063, 0.063]$
Equal Couplings	$\Delta\kappa_Z$	$[-0.058, 0.089]$	$[-0.061, 0.093]$	$[-0.057, 0.080]$	$[-0.061, 0.083]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$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WZ→eνμμ Candidate

WZ→3lν measurements

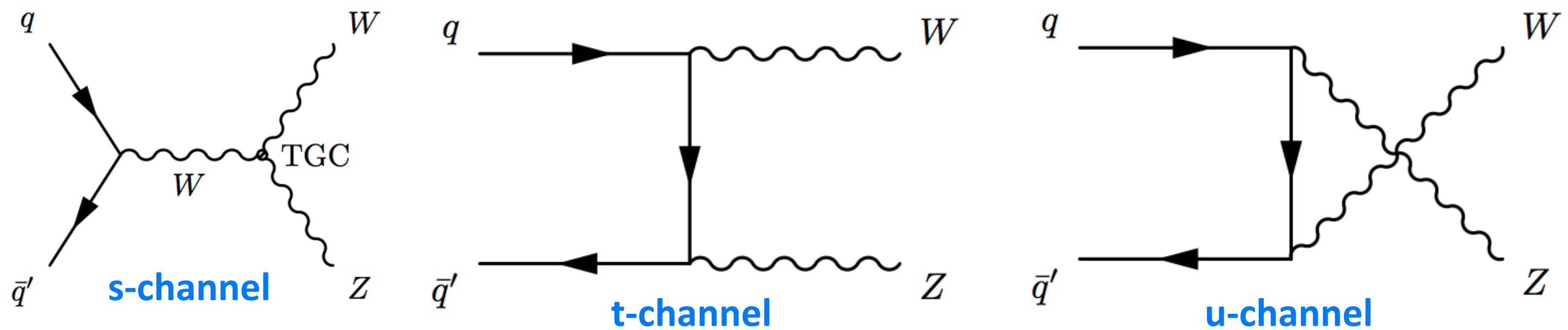
❖ Analysis characteristics:

- ❑ Final states: $e^+e^-e^\pm$, $\mu^+\mu^-\mu^\pm$, $e^+e^-\mu^\pm$, $\mu^+\mu^-e^\pm$
- ❑ Main backgrounds: Z+jets, ZZ, ttbar, Zγ
- ❑ Theoretical prediction from NLO:

$$\sigma_{\mathrm{NLO@7TeV}} = 17.6\,^{+1.1}_{-1.0}\ \mathrm{pb} \qquad \sigma_{\mathrm{NLO@8TeV}} = 20.3 \pm 0.8\ \mathrm{pb}$$

Latest publications:
4.6 fb^{-1}, 7 TeV, paper
arXiv:1208.1390

13 fb^{-1}, 8 TeV, conf. note
ATLAS-CONF-2013-021



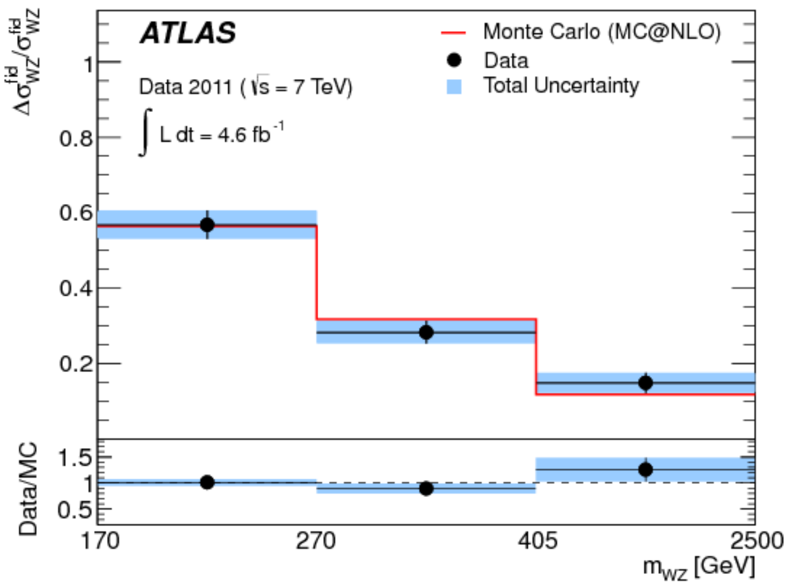
❖ Signal selection:

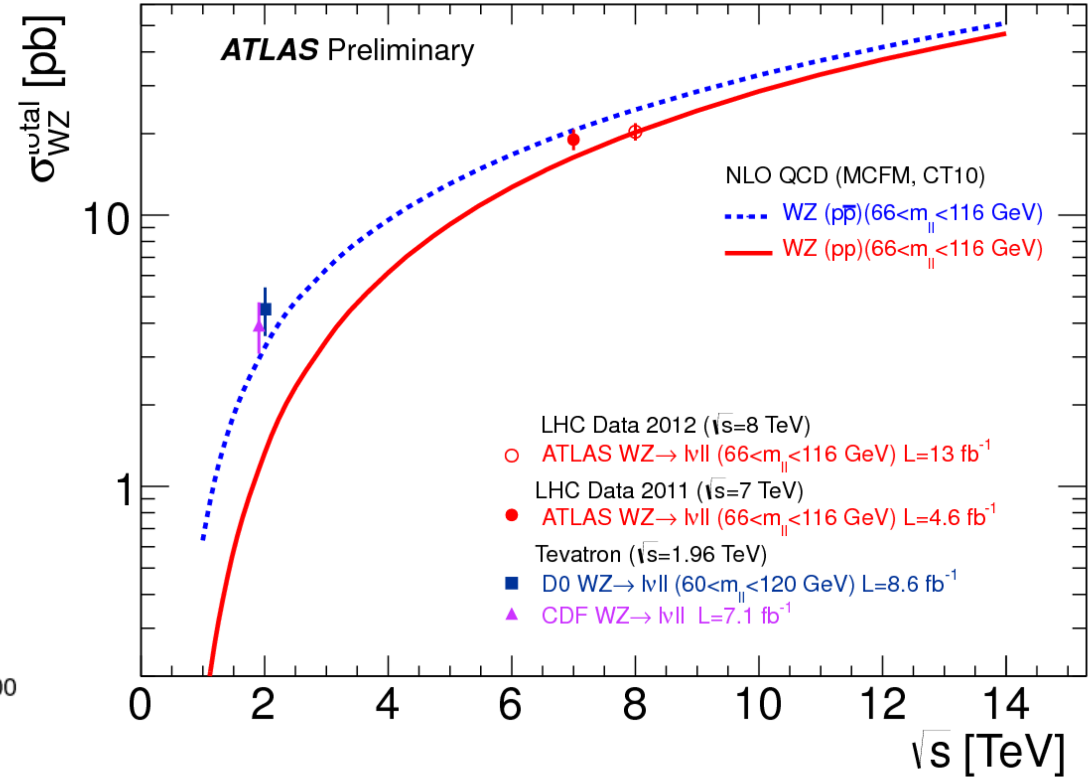
- **Z selection:** 2 oppositely charged leptons, p_T >15 GeV, $|m_{ll} - m_Z| < 10$ GeV
  (tighter w.r.t. other diboson analyses)
- **W selection:** 3rd lepton, $p_T > 20$ GeV, $M_{T,W} > 20$ GeV
- **Missing energy:** $E_T^{miss} > 25$ GeV

WZ→3lν cross-section results

- Results compatible with the Standard model predictions:

  - Unfolded distribution of WZ invariant mass:





Total cross-section:

Energy	Int. lumi.	Theory	Experiment
7 TeV	1.02 fb^{-1}	$\sigma_{NLO@7TeV} = 17.6\ ^{+1.1}_{-1.0}$ pb	$\sigma_{WZ\to3l\nu} = 21.1\ ^{+3.1}_{-2.8}$(stat.) ±1.2 (syst.) $^{+0.9}_{-0.8}$(lumi.) pb
7 TeV	4.6 fb^{-1}	$\sigma_{NLO@7TeV} = 17.6\ ^{+1.1}_{-1.0}$ pb	$\sigma_{WZ\to3l\nu} = 19.0\ ^{+1.4}_{-1.3}$(stat.) ±0.9 (syst.) ±0.4 (lumi.) pb
8 TeV	20.3 fb^{-1}	$\sigma_{NLO@8TeV} = 20.3 \pm 0.8$ pb	$\sigma_{WZ\to3l\nu} = 20.3\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.2}_{-1.1}$(syst.) $^{+0.7}_{-0.6}$(lumi.) pb

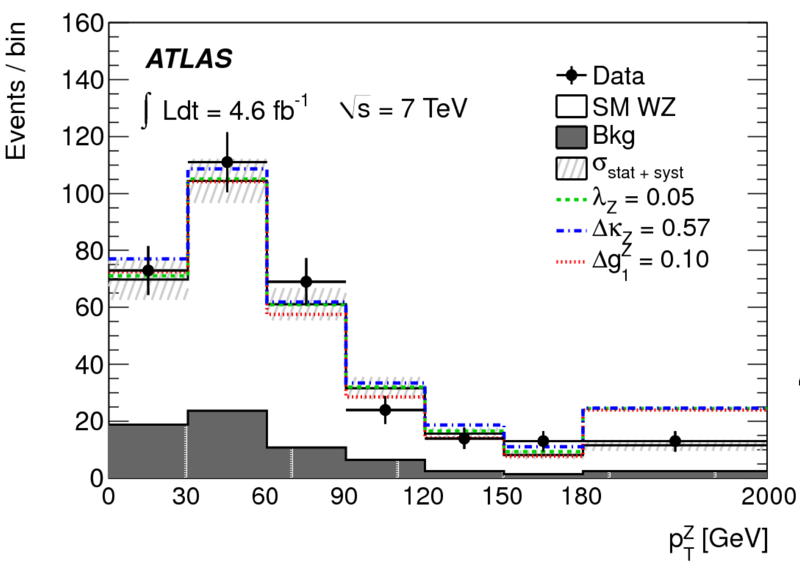
WZ→3lν aTGC results

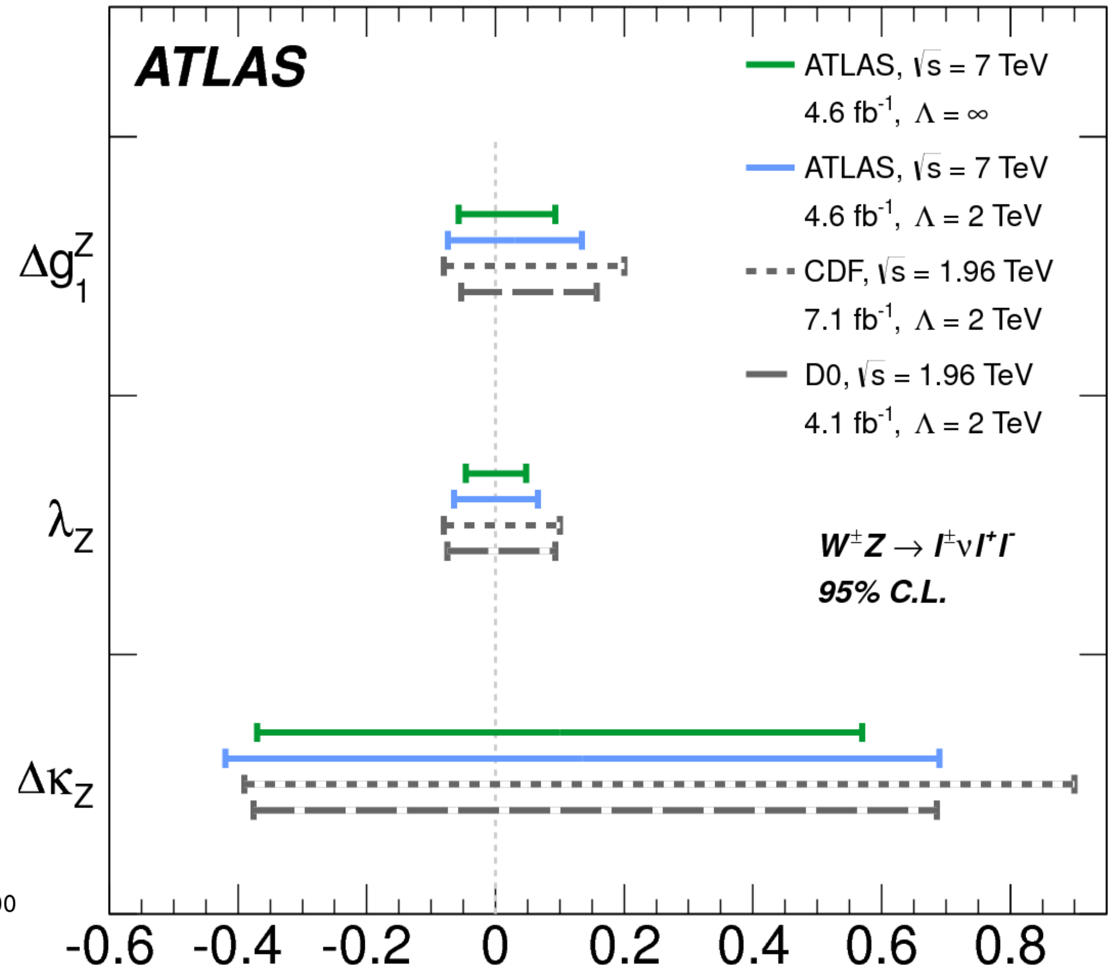
- Anomalous charged gauge boson couplings:
  - Probed using Z boson p_T spectrum
  - Sensitive at high p_T

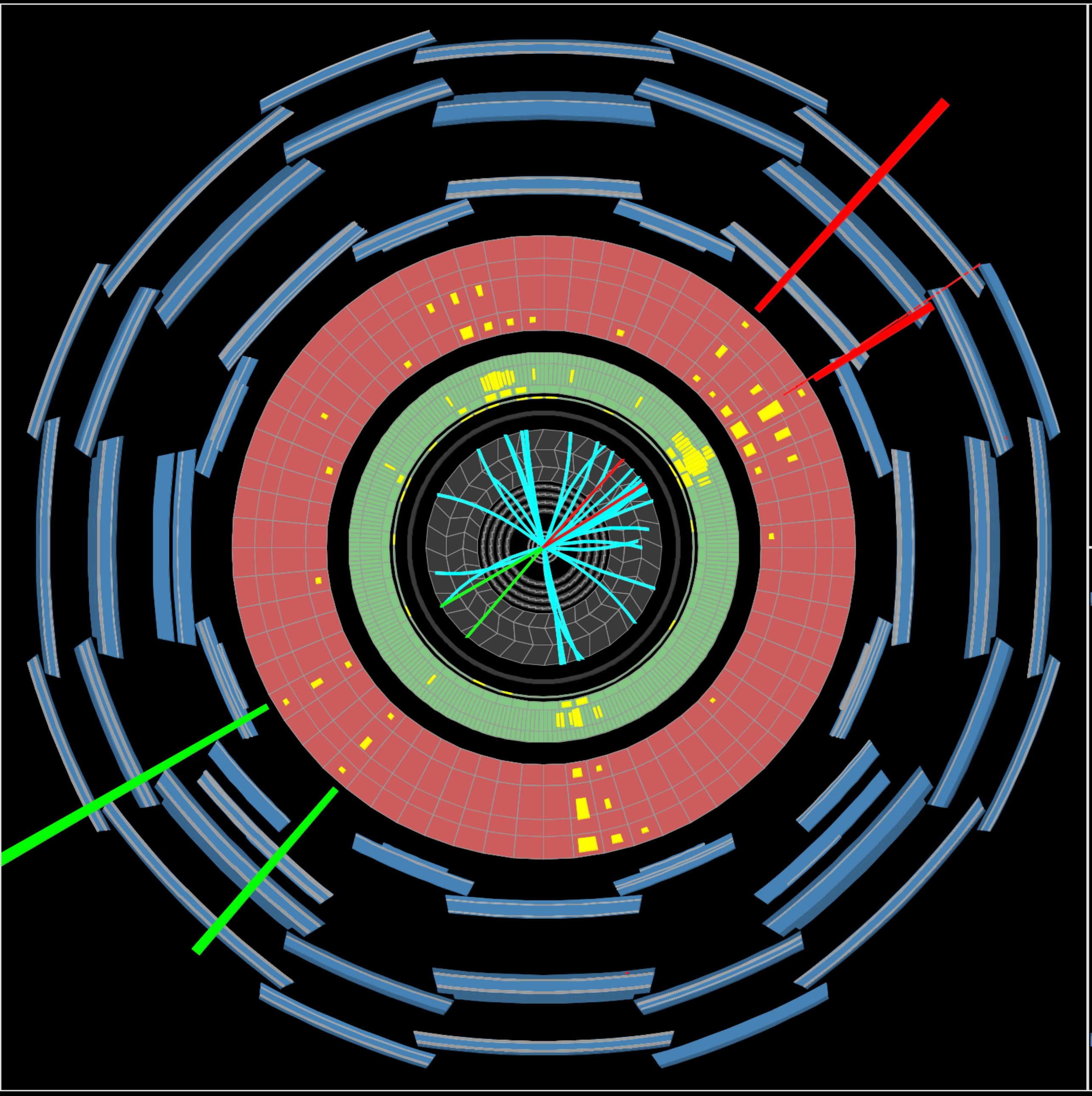
4.6 fb^{-1}, 7 TeV, paper arXiv:1208.1390

- 95% C.L. limits set for:

	Observed $\Lambda = 2$ TeV	Observed no form factor	Expected no form factor
Δg_1^Z	$[-0.074, 0.133]$	$[-0.057, 0.093]$	$[-0.046, 0.080]$
$\Delta\kappa_Z$	$[-0.42, 0.69]$	$[-0.37, 0.57]$	$[-0.33, 0.47]$
λ_Z	$[-0.064, 0.066]$	$[-0.046, 0.047]$	$[-0.041, 0.040]$







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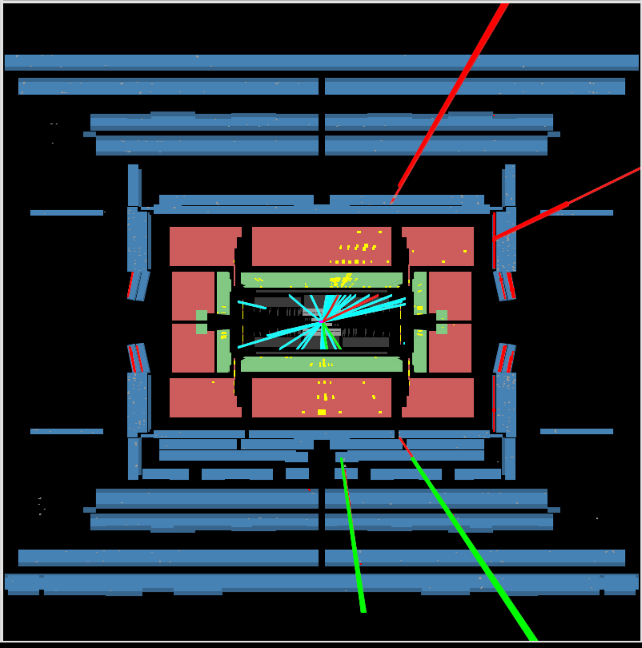


$ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$ **Candidate**

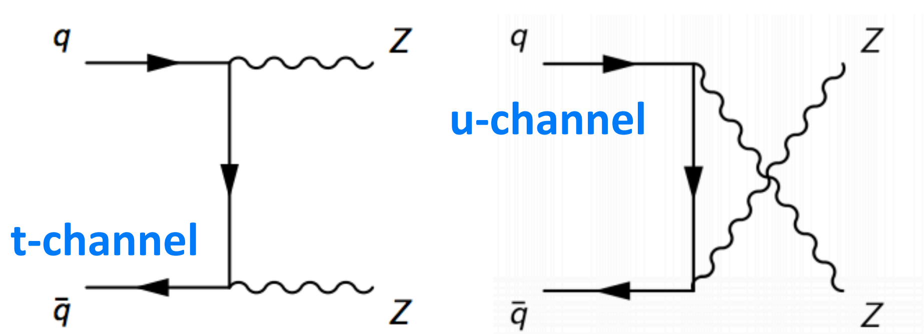
ZZ→4l and ZZ→2l2ν measurements

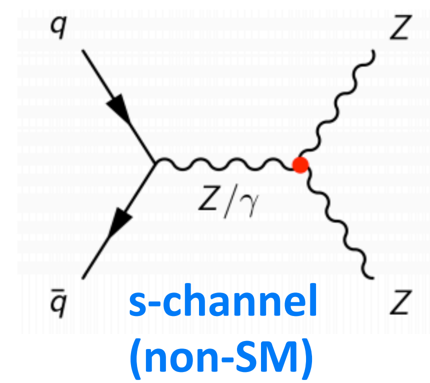
Analysis characteristics:

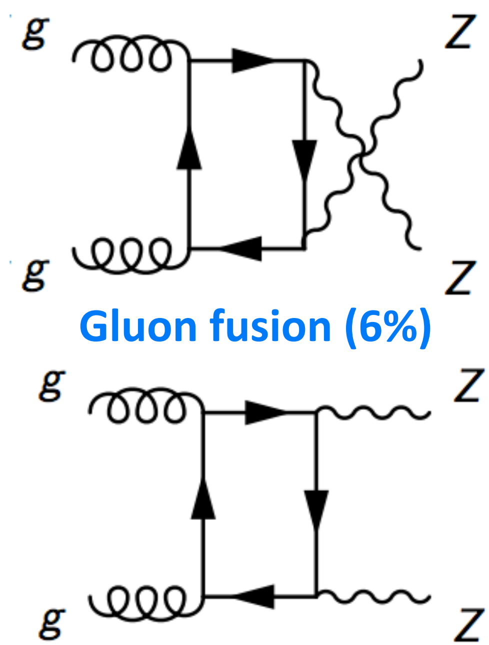
- 4l final states refer to: $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$
- 2l2ν final states refer to: $e^+e^-E_T^{miss}$ and $\mu^+\mu^-E_T^{miss}$
- 4l has very clean signature, backgrounds only significant for 2l2ν process
- Theoretical predictions: $\sigma_{NLO@7TeV} = 5.89^{+0.22}_{-0.18}$ pb $\quad \sigma_{NLO@8TeV} = 7.2^{+0.3}_{-0.2}$ pb

Latest publications:
4.6 fb^{-1}, 7 TeV, paper arXiv:1211.6096

20 fb^{-1}, 8 TeV, conf. note ATLAS-CONF-2013-020







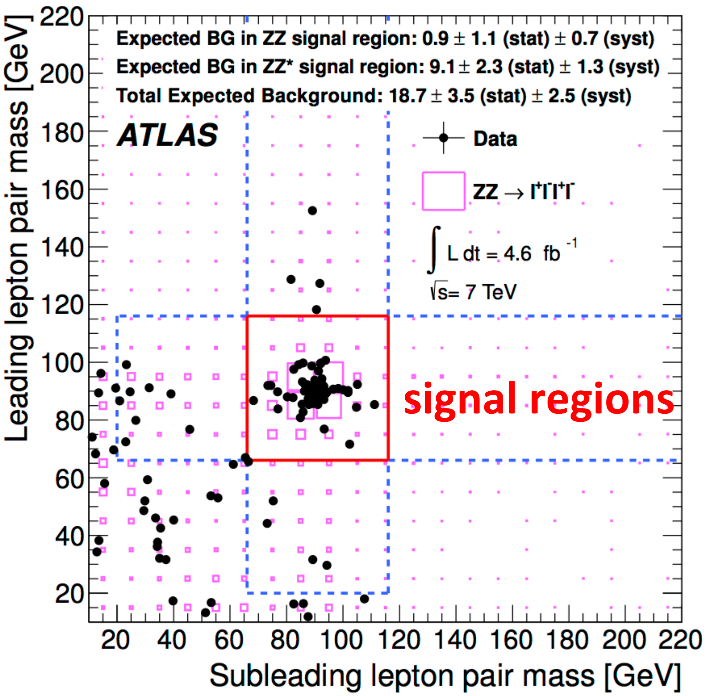
Signal selection:

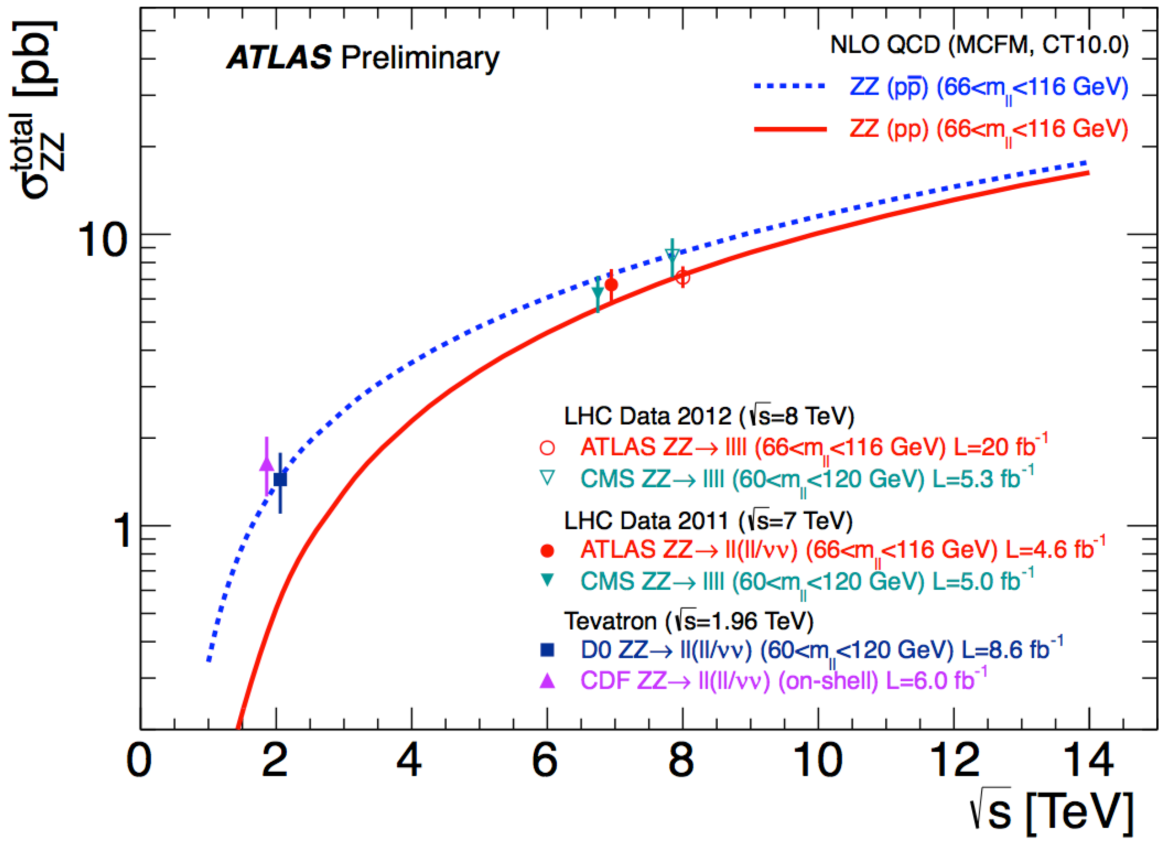
- ZZ → 4l: 4 isolated leptons, $p_T > 7$ GeV, opposite sign same flavour lepton pairs
- **Z mass window:** $66 < |m_{ll} - m_Z| < 116$ GeV

- ZZ→2l2ν: Apply **jet veto:** no jet with $p_T > 25$ GeV, $|\eta| < 4.5$ (ttbar)
- ZZ→2l2ν: Requires **axial-E_T^{miss} > 75 GeV** to suppress Drell-Yan background

ZZ→4l and ZZ→2l2ν cross-section results

- Results compatible with the Standard model predictions
  - For 20.3 fb^{-1} only Z→4l channel available





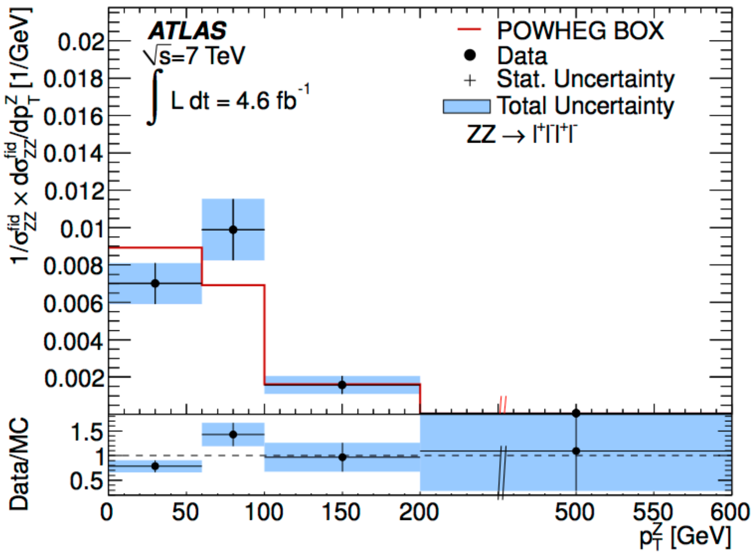
Total cross-section:

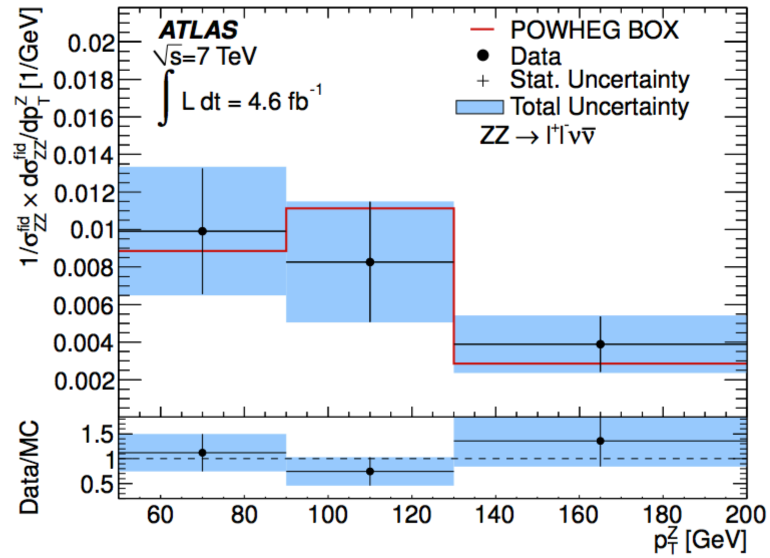
Energy	Int. lumi.	Theory	Experiment
7 TeV	4.6 fb^{-1}	$\sigma_{\mathrm{NLO@7TeV}} = 5.89^{+0.22}_{-0.18}$ pb	$\sigma_{ZZ\to ll(ll\nu\nu)} = 6.7 \pm 0.7\ (\mathrm{stat})\ ^{+0.4}_{-0.3} (\mathrm{syst})\ \pm 0.3\ (\mathrm{lumi})$ pb
8 TeV	20.3 fb^{-1}	$\sigma_{\mathrm{NLO@8TeV}} = 7.2^{+0.3}_{-0.2}$ pb	$\sigma_{ZZ\to llll} = 7.1\ ^{+0.5}_{-0.4}\ (\mathrm{stat})\ \pm 0.3\ (\mathrm{syst})\ \pm 0.2\ (\mathrm{lumi})$ pb

ZZ→4l and ZZ→2l2ν unfolded distributions

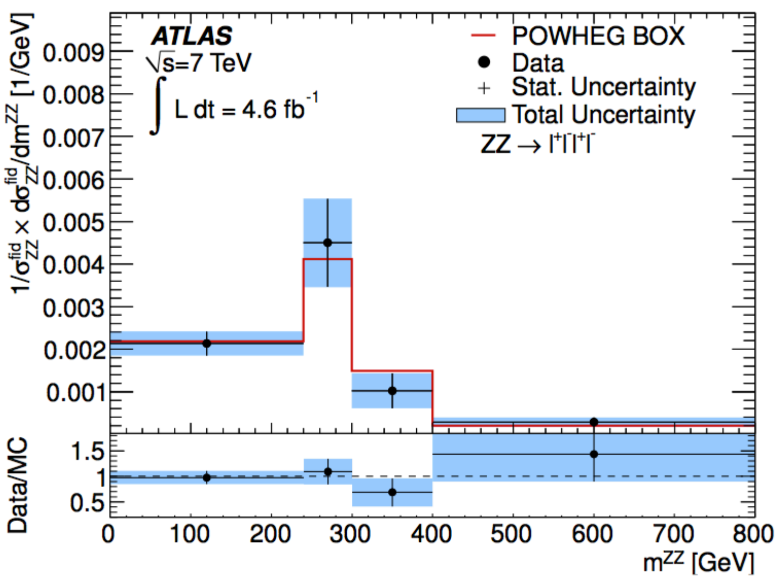
- Unfolded ZZ fiducial cross-sections bin-by-bin:

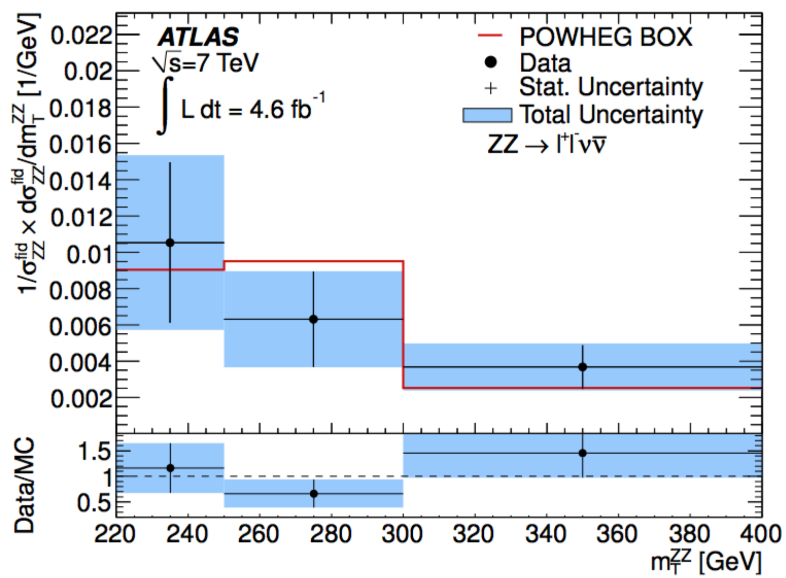
p_T^Z





m^{ZZ}



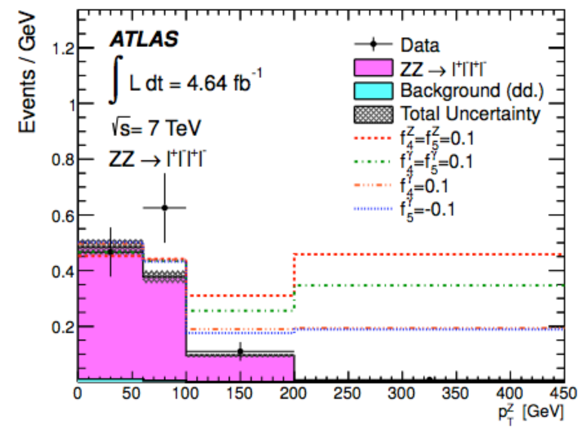


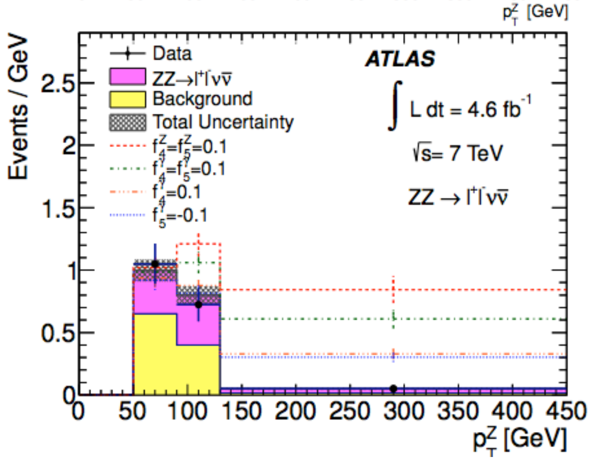
ZZ→4l and ZZ→2l2ν aTGC results

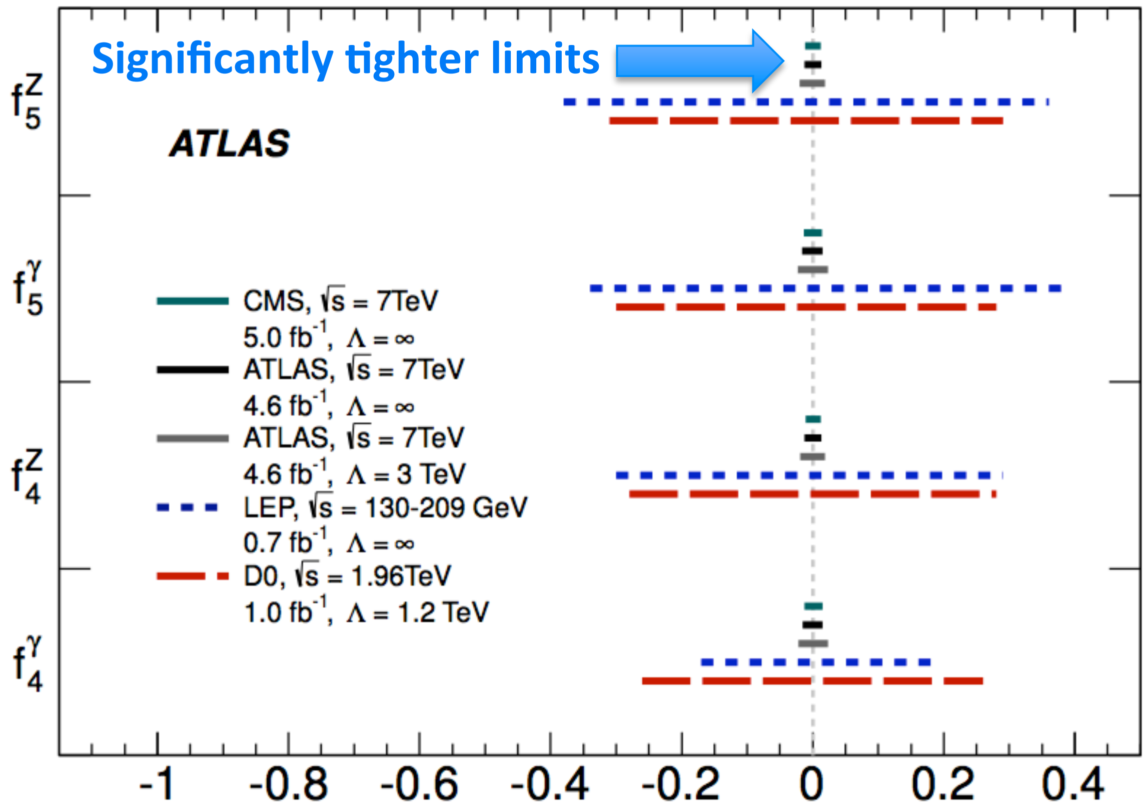
4.6 fb^{-1}, 7 TeV, paper arXiv:1211.6096

- Anomalous neutral gauge boson couplings:
  - Probed using Z boson p_T spectrum
  - Sensitive at high p_T
- 95% C.L. limits for:

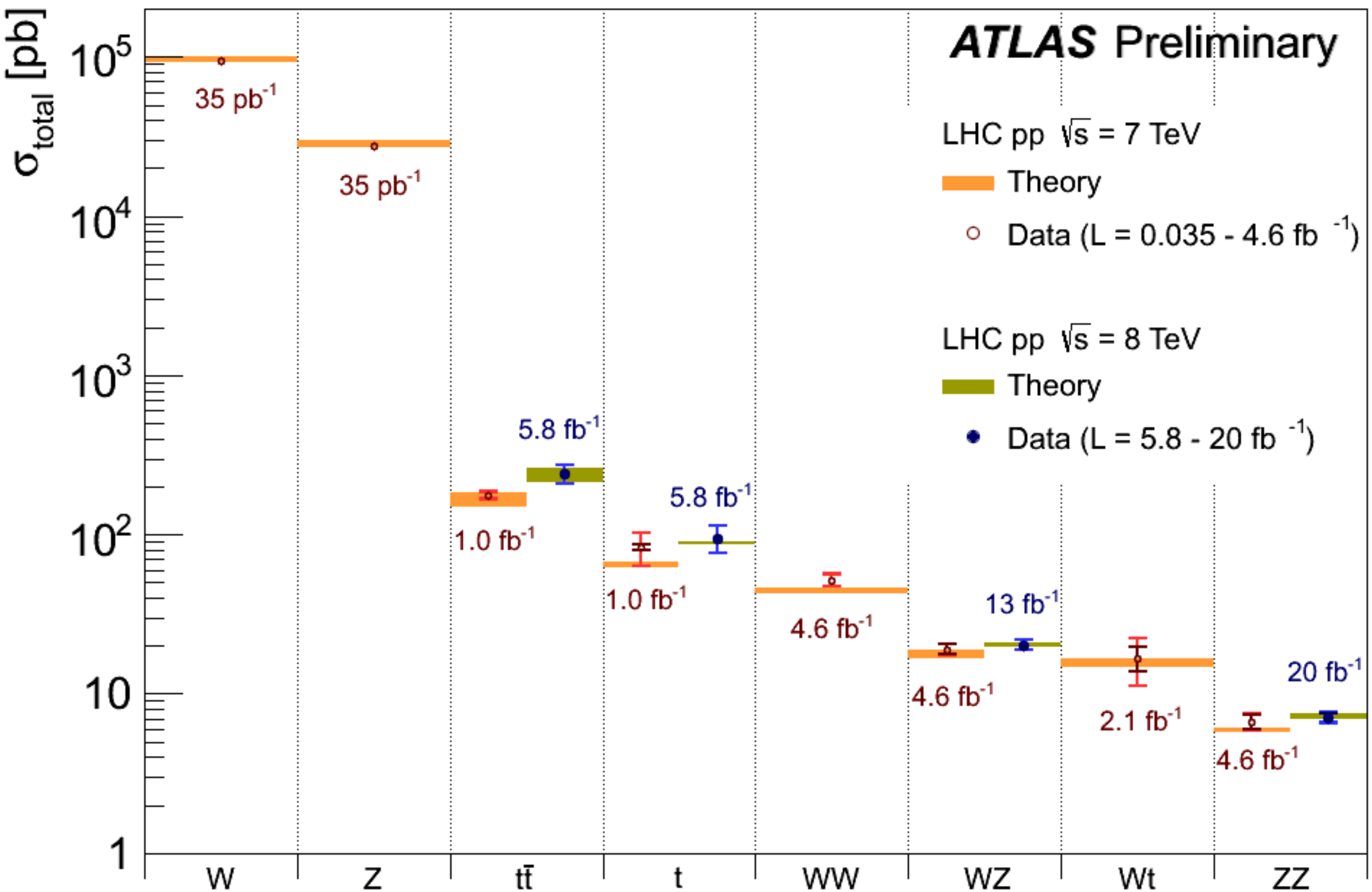
Λ	f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
3 TeV	$[-0.022, 0.023]$	$[-0.019, 0.019]$	$[-0.023, 0.023]$	$[-0.020, 0.019]$
∞	$[-0.015, 0.015]$	$[-0.013, 0.013]$	$[-0.016, 0.015]$	$[-0.013, 0.013]$







Standard Model production cross-sections



- Standard Model total production cross-sections corrected for leptonic branching fractions, compared to theoretical expectations

Conclusions

- Di-boson production cross-section and aTGC measurements have been presented:
  - Using 5 fb^{-1} at 7 TeV for WW.
  - Using 13 fb^{-1} at 8 TeV WZ.
  - Using 20 fb^{-1} at 8 TeV for ZZ.
- No apparent deviation from the Standard Model has been observed:
  - WZ/ZZ @ 7 TeV and ZZ @ 8 TeV results are dominated by statistical uncertainties.
  - The constraints on **charged anomalous TGCs** approach the precision of the combined limits from the four LEP experiments.
  - Limits for **neutral aTGCs** are significantly tighter than LEP and CDF/D0.
- More studies on the 8 TeV dataset in the works
- Thanks to the LHC for its excellent performance in 2012

References

Reference ID	Int. lumi.	Channel	Energy
ATLAS-CONF-2013-020	20.4 fb^{-1}	$ZZ \to llll$	8 TeV
ATLAS-CONF-2013-021	13 fb^{-1}	$WZ \to l\nu ll$	8 TeV
arXiv:1211.6096	4.6 fb^{-1}	$ZZ \to ll(ll/\nu\nu)$	7 TeV
arXiv:1210.2979	4.6 fb^{-1}	$WW \to l\nu l\nu$	7 TeV
arXiv:1208.1390	4.6 fb^{-1}	$WZ \to l\nu ll$	7 TeV
ATLAS-CONF-2011-099	1.02 fb^{-1}	$WZ \to l\nu ll$	7 TeV
arXiv:1203.6232	1.02 fb^{-1}	$WW \to l\nu l\nu$	7 TeV
ATLAS-CONF-2011-015	34 pb^{-1}	$WW \to l\nu l\nu$	7 TeV

Backup slides

2013-04-23

Anomalous couplings

- Anomalous Couplings enhance cross sections at high boson transverse momentum (p_T) or transverse mass (M_T).

Effective Langrangian for Charged TGC

$$\frac{L_{WWZ}}{g_{WWZ}} = i[g_1^Z(W^\dagger_{\mu\nu}W^\mu Z^\nu - W_{\mu\nu}W^{\dagger\mu}Z^\nu) + \kappa^Z W^\dagger_\mu W_\nu Z^{\mu\nu} + \frac{\lambda^Z}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu Z^{\nu\rho}]$$

- where values for SM Langrangian: $g_1^V = \kappa^V = 1$ and $\lambda^V = 0$
- deviations from SM: $\Delta g_1^Z \equiv g_1^Z - 1, \Delta\kappa_\gamma \equiv \kappa^\gamma - 1, \Delta\kappa_Z \equiv \kappa^Z - 1, \lambda^\gamma$ and λ^Z

Effective Langrangian for Neutral TGC

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_a(\partial^a Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

- Four complex, dimensionless couplings: $f_4^Z, f_5^Z, f_4^\gamma, f_5^\gamma$
- Couplings zero at tree level

Form Factor

- To avoid tree level unitarity violation at high centre-of-mass energy

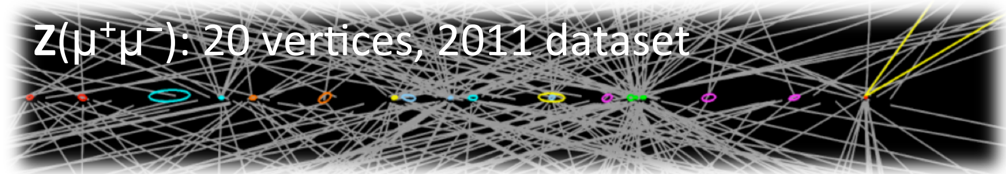
$$a(\hat{s}) = \frac{a_0}{(1+\hat{s}/\Lambda^2)^n}$$

- *Λ: energy (cut-off) scale at which physics BSM would be observed*
- *n: form factor power*

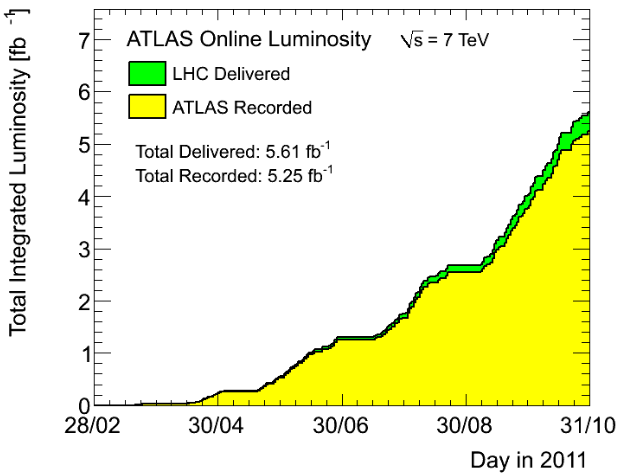
From LHCC Poster Session - CERN, 13 March 2013

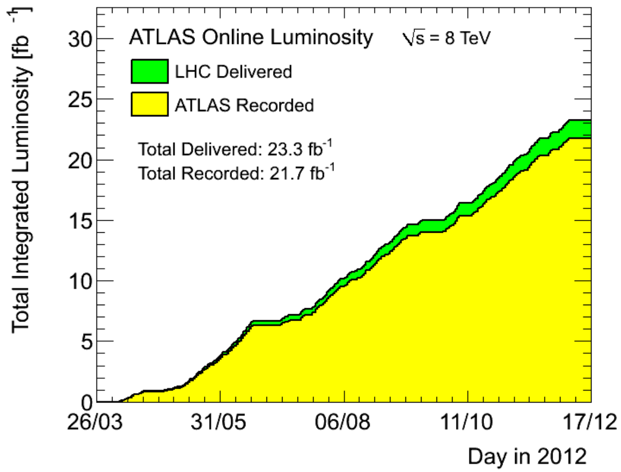
Data sets

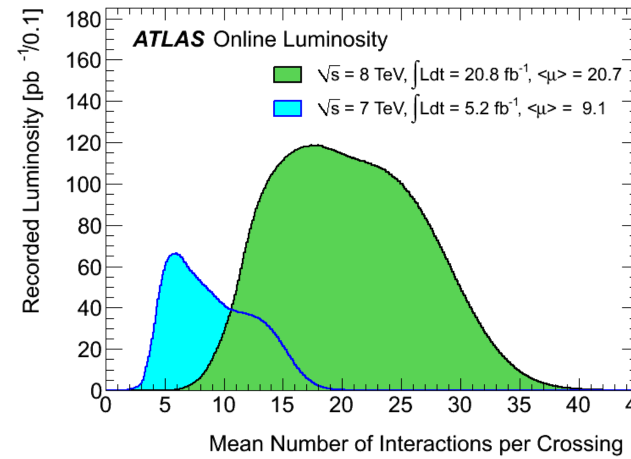
❖ 2011 dataset



- ❑ 5.61 fb^{-1} delivered by **LHC**
- ❑ 5.3 fb^{-1} recorded by **ATLAS**, ~4.6 fb^{-1} after DQ requirements







❖ 2012 dataset

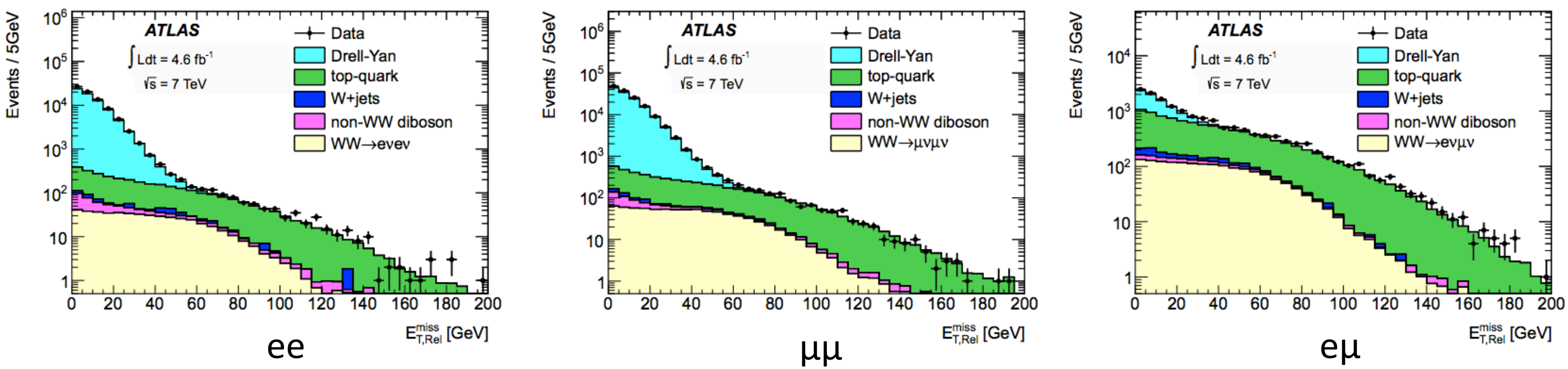
- ❑ 23.3 fb^{-1} delivered by **LHC**,
- ❑ 21.7 fb^{-1} recorded by **ATLAS**, ~20.3 fb^{-1} after DQ requirements
  - Higher number of proton-proton interactions per bunch crossing
  - Challenging to analyses with jets and E_T^{miss} final states in particular

Modified missing E_T in WW→2l2ν selection

- Method to reduce the Z+jets background:
  - Designed to reject events where the apparent E_T^{miss} arises from mis-measurement or pileup (i.e. points in the direction of a lepton/jet)
  - The cut is less strict in eμ channel because the Drell-Yan background is inherently smaller
  - Effectively removes Drell-Yan contributions

$$E_{\mathrm{T,\,Rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \times \sin\left(\Delta\phi_{\ell,j}\right) & \text{if } \Delta\phi_{\ell,j} < \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \end{cases}$$

(azimuthal angle)



Modified missing E_T in $ZZ \to 2l2\nu$ selection

- Method to reduce the Z+jets background:
  - Z bosons tend to be produced back-to-back
  - Axial E_T^{miss} is defined as the projection of the E_T^{miss} along the direction opposite to the $Z \to 2l$ candidate in the transverse plane:

$$\text{axial-}E_T^{miss} = \frac{-\mathbf{E}^{miss} \cdot \mathbf{p}^{Z}}{p_T^{Z}}$$

  - Powerful variable to distinguish $ZZ \to 2l2\nu$ decays from Z+jets.