ATLAS and CMS results in WW, WZ, ZZ

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on behalf of the ATLAS and CMS collaborations

Working Group on Electroweak precision measurements at the LHC

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ATLAS and CMS public results:

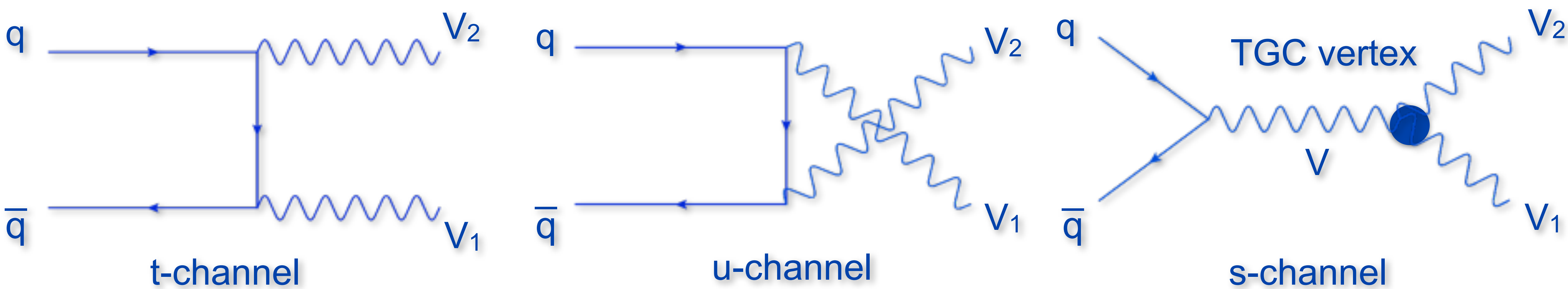
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

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

Outline

- Introduction and physics motivation
- Dibosons Analyses Overview
  - WZ $\longrightarrow \ell\nu\ \ell\ell$
  - WW $\longrightarrow \ell\nu\ \ell\nu$
  - ZZ $\longrightarrow \ell\ell\ \ell'\ell'$
- anomalous TGC measurements
- Conclusions and plans

Introduction and physics motivation



- Di-Boson production cross-sections and couplings at the triple gauge-boson vertices are precisely predicted by SM
  - WWγ and WWZ vertices are predicted and have been measured
  - ZZγ, Zγγ, γγγ and ZZZ vertices are forbidden (previous talk)
  - Provide direct test of SM predictions
- The presence of new physics :
  - anomalous Triple Gauge Couplings (aTGC) and exotics resonances.
  - Modify cross-sections and kinematic distributions
- Di-Bosons are also irreducible background to the Higgs boson measurements.

Introduction

- Today's menu Dibosons measurements performed with :

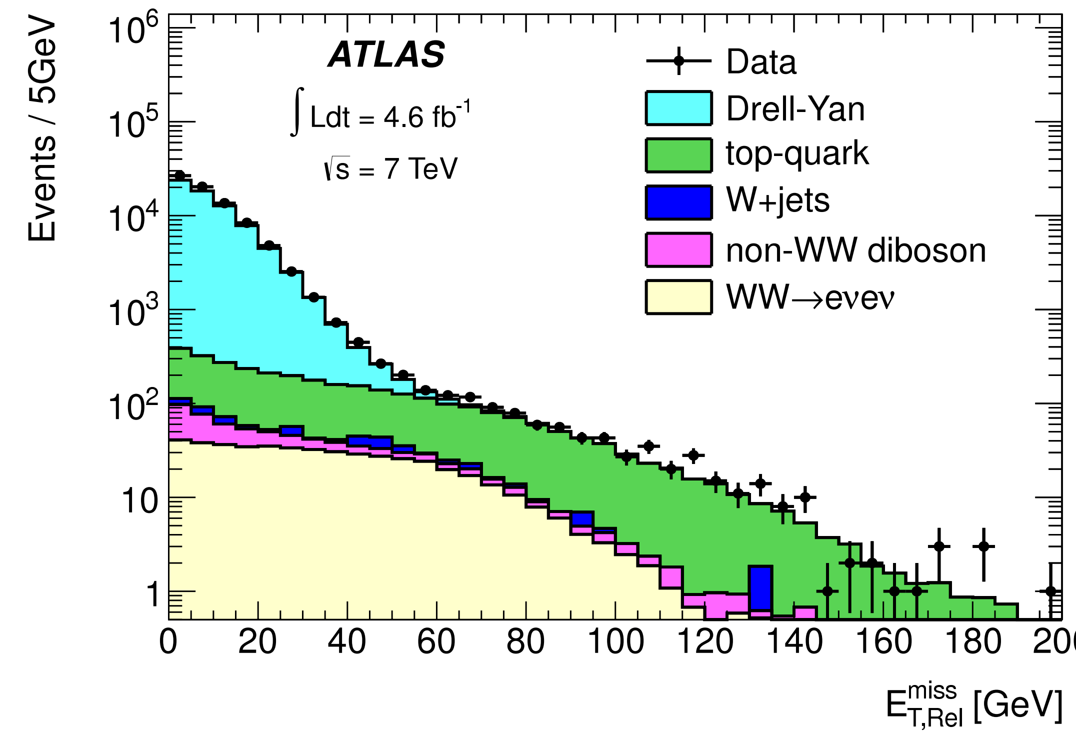
Channel	Atlas	CMS
$WZ \rightarrow \ell\nu\ \ell\ell$	4.6 fb^{-1} at 7 TeV * 13.0 fb^{-1} at 8 TeV	1.1 fb^{-1} at 7 TeV
$WW \rightarrow \ell\nu\ \ell\nu$	4.7 fb^{-1} at 7 TeV *	4.9 fb^{-1} at 7 TeV * 3.5 fb^{-1} at 8 TeV
$ZZ \rightarrow \ell\ell\ \ell'\ell'$	4.7 fb^{-1} at 7 TeV * 20.0 fb^{-1} at 8 TeV	4.9 fb^{-1} at 7 TeV * 5.3 fb^{-1} at 8 TeV

* aTGC limits

- ATLAS and CMS have also performed dibosons measurements with semi-leptonic decays.
- Fully leptonic decay channels allow
  - clean signal, small branching ratio
  - low background
- Common signature :
  - high p_T leptons,
  - missing energy (E_T^{miss}) when ν is present.

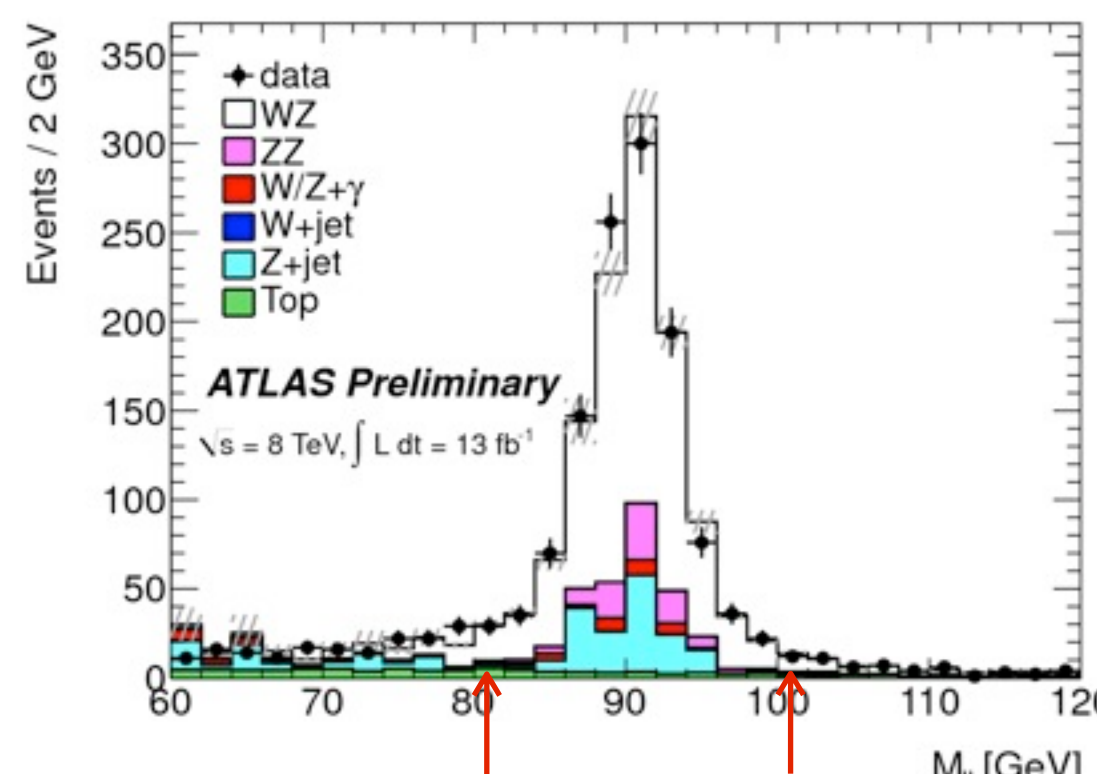
Common signatures and selections:

- **Leptons** (electrons, muons, taus*) :
  - Single or double lepton trigger.
  - High-p_T leptons in the detector geometrical acceptance
  - Calorimeter and track isolation used.



- When a $W \longrightarrow \ell\nu$ is involved :
  - Large E_T^{miss} cuts to account for the neutrino

- When a $Z \longrightarrow \ell\ell$ is involved :
  - Invariant mass close to the Z PDG mass
  - Z mass window



* for some CMS analysis

Common Backgrounds

- Dibosons processes make background to each other $\longrightarrow$ estimated mainly from MC (Powheg, Pythia, Sherpa, MC@NLO)
- Top (single top and $\bar{t}t$) or *W/Z*+jets mimics diboson final states:
  - Real leptons from *Z* or *W* decays
  - Lepton(s) from heavy flavor decays
  - Jet mis-identified as an electron or a photon
- Use data driven methods, since fragmentation functions are difficult to model.

- Different methods (ABCD, Fake factor, Sideband fit, μeμ Control region, matrix method) and Control Region definitions depend on the analysis.

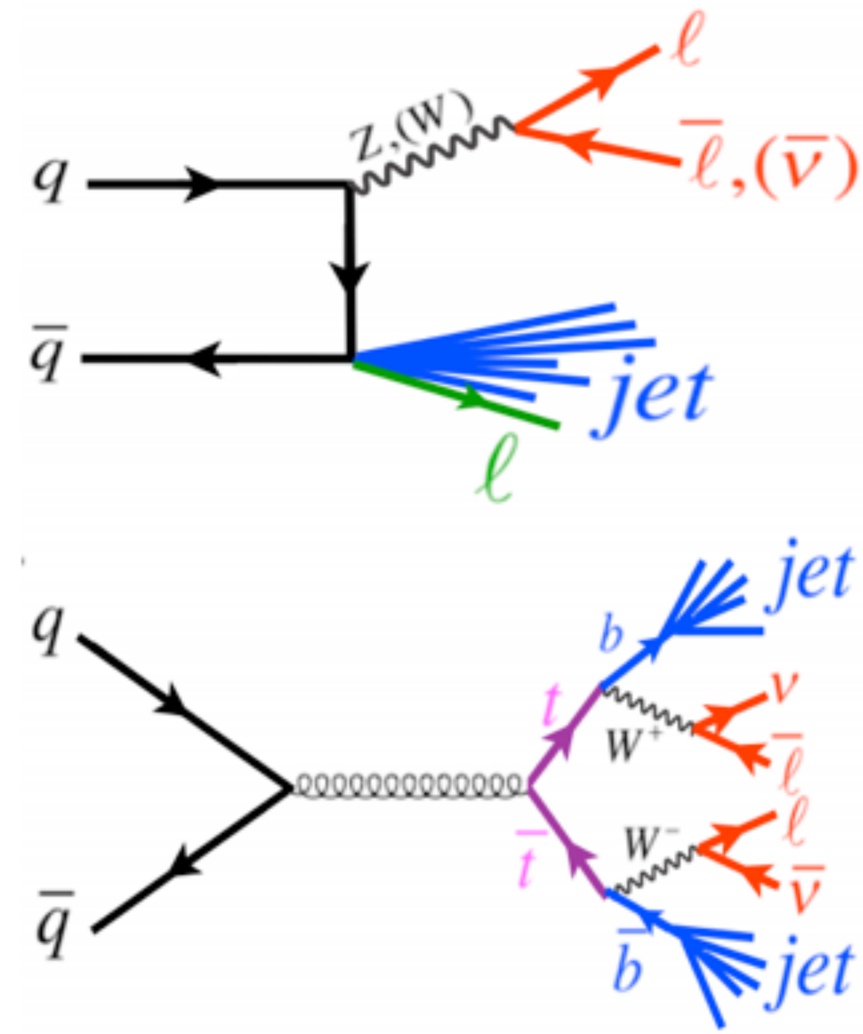


Figure : Feynman diagrams for Z/W+jets (top) and $\bar{t}t$ (bottom) decays

Cross Section

N_{data} = Number of data events
N_{bg} = Number of background events either from MC or data driven methods
L = Luminosity
BR = Branching Ratio

$$C = \frac{N^{\text{MC Reconstructd}}_{\text{evts passing the cuts}}}{N^{\text{MC Fidutial volume}}_{\text{evts generated}}}$$

- Measure a cross section within the fiducial region.

$$\sigma^{fid} = \frac{N_{\text{data}} - N_{\text{bg}}}{C \cdot \int L dt}$$

efficiency corrections

  - The fiducial volume is defined by the limited coverage of our detector (η cut) and is even more reduced when we apply our selection cuts (leptons p_T, dR(l,l)).
  - ATLAS and CMS uses different Z mass widows for the acceptance, WZ and ZZ analyses :
    - ATLAS 66 < m_{ll} <116 GeV and CMS 60 < m_{ll} < 120 GeV
  - ATLAS use "dressed" leptons for truth object selection, this means that final state leptons, includes all photons within ΔR < 0.1.

- Then we extrapolate to the full phase space so we have a total cross section

$$\sigma^{tot} = \frac{N_{\text{data}} - N_{\text{bg}}}{A \cdot C \cdot \int L dt \cdot BR}$$

acceptance

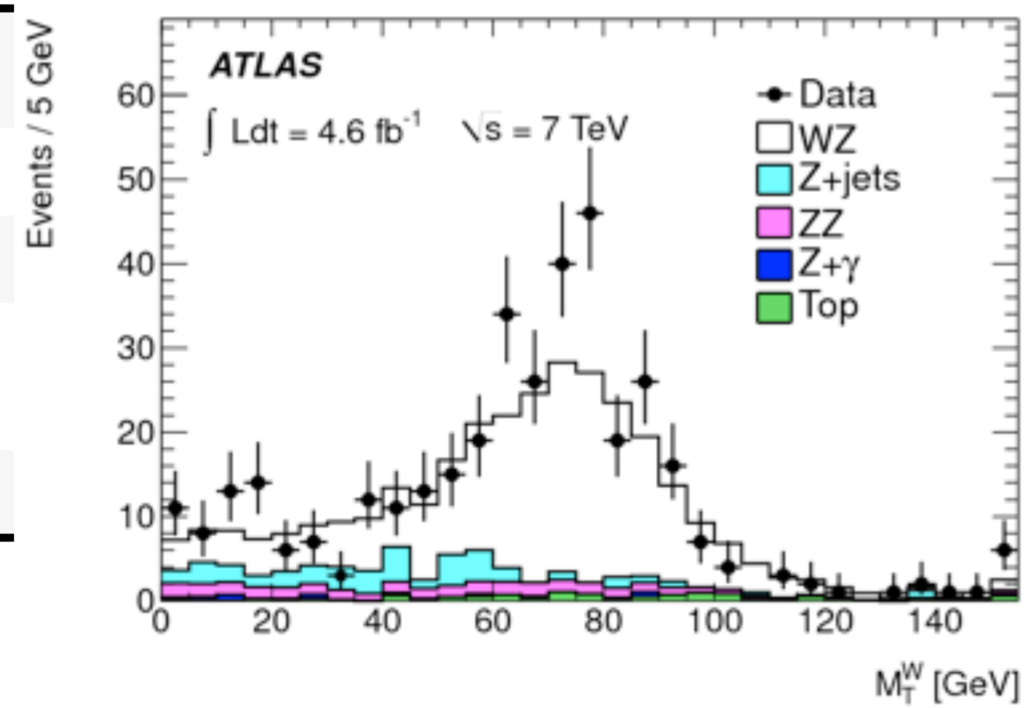
$$A = \frac{N^{\text{MC Fidutial Volume}}_{\text{evts generated}}}{N^{\text{MC All}}_{\text{evts generated}}}$$

- ATLAS provide unfolded distributions:
  - leading lepton p_T in WW,
  - m^{ZZ}, leading Z p_T and Δϕ(l,l) in $ZZ \rightarrow \ell\ell\ \ell\ell$,
  - Z p_T and m_{WZ} in WZ.

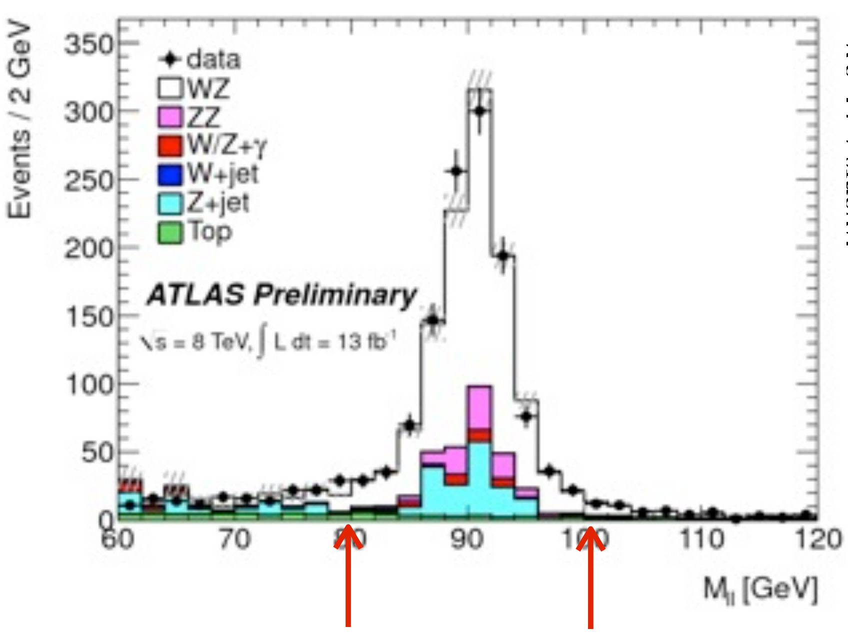
$WZ \to \ell\nu\ \ell\ell$

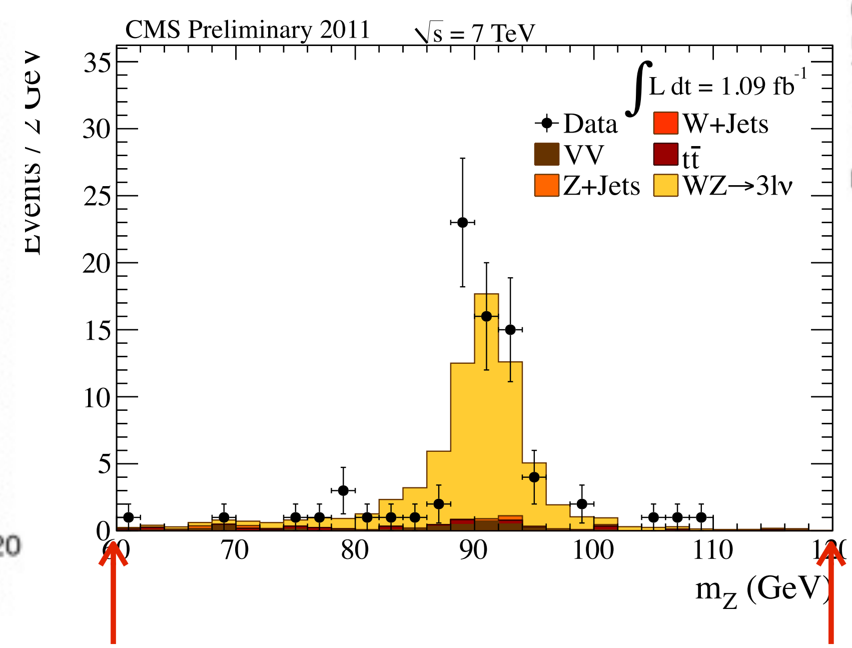
- Selection :

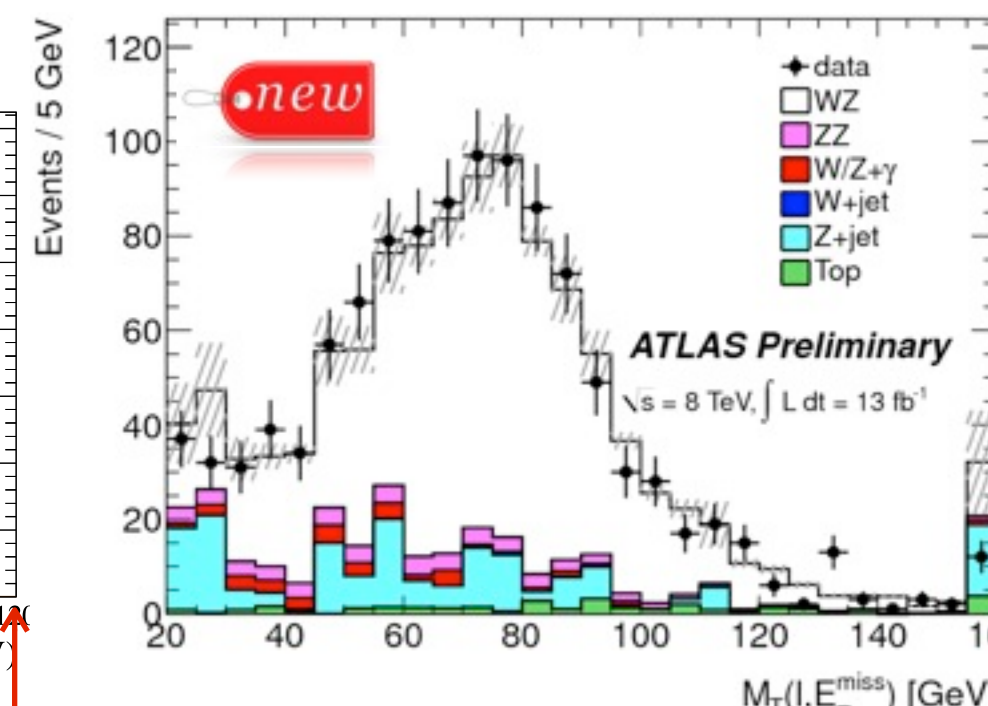
	ATLAS	CMS
3 lepton p_T	$p_T > 15$ GeV	$p_T^{leading} > 20$ GeV $p_T^{subleading} > 15$ GeV
Z mass window	$\lvert m_{ll} - m_Z \rvert < 10$ GeV	$60 < m_{ll} < 120$ GeV
ZZ veto	$N_{leptons} > 3$	if 2 Z can be reconstructed
Tight W lepton, pT > 20, ID and isolation	✔	✔
large E_T^{miss}	$E_T^{miss} > 25$GeV	$E_T^{miss} > 30$GeV



- Major backgrounds :
  - Z+jets, ZZ, W/Z γ, Top.



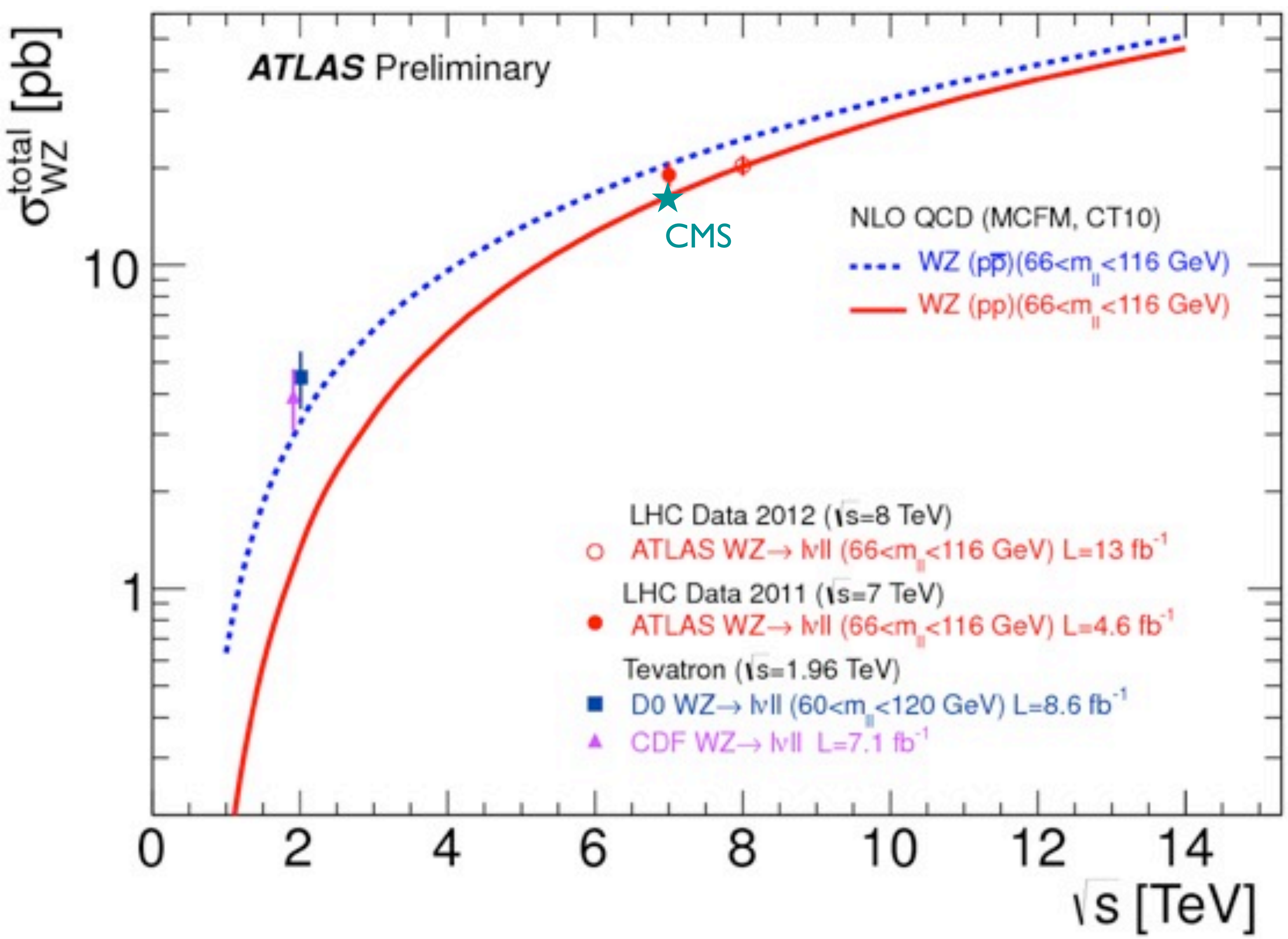




ATLAS 8 TeV : ATLAS-CONF-2013-021
ATLAS 7 TeV : arXiv:1208.1390
CMS 7 TeV : CMS PAS EWK-11-010

WZ $\longrightarrow \ell\nu\ell\ell$ results

- The results are compatible with the SM expectations.
- MCFM NLO+CT10 prediction excellent agreement
- Systematic uncertainties became dominant on the ATLAS 8 TeV analysis. The dominant one is from the data driven background estimation 5%.
- For CMS statistical uncertainties are dominant. The dominant systematics are bkg estimation up to 5.5%, electron ID and isolation up to 3.2%

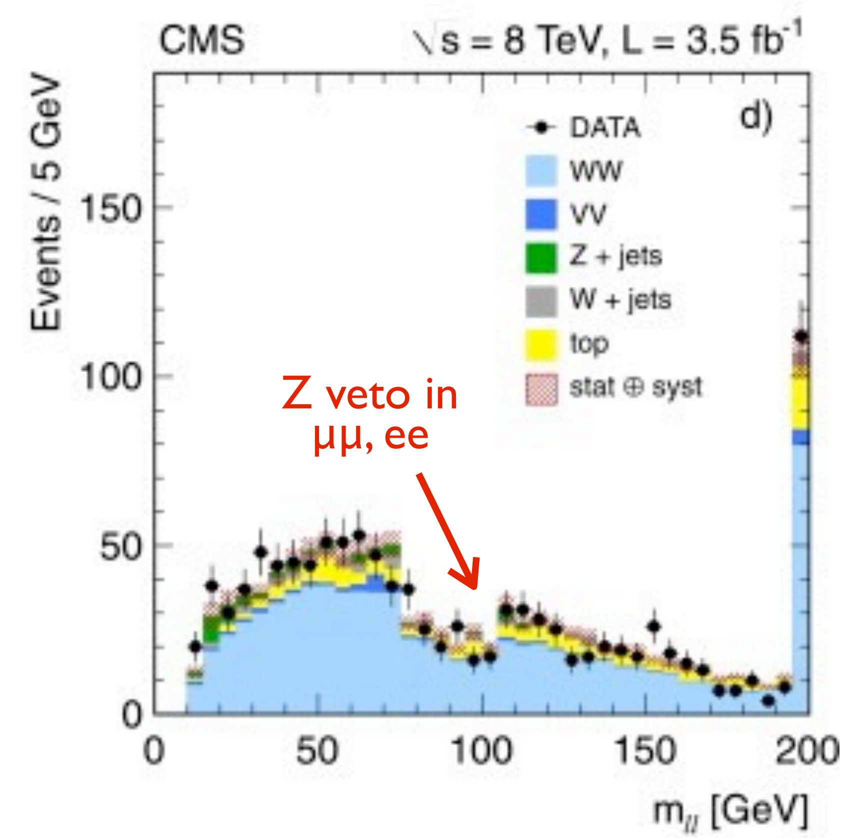


	$\sqrt{s}$	lumi	Measured σ_{total} [pb]	MCFM NLO [pb]	Z mass window in fidutial space
ATLAS	7 TeV	4.6 fb^{-1}	19.0 ± 1.4 (stat) ± 0.8 (sys) ± 0.4 (lumi)	$17.6^{+1.1}_{-1.0}$	81.2 < m_{ll} < 101.2 GeV
CMS	7 TeV	1.1 fb^{-1}	17.0 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lumi)	17.5 ± 0.6	60 < m_{ll} < 120 GeV
ATLAS	8 TeV	13.0 fb^{-1}	20.3 ± 0.7 (stat) ± 1.1 (sys) ± 0.6 (lumi)	20.3 ± 0.8	81.2 < m_{ll} < 101.2 GeV

WW → ℓν ℓν

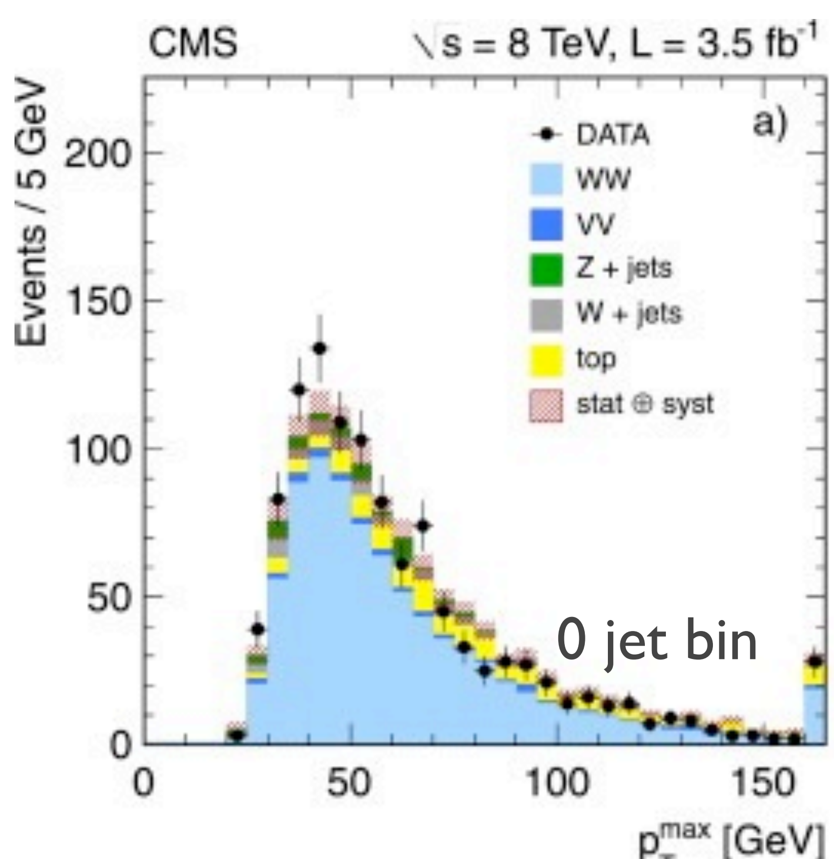
- Selection :

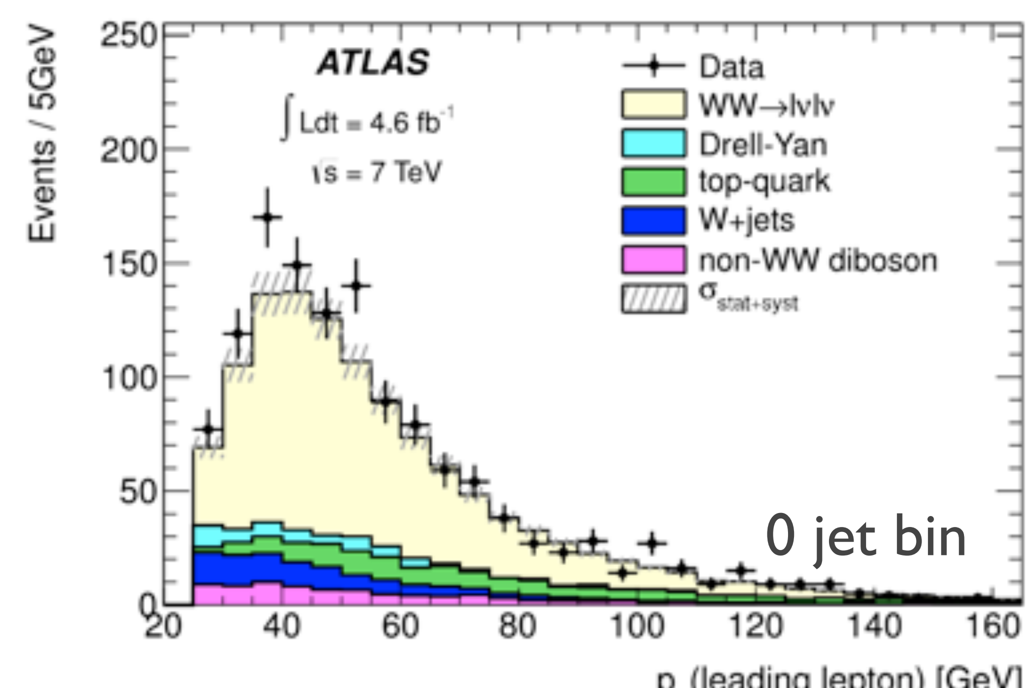
	ATLAS	CMS
ℓ definition	ℓ = e,μ	ℓ = e,μ,τ for τ leptonic decays
2 Leptons p_T	p_T > 20 GeV	p_T > 20 GeV
Z veto	$\|m_{ll} - m_Z\|$ > 15 GeV (ee, μμ) m_{ll} > 15,15,10 GeV (ee, μμ,eμ)	$\|m_{ll} - m_Z\|$ > 15 GeV (ee, μμ) m_{ll} > 12 GeV
Jet veto	veto events jets p_T>25 GeV	veto events jets p_T>30 GeV veto events top-quark-tagged
large E_T^{miss}	$E_T^{miss}{}_{Rel}$ > 45 GeV (ee, μμ) $E_T^{miss}{}_{Rel}$ > 25 GeV (eμ)	$E_T^{miss}{}_{Rel}$ > 45 GeV (ee, μμ) $E_T^{miss}{}_{Rel}$ > 20 GeV (eμ)
di-leptons p_T	p_T^{ll}>30 GeV	p_T^{ll}>45 GeV



Major backgrounds :

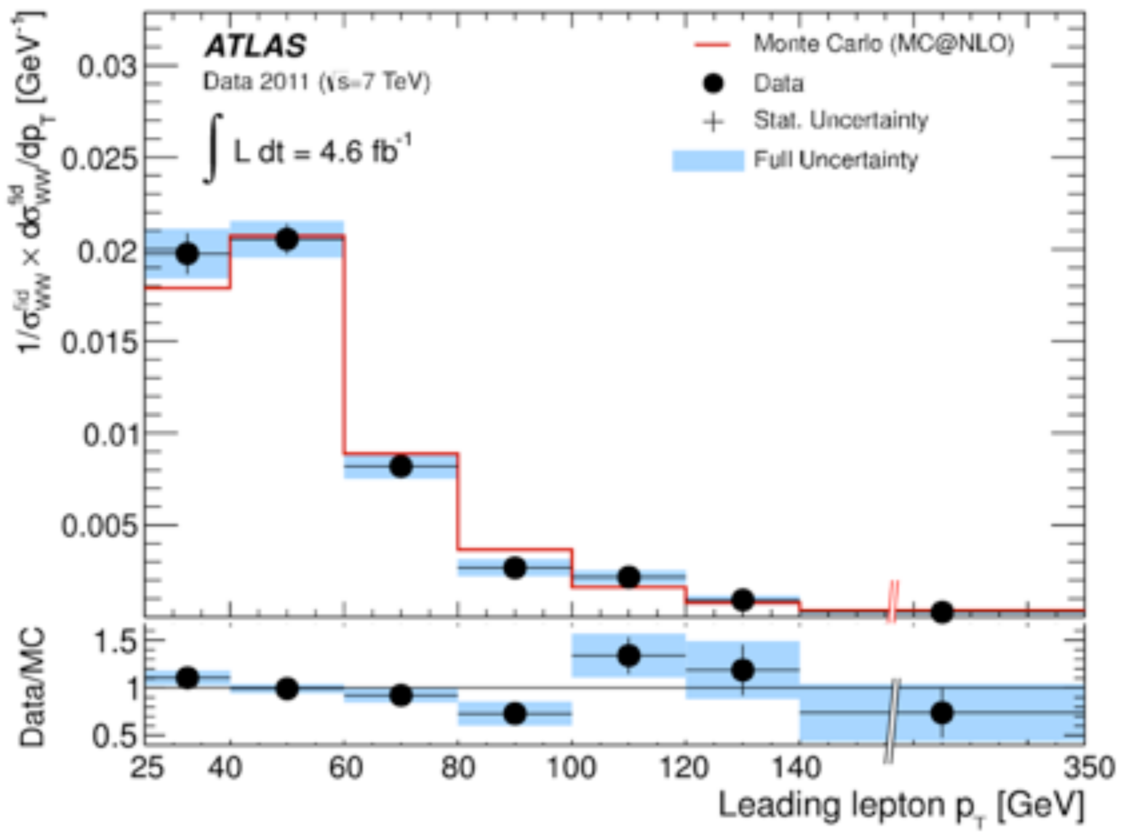
- Drell-Yan, W+jets, Top.





$WW \longrightarrow \ell\nu\ \ell\nu$ results

ATLAS 7 TeV : [arXiv:1104.5225]
CMS 7 TeV : CERN-PH-EP-2012-336
CMS 8 TeV : CERN-PH-EP-2012-376



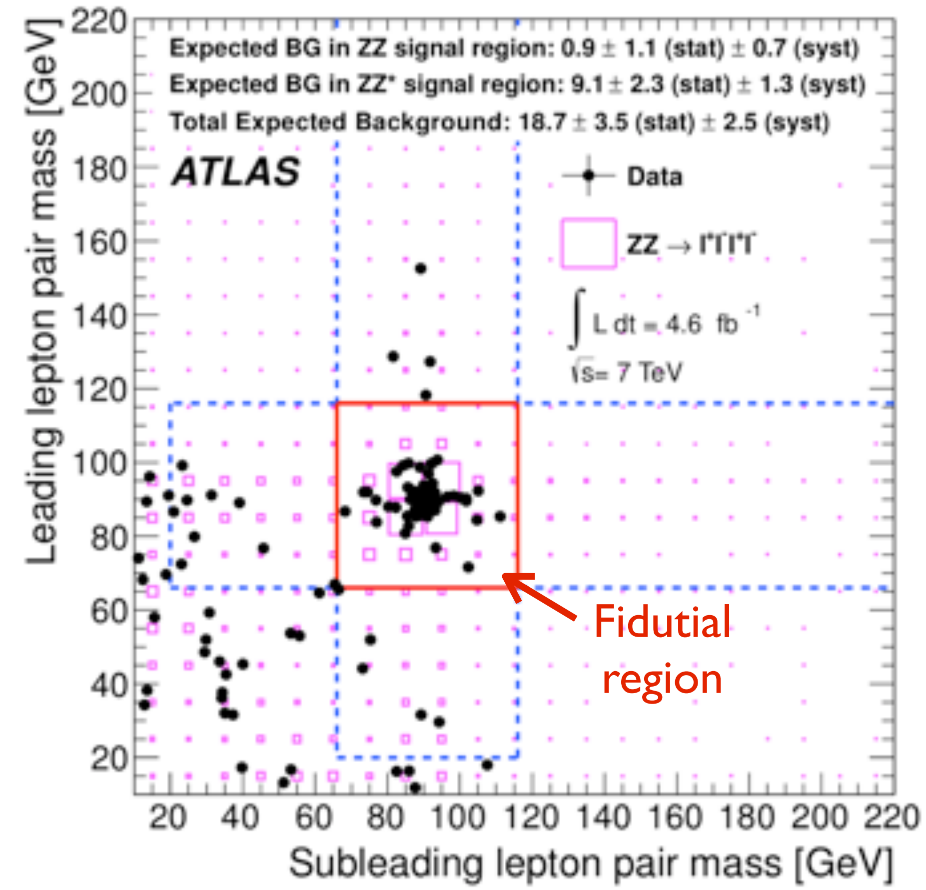
	$\sqrt{s}$	lumi	Measured σ_{total} [pb]	MCFM NLO [pb]
ATLAS	7 TeV	4.7 fb^{-1}	51.9 ± 2.0 (stat) ± 3.9 (sys) ± 2.0 (lumi)	$44.7^{+2.1}_{-1.9}$
CMS	7 TeV	4.9 fb^{-1}	52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lumi)	47.0 ± 2.0
	8 TeV	3.5 fb^{-1}	69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lumi)	$57.3^{+2.4}_{-1.6}$

- ☐ Measurement slightly higher than theoretical prediction.
- ☐ Higgs contribution of the order of 3% (not subtracted in the unfolded distribution)
- ☐ Dominant systematics uncertainty jet veto ~4% (for both ATLAS and CMS).

ZZ $\rightarrow \ell\ell\ \ell'\ell'$

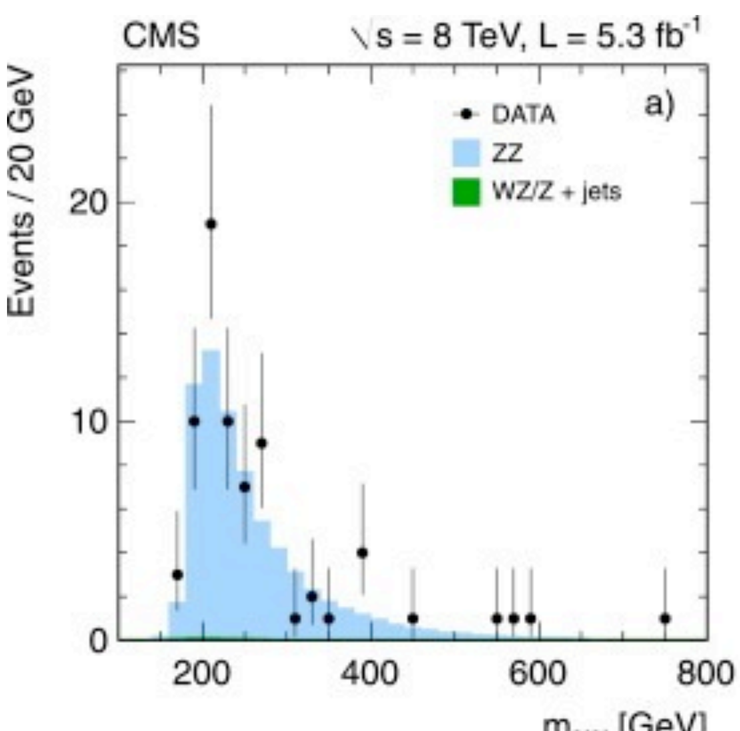
- Selection :

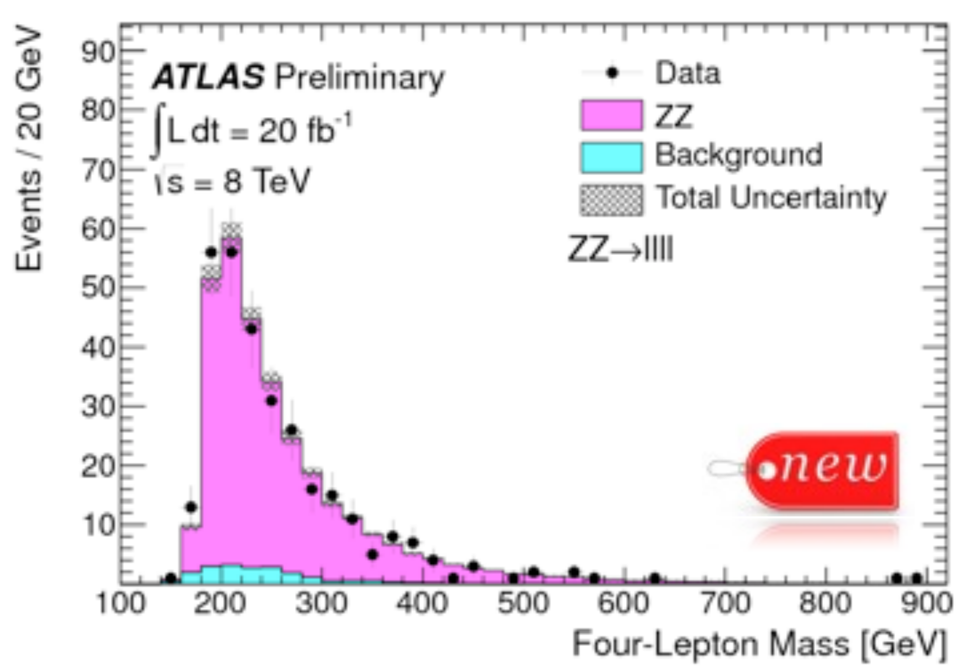
	ATLAS	CMS
ℓ, ℓ' definition	ℓ = e,μ ℓ' = e,μ,ν	ℓ = e,μ,τ all τ decays τ_e, τ_μ, τ_h ℓ' = e,μ
4 isolated leptons	p_T > 7 GeV	p_T > 7 (5) GeV for e (μ) p_T > 20 (10) GeV for τ_h ($\tau_{e,\mu}$)
➔ Z mass window	66< m_{ll} <116GeV	60 < $m_{l'l'}$ < 120 GeV 30 < $m_{\tau\tau}$ < 90 GeV

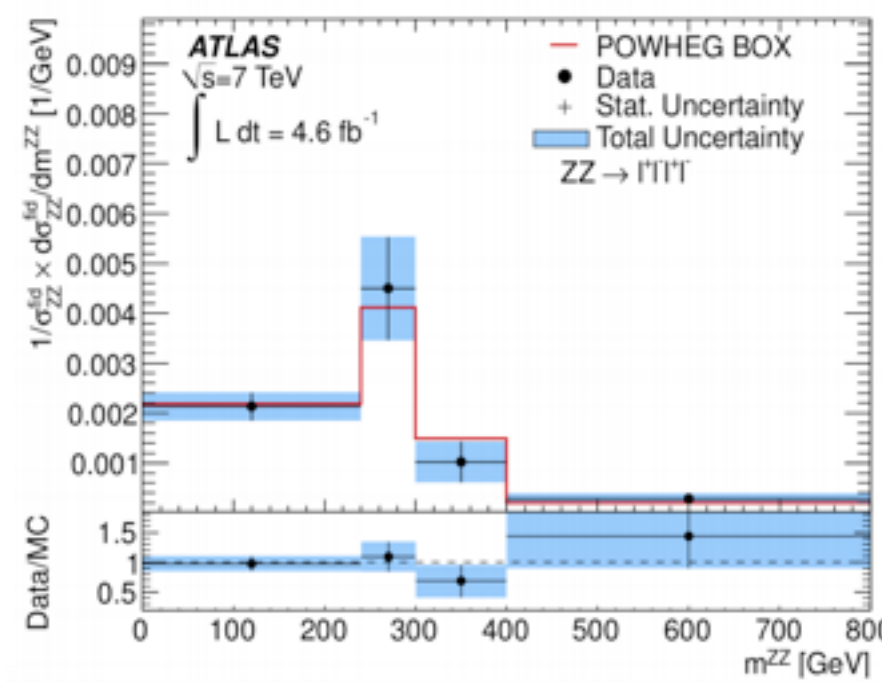


Major backgrounds :

- Very clean signature backgrounds from W/Z+jets, Top, WW, WZ.



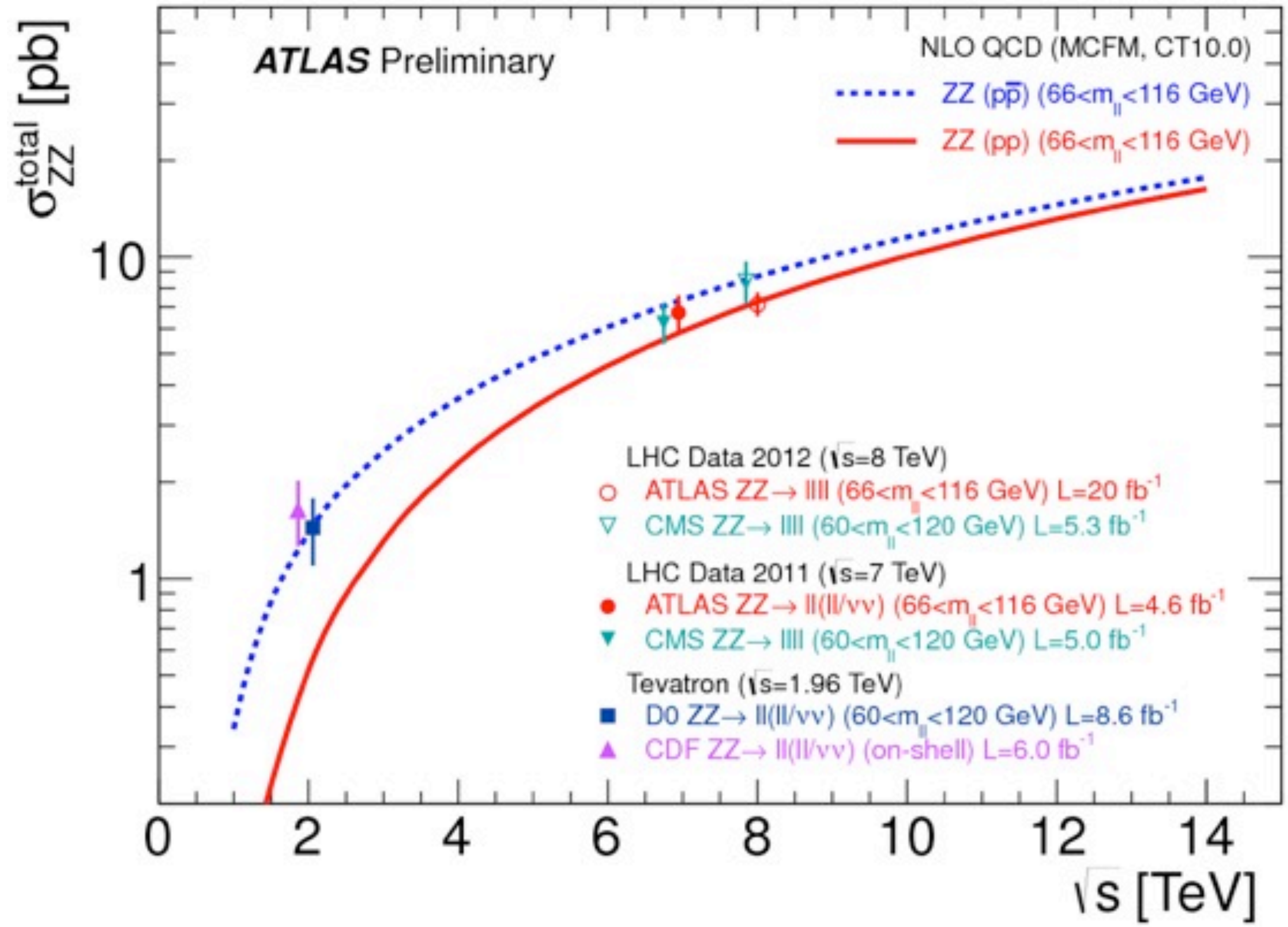




ATLAS 7 TeV : ATLAS-CONF-2012-026
ATLAS 8 TeV : ATLAS-CONF-2013-020
CMS 7 TeV : CERN-PH-EP-2012-336
CMS 8 TeV : CERN-PH-EP-2012-376

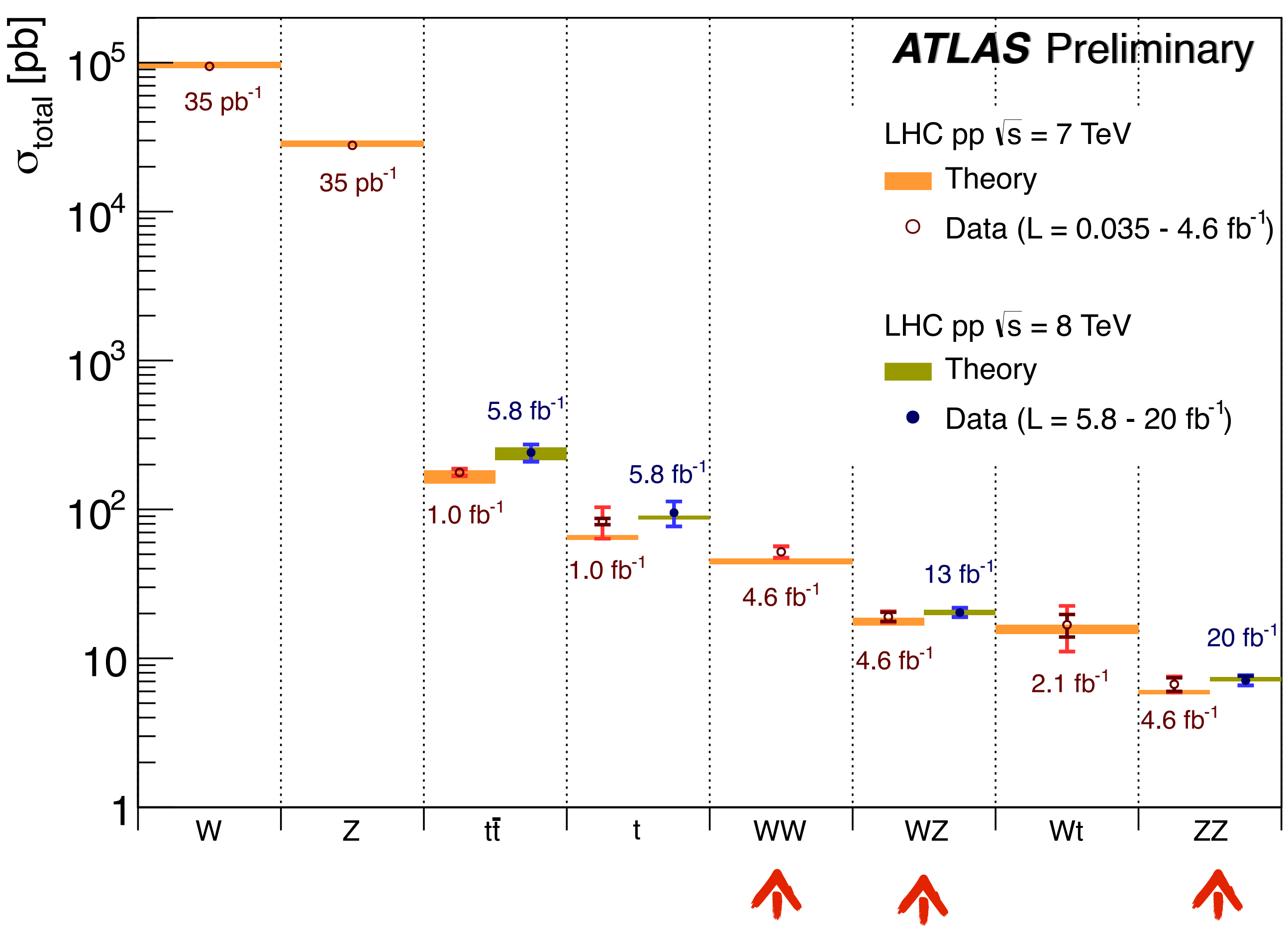
ZZ → ℓℓ ℓ’ℓ’ results

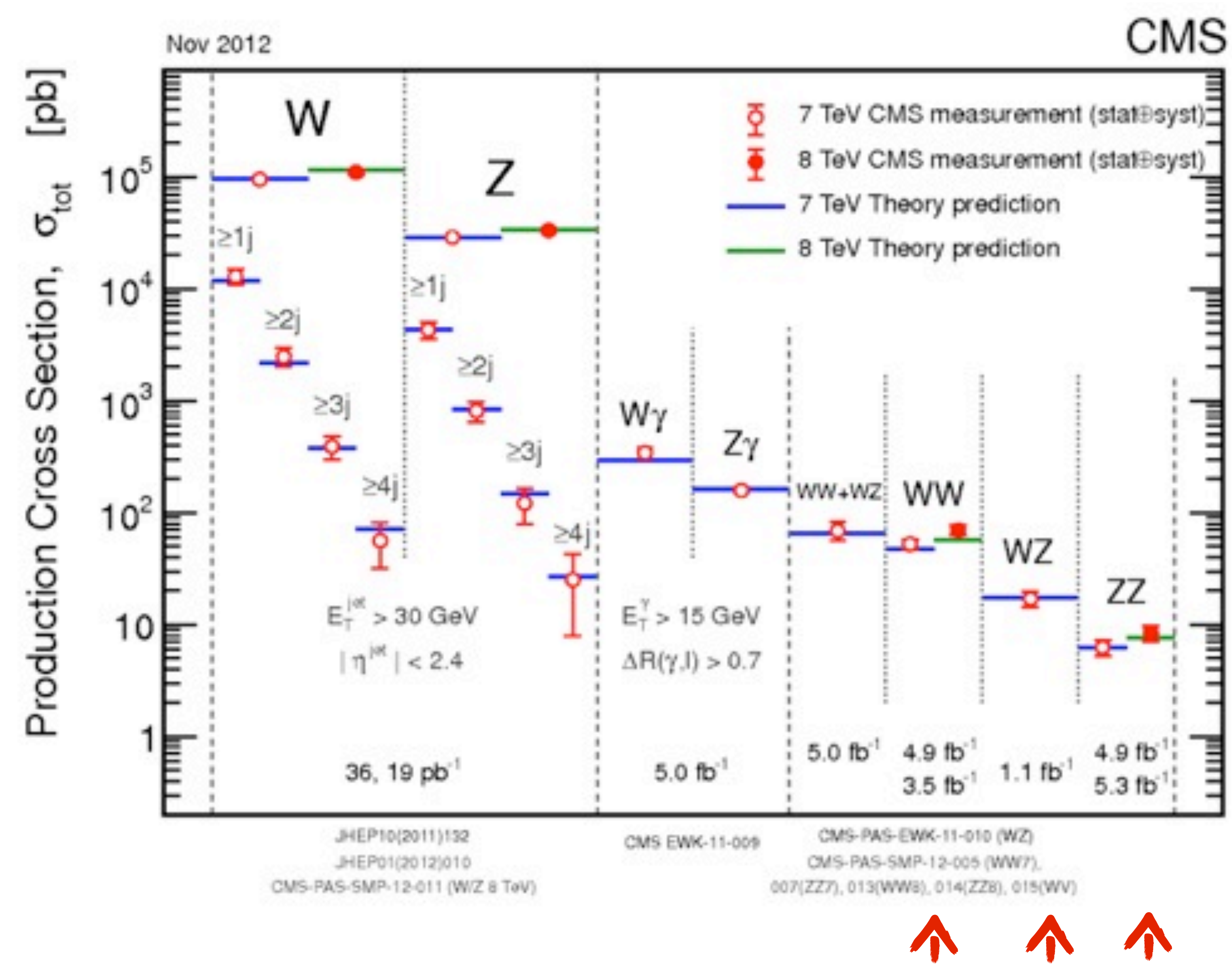
- Good agreement ATLAS/CMS
- Comparison with MCFM NLO +CT10 good agreement
- Statistical uncertainty is still dominant.
- Main systematic uncertainty for ATLAS electron ID (3.8% eeee and 1.9% eeμμ) and muon reconstruction efficiency (1.0% μμμμ and 0.5% eeμμ).
- Main systematic uncertainty for CMS lepton ID 3% lepton isolation 2%



	$\sqrt{s}$	lumi	Measured σ_{total} [pb]	MCFM NLO [pb]	Z mass window in fidutial space
ATLAS	7 TeV	4.7 fb^{-1}	7.2 ± 1.4 (stat) ± 0.8 (sys) ± 0.4 (lumi)	6.5 ± 0.3	66 < m_{ll} <116 GeV
CMS	7 TeV	4.9 fb^{-1}	6.2 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lumi)	6.3 ± 0.4	60 < m_{ll} < 120 GeV
ATLAS	8 TeV	20.0 fb^{-1}	7.1 ± 0.4 (stat) ± 0.3 (sys) ± 0.2 (lumi)	7.2 ± 0.3	66 < m_{ll} < 116GeV
CMS	8 TeV	5.3 fb^{-1}	8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lumi)	7.7 ± 0.4	60 < m_{ll} < 120 GeV

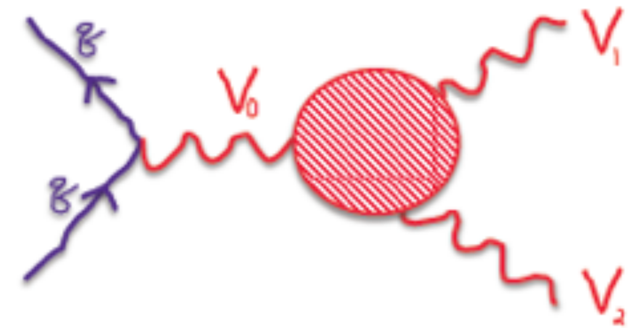
SM total production cross section measurements from ATLAS and CMS...





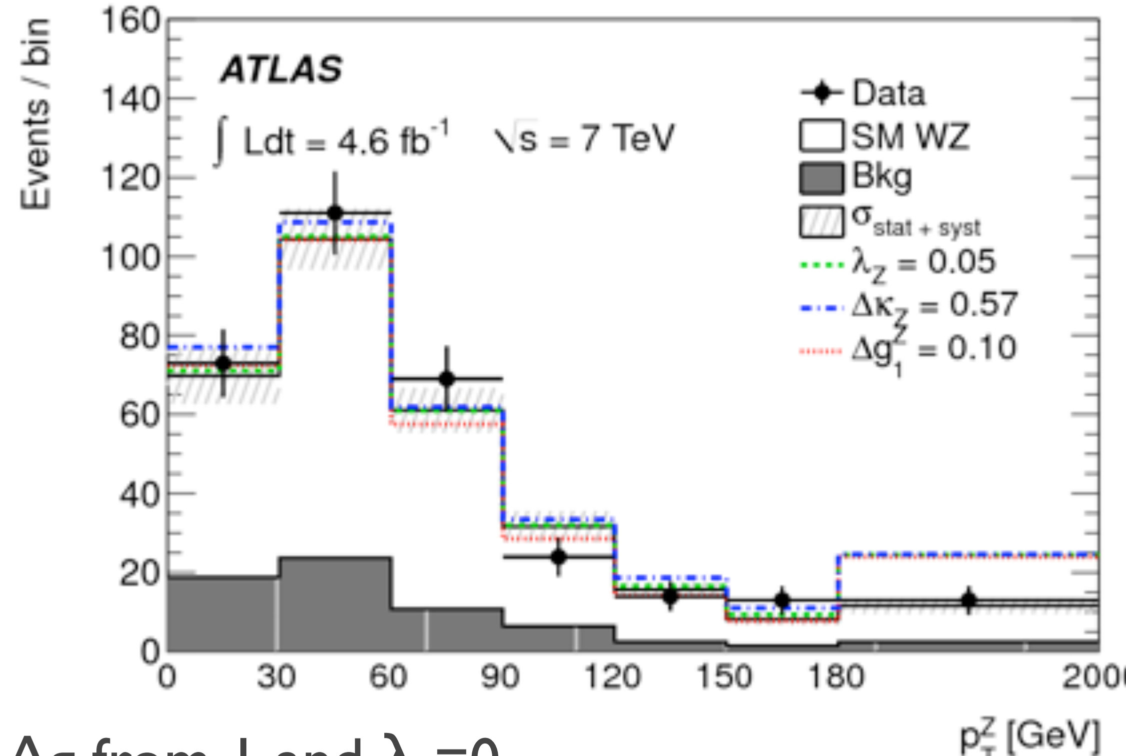
- The Dibosons production cross sections match the NLO SM predictions.

Anomalous couplings



- The effective Lagrangian used to describe the effect of non-SM processes on TGCs depends on a number of parameters (only the ones conserving CP are listed):

coupling	parameters (All = 0 in SM)	channel
$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1{}^Z$	WW, WZ
$Z\gamma Z$	$f_{40}{}^Z, f_{50}{}^Z$	ZZ
ZZZ	$f_{40}{}^\gamma, f_{50}{}^\gamma$	ZZ



- In the SM $\kappa_V, g_1{}^V = 1$, We look for deviations $\Delta\kappa, \Delta g$ from 1 and $\lambda = 0$.
- aTGCs modify total production rate as well as event kinematics. So we can use the cross section or kinematics to constrain aTGCs.
- The expected number of signal events is written as a function of the SM cross sections plus some other terms depending on the aTGC parameters.
- Maximum likelihood fit is done, leaving one (or two) of the aTGC parameter free.
- Form factor defined like :

$\Delta g(s) = \Delta g/(1+s/\Lambda^2)^2$ used in old results and for recent we have $\Lambda=\infty$

WZ aTGC limits

- Measurement performed using the Z boson p_T.
- 30 GeV bins, with larger last bin [180-2000] GeV
- No significant deviation wrt SM predictions is observed.
- LHC results already competitive with Tevatron.

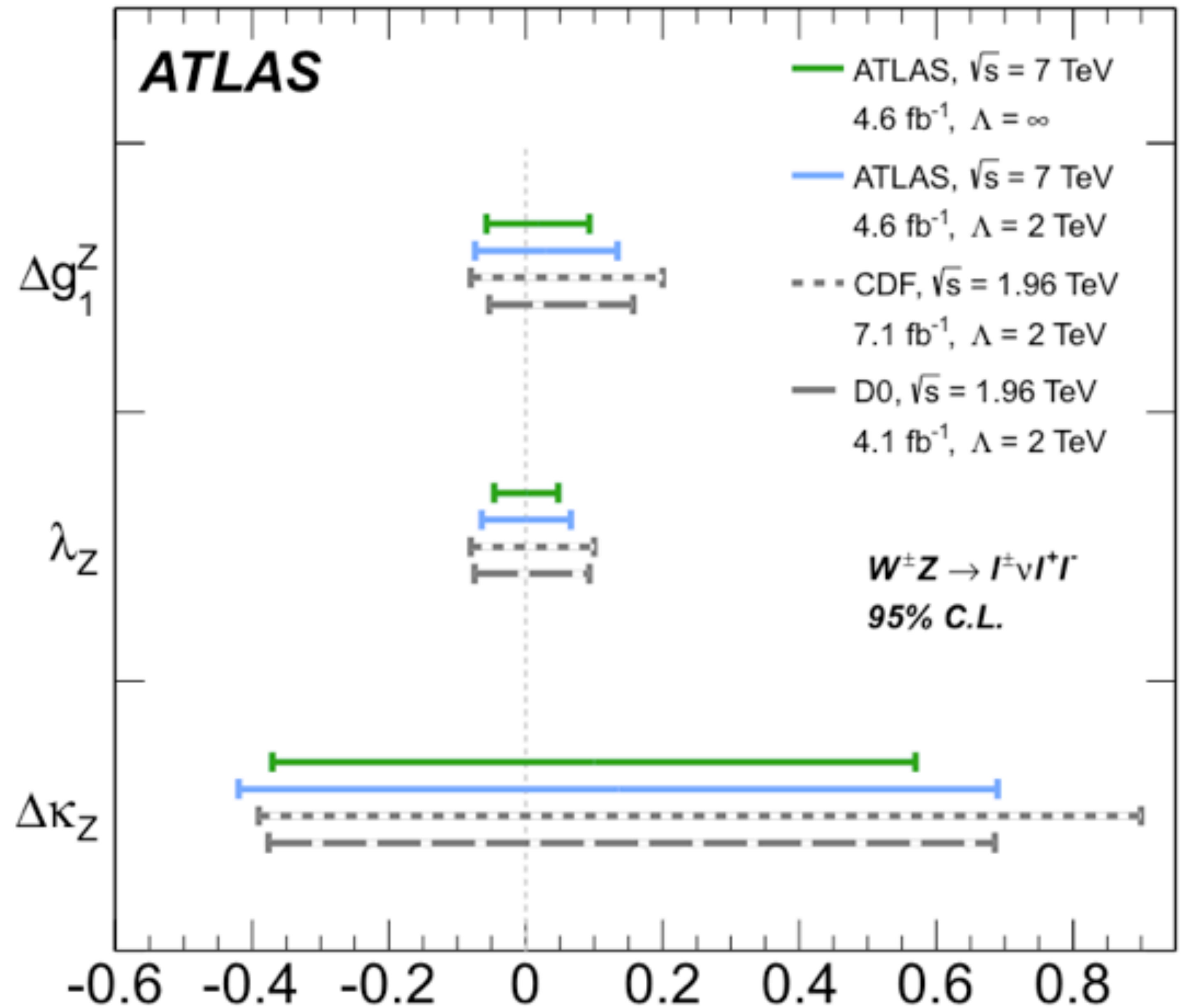
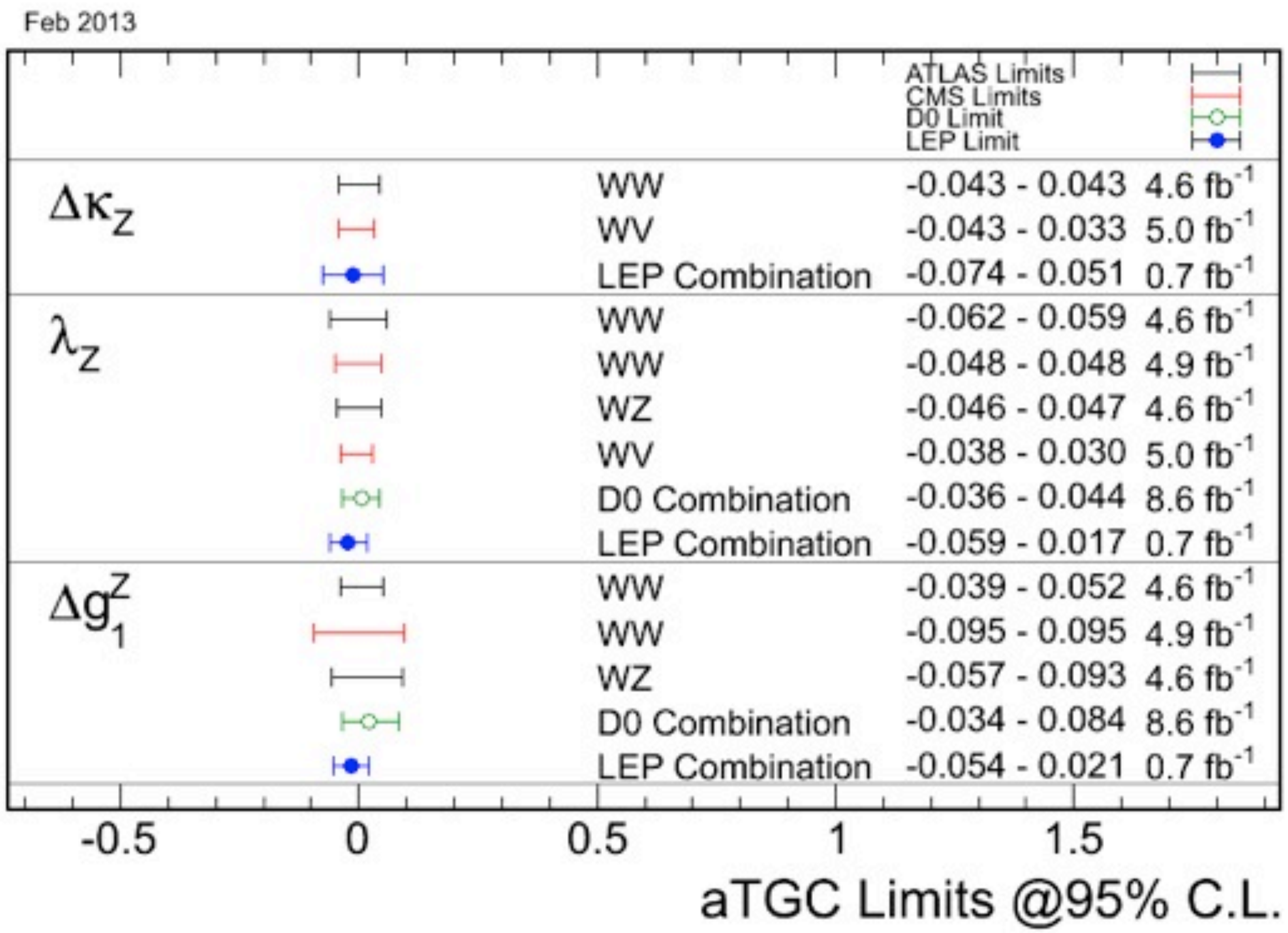
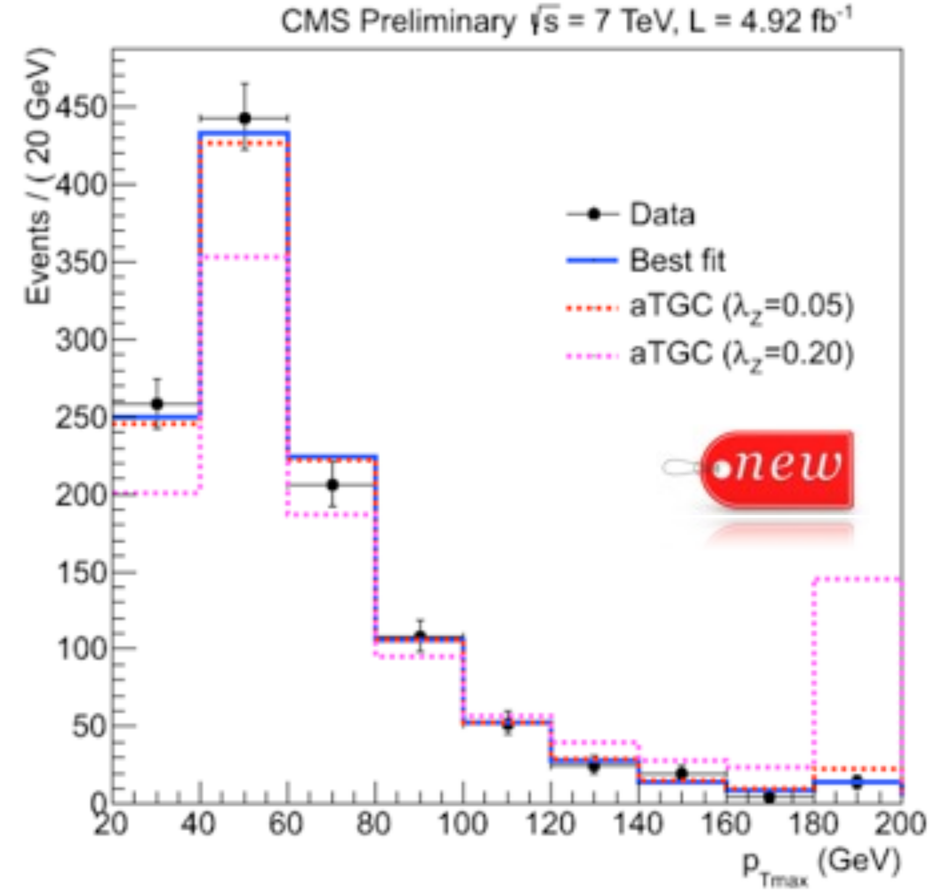


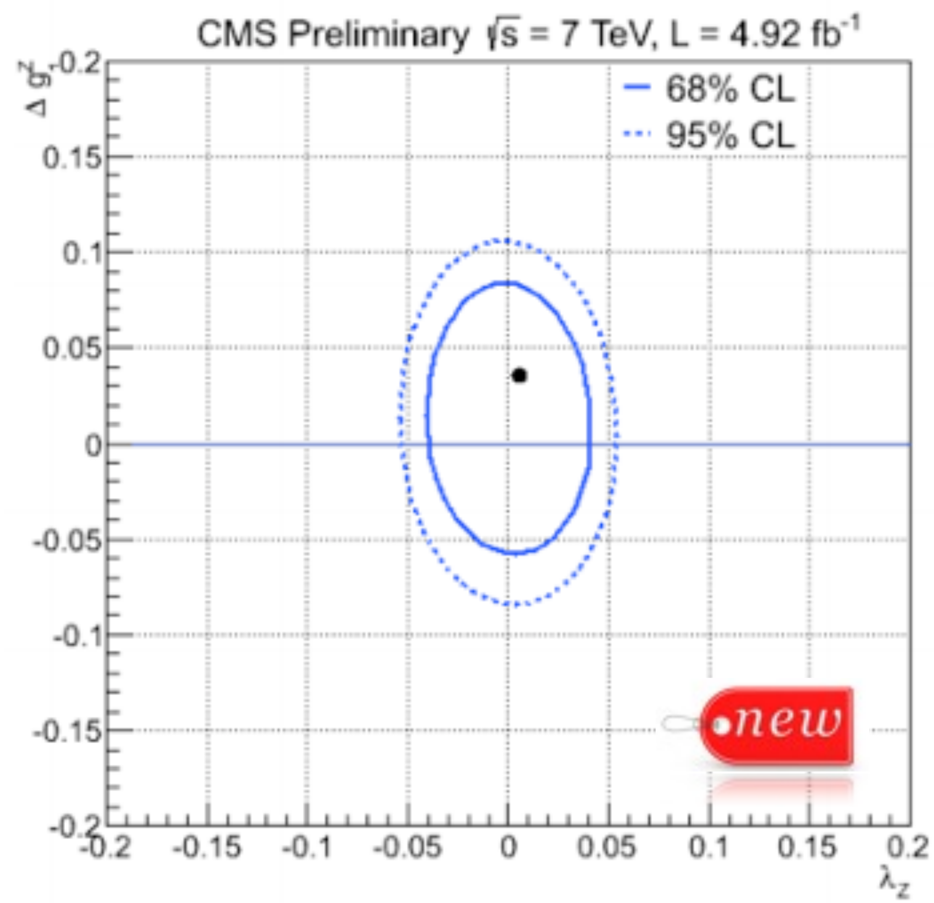
Figure : 95% confidence intervals for anomalous TGCs from ATLAS, CDF and D0. Integrated luminosity, center-of-mass energy and cut-off Λ for each experiment are shown

arXiv:1208.1390

WW aTGC limits





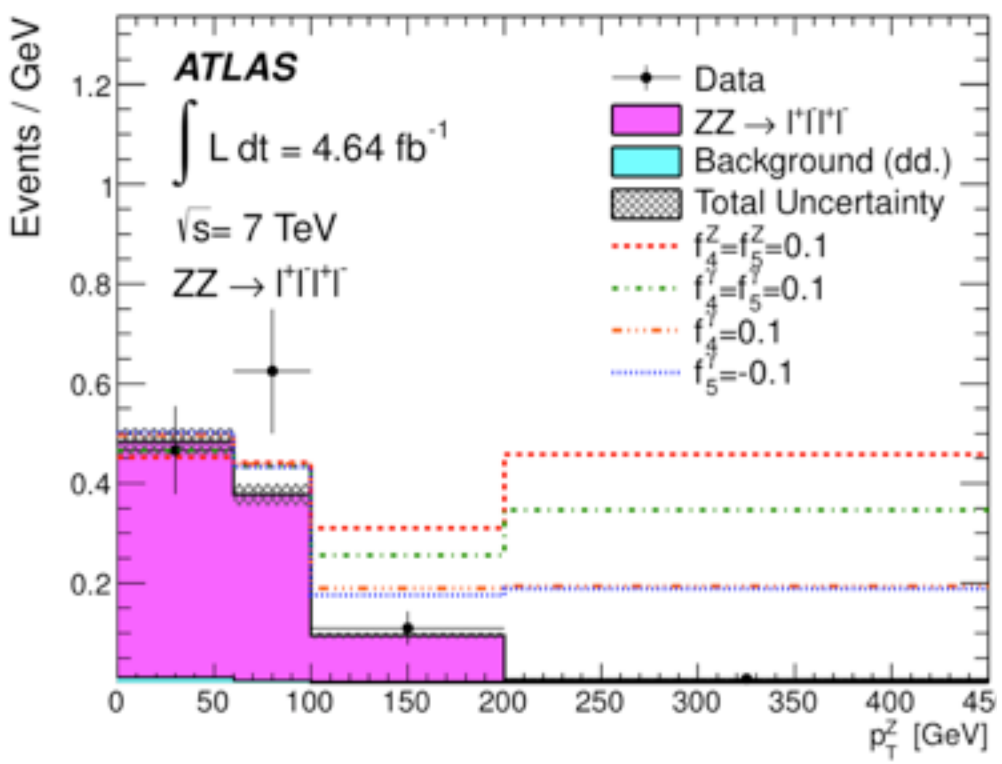


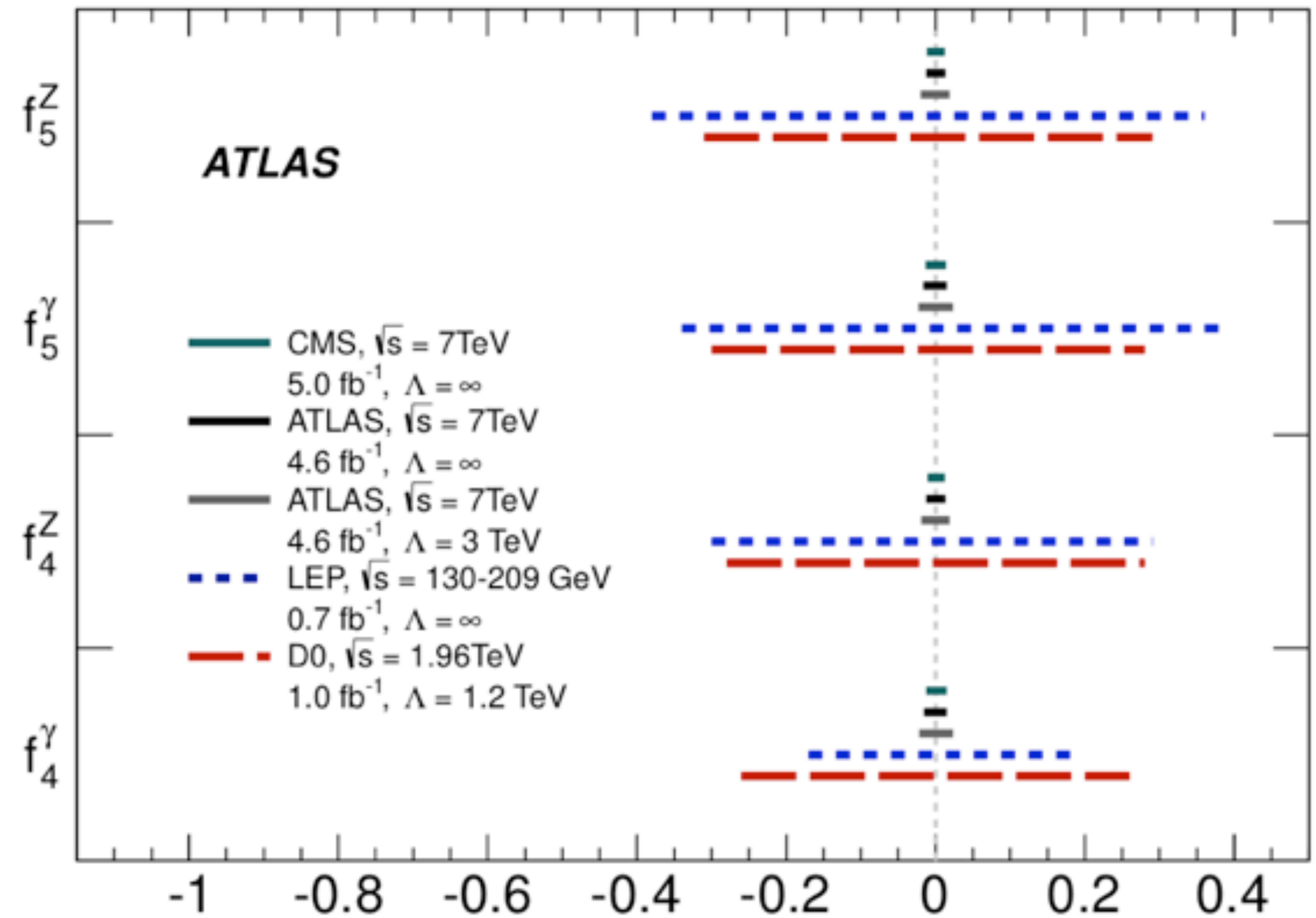
arXiv:1210.2979

- Fit for anomalous couplings using distribution leading lepton p_T
- No significant deviation wrt the SM predictions is observed

ZZ aTGC limits

arXiv:1211.6096





- ☐ No significant deviation wrt SM predictions is observed.
- ☐ ATLAS and CMS results are largely more constraining than LEP and Tevatron

Conclusions

- Dibosons production cross-sections and aTGC parameters have been measured using 7 TeV data and for some channels at 8 TeV data.
- ATLAS in general uses a smaller Z window than CMS.
- ATLAS provided several unfolded distributions:
  - leading lepton p_T in WW,
  - m^{ZZ}, leading Z p_T and $\Delta\phi(l,l)$ in $ZZ \rightarrow \ell\ell\ \ell\ell$,
  - Z p_T and m_{WZ} in WZ.
  - Do we need to include others?
- We have a good agreement with the SM predictions, within uncertainties.
- Most of the results are still dominated by the statistical uncertainties, but ...
- Still most of the LHC data at 8 TeV to be analyzed … more results with improved precision expected soon

Backup

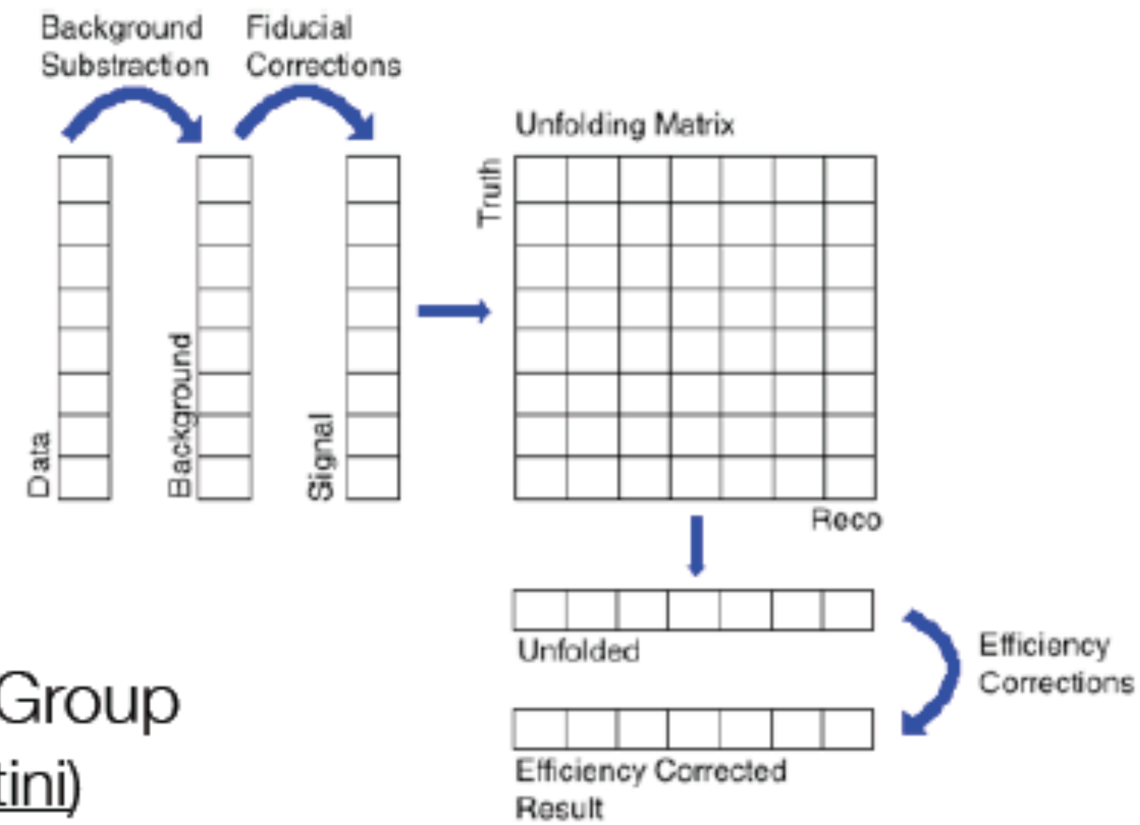
Unfolding methodology

Motivation

Determine **true value** of an observable

Measured value is distorted by detector's

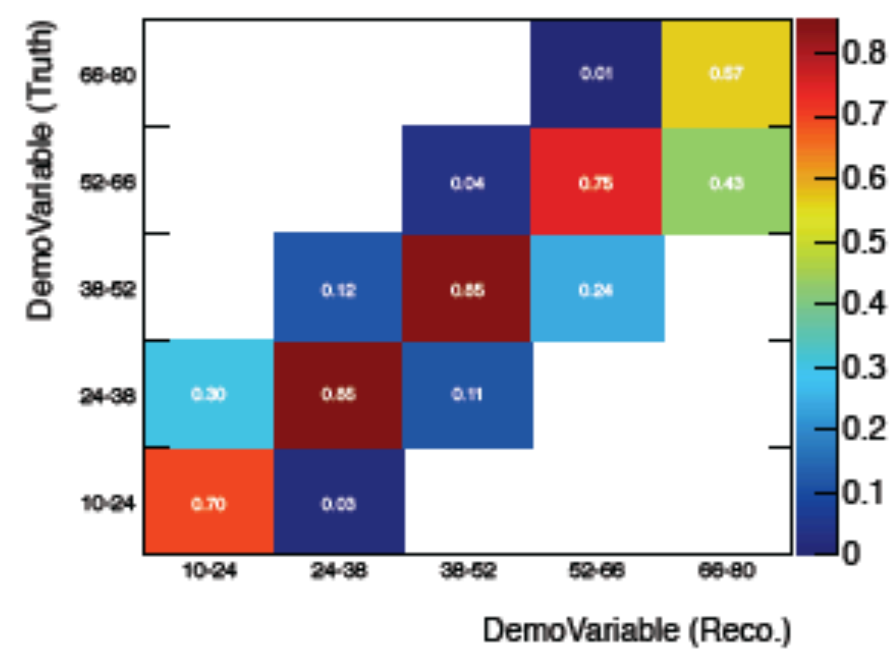
- limited acceptance
- imperfect efficiency
- finite resolution



Method

Common Framework among Electroweak Group

- use **iterative Bayesian unfolding** (d'Agostini)
- **normalized** unfolding within **fiducial region** only
- based on **RooUnfold** using **response matrix**



Published Results

Fractional, binned kinematic distributions

- $\Delta\sigma^{fid}(x)/\sigma^{fid}$

Full correlation matrices (on HEPDATA)

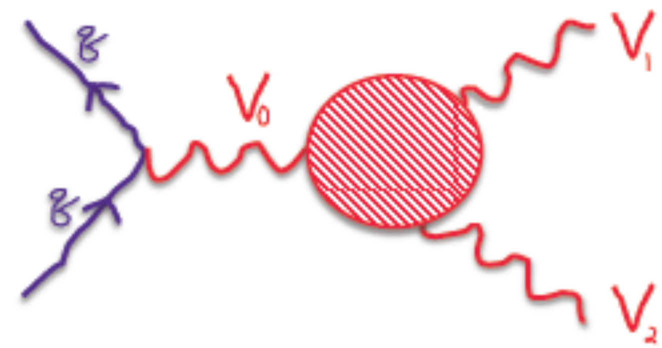
- combined stat, syst, background

Systematics uncertainties on

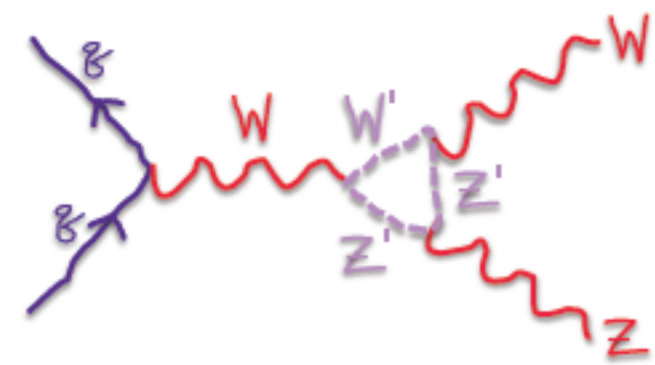
Channel	Main Uncertainties
WW→lνlν	jet veto (3.6%)
W(W/Z)→lνqq	jet energy scale (12%), W/Z+jets normalization (11%)
WZ→lνll	electron identification efficiency (3.5% for eee, 2.3% for eem) muon reconstruction efficiency (0.8% for μμμ, 0.5% for μμe)
Wγ	photon identification (11% for E_T>15GeV, 4.5% for E_T>60,100GeV)
ZZ→llll	electron identification efficiency (3.8% for eeee, 1.9% for eeμμ) muon reconstruction efficiency (1.0% for μμμμ, 0.5% for eeμμ)
ZZ→llνν	jet veto (5.3%)
Zγ	photon identification (11% for E_T>15GeV, 4.5% for E_T>60,100GeV)

Anomalous couplings

- The effective Lagrangian used to describe the effect of non-SM processes on TGCs depends on a number of parameters (only the ones conserving CP are listed):



coupling	parameters (All = 0 in SM)	channel
WWγ	λ_γ, $\Delta\kappa_\gamma$	WW, Wγ
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
ZγZ	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	f_{40}^γ, f_{50}^γ	ZZ



Example: W', Z' could be SUSY, Technicolor, Higgs...

- In the SM κ_V, g_1^V =1, We look for deviations $\Delta\kappa$, Δg from 1 and λ =0.
- aTGCs modify total production rate as well as event kinematics. So we can use the cross section or kinematics to constrain aTGCs.

Anomalous couplings (II)

Experimentally:

- The aTGCs will modify the total production rate as well as event kinematics.
- The expected number of signal events is written as a function of the standard model cross sections plus some other terms depending on the aTGC parameters.
- Example on the WZ case :

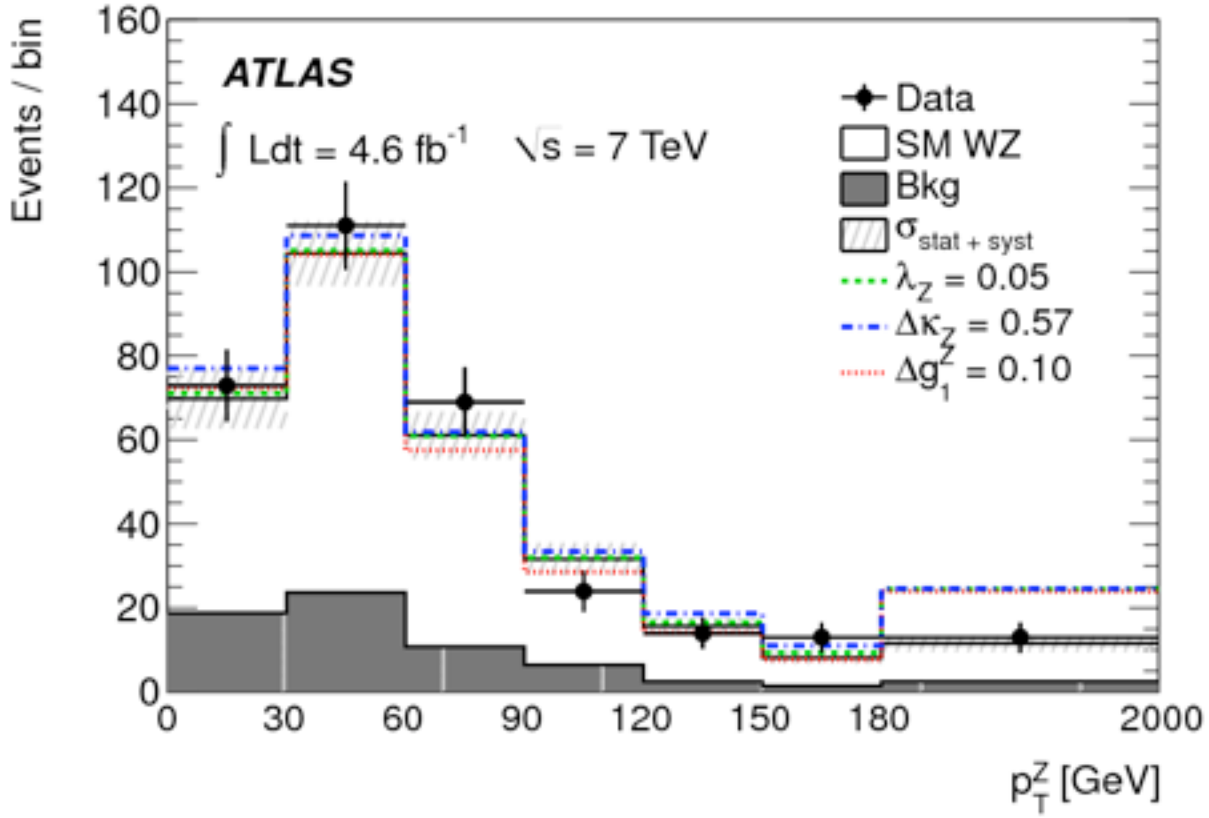
$$
\begin{aligned}
N_s^i(\Delta g_1^Z, \Delta\kappa^Z, \lambda^Z) = W_0^i \quad &+ \quad (\Delta g_1^Z)^2 W_1^i + (\Delta\kappa^Z)^2 W_2^i + (\lambda^Z)^2 W_3^i \\
&+ \quad 2\Delta g_1^Z W_4^i + 2\Delta\kappa^Z W_5^i + 2\lambda^Z W_6^i \\
&+ \quad 2\Delta g_1^Z \Delta\kappa^Z W_7^i + 2\Delta g_1^Z \lambda^Z W_8^i + 2\Delta\kappa^Z \lambda^Z W_9^i
\end{aligned}
$$

SM cross section

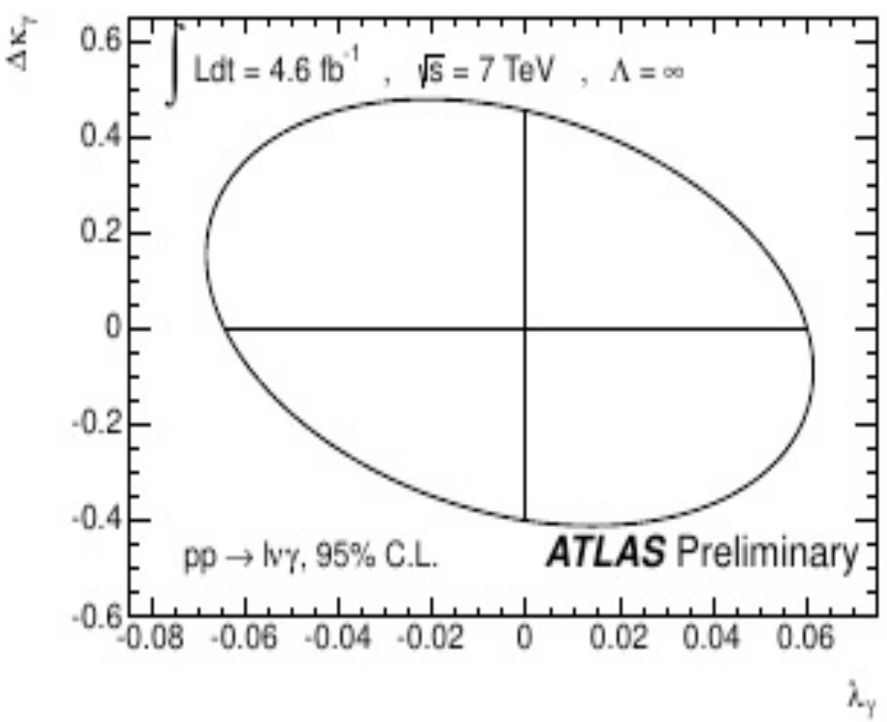
- Maximum likelihood fit is done, leaving one (or two) of the aTGC parameter free.
- The higher aTGC sensitivity at high p_T^Z (high mass or lepton p_T)
- Form factor defined like :

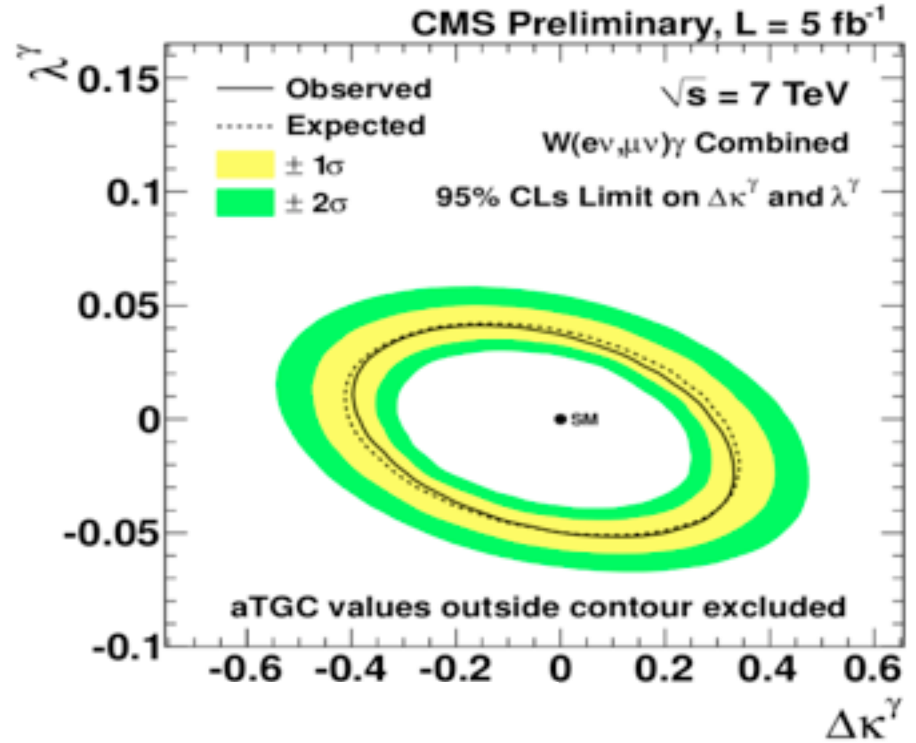
  $\Delta g(s) = \Delta g/(1+s/\Lambda^2)^2$

  used in old results and for recent we have $\Lambda=\infty$



Summary of aTGC

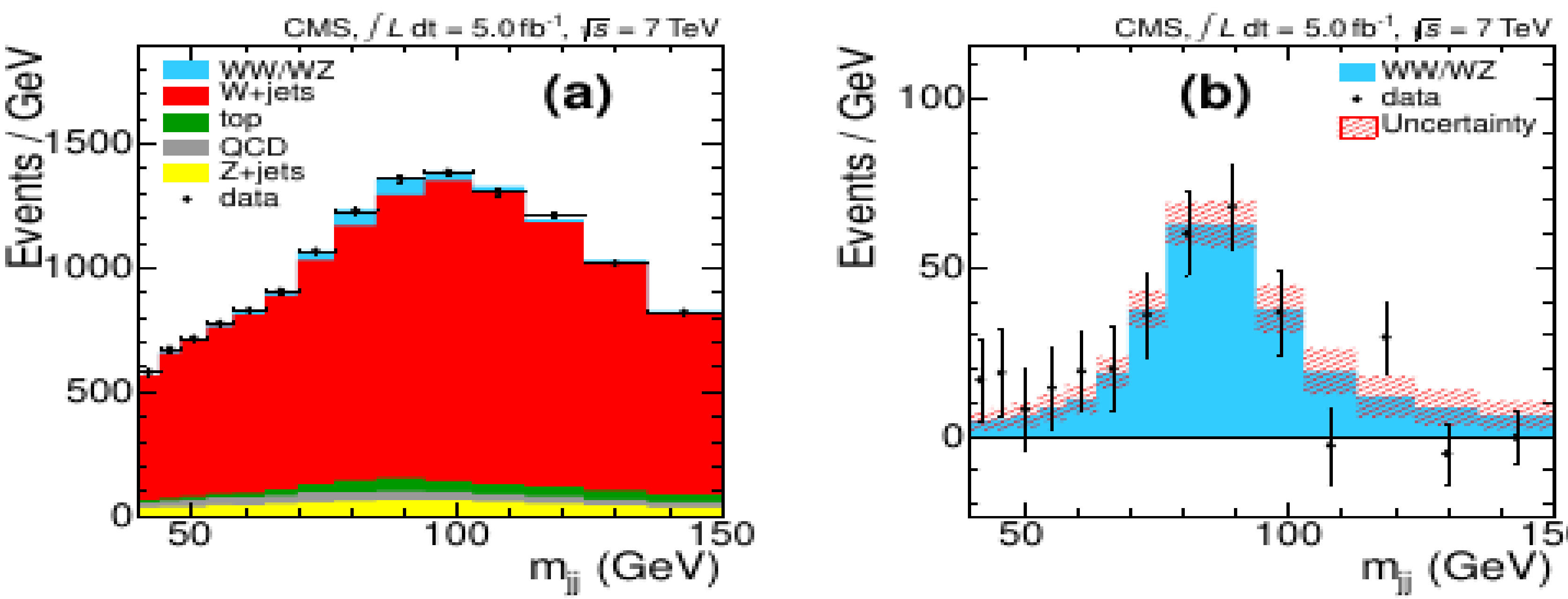




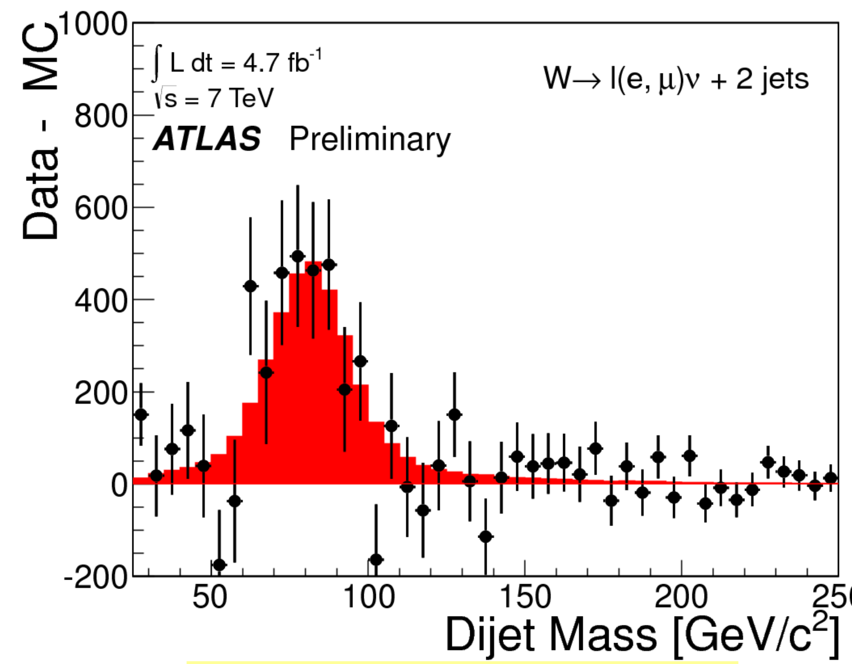
- All channels studied. No deviations from SM expectations
- But sensitivity still low :
  - Channel with highest statistics Wγ give $\Delta\kappa_\gamma < 0.4$ and $\lambda_\gamma < 0.05$
  - while the « interesting » range is rather $\Delta\kappa_\gamma \sim 0.01$ and $\lambda_\gamma \sim 0.001$
- Expected improvements soon with the full 2012 stat to be analysed (23 fb^{-1}) and combination of channels measuring the same couplings.
- The aTGC are proportional to s (or $\sqrt{s}$) it will be interesting to look at the 13 TeV data.
- Need to run at 13 TeV (higher sensitivity with increasing s) and 100 fb^{-1} (2 to 3 years) to probe the « interesting » region.

Diboson with semi-leptonic decays

- Atlas and CMS has measured (WZ+ZZ) $\longrightarrow$qqll



ArXiv:1210.7544



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	$\sqrt{s}$	lumi	Mesured [pb]	MCFM NLO [pb]
ATLAS	7 TeV	4.7 fb^{-1}	72 ± 9 (stat) ± 15 (sys) ± 13 (lumi)	63.4 ± 2.6
CMS	7 TeV	5.0 fb^{-1}	68.9 ± 8.7 (stat) ± 9.7 (sys) ± 1.5 (lumi)	65.6 ± 2.2

Data Driven Methods (I)

- ☐ Data-driven techniques are used for backgrounds containing jets.
- ☐ The concept is to build background enriched Control Regions (CR) by reversing analysis cuts (ex. isolation, E_T^{miss}, impact parameter significance)
- ☐ The background is extrapolated from the control region to the signal region using a transfer factor.
- ☐ Different methods (ABCD, Fake factor, Sideband fit, μeμ Control region, matrix method) and CR definitions depend on the analysis.

Example :

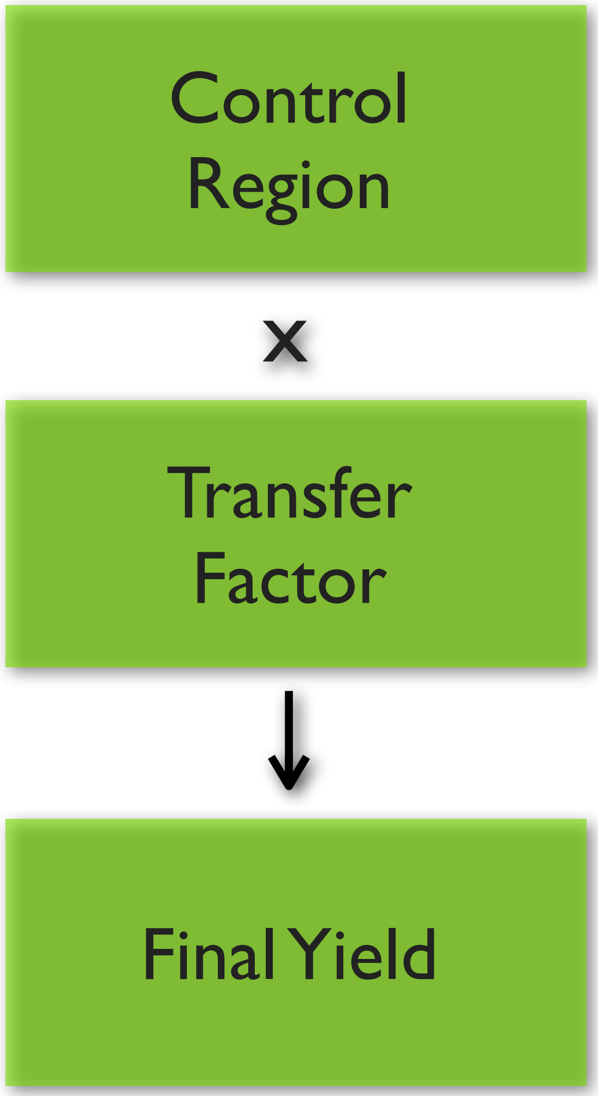


Figure : Data Driven principle. A Control Region enriched with background is built the amount of background in this region is estimated. Then Transfer Factor from the CR to the Signal Region is defined, and used to estimate the Final Yield.

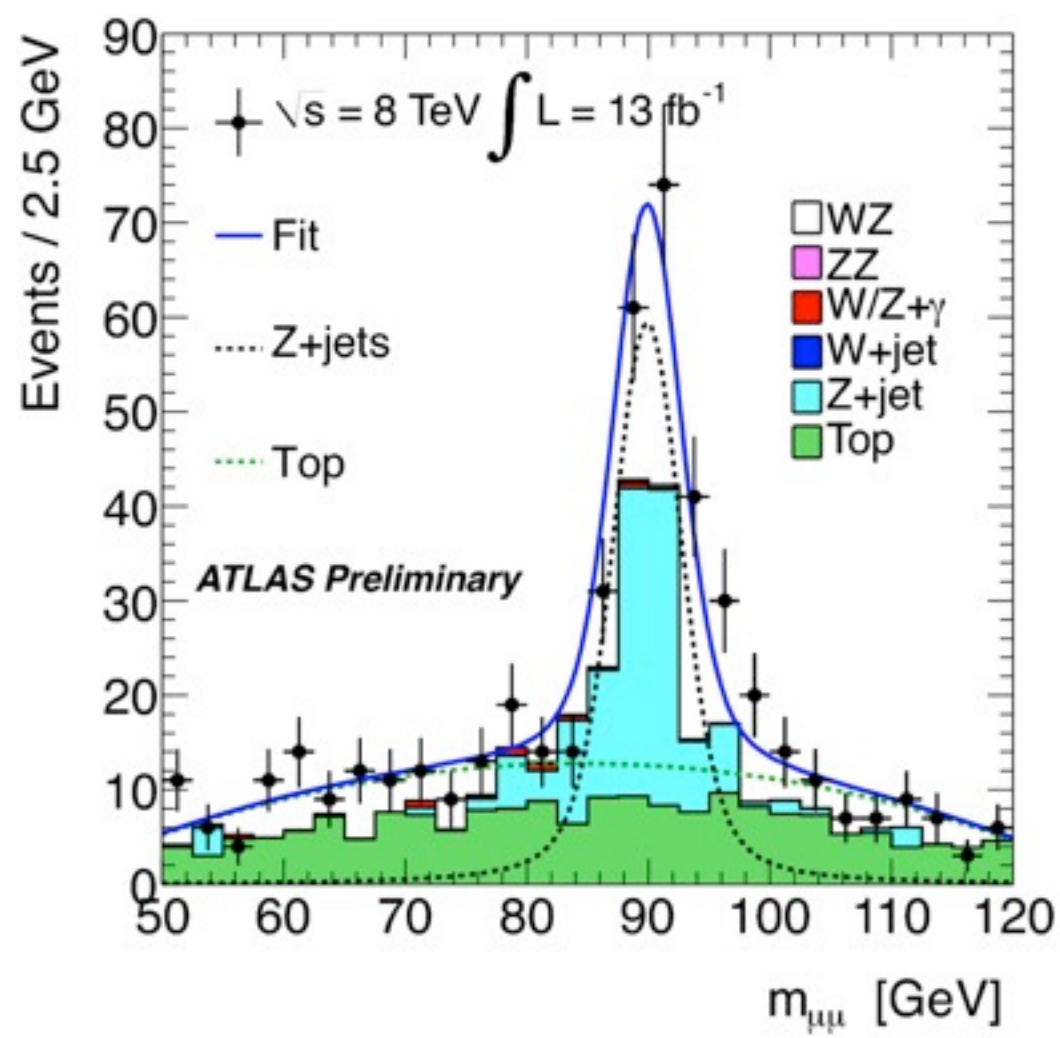
Data Driven Methods (II)

Sideband fit method example : For WZ analysis

- Define a **Control Region**, enriched with $\bar{t}t$ and Z+jets
  - Same Z requirement (except mass window cut).
  - On the W lepton no isolation cut, and reverse the d0 significance cut.
- On this region we will fit the data using :
  - for the $\bar{t}t$ a second order Chebychev polynomial.
  - For the Z+jet a BW line-shape convoluted with a Gaussian resolution.
- To extrapolate to the signal region we use, the **Transfer Factor** extracted from MC :

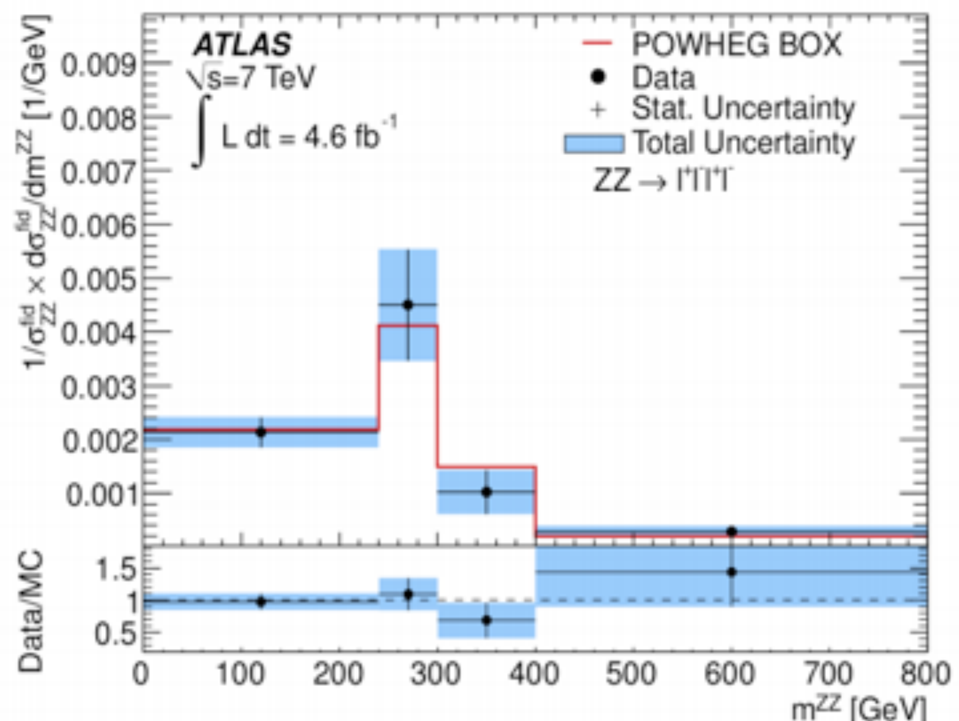
$$f_{\mathrm{transfer}} = \frac{N_{SR}}{N_{CR}}$$

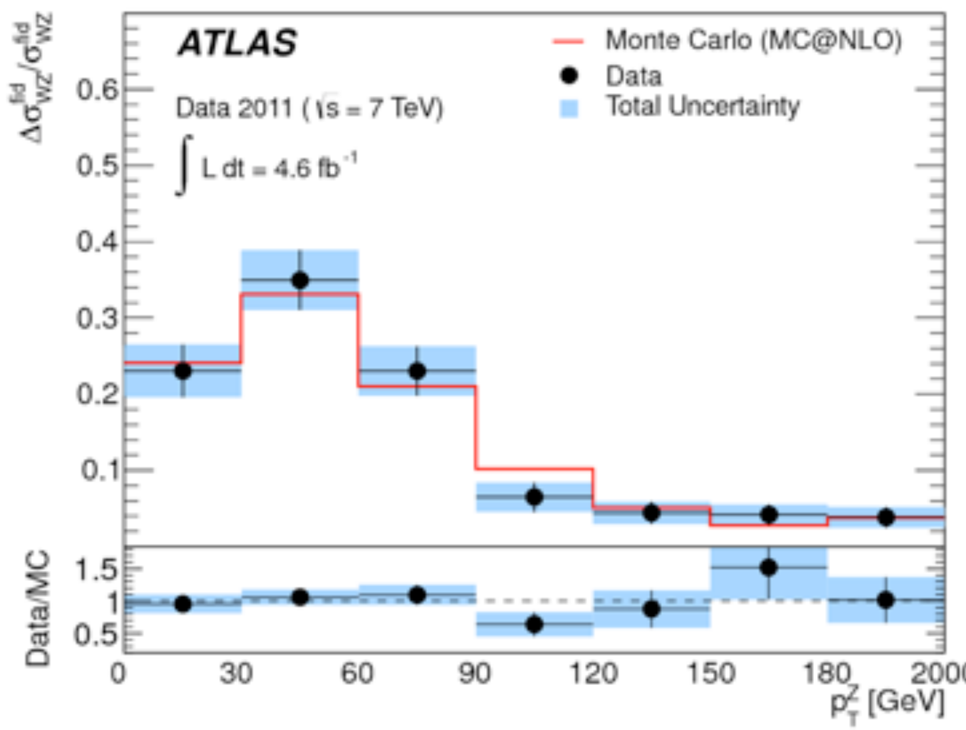
$$f_{\mathrm{transfer}} = \frac{\epsilon_{iso} \times \epsilon_{d_0}}{(1-\epsilon_{d_0})}$$



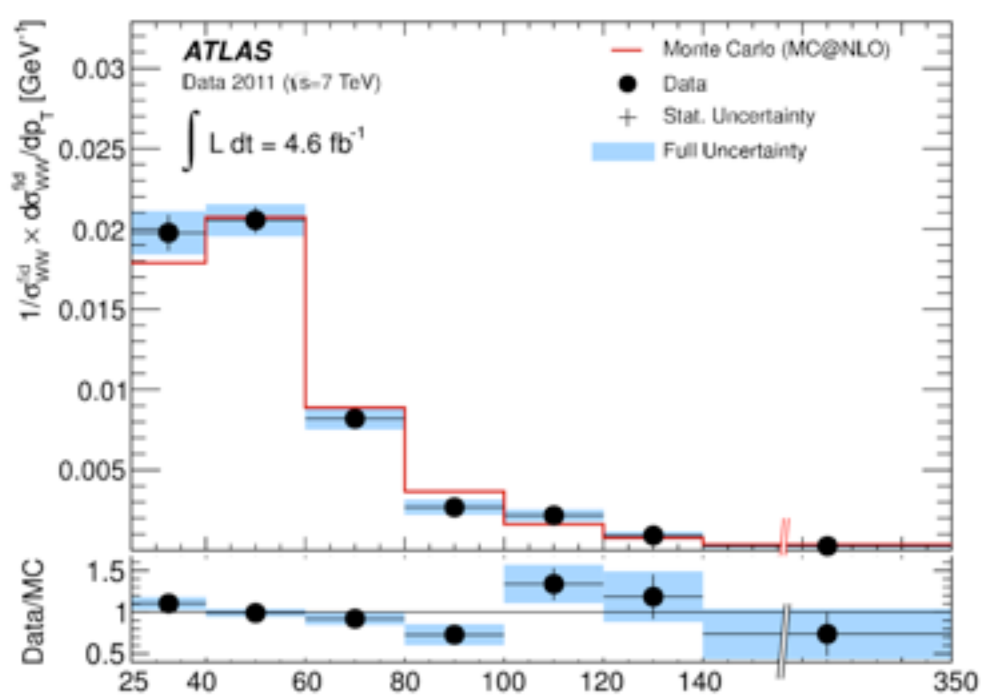
ATLAS Unfolded distributions (I)

- WZ unfolded distributions :



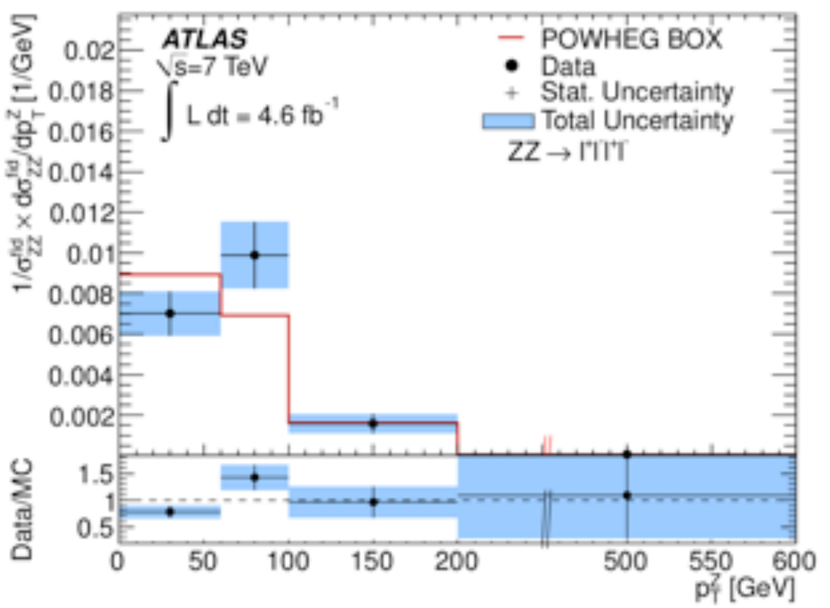


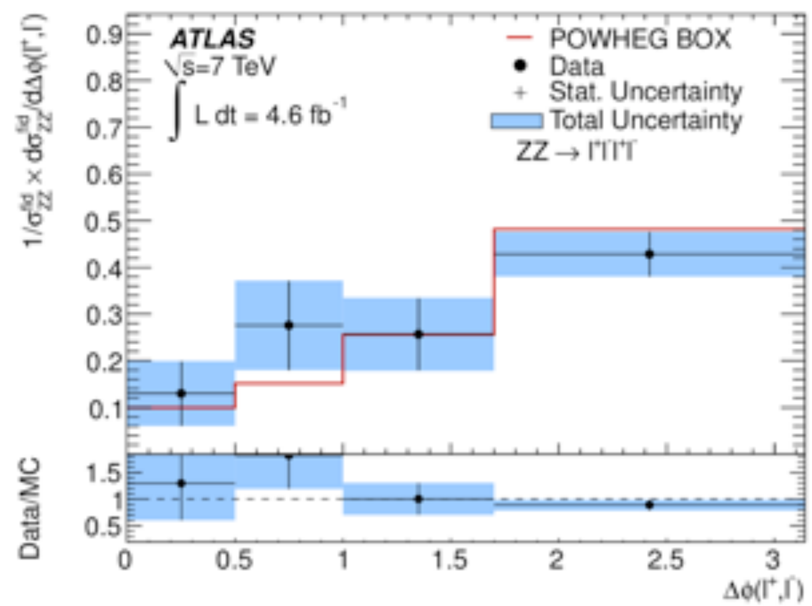
- WW unfolded distributions :

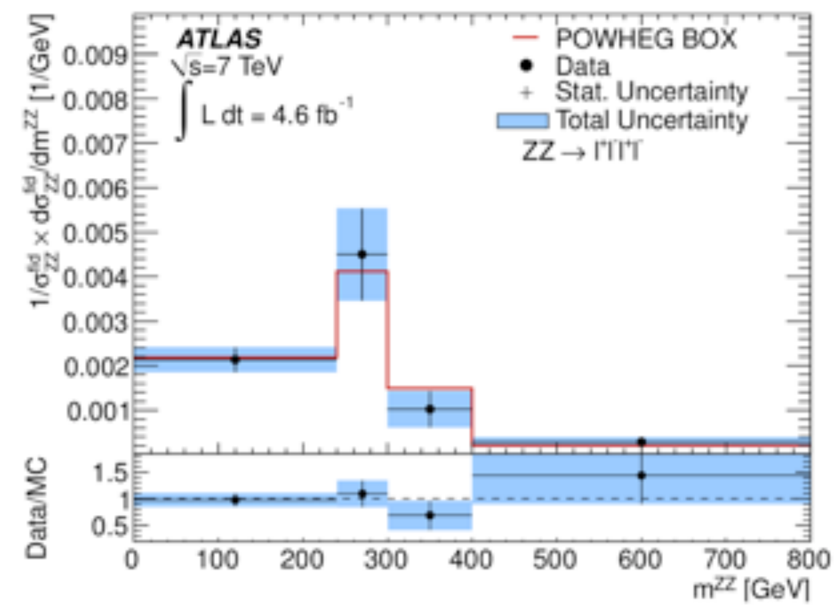


ATLAS Unfolded distributions (II)

- ZZ → ℓℓ ℓℓ unfolded distributions :







- ZZ → ℓℓ νν unfolded distributions :