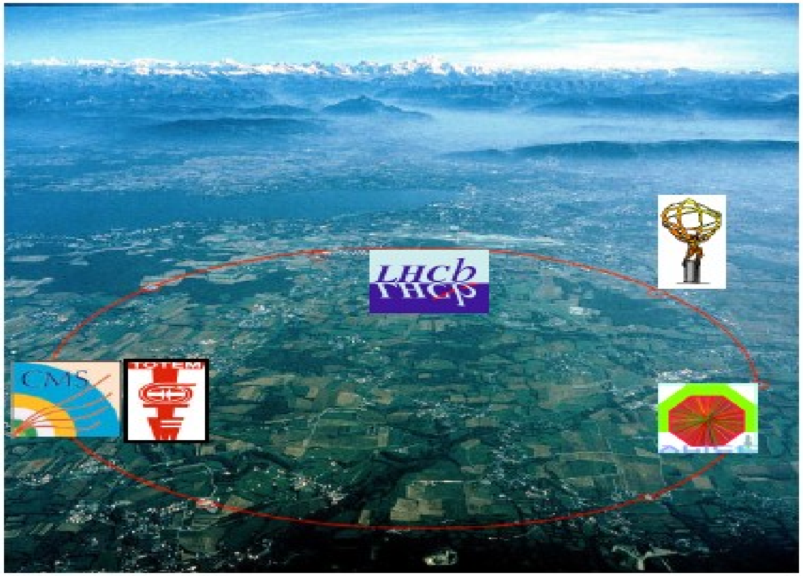
Lecture 8

Physics Program

of the experiments at

Large Hadron Collider



Physics with dibosons

Next topics

- 5.12 – **Higgs (part I)**
- 12.12 – **Higgs (part II)**
- 19.12 - **SUSY**
- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme

Latest news

LHC in Week 47

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY	MONDAY
0:00					SPS VACUUM			
1:00						STABLE BEAMS		
2:00				VdM SET-UP &		VdM		
3:00				QUALIFICATION	LOSS MAPS			
4:00								
5:00		TRANSFER LINE	SPS MAGNET	PM RESET	RB.A12			
6:00	STABLE BEAMS	SET-UP	EXCHANGE		SPS MKD			
7:00				VdM	SWITCH TO VdM	SPS MKD		ACCESS
8:00				ASYNCH DUMP				START MD
9:00								
10:00				RQ10.L8	PC INTERLOCK		STABLE BEAMS	
11:00		LBDS		ACCESS FOR RQ10				
12:00			RB.A23					
13:00						STABLE BEAMS		
14:00					SPS MKD			
15:00	ACCESS		SPS MKD	SPS BQM				
16:00								
17:00		SPS MAGNET						
18:00	LBDS	EXCHANGE						
19:00	LBDS							
20:00			SPS BQM	STABLE BEAMS	STABLE BEAMS			
21:00				VdM	VdM		STABLE BEAMS	
22:00								
23:00	QPS							

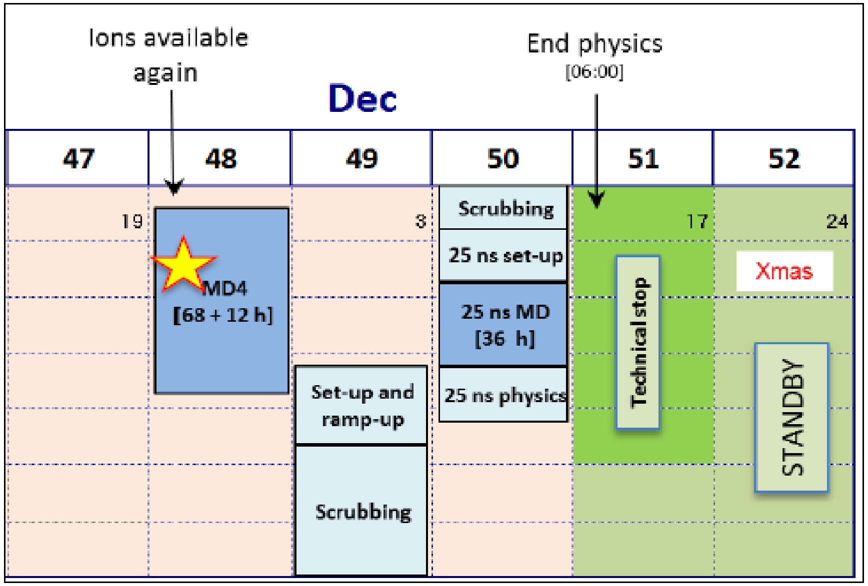
	CYCLING
	FAULT
	SET-UP

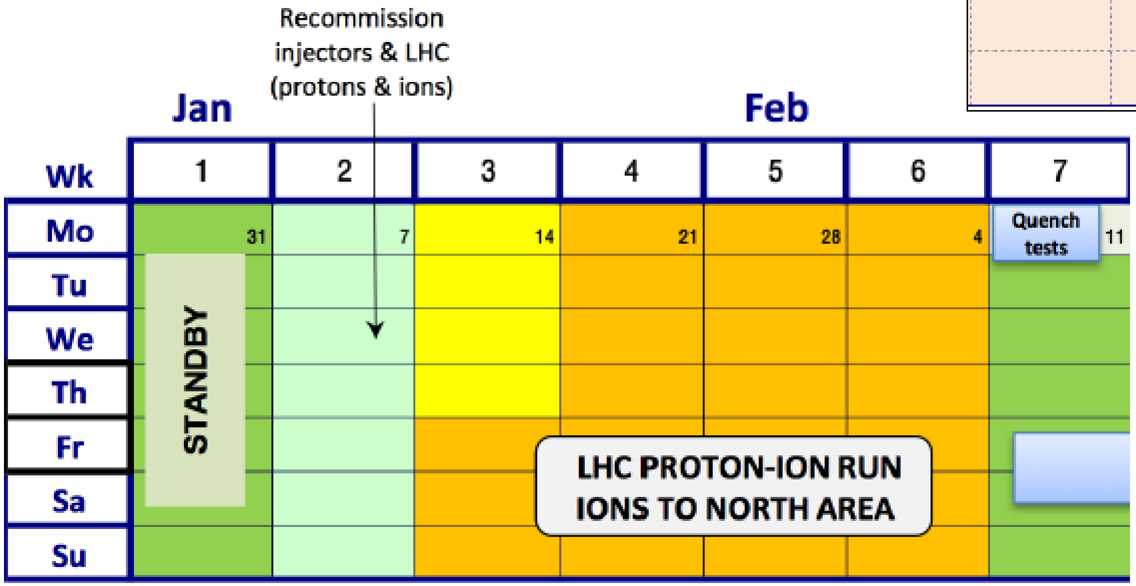
Latest news

Still ~9 physics days to go

- last 3 days are contingency for 25ns running. ATLAS baseline is to use them, if available, for normal 50 ns physics.

25ns: scrubbing, MD, 2 stable beams fills



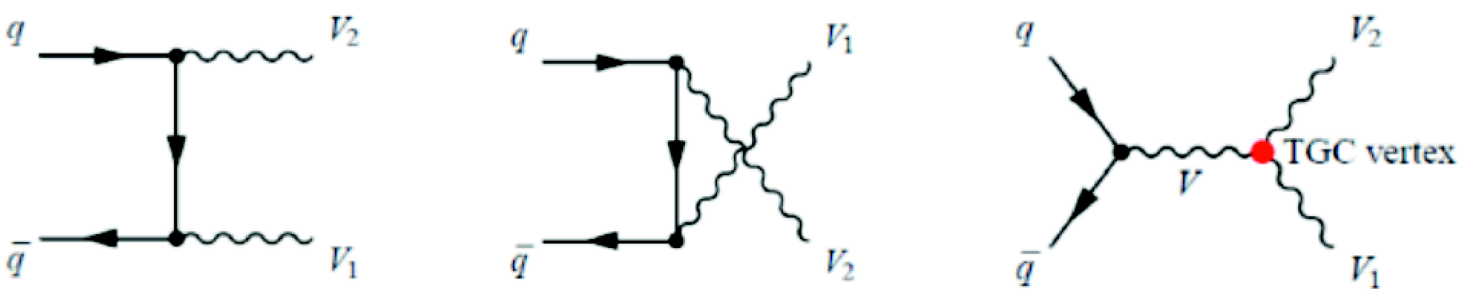


Dibosons at LHC

Motivation

- Test of the Electroweak Sector at the TeV energy regime
- Probe to new physics through deviations of Triple Gauge Couplings from SM predictions
- Sensitive to new phenomena beyond the SM
- Irreducible background in the studies of the Higgs boson ($H \rightarrow ZZ^{(*)}/WW^{(*)}$)

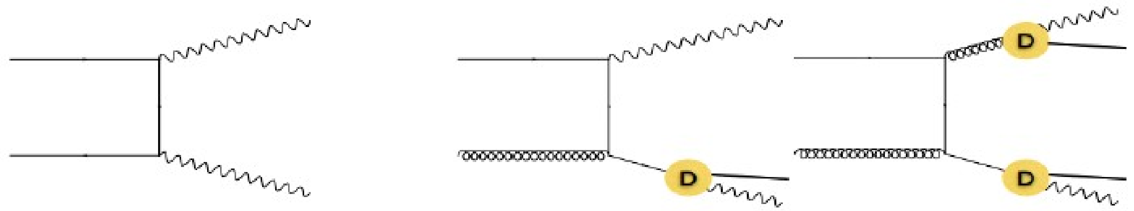
Production mechanisms @ LHC



γγ

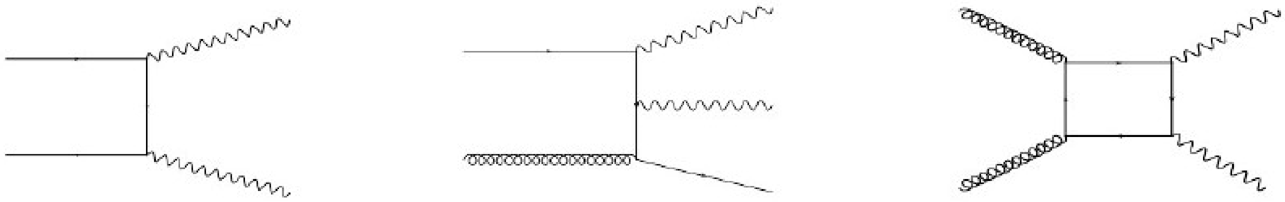
arXiv:1211.1913

- Probe QCD perturbation and framentation
- Two major Leading Order production mechanisms



Direct (point-like) Single and double resolved (collinear fragmentation)

- Sizeable Higher Order Correction

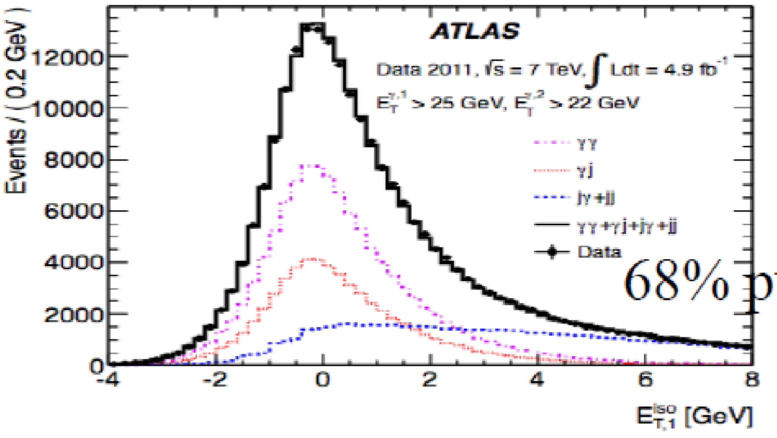


$\mathcal{O}(\alpha_s^0)$ but $q\bar{q}$ Luminosity $\mathcal{O}(\alpha_s)$ but qg Luminosity $\mathcal{O}(\alpha_s^2)$ but gg Luminosity

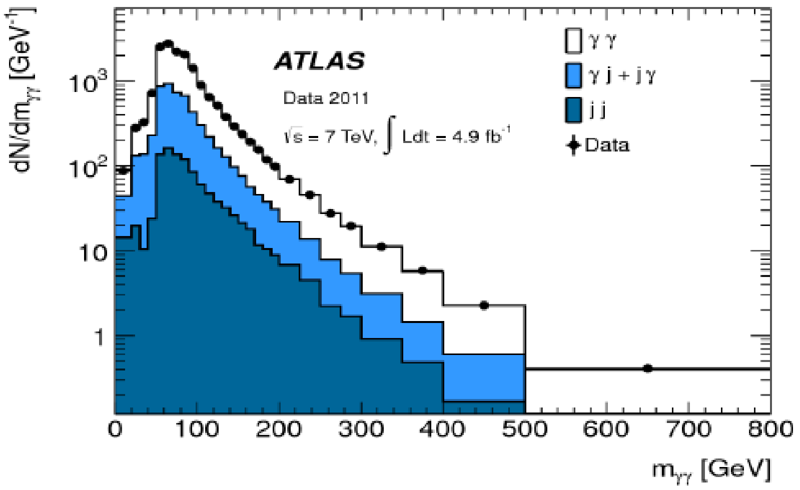
γγ cross-section

- Selection
  - $E_T > 25$ GeV, 22GeV
  - dR(γγ)>0.4
  - Isolation <4 GeV
- Background estimate
  - 2D sideband counting (Iso & γ ID)
  - 2D template fit (Iso)
- Cross-section

Measurement	$44.0^{+3.2}_{-4.2}\ pb$
Pythia/Sherpa	36pb
Diphox+gamma2mc	$39^{+7}_{-6}\ pb$
2γNNLO	$44^{+6}_{-5}\ pb$



68% purity



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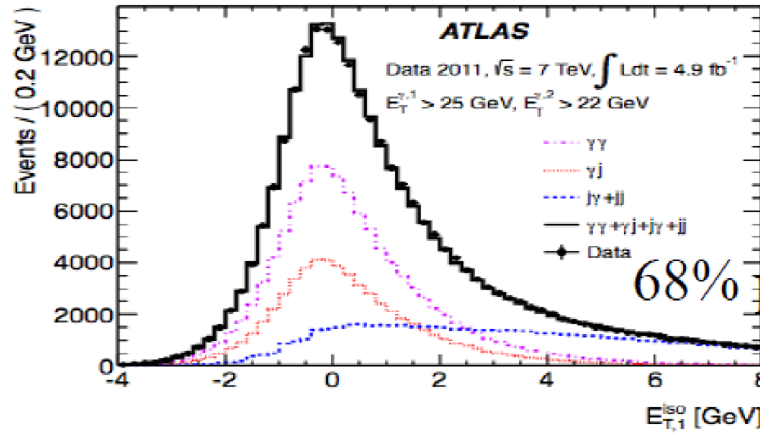

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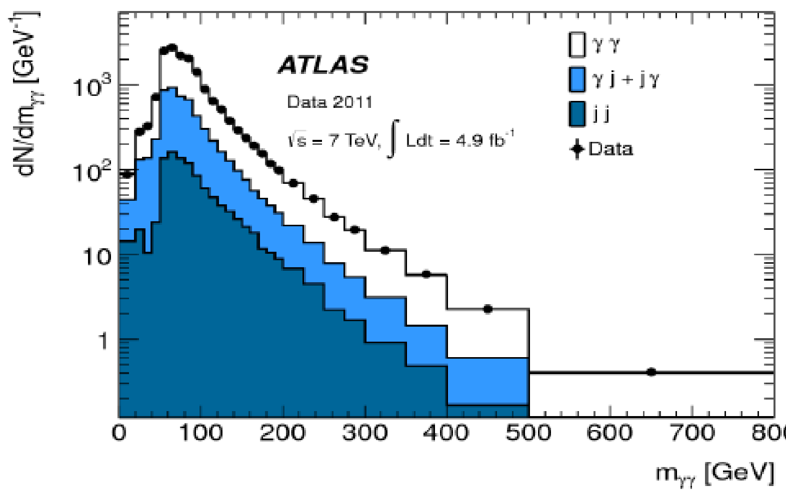
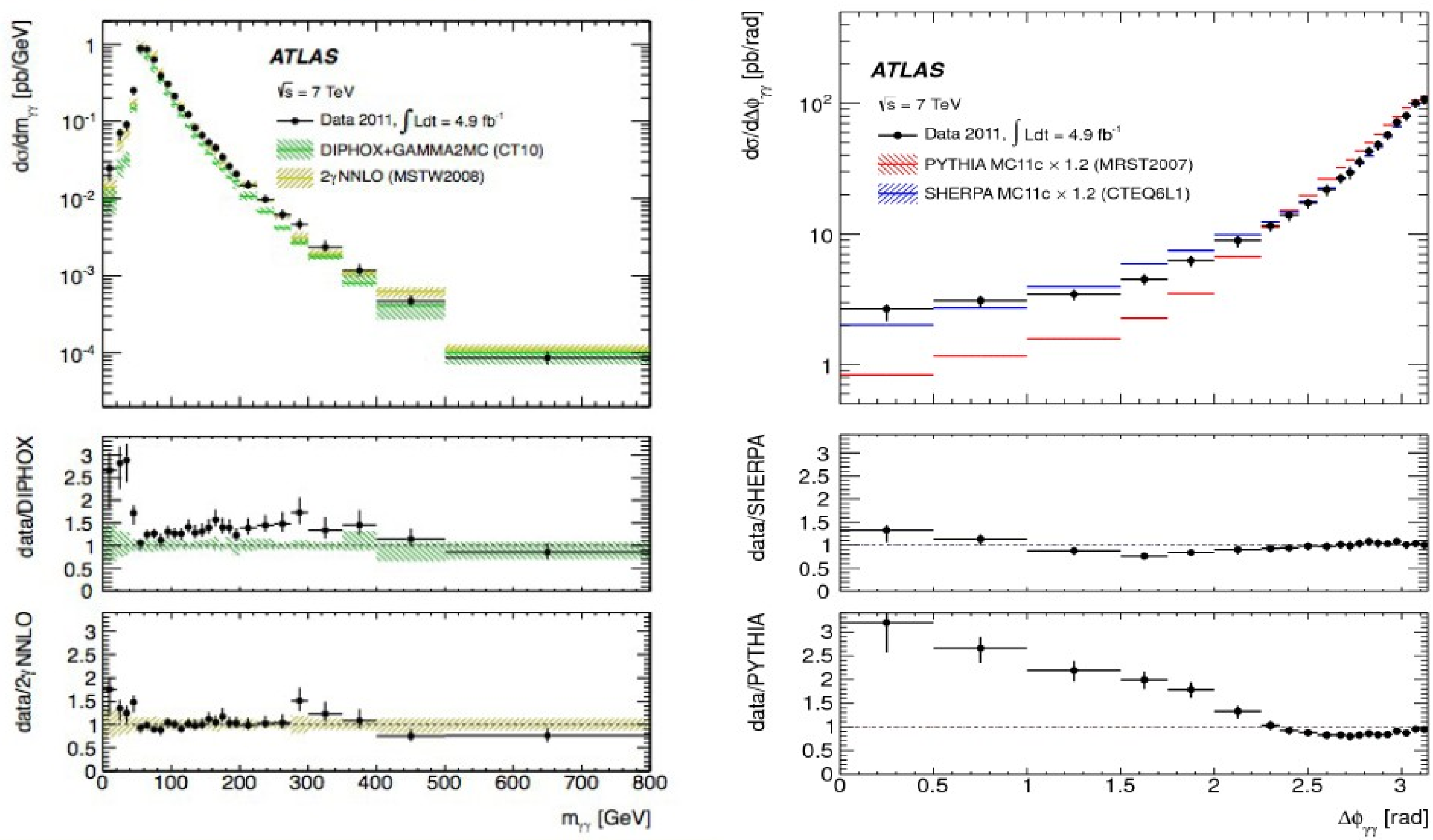


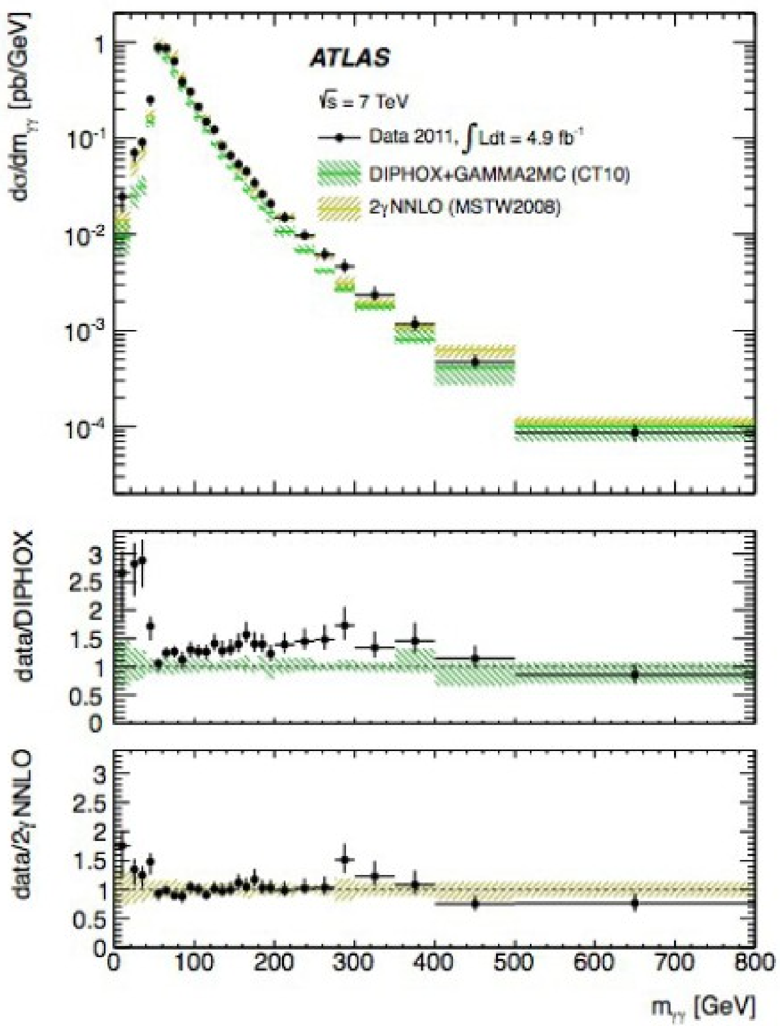
γγ differential cross-section

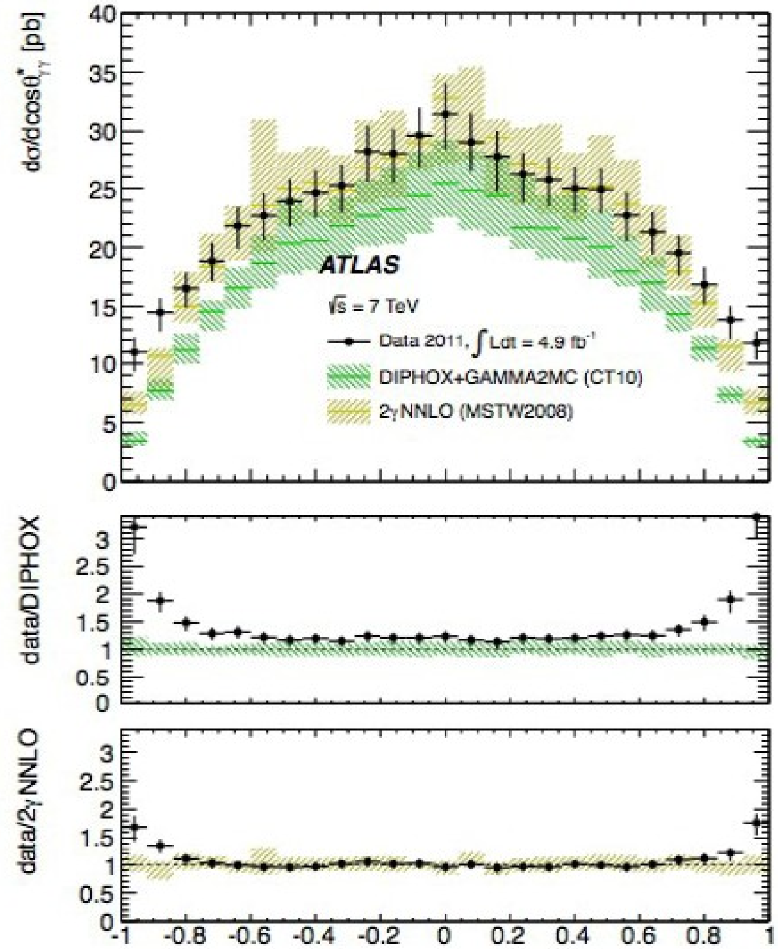
- LO prediction is scaled by 1.2



3

γγ differential cross-section

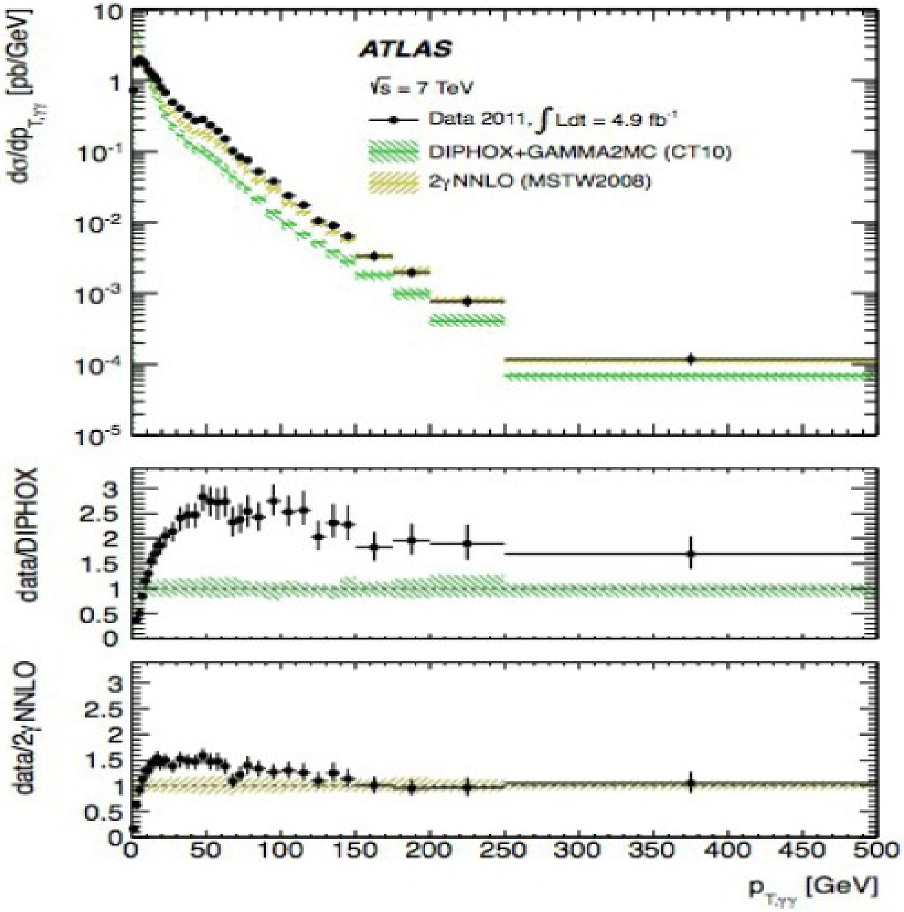


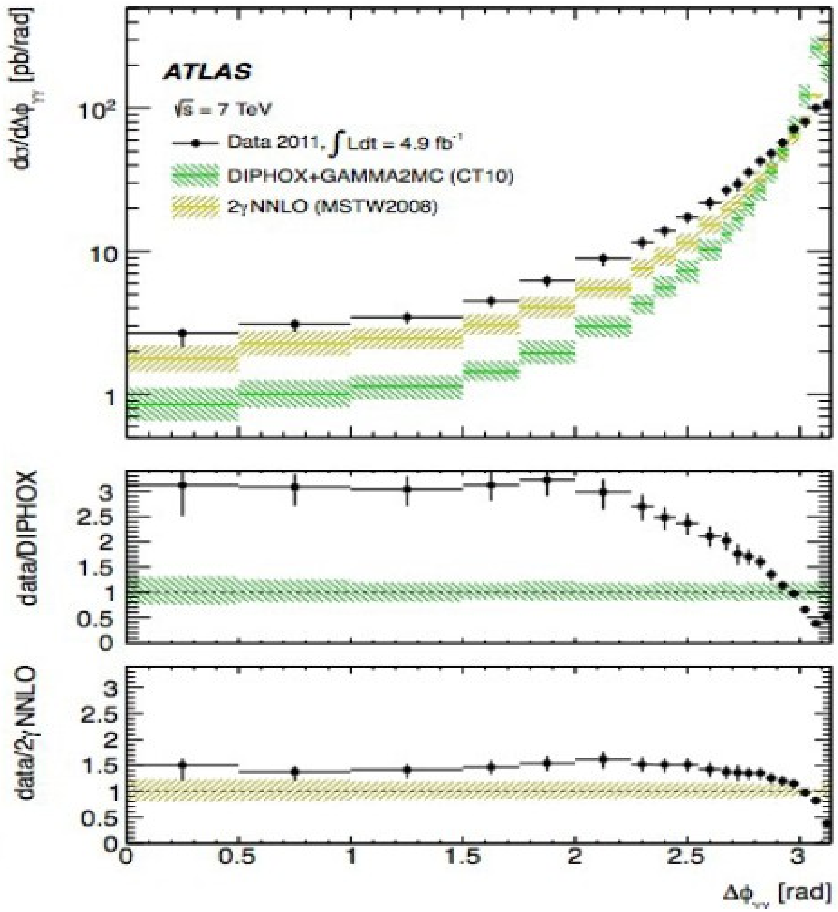


Collins–Soper di-photon rest frame

γγ differential cross-section

Understanding Higher-Order QCD/fragmentation





Dibosons

Datasets :
- 1.0 fb^{-1} at 7 TeV
- 4.7 fb^{-1} at 7 TeV
- 5.8 fb^{-1} at 8 TeV

	Charged VV			Neutral VV	
diboson channels	WW	WZ	Wγ	ZZ	Zγ
decay channels	lνlν	lνll	lνγ	llll	llγ
	lνqq	lνqq		llνν	

Strategy for cross-section measurement

1. Select candidate events

2. Background estimation

3. Correct for selection efficiencies $C_{V_1V_2}$

4. Calculate fiducial cross section

$$\sigma(pp \to V_1V_2) \times BR = \frac{N_{data} - N_{bkg}}{C_{V_1V_2} \times L}$$

5. Correct for branching fraction (BR) for each of the decay modes

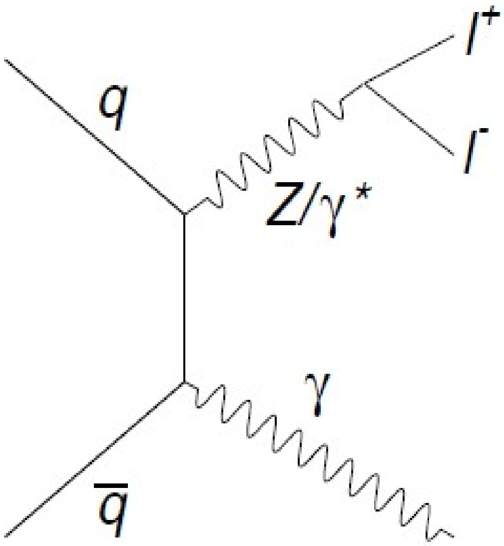
$$W\gamma \to \ell\nu\gamma, Z\gamma \to \ell\ell\gamma, WW \to \ell\nu\ell\nu, WZ \to \ell\nu\ell\ell, ZZ \to \ell\ell\nu\nu, ZZ \to \ell\ell\ell\ell \; (\ell = e, \mu)$$

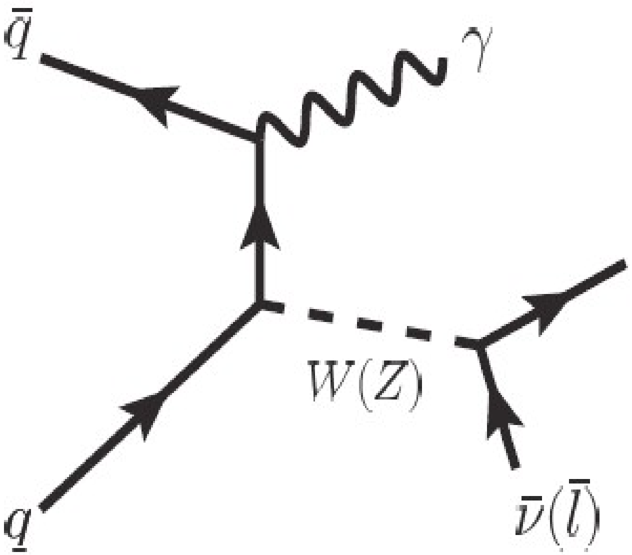
6. Correct for the acceptance of the fiducial volume (kinematic and geometric cuts) $A_{V_1V_2}$

7. Measure total cross section

$$\sigma(pp \to V_1V_2) = \frac{N_{data} - N_{bkg}}{C_{V_1V_2} \times L \times BR \times A_{V_1V_2}}$$

Zγ/Wγ production





Zγ/Wγ production

Selection requirements

Photon (γ)

- E_T > 15 GeV, |η| < 2.4
- Calorimetric isolated
- $\Delta R(\ell,\gamma) > 0.7$ (suppress FSR)

Z boson

- $m_{\ell\ell} > 40$ GeV

W boson

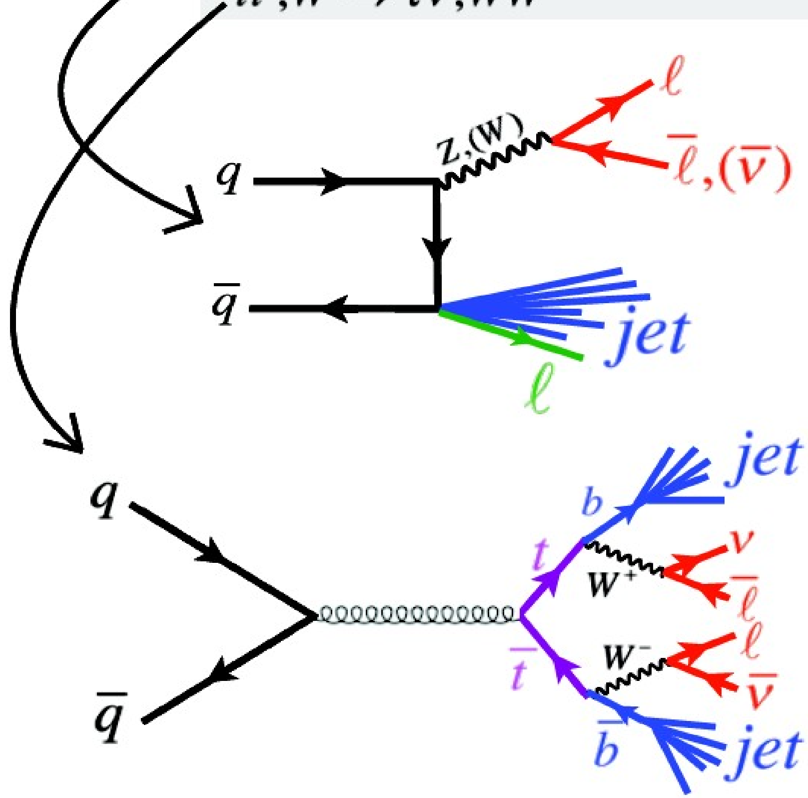
- m_T > 40 GeV

Exclusive Wγ and Zγ measurements

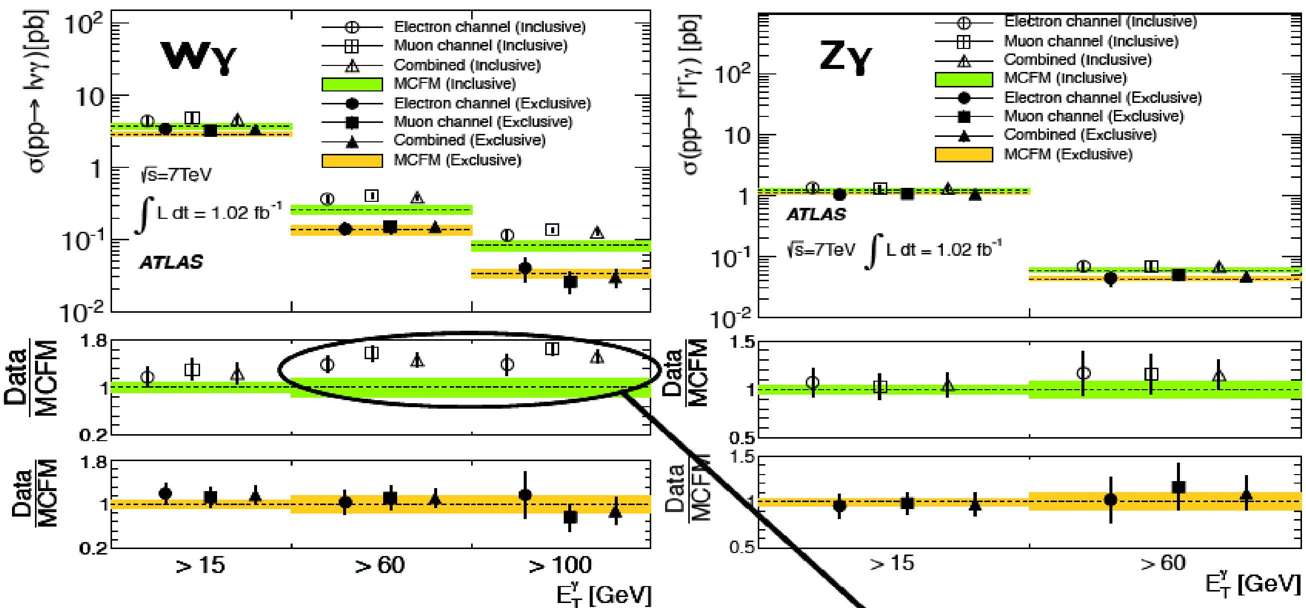
- Jet veto (p_T > 30 GeV)

Background Contamination

- Z/W + jets (dominant)
- $t\bar{t}, W \rightarrow \tau\nu, WW$



Zγ/Wγ production



Disagreement

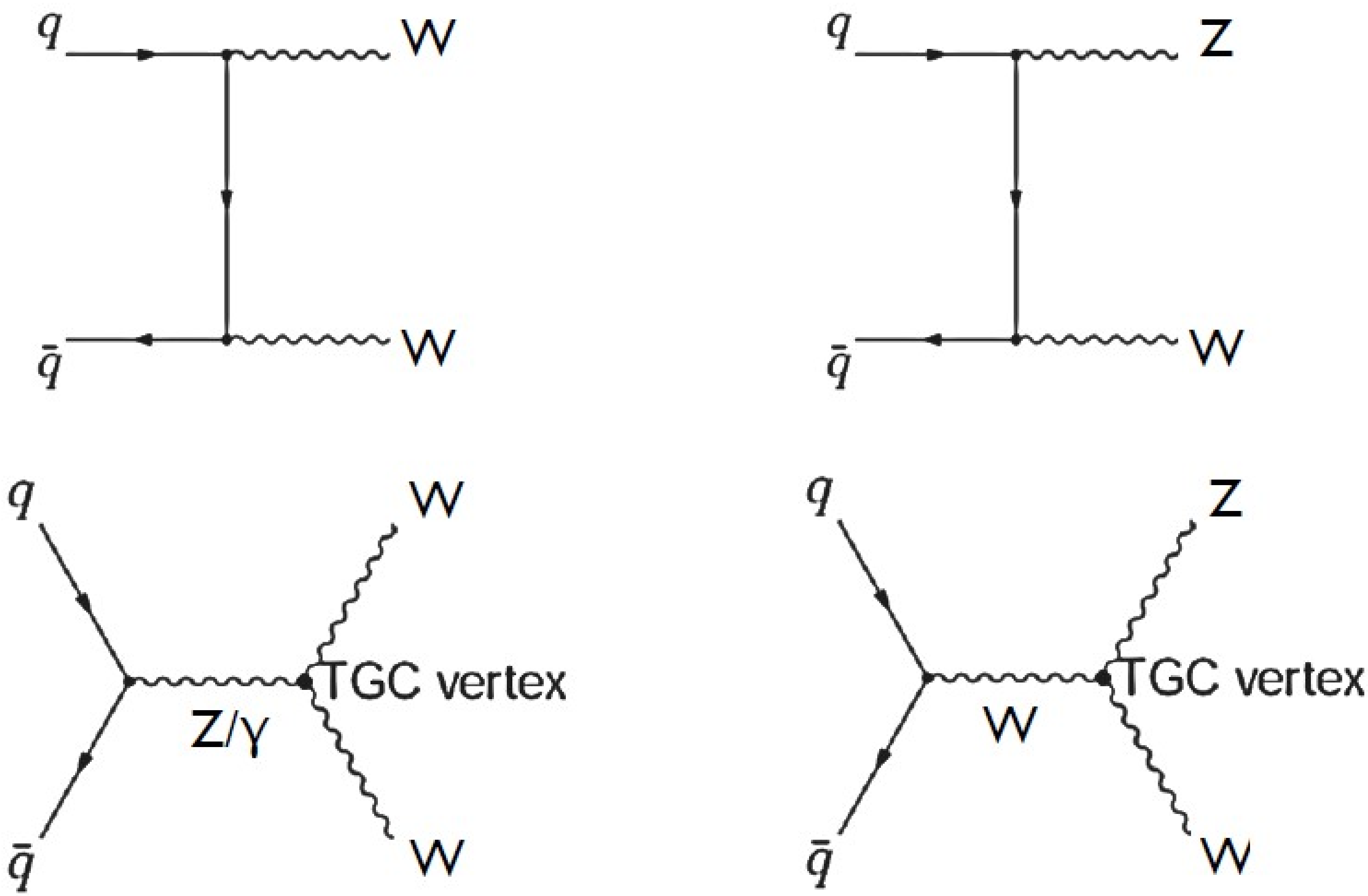
Good agreement for the ***exclusive*** x-section measurements

Disagreement due to lack of higher order QCD contributions in MCFM (W/ Zγ + 0,1,2,3,4... partons)

$E_T^\gamma > 60$ GeV

	$W\gamma \to \ell\nu\gamma$	$Z\gamma \to \ell\ell\gamma$
Exclusive	$\sigma_{exc}^{W\gamma} = 0.15 \pm 0.01 \pm 0.02$ pb	$\sigma_{exc}^{Z\gamma} = 0.047 \pm 0.007 \pm 0.004$ pb
	$\sigma_{exc}^{NLO,W\gamma} = 0.134 \pm 0.021$ pb	$\sigma_{exc}^{NLO,Z\gamma} = 0.043 \pm 0.004$ pb
Inclusive	$\sigma_{inc}^{W\gamma} = 0.38 \pm 0.02 \pm 0.03$ pb	$\sigma_{inc}^{Z\gamma} = 0.068 \pm 0.008 \pm 0.005$ pb
	$\sigma_{inc}^{NLO,W\gamma} = 0.260 \pm 0.038$ pb	$\sigma_{inc}^{NLO,Z\gamma} = 0.059 \pm 0.005$ pb

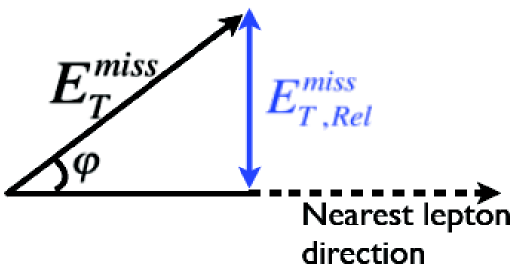
WW/WZ production



WW->lνlν analysis

Selection requirements

- exactly 2 isolated leptons with $p_T > 15$ GeV
- $E_{T,Rel}^{miss} > 25, 50, 55$ (eμ, ee, μμ)
- One OS-SF lepton pair
- Jet veto ($p_T > 25$ GeV)
- Z veto ($|m_{\ell\ell} - m_Z| < 15$ GeV)



Fiducial cross section

$$\sigma_{WW\to\ell\nu\ell\nu}^{fid} = 374.5 \pm 14.9(stat) \pm 28.1(syst) \pm 14.6(lumi)\ \text{fb}$$

NLO Fiducial cross section

$$\sigma_{fid,NLO}^{SM} = 320.3 \pm 26.2\ \text{fb}$$

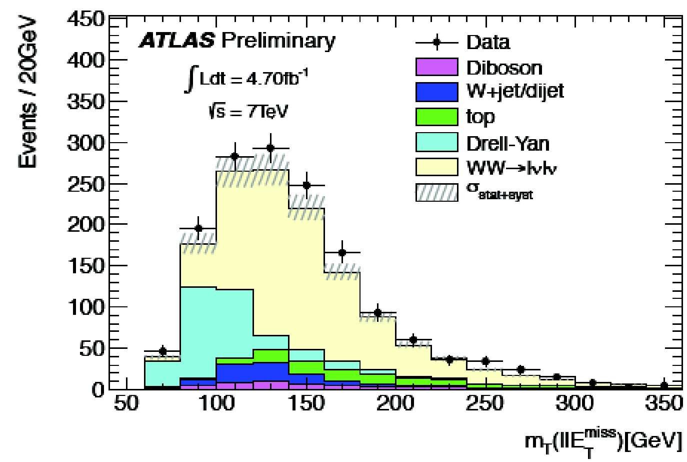
Total cross section

$$\sigma_{WW}^{tot} = 53.4 \pm 2.1(stat) \pm 4.5(syst) \pm 2.1(lumi)\ \text{pb}$$

NLO SM prediction (MC@NLO)

$$\sigma_{NLO}^{SM} = 45.1 \pm 2.8\ \text{pb}$$

Dominant uncertainty:
Systematic due to background estimation



Background Contamination

- Drell-Yan (removed from Z veto and $E_{T,Rel}^{miss}$)
- $t\bar{t}$, Wt (removed by jet veto)
- $W + jets$
- $WZ, ZZ, W\gamma^{(*)}$ (lepton veto if >3 leptons / event)

WZ->lνll analysis

Selection requirements

- 3 isolated leptons with p_T > 15 GeV
- Jet Veto (p_T > 20 GeV)
- Z→ $|m_{\ell\ell} - m_Z| < 10$ GeV
- W→ M_T^W > 20 GeV

Background Contamination

- Drell-Yan
- $t\bar{t}$
- $ZZ, Z\gamma$

Fiducial cross section

$$\sigma^{fid}_{WZ\to\ell\nu\ell\ell} = 92^{+7}_{-6}(stat) \pm 4(syst) \pm 2(lumi) \text{ fb}$$

NLO Fiducial cross section

$$\sigma^{SM}_{fid,NLO} = 82.5^{+5.3}_{-4.8} \text{ fb}$$

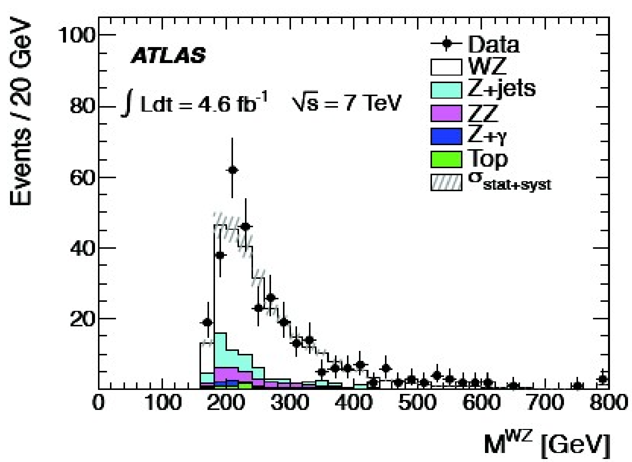
Total cross section

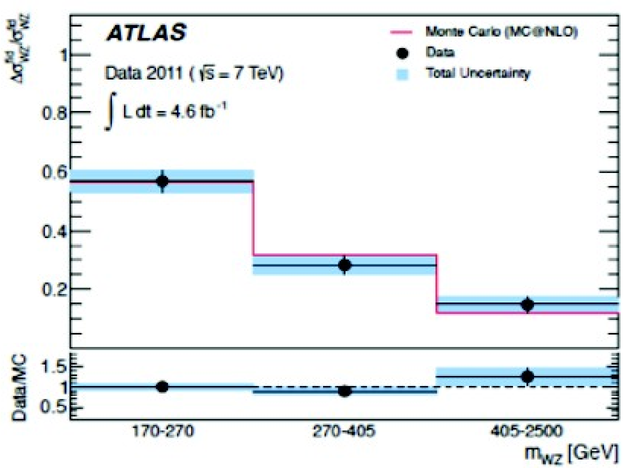
$$\sigma^{tot}_{WZ} = 19.0^{+1.4}_{-1.3}(stat) \pm 0.9(syst) \pm 0.4(lumi) \text{ pb}$$

NLO SM prediction (MCFM)

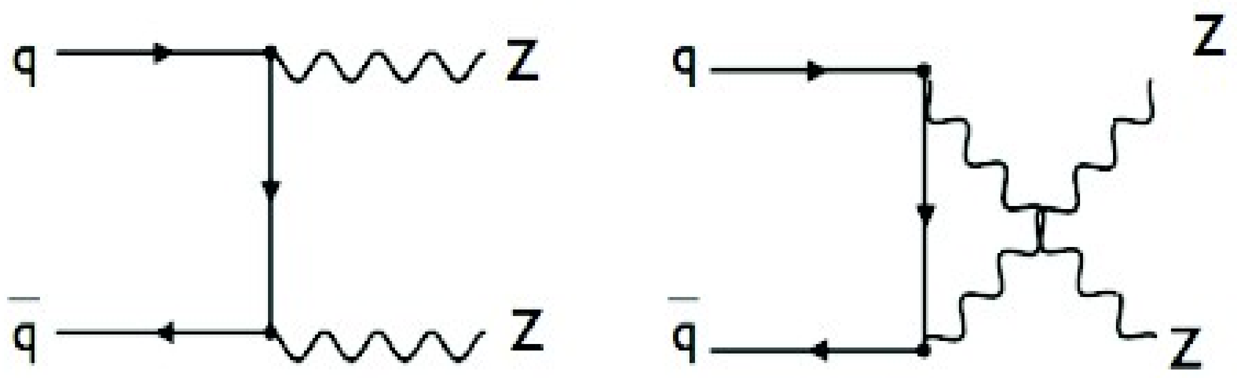
$$\sigma^{SM}_{NLO} = 17.6^{+1.1}_{-1.0} \text{ pb}$$

Dominant uncertainty:
Statistical





ZZ production

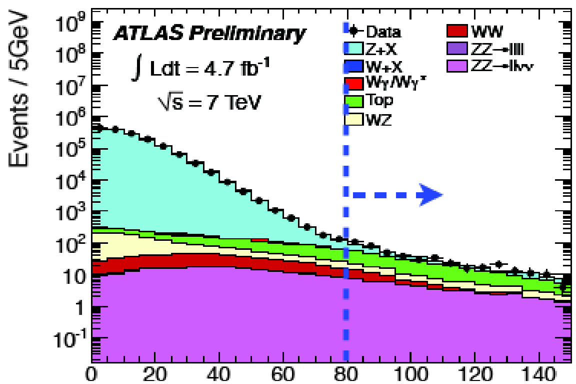


Standard Model Production

ZZ->llνν analysis

Selection requirements

- 2 isolated leptons with $p_T > 20$ GeV and $|\eta| < 2.5$
- One OS-SF lepton pair
- Axial $E_T^{miss} > 80$ GeV
- Jet veto if $p_T > 25$ GeV
- 3rd lepton veto ($p_T > 10$ GeV)
- $|m_{\ell\ell} - m_Z| < 15$ GeV



Background Contamination

- Drell-Yan (suppressed by the axial E_T^{miss} cut)
- $t\bar{t}$ (suppressed by the jet veto)
- WW,WZ (dominant), Wγ

Fiducial cross section

$$\sigma^{fid}_{ZZ\to\ell\ell\nu\nu} = 12.2^{+3.0}_{-2.8}(stat) \pm 1.9(syst) \pm 0.5(lumi)\ \text{fb}$$

NLO Fiducial cross section

$$\sigma^{SM}_{NLO} = 14.7^{+2.4}_{-2.3}\ \text{fb}$$

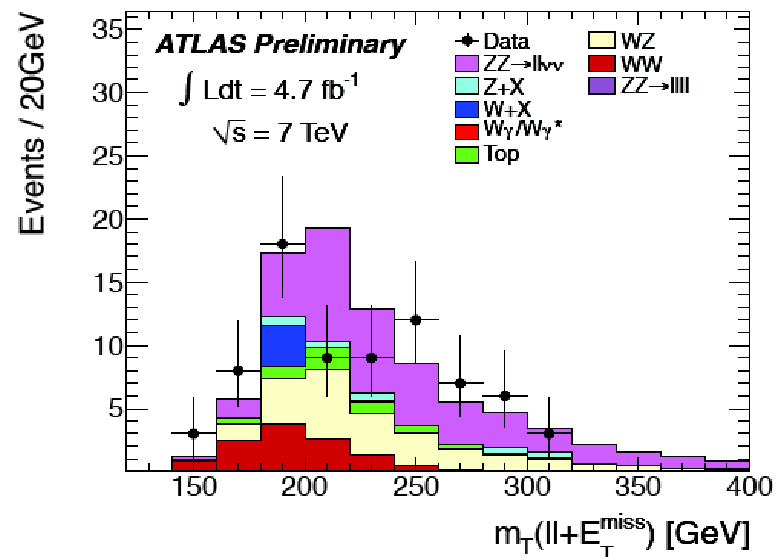
Comparable statistical and systematic uncertainties

Total cross section

$$\sigma^{tot}_{ZZ} = 5.4^{+1.3}_{-1.2}(stat)^{+1.4}_{-1.0}(syst) \pm 0.2(lumi)\ \text{pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 6.5^{+0.3}_{-0.2}\ \text{pb}$$



ZZ production

Selection requirements

- $|\eta_\ell| < 2.7$
- 4 isolated leptons with p_T > 7 GeV
- leading lepton p_T > 20 (25) GeV (e,μ)
- Two SF-OS isolated lepton pairs
- $66 < m_{\ell\ell} < 116$ GeV

Background Contamination

- $Z + jets$ (dominant)
- Background contamination (< 2%)

Fiducial cross section

$$\sigma^{fid}_{ZZ\to 4\ell} = 21.2^{+3.2}_{-2.7}(stat)^{+1.0}_{-0.9}(syst) \pm 0.8(lumi)\ \text{fb}$$

NLO Fiducial cross section

$$\sigma^{SM}_{fid,NLO} = 19.0^{+0.9}_{-0.7}\ \text{fb}$$

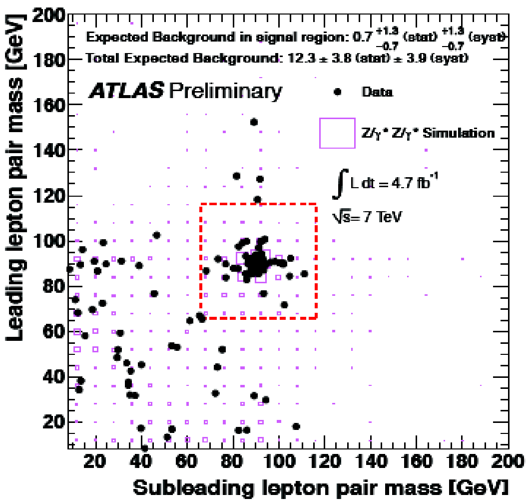
Dominant uncertainty:
Statistical

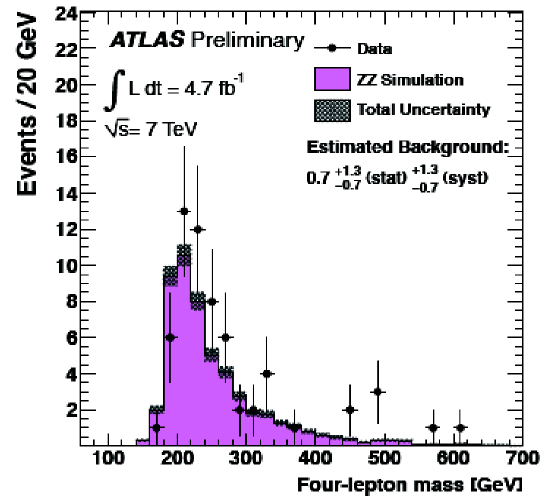
Total cross section

$$\sigma^{tot}_{ZZ} = 7.2^{+1.1}_{-0.9}(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi)\ \text{pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 6.5^{+0.3}_{-0.2}\ \text{pb}$$





ZZ production

Selection requirements

- 4 isolated leptons with p_T > 15 GeV
- leading lepton p_T > 25 GeV
- Two SF-OS isolated lepton pairs
- Mass cut: $66 < M_{ll} < 116$ GeV

Fiducial cross section

$$\sigma^{fid}_{ZZ\to 4\ell} = 21.0^{+2.4}_{-2.2}(stat)^{+0.6}_{-0.5}(syst) \pm 0.8(lumi)\ \text{fb}$$

NLO Fiducial cross section

$$\sigma^{SM}_{fid,NLO} = 16.8^{+0.5}_{-0.3}\ \text{fb}$$

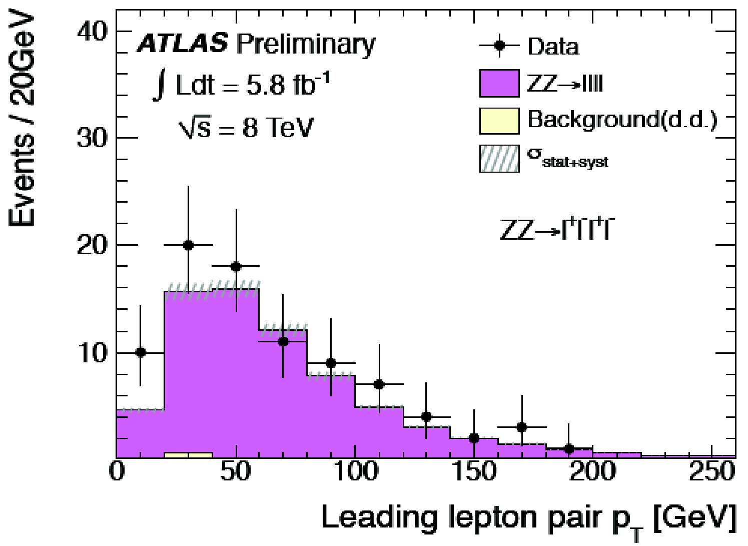
Dominant uncertainty: Statistical

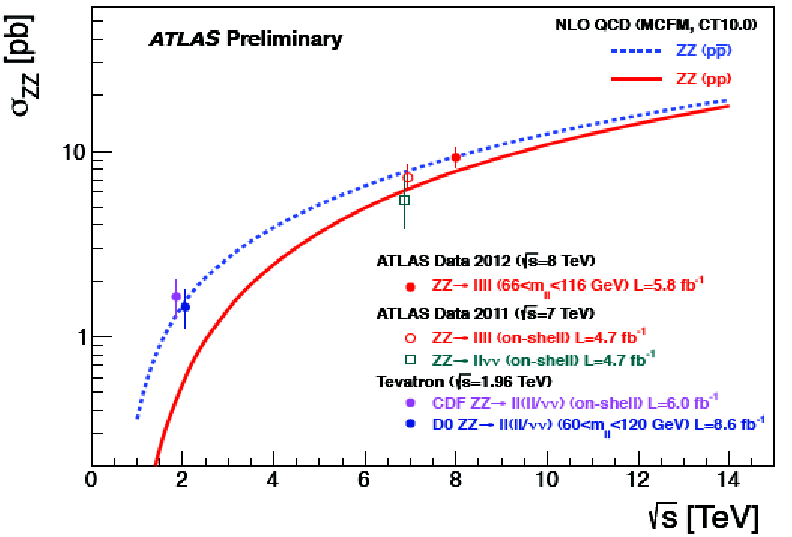
Total cross section

$$\sigma^{tot}_{ZZ} = 9.3^{+1.1}_{-1.0}(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi)\ \text{pb}$$

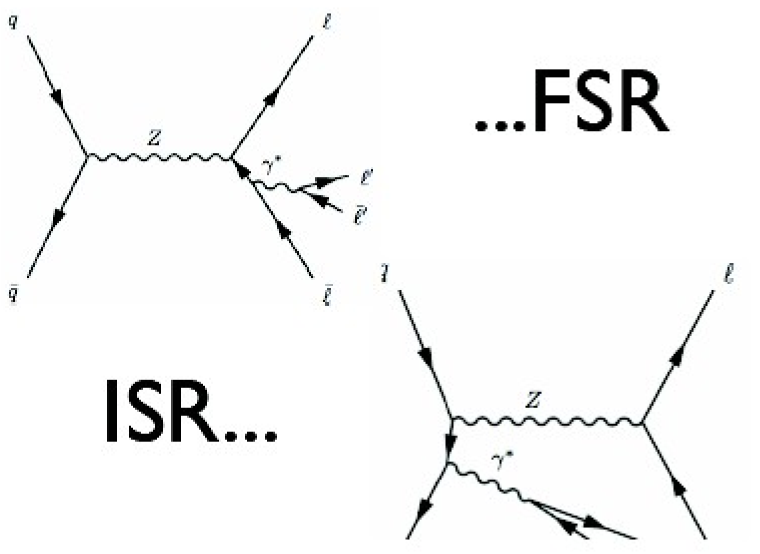
NLO SM prediction (MCFM)

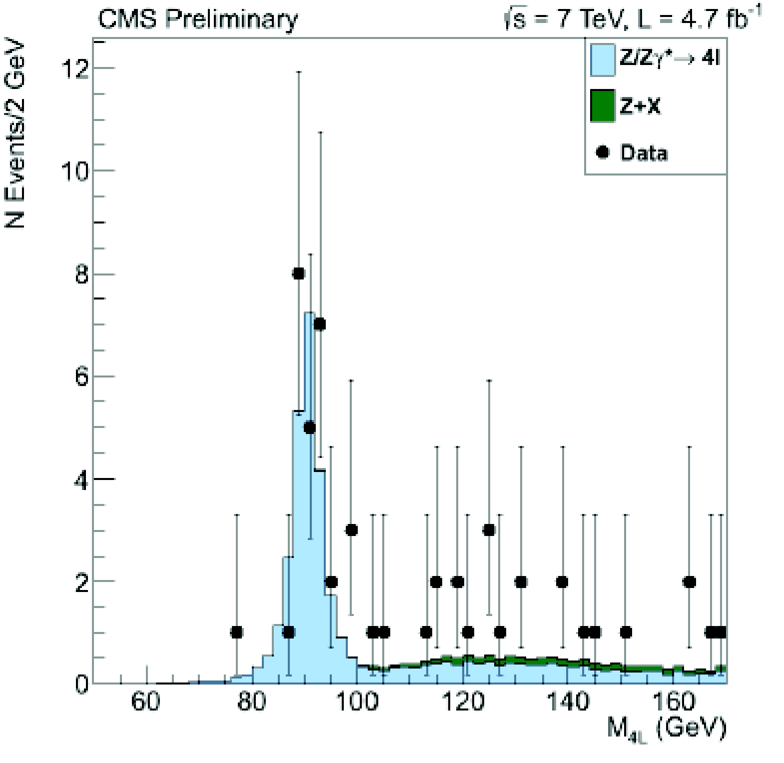
$$\sigma^{SM}_{NLO} = 7.4 \pm 0.4\ \text{pb}$$

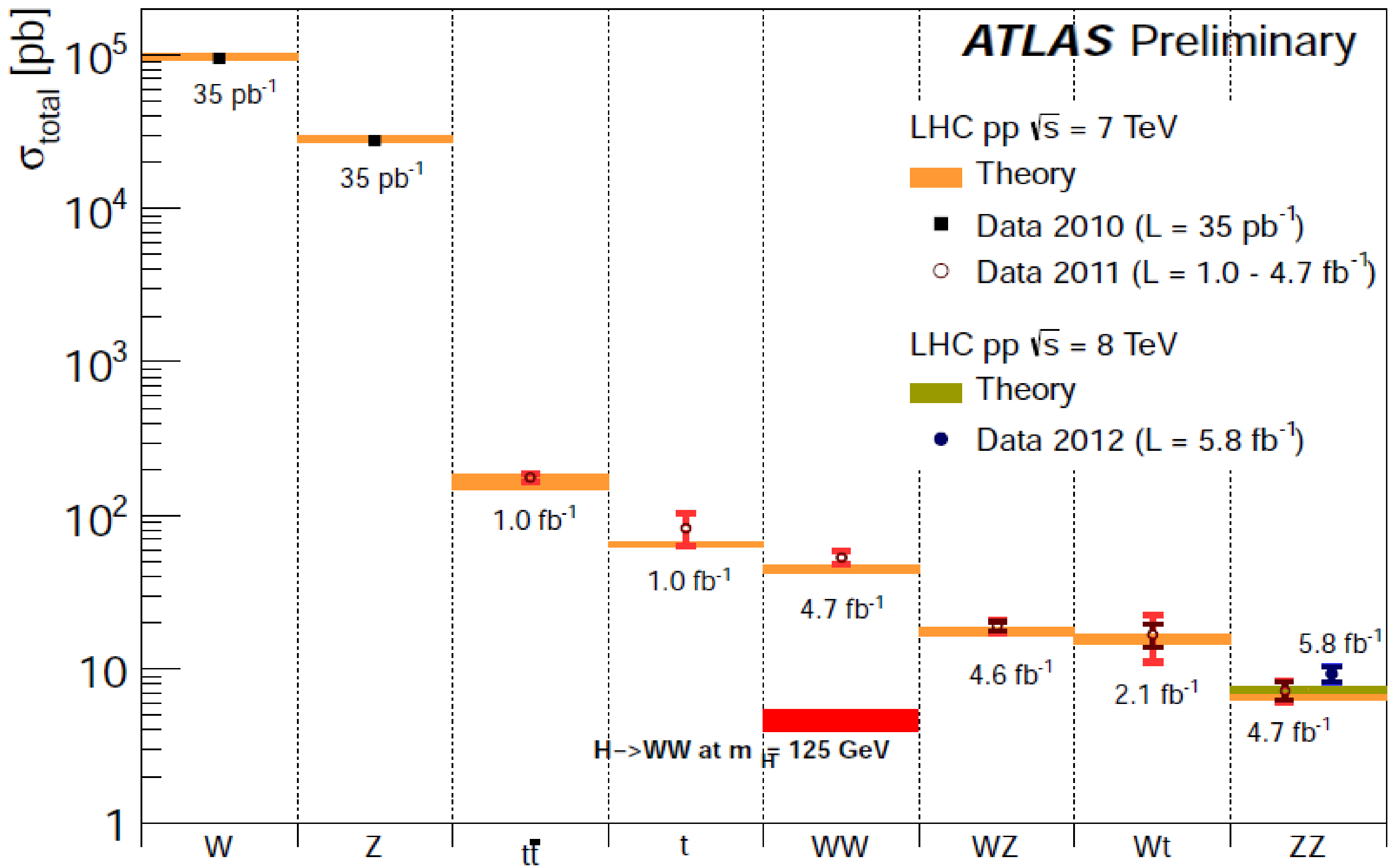




First observation of the Z->4l







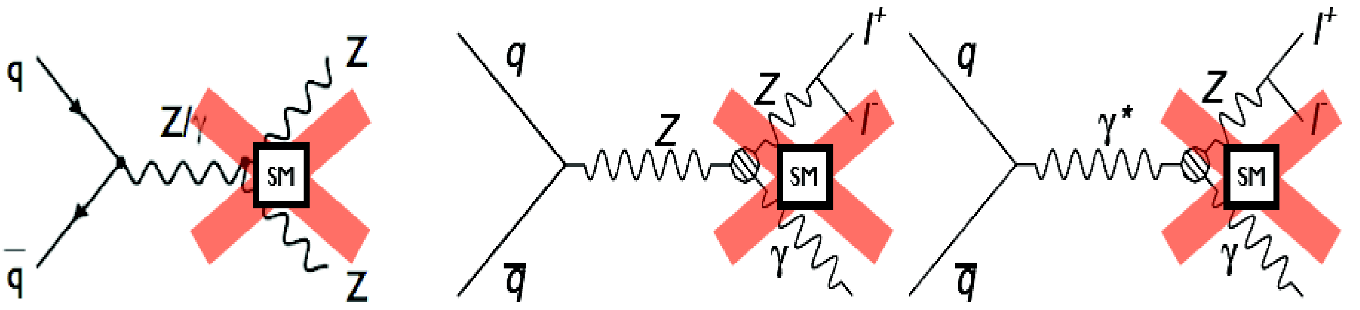
ATLAS Preliminary
σ_total [pb]
10^5
10^4
10^3
10^2
10
1
35 pb^-1
35 pb^-1
1.0 fb^-1
1.0 fb^-1
4.7 fb^-1
4.6 fb^-1
2.1 fb^-1
5.8 fb^-1
4.7 fb^-1
H->WW at m_H = 125 GeV
LHC pp √s = 7 TeV
Theory
Data 2010 (L = 35 pb^-1)
Data 2011 (L = 1.0 - 4.7 fb^-1)
LHC pp √s = 8 TeV
Theory
Data 2012 (L = 5.8 fb^-1)
W
Z
tt̄
t
WW
WZ
Wt
ZZ

Gauge couplings

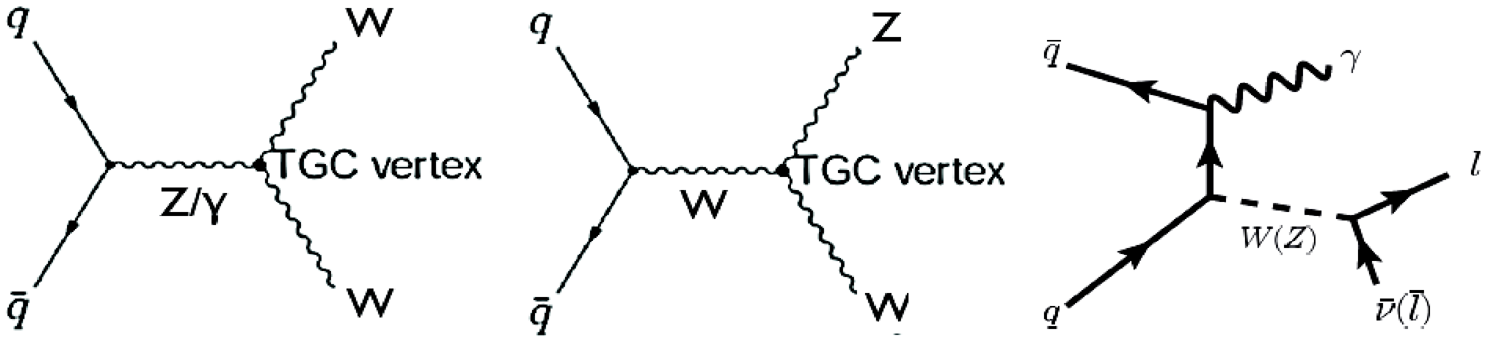
- In Standard Model (SM) non-abelian nature of $SU(2)_L$ x $U(1)_Y$ allow gauge bosons to interact with one another
  - Coupling between 3 gauge bosons=> triple Gauge-Boson Coupling (TGC)
- SM only allows charged coupling (WWZ, WWγ), does not allow pure neutral coupling (ZZZ,ZZγ,Z$\gamma\gamma$,$\gamma\gamma\gamma$) since Z/γ has no charge nor weak isospin.
- Physics beyond SM can introduce anomalous TGCs which may allow neutral couplings or increase the charged TGCs couplings strenght.

Limits

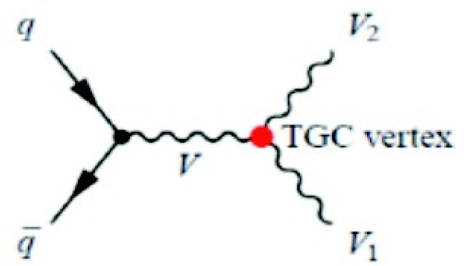
ZZZ/ZZγ/Zγγ   aTGC



WWZ/WWγ   aTGC



Anomalous Triple Gauge Couplings



aTGC → increase of cross section at high invariant mass and high transverse momentum

Effective Lagrangian

$WWV(V=Z,\gamma)$: $\frac{L_{WWV}}{g_{WWV}} = i\left(g_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu\right) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W^\dagger_{\rho\mu} W^\mu_\nu V^{\nu\rho}\right)$

$ZZV(V=Z,\gamma)$: $L = \frac{e}{m_Z^2}\left[f_4^V\left(\partial_\mu V^{\mu\beta}\right)Z_\alpha\left(\partial^\alpha Z_\beta\right) + f_5^V\left(\partial^\sigma V_{\sigma\mu}\tilde{Z}^{\mu\beta}Z_\beta\right)\right]$

Standard Model couplings:

$g_1^V = \kappa_V = 1$

$\lambda_V = f_4^V = f_5^V = h_3^V = h_4^V = 0$

→ Set limits on

$\Delta g_1^Z = g_1^Z - 1, \Delta\kappa_Z = \kappa_Z - 1, \lambda_Z, f_4^V, f_5^V, h_3^V, h_4^V$

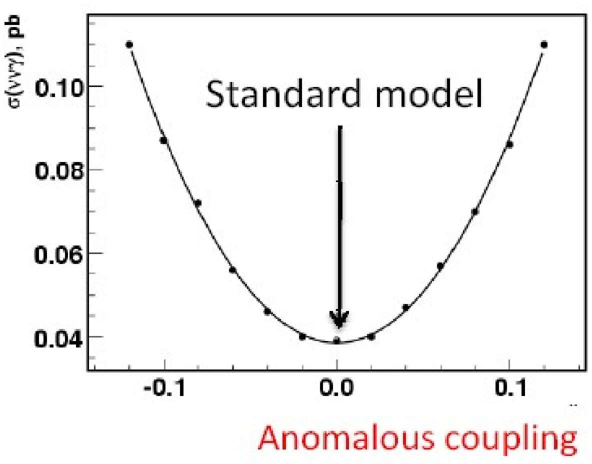
Introduce Form Factors to preserve unitarity at high $\sqrt{\hat{s}}$: $a(\hat{s}) = \frac{a_0}{\left(1+\hat{s}/\Lambda^2\right)^n}$

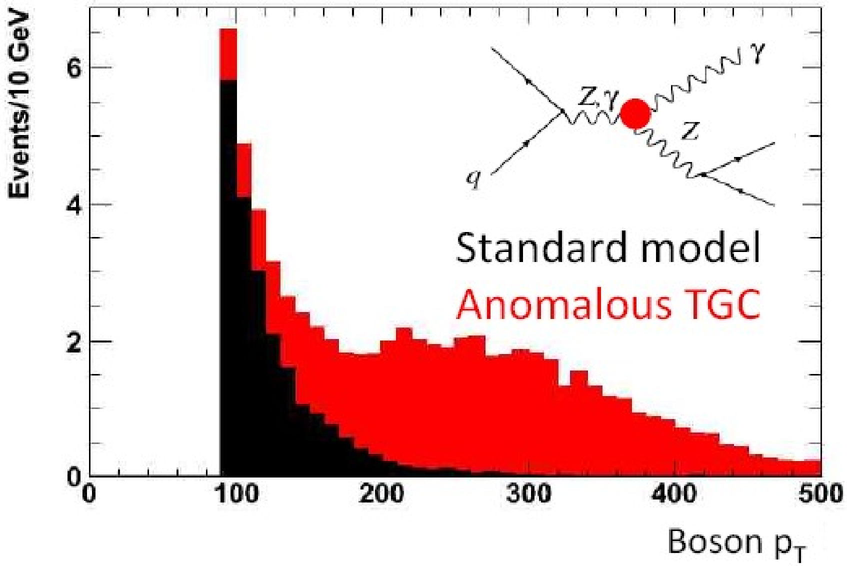
Characteristic of the TGC

- Sensitivity to TGCs comes from four different types of information
  - Cross section: parabolic increase of cross-section with TGC due to the linear Lagrangian: $\sigma \sim (TGC)^2$
  - Energy behaviour: TGC lead to a broad increase in the differential cross-section at large invariant mass $M_{WV,ZV}$ ($V=Z,\gamma$) and transverse momentum $P_T(V)$ ($V=W,Z,\gamma$)
  - Production angle: angular information of the bosons
  - Polarisation: different TGCs contribute to different boson helicity states. Decay angular information enhance sensitivity to individual TGCs.

Effect of anomalous coupling

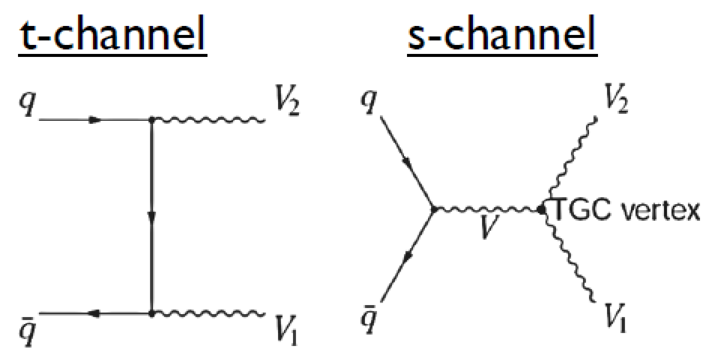
- Any non-zero coupling result in crease of the cross-section and harder p_T spectrum of the outgoing boson.
  - Can be simulated by a number of generators, such as Sherpa, MCFM, Baur, etc.





Anomalous gauge couplings

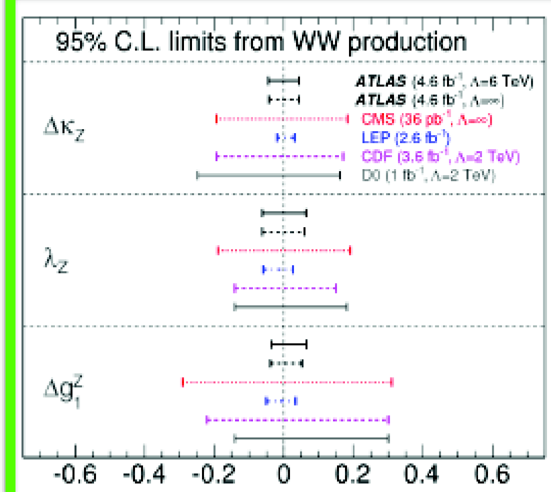
- The s-channel diagram contains a triple gauge coupling vertex
  - Neutral TGC are not allowed in the SM
  - Observation of either neutral TGC or deviations from the SM charged TGC would be evidence of new physics
- aTGC modify both production rate and event kinematics
  - Use measured cross section or event kinematics to constrain aTGC
  - Neutral and charged couplings probed by different channels
  - To stop cross-sections violating unitarity, aTGC is proportional to $1/(1+s/\Lambda)^2$ where Λ is the scale of the new physics that creates the anomalous couplings

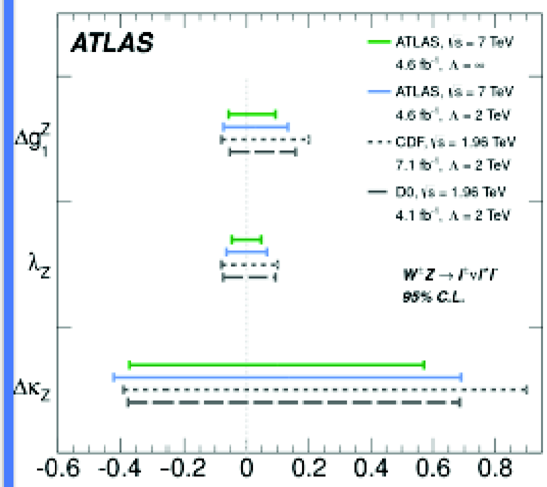


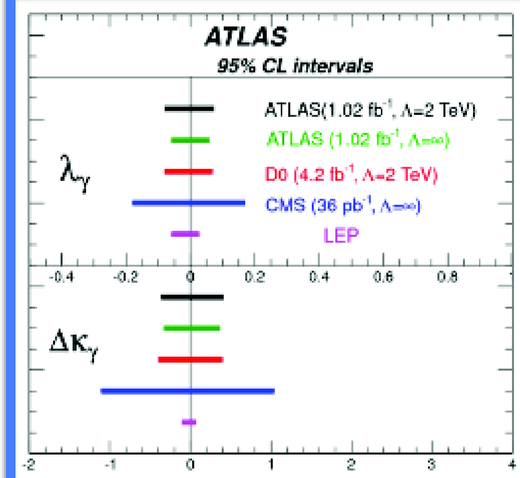
Coupling	Parameters	Channel
WWγ	λ_γ, $\Delta\kappa_\gamma$	WW, Wγ
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZγZ	f_4^γ, f_5^γ	ZZ

Charged aTGC results

WW result : **WZ result :** **Wγ result :**







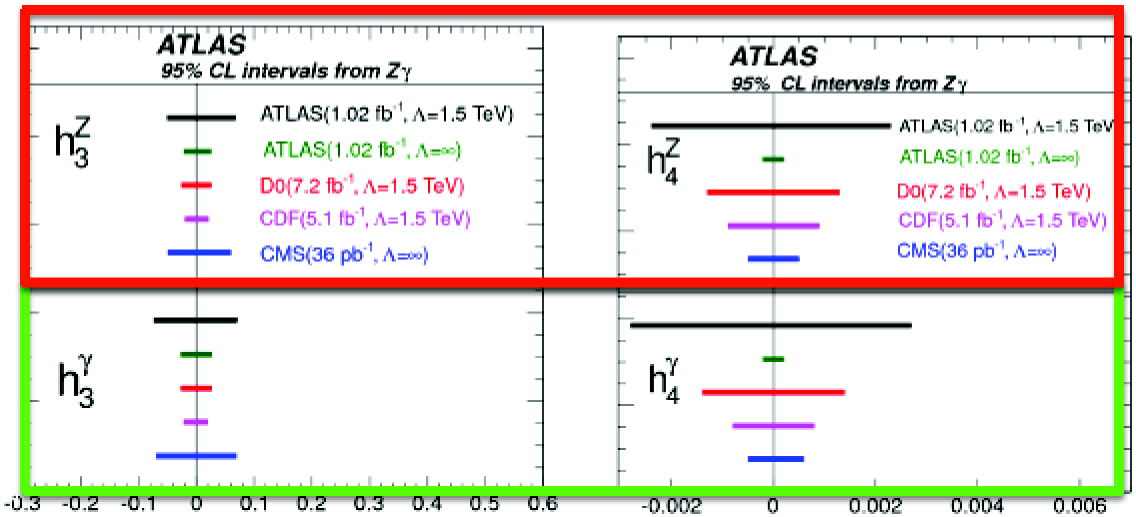
WWZ vertex : $(\Delta g_1^Z = g_1^Z - 1, \ \Delta\kappa_Z = \kappa_Z - 1, \ \lambda_Z = 0)$

WWγ vertex : $(\Delta\kappa_\gamma = \kappa_\gamma - 1, \ \lambda_\gamma = 0)$

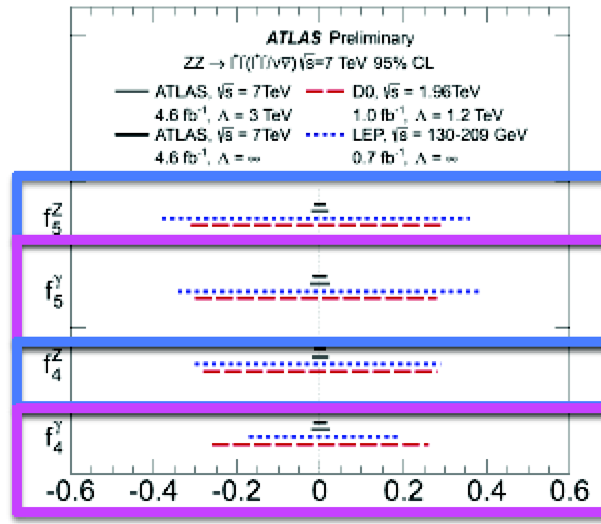
for WW, asumption that $\lambda_Z = \lambda_\gamma$ and $\Delta\kappa_Z = \Delta\kappa_\gamma$ (LEP scenario)

Neutral aTGC results

Zγ result :



ZZ result :



Zγγ vertex : $(h_3^\gamma=0,\ h_4^\gamma=0)$

ZZγ vertex : $(h_3^Z=0,\ h_4^Z=0)$

ZZγ vertex : $(f_4^\gamma = 0,\ f_5^\gamma = 0)$

ZZZ vertex : $(f_4^Z = 0,\ f_5^Z = 0)$

- Diboson measurements have formed a diverse and successful experimental programme at the LHC and Tevatron
  - Cross section measurements have been performed in WW, WZ, Wγ, Zγ and ZZ channels
    - Results typically in agreement with standard model predictions
    - Typical precision comparable to or better than size of NLO corrections
  - Events selected in these channels have been used to impose constraints on new physics
    - Limits on aTGC set using high p_T events to increase sensitivity
    - LHC measurements now most sensitive in most channels
    - Channel combinations emerging from both Tevatron and LHC tend to significantly increase sensitivity to aTGC
- Standard model processes holding up to scrutiny from $\sqrt{s} = 1.96 - 8$ TeV over several orders of magnitude in production cross sections