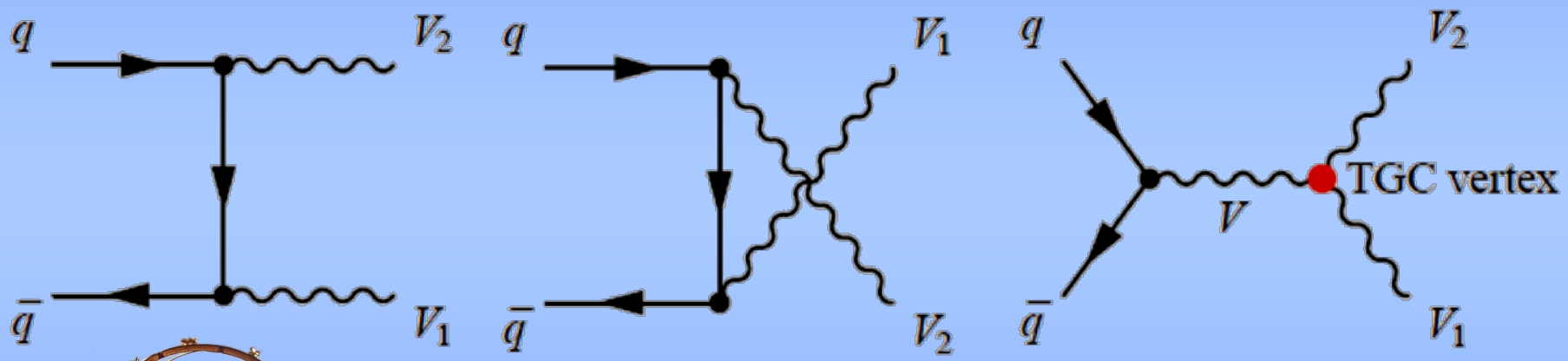
Diboson Production at ATLAS



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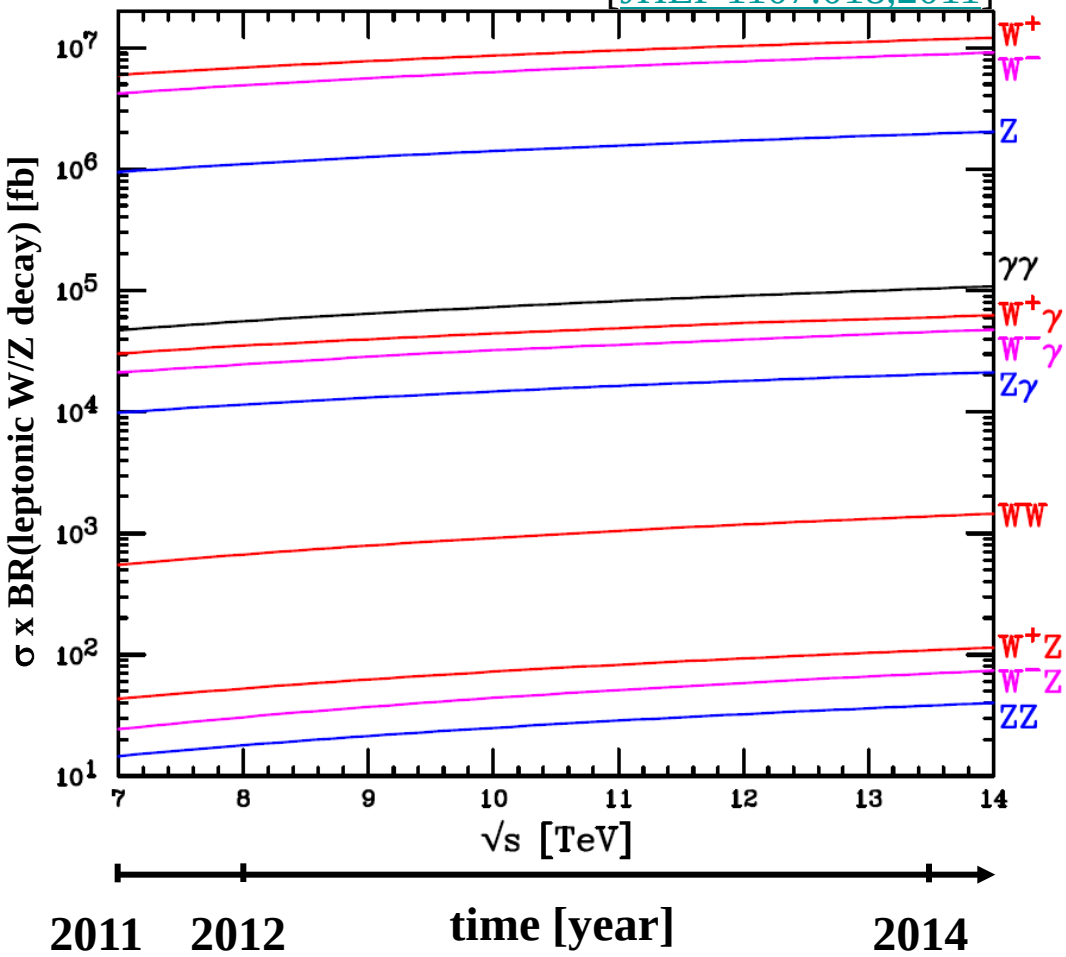
Joint Experimental-Theoretical Physics Seminar, FNAL, August 30 2013

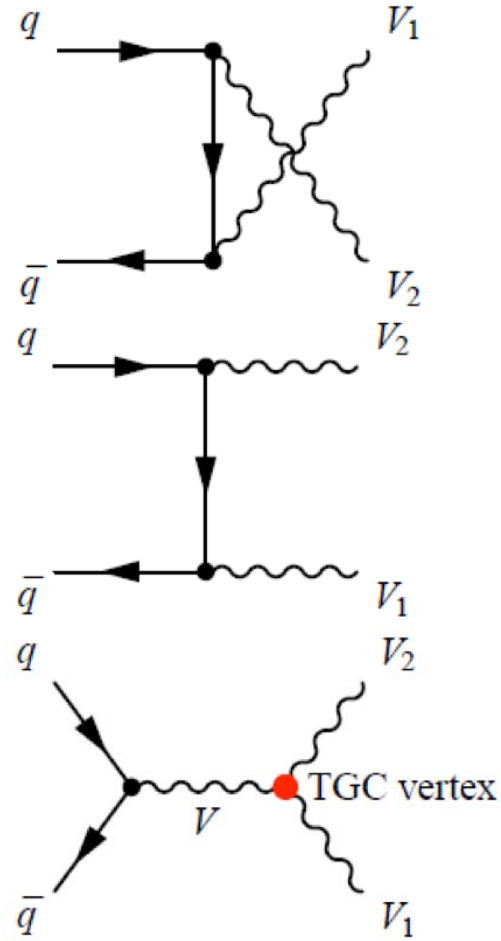
Outline

- Motivation
- Experimental Setup
- Diboson Cross Sections
- Anomalous Triple Gauge Couplings
- Future Plans
- Conclusion

DiBoson Production

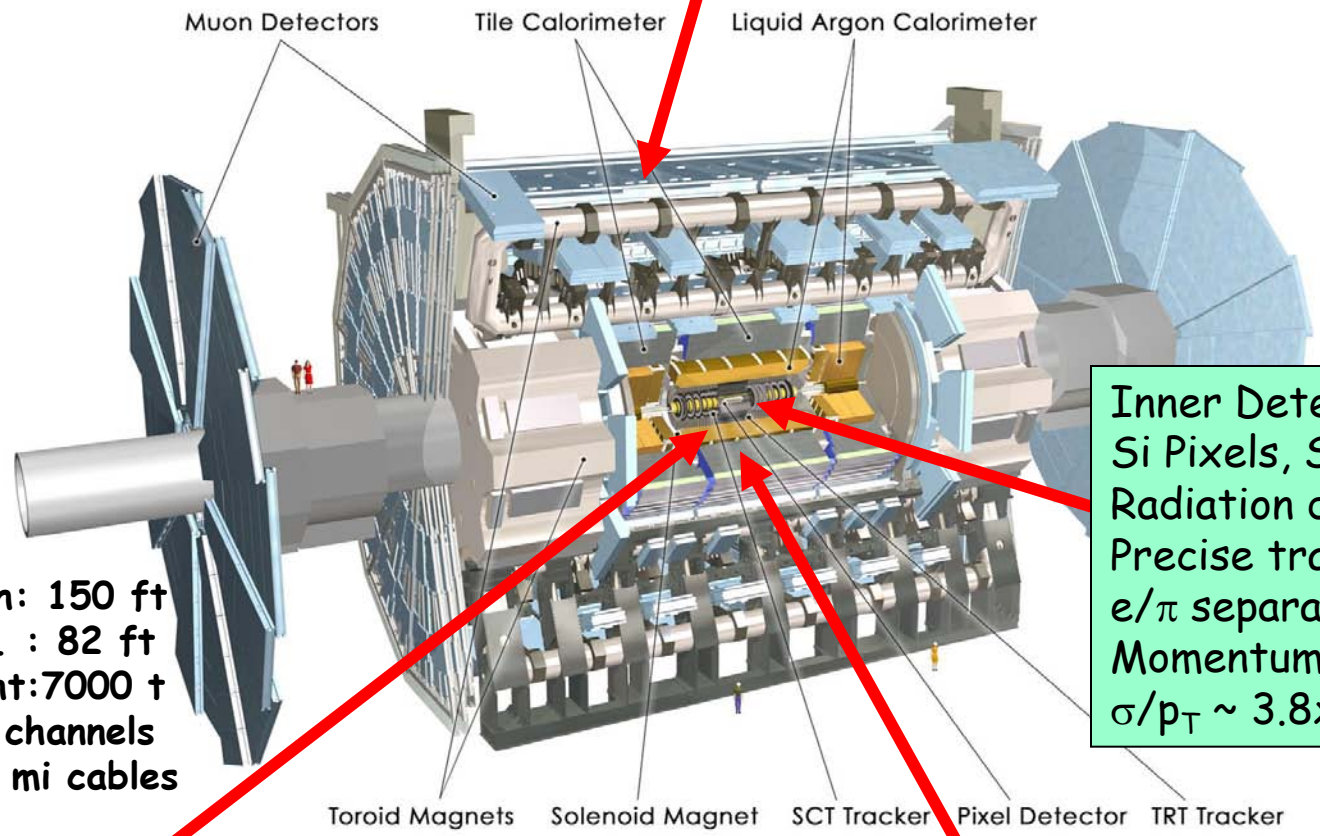
[JHEP 1107:018,2011]





Test SM predictions, probe new phenomena/aTGCs, background to Higgs

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV



3-level **trigger** reducing the rate from 40 MHz to ~200 Hz

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

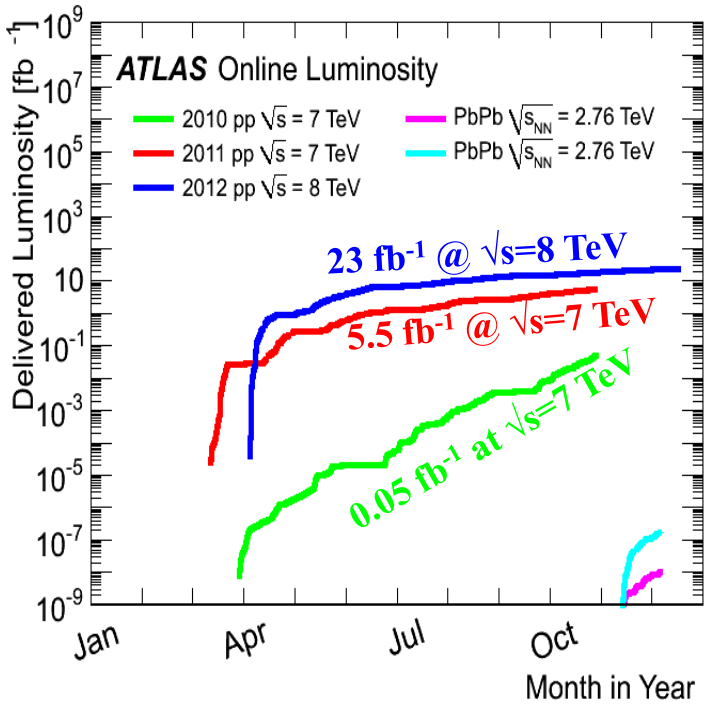
Length: 150 ft
Diam. : 82 ft
Weight:7000 t
~10^8 channels
~2000 mi cables

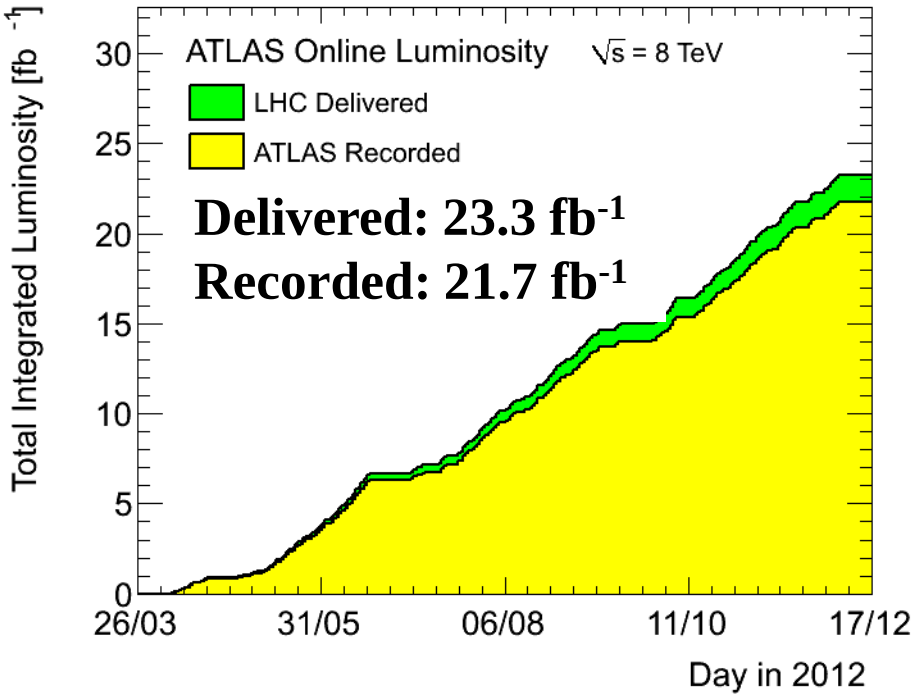
EM calorimeter: Pb-LAr Accordion
e/γ trigger, ID and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

LHC Run I as seen by ATLAS

<u>PDG 2010</u>: So to achieve high luminosity, **all one has to do** is make high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible.



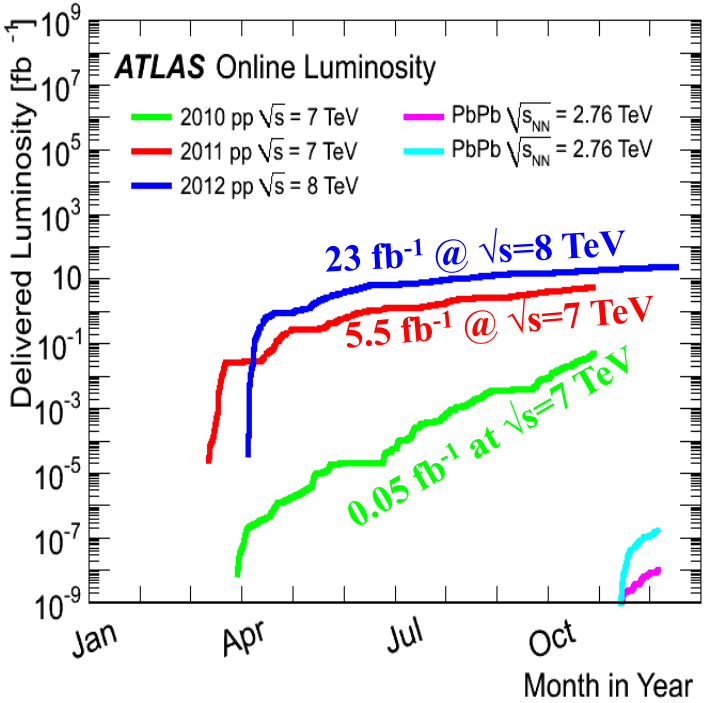


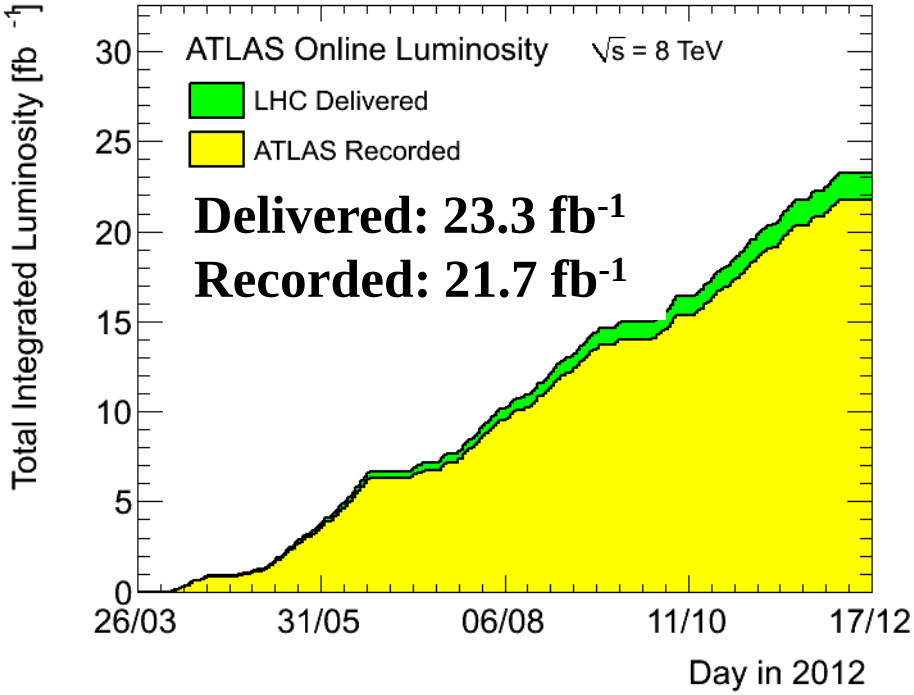
Total pp integrated luminosity in Run I: 29 fb^{-1}.

LHC Run I as seen by ATLAS

ATLAS luminosity in 2012

Peak Stable Luminosity Delivered:	7.73×10^{33} cm^{-2}s^{-1}
Max average interactions per bunch crossing:	37
Max Luminosity in fill/day/week:	237 pb^{-1} /286 pb^{-1} /1350 pb^{-1}
2011 Luminosity uncertainty:	1.8% [EPJ C 73 (2013) 2518]
2012 Luminosity uncertainty:	2.8% (prelim.)





Total pp integrated luminosity in Run I: 29 fb^{-1}.

ATLAS Detector Performance

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

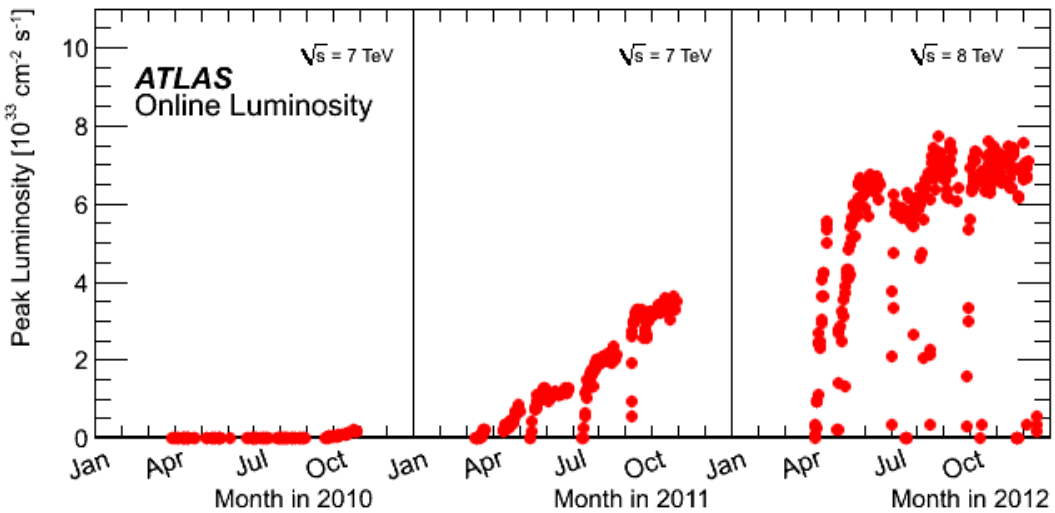
Data-taking efficiency for 2012: 93.5%

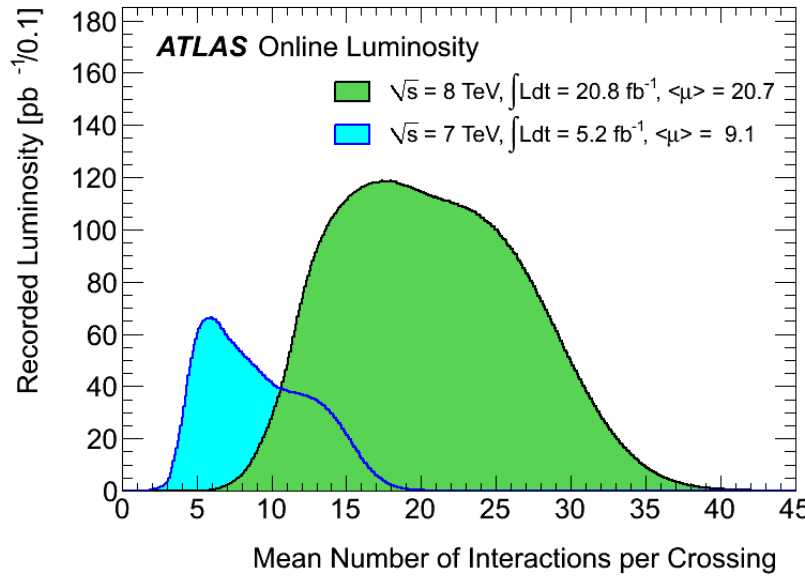
Of 2012 recorded data: 95.8% good for physics analysis

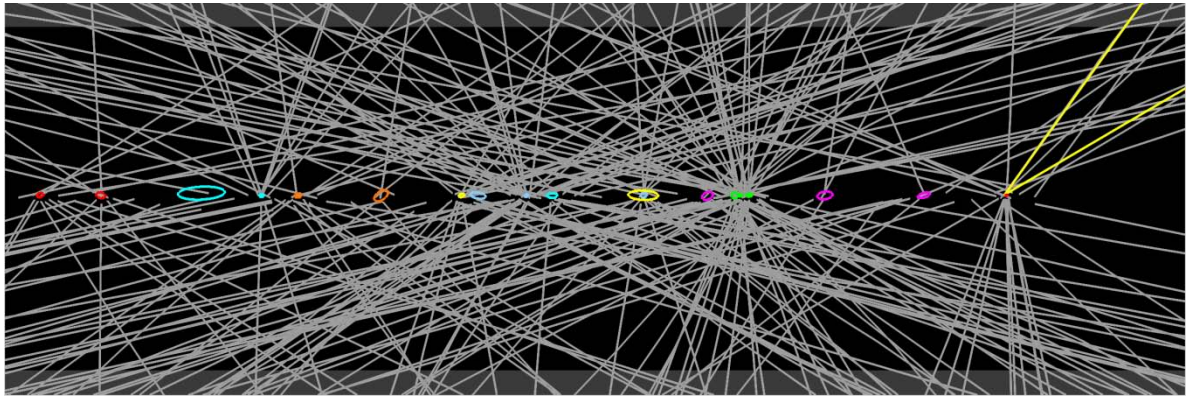
- High DQ partly due recovery from large data reprocessing
- DQ losses at 1% level or less for each individual system
- Given the high DQ efficiency, use a common set of "good quality data" across (almost) all analyses

90% of delivered luminosity is used for physics analysis

The price of high lumi…







Z→ μμ candidate event, w/ 20 reconstructed vertices.

DiBoson Analyses Overview

- Leptonic W/Z decay channels allow signal extraction from large BG (ℓ= e or μ)
- SM BR(W$\rightarrow \ell\nu$) = 0.108, BR(Z$\rightarrow \ell\ell$) = 0.03366
- Experimental signature **isolated high p_T leptons/photons (plus MET if ν present)**
- Common backgrounds: Top, V+jets/γ, other diboson processes
- Data driven methods used where possible

Channel	Int. luminosity	$\sqrt{s}$ [TeV]	[Ref]
W/Z $\gamma \rightarrow \ell\nu\gamma/\ell\ell\,\gamma$, $\nu\nu\gamma$	4.6 fb^{-1}	7	*PRD 87, 112003 (2013)*
WW $\rightarrow \ell\nu\ell\nu$	4.6 fb^{-1}	7	*PRD 87, 112001 (2013)*
WZ $\rightarrow \ell\nu\ell\ell$	4.6 fb^{-1}	7	*EPJ C (2012) 72:2173*
	13 fb^{-1}	8	ATLAS-CONF-2013-021
WV $\rightarrow \ell\nu jj$	4.6 fb^{-1}	7	ATLAS-CONF-2012-157
ZZ $\rightarrow \ell\ell\nu\nu$	4.6 fb^{-1}	7	*JHEP03(2013)128*
ZZ $\rightarrow \ell\ell\ell\ell$	4.6 fb^{-1}	7	
	20 fb^{-1}	8	ATLAS-CONF-2013-020

Cross Section Measurements

Fiducial cross section:

$$\sigma_{fid}^{VV} = \frac{N_{data} - N_{bg}}{C_{VV}\mathcal{L}}$$

C_{VV} = correction factor in fiducial volume ($N_{selected}/N_{truth\ in\ fiducial}$),
mainly experimental uncertainties.
Fiducial cuts mirror analysis cuts, e.g. with MET = $p_T(\nu,\bar{\nu})$

Total cross section:

$$\sigma(pp \to VV) = \frac{N_{data} - N_{bg}}{A_{VV}C_{VV}\mathcal{L}\mathcal{B}} = \frac{\sigma_{fid}^{VV}}{A_{VV}\mathcal{B}}$$

A_{VV} = acceptance factor ($N_{truth\ in\ fiducial}/N_{generated}$) for extrapolation to full phase space,
mainly theoretical uncertainties.

N_{data} = number of observed data events
N_{bg} = estimated background events
$\mathcal{L}$ = integrated luminosity of the data sample
$\mathcal{B}$ = leptonic branching ratio of V

$W\gamma \rightarrow \ell\nu\gamma$

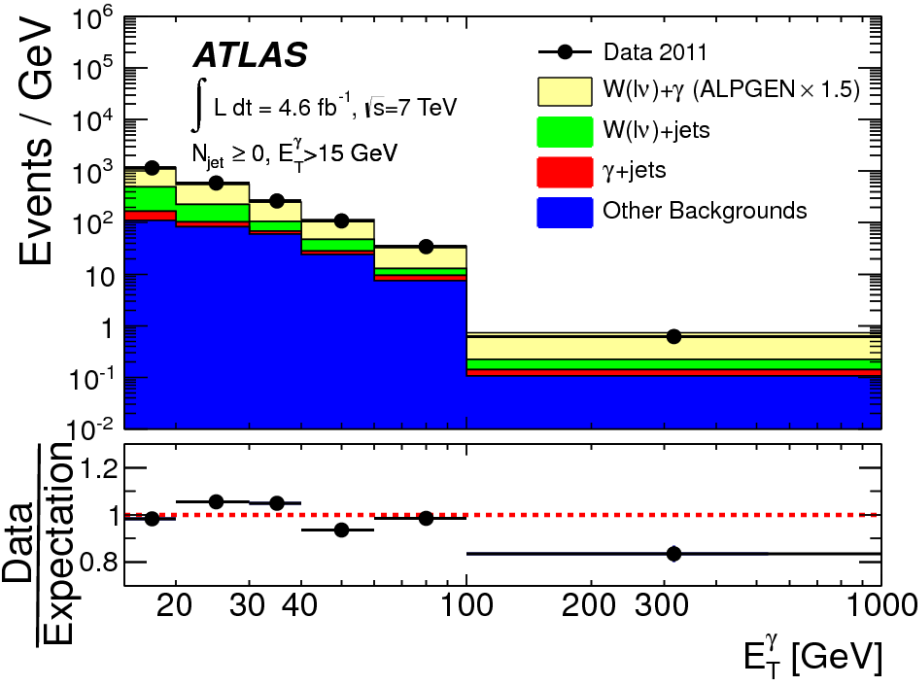
Preselection:

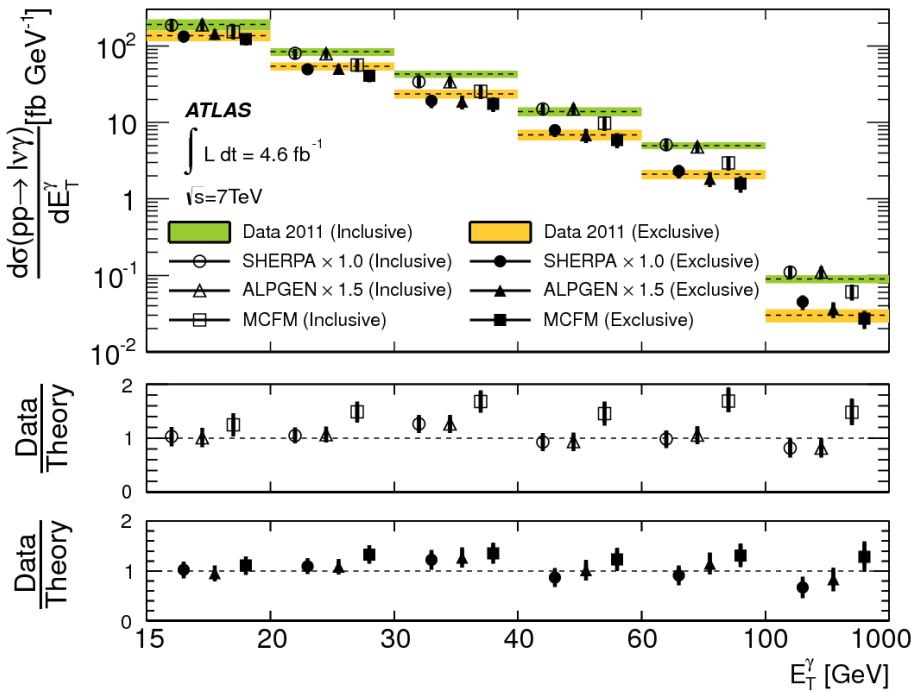
- γ: $E_T > 15$ GeV, $\Delta R(\ell, \gamma) > 0.7$
- 1ℓ, $p_T > 25$ GeV, $|m_{e\gamma}-m_Z| > 15$ GeV
- MET > 35 GeV, $m_T > 40$ GeV
- Jet counting: $E_T > 30$ GeV, $|\eta| < 4.4$

Major backgrounds: W+j, $Z(\ell\ell)$, γ+j

Measured fiducial cross sections:

- Inclusive (#jets ≥ 0) & exclusive (#jets=0)
- Good shape modelling by ALPGEN, SHERPA
- MCFM prediction @ high $E_T(\gamma)$: poor inclusive modelling , better exclusive





$Z\gamma \rightarrow \ell\ell\gamma$

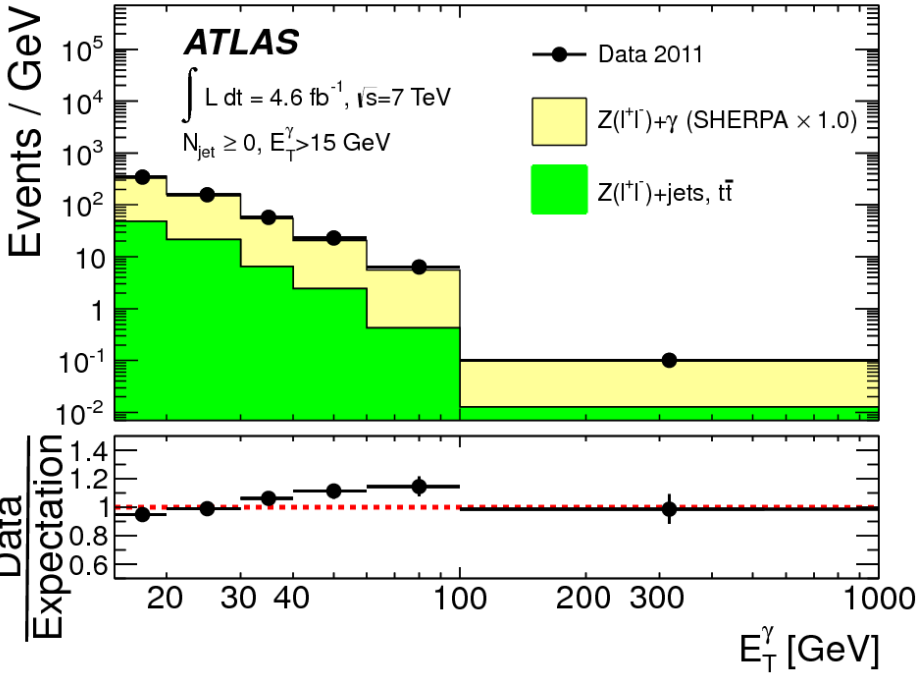
Preselection:

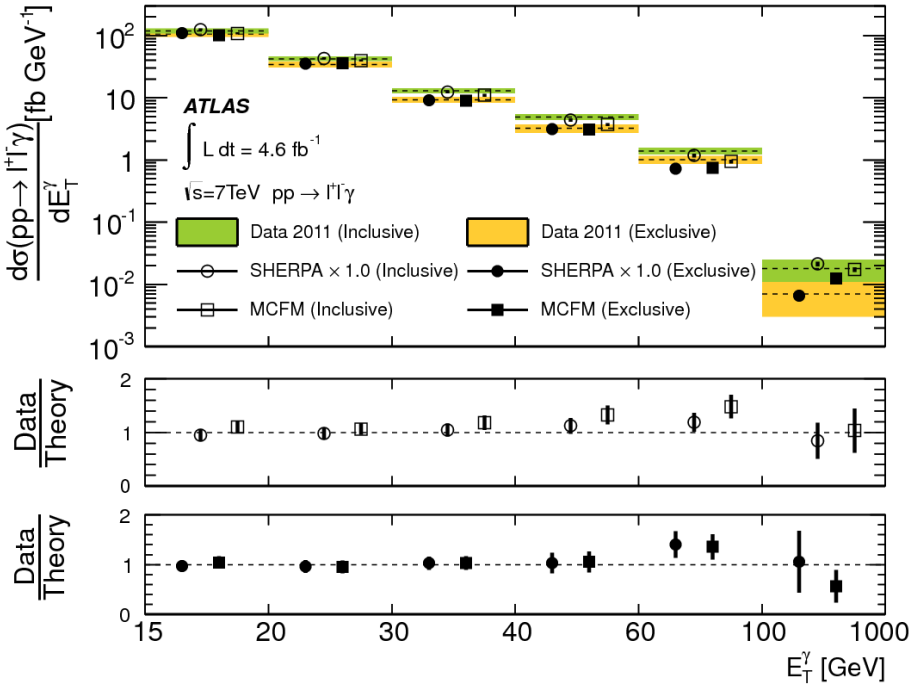
- γ: $E_T > 15$ GeV, $\Delta R(\ell, \gamma) > 0.7$
- 2ℓ, $p_T > 25$ GeV, $m_{\ell\ell} > 40$ GeV
- Jet counting: $E_T > 30$ GeV, $|\eta| < 4.4$

Measured fiducial cross sections:

- Inclusive (#jets ≥ 0) & exclusive (#jets=0)
- Fair shape modelling by SHERPA, MCFM

Major backgrounds: Z+j





$Z\gamma \rightarrow \nu\nu\gamma$ and $V\gamma$ summary

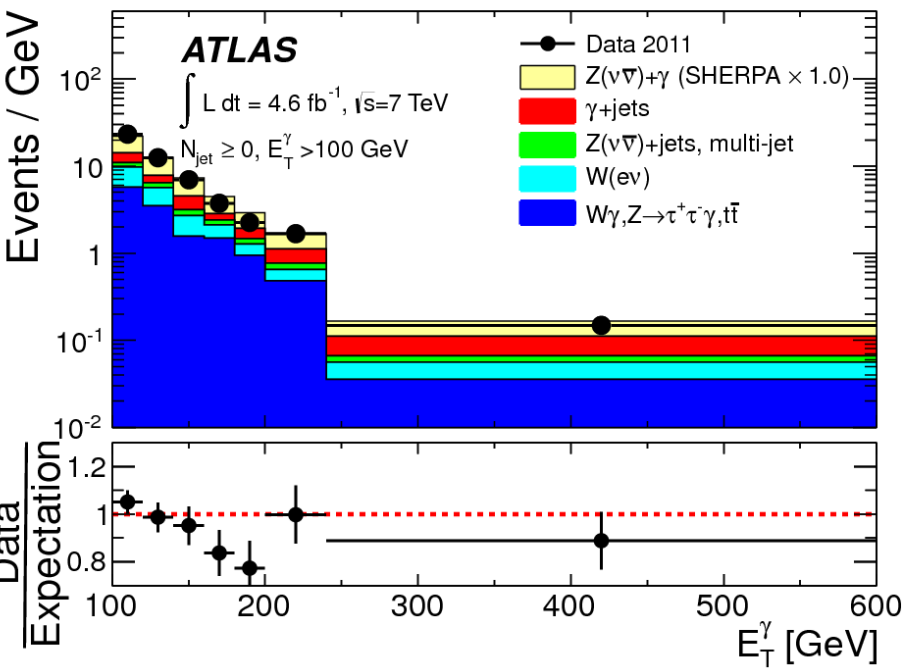
Preselection:

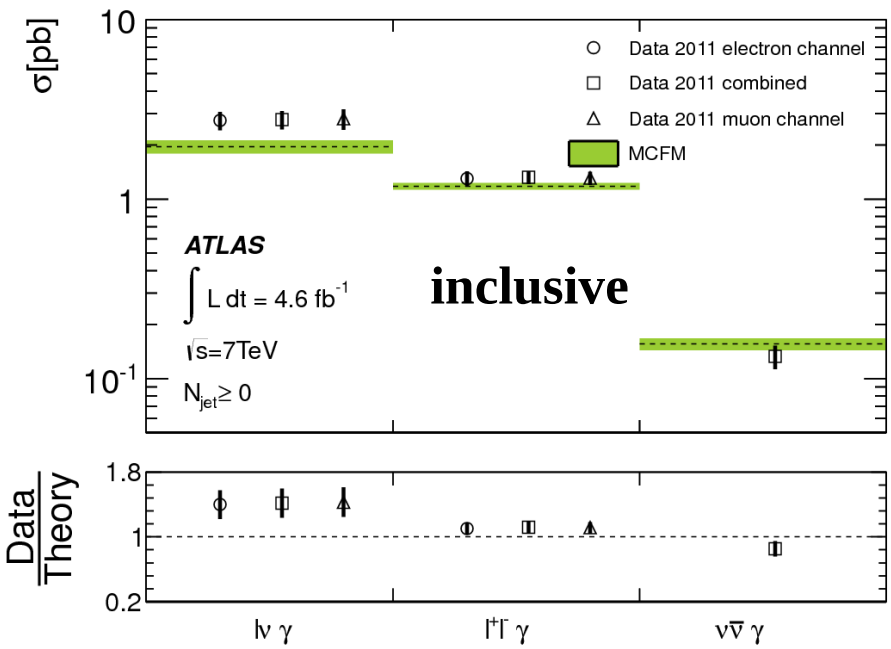
- γ: $E_T > 100$ GeV, $\Delta R(\ell, \gamma) > 0.7$
- MET > 90 GeV
- $\Delta\Phi(\text{MET}, \gamma/j) > 2.6/0.4$, 0 ℓ
- Jet counting: $E_T > 30$ GeV, $|\eta| < 4.4$

Major backgrounds: $W(e\nu)$, $Z(\nu\nu)+j$, $\gamma+j$

$V\gamma$ measured fiducial cross sections summary:

- Inclusive (#jets ≥ 0) & exclusive (#jets=0)
- $Z\gamma$: good agreement
- $W\gamma$: poor agreement for inclusive, better for exclusive





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- $\Delta\Phi(\text{MET}, \gamma/j) > 2.6/0.4$, 0 ℓ
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Major backgrounds: $W(e\nu)$, $Z(\nu\nu)+j$, $\gamma+j$

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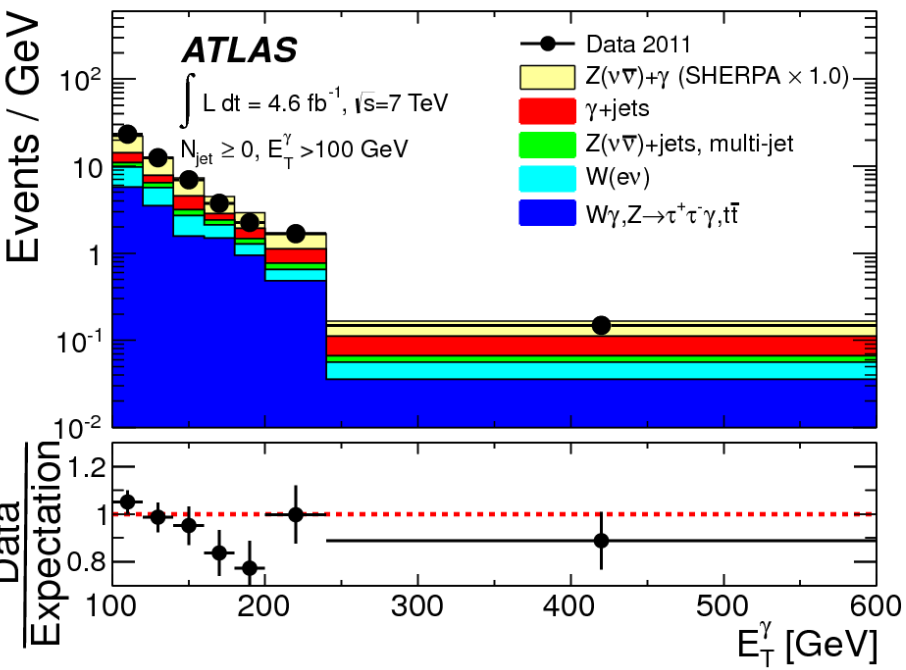
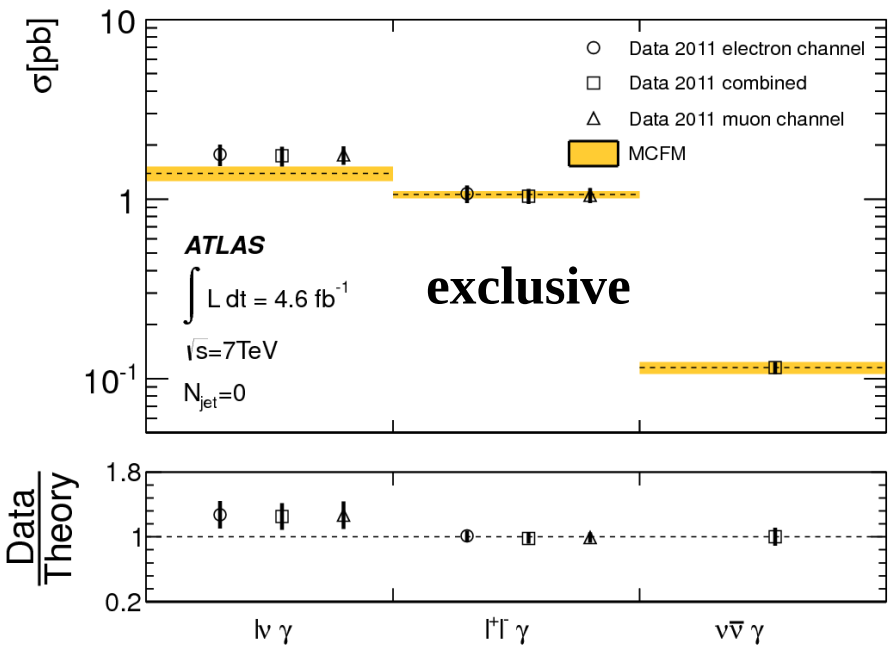




$WW \rightarrow \ell\nu\ell\nu$

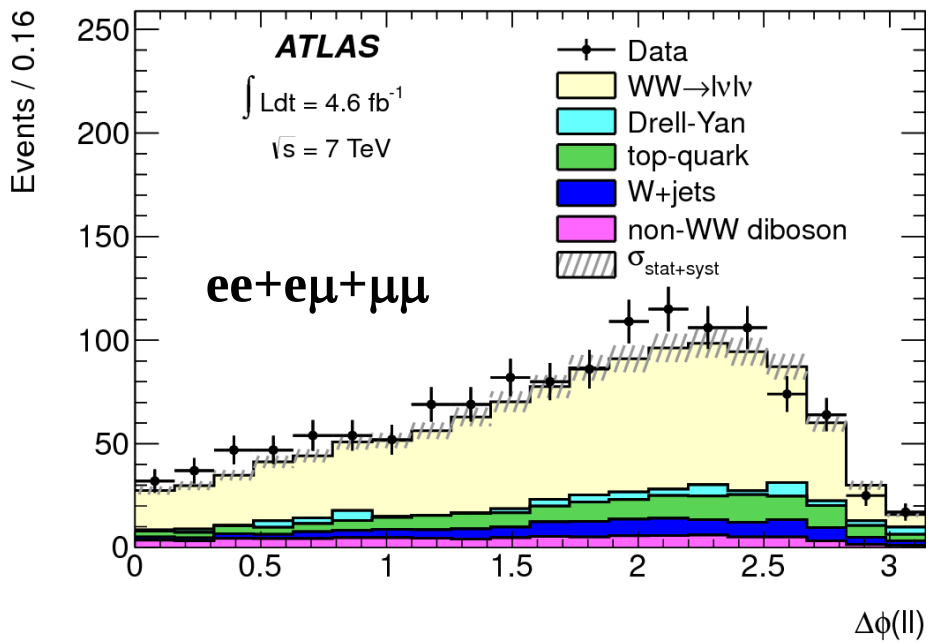
Preselection:

- $p_T(\ell) > 25/20$ GeV (e/e, e/μ, μ/μ)
- $m_{\ell\ell} > 15/15/10$ GeV (ee, μμ, eμ),
- $|m_{\ell\ell}-m_Z| > 15$ GeV (ee, μμ)
- $E^{miss}_{T,Rel} > 45/45/25$ GeV (ee, μμ, eμ)
- No jets with $p_T > 25$ GeV, $|\eta| < 4.5$
- $p_T(\ell\ell) > 30$ GeV

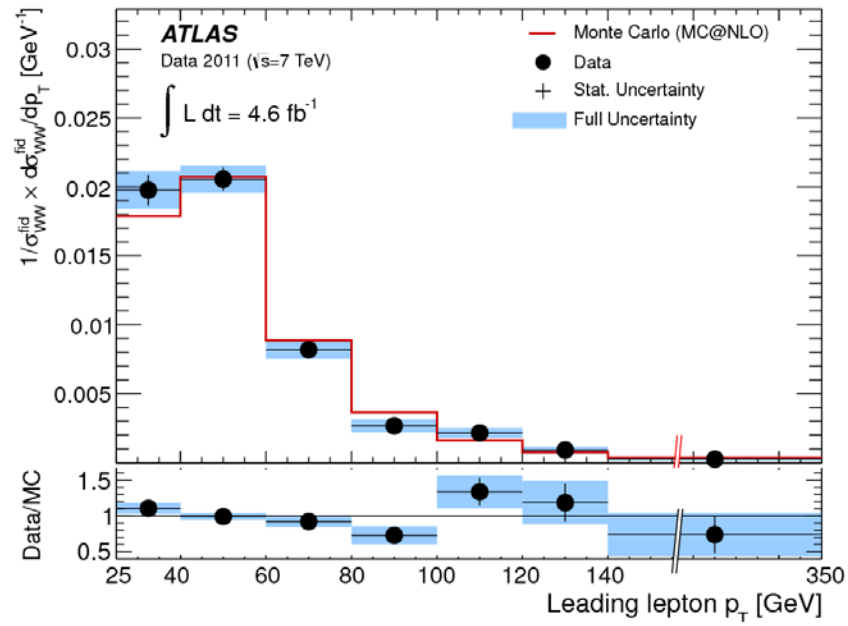
Measured total cross section:

- $\sigma_{WW} = 51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 2.0(lumi)$pb
- SM: σ_{WW} (NLO) = $44.7^{+2.1}_{-1.9}$ pb
- xsecs in fid. volume provided as well

Major backgrounds: V+jets, Top, VV



normalized differential fiducial xsec:



$WZ \rightarrow \ell\nu\ell\ell$

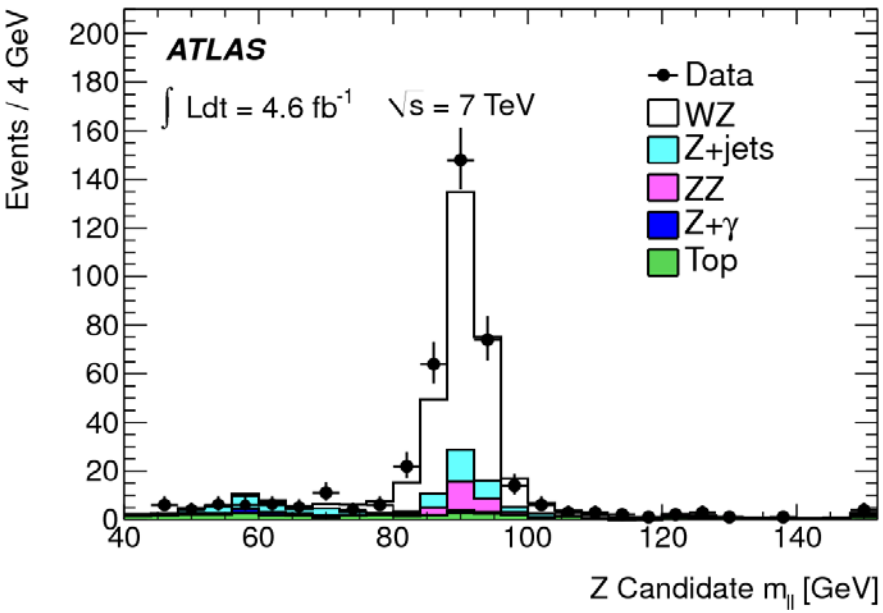
Preselection:

- Z: 2ℓ, $p_T > 15$ GeV, $|m_{\ell\ell} - m_Z| < 10$ GeV
- W: $3^{rd}\ell$, $p_T > 20$ GeV, MET > 25 GeV, $m_T > 20$ GeV

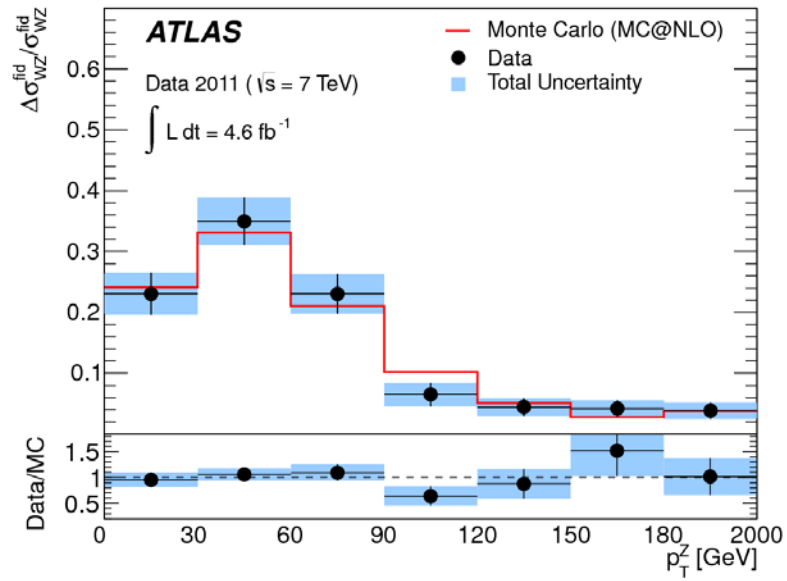
Measured total cross section:

- $\sigma_{WZ} = 19.0^{+1.4}_{-1.3}(\text{stat}) \pm 0.9(\text{syst}) \pm 0.4(\text{lumi})$ pb
- SM: σ_{WZ} (NLO) = $17.6^{+1.1}_{-1.0}$ pb
- xsec in common fid. vol. provided as well

Major backgrounds: Z+j/γ, ZZ, Top



normalized differential fiducial xsec:



$WZ \rightarrow \ell\nu\ell\ell$, 8 TeV

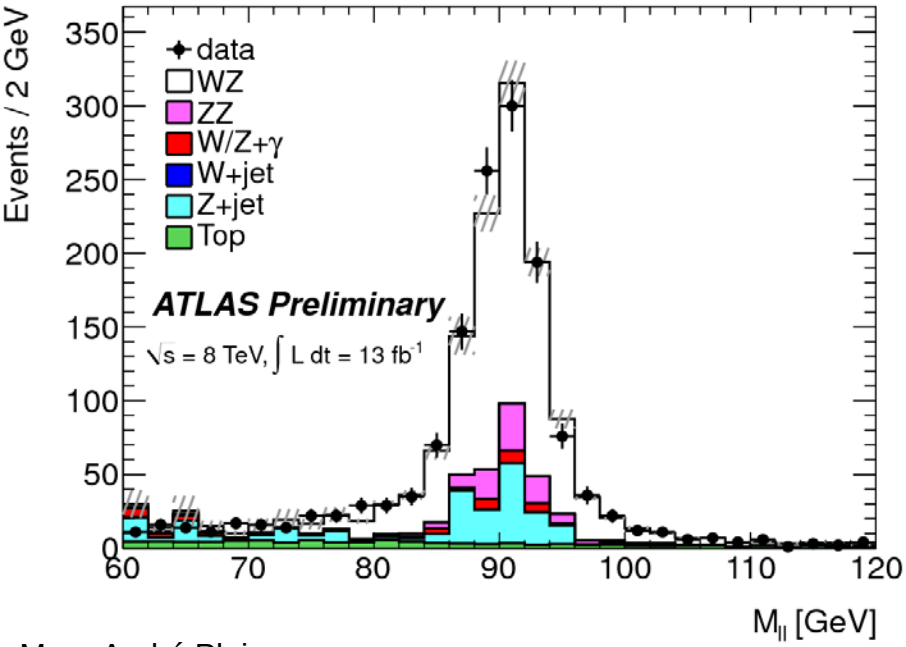
Preselection (same as 7 TeV):

- Z: 2ℓ, $p_T > 15$ GeV, $|m_{\ell\ell} - m_Z| < 10$ GeV
- W: $3^{rd}\ell$, $p_T > 20$ GeV, MET > 25 GeV, $m_T > 20$ GeV

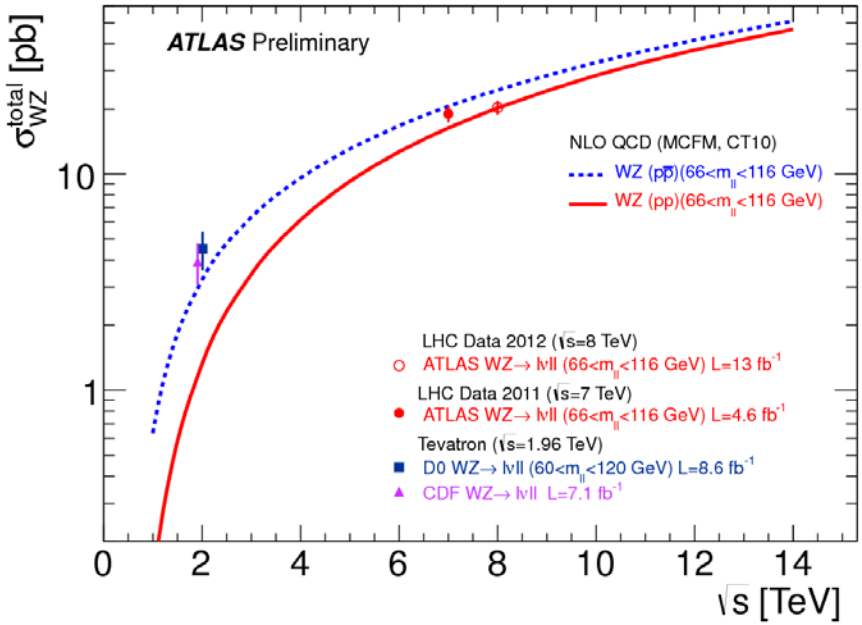
Measured total cross section:

- $\sigma_{WZ} = 20.3^{+0.8}_{-0.7}(\text{stat})^{+1.2}_{-1.1}(\text{syst})^{+0.7}_{-0.6}(\text{lumi})$ pb
- SM: σ_{WZ} (NLO) = 20.3 ± 0.8 pb
- xsecs in common fid. vol. provided as well

Major backgrounds: Z+j/γ, ZZ, Top



WZ xsec vs. center-of-mass energy :



WW/WZ → $\ell\nu jj$

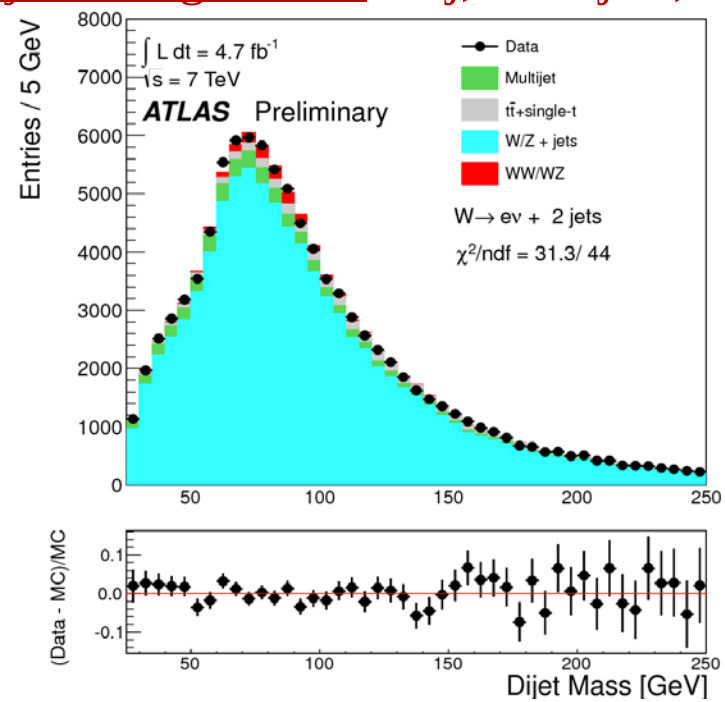
Preselection:

- 1ℓ, $p_T > 25$ GeV,
- MET > 30 GeV, $m_T > 40$ GeV,
- 2 jets with $p_T > 30/25$ GeV, $|\eta| < 2$
- $\Delta\Phi(\text{MET},j_1)>0.8$, $\Delta R(j_1,j_2)>0.7$, $\Delta\eta(j_1,j_2)<1.5$

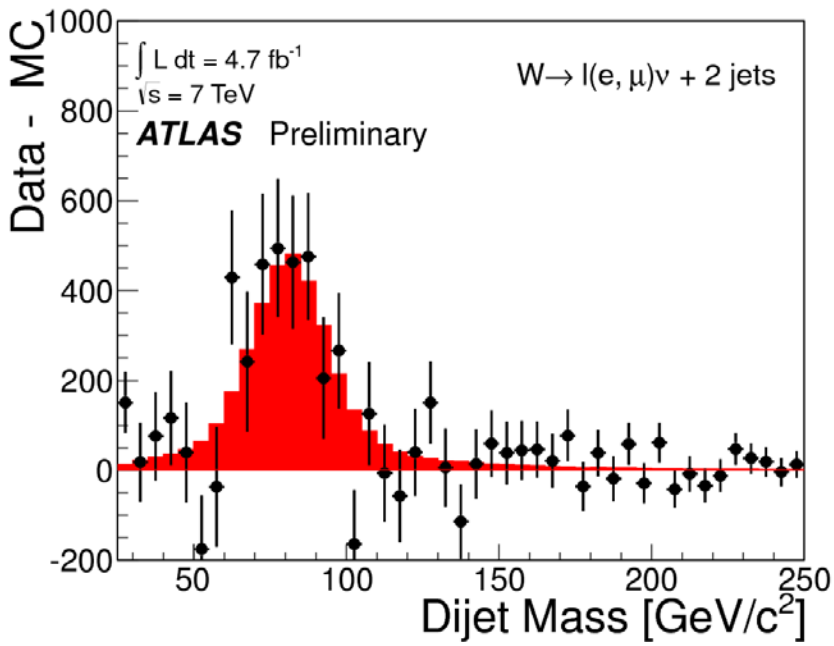
Measured total cross section:

- $\sigma_{WW/WZ}$ = 72 ± 9 (stat.) ± 15 (syst.) ± 13 (MC stat.) pb
- 3.3 σ signal significance (3.0 expected)
- SM: $\sigma_{WW/WZ}$ (NLO) = 63.4 ± 2.6 pb

Major backgrounds: V+j, multijets, Top



BG subtracted m_{jj} distribution after fit:



$ZZ \rightarrow \ell\ell\nu\nu$

Preselection:

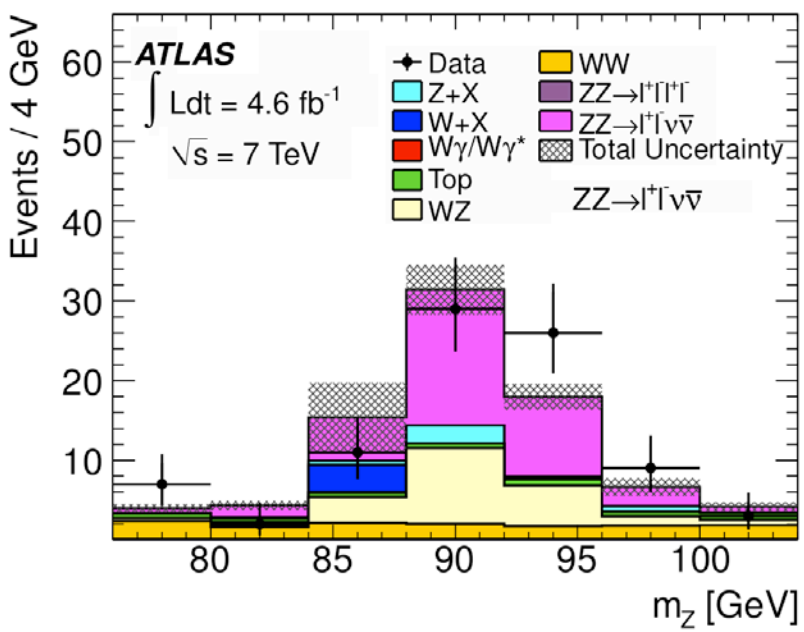
- 2 same flavour leptons of $p_T > 20$ GeV
- 76 GeV < $m_{\ell\ell}$ < 106 GeV
- Axial- $E_T^{miss} > 75$ GeV (projection along $\vec{p}_T^{\,Z}$)
- $\left|E_T^{miss} - p_T^Z\right| / p_T^Z < 0.4$
- No jets with $p_T > 25$ GeV, $|\eta| < 4.5$

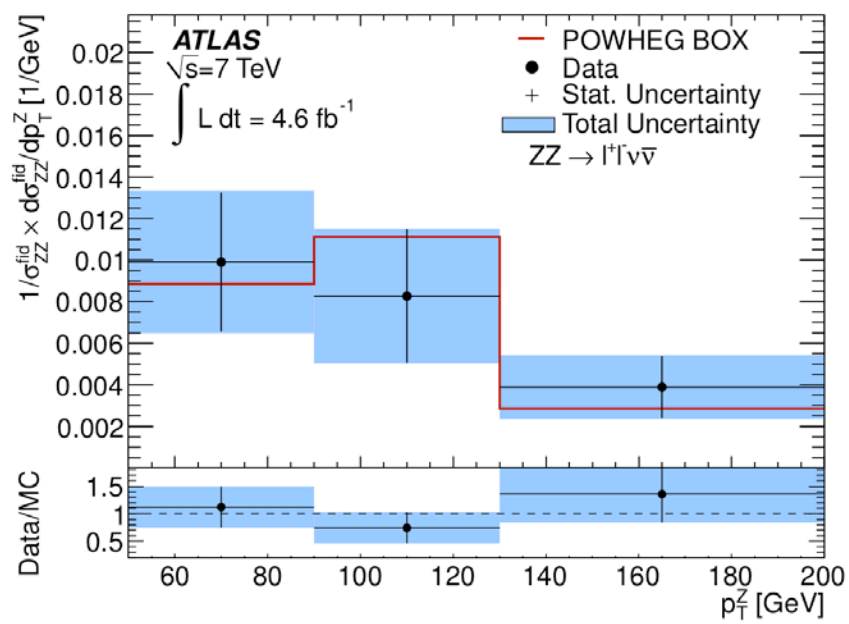
Major backgrounds: WZ, WW, Top, Z(ττ), Z+j

Measured fiducial cross section:

- $\sigma_{ZZ}^{fid} = 12.7^{+3.1}_{-2.9}(\text{stat}) \pm 1.7(\text{syst}) \pm 0.5(\text{lumi})$ fb
- SM: $\sigma_{ZZ}^{fid}(\text{NLO}) = 12.5 \pm 0.1(\text{stat})^{+1.0}_{-1.1}(\text{theory})$ fb
- total xsec: combine with $ZZ \rightarrow 4\ell$

normalized differential fiducial xsec:





$ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Preselection:

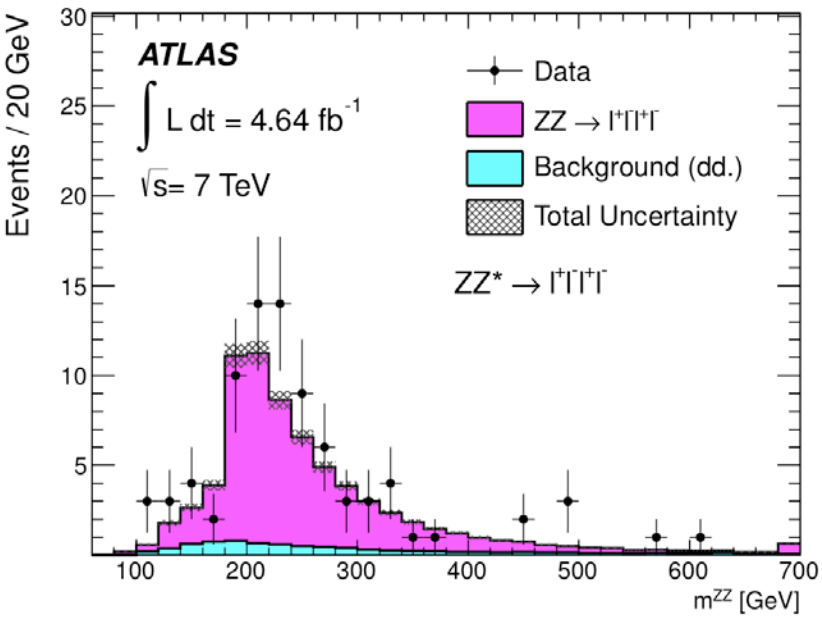
- four leptons with $p_T > 7$ GeV,
- trigger matched ℓ-$p_T > 25/20$ GeV (e/μ),
- $66 \text{ GeV} < m_{\ell\ell} < 116$ GeV
- If 2nd Z outside above: $m_{\ell\ell} > 20$ GeV

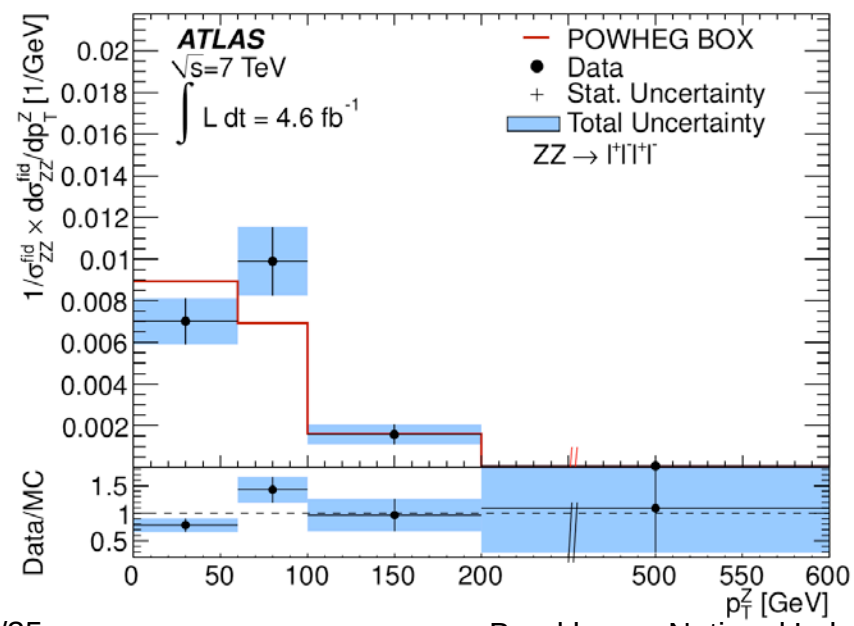
Measured total cross section (combi w/ $\ell\ell\nu\nu$):

- $\sigma_{ZZ} = 6.7 \pm 0.7(\text{stat})^{+0.4}_{-0.3}(\text{syst}) \pm 0.3(\text{lumi})$ pb
- SM: σ_{ZZ} (NLO) = 5.9 ± 0.2 pb (both Z's in mass window)
- xsecs in common fid. vol. provided as well

Major backgrounds: V+j/γ, top, VV

normalized differential fiducial xsec:





$ZZ \rightarrow \ell\ell\ell\ell$, 8 TeV

Preselection:

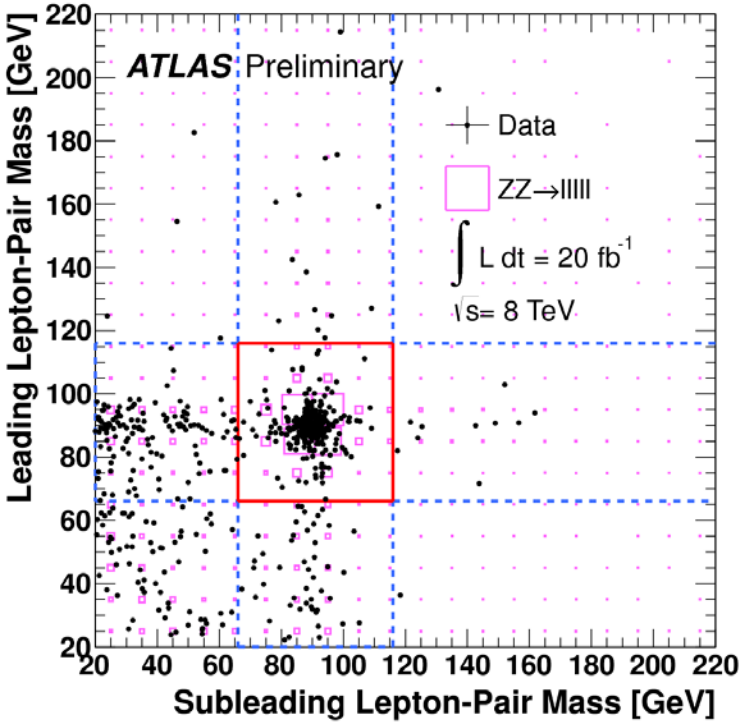
- four leptons with $p_T > 7$ GeV,
- trigger matched ℓ-$p_T > 25$ GeV,
- 66 GeV $< m_{\ell\ell} <$ 116 GeV (each pair)

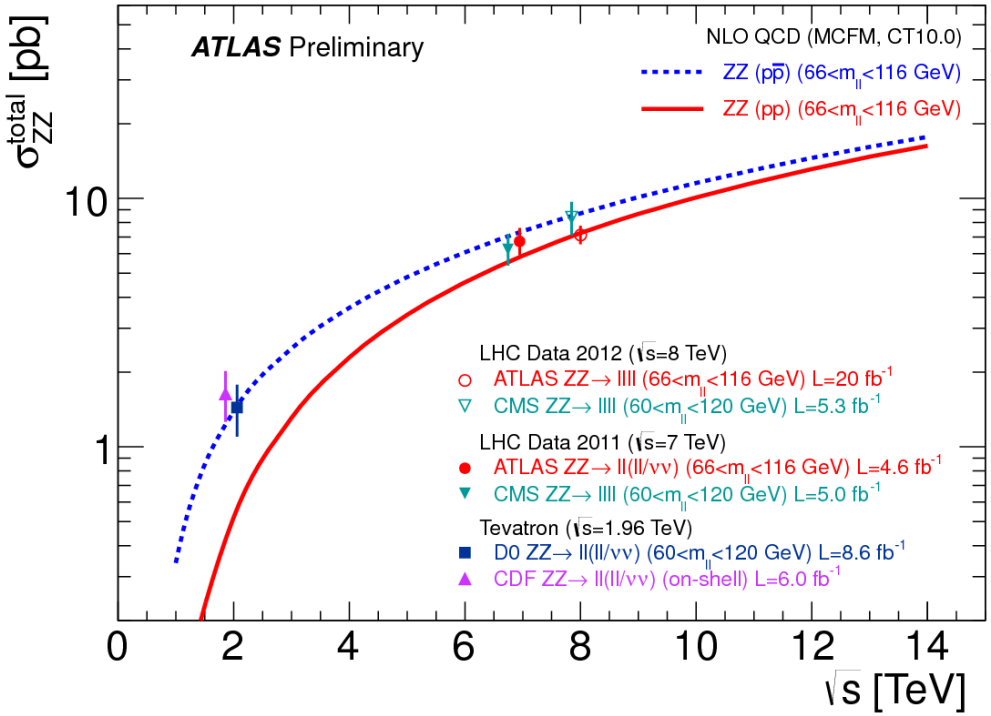
Measured total cross section:

- $\sigma_{ZZ} = 7.1^{+0.5}_{-0.4}(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\text{lumi})$ pb
- SM: σ_{ZZ} (NLO) = $7.2^{+0.3}_{-0.2}$ pb (both Z's in mass window)
- xsecs in common fid. vol. provided as well

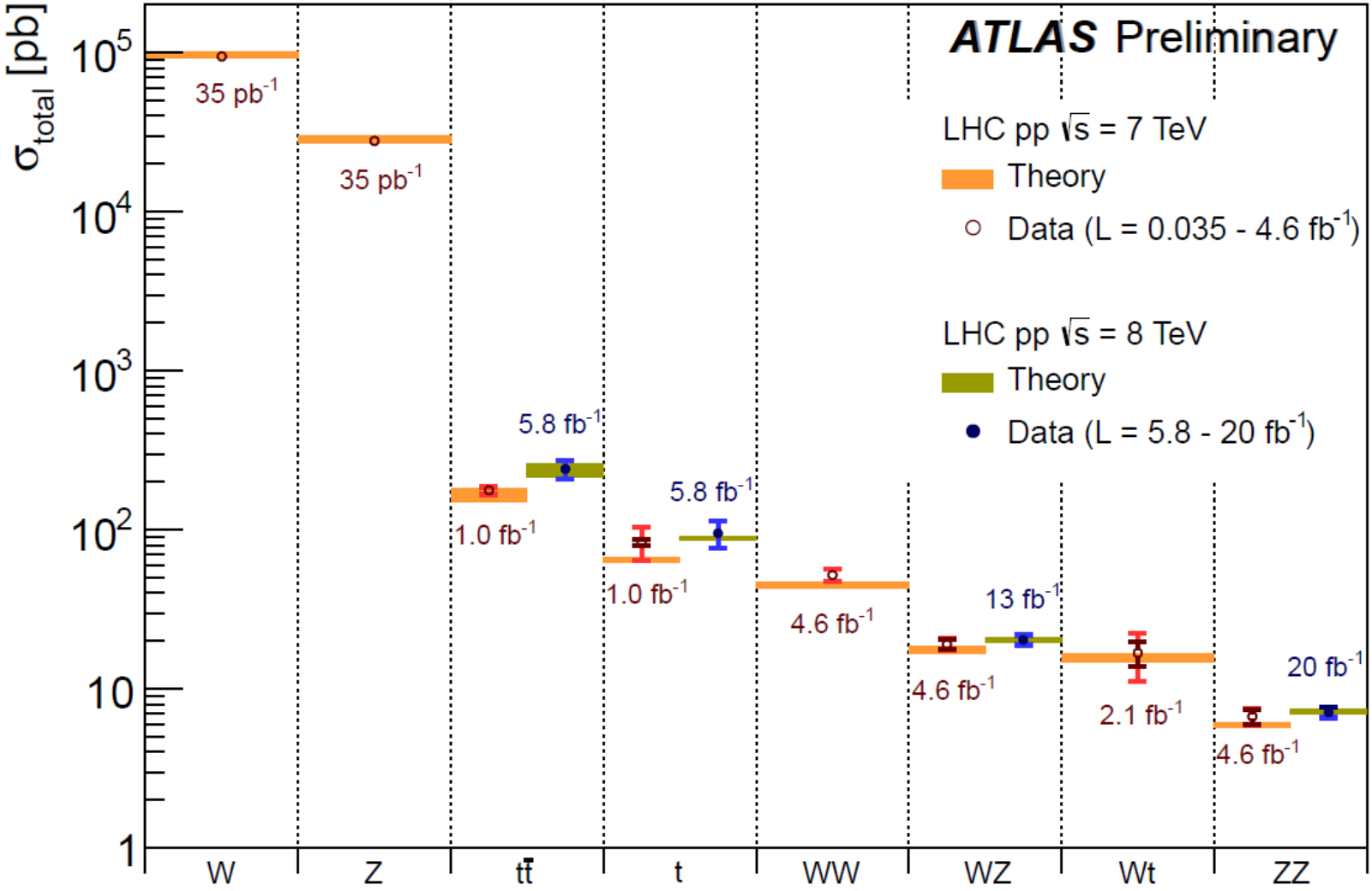
Major backgrounds: V+j/γ, top, VV

ZZ xsec vs. center-of-mass energy :



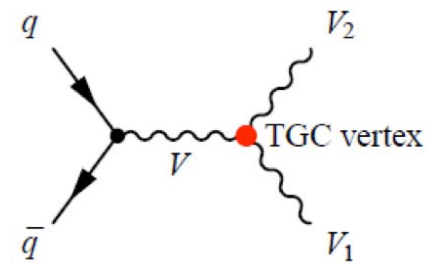


SM total production cross section measurements @ ATLAS…



Testing gauge boson self-couplings

Anomalous triple gauge boson couplings (aTGCs)



- TGCs occur in s-channel production of VV events: WWγ, WWZ, ZZγ, Zγγ & ZZZ couplings possible. Only WWγ, WWZ allowed in SM at tree level, neutral couplings ~10^{-4} through loops.

- Effective Lagrangian used to describe effects of non-SM processes on TGCs (new physics scale Λ out of experimental reach; no direct observation)

- For WWV (V=γ,Z) vertex, assuming C & P conservation:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

- SM couplings: $g_1^V = \kappa_V = 1, \lambda_V = 0.$ Set $\Delta g_1^V \equiv g_1^V - 1, \Delta\kappa_V \equiv \kappa_V - 1$
  g_1^γ fixed to SM value by EM gauge invariance => 5 pars left.

- magnetic dipole moment of W: $\mu_W = \frac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma)$
  electric quadrupole moment of W: $Q_W^e = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$

Anomalous triple gauge boson couplings (aTGCs)

- Overview of studied aTGCs:

Coupling	Parameters	VV channel
$WW\gamma$	$\Delta\kappa_\gamma, \lambda_\gamma$	$WW, W\gamma$
WWZ	$\Delta g_1^Z, \Delta\kappa_Z, \lambda_Z$	WW, WZ
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	h_3^Z, h_4^Z	$Z\gamma$
$ZZ\gamma$	f_4^γ, f_5^γ	ZZ
ZZZ	f_4^Z, f_5^Z	ZZ

SM expectation for all these parameters = 0.
f_4^V violate CP.

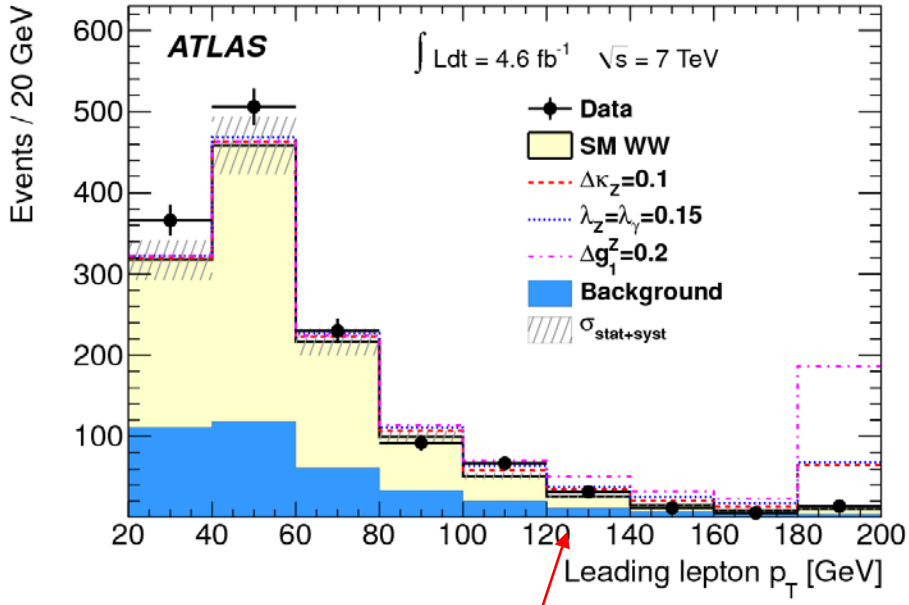
- experimental access: aTGCs modify total production rate as well as event kinematics
  $\Rightarrow$ Use cross-section measurement or kinematics to constrain aTGCs

- A suppression factor depending on a scale Λ ensures conservation of unitarity (divergent cross sections at high $\sqrt{s}$):

$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda^2)^n}$$

$WW \rightarrow \ell\nu\ell\nu$

Leading lepton p_T sensitive to aTGCs:



Anomalous parameters:

$$\Delta g_1^Z,\ \Delta\kappa_Z,\ \Delta\kappa_\gamma,\ \lambda_Z \text{ and } \lambda_\gamma$$

- LEP scenario (3 free pars):

$$\Delta\kappa_\gamma = \cot^2\theta_W(\Delta g_1^Z - \Delta\kappa_Z),\ \lambda_Z = \lambda_\gamma$$

- HISZ scenario (2 free pars) = LEP +

$$\Delta g_1^Z = \Delta\kappa_\gamma/(2\cos^2\theta_W)$$

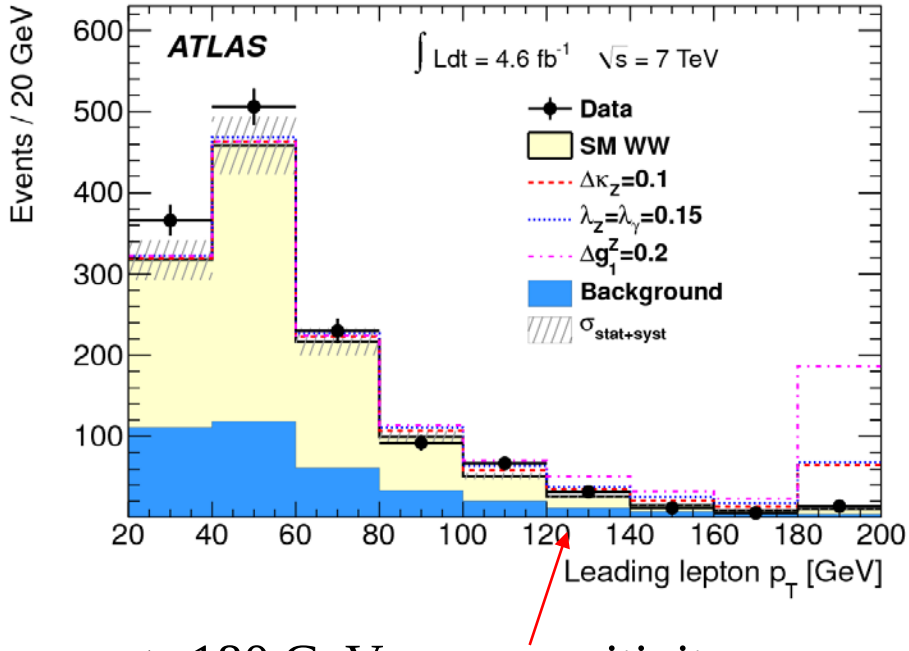
- Equal couplings scenario (2 free pars):

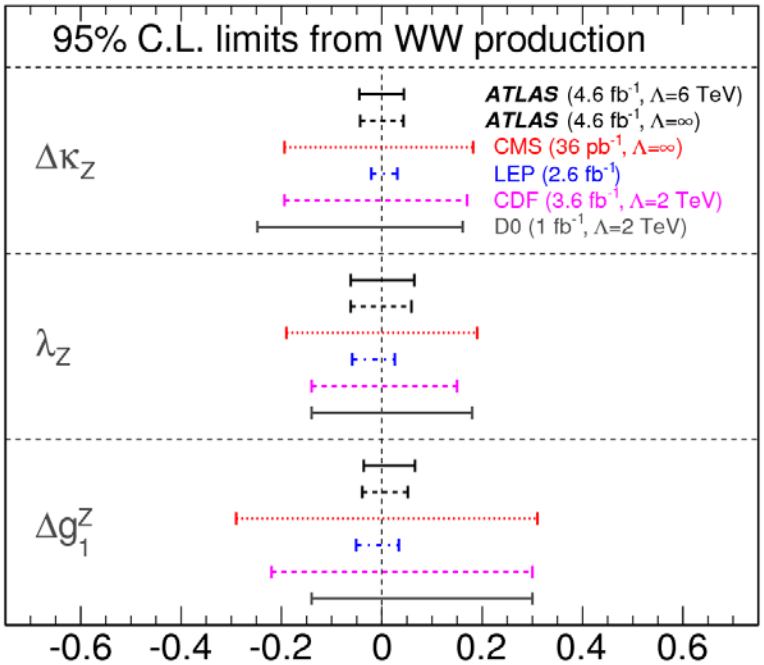
$$\Delta\kappa_Z = \Delta\kappa_\gamma,\ \lambda_Z = \lambda_\gamma,\ \Delta g_1^Z = 0$$

- p_T > 180 GeV: max sensitivity
- Low p_T excess: negligible impact on aTGC limits
- 1D limits assuming no relationships between the five couplings also available
- 2D limits also available

$WW \rightarrow \ell\nu\ell\nu$

Leading lepton p_T sensitive to aTGCs:





- p_T > 180 GeV: max sensitivity
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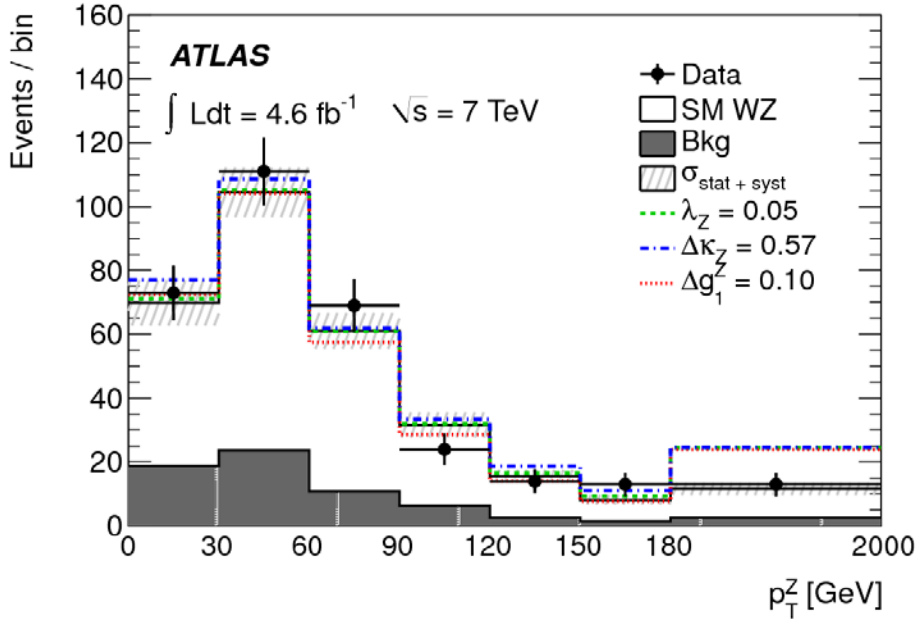
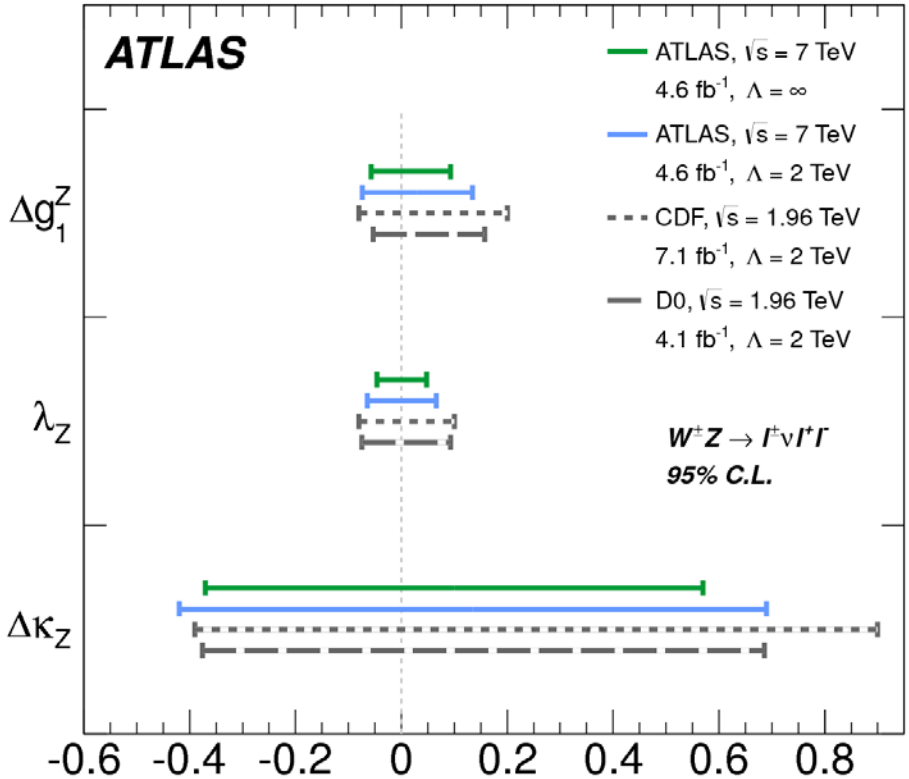
$WZ \rightarrow \ell\nu\ell\ell$

Z boson p_T sensitive to aTGCs:

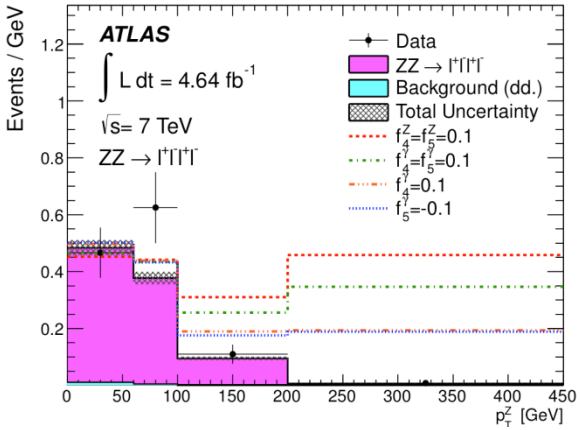


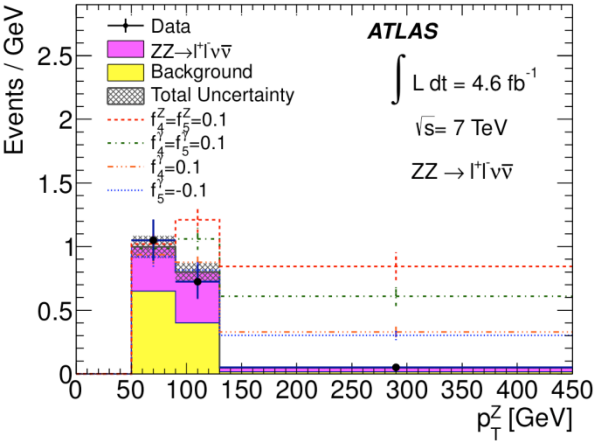


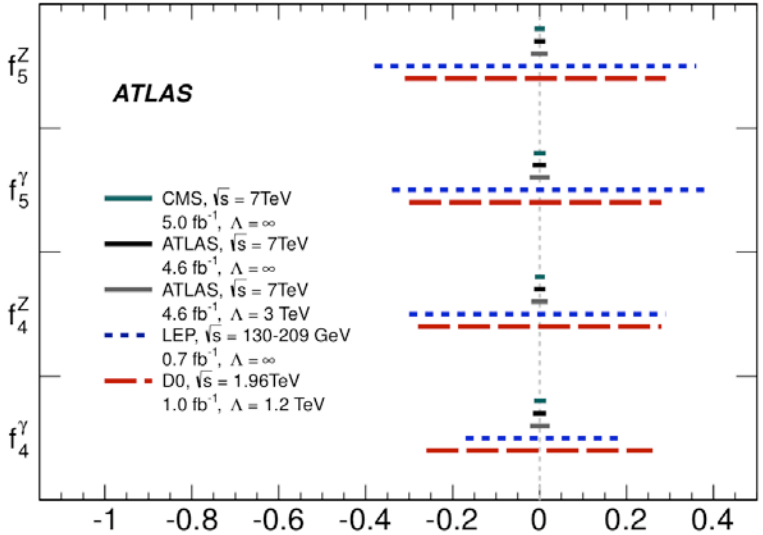
- p_T > 180 GeV: max sensitivity
- 2D limits also available

ZZ → ℓℓνν/ℓℓℓℓ

Z boson p_T sensitive to aTGCs:



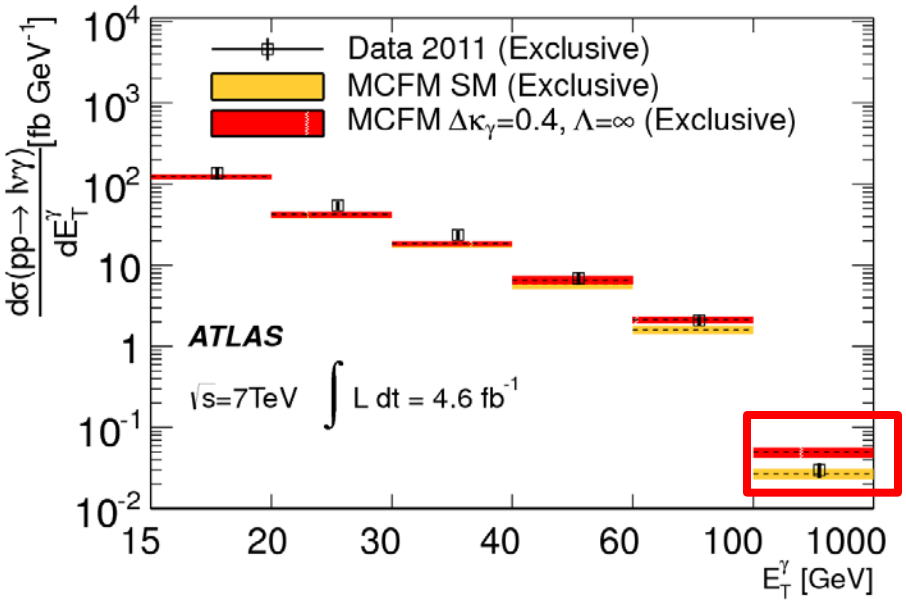


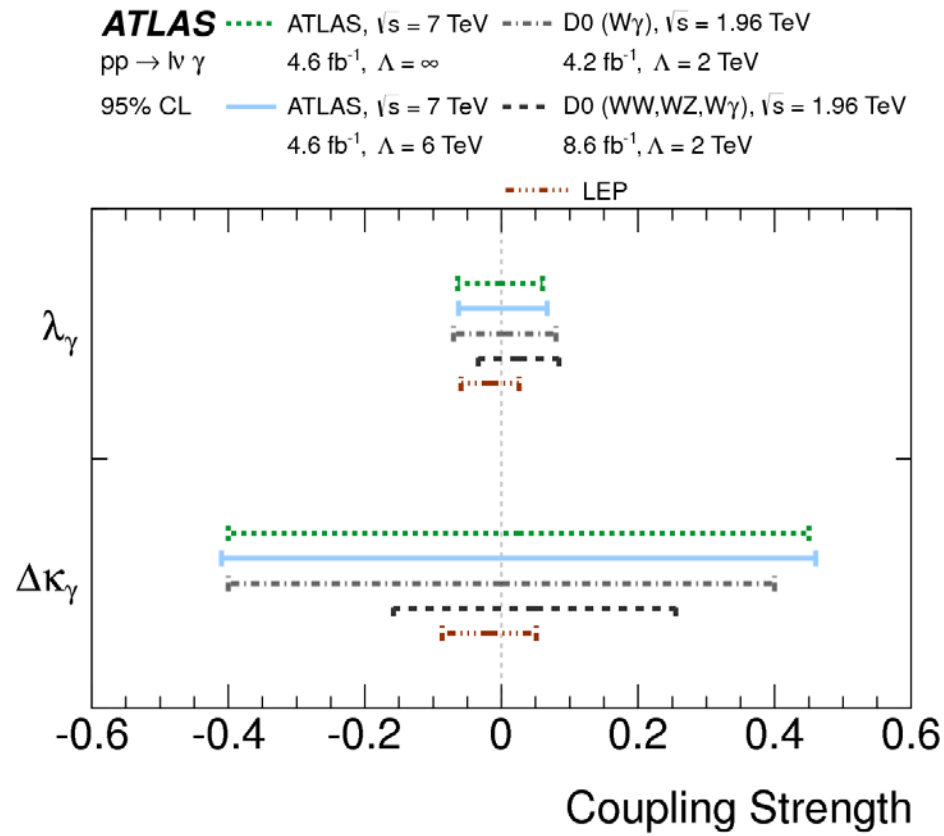


- 2D limits also available

$W\gamma \rightarrow \ell\nu\gamma$

aTGC extraction based on observed photon E_T yield in data > 100 GeV (exclusive zero-jet selection, single bin).

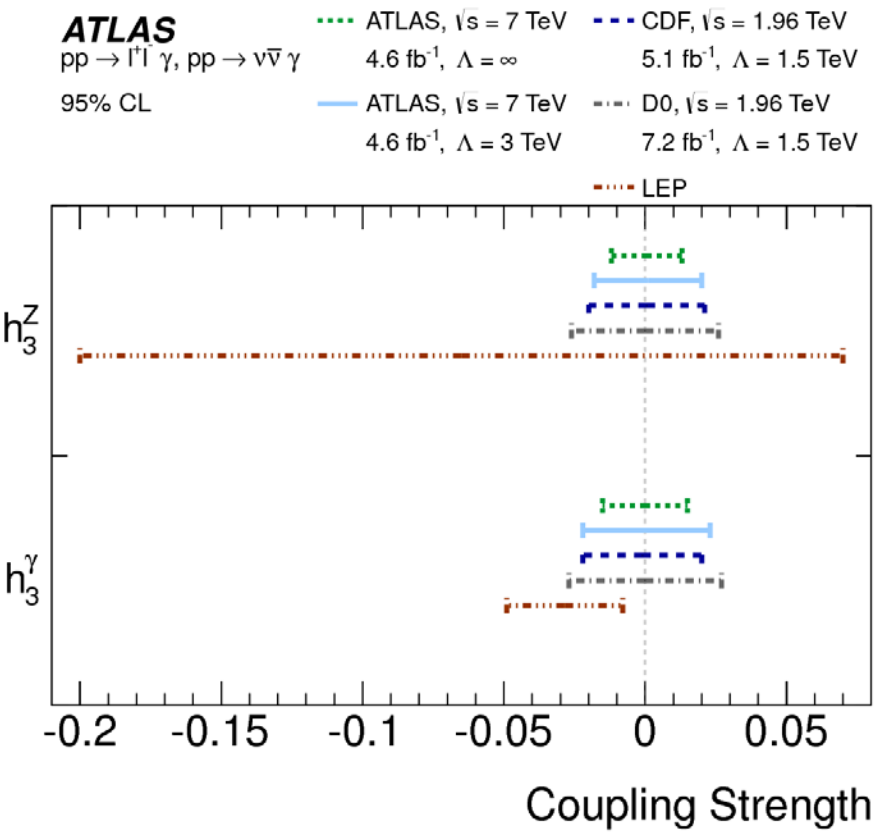


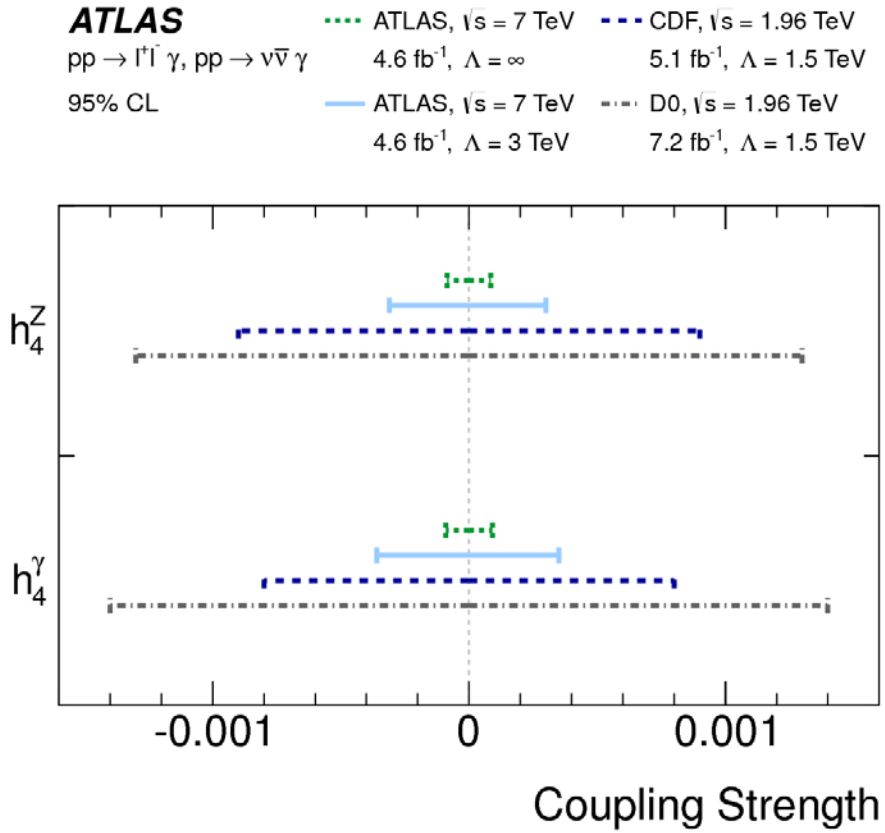


- 2D limits also available

$Z\gamma \rightarrow \ell\ell\gamma / \nu\nu\gamma$

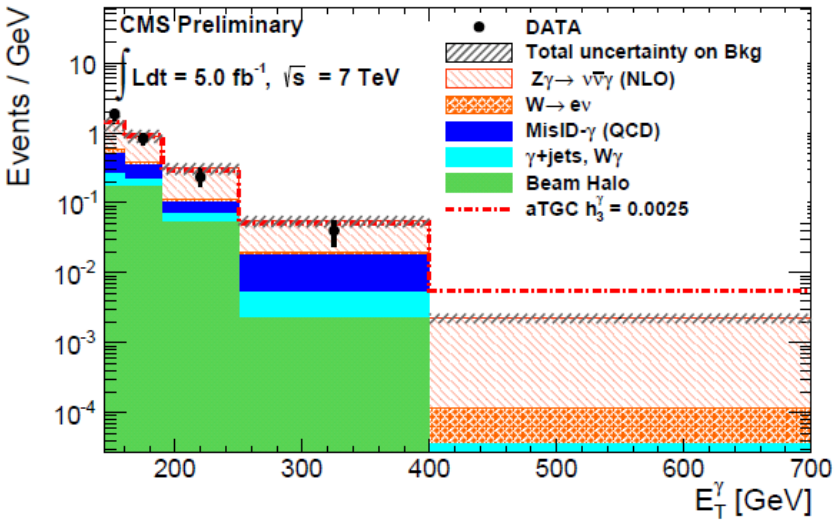
aTGC extraction based on observed photon E_T yield in data > 100 GeV (exclusive zero-jet selection , single bin).

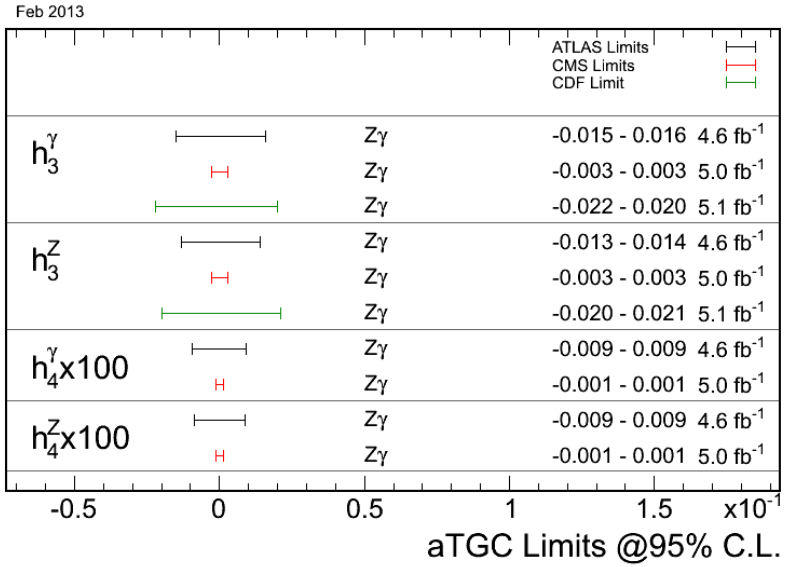


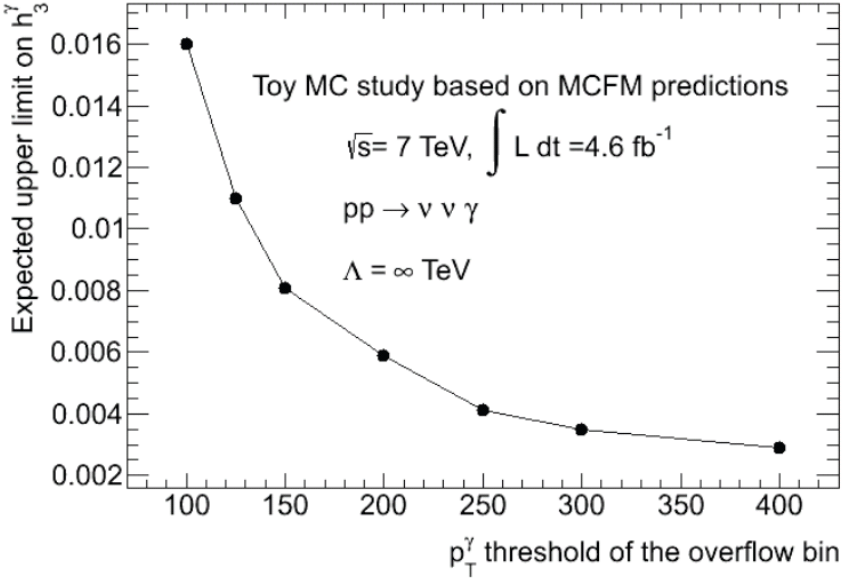


- $Z\gamma \rightarrow \nu\nu\gamma$ contributes significantly to sensitivity!
- 2D limits also available

Binning effects



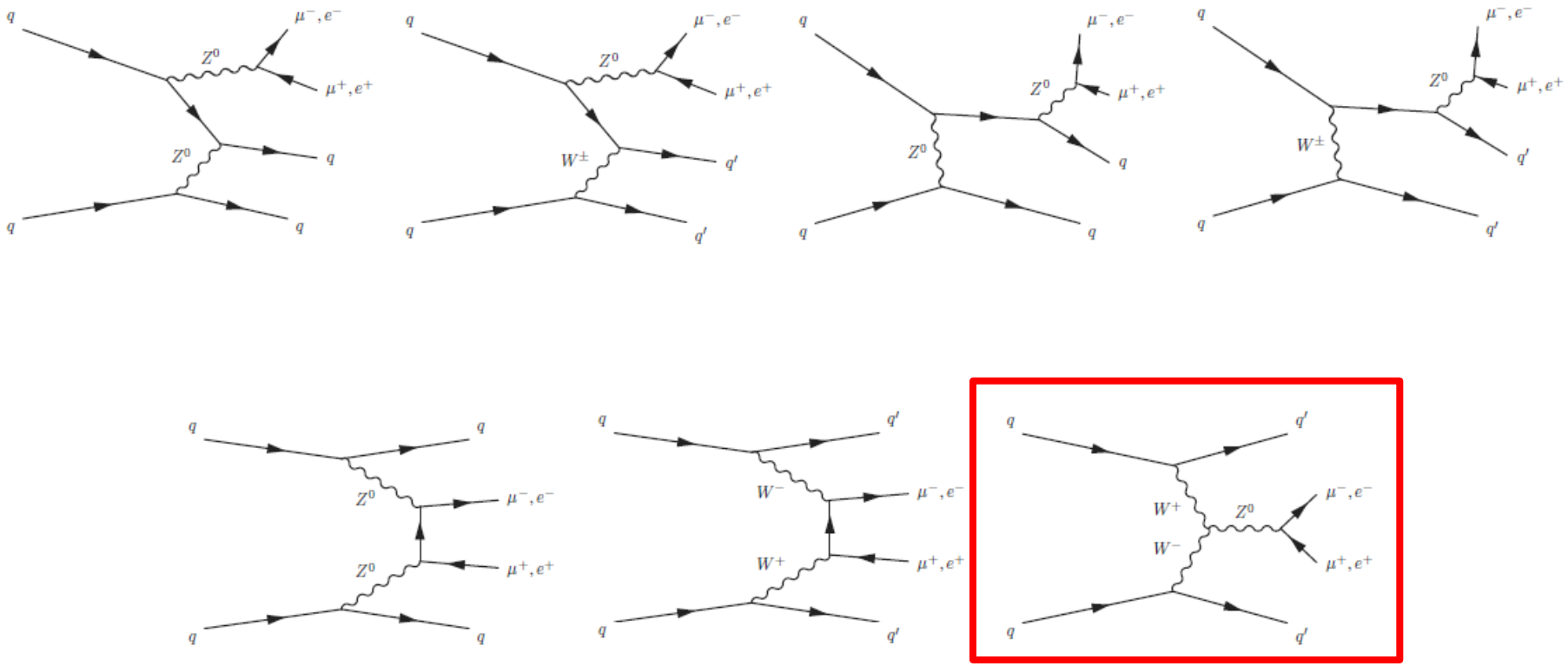




Raising threshold of overflow bin from 100GeV to 400GeV: improve by factor 5!
But: bin population/BG control?
Also: improvement mainly on limit *without* form factor.

Future Plans

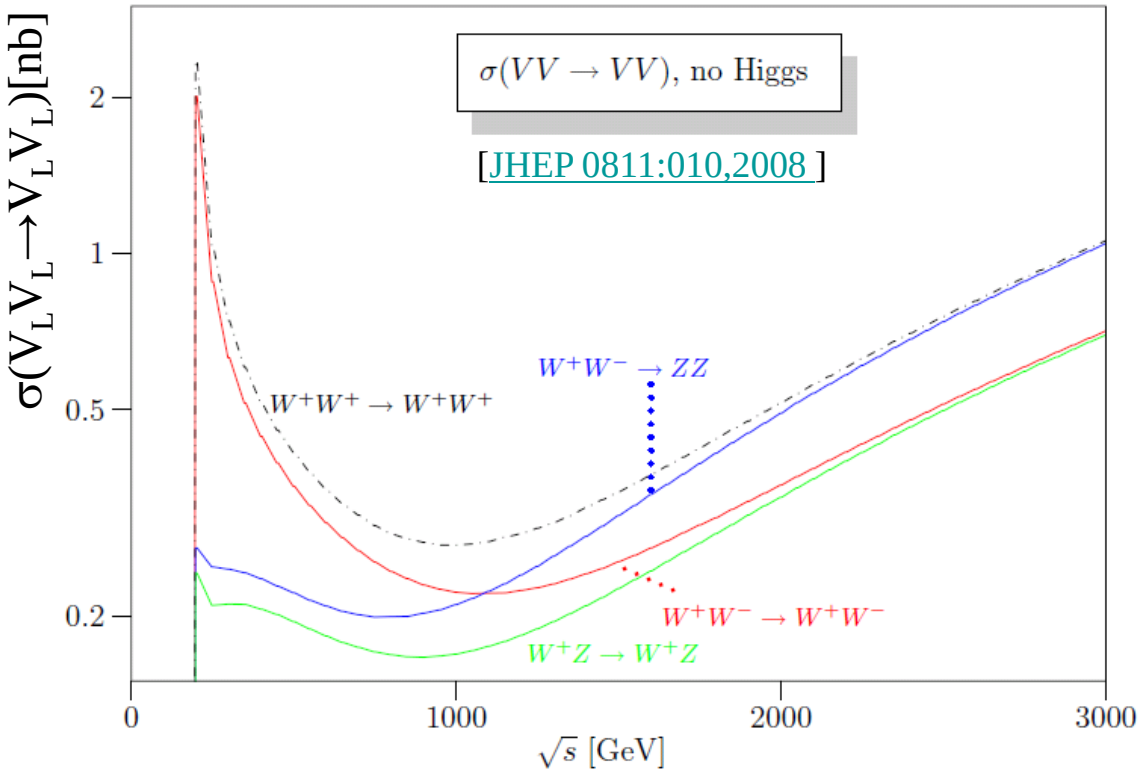
Establish vector boson fusion signal for single V production:



- VBF W,Z signals not yet established
- Complementary access to aTGCs
- VBF kinematics important for H measurements

Future Plans II

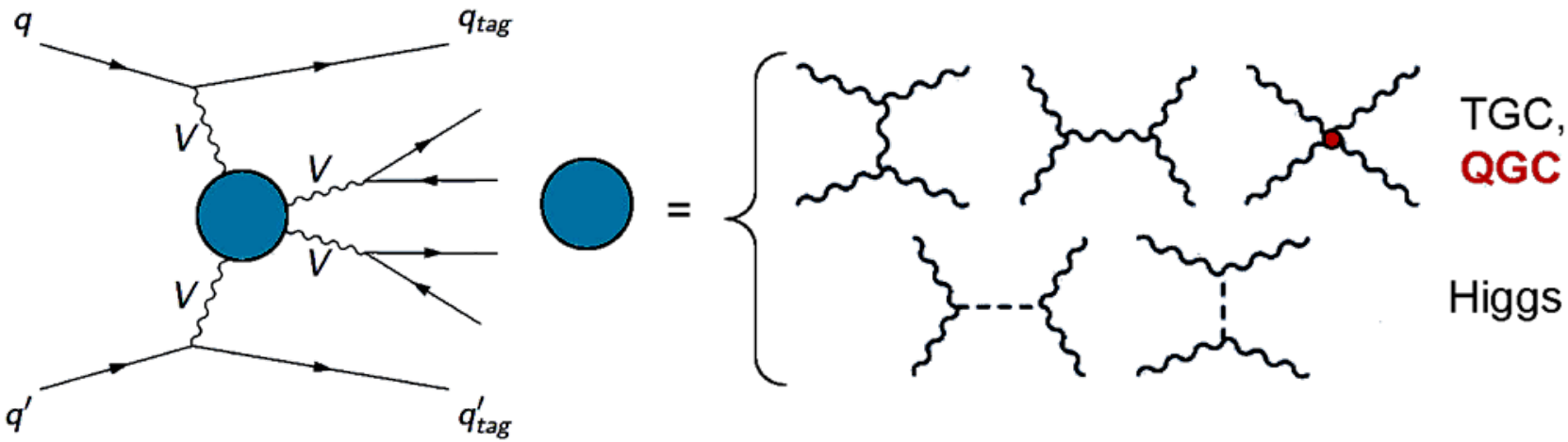
- Vector boson scattering (VBS): VV →VV provides insight into EWSB mechanism
- Divergence of the scattering amplitude for longitudinally polarized heavy bosons:



Unitarity violation > ~ 1 TeV!

Future Plans II

•Vector boson scattering (VBS): VV →VV provides insight into EWSB mechanism
•Divergence of the scattering amplitude for longitudinally polarized heavy bosons:

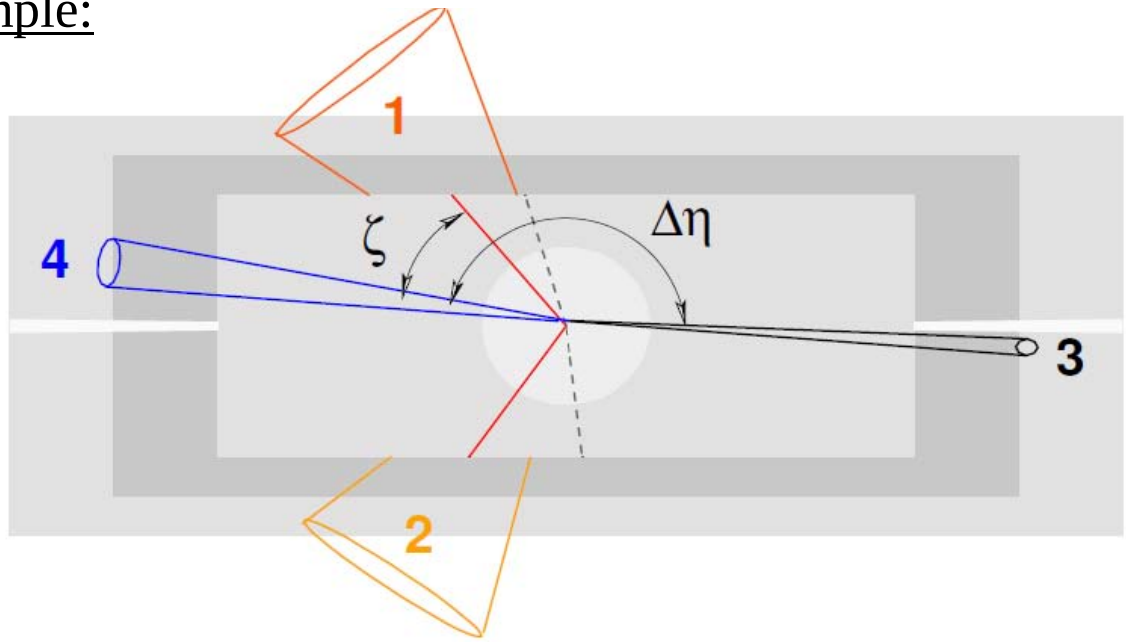


•SM "cure" is Higgs boson. Still need to confirm SM nature of EWSB & check for NP!

VBS Signature

<u>General:</u> qq→4f + dijet

<u>WW decay example:</u>



- 1,2 = Central, high-p_T charged leptons from V decays
- 3,4 = Forward/backward tagging jets (large m_{jj} and well separated in η)
- Utilisation of a "central jet veto" difficult in high-pileup environment

VBS sensitivity studies

- Generator: MadGraph5 with EFT operators (checked with VBF@NLO)
- Signal Processes: VBS Same-Sign WWjj, VBS WZjj and VBS ZZjj, fully leptonic V-decay modes.
- Background Processes: VVjj QCD/EW, charge flips, mis-ID
- Analysis cuts: (same cuts for ssWWjj, WZjj and ZZjj)
  - Lepton: pT>25GeV,
  - Electron: $|\eta|<2.47$ (excluding crack region), Muon: $|\eta|<2.4$
  - Jets: pT>50GeV, $|\eta|<5$
  - M(jj) > 1TeV (optimized for VVjj)
  - M(VV) cutoff at UV boundaries
- Sensitivities are studied for:
  - 300, 3000 fb^{-1} @ 14 TeV using ATLAS Upgrade Parametrized Simulations: ATLAS-PHYS-PUB-2013-006
  - 3000 fb^{-1} @ 14 TeV(140Pileup) and 100 TeV(225Pileup) using SnowMass Delphes Parametrized FastSim (Work in progress…)

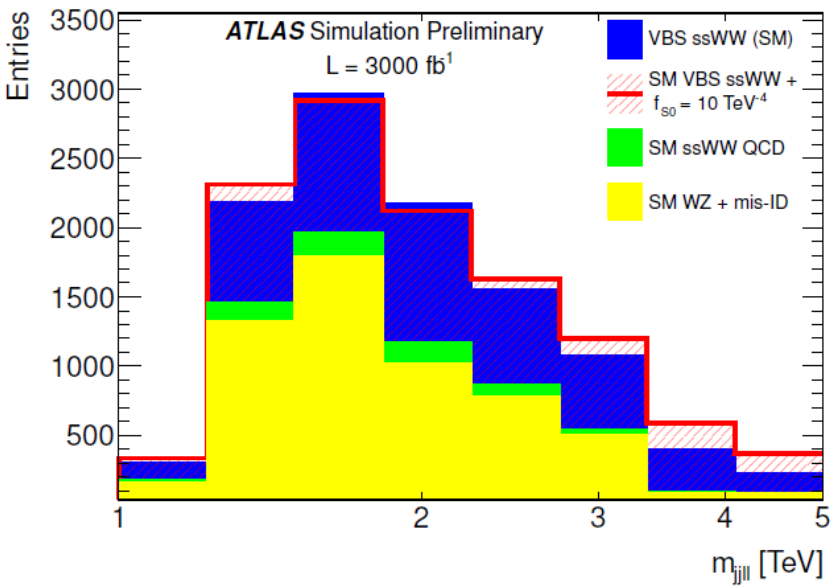
VBS Results

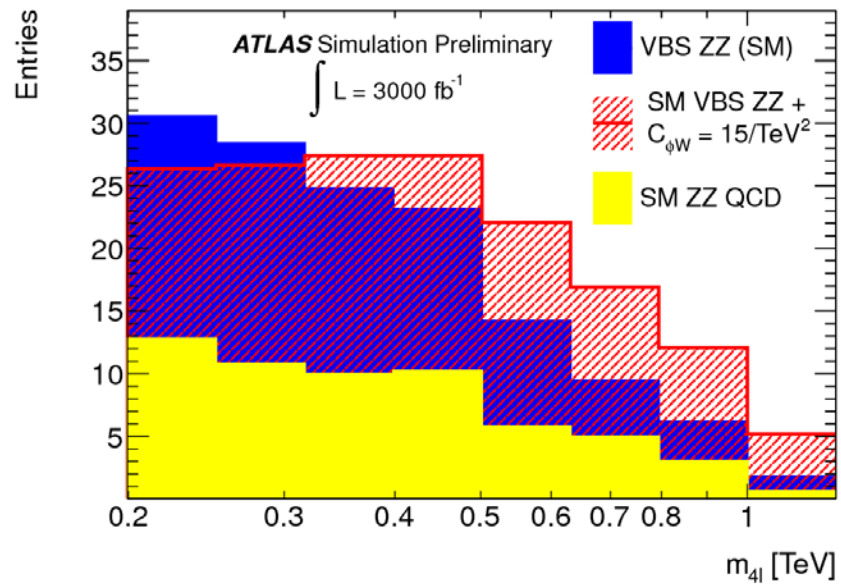
Same-sign WWjj:

- Major background from WZ process
- WZ scaled up for charge flip, mis-id, and Wγ BG
- f_{S0} can be translated to α_4 in EW Chiral Lagrangian

ZZjj:

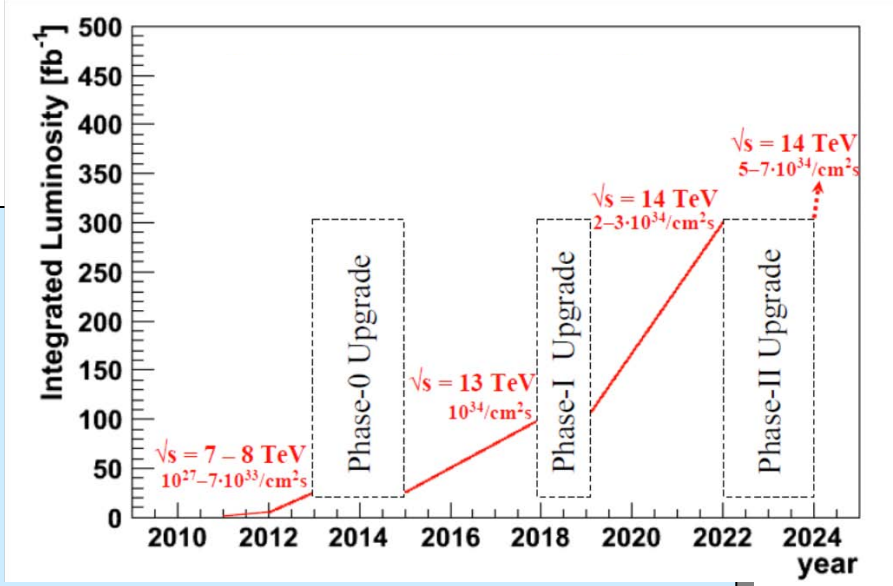
- Major background from ZZ QCD process





Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}

Summary



VV cross sections:

- Compatible with SM expectations
- Differential xsecs probe MC modelling

aTGCs:

- Competitive limits obtained

Plans:

- 8 TeV results are coming
- Analyses for VBF/VBS/VVV are ramping up
- Working towards combination across channels (& experiments?)
- Need for coherent NLO+PS MC for all analyses; NNLO QCD, NLO EW?
- 13/14 TeV data will allow measurements of new rare processes, probe NP.