Electroweak Corrections for LHC Physics
Diboson Production at ATLAS

Lynn Marx
University of Manchester

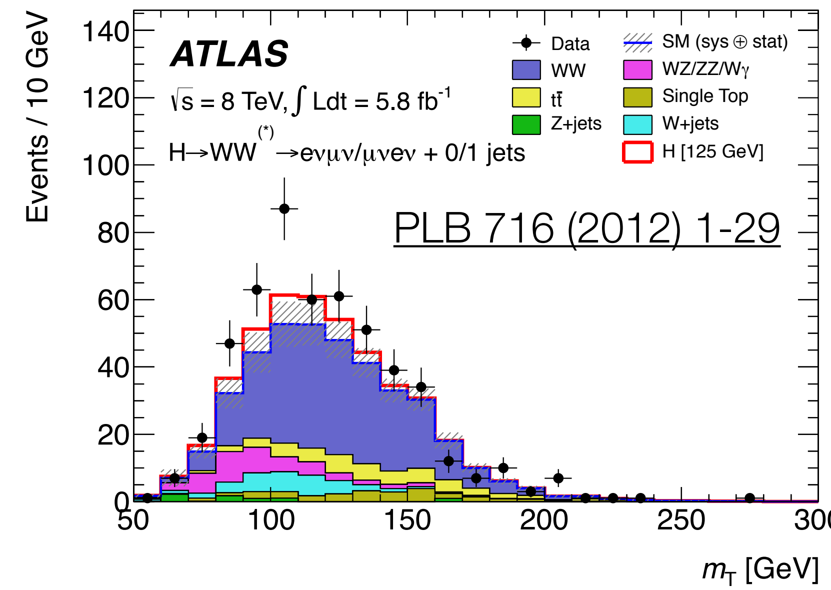
ATLAS EXPERIMENT

MANCHESTER 1824

IPPP Workshop, Durham, UK
September 24, 2012

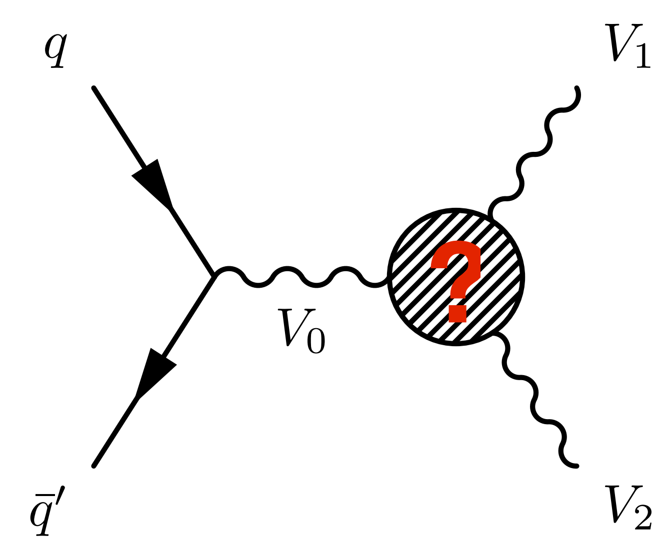
Motivation

A profound understanding of **Diboson Production** is important



- Irreducible **background** to important processes
  - e.g. Higgs production

- Gauge boson **self-couplings**
  - fundamental prediction of non-abelian SU(2)xU(1) gauge symmetry
  - precision test of Standard Model and validity at high energies
  - not yet well measured



- Sensitive to **new physics**
  - SUSY (extended Higgs sectors H$^{\pm}$, $\tilde{\chi}^{\pm}\tilde{\chi}^0$ production)
  - extra vector bosons (W')
  - (technicolor?)

Outline

Present latest ATLAS **Diboson Results**

$W(\rightarrow l\nu)\gamma$
$Z(\rightarrow ll)\gamma$
$WW\rightarrow l\nu l\nu$
$WZ\rightarrow l\nu ll$
$ZZ\rightarrow llll$
$ZZ\rightarrow ll\nu\nu$
$ZZ\rightarrow llll$

7 TeV, 1 fb^{-1}
7TeV, 5 fb^{-1}
8TeV, 6 fb^{-1}

1) **Cross Section Measurements**
2) **Anomalous Gauge Coupling Limits**
3) **Unfolded Distributions** (where available)

... then more specifically

- which **corrections** are **taken into account** as systematic uncertainties?
- where to expect strong **electroweak corrections** and how to address them?

SM Electroweak ATLAS Public Results

Cross Section Measurements - Methodology

Diboson analyses tend to measure **fiducial** and **total** cross sections

$$\sigma_{fid} = \frac{N_{obs} - N_{bkgd}}{\mathbf{C} \times \int \mathcal{L} dt} \qquad \sigma_{tot} = \frac{\sigma_{fid}}{\mathbf{A} \times BR}$$

efficiency corrections

acceptance

Define fiducial phase space cuts

- as close as possible to analysis cuts
- using final state “truth” objects
- using ”dressed” leptons with photons within $\Delta R = 0.1$
- using jets reconstructed with anti-k_T ($\Delta R = 0.4$) algorithm
- to reduce extrapolation to phase space regions with large theoretical uncertainties

Common Selection

Leptons

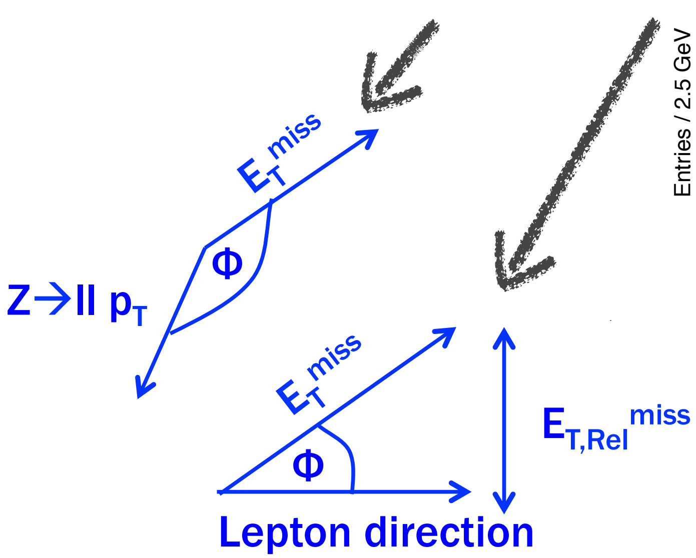
- p_T > 7-25 GeV, |η| < 2.5
- calorimeter and track isolation
- single lepton trigger, matching

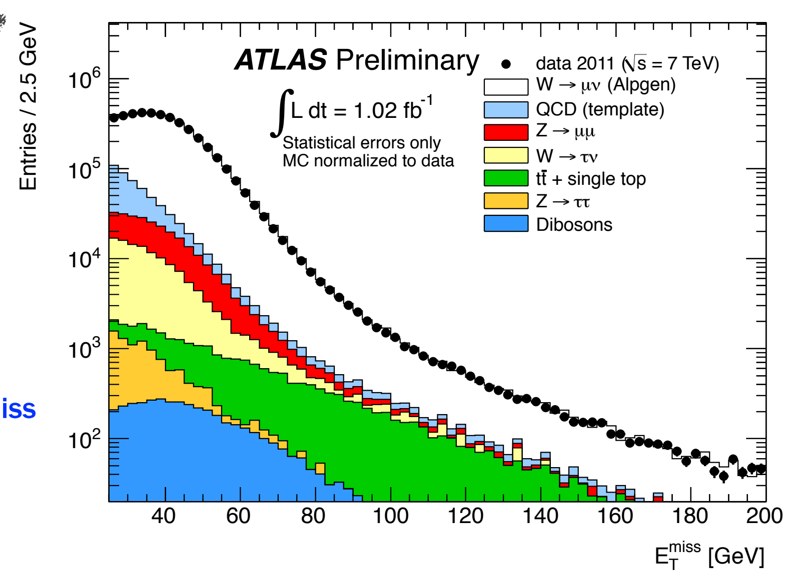
Photons

- p_T > 15 GeV, |η| < 2.37
- calorimeter isolation

Missing Transverse Energy

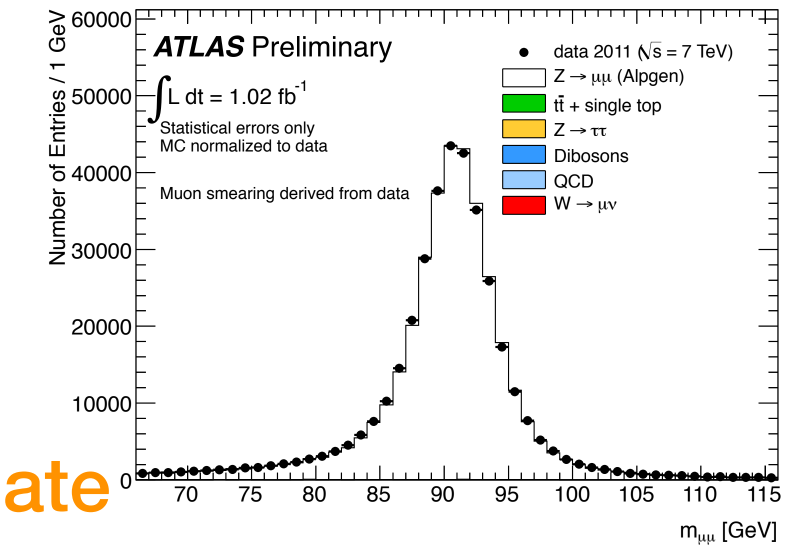
- built from leptons, jets, calo clusters
- |η| < 4.5
- can use axial or relative E_T^{miss}





Z→l⁺l⁻ Candidate

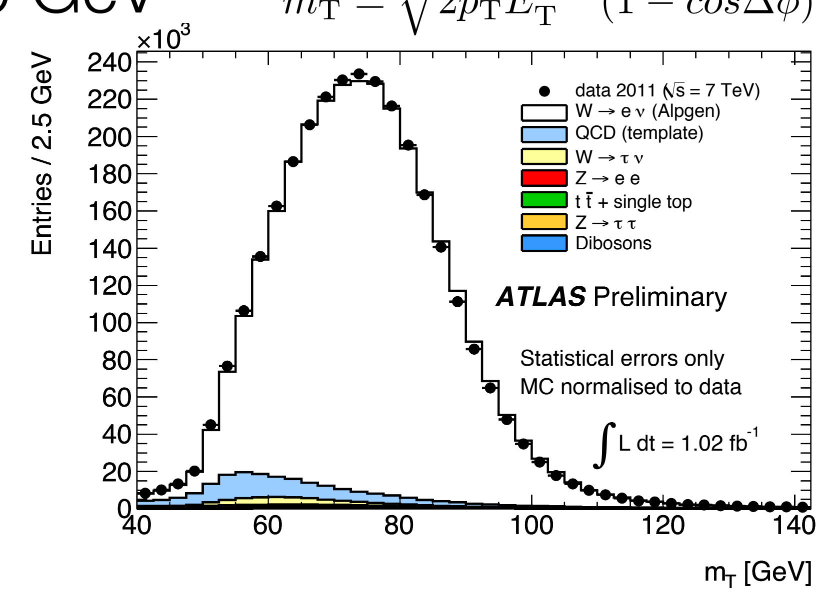
- 2 SF, OS isolated leptons
- mass window 10-25 GeV of PDG



W→l±ν Candidate

- 1 isolated lepton
- E_T^{miss} > 25-45 GeV
- m_T > 20-40 GeV

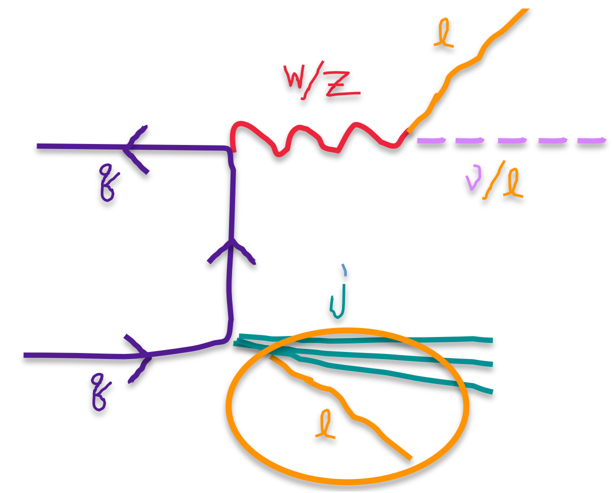
$$m_T = \sqrt{2 p_T E_T^{miss}(1 - cos\Delta\phi)}$$



Common Backgrounds

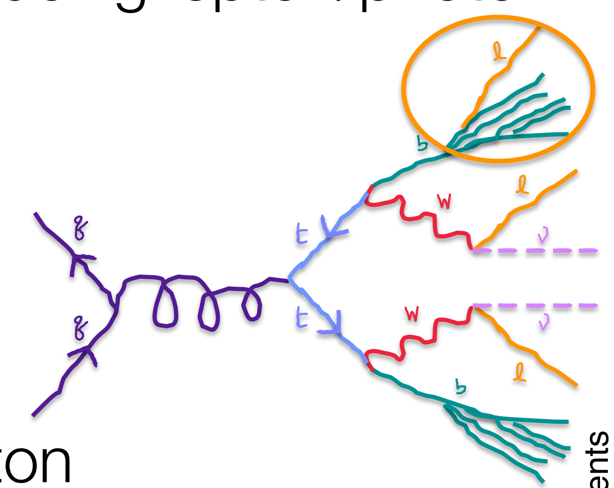
W/Z+jets (dominant)

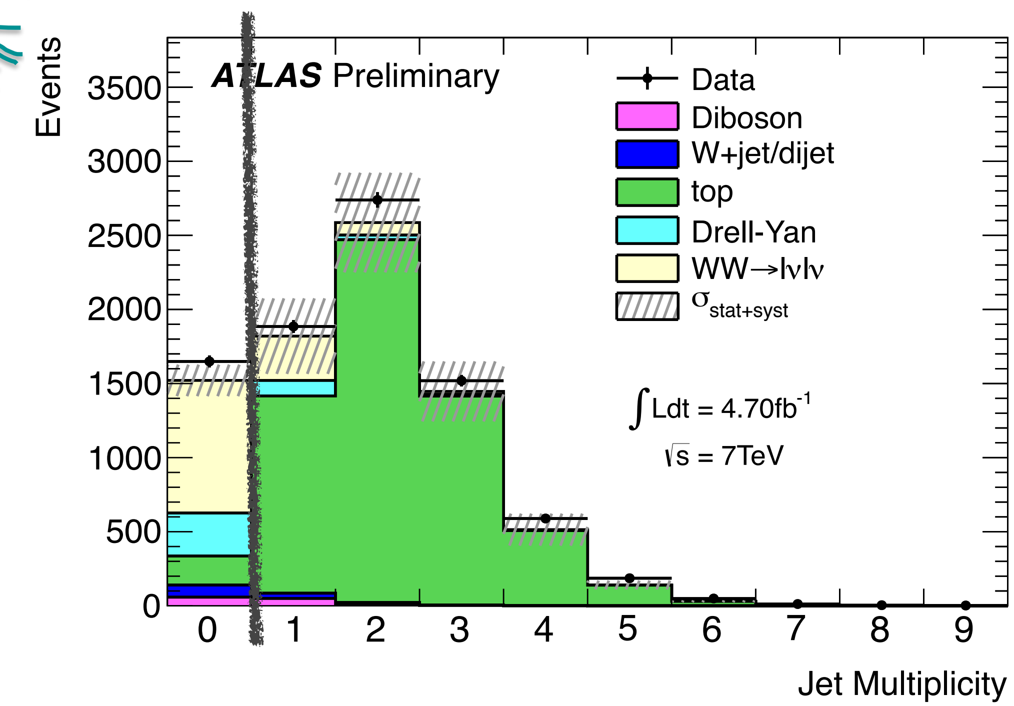
- 1 or 2 prompt, isolated leptons
- real or fake missing energy
- jets can produce a fake or real lepton/photon
- primarily **data-driven estimates**
  - measure probability of jet producing lepton/photon



Top

- 2 prompt, isolated leptons
- real missing energy
- large number of jets/b-jets
  - can produce a fake or real lepton
- remove by applying cuts on e.g.
  - impact parameter d_0
  - N_{jets}
  - m_{ll} (no real Z boson!)



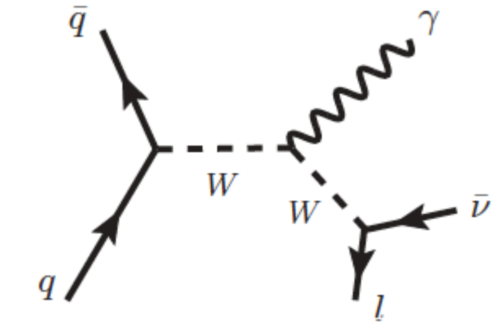


Other diboson

- estimated mostly from **MC** simulation

W($\rightarrow$lν)γ and Z($\rightarrow$ll)γ

arXiv:1205.2531 [hep-ex]

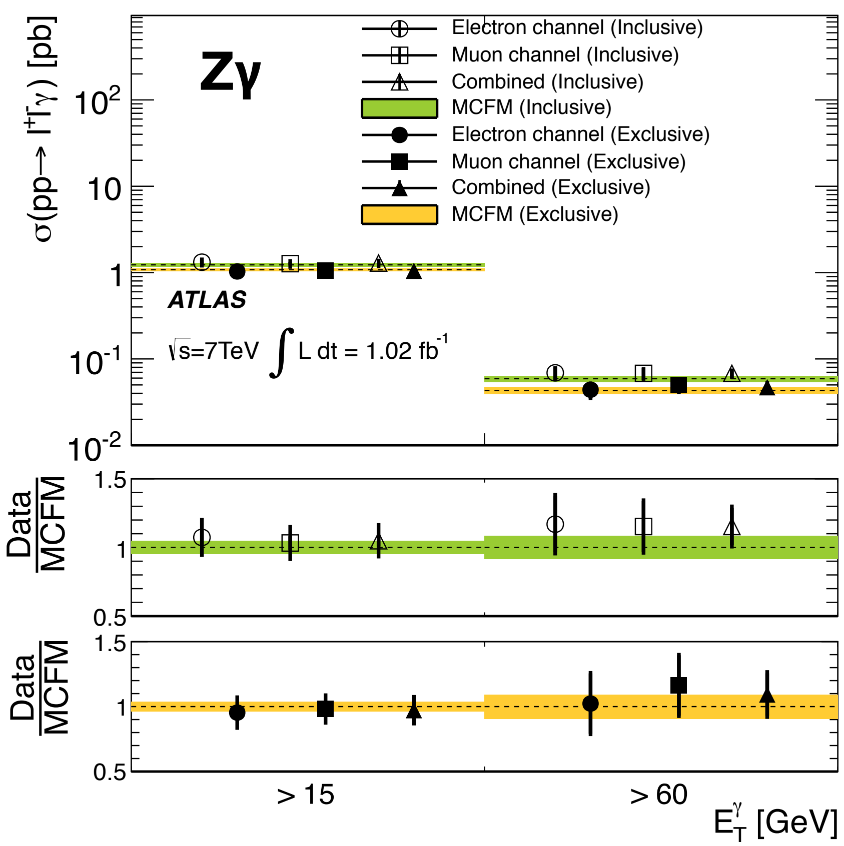


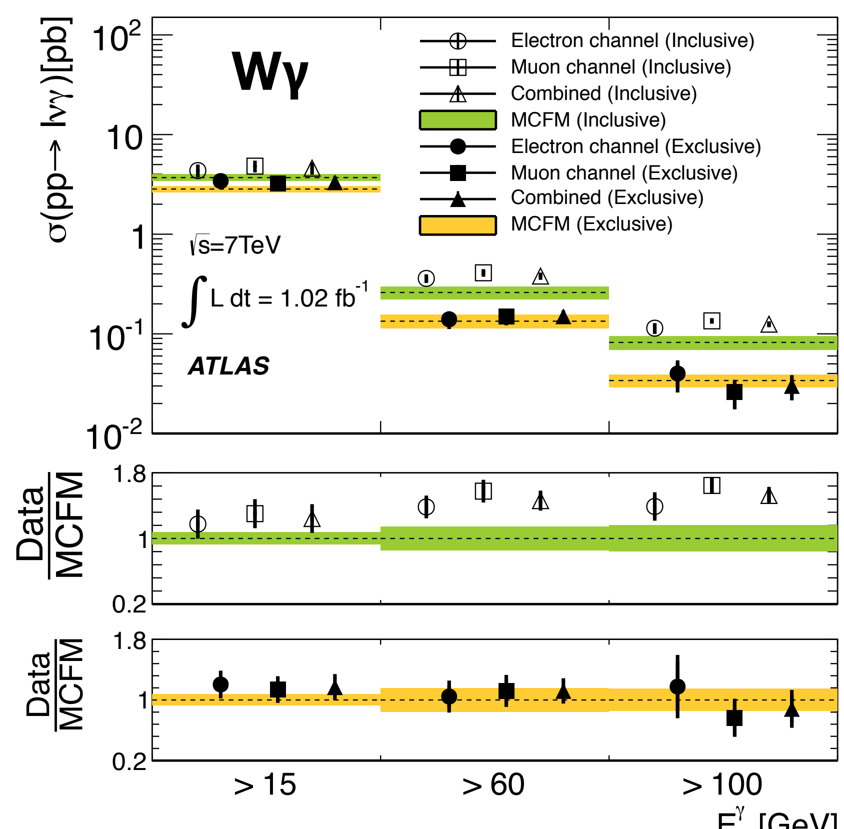
Selection

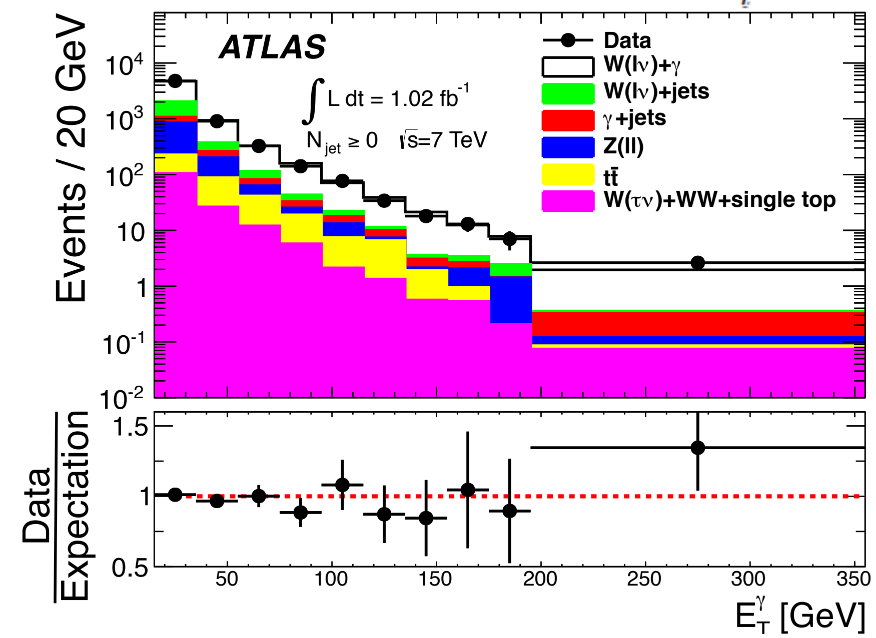
- **W or Z candidate** with m_T or m_{ll} > 40 GeV
- isolated **photon**, E_T > 15 GeV, $\Delta R(l,\gamma)$ > 0.7
- **inclusive and exclusive** (**jet veto** p_T > 30 GeV)

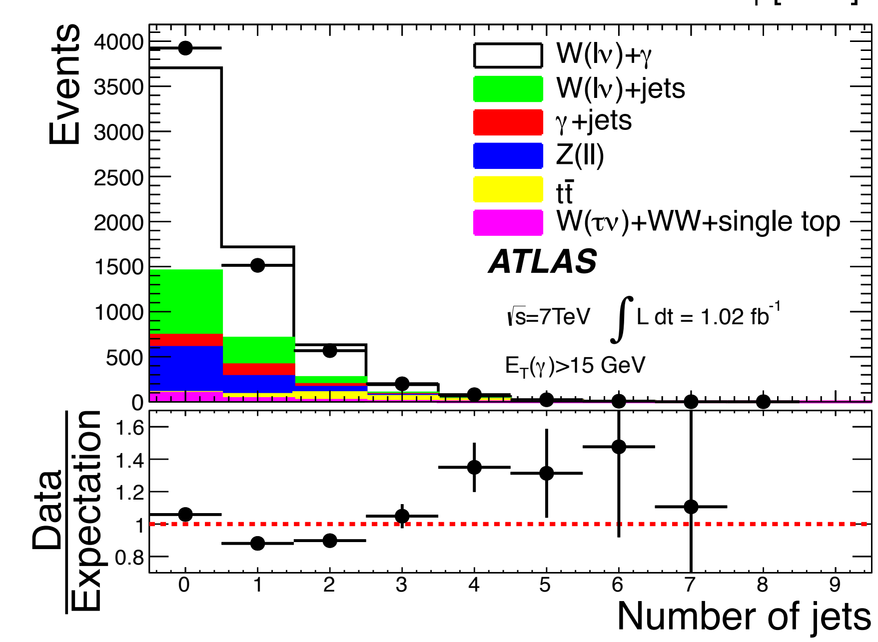
Main Backgrounds

- W/Z+jets (jet faking photon or lepton) → *data-driven (DD)*









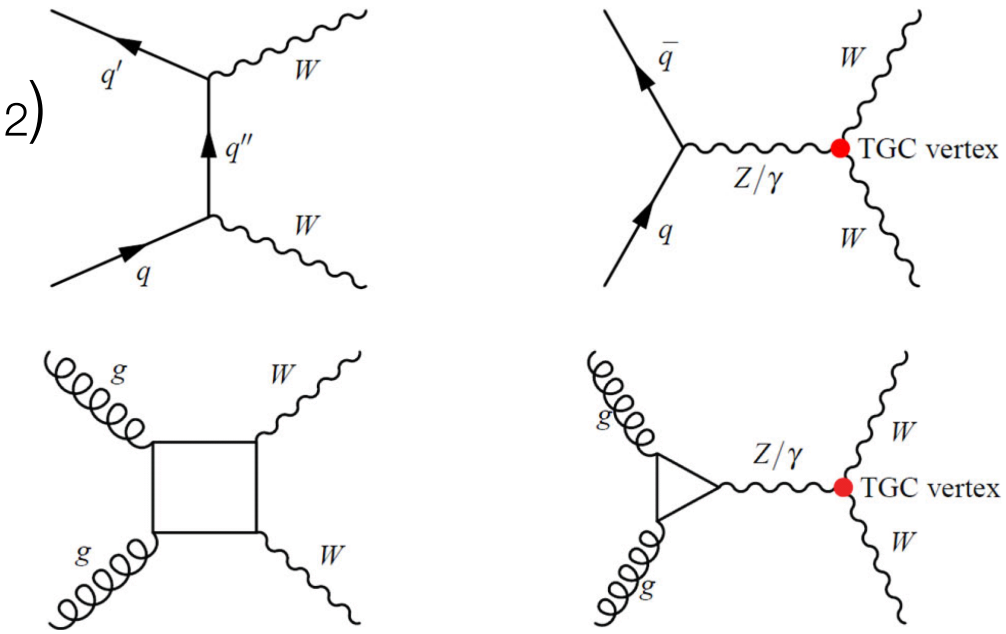
→ **inclusive** need NLO W/Zγ + multiple parton emission

→ **exclusive** good agreement

WW → lνlν

Selection

- **exactly 2** OS isolated **leptons**, $p_T > 20{,}25$ GeV (l_1, l_2)
- **Z veto** $|m_{ll}-m_Z| > 15$ GeV (ee/μμ only)
- $m_{ll} > 15{,}10$ GeV (ee/μμ, eμ)
- $E_{T,Rel}^{miss} > 50, 55, 25$ GeV (ee, μμ, eμ)
- **Jet veto** $p_T > 25$ GeV, $|\eta| < 4.5$
- **b-jet veto** $p_T > 20$ GeV,



Main Backgrounds

- Z+jets → *MC (shape), DD (SF)*
- top → *DD*

includes: gg (≈3%)
does not include:
H→WW (+3% for $m_{H,SM}$=126 GeV)
VBF/VBS or DPS (< 0.1%)

σ^{fid} varies per channel, as different cuts

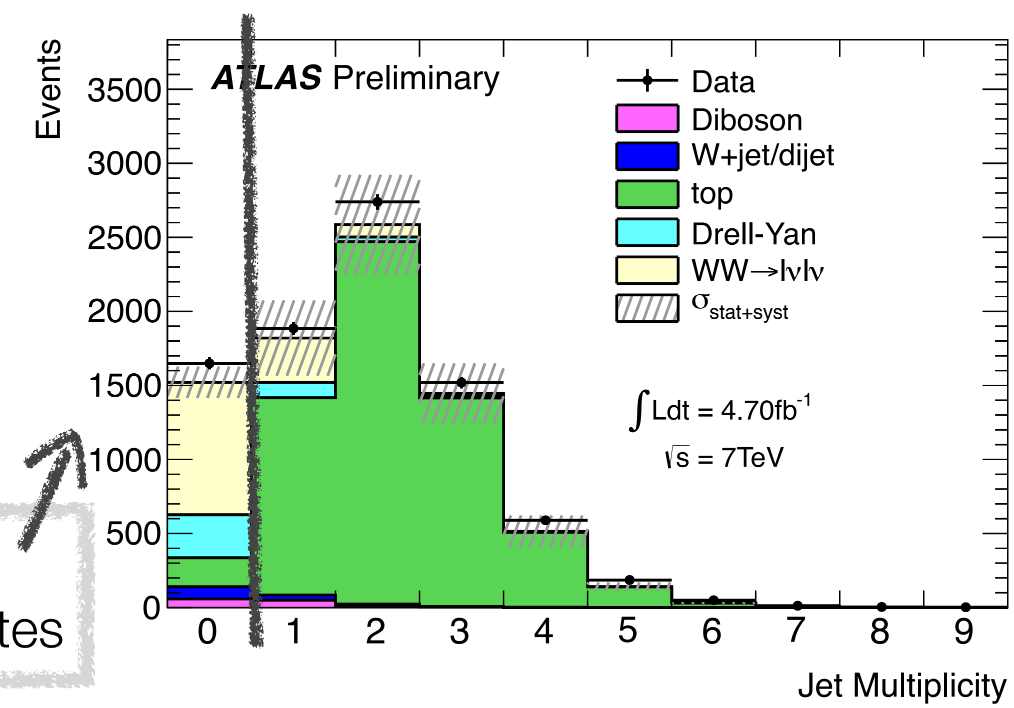
$$\boxed{\sigma_{WW}^{tot} = 53.4 \pm 2.1\ (\mathrm{stat}) \pm 4.5\ (\mathrm{syst}) \pm 2.1\ (\mathrm{lumi})\ \mathrm{pb}}$$

$$\boxed{\sigma_{WW}^{\mathrm{NLO}} = 45.1 \pm 2.8\ \mathrm{pb}}$$ (MCFM)

→ **systematically** dominated

- 6.7% from signal acceptance
- 5.1% from background estimation

1524 candidates



5 fb^{-1}

WZ → lνll

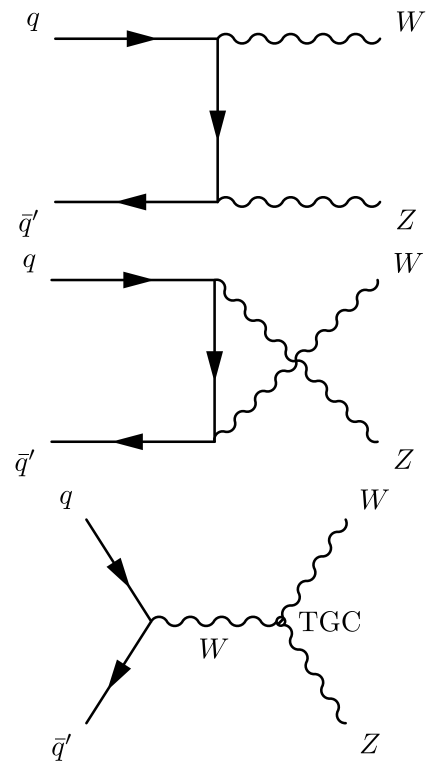
arXiv:1208.1390 [hep-ex]

Selection

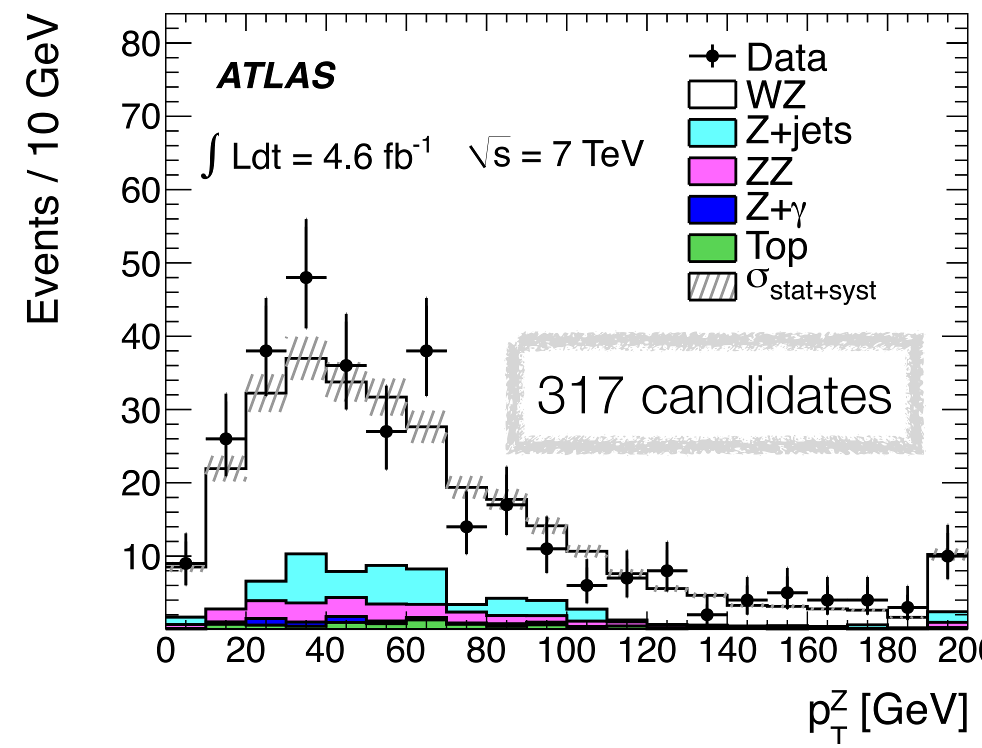
- **≥ 3** isolated **leptons**, p_T > 15 GeV
- **Z candidate** $|m_{ll}-m_Z|$ < 10 GeV
- **E_T^{miss}** > 25 GeV
- **W candidate** m_T > 20 GeV

Main Backgrounds

- Z+jets → *DD*
- ZZ → *MC*
- top → *MC (shape), DD (SF)*



no gg at lower $\mathcal{O}$

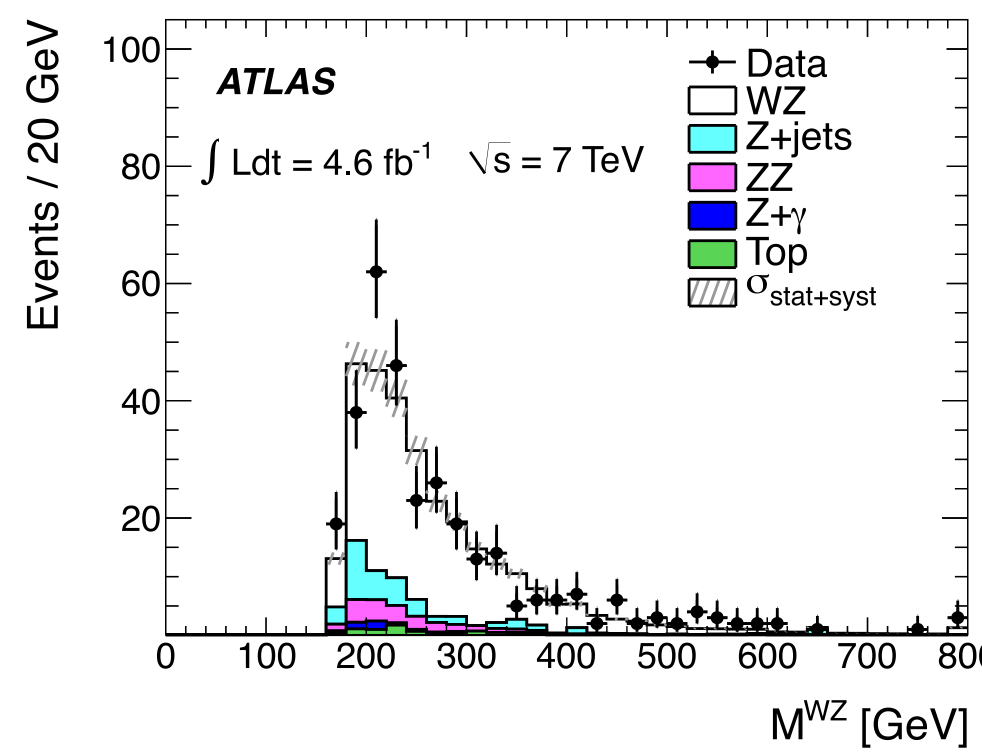


317 candidates

$$\sigma^{fid}_{WZ} = 92^{+7}_{-6}\ (\text{stat}) \pm 4\ (\text{syst}) \pm 2\ (\text{lumi})\ \text{fb}$$
$$\sigma^{tot}_{WZ} = 19.0^{+1.4}_{-1.3}\ (\text{stat}) \pm 0.9\ (\text{syst}) \pm 0.4\ (\text{lumi})\ \text{pb}$$

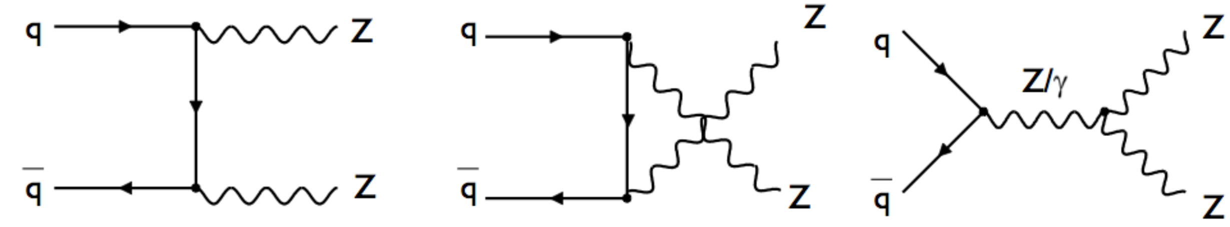
defined within
66<m_{Z/γ^*}<116 GeV

$$\sigma^{\text{NLO}}_{WZ} = 17.6^{+1.1}_{-1.0}\ \text{pb}$$ (MCFM)



→ still **statistically** dominated

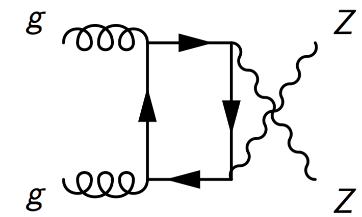
ZZ → llll



Standard Model Production SM Forbidden

Selection

- **exactly 4** isolated leptons, $p_T > 7$ GeV
- leading lepton $p_T > 20{,}25$ GeV (μ,e)
- muons up to **$|\eta| < 2.7$**
- **two Z candidates** with $66 < m_{ll} < 116$ GeV
  - pairing ambiguity solved by minimising $\sum|m_{ll}-m_Z|$



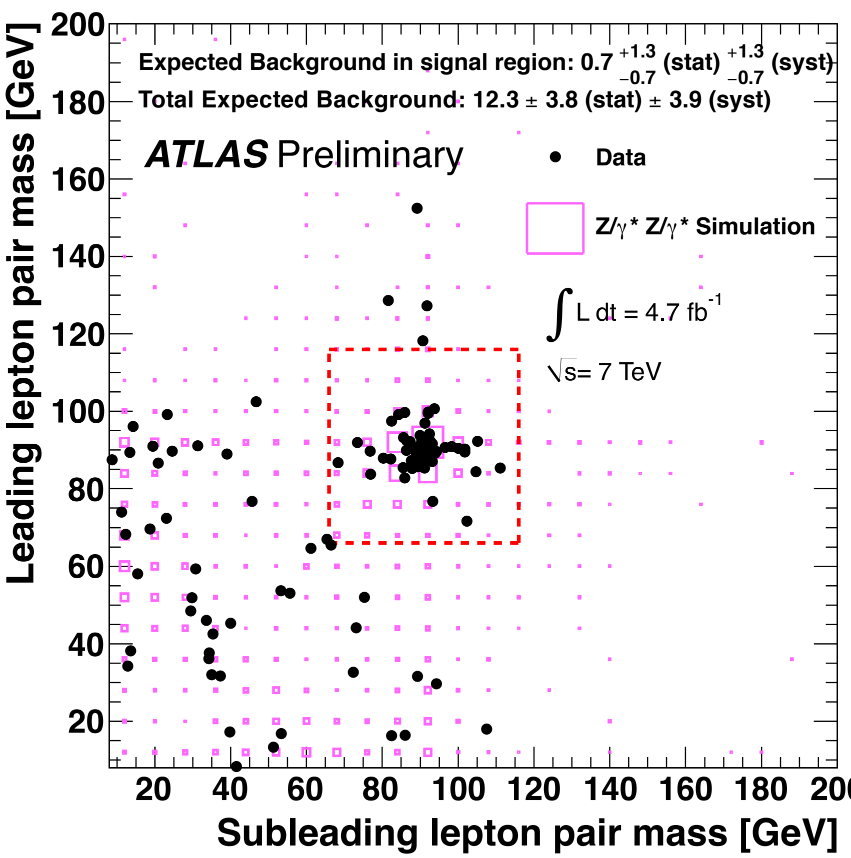
gg≈6%

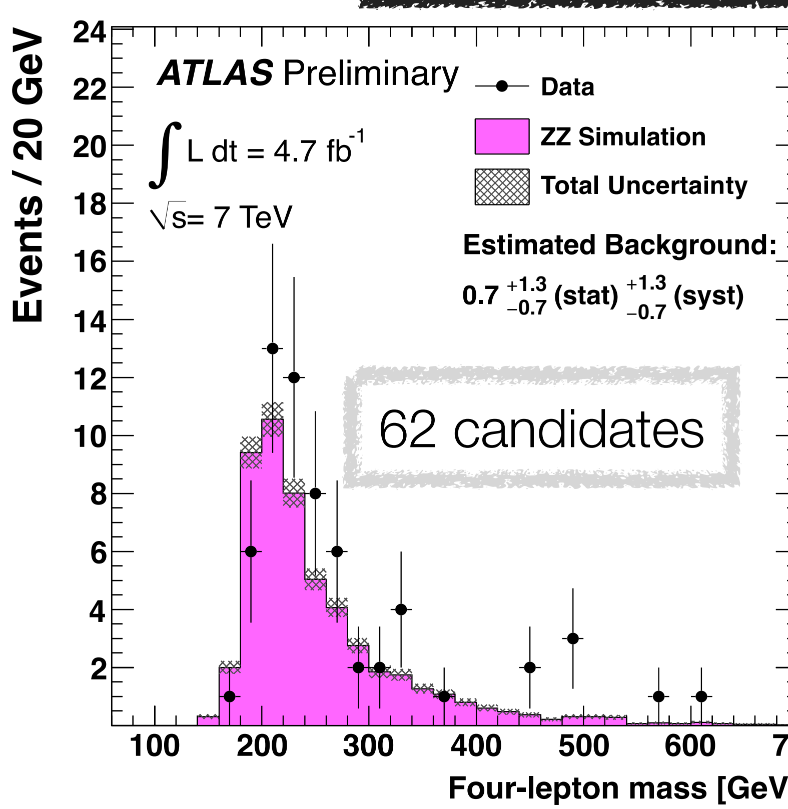
Main Backgrounds

- W/Z+jets, WW/WZ, top → *DD*

$$\sigma^{fid}_{ZZ} = 21.2^{+3.2}_{-2.7}\ (\mathrm{stat})^{+1.0}_{-0.9}\ (\mathrm{syst}) \pm 0.8\ (\mathrm{lumi})\ \mathrm{fb}$$
$$\sigma^{tot}_{ZZ} = 7.2^{+1.1}_{-0.9}\ (\mathrm{stat})^{+0.4}_{-0.3}\ (\mathrm{syst}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb}$$

$$\sigma^{\mathrm{NLO}}_{ZZ} = 6.5^{+0.3}_{-0.2}\ \mathrm{pb}$$ (MCFM)





→ updating soon with enlarged acceptance

$ZZ \rightarrow ll\nu\nu$

ATLAS-CONF-2012-027

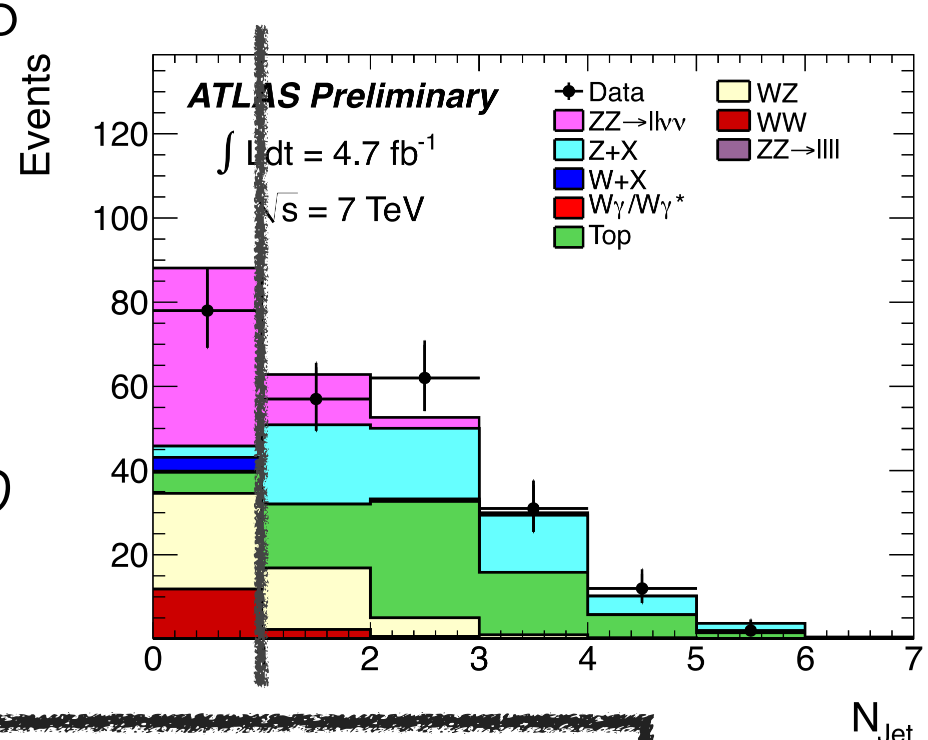
gain in BR but **more background** than llll

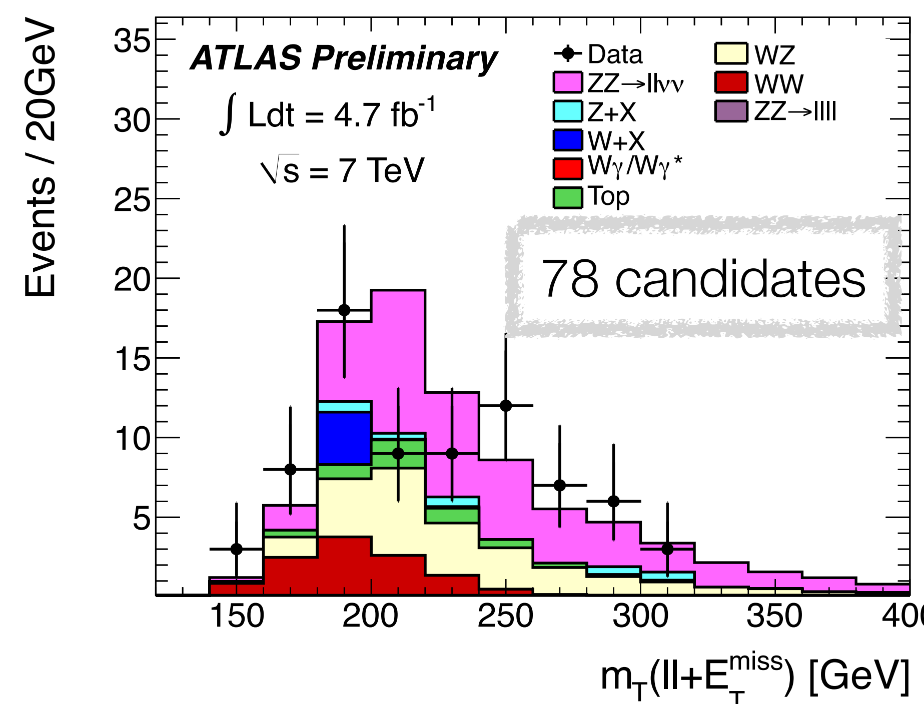
Selection

- **exactly 2** isolated leptons, $p_T > 20$ GeV
- **Z candidate** $|m_{ll} - m_Z| < 15$ GeV
- axial $\mathbf{E_T^{miss}} > 80$ GeV
- $|E_T^{miss} - p_T^{ll}| / p_T^{ll} < 0.6$
- $\Delta R(l,l) > 0.3$
- **jet veto** $p_T > 25$ GeV

Main Backgrounds

- WZ → *MC*
- top, $Z \rightarrow \tau\tau$, WW → *DD*
- Z+jets → *DD*

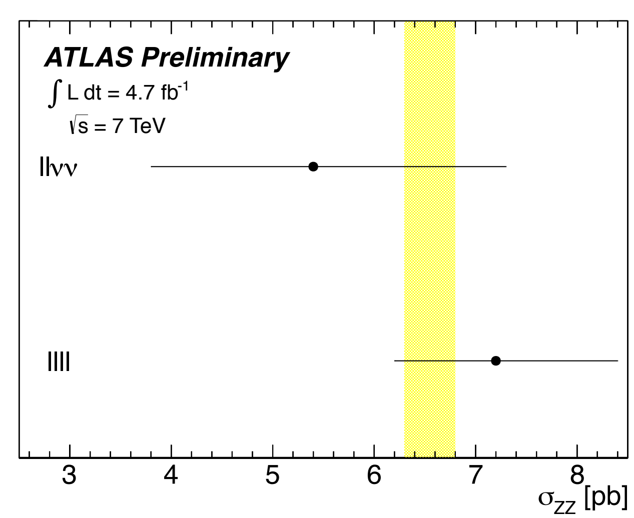




$$\sigma_{ZZ}^{fid} = 12.2^{+3.0}_{-2.8}\ (\text{stat}) \pm 1.9\ (\text{syst}) \pm 0.5\ (\text{lumi})\ \text{fb}$$

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

(MCFM) $$\sigma_{ZZ}^{\text{NLO}} = 6.5^{+0.3}_{-0.2}\ \text{pb}$$



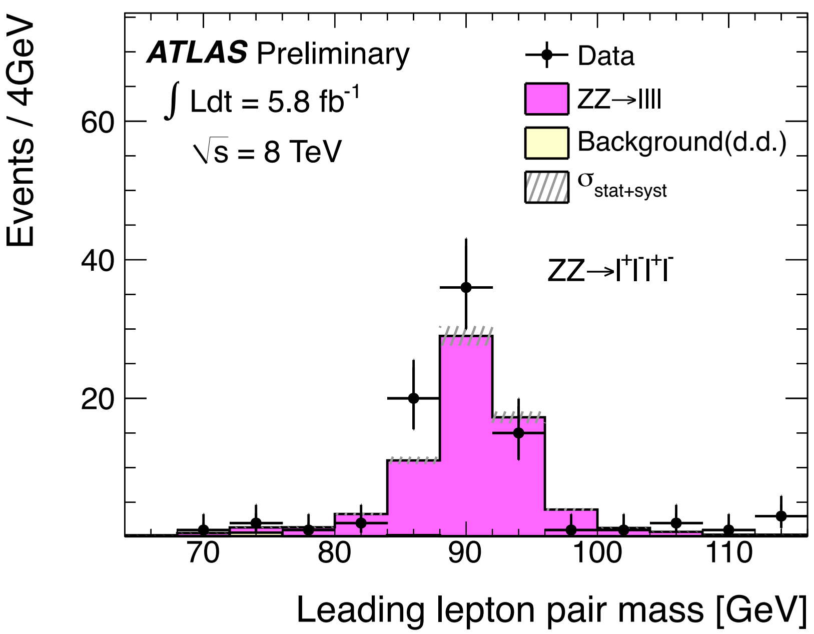
ZZ → llll @ 8TeV

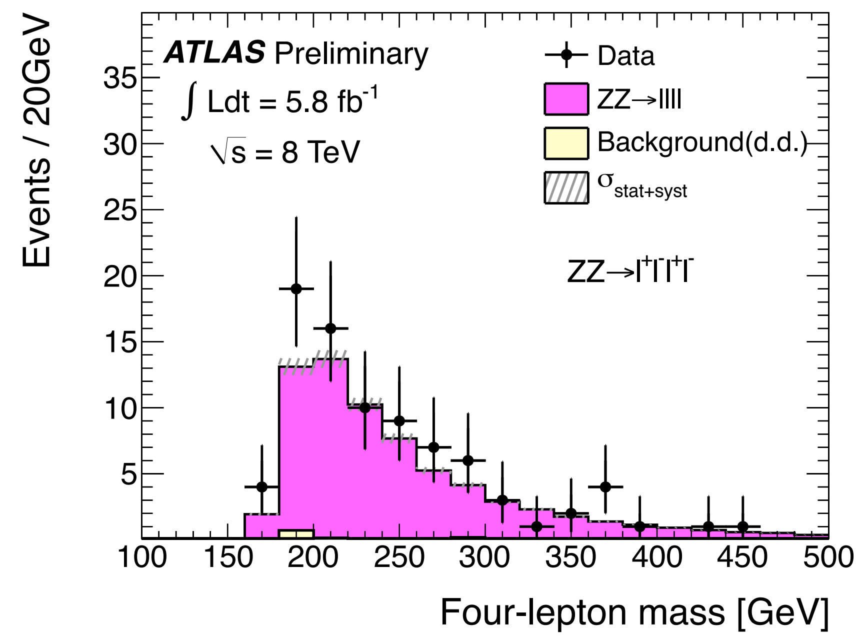
6 fb^{-1}

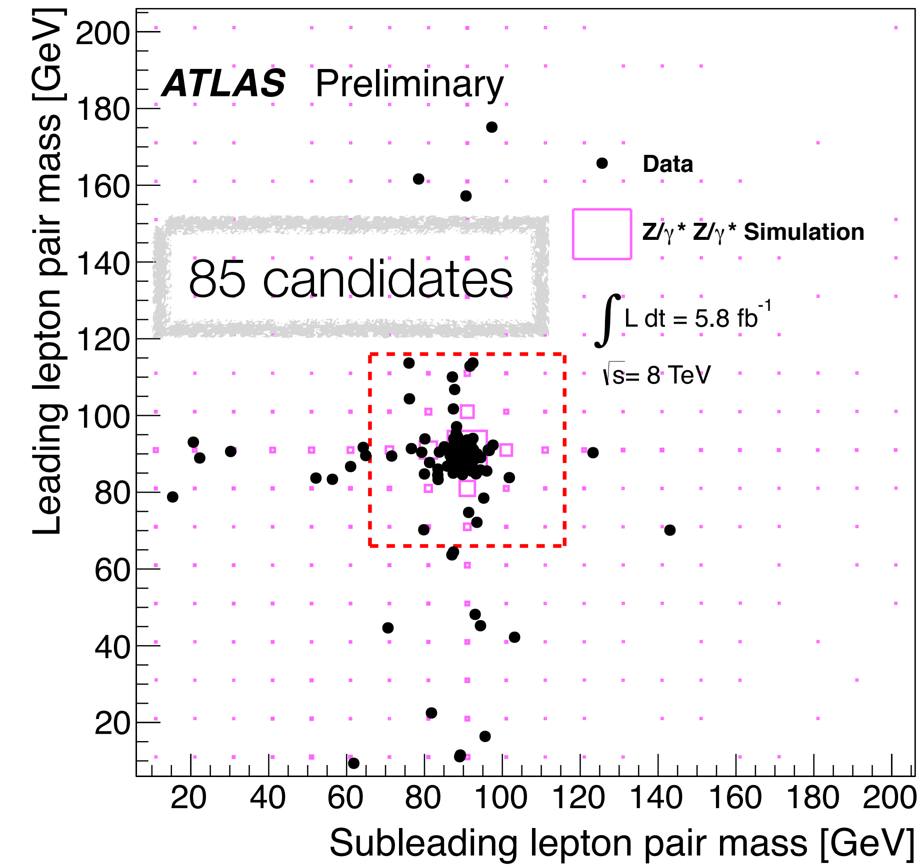
ATLAS-CONF-2012-090

Selection

- same as for 2011 data





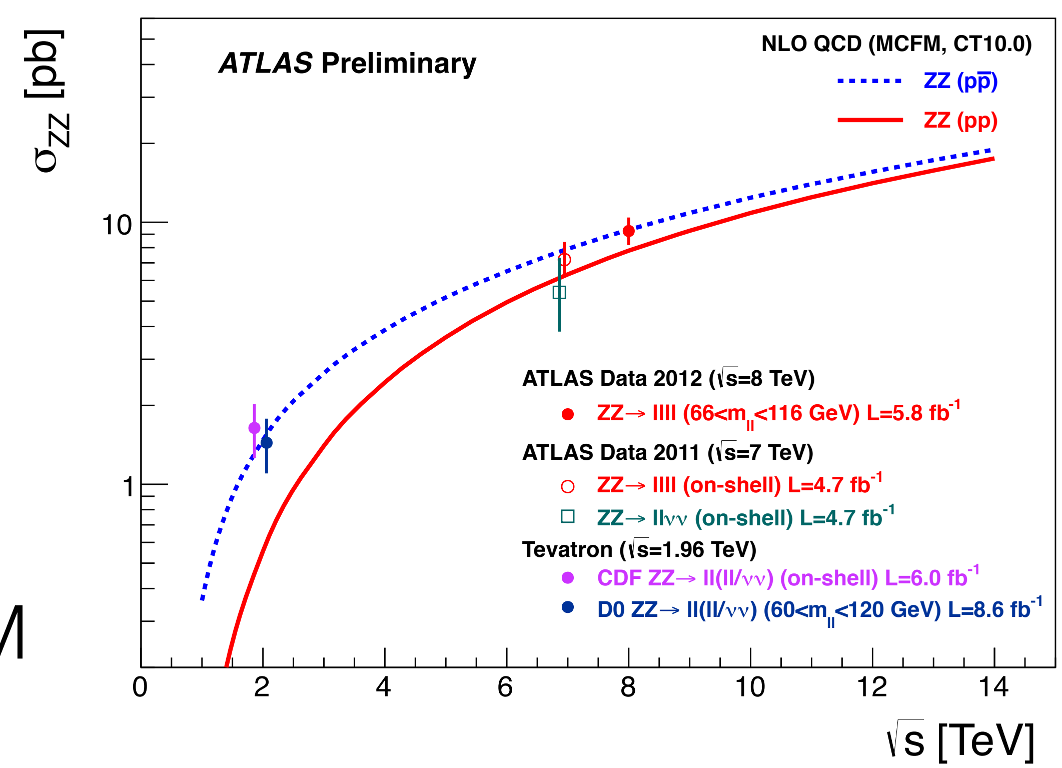


$$\sigma_{ZZ}^{fid} = 21.0^{+2.4}_{-2.2}\ (\mathrm{stat})^{+0.6}_{-0.5}\ (\mathrm{syst}) \pm 0.8\ (\mathrm{lumi})\ \mathrm{fb}$$

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

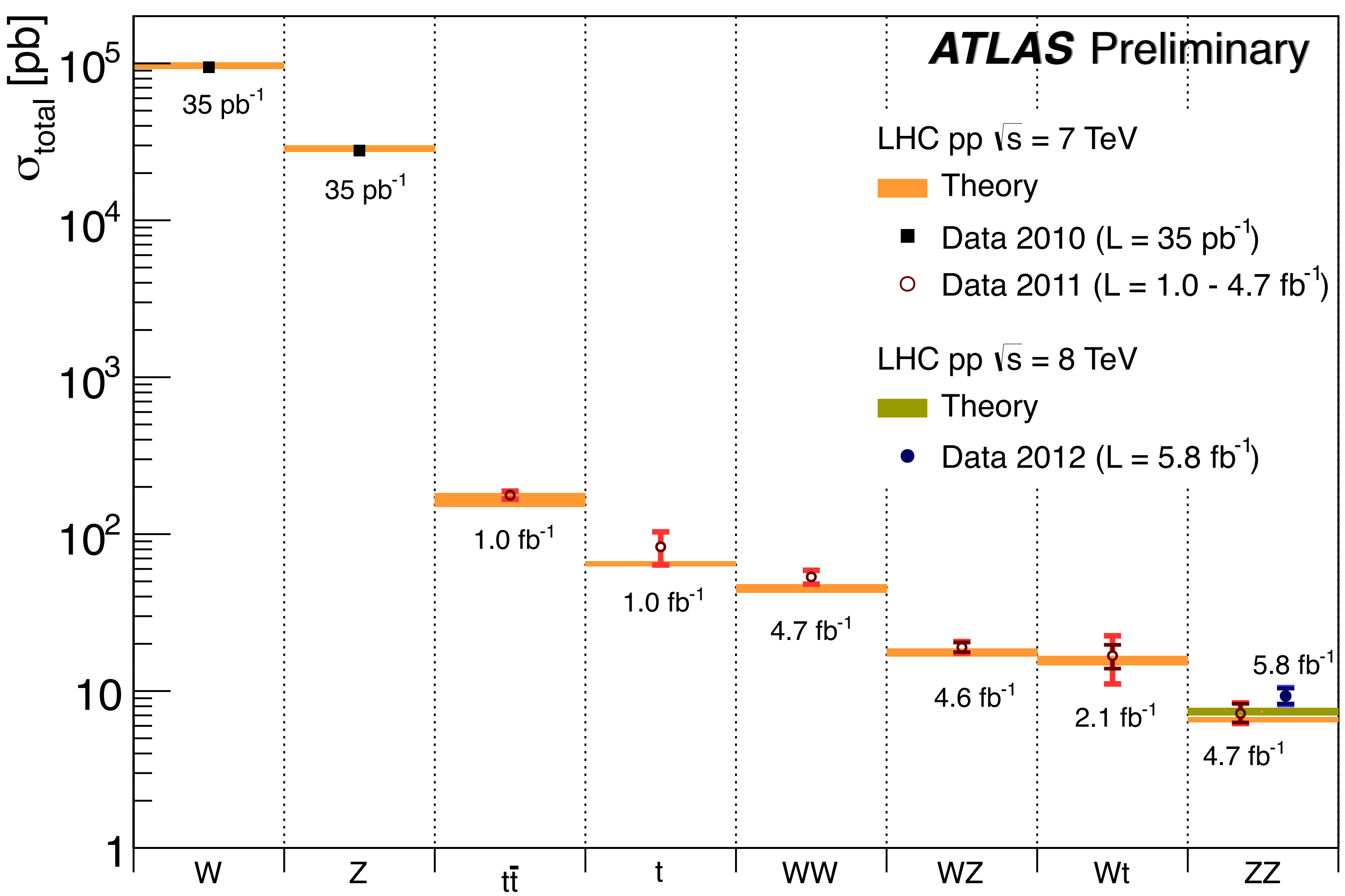
$$\sigma_{ZZ}^{\mathrm{NLO}} = 7.4 \pm 0.4\ \mathrm{pb}$$ (MCFM)

→ fluctuates high but still in agreement with SM



ATLAS Cross Section Summary

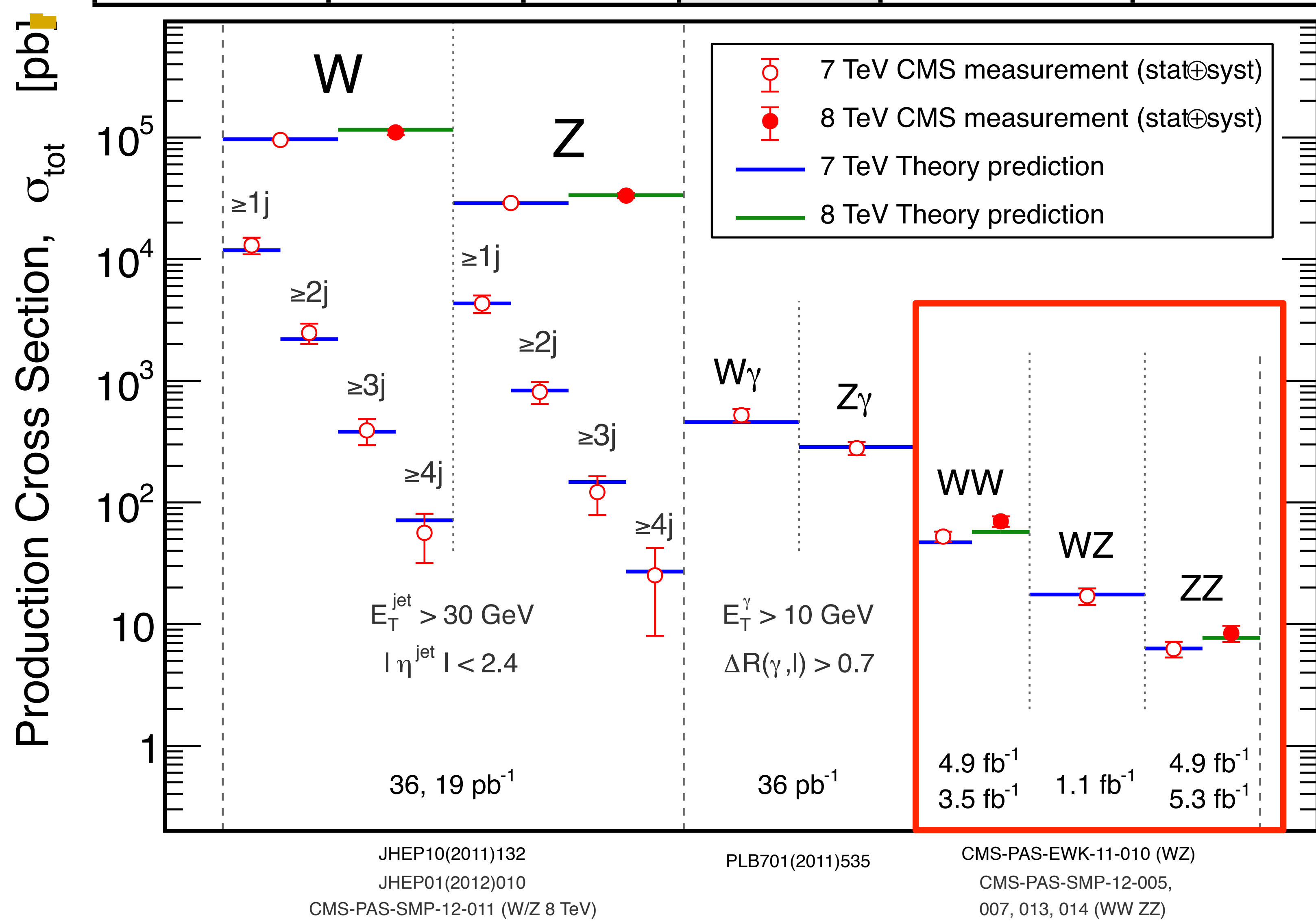
Process	$\sqrt{s}$ [TeV]	L [fb^{-1}]	**σ^{tot} [pb]**	δ stat	δ syst	δ lumi	**σ^{NLO} [pb]**	$\delta\sigma^{NLO}$
W(→lν)γ	7	1	**4.60**	± 0.11	± 0.64	± 0.17	**3.70**	± 0.28
Z(→ll)γ	7	1	**1.29**	± 0.05	± 0.15	± 0.05	**1.23**	± 0.06
WW→lνlν	7	5	**53.4**	± 2.1	± 4.5	± 2.1	**45.1**	± 2.8
WZ→lνll	7	5	**19.0**	+1.4/-1.3	± 0.9	± 0.4	**17.6**	+1.1/-1.0
ZZ→llll	7	5	**7.2**	+1.1/-0.9	+0.4/-0.3	± 0.3	**6.5**	+0.3/-0.2
ZZ→llνν	7	5	**5.4**	+1.3/-1.2	+1.4/-1.0	± 0.2	**6.5**	+0.3/-0.2
ZZ→llll	8	6	**9.3**	+1.1/-1.0	+0.4/-0.3	± 0.3	**7.4**	± 0.4



Most cross sections seem to fluctuate ~1σ high but within uncertainties individually agree with SM predictions

CMS Cross Section Summary

Process	$\sqrt{s}$ [TeV]	L [fb^{-1}]	σ^{tot} [pb]	δ stat	δ syst	δ lumi	σ^{NLO} [pb]	$\delta\sigma^{NLO}$
WW→lνlν	7	5	**52.4**	± 2.0	± 4.5	± 1.2	**47.0**	± 2.0
WW→lνlν	8	3.5	**69.9**	± 2.8	± 5.6	± 3.1	**57.3**	+2.4/-1.6
WZ→lνll	7	1.1	**17.0**	± 2.4	± 1.1	± 1.0	**17.5**	± 0.6
ZZ→llll	7	5	**6.2**	+0.9/-0.8	+0.4/-0.3	± 0.1	**6.3**	± 0.4
ZZ→llll	8	5.3	**8.4**	± 1.0	± 0.7	± 0.4	**7.7**	± 0.4

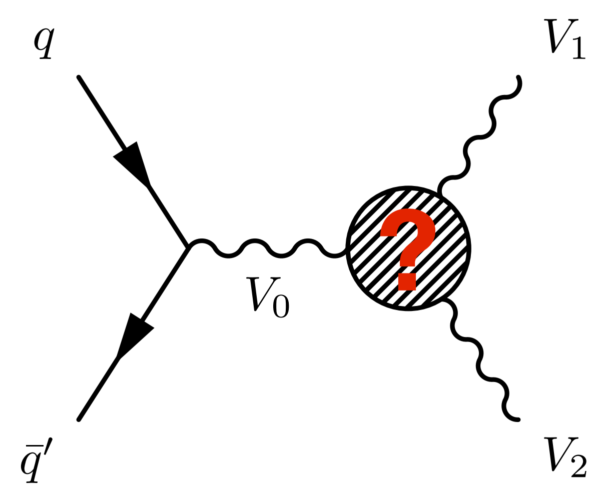


FOR COMPARISON ONLY

For details, please ask CMS experts

Anomalous Gauge Boson Coupling Limits

Model independent TGC **effective Lagrangian** depends on different parameters



SM allowed

$$\mathcal{L}_{WWV} = ig_{WWV}\left[g_1^V(W_{\mu\nu}^\dagger W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W_{\rho\mu}^\dagger W_\nu^\mu V^{\nu\rho}\right]$$

WW,WZ Wγ

SM forbidden

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta)\right]$$

ZZ

$$\mathcal{L}_{Z\gamma V} = -ie\left[h_3^V\tilde{F}^{\mu\nu}Z_\mu\frac{(\Box + m_V^2)}{m_Z^2}V_\nu + h_4^V\tilde{F}^{\mu\nu}Z^\alpha\frac{(\Box + m_V^2)}{m_Z^4}\partial_\alpha\partial_\mu V_\nu\right]$$

Zγ

V = Z,γ

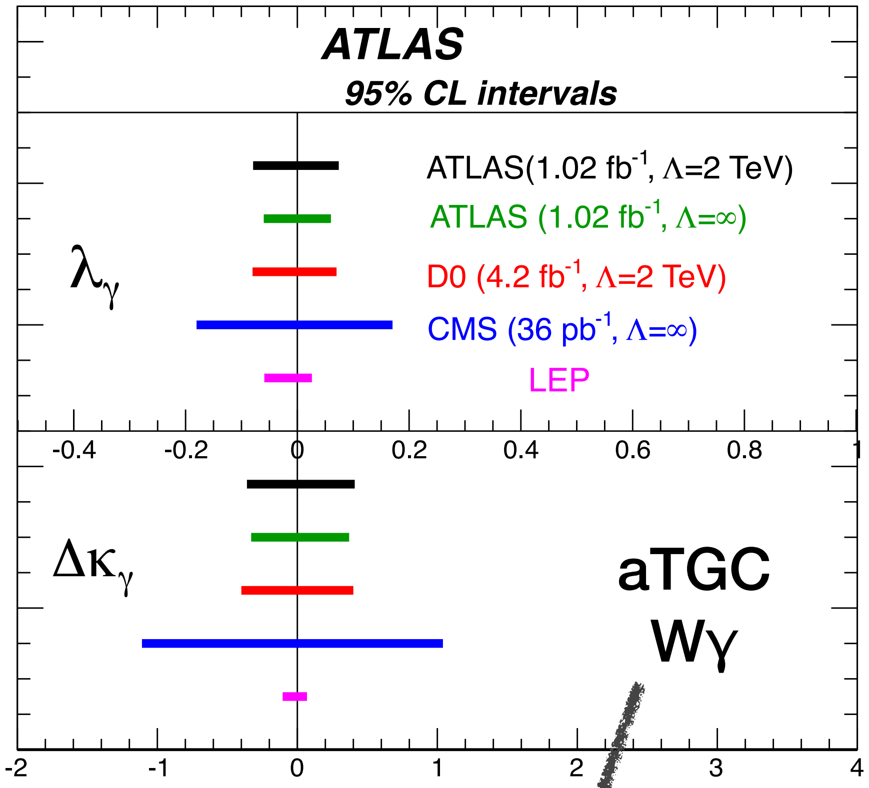
In the Standard Model $g_1^V = \kappa^V = 1$ $\lambda^V = f_4^V = f_5^V = h_3^V = h_4^V = 0$

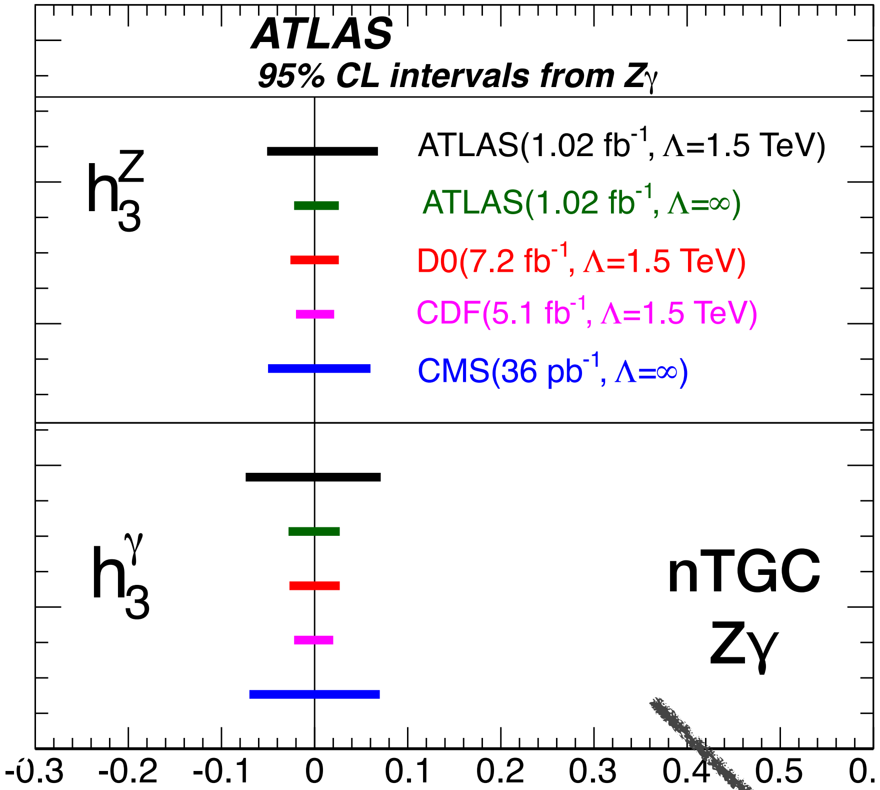
Expect **change in production rate** at high boson/lepton p_T.
ATLAS and CMS use **no form factor Λ** to suppress divergence at high √s
Use **common limit setting code** within ATLAS

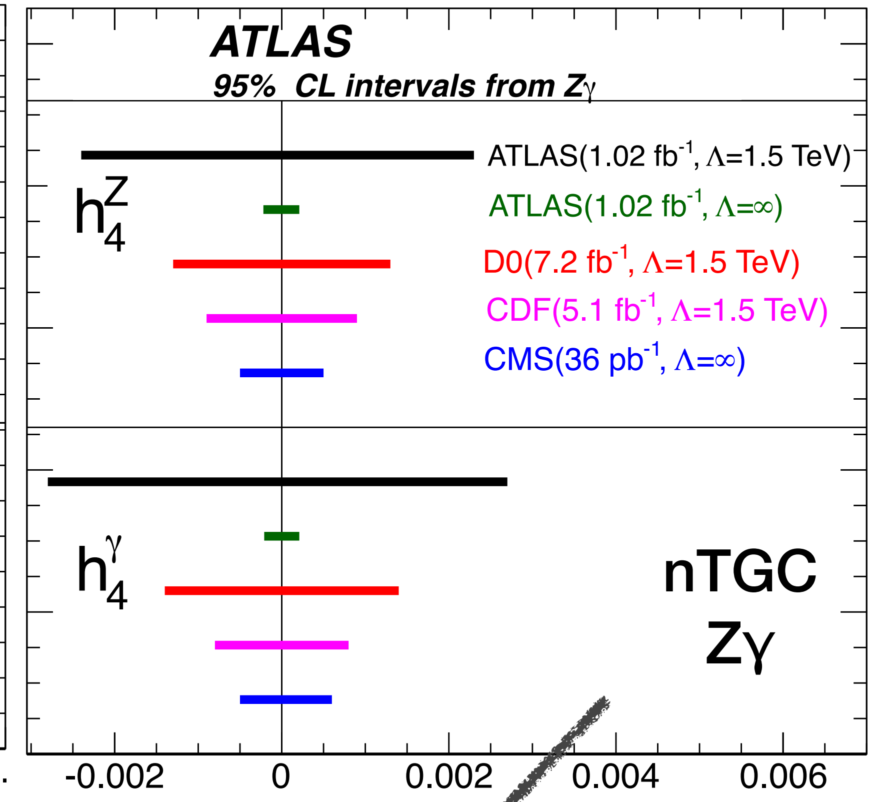
1 fb^{-1}

$W(\rightarrow l\nu)\gamma$ and $Z(\rightarrow ll)\gamma$

arXiv:1205.2531 [hep-ex]







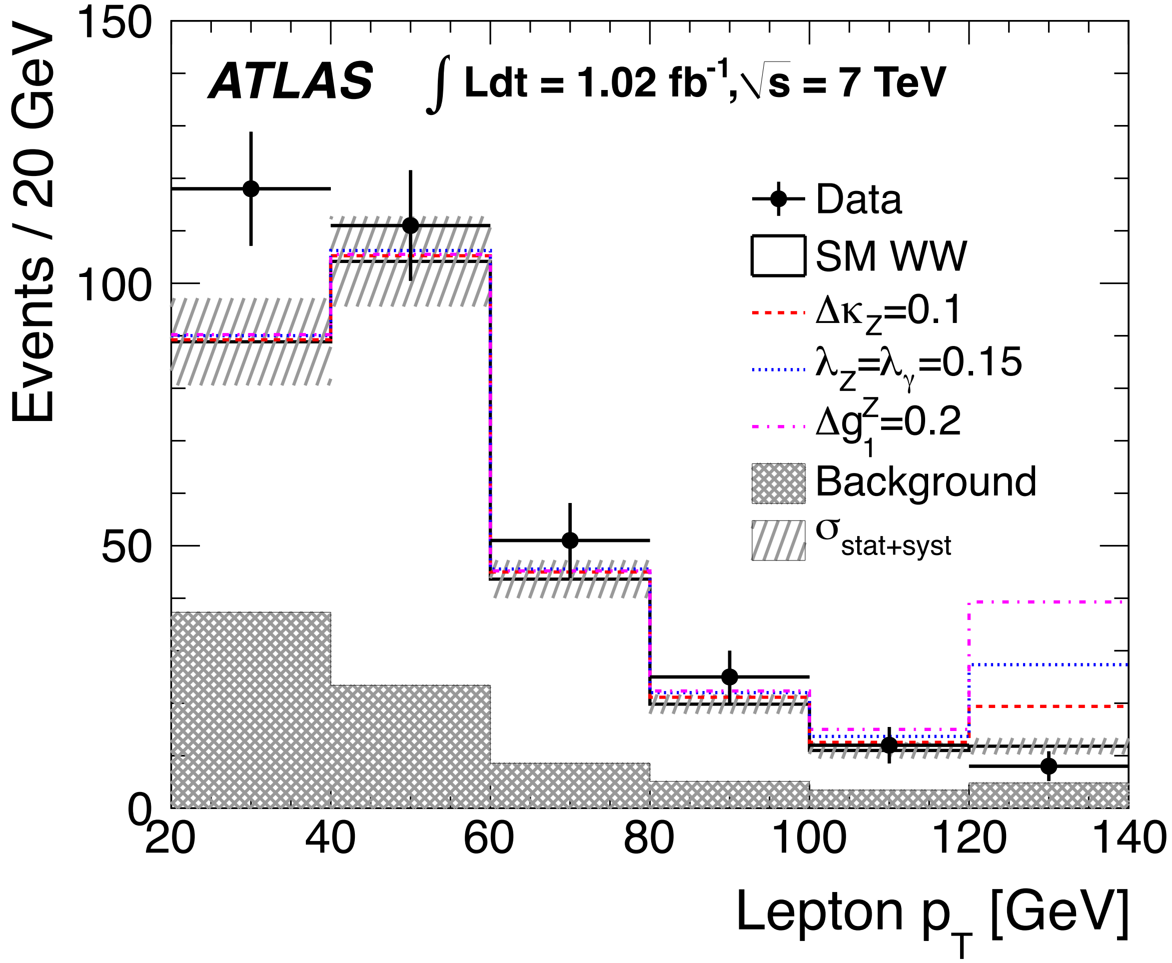
- probes **WWγ** vertex
- fit exclusive $E_T^{\gamma} > 100$ GeV bin
- **improve** on Tevatron limits
- LEP results from WW production (includes WWZ vertex)

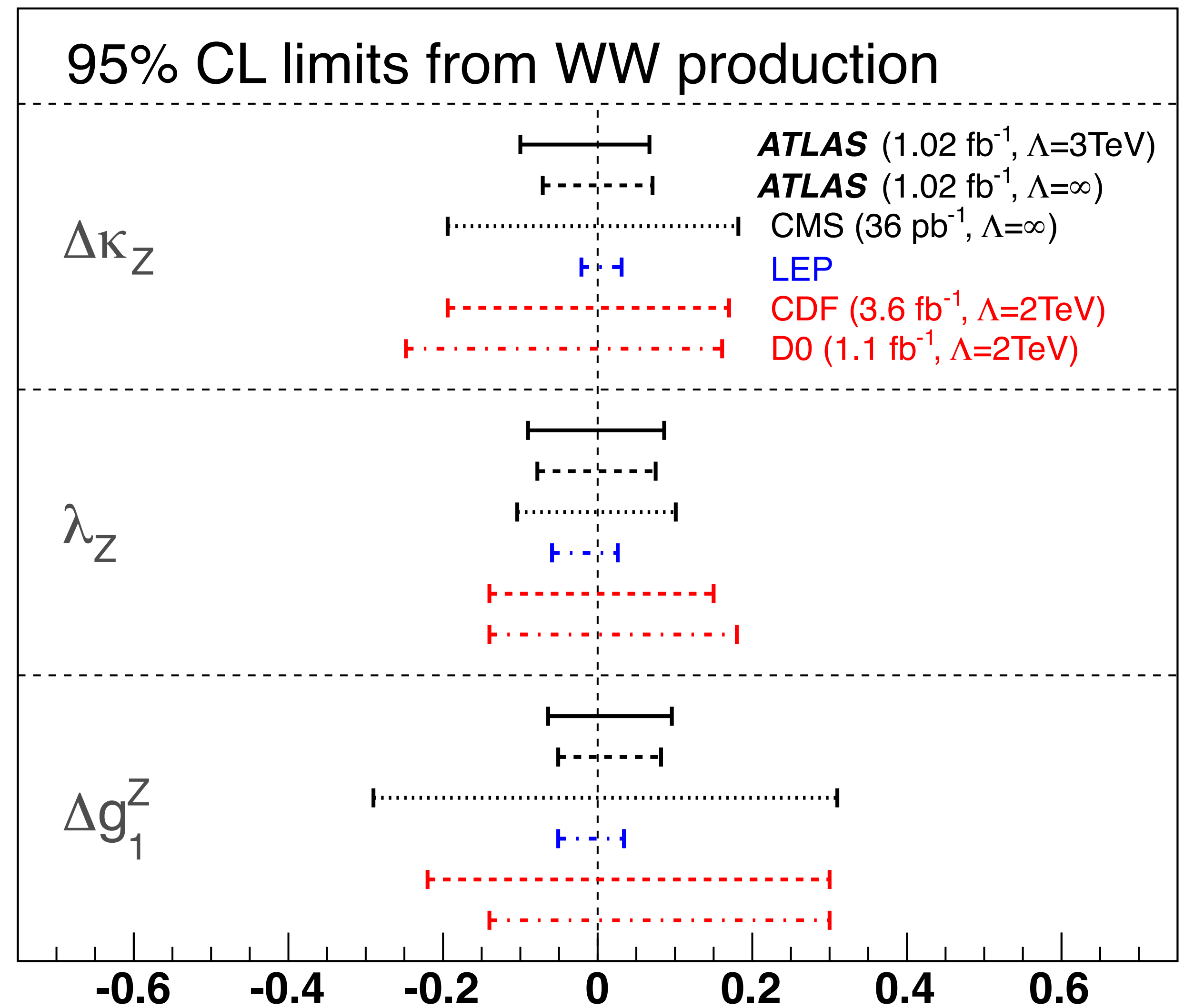
- probes **ZZγ** and **Zγγ** vertices
- **forbidden** in SM
- fit exclusive $E_T^{\gamma} > 60$ GeV bin
- close to or **most stringent** limits
- LEP data not shown (not as sensitive to nTGCs)

$WW \to l\nu l\nu$

arXiv:1203.6232 [hep-ex]

Use **leading lepton p_T** spectrum to set aTGC limits





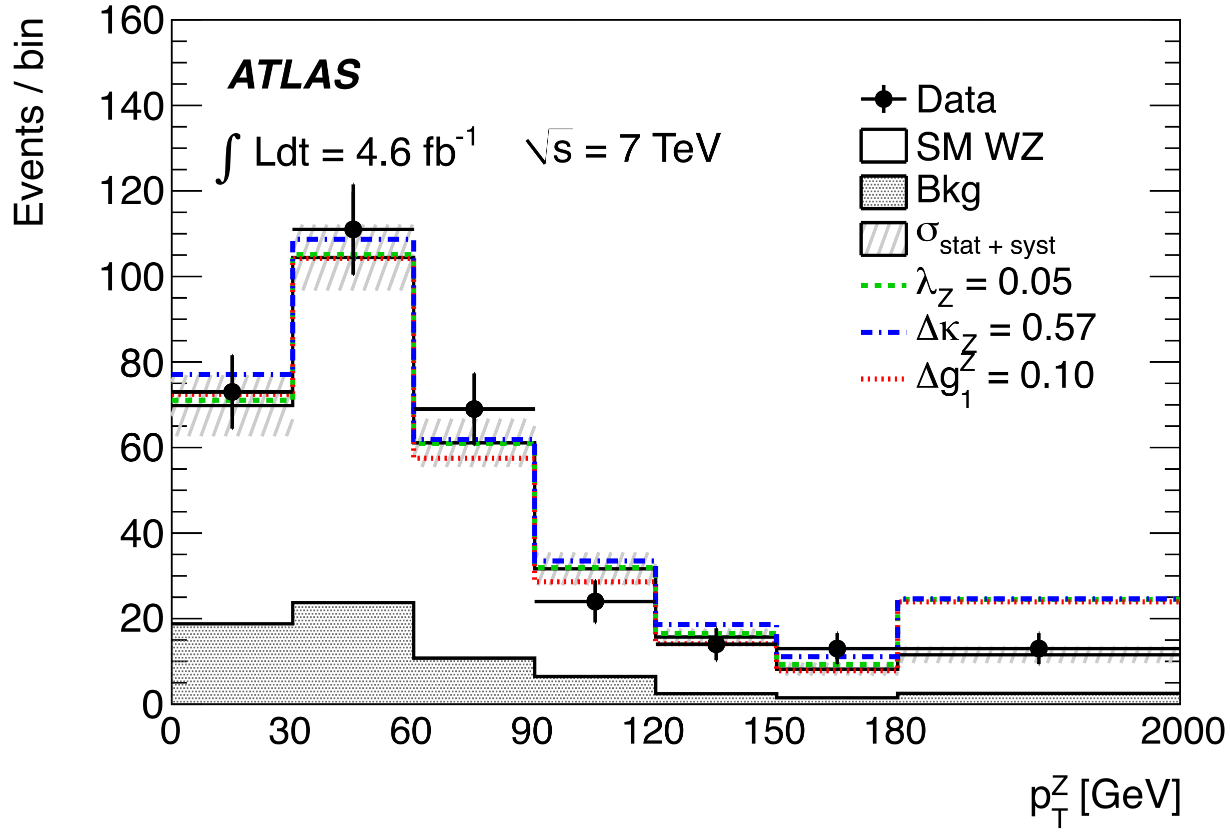
- probes **WWZ** and **WWγ** vertices
- reweight events using $|\mathcal{M}_{aTGC}|^2/|\mathcal{M}_{SM}|^2$ (BHO)
- **improve** on Tevatron, **close** to LEP limits
- **no significant deviation** from SM

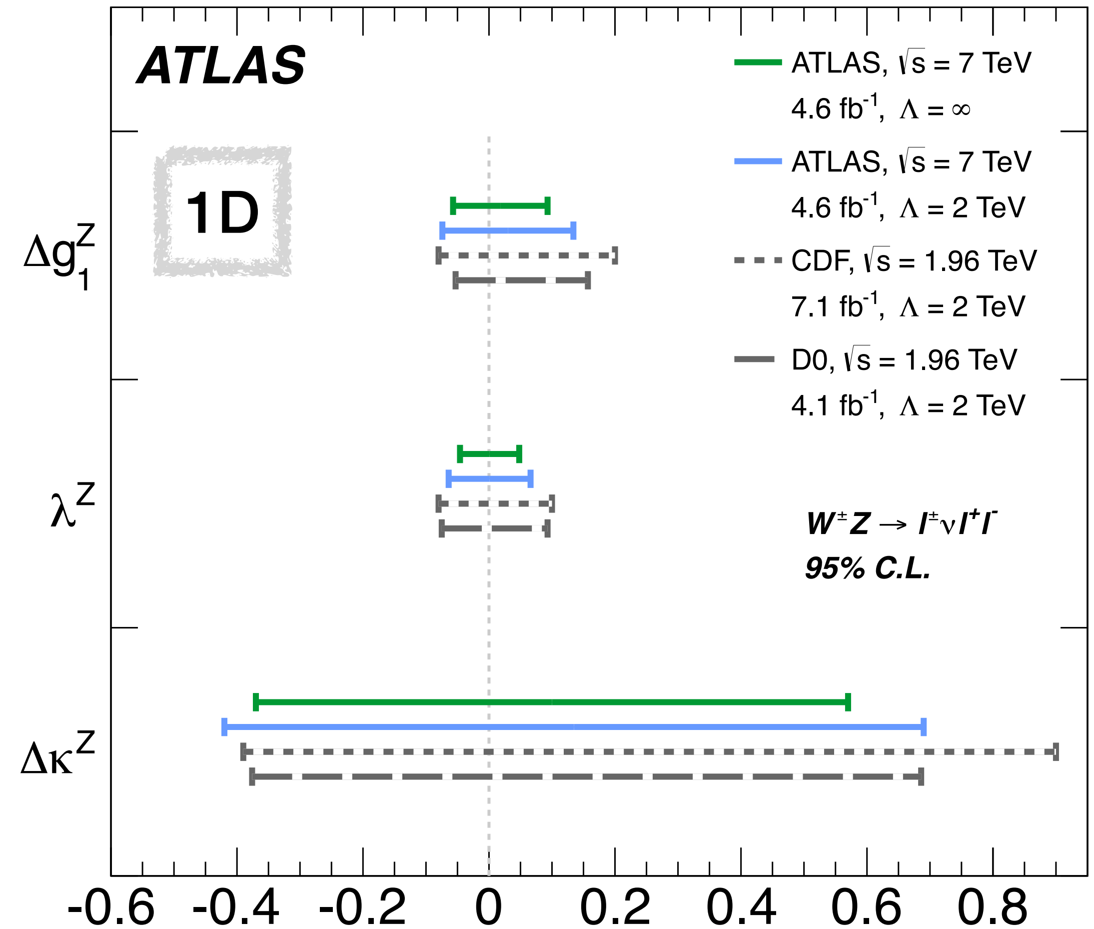
$5\ fb^{-1}$

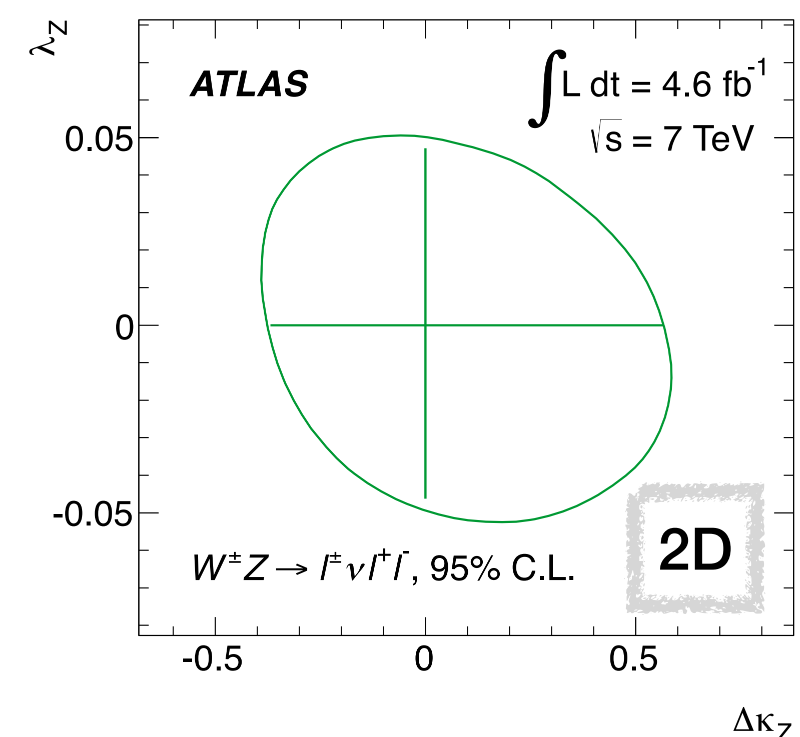
$WZ \rightarrow l\nu ll$

arXiv:1208.1390 [hep-ex]

Use p_T^Z spectrum to set aTGC limits

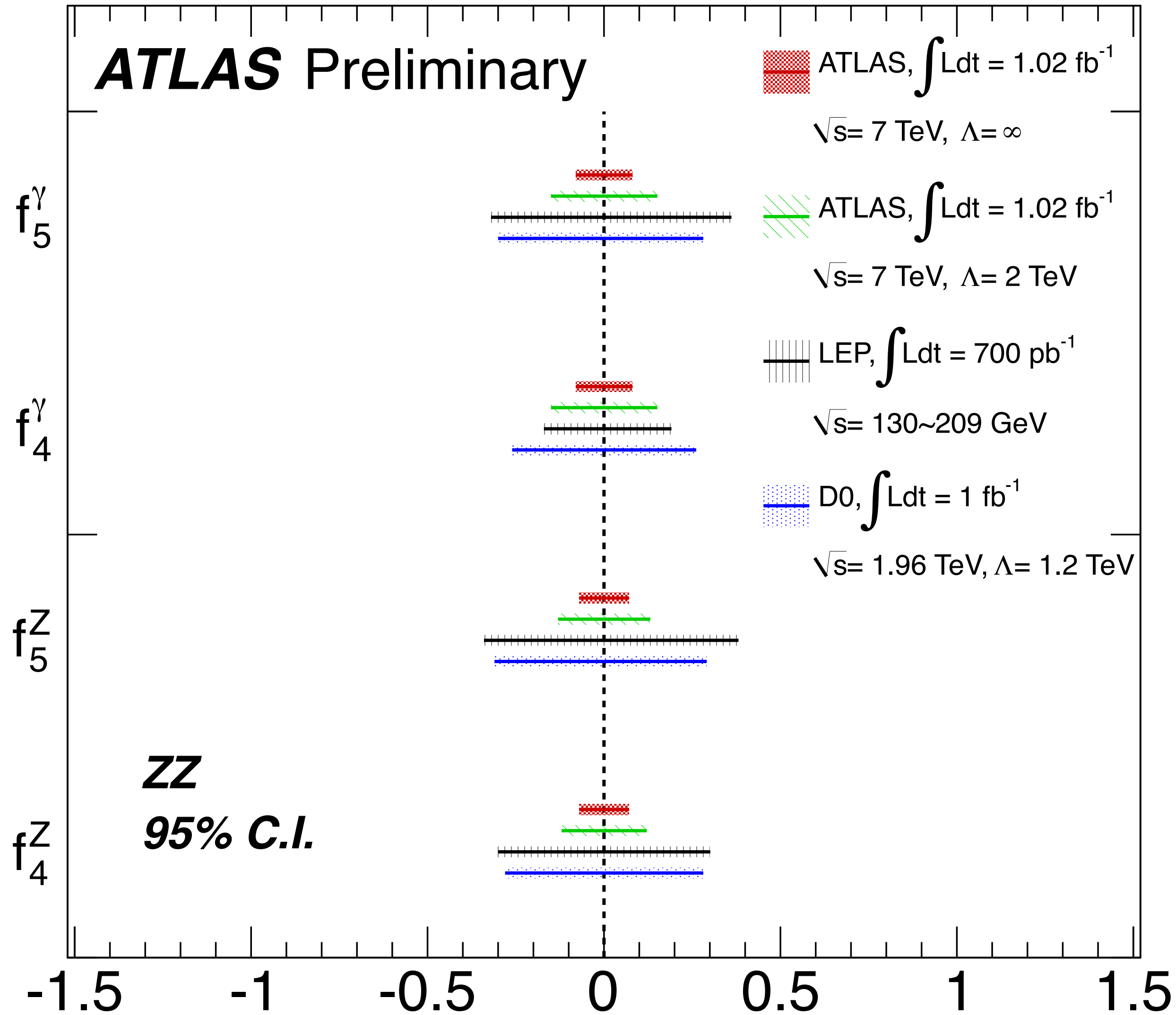






- probes **WWZ** vertex directly
- reweight events within MC@NLO
- **improve** on Tevatron limits (no direct LEP limits)
- publish **1D** and **2D** limits
- observe **no significant deviation** from SM

$ZZ \rightarrow llll$



- probes **ZZZ** and **ZZγ** vertices
- **forbidden** in SM
- reweighting Sherpa
- limit fit using **σ** (i.e. N_{events}) here
- **improve** on LEP and Tevatron limits

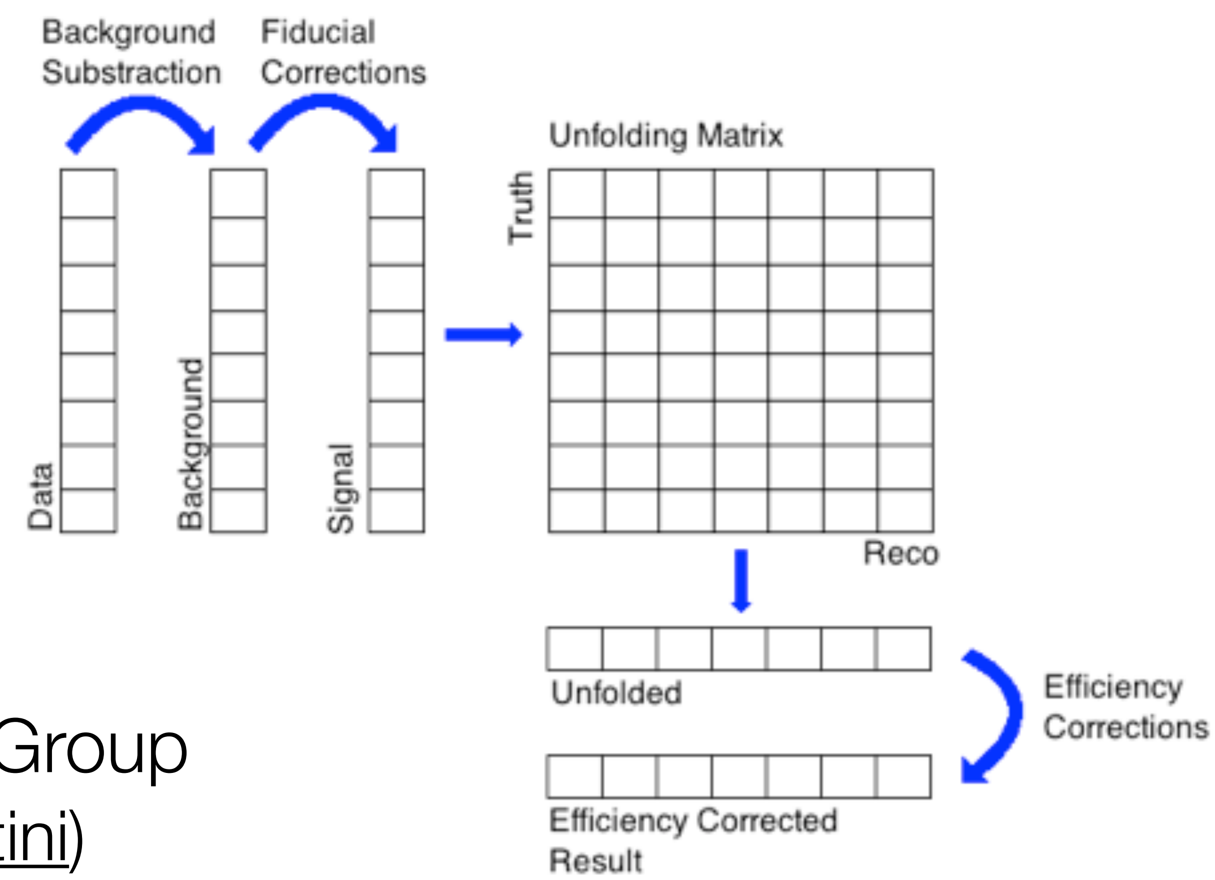
Unfolding - Methodology

Motivation

Determine **true value** of an observable

Measured value is distorted by detector's

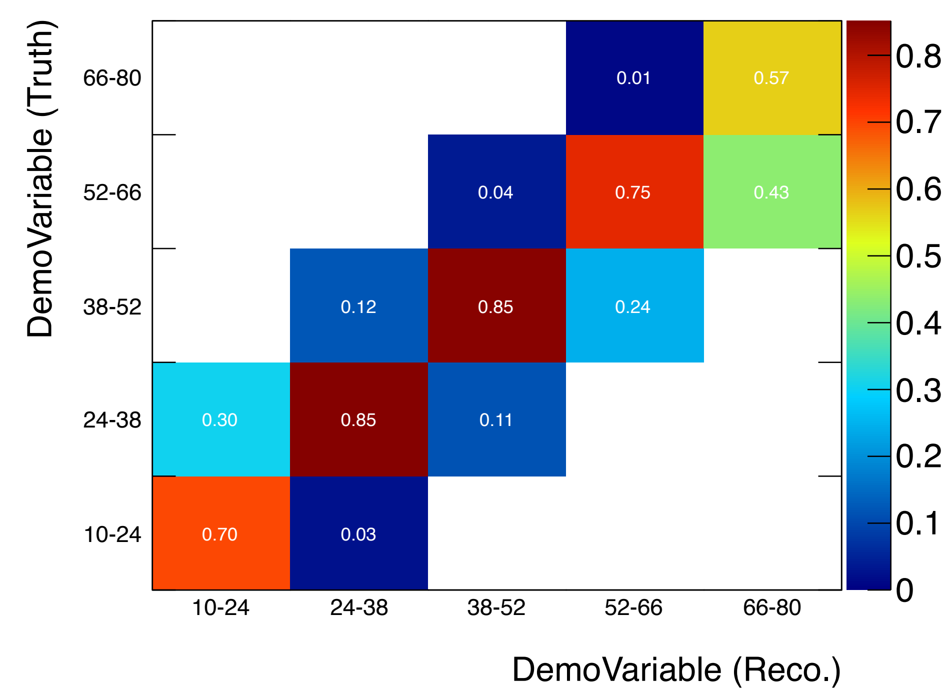
- limited acceptance
- imperfect efficiency
- finite resolution



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

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

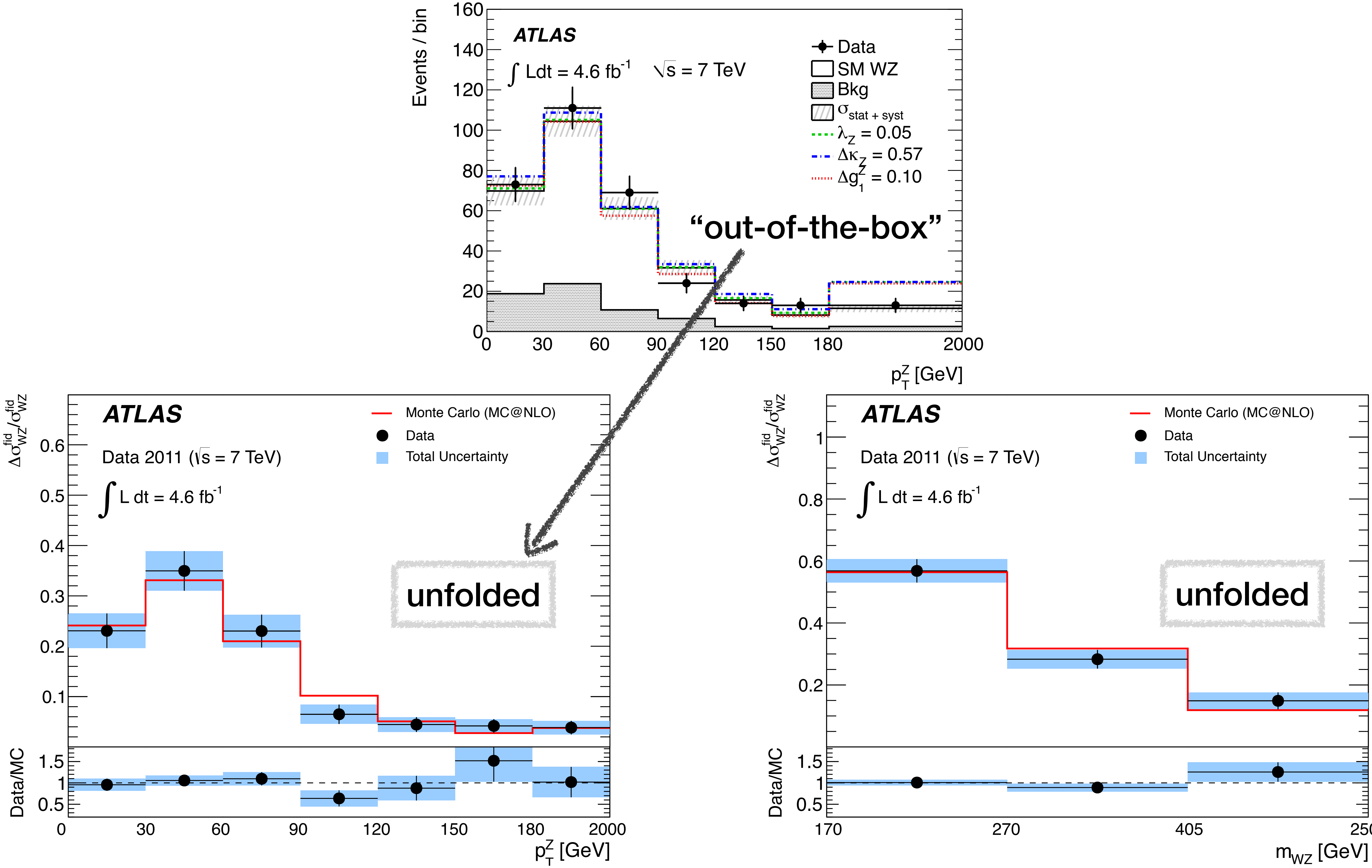
Full correlation matrices (on HEPDATA)

- combined stat, syst, background

WZ → lνll

arXiv:1208.1390 [hep-ex]

Unfold p_T^Z and m_{WZ} spectra



Which corrections are taken into account?

Discuss in more detail different **systematic uncertainties**

1) "Generator" ($\mathcal{O}(\alpha_S)$ mostly)
2) QED FSR
3) PDF
4) Scale (μ_F and μ_R)
5) Parton Shower
6) Jet veto
7) Backgrounds
8) EW settings

Process	Generator	Notes/Issues
$W\gamma$	Alpgen	Np0-5, FSR Photos
$Z\gamma$	Sherpa	Np0-3, FSR Sherpa
WW	MC@NLO / gg2ww	W-width and spin correlations ✔
WZ	MC@NLO	boson widths ✔, Z/γ^* ✘
$ZZ \to llll$	Sherpa	Z/γ^* ✔, scale by K^{NLO}_{MCFM}-factor, unique nTGCs
$ZZ \to ll\nu\nu$	MC@NLO	on-shell, 0-width Z's, scale up for gg

Chose WW/WZ analyses as representative examples (treatment similar across analyses)

Systematic Uncertainties (theoretical)

GENERATOR

- mostly have NLO QCD or multi-leg available, use k-factors
- include gg contribution using k-factor or second generator
- if Z/γ^* interference missing
  - for WZ scale MC@NLO acceptance comparing to MCFM → 1.8%
- differential distributions
  - for WZ compare MC@NLO to Powheg shape → up to ~4% (bin-dependent)

QED FSR

- often dominant effect in ew corrections
- use Photos or Sherpa
- fiducial phase space: dress leptons with photons within $\Delta R < 0.1$

PDF

for $\delta\sigma^{NLO}$ from MCFM

- CT10 52 error sets → ±3%

SCALE

in general: $\mu_F = \mu_R = \mu$ vary by factor 2

- for inclusive
  - WW/ZZ fixed $\mu = m_{WW/ZZ}$ → ±3%
  - WZ fixed $\mu = (m_W+m_Z)/2$ → ±5%
  - W/Zγ fixed $\mu = m_{W/Z}$
- for differential
  - WZ dynamic $\mu^2 = (m^2_W+p^2_{T,W}+m^2_Z+p^2_{T,Z})/2$ → up to 8%

Systematic Uncertainties (theoretical)

PARTON SHOWER

necessary if jet veto in fiducial phase space

- interface PowhegBox to Herwig and Pythia

BACKGROUNDS

correct MC to higher order calculations using k-factors or use data-driven estimates

JET VETO

avoid underestimation of scale uncertainty introduced by restricting QCD radiation

- due to cancellations between higher-order corrections and corrections from jet log dependence
- assume uncertainties in inclusive jet cross section uncorrelated (Stewart-Tackmann method)

EW SETTINGS

- not an uncertainty, but a choice (which should be consistent across analyses/experiments)
  - ATLAS and CMS found 1.4% discrepancy in σ_{WW} using MCFM
- most generators "made" for QCD (only LO ew)
  - default ew settings not always the same
- working group to give exact recommendations
  - i.e. latest PDG values, running Breit-Wigner width, α_{QED}
- want to give σ_{tot} so need to divide by BR, but need to be careful
  - e.g. using pole BR for WZ/ZZ with Z* down to 20 GeV is clearly a problem
  - use BR as a function of mass window? if too far from mass peak only quote leptonic σ?

Electroweak Corrections

No mention yet of electroweak corrections because there are **currently no event generators available that include electroweak corrections (NLO EW&QCD) for diboson production** (but see talk later!)

Important for **high energies** and **event rates** available at LHC (can reach tens of %)
Resulting electroweak corrections

- are negative (strong enhancement of negative corrections if $s \gg m^2_{W,Z}$)
- strongly depend on energy and scattering angle
- strongly increase with p_T
- significantly modify rapidity and angular distributions (e.g. enhance “radiation zero” dip)

Difficulties

- leptonic (and hadronic?) decays of bosons
- need real emission of additional massive vector bosons
- interplay between electroweak and QCD corrections

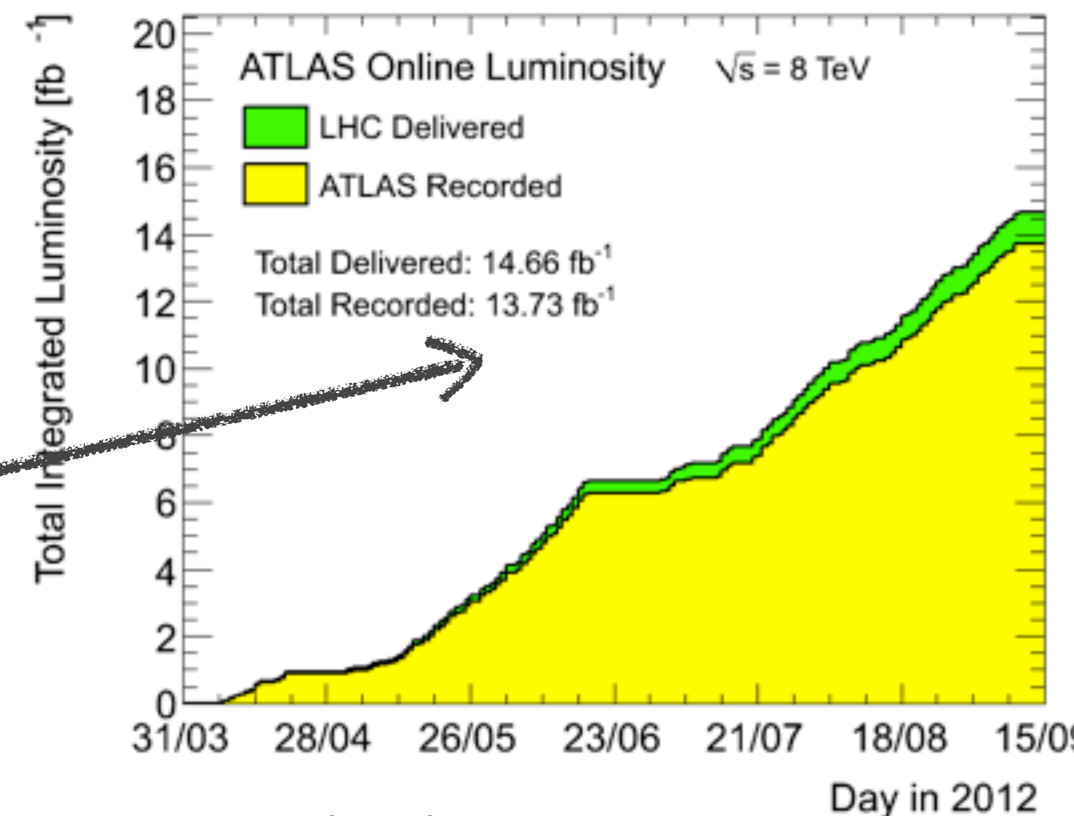
ATLAS measurements

- need QCD order higher than NLO?
- very good sensitivity in hight p_T tails → danger to set wrong limits because electroweak corrections, which bring σ down, not taken into account

Summary and Outlook

Diboson cross sections measured at 7 and 8 TeV with many updates to follow soon

- no deviation from SM observed yet
- setting most stringent TGC limits
- publishing unfolded distributions
- starting to become systematically dominated
  - → entering precision measurements



Thanks to **outstanding LHC performance** much more 8 TeV data to analyse already

In light of higher $\sqrt{s}$, $\mathcal{L}$ and 4th July discovery

- need NLO EW&QCD generators for VV and VVjj (VBS/VBF!) production
- what about electroweak corrections in triboson final states?
- Higgs couplings important to disentangle associated Higgs production from tribosons

Guidance from theorists

- Is what we are doing sensible?
- Do we over/undercover anywhere? Want to avoid spurious systematics
- When/which diboson generators to expect with electroweak corrections?

BACKUP

Bibliography

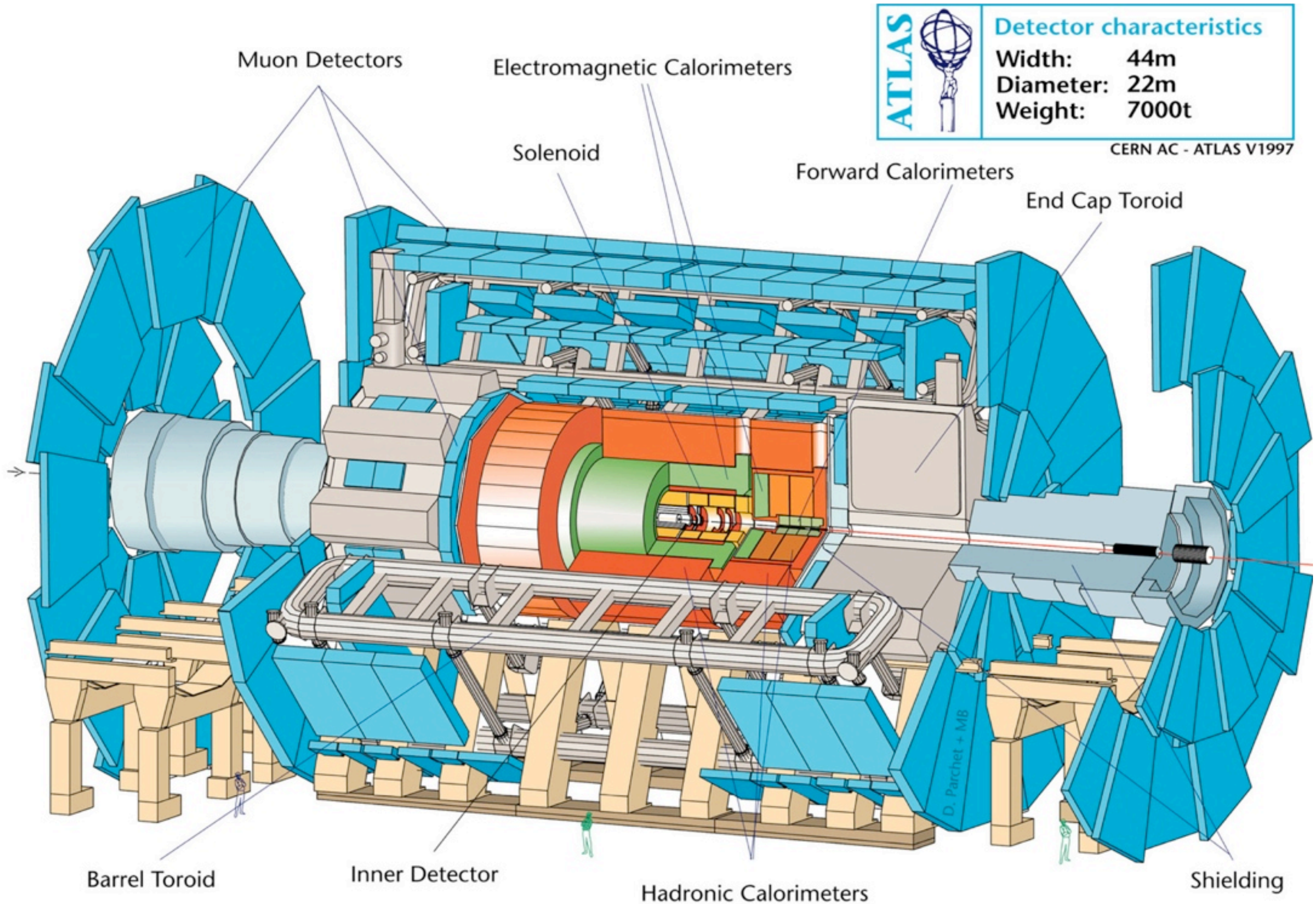
- Measurement of the **Wγ** and **Zγ** production cross sections in pp collisions at $\sqrt{s}$ = 7 TeV and limits on anomalous triple gauge couplings with the ATLAS detector, CERN-PH-EP-2012-059, arXiv:1205.2531.

- Measurement of the **WW** cross section in $\sqrt{s}$ = 7 TeV pp collisions with the ATLAS detector and limits on anomalous gauge couplings, CERN-PH-EP-2012-060, arXiv:1203.6232.
- Measurement of the **WW** production cross section in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, ATLAS-CONF-2012-025.

- Measurement of the **WZ** production in proton-proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, CERN-PH-EP-2012-179, arXiv:1208.1390.

- Measurement of the **ZZ** production cross section and limits on anomalous neutral triple gauge couplings in proton-proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, CERN-PH-EP-2011-166, arXiv:1110.5016.
- Measurement of the total **ZZ** production cross section in the four-lepton channel using 4.7 fb^{-1} ATLAS data, ATLAS-CONF-2012-026.
- Measurement of the total **ZZ** production cross section in the ll$\nu\nu$ channel in proton-proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, ATLAS-CONF-2012-027.
- Measurement of the total **ZZ** production cross section in the four-lepton channel using 5.8 fb^{-1} ATLAS data at $\sqrt{s}$ = 8 TeV, ATLAS-CONF-2012-090.

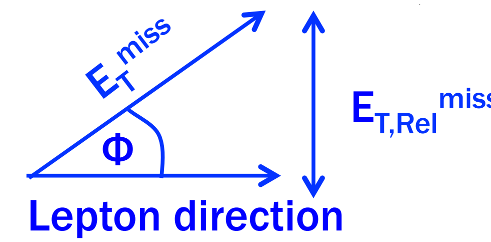
The ATLAS Experiment



E_T^{miss} definitions and coupling scenarios

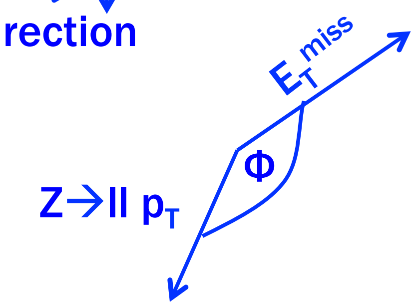
- Relative

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



- Axial

$$E_{\mathrm{T,axial}}^{\mathrm{miss}} = E_{\mathrm{T}}^{\mathrm{miss}} \times \cos(\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p_{\mathrm{T}}}^{\ell\ell}))$$



- Equal Couplings

$$\Delta\kappa_Z = \Delta\kappa_\gamma$$
$$\lambda_Z = \lambda_\gamma$$
$$g_1^Z = 1$$

- LEP

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

- HISZ

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

	WW	WZ
$\Delta g^Z{}_1$	$\sqrt{s}$	s
$\Delta\kappa_Z$	s	$\sqrt{s}$
λ	s	s

Acceptance and S/B numbers

$$A = \frac{N^{Pass\ Fiducial}_{MC\ Truth}}{N^{All\ Generated}_{MC\ Truth}} \qquad C = \frac{N^{Pass\ Cuts}_{MC\ Reco}}{N^{Pass\ Fiducial}_{MC\ Truth}}$$

Process	A (%)	C (%)	S/B
WW→eνeν	6.2	42.0	0.8
WW→μνμν	5.2	76.8	1.2
WW→μνeν	16.3	55.1	2.0
WZ→eνee	33.0	38.0	2.7
WZ→μνee	33.2	52.5	4.7
WZ→eνμμ	33.3	54.8	2.7
WZ→μνμμ	33.8	78.0	3.9
ZZ→eeee	64.8	46.0	16.5
ZZ→μμee	64.8	60.0	89.3
ZZ→μμμμ	64.8	81.0	55.3
ZZ→eeνν	8.4	61.2	1.1
ZZ→μμνν	8.4	75.8	1.0

E_{T}^{γ}	> 15 GeV	> 60 GeV	> 100 GeV
$N_{\mathrm{jet}} = 0$, e channel			
$C_{W\gamma}$	0.402 ± 0.049	0.574 ± 0.045	0.517 ± 0.043
$A_{W\gamma}$	0.762 ± 0.006	0.685 ± 0.017	0.672 ± 0.019
$C_{Z\gamma}$	0.397 ± 0.045	0.592 ± 0.044	-
$A_{Z\gamma}$	0.829 ± 0.014	0.834 ± 0.008	-
$N_{\mathrm{jet}} = 0$, μ channel			
$C_{W\gamma}$	0.453 ± 0.054	0.653 ± 0.057	0.675 ± 0.059
$A_{W\gamma}$	0.908 ± 0.006	0.764 ± 0.019	0.708 ± 0.017
$C_{Z\gamma}$	0.459 ± 0.052	0.641 ± 0.044	-
$A_{Z\gamma}$	0.915 ± 0.016	0.917 ± 0.008	-
$N_{\mathrm{jet}} \geq 0$, e channel			
$C_{W\gamma}$	0.453 ± 0.053	0.598 ± 0.036	0.576 ± 0.035
$A_{W\gamma}$	0.725 ± 0.050	0.657 ± 0.011	0.666 ± 0.017
$C_{Z\gamma}$	0.421 ± 0.044	0.609 ± 0.036	-
$A_{Z\gamma}$	0.826 ± 0.014	0.836 ± 0.050	-
$N_{\mathrm{jet}} \geq 0$, μ channel			
$C_{W\gamma}$	0.511 ± 0.057	0.650 ± 0.035	0.624 ± 0.035
$A_{W\gamma}$	0.872 ± 0.005	0.776 ± 0.019	0.747 ± 0.023
$C_{Z\gamma}$	0.485 ± 0.055	0.645 ± 0.035	-
$A_{Z\gamma}$	0.915 ± 0.016	0.917 ± 0.005	-

Systematic uncertainties

WW

Source of uncertainty	Relative uncertainty (%) $e\nu\mu\nu$ selection	$e\nu e\nu$ selection	$\mu\nu\mu\nu$ selection
Trigger efficiency	1.0	1.0	1.0
Lepton efficiency	2.3	4.1	1.8
Lepton p_{T} scale and resolution	0.4	1.0	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.6	1.0	2.2
Jet energy scale and resolution	1.1	1.1	1.1
Lepton acceptance	2.0	2.1	1.6
Jet veto acceptance	5.0	5.0	5.0
PDFs	1.4	1.2	1.2
Total	6.2	7.2	6.2

WZ

Source	eee	μee	$e\mu\mu$	$\mu\mu\mu$
μ reconstruction efficiency	–	0.3	0.5	0.8
μ p_{T} scale & resolution	–	< 0.1	0.1	0.1
μ isolation & impact param.	–	0.2	0.4	0.6
e reconstruction efficiency	2.5	1.7	0.8	–
e identification efficiency	3.5	2.3	1.2	–
e isolation & impact param.	1.5	1.1	0.4	–
e energy scale	0.5	0.3	0.3	–
e energy resolution	0.1	0.1	< 0.1	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ cluster energy scale	0.4	0.2	0.6	0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ jet energy scale	0.1	0.1	0.1	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ jet energy resolution	0.3	0.3	0.4	0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ pile-up	0.3	0.1	0.3	0.1
Muon trigger	–	0.1	0.1	0.3
Electron trigger	< 0.1	< 0.1	< 0.1	–
Event generator	0.4	0.4	0.4	0.4
PDF	1.2	1.2	1.2	1.2
QCD scale	0.4	0.4	0.4	0.4
Luminosity	1.8	1.8	1.8	1.8

ZZ→4l
dominant from electron identification efficiency (5.8%/2.8% for eeee/eeμμ) and muon reconstruction efficiency (1.3%/0.6% for μμμμ/eeμμ)

ZZ→llνν
dominant from jet veto (5.3%) and track isolation (4.0%/2.1% for eeνν/μμνν)

Jet Veto and Stewart-Tackmann Method

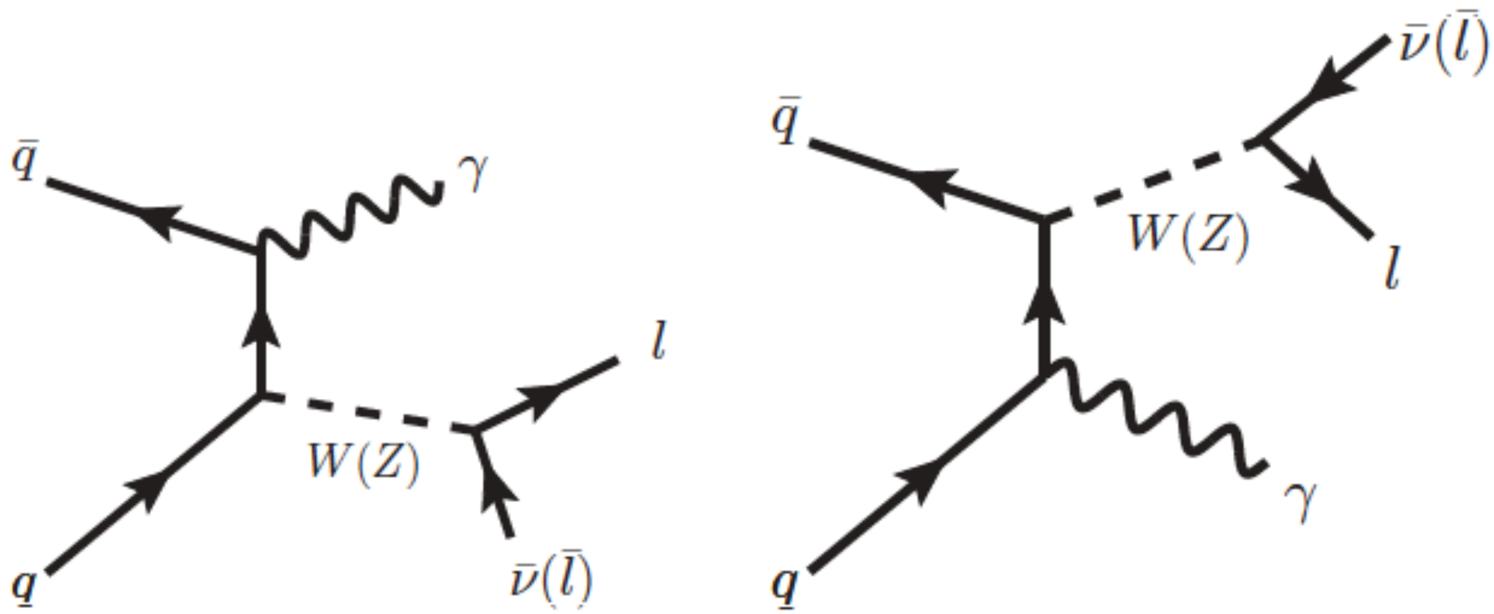
Determine correction factor as $\varepsilon_Z^{data}/\varepsilon_Z^{MC}$ where $\varepsilon=N_{0jet}/N_{\geq 0jet}$
data-driven → reduces uncertainty on jet veto acceptance

Accidental cancellations with log terms introduced by restricting QCD radiation cause the scale uncertainty to be underestimated in a jet-binned analysis
→ assume uncertainties in inclusive jet-binned cross sections are uncorrelated, since the structure of perturbative series are different

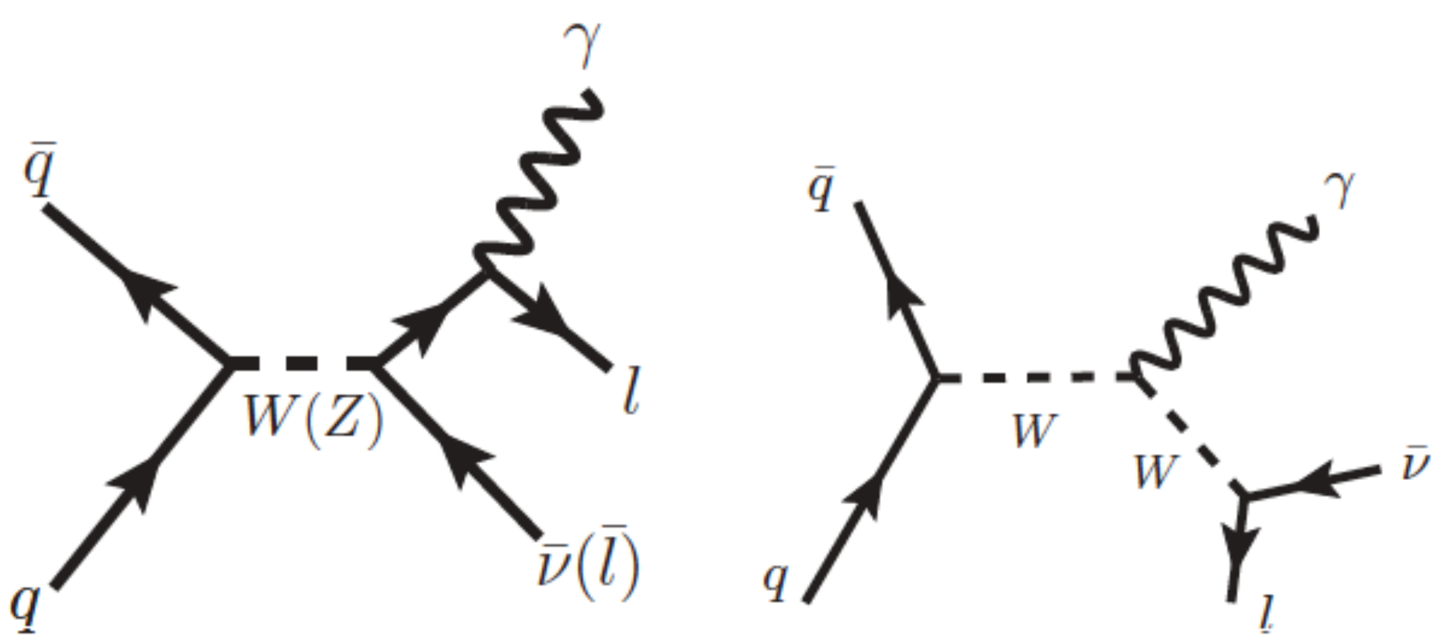
Calculate uncertainty in jet veto acceptance as

$$\frac{\delta\epsilon^2}{\epsilon^2} = \left(\frac{1-\epsilon}{\epsilon}\right)^2 \left(\frac{\delta\sigma_{total}^2}{\sigma_{total}^2} + \frac{\delta\sigma_{\geq 1}^2}{\sigma_{\geq 1}^2}\right)$$

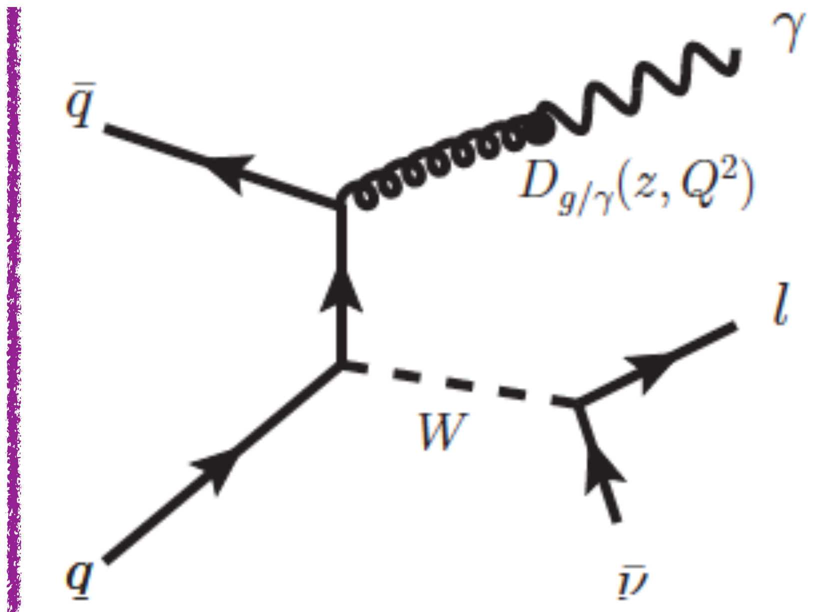
Wγ and Zγ Production Processes



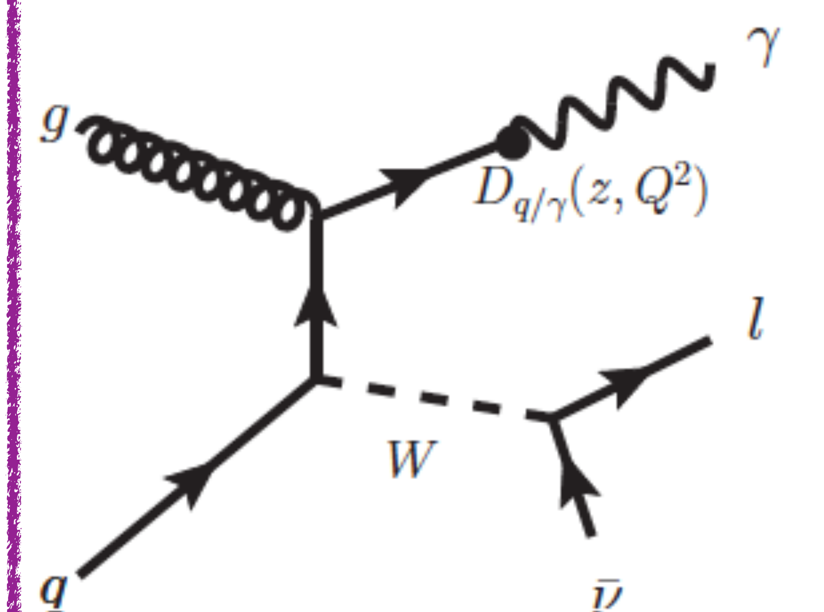
(a) u-channel (b) t-channel



(c) FSR (d) s-channel



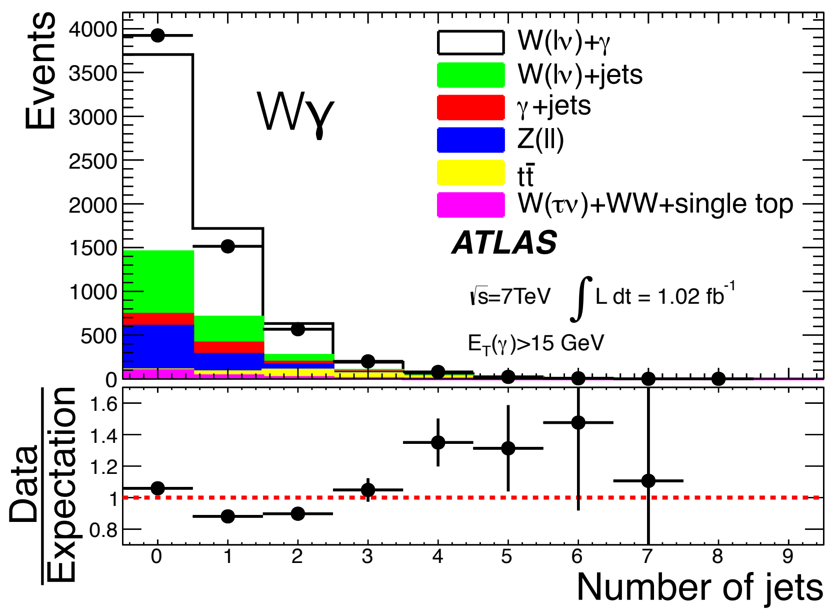
(a)

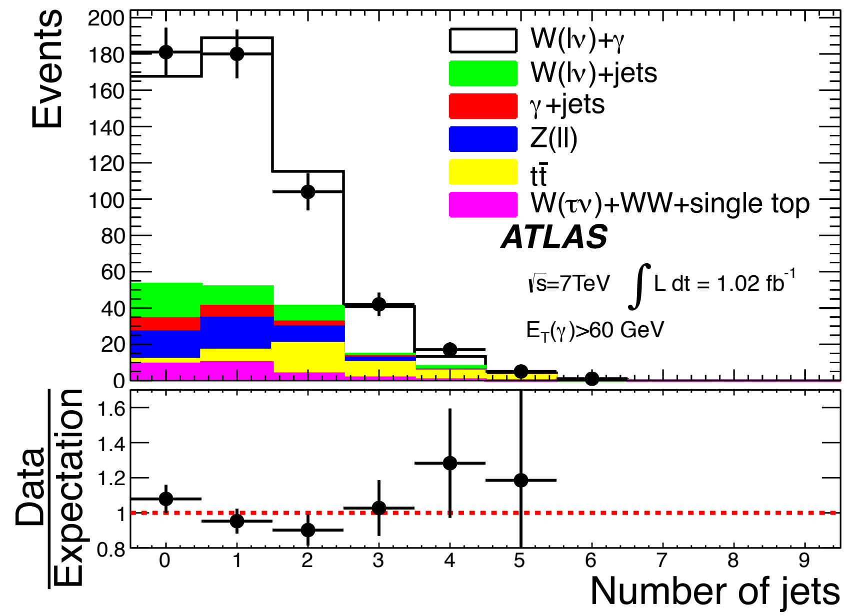


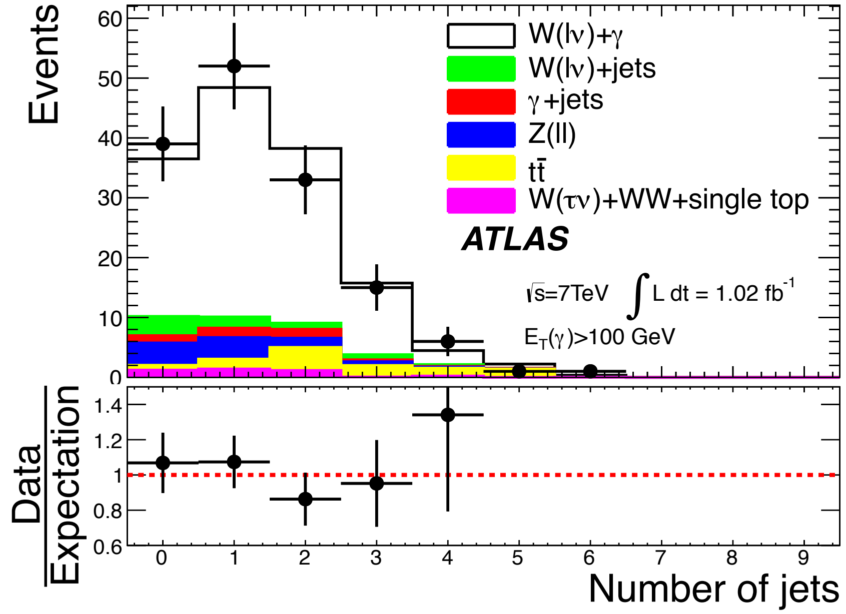
(b)

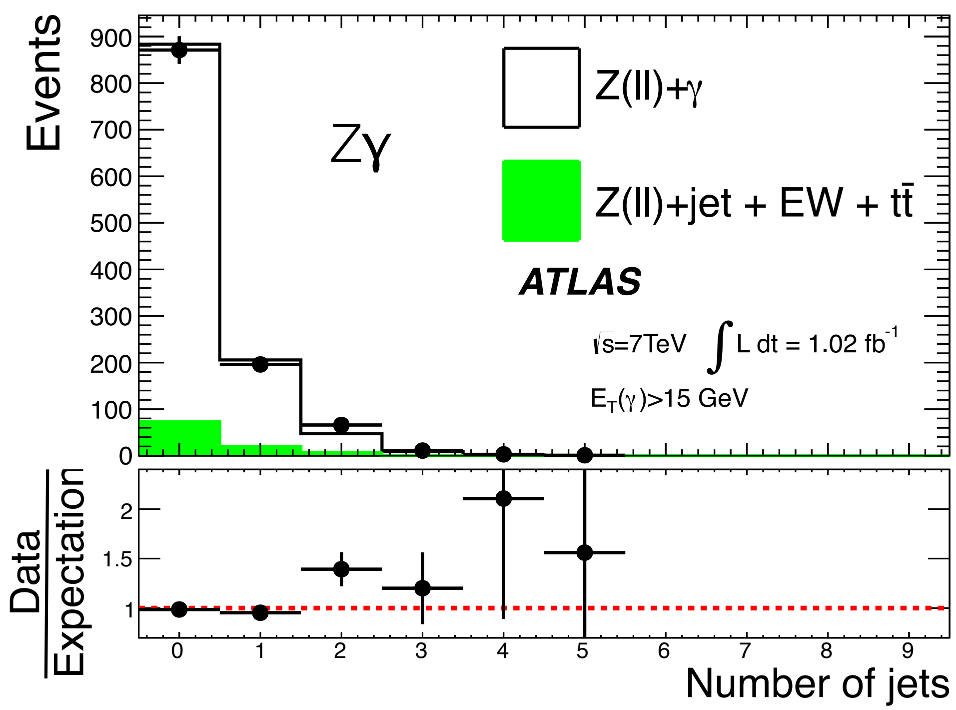
W+q(g)

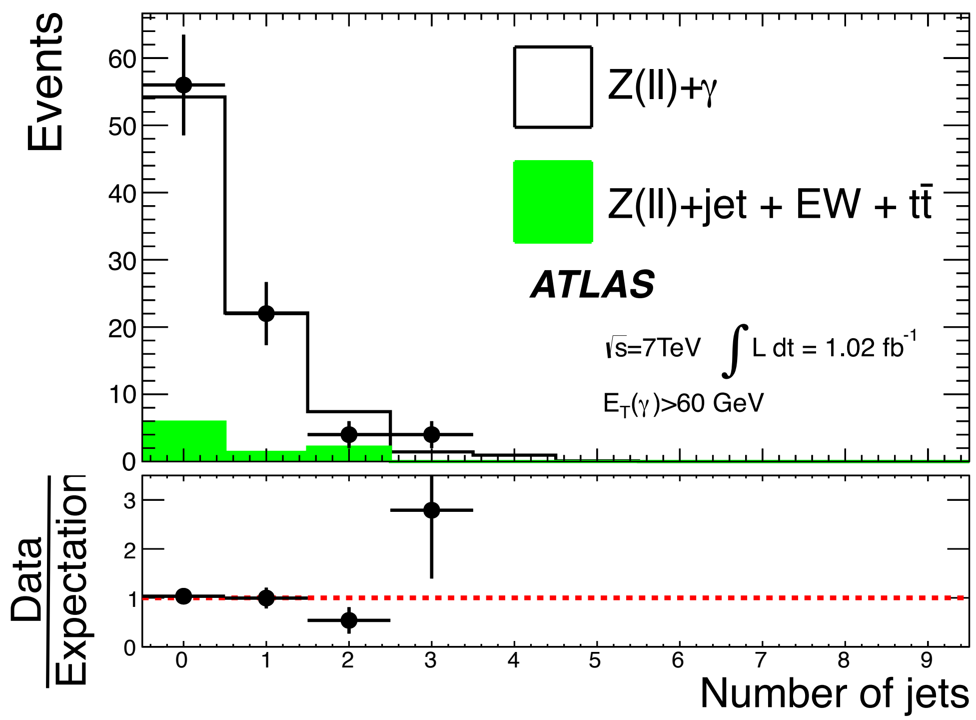
Wγ and Zγ Plots











Wγ and Zγ Cross Sections

	$\sigma^{\text{ext-fid}}$[pb]	$\sigma^{\text{ext-fid}}$[pb]
	$E_T^\gamma > 15$ GeV exclusive	$E_T^\gamma > 15$ GeV inclusive
$e\nu\gamma$	$3.42 \pm 0.14 \pm 0.50$	$4.35 \pm 0.16 \pm 0.64$
$\mu\nu\gamma$	$3.23 \pm 0.14 \pm 0.48$	$4.82 \pm 0.15 \pm 0.64$
$l\nu\gamma$	$3.32 \pm 0.10 \pm 0.48$	$4.60 \pm 0.11 \pm 0.64$
$e^+e^-\gamma$	$1.03 \pm 0.06 \pm 0.13$	$1.32 \pm 0.07 \pm 0.16$
$\mu^+\mu^-\gamma$	$1.06 \pm 0.05 \pm 0.12$	$1.27 \pm 0.06 \pm 0.15$
$l^+l^-\gamma$	$1.05 \pm 0.04 \pm 0.12$	$1.29 \pm 0.05 \pm 0.15$
	$E_T^\gamma > 60$ GeV exclusive	$E_T^\gamma > 60$ GeV inclusive
$e\nu\gamma$	$0.14 \pm 0.02 \pm 0.02$	$0.36 \pm 0.03 \pm 0.03$
$\mu\nu\gamma$	$0.15 \pm 0.02 \pm 0.02$	$0.41 \pm 0.03 \pm 0.03$
$l\nu\gamma$	$0.15 \pm 0.01 \pm 0.02$	$0.38 \pm 0.02 \pm 0.03$
$e^+e^-\gamma$	$0.044 \pm 0.010 \pm 0.004$	$0.069 \pm 0.012 \pm 0.006$
$\mu^+\mu^-\gamma$	$0.050 \pm 0.010 \pm 0.004$	$0.068 \pm 0.011 \pm 0.005$
$l^+l^-\gamma$	$0.047 \pm 0.007 \pm 0.004$	$0.068 \pm 0.008 \pm 0.005$
	$E_T^\gamma > 100$ GeV exclusive	$E_T^\gamma > 100$ GeV inclusive
$e\nu\gamma$	$0.040 \pm 0.011 \pm 0.009$	$0.114 \pm 0.018 \pm 0.010$
$\mu\nu\gamma$	$0.026 \pm 0.008 \pm 0.003$	$0.135 \pm 0.018 \pm 0.010$
$l\nu\gamma$	$0.030 \pm 0.006 \pm 0.006$	$0.125 \pm 0.013 \pm 0.010$

TABLE V. Measured cross sections for the $pp \to l\nu\gamma + X$ and $pp \to ll\gamma + X$ processes at $\sqrt{s} = 7$ TeV in the extended fiducial region defined in Table III. The first uncertainty is statistical and the second is systematic. The 3.7% luminosity uncertainty is not included.

Channel	E_T^γ (GeV)	Cross section exclusive	Cross section inclusive
$pp \to l^\pm\nu\gamma$	> 15	2.84±0.20 pb (2.61±0.16 pb)	3.70±0.28 pb (3.58±0.26 pb)
$pp \to l^\pm\nu\gamma$	> 60	134±21 fb (118±16 fb)	260±38 fb (255±35 fb)
$pp \to l^\pm\nu\gamma$	> 100	34±5 fb (31± 4 fb)	82±13 fb (80±12 fb)
$pp \to l^+\, l^-\gamma$	> 15	1.08±0.04 pb (1.03 ± 0.04 pb)	1.23±0.06 pb (1.22±0.05 pb)
$pp \to l^+\, l^-\gamma$	> 60	43±4 fb (40±3 fb)	59±5 fb (58±5 fb)

TABLE VI. Expected NLO inclusive and exclusive cross sections for the $pp \to l^\pm\nu\gamma + X$ and $pp \to l^+\, l^-\gamma + X$ processes in the extended fiducial region as defined in Table III. The cross sections are quoted at particle (parton) level as described in the text.

WW Fiducial Cross Sections

Channels	expected σ^{fid} (fb)	measured σ^{fid} (fb)	$\Delta\sigma_{stat}$ (fb)	$\Delta\sigma_{syst}$ (fb)	$\Delta\sigma_{lumi}$ (fb)
$e\nu e\nu$	44.9±3.7	41.4	± 6.5	± 5.7	± 1.6
$\mu\nu\mu\nu$	38.0±3.1	48.2	± 4.6	± 3.8	± 1.9
$e\nu\mu\nu$	237.4±19.4	284.9	± 12.7	± 14.1	± 11.1

Table 7: The predicted and measured fiducial W^+W^- production cross sections in the three dilepton channels.

W/Z+Jets Background

- One or two prompt isolated leptons
- Missing energy
- Jets can produce fake or real lepton/γ
- Background estimated in data by measuring probability of jet faking lepton/γ