MANCHESTER 1824

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Measuring gauge-boson production with ATLAS at the LHC

RPM 1 Dec 2011

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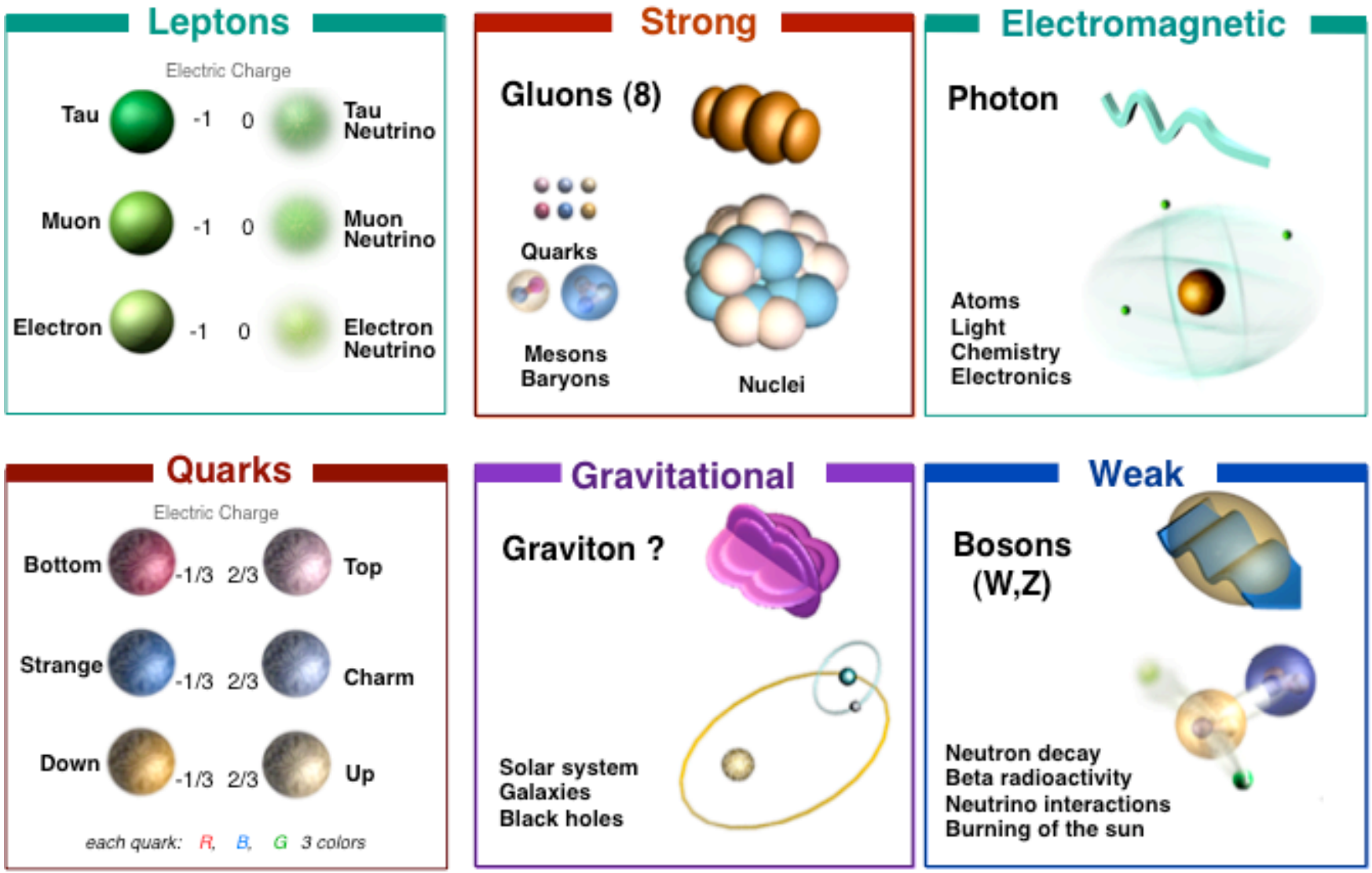
University of Manchester

ATLAS

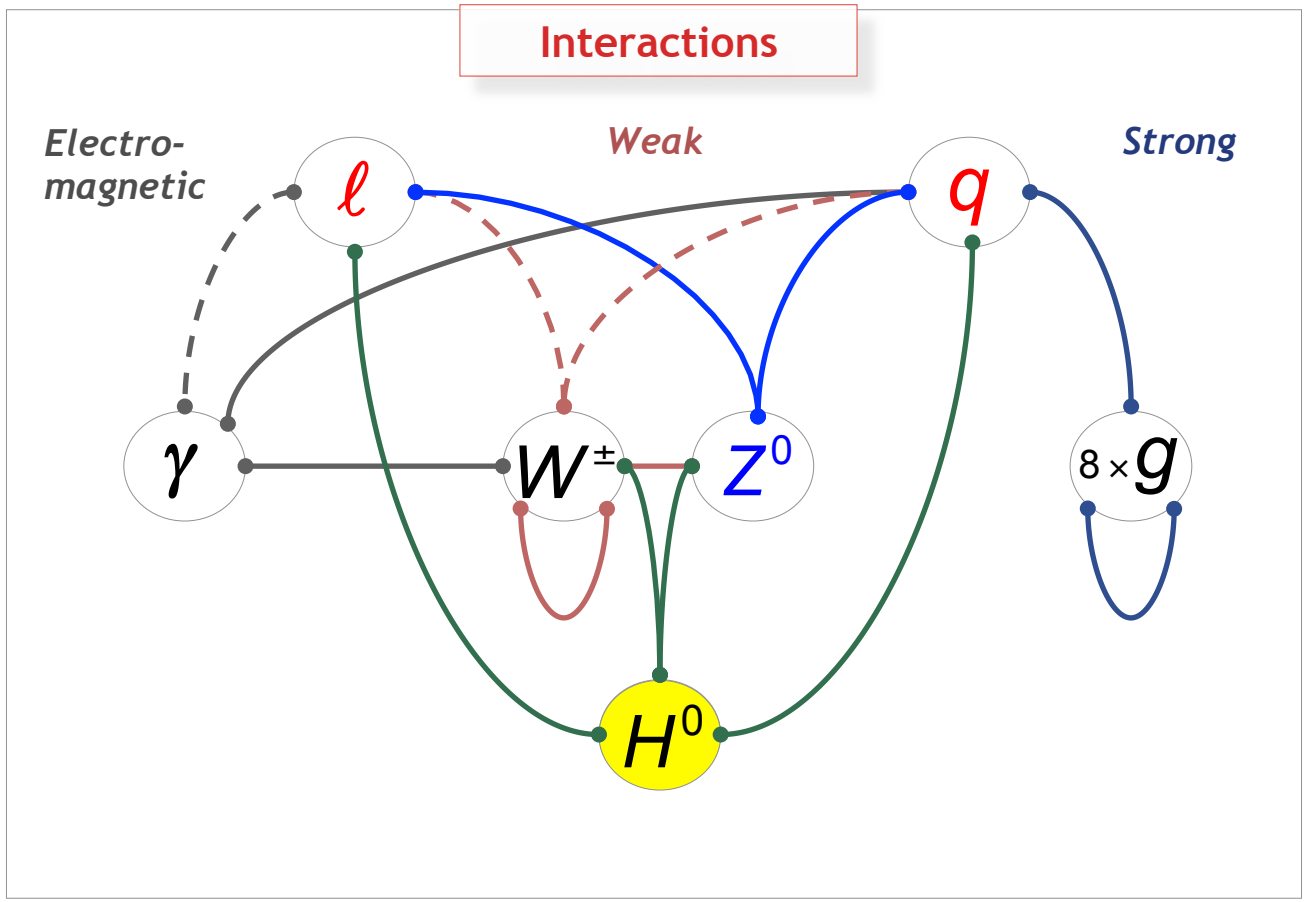
The Standard Model



The particle drawings are simple artistic representations

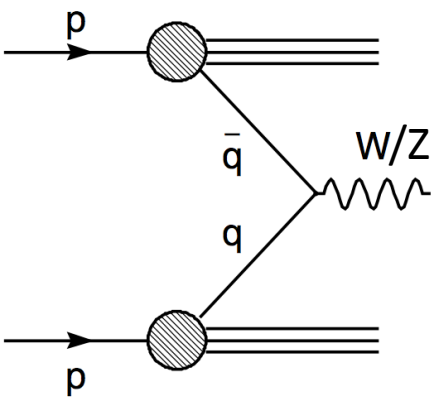
The Standard Model

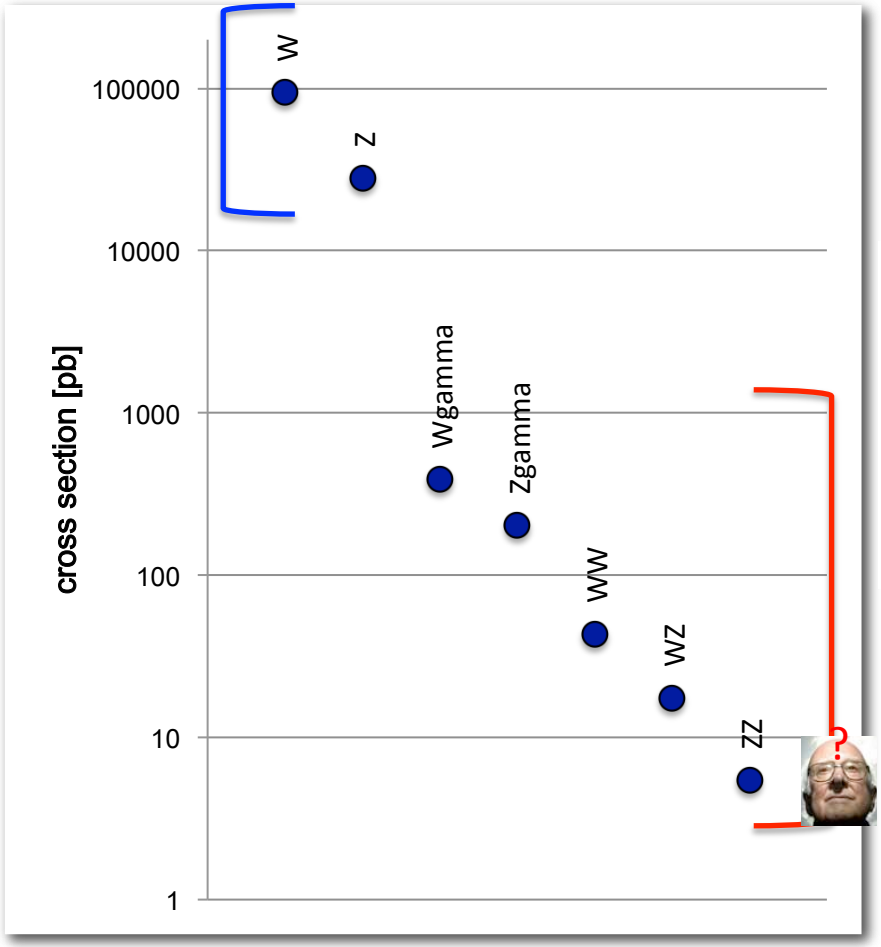
The Standard Model consists of 24 elementary matter particles and 3 forces



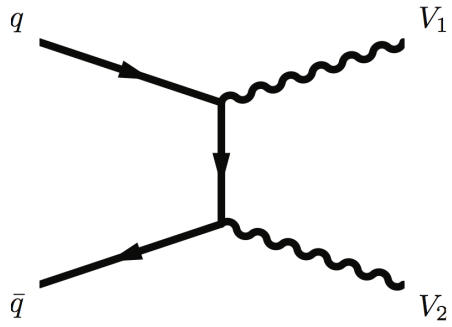
Boson Production

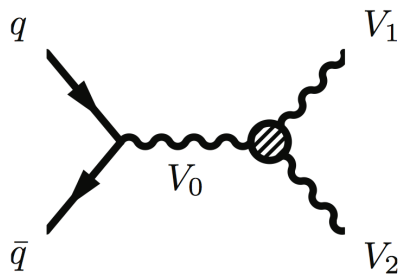
Single-Boson





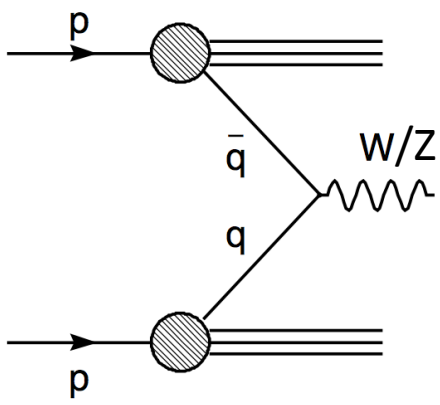
Di-Boson





Boson Production

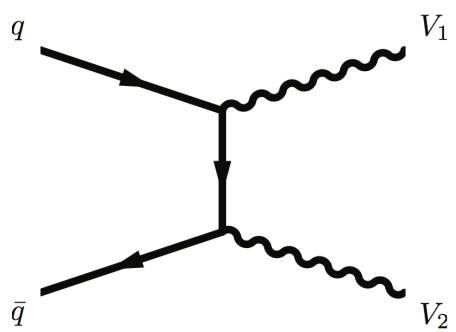
- **Single Boson Production**
  - Test perturbative QCD.
  - Constrain parton density function inside the proton.
  - Background to other SM processes and new physics signals.

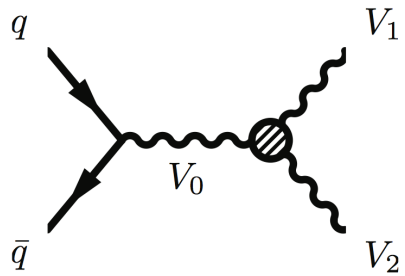


Boson Production

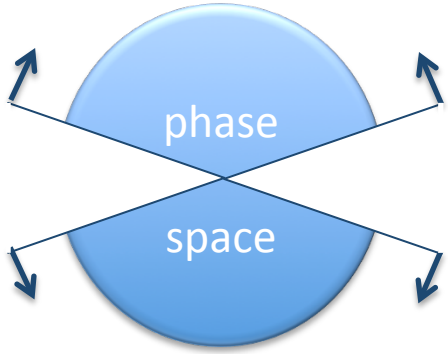
Di-boson production is a O(1-100)pb process.

- **Cross section measurement**
  - Sensitive to new particles decaying into di-bosons:
    - Higgs, W', Z', Technicolor
  - Background to searches of new physics.
- **Triple Gauge Couplings**
  - Determination of Triple Gauge Boson Couplings provide a model independent test for "new" physics.
  - Sensitivity increases with energy reach.





Boson Production



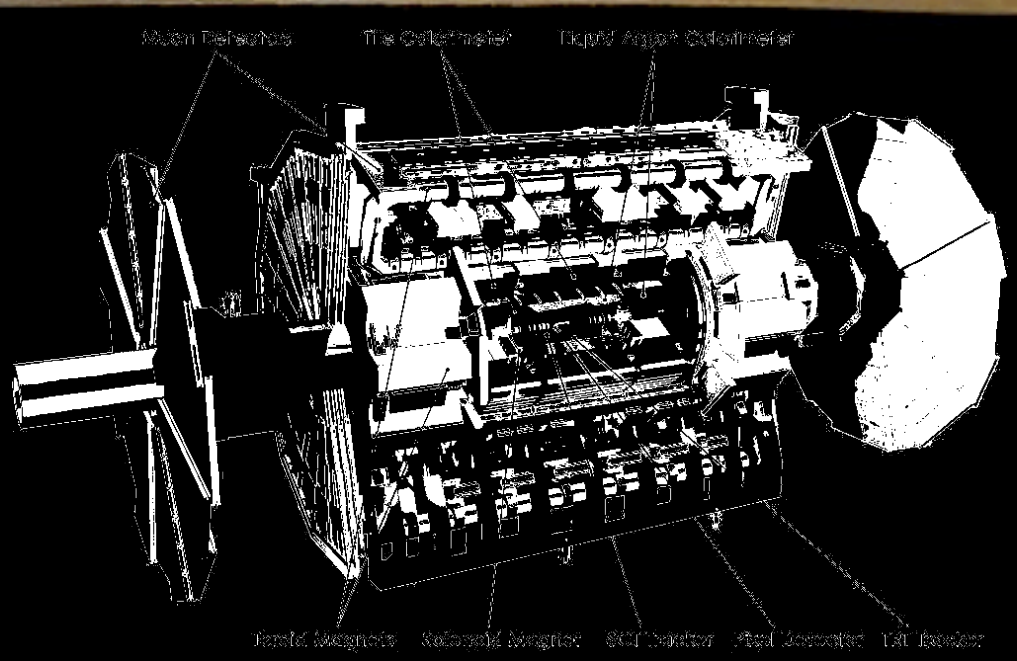
Fiducial Cross sections

- **Minimize theory uncertainties due to phase-space extrapolations.**
  - Define a "fiducial volume" mimicking the detector acceptance.
  - Definition in terms of final state truth particles after showering
    - Charged lepton and photon kinematics.
    - Neutrino transverse energy
    - Vector boson mass calculated from leptons.
  - Leptons are "redressed" with brem photons in ΔR=0.1.
  - Allows theorists to test their favorite model.
    - Analysis results published as HepData and Rivet code.

$$\sigma_{Fiducial} = \frac{N_{Obs} - N_{Bkg}}{C \times L}$$

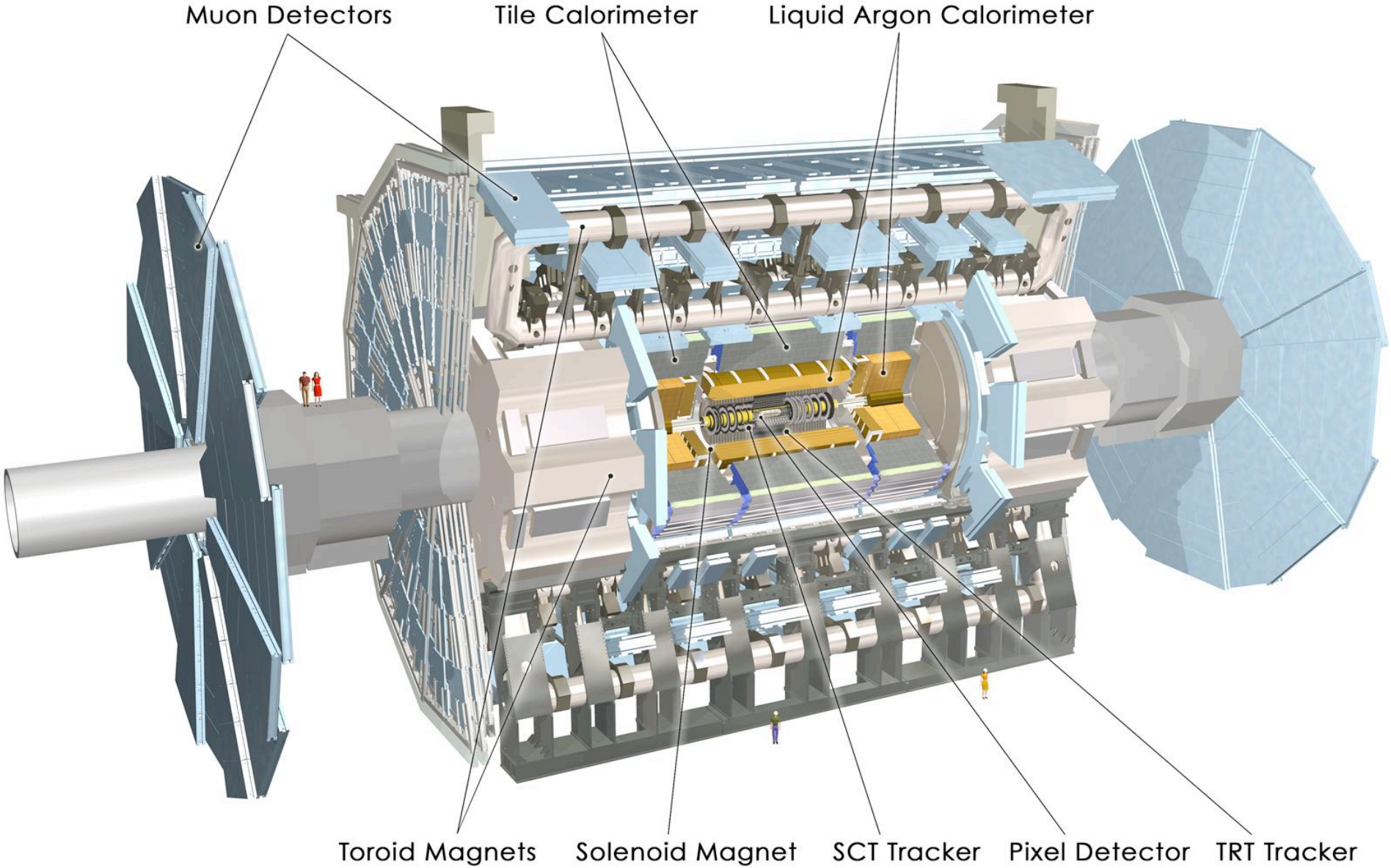
$$C = \frac{N_{MC}^{Reco}}{N_{MC\,Truth}^{Pass\,Fiducial}}$$

ΔR is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.



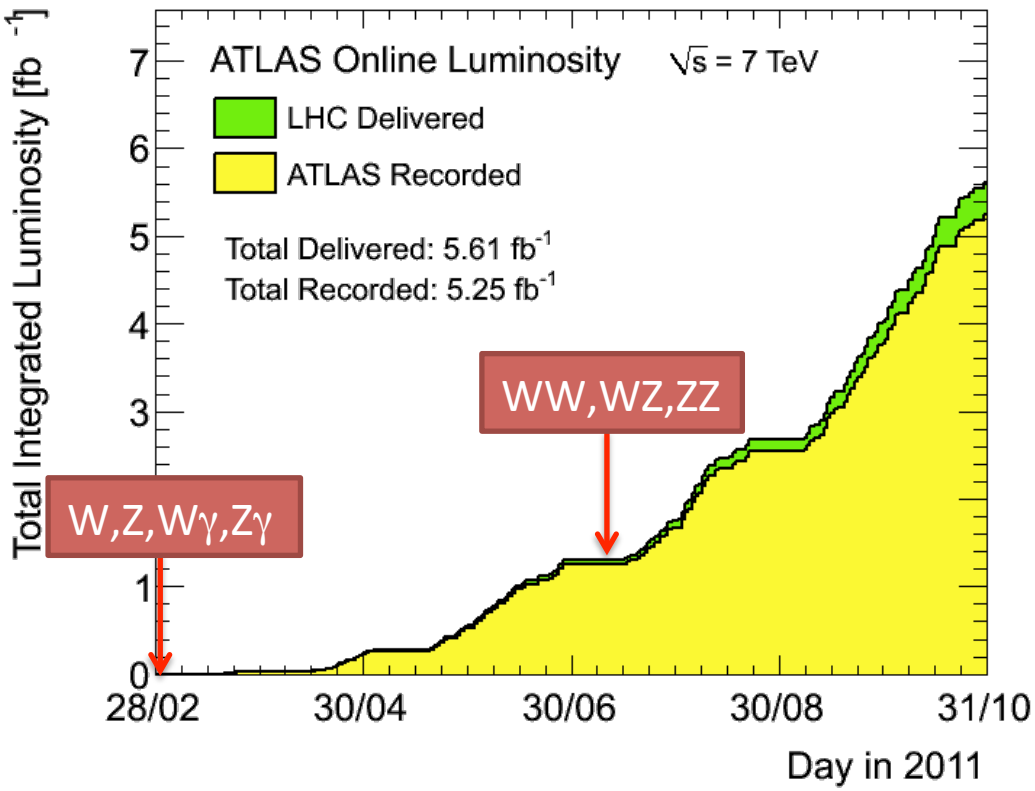
ATLAS and the LHC in 2011

The ATLAS Detector



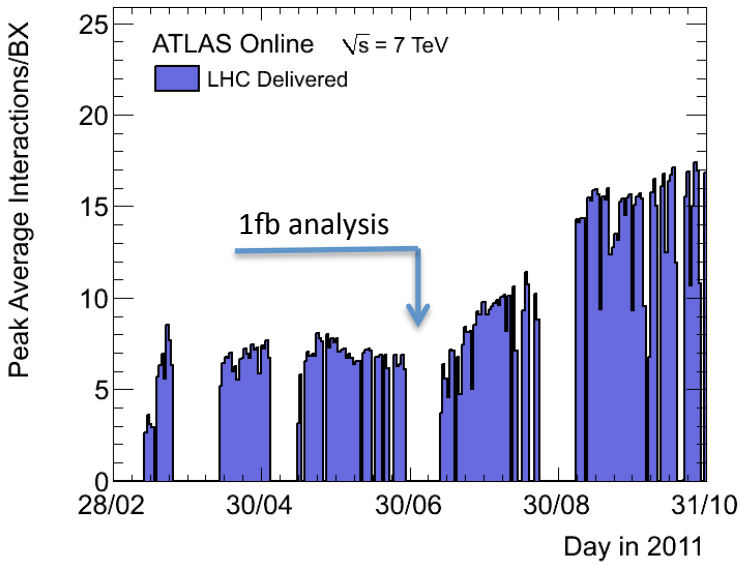
LHC & ATLAS 2011

- Integrated luminosity reached 5.6 fb^{-1}!
  - $\Delta L/L = 3.7\%$
- Single boson analysis limited by systematics.
- Di-bosons analysis no longer a finger counting exercise…
- **Challenges in 2011:**
  - Higher pile-up.
  - Decreasing of statistical error needs better understanding of systematics uncertainties.
  - Background studies cannot rely only on MC anymore.

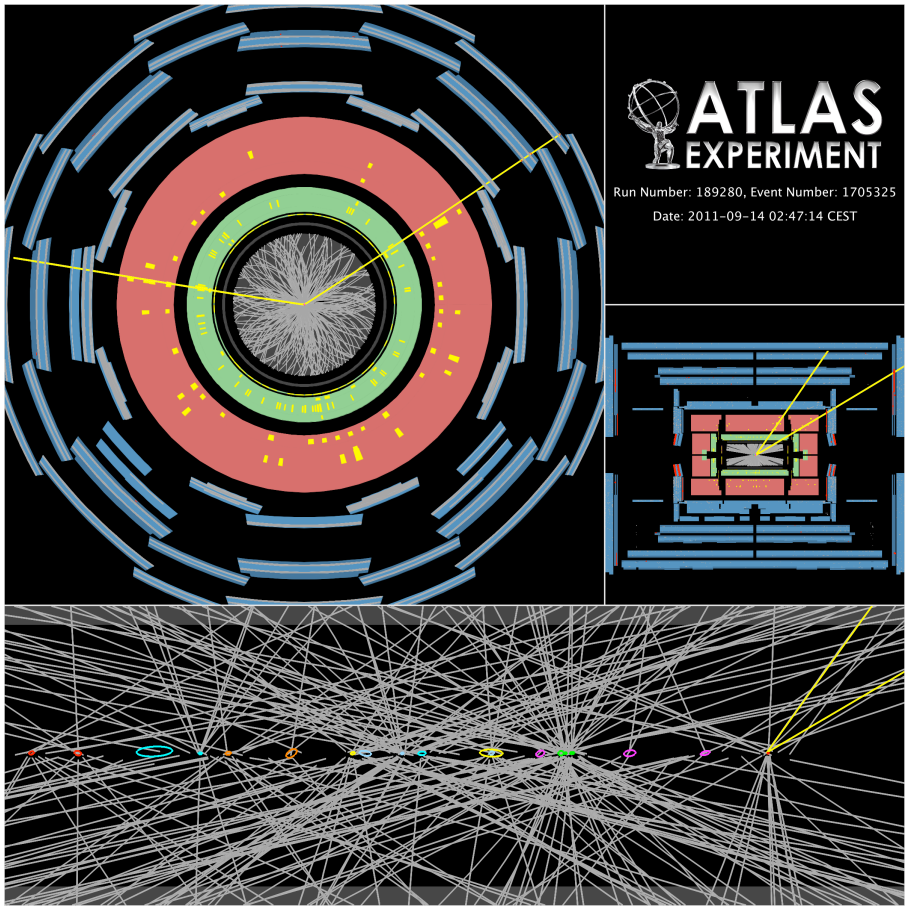


LHC & ATLAS 2011

- Reconstruction challenges ahead for 2011 analysis.

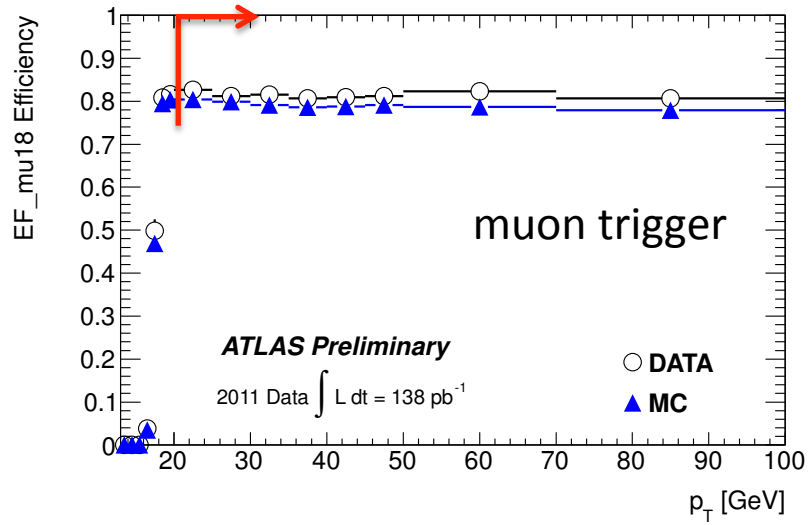


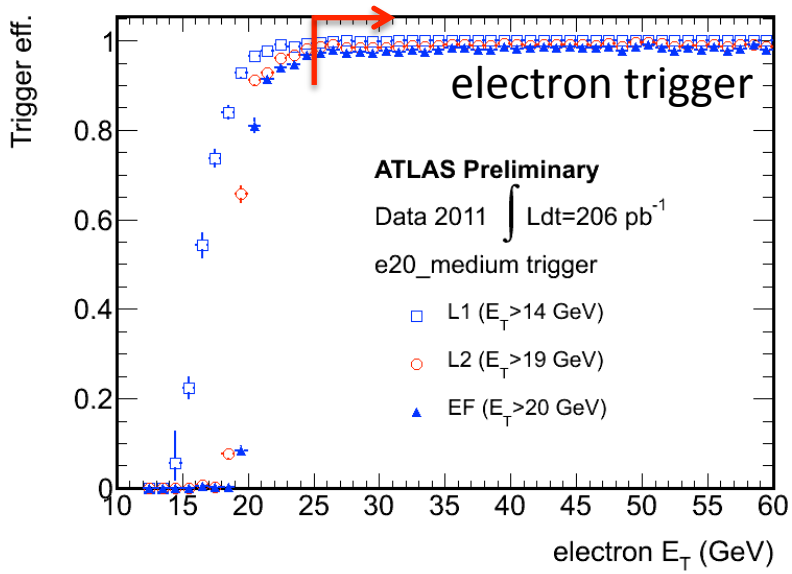
Z->μμ event with 20 vertices



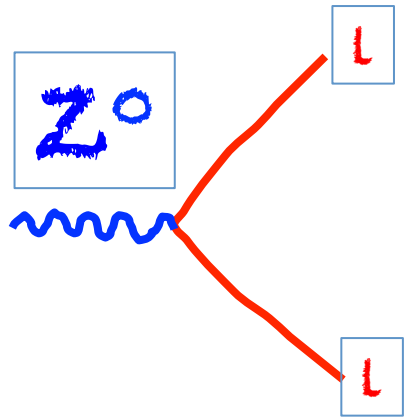
Trigger

- Trigger conditions for leptonic final states
  - Stable trigger for 2011
  - require offline **$p_T(\mu,e) > 20, 25$ GeV**
  - On plateau of trigger efficiency.

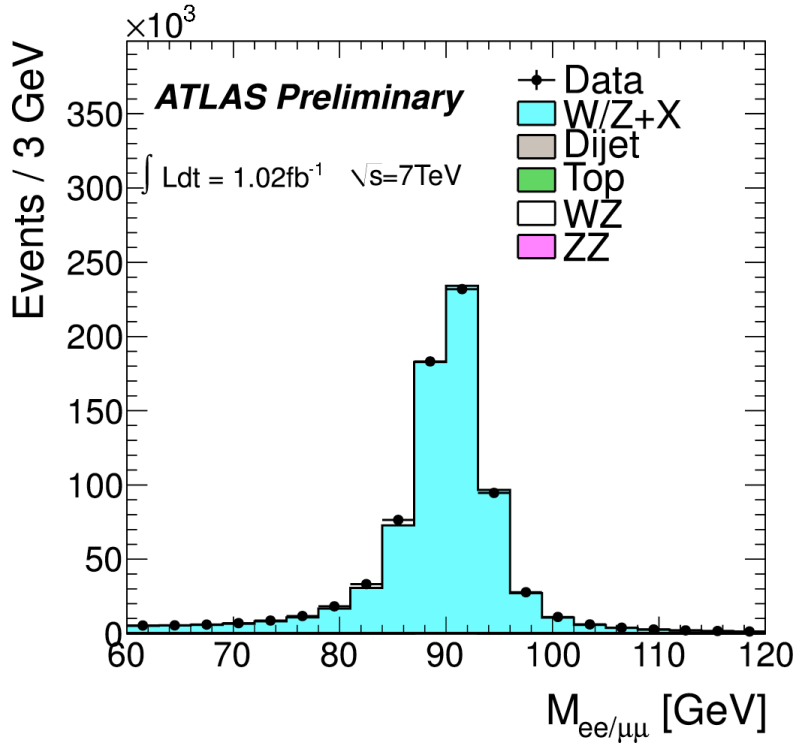




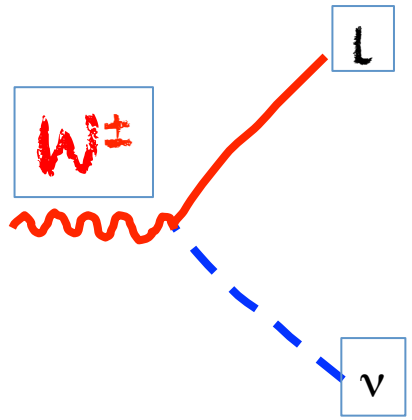
W,Z Reconstruction



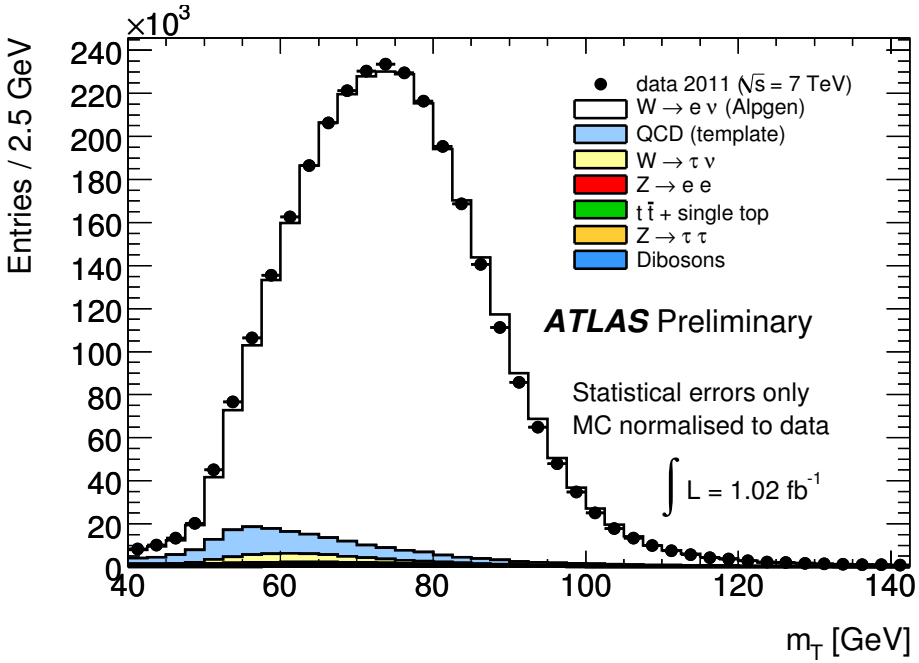
- Lepton selection
  - p_T >15, 20 GeV
  - muons: track based isolation
  - electrons: calo based isolation
  - $|\eta| < 2.5$
- Z selection
  - 2 oppositely charged, same flavor leptons.
  - invariant mass within 10-25 GeV of Z mass.



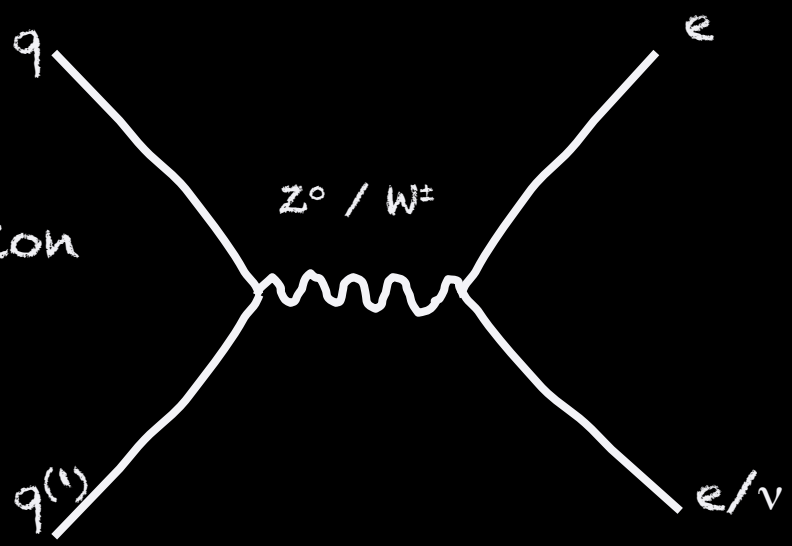
W,Z Reconstruction



- ME_T selection
  - Based on leptons, jets, and calo clusters
  - $|\eta| < 4.5$
- W selection
  - 1 isolated lepton
  - $ME_T > 25\text{-}45$ GeV
  - $WM_T > 20, 40$ GeV



Single Boson Production

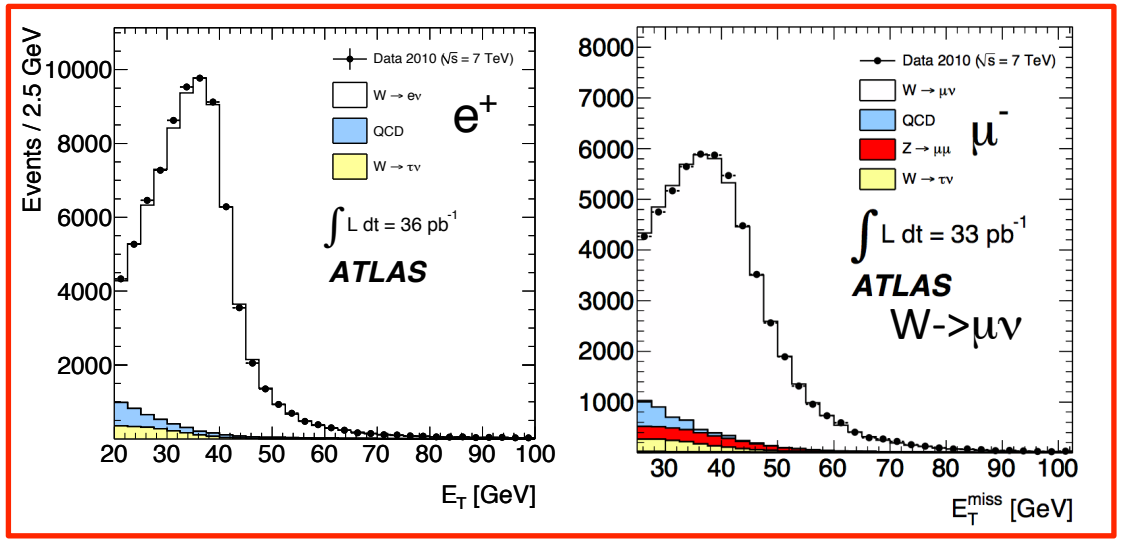


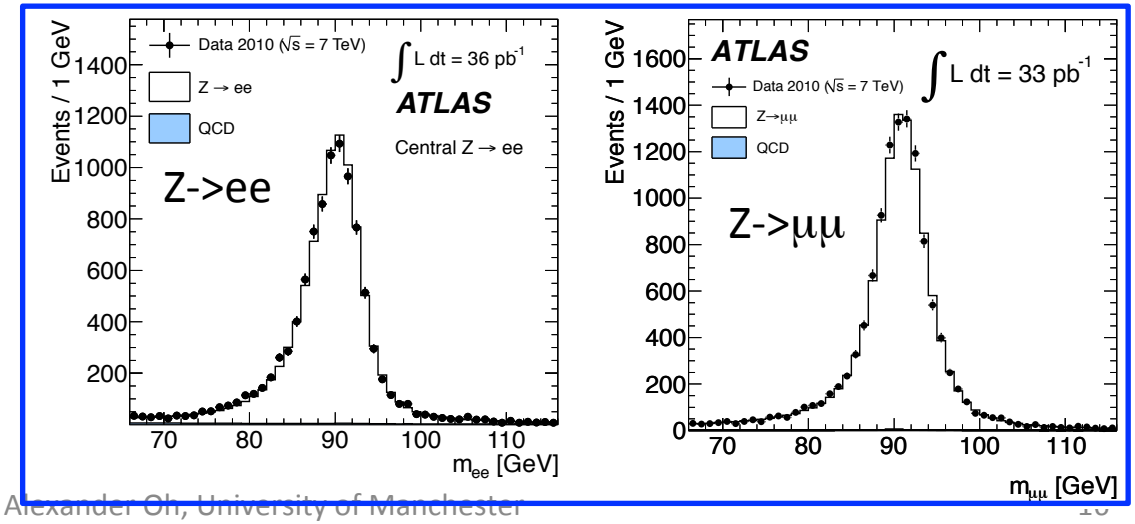
W/Z Results

arXiv:1109.5141
submitted to PRD , 23/9/11

- **Analysis inclusive W/Z production with 33pb^{-1} of 2010 data.**
- Background to W
  - QCD dominant background, estimated from data (3-4%).
  - W -> τ estimated with MC (3-4%).
  - Z->μμ ~3%
- Background to Z
  - QCD estimated from data (0.4%-1.6%).

	N_{sig}	N_{bkg}
$W^{\pm}$	139k	12k
Z	12k	86

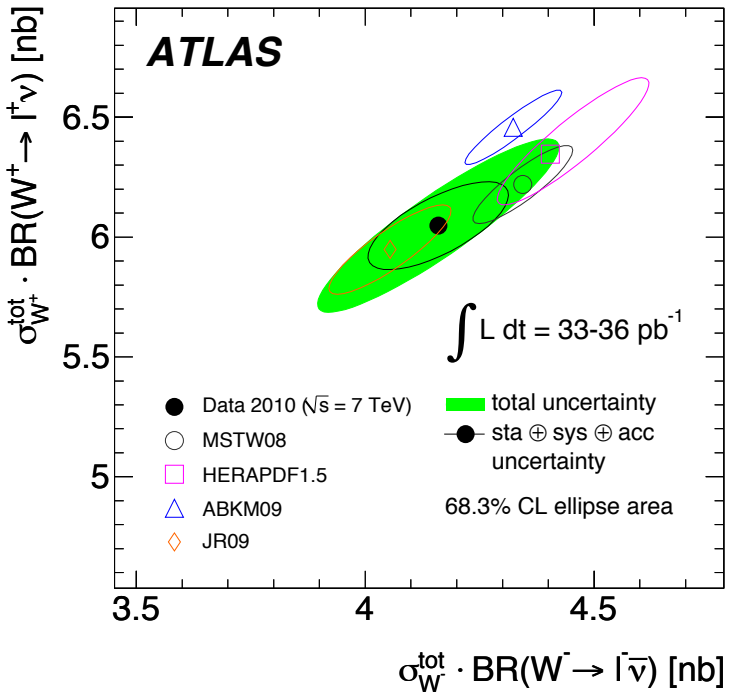


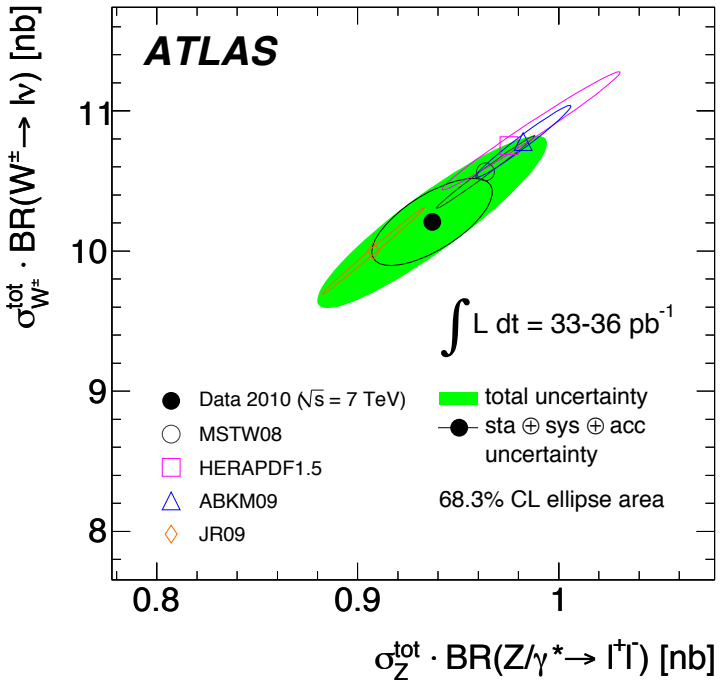


W/Z production

arXiv:1109.5141
submitted to PRD , 23/9/11

- Compare total cross-sections to NNLO QCD calculations.
- Theoretical error on total cross section ~1.5 – 2% (PDF sets, MC generators).

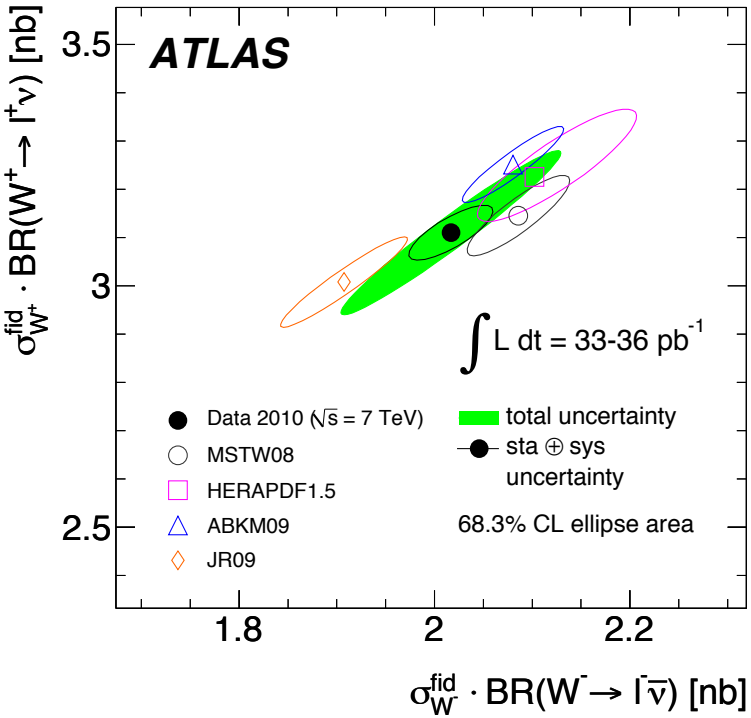


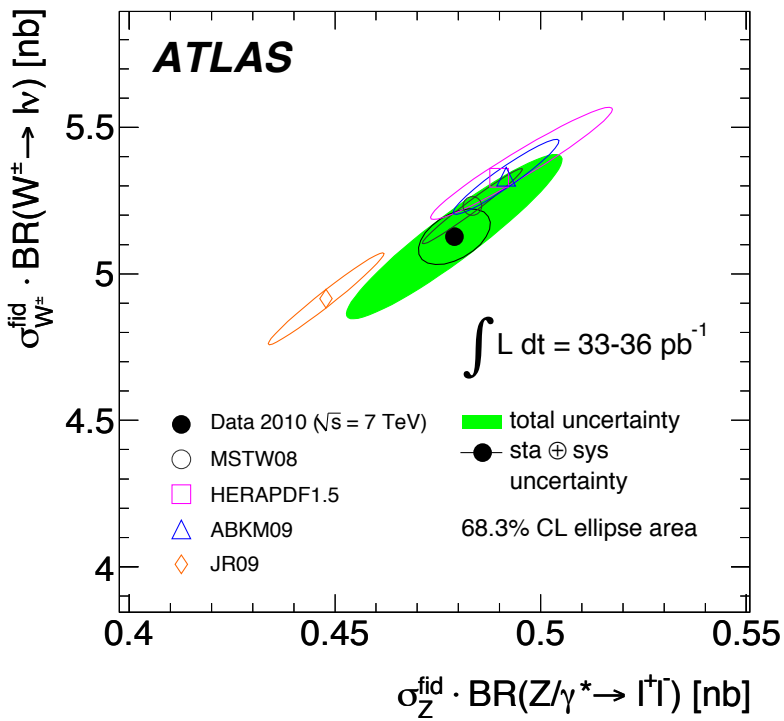


W/Z production

arXiv:1109.5141
submitted to PRD , 23/9/11

- Compare fiducial cross-sections to NNLO QCD calculations.
- No uncertainty due to phase space extrapolation.
- Better separation of theoretical and experimental effects.



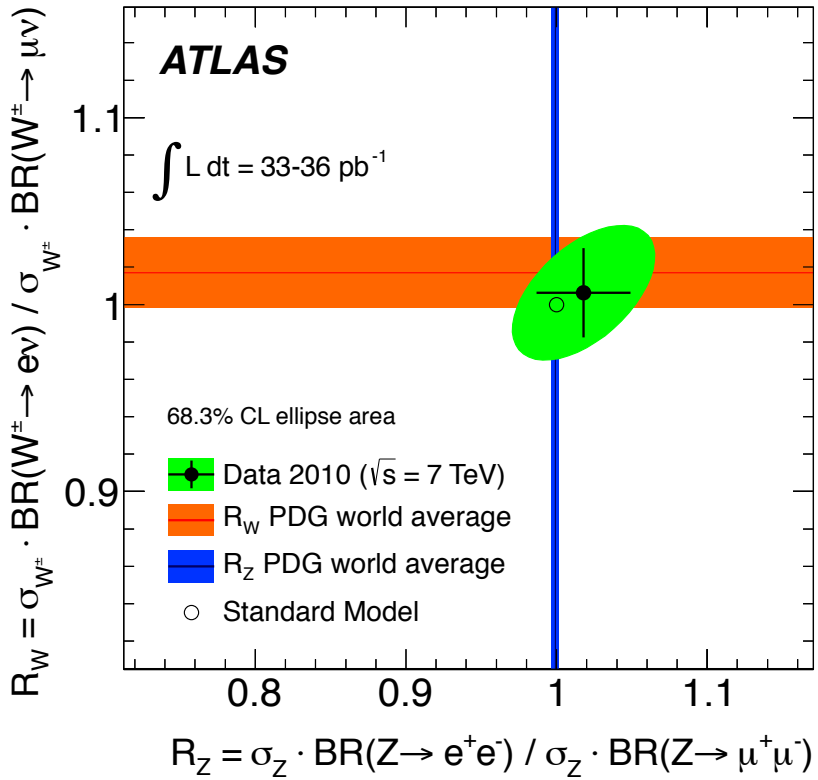


W/Z production

arXiv:1109.5141
submitted to PRD , 23/9/11

- Test of lepton universality in W and Z decays.
  - Dominated by (correlated) systematic uncertainty.
  - Can use PDG value for R_Z to further constrain R_W by reducing correlated systematics:

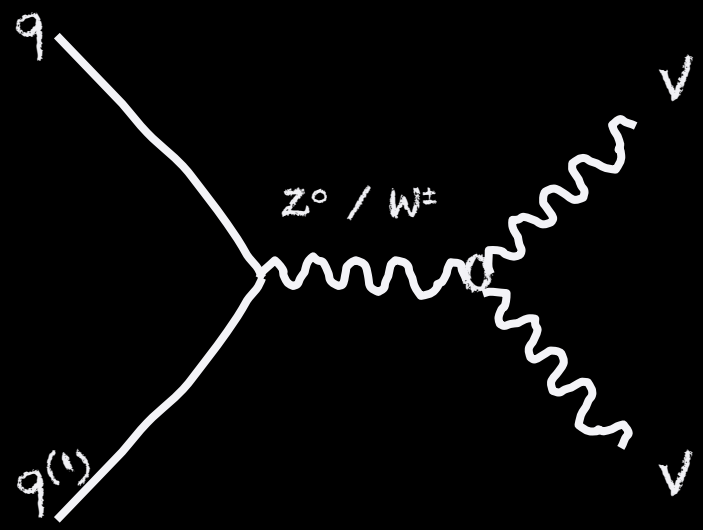
$$R_W = 0.999 \pm 0.021.$$



$$R_W = \frac{\sigma_W^e}{\sigma_W^\mu} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)} = 1.006 \pm 0.004\,(\mathrm{sta}) \pm 0.006\,(\mathrm{unc}) \pm 0.023\,(\mathrm{cor}) = 1.006 \pm 0.024$$

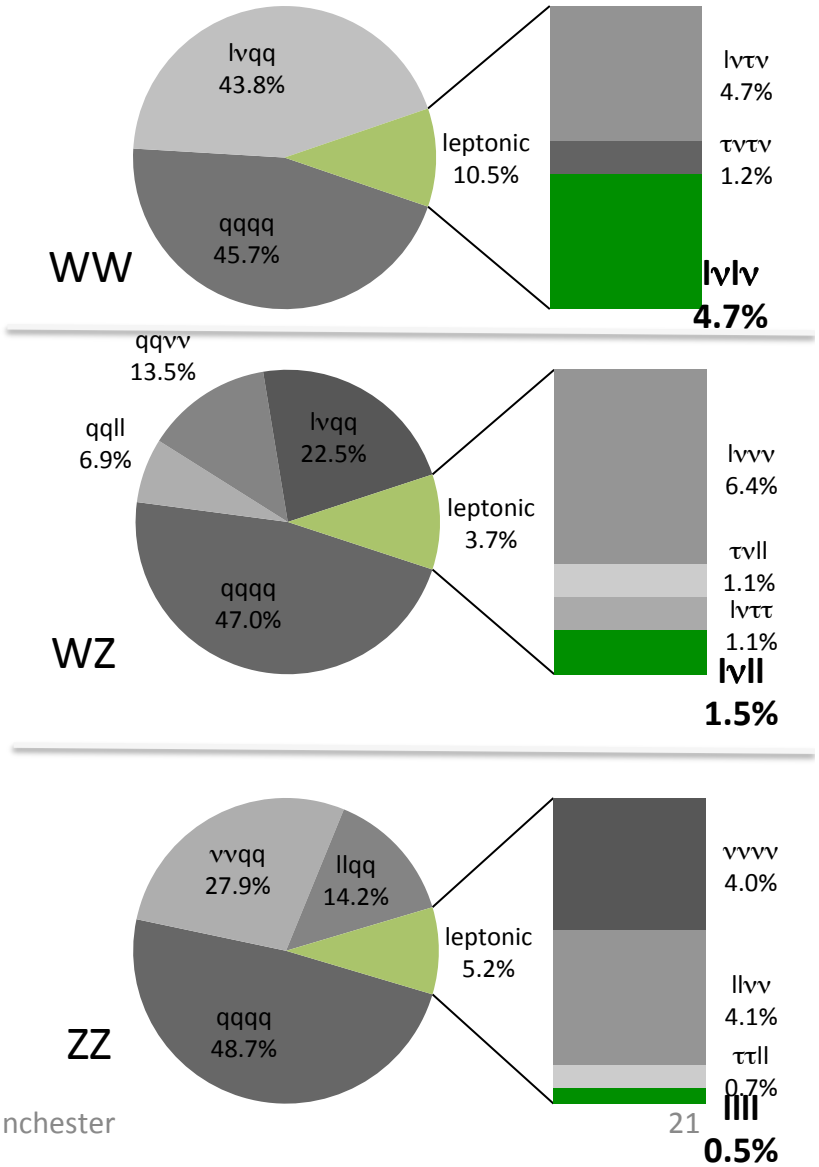
$$R_Z = \frac{\sigma_Z^e}{\sigma_Z^\mu} = \frac{Br(Z \to ee)}{Br(Z \to \mu\mu)} = 1.018 \pm 0.014\,(\mathrm{sta}) \pm 0.016\,(\mathrm{unc}) \pm 0.028\,(\mathrm{cor}) = 1.018 \pm 0.031$$

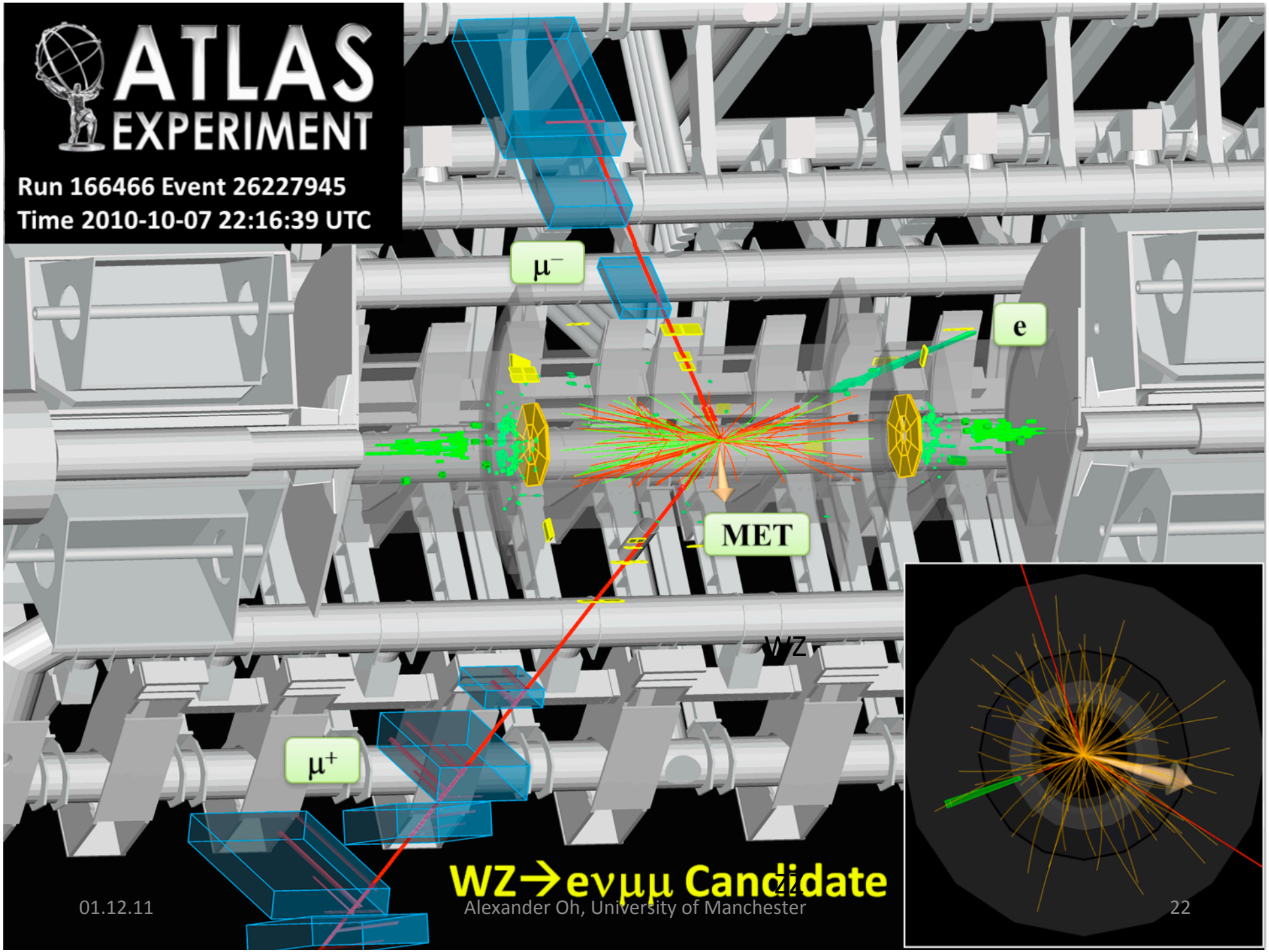
Di-Boson Production



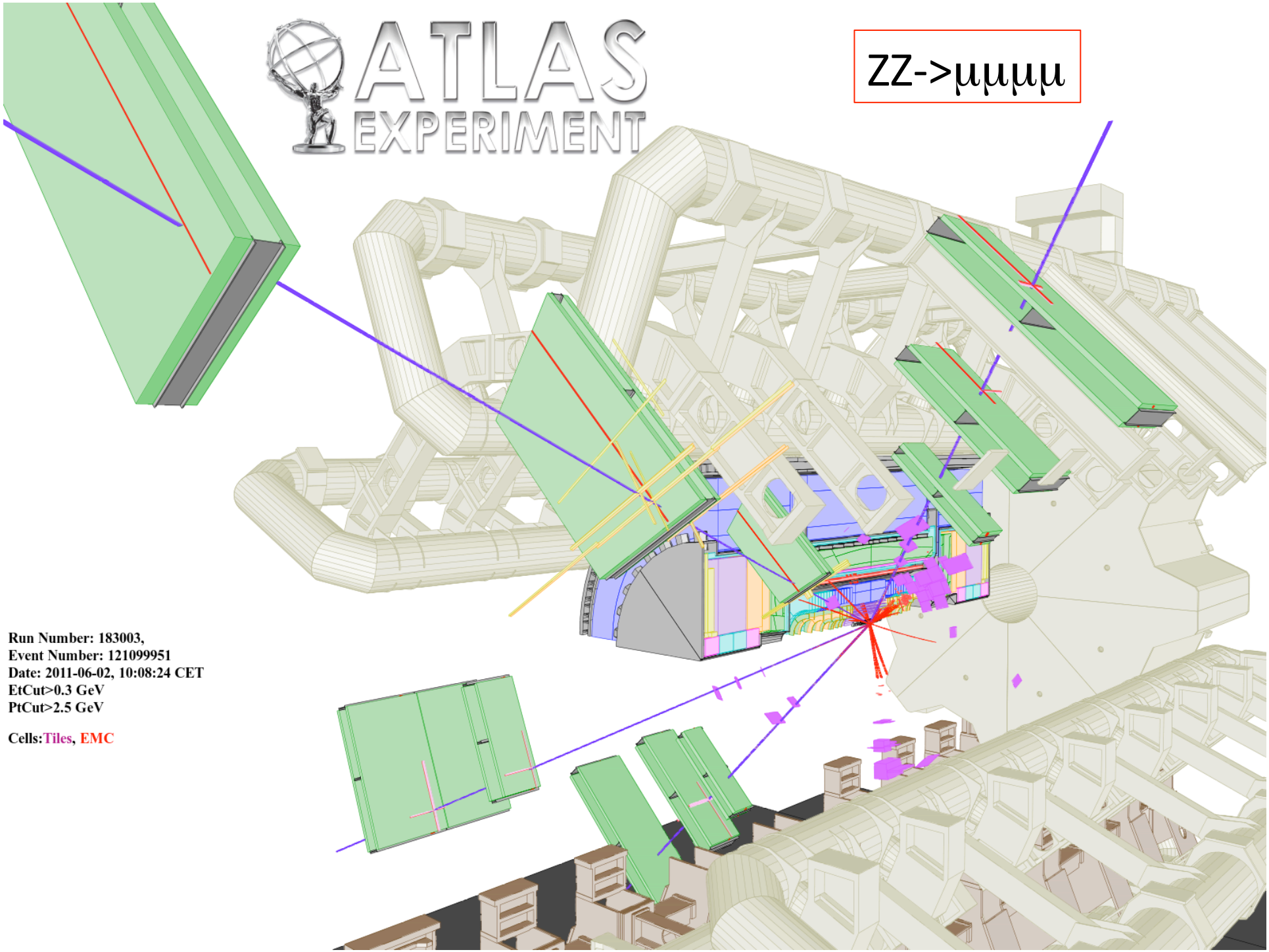
Heavy Di-Boson Production at LHC

- Use leptonic decays:
  - Small Branching Ratios
  - Low background
- Tau decays contribute to e/μ channels
  - Accounted for in cross section extraction.
- Clean but small signal.

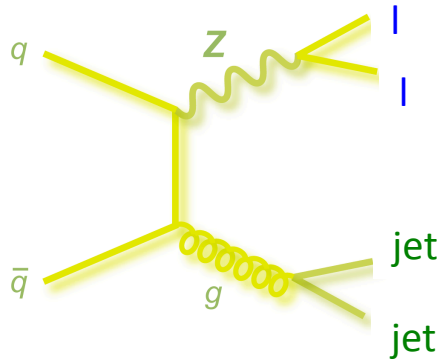


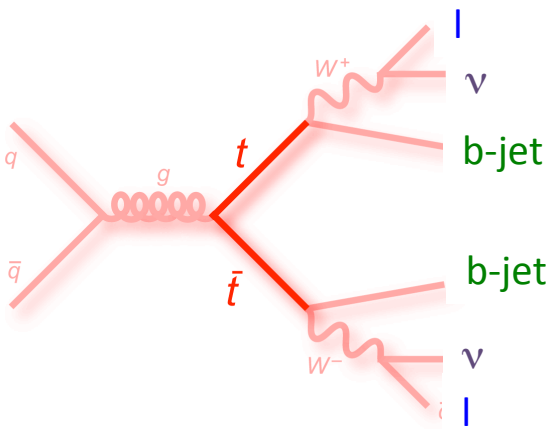


WZ→eνμμ Candidate


ATLAS EXPERIMENT
ZZ->μμμμ
Run Number: 183003,
Event Number: 121099951
Date: 2011-06-02, 10:08:24 CET
EtCut>0.3 GeV
PtCut>2.5 GeV
Cells:Tiles, EMC

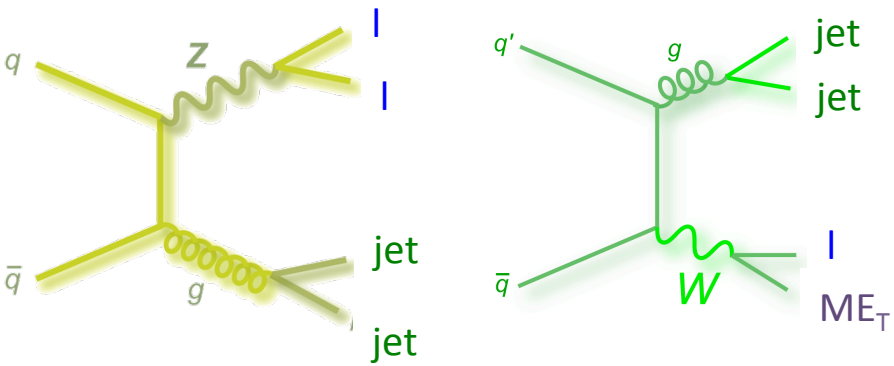
Common Backgrounds





- **W/Z + jets and Top production**
  - Dominant background for di-boson analysis
  - Estimated mainly with data driven methods
- **Di-boson production**
  - Wγ,Zγ,WW,ZZ,WZ are each others background.
  - Estimation by using MC prediction.

Common Backgrounds: **W/Z + jets**



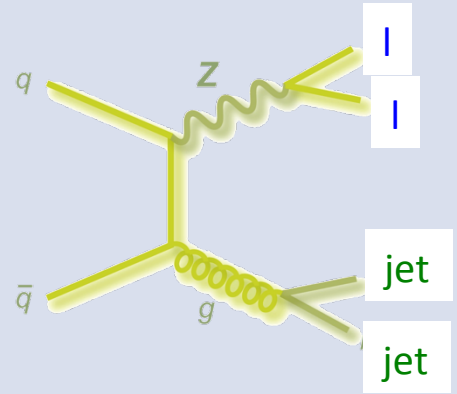
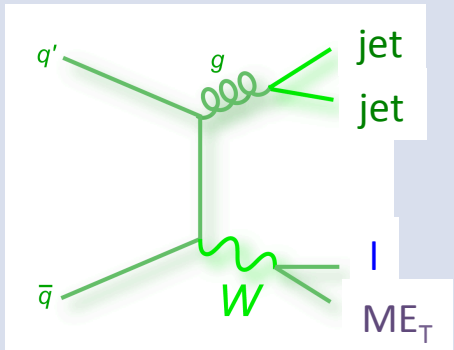
- **W/Z + jets**
  - 1 or 2 real leptons
  - MET
  - additional fake or real lepton from jet.

$$R = \frac{N_{isolated}(e,\mu)}{N_{non-isolated}(e,\mu)}$$

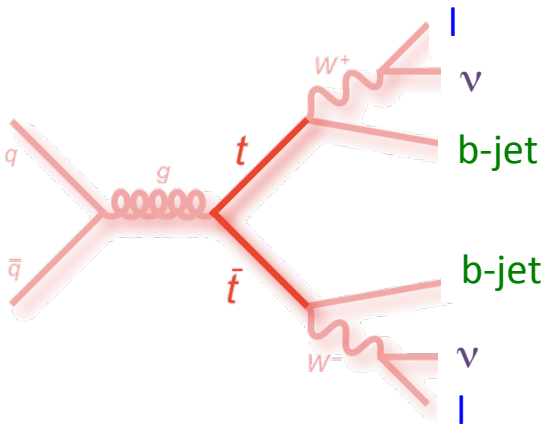
- **Data driven estimate**
  - measure ratio of isolated to non-isolated leptons in a jet sample.
  - apply ratio to W/Z+jets control sample to estimate rate in signal region.

Common Backgrounds: **W/Z + jets**

- **W/Z + jets contribution to VV analysis**

		
WW	13% (MC)	13%
WZ	11%	-
ZZ	< 3%	< 3%
Wγ	-	18%
Zγ	15% (MC)	-

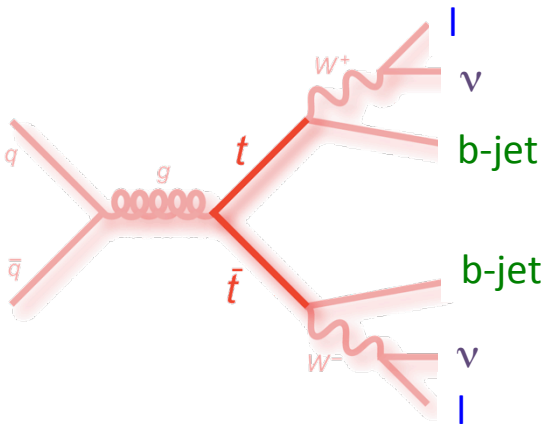
Common Backgrounds: **Top**



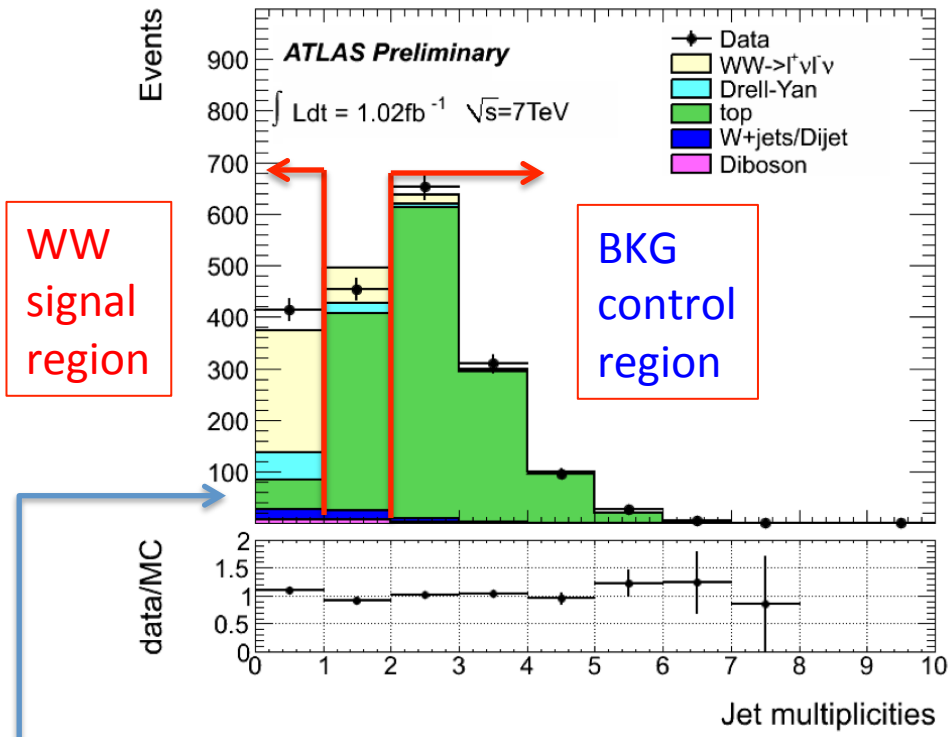
- **Top pairs**
  - 2 real leptons
  - MET
  - additional fake or real lepton/γ from jet.

- **WZ / ZZ**
  - Estimated from data driven methods.
  - Small contribution:
    WZ ~ 3%
    ZZ < 3%
- **Wγ / Zγ**
  - Estimated from MC.
  - Small contribution.

Common Backgrounds: **Top**

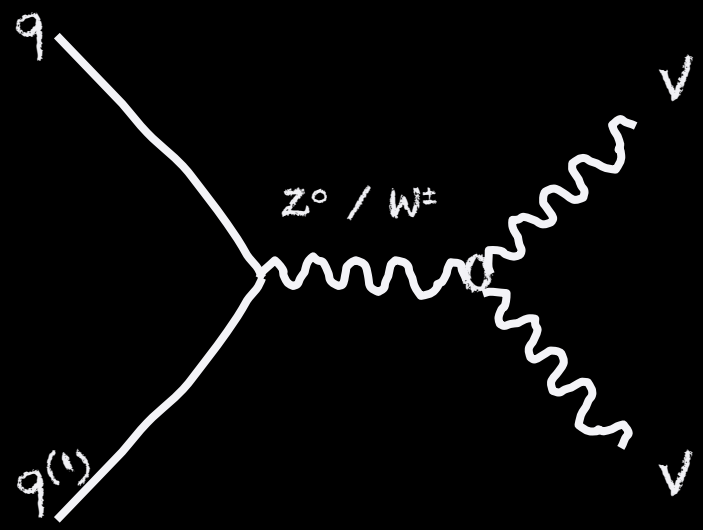


- **WW**
  - Signal region: 0 jets
  - Estimate in >2 jets control region
  - contribution in 0 jet bin ~14%.



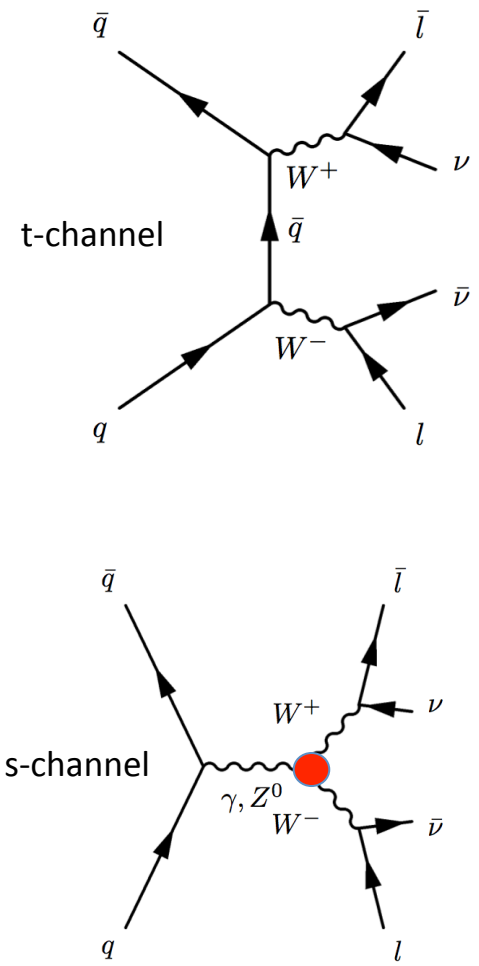
Di-Boson Production

<u>Cross section results</u>

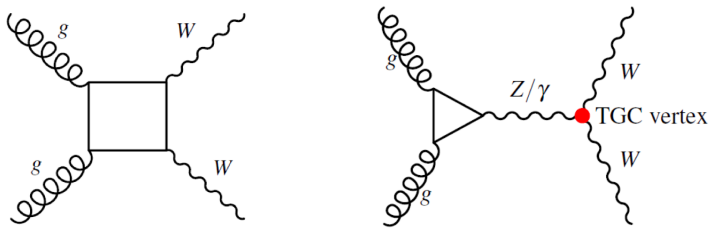


WW-> lνlν

ATLAS-CONF-2011-110



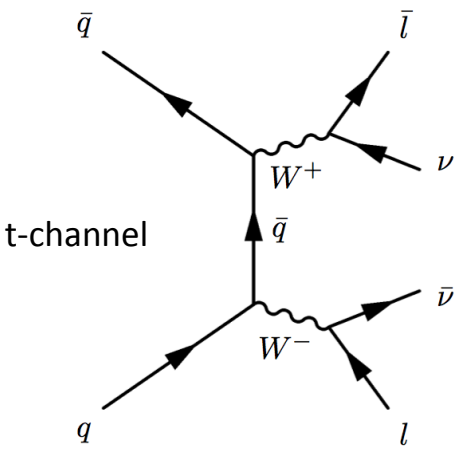
- Signature two leptons and MET.
- Small contribution (3%) from gg:

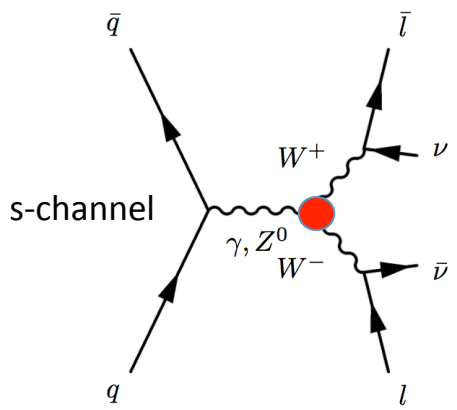


- Important background to H->WW studies!

  (see “Search for Higgs to WW”,ID297)

WW-> lνlν





Selection
- Exactly 2 leptons opposite signs, p_T > 20GeV
- Leading electron p_T > 25 GeV
- m_{ll} > 15GeV, $m_{e\mu}$ > 10GeV
- Z veto ($|m_{ll}-m_Z|$ < 15GeV
- MET (rel) > (45,40,25) GeV, (μμ,ee,eμ)
- Jet veto (pT>30GeV, |eta|<4.5,anti-kt,DR=0.4)

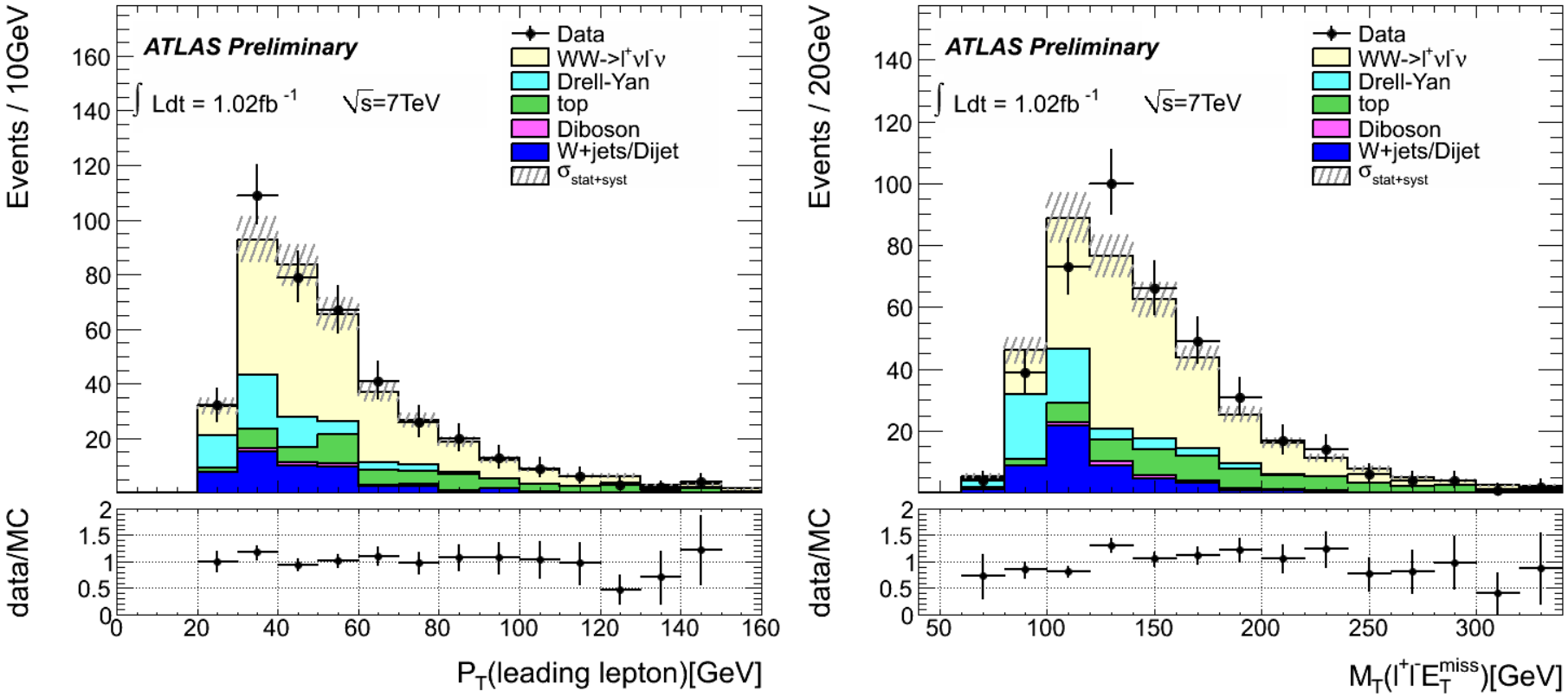
- MET:
  - Use MET relative to nearest lepton: $MET_{rel}=\sin(\Delta\phi)*MET$ for $\phi < 90°$
  - Reduces DY contribution for miss-measured jets/leptons and Z->ττ.
- Backgrounds:
  - Use DD backgrounds for W+jets and ttbar.
  - Use MC for DY and Di-Boson.

WW-> lνlν

L=1.0 fb^{-1}

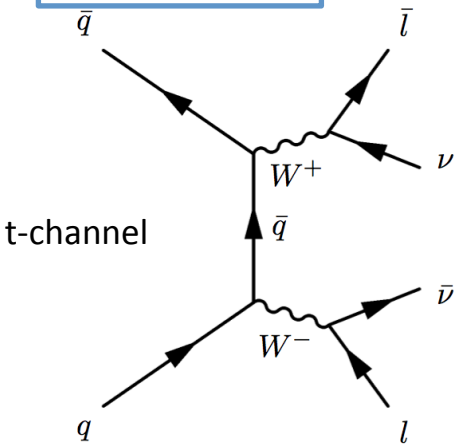
Kinematic Distribution after all selection cuts

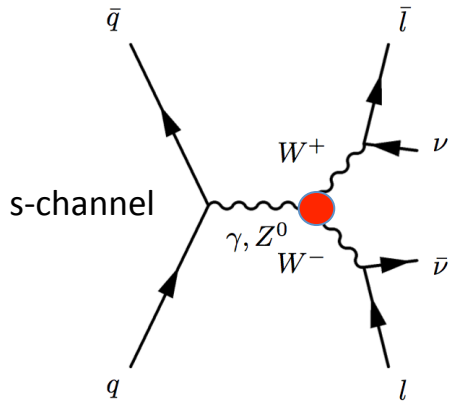
N(cand) = 414 , N(bckgnd) = 170±28



WW-> lνlν

L=1.0 fb^{-1}





Total production cross section result

σ_{total}=48.2± 4.0(stat)± 6.4(sys) ± 1.8(lumi) pb

Fiducial production cross section result

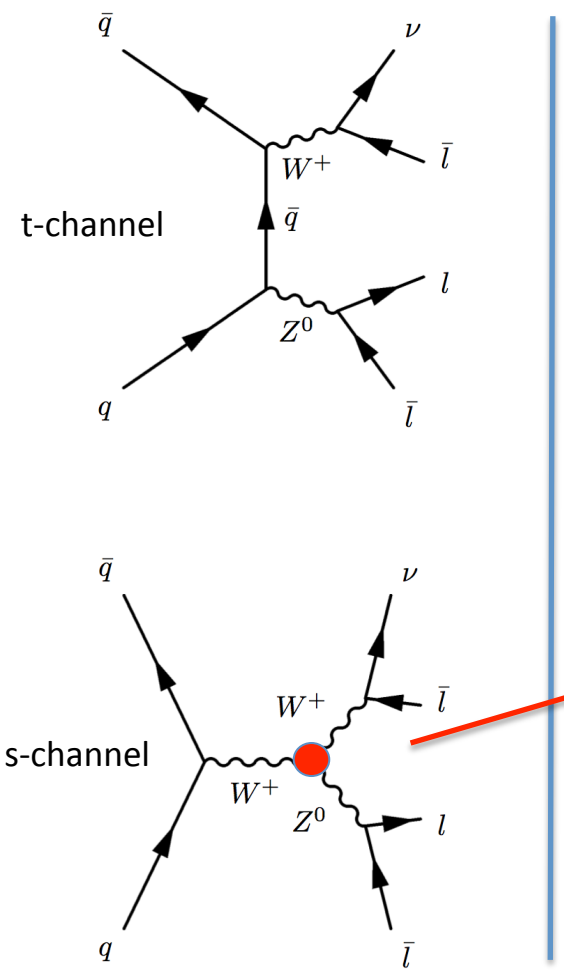
Channels	expected σ^{fid} (fb)	measured σ^{fid}(fb)	$\Delta\sigma_{stat}$(fb)	$\Delta\sigma_{syst}$(fb)	$\Delta\sigma_{lumi}$(fb)
$e\nu e\nu$	66.8	90.1	± 18.9	± 11.3	± 3.3
$\mu\nu\mu\nu$	63.8	62.0	± 12.1	± 10.7	± 2.3
$e\nu\mu\nu$	245.1	252.0	± 24.6	± 29.4	± 9.3

Phase space mimics selection cuts, different for ee,eμ,μμ.

- NLO SM expectation: σ_{total}=46±3 pb
- Limited by systematic
  - Dominated by Data Driven background estimation.

WZ-> lllν

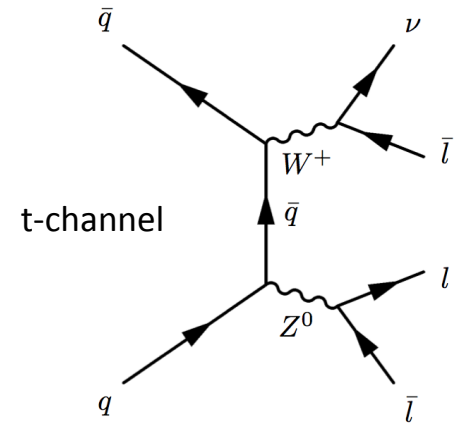
arXiv:1111.5570
(PLB submitted on Nov 24)

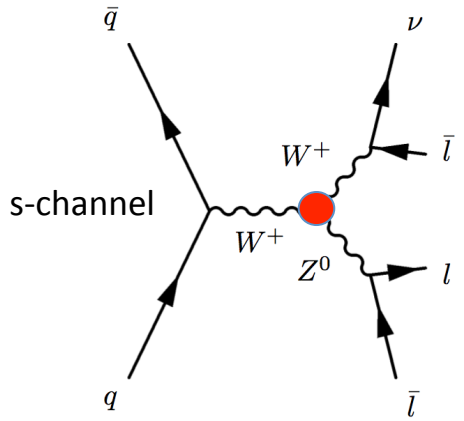


- Signature:
  Three leptons and MET.
- Presence of Z allows effective suppression of ttbar backgrounds.
  - Dominant background source Z +jets.
- Cross section and anomalous **<u>triple gauge couplings</u>** determined.

WZ-> lllν

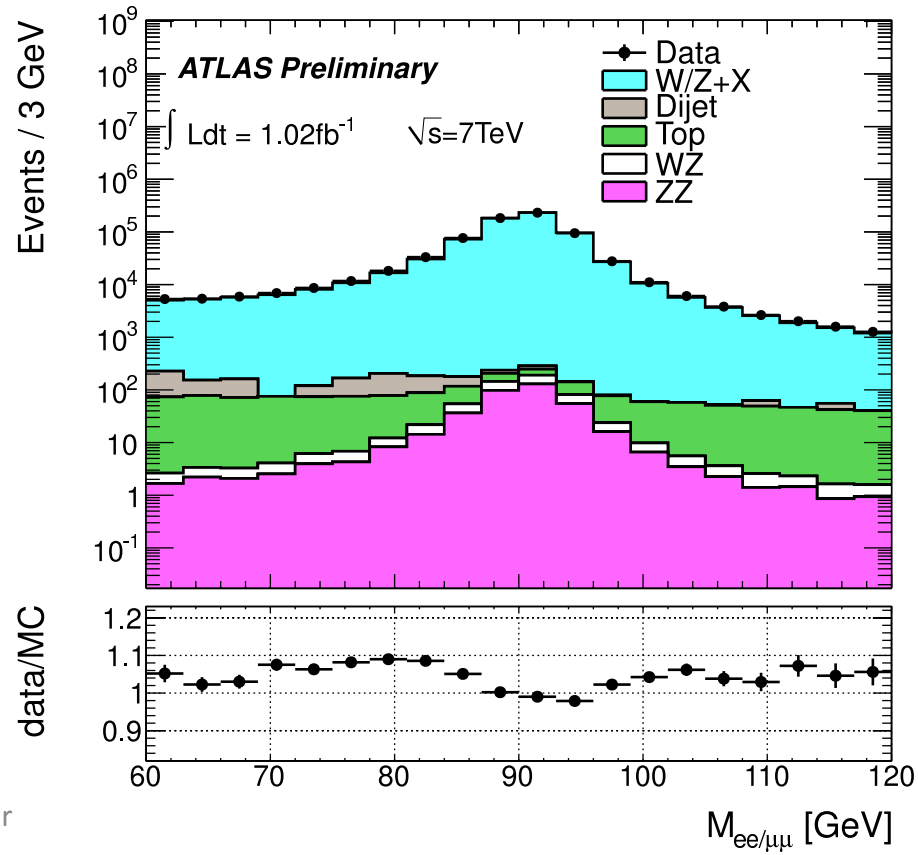
L=1.0 fb^{-1}





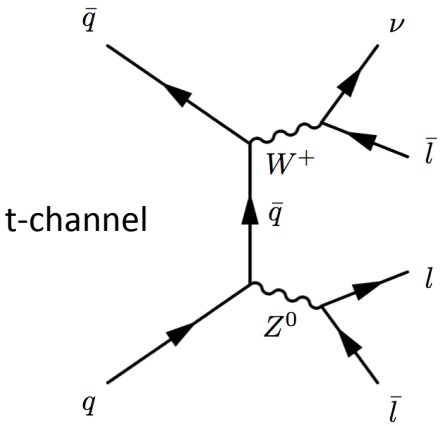
Selection

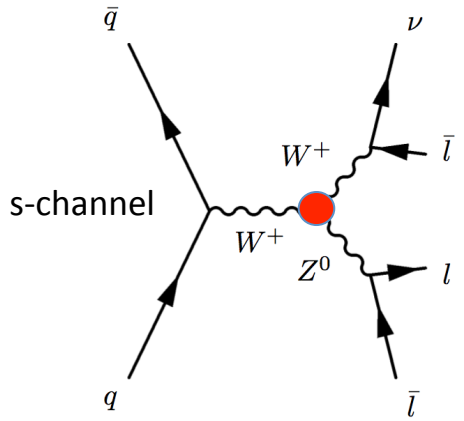
- Z $|m_{ll}-m_Z| < 10$ GeV
- 3 leptons, $p_T > 15$ GeV
- MET > 25GeV
- W MT > 20 GeV
- Trigger Match with $p_T(e,\mu) > (25,20)$ GeV



WZ-> lllν

L=1.0 fb^{-1}

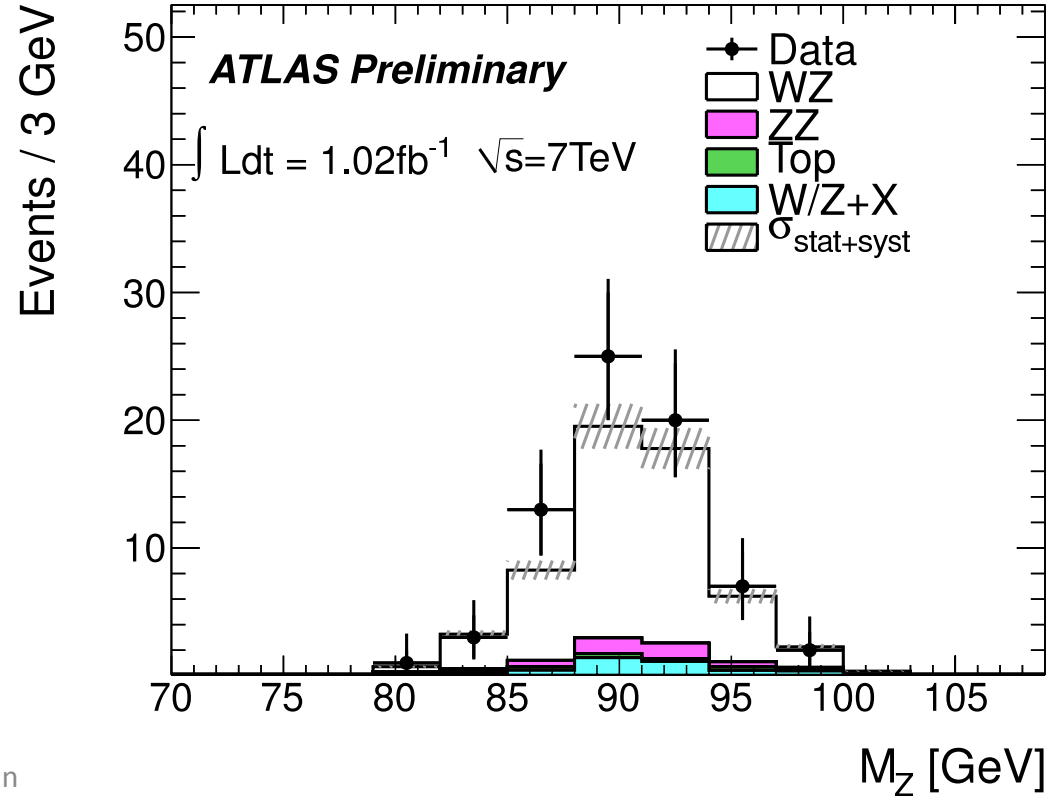




Selection

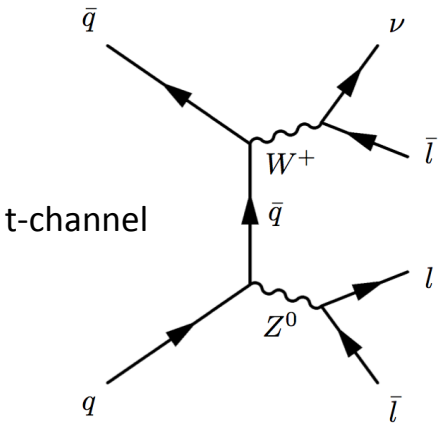
- Z $|m_{ll}-m_Z| < 10$ GeV
- MET > 25GeV
- W MT > 20 GeV
- Trigger Match with $p_T(e,\mu) > (25,20)$ GeV

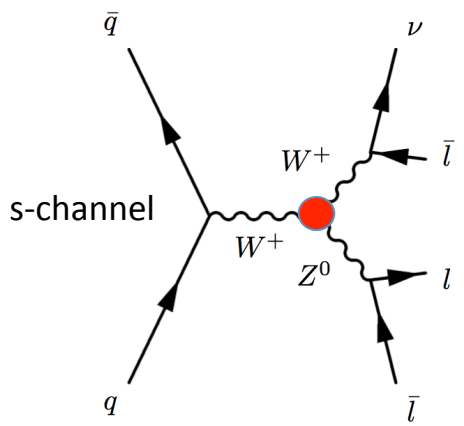
N(Data) = 71 , N(bkg MC) = 10.5



WZ-> lllν

L=1.0 fb^{-1}





Total cross section:

$$\sigma_{WZ}^{tot} = 21.1^{+3.1}_{-2.8}(\text{stat})\ ^{+1.2}_{-1.2}(\text{syst})\ ^{+0.9}_{-0.8}(\text{lumi})\ \text{pb}$$

SM NLO expectation 17.2±1pb

Good agreement with the Standard Model.

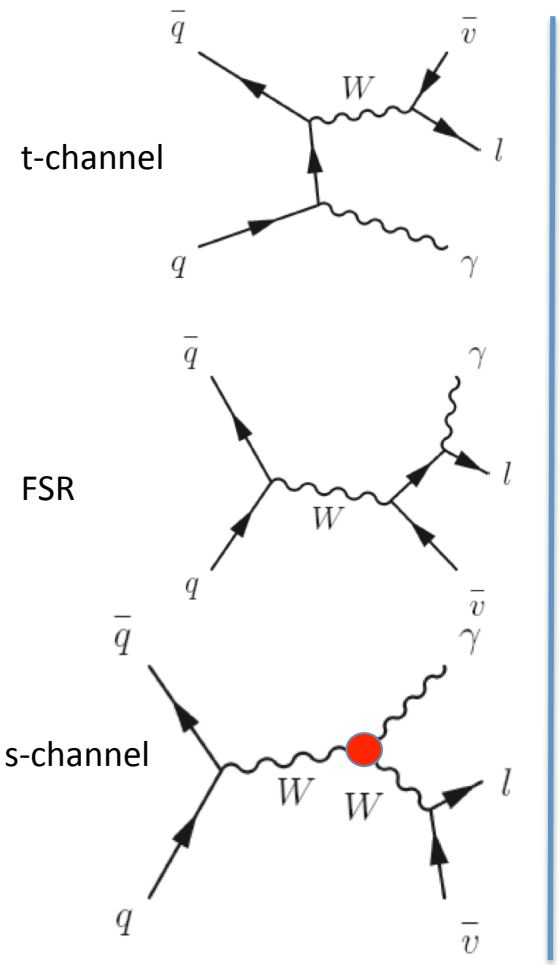
Fiducial Cross section:

- $p_T(l) > 15$ GeV, $|\eta| < 2.5$, $pT(\nu) > 25$ GeV
- $M(ll)-M_Z < 10$ GeV
- $M_T(W) > 20$ GeV

$$\sigma_{WZ\to\ell\nu\ell\ell}^{fid} = 118^{+18}_{-16}(\text{stat})\ ^{+6}_{-6}(\text{syst})\ ^{+5}_{-5}(\text{lumi})\ \text{fb}$$

Wγ-> lνγ, Zγ-> llγ

arXiv:1106.1592

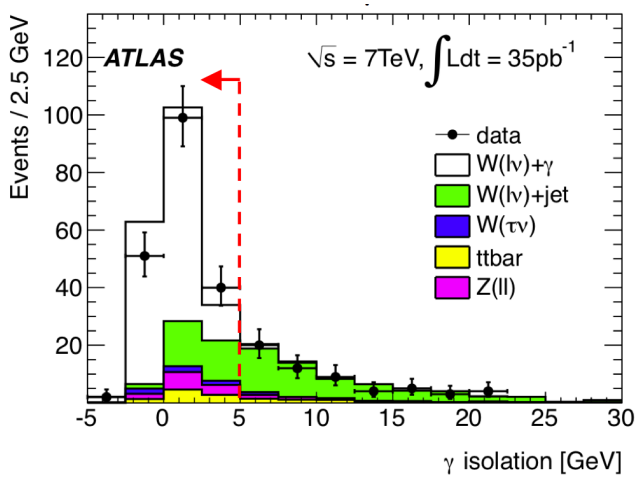


- Signature:
  One lepton, photon and MET
  Two same flavor leptons, photon

- Use also converted γ.
- $E_T(\gamma) > 15$ GeV.
- Photon isolation $E_T(\Delta R=0.4) < 5$ GeV.
- M(ll) > 40 GeV (for Zγ)
- FSR contribution suppressed by $\Delta R(\gamma,l)>0.7$ cut
- Dominant background source
  W+jets.

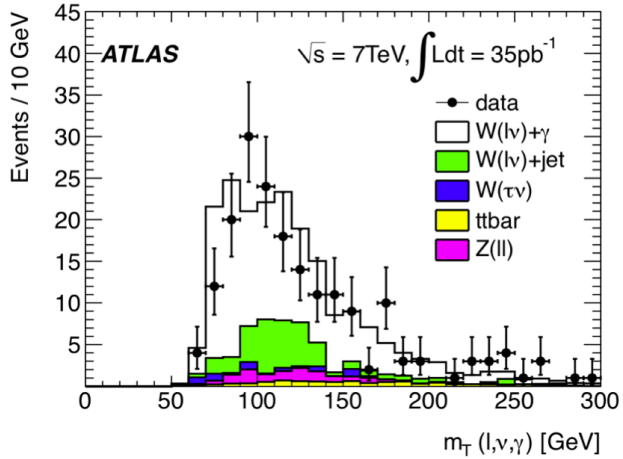
Wγ-> lνγ, Zγ-> llγ

arXiv:1106.1592

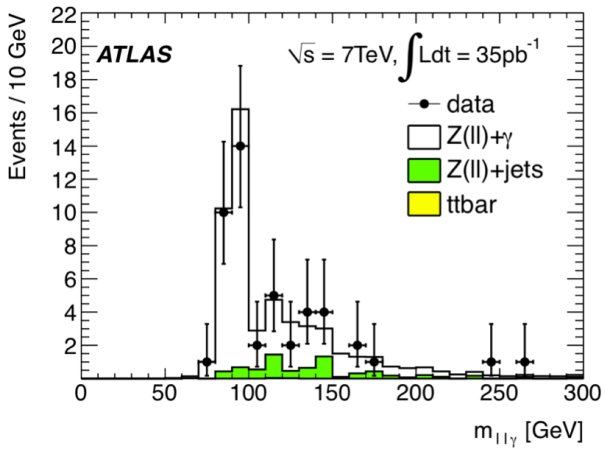


γ isolation before applying the isolation cut for Wγ events.

Transverse mass of the Wγ system after all selection cuts



Invariant mass of the Zγ system after all selection cuts

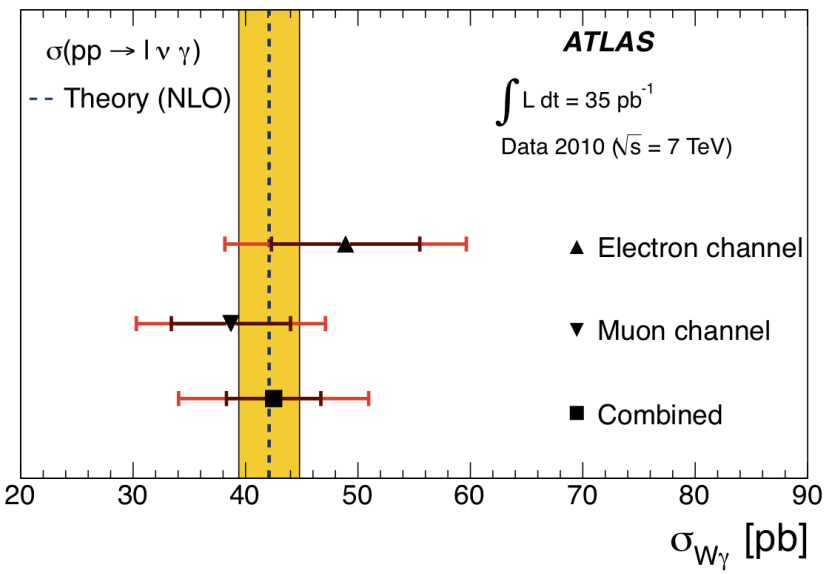


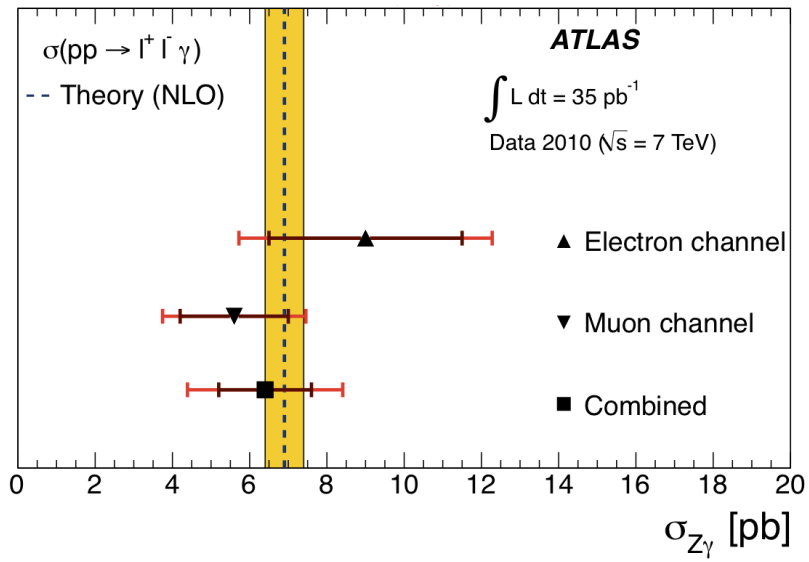
Wγ-> lνγ, Zγ-> llγ

arXiv:1106.1592

- Results

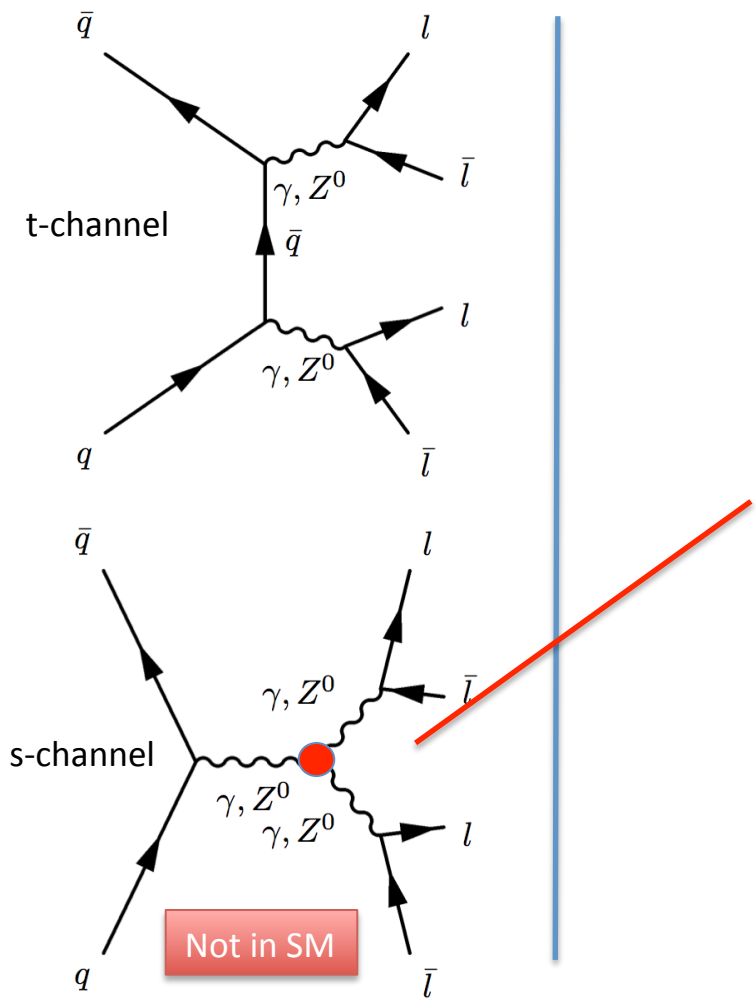
Process	N observed	N Bkg expected
Wγ->lνγ	192	56±13
Zγ->llγ	48	7±7





ZZ-> llll

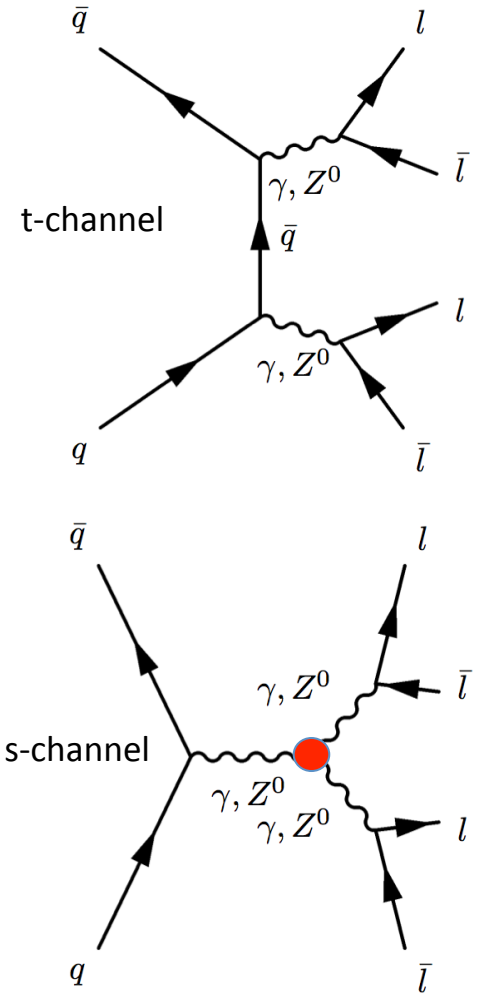
arXiv:1111.4116
(PRL accepted on Nov 23)



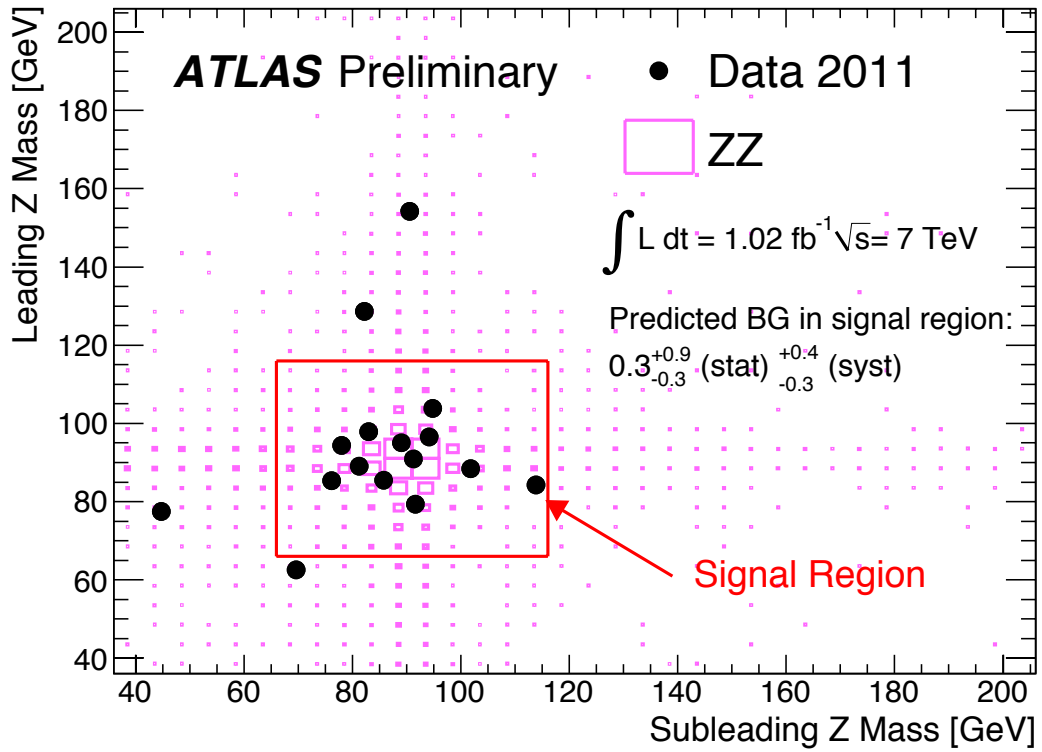
- Signature:
  Four leptons.
- Presence of two Z make this channel effectively background free.
  - Enhanced acceptance by loosened object definitions.
- Cross section and **anomalous triple gauge couplings** determined.

ZZ-> llll

L=1.0 fb^{-1}



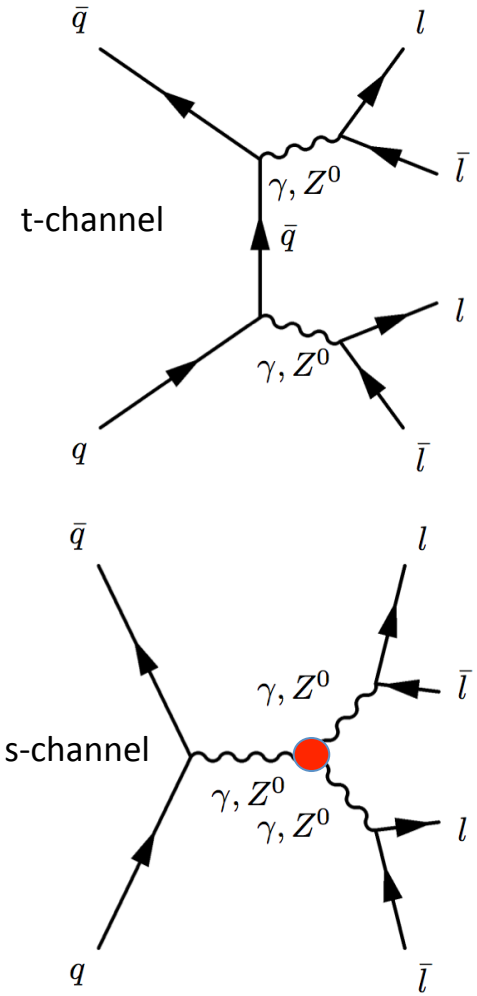
- Background for H->ZZ
  (see "Search for Higgs to ZZ", ID298)
- Anomalous coupling vertex in s-channel (forbidden in SM).
- Selection:
  - 4 leptons, pT>15GeV, |η|<2.5, leading μ(e) pT>20 (25) GeV
  - 2 Z candidates with $|M_{ll}-M_z| < 25$GeV.
- Background estimate from Data driven methods.



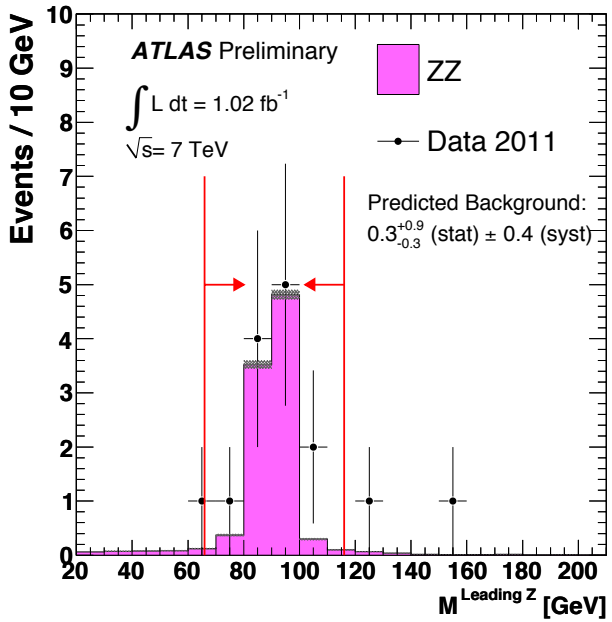
ZZ-> llll

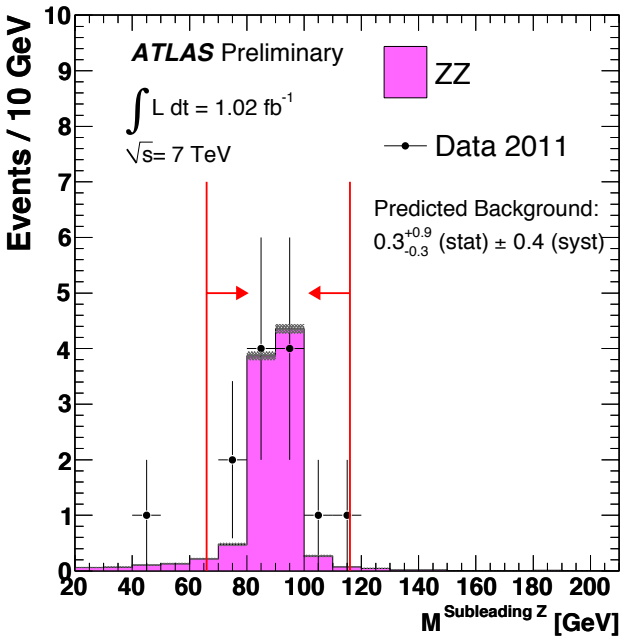
L=1.0 fb^{-1}

- Found 12 candidate events.



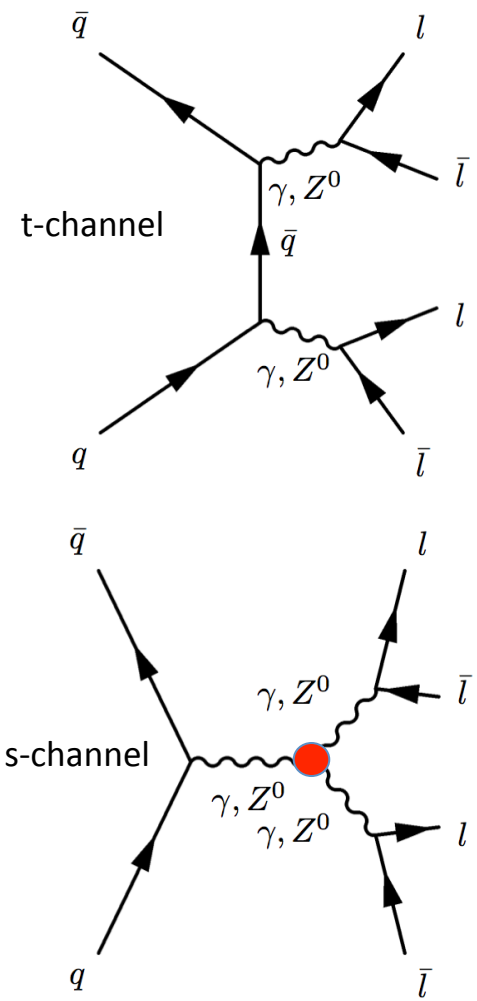
Final State	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell^+\ell^-$
Observed	2	8	2	12
Bkg(data-driven)	$0.01^{+0.03+0.05}_{-0.01-0.01}$	$0.3^{+0.9}_{-0.3} \pm 0.3$	$< 0.01^{+0.03}_{-0.01}$	$0.3^{+0.9+0.4}_{-0.3-0.3}$
Expected ZZ	1.57±0.03±0.11	3.09±0.04±0.06	4.5±0.1±0.2	9.1±0.1±0.3



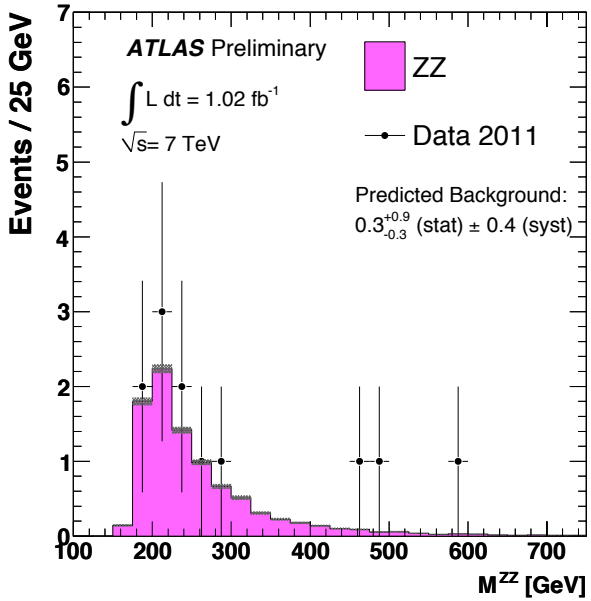


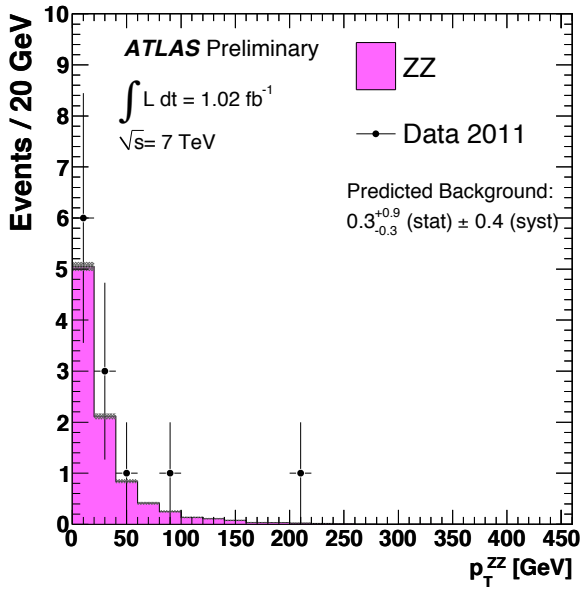
ZZ-> llll

L=1.0 fb^{-1}



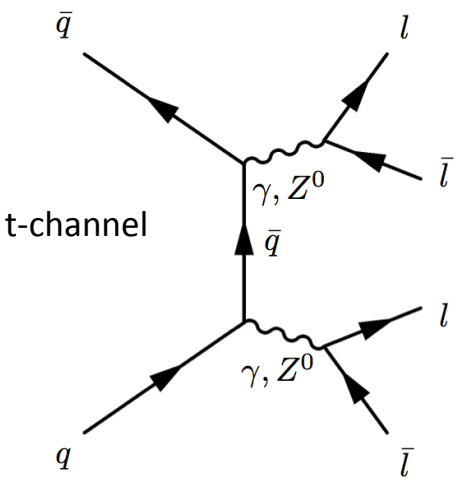
- Kinematic distributions p_T(ZZ), M(ZZ)
- Agreement with SM expectations.

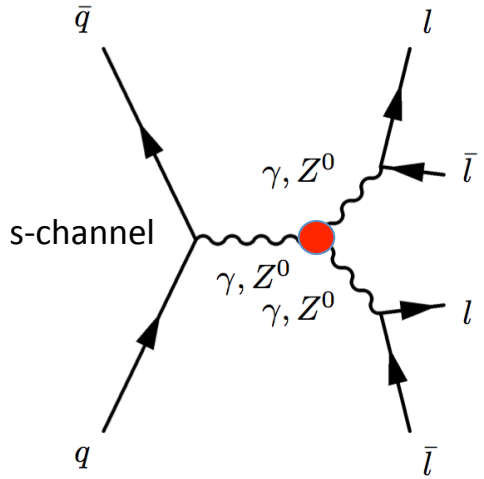




ZZ-> llll

L=1.0 fb^{-1}





Total cross section:

$$\sigma_{ZZ}^{tot} = 8.7^{+3.1}_{-2.5}\ (stat)\ ^{+0.5}_{-0.9}\ (syst)\ \pm 0.4\ (lumi)\ pb$$

SM NLO expectation 6.5±0.3pb

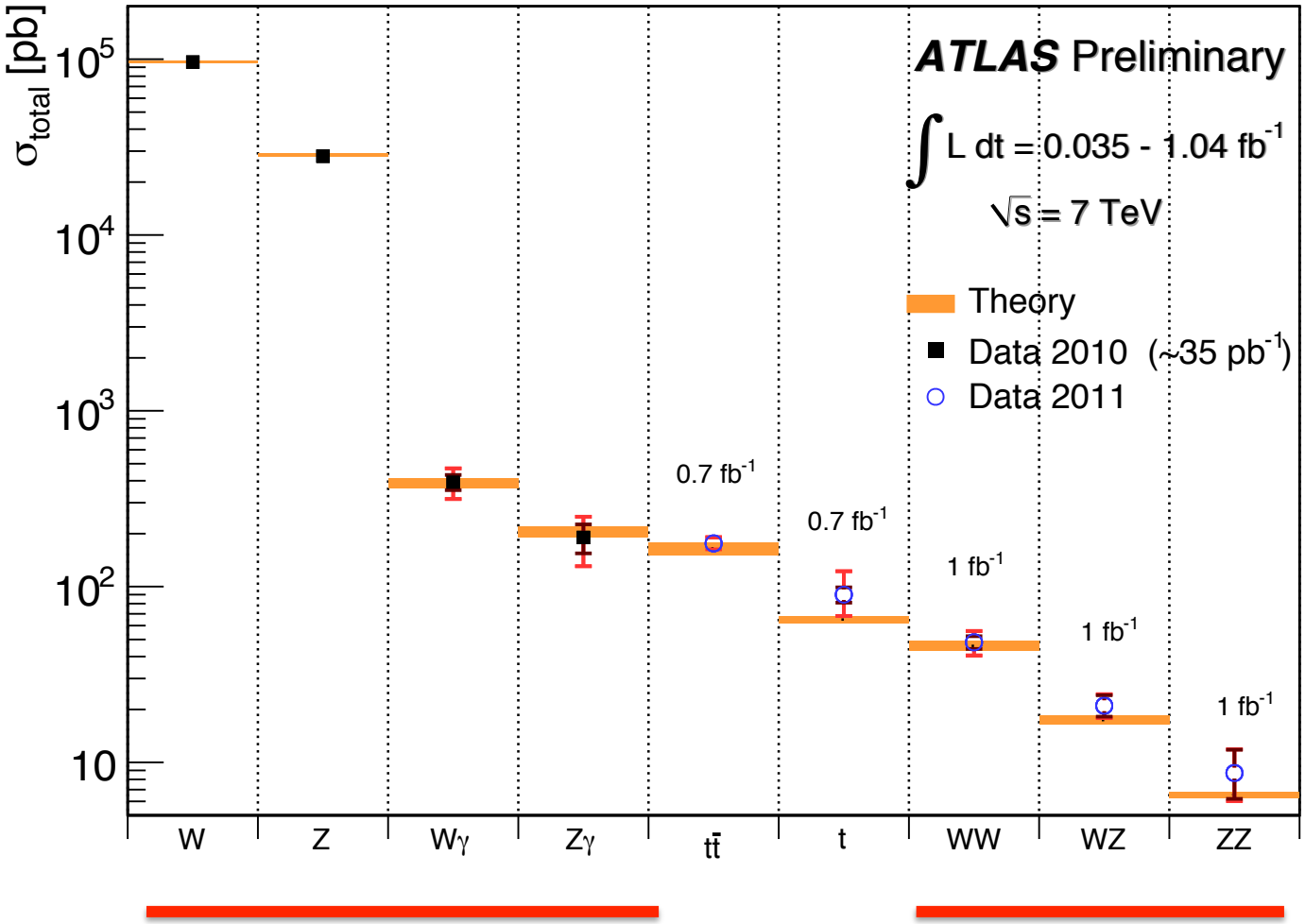
Good agreement with the Standard Model.

Fiducial Cross section:

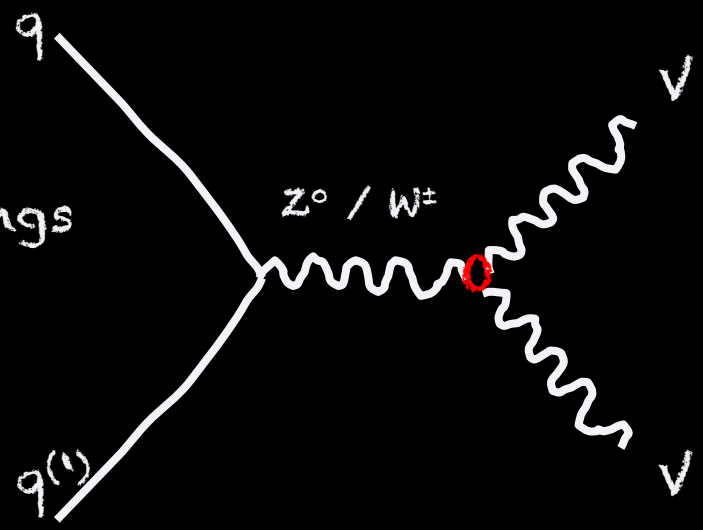
- $p_T(l) > 15$ GeV, $|\eta| < 2.5$
- $|M(ll)-M_Z| < 25$ GeV

$$\sigma^{fid}_{ZZ\to\ell^+\ell^-\ell^+\ell^-} = 5.0^{+1.8}_{-1.5}\ (stat)\ ^{+0.3}_{-0.5}\ (syst)\ \pm 0.2\ (lumi)\ fb$$

Cross Section Summary



Triple Gauge Couplings



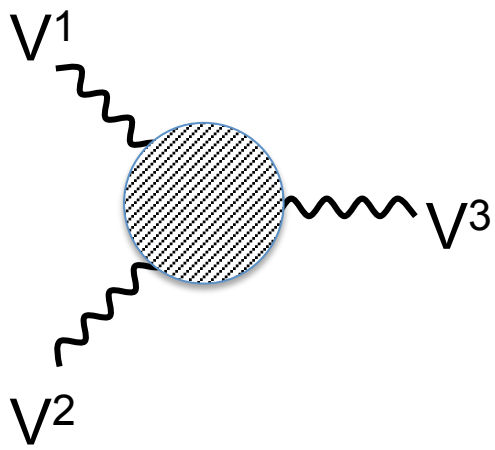
anomalous
Triple Gauge Boson Couplings

- Extend SM to describe BSM physics with an effective Lagrangian approach.

Charged aTGC

WWZ

WWγ



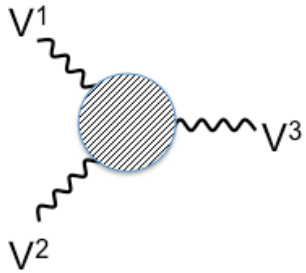
Neutral aTGC

ZZZ

ZZγ

Anomalous
Triple Gauge Boson Couplings

- Effective Lagrangian parameters (simplified).



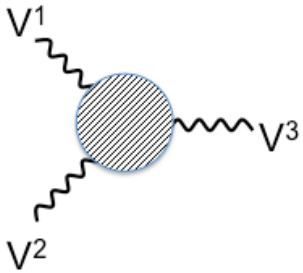
NB:
V = Z, γ. In the SM case anomalous coupling = 0.

Charged aTGC: Δg1=g1-1, Δκ=κ-1, λ

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

Neutral aTGC: f4, f5

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



Anomalous Triple Gauge Boson Couplings

Charged aTGC:

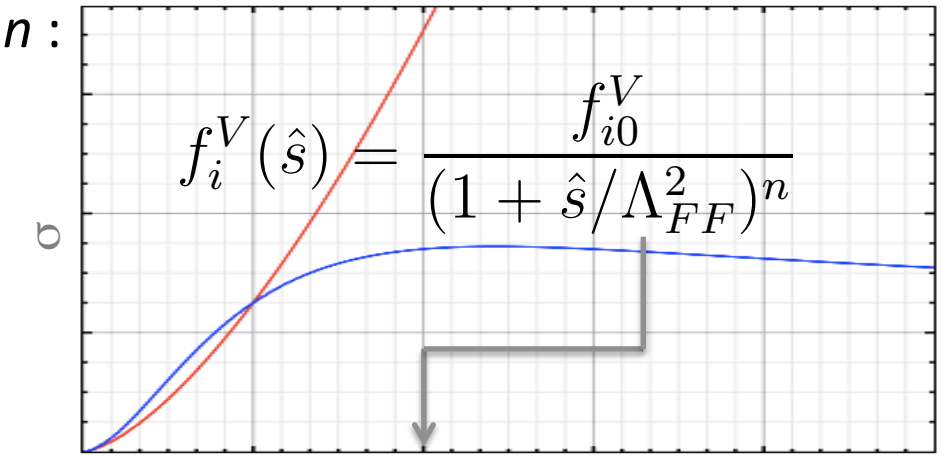
$\Delta g1$, $\Delta\kappa$: $\hat{s}^{1/2}$

λ : $\hat{s}$

Neutral aTGC:

f4, f5 : $\hat{s}^{3/2}$

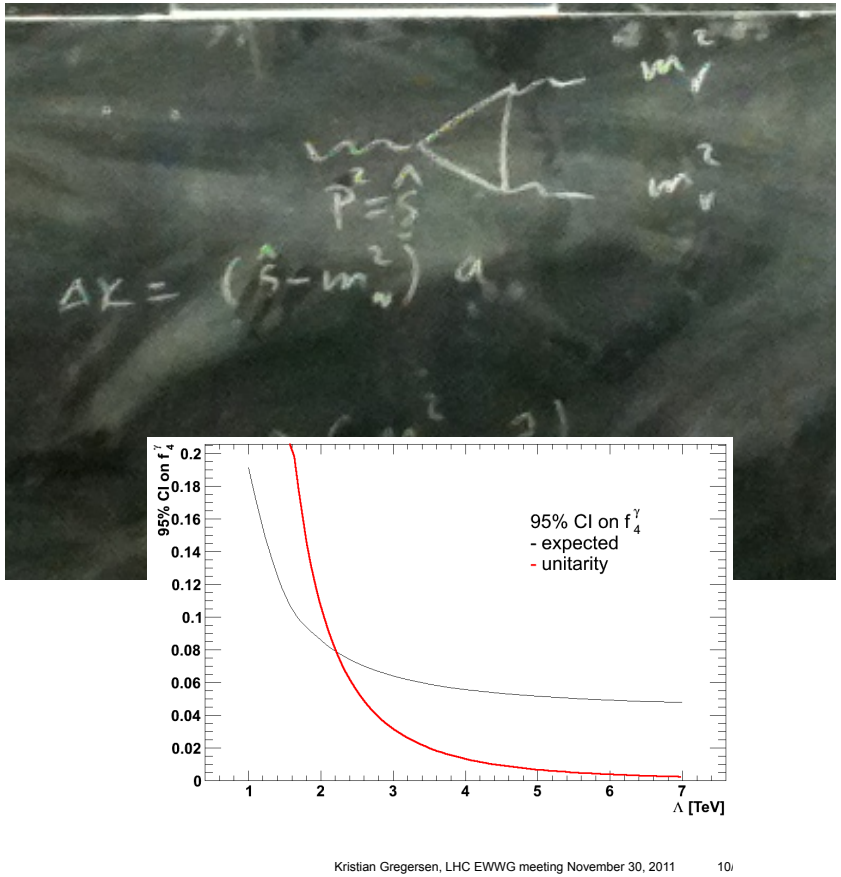
- Di-boson cross section with aTGC has a strong energy dependence and will grow severely with the parton centre of mass energy.
- Need to introduce **form factor** to guard unitarity.
- Typical ansatz is a dipole form factor with some power *n* :



Some theorists opinions about Form Factors:

- Provide unfolded σ as function of ($\hat{s}$) and let the theorist do the interpretation.
- Not using FF is nonsense / is ok.
- Not using FF and deriving aTGC might obscure signals at "low" *s*.
- "Don't measure aTGC".

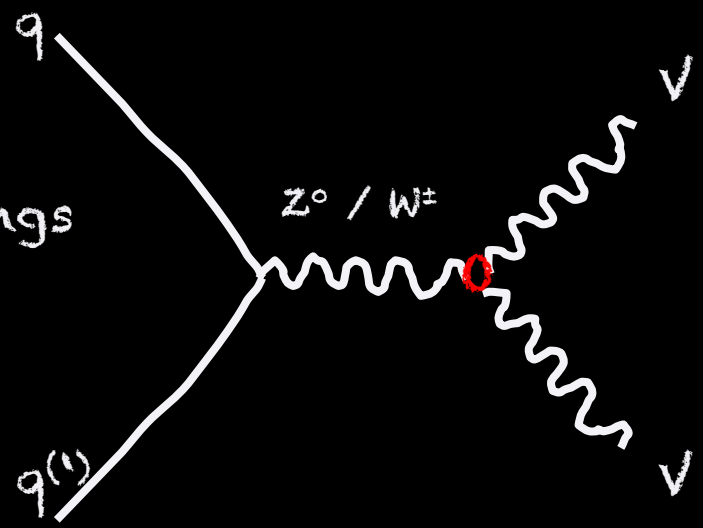
- <u>Provide limits as function of FF scale?</u>



… ongoing discussion at CERN LHC EW WG meeting yesterday.

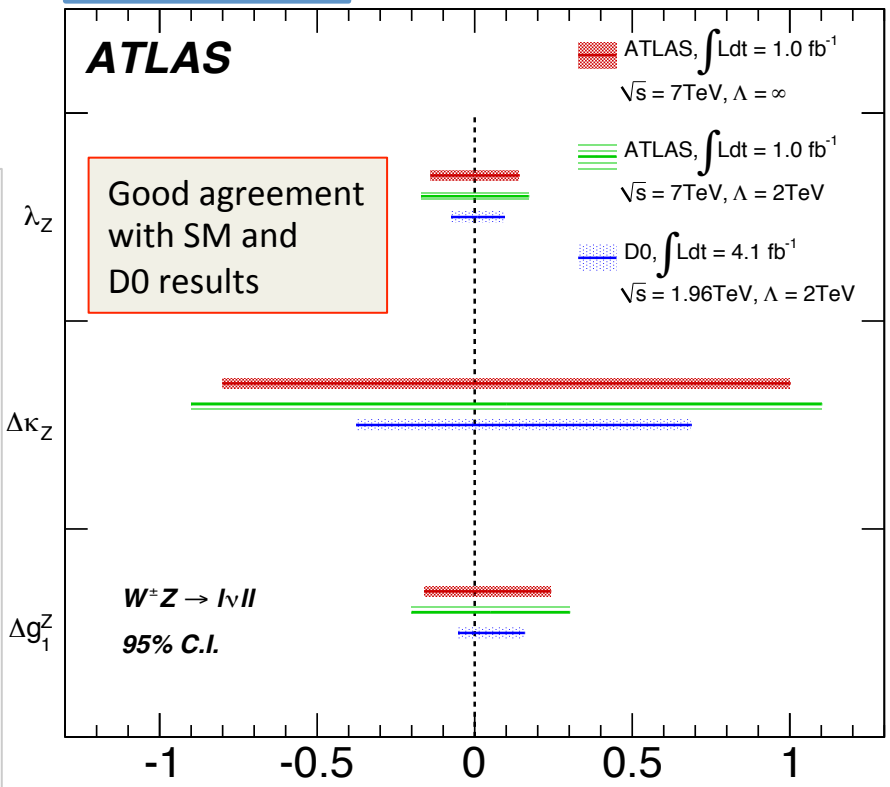
Triple Gauge Couplings

<u>Results from Data</u>



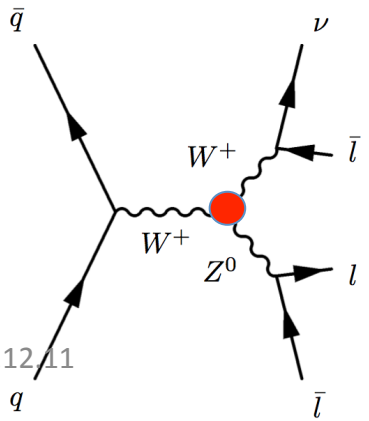
WZ-> lllν

L=1.0 fb^{-1}



Extraction of anomalous triple gauge boson couplings

- Use total cross section to fit TGC.
- NLO MC with reweighting technique.
- Use cut-off of Λ=3TeV
- Profile likelihood ratio, including systematics as nuisance parameters.
- Confidence Intervals obtained by Neyman construction based on cross section.



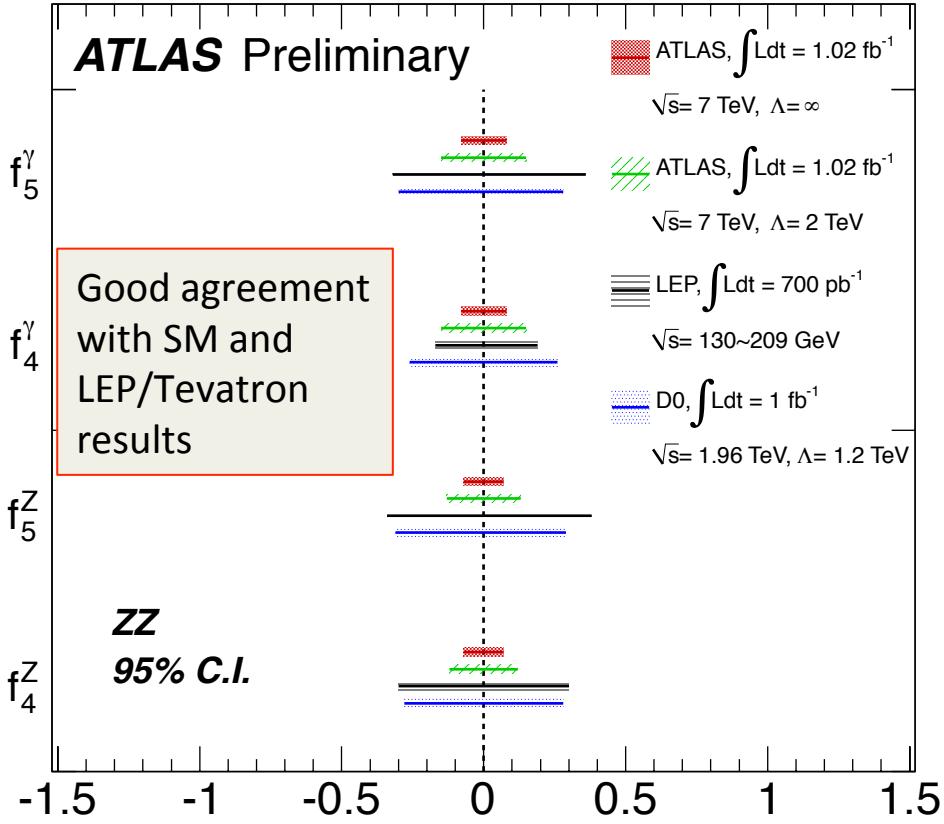
Coupling	Observed ($\Lambda = 2$ TeV)	Observed ($\Lambda = \infty$)	Expected ($\Lambda = \infty$)
Δg_1^Z	$[-0.20, 0.30]$	$[-0.16, 0.24]$	$[-0.12, 0.20]$
$\Delta\kappa_Z$	$[-0.9, 1.1]$	$[-0.8, 1.0]$	$[-0.6, 0.8]$
λ_Z	$[-0.17, 0.17]$	$[-0.14, 0.14]$	$[-0.11, 0.11]$

ZZ-> llll

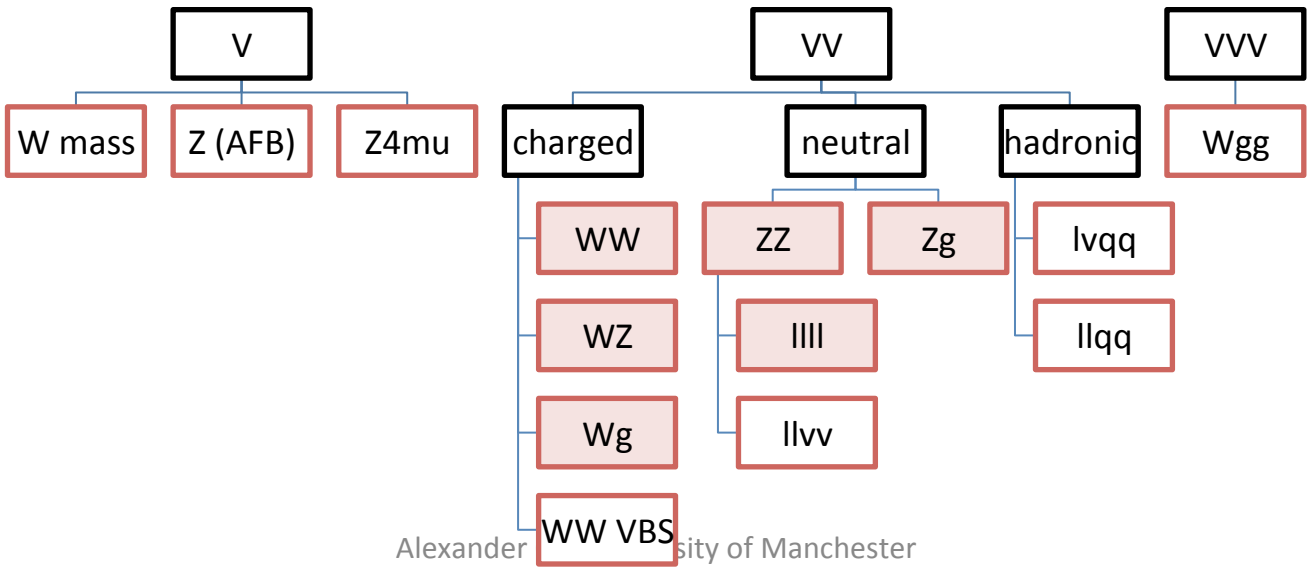
L=1.0 fb^{-1}

Extraction of anomalous triple gauge boson couplings

- Use total cross section to fit TGC.
- LO reweighting technique with NLO correction (Baur-Rainwater + Sherpa)
- Use cut-off of Λ=2TeV, ∞
- Profile likelihood ratio, including systematics as nuisance parameters.
- 95% Confidence Intervals obtained by ΔL=1.92



Coupling 95% CI	f_4^γ	f_4^Z	f_5^γ	f_5^Z
$\Lambda = 2$ TeV	$[-0.15, 0.15]$	$[-0.12, 0.12]$	$[-0.15, 0.15]$	$[-0.13, 0.13]$
$\Lambda = \infty$	$[-0.08, 0.08]$	$[-0.07, 0.07]$	$[-0.08, 0.08]$	$[-0.07, 0.07]$

Wrap-up

- Observed and measured cross sections of all di-boson states WW, Wγ, WZ, Zγ, ZZ with ATLAS.
- Set first limits on anomalous triple gauge boson couplings.
- With rapidly increasing luminosity expect tighter limits soon and more results on boson physic.
- Exiting times ahead!