Standard Model ElectroWeak Physics at ATLAS

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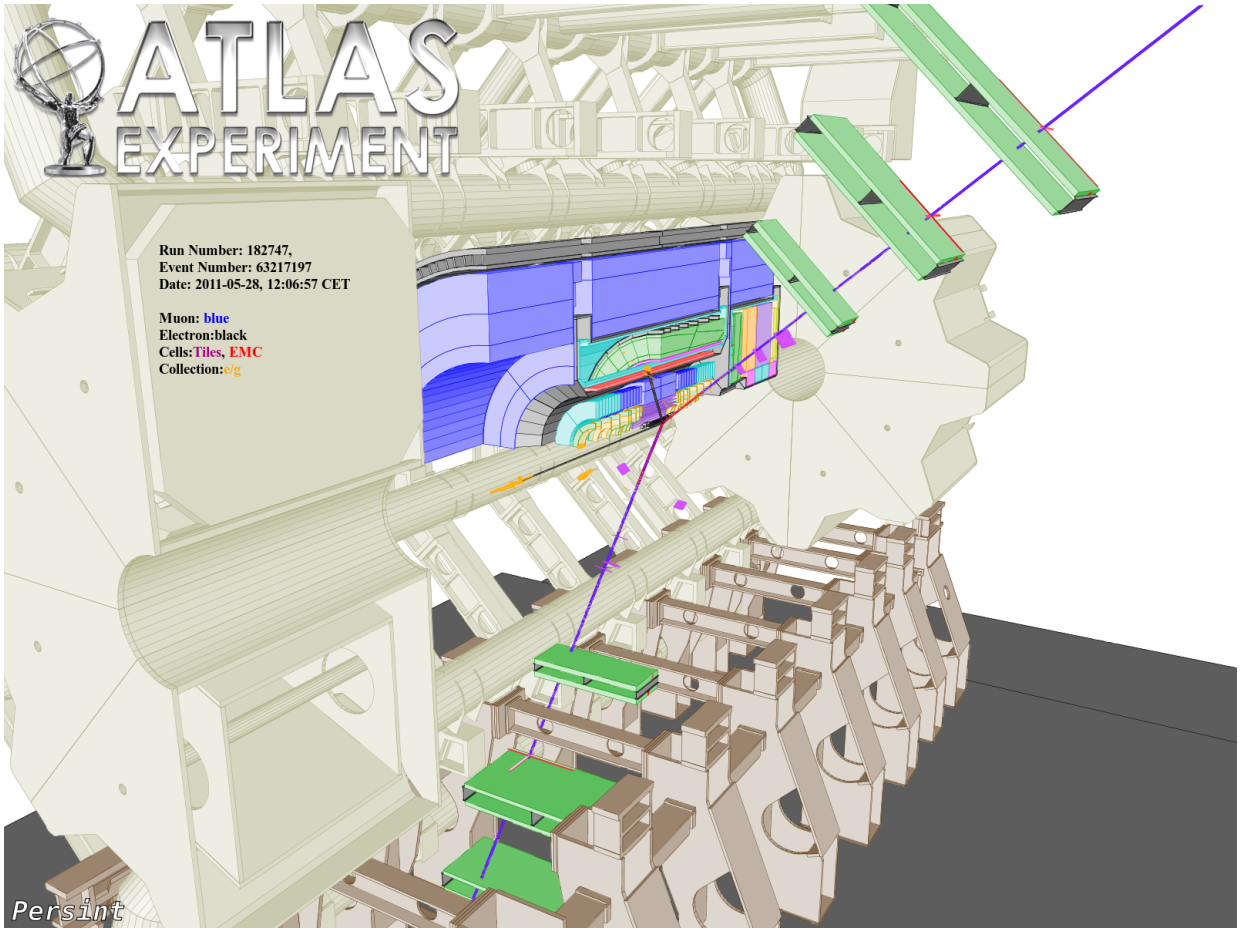
16th November 2011



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Outline

- Overview of ATLAS detector, data-taking and detector performance
  - Detector, trigger, data, luminosity measurement
  - Lepton reconstruction and performance
- Measurements with single W and Z bosons
  - Cross-section and cross-section ratio
  - Transverse momentum distributions, charge asymmetry
- Diboson production
  - Wγ, Zγ, WW, WZ, ZZ production cross-sections
  - Limits on anomalous triple gauge boson couplings
- Future Prospects

Why SM EW Physics at LHC?

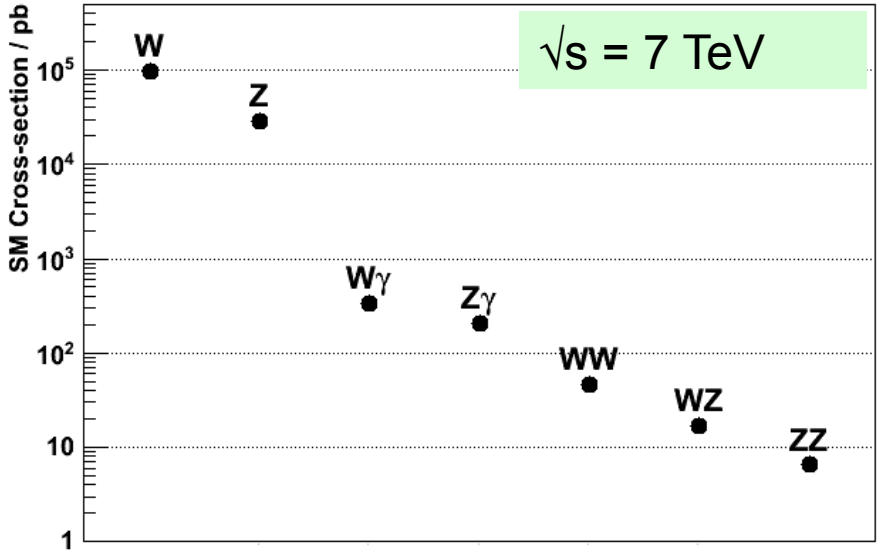
- Many SM parameters measured to high precision at LEP or Tevatron
- So why measure SM EW processes at LHC?
- Test SM in new high energy regime
- Improve measurements of some parameters
  - W mass and width
  - Triple gauge boson couplings
- Backgrounds to new physics – need to be understood
  - e.g. H ➔ WW, ZZ
- Discrepancies with SM may be first sign of new physics if this is not an 'expected model'

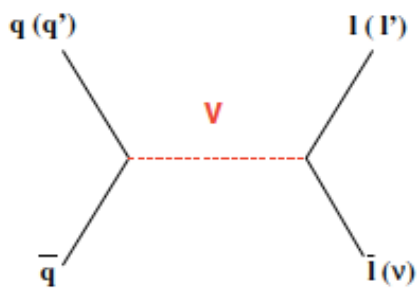
	Value [PDG]	Relative precision
m_Z	91.1876 ± 0.0021 GeV	2×10^{-5}
Γ_Z	2.4952 ± 0.0023 GeV	9×10^{-4}
g_a^l	-0.50123 ± 0.00026	5×10^{-4}
g_v^l	-0.03783 ± 0.0041	1%
m_W	80.399 ± 0.023 GeV	3×10^{-4}
Γ_W	2.085 ± 0.042 GeV	2%
m_t	172.9 ± 0.6 ± 0.9 GeV	0.6%

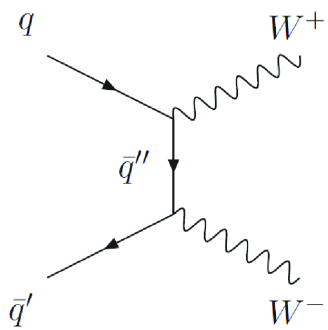
Electroweak Bosons at LHC

- Cross-sections span several orders of magnitude:

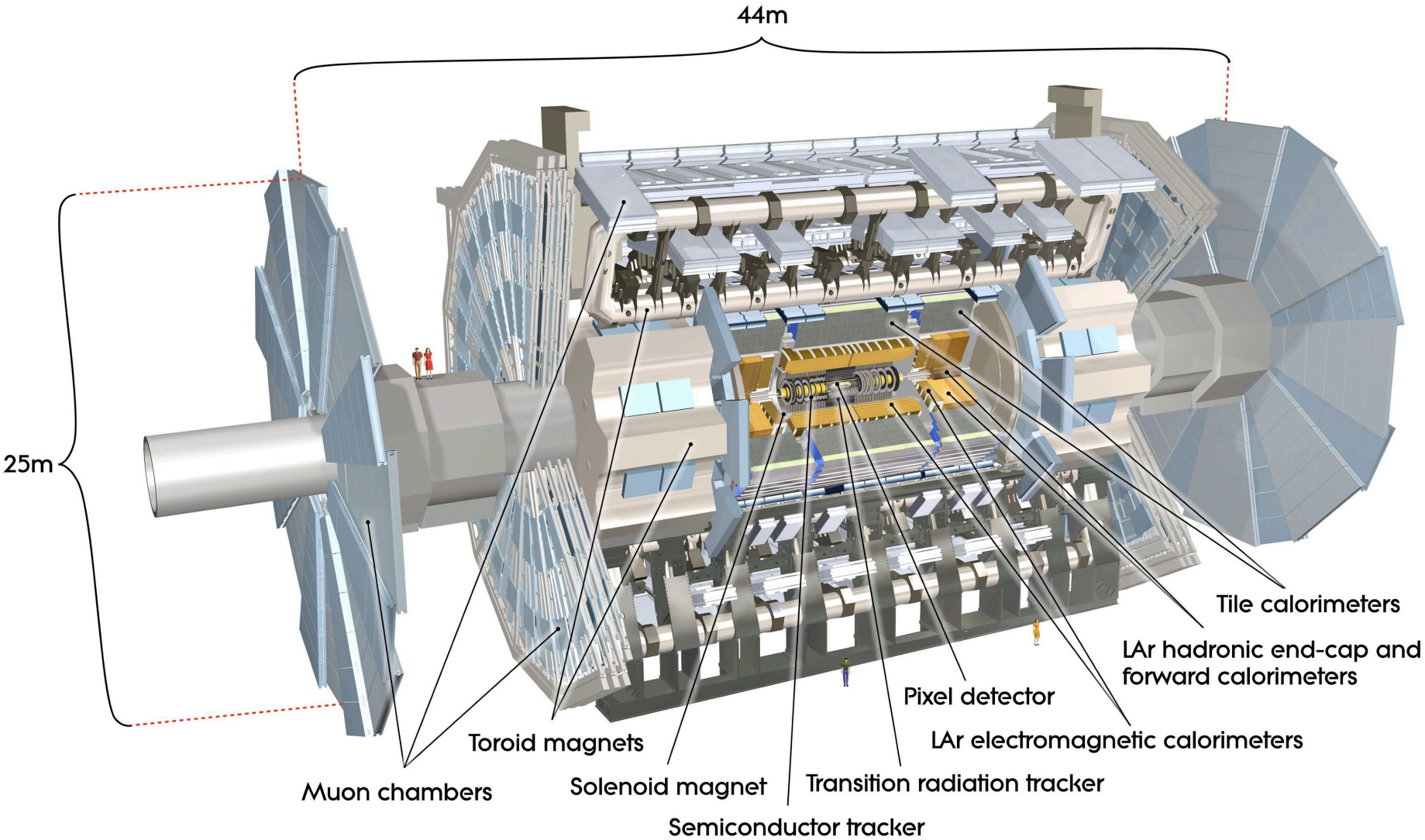
  σ(W) ~ 15000 x σ(ZZ)
- W and Z cross-sections calculated to NNLO
  - Important test of QCD
- Diboson cross-sections calculated to NLO
  - Gluon fusion contributes ~3% to WW and ~6% to ZZ
- Measured in leptonic decay channels: W➔lν, Z➔ll
  - Low branching ratios but experimentally clean signatures





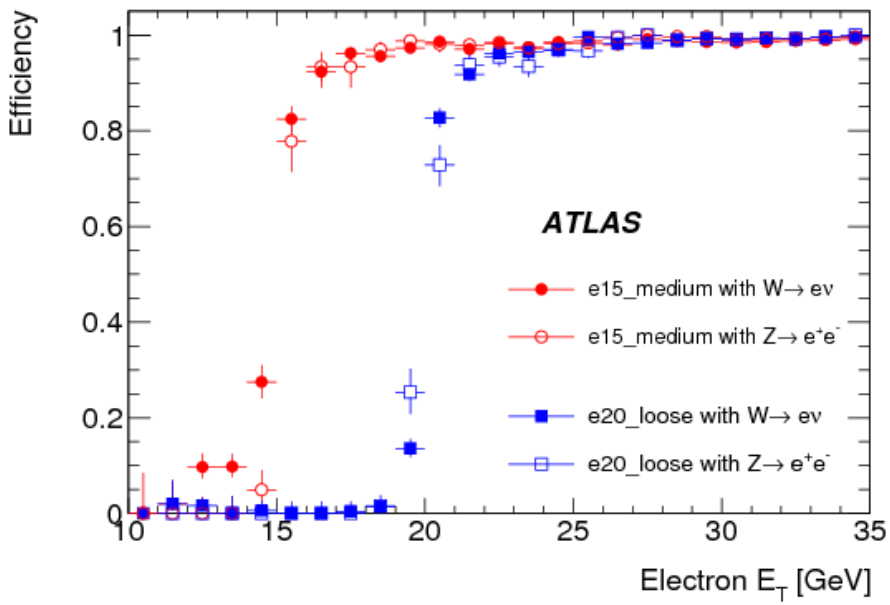


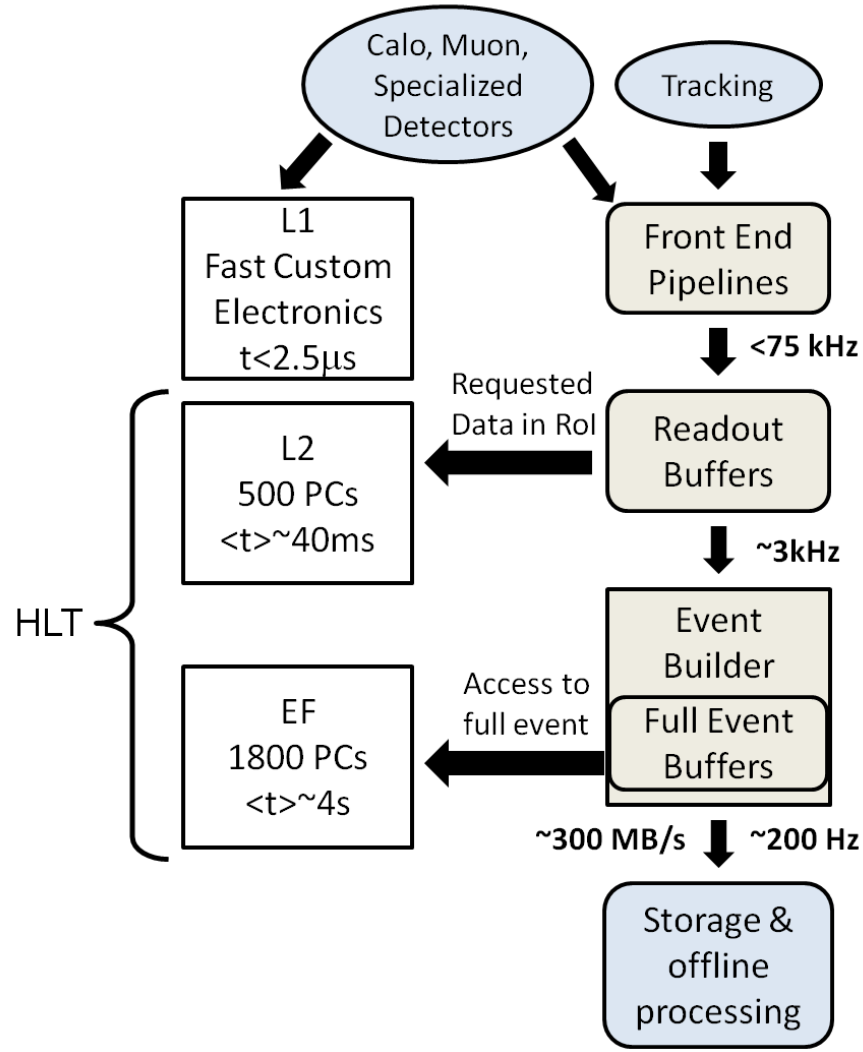
ATLAS Detector



Trigger

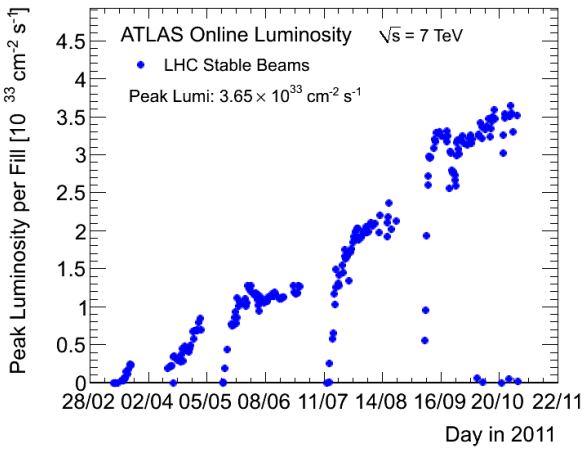
- W / Z leptonic final states selected with single-electron and single-muon triggers
- Nominal thresholds
  - e / μ = 15 / 13 GeV (2010)
  - e / μ = 20 / 18 GeV (early 2011)

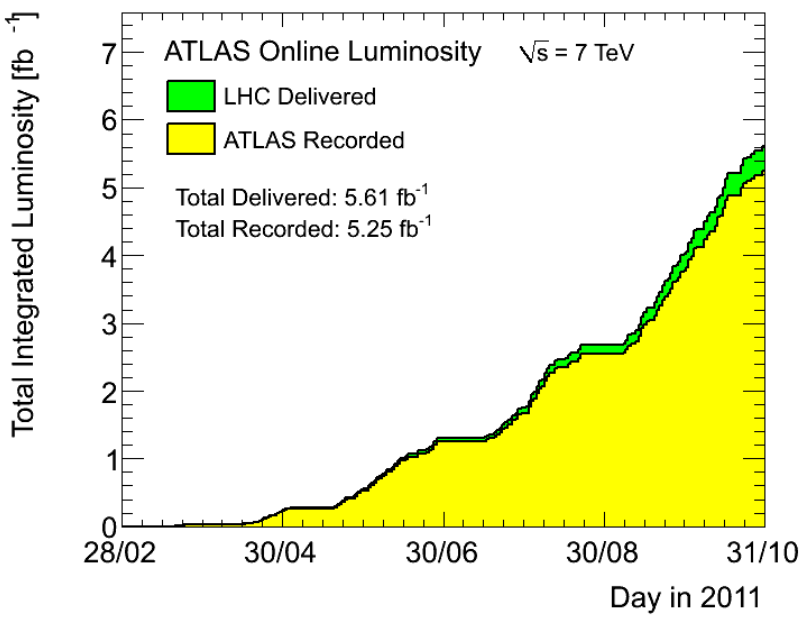


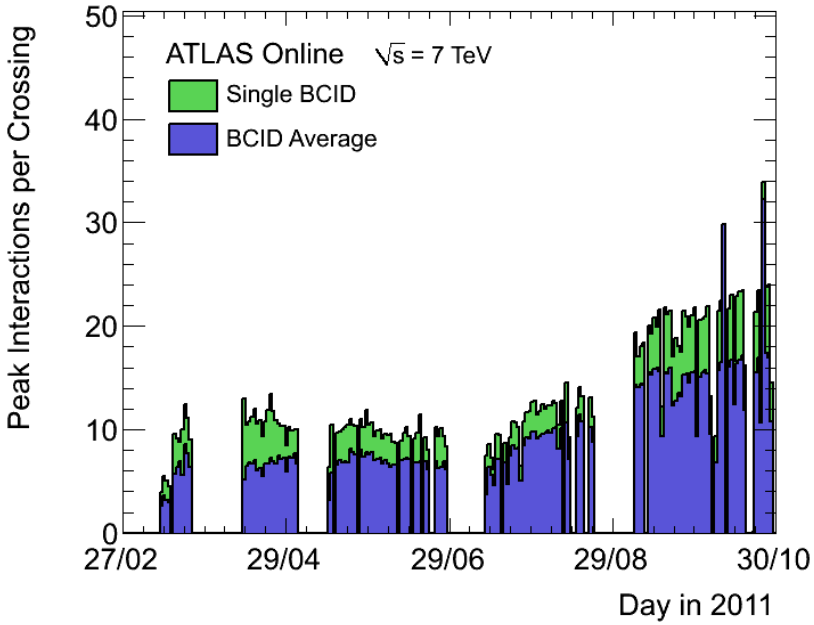


Data

	2010	2011
ATLAS recorded integrated luminosity	45 pb^{-1}	5.25 fb^{-1}
Peak luminosity	2.1 x 10^{32} cm^{-2} s^{-1}	3.65 x 10^{33} cm^{-2} s^{-1}
Mean interactions / bunch crossing	~2	6.3 / 11.6

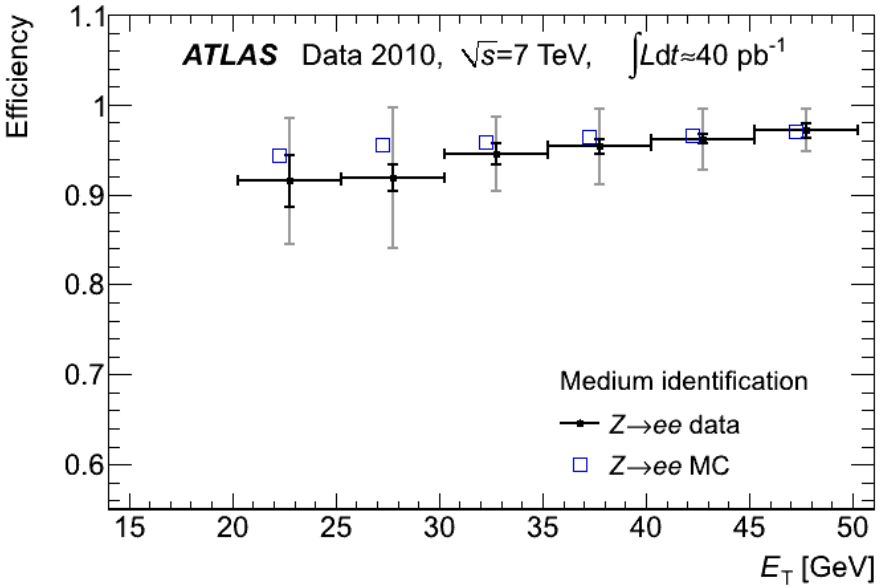


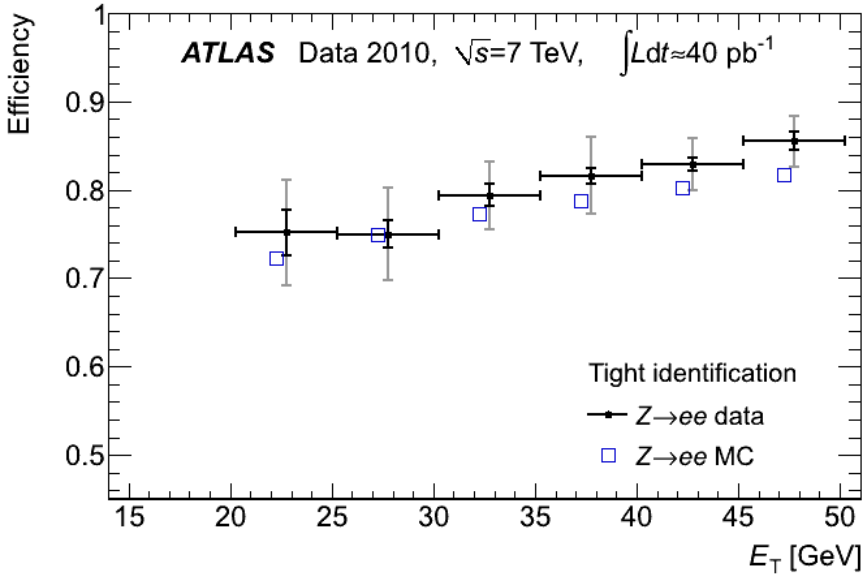




Electron Identification

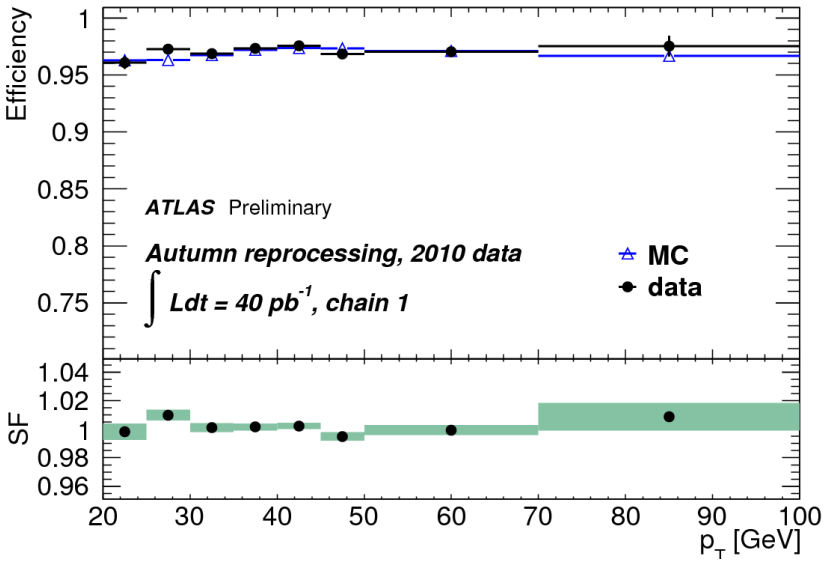
- Match EM cluster to ID track
- Loose (jet rejection factor ~500):
  - EM shower shape in middle layer, hadronic leakage
- Medium (~5000):
  - +EM strip layer, track quality and track/cluster matching
- Tight (50000):
  - +E/p, TRT high threshold hits, tighter track cuts to remove photon conversions
- Measure reconstruction and ID efficiencies using tag-and-probe in W➔eν, Z➔ee, J/ψ➔ee events

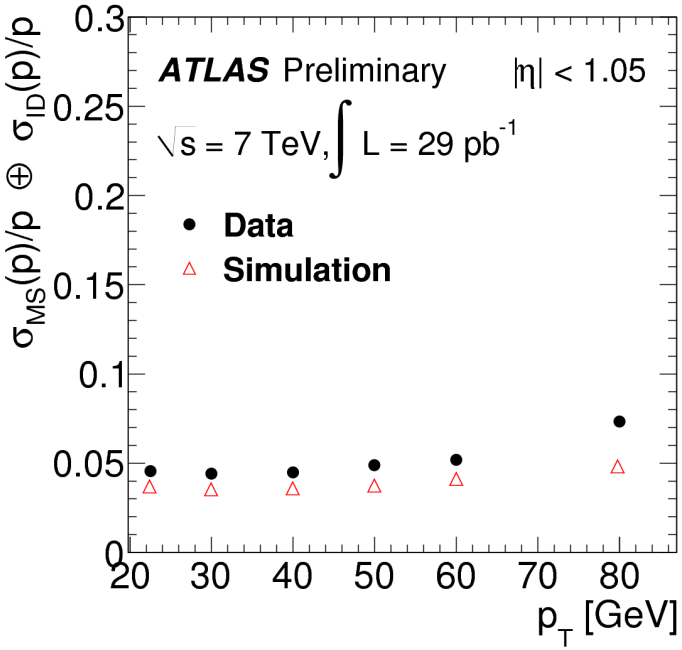




Muon Identification

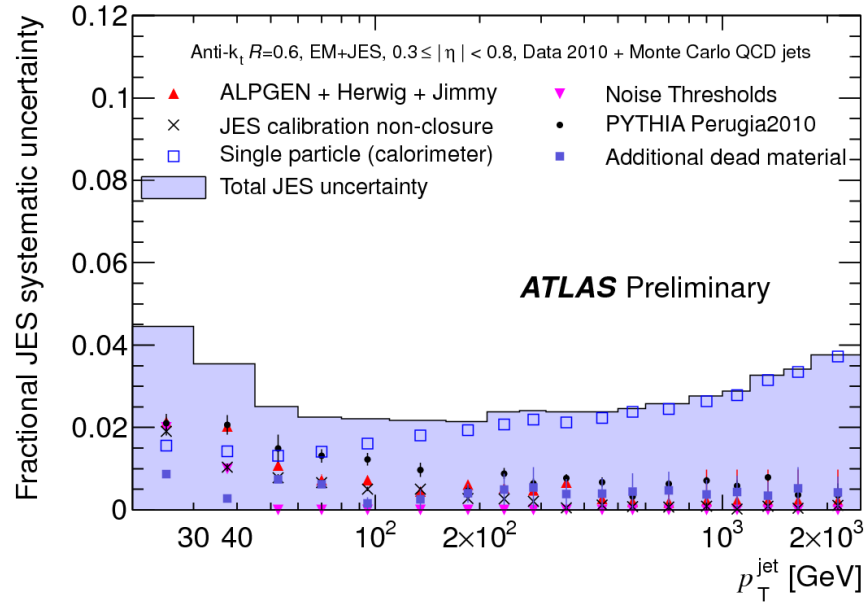
- `Combined' muon:
  - Match ID track with MS track
  - Combine parameters
- `Segment-tagged' muon:
  - ID track matched to MS track segment
  - Used for regions with too few MS hits for momentum meas.
- Measure efficiency using tag-and-probe in Z➔μμ events
  - >96% and agrees with MC to better than 1%
- Momentum resolution measured from Z ➔μμ mass distribution
  - Design: <3.5% (p_T<200GeV); <10% (p_T<1TeV)

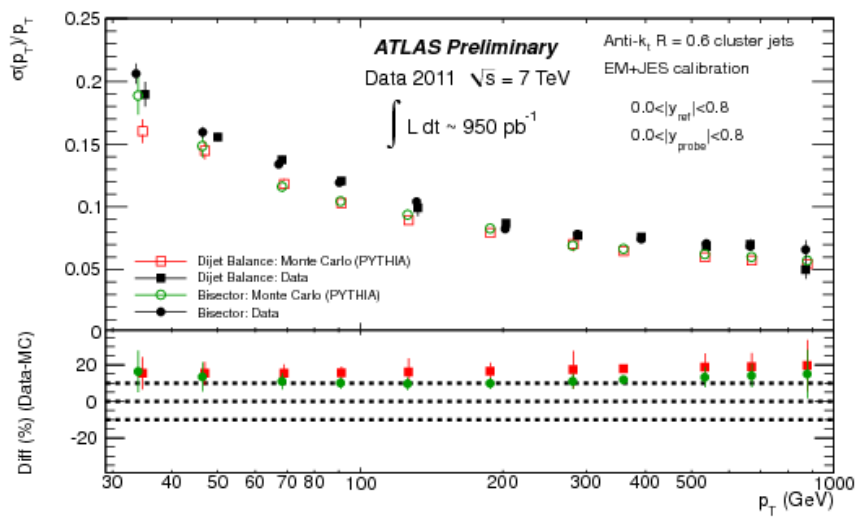




Jets and Missing ET

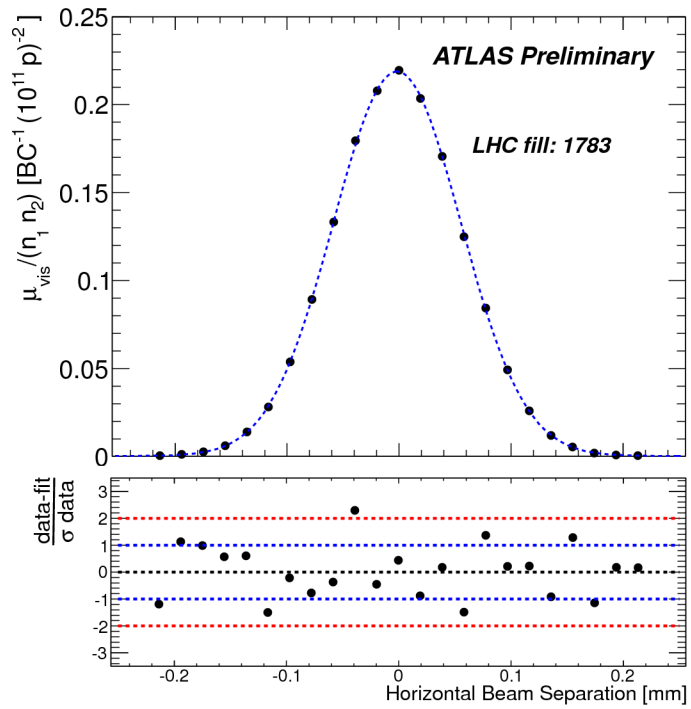
- Jets reconstructed from calorimeter clusters
- Anti-k_T algorithm, R=0.4 or 0.6
- Jet energy scale (i.e. EM ➔ hadronic) calibrated using MC
- Checked with data, e.g. track jets, jet-photon p_T balance
- Missing transverse energy calculated using e/μ/jets plus unassociated calorimeter clusters in $|\eta| < 4.5$
  - Clusters calibrated as em or hadronic depending on topology
  - Correction for muon energy in calorimeter

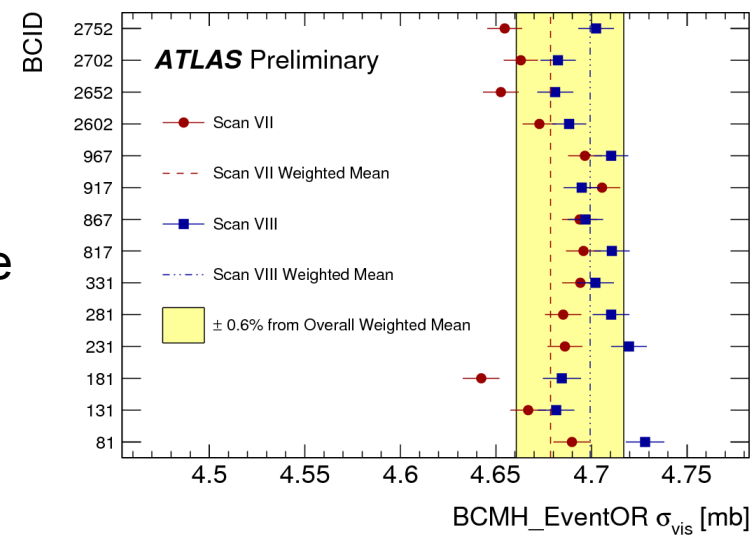




Luminosity Measurement

- Measure event rates in lumi. detectors
  - BCM: diamond sensors z = ±1.84m, |η| ~ 4.2
  - LUCID: Cerenkov tubes z = ± 17m, 5.6< |η| < 6.0
- $L = \mu_{vis} n_b f_r / \sigma_{vis}$ μ_{vis} = interaction rate / BX
- Calibrate rates (i.e. measure σ_{vis}) using van der Meer (beam separation) scans
- Separate beams in steps of known distance to measure beam profiles $\Sigma_x \Sigma_y$
  - Length scale checked using ATLAS primary vertex position
- $L = n_b f_r n_1 n_2 / 2\pi \Sigma_x \Sigma_y$
- Main systematic (3%) from measurement of beam currents
- Overall error on integrated L
  - 2010: 3.4%
  - 2011: 3.7%

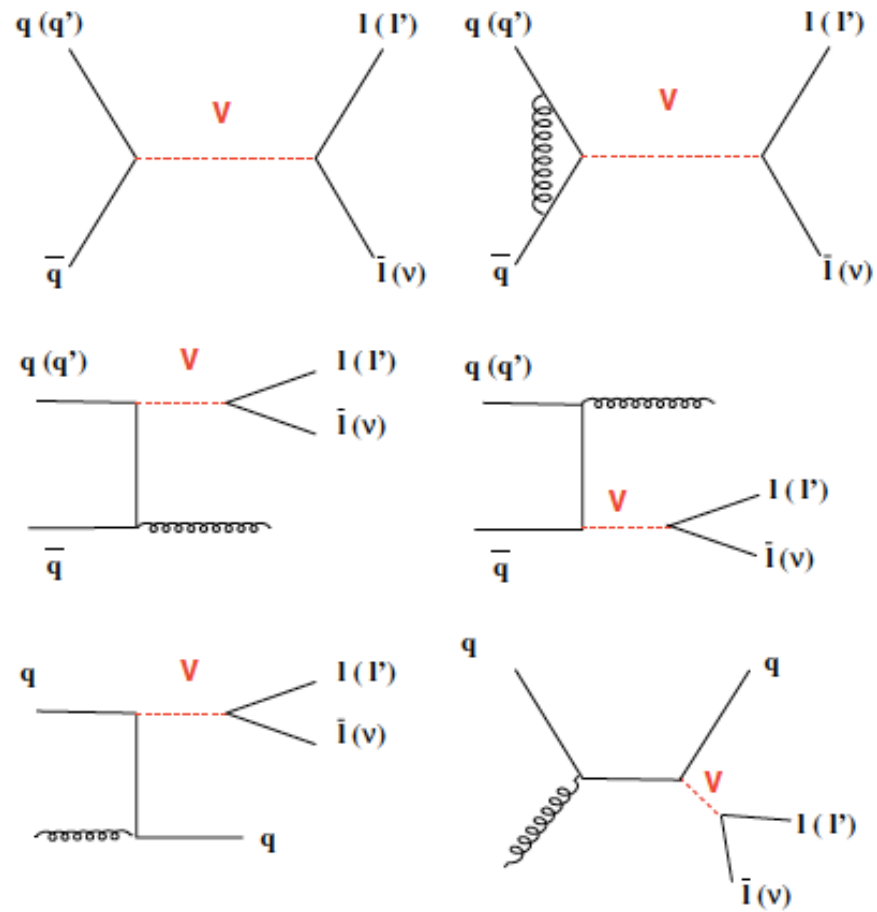




Measure for each BCID

W and Z Boson Production

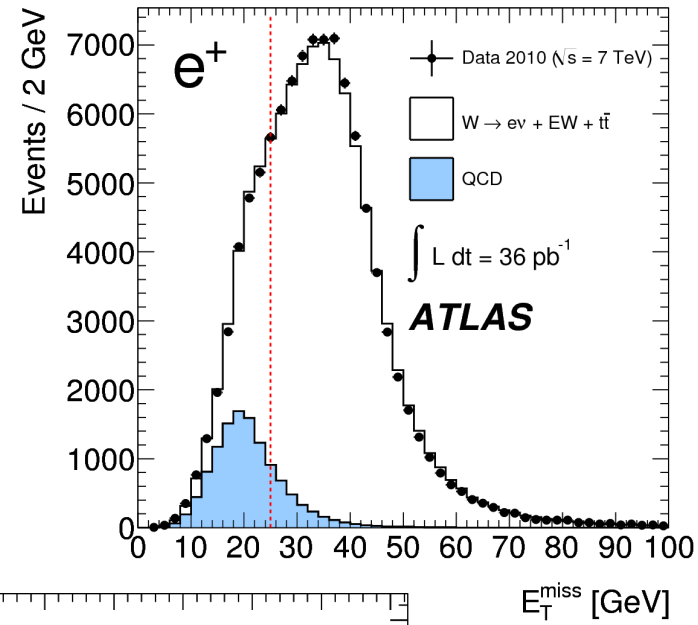
- Source of high-p_T electrons and muons for detector calibration and performance measurements
- Probes proton PDFs – particularly W^+/W^- ratio
- W/Z ratio can provide constraints on Γ_W and is sensitive to new physics
- Measure m(W)
  - Needs high statistics, precise measurement of W p_T distribution etc.
- Measured in leptonic decay channels: W➔lν, Z➔ll

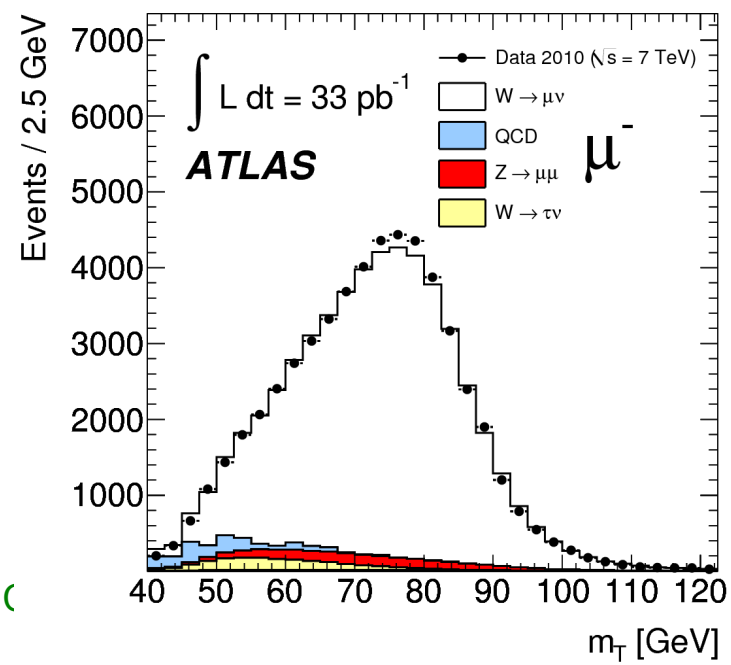


CDF, J.Phys.G34 (2007) 2457

W ➔ lν Event Selection

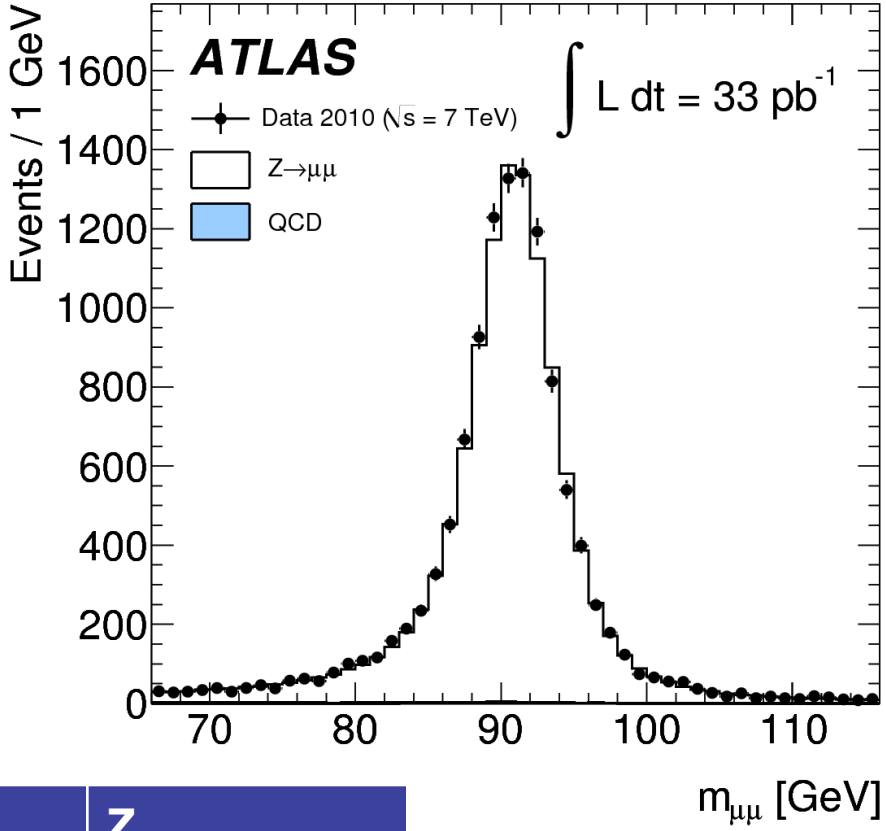
- Signature: high p_T isolated lepton and missing transverse energy
- Electron
  - Medium + b-layer hit
  - $E_T > 20$ GeV
  - $|\eta| < 2.47$ (excl. 1.37 – 1.52)
  - Isolation: $E^{0.3} < E_{max}$
- Muon
  - $p_T > 20$ GeV
  - $|\eta| < 2.4$
  - $|z_0^{PV}| < 1$ cm, ID hit req.
  - Isolation: $\Sigma p_T^{0.2} < 0.1\ p_T^{\mu}$
- $E_T^{Miss} > 25$ GeV
- $m_T > 40$ GeV





Z ➔ ll Event Selection

- Opposite-sign same-flavour lepton pair
  - Lepton selection similar to W
- 66 GeV < m(ll) < 116 GeV



- Selected events in 33 / 36 pb^{-1} (2010 data)

	W^+	W^-	Z
e	77875	52856	9725
μ	84514	55234	11709

W / Z Cross-section Measurement

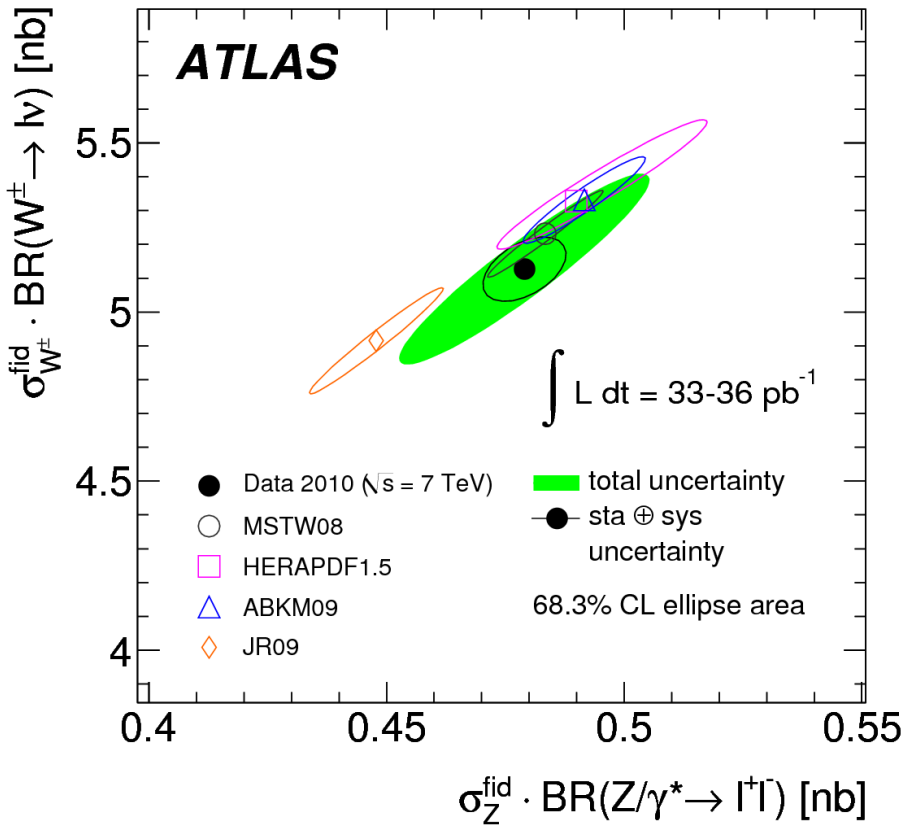
- QCD background
  - Jets faking electrons
  - Muons from heavy flavour decays
- Estimated using control samples in data
  - Invert electron ID cuts or muon isolation
- 2% – 5% in W channels
- < 2% in Z channels
- Electroweak background
  - W ➔ τν, Z ➔ ττ, ttbar, diboson
- Estimated from MC
- 3% - 7 % in W channels
- ~0.5% in Z channels

- Signal efficiencies and acceptances
- Determined from MC
  - Scaling and smearing applied to MC to reproduce lepton efficiencies measured in data
- Efficiencies ~70% (80%) for e (μ) channels
  - i.e to correct to fiducial cross-section
- Acceptances 45% – 50%
  - i.e. to obtain total cross-section from fiducial cross-section

Fiducial Cross-sections

arXiv:1109.5141v2 [hep-ex]

- Fiducial cross-sections measured in kinematic phase-space corresponding to experimental acceptance
  - No uncertainty from extrapolation
- Reasonable agreement with NNLO predictions
- Universality of PDFs and pQCD work up to kinematic range of W and Z at LHC
- Luminosity error dominates - unable to distinguish different PFD sets

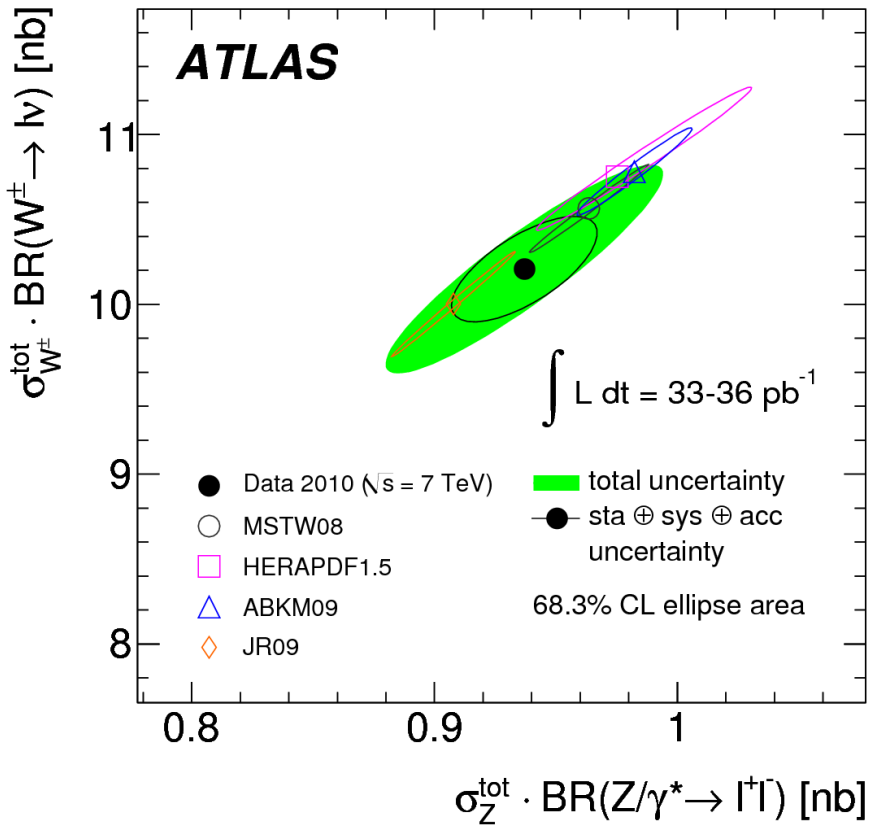


Total Cross-sections

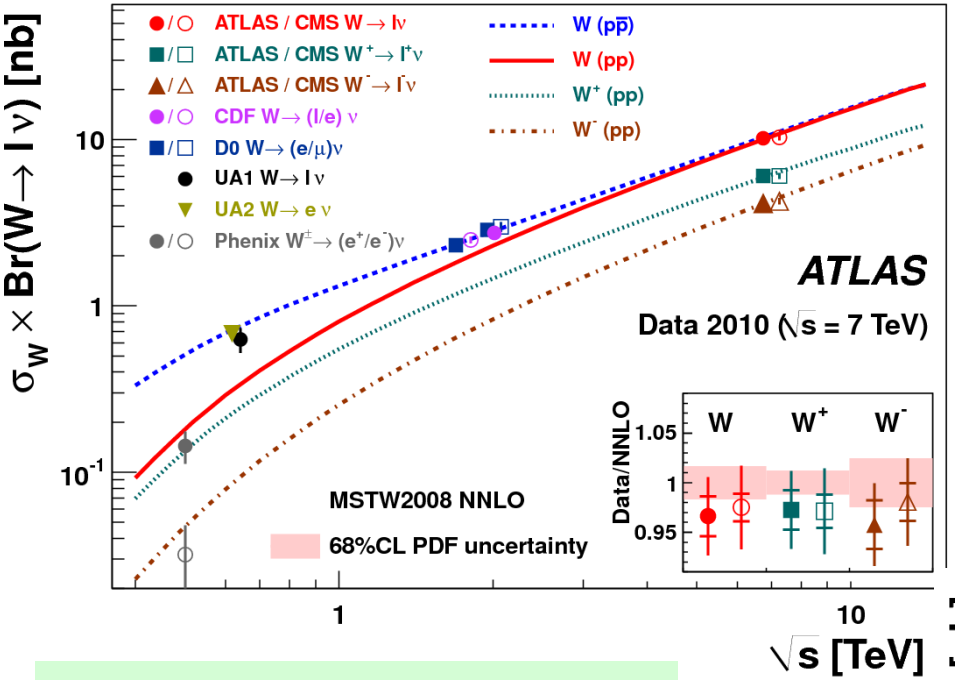
- Error from extrapolation to full phase space ~2% is bigger than experimental systematic
- Less able to discriminate between different PDFs

$\sigma_W^{tot} \cdot \mathbf{BR}(W \to \ell\nu)$ [nb]				
	sta	sys	lum	acc
W^+	$6.048 \pm 0.016 \pm 0.072 \pm 0.206 \pm 0.096$			
W^-	$4.160 \pm 0.014 \pm 0.057 \pm 0.141 \pm 0.083$			
$W^\pm$	$10.207 \pm 0.021 \pm 0.121 \pm 0.347 \pm 0.164$			

$\sigma_{Z/\gamma^*}^{tot} \cdot \mathbf{BR}(Z/\gamma^* \to \ell\ell)$ [nb] $66 < m_{\ell\ell} < 116$ GeV				
	sta	sys	lum	acc
Z/γ^*	$0.937 \pm 0.006 \pm 0.009 \pm 0.032 \pm 0.016$			



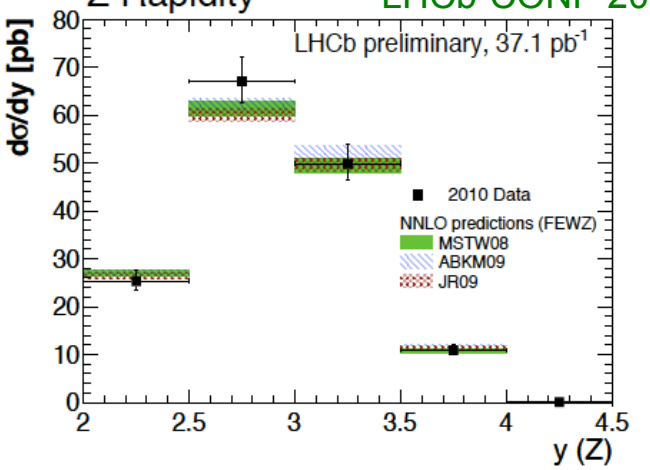
Energy Dependence

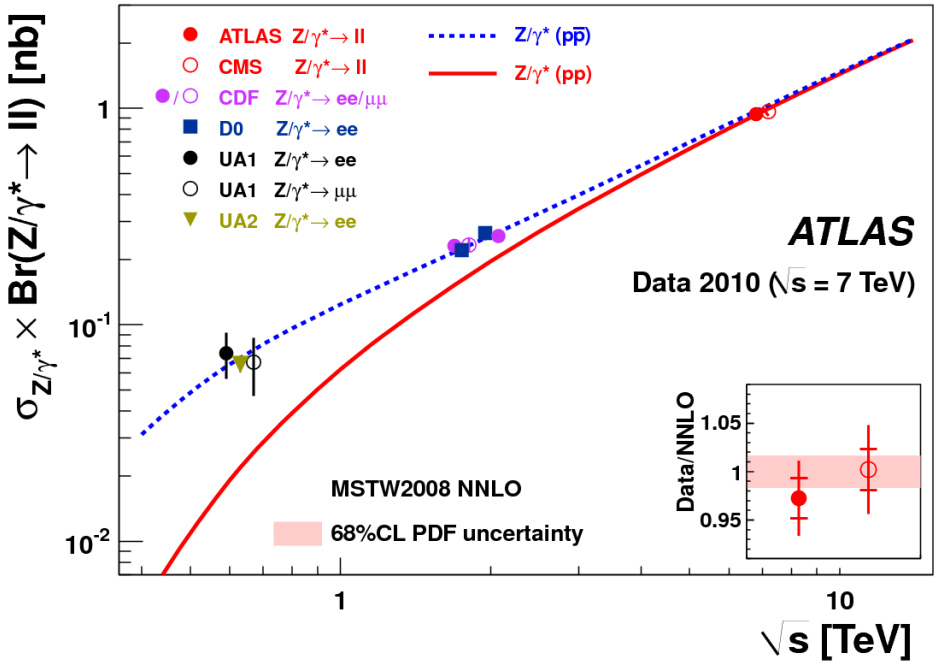


ATLAS results consistent with similar results from CMS [JHEP 10 (2011) 132]

LHCb measure forward W/Z

Z Rapidity LHCb-CONF-2011-039





C. P.

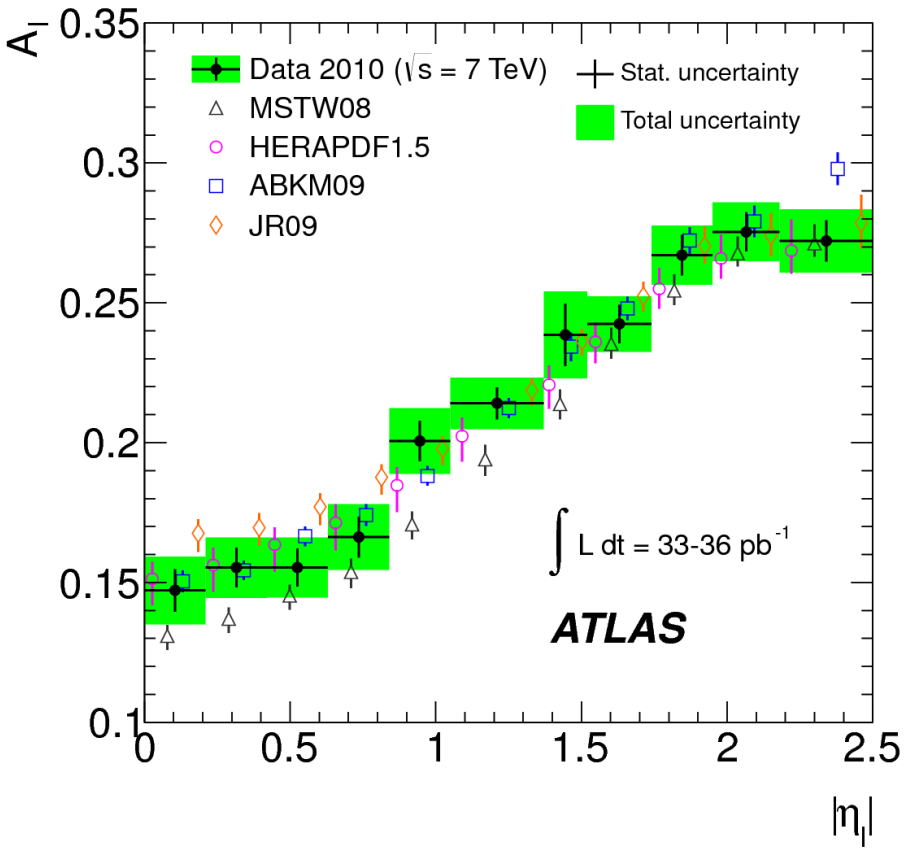
W Charge Asymmetry

- Sensitive to valence quark distributions

$$A_\ell(\eta_\ell) = \frac{d\sigma_{W^+}/d\eta_\ell - d\sigma_{W^-}/d\eta_\ell}{d\sigma_{W^+}/d\eta_\ell + d\sigma_{W^-}/d\eta_\ell},$$

- Asymmetry measured in $p_{T,l} > 20$ GeV, $p_{T,\nu} > 25$ GeV, $m_T > 40$ GeV
  - Charge misID from like-sign Z events
  - 1% for 'medium' electrons
  - Negligible for muons

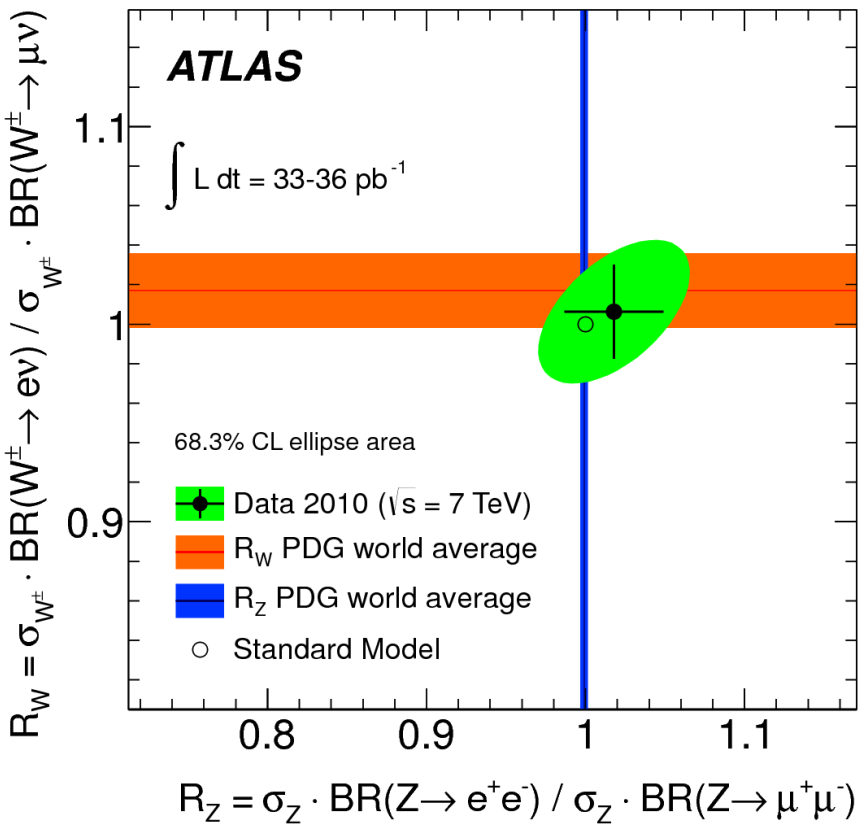
- NNLO predictions roughly compatible with measurements



Electron-muon Universality

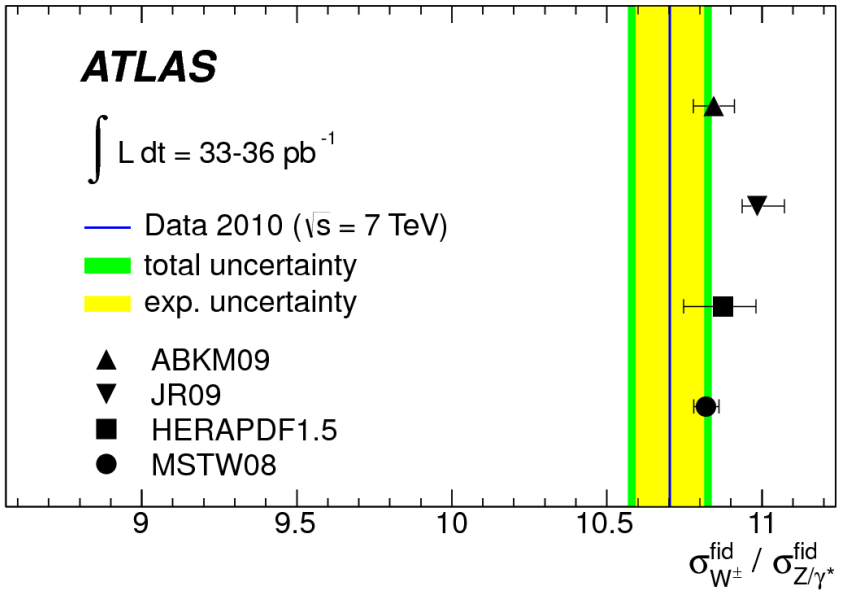
- $R_W = \sigma_W(e)/\sigma_W(\mu)$
  $= Br(W \rightarrow e\nu)/Br(W \rightarrow \mu\nu)$
  $= 1.006 \pm 0.024$
  - PDG: 1.017±0.019
  - CDF: 1.018±0.025

- $R_Z = \sigma_Z(e)/\sigma_Z(\mu)$
  $= Br(Z \rightarrow ee)/Br(Z \rightarrow \mu\mu)$
  $= 1.018 \pm 0.031$
  - PDG: 0.9991±0.0024



W / Z Cross-section Ratio

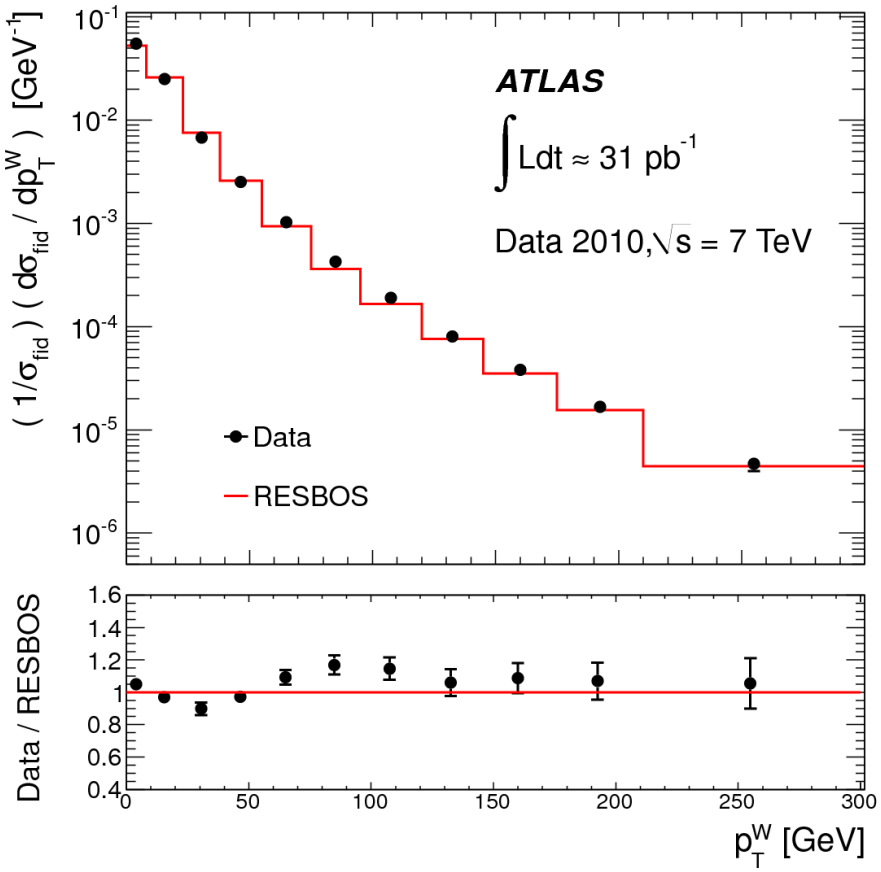
- W / Z cross-section ratio insensitive to PDFs if sea is flavour symmetric
- Hence all PDF sets give similar predictions
- Agreement with measurement supports assumption of flavour independent sea at high scales and x~0.01
- Future: use to determine Γ_W ?
- $R = \frac{\sigma(W)\ \Gamma(W \to l\nu)\ \Gamma_Z}{\sigma(Z)\ \ \Gamma(Z \to ll)\ \ \Gamma_W}$
  - $\sigma(W)/\sigma(Z)$ calculated from couplings, PDFs
  - Γ_Z, $\Gamma(Z \to ll)$ measured at LEP

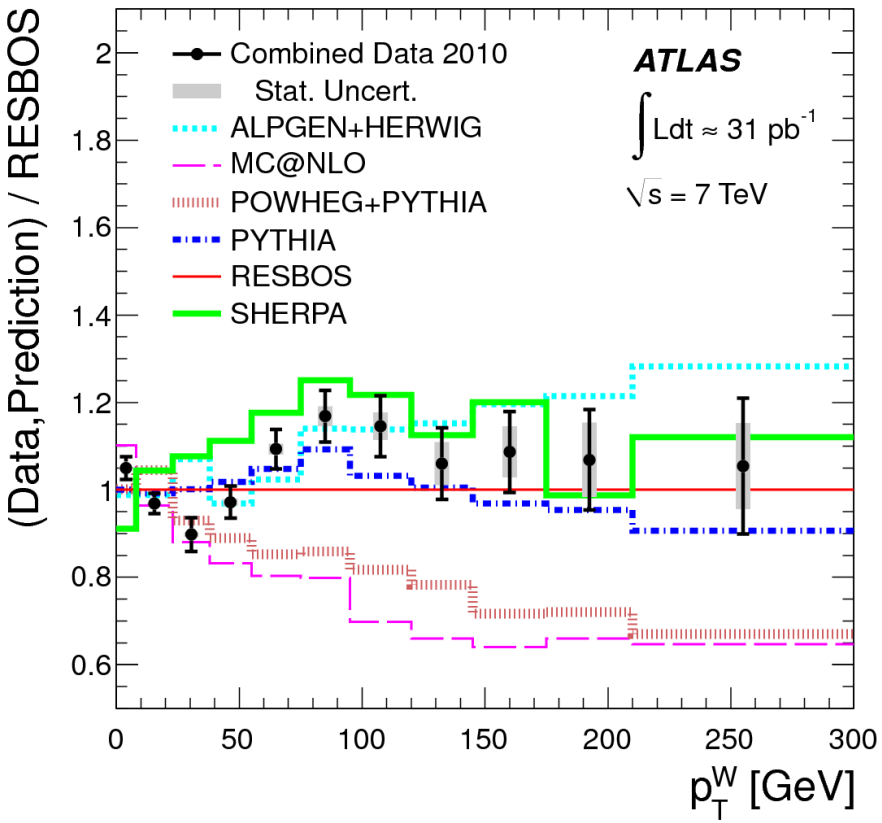


- Hence R measures $Br(W \to l\nu)$
- Using SM value of $\Gamma(W \to l\nu)$ can determine Γ_W
- Method has been used by CDF to determine Γ_W with precision of 42 MeV

W p_T Distribution

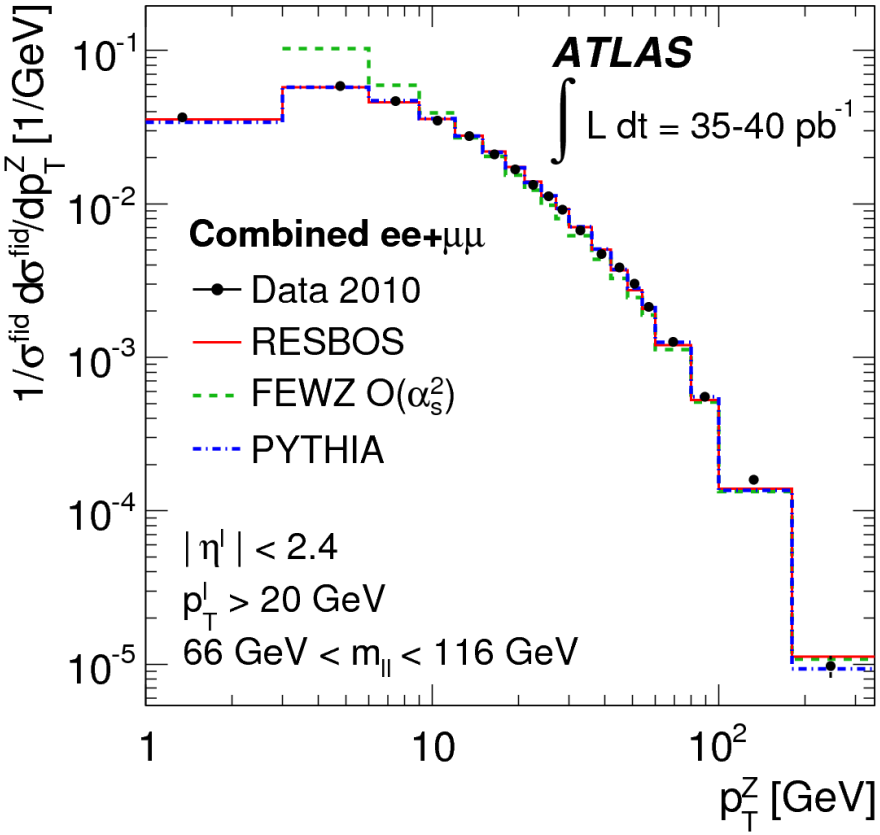
arXiv:1108.6308 [hep-ex]

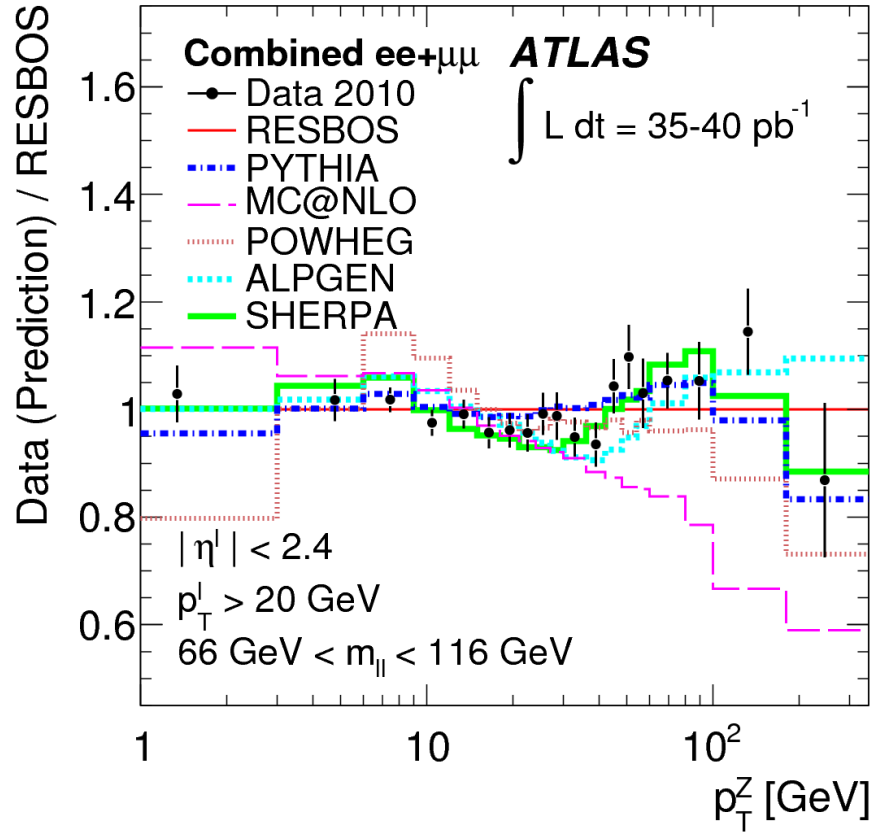




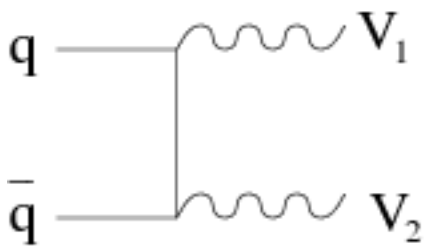
Z p_T Distribution

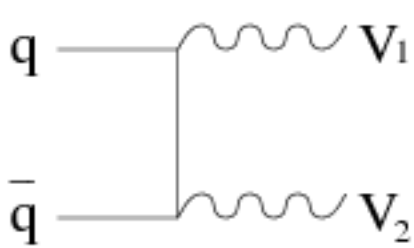
arXiv:1107.2381 [hep-ex]

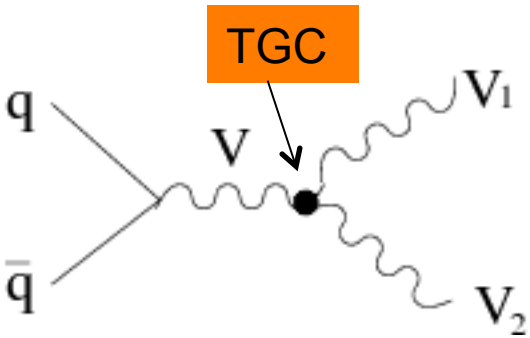




Diboson Production







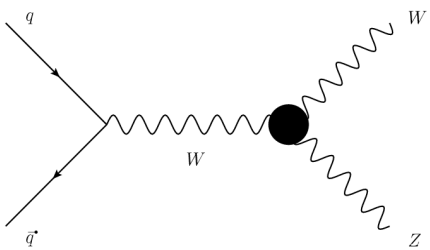
- Measurements of diboson production (Wγ, Zγ, WW, WZ, ZZ) test gauge structure of SM
- s-channel diagram contains triple gauge boson coupling (TGC) vertex
- TGC predicted by SM
  - Zero for 3 neutral bosons
  - Measured at LEP and Tevatron
- Non-SM TGC values typically increase cross-section at high diboson mass and transverse momentum

Charged TGCs

- Effective Lagrangian for WWV vertex (V = Z, γ), considering only terms that conserve C and P separately:

$$L/g_{WWV} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{*\mu}V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2}W^*_{\rho\mu}W^\mu_\nu V^{\nu\rho}$$

- 3 dimensionless coupling parameters for each of WWZ, WWγ: g_1^V, κ^V, λ^V
- In SM, $g_1^V = \kappa^V = 1$; $\lambda^V = 0$
- Hence define anomalous couplings: $\Delta g_1^V = g_1^V - 1$; $\Delta\kappa^V = \kappa^V - 1$; λ^V
- WW production measures mixture of WWZ and WWγ
- WZ production measures WWZ vertex only
- To avoid unitarity violation at high energies, may use form factor, e.g.
- $\Delta\kappa(s') = \Delta\kappa / (1 + s' / \Lambda^2)^n$ $\sqrt{s'}$ = parton cm energ
- Λ = energy scale of new physics
- ATLAS limits from WZ use Λ=2 TeV, n=2 and Λ = ∞



Neutral TGCs

- For on-shell ZZ production, effective Lagrangian for ZZV vertex is

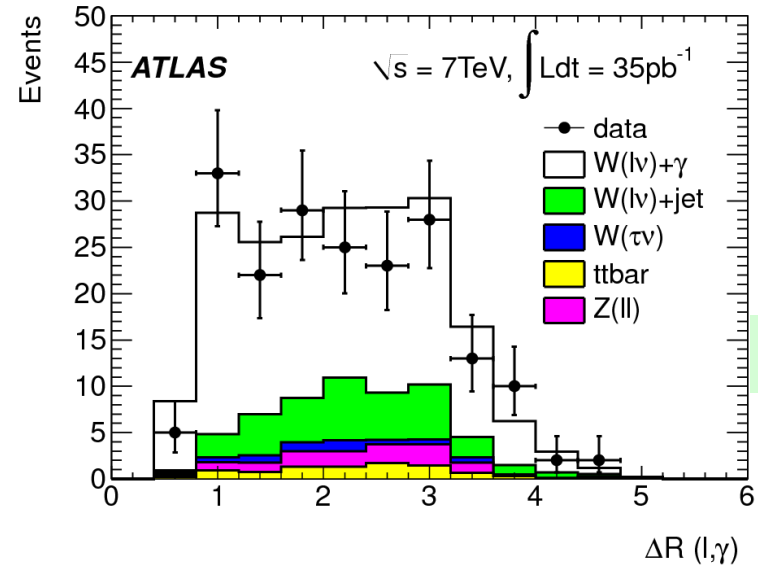
$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

- 2 dimensionless parameters for each of ZZZ,ZZγ: **f_4^V, f_5^V**
- **f_4^V** violates CP, **f_5^V** violates P
- In SM all **f = 0**
- Use form-factor as for charged TGCs to prevent unitarity violation at high energy
- ATLAS ZZ limits use n=3, Λ=2 TeV and Λ = ∞

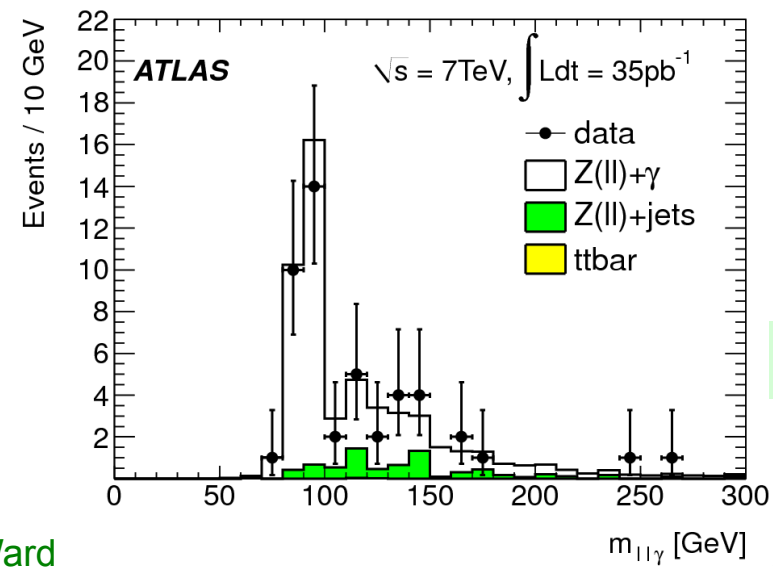
Wγ and Zγ

JHEP 09 (2011) 072

- Wγ selection:
  - Lepton with p_T > 20 GeV
  - E_T^{Miss} > 25 GeV
  - $m_T(l,\nu)$ > 40 GeV
- Zγ selection
  - Opposite-sign same-flavour lepton pair
  - m(ll) > 40 GeV
- Wγ and Zγ
  - Photon E_T > 15 GeV
  - Isolated: $E_T^{0.4}$ < 5 GeV
  - ΔR(l,γ) > 0.7 (suppress FSR)



Wγ



Zγ

Wγ and Zγ

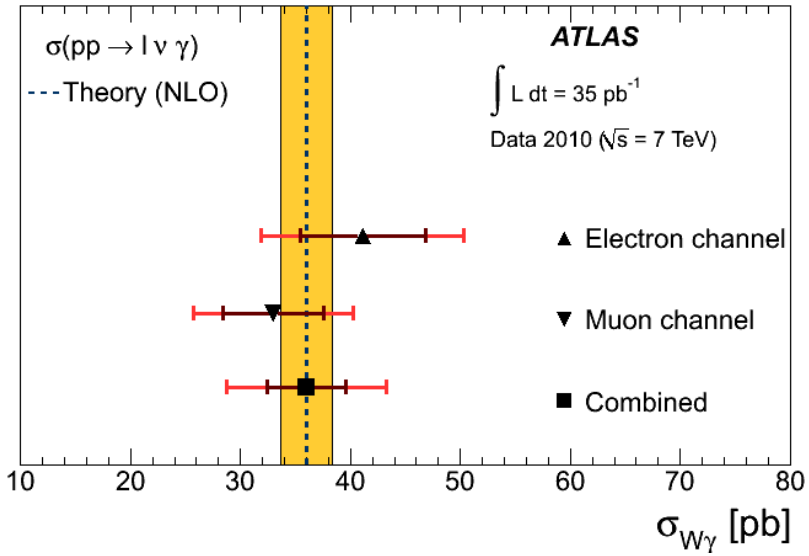
- Main background W+jets
  - Estimated from data
- Results
  - $p_T(\gamma) > 15$ GeV
  - $\Delta R(l,\gamma) > 0.7$
  - $\varepsilon_h^p < 0.5$

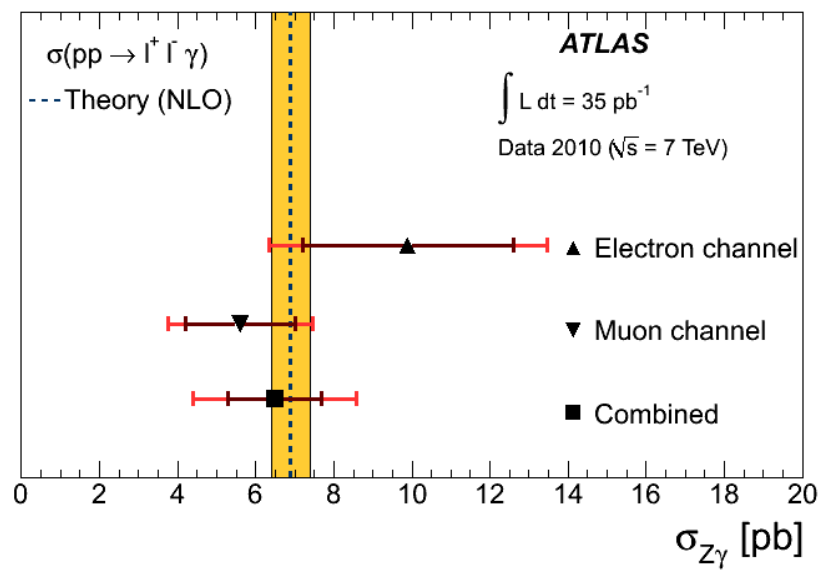
$\varepsilon_h^p = \Sigma E\,(\text{frag}) / E(\gamma)$ in $\Delta R = 0.4$

- Main systematic photon efficiency (~ 10%)

	σ(meas) / pb	σ (SM) / pb
pp ➔ $l^{\pm}\nu\gamma$	36.0 ± 3.6 ± 6.2 ± 1.2	36.0 ± 2.3
pp ➔ $l^{\pm}l^{\pm}\gamma$	6.5 ± 1.2 ± 1.7 ± 0.2	6.9 ± 0.5

- Good agreement with SM

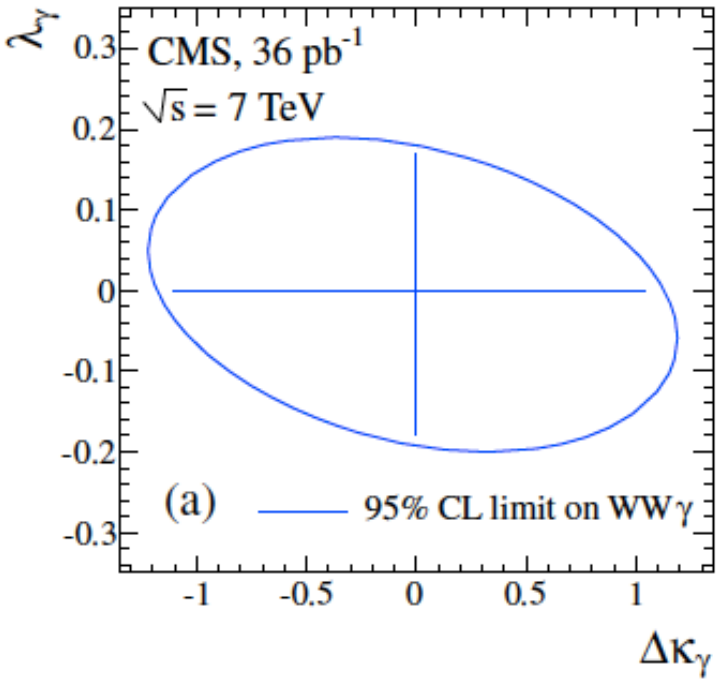


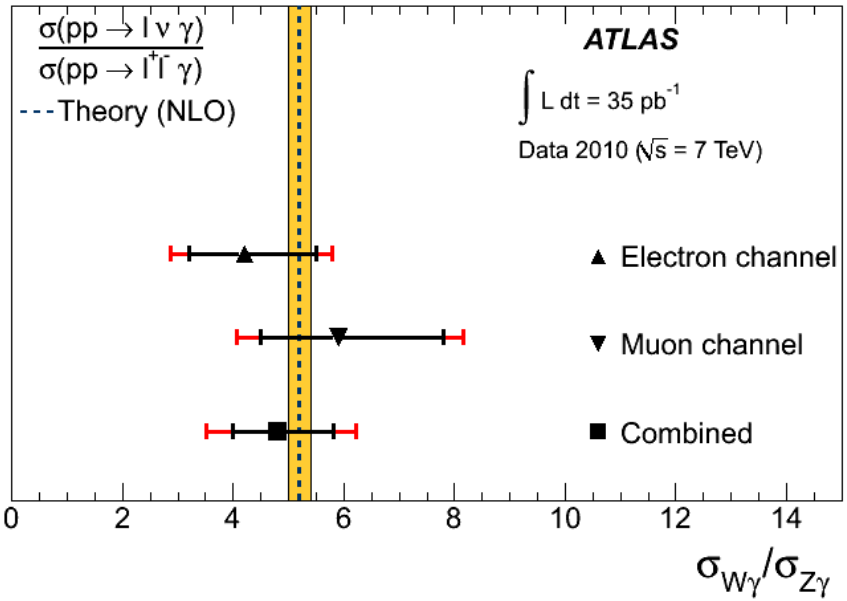


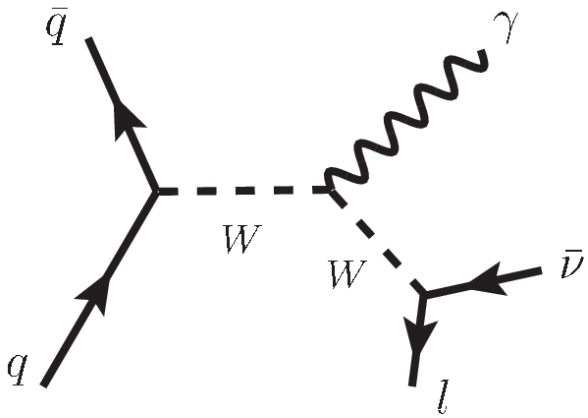
Wγ / Zγ Ratio

- Cross-section ratio is test of WWγ TGC
- Measured ratio in good agreement with SM
- Future: limits on WWγ, ZZγ,Zγγ TGC

CMS: PLB 701 (2011) 535







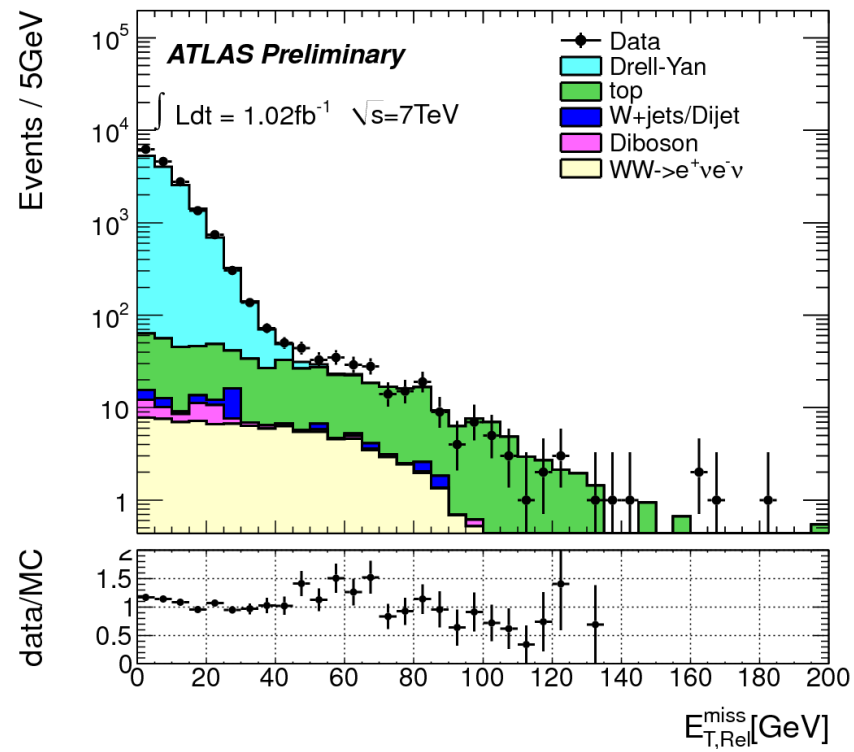
C. P. Ward

UNIVERSITY OF CAMBRIDGE

WW ➔ lνlν

ATLAS-CONF-2011-110

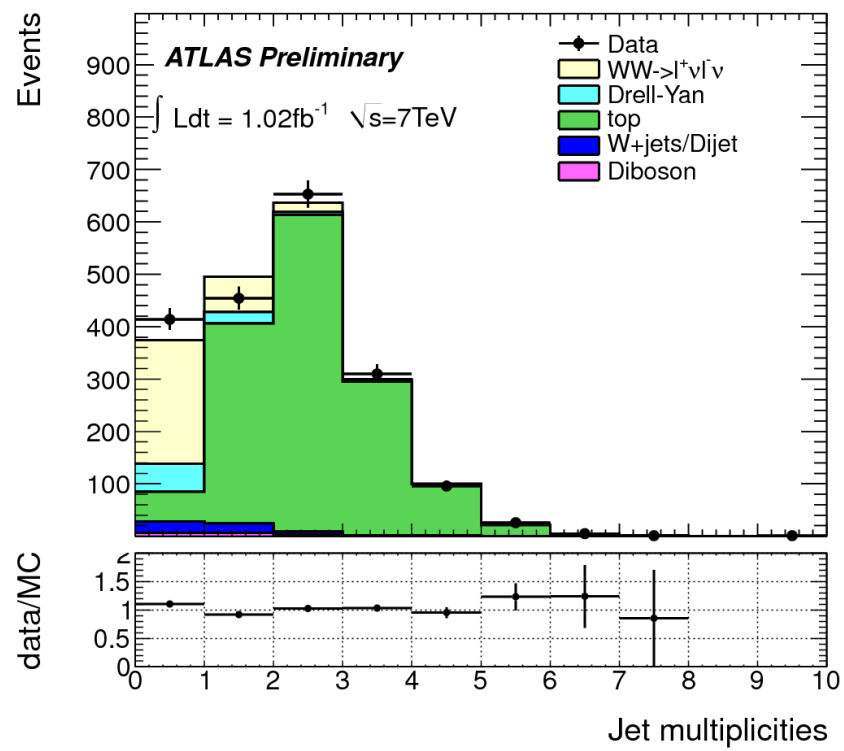
- Signature: 2 high-p_T isolated leptons + MET
- Selection:
- Exactly 2 leptons, opposite sign, p_T > 20 GeV (W,Wγ,WW,ZZ)
  - Leading e p_T > 25 GeV
  - Trigger match
- Z veto (Z)
  - |m(ll) – m(Z)| > 15 GeV
  - m(ll) > 15 GeV, m(eμ) > 10 GeV
- MET (Z)
  - $E_{T,Rel}^{Miss}$ > (45,40,20) GeV (μμ,ee,eμ)
- Jet veto (Z, ttbar)
  - No jet (anti-k_T, ΔR=0.4) with p_T>30 GeV, |η| <4.5)



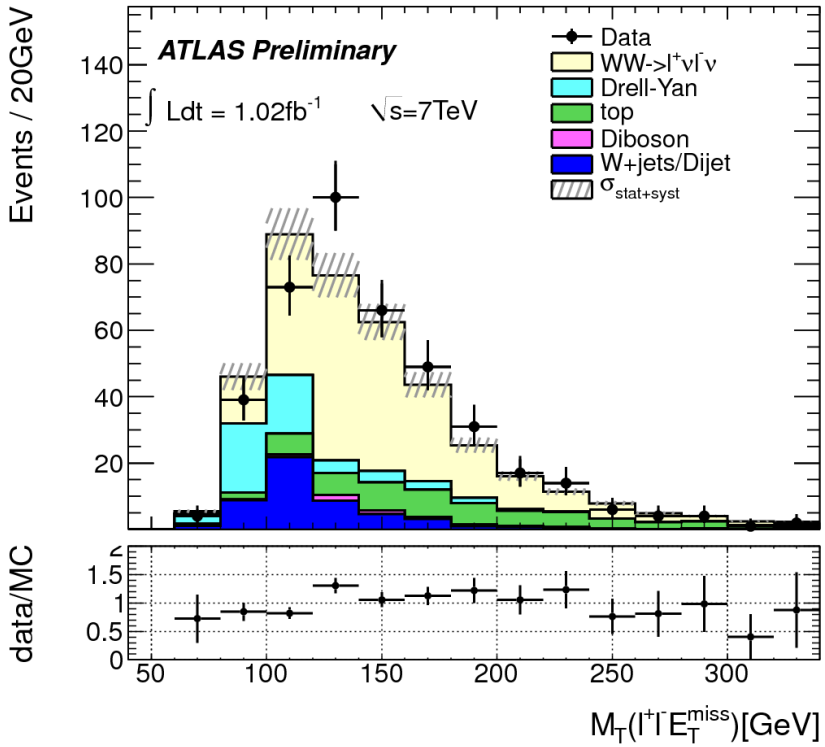
ee channel, after Z veto

WW → lνlν

- Background estimation:
- ttbar: from events in data with >=2 jets, scaled by 0 / >=2 ratio in top MC
- W+jets:
  - Data control sample with lepton + `lepton-like jet'
  - Scale by $f(p_T) = P(l)/P(j)$
  - f measured in dijet sample
- Otherwise MC



WW → lνlν



Observed events	414
Total background	169.8 ± 6.4 ± 27.1
Expected WW	232.4 ± 0.9 ± 21.5

- Main systematics:
  - Lepton reconstruction, identification and isolation efficiencies
  - Uncertainty in E_T^{Miss}
  - Jet veto

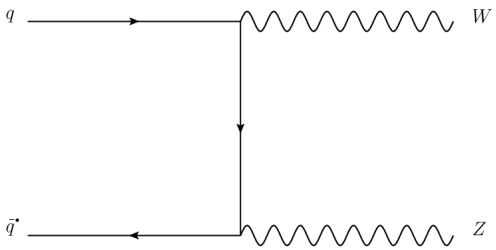
Total cross-section	48.2 ± 4.0 ± 6.4 ± 1.8 pb
SM	46 ± 3 pb

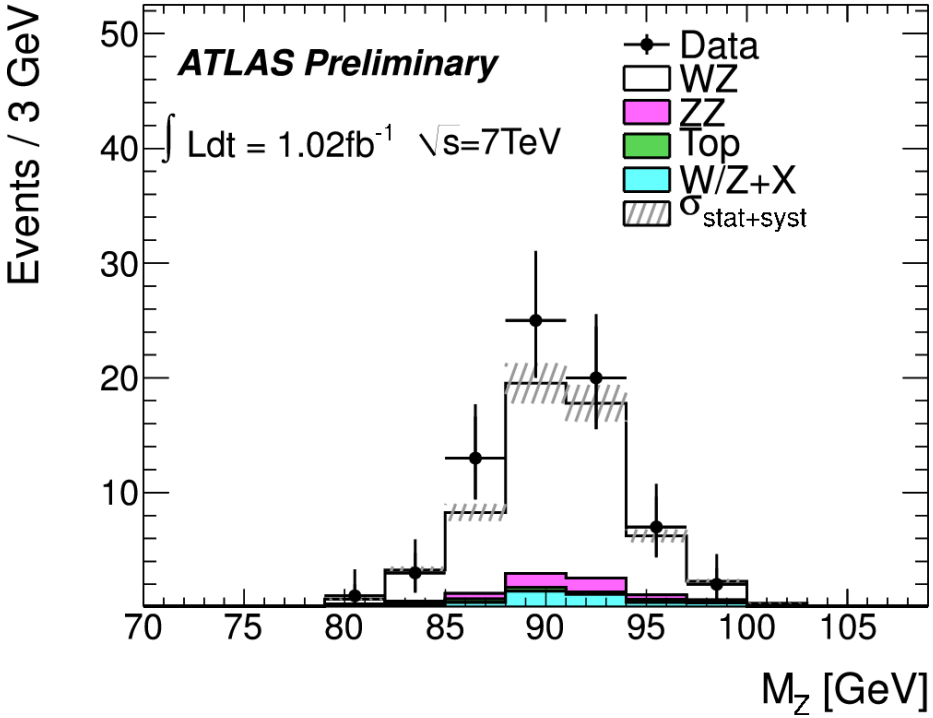
Good agreement with SM

WZ → lvll

ATLAS_CONF_2011-099

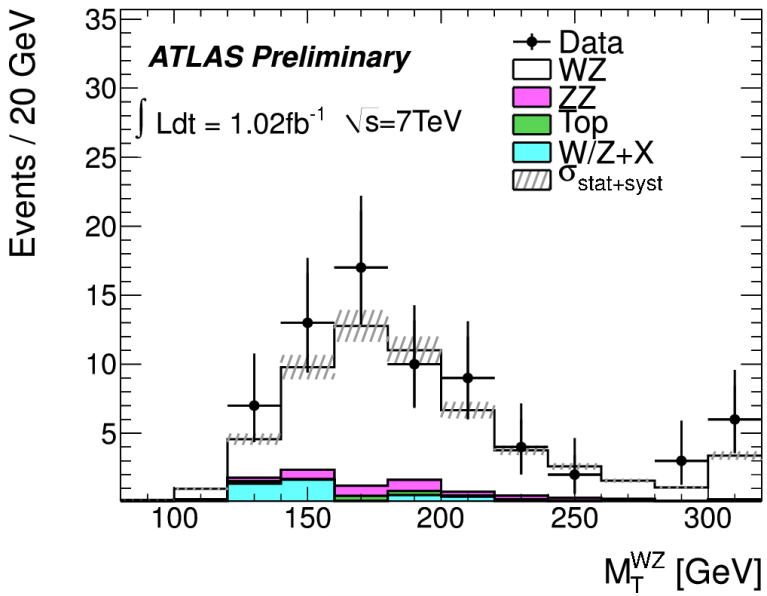
- Signature: 3 high-p_T isolated leptons + MET
- Selection:
  - 3 leptons p_T > 15 GeV
  - |m(ll) – m(Z)| < 10 GeV
  - 3rd lepton 'tight', p_T > 20 GeV
  - MET > 25 GeV
  - m_T(W) > 20 GeV
  - Trigger match with p_T(e,mu) > (25,20) GeV
- Background
  - Z+jets, ttbar from data
- Efficiencies, acceptances
  - MC with data corrections

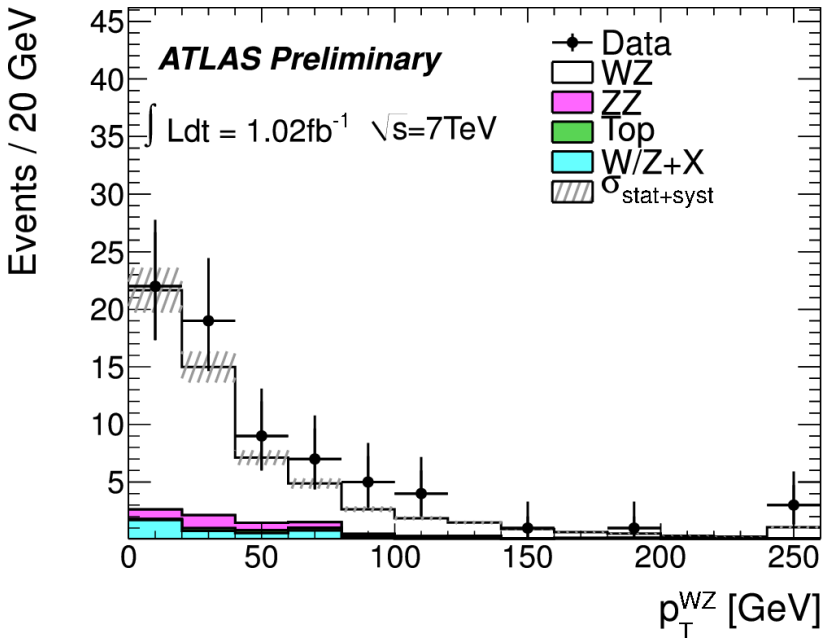




WZ → lνll

Observed events	71
Total background	$10.5 \pm 0.8\ ^{+2.9}_{-2.1}$
Expected WZ	$49.1 \pm 0.4 \pm 3.0$



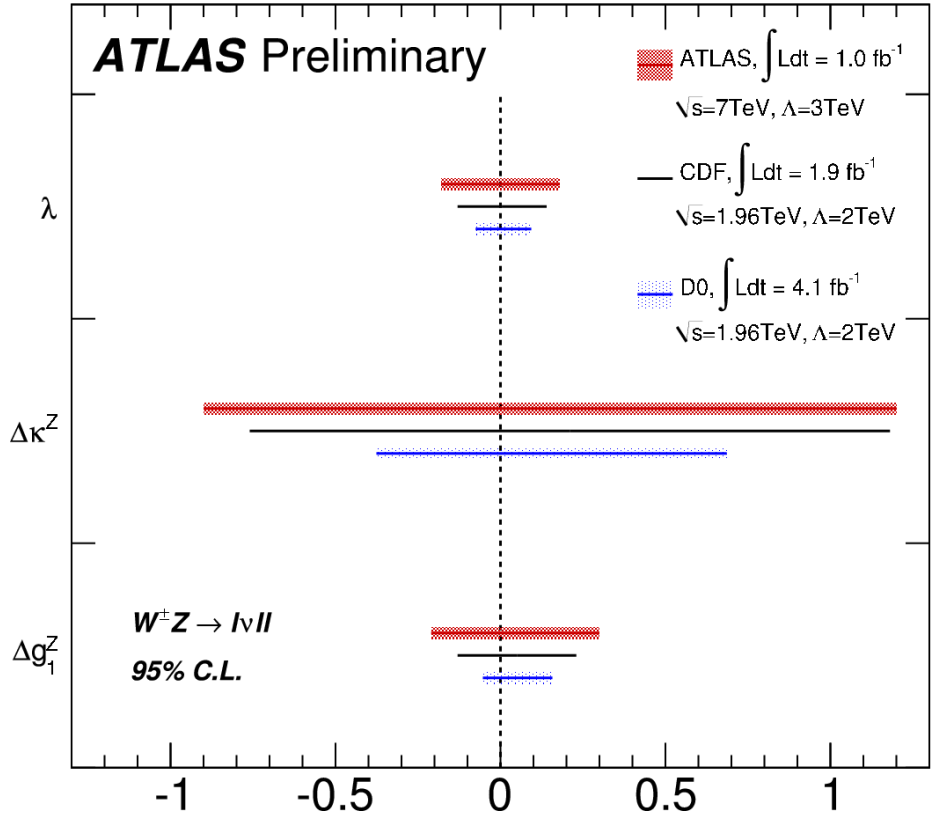


Good agreement with SM

Total cross-section	$21.1\ ^{+3.1}_{-2.8} \pm 1.2\ ^{+0.9}_{-0.8}$ pb
SM	$17.3\ ^{+1.3}_{-0.8}$ pb

Charged TGC from WZ Production

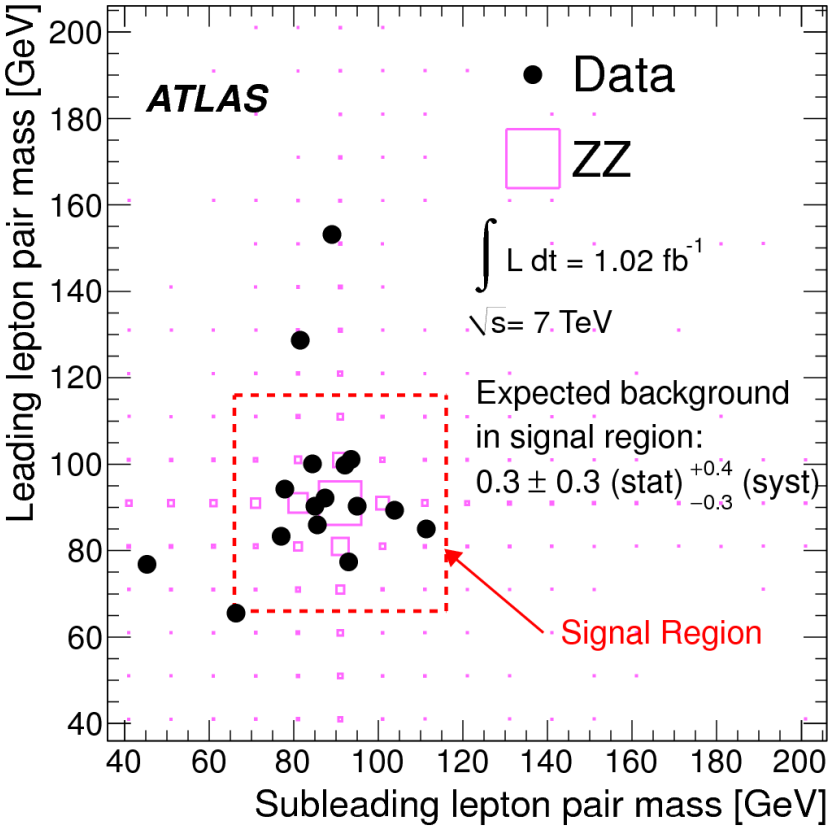
- Limits from total event yield; profile likelihood ratio as test statistic
- Reweight fully-simulated events (MC@NLO) to find expected numbers for different coupling values
- Find range of coupling for which 5% of pseudo-experiments give smaller value of likelihood ratio than data
- Limits assume other couplings = SM values



ZZ → llll

arXiv:1110.5016 [hep-ex]

- Signature: 4 high-p_T, isolated leptons
- Very low background
- Selection:
  - 4 leptons, p_T > 15 GeV, |η| < 2.5 (μ) / 2.47 (e)
  - Isolation: $\Sigma p_T^{0.2} < 0.15\ p_T^l$
  - One with p_T > 20 (μ) / 25 (e) GeV trigger-matched
  - Two opposite-sign same-flavour pairs in |m(ll) – m(Z)| < 25 GeV
- Background (Z+jets, ttbar)
  - Data-driven – using events with `lepton-like jets'



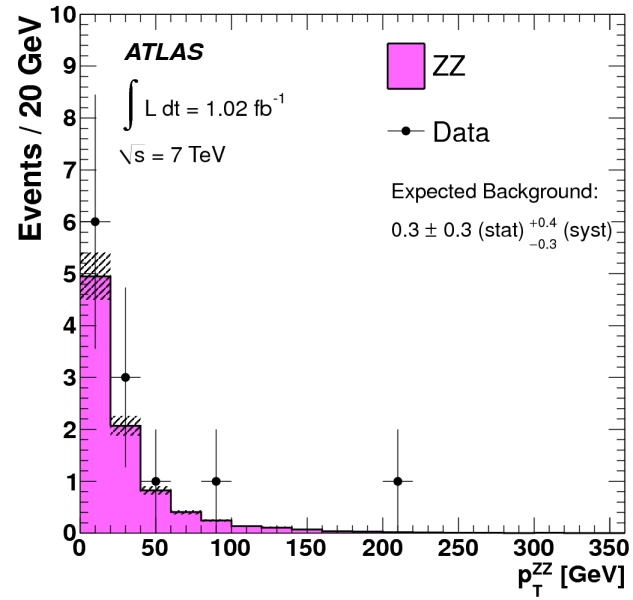
ZZ -> llll

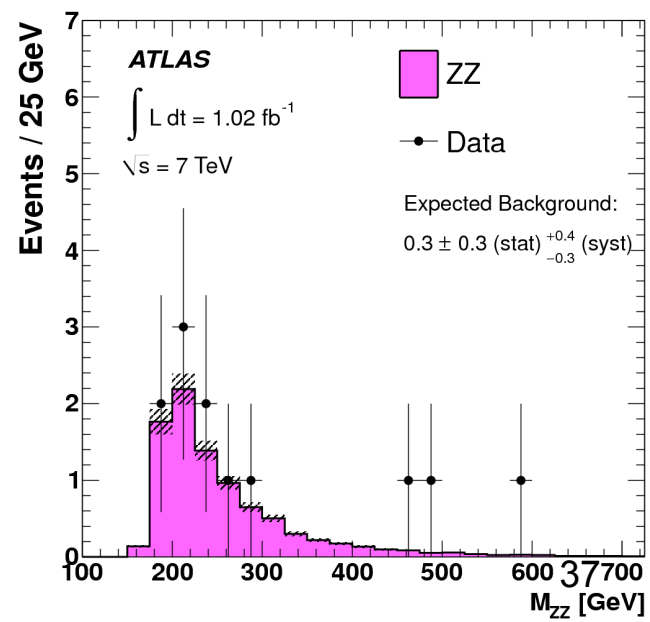
Observed events	12
Total background	$0.3 \pm 0.3\ ^{+0.4}_{-0.3}$
Expected ZZ signal	$8.9 \pm 0.1 \pm 0.3$

- 4-muon channel
  - Observe 8 events
  - Expect $3.3\ ^{+0.4}_{-0.3}$
  - Prob = 3.2%

Total cross-section	$8.5\ ^{+2.7}_{-2.3}\ ^{+0.4}_{-0.3} \pm 0.3$ pb
SM	6.5 pb

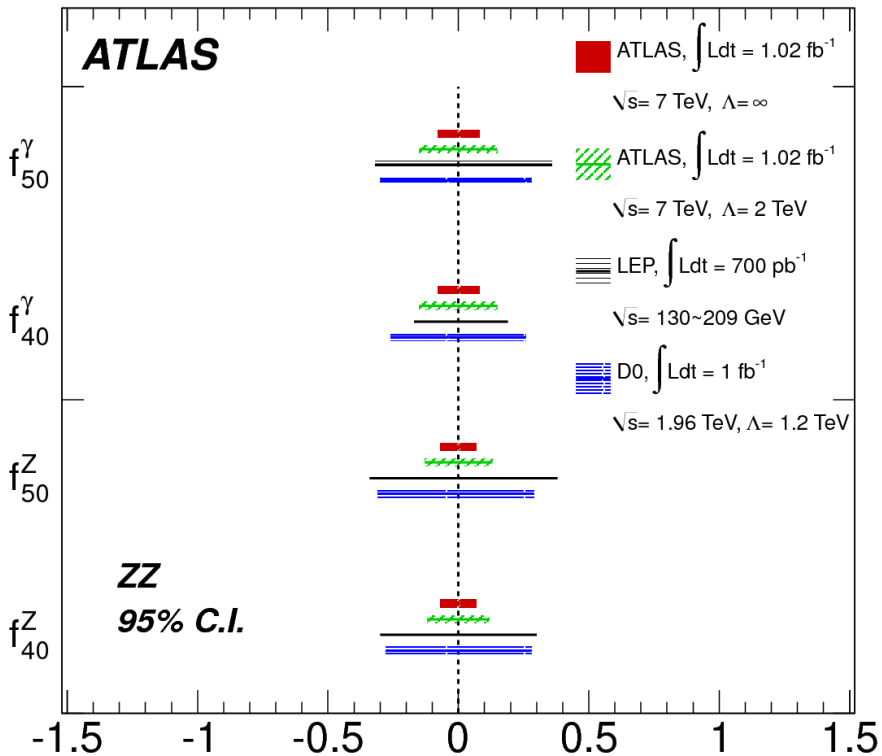
Good agreement with SM





Neutral TGCs

- Limits from total event yield
- Reweight events generated with SHERPA to determine expected yield for different couplings
- Determine limits from maximum profile likelihood fit
- Assume couplings real, and others are SM values
- Limits dominated by statistics, but are tighter than LEP, Tevatron



Λ	f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
2 TeV	$[-0.15, 0.15]$	$[-0.12, 0.12]$	$[-0.15, 0.15]$	$[-0.13, 0.13]$
∞	$[-0.08, 0.08]$	$[-0.07, 0.07]$	$[-0.08, 0.08]$	$[-0.07, 0.07]$

Future Prospects

- ATLAS has now recorded >5 fb^{-1} of 7 TeV pp collision data
  - Factor 4-5 increase in diboson statistics (statistically limited)
  - Improved understanding of systematics - more detailed studies of W/Z
- Many updates to full dataset are planned for Moriond
- Add extra decay channels, e.g. ZZ ➔ llvv
  - Branching ratio 6 times ZZ ➔ 4l, but higher background
- Use kinematic information to improve limits on anomalous couplings from WZ and ZZ production
  - Expect 20 – 40% improvements compared with using total yield, depending on coupling
- Anomalous coupling limits from WW, Wγ, Zγ and combinations where appropriate

Future Prospects

- Work in progress on other SM EW measurements
- Measurement of $\sin^2\theta_W^{eff}$
  - Interference of vector and axial-vector couplings leads to asymmetry in polar angle of lepton wrt initial quark direction in q qbar ➔ Z/ γ* ➔ l^+l^-
  - Asymmetry used to measure $\sin^2\theta_W^{eff}$ at LEP, Tevatron
    - Precision ~0.1%
  - In pp collisions can only determine q / qbar statistically
  - Recent results from CMS using Z ➔ μμ in 1.1 fb^{-1} data [arXiv:1110.2682]:
    - $\sin^2\theta_W^{eff} = 0.2287 \pm 0.0020 \pm 0.0025$
    - Precision ~1%
- Measurement of W mass
  - Needs detailed understanding of energy scales

Summary

- ATLAS has collected more than $5fb^{-1}$ of pp collision data at sqrt{s} = 7 TeV
- Detector performance has been excellent, and many SM measurements have been made:
  - W/Z production cross-sections – limited by systematics with only a fraction of the data
  - W/Z differential cross-sections, W/Z+jets
  - Diboson (Wγ, Zγ, WW, WZ, ZZ) production cross-sections
  - Limits on nTGCs already tighter than LEP / Tevatron with only $1fb^{-1}$ data
- No deviations from SM expectations yet
- Work in progress on many measurements, e.g.
  - More precise diboson measurements and TGC limits
  - Z asymmetry and $\sin^2\theta_W^{eff}$
  - W boson mass

Backup

Data Quality

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	100	98.4	99.3	99.4	98.3	99.8	99.5	99.8	99.9	99.7	99.5

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and August 24th (in %), after the summer 2011 reprocessing campaign.

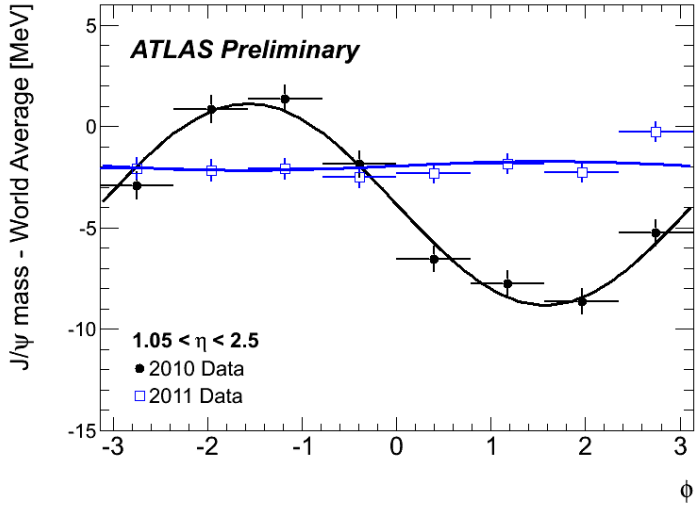
2011

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.

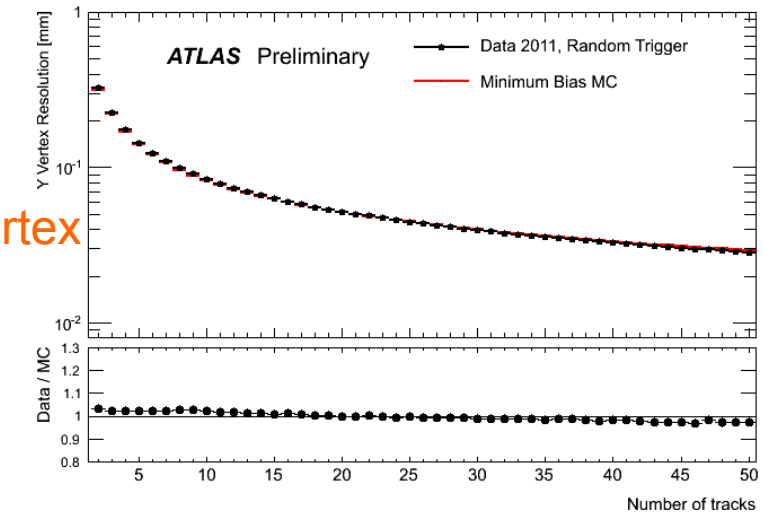
2010

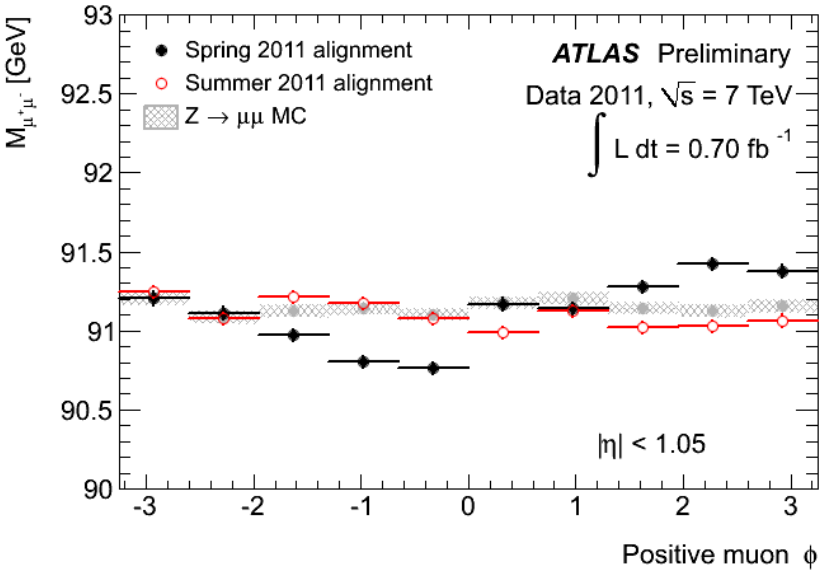
Inner Detector Tracking Performance



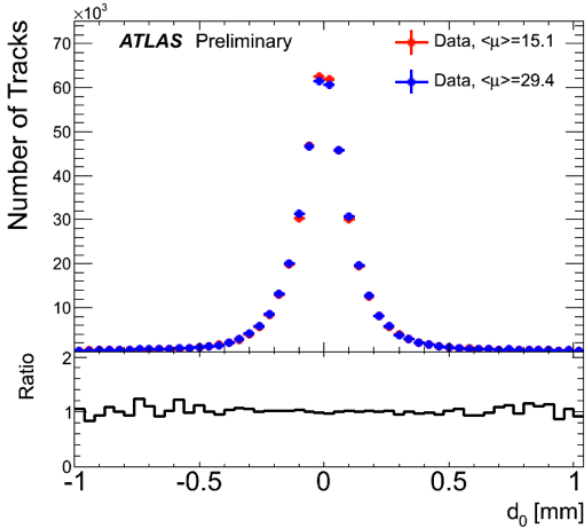
Excellent alignment

Primary vertex resolution



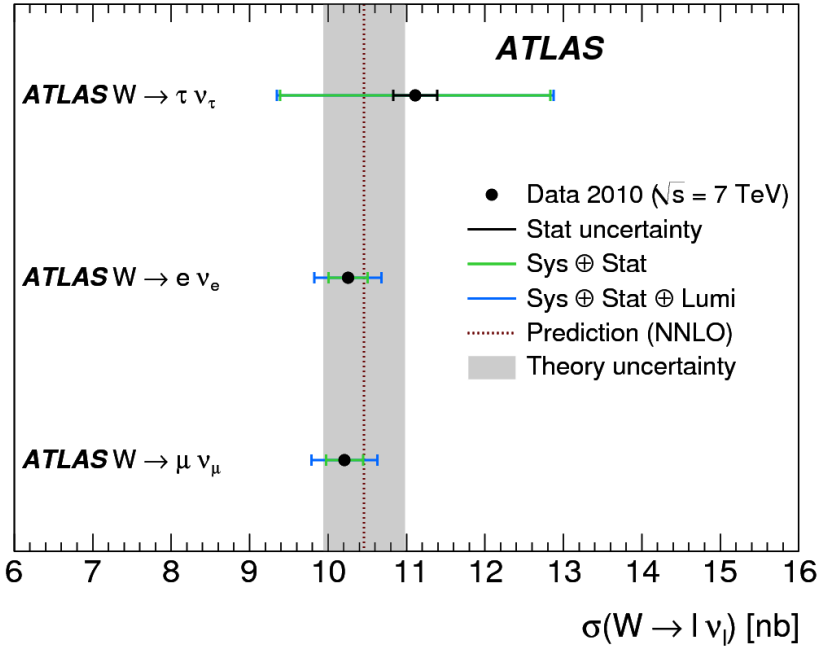


Pile-up performance

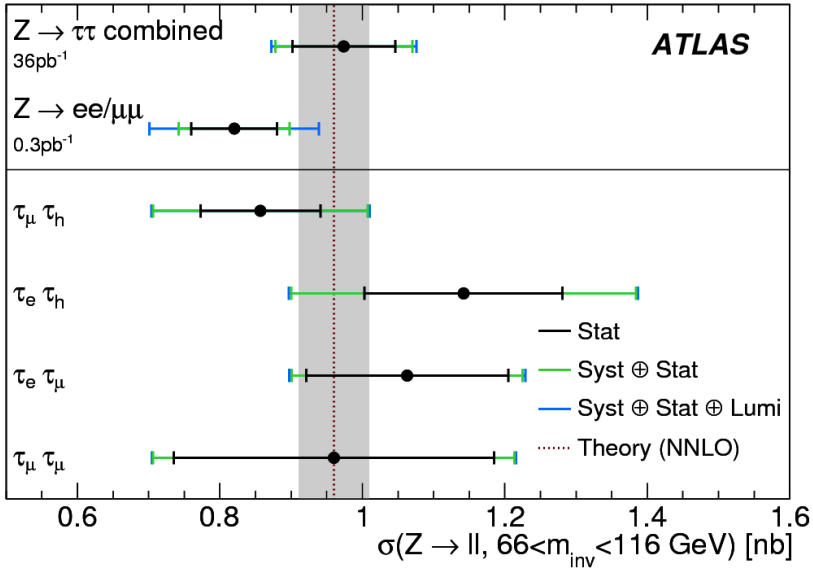


W / Z Measurement with τ Leptons

arXiv:1108.4101 [hep-ex]



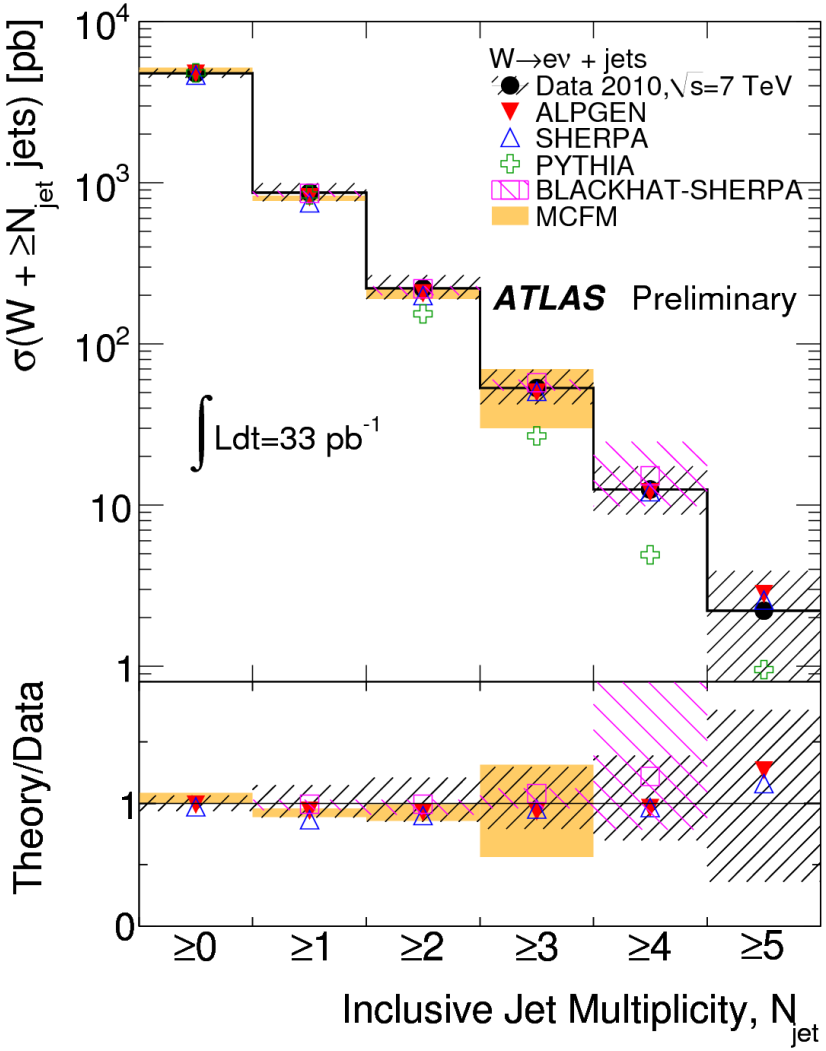
arXiv:1108.2016 [hep-ex]

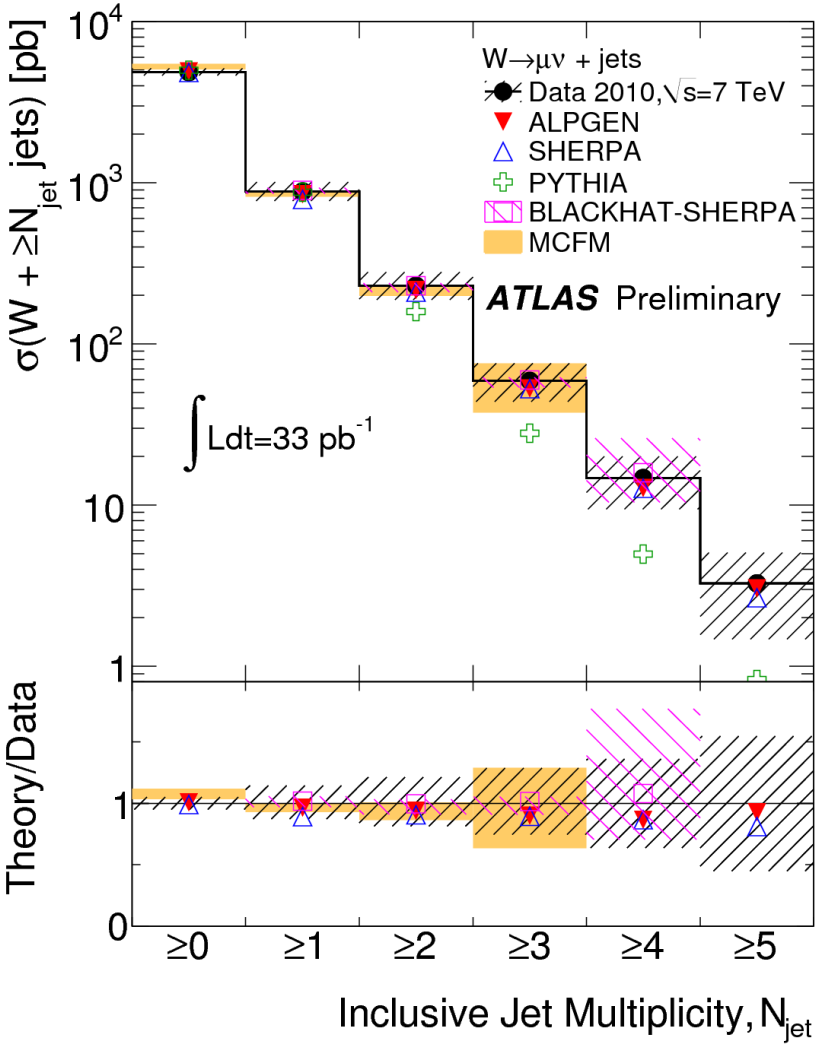


Cross-sections measured in τ channels agree well with those measured in e/μ channels

W + jets

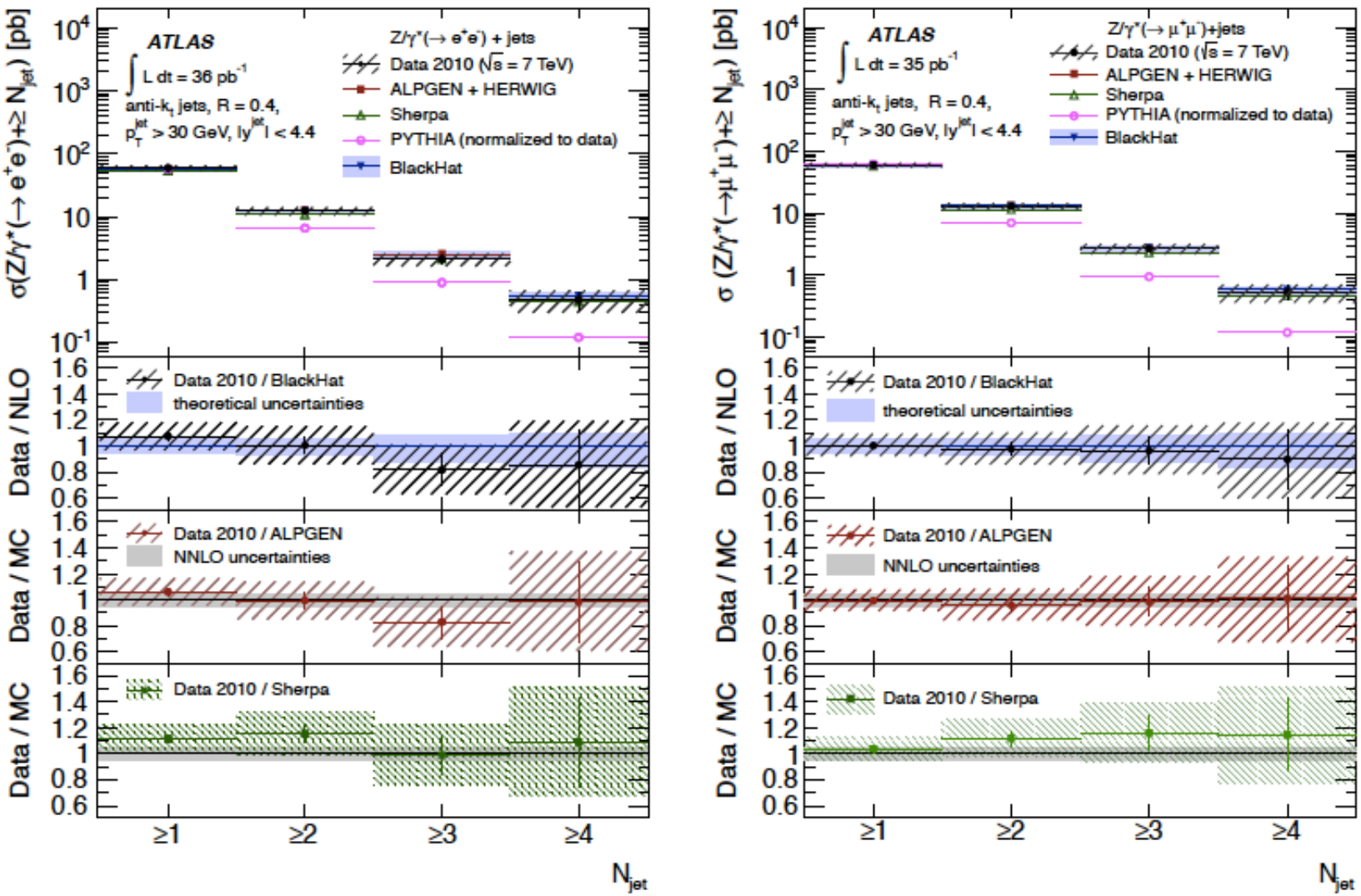
ATLAS-CONF-2011-060





Z + jets

arXiv:1111.2690 [hep-ex]



WW ➔ lvlv

Final State	$e^+e^-E_T^{miss}$	$\mu^+\mu^-E_T^{miss}$	$e^\pm\mu^\mp E_T^{miss}$	Combined
Observed Events	74	97	243	414
Background estimations				
Top(data-driven)	9.5±0.3±3.6	12.3 ±0.4±4.7	36.8±1.3±14.0	58.6±2.1±22.3
W+jets (data-driven)	5.3±0.4±1.7	12.4±2.9±5.2	32.9±3.8±9.2	50.5±4.8±14.7
Drell-Yan (MC/data-driven)	18.7±1.9±1.9	19.2±1.7±2.1	16.0±2.8±1.7	54.0±3.7± 4.5
Other dibosons (MC)	0.9±0.1±0.1	2.4±0.2±0.3	3.4±0.3±0.4	6.8±0.4±0.8
Total Background	34.4±2.0±4.4	46.3±3.4±7.3	89.1±4.9±16.8	169.8±6.4±27.1
Expected WW Signal	29.5±0.3±3.0	52.5±0.4±4.9	150.5±0.7±13.4	232.4±0.9±21.5
Significance ($S/\sqrt{B}$)	5.0	7.7	15.9	17.8

WZ → lνll

Final State	$eee + E_T^{miss}$	$ee\mu + E_T^{miss}$	$e\mu\mu + E_T^{miss}$	$\mu\mu\mu + E_T^{miss}$	combined
Observed	11	9	22	29	71
ZZ	0.34±0.07	1.03±0.13	0.82±0.12	1.40±0.15	3.55±0.24±0.17
W/Z+jets	2.03±0.38	0.64±0.18	2.03±0.38	0.44±0.15	$5.14\pm0.59^{+2.97}_{-2.08}$
Top	0.26±0.10	0.31±0.09	0.41±0.12	0.60±0.15	1.58±0.23±0.10
$W/Z+\gamma$	0.49±0.28	–	0.56±0.39	–	1.05±0.48±0.08
Total Background	3.08±0.49	1.98±0.24	3.82±0.56	2.44±0.21	$10.5\pm0.8^{+2.9}_{-2.1}$
Expected Signal	7.55±0.17	11.27±0.20	12.12±0.22	18.16±0.27	49.1±0.4±3.02
Expected S/B	2.5	5.7	3.2	7.4	4.3

ZZ → llll

Channel	Observed	BG(data-driven)	Expected ZZ
$e^+e^-e^+e^-$	2	$0.01^{+0.03+0.05}_{-0.01-0.01}$	$1.53\pm0.03\pm0.10$
$\mu^+\mu^-\mu^+\mu^-$	8	$0.3 \pm 0.3 \pm 0.3$	$3.03\pm0.04\pm0.06$
$e^+e^-\mu^+\mu^-$	2	$< 0.01^{+0.03}_{-0.01}$	$4.37\pm0.04\pm0.14$
$\ell^+\ell^-\ell^+\ell^-$	12	$0.3 \pm 0.3^{+0.4}_{-0.3}$	$8.9\pm0.1\pm0.3$