Weak Vector Boson Measurements at the LHC (run 1)

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Physics 290E
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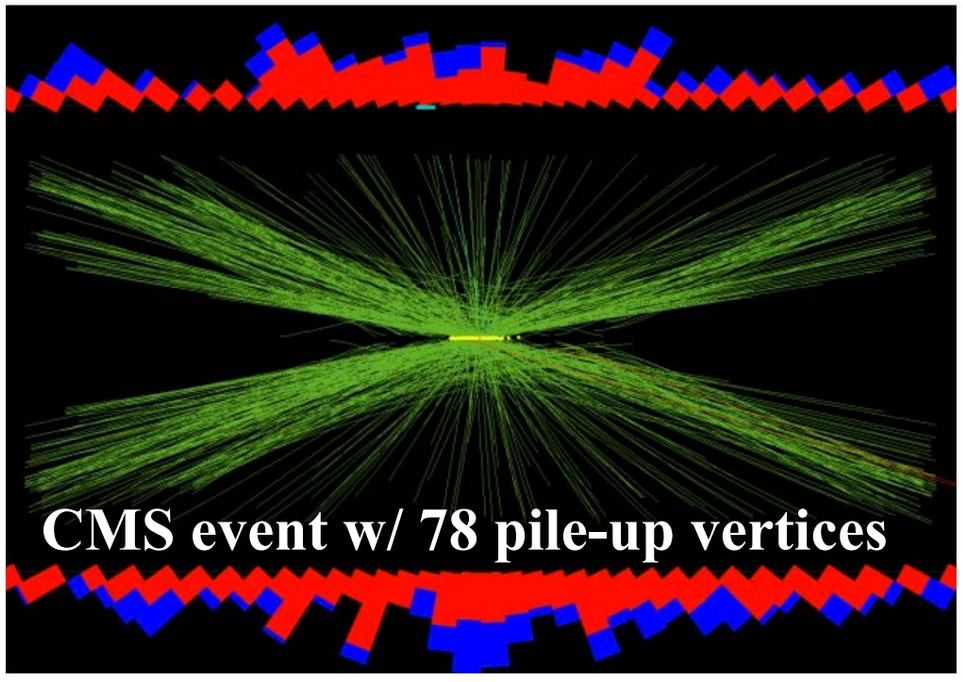
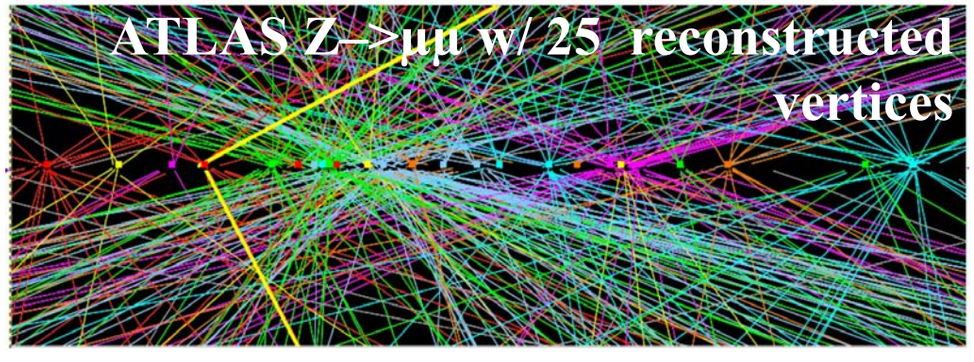
The W and Z bosons

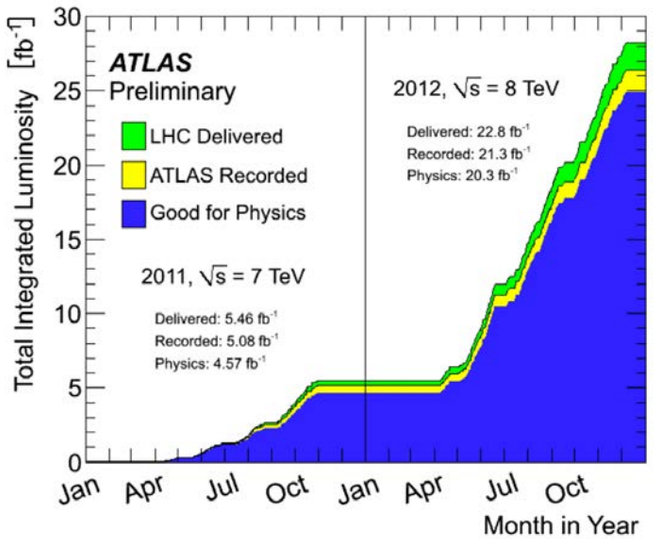
- Massive vector gauge bosons
- Mediators of weak interaction—stems from Standard Model's foundation around local gauge symmetries
- $m_W = 80.385 \pm 0.015$ GeV
- $m_Z = 91.1876 \pm 0.0021$ GeV
- $Q_W = \pm 1$ e
- $Q_Z = 0$ e
- Spin = 1
- Gamma(W) = 2.085 ± 0.042 GeV
- Gamma(Z) = 2.3952 ± 0.0023 GeV

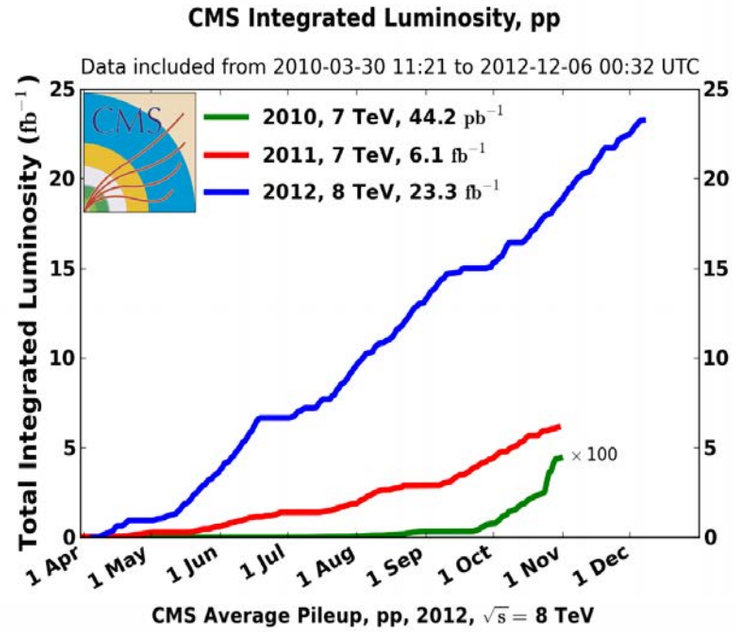
LHC Data

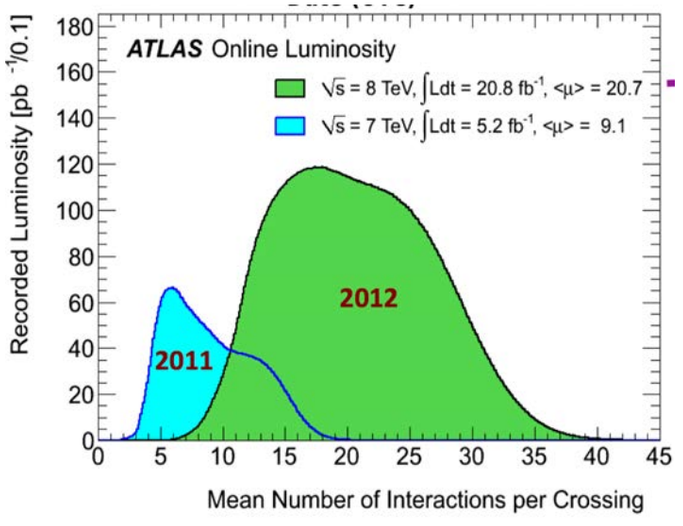
- 7TeV or 8TeV energy in Run 1
- High luminosity
  - 50ns bunch spacing, more p's

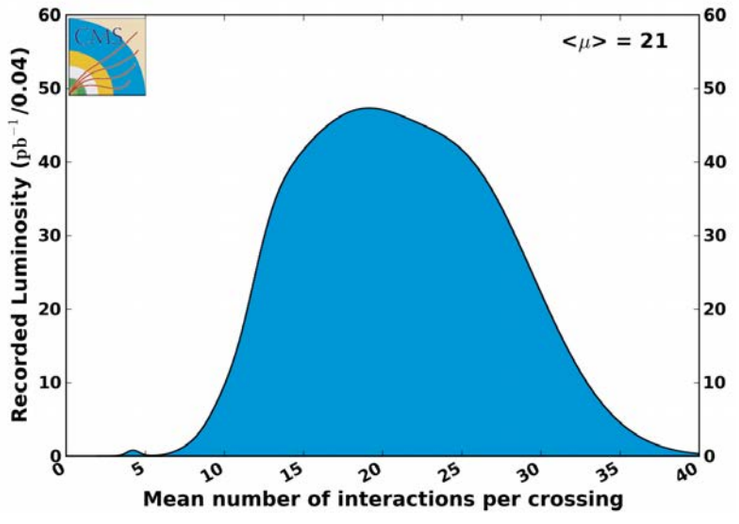






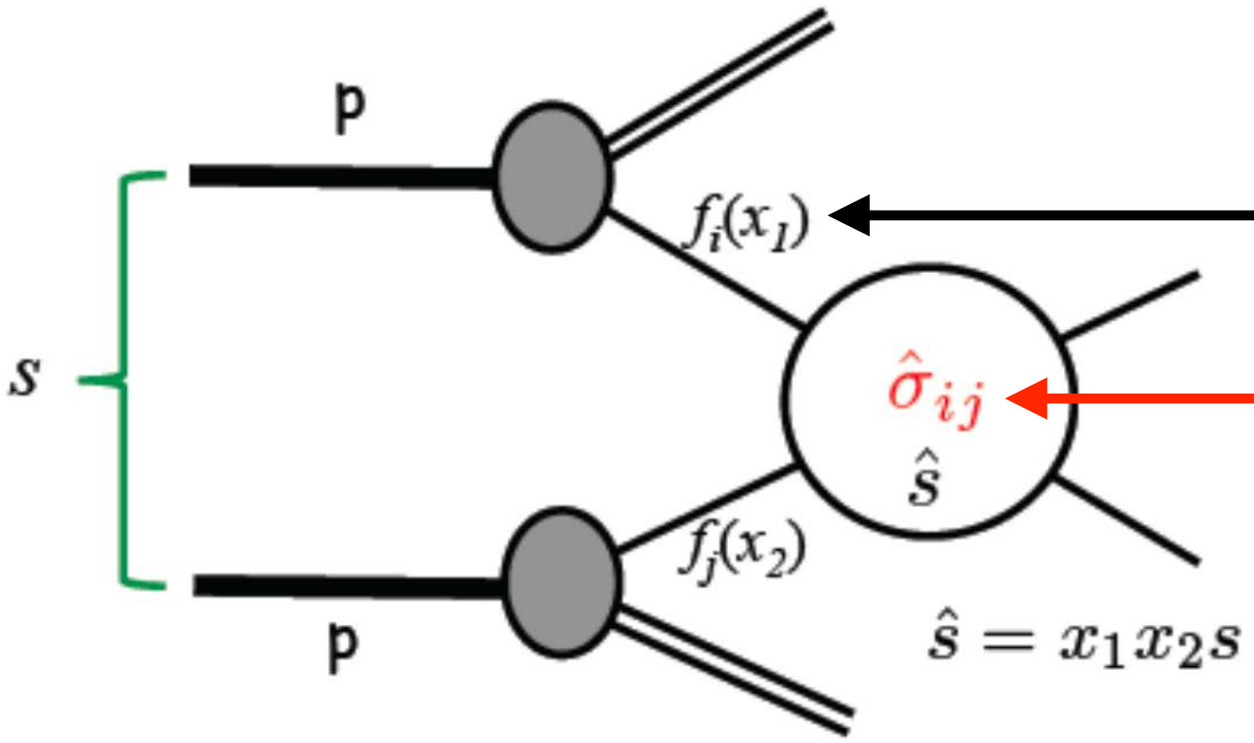






- great for discovery,
- makes EW precision physics challenging…

pp Cross Sections



Parton Distribution Functions

Partonic cross section (QCD, EW)

$$\sigma(pp \to X) \sim \sum_{i,j} \int\int dx_1 dx_2 f_i(x_1, \mu_f) f_j(x_2, \mu_f) \hat{\sigma}_{ij}(s, \mu_f^2/Q^2, \mu_r^2/\mu_f^2)$$

non-perturbative perturbative

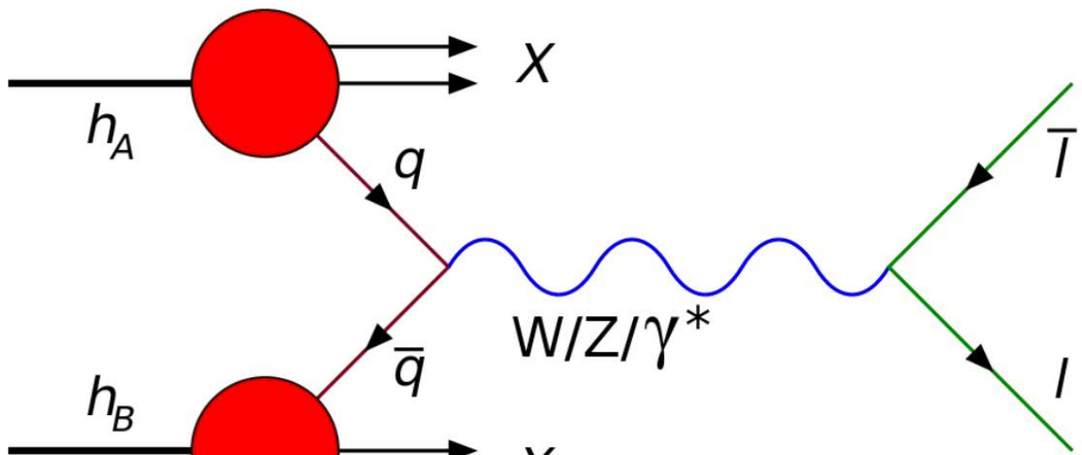
- Measurements of W and Z cross sections provide constraints on PDF, test models.

The $W^{\pm} \rightarrow l\nu$ and $Z/\gamma^{*} \rightarrow ll$ Drell-Yan processes in ATLAS

Phys. Rev. D85, 072004 (2012)
Phys.Rev.Lett. 109 (2012) 012001

Production of single W and Z bosons

- Lowest order: Drell-Yan process from valence quark and sea antiquark in pp collision:



$$\frac{d^2\sigma}{dQ^2 dx} \sim \Sigma_i q_i(x)\bar{q}_i(x)\hat{\sigma}(Q^2)$$

$$u + \bar{d}(\bar{s}) \rightarrow W^+$$

$$d + \bar{u}(\bar{c}) \rightarrow W^-$$

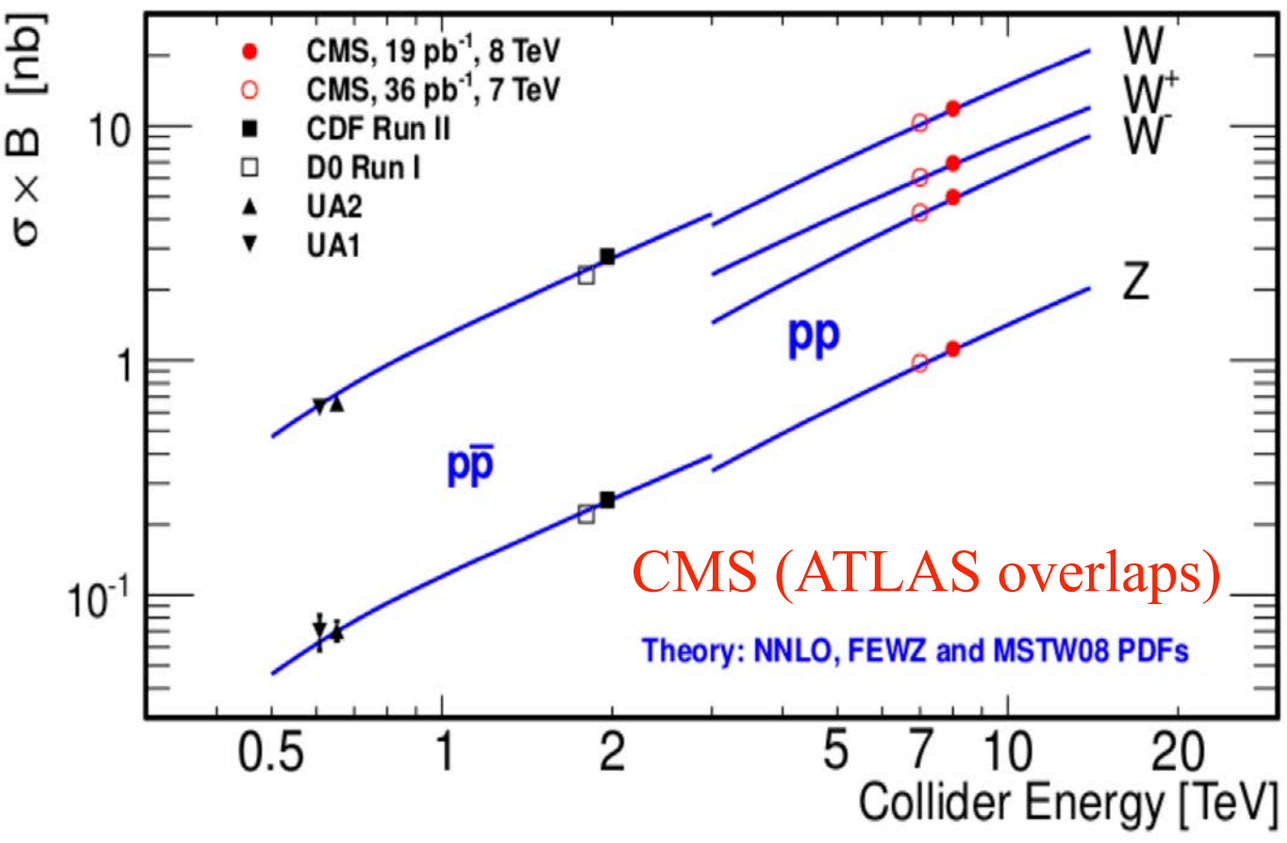
$$u + \bar{u} \rightarrow Z$$

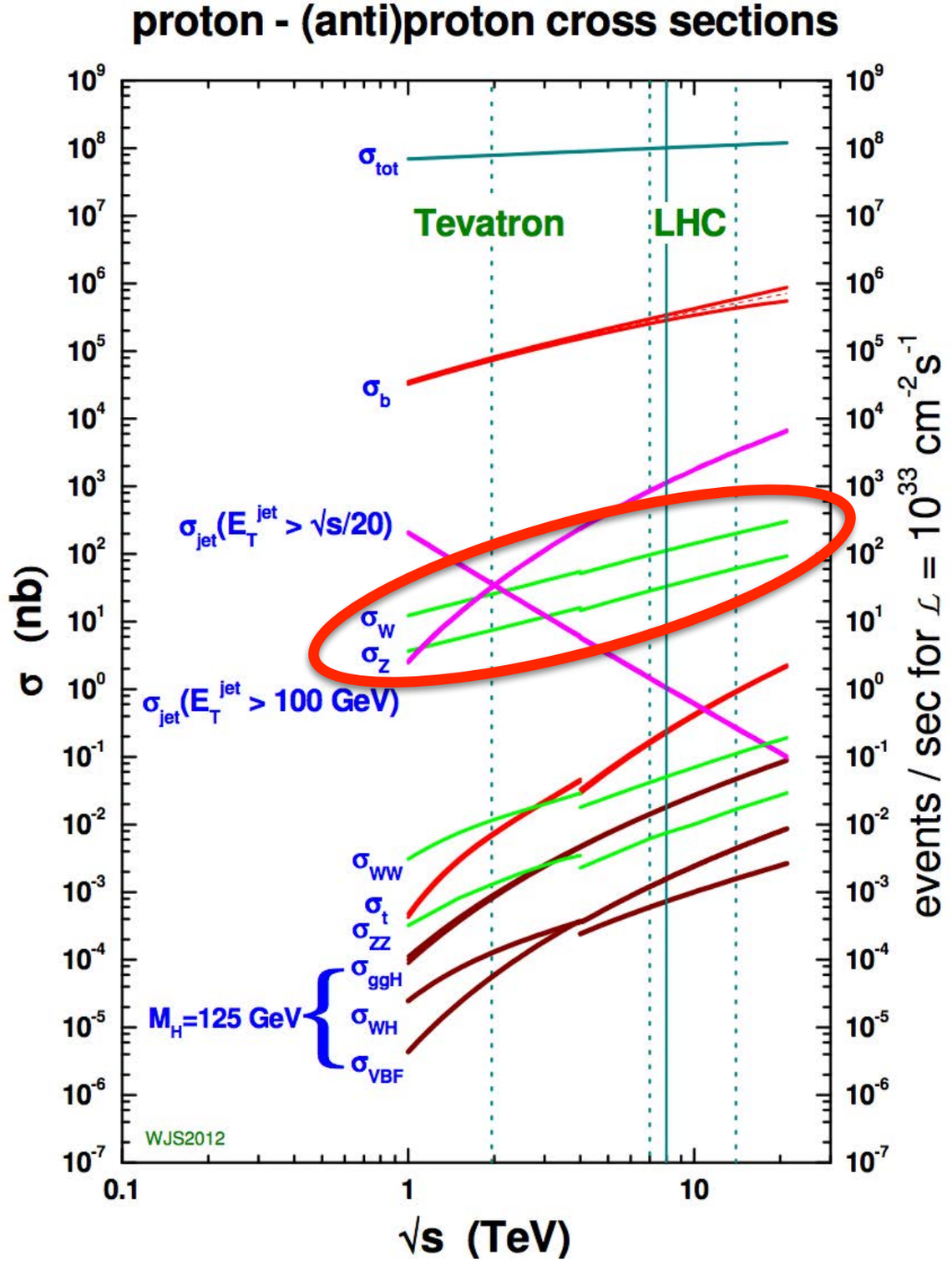
$$d + \bar{d} \rightarrow Z$$

- ~1.4x more W^+ than W^- from 2x more u than d in pp + dilution from symmetric sea-sea production).

- Sensitive to higher-order strong effects, proton structure, electroweak corrections…

Cross sections: big picture





Cross sections analysis and definitions

- $W^{\pm} \rightarrow l\nu$ and $Z/\gamma* \rightarrow ll$ (l = e, μ)
- differential cross sections measured as a function of W decay lepton pseudorapidity and Z boson rapidity
- Fiducial vs total cross-sections:

candidate events ↓ ↓ # background events

$$\sigma_{\text{fid}} = \frac{N - B}{C_{W/Z} \cdot L_{\text{int}}}$$

← integrated luminosity

↑ efficiency from MC + correction from data

$$\sigma_{\text{tot}} = \sigma_{W/Z} \times BR(W/Z \rightarrow \ell\nu/\ell\ell) = \frac{\sigma_{\text{fid}}}{A_{W/Z}}$$

acceptance from MC and uncertainties ↑

Fiducialization with kinematic parameters:

- Fiducial regions for σ_{fid}:

$W \to e\nu$: $p_{T,e} > 20$ GeV, $|\eta_e| < 2.47$, excluding $1.37 < |\eta_e| < 1.52$, $p_{T,\nu} > 25$ GeV, $m_T > 40$ GeV;

$W \to \mu\nu$: $p_{T,\mu} > 20$ GeV, $|\eta_\mu| < 2.4$, $p_{T,\nu} > 25$ GeV, $m_T > 40$ GeV;

$$= \sqrt{2 p_{T,\ell} p_{T,\nu} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

where $\Delta\varphi_{l,\nu}$ is the azimuthal separation between l and ν trajectories

$Z \to ee$ (central): $p_{T,e} > 20$ GeV, both $|\eta_e| < 2.47$, excluding $1.37 < |\eta_e| < 1.52$, $66 < m_{ee} < 116$ GeV;

Forward $Z \to ee$: $p_{T,e} > 20$ GeV, one $|\eta_e| < 2.47$, excluding $1.37 < |\eta_e| < 1.52$, other $2.5 < |\eta_e| < 4.9$, $66 < m_{ee} < 116$ GeV;

$Z \to \mu\mu$: $p_{T,\mu} > 20$ GeV, both $|\eta_\mu| < 2.4$, $66 < m_{\mu\mu} < 116$ GeV.

Efficiency calculation

- "Tag and probe method:"
- $C_{W/Z}$ calculated from simulation
  - corrected for differences in reconstruction, trigger efficiencies between simulation and data
- Tagging: where possible, efficiency derived from $Z \rightarrow ll$ and $W \rightarrow e\nu$, triggering and selecting "pure" events:
  - using only one lepton for $Z \rightarrow ll$
  - only events with significant missing E_T in $W \rightarrow e\nu$.
- Probing: second loosely-defined lepton used as probe to estimate efficiencies after background subtraction.

$$\sigma_{\text{fid}} = \frac{N - B}{C_{W/Z} \cdot L_{\text{int}}}$$

$$C_{W/Z} = \frac{N_{\text{MC,rec}}}{N_{\text{MC,gen,cut}}}$$

- $N_{MC,rec}$ = sum of weights after simulation, reconstruction and selection;
- $N_{MC,gen,cut}$ — at generator level after fiducial cuts

Total cross section and acceptance

$$\sigma_{\text{tot}} = \sigma_{W/Z} \times BR(W/Z \to \ell\nu/\ell\ell) = \frac{\sigma_{\text{fid}}}{A_{W/Z}}$$

- Acceptance $A_{W/Z}$ used to extrapolate from measured fiducialized value to full kinematic volume

- $A_{W/Z}$ derived from MC (Mc@Nlo), simulation and PDF (CTEQ 6.6 set) uncertainties, additional measurement uncertainty…

- Analogously to $C_{W/Z}$:

$$A_{W/z} = \frac{N_{\text{MC,gen,cut}}}{N_{\text{MC,gen,all}}}$$

  - Where $N_{MC,gen,all}$ is the sum of weights of all generated MC events

Monte Carlo results: cross section

Physics process	Generator	$\sigma\cdot$ BR [nb]	
$W^+ \to \ell^+\nu$ $(\ell = e, \mu)$	MC@NLO	6.16±0.31	NNLO
$W^- \to \ell^-\bar{\nu}$ $(\ell = e, \mu)$	MC@NLO	4.30±0.21	NNLO
$Z/\gamma^* \to \ell\ell$ $(m_{\ell\ell} > 60$ GeV, $\ell = e, \mu)$	MC@NLO	0.99±0.05	NNLO
$W \to \tau\nu$	PYTHIA	10.46±0.52	NNLO
$Z/\gamma^* \to \tau\tau$ $(m_{\tau\tau} > 60$ GeV)	PYTHIA	0.99±0.05	NNLO
$t\bar{t}$	MC@NLO	$0.165^{+0.011}_{-0.016}$	$\approx$NNLO
WW	HERWIG	0.045±0.003	NLO
WZ	HERWIG	0.0185±0.0009	NLO
ZZ	HERWIG	0.0060±0.0003	NLO
Dijet (e channel, $\hat{p}_{\mathrm{T}} > 15$ GeV)	PYTHIA	1.2×10^6	LO
Dijet (μ channel, $\hat{p}_{\mathrm{T}} > 8$ GeV)	PYTHIA	10.6×10^6	LO
$b\bar{b}$ (μ channel, $\hat{p}_{\mathrm{T}} > 18$ GeV, $p_{\mathrm{T}}(\mu) > 15$ GeV)	PYTHIA	73.9	LO
$c\bar{c}$ (μ channel, $\hat{p}_{\mathrm{T}} > 18$ GeV, $p_{\mathrm{T}}(\mu) > 15$ GeV)	PYTHIA	28.4	LO

Monte Carlo results: $A_{W/Z}$ and extrapolation

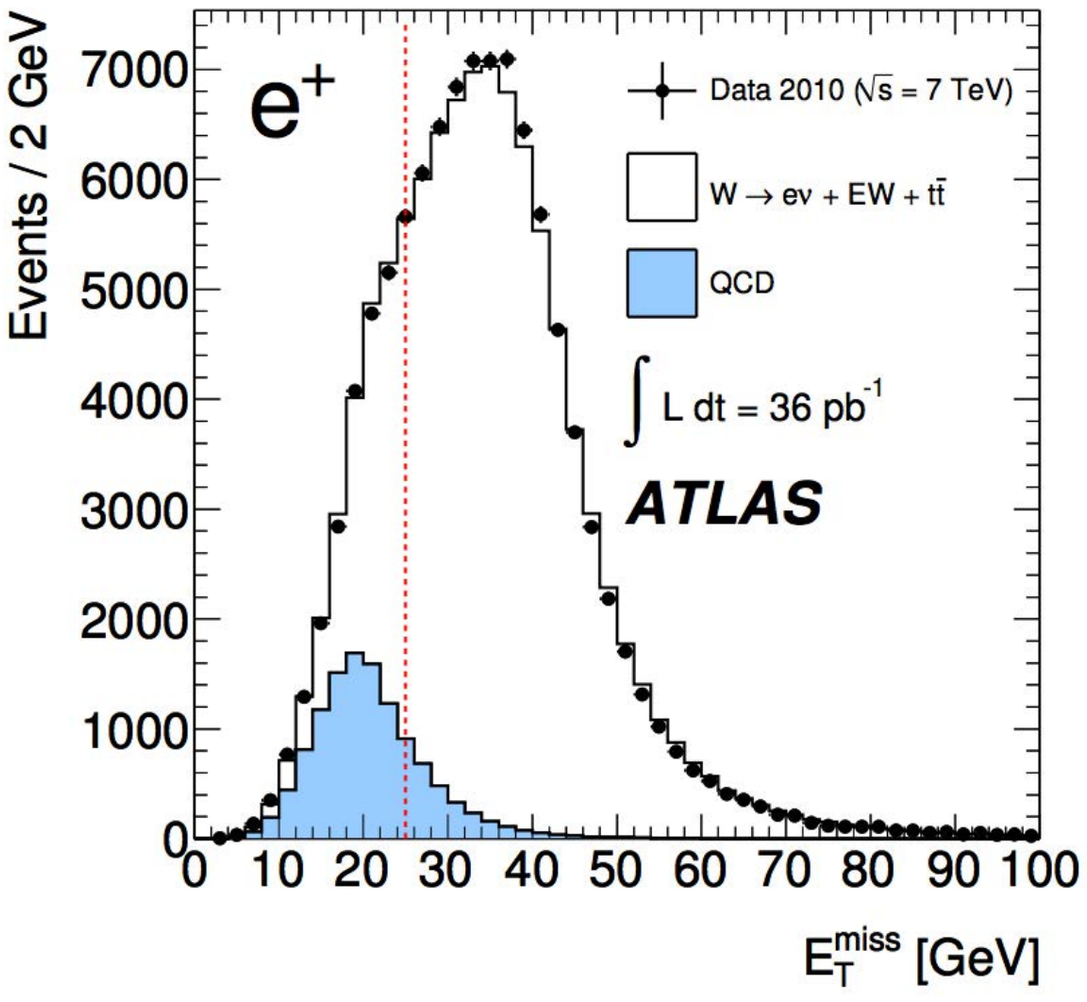
	A	$\delta A^{\rm pdf}_{\rm err}$	$\delta A^{\rm pdf}_{\rm sets}$	$\delta A_{\rm hs}$	$\delta A_{\rm ps}$	$\delta A_{\rm tot}$
Electron channels						
W^+	0.478	1.0	0.7	0.9	0.8	1.7
W^-	0.452	1.5	1.1	0.2	0.8	2.0
$W^\pm$	0.467	1.0	0.5	0.6	0.8	1.5
Z	0.447	1.7	0.6	0.2	0.7	2.0
Muon channels						
W^+	0.495	1.0	0.8	0.6	0.8	1.6
W^-	0.470	1.5	1.1	0.3	0.8	2.1
$W^\pm$	0.485	1.0	0.5	0.4	0.8	1.5
Z	0.487	1.8	0.6	0.2	0.7	2.0

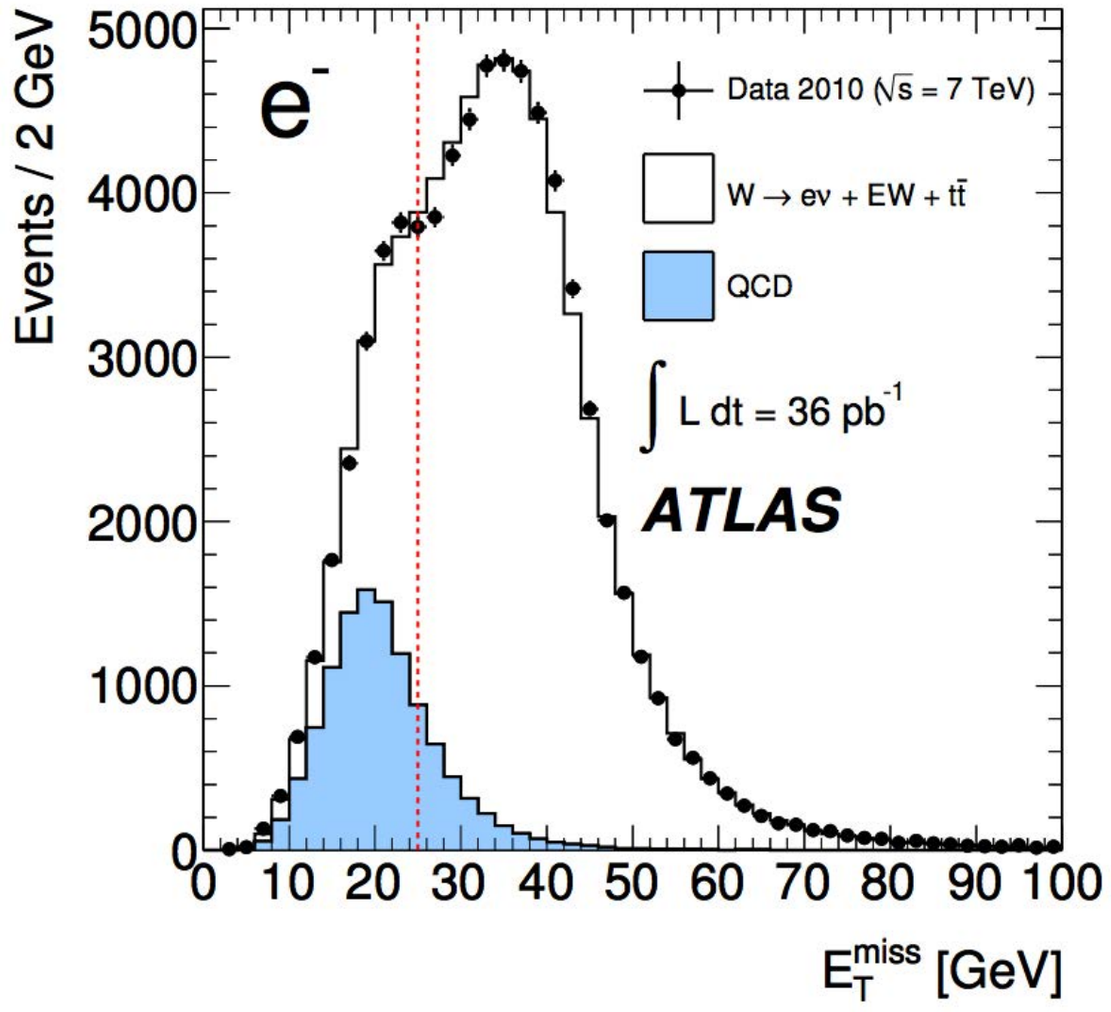
Acceptance values (A) and their relative uncertainties (δA) in percent for W and Z production in electron and muon channels. The various components of the uncertainty are defined in the text. The total uncertainty (δA_{tot}) is obtained as the quadratic sum of the four parts.

y_Z^{min}	y_Z^{max}	$Z \to \mu\mu$	Central $Z \to ee$	Forward $Z \to ee$
0.0	0.4	1.000(0)	0.954(1)	-
0.4	0.8	1.000(0)	0.903(1)	-
0.8	1.2	0.984(1)	0.855(2)	-
1.2	1.6	0.849(2)	0.746(3)	0.103(1)
1.6	2.0	0.578(5)	0.512(4)	0.327(3)
2.0	2.4	0.207(5)	0.273(5)	0.590(7)
2.4	2.8	-	-	0.797(1)
2.8	3.6	-	-	0.404(4)

Central values and absolute uncertainties (in parenthesis) of extrapolation correction factors from fiducial regions to full lepton pseudorapidity η phase space. The factors are provided in bins of Z boson rapidity for $Z \to \mu\mu$ and for central and forward $Z \to ee$ measurements.

Electron event selection



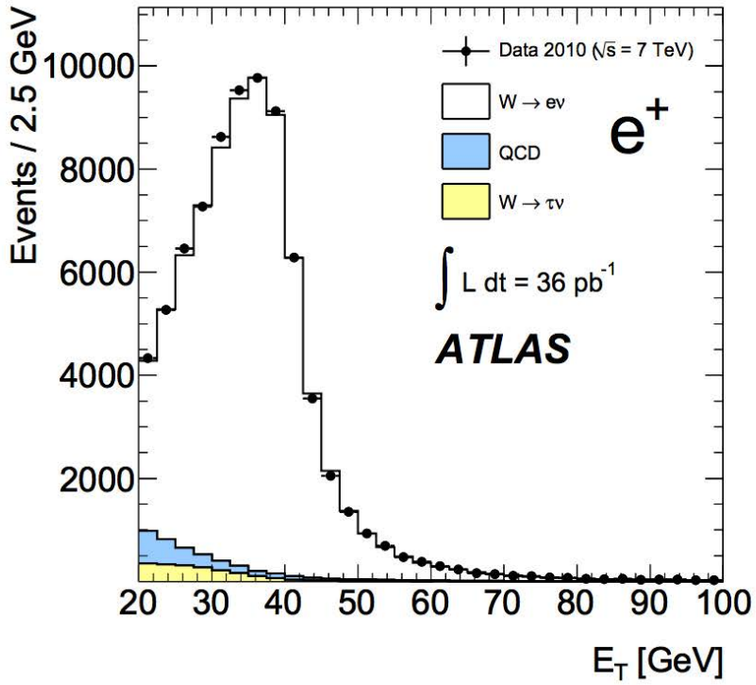


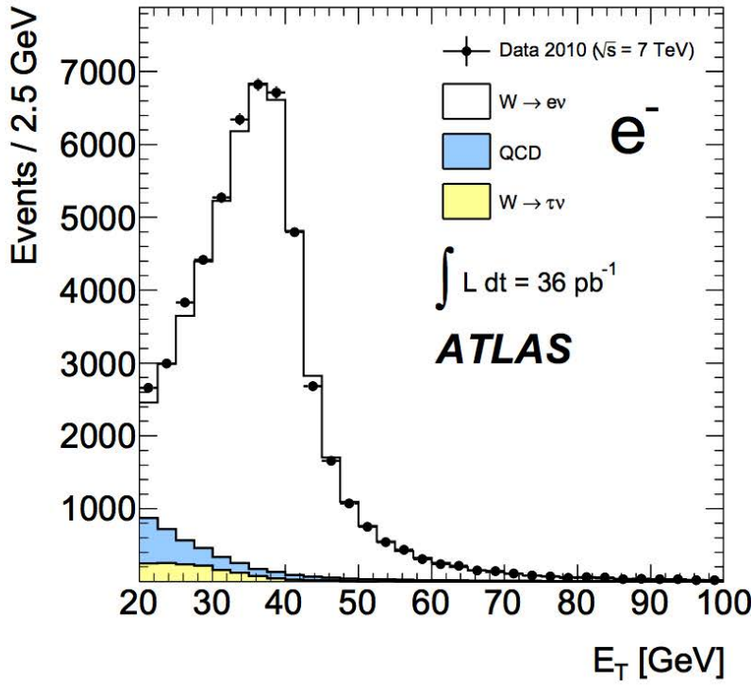
- $W \rightarrow ev$: 77885 W^+ and 52856 W^- events are selected. $E^{miss}_T > 25$ GeV.
- $Z \rightarrow ee$: 9725 central and 3376 forward events selected

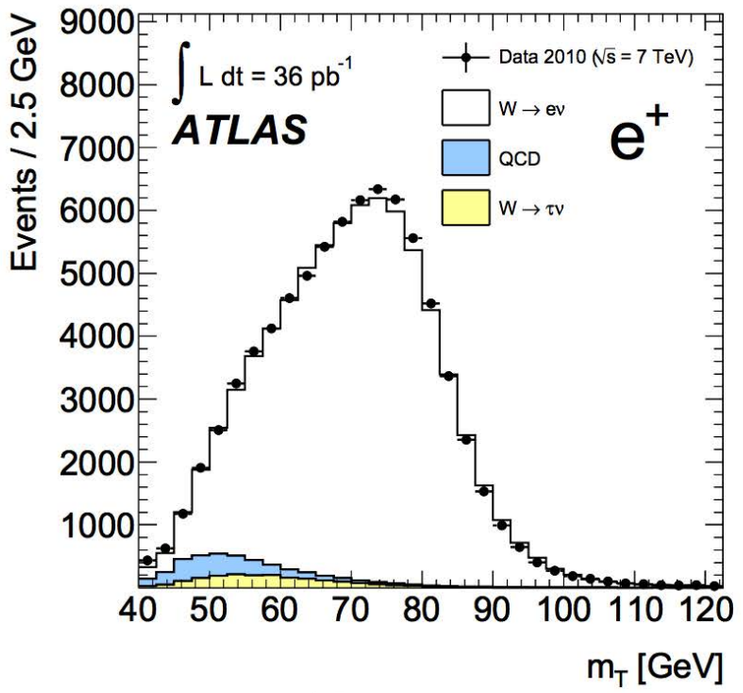
	N	B	$C_{W/Z}$	$A_{W/Z}$
W^+	77885	5130 ± 350	0.693 ± 0.012	0.478 ± 0.008
W^-	52856	4500 ± 240	0.706 ± 0.014	0.452 ± 0.009
$W^\pm$	130741	9610 ± 590	0.698 ± 0.012	0.467 ± 0.007
Z	9725	206 ± 64	0.618 ± 0.016	0.447 ± 0.009

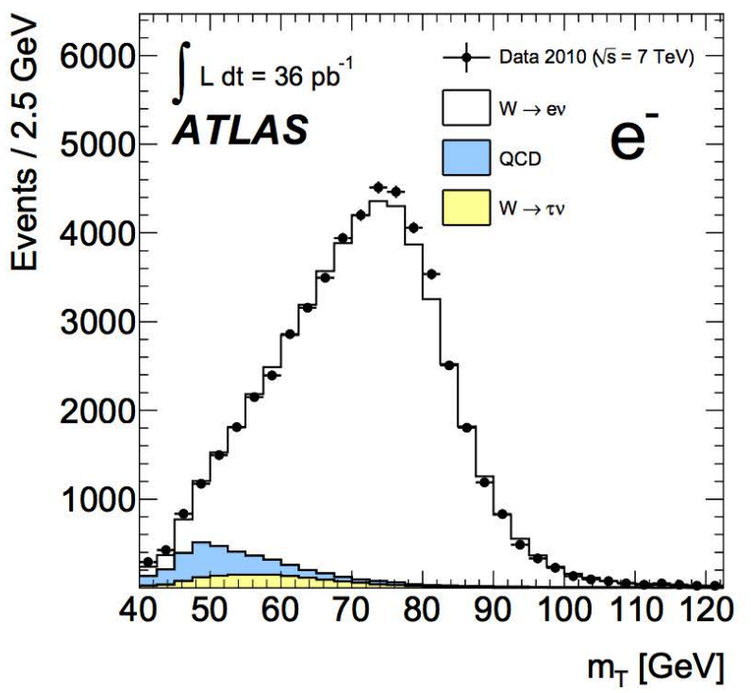
W → eν: transverse energy and mass

- Distributions after all cuts.
- Simulation/QCD background normalized to data/fit.
- QCD background shapes taken from
  - background control samples (E_T).
  - MC simulation with relaxed electron identification criteria (m_T).



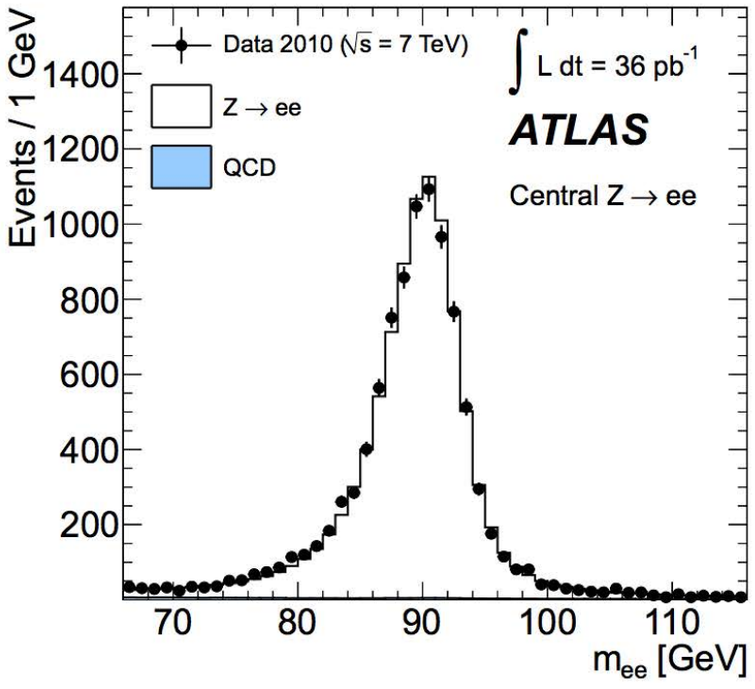


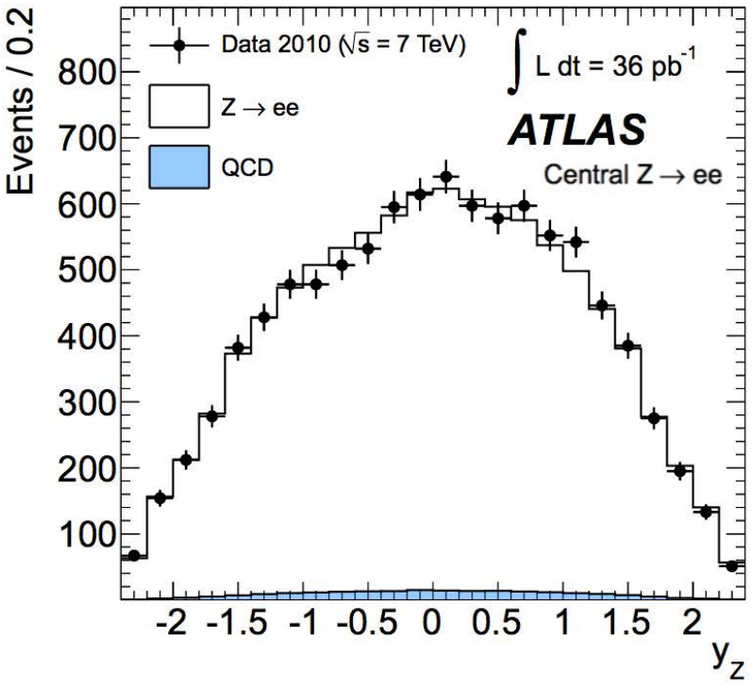


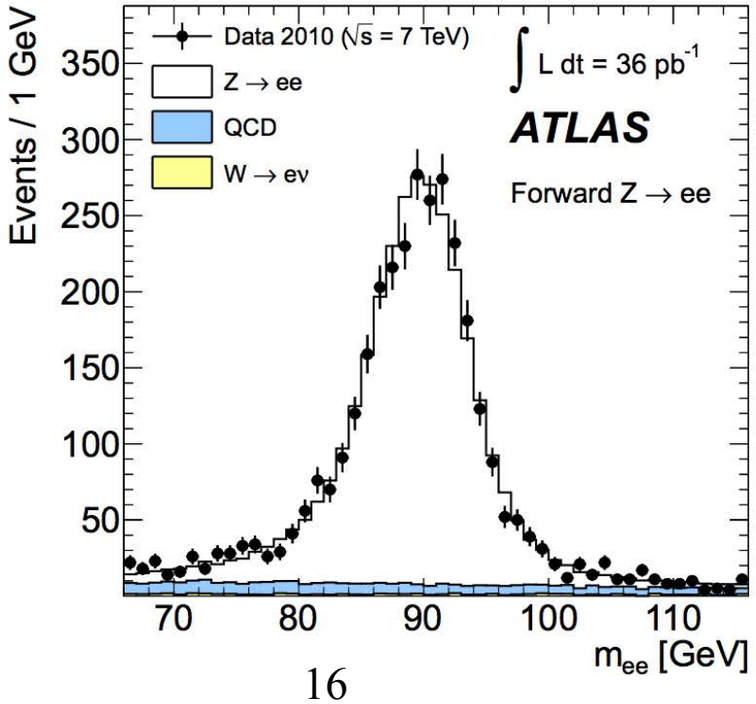


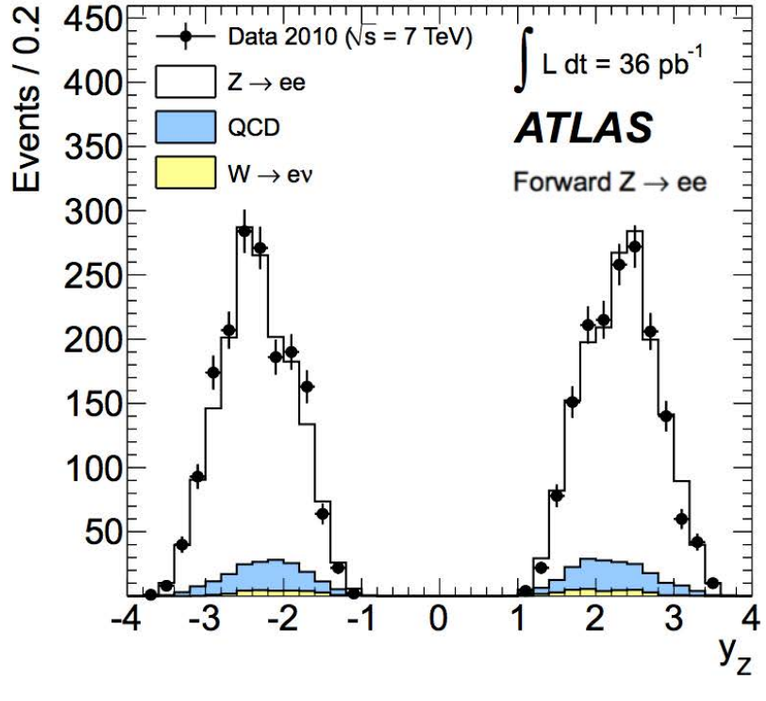
$Z \rightarrow ee$: invariant mass and Z rapidity

- Distributions after all cuts.
- Simulation/QCD background normalized to the data/fit.
- QCD background shapes taken from background control samples.

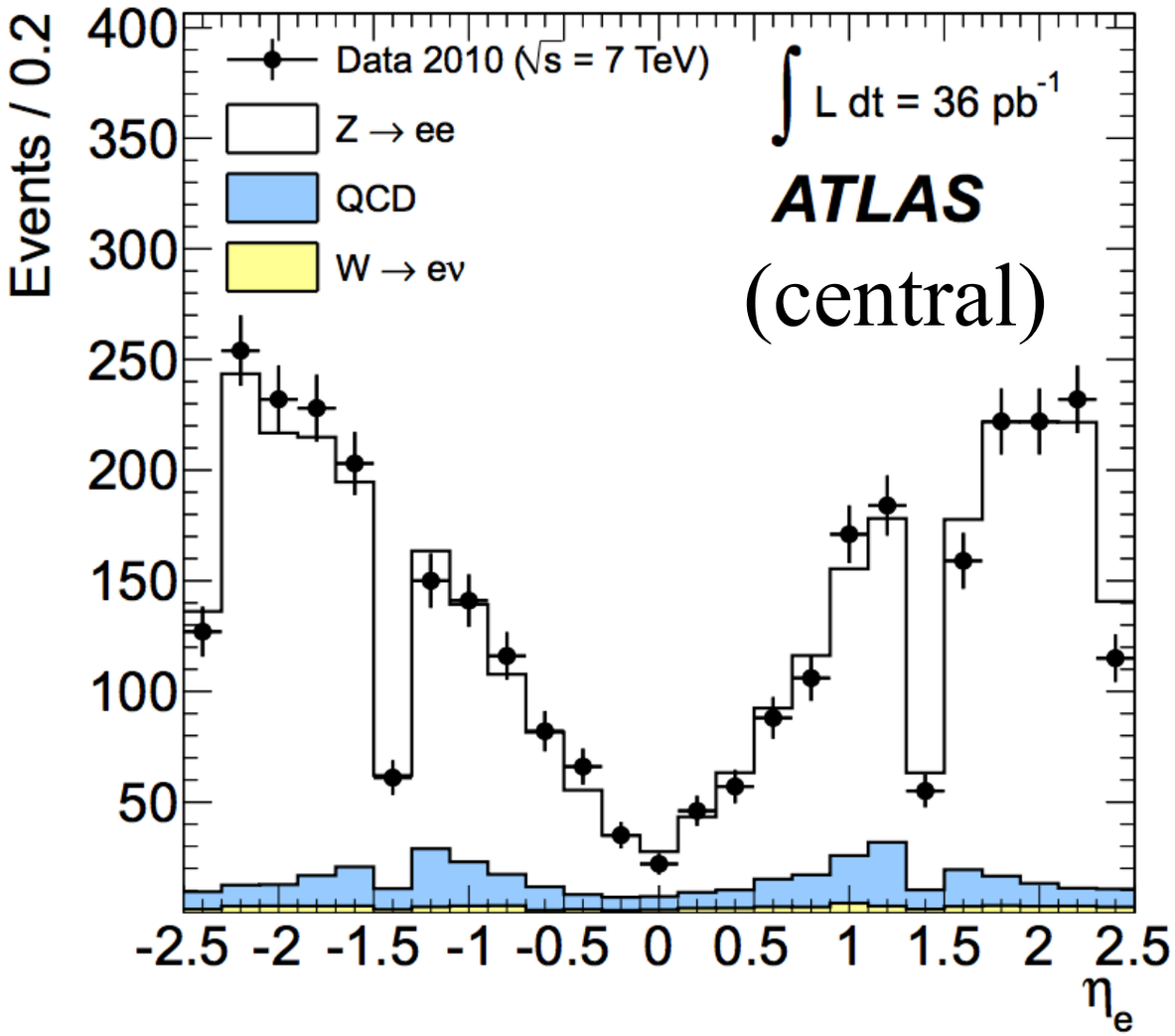


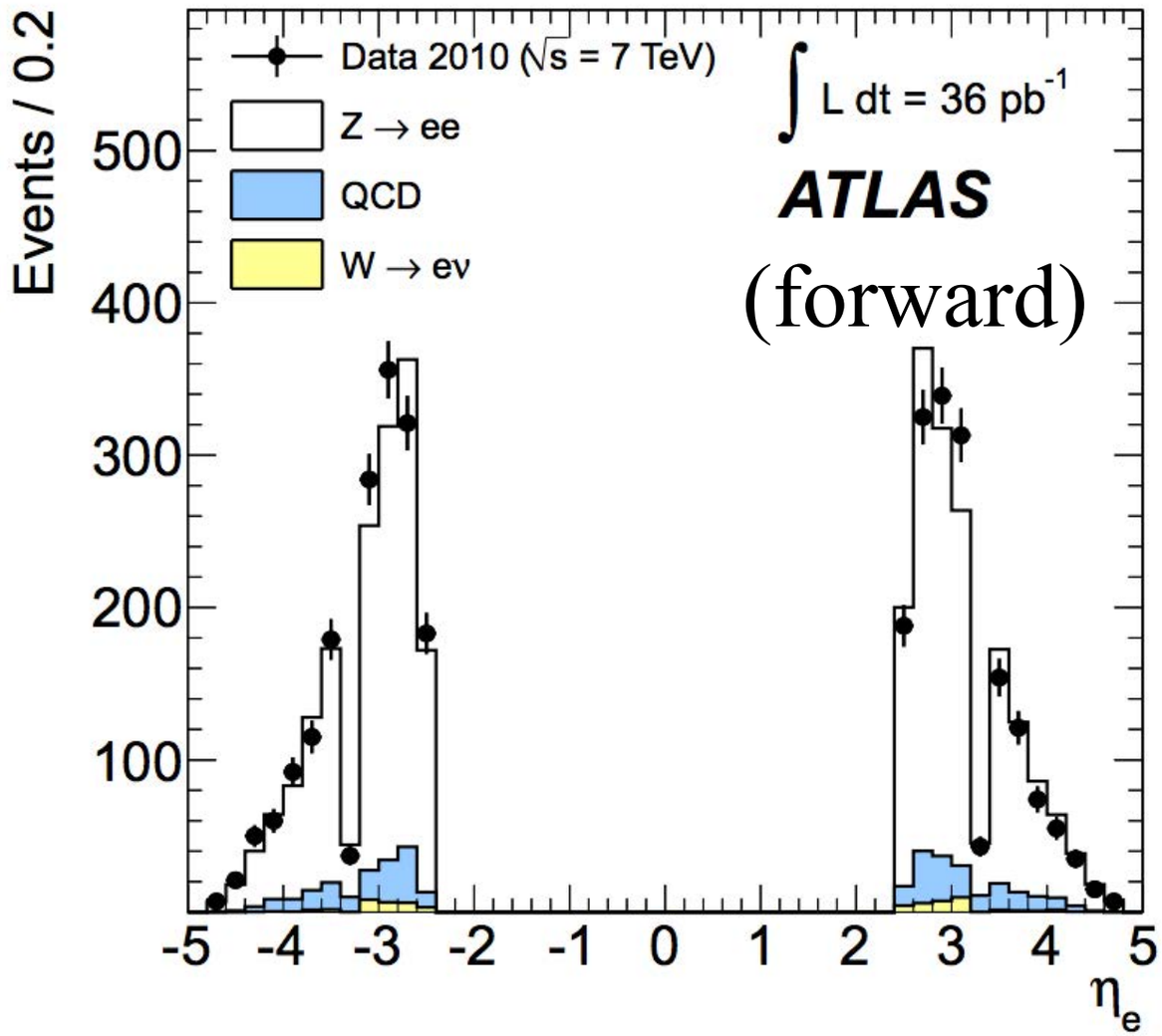






Z → ee: electron pseudorapidity



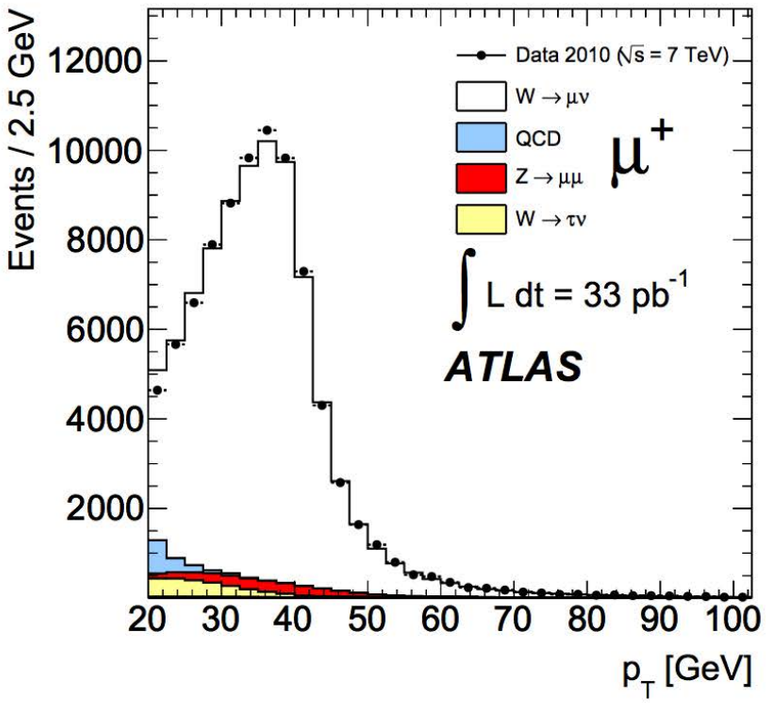


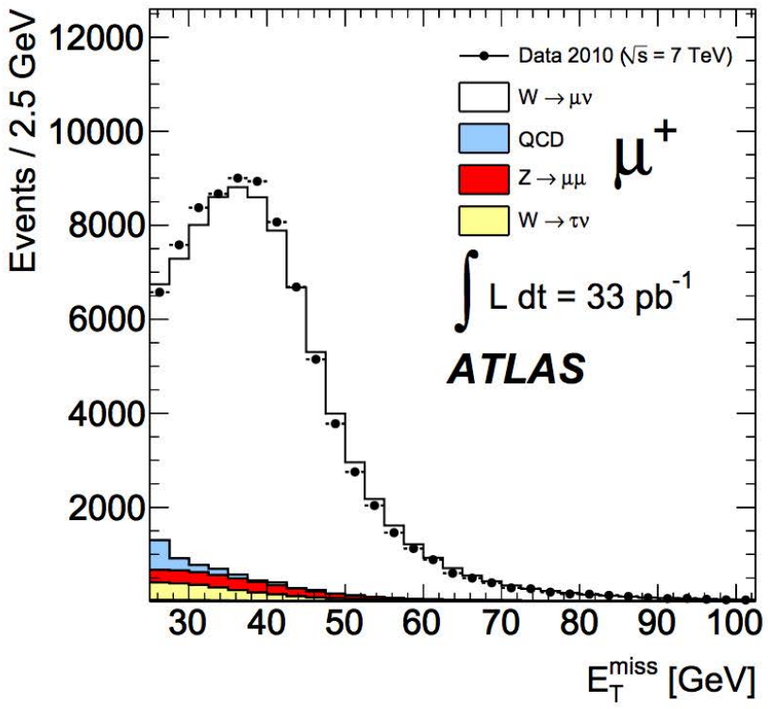
- Distributions after all cuts.
- Simulation/QCD background normalized to the data/fit.

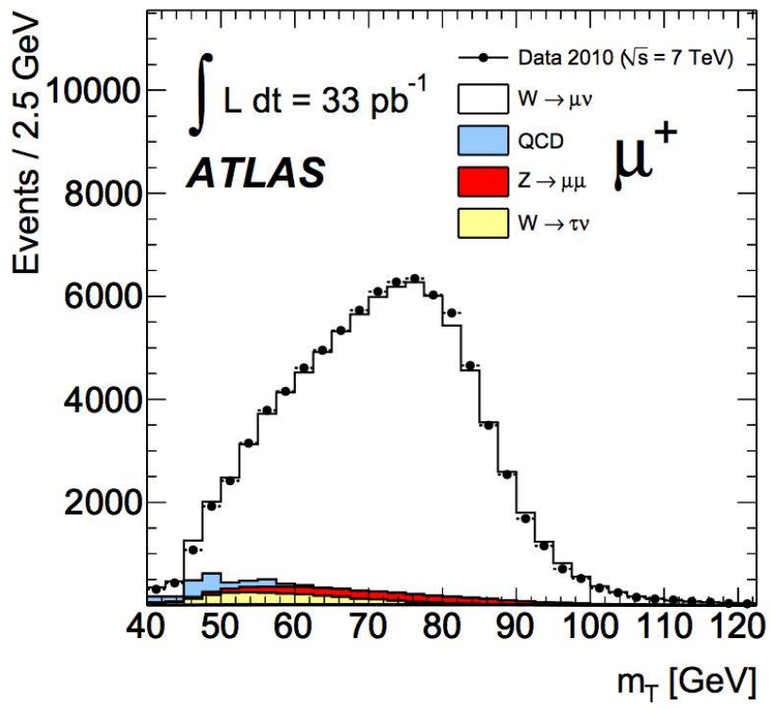
Muon event selection

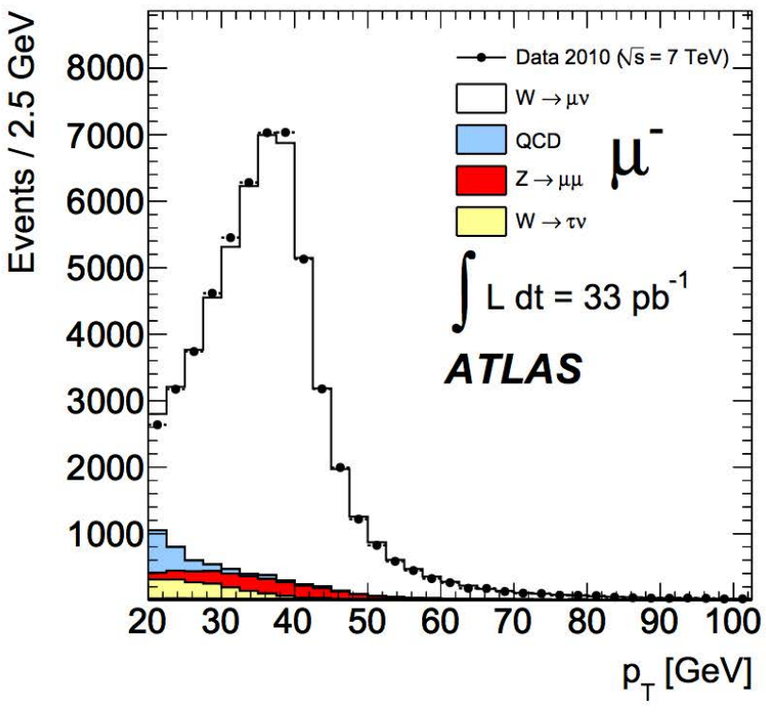
	N	B	$C_{W/Z}$	$A_{W/Z}$
W^+	84514	6600 ± 600	0.796 ± 0.016	0.495 ± 0.008
W^-	55234	5700 ± 600	0.779 ± 0.015	0.470 ± 0.010
$W^\pm$	139748	12300 ± 1100	0.789 ± 0.015	0.485 ± 0.007
Z	11709	86 ± 32	0.782 ± 0.007	0.487 ± 0.010

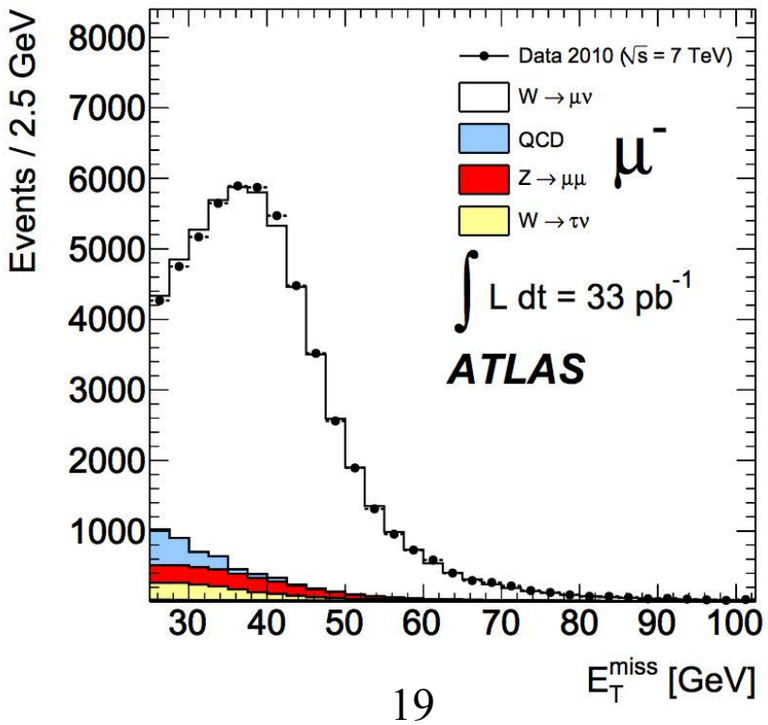
$W \rightarrow \mu\nu$: kinematic variables and transverse mass

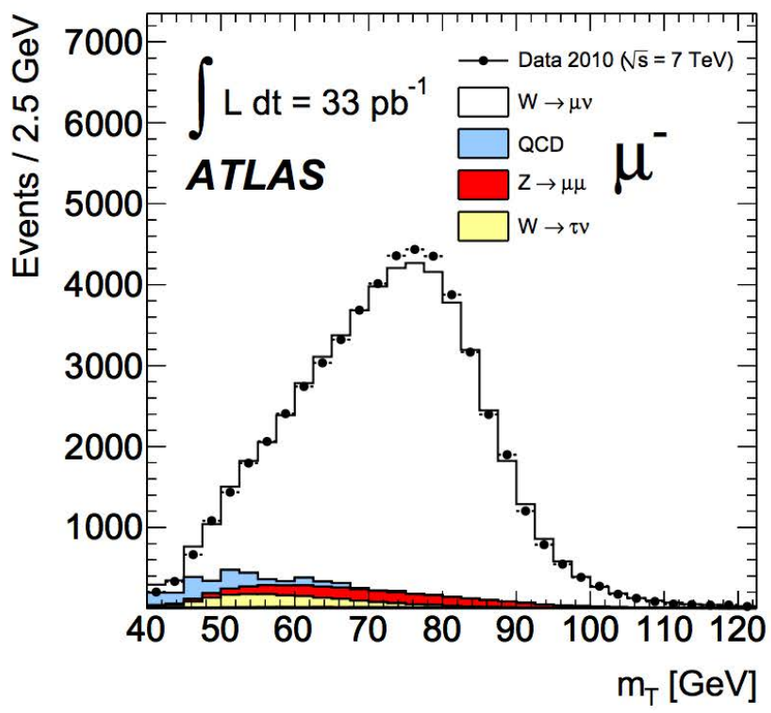




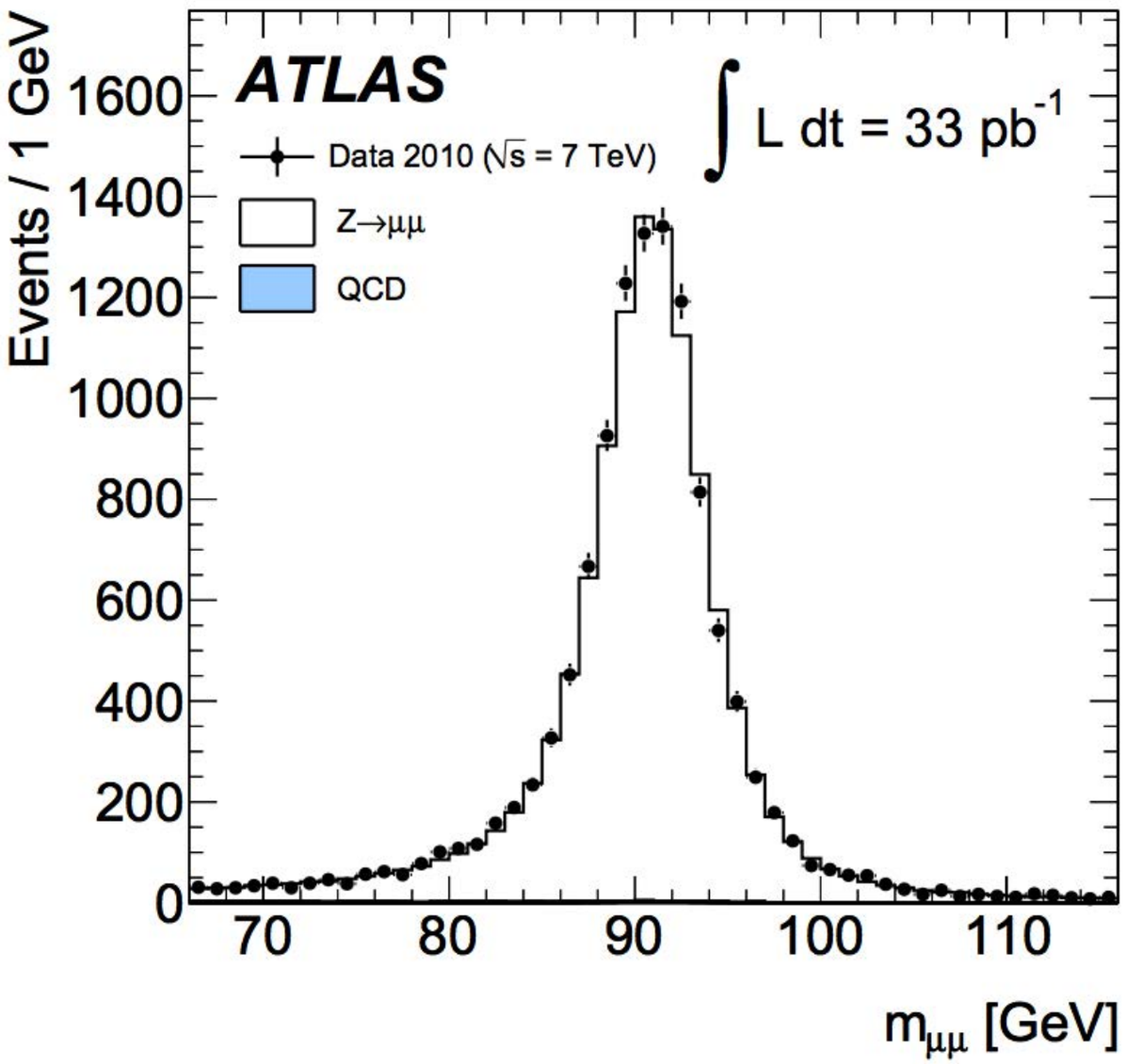


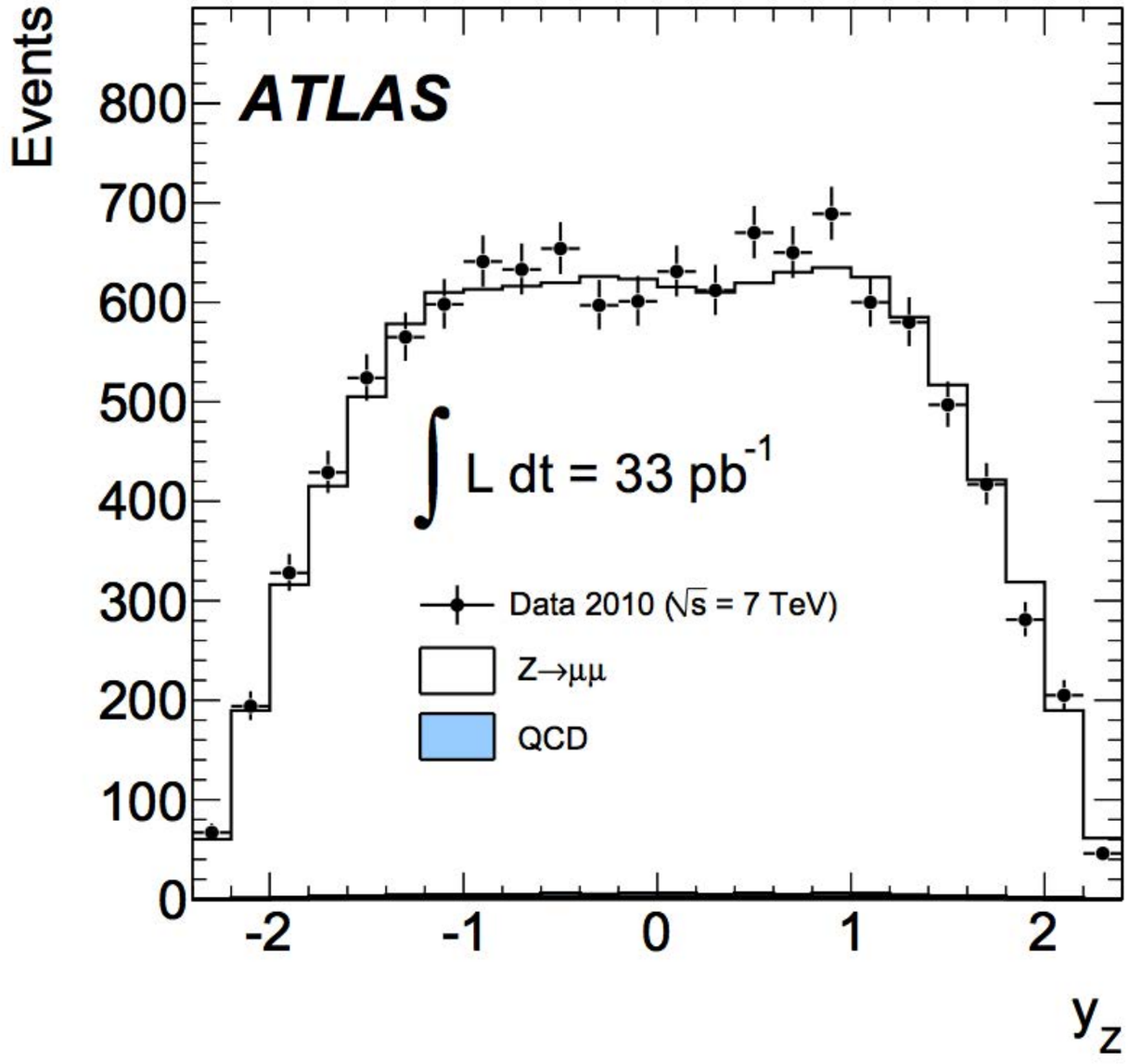






$Z \rightarrow \mu\mu$: invariant mass and Z rapidity





σ_{fid} and σ_{tot} results

$\sigma_W^{fid} \cdot \mathbf{BR}(W \to e\nu)$ [nb]			
	sta	sys	lum
W^+	$2.898 \pm 0.011 \pm 0.052 \pm 0.099$		
W^-	$1.893 \pm 0.009 \pm 0.038 \pm 0.064$		
$W^\pm$	$4.791 \pm 0.014 \pm 0.089 \pm 0.163$		

$\sigma_W^{tot} \cdot \mathbf{BR}(W \to e\nu)$ [nb]				
	sta	sys	lum	acc
W^+	$6.063 \pm 0.023 \pm 0.108 \pm 0.206 \pm 0.104$			
W^-	$4.191 \pm 0.020 \pm 0.085 \pm 0.142 \pm 0.084$			
$W^\pm$	$10.255 \pm 0.031 \pm 0.190 \pm 0.349 \pm 0.156$			

$\sigma_{Z/\gamma^*}^{fid} \cdot \mathbf{BR}(Z/\gamma^* \to ee)$ [nb]			
	sta	sys	lum
Z/γ^*	$0.426 \pm 0.004 \pm 0.012 \pm 0.014$		

$\sigma_{Z/\gamma^*}^{tot} \cdot \mathbf{BR}(Z/\gamma^* \to ee)$ [nb]				
	sta	sys	lum	acc
Z/γ^*	$0.952 \pm 0.010 \pm 0.026 \pm 0.032 \pm 0.019$			

$\sigma_W^{fid} \cdot \mathbf{BR}(W \to \mu\nu)$ [nb]			
	sta	sys	lum
W^+	$3.002 \pm 0.011 \pm 0.050 \pm 0.102$		
W^-	$1.948 \pm 0.009 \pm 0.034 \pm 0.066$		
$W^\pm$	$4.949 \pm 0.015 \pm 0.081 \pm 0.168$		

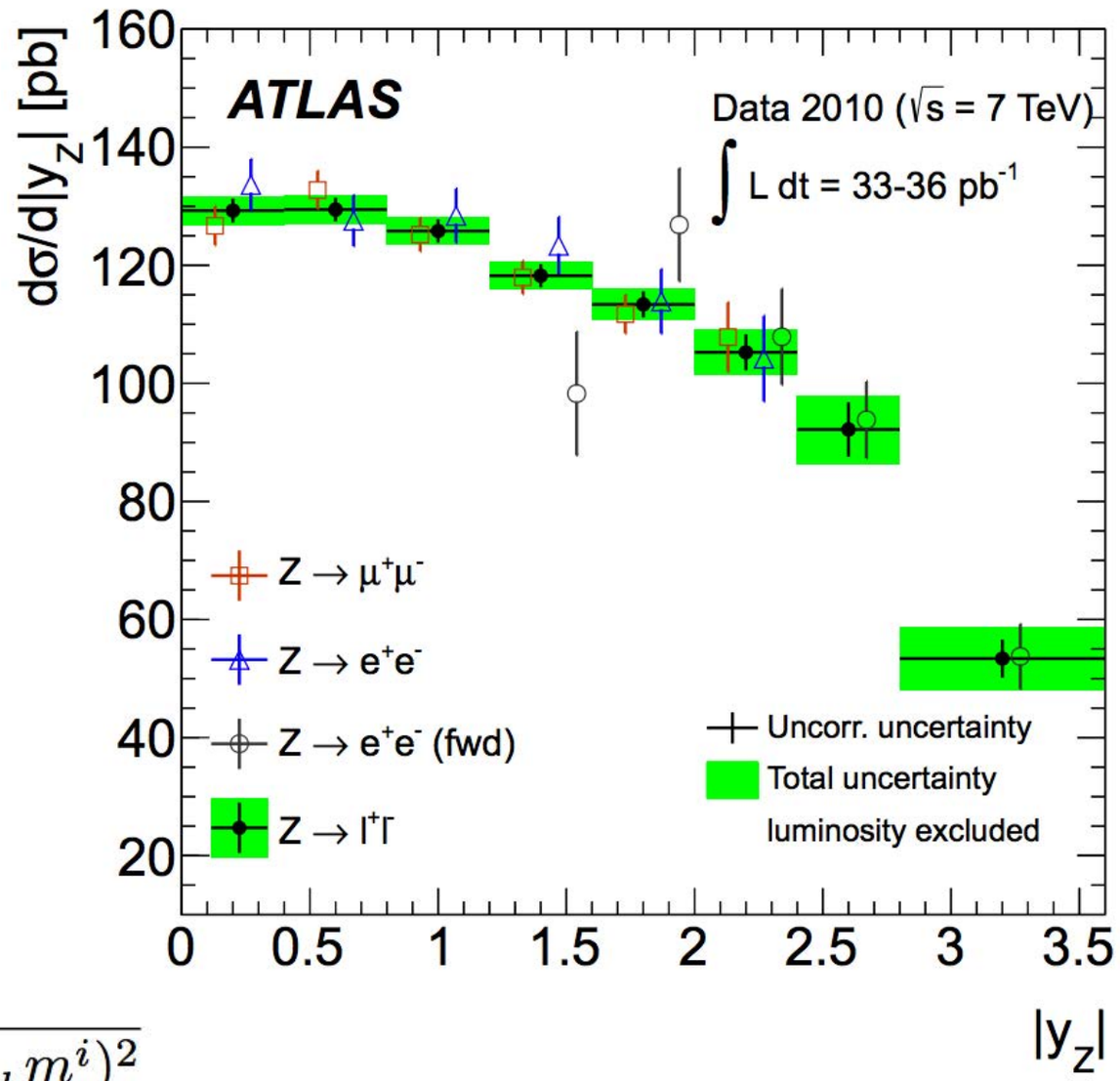
$\sigma_W^{tot} \cdot \mathbf{BR}(W \to \mu\nu)$ [nb]				
	sta	sys	lum	acc
W^+	$6.062 \pm 0.023 \pm 0.101 \pm 0.206 \pm 0.099$			
W^-	$4.145 \pm 0.020 \pm 0.072 \pm 0.141 \pm 0.086$			
$W^\pm$	$10.210 \pm 0.030 \pm 0.166 \pm 0.347 \pm 0.153$			

$\sigma_{Z/\gamma^*}^{fid} \cdot \mathbf{BR}(Z/\gamma^* \to \mu\mu)$ [nb]			
	sta	sys	lum
Z/γ^*	$0.456 \pm 0.004 \pm 0.004 \pm 0.015$		

$\sigma_{Z/\gamma^*}^{tot} \cdot \mathbf{BR}(Z/\gamma^* \to \mu\mu)$ [nb]				
	sta	sys	lum	acc
Z/γ^*	$0.935 \pm 0.009 \pm 0.009 \pm 0.032 \pm 0.019$			

Combining data

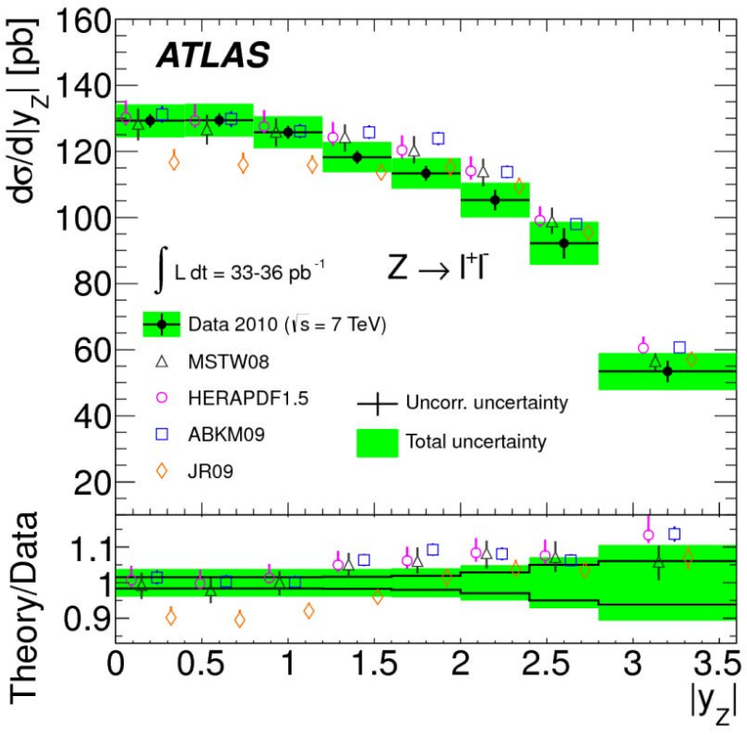
- Measured σ's can be combined for both e and μ channels to decrease uncertainty assuming lepton universality.
- 59 differential cross section measurements
- 30 sources of correlated uncertainty
- Special averaging procedure minimizes χ^2 :

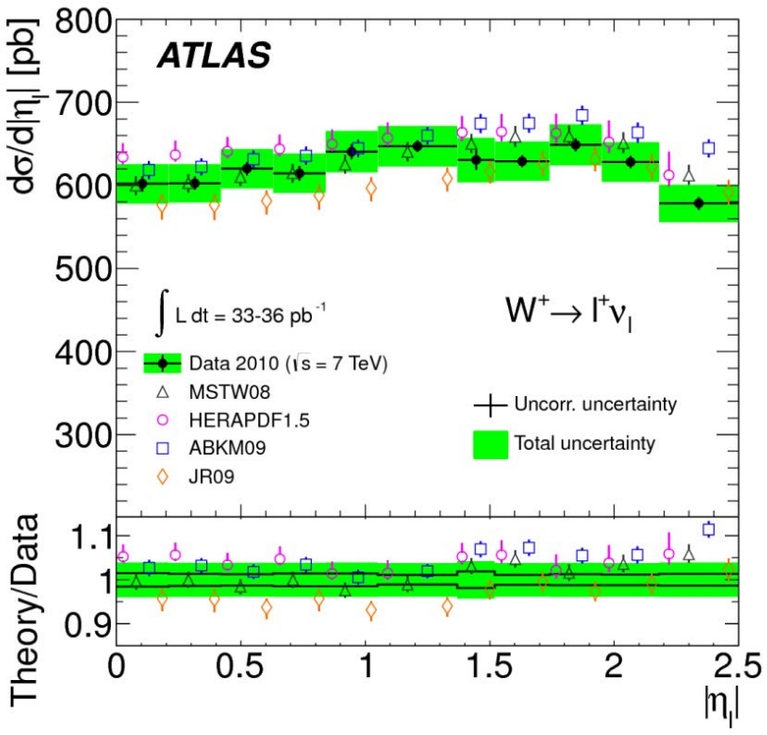


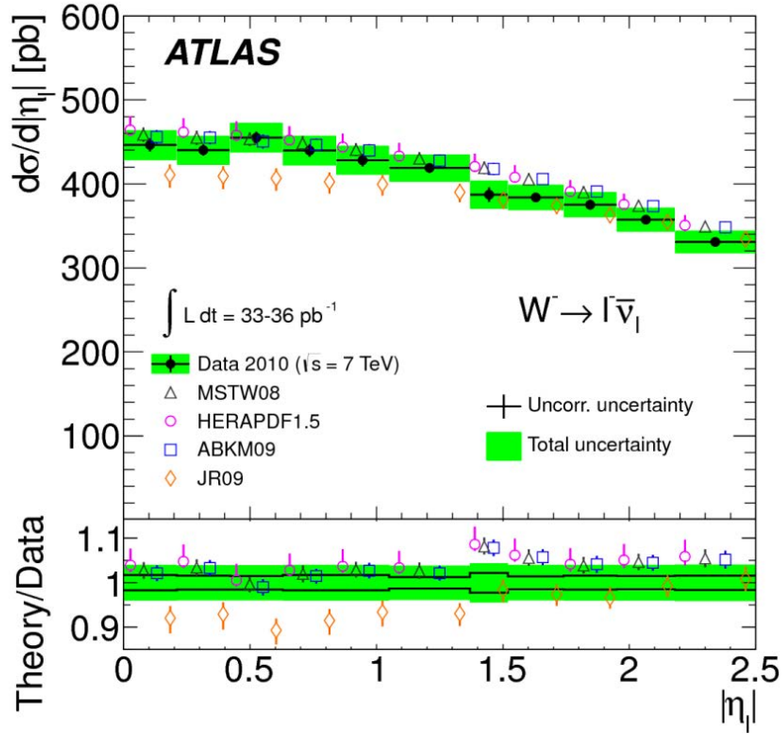
$$\chi^2 = \sum_{k,i} w_k^i \frac{\left[m^i - \left(\mu_k^i + \sum_j \gamma_{j,k}^i m^i b_j\right)\right]^2}{(\delta_{\mathrm{sta},k}^i)^2 \mu_k^i (m^i - \sum_j \gamma_{j,k}^i m^i b_j) + (\delta_{\mathrm{unc},k}^i m^i)^2} + \sum_j b_j^2.$$

$\chi 2/\mathrm{dof} = 33.9/29$ (all), $15.5/9$ (Z), $10.2/10$ (W^+), $7.0/10$ (W^-)

Final differential cross section results and theory comparison







- $d\sigma/d|y_Z|$ and $d\sigma/d|\eta_l|$ compared to NNLO theoretical predictions with various PDF sets.
- Kinematic requirements:

$66 < m_{ll} < 116$ GeV, $p_{T,l} > 20$ GeV, $p_{T,\nu} > 25$ GeV, and $m_T > 40$ GeV

W charge asymmetry

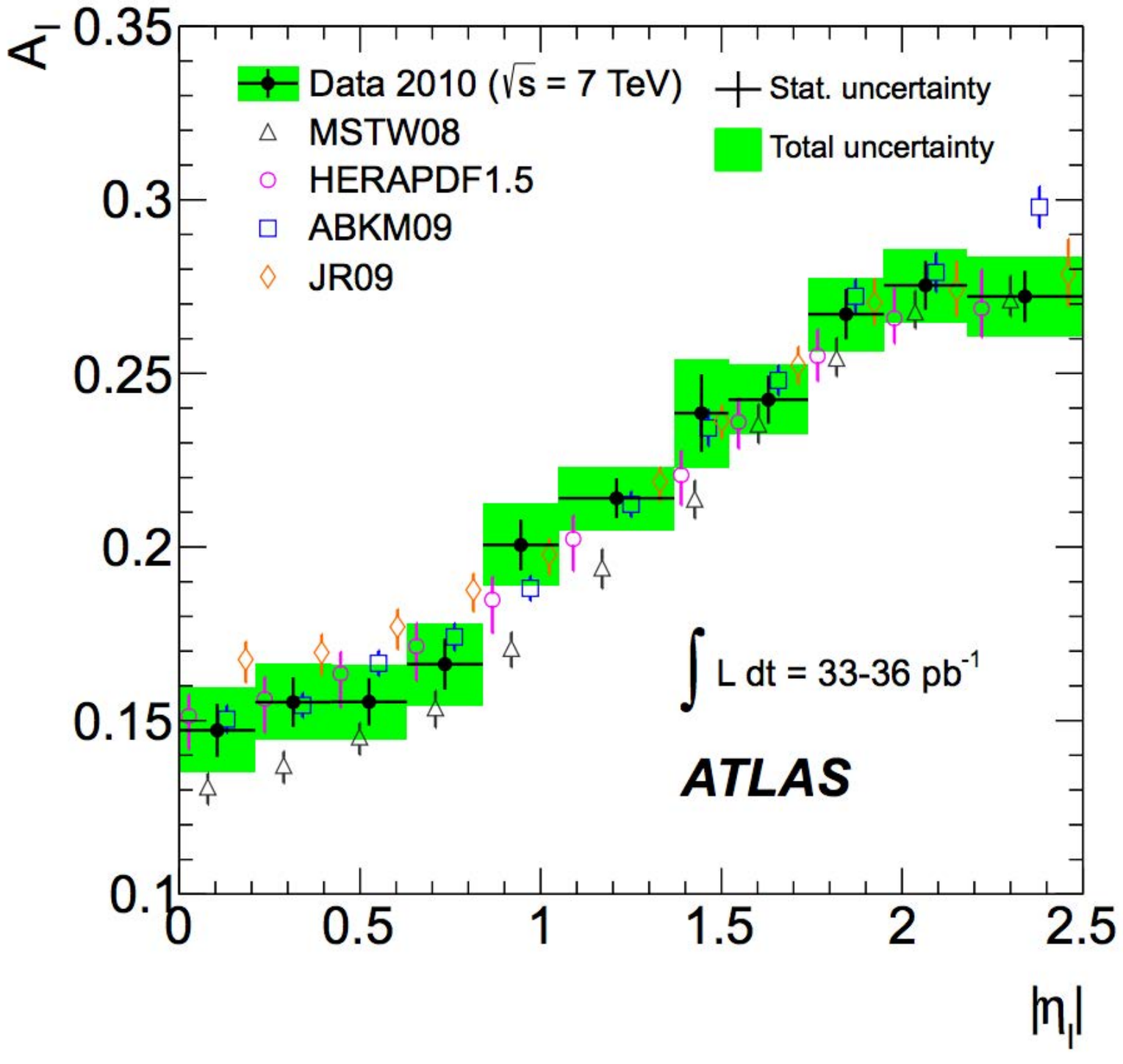
- Measured W charge asymmetry as a function of lepton pseudorapidity compared to NNLO theoretical predictions with various PDF sets.

- Calculated from differential cross section data:

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

- Kinematic requirements:

$p_{T,l} > 20$ *GeV*, $p_{T,\nu} > 25$ *GeV*, and $m_T > 40$ *GeV*



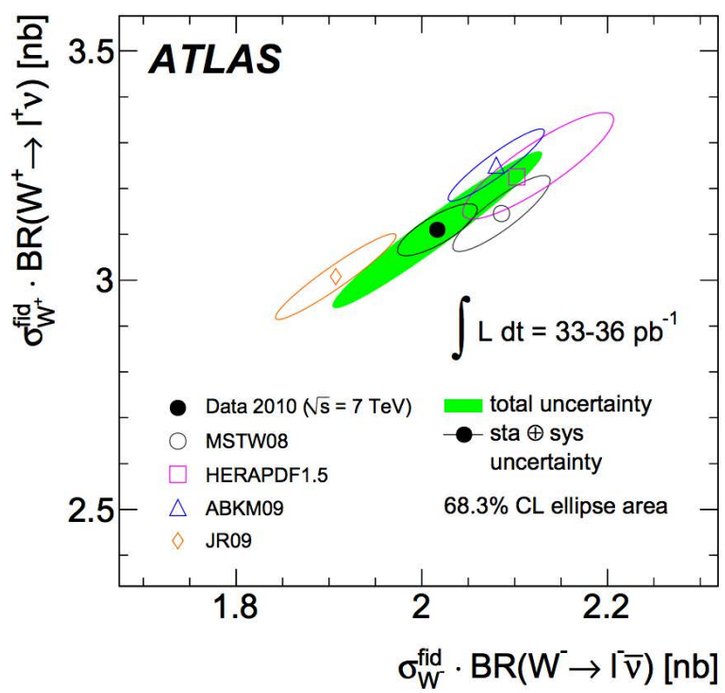
Integrated cross sections

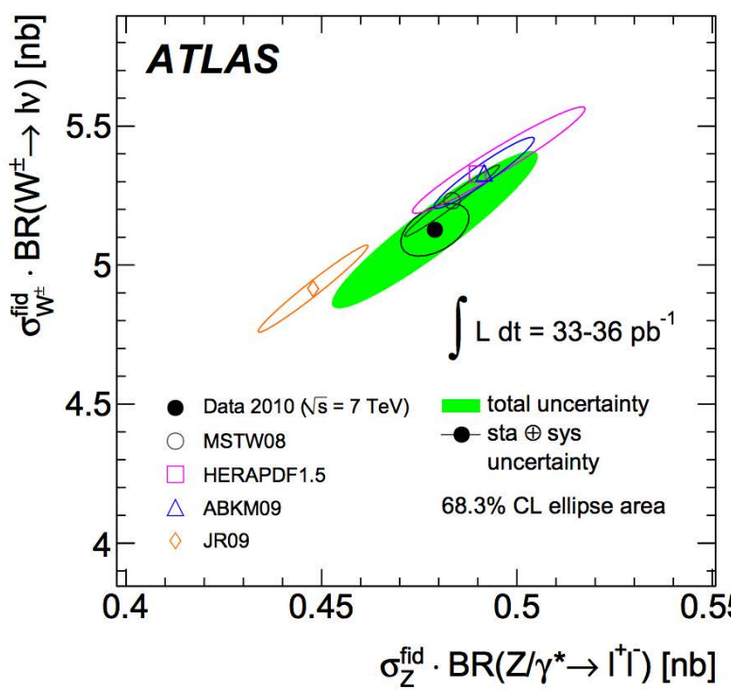
$\sigma_W^{\text{fid}} \cdot \mathbf{BR}(W \to \ell\nu)$ [nb]				
$\lvert\eta_\ell\rvert < 2.5$, $p_{T,\ell} > 20$ GeV,				
$p_{T,\nu} > 25$ GeV and $m_T > 40$ GeV				
	sta	sys	lum	acc
W^+	$3.110 \pm 0.008 \pm 0.036 \pm 0.106 \pm 0.004$			
W^-	$2.017 \pm 0.007 \pm 0.028 \pm 0.069 \pm 0.002$			
$W^\pm$	$5.127 \pm 0.011 \pm 0.061 \pm 0.174 \pm 0.005$			

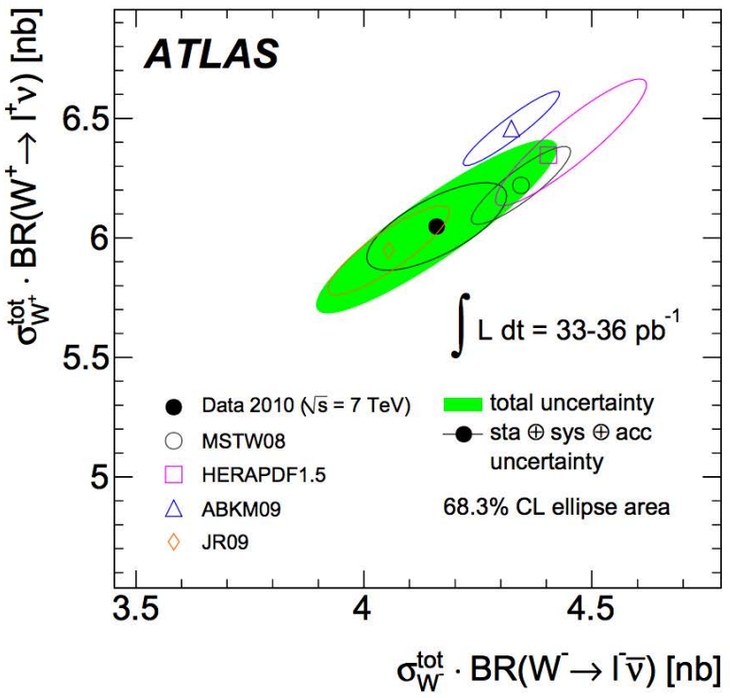
$\sigma_{Z/\gamma^*}^{\text{fid}} \cdot \mathbf{BR}(Z/\gamma^* \to \ell\ell)$ [nb]				
$\lvert\eta_\ell\rvert < 2.5$, $p_{T,\ell} > 20$ GeV				
and $66 < m_{\ell\ell} < 116$ GeV				
	sta	sys	lum	acc
Z/γ^*	$0.479 \pm 0.003 \pm 0.005 \pm 0.016 \pm 0.001$			

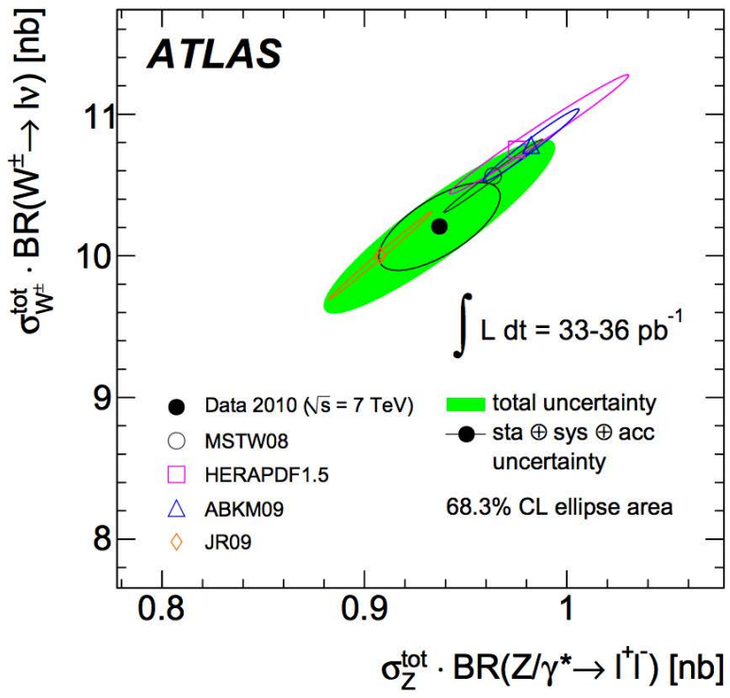
$\sigma_W^{\text{tot}} \cdot \mathbf{BR}(W \to \ell\nu)$ [nb]				
	sta	sys	lum	acc
W^+	$6.048 \pm 0.016 \pm 0.072 \pm 0.206 \pm 0.096$			
W^-	$4.160 \pm 0.014 \pm 0.057 \pm 0.141 \pm 0.083$			
$W^\pm$	$10.207 \pm 0.021 \pm 0.121 \pm 0.347 \pm 0.164$			

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







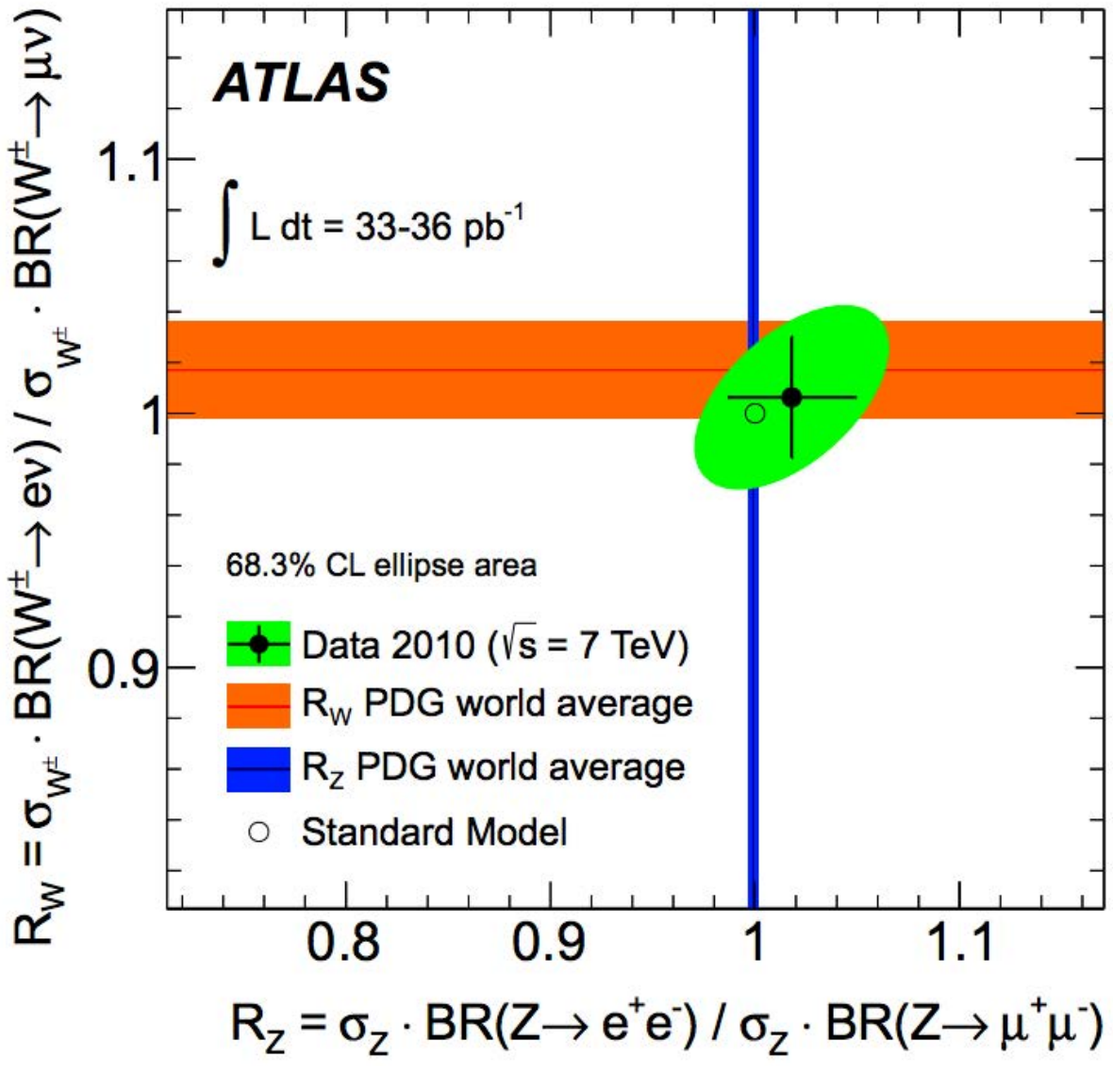


Ratios of cross sections: e–μ universality

Results:

$$R_W = \frac{\sigma_W^e}{\sigma_W^\mu} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)}$$
$$= 1.006 \pm 0.004\,(\text{sta}) \pm 0.006\,(\text{unc}) \pm 0.022\,(\text{cor})$$
$$= 1.006 \pm 0.024.$$

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



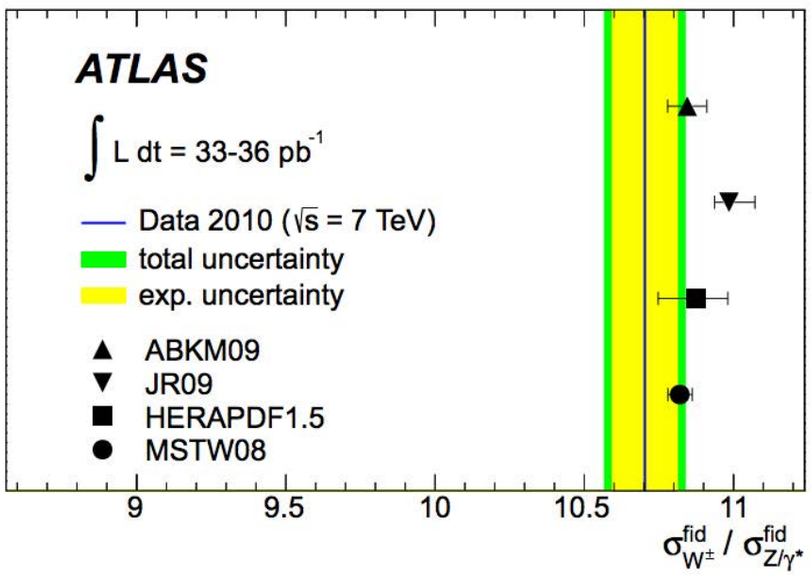
World averages:

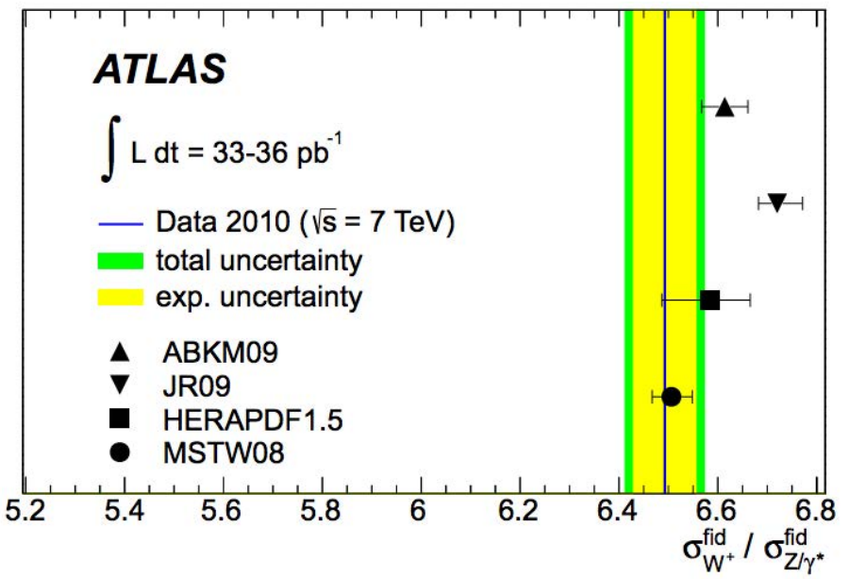
$R_W = 1.017 \pm 0.019$

$R_Z = 0.9991 \pm 0.0024$

↳ using R_Z *(world avg.)* as constraint, R_W *(experimental)* $= 0.999 \pm 0.020$

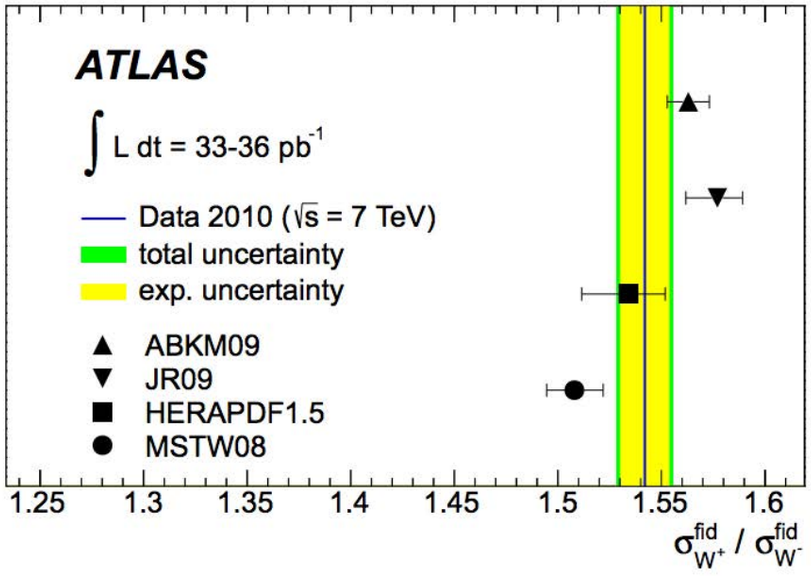
Combined cross section ratios

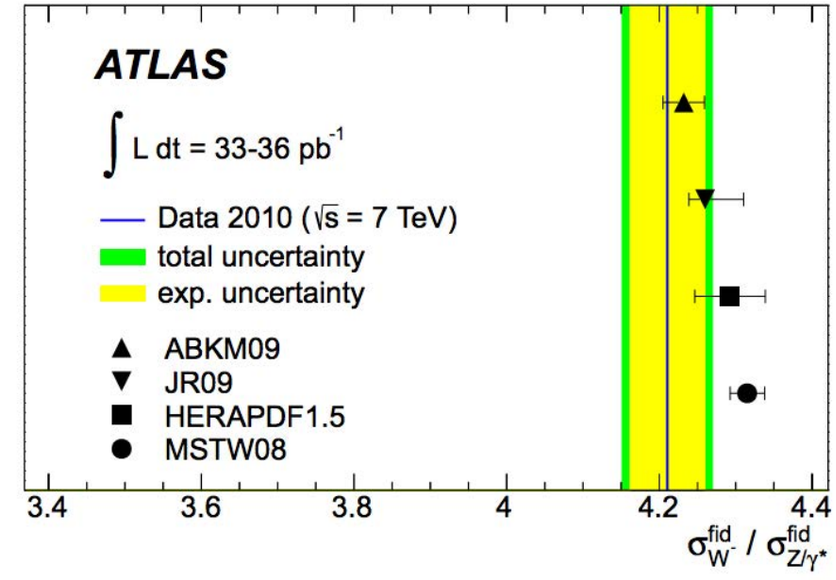




Fiducial:

	sta	sys	acc
W^+/W^-	$1.542 \pm 0.007 \pm 0.012 \pm 0.001$		
W^+/Z	$6.493 \pm 0.049 \pm 0.064 \pm 0.005$		
W^-/Z	$4.210 \pm 0.033 \pm 0.049 \pm 0.003$		
$W^\pm/Z$	$10.703 \pm 0.078 \pm 0.110 \pm 0.008$		



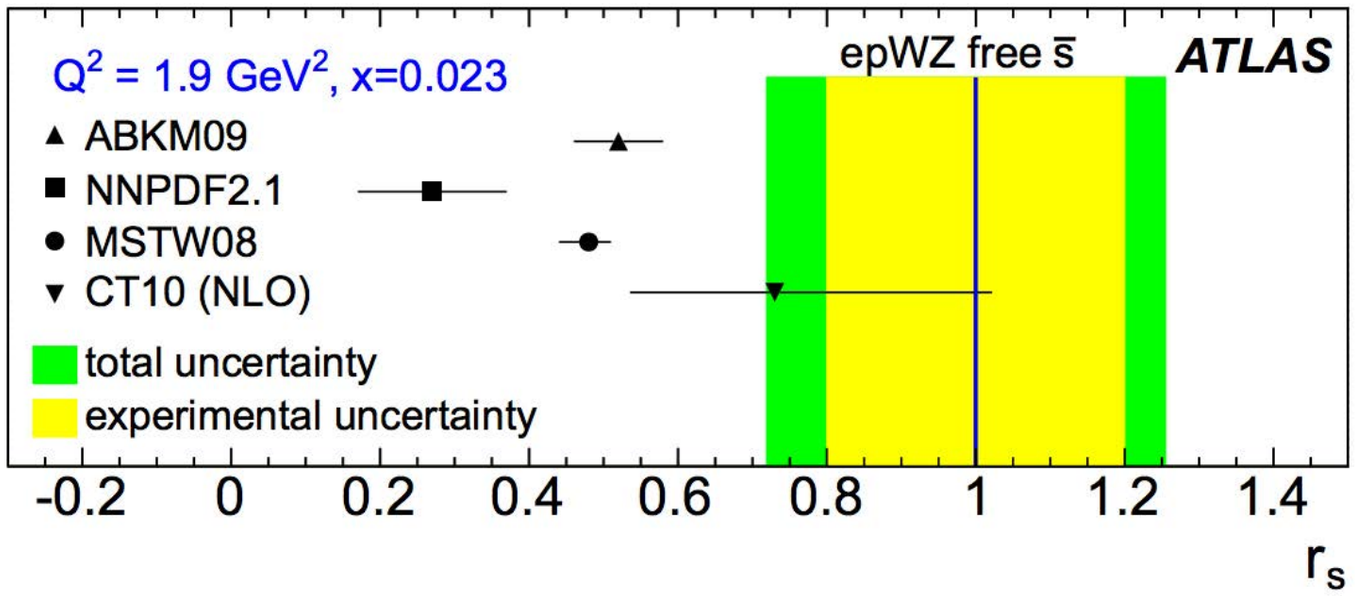


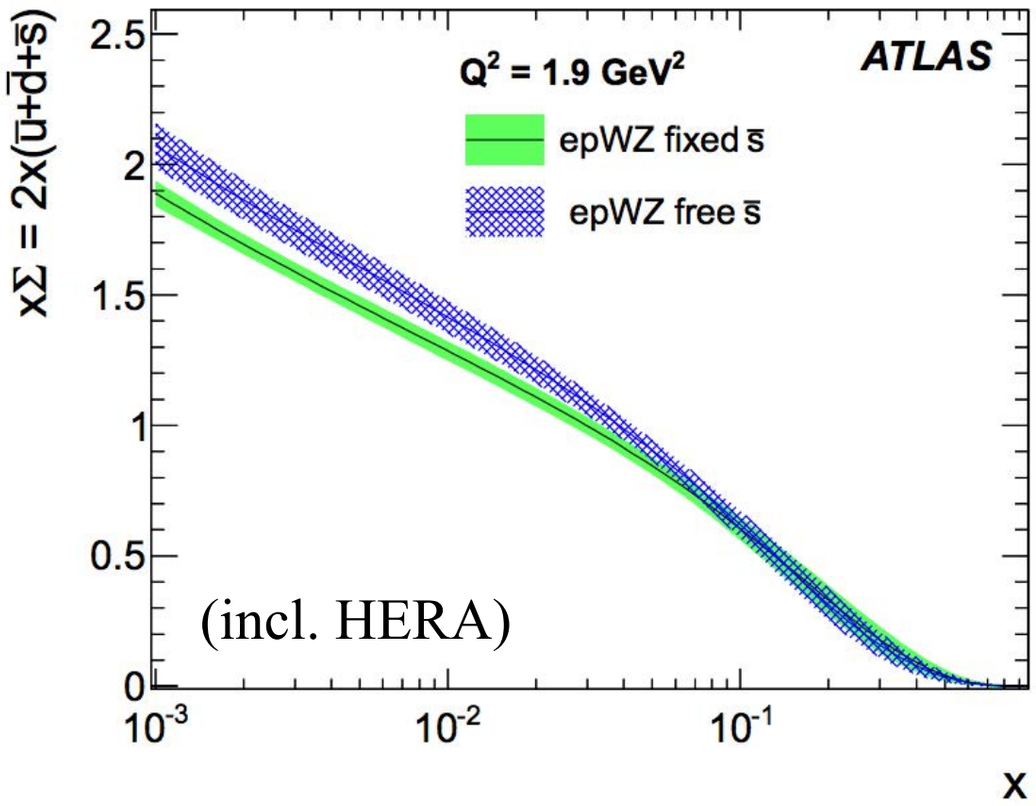
Total (extrapolated):

	sta	sys	acc
W^+/W^-	$1.454 \pm 0.006 \pm 0.012 \pm 0.022$		
W^+/Z	$6.454 \pm 0.048 \pm 0.065 \pm 0.072$		
W^-/Z	$4.439 \pm 0.034 \pm 0.050 \pm 0.049$		
$W^\pm/Z$	$10.893 \pm 0.079 \pm 0.110 \pm 0.116$		

- ratios of W^+/W^-, W^+/Z, W^-/Z and $(W^+ + W^-)/Z$, combining the electron and muon final states.
- Experimental uncertainty (yellow) includes systematics; total uncertainty (green) includes statistics and acceptance correction. Uncertainties are 68% CL.

QCD: strange quark density of the proton





- At Bjorken $x = 0.023$, initial QCD fit scale $Q_0^2 = 1.9$ GeV^2:

$$r_s = \frac{(s+\bar{s})}{2\bar{d}} = 1.00^{+0.25}_{-0.28}$$

- Consistent with other experiments/
- Combined HERA, ATLAS, CDF:

$$r_s = 0.95 \pm 0.17_{exp}$$

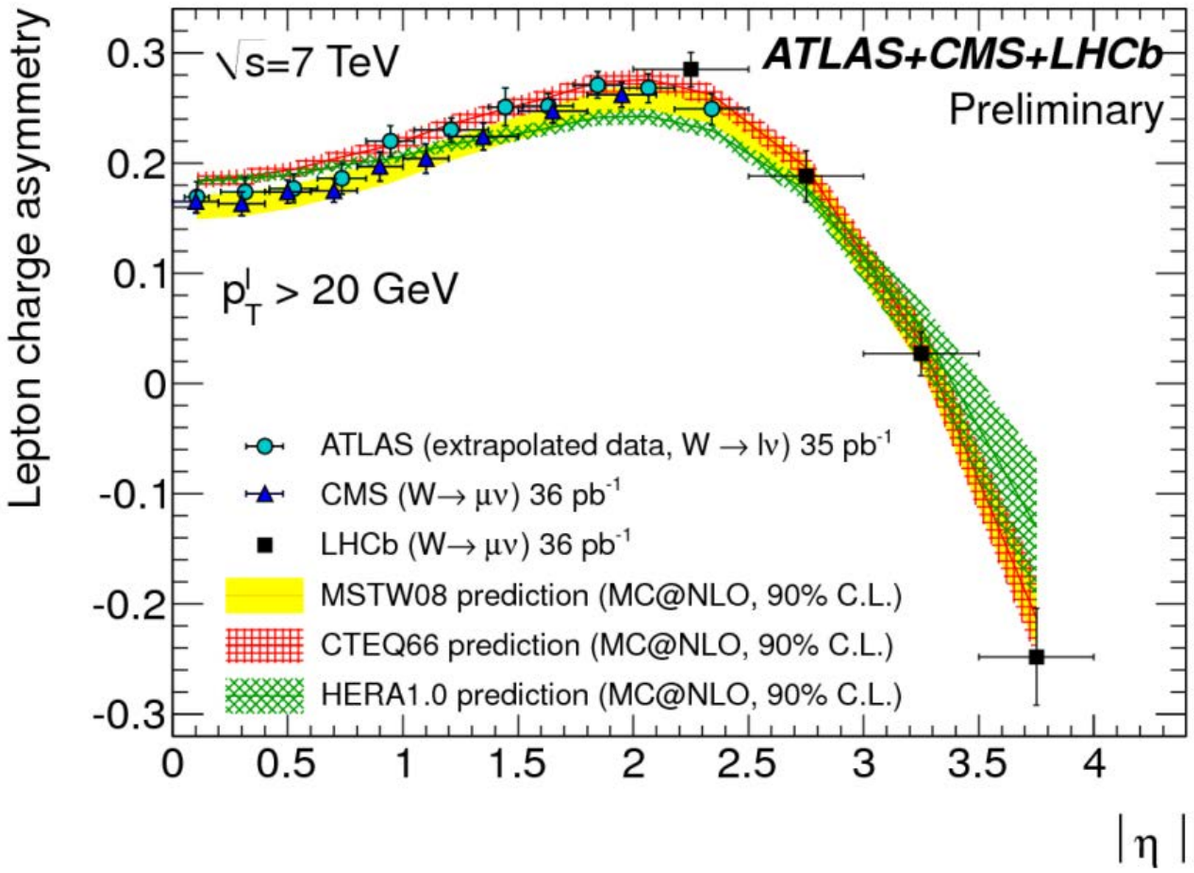
- Light quark sea at low x is flavor symmetric
- total sea

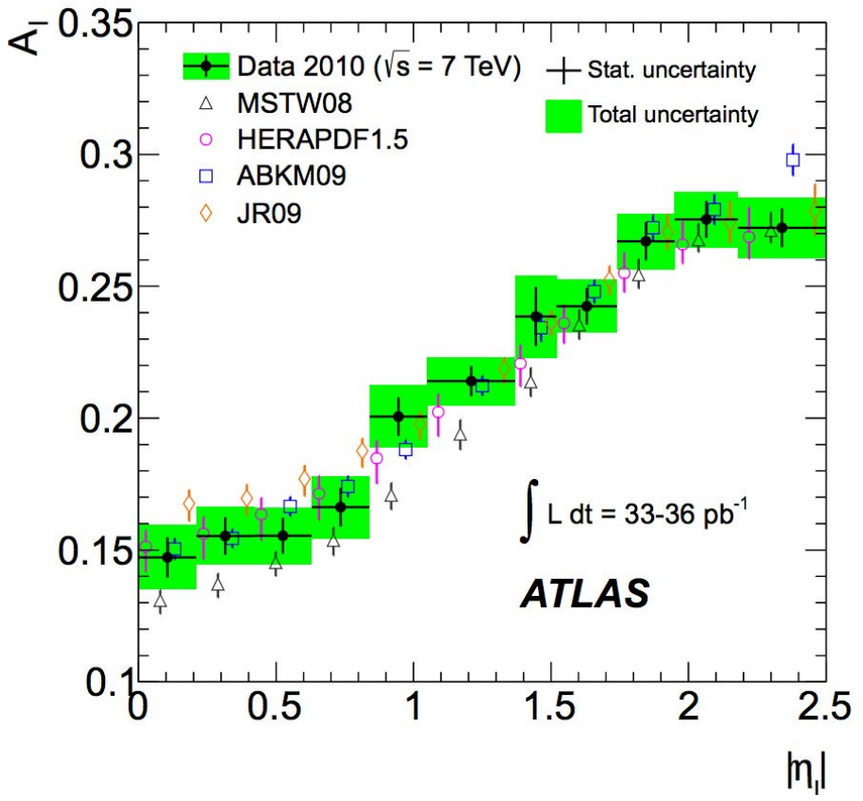
$$x\Sigma = 2x(\bar{u} + \bar{d} + \bar{s})$$

enhanced by ~8% compared to situation where $s \sim 0.5d$ (models).

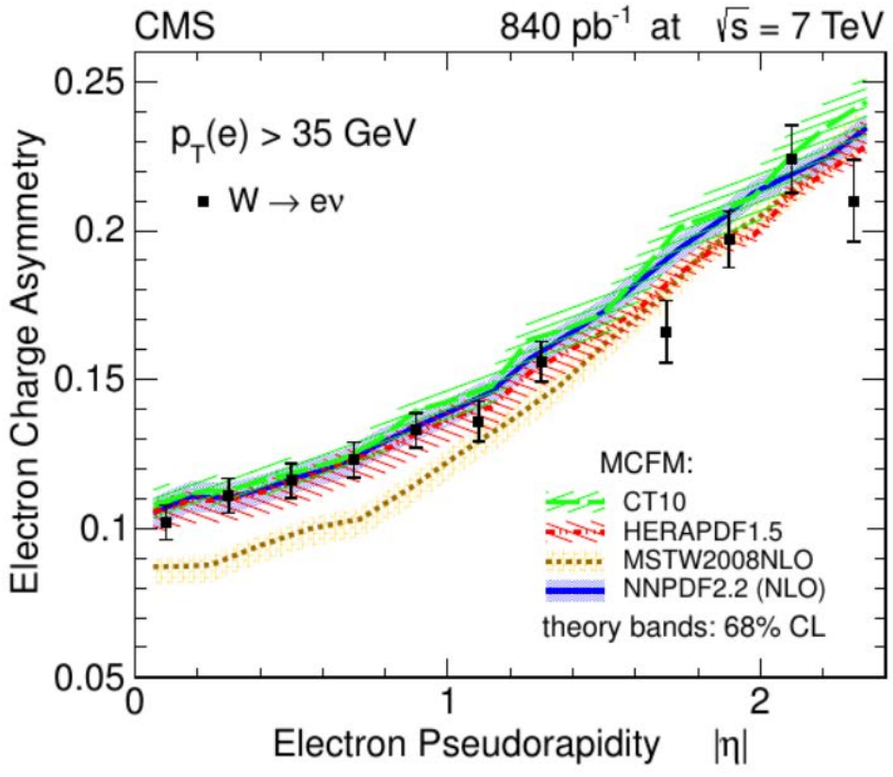
Similar measurements with other experiments…

W charge asymmetry

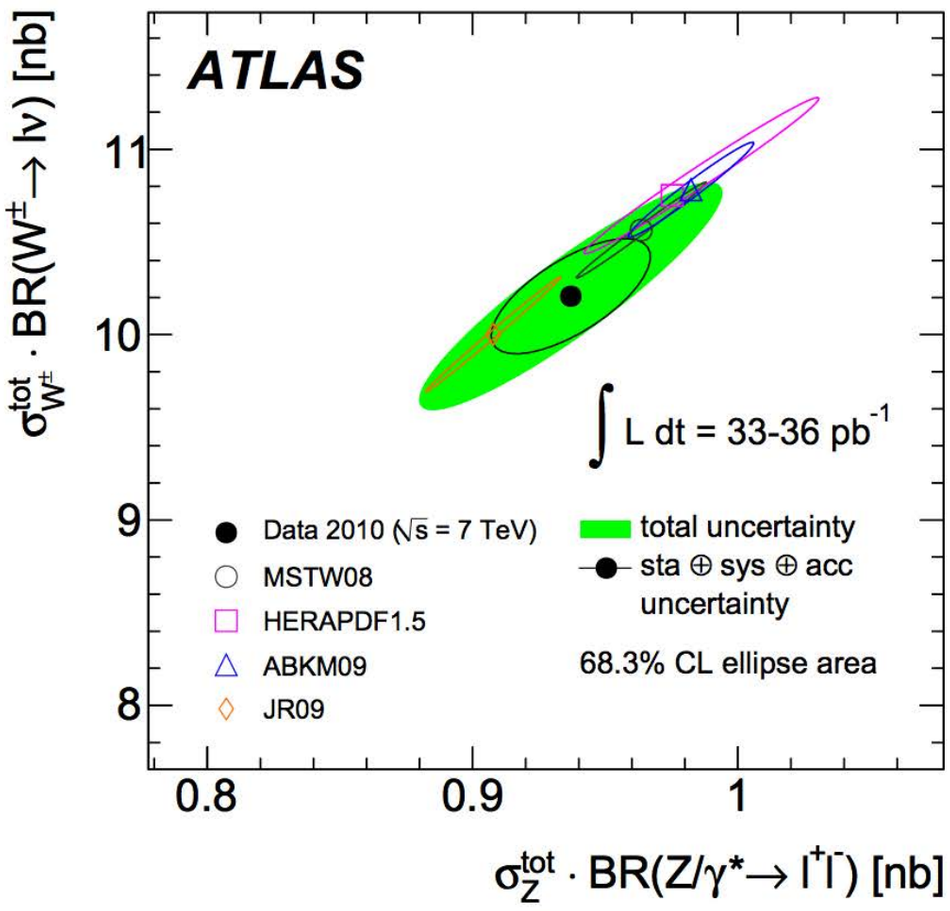


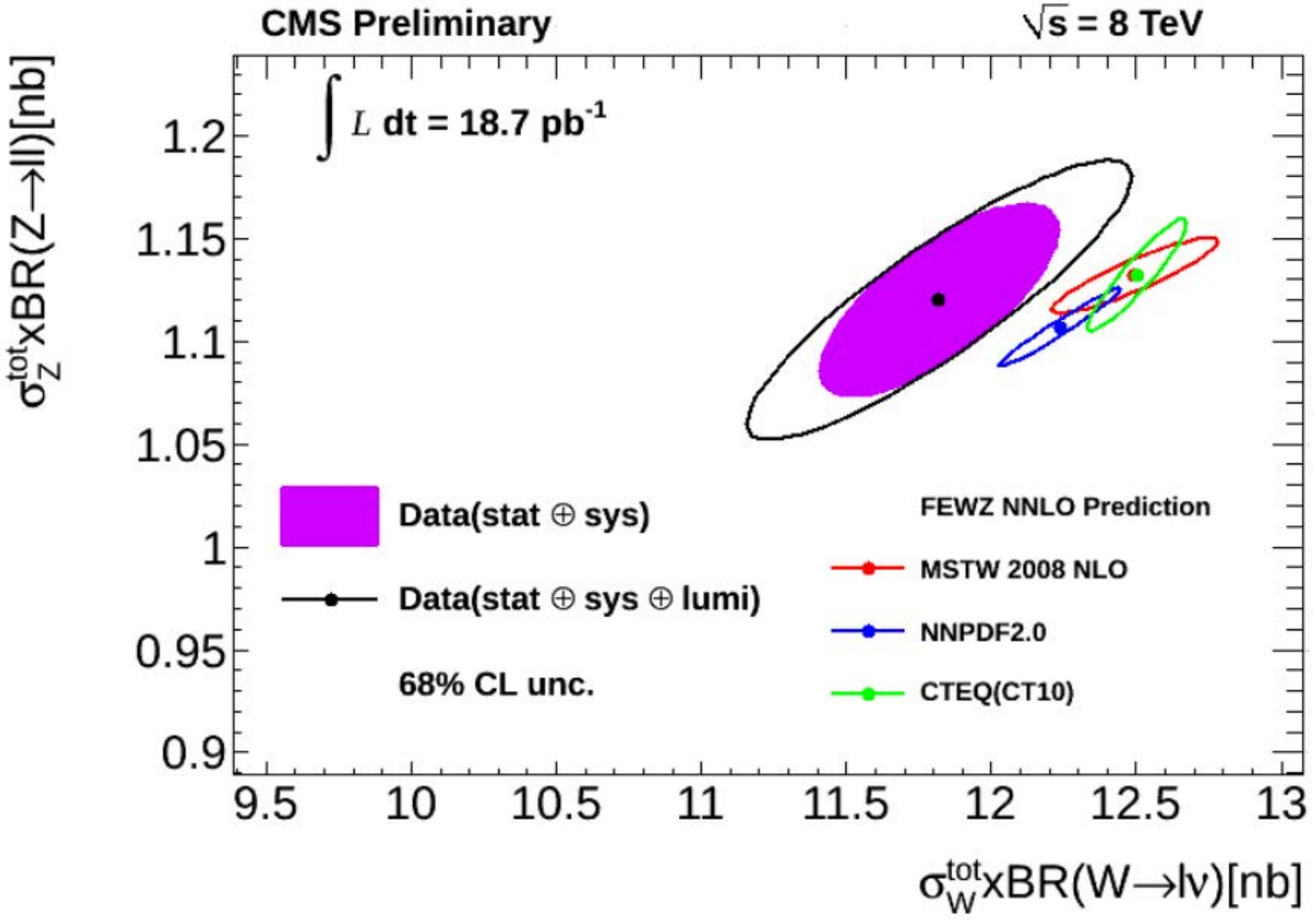


- ATLAS and CMS: small-medium rapidity, light quarks.
- LHCb: high rapidity

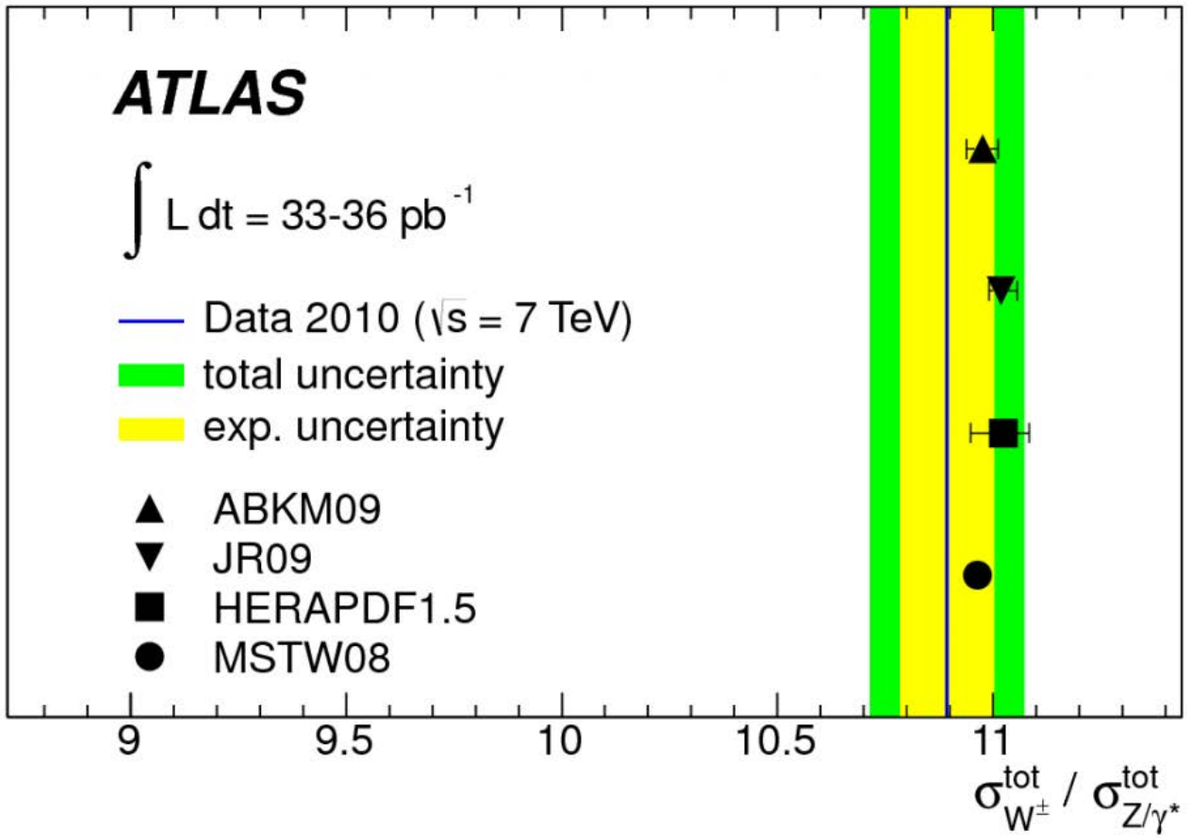


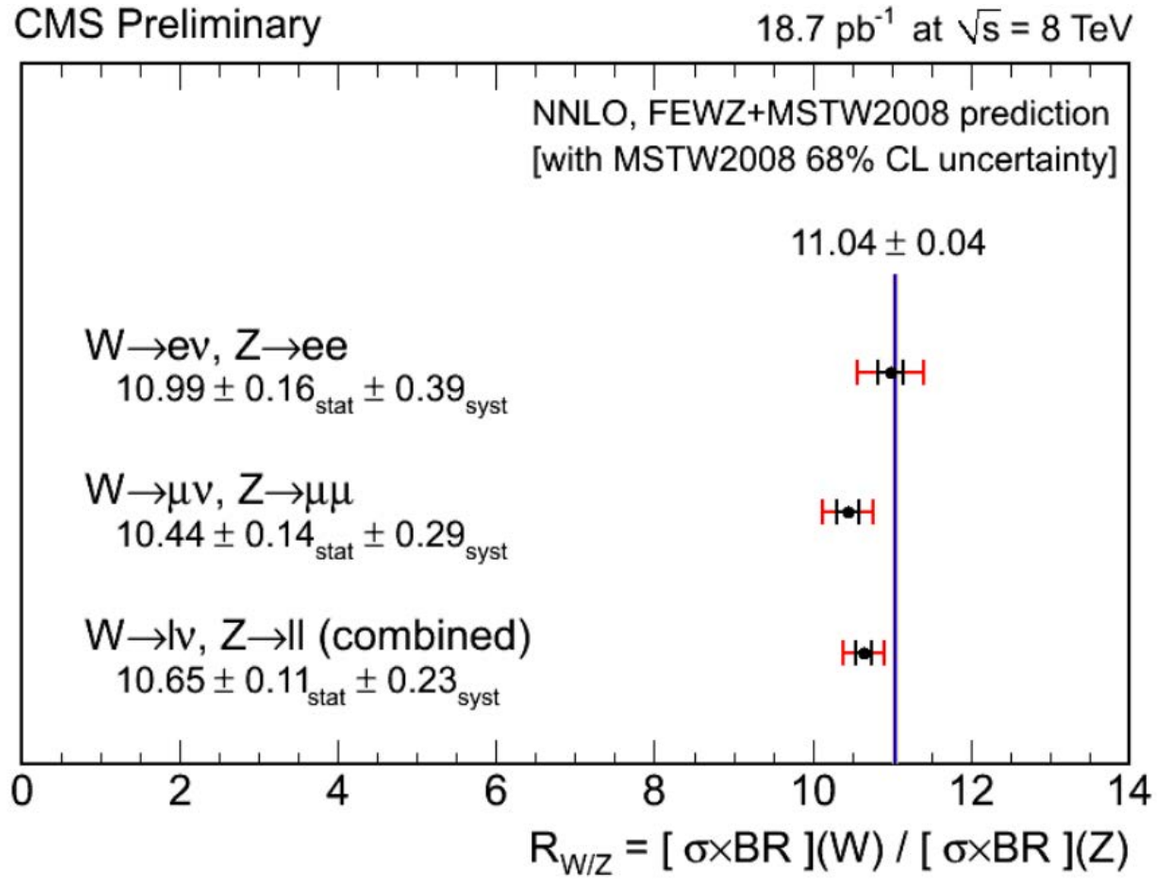
Integrated cross sections





Combined cross section ratios





		experiment	theory
ATLAS	7 TeV	10.893 ± 0.079 (stat) ± 0.110 (syst) ± 0.116 (acc)	10.74 ± 0.04
CMS	7 TeV	10.54 ± 0.07 (stat) ± 0.08 (syst) ± 0.16 (th)	
CMS	8 TeV	10.65 ± 0.11 (stat) ± 0.23 (syst)	11.04 ± 0.04

Many other interesting measurements…

- Diboson production
  - WW
  - ZZ
  - WZ
- Single and double W's and Z's + jets
- $Z \rightarrow 4l$
- $pp \rightarrow l\nu\gamma$
- $pp \rightarrow ll\gamma$, $pp \rightarrow \nu\nu\gamma$
- Vector Boson Fusion and Scattering
- EW precision measurements: W mass, Z mass, θ_W

- …

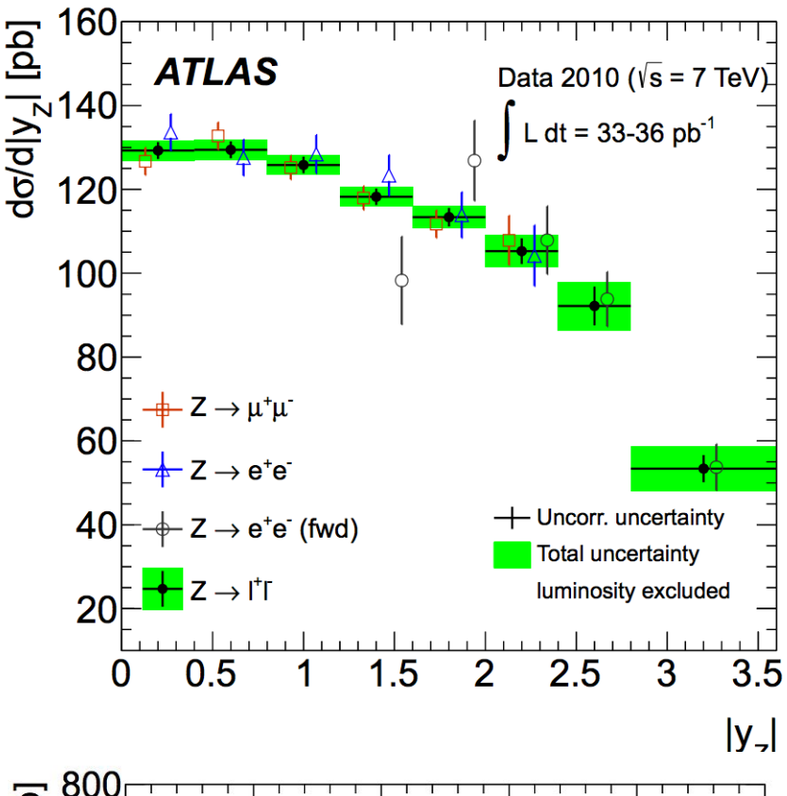
backup

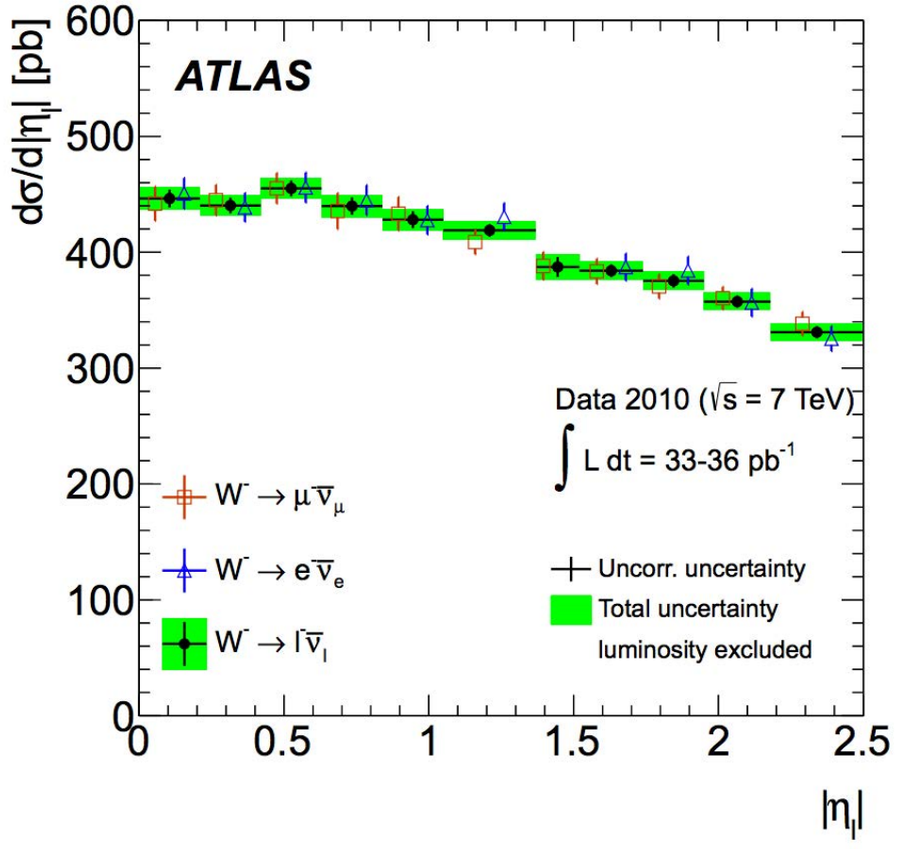
Systematic uncertainties

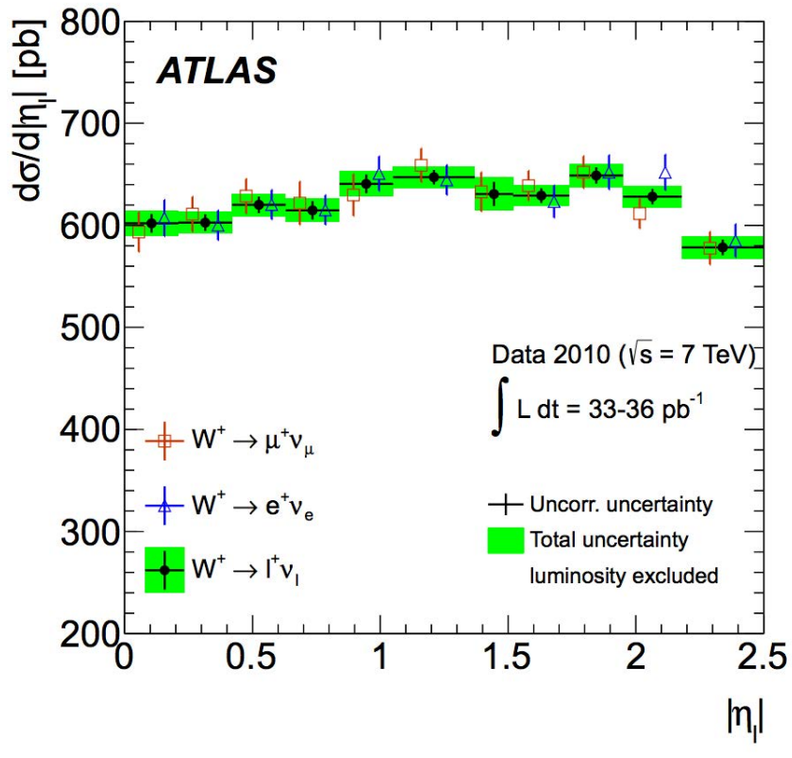
	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
Trigger	0.4	0.4	0.4	<0.1
Electron reconstruction	0.8	0.8	0.8	1.6
Electron identification	0.9	0.8	1.1	1.8
Electron isolation	0.3	0.3	0.3	—
Electron energy scale and resolution	0.5	0.5	0.5	0.2
Non-operational LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	0.0	0.1	0.1	0.6
QCD background	0.4	0.4	0.4	0.7
Electroweak+$t\bar{t}$ background	0.2	0.2	0.2	<0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$scale and resolution	0.8	0.7	1.0	—
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.6	0.6	0.6	0.3
Total experimental uncertainty	1.8	1.8	2.0	2.7
$A_{W/Z}$ theoretical uncertainty	1.5	1.7	2.0	2.0
Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity	3.4			

	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
Trigger	0.5	0.5	0.5	0.1
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_{T} resolution	0.04	0.03	0.05	0.02
Muon p_{T} scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Electroweak+$t\bar{t}$ background	0.4	0.3	0.4	0.02
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution and scale	0.5	0.4	0.6	-
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.8	0.8	0.7	0.3
Total experimental uncertainty	1.6	1.7	1.7	0.9
$A_{W/Z}$ theoretical uncertainty	1.5	1.6	2.1	2.0
Total excluding luminosity	2.1	2.3	2.6	2.2
Luminosity	3.4			

Combining data (the other channels)







Combined cross sections with correlation matrices

	$\sigma_W^{\text{fid}} \cdot \mathbf{BR}(W \to \ell\nu)$ [nb]			
	$\lvert\eta_\ell\rvert < 2.5$, $p_{T,\ell} > 20$ GeV,			
	$p_{T,\nu} > 25$ GeV and $m_T > 40$ GeV			
	sta	sys	lum	acc
W^+	$3.110 \pm 0.008 \pm 0.036 \pm 0.106 \pm 0.004$			
W^-	$2.017 \pm 0.007 \pm 0.028 \pm 0.069 \pm 0.002$			
$W^\pm$	$5.127 \pm 0.011 \pm 0.061 \pm 0.174 \pm 0.005$			
	$\sigma_{Z/\gamma^*}^{\text{fid}} \cdot \mathbf{BR}(Z/\gamma^* \to \ell\ell)$ [nb]			
	$\lvert\eta_\ell\rvert < 2.5$, $p_{T,\ell} > 20$ GeV			
	and $66 < m_{\ell\ell} < 116$ GeV			
	sta	sys	lum	acc
Z/γ^*	$0.479 \pm 0.003 \pm 0.005 \pm 0.016 \pm 0.001$			

TABLE X. *Combined cross sections times leptonic branching ratios for W^+, W^-, $W^\pm$ and Z/γ^* production within the corresponding fiducial regions of the measurements. The uncertainties denote the statistical (sta), the experimental systematic (sys), the luminosity (lum), and the extrapolation (acc) uncertainties.*

	Z	W^+	W^-
Z	1.00	0.94	0.93
W^+	0.94	1.00	0.97
W^-	0.93	0.97	1.00

	Z	W^+	W^-
Z	1.00	0.48	0.44
W^+	0.48	1.00	0.79
W^-	0.44	0.79	1.00

TABLE XI. *Correlation matrix for the measurements of the Z, W^+ and W^- cross sections in the fiducial volume, for the full uncertainty (left) and for all but the luminosity uncertainty (right).*

	$\sigma_W^{\text{tot}} \cdot \mathbf{BR}(W \to \ell\nu)$ [nb]			
	sta	sys	lum	acc
W^+	$6.048 \pm 0.016 \pm 0.072 \pm 0.206 \pm 0.096$			
W^-	$4.160 \pm 0.014 \pm 0.057 \pm 0.141 \pm 0.083$			
$W^\pm$	$10.207 \pm 0.021 \pm 0.121 \pm 0.347 \pm 0.164$			
	$\sigma_{Z/\gamma^*}^{\text{tot}} \cdot \mathbf{BR}(Z/\gamma^* \to \ell\ell)$ [nb]			
	$66 < m_{\ell\ell} < 116$ GeV			
	sta	sys	lum	acc
Z/γ^*	$0.937 \pm 0.006 \pm 0.009 \pm 0.032 \pm 0.016$			

TABLE XII. *Combined total cross sections times leptonic branching ratios for W^+, W^-, W and Z/γ^* production. The uncertainties denote the statistical (sta), the experimental systematic (sys), the luminosity (lum), and the extrapolation (acc) uncertainties.*

	Z	W^+	W^-
Z	1.00	0.91	0.91
W^+	0.91	1.00	0.91
W^-	0.91	0.91	1.00

	Z	W^+	W^-
Z	1.00	0.67	0.71
W^+	0.67	1.00	0.70
W^-	0.71	0.70	1.00

TABLE XIII. *Correlation matrix for the measurements of the total Z, W^+ and W^- cross sections for the full uncertainty (left) and for all but the luminosity uncertainty (right).*