Precision W and Z cross sections
and the first measurement of the W-boson mass with ATLAS

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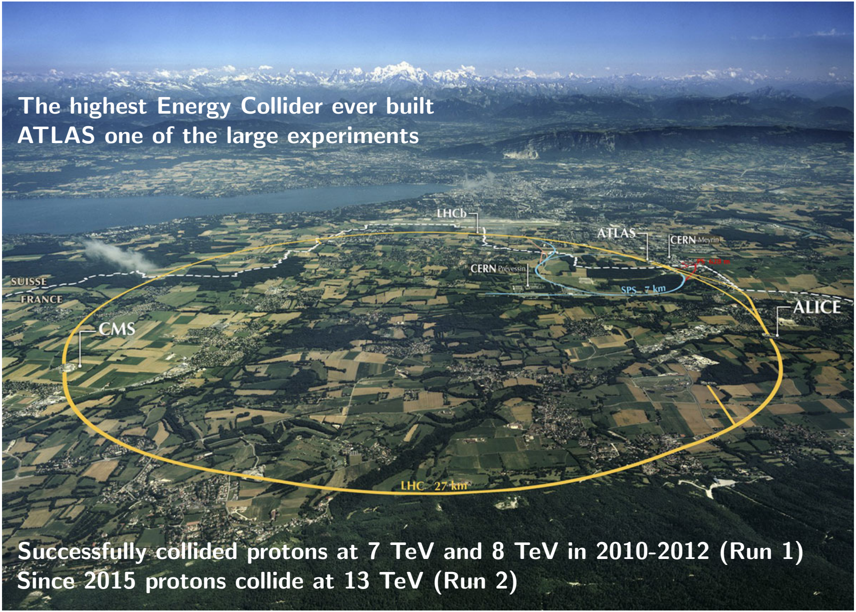
ATLAS EXPERIMENT

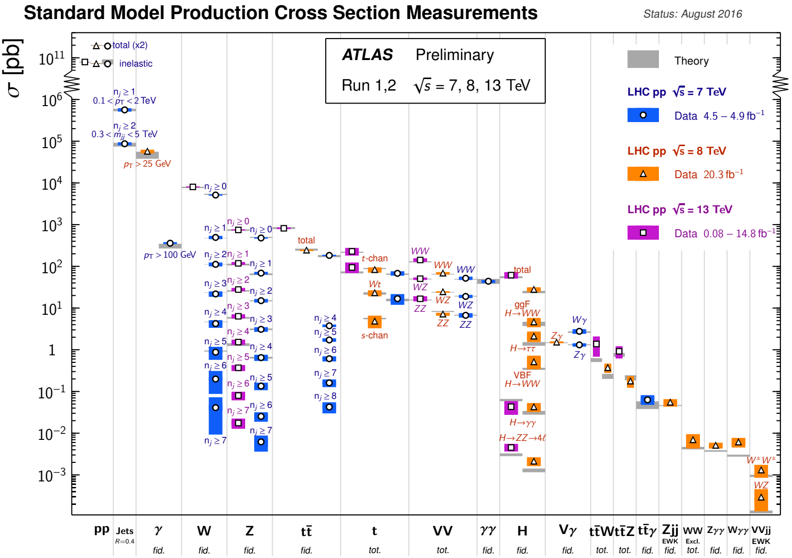
UNIVERSITY OF LIVERPOOL

The Large Hadron Collider & ATLAS



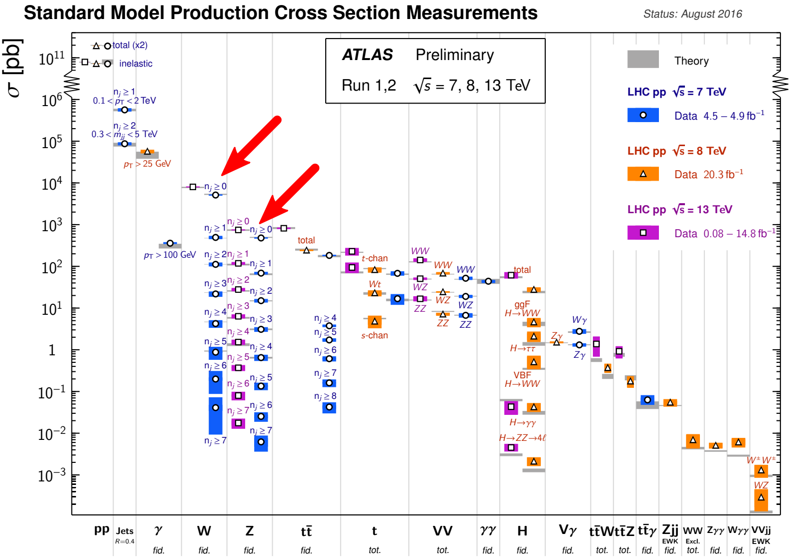
The ATLAS Physics Menu

Large variety of searches and measurements



The ATLAS Physics Menu

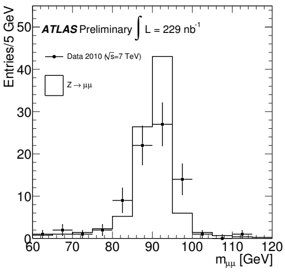
Large variety of searches and measurements ... focus on W and Z production



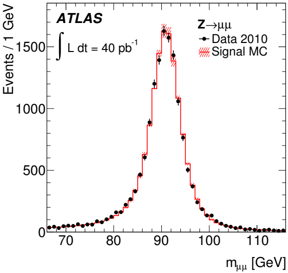
LHC: A W and Z "Factory"

- W and Z massive gauge bosons of the electro-weak $SU(2)_L \times U(1)_Y$ symmetry, broken spontaneously by the Higgs mechanism
- Leptonic decays $Z \to \ell\ell$ and $W \to \ell\nu$ leave a unique signature at a hadron collider
- High integrated luminosity delivered by LHC means more $Z \to \ell\ell$ and $W \to \ell\nu$ events than any collider before have been produced
- ATLAS so far recorded > 10 million $Z \to \ell\ell$ and > 100 million $W \to \ell\nu$ events

July 2010



Full 2010 data



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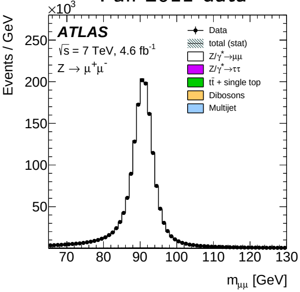

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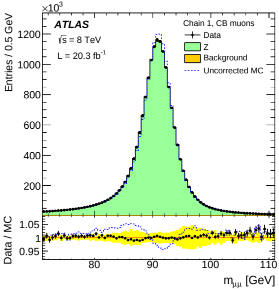
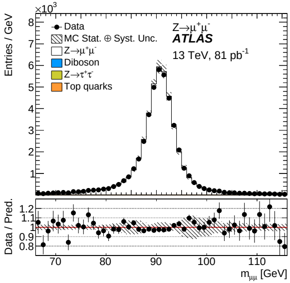
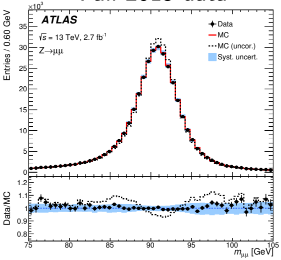


July 2015

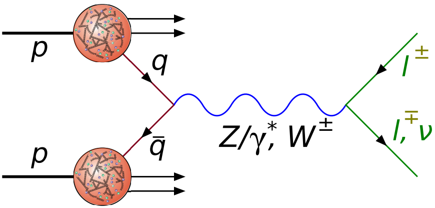


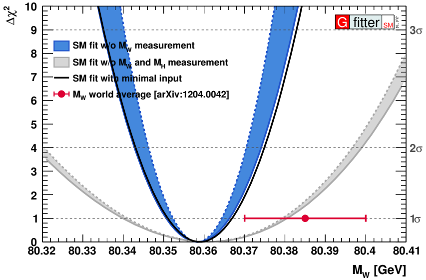
Full 2015 data



W and Z Bosons Physics at LHC

- $W^\pm$ and Z/γ^* bosons produced in Drell-Yan process
- Measurements primarily require lepton detection — very high experimental precision can be achieved
- **Precision cross-section measurement**: probe of strong interaction and the **proton structure (Parton Distribution Functions, PDFs)**, arXiv:1612.03016:
  - Major Liverpool contributions (Max, Uta, Jan) — from initial planning in 2008 to paper writing
  - What can be learned beyond *ep* scattering?
- **First measurement of the W-boson mass**: test **consistency of the Standard Model** and constrain Beyond-SM physics, STDM-2014-18, submitted to arXiv:
  - Major collaborative effort of ATLAS W, Z group with strong Liverpool contributions in many areas
  - Can we go beyond Tevatron measurements of $\sim$ 20 MeV uncertainty?

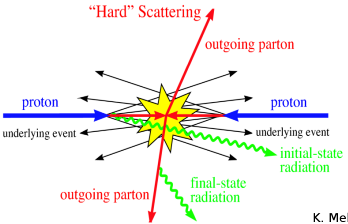


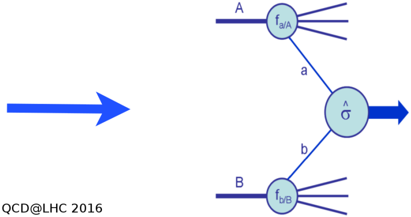


Predictions for W and Z Production in Hadron Collisions

- Cross section calculation with hadrons factorises in
  - *Matrix element* calculation, arranged in a perturbative series in α_s: Leading order (LO), Next-to-leading order (NLO), NNLO, ...
  - *Parton distribution functions* (PDFs)
- $W \to \ell\nu$ and $Z \to \ell\ell$ known to NLO since $\sim$ 1980, initial NNLO results date back to early 1990's, fully differential calculation since 2006 in FEWZ and DYNNLO
- Next level of complexity mastered in last years ($gg \to H$ at N^{3}LO and $2 \to 2$ processes like Z+jet at NNLO), but absolute cross sections predicted to $\lesssim 1\%$ precision is still unique in hadron collisions
- Beyond fixed order QCD: higher order EWK ($\alpha_s^2 \sim \alpha$) and resummation

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \mathrm{d}\sigma_{ij}(x_1, x_2) F_J \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$



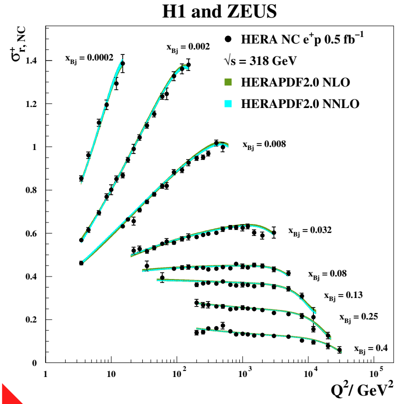


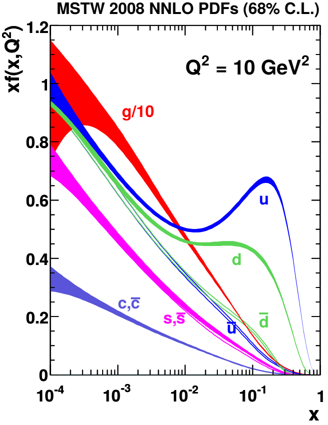
K. Melnikov, QCD@LHC 2016

PDFs and Deep Inelastic Scattering

[EPJC (2015) 75:580, EPJC (2009) 63:189]

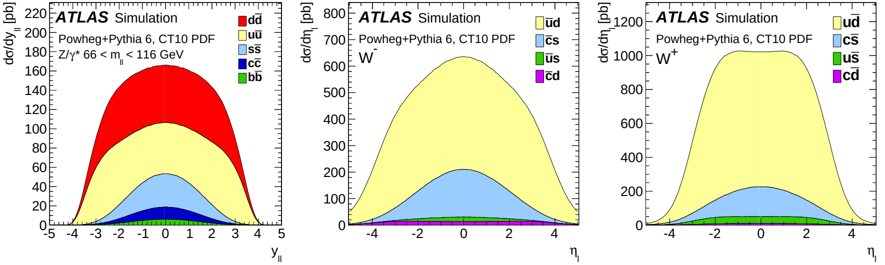
- DIS experiments at SLAC in 1969 ($ep \to eX$) found cross section to be $\sim$independent of momentum transfer Q^2: proton consists of point-like *quarks*
- Further precise measurements, e.g. at HERA *ep* collider, over wide range of x, Q^2: neutral current (γ^* exchange) constrains $\sum e_q^2(q+\bar{q})$, at low momentum fraction x strong *scaling violations* due to gluons
- A big unknown is the flavour decomposition of light-quark sea at $x < 10^{-2}$: $\bar{u} \sim \bar{d}$, strange suppressed?



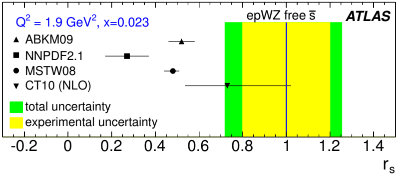


PDFs for W and Z Production at LHC

[PRL 109 (2012) 012001]



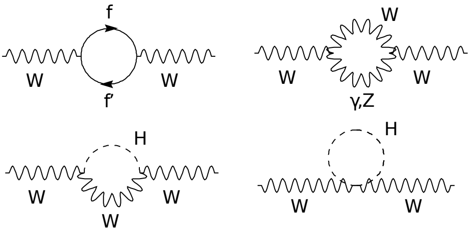
- At LO cross sections determined by sum of different $q\bar{q}$ combinations
  - Different electro-weak couplings for γ^* (e_q^2) and Z $(v_q^2 + a_q^2)$ + their interference
  - Weighted by CKM elements $V_{q\bar{q}}$ for $W^\pm$
- Different composition of flavours than constrained by the HERA dataset:
  - W-boson mass measurement subject to significant PDF uncertainties
  - Precise cross section measurements improves our knowledge of the proton structure
  - 2010 ATLAS W, Z data suggested a larger than expected strange-quark contribution: $r_s = \bar{s}/\bar{d} \approx 1$

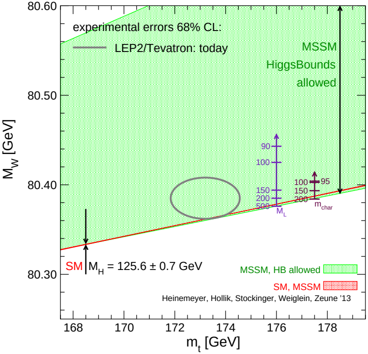


- With the discovery of the Higgs boson, the EW sector of the SM is over-constrained
- W-boson mass currently measured to ± 15 MeV and predicted to ± 8 MeV; many other EWK parameters measured far better than SM prediction
- m_W prediction sensitive to loop-corrections: QED, top, H, ... BSM?

$$m_W^2 \sin^2 \theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Current Tevatron results use $\sim 100,000$ Z and $1-2$M W events ($+$ J/ψ)
- Already 2011 ATLAS sample has ~ 2M Z and ~ 20M W events





W-boson mass and Electroweak fit

[JHEP 12 (2013) 084, Gfitter]

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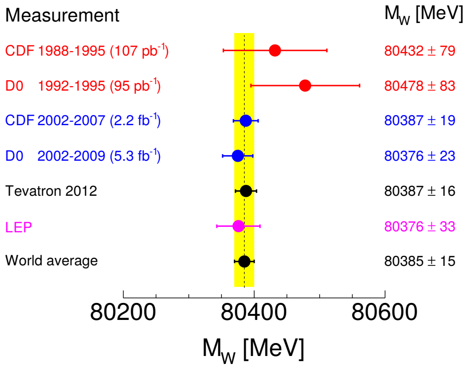
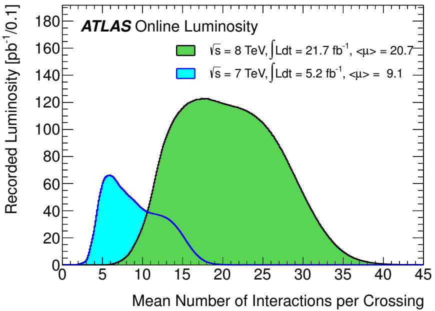
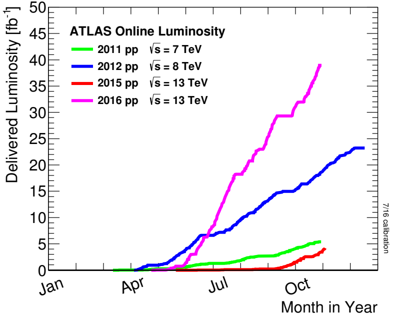


Data sample

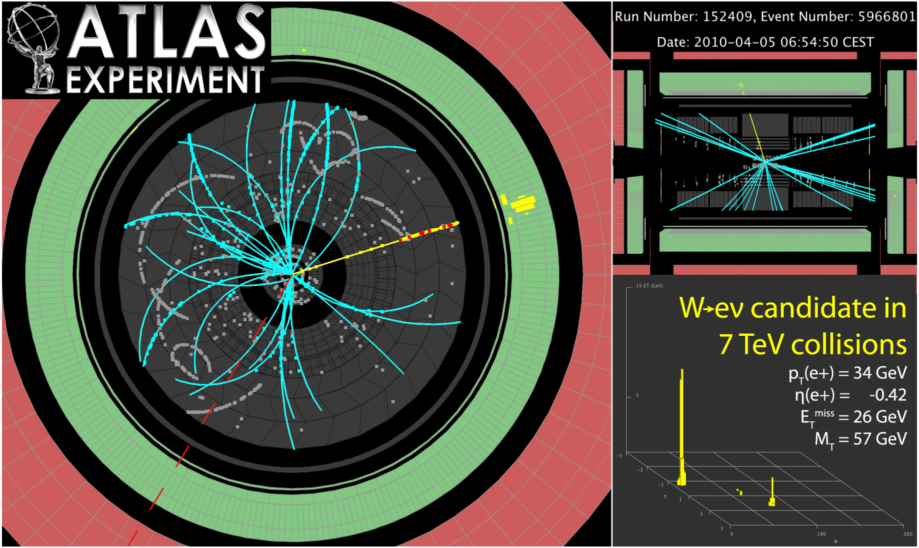
Data sample

- Both analyses presented use the 2011 data set of $4.6\,\mathrm{fb}^{-1}$:
  - Understanding of detector performance and analysis takes time!
  - Moderate pileup: "only" 9 simultaneous *pp* interactions on average
- LHC and ATLAS performance has been exceptional in the last years: none of the measurements presented are (directly) limited by data statistics, but detector systematics can typically be improved with larger calibration samples
- Analyse simultaneously both the electron- and muon-decay channels: $W \to e\nu$, $W \to \mu\nu$, $Z \to ee$, $Z \to \mu\mu$
  $\Rightarrow$ critical to gain confidence in results and achieve the ultimate precision

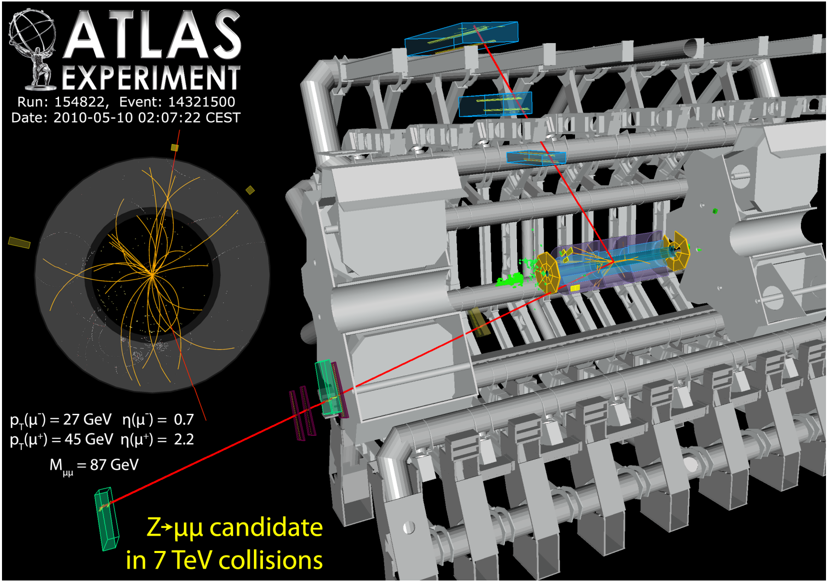




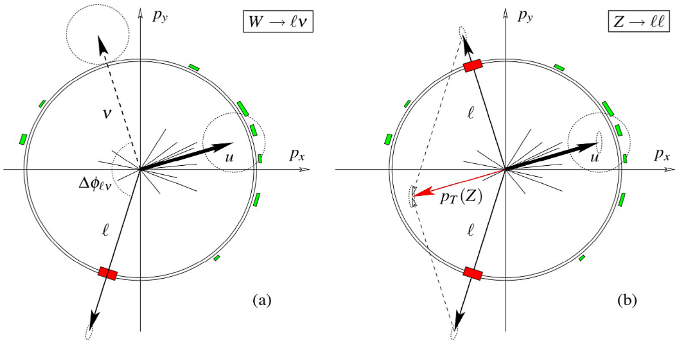
A $W \to e\nu$ candidate



A $Z \to \mu\mu$ candidate



Event reconstruction and selection



- $W \to \ell\nu$:
  - one isolated lepton (e or μ) with $p_T^\ell > 25$ GeV and $|\eta^\ell| \lesssim 2.4$
  - remainder of the event: "hadronic recoil" $\vec{u}_T$ ($u_T < 30$ GeV for W mass)
  - neutrino inferred using $\vec{p}_T^{\,\mathrm{miss}} = -(\vec{p}_T^{\,\ell} + \vec{u}_T) > 25$ GeV
  - transverse mass $m_T = \sqrt{2 p_T^\ell p_T^{\mathrm{miss}} (1 - \cos\Delta\phi)} > 40$ GeV
- $Z \to \ell\ell$: two isolated leptons (ee or $\mu\mu$) with $p_T^\ell > 20$ GeV and $|\eta^\ell| \lesssim 2.4$, invariant mass $m_{\ell\ell} = 46 - 150$ GeV
- Selection for cross-section measurements, for W-mass slightly tighter criteria applied

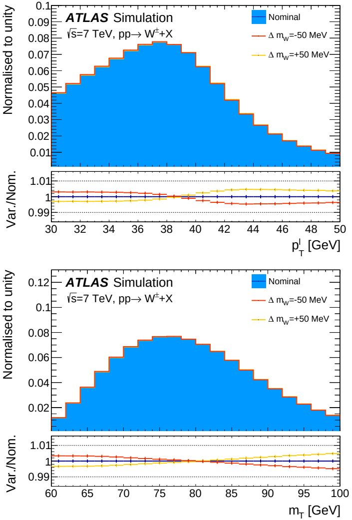
Analysis strategies

Cross-section analysis

- Binned event yields (N) corrected for background (B), efficiencies and migrations ($C = N^{\mathrm{MC}}_{\mathrm{rec}} / N^{\mathrm{MC}}_{\mathrm{gen}}$) to obtain (differential) cross sections

$$\sigma^{\mathrm{fid}} = \frac{N - B}{C \cdot \mathcal{L}_{\mathrm{int}}}$$

- Combination of e and μ channels
- Comparison to NNLO QCD + NLO EWK predictions, QCD analysis → new PDF set



W-boson mass analysis

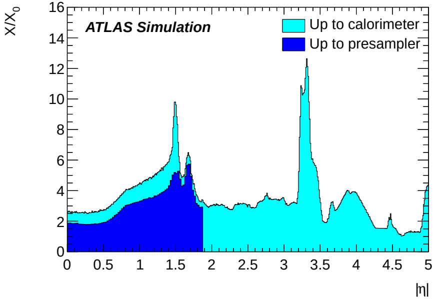
- Simulated events reweighted best theory of W production and decay and a series of different m_W values
- Fit to sensitive distributions (p^{ℓ}_{T}, m_T) to determine best m_W value
- Initial blinding of m_W by an unknown, common offset

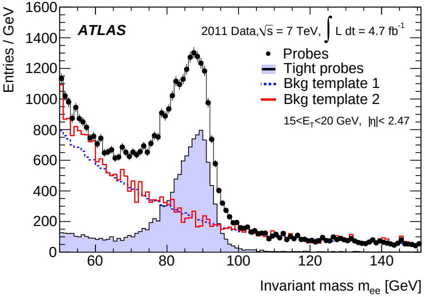
Common: detector performance needs to be understood at very high level

Detector calibration

Electron Efficiency

- Electron detection complicated by large amount of material in the detector and significant background from jets
- Efficiency controlled in several steps using "tag-and-probe": relies mostly on $Z \to \ell\ell$ events selected with looser criteria on one leg
- Simulation not perfect $\to$ correct simulation double-differentially in (η^ℓ, p_T^ℓ) by measured $\epsilon_{\text{data}}/\epsilon_{\text{MC}}$, known to typically $\sim 0.2 - 1\%$ in relevant range $p_T^\ell > 25$ GeV
- Directly relevant as systematics for cross-section measurement, important to control p_T^ℓ-dependent slopes for m_W
- Muon efficiencies controlled in similar way, just easier





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[EPJ C74 (2014) 3071, EPJ C74 (2014) 2941]

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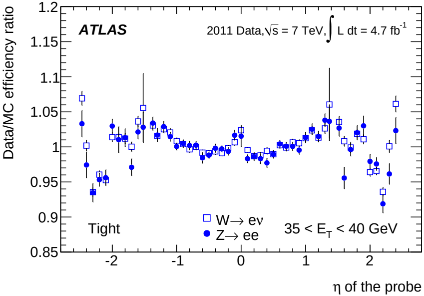
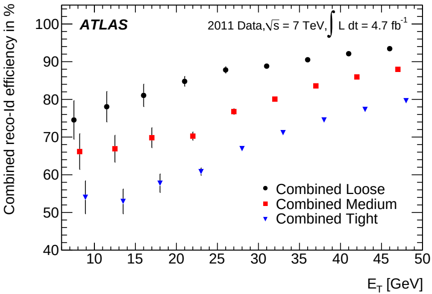
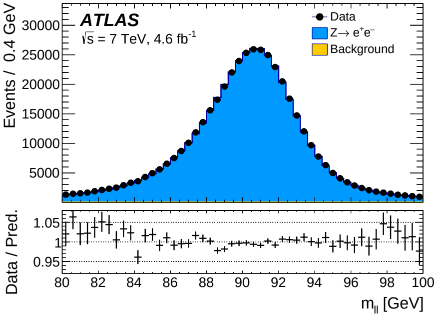


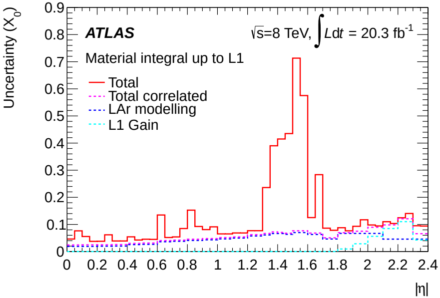


Electron Calibration

[EPJ C74 (2014) 3071]

- Overall electron energy scale and resolution set to match the Z-boson parameters known precisely from LEP
- Understand possible non-linearities in $Z \to W$ extrapolation from passive material: controlled with muons (MIPs), longitudinal shower development of electrons and photons
- Precision of 10^{-4} equals ± 8 MeV on m_W: reached, secondary effect for cross-section measurement





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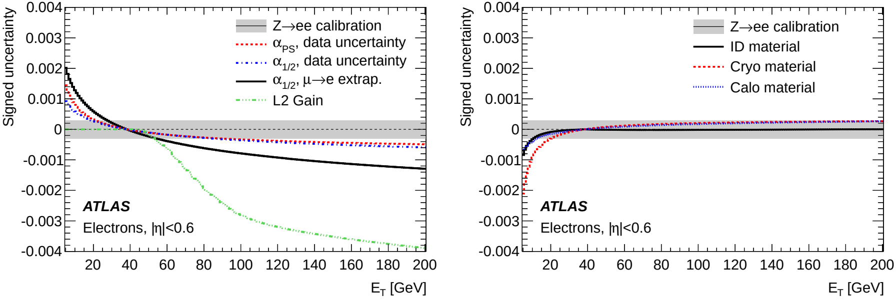
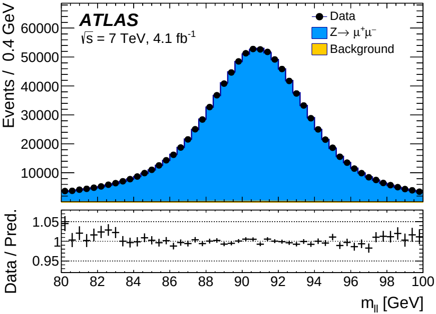


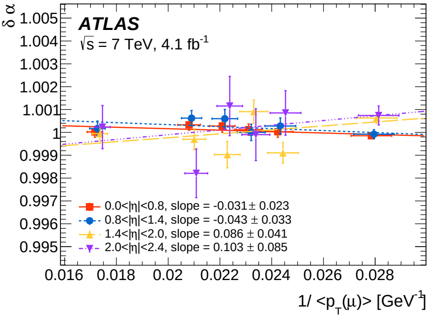
Muon Calibration

- Overall momentum scale and resolution set to match the Z-boson parameters
- Non-linearities controlled from $Z \to \mu\mu$ sample
- Reached the 10^{-4} precision required for W mass
- Rotational detector deformations and flaws in alignment procedure can introduce charge-dependent sagitta bias δ – best controlled with E/p in $W^{\pm} \to e^{\pm}\nu$ events:

$$p_T^{\text{corr}} = \frac{p_T}{1 + q \cdot \delta(\eta, \phi) \cdot p_T}$$

- Sagitta effect important to control W^{+}/W^{-} mass and cross-section ratio





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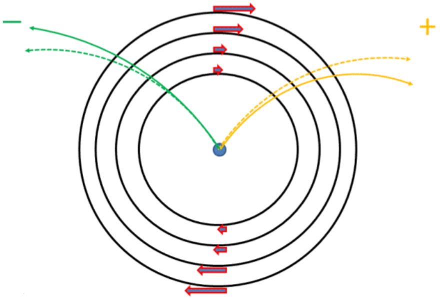
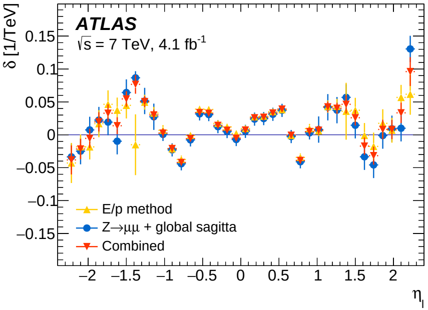
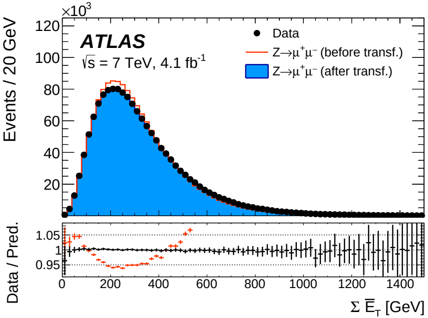
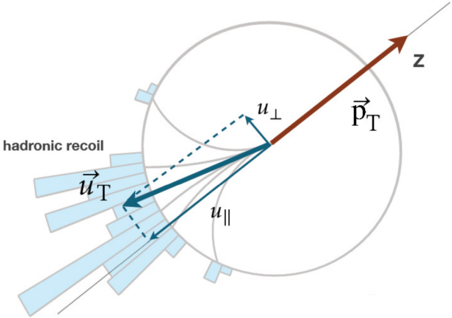




Hadronic Recoil Calibration

- Hadronic recoil reconstructed from all calorimeter clusters in the event after removing cones around identified leptons & replacing by a "random" cone
- Affected by pileup and underlying event, all of which is not necessarily well modelled
- Reweighting to equalise event activity
- Scale and resolution calibration using projections parallel and transverse to Z direction





$$\sum \bar{E}_T = \left(\sum_i E_T^i\right) - u_T$$

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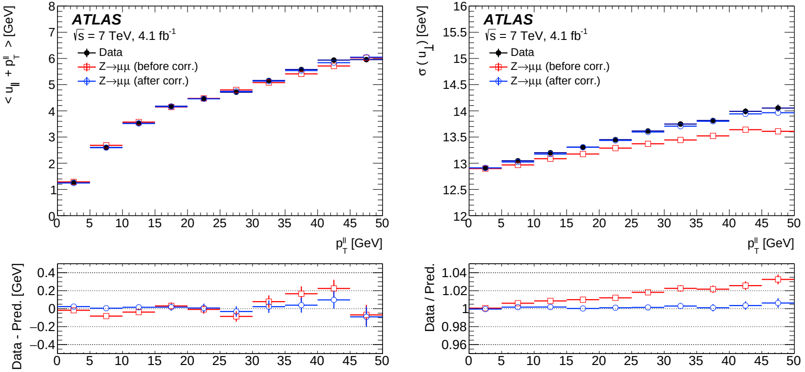
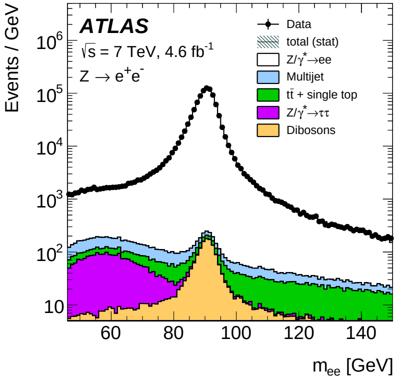
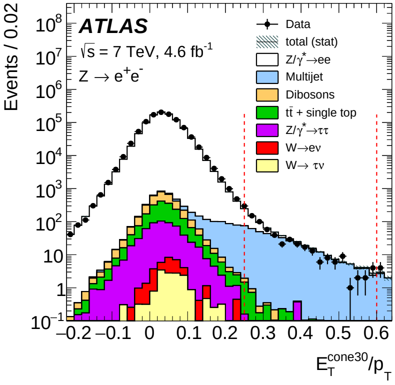


Backgrounds

- Very small background for $Z \to ee$ and $Z \to \mu\mu$:
  $\sim 0.2\%$ at Z peak and a few % in off-peak region
- Background to $W \to \ell\nu$ more difficult:
  - $W \to \tau\nu$ and $Z \to \ell\ell$ taken from MC – need to account for correct modelling of veto-efficiency for W-mass analysis!
  - Multi-jet background not large, but determination using a data template hard to control – done via extrapolation procedure





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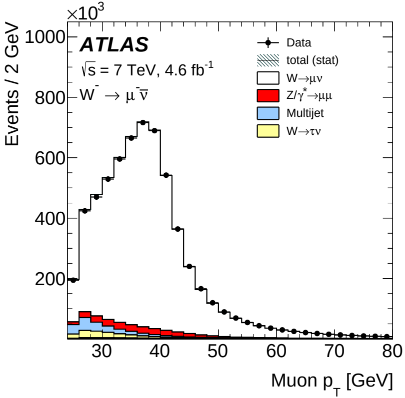
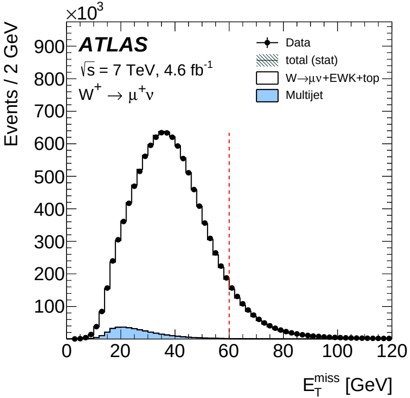
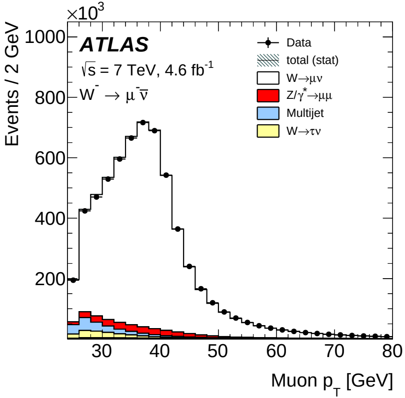
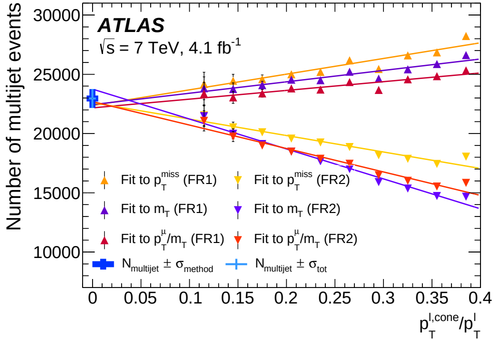




Backgrounds

- Very small background for $Z \to ee$ and $Z \to \mu\mu$: $\sim 0.2\%$ at Z peak and a few % in off-peak region
- Background to $W \to \ell\nu$ more difficult:
  - $W \to \tau\nu$ and $Z \to \ell\ell$ taken from MC – need to account for correct modelling of veto-efficiency for W-mass analysis!
  - Multi-jet background not large, but determination using a data template hard to control – done via extrapolation procedure

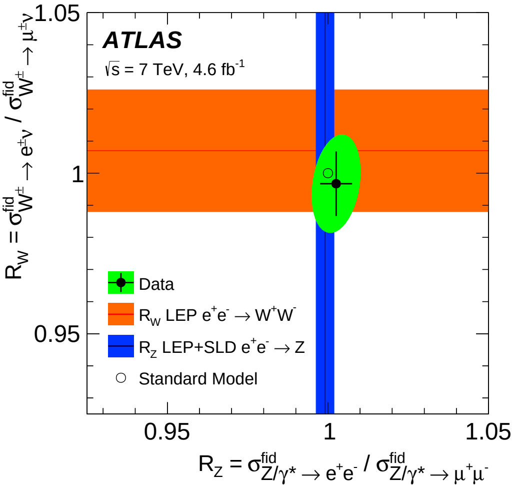




Cross-section results

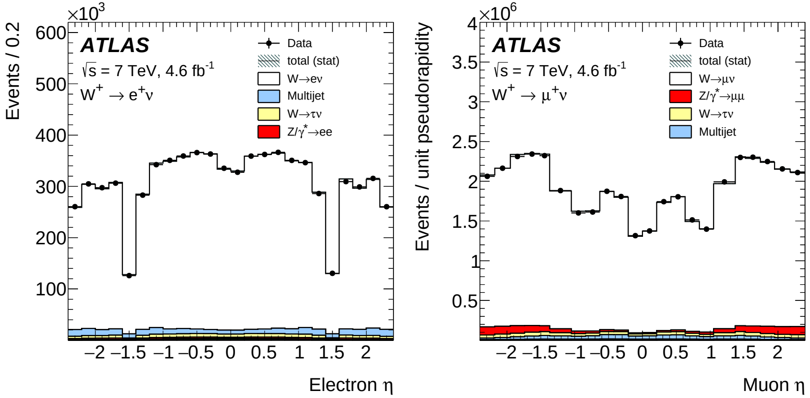
Integrated cross-section results and combination

- Integrated cross sections measured to 0.6 − 1.0% for W and 0.4% for Z plus 1.8% luminosity uncertainty
- Combination interpreted as test of $e - \mu$ universality: most precise test for on-shell W, "only" factor 2 worse than LEP for Z



Differential cross-section combination

- 105 measurement points: $W^{\pm}$ as function of charged lepton rapidity $|\eta^{\ell}|$, Z/γ^* as function of di-lepton rapidity $|y_{\ell\ell}|$
- Different detection challenges for electrons and muons
- $e - \mu$ combination to 61 final points including all correlations: $\chi^2/\mathrm{n.d.f.} = 59.5/53$



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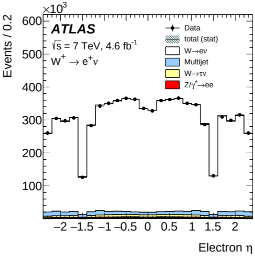

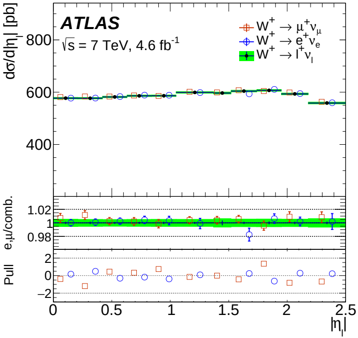

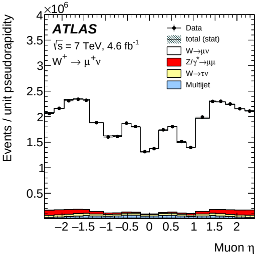

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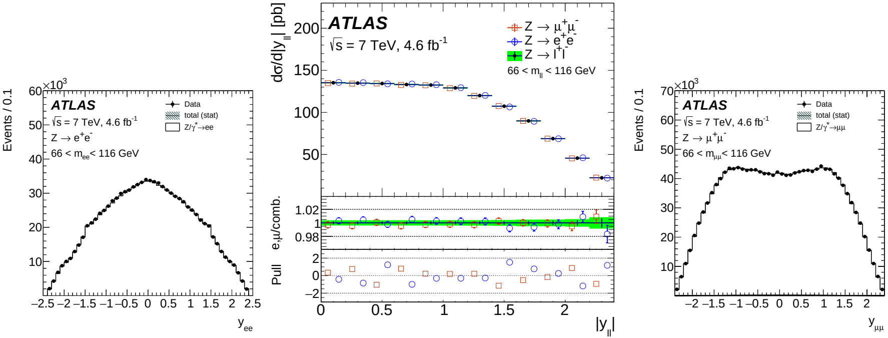
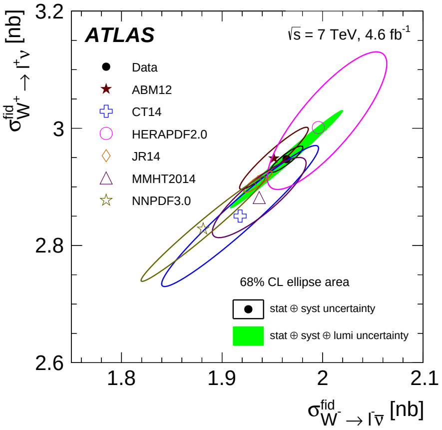
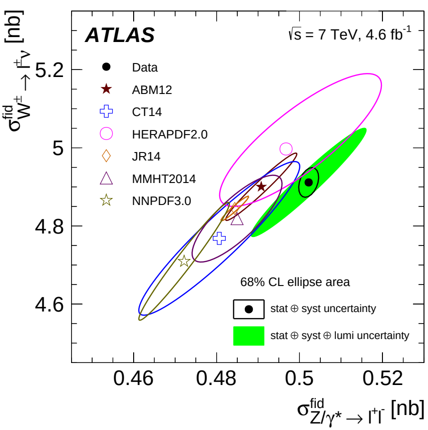


Integrated cross section vs. Theory

- Interpretation of measurement in terms of PDFs relies on accurate theory calculations at NNLO QCD and NLO EWK
- Measured integrated fiducial cross sections more precise than most PDF sets: $W^{\pm}$ well described, W/Z ratio systematically different





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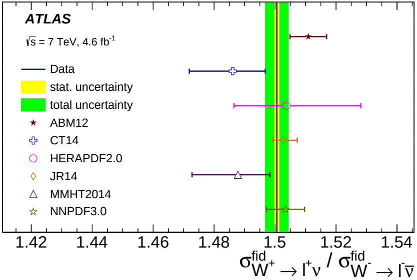

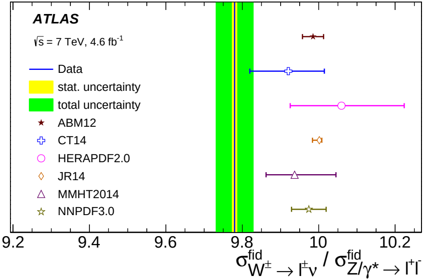

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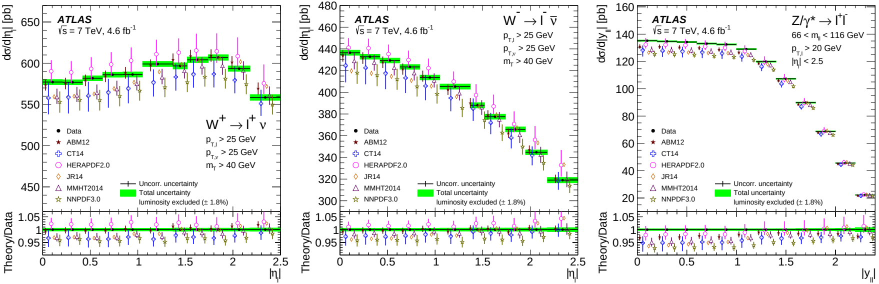


- Challenge for theory to describe the data at sub-percent level
- Quantitative χ^2 analysis of theory/data agreement using all differential distributions: CT14 ($\chi^2/\mathrm{n.d.f.} = 103/61$) best, NNPDF3.0 ($\chi^2/\mathrm{n.d.f.} = 147/61$) worst

Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+\nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^-\bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 46-66$ GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66-116$ GeV)	12	24|51	16|66	20|116	14|109	18|26
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66-116$ GeV)	9	7.3|9.3	10|12	12|13	14|18	6.8|7.5
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116-150$ GeV)	6	6.1|6.6	6.3|6.1	5.9|6.6	6.1|8.8	6.7|6.6
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116-150$ GeV)	6	4.2|3.9	5.1|4.3	5.6|4.6	5.1|5.0	3.6|3.5
Correlated χ^2		57|90	39|123	43|167	69|157	31|48
Total χ^2	61	136|222	103|290	118|396	147|351	113|159

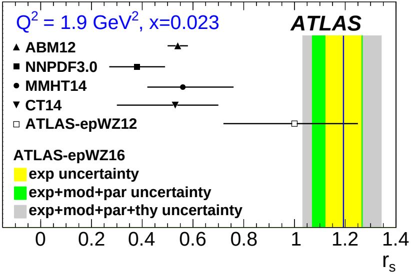
χ^2 {with | without} uncertainties from PDF sets

QCD fit analysis and the strange-quark density

Fit to final HERA DIS data and new ATLAS W and Z data $\rightarrow$ ATLAS-epWZ16 PDF set

μ_r	μ_f	χ^2/n.d.f. Total	χ^2/n.d.f. ATLAS	$r_s = \frac{s+\bar{s}}{2\bar{d}}$	$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$
1	1	1321 / 1102	108 / 61	1.193	1.131
1/2	1/2	1297 / 1102	85 / 61	1.093	1.066
2	2	1329 / 1102	115 / 61	1.270	1.186
1	1/2	1307 / 1102	94 / 61	1.166	1.115
1	2	1312 / 1102	100 / 61	1.201	1.130
1/2	1	1304 / 1102	94 / 61	1.128	1.088
2	1	1321 / 1102	107 / 61	1.241	1.165

- QCD can describe data: nominal $\chi^2 = 108/61$ high, theory at half of conventional μ_r, μ_f scales improves fit χ^2 significantly $\chi^2 = 85/61$
- Confirmation of large strange-quark sea at low $Q^2 = 1.9\ \text{GeV}^2$ and low $x = 0.023$: $r_s = \bar{s}/\bar{d} = 1.19 \pm 0.05\,(\text{exp}) \pm 0.16\,(\text{fit} + \text{thy})$
- Tension with neutrino–fixed target DIS di-muon data, which favours $r_s \sim 0.5$?



	$r_s = \frac{s+\bar{s}}{2\bar{d}}$	$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$
Central value	1.19	1.13
Experimental data	± 0.07	± 0.05
Model (m_b, Q^2_{min}, Q^2_0 & m_c)	± 0.02	± 0.02
Parameterization	$^{+0.02}_{-0.10}$	$^{+0.01}_{-0.06}$
α_S	$^{+0.00}_{-0.01}$	± 0.01
Beam energy E_p	± 0.03	$^{+0.01}_{-0.02}$
EW corrections	± 0.01	± 0.00
QCD scales	$^{+0.08}_{-0.10}$	$^{+0.06}_{-0.07}$
FEWZ 3.1b2	$+0.10$	$+0.08$
Total uncertainty	$^{+0.15}_{-0.16}$	± 0.11

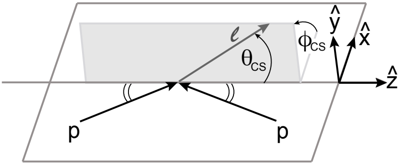
W-boson mass results

Fully differential physics model for DY

- None of the standard MC generators provides a sufficiently precise description of production and decay of $W^{\pm} \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$
- Factorisation of five-dimensional DY cross section allows reweighting

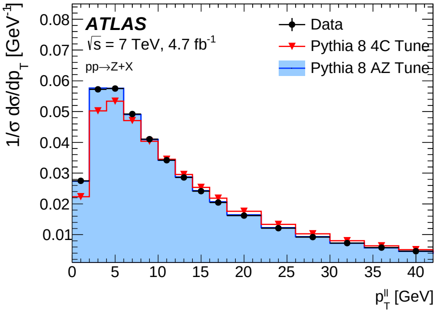
$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}p_{T,\ell\ell}\mathrm{d}y_{\ell\ell}}\left[1+\cos^2\theta_{CS}+\sum_{i=0}^{7}A_i(m_{\ell\ell},p_{T,\ell\ell},y_{\ell\ell})f_i(\theta_{CS},\phi_{CS})\right]$$

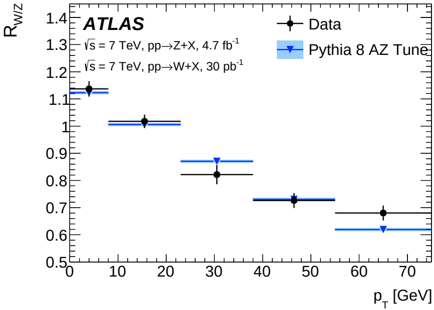
- $m_{\ell\ell}$: "simple" BW-resonance, scan m_W...
- $y_{\ell\ell}$, angular coefficients A_i: fixed-order NNLO QCD with CT10 (large strange!), validated by measured W, Z cross-sections and $Z \to \ell\ell$ angular correlations (JHEP08(2016)159)
- $p_{T,\ell\ell}$: needs resummation or parton shower
- Higher order QED effects simulated, missing EWK pieces as systematics



Transverse momentum distribution

- Easy to measure for $Z \to \ell\ell$, hard for $W \to \ell\nu$ $\to$ tune on Z, predict W
- $Z \to W$ translation: PDF and heavy-quark effects, large cs contribution to W
- Advanced resummed prediction like DYRES, ResBos etc (NNLO + NNLL) fail — Pythia8 left as only working choice: validated by $u_{||}^{\ell}$ distribution
- Perform variations on Pythia8: factorisation scale (separate for light and heavy quarks), m_c, m_b, PDF in parton shower and matrix element





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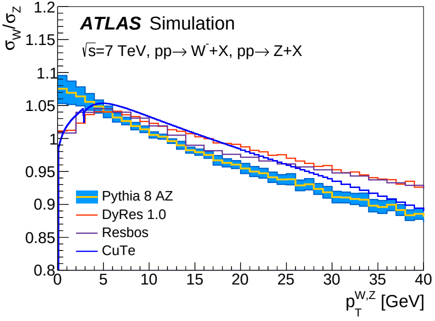

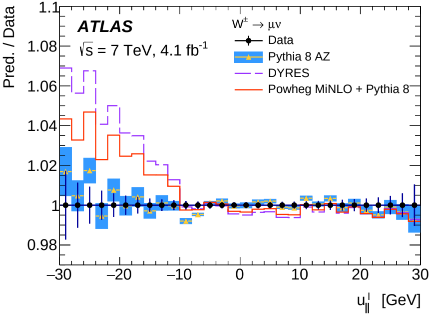

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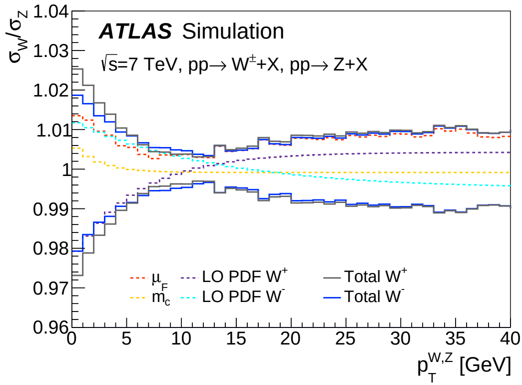
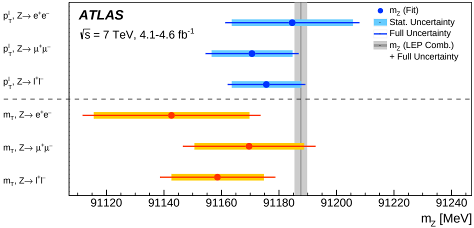
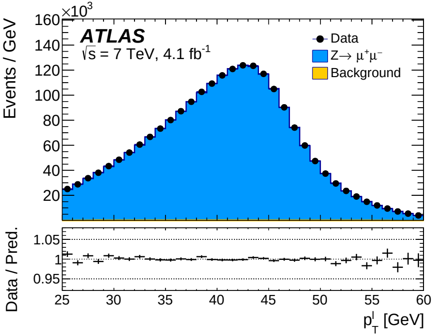
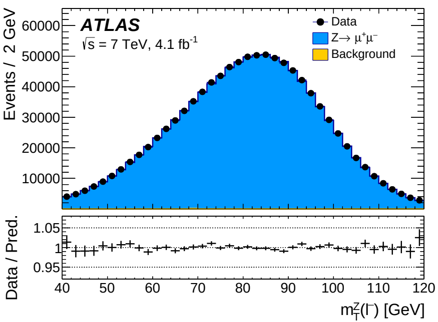


W-like cross-checks with Z events

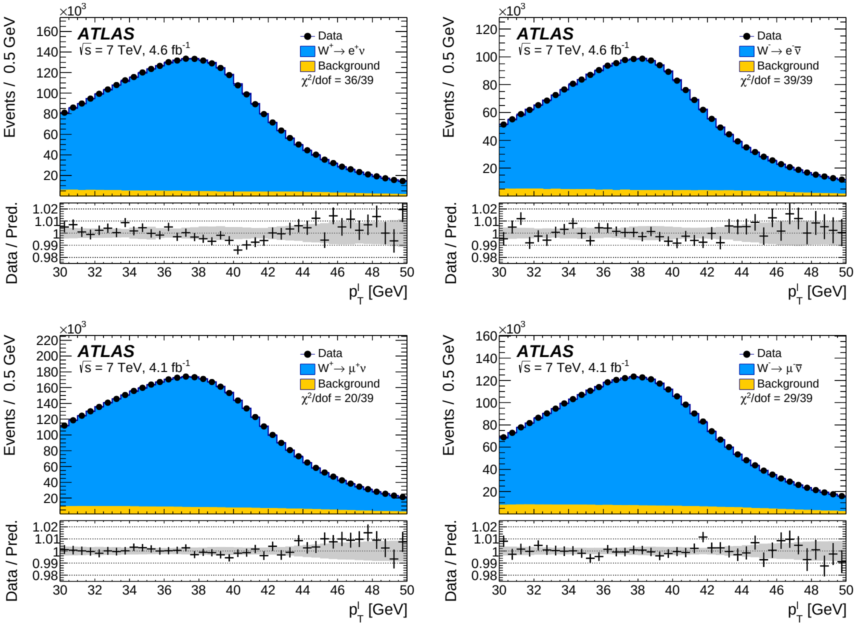
Extract Z-mass using W-like distributions of p_T^ℓ and m_T as closure test
$\Rightarrow$ statistics dominated, ok at $\sim 1.5\sigma$



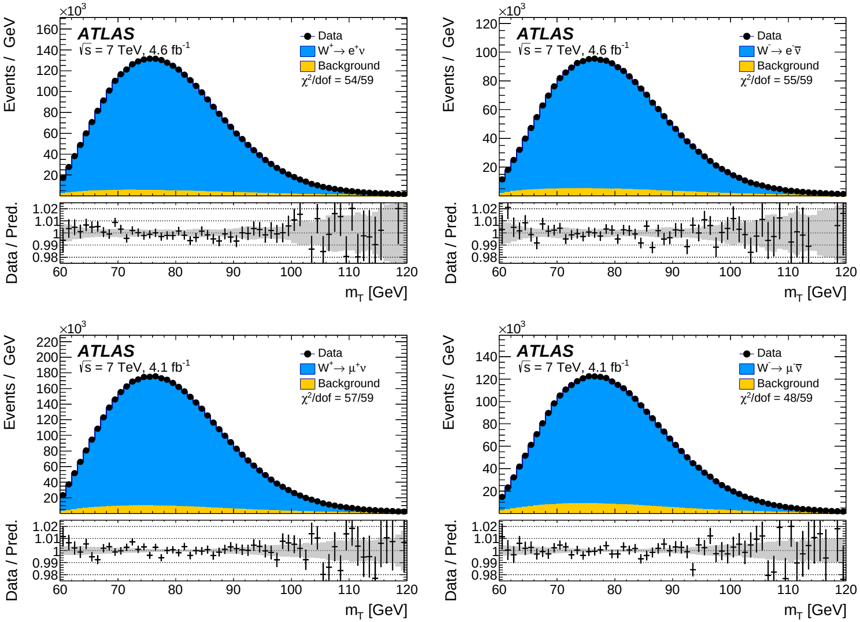




W-boson mass fit distributions: p_T^ℓ

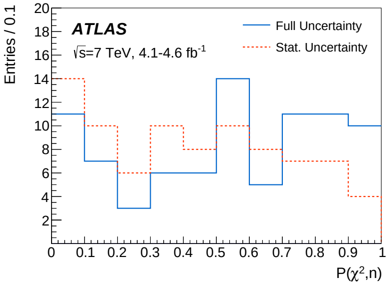


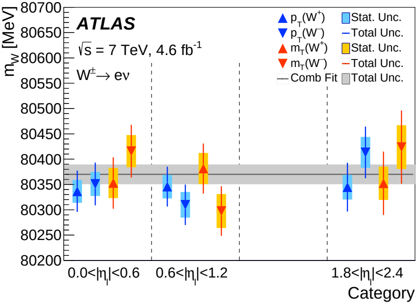
W-boson mass fit distributions: m_T

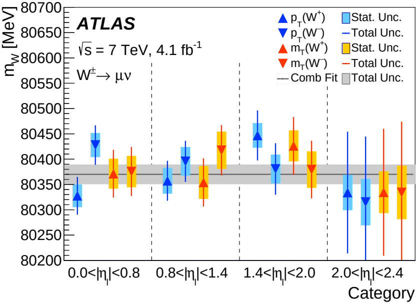


W-boson mass result per category

- Analysis binned in $|\eta|$ and $W^{\pm}$-charge categories and fit performed in both p_T^{ℓ} and m_T
- $P(\chi^2)$ distribution over all fit categories: uncertainties well calibrated
- Combination including correlations: $\chi^2/\text{n.d.f.} = 29/27$







W-boson mass result per category

Channel m_T-Fit	m_W [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80371.3	29.2	12.4	0.0	15.2	8.1	9.9	3.4	28.4	47.1
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80354.1	32.1	19.3	0.0	13.0	6.8	9.6	3.4	23.3	47.6
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80426.3	30.2	35.1	0.0	14.3	7.2	9.3	3.4	27.2	56.9
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.6	40.9	112.4	0.0	14.4	9.0	8.4	3.4	32.8	125.5
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80375.5	30.6	11.6	0.0	13.1	8.5	9.5	3.4	30.6	48.5
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80417.5	36.4	18.5	0.0	12.2	7.7	9.7	3.4	22.2	49.7
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80379.4	35.6	33.9	0.0	10.5	8.1	9.7	3.4	23.1	56.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.2	52.4	123.7	0.0	11.6	10.2	9.9	3.4	34.1	139.9
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80352.9	29.4	0.0	19.5	13.1	15.3	9.9	3.4	28.5	50.8
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80381.5	30.4	0.0	21.4	15.1	13.2	9.6	3.4	23.5	49.4
$W^+ \to e\nu, 1{,}8 < \lvert\eta\rvert < 2.4$	80352.4	32.4	0.0	26.6	16.4	32.8	8.4	3.4	27.3	62.6
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80415.8	31.3	0.0	16.4	11.8	15.5	9.5	3.4	31.3	52.1
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80297.5	33.0	0.0	18.7	11.2	12.8	9.7	3.4	23.9	49.0
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80423.8	42.8	0.0	33.2	12.8	35.1	9.9	3.4	28.1	72.3
p_T-Fit										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80327.7	22.1	12.2	0.0	2.6	5.1	9.0	6.0	24.7	37.3
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80357.3	25.1	19.1	0.0	2.5	4.7	8.9	6.0	20.6	39.5
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80446.9	23.9	33.1	0.0	2.5	4.9	8.2	6.0	25.2	49.3
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.1	34.5	110.1	0.0	2.5	6.4	6.7	6.0	31.8	120.2
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80427.8	23.3	11.6	0.0	2.6	5.8	8.1	6.0	26.4	39.0
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80395.6	27.9	18.3	0.0	2.5	5.6	8.0	6.0	19.8	40.5
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80380.6	28.1	35.2	0.0	2.6	5.6	8.0	6.0	20.6	50.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80315.2	45.5	116.1	0.0	2.6	7.6	8.3	6.0	32.7	129.6
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80336.5	22.2	0.0	20.1	2.5	6.4	9.0	5.3	24.5	40.7
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80345.8	22.8	0.0	21.4	2.6	6.7	8.9	5.3	20.5	39.4
$W^+ \to e\nu, 1{,}8 < \lvert\eta\rvert < 2.4$	80344.7	24.0	0.0	30.8	2.6	11.9	6.7	5.3	24.1	48.2
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80351.0	23.1	0.0	19.8	2.6	7.2	8.1	5.3	26.6	42.2
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80309.8	24.9	0.0	19.7	2.7	7.3	8.0	5.3	20.9	39.9
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80413.4	30.1	0.0	30.7	2.7	11.5	8.3	5.3	22.7	51.0

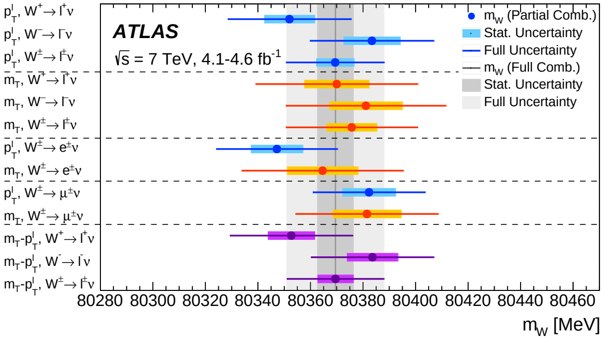
|η| comb e → ~15 MeV
μ → ~11 MeV

Strongly correlated

Strongly correlated

|η| comb. → ~14 MeV
W+/W- comb → ~9 MeV

W-boson mass result

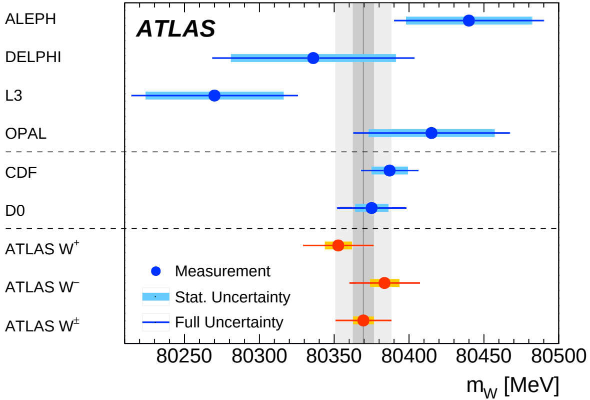


Combination	Weight
Electrons	0.427
Muons	0.573
m_{T}	0.144
p_{T}^{ℓ}	0.856
W^+	0.519
W^-	0.481

- Good compatibility between partial combinations
- p_T^{ℓ} fit dominates – as expected, m_T important validation
- Electrons contribute significantly!
- W^+–W^- mass difference

$$m_{W^+} - m_{W^-} = -29 \pm 13\,\mathrm{MeV(stat.)} \pm 7\,\mathrm{MeV(exp.\ syst.)} \pm 24\,\mathrm{MeV(mod.\ syst.)}$$
$$= -29 \pm 28\,\mathrm{MeV}$$

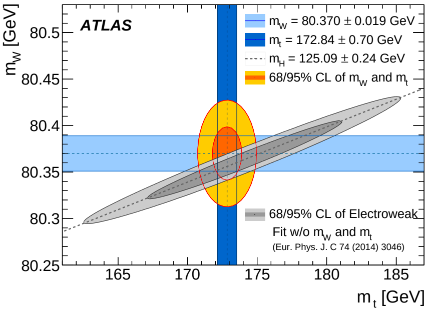
First ATLAS W-boson mass result

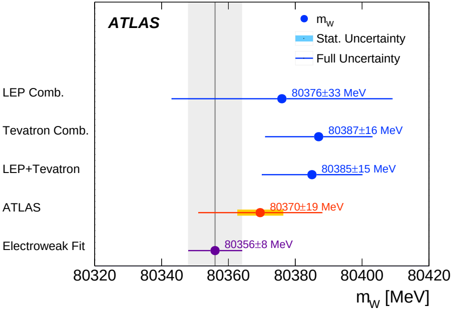


$$m_W = 80370 \pm 7\,\mathrm{MeV(stat.)} \pm 11\,\mathrm{MeV(exp.\ syst.)} \pm 14\,\mathrm{MeV(mod.\ syst.)}$$
$$= 80370 \pm 19\,\mathrm{MeV}$$

Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	
6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	[MeV]

First ATLAS *W*-boson mass result





Good agreement with the Standard Model

Summary & Outlook

Two milestones from the LHC precision frontier:

- Precision cross-sections at $< 1\%$ level: strong constraints on PDFs — flavour-symmetry of light-quark sea
- First measurement of the W-boson mass at LHC: many thought it would be impossible at this precision; good agreement with SM prediction

Final uncertainties on the interpretation dominated by theory:

- Possibly not completely unexpected for *pp* collisions
- Some theory limitations can be reduced by performing and incorporating additional measurements (8 TeV and 13 TeV)
- Help from the theorists to improve modelling

Backup - A largely random collection

W mass: physics model uncertainties

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

W mass: electron uncertainties

$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

W mass: muon uncertainties

$\|\eta_\ell\|$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

W mass: recoil uncertainties

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

W mass: background uncertainties

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

W mass: category summary

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

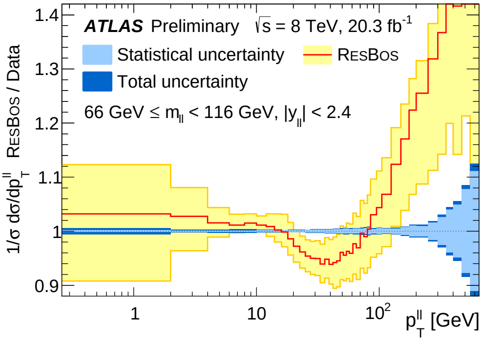
W mass: x-checks

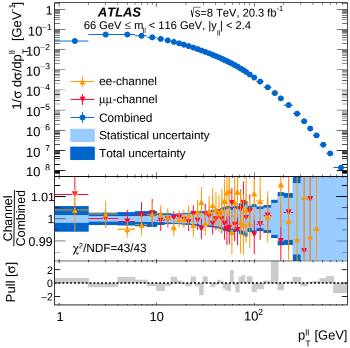
Decay channel	$W \to e\nu$		$W \to \mu\nu$		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Δm_W [MeV]						
$\langle\mu\rangle$ in $[2.5, 6.5]$	8 ± 14	14 ± 18	-21 ± 12	0 ± 16	-9 ± 9	6 ± 12
$\langle\mu\rangle$ in $[6.5, 9.5]$	-6 ± 16	6 ± 23	12 ± 15	-8 ± 22	4 ± 11	-1 ± 16
$\langle\mu\rangle$ in $[9.5, 16]$	-1 ± 16	3 ± 27	25 ± 16	35 ± 26	12 ± 11	20 ± 19
u_T in $[0, 15] GeV$	0 ± 11	-8 ± 13	5 ± 10	8 ± 12	3 ± 7	-1 ± 9
u_T in $[15, 30] GeV$	10 ± 15	0 ± 24	-4 ± 14	-18 ± 22	2 ± 10	-10 ± 16
$u_\parallel^\ell < 0\, GeV$	8 ± 15	20 ± 17	3 ± 13	-1 ± 16	5 ± 10	9 ± 12
$u_\parallel^\ell > 0\, GeV$	-9 ± 10	1 ± 14	-12 ± 10	10 ± 13	-11 ± 7	6 ± 10
No p_T^{miss}-cut	14 ± 9	-1 ± 13	10 ± 8	-6 ± 12	12 ± 6	-4 ± 9

Z/γ^* transverse momentum

[EPJC 76(5), 1-61 (2016), arXiv:1605.04295]

- Vector bosons are produced with non-zero transverse momentum: interesting interplay of effects from resummation and hard (jet) emissions
- High precision 2011 and 2012 results with $\lesssim 0.5\%$ precision after $ee + \mu\mu$ combination over a wide range!
- 2012 analysis extent to off-peak measurements: data/theory agreement not good at $\mathcal{O}(\alpha_s^2)$, improved with very recent $\mathcal{O}(\alpha_s^3)$ calculation – remainder PDFs?
- Important for W mass measurement, Higgs predictions, BSM searches...





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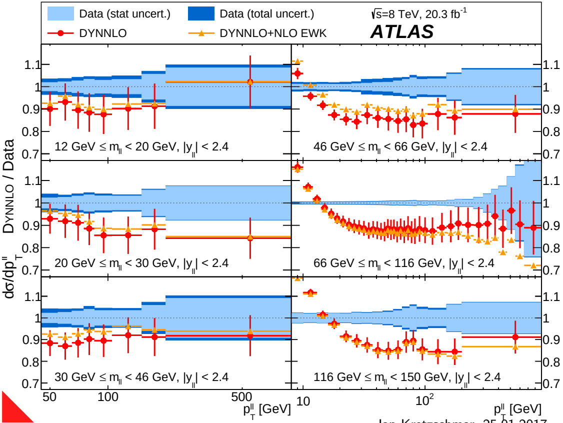

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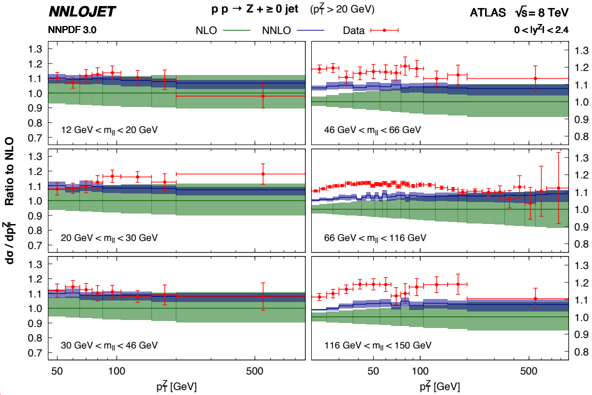


Proton structure

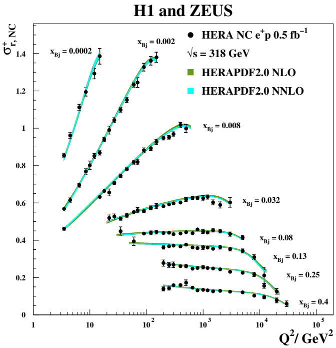
EPJ C75 (2015) 580

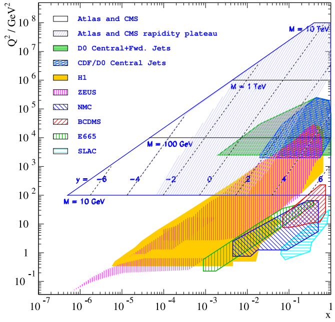
- Proton is not a point-like particle: complex structure with valence quarks, light and heavy sea quarks, and gluons → PDFs
- QCD the evolution of quark given by equations as described e.g. in the paper by Altarelli and Parisi (1977) (*DGLAP equations*)

$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{q^i q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^i G}\left(\frac{x}{y}\right)\right] \qquad (22)$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{G q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right] \qquad (23)$$

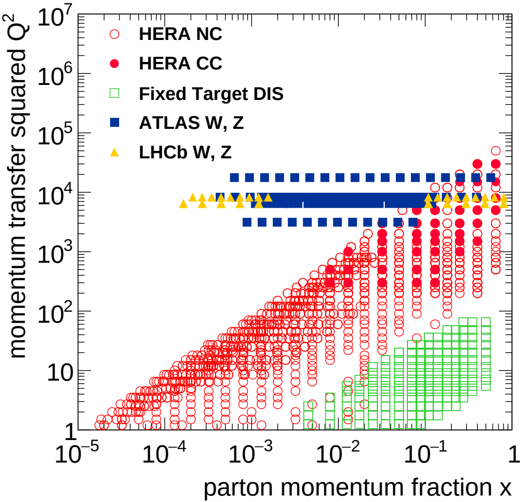
$(t = \ln Q^2/Q_0^2)$



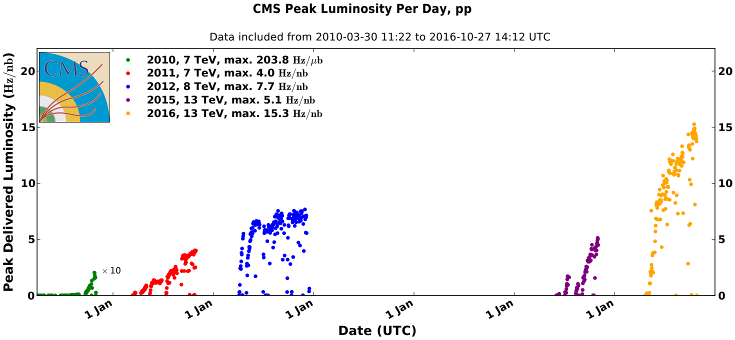


x, Q^2 plane

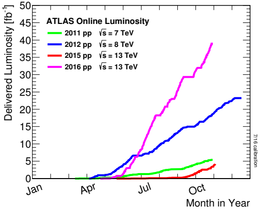
- Parametrise all PDFs at fixed starting scale $f(x, Q_0^2)$:
  DGLAP evolution gives result for all $f(x, Q^2)$
- Full LHC W, Z production x range only covered by HERA NC data



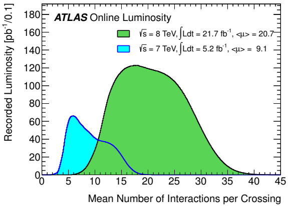
Data sample



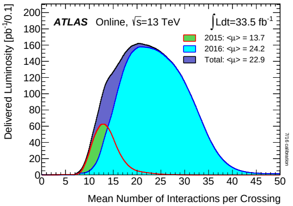
CMS Peak Luminosity Per Day, pp
Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC
CMS
2010, 7 TeV, max. 203.8 Hz/μb
2011, 7 TeV, max. 4.0 Hz/nb
2012, 8 TeV, max. 7.7 Hz/nb
2015, 13 TeV, max. 5.1 Hz/nb
2016, 13 TeV, max. 15.3 Hz/nb
× 10
Peak Delivered Luminosity (Hz/nb)
1 Jan
Date (UTC)



ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
Delivered Luminosity [fb⁻¹]
Jan
Apr
Jul
Oct
Month in Year
7/16 calibration

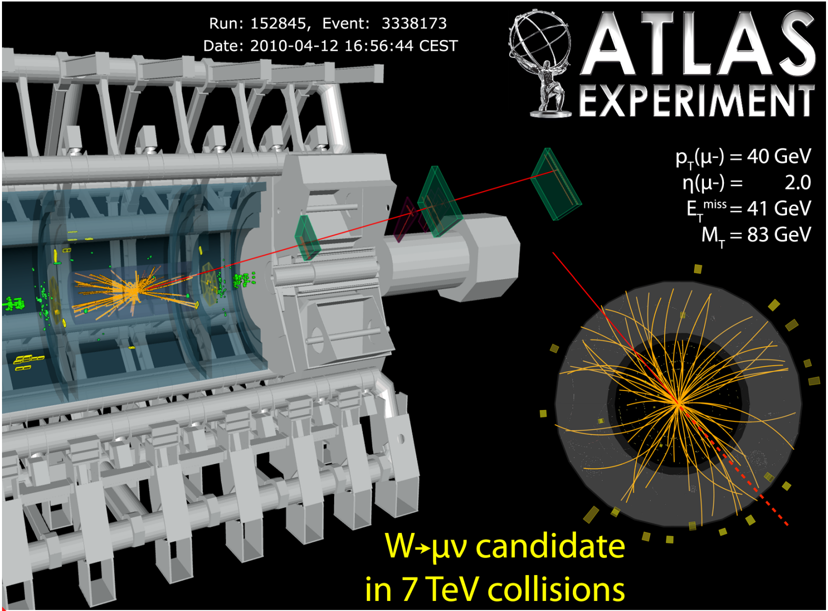


ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 21.7 fb⁻¹, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing

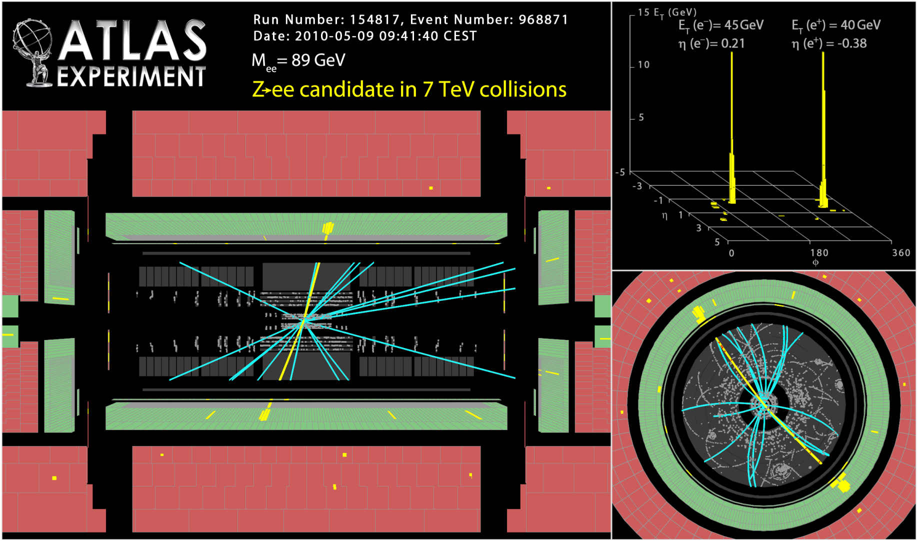


ATLAS Online, √s=13 TeV
∫Ldt=33.5 fb⁻¹
2015: <μ> = 13.7
2016: <μ> = 24.2
Total: <μ> = 22.9
Delivered Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
7/16 calibration

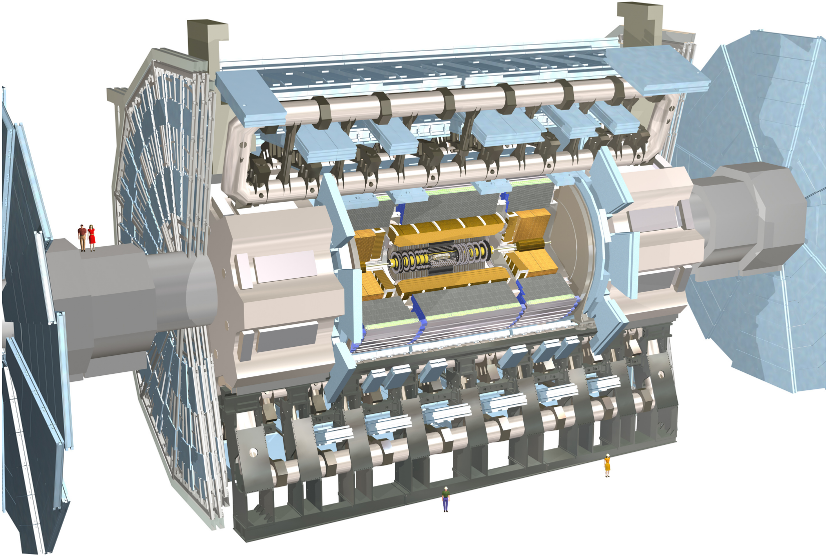
A $W \to \mu\nu$ candidate



A $Z \to ee$ candidate



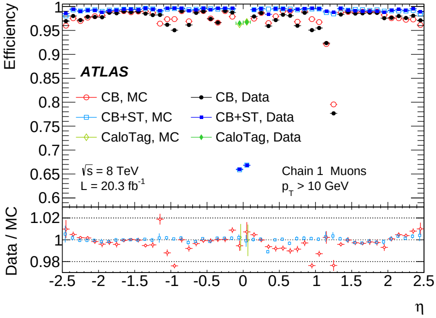
The ATLAS Detector

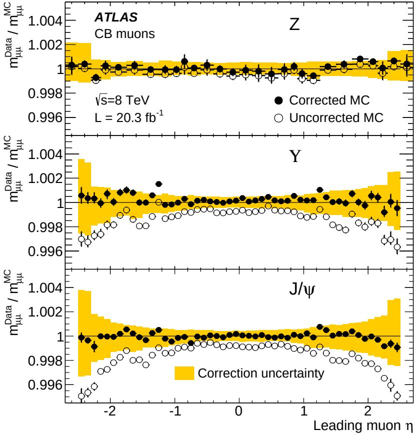


Run 1 Lepton Performance: Muons

[EPJ C74 (2014) 3130]

- Main experimental issue for W and Z is quantitative understanding of lepton performance: selection efficiencies, energy/momentum scales
- Thanks to the large $Z \to \ell\ell$ samples this is mostly an exercise in time and dedication
- Muon efficiencies and calibration both known at the $< 0.1\%$ level (non-uniformities in muon spectrometer and ID+MS alignment at μm level)





Cross-section measurements

- $W^+ \to \ell^+\nu$ and $W^- \to \ell^-\nu$ measured integrated and as function of charged lepton rapidity $|\eta_\ell|$: typical precision $0.6 - 1.0\%$
- $Z/\gamma^* \to \ell\ell$ measured integrated and as function of di-lepton rapidity $|y_{\ell\ell}|$ and di-lepton mass $m_{\ell\ell}$: typical precision 0.4%, forward Z 2.3%

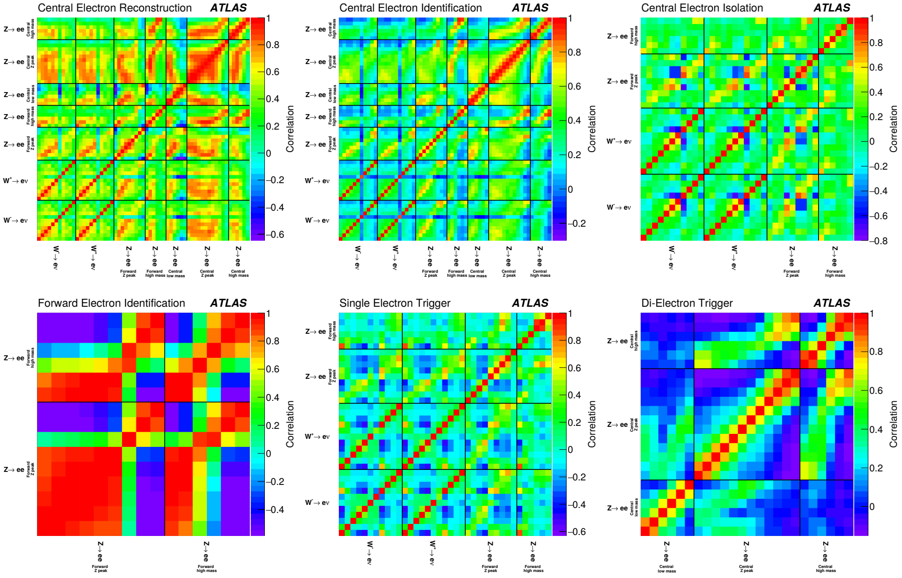
Electron channels

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_Z$ [%]	$\delta\sigma_{\text{forward } Z}$ [%]
Trigger efficiency	0.03	0.03	0.05	0.05
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
Forward identification efficiency	–	–	–	1.51
Isolation efficiency	0.03	0.03	–	0.04
Charge misidentification	0.04	0.06	–	–
Electron p_T resolution	0.02	0.03	0.01	0.01
Electron p_T scale	0.22	0.18	0.08	0.12
Forward electron p_T scale + resolution	–	–	–	0.18
E_T^{miss} soft term scale	0.14	0.13	–	–
E_T^{miss} soft term resolution	0.06	0.04	–	–
Jet energy scale	0.04	0.02	–	–
Jet energy resolution	0.11	0.15	–	–
Signal modelling (matrix-element generator)	0.57	0.64	0.03	1.12
Signal modelling (parton shower and hadronization)	0.24	0.25	0.18	1.25
PDF	0.10	0.12	0.09	0.06
Boson p_T	0.22	0.19	0.01	0.04
Multijet background	0.55	0.72	0.03	0.05
Electroweak+top background	0.17	0.19	0.02	0.14
Background statistical uncertainty	0.02	0.03	<0.01	0.04
Unfolding statistical uncertainty	0.03	0.04	0.04	0.13
Data statistical uncertainty	0.04	0.05	0.10	0.18
Total experimental uncertainty	0.94	1.08	0.35	2.29
Luminosity			1.8	

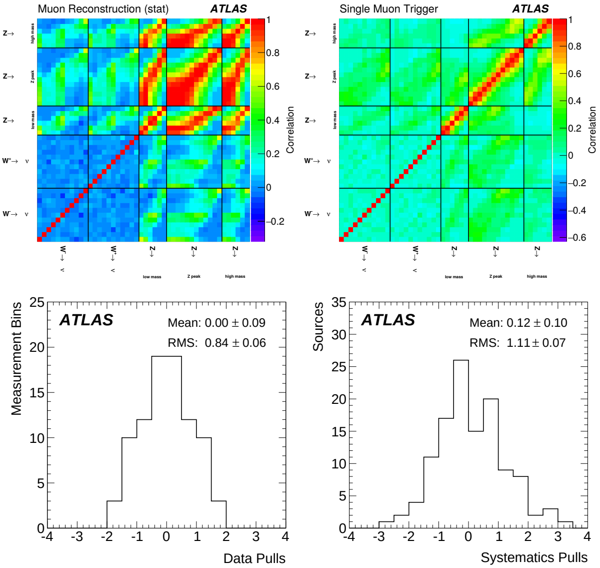
Muon channels

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_Z$ [%]
Trigger efficiency	0.08	0.07	0.05
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_T resolution	0.01	0.01	<0.01
Muon p_T scale	0.18	0.17	0.03
E_T^{miss} soft term scale	0.19	0.19	–
E_T^{miss} soft term resolution	0.10	0.09	–
Jet energy scale	0.09	0.12	–
Jet energy resolution	0.11	0.16	–
Signal modelling (matrix-element generator)	0.12	0.06	0.04
Signal modelling (parton shower and hadronization)	0.14	0.17	0.22
PDF	0.09	0.12	0.07
Boson p_T	0.18	0.14	0.04
Multijet background	0.33	0.27	0.07
Electroweak+top background	0.19	0.24	0.02
Background statistical uncertainty	0.03	0.04	0.01
Unfolding statistical uncertainty	0.03	0.03	0.02
Data statistical uncertainty	0.04	0.04	0.08
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	

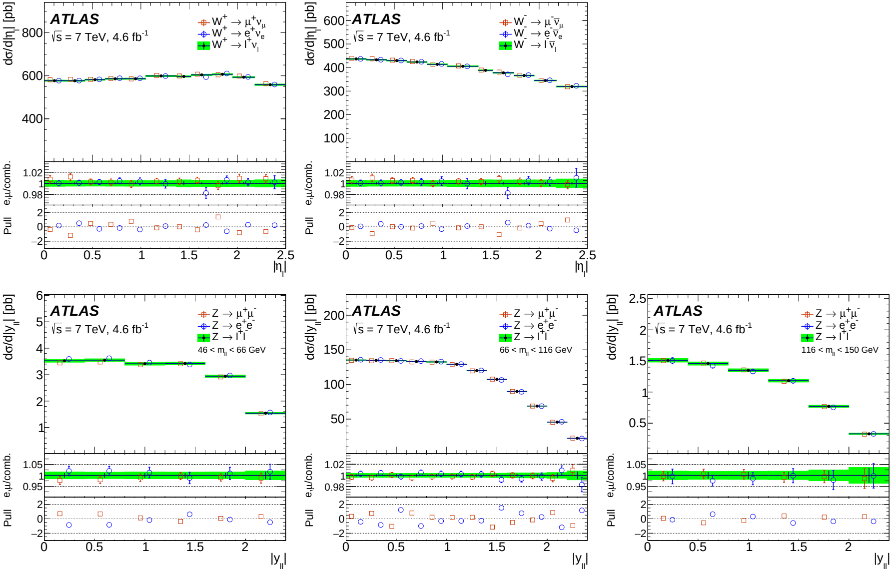
W, Z Combination



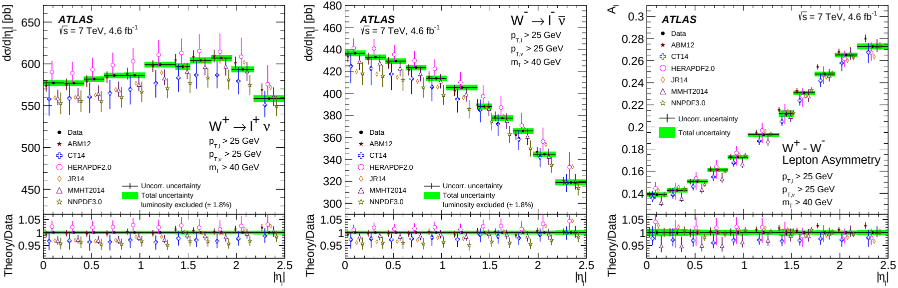
W, Z Combination



W, Z Combination

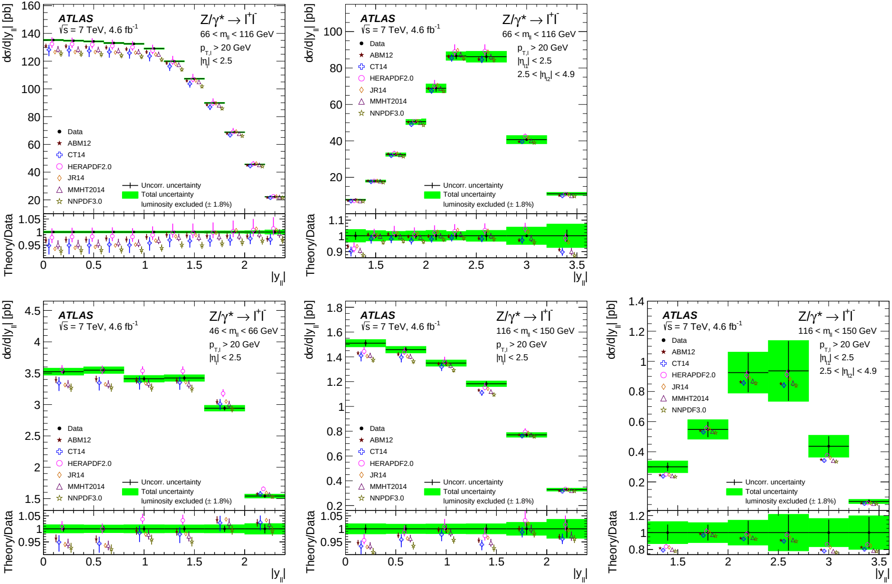


ATLAS *W*

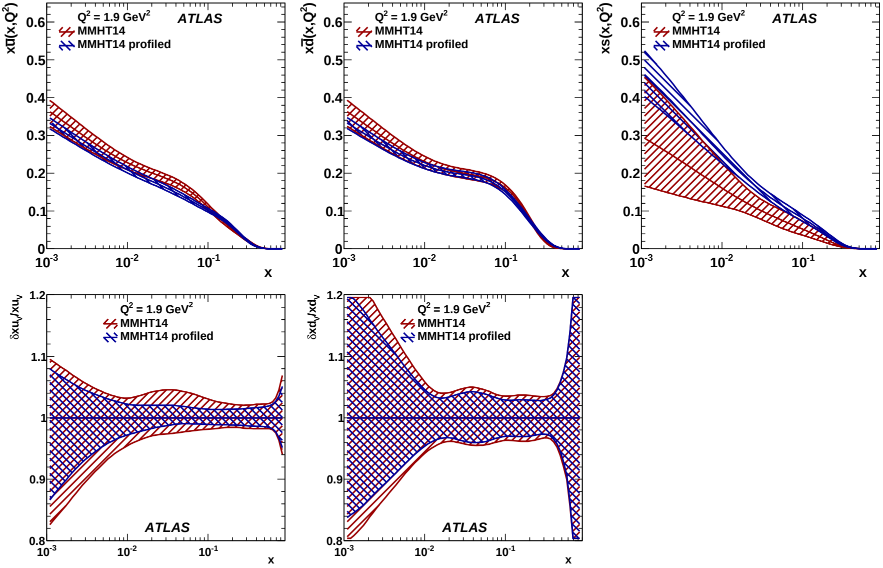


ATLAS
√s = 7 TeV, 4.6 fb-1
W+ → l+ ν
pT,l > 25 GeV
pT,ν > 25 GeV
mT > 40 GeV
W- → l- ν̄
Data
ABM12
CT14
HERAPDF2.0
JR14
MMHT2014
NNPDF3.0
Uncorr. uncertainty
Total uncertainty
luminosity excluded (± 1.8%)
W+ - W-
Lepton Asymmetry
dσ/d|ηl| [pb]
Al
Theory/Data
|ηl|

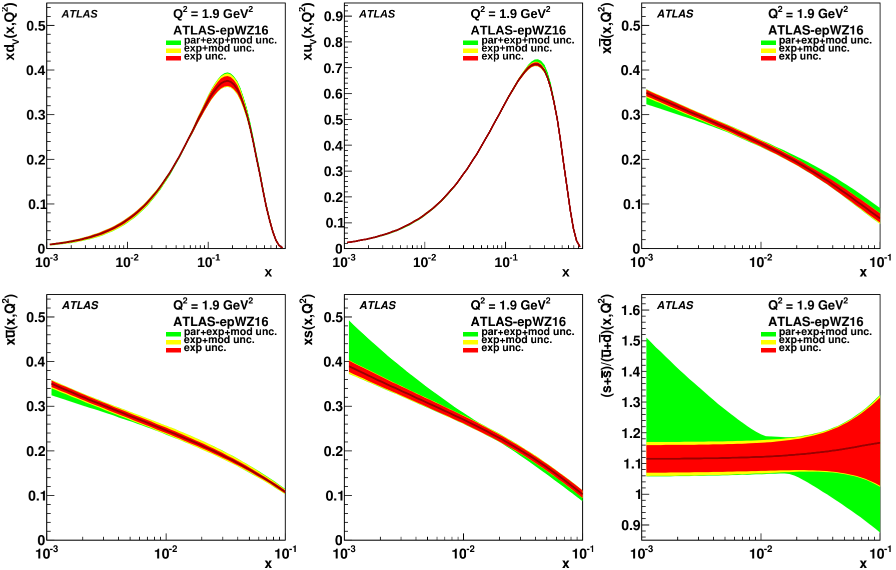
ATLAS Z


ATLAS
√s = 7 TeV, 4.6 fb-1
Z/γ* → l+l-
66 < mll < 116 GeV
pT,l > 20 GeV
|ηl| < 2.5
2.5 < |ηl2| < 4.9
46 < mll < 66 GeV
116 < mll < 150 GeV
Data
ABM12
CT14
HERAPDF2.0
JR14
MMHT2014
NNPDF3.0
Uncorr. uncertainty
Total uncertainty
luminosity excluded (± 1.8%)
dσ/d|yll| [pb]
Theory/Data
|yll|

PDF profiling

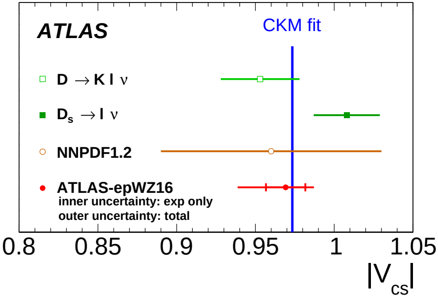


ATLAS-epWZ16



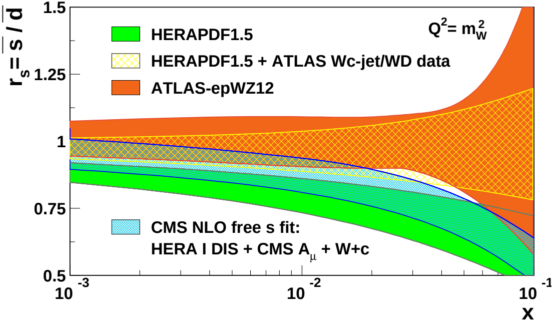
CKM matrix element $|V_{cs}|$

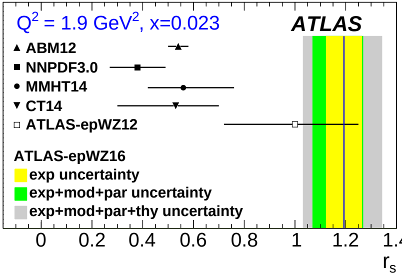
- Data is also sensitive to the magnitude of the CKM matrix element $|V_{cs}|$, which is not well measured experimentally (although well determined when imposing CKM unitarity)
- Related to strange density, as dependence is through $cs \to W$ contribution ($20 - 30\%$ of W cross section)
- Determination competitive with existing values, much improved compared to earlier NNPDF1.2 fit

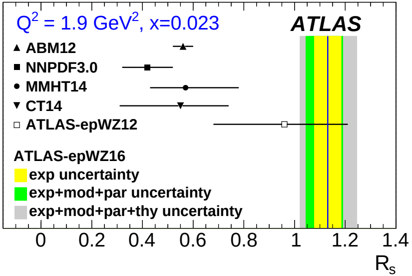


	$\lvert V_{cs}\rvert$
Central value	0.969
Experimental data	± 0.013
Model (m_b, $Q^2_{\min}$, Q^2_0 & m_c)	$^{+0.006}_{-0.003}$
Parameterization	$^{+0.003}_{-0.027}$
α_S	± 0.000
Beam energy E_p	± 0.001
EW corrections	± 0.004
QCD scales	$^{+0.000}_{-0.003}$
FEWZ 3.1b2	$+0.011$
Total uncertainty	$^{+0.018}_{-0.031}$

Strange


$r_s = \bar{s}/\bar{d}$
$Q^2 = m_W^2$
HERAPDF1.5
HERAPDF1.5 + ATLAS Wc-jet/WD data
ATLAS-epWZ12
CMS NLO free s fit:
HERA I DIS + CMS A_μ + W+c
1.5
1.25
1
0.75
0.5
10^{-3}
10^{-2}
10^{-1}
x


$Q^2 = 1.9\ GeV^2$, x=0.023
ATLAS
ABM12
NNPDF3.0
MMHT14
CT14
ATLAS-epWZ12
ATLAS-epWZ16
exp uncertainty
exp+mod+par uncertainty
exp+mod+par+thy uncertainty
0 0.2 0.4 0.6 0.8 1 1.2 1.4
r_s


$Q^2 = 1.9\ GeV^2$, x=0.023
ATLAS
ABM12
NNPDF3.0
MMHT14
CT14
ATLAS-epWZ12
ATLAS-epWZ16
exp uncertainty
exp+mod+par uncertainty
exp+mod+par+thy uncertainty
0 0.2 0.4 0.6 0.8 1 1.2 1.4
R_s

Strange

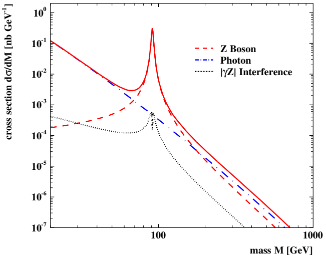
PDF parameterised at starting scale Q_0^2 with 15 free parameters

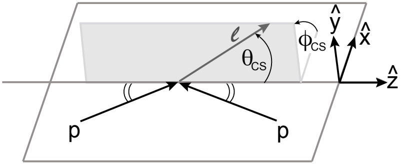
$$
\begin{aligned}
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2) \, , \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} \, , \\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}} \, , \\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}} \, , \\
xg(x) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g} \, , \\
x\bar{s}(x) &= A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}} \, ,
\end{aligned}
$$

The five-dimensional DY cross sections

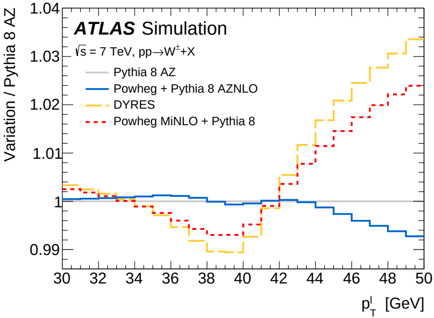
- Description of production and decay of single $W^{\pm} \to \ell\nu$ and $Z/\gamma^{*} \to \ell\ell$ depends on five kinematic variables:
  - Boson 4-vector: di-lepton mass $m_{\ell\ell}$, transverse momentum $p_{T,\ell\ell}$ and rapidity $y_{\ell\ell}$
  - Spin-1 of $W/Z/\gamma^{*}$ bosons and EWK coupling effects the two decay leptons have non-trivial angular correlations (θ_{CS} and ϕ_{CS})
- Can be factorised as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}p_{T,\ell\ell}\mathrm{d}y_{\ell\ell}}\left[1+\cos^2\theta_{CS}+\sum_{i=0}^{7}A_i(m,p_T,y)f_i(\theta_{CS},\phi_{CS})\right]$$

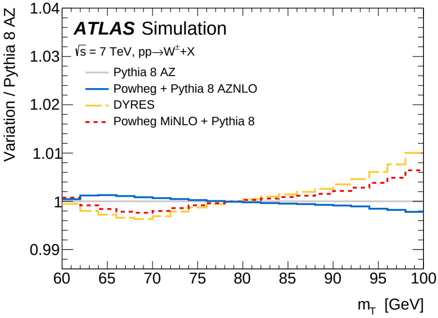




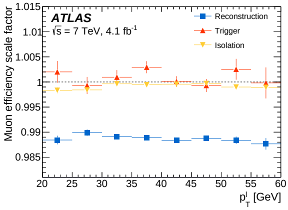
W mass



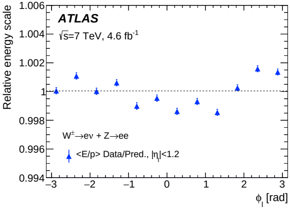
ATLAS Simulation
√s = 7 TeV, pp→W±+X
Pythia 8 AZ
Powheg + Pythia 8 AZNLO
DYRES
Powheg MiNLO + Pythia 8
Variation / Pythia 8 AZ
1.04
1.03
1.02
1.01
1
0.99
30
32
34
36
38
40
42
44
46
48
50
p_T^l [GeV]



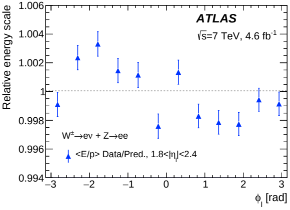
ATLAS Simulation
√s = 7 TeV, pp→W±+X
Pythia 8 AZ
Powheg + Pythia 8 AZNLO
DYRES
Powheg MiNLO + Pythia 8
Variation / Pythia 8 AZ
1.04
1.03
1.02
1.01
1
0.99
60
65
70
75
80
85
90
95
100
m_T [GeV]



ATLAS
√s = 7 TeV, 4.1 fb-1
Reconstruction
Trigger
Isolation
Muon efficiency scale factor
1.015
1.01
1.005
1
0.995
0.99
0.985
20
25
30
35
40
45
50
55
60
p_T^l [GeV]

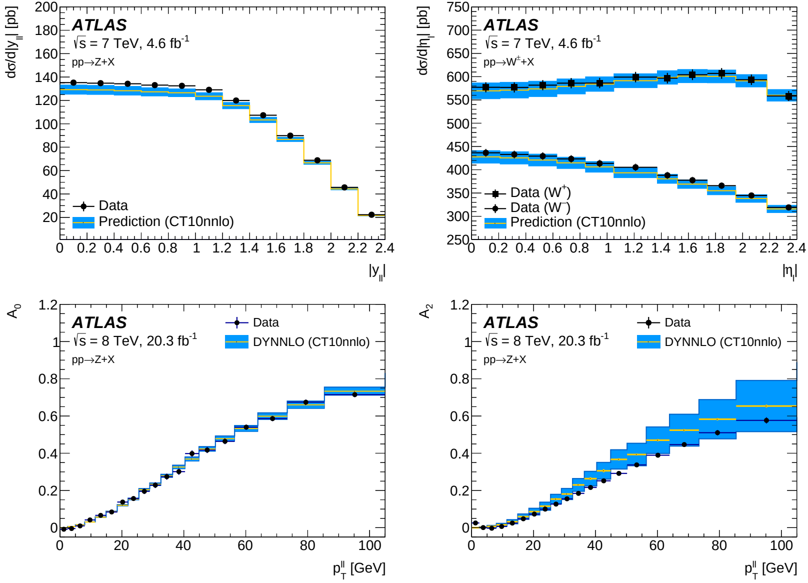


ATLAS
√s=7 TeV, 4.6 fb-1
W±→eν + Z→ee
<E/p> Data/Pred., |η_l|<1.2
Relative energy scale
1.006
1.004
1.002
1
0.998
0.996
0.994
−3
−2
−1
0
1
2
3
φ_l [rad]



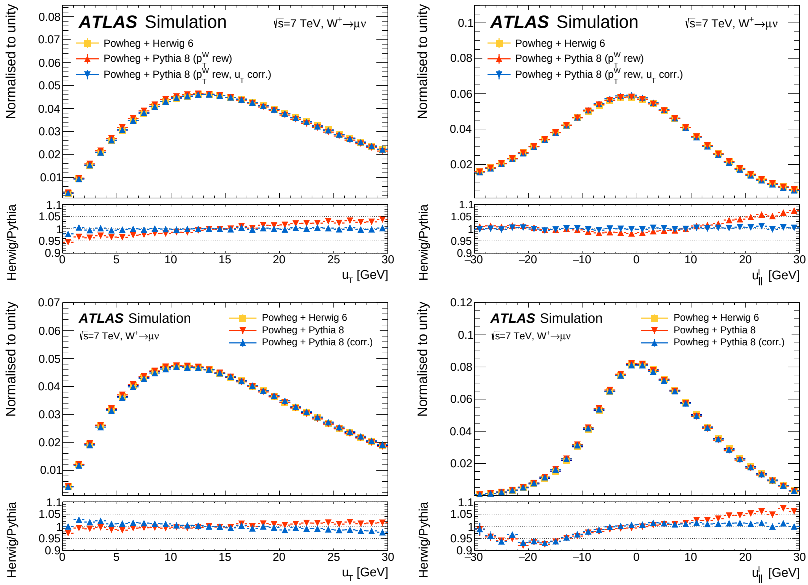
ATLAS
√s=7 TeV, 4.6 fb-1
W±→eν + Z→ee
<E/p> Data/Pred., 1.8<|η_l|<2.4
Relative energy scale
1.006
1.004
1.002
1
0.998
0.996
0.994
−3
−2
−1
0
1
2
3
φ_l [rad]

W mass



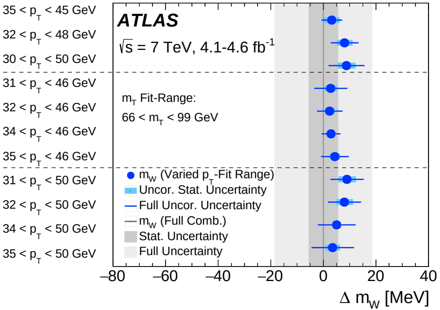
ATLAS
√s = 7 TeV, 4.6 fb^-1
pp→Z+X
Data
Prediction (CT10nnlo)
dσ/d|y_ll| [pb]
|y_ll|
ATLAS
√s = 7 TeV, 4.6 fb^-1
pp→W±+X
Data (W+)
Data (W−)
Prediction (CT10nnlo)
dσ/d|η_l| [pb]
|η_l|
ATLAS
√s = 8 TeV, 20.3 fb^-1
pp→Z+X
Data
DYNNLO (CT10nnlo)
A0
p_T^ll [GeV]
ATLAS
√s = 8 TeV, 20.3 fb^-1
pp→Z+X
Data
DYNNLO (CT10nnlo)
A2
p_T^ll [GeV]

W mass

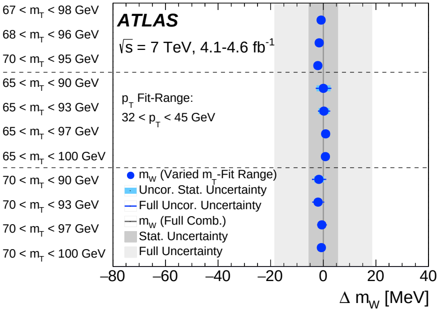


ATLAS Simulation
√s=7 TeV, W±→μν
Powheg + Herwig 6
Powheg + Pythia 8 (p_T^W rew)
Powheg + Pythia 8 (p_T^W rew, u_T corr.)
Powheg + Pythia 8
Powheg + Pythia 8 (corr.)
Normalised to unity
Herwig/Pythia
u_T [GeV]
u_∥^l [GeV]

W mass

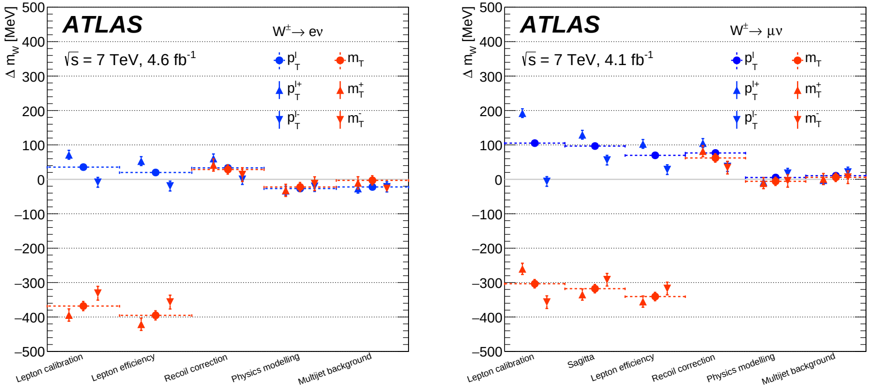


ATLAS
√s = 7 TeV, 4.1-4.6 fb^{-1}
m_T Fit-Range:
66 < m_T < 99 GeV
m_W (Varied p_T-Fit Range)
Uncor. Stat. Uncertainty
Full Uncor. Uncertainty
m_W (Full Comb.)
Stat. Uncertainty
Full Uncertainty
35 < p_T < 45 GeV
32 < p_T < 48 GeV
30 < p_T < 50 GeV
31 < p_T < 46 GeV
32 < p_T < 46 GeV
34 < p_T < 46 GeV
35 < p_T < 46 GeV
31 < p_T < 50 GeV
32 < p_T < 50 GeV
34 < p_T < 50 GeV
35 < p_T < 50 GeV
–80 –60 –40 –20 0 20 40
Δ m_W [MeV]



ATLAS
√s = 7 TeV, 4.1-4.6 fb^{-1}
p_T Fit-Range:
32 < p_T < 45 GeV
m_W (Varied m_T-Fit Range)
Uncor. Stat. Uncertainty
Full Uncor. Uncertainty
m_W (Full Comb.)
Stat. Uncertainty
Full Uncertainty
67 < m_T < 98 GeV
68 < m_T < 96 GeV
70 < m_T < 95 GeV
65 < m_T < 90 GeV
65 < m_T < 93 GeV
65 < m_T < 97 GeV
65 < m_T < 100 GeV
70 < m_T < 90 GeV
70 < m_T < 93 GeV
70 < m_T < 97 GeV
70 < m_T < 100 GeV
–80 –60 –40 –20 0 20 40
Δ m_W [MeV]

W mass


ATLAS
W±→ eν
√s = 7 TeV, 4.6 fb-1
Δ mW [MeV]
Lepton calibration
Lepton efficiency
Recoil correction
Physics modelling
Multijet background
ATLAS
W±→ μν
√s = 7 TeV, 4.1 fb-1
Δ mW [MeV]
Lepton calibration
Sagitta
Lepton efficiency
Recoil correction
Physics modelling
Multijet background

W mass: weights

Observable	Channel	η range	Weight
m_{T}	$W^+ \to \mu\nu$	$\lvert\eta\rvert < 0.8$	0.018
		$0.8 < \lvert\eta\rvert < 1.4$	0.022
		$1.4 < \lvert\eta\rvert < 2.0$	0.003
		$2.0 < \lvert\eta\rvert < 2.4$	0.006
	$W^- \to \mu\nu$	$\lvert\eta\rvert < 0.8$	0.020
		$0.8 < \lvert\eta\rvert < 1.4$	0.018
		$1.4 < \lvert\eta\rvert < 2.0$	0.022
		$2.0 < \lvert\eta\rvert < 2.4$	0.001
	$W^+ \to e\nu$	$\lvert\eta\rvert < 0.6$	0.013
		$0.6 < \lvert\eta\rvert < 1.2$	0.001
		$1,8 < \lvert\eta\rvert < 2.4$	0.010
	$W^- \to e\nu$	$\lvert\eta\rvert < 0.6$	0.008
		$0.6 < \lvert\eta\rvert < 1.2$	0.000
		$1.8 < \lvert\eta\rvert < 2.4$	0.002
p_{T}^{ℓ}	$W^+ \to \mu\nu$	$\lvert\eta\rvert < 0.8$	0.101
		$0.8 < \lvert\eta\rvert < 1.4$	0.076
		$1.4 < \lvert\eta\rvert < 2.0$	0.050
		$2.0 < \lvert\eta\rvert < 2.4$	0.011
	$W^- \to \mu\nu$	$\lvert\eta\rvert < 0.8$	0.097
		$0.8 < \lvert\eta\rvert < 1.4$	0.071
		$1.4 < \lvert\eta\rvert < 2.0$	0.047
		$2.0 < \lvert\eta\rvert < 2.4$	0.010
	$W^+ \to e\nu$	$\lvert\eta\rvert < 0.6$	0.056
		$0.6 < \lvert\eta\rvert < 1.2$	0.071
		$1,8 < \lvert\eta\rvert < 2.4$	0.081
	$W^- \to e\nu$	$\lvert\eta\rvert < 0.6$	0.062
		$0.6 < \lvert\eta\rvert < 1.2$	0.056
		$1.8 < \lvert\eta\rvert < 2.4$	0.067

DY