Parton Distribution Functions and electroweak measurements, including the W mass, in ATLAS

A M Cooper-Sarkar on behalf of ATLAS

Benasque 2015

Now that the Higgs mass is known all the parameters of the SM are known- but with what accuracy?

Precision EW measurements test the self-consistency of the SM- and thus can give hints of BSM physics

Precision measurements of

- **$\sin^2\theta_W$**
- **W-mass**

Are limited by PDF uncertainties

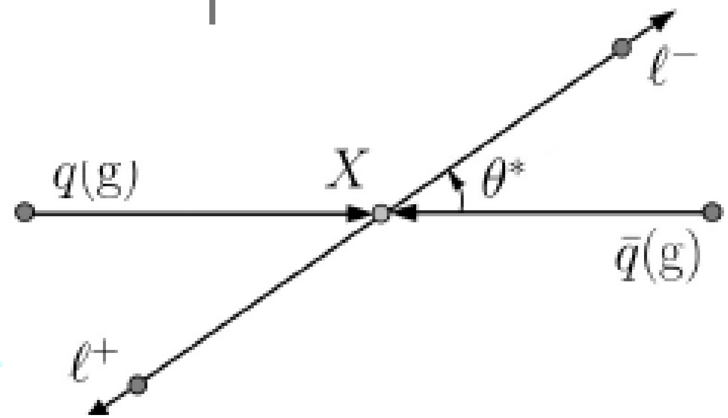
There are also limitations from experimental uncertainties and non-perturbative modelling for which we use measurements of

- **Z mass (for calibration)**
- **Zpt or Z φ^* for low pt modelling**

The weak mixing angle θ_W can be measured from the Forward-Backward asymmetry on the Z ZAFB

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{8}(A(1+\cos^2\theta)+B\cos\theta\right]$$

The coefficients A and B depend on $\boldsymbol{\theta_W}$
The linear term in cosθ gives rise to a forward-backward asymmetry in the scattering angle θ*, which changes sign at the Z pole.
We use the Collins-Soper definition of the angle



$$\cos\theta^*_{\mathrm{CS}} = \frac{p_{\mathrm{z},\ell\ell}}{|p_{\mathrm{z},\ell\ell}|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2+p_{\mathrm{T},\ell\ell}^2}}$$

$$p_i^\pm = \frac{1}{\sqrt{2}}(E_i \pm p_{\mathrm{z},i})$$

The variables $p_{z,ll}$, m_{ll} and $p_{T,ll}$ are longitudinal momentum, invariant mass and transverse momentum of the di-lepton system

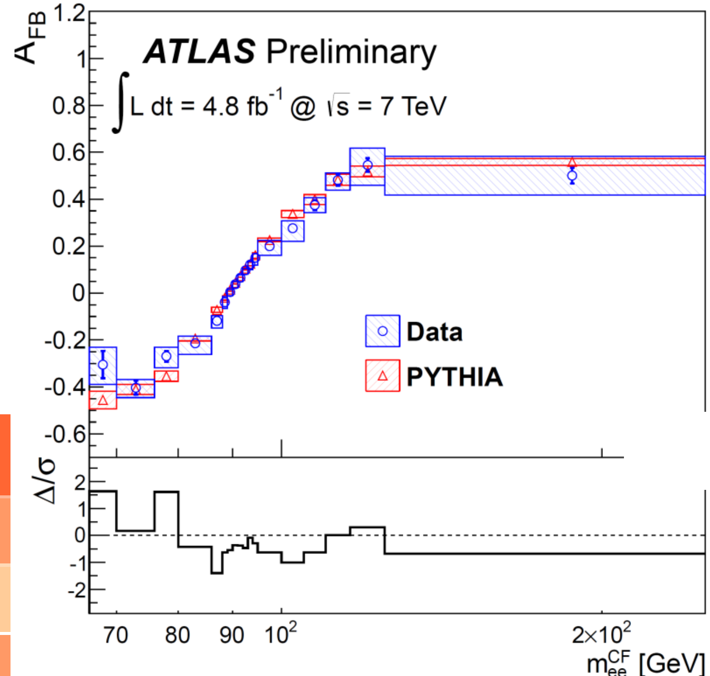
In p-p the direction of the incoming quark is unknown -- it is assumed to be the direction of the boost of the lepton pair
Only valence quarks will give an asymmetry --and they are not dominant as in p-pbar
Hence the effect is diluted and PDF dependent

$$A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$$

ATLAS-CONF-2013-043

θ_W is extracted from template fits to ZAFB
Templates are differential in m_{ll} and $\cos\theta_{CS}$

This is done for electron pairs Central-Central (CC) and Central-Forward (CF) in the detector and for muon pairs. The most accurate result comes from CF where the direction of the incoming quark is better constrained



	$\sin^2(\theta_W^{eff})$
ATLAS 7 TeV 4.8 fb^{-1}	0.2297 ± 0.0004(stat) ± 0.0009(syst)
CMS 7 TeV 1.1 fb^{-1}	0.2287 ± 0.0020(stat) ± 0.0025(syst)
LEP+SLD	0.23153 ± 0.00016

Uncertainty source	CC electrons (10^{-4})	CF electrons (10^{-4})	Muons (10^{-4})	Combined (10^{-4})
PDF	9	5	9	7
MC statistics	9	5	9	4
Electron energy scale	4	6	–	4
Electron energy smearing	4	5	–	3
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

- **Still 10 times worse than LEP+SLD**
- **ATLAS measurement is limited by PDF uncertainty**

PDF uncertainties here just from CT10 eigenvectors at 68%

Can we do better?

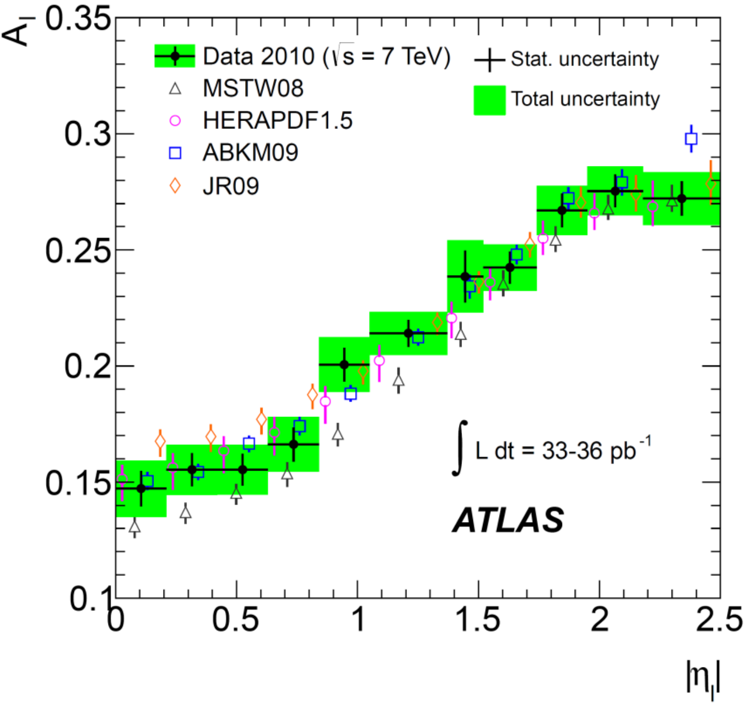
This is not easy

The PDF uncertainties were evaluated from CT10 eigenvectors

But the result also depends on which PDF is chosen

For example MSTW2008 produces a significant shift of -0.002 in $\sin^2\theta_W$

Of course it is now well known that this PDF does not describe the low-x u and d-valence quark distributions very well -- as illustrated by the ATLAS measurement of the W-asymmetry which depends on $u_{valence}$-$d_{valence}$ at LO



Phys Rev D85(2012)072004

Thus doing better can depend on further precision measurements of Z and W rapidity distributions

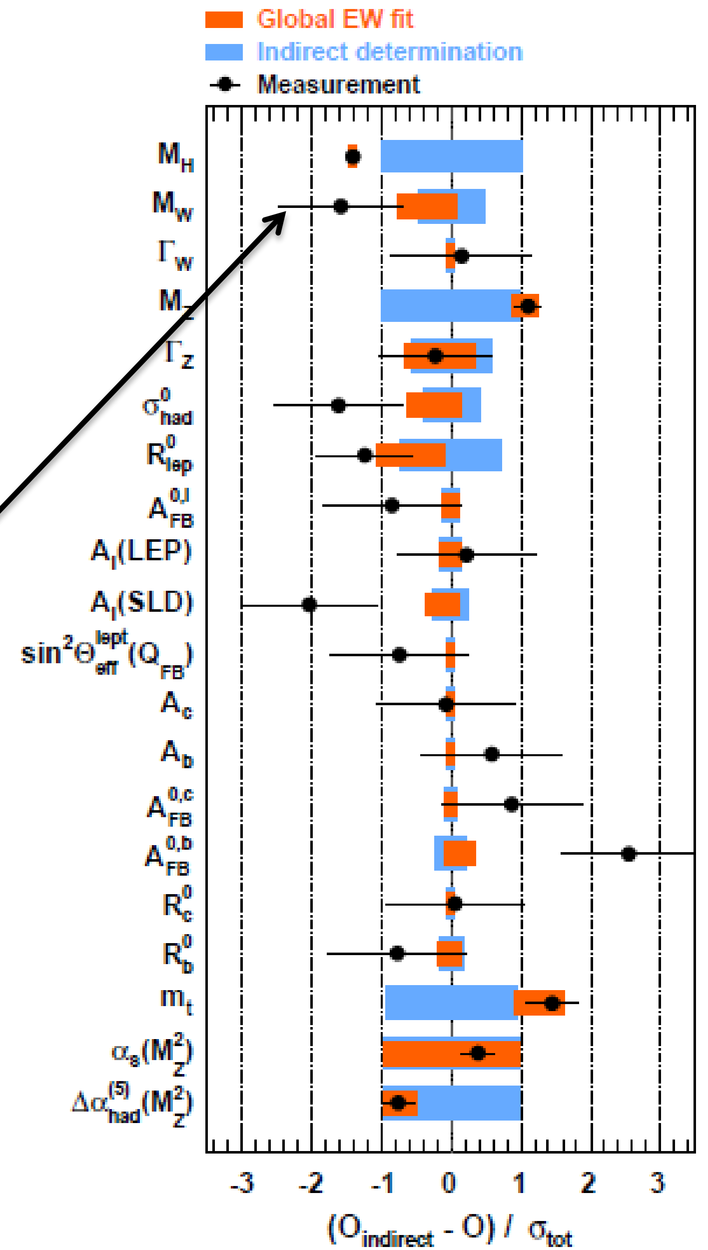
Forthcoming MUCH more precise (<1%) W+,W- and Z differential distributions from the ATLAS 2011 data with 5 fb^{-1}

The top mass, the W-mass and the Higgs mass are tied together by loop corrections in the SM. If there are new heavy particles then the relationship between them will change. Thus we need accurate measurements of all three

The indirect determination of the W mass from the Global EW fit is more accurate (±8MeV) than the experimental measurement

Thus we need to measure M_W to an accuracy of < 10 MeV.

The PDF uncertainty is currently greater than this .



Eur. Phys.J.C74(2014)3046

The W mass measurement is difficult since the leptonic decay channels in which it can be identified have missing neutrinos. Thus we use template fits to observables sensitive to M_W

Lepton transverse momentum	p_T^l
W transverse mass	$M_T = \sqrt{2 \cdot p_T^l p_T^\nu \cdot (1 - \cos\Delta\phi(l,\nu)}$

p_T^l	M_T
Observable does not depend on hadronic recoil, smaller experimental uncertainty	Depends on hadronic recoil measurement, expected larger experimental uncertainties
Larger theory uncertainty due to higher order QCD, p_T^W modelling, PDF, W polarisation, charm mass	M_T is quite stable wrt perturbative QCD corrections, smaller PDF uncertainties, smaller non-perturbative QCD uncertainties

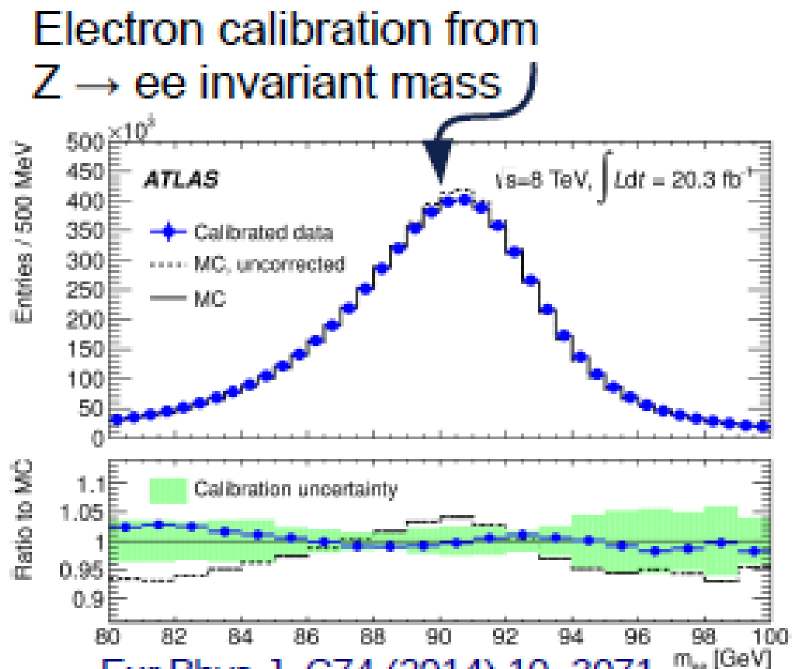
The LHC measurement differs from the Tevatron in several respects

1. Higher pile-up, affects the hadronic recoil that give us p_T^ν
2. p-p rather than p-pbar makes contributing PDFs different
3. and W^+ and W^- non- symmetric

Because of 1. we may prefer to use p_T^l rather than M_T

How can we constrain experimental uncertainties?

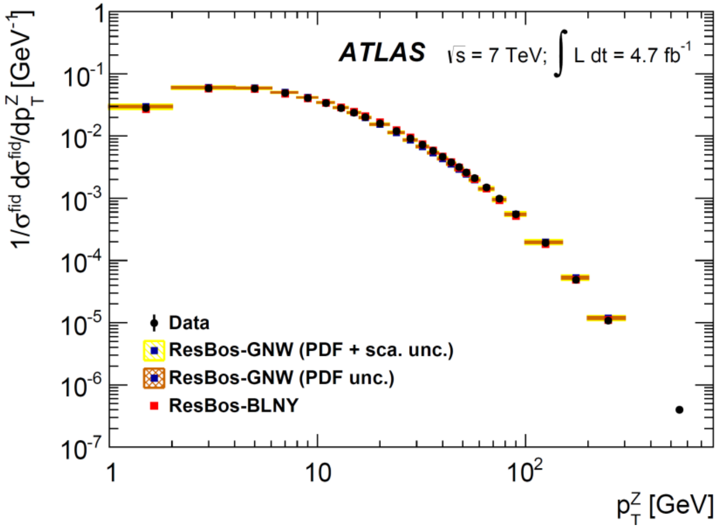
Measure the Z mass by the same technique- throw away one of the leptons and extract M_Z from p_T^l
The lepton energy scale is calibrated by comparing the M_Z obtained to the LEP measurements of M_Z

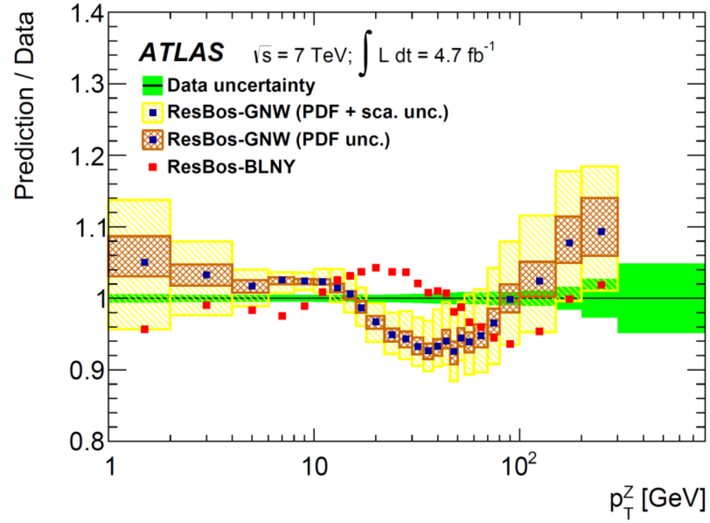


Eur.Phys.J. C74 (2014) 10, 3071

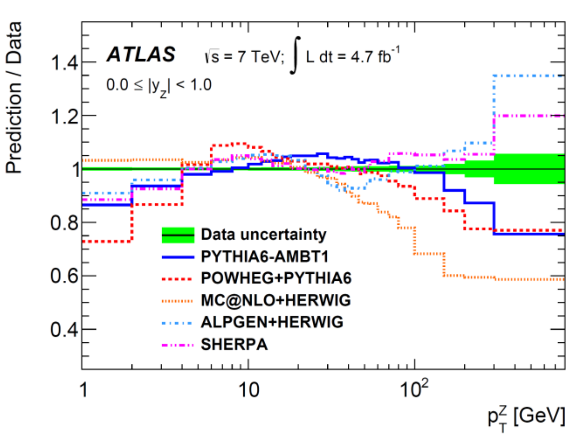
How can we improve the modelling of low p_T^W?

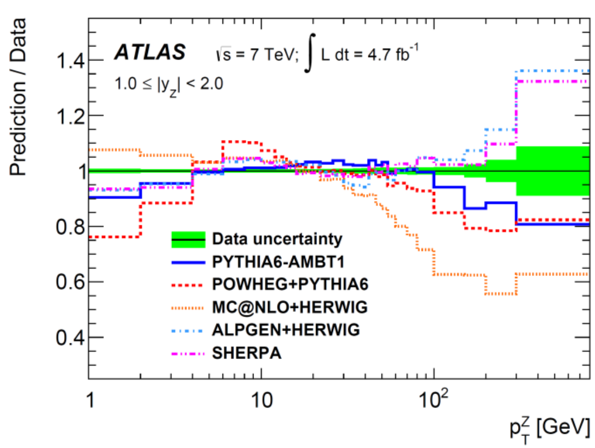
Measure the Z p_T or Z φ*

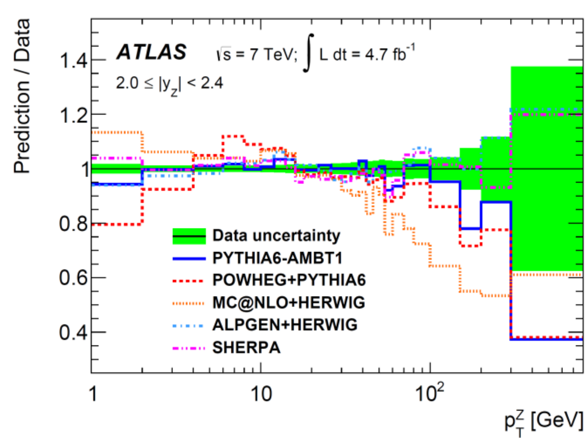




p_T^Z is compared to predictions from RESBOS and various MCs in rapidity bins
JHEP09(2014)145



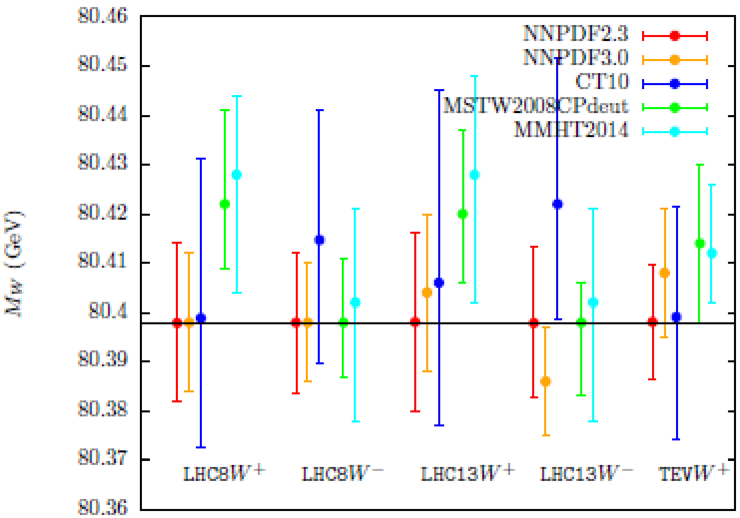


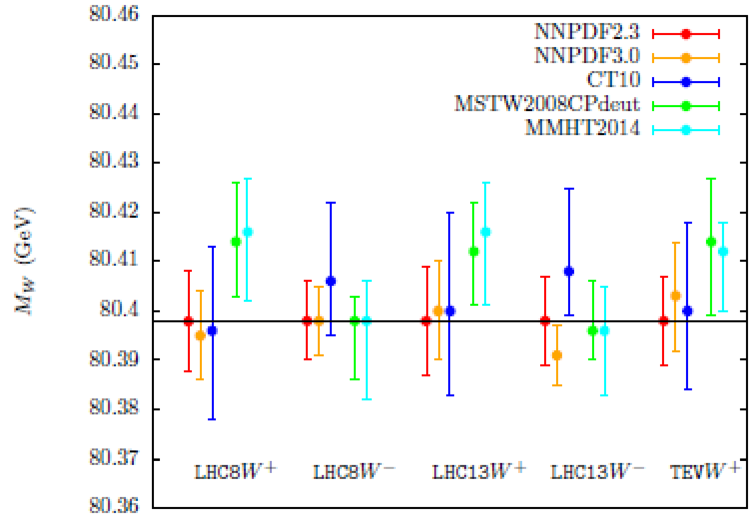


Can we improve the PDF uncertainties? What is the current level of uncertainty?

Theoretical study by Vicini, Rojo, Bozzi (PDF4LHC meeting Jan 21st 2015)

Numerical results for MW, with and without a PTW cut





The P_T^W cut suppresses large x contributions

Individual sets can achieve 10 MeV but the spread between them makes the envelope much larger

W^- seems better than W^+

HOW to improve this? Can we disentangle which flavours contribute most to the W-mass uncertainty?

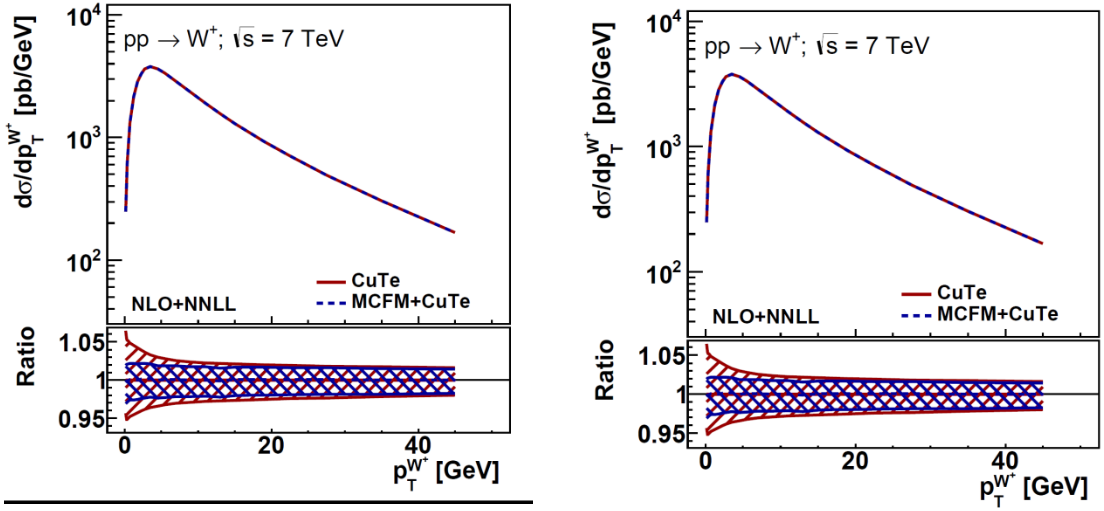
The answer is not trivial because of correlations

ATLAS has done a study (ATL-PHYS_PUB-2014-15) of the uncertainties coming from u,d,s,c flavours (as well as experimental resolution and parton shower modelling)

The remaining slides concentrate on the results from this study

- This uses normalised p_T^{μ} and a dedicated PDF
- Uses the Gμ scheme and PDG2012 values of parameters but CKM Vtx=0 , no top
- Uses a combination of MCFM and Cute to model the lepton pT spectrum in order to get an NLO+NNLL calculation (Cute) and also finite-width, lepton decay and spin-correlations (MCFM at NLO)

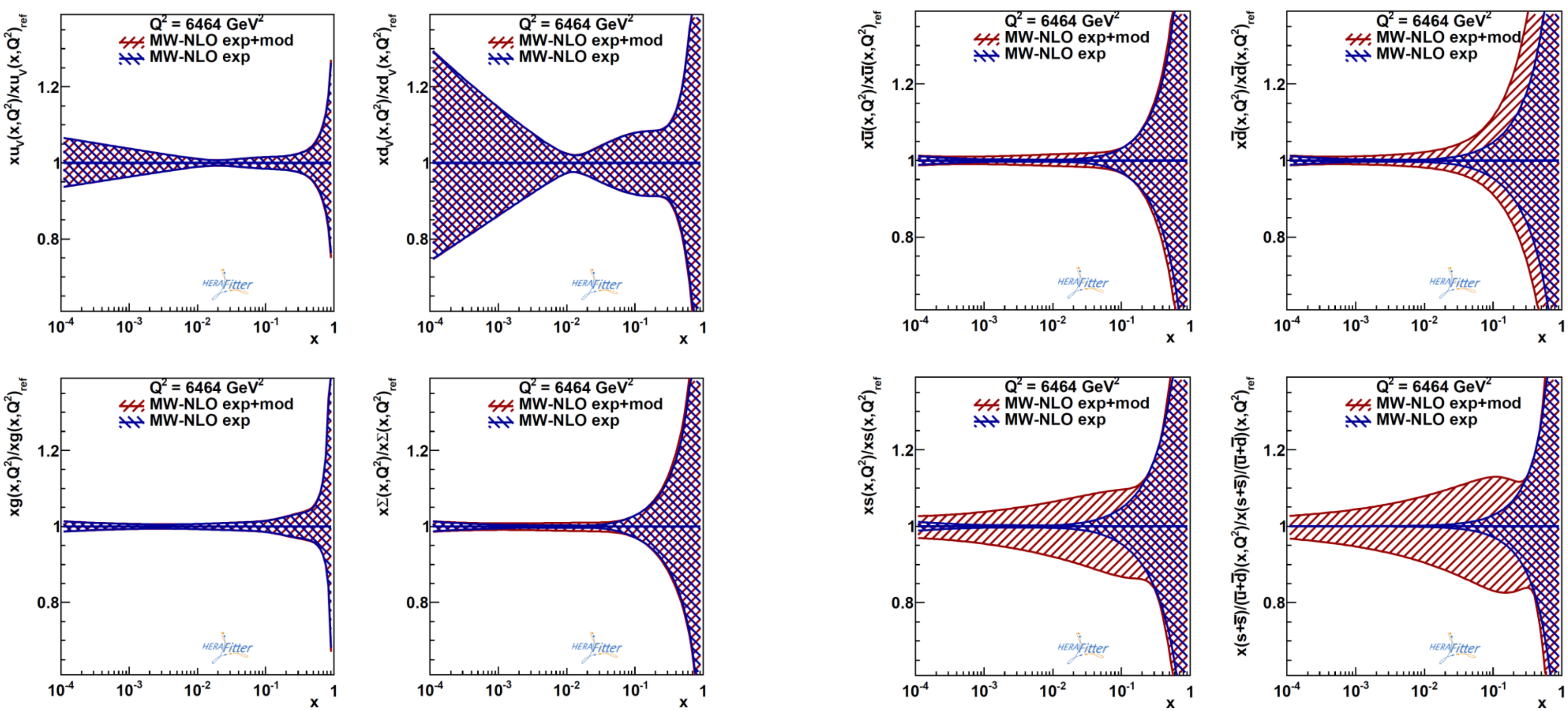
Reweighting of NLO to NLO+NNLL is decomposed in terms of the CKM matrix in order to account for heavy flavour effects



The dedicated PDF set has a simple set up to allow breakdown of uncertainties

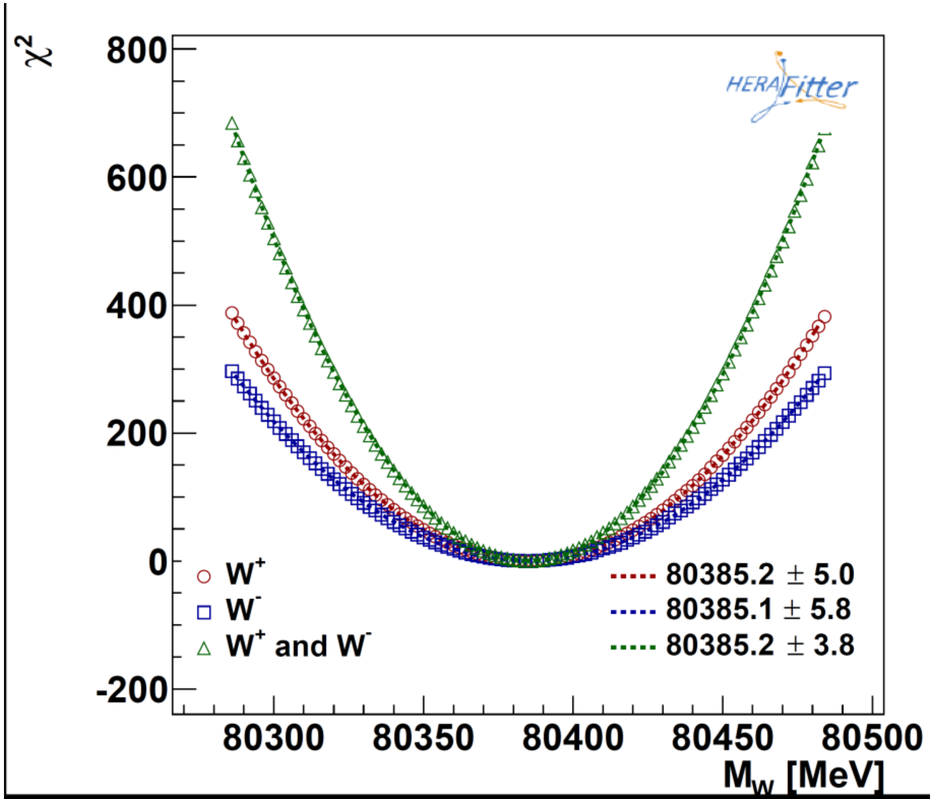
- NLO Fit to HERA I data
- Starting scale $Q_0^2 = 1.7$ GeV^2
- charm mass $m_c = 1.38$ GeV
- bottom mass $m_b = 4.75$ GeV
- top mass $m_t = 3.5$ TeV $\rightarrow$ 5 flavour
- strange fraction $r_s = s/\bar{d} = 1$
- 13p parametrisation
- 26 hessian variations
- 4 model variations: $m_c = 1.32, 1.44$, $r_s = 0.72, 1.25$
- Total of 30 variations

The valence PDFs are dominated by experimental uncertainties and the sea PDFs by model uncertainties



How to determine the W-mass from pseudo-data produced using the central PDF set and all of its experimental eigen-sets and model variations?

- The pseudo data are generated with M_W=80.385 GeV, assuming 5 fb^{-1} and only statistical uncertainties (at first).
- Normalised p_T^l distributions in bins of 0.5GeV are considered.
- Cuts of M_T >60 GeV, η^l <2.4, p_T^ν>30GeV and 30 < p_T^l < 50 GeV are applied
- A $\chi2$ profile is constructed between a reference p_T^l distribution generated with M_W=80.385 GeV and p_T^l distributions generated with different M_W values ±100MeV in steps of 2MeV and this is fitted with a parabolic form
- This is done for W^+ and W^- separately and combined for the central PDF
- We can see the purely statistical uncertainty is ~5 MeV from the plot below



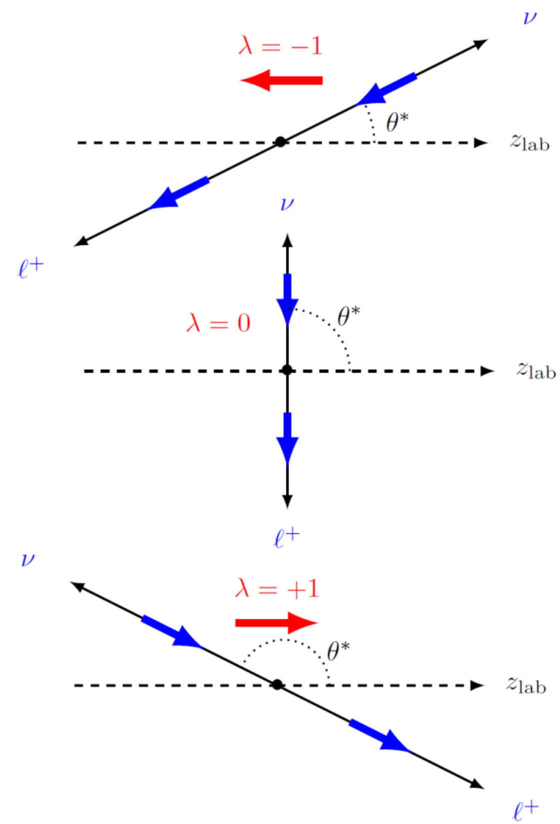
The PDF uncertainty due to any PDF variation is then the difference between the minimum value of M_W for the central PDF and that for the variation in question as determined by this method

.

Now to consider spin correlations

W from u-dbar can come from either beam thus there are two helicity states λ= ± 1

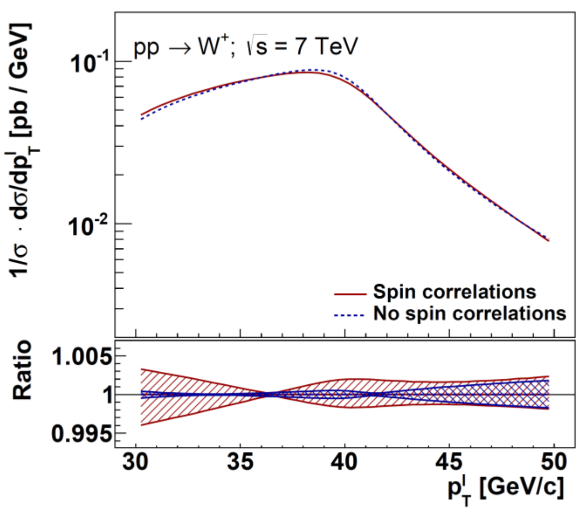
$$\sigma_{W^+}(y) \propto u(x_1) \cdot \bar{d}(x_2) + \bar{d}(x_1) \cdot u(x_2) \quad (1)$$
$$\sigma_{W^-}(y) \propto d(x_1) \cdot \bar{u}(x_2) + \bar{u}(x_1) \cdot d(x_2) \quad (2)$$

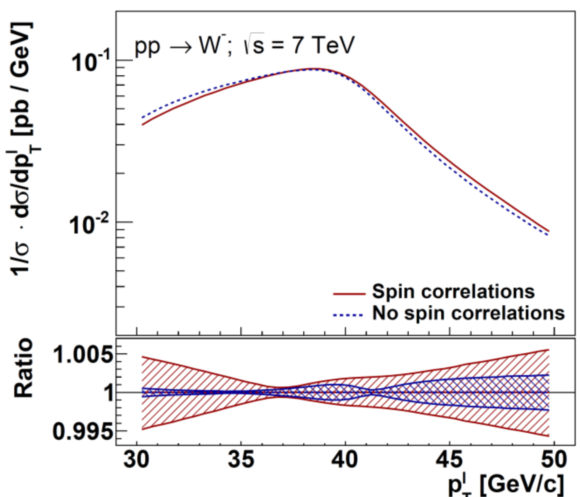


At y=0, x1=x2 and the two terms are equal, but not otherwise
Uncertainty in the u and d PDFs will give an uncertainty in the polarisation which propagates into the p_T^l spectrum

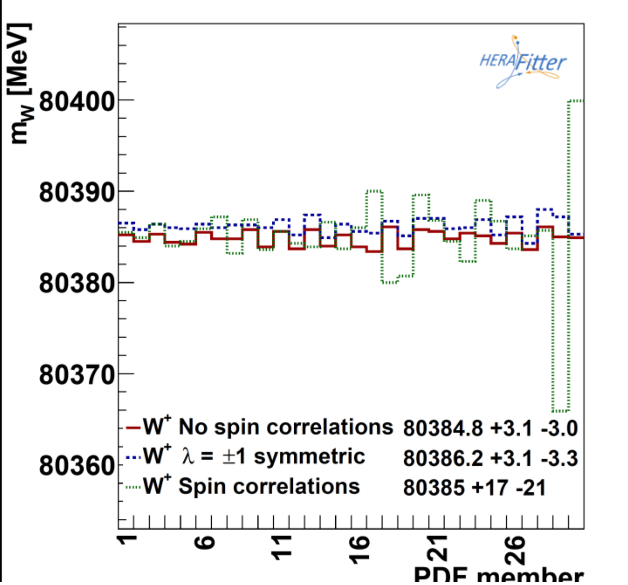
To disentangle the effects of polarisation

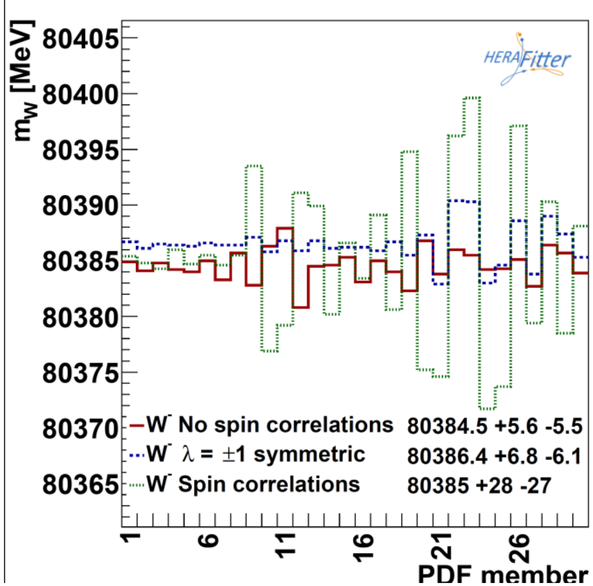
- Keep only Vud
- Apply a random rotation to the decay angle of the leptons in the W rest frame– no spin correlations
- Apply a sign flip to lepton momentum in W rest frame so that λ= ± 1 are symmetric
- Compare this to the analysis WITH spin correlations





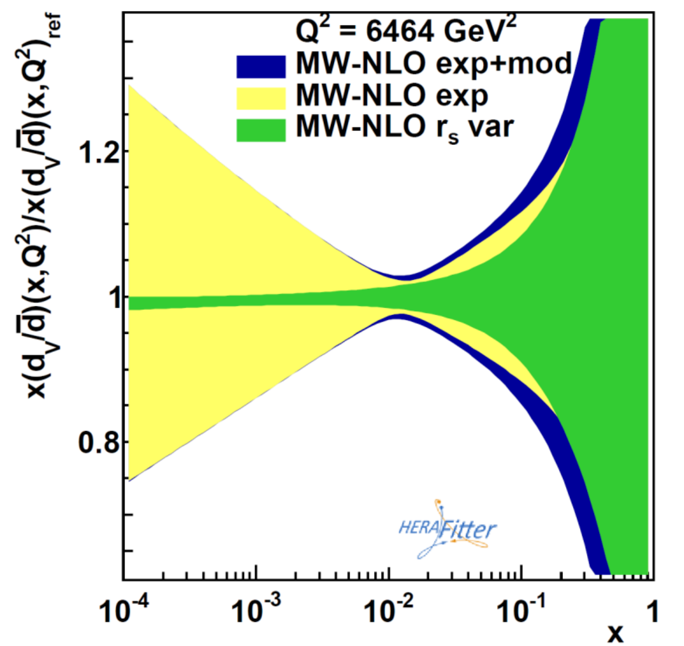
Spin correlations increase the PDF uncertainty on $p_T l$





Now look at the M_W determination for all the eigenvectors and model variations under different settings for spin correlations

- Sets 1-26, hessian variations
- Set 27 $m_c = 1.32$, Set 28 $m_c = 1.44$
- Set 29 $r_s = 0.72$, Set 30 $r_s = 1.25$
- $\sim$ 20 MeV effect in W^+, mostly due r_s variations
- $\sim$ 25 MeV effect in W^-, spread across eigenvector variations

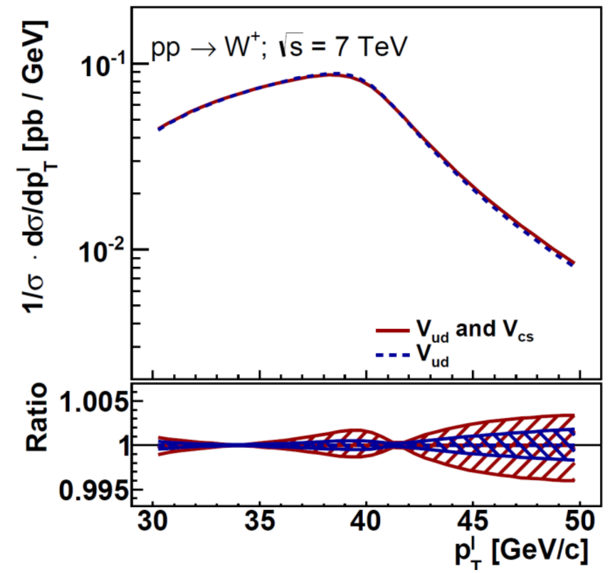


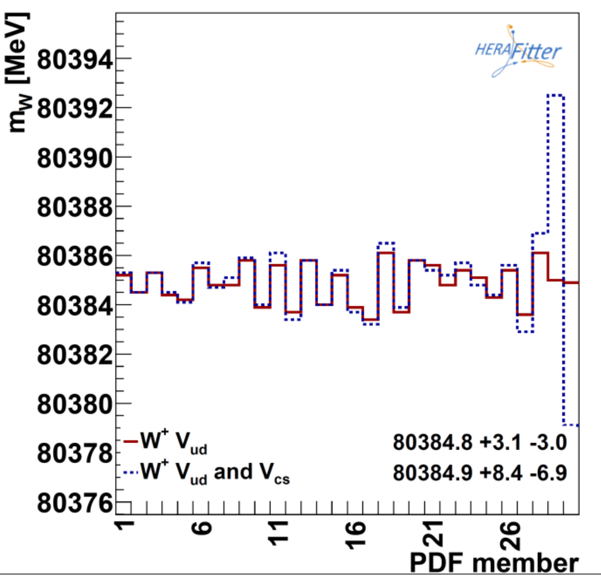
Why does the strangeness fraction affect PDF uncertainties when only u and d have been used? Because it is a fraction of d-type, sea so the dvalence/d sea ratio is altered

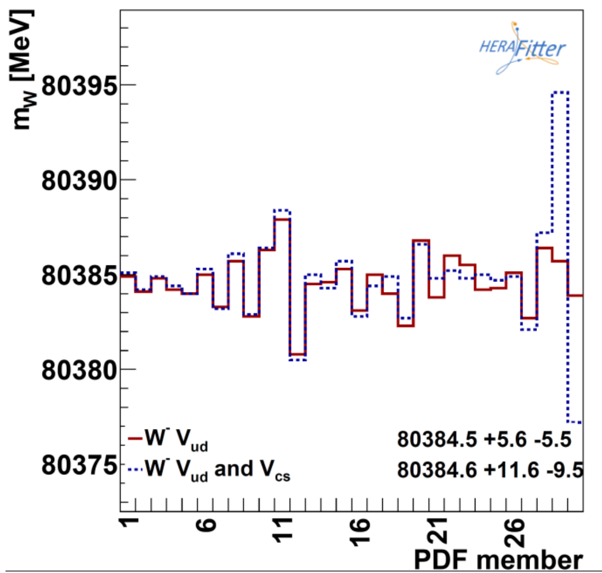
Since PDF uncertainties are different between W^+ and W^- using the two spectra simultaneously gives the best result ΔM_W ~15MeV

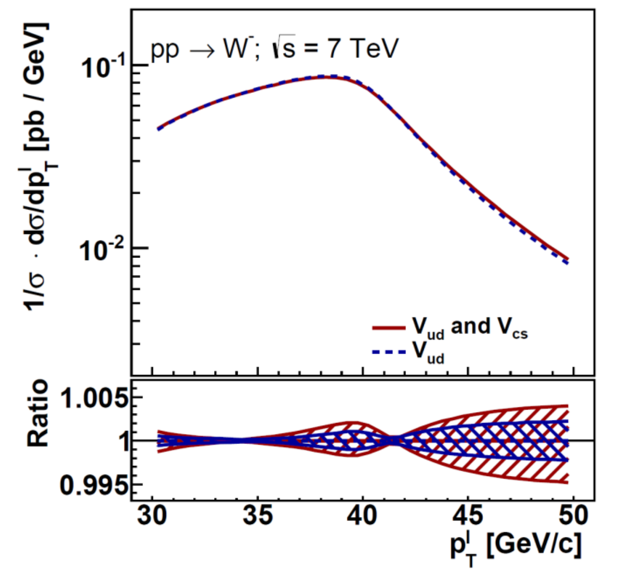
Now let's consider the role of the charm quark

- Switch on Vcs as well as Vud
- Charm brings a 'kick' of about 1.4GeV in the p_T^W shape
- Charm also changes the balance between valence quark and sea quark initiated processes, which will affect W-polarisation and the p_T^l sectrum
- Randomise the decay angle of the leptons in W rest frame to get unpolarised W





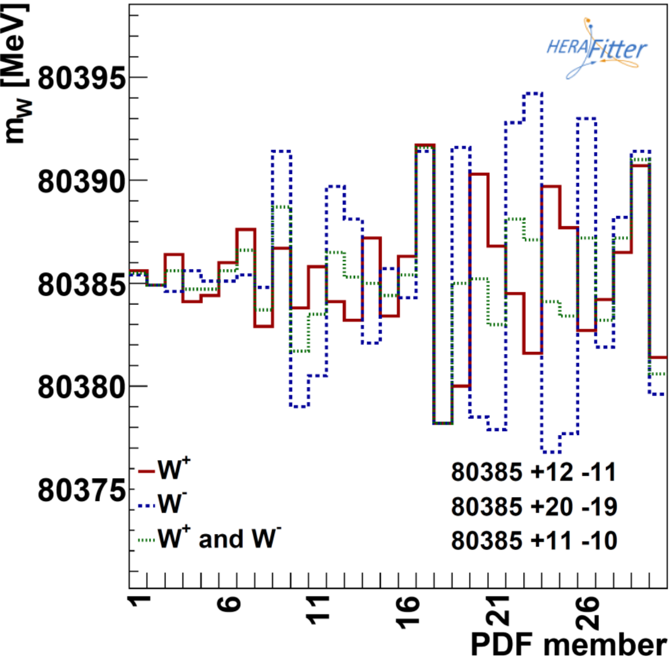




- Sets 1-26, hessian variations
- Set 27 $m_c = 1.32$, Set 28 $m_c = 1.44$
- Set 29 $r_s = 0.72$, Set 30 $r_s = 1.25$
- ~ 5 MeV effect in W^+ and W^- due to r_s variations

No longer any advantage in using both W+ and W- since rs variations are now correlated between them

Now if we consider charm effects and polarisation at the same time..
There is a partial cancellation between these effects

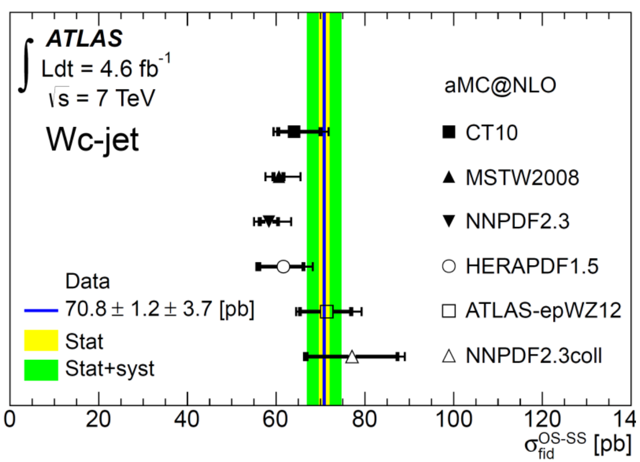


This means that reducing the uncertainty on the badly known strange PDF is perhaps not as important as one might first think- after all Vcs accounts for about 20% of the xsecn

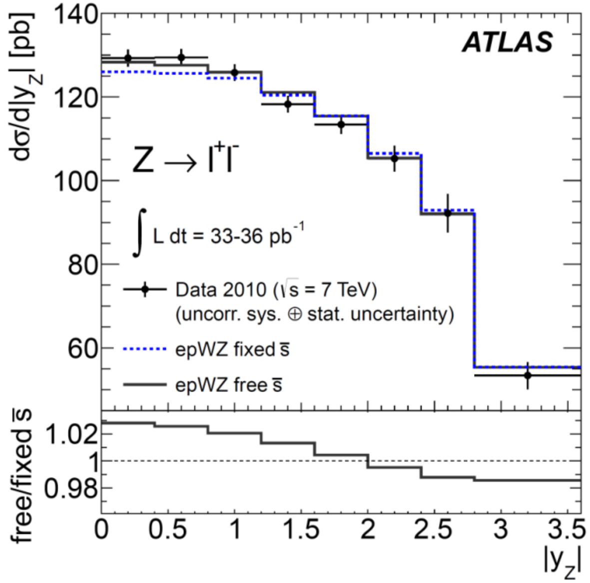
Reducing uncertainty on u and d is still the main concern– from W^+, W^- inclusive rapidity spectra as we have already seen for $\sin^2\theta_W$

What measurements reduce strange uncertainty?

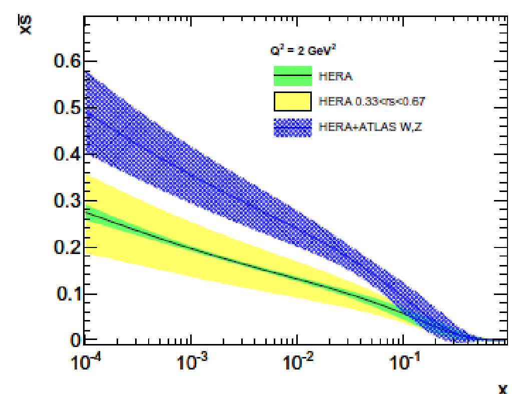
1.W+c JHEP09(2014)068



2. Inclusive Z spectra plus Z/W ratio



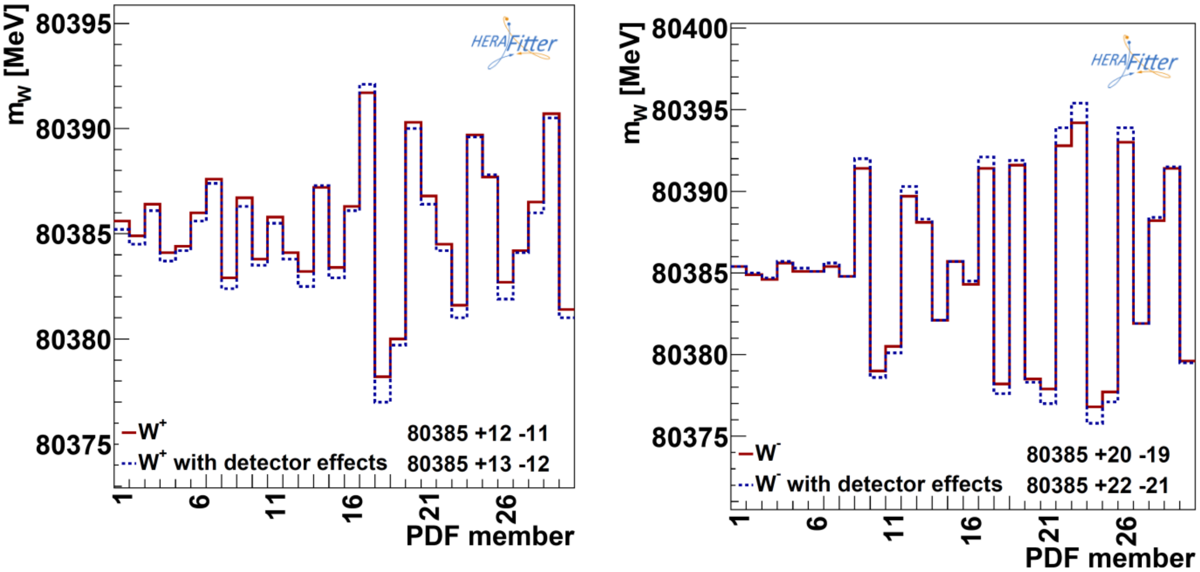
PRL109(2012)012001



The ATLAS study also considers muon p_T smearing

This increases PDF uncertainties by ~10%, a small effect,

Hadronic recoil effects are not accounted but this only affects event selection.

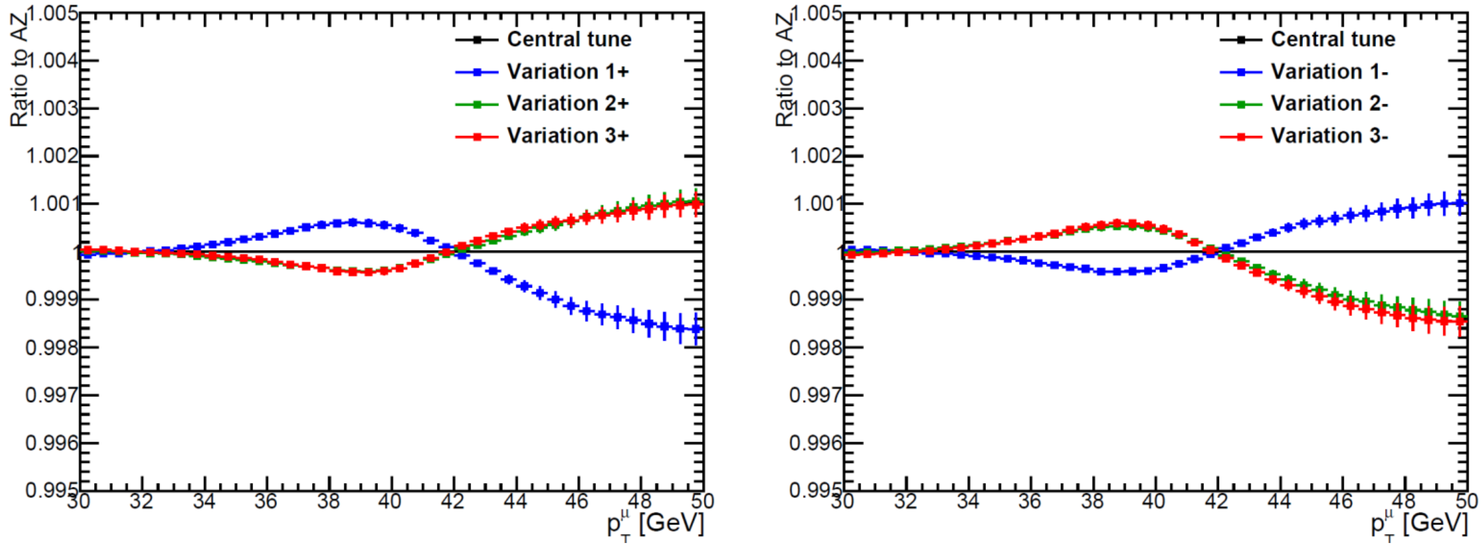


The last effect to be considered is the modelling of the p_T^W spectrum

Which is studied using the measured p_T^Z spectrum to constrain the non-perturbative QCD parameters at low p_T, assuming the universality of the Parton Shower modelling.

Pythia and Powheg +Pythia8 tunes were studied for p_T^Z and the uncertainty was propagated to p_T^W using Hessian uncertainties from AZ eigen-tunes

Different samples are generated for variation of the tunes and the M_W fits repeated.



Tune	AZ	AZNLO	4C
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
$\alpha_s^{ISR}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-

Tune Variation	Positive	Negative
$1\pm$	3	-4
$2\pm$	3	-4
$3\pm$	3	-4
Total	5	7

AZ for Pythia 8 and AZNLO for POWHEG+Pythia8, 4C is the Pythia default

AZ does well for p_T^Z split in rapidity ranges

An uncertainty on ΔM_W ~6 MeV results from this modelling

Is there any correlation between non-pQCD uncertainties and the PDF?

Primordial K_T is related to the Transverse Momentum Dependent TMD-PDFs

The RESBOS non-pQCD parametrisation is based on TMD factorisation.

Should we be using TMD PDFs?

Or at least the same PDF in the PS as in the hard ME? Is this even possible given the different orders of calculation

Summary and Outlook

Precision measurements of quantities like $\sin^2\theta_W$ and M_W are important because they can give hints of BSM physics BUT they are limited by PDF uncertainties

- Measurements of W^+, W^- and Z rapidity spectra and W,Z+heavy flavour production can further constrain the PDFs
- Measurements of Z pT spectra can constrain the low p_T modelling

Can we do better in future ?

- Forthcoming W+,W-, Z precision measurement from 2011 data.
- Are measurements at 13 TeV vs 7 or 8TeV useful?-

We are moving to lower x, PDF uncertainties are not getting smaller and the role of NLO qg processes increases in W, Z production

- But one may be able to measure W,Z polarisation coefficients more differentially for an alternative extraction of θ_W
- And Z/W ratios may yield Γ_W

extras

The PDF uncertainties on M_W from this ATLAS study with the dedicated PDF are comparable to those from other global PDFs

	MW-NLO	CT10nlo	MSTW2008CPdeutnlo	NNPDF30_nlo_as_118
W^+	+13 -12	+18 -22	+11 -10	+8 -10
W^-	+22 -22	+18 -23	+11 -10	+8 -9
$W^\pm$	+11 -11	+14 -18	+7 -7	+6 -5

CT10 is already scaled to 68%

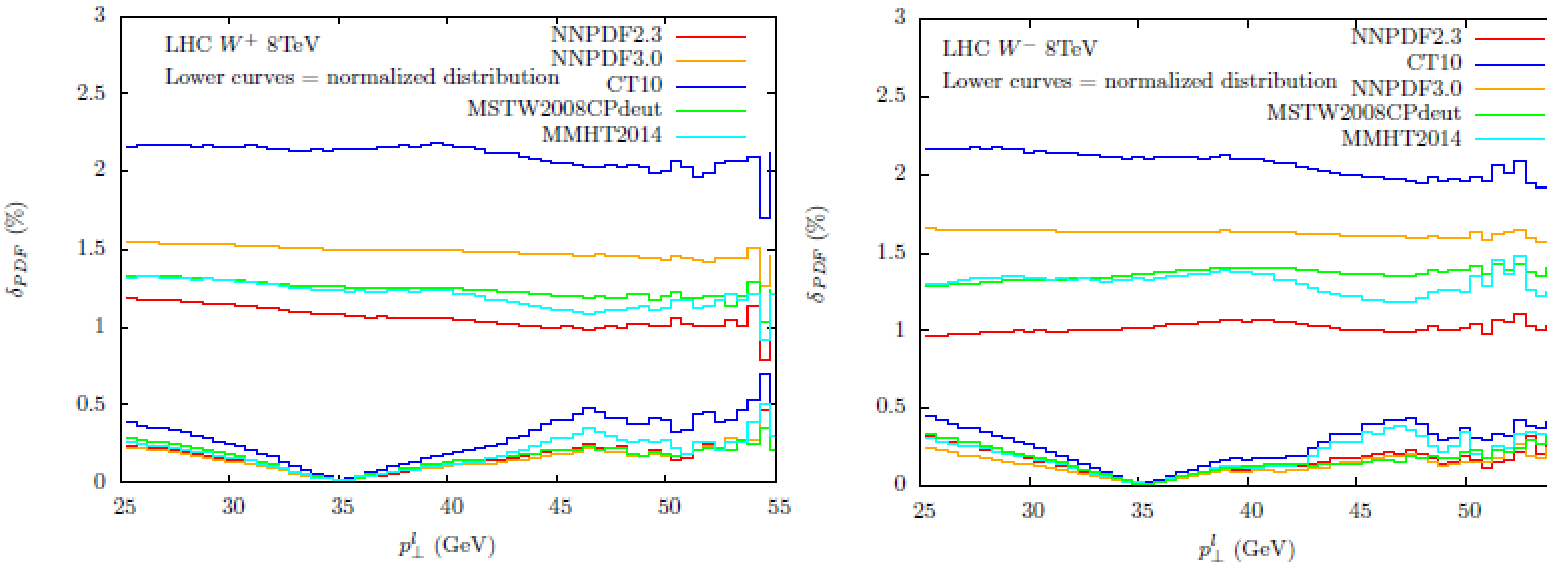
The purely HERA dedicated PDF lacks information in the d-sector thus W- is worst. This also leads to a larger bias

	MW-NLO	CT10nlo	MSTW2008CPdeutnlo	NNPDF30_nlo_as_118
W^+	-9	-0.1	-20	-1.2
W^-	+48	+0.2	+13	+12
$W^\pm$	+16	0.0	-6	+5

Biases here are assessed wrt CT10 as central

Can we understand the PDF dependence of the M_W measurement better?

Using POWHEG+PYTHIA 6.4.21
Acceptance cuts: p_T^l >25, p_T^ν >25 GeV, η^l<2.5
Additonal cuts p_T^W<15 GeV, M_T<100GeV
Use normalised distributions of lepton Pt distributions, which have PDF uncertainties only due to shape



Generate pseudo data at fixed M_W=80.398 using several different PDFsets and ALL their eigenvectors/replicas
Compare to templates generated at different M_W using only one fixed central PDFset (NNPDF2.3 central replica)

Numerical results: PDF4LHC envelope and spread of central values

δ_{PDF} is the half-width of the PDF4LHC envelope

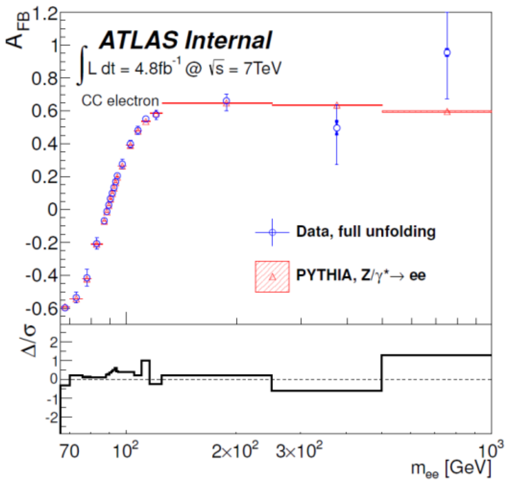
Δ_{sets} is the spread (max-min) of the central values

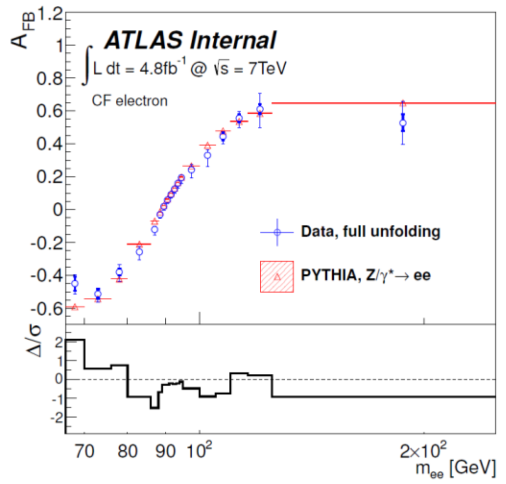
CT10, MSTW2008CPdeut, NNPDF2.3

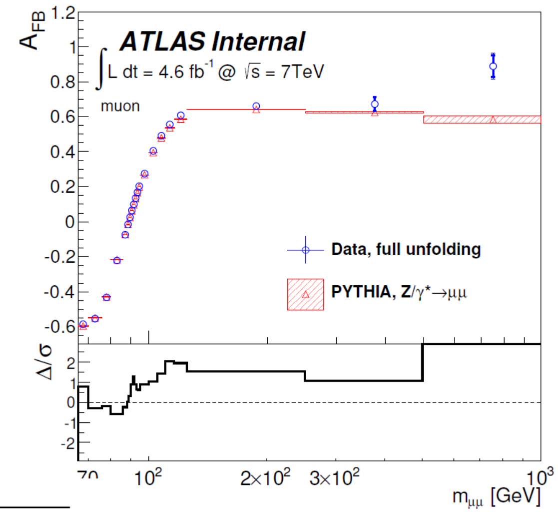
	no $p_\perp^W$ cut		$p_\perp^W < 15$ GeV	
	δ_{PDF} (MeV)	Δ_{sets} (MeV)	δ_{PDF} (MeV)	Δ_{sets} (MeV)
Tevatron 1.96 TeV	27	16	21	15
LHC 8 TeV W^+	33	26	24	18
W^-	29	16	18	8

MMHT2014, NNPDF3.0

	no $p_\perp^W$ cut		$p_\perp^W < 15$ GeV	
	δ_{PDF} (MeV)	Δ_{sets} (MeV)	δ_{PDF} (MeV)	Δ_{sets} (MeV)
Tevatron 1.96 TeV	16	4	13	9
LHC 8 TeV W^+	32	33	21	21
W^-	22	6	12	0







	$\sin^2\theta_W^{\text{eff}}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0013(\text{syst.}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0012(\text{syst.}) = 0.2312 \pm 0.0014$
muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0012(\text{syst.}) = 0.2307 \pm 0.0015$
electron combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0012(\text{syst.}) = 0.2308 \pm 0.0013$
combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0011(\text{syst.}) = 0.2308 \pm 0.0012$

Final ZAFB result not yet approved
Add these plots and new results if in time

Uncertainty source	CC electrons (10^{-4})	CF electrons (10^{-4})	Muons (10^{-4})	Combined (10^{-4})
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron momentum resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

New PDF uncertainties from ATLAS epWZ LO PDF which fits the data best.
Effect of varying the strange PDF is only ~25% of this PDF uncertainty

	$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$	Δ/σ (wrt LEP+SLC)	Δ/σ (wrt ATLAS)
ATLAS	0.2308 ± 0.0012	-0.6	–
CMS [5]	0.2287 ± 0.0032	-0.9	-0.6
D0 [4]	0.23146 ± 0.00047	-0.1	0.5
CDF [3]	0.2315 ± 0.0010	-0.03	0.4
LEP, $A_{\mathrm{FB}}^{0,b}$ [2]	0.23221 ± 0.00029	–	1.2
LEP, $A_{\mathrm{FB}}^{0,l}$ [2]	0.23099 ± 0.00053	–	-0.1
SLC, A_{LR} [2]	0.23098 ± 0.00026	–	-0.1
LEP+SLC [2]	0.23153 ± 0.00016	–	0.6
PDG global fit [39]	0.23146 ± 0.00012	-0.4	0.6