Studies of PDF uncertainties for the measurement of the mass of the W boson at the LHC

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PDF uncertainties on m_W

- ATL-PHYS-PUB-2014-015
  "Studies of theoretical uncertainties for the measurement of the mass of the W boson at the LHC"
  - Introduction
  - Theory predictions and PDF uncertainties
  - Event selection and methodology
  - W polarization and PDF uncertainties
  - Charm-initiated W production and PDF uncertainties
  - Detector effects and summary of PDF uncertainties
  - Parton shower uncertainties
  - Conclusions

- Points of discussion for a coherent treatment of PDF uncertainties between ATLAS and CMS

Introduction

- The extraction of m_W from the p_T^ℓ spectrum, is likely to be limited by theoretical uncertainties.
- This study addresses PDF uncertainties, and non-perturbative QCD uncertainties related to the parton shower model
- We need not only a precise estimation of PDF and other theoretical uncertainties, but also a roadmap to control and reduce them, by mean of precise experimental measurements of alternative observables
- The idea is to perform a breakdown of the physical mechanisms behind the PDF uncertainties, and estimate which are the most relevant sources of uncertainties.
- By pointing out the largest uncertainties, the idea is to provide a pattern to reduce them, rather than a precise estimation to be used in our measurement

Introduction

- PDF uncertainties for the extraction M_W from p_T^ℓ at the Tevatron are 9 MeV (CDF) and 11 MeV (D0)
- It has been suggested in Eur. Phys. J. C 69 (2010) 379397 [Krasny, Dydak, Fayette, Placzek, Siodmok, '10] that PDF uncertainties in proton-proton collisions could be larger than in proton-antiproton collisions for
  - 1st quark generation effect: u and d PDF uncertainties on W boson polarisation
  - 2nd quark generation effect: strange-quark PDF uncertainty on charm-initiated W boson production
  - 3rd quark generation effect: bottom quark mass uncertainty in the extraction of non pertubative parameters from p_T^Z
- The idea of this study is to estimate such effects with standard tools for theory predictions and Monte Carlo, and get feedback from the theory community
  - Are we missing something important?
  - Do we need better, additional theoretical predictions to estimate these effects?

Introduction - disclaimer

- The emphasis is on tracking the physical sources of the uncertainties, we are not estimating the uncertainties to be used in the measurement
- This is not the ATLAS final word on PDF and PS uncertainties for the W mass, and on theory uncertainties
- We are considering in this study:
  - u and d valence and sea PDF uncertainties
  - Strange PDF uncertainties
  - PS uncertainties, assuming they can be extrapolated from the measurement of p_T^Z to the modelling of p_T^W
  - Detector effects on the muon momentum resolution
- We are **not** considering in this study:
  - Gluon PDF uncertainties in all-order resummation (gluon PDF is varied only at NLO)
  - Heavy flavour masses in the matrix-element calculations
  - Differences in the heavy flavour content of W and Z production when propagating PS uncertainties from p_T^Z to p_T^W
  - Any QED FSR, and NLO EW effect
  - Detector effects on the measurement of the hadronic recoil

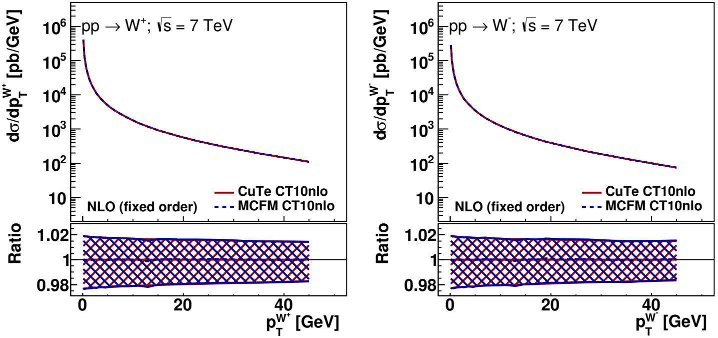
Theory predictions

- EW scheme
  - G_μ-scheme: with G_F, M_Z, M_W as inputs from PDG 2012, α and θ_W calculated at tree level
  - Γ_Z and Γ_W measured value from PDG 2012
  - CKM from PDG 2012, but $V_{tx} = 0$, no top in the initial state
- Theory predictions and tools
  - MCFM
    - W+j production at LO O(α_s), which is the real part of W inclusive calculation at NLO
    - finite width, leptonic decay, spin correlations
  - CuTe
    - differential W p_T at NNLL with matching corrections at O(α_s) (NLO+NNLL)
    - zero width approximation
    - no decay of the W
  - APPLGRID: Fast PDF convolution
- Need to combine the two codes, MCFM and CuTe, to get a realistic prediction of the lepton p_T spectrum

CuTe

- Infrared Safety from the Collinear Anomaly [Becher, Neubert, Wilhelm '11]
- The factorisation scale is set to $\mu = q^* + q_T$, with $q^* \sim 1.82$ GeV
- The non-perturbative scale $q^* \sim e^{-C/\alpha_s(m_V)}$ protects the processes from receiving large long-distance hadronic contributions
- Allows to calculate the derivative of $p_T^{W,Z}$ for $p_T \to 0$ with perturbative QCD
- One additional non perturbative parameter $\Lambda_{NP} = 0.6$ GeV introduce a gaussian smearing for hadronic non-pQCD effects
- **Public C++ code, very fast**

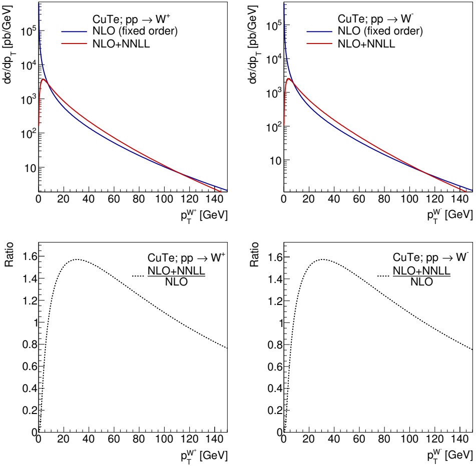
Theory predictions - benchmark



Perfect agreement between the two codes, at fixed order $O(\alpha_s)$, zero width, no decay.

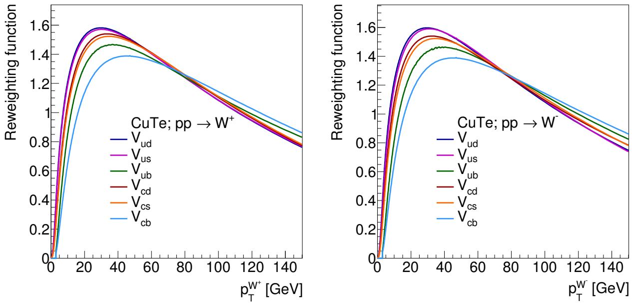
Theory predictions - combination

- Reweighting function defined as $r(p_T) = \frac{\mathrm{NLO+NNLL}}{\mathrm{NLO}}$
- The reweighing is applied, in the range $0.1 < q_T < 150$ GeV, outside this range the weight is set to 0

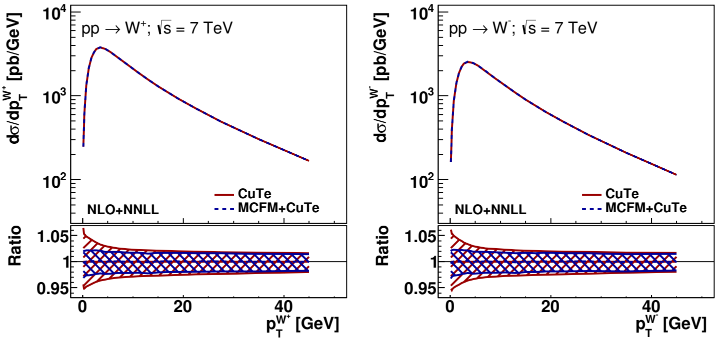


CKM decomposition of the reweighting function

- The NLO+NNLL/NLO ratio has a significant dependence on the flavour of the quarks initiating the W-boson production process: heavy quarks result in a harder p_T^W spectrum and a harder ratio between resummed and fixed order predictions
- The reweighting function is decomposed in terms of the CKM matrix: 6×2 functions are the NLO+NNLL/NLO ratios evaluated by setting to 0 all the CKM matrix except the V_{xy} term, separately for W^+ and W^-



Theory predictions - benchmark



Good agreement at NLO+NNLL after reweighting.

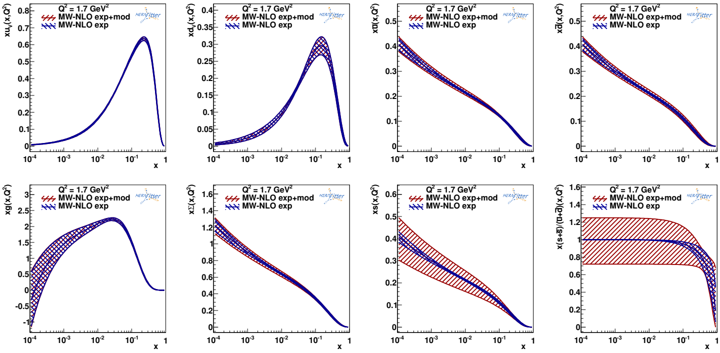
PDF uncertainties reproduced at high p_T, at low p_T CuTe has larger PDF uncertainties.

In CuTe the factorisation scale is set to $\mu = q^* + q_T$, with $q^* \sim 1.82$ GeV, $\rightarrow$ CuTe is sensitive to larger PDF uncertainties associated with the low x region. In MCFM prediction, the factorisation scale is set to 80 GeV.

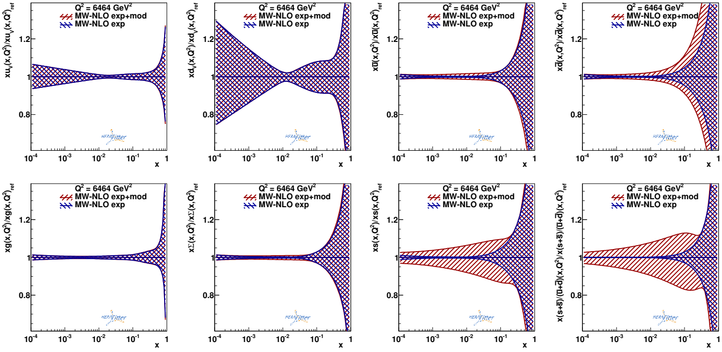
Dedicated PDF set

- A dedicated PDF set has been produced to study the PDF uncertainties for M_W extraction from p_T^l
- Simple setup which allows breakdown of uncertainties, not intended for final estimate of PDF 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

PDF at the starting scale



- Blue band: experimental (hessian) uncertainties
- Red band: experimental uncertainties plus model variations, r_s and m_c

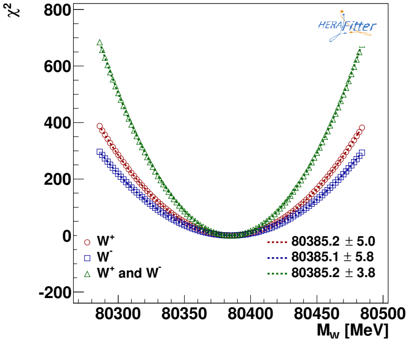


- Valence PDF dominated by experimental uncertainties from the HERA I data
- $\bar{u}$, $\bar{d}$ and strange PDF dominated by model variations, r_s and m_c

Methodology and event selection

- Event selection
  - $|\eta^l| < 2.4$
  - $p_T^\nu > 30$ GeV
  - $M_T > 60$ GeV
  - $30 < p_T^l < 50$ GeV
- Generate a test sample with $M_W = 80.385$
- Estimate only statistical experimental uncertainty in 5 fb^{-1}, assuming no efficiency loss
- Consider normalised p_T^l distribution, in bins of 0.5 GeV
- Calculate a χ^2 profile as a function of M_W, in the region $\pm$100 MeV ($80.286 < M_W < 80.484$), in steps of 2 MeV
- Fit the χ^2 profile with a parabolic function to find minimum and sigma at $\Delta\chi^2 = 1$
- Compute the minimum for each PDF variation of a given PDF set, calculate PDF uncertainty as the difference between the minimum for the central PDF and each PDF variation
- Repeat the analysis for W^+ only, W^- only and both W^+ and W^-

Methodology and event selection - Example of χ^2 profile



- The procedure gives us a rough estimate of the statistical uncertainty expected from the 2011 data set at 7 TeV. Detector resolution effect are not yet included in this plot
- The statistic of the MC sample is much higher, the statistical bias on the central value of $M_W = 80.385$ is below 0.2 MeV

W polarization and PDF uncertainties

The production of W by u and d quarks at LO, at a given rapidity y can be decomposed in two terms corresponding to $\lambda = +1, -1$ helicity states:

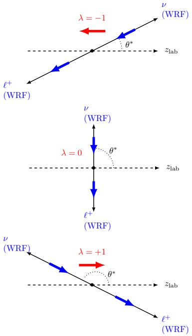
$$\sigma_{W^+}(y) \propto u(x_1) \cdot \bar{d}(x_2) + \bar{d}(x_1) \cdot u(x_2) \tag{1}$$
$$\sigma_{W^-}(y) \propto d(x_1) \cdot \bar{u}(x_2) + \bar{u}(x_1) \cdot d(x_2) \tag{2}$$

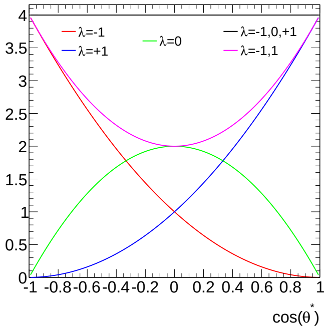
$x_{1,2} = \frac{M_W}{\sqrt{s}} \cdot e^{\pm y}$

- At central rapidity $y = 0$, $x_1 = x_2$, the two terms are equal, $\rightarrow$ unpolarised W
- For $y \neq 0$, the two terms are different, the W is polarised on average

The uncertainty in the u and d valence and sea PDF determines an uncertainty in the average polarisation of the W, which in turns propagates into an uncertainty on the p_T^l spectrum.

W polarization and PDF uncertainties





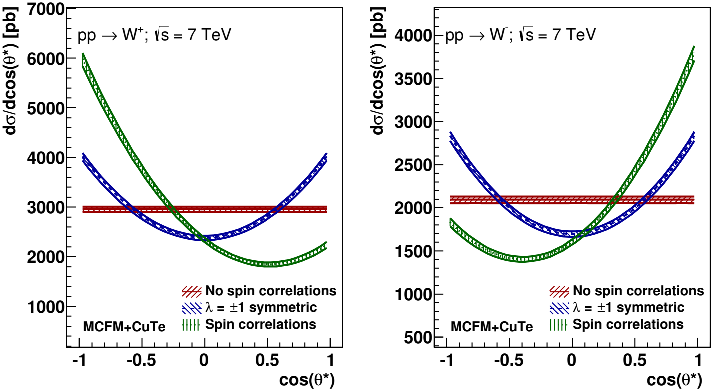
The $\lambda = +1, -1$, and 0 helicity states correspond to different distribution of the polar angle θ^* between the direction of the momentum of the incoming quark in the laboratory frame, assumed to be parallel to the beam axis, and the direction of the leptons momenta in the W-boson rest frame

W polarization and PDF uncertainties

- The uncertainty on the u and d valence and sea PDF translates into an uncertainty in the average W polarisation, which affects the p_T^l distribution
- Simple setup to disentagle the effect of W polarisation
- Keep only $V_{ud} \neq 0$ and set all the other terms of the CKM matrix to 0
- Apply a random rotation to the decay angle of the leptons in the W rest frame $\rightarrow$ No spin correlations
- Apply a sign flip to the lepton momentum in W rest frame $\rightarrow$ $\lambda = \pm 1$ symmetric
- Switch on spin correlations and compare PDF uncertainties

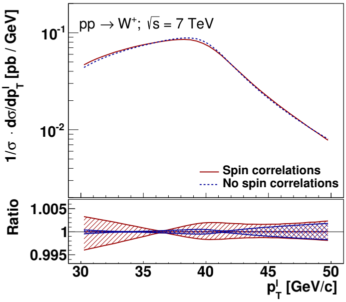
Thanks to Paolo Nason for the idea of randomising the lepton momenta to switch off spin correlations

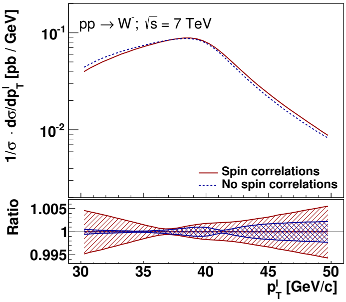
W polarization and PDF uncertainties



- $\cos\theta^*$ distributions in the 3 samples
- The dashed bands show PDF uncertainties, only in the sample with spin correlations the PDF uncertainties affect the average W polarisation

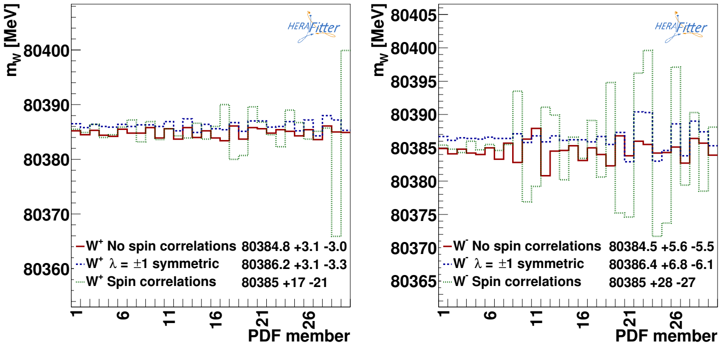
W polarization and PDF uncertainties





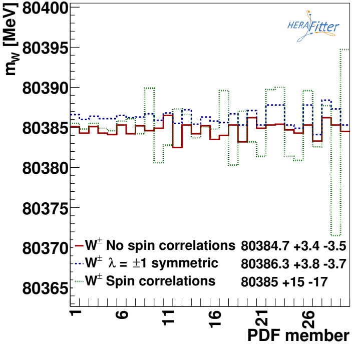
- Dramatic shrink of the PDF uncertainties on p_T^ℓ distribution when spin correlations are switched off

W polarization and PDF uncertainties



- 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 $r_s = 1.25$
- ~ 20 MeV effect in W^+, mostly due r_s variations
- ~ 25 MeV effect in W^-, spread across eigenvector variations

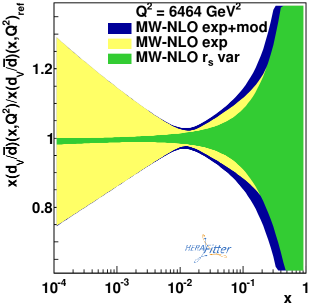
W polarization and PDF uncertainties



- Since PDF variations are different between W^+ and W^-, when W^+ and W^- spectra are used simultaneously, the uncertainty is reduced to $\sim$ 15 MeV

W polarization and PDF uncertainties

- Why r_s variations affects the W-boson polarisation, when only u- and d- initiated W production is considered?

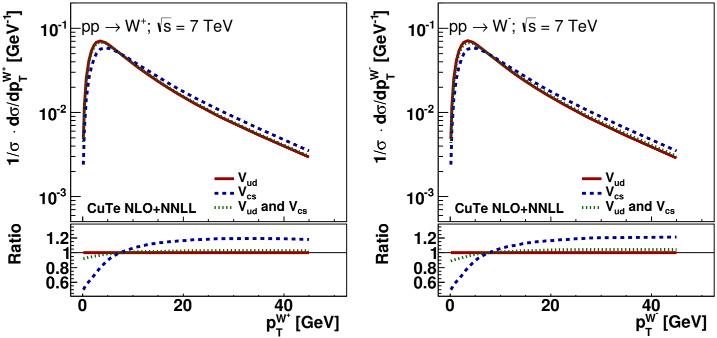


- DIS data constrains the sum of $\bar{d}$ and strange PDF
- In the medium and high x region, variations of the ratio of the strange-quark PDF over the $\bar{d}$ PDF, corresponding to $r_s = 0.72$ and $r_s = 1.25$, give a significant contribution to the total PDF uncertainty of the $d_V/\bar{d}$ ratio.

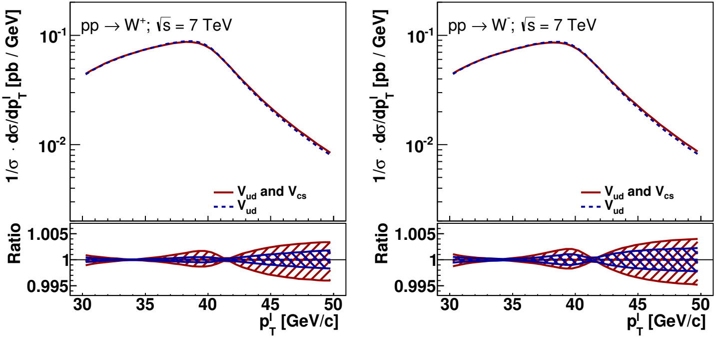
Charm quark in the initial state and strange PDF

- A charm in the initial state is expected to alter the kinematic of the W productions
- Roughly, a kick of the order of $m_c = 1.4$ GeV in the p_T^W spectrum is expected
- Randomise decay angle of the leptons in the W rest frame $\rightarrow$ unpolarised W
- Switch between a setup with only V_{ud} term in the CKM matrix, and a setup with V_{ud} and V_{cs} terms
- However, the amount of charm initiated W production will also alter the balance between valence quark initiated and sea quark initiated production, which in turns affect the W polarisation and the W p_T^l spectrum

Charm mass effect

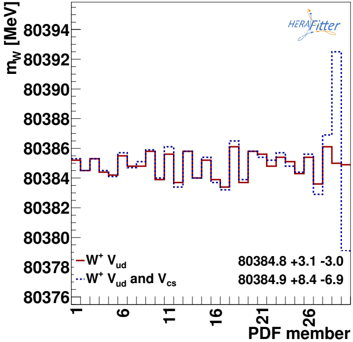


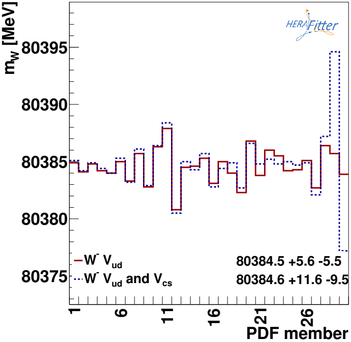
- As expected, the p_T^W spectrum acquires a kink from charm-initiated production
- Notice that the charm is treated as massless in the ME calculation, the effect of the charm mass we see is encoded in the PDF, as a threshold between 3 and 4 flavours



- Significant shrink of the PDF uncertainties on p_T^ℓ distribution when charm-initiated W production is switched off

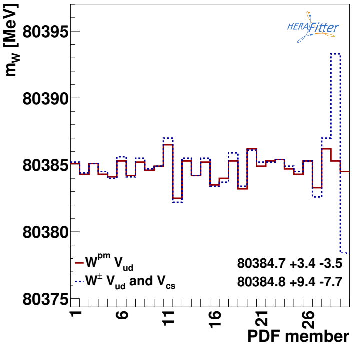
Charm quark in the initial state and strange PDF





- 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

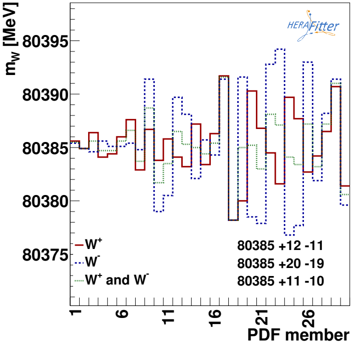
Charm quark in the initial state and strange PDF



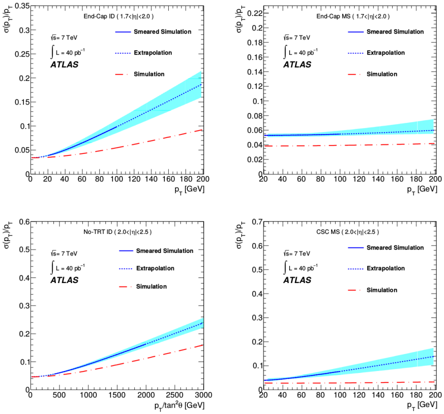
- Since the r_s variations are correlated between W^+ and W^-, there is no significant reduction of the uncertainty when W^+ and W^- p_T^ℓ spectra are used simultaneously

Total PDF uncertainties

- Consider altogether polarisation and charm-initiated effects, by using normal spin correlations and SM CKM matrix
- Observed a partial cancellation of the two effects

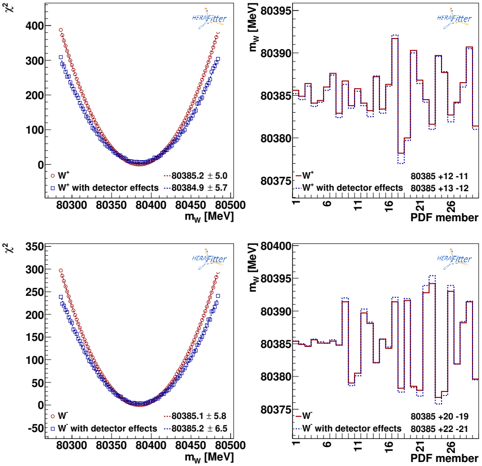


Detector effects - Muon p_T smearing



Implemented detector p_T smearing for muons from arXiv:1404.4562, to asses the impact of detector smearing on PDF uncertainties

Detector effects - Muon p_T smearing



- Small effect, increase of the PDF uncertainties by $\sim 10\%$
- However, detector effects on the hadronic recoil are not considered

Summary of PDF uncertainties

	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

- CT10nlo scaled to 68 cl
- The dedicate PDF set used for the study has a reasonable uncertainty compared to the global PDF set
- The larger W^- uncertainty is due to missing constraints from additional dataset like Tevatron (and LHC) W asymmetry

Summary of PDF uncertainties

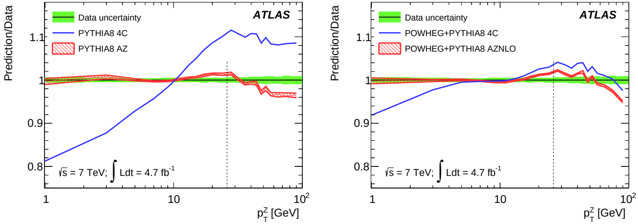
Difference between the input value of $m_W = 80385$ MeV and the extracted value of m_W, when using CT10nlo as PDF for the reference p_T^ℓ spectrum, and another PDF for the test spectra with various values of m_W

	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

- Large, unrealistic shift for the dedicated PDF set MW-NLO for W^- production
- Known issue related to the limited number of parameters (13 parameters), and not enough constraints from HERA data on the d valence PDF

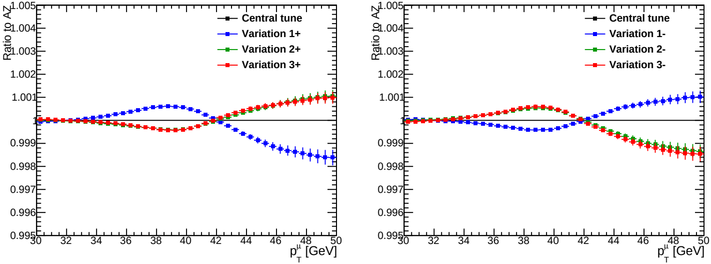
Low p_T^W modelling uncertainty

- Exploit the p_T^Z data to constrain the non perturbative QCD parameters at low p_T of Pythia8: Tune AZ
- Propagate the data uncertainty to the p_T^W by mean of eigentunes hessian uncertainties



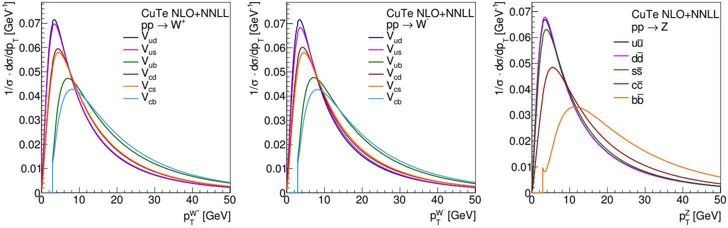
Tune	AZ	AZNLO	4C
Primordial k_{T} [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
$\alpha_{\mathrm{s}}^{\mathrm{ISR}}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-

Low p_T^W modelling uncertainty



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

Low p_T^W modelling uncertainty



- Heavy flavour production results in different distorsions of the W and Z p_T spectrum
- Differences in the heavy flavour content of W and Z production when propagating PS uncertainties from p_T^Z to p_T^W are not accounted

Summary and conclusions

- Performed a breakdown of most important PDF uncertainties for the M_W extraction from p_T^ℓ, by tracking the physical mechanism which give rise to PDF uncertainties
- Large contribution of polarisation, of the order of $10 - 20$ MeV, can be improved by better knowledge of u, d valence and sea PDF
- Strange-quark PDF uncertainty due to charm-initiated W production is at the level of 5 MeV, but partially cancel the effect of strange-quark PDF on polarisation
- Preliminary and partial estimation of parton shower uncertainties at the level of $5 - 7$ MeV

POINTS FOR DISCUSSION

With inputs from Luca Perozzi and Maria Rosaria D'Alfonso

Coherent treatment of PDF uncertainties between ATLAS and CMS

- Various theory predictions can be used to evaluate PDF uncertainties: MCFM, RESBOS, DYRES, POWHEG, aMC@NLO.
  Should we expect such tools to provide the same estimation of PDF uncertainties? Should we agree on which prediction(s) can be safely used?
- Various PDF set are available on the market, at least CT10, MSTW, NNPDF, but also ABM, JR, HERAPDF, and recently also ATLAS and CMS PDF sets. Do we want to agree on a common PDF set? We should at least be sure that ATLAS and CMS results can be combined accounting for the correlation of PDF uncertainties
- Prescription for evaluating PDF uncertainties: single set? envelope as in PDF4LHC prescription? META-PDF?

How to reduce PDF uncertainties for m_W

- Is the measurement of m_W at different collider energies, 7, 8, 13 TeV, beneficial for the reduction of PDF uncertainties?
- Which LHC measurements can further constrain the PDF uncertainties for m_W?

BACKUP

Choice of ptsqmin 4.0 in POWHEG+PYTHIA8