Combined EW+PDF fits

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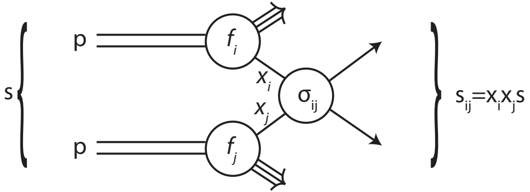
2023.04.26

EW parameters and proton PDFs



$$\sigma_{pp\to X} = \sum_{i,j}\int \mathrm{d}x_1\mathrm{d}x_2\, \underbrace{f_i^p(x_1,Q^2)}_{PDF}\,\underbrace{f_j^p(x_2,Q^2)}_{PDF} \times \sigma_{ij}(x_1x_2s,\alpha_S(Q^2))$$

$$\text{HERAPDF style}: \quad xf_i(x) = A_i x^{B_i}(1-x)^{C_i}(1+D_ix+E_ix^2) \quad \underbrace{-A'_g x^{B'_g}(1-x)^{C'_g}}_{\text{term used exclusively for the gluon}}$$

Most studies take the EW and PDF parts as decoupled, using one to find the other:

- EW SM values are assumed in order to fit PDFs

or

- PDFs are fixed to find the value of EW parameters

AIM → to perform combined EW+PDF fits

Combined fit motivation: W-boson mass uncertainty breakdown

	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_{W^+}	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4
m_{W^-}	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4
$m_{W^\pm}$	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

Uncertainty breakdown for m_W in MeV, as obtained in the study arXiv:1701.07240.

PDF is the main source of systematic uncertainties in EW measurements

$\Downarrow$

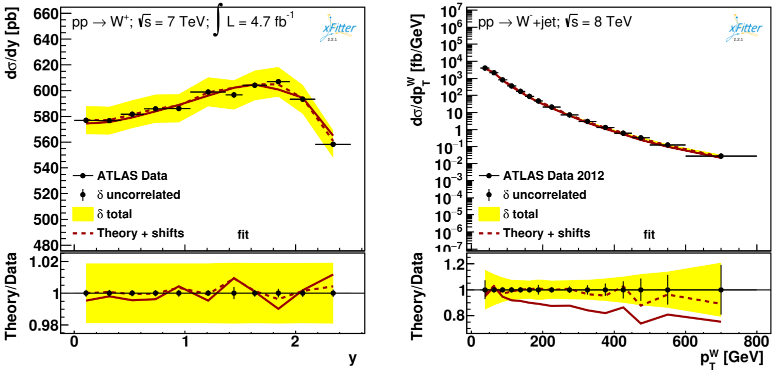
Neglecting the correlation to the PDF uncertainty can translate into an important mis-estimation of the corresponding total uncertainty

$\Downarrow$

We are not particularly interested in improving central EW values
$\rightarrow$Instead, we want to find the correlation between the EW and QCD parts via a simultaneous fit

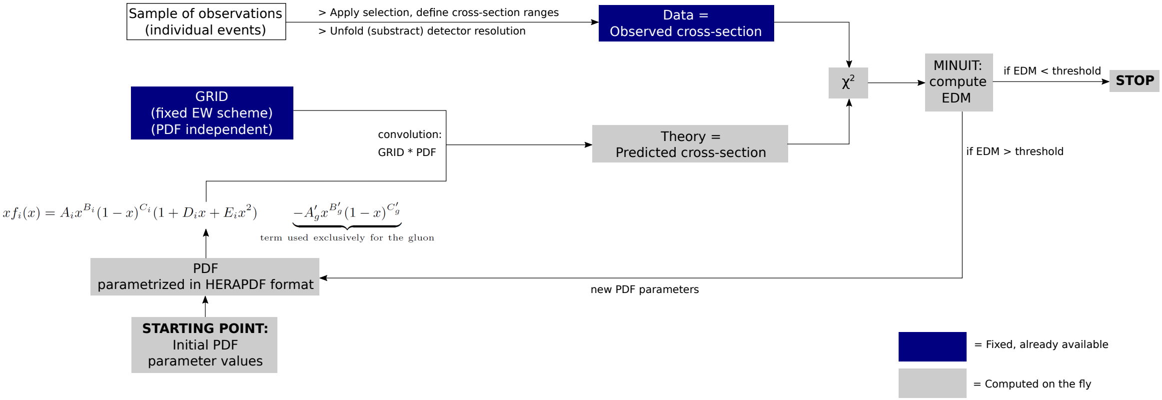
Fitting PDFs: datasets and χ^2 examples

General examples of measured cross-sections (black dots), their post-PDF-fit prediction (solid red line), and post-fit prediction + systematics shifts (dotted red line):



e.g. $$\chi^2 = \sum_i \frac{(\mu_i - \hat{m}_i)^2}{(\sigma_{i,\mathrm{stat}})^2 + (\sigma_{i,\mathrm{uncorr}})^2} + \sum_\alpha b_\alpha^2 \quad \text{where} \quad \hat{m}_i = m_i + \sum_\alpha \Gamma^i_\alpha b_\alpha$$

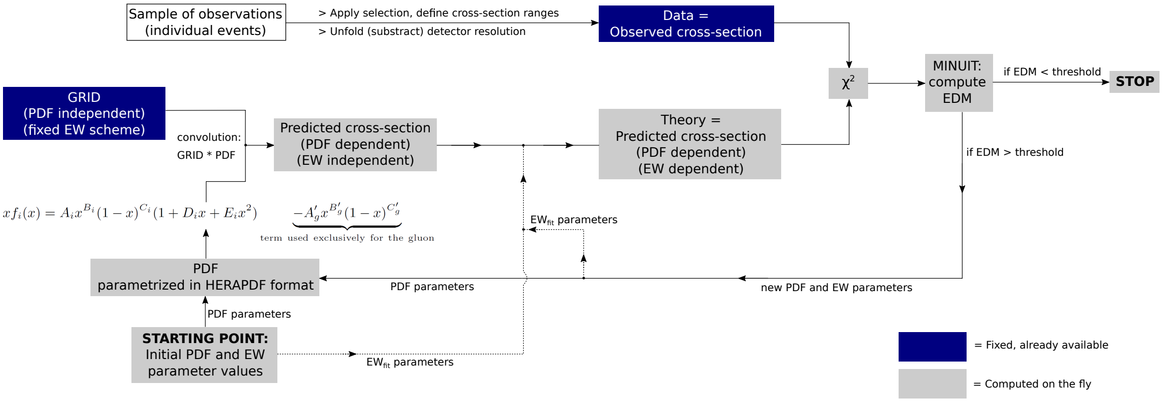
Fitting PDFs: the standard way (as used in xFitter)



The GRID is computed for fixed EW values $\rightarrow$ insensitive to these changes (straight out of the box)

Like this, one cannot fit an EW parameter on the fly!

Fitting PDFs: the combined EW+PDF fit approach



Strategy

We can write the prediction of a differential cross-section with respect to some variable Y (called $\frac{\mathrm{d}\sigma}{\mathrm{d}Y}$) as a function of a PDF set and EW values as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Y}(\mathrm{PDF}, \mathrm{EW\ variation}) = [\mathrm{GRID_{NLO}} * \mathrm{PDF}] \times K^{\mathrm{QCD,NLO\to NNLO}}_{\mathrm{EW,LO\to NLO}} \times f_Y(\mathrm{EW\ variation})$$

where

- $\mathrm{GRID_{NLO}}$ is an existent APPLgrid at Fixed Order NLO, obtained for a fixed set of EW parameters.
- $\mathrm{GRID_{NLO}} * \mathrm{PDF}$ is the convolution of the fixed APPLgrid and the PDF being fitted
  $\rightarrow$ gives the corresponding Fixed Order NLO cross-section prediction.
- $K^{\mathrm{QCD,NLO\to NNLO}}_{\mathrm{EW,LO\to NLO}}$ are DYTURBO K-factors
- $f_Y(\mathrm{EW\ variation})$ is a function (specific to each bin Y), whose parameters are fitted by looking at the relative change of XS by comparing several $\mathrm{XS(Various\ EW\ values)}$ with the nominal prediction $\mathrm{XS(EW\ nominal)}$. It allows to reweight from nominal EW values to the ones of interest for the fit.

We have a strategy, now what?

One must find a useful cross-section measurement and electroweak parameter to implement the combined EW+PDF fit. In other words:

- Choose an EW parameter
- Look for differential cross-section measurements $\mathrm{d}\sigma/\mathrm{d}Y$ which are sensitive to the EW parameter
  - sensitive := a change of the EW parameter induces a change in the shape of $\mathrm{d}\sigma/\mathrm{d}Y$
- Obtain a reliable APPLgrid for the cross-section prediction at NLO (Fixed Order)
  - in the current study, we are using MadGraph5 2.9.3 + aMCfast 1.3.0
- Compute the [QCD NLO $\rightarrow$ NNLO, EW LO $\rightarrow$ NLO] K-factors
- Using a given PDF (e.g. CT18NNLO), parameterize the dependency of $\mathrm{d}\sigma/\mathrm{d}Y$ as a function of the EW parameter

The dataset and prediction sensitive to $m_W \Rightarrow \mathrm{d}\sigma/\mathrm{d}p_l^T$ in $W^{\pm} \to l\ \nu_l$

- Plan towards using the results of the low-pileup W-boson $\mathrm{d}\sigma/\mathrm{d}p_l^T$ cross-section study (ongoing analysis)
- Data: Simulated differential p_l^T cross-sections (= Pseudodata @ $m_W = 80.4$ GeV, $\sqrt{s} = 5$TeV), 1 GeV bins in the $p_l^T \in [25, 60]$ GeV range (including systematic uncertainties, scaled to the Pseudodata)
- Prediction @ $m_W = 80.4$ GeV: [APPLgrid Fixed Order grids $*$ PDF] $\times$ k-factor, where

$$\mathrm{k-factor} = \frac{\mathrm{DYTURBO\ at\ NNLO\ using\ PDF,\ with\ resummation}}{\mathrm{APPLgrid} * \mathrm{PDF}}$$

$\rightarrow$ one can absorb most of the lack-of-resummation effect with the k-factor

- EW variations: at each p_l^T bin, the differential cross-section change as a function of m_{W} can be defined as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_l^T}(m_{\mathrm{W}}) = \frac{\mathrm{d}\sigma}{\mathrm{d}p_l^T}(m_{\mathrm{W}}^{\mathrm{nominal}} = 80.400\ \mathrm{GeV}) \left[1 + \mathrm{factor}_{p_l^T}(m_{\mathrm{W}} - 80.400\ \mathrm{GeV})\right]$$

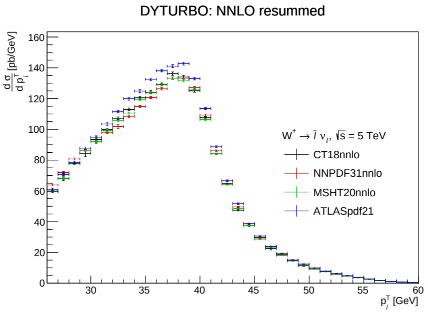
where each $\mathrm{factor}_{p_l^T}$ is determined (using reweighted Powheg+Pythia NLO samples) before proceeding to the PDF fit

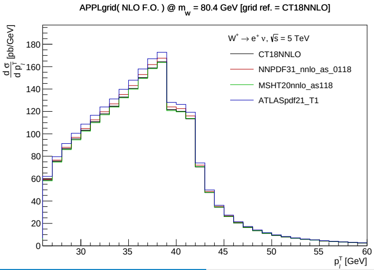
Useful to remember: given a correlation matrix C, the global correlation of a parameter k is defined as

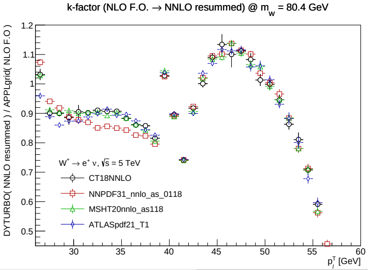
$$\rho_k^2 = 1 - \left[C_{kk} * (C^{-1})_{kk}\right]^{-1}$$

[https://doi.org/10.1016/0010-4655(75)90039-9, page 356]

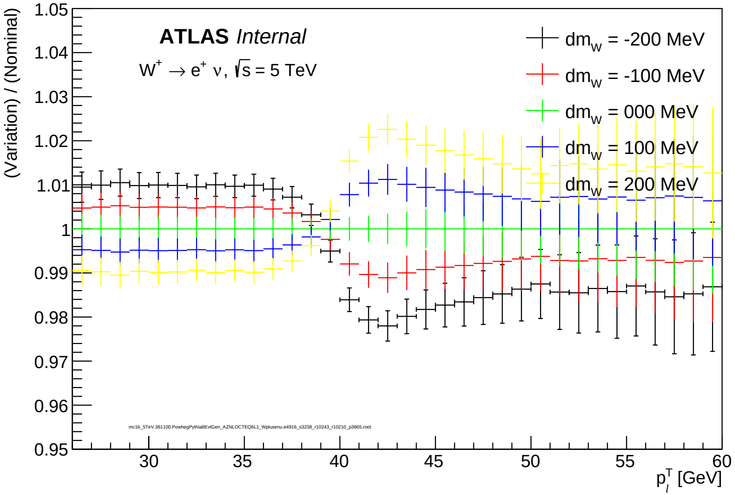
Overview of the $\mathrm{d}\sigma/\mathrm{d}p_l^T$ pseudodata and corresponding prediction







Overview of the $\mathrm{d}\sigma/\mathrm{d}p_l^T$ pseudodata samples: m_W dependency



Data sets

Ultimate goal: include all the data sets used in ATLASpdf21, i.e.

- epWZ16: HERA [1506.06042, main PDF constraint] + WZ production [1612.03016]
- ttbar8TeV [1511.04716, 4 correlation files]
- Vjets [1711.03296 (W) and 1907.06728 (Z)]
- z3d [1710.05167]
- Wxs8TeV [1904.05631]
- photon [1901.10075]
- top13TeV [1908.07305, 6 correlation files]
- jets [1706.03192]

+ a dataset sensitive to m_W:

- LowPileup: 5 TeV W-boson p_l^T cross-sections [4 channels]

Simple closure test

Use only the LowPileup pseudodata sets, where $m_W = 80.4$ GeV

Approach:

1. Do a PDF only fit on both datasets by fixing $\mathrm{Mw\_fit} = 80.4$
2. Fix all the PDF parameters to the value of the fit, release $\mathrm{Mw\_fit}$, run m_W only fit → should recover 80.4

→ This simplified closure test recovers the truth value of m_W!

At the very least, it suggests that we haven't broken xFitter and it still works as intended

Parameter	PDFonly	mWonly
'Adbar'	0.2892 ± 0.0025	0.2892
'Adv'	1.0000	1.0000
'Ag'	1.0000	1.0000
'Agp'	0.182 ± 0.024	0.1815
'Auv'	1.0000	1.0000
'Bdbar'	0.0403 ± 0.0025	0.04028
'Bdv'	0.688 ± 0.014	0.6884
'Bg'	−0.451 ± 0.014	−0.4514
'Bgp'	−0.597 ± 0.013	−0.5974
'Buv'	0.744 ± 0.010	0.7445
'Cdbar'	6.57 ± 0.79	6.572
'Cdv'	3.64 ± 0.11	3.635
'Cg'	2.226 ± 0.062	2.226
'Cgp'	25.00	25.00
'Cstr'	8.6 ± 2.7	8.608
'Cubar'	8.30 ± 0.50	8.299
'Cuv'	4.789 ± 0.043	4.789
'Dubar'	−0.96 ± 0.57	−0.9633
'Euv'	9.85 ± 0.44	9.850
'Mw_fit'	80.40	80.400 ± 0.013
'rs'	0.57 ± 0.12	0.5706

First combined fits using more data

Run fits using all the HERA data (6 datafiles) + a single channel of the Low Pileup pseudodata

Parameter	Wminusenu	Wplusenu	Wminusmunu	Wplusmunu
'Adbar'	0.127 ± 0.017	0.0910 ± 0.0088	0.128 ± 0.016	0.0914 ± 0.0088
'Adv'	1.0000	1.0000	1.0000	1.0000
'Ag'	1.0000	1.0000	1.0000	1.0000
'Agp'	0.391 ± 0.078	0.499 ± 0.088	0.390 ± 0.077	0.494 ± 0.089
'Auv'	1.0000	1.0000	1.0000	1.0000
'Bdbar'	−0.141 ± 0.018	−0.174 ± 0.017	−0.141 ± 0.018	−0.173 ± 0.017
'Bdv'	0.88 ± 0.10	0.816 ± 0.086	0.884 ± 0.100	0.814 ± 0.086
'Bg'	−0.46 ± 0.13	−0.505 ± 0.098	−0.46 ± 0.13	−0.51 ± 0.12
'Bgp'	−0.552 ± 0.075	−0.575 ± 0.066	−0.552 ± 0.077	−0.578 ± 0.079
'Buv'	0.741 ± 0.036	0.681 ± 0.039	0.741 ± 0.036	0.680 ± 0.039
'Cdbar'	20.4 ± 5.2	0.88 ± 0.24	20.3 ± 5.2	0.88 ± 0.24
'Cdv'	4.28 ± 0.39	4.98 ± 0.53	4.28 ± 0.39	4.97 ± 0.52
'Cg'	3.64 ± 0.82	5.06 ± 0.89	3.63 ± 0.83	5.01 ± 0.96
'Cgp'	25.00	25.00	25.00	25.00
'Cstr'	6.1 ± 3.5	21.4 ± 6.2	6.0 ± 3.4	21.3 ± 6.1
'Cubar'	8.7 ± 1.0	10.2 ± 1.1	8.7 ± 1.0	10.2 ± 1.1
'Cuv'	4.902 ± 0.081	5.34 ± 0.16	4.901 ± 0.081	5.34 ± 0.16
'Dubar'	8.3 ± 3.3	22.0 ± 4.6	8.2 ± 3.3	21.8 ± 4.6
'Euv'	13.4 ± 2.0	21.5 ± 3.8	13.4 ± 2.0	21.5 ± 3.8
'Mw_fit'	80.407 ± 0.053	80.469 ± 0.037	80.406 ± 0.051	80.467 ± 0.036
'rs'	1.23 ± 0.45	1.91 ± 0.41	1.21 ± 0.43	1.90 ± 0.41
Fit status	converged	converged	converged	converged
Uncertainties	migrad-hesse	migrad-hesse	migrad-hesse	migrad-hesse

The fitted mass of the W^+ channels is outside of the statistical error!

Combined m_W + PDF fits with more data carry the same problem

Parameter	HERA+LowPileup	+epWZ16	+ttbar	+Vjets	+Wxs8TeV
'Adbar'	0.0975 ± 0.0092	0.1029 ± 0.0063	0.1030 ± 0.0057	0.0975 ± 0.0051	0.348 ± 0.062
'Adv'	1.0000	1.0000	1.0000	1.0000	1.0000
'Ag'	1.0000	1.0000	1.0000	1.0000	1.0000
'Agp'	0.413 ± 0.068	0.360 ± 0.059	0.351 ± 0.039	0.318 ± 0.028	0.239 ± 0.027
'Aubar'	-	-	-	-	0.0928 ± 0.0048
'Auv'	1.0000	1.0000	1.0000	1.0000	1.0000
'Bdbar'	−0.171 ± 0.015	−0.169 ± 0.010	−0.1695 ± 0.0097	−0.1776 ± 0.0092	0.019 ± 0.030
'Bdv'	0.581 ± 0.039	0.679 ± 0.027	0.678 ± 0.027	0.663 ± 0.024	0.531 ± 0.017
'Bg'	−0.53 ± 0.12	−0.594 ± 0.090	−0.592 ± 0.074	−0.629 ± 0.059	−0.553 ± 0.069
'Bgp'	−0.596 ± 0.080	−0.644 ± 0.067	−0.644 ± 0.053	−0.675 ± 0.042	−0.650 ± 0.036
'Bstr'	-	-	-	-	0.341 ± 0.080
'Bubar'	-	-	-	-	−0.2184 ± 0.0095
'Buv'	0.735 ± 0.023	0.737 ± 0.012	0.735 ± 0.011	0.723 ± 0.011	0.710 ± 0.011
'Cdbar'	4.4 ± 2.1	2.46 ± 0.50	2.45 ± 0.48	1.84 ± 0.33	27.7 ± 3.6
'Cdv'	2.84 ± 0.24	3.69 ± 0.25	3.70 ± 0.25	3.72 ± 0.21	2.66 ± 0.15
'Cg'	3.67 ± 0.85	2.69 ± 0.67	2.61 ± 0.46	2.24 ± 0.35	2.11 ± 0.31
'Cgp'	25.00	25.00	25.00	25.00	25.00
'Cstr'	5.1 ± 2.7	10.3 ± 1.7	10.6 ± 1.7	11.4 ± 1.4	7.0 ± 1.0
'Cubar'	8.2 ± 1.0	6.0 ± 1.3	6.0 ± 1.3	7.0 ± 1.0	4.39 ± 0.38
'Cuv'	5.015 ± 0.096	4.848 ± 0.076	4.852 ± 0.076	4.926 ± 0.084	4.904 ± 0.078
'Dubar'	7.7 ± 3.3	2.0 ± 1.8	2.0 ± 1.8	3.5 ± 1.7	-
'Euv'	13.7 ± 1.7	10.92 ± 0.92	11.04 ± 0.92	11.97 ± 0.93	12.54 ± 0.95
'Mw_fit'	80.446 ± 0.020	80.432 ± 0.018	80.432 ± 0.018	80.421 ± 0.017	80.454 ± 0.017
'rs'	1.54 ± 0.31	1.307 ± 0.068	1.308 ± 0.068	1.371 ± 0.065	2.72 ± 0.65
Fit status	converged	converged	converged	converged	converged
Uncertainties	migrad-hesse	migrad-hesse	migrad-hesse	pos-def-forced	migrad-hesse

Global Correlation	0.61816	0.46116	0.45988	0.41180	0.44756

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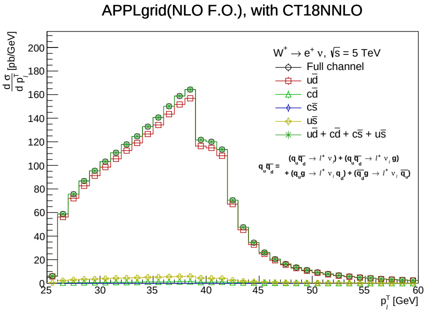
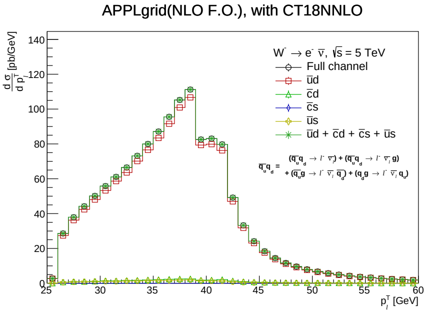
Current state of the combined fit study: investigating the non-closure problem

Working to better understand the quark flavour treatment used by MadGraph5 2.9.3





cs contribution appears to be absorbed in ud !

- Could the non-closure be related to improper APPLgrids?
- Maybe the mass shift is a real effect of the correlation between m_W and the PDF?

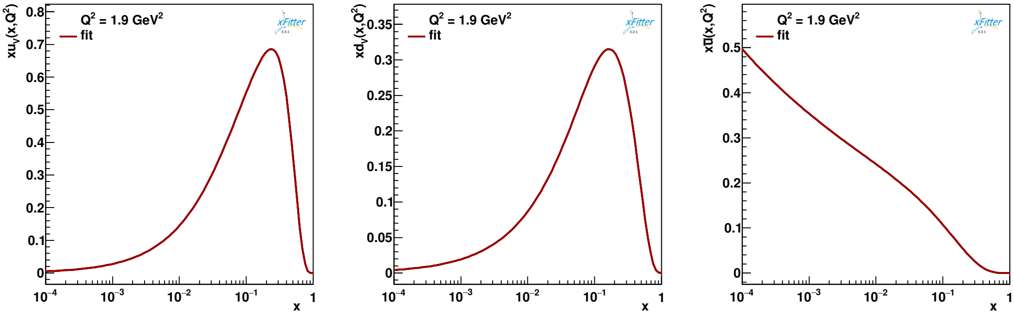
Currently investigating

Summary

- This technique allows to simultaneously fit a proton PDF and an EW variable of interest
- Such technique can shed light on the EW-PDF correlation
- Ultimately, we aim to do a fit using all the ATLASpdf21 datasets plus the Low Pileup W cross-sections
- Implementing the fit of the EW part implies prior studies, such as
  - Choose EW parameter (in the aforementioned case, m_W)
  - Search for a sensitive enough differential cross-section channel
  - Study the accuracy of the Fixed Order grid predictions
  - Parameterize the m_W dependency
  - Modify xFitter accordingly
- This kind of study relies on many moving parts (xFitter, MadGraph, aMCfast, APPlgrid, etc.), so many things can go wrong if one is not careful
  - Non-trivial problems may arise due to the complexity of these frameworks. Currently we are exploring a problem of such sort,
    - it could be related to the quark flavour treatment used for the APPLgrids,
    - it could also be real physics derived from the EW-PDF correlation,
    - or maybe it is an user error in either of the many used frameworks

Backup

Examples of proton PDFs



$$\text{HERAPDF style :} \qquad xf_i(x) = A_i x^{B_i}(1-x)^{C_i}(1+D_i x + E_i x^2) \qquad \underbrace{-A'_g x^{B'_g}(1-x)^{C'_g}}_{\text{term used exclusively for the gluon}}$$

Combined fit motivation: effective leptonic weak mixing angle uncertainty breakdown

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

Uncertainty breakdown for $\sin^2 \theta_W$, as obtained in the study ATL-CONF-2018-037.

Combined fit motivation: W-boson mass uncertainty breakdown

	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_{W^+}	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4
m_{W^-}	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4
$m_{W^\pm}$	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

Uncertainty breakdown for m_W in MeV, as obtained in the study arXiv:1701.07240.

PDF is the main source of systematic uncertainties in EW measurements

$\Downarrow$

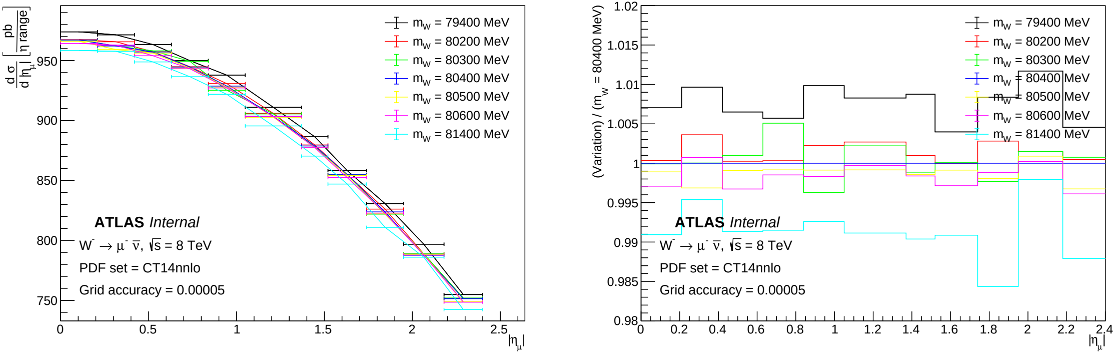
Neglecting the correlation to the PDF uncertainty can translate into an important mis-estimation of the corresponding total uncertainty

Sensitivity studies of various datasets to m_W

EW variable	Dataset	Channel	Sensitive?
m_W	W inclusive cross-sections (1904.05631)	$\frac{\mathrm{d}\sigma}{\mathrm{d}\lvert\eta_\mu\rvert}$	No
m_W	W inclusive cross-sections (low-μ samples)	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_W^T}$	Maybe
m_W	W inclusive cross-sections (low-μ samples)	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_l^T}$	**Yes**
m_W	W+jets (1711.03296)	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_W^T}$	Maybe
quark-Z couplings	Z3D (1710.05167)	$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{ll}\mathrm{d}\lvert y_{ll}\rvert\mathrm{d}\cos\theta^*}$	To see

Cross-section grids for different EW values are obtained with stand-alone MadGraph at Fixed Order:
MG5_aMC_v2.9.3 + amcfast-1.3.0 + applgrid-1.6.27

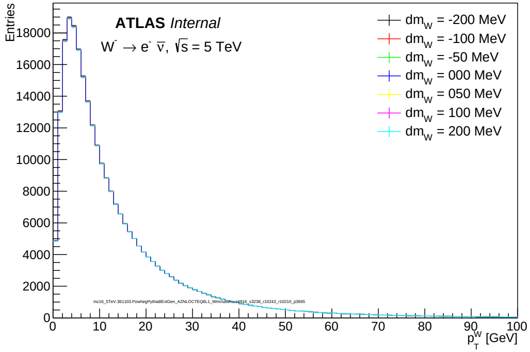
Not sensitive to changes in m_W

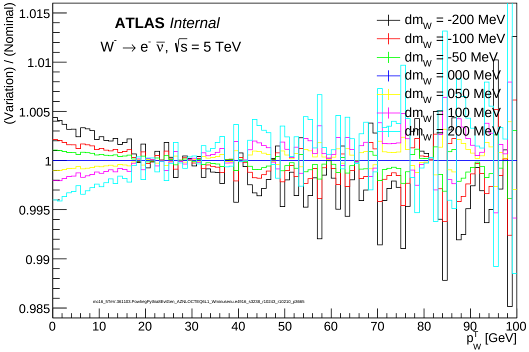


Cross-section predictions obtained with APPLGrids and CT14nnlo

m_W in W inclusive $\mathrm{d}\sigma/\mathrm{d}p_W^T$ (checked with low-μ samples)

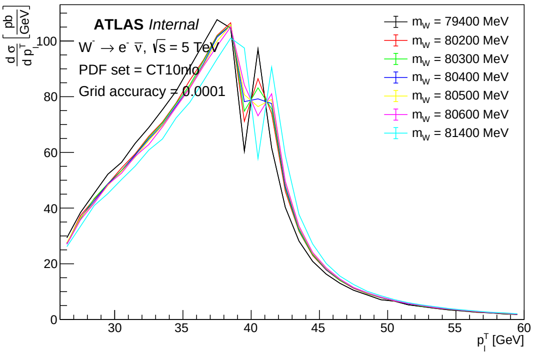
Not sensitive to changes in m_W

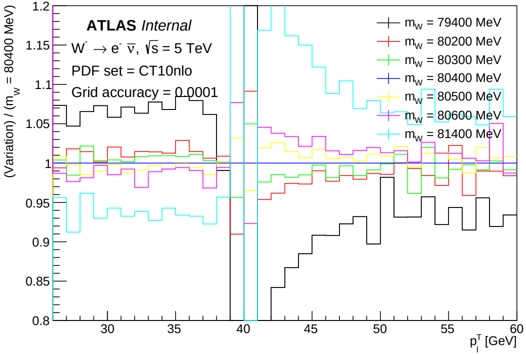




Sample distribution predictions obtained via HistMaker reweighting of W samples

Very sensitive to m_W, **but** there is a non-physical kink at $p_l^T \approx m_W/2$:
since cross-section grids are estimated at Fixed Order (QCD NLO + EW LO), they do not include LL resummed corrections coming from the PS and the higher order LL corrections from small-qT/high-threshold resummation

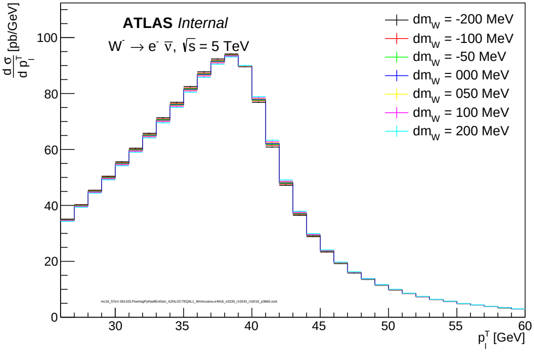


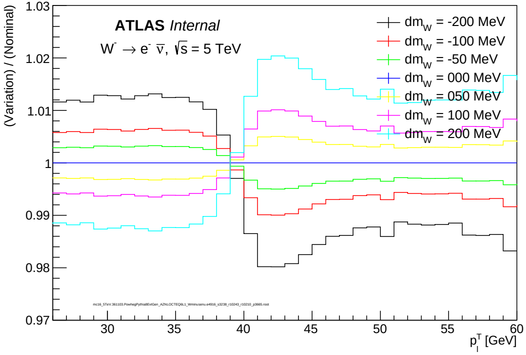


Cross-section predictions obtained with APPLGrids and CT10nlo

m_W in W inclusive $\mathrm{d}\sigma/\mathrm{d}p_l^T$ (low-pileup study, using Powheg+Pythia samples)

Very sensitive to m_W!





Cross-section predictions obtained with Powheg+Pythia samples (histogrammed with HistMaker)

m_W in W inclusive $\mathrm{d}\sigma/\mathrm{d}p_l^T$ at 5 TeV: bin-by-bin m_W dependence