Electron energy resolution corrections in the ATLAS experiment & combined EW+QCD studies

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ATLAS - IJCLab

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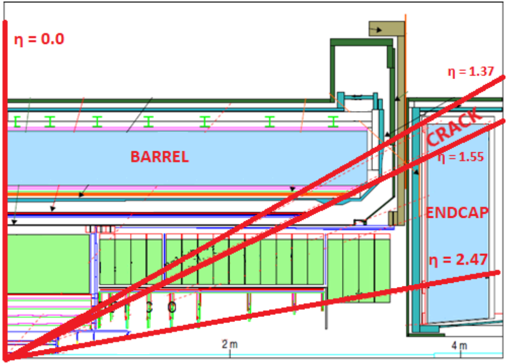
Electron energy resolution corrections

The LAr Electromagnetic Calorimeter of the ATLAS experiment



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

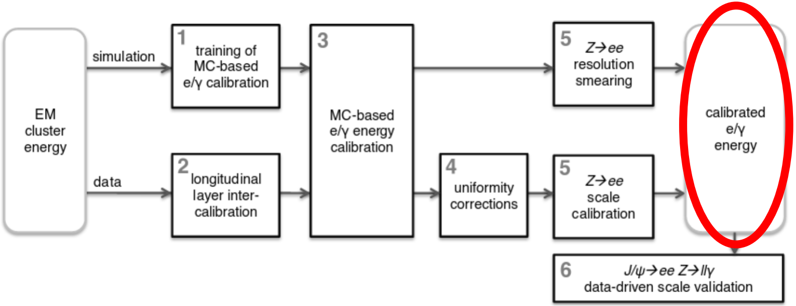
Proper calorimeter calibration (both on the Data and MC sides) is vital for precision measurements, such as:

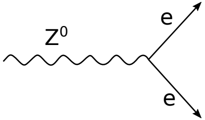
- W-boson mass
- Higgs boson mass

$\Rightarrow$ continuous efforts to improve it

LAr calorimeter e/γ calibration chain: based on $Z \to ee$ sub-samples

The study shown here is done at the level of the step highlighted with the red circle.





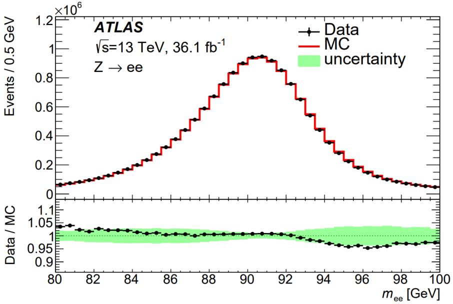
$$m_Z = 91.1876 \pm 0.0021 \text{ GeV} \quad \text{(LEP)}$$

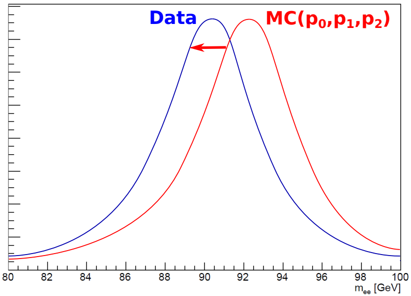
$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV} \quad \text{(LEP)}$$

electrons are described by their $[E,\ \eta,\ \phi]$

$$\text{Reminder} : m_{ee}^2 \approx 2E_1E_2(1 - \cos\theta_{12}) = 2p_1^T p_2^T\,(\cosh(\eta_1 - \eta_2) - cos(\phi_1 - \phi_2)) \qquad \text{where } p^T = \frac{E}{\cosh\eta}$$

Mass line shape discrepancy (2018 $Z \to ee$ Data/MC)





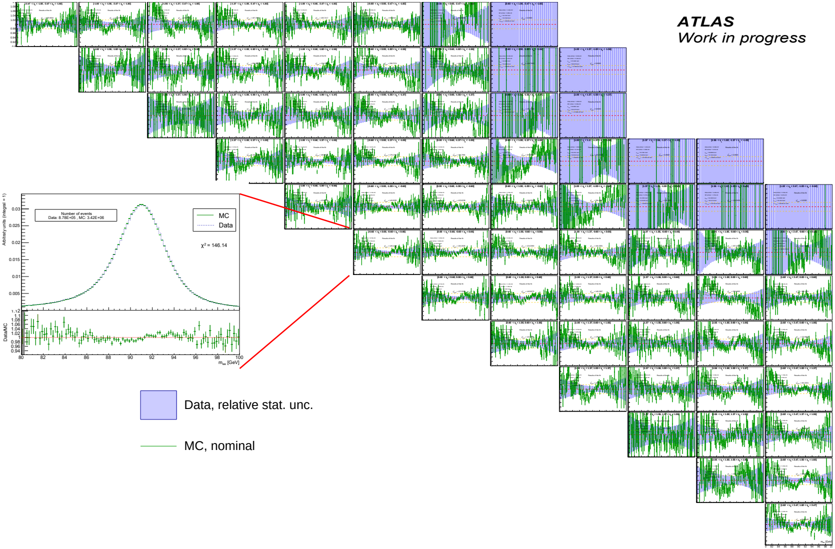
Seeking to understand better the difference between Data and MC

Using method proposed by USTC group: **MC electron-by-electron energy resolution correction**

$$\Delta = E_{reco} - E_{truth} \to \Delta' = f(\Delta)$$

$$E'_{reco} = E_{truth} + \Delta' \qquad \text{with e.g. } \Delta' = p_0\Delta + p_1\Delta^2 + p_2$$

Grid on $[\eta_1, \eta_2]$ of nominal Data/MC mass line shape ratios



Optimization approach and the problem with the χ^2 curve

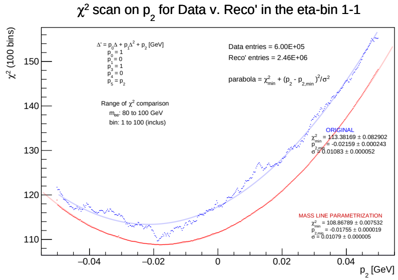
Let

$$\chi^2(p_0, p_1, p_2) = \sum_{i}^{n\ \text{bins}} \frac{\left[\text{bin}_i^{\text{MC}}(p_0, p_1, p_2) - \text{bin}_i^{\text{DATA}}\right]^2}{[\sigma_i^{\text{MC}}(p_0, p_1, p_2)]^2 + [\sigma_i^{\text{DATA}}]^2}$$

→ the χ^2 is computed between mass histograms (i.e. finite number of bins)
→ change in Δ' parameters = **migration of events from one bin to another**
→ MC' histogram does not transform continuously as a function of p_0, p_1, etc.
→ χ^2 curve is not continuous!
↳ (opposite from traditional cases, which compare hist. v. pdf)

We had to develop a method capable of treating the χ^2 fluctuations → in the process to become an ATLAS PubNote

- Blue: χ^2 between 2 histograms (affected by migration)
- Red: χ^2 between a (fixed) histogram and the fit of the other one (**using method proposed in the PubNote**)

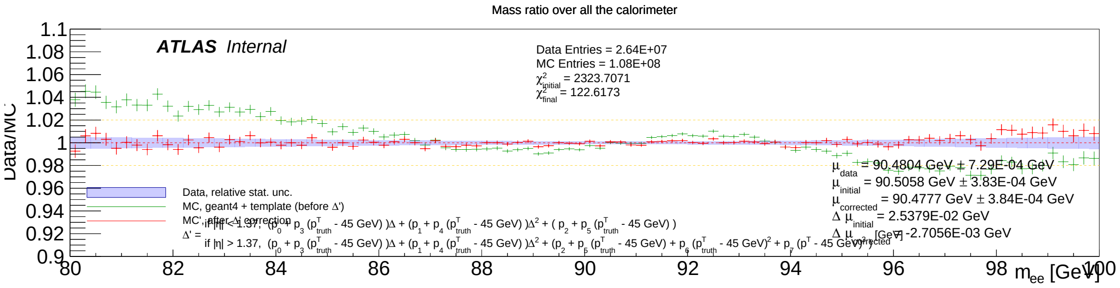


And after trying many $\Delta' = f(\Delta)$ parametrizations...

Best compromise (so far): combined first and third order E^T dependence

First order in the barrel, third order in the crack+endcap:

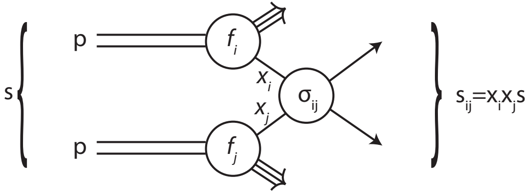
$$\Delta' = \left[p_0 + p_3(E^T_{\text{truth}} - 45\text{ GeV})\right]\Delta + \left[p_1 + p_4(E^T_{\text{truth}} - 45\text{ GeV})\right]\Delta^2$$
$$+ \begin{cases} \left[p_2 + p_5(E^T_{\text{truth}} - 45\text{ GeV})\right] & \text{if } |\eta| < 1.37 \\ \left[p_2 + p_5(E^T_{\text{truth}} - 45\text{ GeV}) + p_6(E^T_{\text{truth}} - 45\text{ GeV})^2 + p_7(E^T_{\text{truth}} - 45\text{ GeV})^3\right] & \end{cases}$$



- Currently, Edison Carrera (internship student) is studying the impact of this calibration on the W-boson mass measurement

Combined EW+QCD studies

EW parameters and PDFs



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

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

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 (by modifying σ_{ij})

	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.

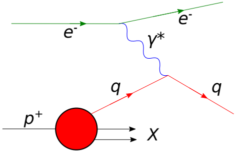
PDF is the main source of systematic uncertainties in EW measurements

$\Downarrow$

Neglecting the correlation to the PDF uncertainty translates into a misestimation of the corresponding total uncertainty

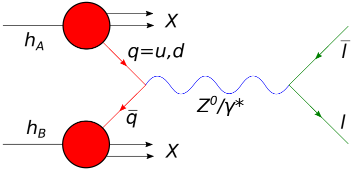
- Deep Inelastic Scatering (DIS): $e^{-}p^{+}$ data

$\rightarrow$ Main constraint of the PDF



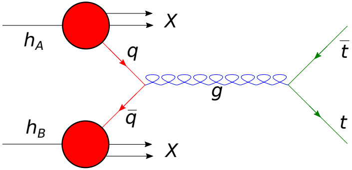
- $pp \rightarrow \mathrm{W/Z}$ cross-sections (e.g. Drell-Yan)

$\rightarrow$ sensitive to u- and d-quarks structure functions



- $pp \rightarrow t\bar{t}$ cross-sections

$\rightarrow$ sensitive to gluon structure functions



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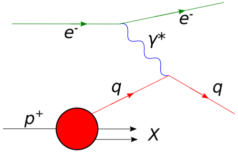

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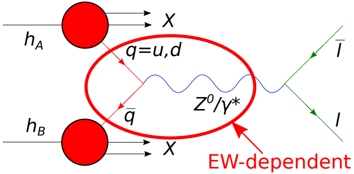

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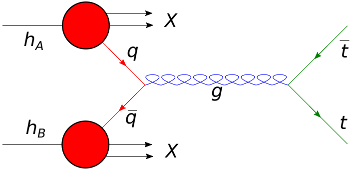


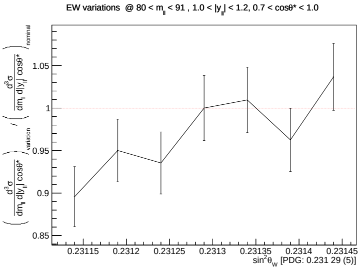
Example of dependency on an EW parameter

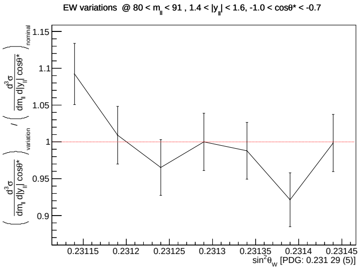
We will focus on the Z3D dataset (1710.05167):
Drell–Yan ($Z/\gamma^* \to l^+l^-$) triple-differential cross-section in pp collisions at $\sqrt{s} = 8$ TeV

Cross-section binning:

- m_{ll} : $[46, 66, 80, 91, 102, 116, 150, 200]$ GeV
- y_{ll} : $[0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4]$
- $\cos\theta^*$: $[-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0]$

Relative impact on differential cross-section due to variations of $\sin^2\theta_W$:





Lots of work still to come...

Currently:

- Understanding the dependency on the EW parameter (and extend to others, such as quark-Z couplings)
- Deciding on a (stable) way to interpolate

  $\rightarrow$ This will be particularly important when fitting multiple EW parameters
-

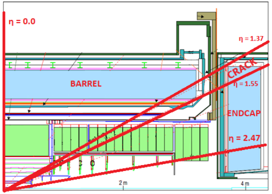
Backup

Energy resolution correction

- Best Δ' parameters sought with Minuit2.
- Minimizing the shape difference between the Data and MC mass distributions.
- The most simple form of the correction looks like $\Delta' = f(\Delta) = p_0\Delta + p_1\Delta^2 + p_2$
- η-binning defined as: $\{0.0, 0.6, 1.0, 1.37, 1.55, 1.82, 2.47\}$ (positive and negative)

  e.g. η-bin 1 $= -2.47 < \eta < -1.82$

  η-bin 7 $= 0.0 < \eta < 0.6$
- $Z \rightarrow ee$ gives two electrons (each with their own η and energy)
  - study done in a 2-D grid defined by $[\eta_1, \eta_2]$
- N.B. 12 regions in $\eta \rightarrow$ 12 sets of parameters $\vec{p_\eta} = (p_0, p_1, p_2, ..)$
- The current study is done on top of the latest official calibration



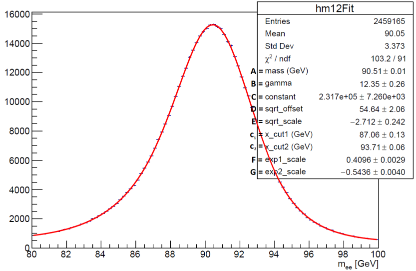
Getting rid of the migration: profiling the MC mass lineshape

TREATMENT TO MIGRATION: Fit a function (PDF) on the MC' histogram, and use it to predict the corresponding MC' value at each bin ($\int_{\text{bin}} f(x)dx/\text{bin}$). Since there is correlation between bins and propagated errors from the fit, the χ^2 looks like

$$\chi^2 = d^{\mathrm{T}} V^{-1} d.$$

$\Rightarrow$ Example of Breit-Wigner core with exponential tails fitted on MC:

$$f(x) = \begin{cases} 80 < x < c_1 : & e^{F(x-P)} + R \\ c_1 < x < c_2 : & \dfrac{C}{(x-A)^2 + B} + E(x-D)^2 \\ c_2 < x < 100 : & e^{G(x-Q)} + S \end{cases}$$



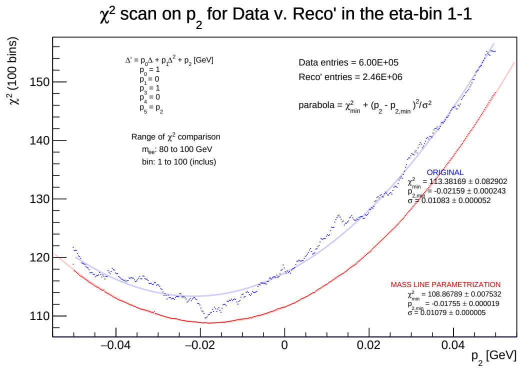
c_1 and c_2 are the transition nodes, their values are also fitted

R and S assure continuity of the function
P and Q assure continuity of the derivative

$\rightarrow$ in total, the function depends on 9 free parameters: $A,\ B,\ C,\ D,\ E,\ F,\ G,\ c_1,\ c_2$

Getting rid of the χ^2 fluctuations

- Blue: χ^2 between 2 histograms
- Red: χ^2 between a (fixed) histogram and the fit of the other one (which is constantly changing)



For the following results, MINUIT "sees" only the red curve.

Parametrizations of the resolution correction

Looking for the "magic" parametrization that improves all (or most) of the η-bins

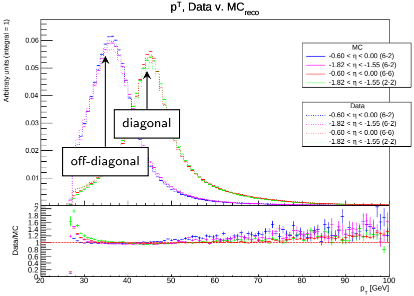
As shown before, it is very likely that there is a p^{T} dependence.

Let us concentrate on two equivalent parametrizations:

- A: $\Delta' = p_0\Delta + p_1\Delta^2 + p_2$
- L: $\Delta' = \left(p_0 + p_3(p^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})\right)\Delta + \left(p_1 + p_4(p^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})\right)\Delta^2 + \left(p_2 + p_5(p^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})\right)$

Why $-45\ \mathrm{GeV}$?

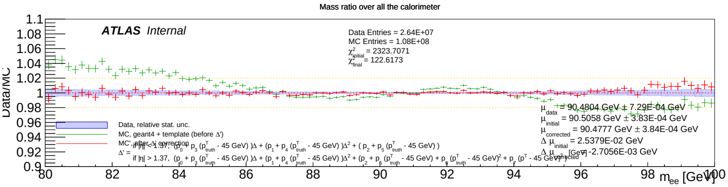
If there was no width of the Z, $p^{\mathrm{T}}_Z \approx 0$ and no resolution effects, at first order, the p^{T} for diagonal bins (e.g. 2-2 and 6-6) would be around $\frac{m_Z}{2} \approx 45\ \mathrm{GeV}$



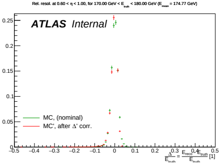
Best compromise (so far): combined first and third order E^{T} dependence

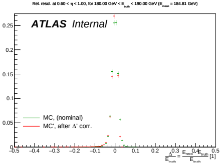
First order in the barrel, third order in the crack+endcap:

$$\Delta' = \left[p_0 + p_3(E^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})\right]\Delta + \left[p_1 + p_4(E^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})\right]\Delta^2$$
$$+ \begin{cases} \left[p_2 + p_5(E^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})\right] & \text{if } |\eta| < 1.37 \\ \left[p_2 + p_5(E^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV}) + p_6(E^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})^2 + p_7(E^{\mathrm{T}}_{\mathrm{truth}} - 45\ \mathrm{GeV})^3\right] & \end{cases}$$



Resolution at higher energies look better, although not yet perfect:





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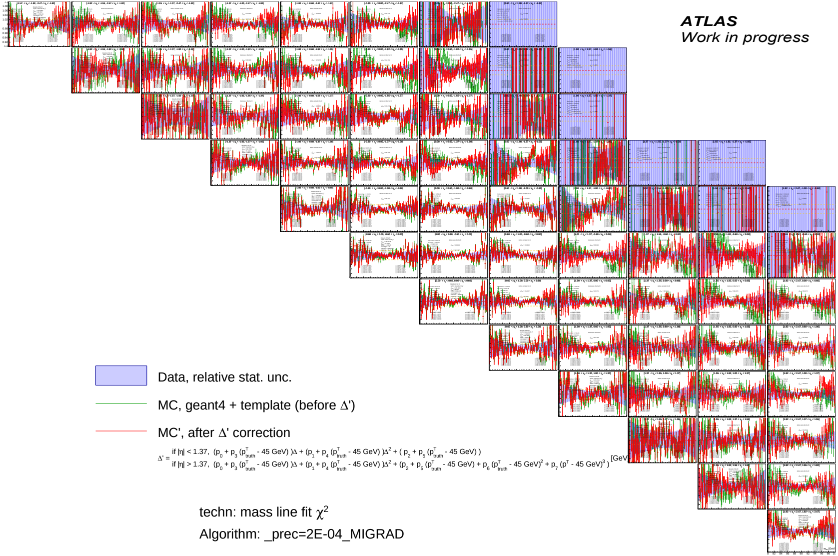


Data, relative stat. unc.

MC, geant4 + template (before Δ')

MC', after Δ' correction

$$\Delta' = \begin{cases} \text{if } |\eta| < 1.37, & (p_0 + p_3 (p^T_{truth} - 45\ \text{GeV}))\Delta + (p_1 + p_4 (p^T_{truth} - 45\ \text{GeV}))\Delta^2 + (p_2 + p_5 (p^T_{truth} - 45\ \text{GeV})) \\ \text{if } |\eta| > 1.37, & (p_0 + p_3 (p^T_{truth} - 45\ \text{GeV}))\Delta + (p_1 + p_4 (p^T_{truth} - 45\ \text{GeV}))\Delta^2 + (p_2 + p_5 (p^T_{truth} - 45\ \text{GeV}) + p_6 (p^T_{truth} - 45\ \text{GeV})^2 + p_7 (p^T - 45\ \text{GeV})^3) \end{cases} [\text{GeV}]$$

techn: mass line fit χ^2

Algorithm: _prec=2E-04_MIGRAD

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

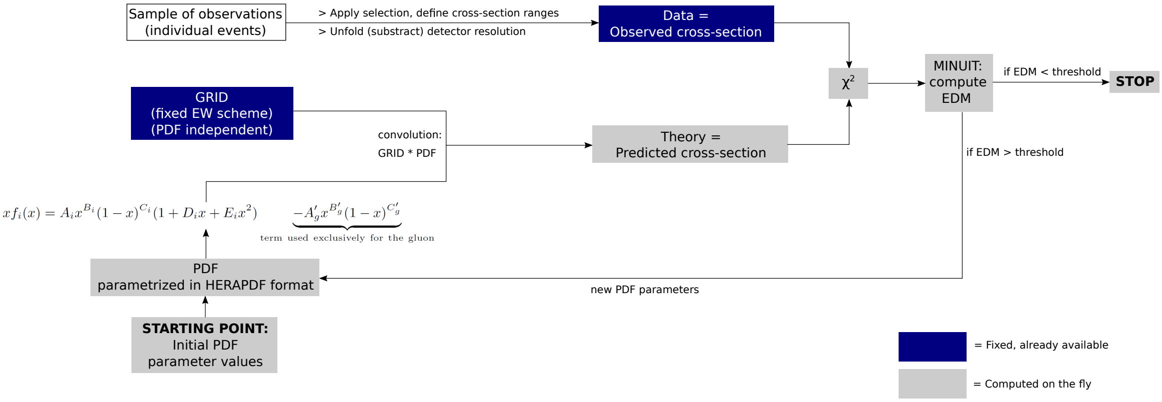
First off, how do we simulate cross-sections for some process?

- The observed cross-sections are estimated with data (given some selection), unfolded from detector resolution effects. Once unfolded, this remains constant.
- The estimation of the prediction is GREATLY dependent on the proton PDF
  $\rightarrow$ Very computationally expensive for proton-proton collisions (as at LHC)
  In order to speed it up, we use cross-section grids:
  - For a fixed EW scheme, an intermediate step of the cross-section (at some QCD order) is computed, right before using information about the proton's content. This is what we call a GRID
    $\rightarrow$ this is also expensive to compute, but it's done only once, and it is PDF-independent
  - For a given PDF, the corresponding (differential) cross-section is given by the convolution with the Grid i.e.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X}(\mathrm{PDF},\mathrm{EW}) = [\mathrm{GRID}_{\mathrm{NLO}} * \mathrm{PDF}]$$

  - This is quick to compute, and can be performed on the fly when optimizing the PDF

Fitting PDFs: the standard way



Fitting PDFs: the limitation for a combined EW+PDF fit

Using the previous approach, one cannot fit an EW parameter at the same time!:

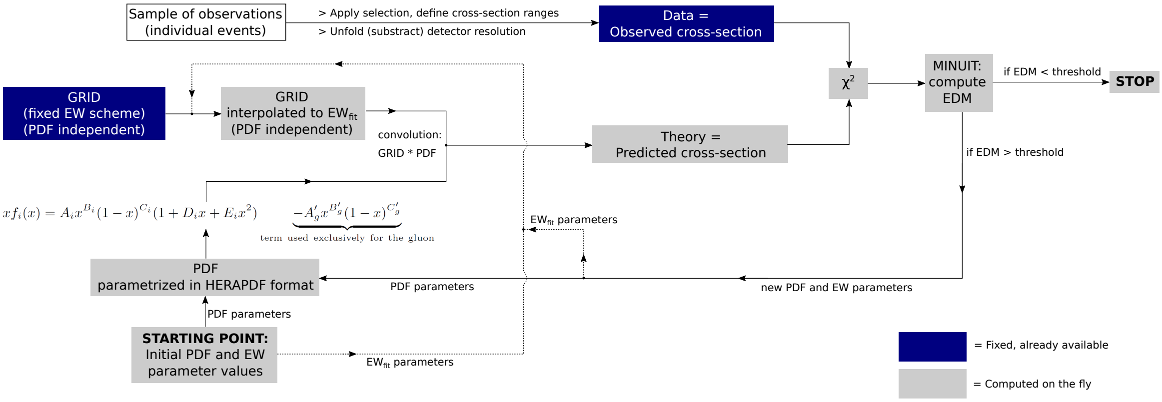
The GRID is computed for fixed EW values $\rightarrow$ insensitive to these changes (straight out of the box)

$\downarrow$

UNLESS

$\downarrow$

We modify the GRID/prediction accordingly


Sample of observations
(individual events)
> Apply selection, define cross-section ranges
> Unfold (substract) detector resolution
Data =
Observed cross-section
GRID
(fixed EW scheme)
(PDF independent)
GRID
interpolated to EW_fit
(PDF independent)
convolution:
GRID * PDF
Theory =
Predicted cross-section
χ²
MINUIT:
compute
EDM
if EDM < threshold
STOP
if EDM > threshold
$xf_i(x) = A_i x^{B_i}(1-x)^{C_i}(1+D_i x+E_i x^2)$ $-A'_g x^{B'_g}(1-x)^{C'_g}$
term used exclusively for the gluon
EW_fit parameters
PDF
parametrized in HERAPDF format
PDF parameters
new PDF and EW parameters
PDF parameters
STARTING POINT:
Initial PDF and EW
parameter values
EW_fit parameters
= Fixed, already available
= Computed on the fly

Strategy

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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X}(\mathrm{PDF},\mathrm{EW}) = [\mathrm{GRID}_{\mathrm{NLO}} * \mathrm{PDF}] \times K^{\mathrm{QCD}}_{\mathrm{NLO}\to\mathrm{NNLO}} \times \frac{\mathrm{POWHEG}(\mathrm{EW\ couplings})}{\mathrm{POWHEG}(\mathrm{NNLOJET\ scheme})}$$

where

- $\mathrm{GRID}_{\mathrm{NLO}}$ is an existent APPLgrid at NLO, obtained for a fixed set of EW parameters
- $\mathrm{GRID}_{\mathrm{NLO}} * \mathrm{PDF}$ is the convolution of the fixed APPLgrid and the PDF being fitted
  $\to$ gives the corresponding NLO cross-section prediction
- $K^{\mathrm{QCD}}_{\mathrm{NLO}\to\mathrm{NNLO}}$ are existent NNLOJET factors to scale NLO predictions to NNLO
  $\to$ these were obtained using a specific scheme
- $\frac{\mathrm{POWHEG}(\mathrm{EW})}{\mathrm{POWHEG}(\mathrm{NNLOJET\ scheme})}$ allows to go from nominal EW values to the ones of interest for the fit

The POWHEG factors

How can we compute the $K^{\mathrm{EW}}_{\mathrm{nom}\to\mathrm{var}} = \dfrac{\mathrm{POWHEG(EW)}}{\mathrm{POWHEG(NNLOJET\ scheme)}}$ factors?

For the numerator and denominator (separately), the following procedure is performed:

1. Generate a sample of events using POWHEG-BOX-2
   - This is generated under the same scheme as the NNLOJET K-factors
2. Shower it with Pythia8
3. Using the same cuts and regions of the cross-section study, we can build the numerical cross-section values from the sample

   $\to$ This will correspond to the **denominator**
4. Repeat by changing the EW values of interest in the configuration of POWHEG

   $\to$ This will give the **numerator**

Obtaining the POWHEG factors