EW and mixed EW+QCD uncertainties in the W boson mass measurement

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W mass measurement in hadron colliders

- The measurement of the W boson mass is a very important test of consistency of the SM (or door to new physics).
- At hadron colliders, the W boson mass is measured using template fits to data: The theoretical model on which the fit is based should be as accurate as possible, any uncertainty on the theoretical model is a source of systematic uncertainty on the measurement [Talks: Jakup Cuth, Alessandro Vicini].
- The theoretical uncertainties can be divided in 3 main components:
  - Parton distribution functions (PDFs).
  - Modeling of W boson transverse momentum (perturbative and non perturbative QCD effects).
  - **Electroweak and mixed EW-QCD corrections**.
- Example: D0 2012 measurement, 11 MeV (PDF), 2 MeV (boson pT), 7 MeV (corrections), out of a total uncertainty of 26 MeV [Phys. Rev. Lett. 108 (2012) 151804].

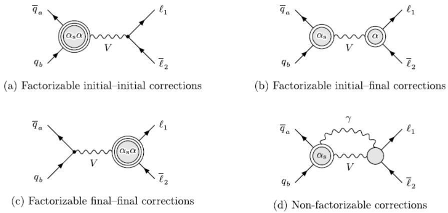
Higher order corrections for charged DY: state of the art

$$\sigma_{DY} = \alpha(A + \alpha_s B_1 + \alpha_s^2 B_2 + ... + \alpha C_1 + \alpha^2 C_2 + ... + \alpha_s \alpha D + ...)$$

- QCD corrections: NNLO accuracy (B_2) supplemented by leading logs (LL) and next to leading logs (NLL).
- EW corrections: NLO accuracy (C_1) supplemented by leading logs.
- Mixed corrections (D) are not known exactly. Partial results have been published [Kilgore and Sturm, PoS EPS-HEP2011, arXiv:1107.4798] [Bonciani et al. arXiv:1604.08581]. A systematic approach to their calculation has been presented recently adopting the pole approximation [Dittmaier, Schwinn et al, arXiv:1403.3216, arXiv:1405.6897, arXiv:1511.08016, arXiv:1601.02027].

Higher order corrections for charged DY: state of the art

The pole approximation allows to split to contributions to the $\mathcal{O}(\alpha_s\alpha)$ into 4 types [Talk by Christian Schwinn]:



(a) Factorizable initial–initial corrections
(b) Factorizable initial–final corrections
(c) Factorizable final–final corrections
(d) Non-factorizable corrections

- Non factorizable: virtual and soft real particles connecting the initial and final state. Not enhanced by collinear logarithms, negligible impact on M_W.
- Factorizable initial-initial: virtual and real parton and photon insertions in the initial state.
- **Factorizable initial-final**: consisting of NLO QCD (virtual and real) corrections to the W production process and NLO EW (virtual and real) corrections to the W decay, give the bulk of the contribution.
- Factorizable final-final: virtual contributions from two-loop counterterms, no impact on the shape of distributions.

Mixed EW-QCD uncertainty

- The models used by experimentalists to extract the W mass normally incorporate QCD NLO and QED LL in a PS matched approach, i.e POWHEG(NLO QCD)+PYTHIA(PS QCD)+PHOTOS.
- These predictions effectively include the leading structures of the factorizable $\mathcal{O}(\alpha_s\alpha)$ corrections.
- **Can we use the POWHEG implementation of DY to provide an estimate of the theoretical uncertainty on the W mass extraction, coming from the missing $\mathcal{O}(\alpha_s\alpha)$ corrections?**
- Using the POWHEG implementation of charged DY, which includes QCD and EW NLO corrections, matched to QCD and QED showers, we can partially answer this question.
- In the process we validate and assess the accuracy of the POWHEG implementation of DY.

Methodology: POWHEG

- POWHEG provides NLO accuracy, both for QCD and EW, matched to parton showers (NLO EW corrections are turned off by a flag).
- The matching is done by generating the hardest emission with NLO accuracy (POWHEG), then restricting the relative p_T of subsequent emissions, interfacing to another SMC (PYTHIA and PHOTOS).
- The matched POWHEG prediction contains part of the QCD-EW corrections. In the pure QED shower approach (no NLO EW):

$$D \approx \left(c_2 L_{\mathrm{QCD}}^2 + c_1 L_{\mathrm{QCD}} + c_0\right)\left(c_{11} L_{\mathrm{QED}} l_{\mathrm{QED}} + c_{10} L_{\mathrm{QED}} + c_{01} l_{\mathrm{QED}}\right)$$

- With NLO EW matched to QED PS:

$$D \approx \left(c_2 L_{\mathrm{QCD}}^2 + c_1 L_{\mathrm{QCD}} + c_0\right)\left(c_{11} L_{\mathrm{QED}} l_{\mathrm{QED}} + c_{10} L_{\mathrm{QED}} + c_{01} l_{\mathrm{QED}} + c_{00}\right)$$

- The c_{00} term in the last equation generates the extra part not included when using a pure shower approach for QED.

Methodology: POWHEG

- The modeling of the radiated particle from the W decay is crucial, specially for observables like the transverse mass (the main EW effect comes from the decay of the W, i.e. FSR).
- In principle, comparing the two implementations of POWHEG DY (with and without NLO EW correction), allows to estimate the effect of the missing $\mathcal{O}(\alpha_s \alpha)$ in the pure QED shower approach.
- But, thanks to interactions with experimentalists (M. Boonekamp and L. Perrozzi), we discover a problem in the matching of the EW implementation with the QED shower:
  - The POWHEG standard mechanism selects one of the possible extra radiations (on top of the underlying Born structure).
  - Most of the times, the selected extra radiation is a parton from the initial state: 1) The QED radiation is still pure shower like, 2) The scale of this ISR radiation can not be used to match to the QED shower.
- Solution: Extend POWHEG to handle two extra radiated particles (and two matching scales, one for the ISR shower and one for the QED shower).

Methodology: POWHEG

- Recently, a new version of POWHEG-BOX has been released (POWHEG-BOX-RES), which handles multiple resonances and off-shell effects, first developed in the context of the $t\bar{t}$ process [Jezo, Nason arXiv:1509.09071] [talk by Jonas Lindert].
- This new version also handles multiple extra radiated particles.
- We updated the V2 implementation of the DY, (from now on called "two-rad" version), based on the approach of the POWHEG-BOX-RES for the handling on multiple extra radiation (note: not an implementation of DY in the POWHEG-BOX-RES, but a "local" update of the DY process in V2).
- Once the new treatment of the radiation is implemented, we can keep track of two extra radiated particles, both ISR and FSR, so the matching of both showers can be done without ambiguity. Moreover, the hardest particle in both showers is described with NLO accuracy.
- Technical comment: The LHE interface contains up to 7 particles, and two scales (extra information lines) to be used to match with the QCD and QED showers.

Methodology

- Selection of events:

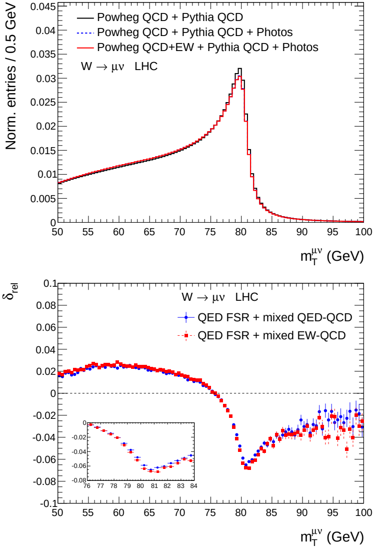
LHC	Tevatron
$\sqrt{s} = 14$ TeV, pp	$\sqrt{s} = 1.96$ TeV, p$\bar{p}$
400 M events	100 M events
$\|\eta^l\| < 2.5$	$\|\eta^l\| < 1.05$
$p_T^l > 20$ GeV	$p_T^l > 25$ GeV
$p_T^\nu > 20$ GeV	$p_T^\nu > 25$ GeV
$p_T^W < 15$ GeV	$p_T^W < 30$ GeV

- The analysis in the muon channel is done using "bare" definition, and in the electron channel using the "dressed one" (recombining photons with the emmiter electron when they have a $\Delta R < 0.1$ (R defined in the η, ϕ space).
- All the samples were generated with $m_W^{nom} = 80.398$ GeV and $\Gamma_W = 2.141$ GeV. The reweighting is done for m_W values spanning ≈ 1 GeV around m_W^{nom}.
- We perform the fits using the lepton pair transverse mass distribution: $m_T^W = \sqrt{2|p_T^\mu||p_T^{\nu_\mu}|(1-\cos\Delta\phi)}$, and the charged lepton p_T.

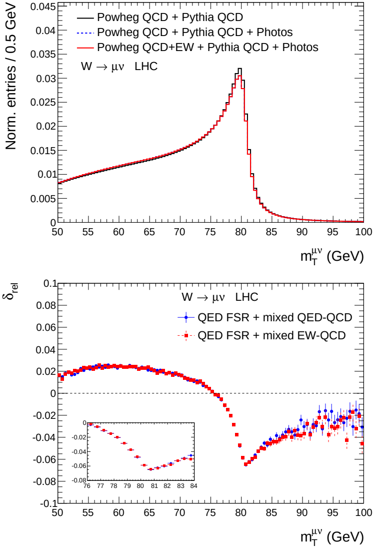
Example of distributions

- Effect of the EW correction, for the old and updated versions of POWHEG.

V2

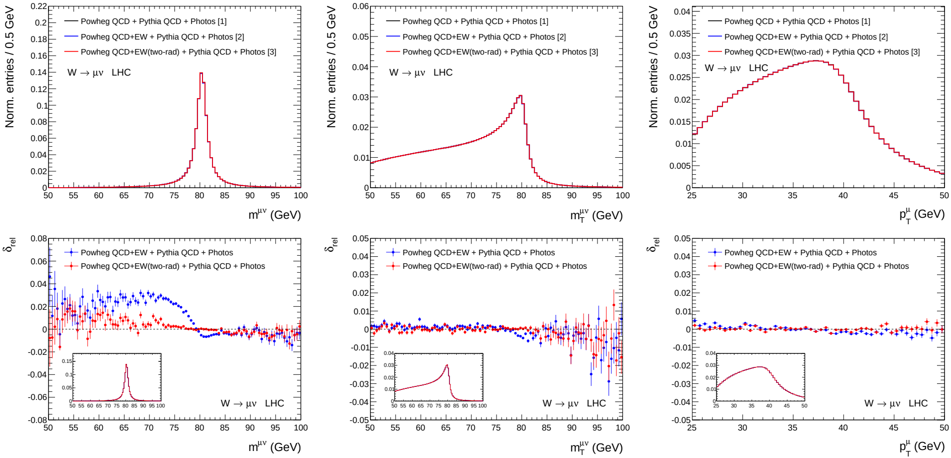


V2-two-rad



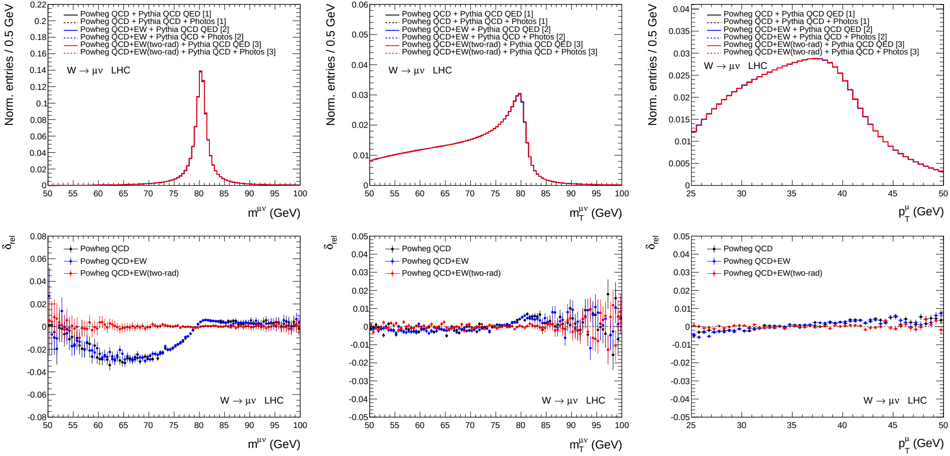
Example of distributions

- Comparing distributions with different levels of EW accuracy (pure shower approach vs. EW NLO matched to PS).



Example of distributions

- Comparing PYTHIA QED and PHOTOS models.



Methodology: Fits

In order to propagate the effects under study up to the extraction of M_W we use a procedure similar to the experimental one:

- Generate 2 different MC samples, using the same value of m_W as input (m_W^{nom}). The samples have different level of EW accuracy.
- Generate templates distribution, using a reweighting procedure of sample 1. (using the Breit-Wigner dependence of the cross section). This way we obtain distributions as if produced with different input values of m_W. This is called the "template sample".
- Compare the templates with the distribution in the other sample ("pseudodata"). Each comparison gives a χ^2 value. We then find the minimum of the χ^2 vs. m_W plot (using a parabolic fit), and obtain m_W^{meas}. The error on the fit is extracted using $\Delta\chi^2 = 1$.
- The shift $m_W^{meas} - m_W^{nom}$ is a measure of the impact on the measurement of m_W, of the different EW accuracy used in sample 2 with respect to that of sample 1.

Results

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+$(QCD+QED)_{PS}$	Pythia	-95.2 ±0.6	-400 ±3	-38.0 ±0.6	-149 ±2
2	NLO-QCD+$(QCD+QED)_{PS}$	Photos	-88.0 ±0.6	-368 ±2	-38.4 ±0.6	-150 ±3
3	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Pythia	-101.8 ±0.4	-423 ±2	-45.0 ±0.6	-179 ±2
4	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Photos	-94.2 ±0.6	-392 ±2	-45.2 ±0.6	-181 ±2
5	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Pythia	-89.0 ±0.6	-371 ±3	-38.8 ±0.6	-157 ±3
6	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Photos	-88.6 ±0.6	-370 ±3	-39.2 ±0.6	-159 ±2

- LHC setup, POWHEG events.
- The templates are done with POWHEG(QCD)+PYTHIA(QCD).
- Each line gives a different approach for the implementation of the EW and mixed QCD-EW effects.

Results

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
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- 1 vs 2: Genuine difference between the predictions of Pythia and Photos QED models.

Results

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
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- 1 vs 5 and 2 vs 6: gives an estimation of the effect of the missing mixed EW-QCD correction in the pure shower approach. Notice that this effect depends on the QED shower model used. The PHOTOS model provides a closer model to the full precision one.

Results

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
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6	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Photos	-88.6 ±0.6	-370 ±3	-39.2 ±0.6	-159 ±2

- 1 vs 3 and 2 vs 4: Measures the same effect as above, but a wrong one, due to the ambiguity related to the radiation from the resonance, in POWHEG-V2.

Results

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+$(QCD+QED)_{PS}$	Pythia	-95.2 ±0.6	-400 ±3	-38.0 ±0.6	-149 ±2
2	NLO-QCD+$(QCD+QED)_{PS}$	Photos	-88.0 ±0.6	-368 ±2	-38.4 ±0.6	-150 ±3
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4	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Photos	-94.2 ±0.6	-392 ±2	-45.2 ±0.6	-181 ±2
5	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Pythia	-89.0 ±0.6	-371 ±3	-38.8 ±0.6	-157 ±3
6	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Photos	-88.6 ±0.6	-370 ±3	-39.2 ±0.6	-159 ±2

- 5 vs 6: The description with EW NLO accuracy of the photon radiation makes the prediction independent of the QED shower model used (the difference between the models becomes a higher order effect).

Results

- Tevatron setup, POWHEG events, same observations apply.

Templates: NLO-QCD+QCD_{PS}			M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+$(QCD+QED)_{PS}$	Pythia	-91 ±1	-308 ±4	-37 ±1	-116 ±4
2	NLO-QCD+$(QCD+QED)_{PS}$	Photos	-83 ±1	-282 ±4	-36 ±1	-114 ±3
3	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Pythia	-96 ±1	-323 ±3	-45 ±1	-129 ±3
4	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Photos	-89 ±1	-300 ±3	-44 ±2	-134 ±3
5	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Pythia	-86 ±1	-291 ±3	-38 ±1	-115 ±3
6	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Photos	-85 ±1	-290 ±4	-37 ±2	-113 ±3

Results

- When using the pure shower approach i.e. (POWHEG(NLO QCD)+PYTHIA(QCD)+QED model), the uncertainty due to the missing mixed QCD-EW corrections, is estimated to be (in MeV)

	LHC				Tevatron			
	$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
	M_T	p_T^ℓ	M_T	p_T^ℓ	M_T	p_T^ℓ	M_T	p_T^ℓ
PYTHIA QED	$\approx 6 \pm 1$	$\approx 29 \pm 4$	$\approx 1 \pm 1$	$\approx 8 \pm 4$	$\approx 5 \pm 1$	$\approx 17 \pm 5$	$\approx 1 \pm 1$	$\approx 1 \pm 5$
PHOTOS	$\approx 1 \pm 1$	$\approx 2 \pm 4$	$\approx 1 \pm 1$	$\approx 9 \pm 4$	$\approx 2 \pm 1$	$\approx 8 \pm 6$	$\approx 1 \pm 2$	$\approx 1 \pm 4$

- If ones uses the version with full EW corrections (POWHEG(NLO QCD NLO EW)+PYTHIA(QCD)+QED model), the remaining mixed EW-QCD is reduced.

Results

- Recently (in the same paper by Dittmaier et al, [Talk by Christian Schwinn]), an estimation of the effect on the W mass of the mixed corrections have been done. The effect is of order 14 MeV on the transverse mass.
- Note that this estimation includes the effect of the full factorizable $\mathcal{O}(\alpha_s \alpha)$ corrections computed in the pole approximation, whereas our estimation includes only a part of it.
- Also, the setup used for the study (cuts) is different to ours.

Summary and conclusions

- We have updated and validated the DY implementation of POWHEG (with QCD and EW NLO corrections), which can be now correctly matched to QED shower MonteCarlo (it will be public soon).
- Special care have to be taken when matching to the showers. We provide an interface to PYTHIA QED and PHOTOS (we still need to document it, ask us if you need information).
- We have estimated the uncertainty due to mixed QCD-EW corrections, needed to be taken into account when traditional tools with pure QED shower approach are used.
- We are preparing a paper reporting this results, also including effects of pure EW origin (photon conversion into lepton pairs, and EW scheme dependence).
- We plan to reproduce our results in a setup similar to the one used in the recent study of mixed corrections (pole approximation), in order to be able to compare.
- We also plan to put on top of our results the DELPHES detector simulation (we saw in the past that the detector simulation preserved the observed shifts, but this needs an update).

Thanks for your attention!

Backup

Reweighting

For every event "i", compute weights given by $wt_i = BW(s_i, m^W_{temp})/BW(s_i, m^W_{nom})$, where:

- $BW(s, m) = \frac{s}{(s-m^2)^2+m^2\Gamma^2}$
- s_i: Invariant mass squared of the lepton pair $(\mu + \nu_\mu)$ of the event "i".
- m^W_{temp}: W mass of the template.
- m^W_{nom}: Fixed W mass of the generation (80.398 GeV).
- Γ: W decay width of the generation (2.141 GeV).

With these weights, filling distributions for every value of m^W_{temp}.

A partonic cross section can be cast in the following schematic way, with respect to EW accuracy:

$$\begin{aligned}\sigma =& a_0 + \\ & a_1 \alpha L + b_1 \alpha + \\ & a_2 \alpha^2 L^2 + b_2 \alpha^2 L + c_2 \alpha^2 + \\ & a_3 \alpha^3 L^3 + b_3 \alpha^3 L^2 + c_3 \alpha^3 L + d_3 \alpha^3 + \cdots\end{aligned}$$

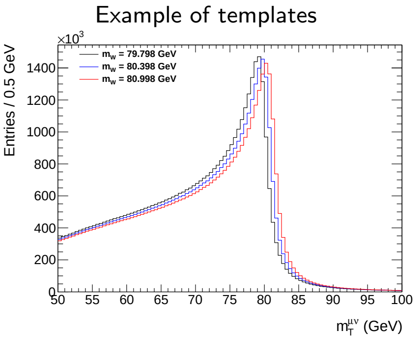
Where the corrections are added on top of a given QCD accuracy, and the corresponding convolution with PDF's and addition of higher order QCD effects are understood. In this formula:

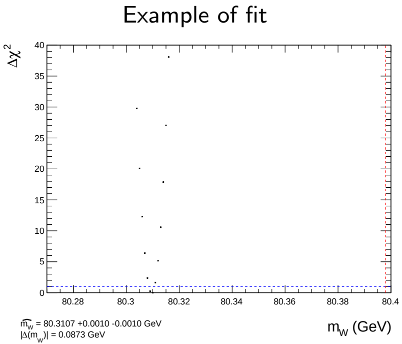
- a_0 : Leading order cross section.
- L are logarithms enhanced in some regions of phase space.
- The second line (NLO correction) is currently available from a number of independent calculations (e.g. POWHEG, HORACE...).
- The a_n series, called leading logs (LL), can be included using resummation or parton showers (e.g. WINHAC, PHOTOS, PYTHIA...).

According to the POWHEG method, the cross section for a given process is written as:

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \Bigg\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \Bigg\}. \quad (1)$$

Example of fits





- The “measured” m_W value is obtained from the x coordinate of the parabola minimum.
- The error on the fit is extracted using $\Delta\chi^2 = 1$.