EW theoretical uncertainties on the W mass measurement

Luca Barze\textsuperscript{1}, Carlo Carloni Calame\textsuperscript{2}, \textbf{Homero Martinez}\textsuperscript{3}, Guido Montagna\textsuperscript{2}, Oreste Nicrosini\textsuperscript{3}, Fulvio Piccinini\textsuperscript{3}, Alessandro Vicini\textsuperscript{4}

\textsuperscript{1}CERN
\textsuperscript{2}Universita di Pavia
\textsuperscript{3}INFN Pavia
\textsuperscript{4}Universita di Milano

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Outline

- Introduction and motivation.
- Methodology.
- Preliminary results.
- Conclusions and remarks.
- Work in progress.
At hadron colliders, the W boson mass is measured using template fits to data. The templates are obtained from Monte Carlo (MC), so the uncertainty on the theoretical model is a source of systematic uncertainty on the measurement. The theoretical uncertainties can be divided in 3 main components:

- Parton distribution functions (PDFs).
- Modelling of W boson transverse momentum (perturbative and non-perturbative QCD effects).
- Electroweak and mixed EW-QCD corrections.
Electroweak corrections in Drell-Yan processes are known up to NLO level (exact). Leading effects at each order are implemented up to LL accuracy. The corrections are available from different tools:

- NLO corrections are currently available from a number of independent calculations (e.g. POWHEG, HORACE, WZGRAD, SANC...).
- The QED leading logs (LL) are included using resummation or parton showers (e.g. WINHAC, PHOTOS, PYTHIA, HERWIG...).
Electroweak uncertainties

The EW uncertainties starts at NNLO:

- LL corrections (e.g. pair production) and NLL QED corrections.
- Choice of EW input parameters scheme.

We perform a comparison of the available tools, in order to:

- Classify and quantify the effects that are under control.
- Provide estimations of the uncertainty.
Methodology

Mimic the experimental procedure (template fits), in order to estimate the impact of different corrections.

- 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 $\chi^2$ value. We then find the minimum of the $\chi^2$ vs. $m_W$ plot (using a parabolic fit), and obtain $m_W^{meas}$.

- 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.
Methodology

We use the following tools:

- **POWHEG** to generate the Drell-Yan W events ($pp \to W^+ + X \to \mu^+ + \nu_\mu + X$). We use two versions:
  - Version with QCD NLO corrections: $\sigma \sim \sigma_{LO}(1 + \mathcal{O}(\alpha_s))_{PS}$.
  - Version with both QCD and EW NLO corrections: $\sigma \sim \sigma_{LO}(1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha))_{PS}$.

- QCD showers are performed with PYTHIA or HERWIG.

- QED corrections are incorporated with 3 different implementations, all accurate up to LL:
  - PYTHIA ($p_T$ ordered shower).
  - HERWIG++ (YFS exponentiation).
  - PHOTOS (soft and collinear photon radiation, with matrix element correction for DY).
Methodology

- We use also the HORACE generator (which includes EW NLO corrections matched to a QED parton shower), in order to test the effect of splitting $\gamma \rightarrow l^+l^-$ in the QED shower.
- We perform the tests at particle level and also at detector level. A generic detector is simulated using the DELPHES fast simulation package.
- The fits of the $\chi^2$ distributions are done using the MINUIT package as implemented in ROOT.
Some technical details about the analysis:

- The events are generated with $\sqrt{s} = 14$ TeV. The samples contain 100 M events (or 10 M for some tests).
- 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 1.2 GeV around $m_{W}^{nom}$ and separated 1 MeV from each other.
- We perform the fits using the lepton pair transverse mass distribution $m_{W}^{T} = \sqrt{2|p_{T}^{\mu}||p_{T}^{\nu}|(1 - \cos \Delta \phi)}$
- We use the selection:
  - $p_{T}^{\mu} > 20$ GeV
  - $p_{T}^{\nu}, E_{T}^{miss} > 20$ GeV
  - $|\eta^{\mu}| < 2.5$
  - $50 \text{ GeV} < m_{T}(W) < 100\text{ GeV}$
Events generated with POWHEG(QCD)+PYTHIA(QCD)+(QED).

This shows the impact in $m_T(W)$ of the QED corrections.

We are interested in quantifying the tiny difference between the two color curves (different implementations).
The “measured” $m_W$ value is obtained from the $x$ coordinate of the parabola minimum.

The error on the fit is extracted using $\Delta \chi^2 = 1$. 

Preliminary results

Mass shifts obtained using the transverse mass distribution (preliminary!)

<table>
<thead>
<tr>
<th>#</th>
<th>Templates</th>
<th>Pseudodata</th>
<th>Mass shift (MeV)</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Particle level</td>
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<tr>
<td></td>
<td></td>
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<td>Detector level</td>
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<td>Powheg(QCD)+Pythia(QCD)</td>
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<td>2</td>
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<td></td>
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<td>-119.4 ± 2.4</td>
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<tr>
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<tr>
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<td></td>
<td></td>
<td>-118.0 ± 9.1</td>
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<tr>
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<td>Powheg(QCD+EW)+Pythia(QCD)+Photos</td>
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<tr>
<td></td>
<td></td>
<td>Horace + lepton pairs</td>
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<td>5</td>
<td>Horace</td>
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- We observe a shift of the order of $\sim 100$ MeV, due to the inclusion of QED effects (starting at order $\alpha$ and containing approximate $\alpha_s \alpha$).
- Comparing the QED implementations: PYTHIA vs PHOTOS, we observe a difference of the order of $\sim 10$ MeV.
- Before interpreting this shift as a systematic, we need to perform a more detailed check of the internal settings of each code.
The test number (4) (impact of exact NLO EW corrections) is to be completed soon.

From the HORACE test, we see that the impact of the introduction of lepton pair production is small, of the order of few MeV.
Conclusions and comments

- We have started an analysis aiming to test the compatibility of available tools, quantify the EW effects that are known, and provide an estimate of the uncertainties.
- So far, the tests seem to give consistent results.
Work in progress

- Complete the test involving exact EW corrections.
- Improve the accuracy of the QED comparisons (check the internal setting of each code).
- Perform the analysis using different distributions: lepton transverse momentum $p_T^\mu$ and neutrino transverse momentum $p_T^\nu$ (or $E_T^{miss}$ at detector level). Here, some work need to be done in order to understand the impact of QCD in $p_T$ modeling.
- So far we have worked with muons (bare), but we plan to do the same tests with electrons.
Thanks!
Backup
For every event "i", compute weights given by \( wt_i = \frac{BW(s_i, m_W^{temp})}{BW(s_i, m_W^{nom})} \), 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).
- \( \Gamma \): W decay width of the generation (2.141 GeV).

With these weights, filling distributions for every value of \( m_W^{temp} \).
Preliminary results done with HORACE, with different configurations and different input schemes.

<table>
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<tr>
<th>line</th>
<th>approx. 1</th>
<th>approx. 2</th>
<th>$m_T$</th>
<th>$p_T$</th>
<th>$R_T$</th>
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<td>$\mathcal{O}(\alpha)G_\mu - I$</td>
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<td>-0.2</td>
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<td>$\mathcal{O}(\alpha)G_\mu - II$</td>
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<td>10.6</td>
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<td>1.1</td>
<td>1.3</td>
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<td>6</td>
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<td>matched $G_\mu - II$</td>
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