A few comments on the MW and Mtop determination at hadron colliders

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LHCP 2019
Relevance of new high-precision measurements
de Blas et al, arXiv:1608.01509

A precise measurement of $M_W$ and of $\sin^2\theta_{\text{eff}}$ constrains several dim-6 operators contributing to Higgs and gauge interaction vertices. Today still one of the strongest constraints

A precise measurement of $m_{\text{top}}$ is crucial to determine the vacuum stability in the SM.
What can we measure in a scattering process?

Cross sections and asymmetries are observables based on a counting procedure → always available

The determination of other parameters (masses, coupling constants) requires

· the choice of a model (e.g. the SM)

· the choice of an input scheme linking

  the renormalised Lagrangian parameters to experimental observables

e.g.

\[ \mathcal{L}_{SM} = \mathcal{L}_{SM}(G_\mu, M_W, M_Z; M_H; m_t, m_f, CKM; \alpha_s) \]
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→ we need to define observables which are sensitive to the Lagrangian parameter of interest

\[ \mathcal{O} = \mathcal{O}(M_W, \ldots) \]
\[ \mathcal{S}_\mathcal{O} = \frac{\partial \mathcal{O}(M_W)}{\partial M_W} \]
\[ \chi^2_{M_W} \propto \left( \mathcal{O}^{\text{th}}(M_W) - \mathcal{O}^{\text{exp}} \right)^2 \]
\[ \sigma_{\text{exp} + \text{th}}^2 \]

and maximise the discrimination power between different parameter value hypotheses
MW determination at hadron colliders

In charged-current DY, it is **NOT** possible to reconstruct the lepton-pair invariant mass. Full reconstruction is possible (but not easy) only in the transverse plane.

MW extracted from the study of the `shape` of the $MT, pt_{lep}, ET_{miss}$ distributions in CC-DY thanks to the jacobian peak that enhances the sensitivity to MW:

$$\frac{d}{dp^2_{\perp}} \rightarrow \frac{2}{s} \frac{1}{\sqrt{1 - 4p^2_{\perp}/s}} d \cos \theta$$
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$$\frac{d}{dp_T^2} \rightarrow \frac{2}{s} \frac{1}{\sqrt{1 - 4p_T^2/s}} \frac{d}{d \cos \theta}$$

\(m_W = 80369.5 \pm 6.8 \text{ MeV(stat.)} \pm 10.6 \text{ MeV(exp. syst.)} \pm 13.6 \text{ MeV(mod. syst.)}
\[= 80369.5 \pm 18.5 \text{ MeV},\]

ATLAS error dominated by modelling systematics.
MW determination at hadron colliders

**MT**
- **Pros:** very good theoretical stability
- **Cons:** the smearing of the distributions due to the difficult neutrino reconstruction

**pTlep**
- **Pros:** well defined experimental system
- **Cons:** strong sensitivity to the modelling of initial state QCD effects

Challenging shape measurement performed via template fit:
A distortion at the per mil level yields a shift of \(O(10 \text{ MeV})\) of the MW value.
Comments on the MW measurement approach

The chosen observable (what we measure) is the proxy to MW (what we fit):

→ robust experimental and theoretical definitions are important to guarantee excellent measurements/predictions

cfr. leptonic vs hadronic final states: important differences between MW and mtop
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cfr. leptonic vs hadronic final states: important differences between MW and mtop

The outcome of the fitting procedure depends on the template.

→ uncertainties on the template propagate to the MW value as theoretical systematics.
   → missing higher-orders and different perturbative ambiguities
   → non-perturbative effects are modelled and the precision of the model must be estimated

The accuracy in the data description is a further evaluation parameter
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Non-perturbative effects may alter in different ways the sensitivity of the chosen observable,
but also shift/bias the outcome of the fit
\[ \mathcal{O}(M_W) = \mathcal{O}^{pert}(M_W) + \mathcal{O}^{non\,pert}. \]
yielding a model dependence of the final result,
with problematic interpretation of its meaning and estimate of its uncertainty
Vector boson production in hadronic collisions

\[ \sigma(P_1, P_2; m_V) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{h_1,a}(x_1, M_F) f_{h_2,b}(x_2, M_F) \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2, \alpha_s(\mu), M_F) \]

We need

- best description of the partonic cross section including fixed- and all-orders radiative corr. QCD, EW, mixed QCD\times EW
- accurate and consistent description of the QCD environment including PDFs, intrinsic partonic kt, QED DGLAP PDF evolution

> QCD modelling       both perturbative and non-perturbative QCD contributions
  
  - transverse d.o.f.   \rightarrow gauge bosons PT spectra \rightarrow non-pert contributions at low PTZ
  - longitudinal d.o.f. \rightarrow rapidity distributions \rightarrow PDF uncertainties

> EW and mixed QCD\times EW effects
  
  important QED/EW corrections modulated by the underlying QCD dynamics
modelling of longitudinal d.o.f.
PDF uncertainty affecting MW extracted from the ptlep distribution

The propagation of the PDF uncertainty due to the experimental error on the data used to extract the PDFs

- Modern individual PDF sets provide not-pessimistic estimates, $\Delta MW \sim O(10\text{ MeV})$, but the global envelope in 2015 was showing large discrepancies of the central values.

- The Tevatron analyses did not adopt the PDF4LHC approach.

- Conclusions recently confirmed in arXiv:1905.00110 with the CT14 PDF set.

<table>
<thead>
<tr>
<th></th>
<th>no $p_T^{W}$ cut</th>
<th>$p_T^{W} &lt; 15$ GeV</th>
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<tbody>
<tr>
<td>$\delta_{PDF}$ (MeV)</td>
<td>$\Delta_{sets}$ (MeV)</td>
<td>$\delta_{PDF}$ (MeV)</td>
</tr>
<tr>
<td>Tevatron 1.96 TeV</td>
<td>27</td>
<td>16</td>
</tr>
<tr>
<td>LHC 8 TeV $W^+$</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>$W^-$</td>
<td>29</td>
<td>16</td>
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<tr>
<td>LHC 13 TeV $W^+$</td>
<td>34</td>
<td>22</td>
</tr>
<tr>
<td>$W^-$</td>
<td>34</td>
<td>24</td>
</tr>
</tbody>
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The PDF4LHC recipe defines the half-width of the envelope $\delta_{PDF}$ and the spread of the central values $\Delta_{sets}$.
Prospects for the reduction of the PDF uncertainty

Different complementary approaches:

· full exploitation in CC-DY of different kinematic regions (e.g. including MW measurements at LHCb)
· of the combination of W+ and W- results
· of different colliders (e.g. including Tevatron results)
· of 2-dimensional differential distributions

Common rational behind all these approaches:

Individual parton densities satisfy various sum rules
→ these constraints induce (anti-)correlations between the observable and
the parton-parton luminosities w.r.t. to PDF replica variations
→ PDF error reduction in appropriate combinations of obs that exploit the (anti-)correlations

in other words:

there are intrinsic not reducible PDF uncertainties in the individual measurements

but

the nature of the uncertainty is such that

a combination of complementary (anti)correlated measurements suffers of a reduced error

Collinear PDFs are a model, but thanks to factorisation theorems the proton is universal
→ we can search for useful combination of several observables and minimise the model dependency
PDF uncertainty and acceptance cuts; anticorrelations

The dependence of the MW PDF uncertainty on the acceptance cuts provides interesting insights

| normalized distributions | cut on $p_T^W$ | cut on $|\eta|$ | CT10       | NNPDF3.0 |
|---------------------------|----------------|----------------|------------|----------|
| inclusive                 | $|\eta| < 2.5$  | 80.400 + 0.032 − 0.027 | 80.398 ± 0.014 |
| $p_T^W < 20$ GeV          | $|\eta| < 2.5$  | 80.396 + 0.027 − 0.020 | 80.394 ± 0.012 |
| $p_T^W < 15$ GeV          | $|\eta| < 2.5$  | 80.396 + 0.017 − 0.018 | 80.395 ± 0.009 |
| $p_T^W < 10$ GeV          | $|\eta| < 2.5$  | 80.392 + 0.015 − 0.012 | 80.394 ± 0.007 |
| $p_T^W < 15$ GeV          | $|\eta| < 1.0$  | 80.400 + 0.032 − 0.021 | 80.406 ± 0.017 |
| $p_T^W < 15$ GeV          | $|\eta| < 2.5$  | 80.396 + 0.017 − 0.018 | 80.395 ± 0.009 |
| $p_T^W < 15$ GeV          | $|\eta| < 4.9$  | 80.400 + 0.009 − 0.004 | 80.401 ± 0.003 |
| $p_T^W < 15$ GeV          | 1.0 < $|\eta|$ < 2.5 | 80.392 + 0.025 − 0.018 | 80.388 ± 0.012 |

- the normalized ptlep distribution, integrated over the whole lepton-pair rapidity range, does not depend on $x$ and depends very weakly on the PDF replica

- PDF sum rules →
  non trivial compensations between different rapidity intervals among different flavours

- MW measurement at LHCb could significantly reduce the global PDF uncertainty
- W+ and W- determinations are anti correlated w.r.t. PDFs
  their combination benefits of a reduction of the PDF error
The strong kinematic correlations between the helicities of intermediate $W^+$ / $W^-$ boson and $(pt_{lep}, \eta_{lep})$ 2D distribution allows to make a strongly motivated guess about the kinematics of the intermediate boson.

The reconstructed rapidity distribution of the intermediate boson is in turn very sensitive to the proton PDFs.

The 2D lepton-(pt,eta) distribution is thus an interesting tool to probe PDFs. It offers the possibility of an “in situ” reduction of the PDF uncertainty by selecting those PDF replicas most compatible with new DY data.
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The estimate of the reduction of the PDF uncertainty induced by new data can not replace a full global PDF fit.

→ quantitative problem: a single very precise data point may lead to overestimate theunc.reduction
→ qualitative problem: the proton is a universal function, not a DY function.
modelling of transverse d.o.f.
QCD-ISR yields the dominant contribution to $p_{T}W$

it strongly distorts the LO $p_{T}\ell\ell$ distribution

reducing the sensitivity to MW

A very precise knowledge of $p_{T}W$, at worst at the 1% level, is needed to preserve the 10 MeV precision goal on MW

$p_{T}\ell\ell$ is a problematic distribution, because it requires the log($p_{T}V$) resummation to all orders to describe the jacobian peak (which is the region of highest sensitivity to MW)

non-perturbative effects possible in the low $p_{T}V$ region → if present, they affect the $p_{T}\ell\ell$ jacobian peak

no conclusive statements so far about the existence/need of non-perturbative corrections

theoretical predictions describe the data, within the theoretical uncertainty bands (still large…)

their inclusion via a model improves in general the quality of the fit to the data

adding parameters, universal or even flavour dependent, weakens the interpretation step
The ptW distribution at $N3LL+NNLO$-QCD

Impressive theoretical progress! State-of-the-art pQCD prediction for ptW.

Theoretical uncertainty bands larger than the 1% needed for a “safe” stand-alone ptlep simulation

A non-perturbative model may improve the accuracy in the description of ptlep data and in turn the $\chi^2$ of the fit, but the absence of a very precise measurement of ptW does not allow yet to pursue this approach directly
Lepton-pair transverse momentum distribution

- a precise ptW measurement is not yet available → we rely on ptZ and extrapolate from it
- ptZ is used to calibrate 1) detectors 2) Monte Carlo tools (Parton Shower at low-ptZ)

Similarly CMS extracted a Pythia Z2 tune
Lepton-pair transverse momentum distribution

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Which are the uncertainties of a simulation of CC-DY based on a NC-DY tune?
Lepton-pair transverse momentum distribution: $Z$ to $W$ extrapolation

The parameters (intrinsic $kt$, $\alpha_s$ in the PS, hadronization) derived from the calibration on $ptZ$ are used in the CC-DY studies to determine $MW$.

- are these param’s
  1) universal? (i.e. flavour independent)
  2) scale independent ( $MW \neq MZ$! )?

- the flavour structure of CC-DY and NC-DY is different
  CC-DY: $u\, d\bar{b}, \, c\, s\bar{b}, \ldots \rightarrow W^+ \rightarrow l^+\nu$
  NC-DY: $u\, \bar{u}, \, d\, \bar{d}, \, c\, \bar{c}, \, s\, \bar{s}, \ldots \rightarrow \gamma^*/Z \rightarrow l^+l^-$

how do the different flavour structures affect ($Z$ to $W$)?

e.g. is the effect of scale variations different (different DGLAP evolution)?

role of heavy quarks?
Lepton-pair transverse momentum distribution: Z to W extrapolation

The parameters (intrinsic $k_t$, $\alpha_s$ in the PS, hadronization) derived from the calibration on $p_tZ$ are used in the CC-DY studies to determine $M_W$.

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For a realistic estimate of the QCD theoretical uncertainties, we need:

- an improved description of all the elements of difference between CC-DY and NC-DY
- a good control over the correlation between $Z$ and $W$ w.r.t. the different sources of uncertainty
  any uncertainty estimate (PDFs, scale variations, etc.) based on CC-DY alone leads to an overestimate of the uncertainty

The $M_W$ measurement studies the $M_Z$-$M_W$ interdependence; it’s not an absolute measurement of $M_W$
In a purely massless approximation, the QCD dynamics of CC-DY and NC-DY is very similar. Main differences are: MW,MZ values, the initial state flavour composition and DGLAP evolution $\rightarrow R \neq 1$

The choice of pQCD scales in numerator and denominator represents an ambiguity.

Higher-order corrections strongly stabilise the ratios, even in the fully uncorrelated case.

The ratio expresses the pQCD component of the physical differences between the channels.

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Improving the description of the bottom contributions to $ptZ$

The standard MW analysis is based on massless 5FS description of Drell-Yan processes. Which would be the impact of a description of the bottom as a massive quark? 1) on $ptZ$; 2) on MW

- A combination of 4FS and 5FS results improves the $ptZ$ description, in the region $ptZ \sim 0-25$ GeV
- The tuning of the Parton Shower would be affected by this improved NC-DY description
- The change in the CC-DY simulation would be in turn modified

If the elements of difference between Z and W are explicitly computed, then the effects encoded in the PS tunes become “more universal”

Analogous approach studies the flavour dependence in the TMD framework, Bozzi et al., arXiv:1807.02101

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mixed QCDxEW effects
Combination of QCD and QED corrections: POWHEG results

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

Does the convolution with QCD corrections preserve the QED effects?

the difference between red and blue is due to mixed QCDxQED terms

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Puebla, May 23rd 2019
Is the impact of QED corrections preserved in a QCD environment?

**Template fit applied to classify the impact of sets of radiative corrections**

<table>
<thead>
<tr>
<th>Pseudodata accuracy</th>
<th>Templates accuracy: LO</th>
<th>( M_W ) shifts (MeV)</th>
<th>( W^+ \rightarrow \mu^+\nu )</th>
<th>( W^+ \rightarrow e^+\nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( M_T )</td>
<td>( p_T^\ell )</td>
<td>( M_T )</td>
<td>( p_T^\ell )</td>
</tr>
<tr>
<td>1 HORACE only FSR-LL at ( \mathcal{O}(\alpha) )</td>
<td>-94±1</td>
<td>-104±1</td>
<td>-204±1</td>
<td>-230±2</td>
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<tr>
<td>2 HORACE FSR-LL</td>
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<tr>
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<tr>
<td>4 HORACE FSR-LL + Pairs</td>
<td>-94±1</td>
<td>-102±1</td>
<td>-182±2</td>
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<tr>
<td>5 PHOTOS FSR-LL</td>
<td>-92±1</td>
<td>-100±2</td>
<td>-182±1</td>
<td>-199±2</td>
</tr>
</tbody>
</table>

**\( pp \rightarrow W^+, \sqrt{s} = 14 \, \text{TeV} \)**

<table>
<thead>
<tr>
<th>Pseudodata accuracy</th>
<th>Templates accuracy: NLO-QCD+QCD(_\text{PS} )</th>
<th>QED FSR</th>
<th>( M_W ) shifts (MeV)</th>
<th>( W^+ \rightarrow \mu^+\nu )</th>
<th>( W^+ \rightarrow e^+\nu(\text{dres}) )</th>
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<td></td>
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<tr>
<td>1 NLO-QCD+(QCD+QED)(_\text{PS} )</td>
<td>PYTHIA</td>
<td>-95.2±0.6</td>
<td>-400±3</td>
<td>-38.0±0.6</td>
<td>-149±2</td>
</tr>
<tr>
<td>2 NLO-QCD+(QCD+QED)(_\text{PS} )</td>
<td>PHOTOS</td>
<td>-88.0±0.6</td>
<td>-368±2</td>
<td>-38.4±0.6</td>
<td>-150±3</td>
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<tr>
<td>3 NLO-(QCD+EW)+(QCD+QED)(_\text{PS two-rad} )</td>
<td>PYTHIA</td>
<td>-89.0±0.6</td>
<td>-371±3</td>
<td>-38.8±0.6</td>
<td>-157±3</td>
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<td>4 NLO-(QCD+EW)+(QCD+QED)(_\text{PS two-rad} )</td>
<td>PHOTOS</td>
<td>-88.6±0.6</td>
<td>-370±3</td>
<td>-39.2±0.6</td>
<td>-159±2</td>
</tr>
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</table>

**Lepton-pair transverse mass: yes!**

**Lepton transverse momentum: no, the shifts are sizeably amplified**

(these effects are already taken into account in the Tevatron and LHC analyses)

The lepton transverse momentum has a 85% weight in the final ATLAS MW combination and a sound estimate of the uncertainty on the QCD\(_{\text{XEW}} \) effects is crucial.
Top mass definitions

Renormalisation → pole mass definition  
the renormalised mass is the pole of the propagator

→ MSbar mass definition
only $1/\varepsilon + \gamma_E - \ln 4\pi$ are subtracted with the mass $c_t$

The infrared sensitivity of the quarks makes the very concept of mass problematic

→ contribution of infrared renormalons

→ given a final state, defined an observable, which part of QCD radiation has to be associated with the top field? or:
  how does the sensitivity to $m_{top}$ of a given observable change with radiation?

→ the description of QCD radiation entails a certain modelling, making $m_{top}$ model dependent
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$\rightarrow$ the description of QCD radiation entails a certain modelling, making $m_{top}$ model dependent

$$m_t^{MC} = m_t^{pole} + \Delta_m^{pert} + \Delta_m^{non\; pert} + \Delta_m^{MC}$$

The notion of MC mass assigns a status of mass, a primitive concept,
to the non universal, process and observable dependent corrections of (non-)perturbative modelling,
whereas all these effects
modify the accuracy of the description of the chosen observable and bias the result of the fit
but do not affect the template fit logic, where it is the Lagrangian parameter to be varied in the fit

in the MW case QCD corrections modify in completely different ways MT and $p_{tlep}$ and in turn MW
Recent development of Monte Carlo generators
recent evolution in the description of top production and decay:

- hvq: NLO-QCD production
- tTdec: NLO-QCD in production and decay, narrow-width approximation
- bB4l: full NLO-QCD, off-shell effects, full width dependence, NLO mass renormalization

The usage of most advanced and complete tool (bB4l) recommended

important role, in lower approximations, of the matrix element description of radiation off the b quark

when using Pythia8.2 as showering tool a consistent picture emerges, with MC uncertainties smaller
than the current experimental limits

important, severe, differences in the simulation matched with Pythia8.2 vs Herwig 7.1 showers
amplified by the smearing effects mimicking the experimental resolution
also in the bB4l case and also for leptonic observables

the Herwig7.1 angular ordering is one of the possible sources of algorithmic difference
Conclusions

1) QCD modelling represents one of the current challenges in the determination of masses/couplings

2) The universality of the model dependent components is a crucial feature to reduce the associated uncertainties (cfr PDFs)

3) Z production is a standard candle useful for calibration; porting this information to other processes requires to dig out all differences and correlations

4) the impact of QCD/EW corrections depends on the observable under study in turn the result of the template fit to different observables can receive very different shifts → it is difficult to introduce an observable independent mass shift associated to a set of corrections
backup slides
High-precision measurements

\[ \frac{\Delta m_t}{m_t} \sim \mathcal{O}(3 \cdot 10^{-3}) \]

\[ \frac{\Delta M_W}{M_W} \sim \mathcal{O}(2 \cdot 10^{-4}) \]
Lepton-pair transverse momentum distribution

- The precision of the theoretical prediction for $p_tZ$, in dedicated calculations/tools, depends on:
  - logarithmic accuracy (N3LL) in the $\log(p_tZ/M_Z)$ resummation → relevant at small $p_tZ$
  - fixed-order accuracy (NNLO) in the $p_tZ$ spectrum → relevant at large $p_tZ$
  - matching prescription → relevant at intermediate $p_tZ$

- good stability of the RadISH predictions under changes of the matching scheme