Impact of LHeC PDFs on W mass and weak mixing angle measurements

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CEA Saclay

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Outline

• Why high precision is important?
• W-boson mass measurement in ATLAS
• HL-LHC prospects for a W-boson mass measurement
• LHeC importance in the precise W-boson mass determination
• Weak mixing angle measurement
• HL-LHC prospects for a weak mixing angle measurement
• LHeC importance in a weak mixing angle measurement
Why do we need precision?
Nature and beauty are always about precision!
Precision measurements: examples
Direct searches

Huge numbers of new results from the LHC - astonishing achievement. No significant signals - updated limits. More still to come with future data.

Indirect searches: precision measurements in EW sector (Higgs couplings, $\sin^2 \theta_W$, $m_W$...)

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ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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**Small radial (large radial) jets are denoted by the letter r, s.**
W-boson mass
**W-boson mass**

In the electroweak sector of the SM, the W mass at the tree level:

\[ m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2} G_F} \]

at the loop level:

\[ m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r) \]

In SM, \( \Delta r \) reflects loop corrections and depends on \( m_t^2 \) and \( \ln m_H \)

The relation \( M_W, m_t, \) and \( M_H \) provides stringent test of the SM and is sensitive to NP
**W-boson mass measurement**


![Graph showing W-boson mass measurements](chart)

**LEP+Tevatron: M_W uncertainty ~ 15 MeV**

Best individual measurement:

CDF M_W uncertainty 19 MeV

Long thought as not possible to reach high precision at the LHC: challenging measurement due to pp collisions and high pile-up environment.

**Measurement by ATLAS:**

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

The ATLAS result is consistent with the **SM expectation**, compatible with the world average and competitive in precision to the currently leading measurements by CDF.
ATLAS W-boson mass measurement

Dominant uncertainties:

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<td>6.6</td>
<td>6.4</td>
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PDF variations (25 error eigenvectors) of CT10nnlo, very similar between $p_T^\ell$ and $m_T$ but strongly anti-correlated between $W^+$ and $W^-$. Dominated by knowledge of valence quark PDFs (in particular $d_v$)
## ATLAS W-boson mass measurement

### Dominant uncertainties:

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$p_T^W$ modelling related uncertainties are also important.
Second generation quark PDFs play a larger role at the LHC \((25\% \text{ of the } W\text{-boson production is induced by at least one second generation quark } s \text{ or } c)\) than at the Tevatron.

Precision cross-section measurement: probe of strong interaction and the proton structure (PDFs)

ATLAS \(W,Z\) data suggests a larger than expected strange-quark sea contribution: \(R_s > 1\) \(\rightarrow\) impact on \(p_T^W\) modelling from least known strange PDF
Future improvements

- Combination with CMS (when available) and Tevatron…

- More data are available with the 8 and 13 TeV datasets which can be used to improve the analysis and to further constrain the PDFs (even though we are getting at the limit of what the current theory can do). Experimentally, with the increase of the statistics in Z sample, most of the experimental uncertainties can be reduced. Still challenging: the recoil resolution is worsened with the increased pileup.

- **Low pileup data** were taken in ATLAS at 5 (~250 pb$^{-1}$ $\mu=0.5-4$) and 13 TeV (~150 pb$^{-1}$ $\mu=2$) which will allow a measurement of the W transverse momentum at low $p_T$ to 1% and to measure the W mass using $m_T$ ATLAS-PUB-2017-021 with a statistical uncertainty of 13 MeV. More low pileup data to come probably shortly.
Beyond the LHC

- W mass measurement at the HL-LHC extremely challenging ($\mu=200$) but might be possible if a low pileup run is foreseen to benefit from increase in the detector acceptance up to $|\eta|=4$.

Of course experimentally, the picture is more complicated, but still some gain (to be quantified soon) is expected.
LHeC NC and CC measurements will improve PDF knowledge by large factor in a largely extended kinematic region. LHeC CC DIS $W^+ \rightarrow c$ with charm tagging would provide good measurement of $s$ and $s'$ quarks (and test $u'/d'$).
Using PDF set from LHeC gives a $\sim 3$ MeV uncertainty on the W mass measurement (no categories used), very interesting input to LHC/HL-LHC $m_W$ measurements.

$W$ mass can be fitted from PDF + EW parameter fits in the space-like regime using $ep$ data providing a complementary testing ground.
Weak mixing angle
Weak mixing angle

Another key parameter in EW sector of SM

At tree level: \( \sin^2(\theta_W) = 1 - \frac{m_W^2}{m_Z^2} \)

At higher orders, vertex corrections lead to the effective weak mixing angle:

\[
\sin^2 \left( \theta_{\text{eff.}}^{\text{lept.}} \right) = \kappa_f \sin^2(\theta_W)
\]

The two most precise measurements (LEP, SLD) disagree by about 3 sigmas.

Provides also an indirect measurement of the W mass: \( 16 \times 10^{-5} \) corresponds to a precision of 8 MeV on the W mass.
Weak mixing angle: LHC

Presence of vector and axial-vector couplings introduces a forward-backward asymmetry.

\[ A_{FB} = \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\cos \theta^* > 0) + N(\cos \theta^* < 0)} \]

The AFB distributions are different for different flavour quarks and thus depend on PDFs.

CMS result:

\[ \sin^2 \theta_{\text{eff}} = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (PDF)} \]

The dominant systematic uncertainty is due to PDF uncertainties.
**Weak mixing angle: HL-LHC**

CMS, FTR-17-001-PAS  
https://indico.cern.ch/event/702717/contributions/2897074/attachments/1611646/2559385/zafb_hllhc.pdf

**CMS**: muon channel (CC and extended up to $|\eta|<2.8$) PDF constraints replicas  
**ATLAS**: electron channel (CC, CF, FF up to $|\eta|<4.2$) PDF profiling $\rightarrow$ estimates total uncertainty $19\times10^{-5}$ dominated by PDF uncertainties $17\times10^{-5}$

Using full HL-LHC program, reach similar precision than LEP+SLD (more gain combining experiments). We expect that using HL-LHC in-situ analysis like W asymmetry we can in principle to improve the PDF uncertainty by a ~factor 2.
Using LHeC prospect PDFs, the PDF uncertainties are expected to be reduced by a factor of ~10 and the total uncertainty by a factor of 5. If using HL-LHC prospect result expect: $4 \times 10^{-5}$ — more than a factor of 4 better than LEP + SLD combination.

High luminosity ep data may directly constrain the weak mixing angle through PDF+EW fits.

ep data can probe the scale dependence of the weak mixing angle using polarisation asymmetry.

The LHeC measurements are expected to be precise and to cover a large energy range.
Conclusions

• The LHeC project provides an unprecedented precision in PDF for a large range of kinematics

• The LHeC would provide a very important input to the LHC/HL-LHC results

• In particular, EW precision measurements such as W-boson mass and weak mixing angle are limited by PDF uncertainties and would highly benefit from the LHeC improvements.

• The LHeC therefore is a rich and complementary program for the LHC/HL-LHC. It will for sure be essential to explore new physics.
Backup Slides
In ATLAS we consider 3 categories: CC, CF, FF, where C is a central ($|\eta|<2.5$) and F is a forward ($2.5 < |\eta| < 4.2$) electron, with $p_T > 25$ GeV.
- Precise differential $W, Z$ data can constrain PDFs, especially the strange-quark density
- ATLAS-epWZ16 fit fixed-order NNLO QCD + NLO EW: theory uncertainty dominant

- Differences between predictions at fixed-order and with boson $p_T, \nu$ resummation $\sim 0.5\%$ effect similar to experimental precision — ensure predictions in PDF fits consistent with application to parton shower MCs to extract results
Simultaneous measurement as function of dilepton mass $m_{\ell\ell}$ and rapidity $y_{\ell\ell}$ and $\cos \theta^*$ in Collins–Soper frame

Sensitive to PDFs as well as $\sin^2 \theta_W$ through forward-backward asymmetry $A_{FB}$
Multi-differential $Z/\gamma^* \to \ell\ell$

- Simultaneous measurement as function of dilepton mass $m_{\ell\ell}$ and rapidity $y_{\ell\ell}$ and $\cos\theta^*$ in Collins–Soper frame
- Sensitive to PDFs as well as $\sin^2\theta_W$ through forward-backward asymmetry $A_{FB}$

![Graph showing $A_{FB}$ as a function of $m_{\ell\ell}$ and $y_{\ell\ell}$ with data and fit comparison]

Jan Kretzschmar, 16.4.2018
PDFs for $\sin^2 \theta_W$

- Valence-quark shape determines the "dilution" of $A_{FB}$ and is a significant uncertainty
- In-situ constraint using the $m_{\ell\ell}$-$\gamma_{\ell\ell}$ dependence by factor $\sim 2$
- Differences between PDFs similar to NNPDF3.0 uncertainty

Final result: $\sin^2 \theta_{\ell\ell} = 0.23101 \pm 0.00036\text{(stat)} \pm 0.00018\text{(syst)} \pm 0.00016\text{(theory)} \pm 0.00030\text{(pdf)}$