Towards a 1\textsuperscript{st} measurement of $M_W$ at the LHC

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on behalf of the ATLAS and CMS Collaborations
Outline

• Motivation. Principle of the measurement
• Statistical sensitivity and calibration systematics
• Modeling of W production and decay
• Uncertainties and constraints
Motivation

- $M_W$ is the leading uncertainty in SM consistency tests.
- The indirect determination, and existing and future Tevatron measurements set a natural goal of $\delta M_W < 10$ MeV at the LHC

Uncertainties – Tevatron experience and LHC expectations

Current best measurements: \[ \delta_{\text{stat}} \approx \delta_{\text{QCD}} \approx \delta_{\text{calib}} \]
Extrapolating to the LHC (and the next Tevatron): \[ \delta_{\text{QCD}} > \delta_{\text{calib}} > \delta_{\text{stat}} \]

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<th>Source</th>
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| Total                               | 19          | CDF, Phys. Rev. D 89, 072003 (2014)

\(M_W\) measurements now dominated by modeling. Requires investing in:
- Ancillary measurements (\(\rightarrow\) constrain physics model)
- Analysis strategy (\(\rightarrow\) minimize model-dependence)
W & Z final states

- Basic objects: electron or muon ($l$); recoil ($u$)
- Derived quantities in W events:
  \[ \vec{p}_T^\nu = -\left( \vec{p}_T^l + \vec{u} \right), \quad E_T^{\text{miss}} = \|\vec{p}_T^\nu\|, \quad M_T = \sqrt{p_T^l p_T^\nu (1 - \cos(\Delta\phi))} \]
- Z events can be exploited for calibration: $M_{ul} \approx M_Z$, $\vec{u} \approx -\vec{p}_T^l$
Measurement principle

- Example cuts at the LHC (compromise btw. statistics & systematics), at 7 TeV:
  - ATLAS: \( p_T^{l \nu} > 30 \text{ GeV}, \quad M_T > 60 \text{ GeV}, \quad u < 30 \text{ GeV} \)
  - 6-9M evts/channel \( \delta M_W (\text{stat}) \approx 6 \text{ MeV} \)
  - CMS: \( 55 > p_T^{l \nu} > 30 \text{ GeV}, \quad 100 > M_T > 60 \text{ GeV}, \quad u < 15 \text{ GeV} \)
  - 3-5M evts \( \delta M_W (\text{stat}) \approx 10 \text{ MeV} \)
  - \( M_W \) is extracted from the comparison of data with Monte-Carlo templates of the mass-sensitive distributions: \( p_T^{l}, M_T \)
Lepton calibration

- Z boson sample constitutes the primary calibration reference
  - Probes the energy / momentum scale to <5 MeV/channel
  - >1M evts, RMS of $M_{ll}$ distribution ~3 GeV
- In addition, consider an energy extrapolation uncertainty: $p_T^l \approx \frac{M_Z}{2} \rightarrow \frac{M_W}{2}$
  - E.g ATLAS, electron channel: $\delta E \approx 4 - 5$ MeV over this range.

\[ \begin{align*}
\end{align*} \]
Recoil calibration with Z events

- Useful projections: $u_\perp, u_\parallel$
- projections of $\vec{u}$ on axis perpendicular resp. parallel to $p_T^Z$
- Use to compare recoil resolution and response in data and MC

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME2012MET
Kinematic peaks after selections

- CMS: from inclusive cross section measurement, 2010 data
Kinematic peaks after selections

- ATLAS: $M_T$ in $W \rightarrow \mu \nu$ at 7 TeV, in 2010 (33 $\text{pb}^{-1}$, $\mu \sim 1$) and 2011 (1st $\text{fb}^{-1}$, $\mu < 5$)
  - Visible degradation in the recoil resolution

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicCollisionPlots
Proton PDFs and W, Z production

• Pre-LHC: proton model dominated by DIS
  • Measured/fitted: $u_V, d_V, g, \text{sea } (\alpha_S)$
  • Theory: $c, b, \text{evol}(Q^2) \ (\alpha_S)$
  • Assumed: $\bar{u} \approx \bar{d}; \ s \approx \bar{s} \approx \bar{d}/2$

• Very precise data, but little experimental information on the flavour composition of the proton. A (very) simplified view:
  • $\sigma^{NC}, \sigma^{CC} \to u_V(x), d_V(x), \text{sea}(x)$
  • Jet prod. $\to g(x)$
  • $(F_2^c, \ldots)$

• $Wq\bar{q}'$ and $Zq\bar{q}$ couplings $\sim$ flavour democratic
  $\to$ Hadron colliders probe different parton combinations than those tightly constrained by DIS
Proton PDFs and W, Z production

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  → Hadron colliders probe different parton combinations than those tightly constrained by DIS
PDF effects on the $p_T^l$ & $M_T^W$ distributions

- Valence/sea PDF uncertainties
  - Determine the rapidity distribution $\rightarrow$ acceptance effects
  - Valence PDFs polarize the $W$ decay (at any $y_W \neq 0$), with corresponding uncertainties:

Sea: symmetric, unpolarized

Including $u_V$, $d_V$ leads to an overall polarization along $z$
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PDF effects on the $p_T^l$ & $M_T^W$ distributions

• Transverse momentum distribution uncertainties
  • « physics smearing » of the Jacobian peaks from uncertainties in the $p_T^W$ distribution
  • Contributions from non-perturbative parameters (intrinsic $k_T$, ...) and from heavy quark PDFs

Uncertainty on HQ mass treatment vs. $M_W$ variations

PDF effects on the $p_T^l$ & $M_T^W$ distributions

- In short, PDF uncertainties on $M_W$ are dominated by the valence/sea ratio, and by 2nd generation partons
  - (some) anti-correlation between the two effects: enhanced strange & charm PDFs increase the total sea, reducing the impact of valence uncertainties
- Current uncertainty estimates find ~10 MeV for the most optimistic/advanced sets, but differences between sets makes the envelope larger: 20-30 MeV

Caveats:
- PDF uncertainties are generally estimated via an approximate reweighting
- Detector effects at best partially taken into account

arXiv:1501.05587
Constraining PDFs: W charge asymmetry

• vs rapidity: \( A(y) \approx \frac{u_V - d_V}{u_V + d_V + 2 r_s c} \) (\( r_s \approx \bar{s}/\bar{d} \) and assuming \( \bar{u} \approx \bar{d} \) and \( s \approx \bar{s} \)).

• Experiments only access \( \eta_{lep} \): effect blurred by V-A. Still very discriminating information: probes a mixture of \( u_V/d_V \) and second generation quark PDFs.

Constraining PDFs: W & Z cross sections and distributions

- Detailed measurements performed by ATLAS, CMS, LHCb
- Measured enhancement of Z production at $y_Z \approx 0$ is interpreted as enhanced strange density. Increasing $s(x)$ (to $r_s \approx 1$) catches the Z data, leaving W distributions mostly unchanged:

Constraining PDFs: $W + D$ & $W + c$

- Direct probe of the strange density (at LO): $g\bar{s} \rightarrow W^+\bar{c}$, $gs \rightarrow W^-c$
- Final states used: $Wc (c \rightarrow \mu)$, $WD^\pm, WD^*$
  - Complication: final state definition. Quark, parton or hadron level?
- ATLAS tends to « see » more charm:

![Graph comparing ATLAS and CMS predictions for $W^+c$ production with jets and leptons](image)

References:
- JHEP 05 (2014) 068
- JHEP 02 (2014) 013
Implications: Valence distributions

- Strategy (largely common to ATLAS and CMS): use HERA data by necessity; add only collider data
  - Avoid data subject to larger theoretical uncertainty
- Impact of asymmetry measurement: most significant improvement in $d_V$
  - $d_V$ has more freedom as $u_V$ is better constrained by HERA data

Implications: Strange density

- Marginal agreement: ATLAS sees $r_s \approx 1$ (consistently in W/Z ratios and W+c), CMS prefers $r_s < 1$ for $x > \approx 10^{-2}$ at $Q^2 \approx M_W$
- Impact: $\sim 20\%$ difference in charm-induced W production, affecting $y_W, p_T^W$


JHEP 05 (2014) 068
Modeling of $p_T^W$ : constraints from $p_T^Z$

- Traditional ansatz: W and Z production are analogous, and non-perturbative effects are universal and factorize from PDFs
  - Measure $p_T^Z$, tune parton shower (or resummation params.), apply to W
  - Constraints from ATLAS measurement: $\delta M_W < 5$ MeV, assuming no extrapolation uncertainties

- Caution needed at the LHC: Z, $W^+$ and $W^-$ all have different contributions from 2nd and 3rd generation PDFs (4-8 times larger than at the Tevatron)
An alternative: direct measurement of $p_T^W$

- Unfolded measurement of the recoil distribution, from ATLAS (35 pb$^{-1}$, 7 TeV) and CMS (18 pb$^{-1}$, 8 TeV). Requires low pile-up conditions
- Experimentally poorer than $p_T^Z$, but avoids a significant theoretical extrapolation
  - At low $p_T$: 3-5 bins, 2-3% accuracy for W (compared to ~10 bins with ~0.5% accuracy for Z)
- Worthwhile to pursue with larger luminosity
  - Needs $\approx 250$ pb$^{-1}$ at $\mu \approx 1$, driven by Z statistics
$A_{FB}$ and $\sin^2 \theta_W$

- Recent ATLAS result: $\sin^2 \theta_W \approx 0.2308 \pm 0.0012$; PDFs contribute 75% of the uncertainty

- Uncertainty $\sim$10 times the world average, but only $\sim$4 times that of the leading (and discrepant) measurements, and near the size of the LEP-SLC discrepancy: pursuing this type of measurements will help clarifying the overall picture

- Improved PDF constraints are as critical as for $M_W$
Summary

- Detector calibration is at the level required for a first competitive measurement.

- Physics modeling of W production is a major challenge. Factorizing the longitudinal and transverse QCD degrees of freedom is not maintainable.
  - A consistent treatment should rely on a combined PDF / resummation analysis.
  - Most relevant effects to disentangle:
    - valence PDFs; 2nd generation partons; resummation parameters
  - Theoretical estimates of PDF uncertainties give $\delta M_W \approx 20 - 30$ MeV. Precise estimates at the analysis level will strongly depend on the measurement procedure.

- DY measurements are critical to constrain the models.
  - W&Z cross sections; W charge asymmetry; W+charm of particular importance for the PDFs.
  - $p_T^Z$ can be measured very accurately, but PDF flavour decomposition is a pre-requisite for a correct interpretation of this measurement.
  - Existing measurements are %-level or below: check experimental consistency ahead of higher-level interpretation!
Back-up
Constraining PDFs: W, Z inclusive cross sections & distributions

- Total cross sections are a test of the overall parton-parton luminosity. Ratios and distributions allow a partial decomposition of flavour contributions

- ATLAS: inclusive W & Z cross sections (7 TeV data, 33-36 pb⁻¹)
Constraining PDFs: Drell-Yan production at and away from the Z peak

- Direct \((x, Q^2)\) mapping of neutral-current parton-parton luminosity
- Potential flavour separation via the different \(\gamma^*\) and Z couplings to quarks
  - Down-type fermions suppressed in \(\gamma^* \rightarrow q\bar{q}\)
- CMS rapidity distributions in DY production (8 TeV, 20 fb-1)

\[
\gamma u\bar{u} \gg \gamma d\bar{d}, \gamma s\bar{s}
\]

\[
Z u\bar{u} \approx Z d\bar{d}, Z s\bar{s}
\]
Constraining PDFs: Drell-Yan production at and away from the Z peak

- Direct \((x,Q^2)\) mapping of neutral-current parton-parton luminosity
- Potential flavour separation via the different \(\gamma^*\) and Z couplings to quarks
  - Down-type fermions suppressed in \(\gamma^* \rightarrow q\bar{q}\)
- NNLO QCD is needed to describe the data; NLO predictions are insufficient.
Partonic contributions to W,Z production : Tevatron → LHC
$p_T^Z \rightarrow p_T^W$ extrapolation: effect of flavour composition

- The inclusive $p_T^Z$ spectrum combines several parton configurations with different shapes. If the assumed u/d/s/c/b fractions are wrong, the resulting effect is wrongly absorbed in the non-perturbative parameters, and transmitted to $p_T^W$. 

![Graphs showing the $p_T^Z$ and $p_T^W$ spectra](ATL-PUB-2014-015)
Modeling of $p_T^W$ : constraints from $p_T^Z$

- Traditional ansatz: W and Z production are analogous, and non-perturbative effects are universal
  - Measure $p_T^Z$, tune parton shower or resummation, apply to W
  - Impact of ATLAS measurement: $\delta M_W < 5$ MeV, assuming no extrapolation uncertainties
- This was justified at the Tevatron (up to now) but is questionable at the LHC:
  - W+ and W- production very different in $pp$ (vs $p\bar{p}$); influence of 2nd generation PDFs ~5 times larger
  - Visible PDF dependence in data/theory comparisons: ~3% in low-pT region

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Afb systematics

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<th>ATLAS-epWZ12</th>
<th>CT10</th>
<th>HERAPDF1.5LO</th>
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<td>CC electron</td>
<td>$0.2302 \pm 0.0009\text{(stat.)} \pm 0.0008\text{(syst.)} \pm 0.0010\text{(PDF)} = 0.2302 \pm 0.0016$</td>
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<td>Combined</td>
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