Precision weak boson production cross section measurements at LHCb

Colin Barschel
on behalf of the LHCb collaboration

La Thuile 2013
$\sigma = \frac{N}{\int L}$

W$\rightarrow$μν  
Z$\rightarrow$μμ  
Z$\rightarrow$ee

Beam-gas imaging  
A novel method exclusive to LHCb
Uniquely low thresholds muon trigger:
- $p_T > 1.5$ GeV/c (for single muon)
- $M_{\mu\mu} > 2.7$ GeV/c$^2$ (for dimuons)
- $p_T^2 > 1.4$ (GeV/c)$^2$
LHCb explored kinematics

Collision between proton $A$ and $B$ with partons $a$ and $b$

$$ \sigma_{AB}(x,Q^2) = \int dx_a dx_b \ f_{a/A}(x_a,Q^2)f_{b/B}(x_b,Q^2) \sigma_{ab}(x_a,x_b,Q^2) $$

Hadronic cross-section

Proton structure parameterized with the PDFs
PDFs: $\mathcal{O}(2-8\%)$

Partonic cross-section
NNLO: $\mathcal{O}(2-8\%)$ in forward region

LHCb probes 2 regions:
High $x$: PDFs are well known
Low $x$: PDFs are essentially unknown

PDF uncertainties are large (5-8%) at large rapidities $2<y<5$ accessible to LHCb
LHCb electroweak measurements provide valuable input for the PDF fits

Low mass DY $y^*$
$Q^2$ (25 GeV$^2$)
$x = 8 \times 10^{-6}$

$Q^2 = M^2$
$x_{1,2} = (M/\sqrt{s}) e^{\pm y}$

$Z/W$
$Q^2$ (10'000 GeV$^2$)
$x = 1.7 \times 10^{-4}$

Low mass + high rapidity $\rightarrow$ low $x$
Cross-section measurement

What are the major ingredients:

\[
\sigma = \frac{\rho}{\int L \, dt} \sum_{i=1}^{N\text{events}} \frac{1}{\text{efficiencies}}
\]

**Purity** \( \rho \) = the number of signal events / total number of events

Experimental **efficiencies** (tracking, identification, trigger) are calculated per event: as function of \( \eta \) and \( p_T \) of the two leptons --> mostly determined from data

**Luminosity** is measured in dedicated fills with 2 independent methods:
“van der Meer scan” (VDM) and Beam-Gas Imaging (BGI)
Present uncertainty is 3.5% (LHCB-PAPER-2011-015)

+ Acceptance; final state radiation corrections
$W \rightarrow \mu \nu$ cross-section

Data: single $\mu$ with $p_T > 10$ GeV/c
$20 < p_T^\mu < 70$ GeV/c; $2.0 < \eta_\mu < 4.5$

$W \rightarrow \mu \nu$ (shape from simulation)

K, $\pi$ decay in flight (shape from data)

$Z/\gamma^*$ with 1 muon in acceptance (shape from simulation)

Uncertainties:

<table>
<thead>
<tr>
<th>Process</th>
<th>Statistical</th>
<th>Systematic</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \rightarrow \mu^+\nu$</td>
<td>1.1%</td>
<td>3.2%</td>
<td>3.5%</td>
</tr>
<tr>
<td>$W^- \rightarrow \mu^-\bar{\nu}$</td>
<td>1.2%</td>
<td>2.9%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

$N_{W+} = 14660$
$\rho_{W+} = 78.8\%$

$N_{W-} = 11618$
$\rho_{W-} = 78.4\%$

W analysis already limited by luminosity with 2010 data only
Reduce luminosity uncertainty: valuable input to PDFs

Ratio: most systematic uncertainties cancel → Precise measurement 1.7%

Predicted in: LHCb-PAPER-2012-008

Prediction: NNLO with DYNNO; PDF uncertainties at 68% CL
$J_{L} \ 37.5 \ \text{pb}^{-1} \ (2010)$

Data: single $\mu$ with $p_{T} > 10 \ \text{GeV/c}$
Selection: two muons
$p_{T\mu} > 20 \ \text{GeV/c}; \ 2.0 < \eta_{\mu} < 4.5$
$60 < M(\mu\mu) < 120 \ \text{GeV/c}^{2}$

$Z\rightarrow\mu\mu$ signal

Low background:
$Z\rightarrow\tau\tau; \ W$-pair; Top-pair; QCD

Uncertainties:

$Z\rightarrow\mu\mu$
statistical \ 2.2\%
systematic \ 4.3\%
luminosity \ 3.5\%

Dominated by efficiencies
Determined from data -> of statistical nature

$N_{Z} = 1966$
$Bkg = 4.8\pm1.0$
$\rho_{Z} = 99.7\%$

$\int L = 37.5 \ \text{pb}^{-1} \ (2010)$

Data: single $\mu$ with $p_{T} > 10 \ \text{GeV/c}$
Selection: two muons
$p_{T\mu} > 20 \ \text{GeV/c}; \ 2.0 < \eta_{\mu} < 4.5$
$60 < M(\mu\mu) < 120 \ \text{GeV/c}^{2}$

$Z\rightarrow\mu\mu$ signal

Low background:
$Z\rightarrow\tau\tau; \ W$-pair; Top-pair; QCD

Uncertainties:

$Z\rightarrow\mu\mu$
statistical \ 2.2\%
systematic \ 4.3\%
luminosity \ 3.5\%

Dominated by efficiencies
Determined from data -> of statistical nature
Z → ee cross section

Data:
- single electron with $p_T > 15$ GeV/c
- two electrons
- $p_{Te} > 20$ GeV/c; $2.0 < \eta_e < 4.5$
- $M(\text{ee}) > 40$ GeV/c$^2$

Selection:
- two electrons
- $p_{Te} > 20$ GeV/c; $2.0 < \eta_e < 4.5$
- $M(\text{ee}) > 40$ GeV/c$^2$

Uncertainties:
- Z → ee
  - statistical: 1.1%
  - systematic: 3.1%
  - luminosity: 3.5%

Detector characteristics prevent a sharp Z peak
- Calorimeter saturates; good momentum measurement but energies are underestimated due to bremsstrahlung.
- Still possible to select Z → ee with high purity
Z→dilepton cross section

Other measurements not shown here:

Z→ττ ∫L 1028 pb⁻¹
Precision (%): 5.0 (stat) 3.9 (sys) 3.5 (lumi)
LHCb-PAPER-2012-029 arXiv:1210.6289 (JHEP)

γ*→μμ ∫L 37 pb⁻¹ 5 ≤ Mμμ ≤ 120 GeV/c²
With ∫L 1 fb⁻¹ analysis will be limited by luminosity in higher mass bins
LHCb-CONF-2012-013
With the full 2011 and 2012 data set

Uncertainties on electroweak cross sections are now mostly dominated by systematic uncertainties
- Most systematic uncertainties are of statistical nature -> will improve with more data
- Ideally the major electroweak cross section measurements should be limited by the detector performance
Measurements should not be dominated by luminosity uncertainty (now 3.5%)
  - Precision on integrated luminosity of 2% (or less) is therefore necessary

Precision EW measurements are only possible together with a precision luminosity measurement

\[ N = \int L \sigma \]

\[ N_1 N_2 \cdot \text{Overlap} \]
\[ L = f \cdot N_1 N_2 \cdot \text{Overlap} \]

- Bunch intensity \((N_1 N_2)\) measured by LHC instrumentation. Uncertainties: 2.8\% in 2010; O(0.3\%) in 2011, 2012
- Overlap integral depends on beams properties (e.g. beam width, position, angle, shape)
  Determined with 2 independent methods:
  1. Classic “van der Meer scan” (VDM) used by all 4 LHC experiments
  2. Beam-gas imaging (BGI): new method exclusive to LHCb
**Beam-Gas Imaging (BGI)**

\[ L = f \cdot N_1 N_2 \cdot \text{Overlap} \]

\[ \text{Overlap} = \int \rho_1(x,y,z,t) \rho_2(x,y,z,t) \, dx \, dy \, dz \, dt \]

**Overlap integral** depends on:
- Single bunch profiles (X,Y width, shape)
- Beam crossing angle
- Offset (head-on or displaced)

All parameters are measured using interactions between beam and residual gas

Interaction between beam and residual gas molecule

Measuring the shape of the bunches
Global fit

Measurement per 20 minutes and per bunch pair (≈10⁵ beam gas and 10⁶ beam beam vertices)

- Fit single beams and beam spot in one global fit
- Free parameters are: beam widths (double Gaussian, weight), position, angle
  (only amplitudes are free parameters for beam spot -> strong fit constrain)

Shape and position of beam spot is fully predicted by single beam parameters
Vertex resolution

Beam gas vertices are measured with the VERTex LOcator (VELO) detector - Geometry and proximity to the beam permits to achieve high precision in vertex position

Knowledge of the resolution is important:
**Measured beam width is a convolution of true beam widths with the resolution**

Resolution depends on:
• Z position of vertex
• Number of tracks
• Beam gas or beam beam events have different track distributions → Additional parameterization needed for beam gas events and Z position

Parameterization example for pp resolution

![Vertex resolution graph](image)

Resolution distribution

$R(x) = \sum_{n=1}^{N} c_n g_n(x; \sigma_n)$

Deconvolution example

Beam width: 90μm

LHCb preliminary

![Deconvolution graph](image)
Gas injection to increase beam gas rate

- To increase the accuracy of the beam gas method a larger beam gas rate is necessary
- In 2012 a gas injection system (called SMOG) has been used in dedicated fills
- By injecting neon at the Interaction Point (IP), the vacuum is degraded: from \( \approx 10^{-9} \) mbar to \( \approx 10^{-7} \) mbar

- Shortened integration time \( \approx 20 \) minutes vs. 2-3 hours
- Higher fit accuracy and better shape description

Additionally:
- Measure single bunch relative intensity in a statistical way (independent of LHC devices)
- Measure charges outside nominal filled LHC bunches (so-called “ghost charges”, not seen by LHC instrument)
- Measure beam size evolution over time

LHCb provides this data to the other experiments and to the LHC
Luminosity uncertainties

Final analysis is underway

Major uncertainties for beam gas method

- Statistical and fit uncertainty: O(1%) per bunch pair
  ≈1000 measurements in 2012

- Knowledge of the vertex resolution
  Affects beam width
  Resolution uncertainty of 5% and 10 m β*
  optics: O(1-2%) on cross section

- X/Y factorizability*
  O(1%)

- Crossing angle correction
  O(0.2%)

Luminosity uncertainties not related to beam gas method

- Stability of luminosity counters over full dataset
  O(0.5%)

- Beam total intensity scale
  O(0.3%) (was 2.8% in 2010!) (LHC device)

- Single bunch intensity
  (measured by LHCb or LHC device)
  O(0.2%)

- Ghost charges correction
  O(0.1%) Measured by LHCb for all experiments

*VDM method used by other experiments assumes “factorizable beams” i.e. X shape does not depend on Y position.
→ Not true! Can be seen and measured with beam gas at LHCb
Conclusion and outlook

**Luminosity:** (LHCb-PAPER-2011-015)
- High accuracy of beam gas method possible in 2012 with gas injections (SMOG)
- No gas injection in 2011 but beam gas method still possible with less accuracy
- Uncertainty on beam intensity absolute scale is now reduced by x10 for 2011 and 2012
- Combine van der Meer and beam gas methods (independent methods $\rightarrow$ strong constrain)

$\rightarrow$ Ideally no measurement should be limited by the luminosity uncertainty

**LHCb electroweak measurements**

1 fb$^{-1}$ in 2011 (Vs 7 TeV)
- W/Z production
- Low mass Drell-Yan $\gamma^*\rightarrow\mu\mu$
- $Z\rightarrow ee$

will improve using full dataset ($\approx30\times$ more data)

In some cases limited by present luminosity uncertainty limited by present luminosity uncertainty

2 fb$^{-1}$ in 2012 (Vs 8 TeV)
- New kinematics
- Twice the data
- High precision luminosity


3. Inclusive low mass Drell-Yan production in the forward region at $s\sqrt{s} = 7$ TeV, LHCb Collaboration, 2012, LHCb-CONF-2012-013


6. Results of the LHC DCCT Calibration Studies, C. Barschel et al. ,2012, CERN-ATS-Note-2012-026

7. "LHC Bunch Current Normalisation for the April-May 2010 Luminosity Calibration Measurements” G. Anders et al. (BCNWG note1), CERN-ATS-Note-2011-004 PERF

8. "LHC Bunch Current Normalisation for the October 2010 Luminosity Calibration Measurements" A. Alici et al. (BCNWG note2), CERN-ATS-Note-2011-016 PERF


Backup slides
Low mass Drell-Yan production cross-section $\gamma^* \rightarrow \mu\mu$

Results compared to NLO calculations (data not corrected for FSR)
Theoretical errors include the NLO prediction uncertainties and PDFs uncertainties (at 68% C.L.)
Bins $M_{\mu\mu} > 40$ GeV/c$^2$ have a cut of $p_T > 15$ GeV/c (for both data and predictions)
Cross-section in Z bin compatible with previous Z cross-section measurement LHCb-PAPER-2012-008

With more data: result in higher mass bin will be limited by present luminosity precision

References:
Drell-Yan production cross-section (in mass bins)

Results vs. different PDF sets with NLO from FEWZ (data not corrected for FSR)
Only PDF uncertainties at 68% C.L. are shown
Bins $M_{\mu\mu} > 40$ GeV/c$^2$ have a cut of $p_T > 15$ GeV/c (for both data and predictions)

LHCb Preliminary, $\sqrt{s} = 7$ TeV

<table>
<thead>
<tr>
<th>PDF set</th>
<th>Data$_{\text{stat}}$</th>
<th>Data$_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTW08 (FEWZ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNPDF20 (FEWZ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTEQ66 (FEWZ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF uncertainties only</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$2.0 < \eta^\mu < 4.5$
$p^\mu > 10$ GeV/c
$p_T^\mu > 3$ (15) GeV/c