Perspectives for forward physics with electroweak bosons at LHCb

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on behalf of the LHCb Collaboration

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May 13, 2015

Physics at the High-Luminosity LHC
Luminosity and Detector

- projected luminosity (see V. Vagnoni (2015) HL-LHC)

<table>
<thead>
<tr>
<th>LHC era</th>
<th></th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1(a) 2011</td>
<td>Run 1(b) 2012</td>
<td>Run 2 2015 - 2018</td>
</tr>
<tr>
<td>1 fb⁻¹</td>
<td>2 fb⁻¹</td>
<td>5 fb⁻¹</td>
</tr>
</tbody>
</table>

- LHCb upgrade during LS 2
  - LHCb-PUB-2014-040
  - replacement of ring imaging Cherenkov detectors
  - replacement of tracking detectors
  - full software trigger, see LHCB-TDR-016
    - currently limited by hardware readout at 1 MHz
    - upgrade will read out entire detector at 40 MHz
- no dedicated electroweak boson performance studies (yet)
  - assume Run 1 performance for EWK objects
  - trigger on anything reasonable
## Run 1 Analyses

- excellent constraints on low-\(x\) and high-\(x\) PDFs
- forward tests of pQCD, precision measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Publication</th>
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<tbody>
<tr>
<td>(W[\mu] + j, c, b) ratios at 7 and 8 TeV</td>
<td>LHCB-PAPER-2015-021</td>
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<tr>
<td>(Z[\mu\mu]) cross-section at 7 TeV</td>
<td>LHCB-PAPER-2015-001</td>
</tr>
<tr>
<td>(Z[ee]) cross-section at 8 TeV</td>
<td>arXiv:1503.00963 [hep-ex]</td>
</tr>
<tr>
<td>(Z[ee]) cross-section at 7 TeV</td>
<td>JHEP 1302 (2013) 106</td>
</tr>
<tr>
<td>(Z[\mu\mu] + b) cross-section at 7 TeV</td>
<td>JHEP 1501 (2015) 064</td>
</tr>
<tr>
<td>(W[\mu]) cross-section at 7 TeV</td>
<td>JHEP 1412 (2014) 079</td>
</tr>
<tr>
<td>(Z[\mu\mu]) cross-section in proton-lead</td>
<td>JHEP 1409 (2014) 030</td>
</tr>
<tr>
<td>(Z[\mu\mu] + D) cross-section at 7 TeV</td>
<td>JHEP 1409 (2014) 030</td>
</tr>
<tr>
<td>(Z[\mu\mu] + j) cross-section at 7 TeV</td>
<td>JHEP 1401 (2014) 033</td>
</tr>
<tr>
<td>(Z[\tau\tau]) cross-section at 7 TeV</td>
<td>JHEP 1301 (2013) 111</td>
</tr>
<tr>
<td>(H[\tau\tau]) limits at 7 TeV</td>
<td>JHEP 1305 (2013) 132</td>
</tr>
</tbody>
</table>
Run 4+ Analyses

- inclusive $W$ and $Z$
- di-boson production
- top and $W + b$
- Higgs
Assumptions

- physics objects with $p_T > 20$ GeV and $2 < \eta < 5$
  - leptons ($\ell$) are electrons and muons
  - jets are anti-$k_T$ with $R = 0.5$
  - Z-boson mass within $60 < m < 120$ GeV
- theory predictions are performed with MC@NLO at NLO
  - fiducial definitions above used
  - these are estimates!
- detector performance similar to Run 1
  - lepton and jet reconstruction $\approx 95\%$
  - $b$-jet tagging $\approx 65\%$, $c$-jet tagging $\approx 25\%$
  - photon reconstruction $\approx 50\%$
  - hadronic $\tau$ reconstruction $\approx 60\%$ (assumed from CMS and ATLAS), branching $\approx 65\%$
  - 100% trigger efficiency!
- 150 fb$^{-1}$ of integrated luminosity
**Z[\ell\ell] Run 1**

- muon channel, 7 TeV, 1 fb$^{-1}$
- $5.8 \times 10^4$ events selected
- 18 bins of rapidity, 14 bins of $p_T$
- statistical $\approx 2\%$, systematic $\approx 1\%$

<table>
<thead>
<tr>
<th>source</th>
<th>$\delta \sigma(Z) [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>trigger efficiency</td>
<td>0.07</td>
</tr>
<tr>
<td>identification efficiency</td>
<td>0.23</td>
</tr>
<tr>
<td>tracking efficiency</td>
<td>0.53</td>
</tr>
<tr>
<td>FSR</td>
<td>0.11</td>
</tr>
<tr>
<td>purity</td>
<td>0.22</td>
</tr>
<tr>
<td>global event cut efficiency</td>
<td>0.26</td>
</tr>
</tbody>
</table>

LHCb Preliminary

LHCb, $\sqrt{s} = 7$ TeV
- Data
- Data stat @ syst
- Data tot
- MSTW08
- NNPDF23
- CT10
- ABM12
- HERA15
- JR09

$p_T^\mu > 20$ GeV/c
$2.0 < \eta^\mu < 4.5$
$Z: 60 < M_{\mu\mu} < 120$ GeV/c$^2$
68.3$\%$ CL ellipse area
**Z[ℓℓ] Run 4+**

- expected cross-section $4.7 \times 10^5$ fb
  - $\rightarrow 6.4 \times 10^7$ events
- keep the same binning of 18 bins
  - statistical precision $\approx 0.05\%$
- keep the same statistical precision of 2%
  - single differential: $\approx 25000$ bins ($y$)
  - double differential: $\approx 160$ bins ($y$, $p_T$)
  - triple differential: $\approx 30$ bins ($y$, $p_T$, ?)
- FSR uncertainty currently at 0.11%, more important at 14 TeV
- all other uncertainties statistically driven from data
**Inclusive W and Z**

**W[ℓ] Run 1**

- muon channel, 7 TeV, 1 fb$^{-1}$
- $8.1 \times 10^5$ events selected
- 8 bins of pseudo-rapidity
- statistical $\approx 1\%$, systematic $\approx 2\%$

<table>
<thead>
<tr>
<th>source</th>
<th>$\delta_{\sigma}(W^+)$ [%]</th>
<th>$\delta_{\sigma}(W^-)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>template shape</td>
<td>0.28</td>
<td>0.39</td>
</tr>
<tr>
<td>template normalization</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>reconstruction efficiency</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>selection efficiency</td>
<td>0.33</td>
<td>0.32</td>
</tr>
<tr>
<td>acceptance and FSR</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>luminosity</td>
<td>1.17</td>
<td>1.17</td>
</tr>
</tbody>
</table>
$W[\ell]$ Run 4+

- expected cross-section $7.9 \times 10^6$ fb
  - $\rightarrow 4.3 \times 10^8$ events
- keep the same binning of 8 bins
  - statistical precision $\approx 0.01\%$
- keep the same statistical precision of 1%
  - single differential: $\approx 40000$ bins ($\eta$)
  - double differential: $\approx 200$ bins ($\eta$, $p_T$)
  - triple differential: $\approx 40$ bins ($\eta$, $p_T$, ?)
- limited by current theory driven systematic of $\approx 0.3\%$
- reconstruction efficiency systematic may not reduce as expected
W[τ] Production

- interest from LEP measurements, hep-ex/0511027
  \[
  \frac{2\sigma(W[\tau])}{\sigma(W[\mu]) + \sigma(W[e])} = 1.077 \pm 0.026
  \]

- looking at \( W \rightarrow \tau[\mu] \) in Run 1 (no trigger for hadronic \( \tau \))
  - systematic uncertainty will not be competitive

- expected cross-section \( 4.0 \times 10^6 \) fb
  - \( \rightarrow 1.6 \times 10^6 \) hadronic \( \tau \) events

- systematic uncertainties
  - hadronic \( \tau \) reconstruction, partially driven by \( Z \rightarrow \tau\tau \) statistics
  - FSR corrections
  - hadronic \( \tau \) acceptance
**WW, WZ, ZZ, Wγ, and Zγ Production**

- no Run 1 di-boson measurements
- expected $WW[\ell, \ell]$ cross-section 300 fb
  - $\rightarrow 2.0 \times 10^4$ events ([$e, \mu$] final state)
  - clean signature, precision measurement
  - backgrounds primary systematic uncertainty ($Z \rightarrow \tau\tau[e, \mu]$)
- expected $WZ[\ell, \ell, \ell]$ cross-section 16 fb
  - $\rightarrow 2000$ events
- expected $ZZ[\ell, \ell, \ell, \ell]$ cross-section 3.1 fb
  - $\rightarrow 380$ events

- $V\gamma$ measurements difficult with current detector (ECAL response)
- expected $W\gamma[\ell, \gamma]$ cross-section 3700 fb
  - $\rightarrow 2.6 \times 10^5$ events
- expected $Z\gamma[\ell, \ell, \gamma]$ cross-section 780 fb
  - $\rightarrow 5.6 \times 10^4$ events
Jet Tagging Run 1

- $n$-body secondary vertex algorithm
- require vertex flight direction within jet, $\Delta R(SV, \text{jet}) < 0.5$
- two BDTs
  - BDT($bc|udsg$): separates $udsg$-jet from $b, c$-jet
  - BDT($b|c$): separates $b$-jet from $c$-jet
Jet Tagging

Jet Flavor Run 1

$b$-enhanced ($B + \text{jet}$) data sample

data distribution

fit distribution

BDT($bc|\text{udsg}$) proj.

BDT($b|c$) proj.
<table>
<thead>
<tr>
<th>source</th>
<th>$\delta_\varepsilon(b)$ [%]</th>
<th>$\delta_\varepsilon(c)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT templates*</td>
<td>$\approx 2$</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td><em>udsg</em>-jet large IP component*</td>
<td>$\approx 5$</td>
<td>$\approx 10 - 30$</td>
</tr>
<tr>
<td>hadron-as-muon (hardest-$\mu$ only)</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>gluon splitting</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>total (combined fit)</td>
<td>$\approx 10$</td>
<td>$\approx 10$</td>
</tr>
</tbody>
</table>

*dependent on jet type and $p_T$

- possible inclusion of $s$-tagging
  - utilize RICH information and vertexing
- primary uncertainty from $\chi^2_{IP}$ fit (denominator of efficiency)
  - not dependent on statistics
  - $s$-tagging development could reduce this
- work needed for precision measurements
$W + j, b, c[\mu]$ Run 1

LHCb-PAPER-2015-021

$\sigma(Wx)/\sigma(Wj) \times 100$

$\sigma(Wj)/\sigma(Zj)$

A($Wx$)

points data (total, stat)
fills MCFM NLO theory
CT10 (scale + PDF)
green $W + c$-jet
red $W + b$-jet
blue $W^+ +$ jet
magenta $W^- +$ jet

LHCb Preliminary
### $W + j, b, c[\ell] \text{ Run 4+}$

<table>
<thead>
<tr>
<th>source</th>
<th>$\frac{\sigma(Wb)}{\sigma(Wj)}$</th>
<th>$\frac{\sigma(Wc)}{\sigma(Wj)}$</th>
<th>$\frac{\sigma(Wj)}{\sigma(Zj)}$</th>
<th>$A(Wb)$</th>
<th>$A(Wc)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b, c)-tag efficiency</td>
<td>10%</td>
<td>10%</td>
<td>$\sigma(Zj)$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>isolation templates</td>
<td>10%</td>
<td>5%</td>
<td>4%</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>top</td>
<td>13%</td>
<td>$-$</td>
<td>$-$</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>SV-tag BDT templates</td>
<td>5%</td>
<td>5%</td>
<td>$-$</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>$-$</td>
<td>3%</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

- expected $W + j[\ell, j]$ cross-section $9.4 \times 10^5$ fb
  - $\rightarrow 1.3 \times 10^8$ events
- expected $W + c[\ell, c]$ cross-section $6.9 \times 10^4$ fb
  - $\rightarrow 2.3 \times 10^6$ events
- expected $W + b[\ell, b]$ cross-section 7300 fb
  - $\rightarrow 6.4 \times 10^5$ events
  - $10^2$ bins $\rightarrow \approx 1\%$ statistical uncertainty
- excellent potential for constraints on $s$ and $b$ PDFs
Run 1 analysis coming soon!
lepton and $b$-jet final state
  - expected $t\bar{t}[\ell, b]$ 2600 fb
    - $2.5 \times 10^5$ events
  - expected $t[\ell, b]$ ($t$-channel) 1800 fb
    - $1.5 \times 10^5$ events
  - expected $t[\ell, b]$ ($s$-channel) 210 fb
    - $1.8 \times 10^4$ events
  - expected $Wt[\ell, b]$ 60 fb
    - 5300 events
  - expected $Wt[\ell, \ell, b]$ 20 fb
    - 1600 events
  - expected $t\bar{t}[\ell, \ell, b, b]$ 317 fb
    - $1.6 \times 10^4$ events
$V_{ts}$ Run 4+

- best indirect (single) result from precision $B_s^0 - \bar{B}_s^0$ measurement by LHCb, *New J. Phys.* 15 (2013) 053021
  - $|V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$
- no tree level measurements (yet)
- look for $s$-channel production with lepton and 2 $b$-jet final state
  - requires $s$-jet tagging with excellent $b$-jet rejection
  - needs further investigation
- expected $t[\ell, b, b]$ ($s$-channel) 150 fb
  - assume 10% $s$-tag efficiency, 0.1% fake rate
  - 50 $s$-tagged signal, 10 mis-tagged $b$-jet events
  - ignoring other backgrounds ...
Top Asymmetry Run 4+

- use electron, muon, and $b$-jet final state

\[
\frac{dA_{FB}^{\ell\ell}}{d\Delta y} = \frac{(d\sigma(\mu eb, \Delta y > 0) - d\sigma(\mu eb, \Delta y < 0))}{d\Delta y} / d\sigma(\mu eb)/d\Delta y
\]
Higgs

Higgs Production Run 4+

• no Run 1 Higgs observations from LHCb (only limits)
• possibility of $H \to c\bar{c}$ via VBF or associated vector?
• four-lepton modes still largely out of reach

• expected $H[b, b, j] \ (\text{VBF})$ cross-section 70 fb
  - $\rightarrow$ 3800 events
• expected $H[\tau, \tau, j] \ (\text{VBF})$ cross-section 7.9 fb
  - $\rightarrow$ 150 events
• expected $H[c, c, j] \ (\text{VBF})$ cross-section 3.6 fb
  - $\rightarrow$ 27 events
• expected $H + W[b, b, \ell]$ cross-section 12 fb
  - $\rightarrow$ 680 events
• expected $H + W[\tau, \tau, \ell]$ cross-section 1.4 fb
  - $\rightarrow$ 30 events
Summary

- double differential precision measurements with $W$ and $Z$ possible
  - Drell-Yan to very low masses also possible
  - provide comprehensive low-$x$ and high-$x$ dataset for PDFs
- forward di-boson cross-section measurements possible, particularly $WW[e, \mu]$
- vector boson and photon measurements (assuming updated ECAL)
  - not explored here but very interesting, vector boson CEP
- precision differential $W + j, b, c$ measurements
  - absolute cross-sections will be dominated by tagging
  - high precision with normalized
- enough top events for interesting forward measurements
- forward observation of the Higgs within reach
- fully instrumented between $2 < \eta < 5$
- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of $13 - 20 \, \mu m$ for tracks
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3) \, mm$ in $xy(z)$
• muon reconstruction and trigger efficiencies from tag-and-probe
• heavy flavor background from displaced and non-isolated sidebands
• muon mis-identification from minbias, validated against same-sign
- ECAL saturation leads to smeared $Z$ peak shape
- electron tracking efficiency large systematic uncertainty
  - can be determined from data, but not as a function of momenta
$Z[ee]$ Run 1b

\begin{align*}
\text{LHCb} \\
\frac{d\sigma}{dy_Z} & \text{ [pb]} \\
2 & 2.5 & 3 & 3.5 & 4 \\
0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
8 \text{ TeV } Z \rightarrow e^+e^- \\
\text{Data (stat.)} & \text{Data (tot.)} \\
\bullet \text{ NNLO/MSTW08} & \square \text{ NNLO/CT10} \\
\triangle \text{ NNLO/NNPDF23} & \diamond \text{ NNLO/NNPDF30} \\
\blacktriangle \text{ NNLO/ABM12} \\
\end{align*}

\begin{align*}
\text{Prediction/data} & \text{ [\%]} \\
0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 & 1.6 & 1.8 & 2 \\
8 \text{ TeV } Z \rightarrow e^+e^- \\
\text{Data (stat.)} & \text{Data (tot.)} \\
\text{Pythia8.1} & \text{Resbos} & \text{Powheg} \\
\end{align*}
- utilized $\mu\mu$, $e\mu$, $h\mu$, and $eh$ final states
- only selected single prong $\tau$ decays

\[ M_{\mu\mu} \text{ [GeV/c}^2\text{]} \]

\[ M_{\mu e} \text{ [GeV/c}^2\text{]} \]
- search for isolated high $p_T$ muons
- bin as a function of $\eta$ and charge
- fit the muon $p_T$ spectrum
<table>
<thead>
<tr>
<th>variable</th>
<th>separation</th>
<th>variable</th>
<th>separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(SV)$</td>
<td>udsgc</td>
<td>$M_{\text{cor}}(SV)$</td>
<td>udsgb</td>
</tr>
<tr>
<td>$\text{min}(F_{\text{D}}T(SV))$</td>
<td>udsg</td>
<td>$p_T(SV)/p_T(\text{jet})$</td>
<td>udsg</td>
</tr>
<tr>
<td>$\Delta R(SV, \text{jet})$</td>
<td>udsg</td>
<td>$N(\text{trk})$</td>
<td>udsgc</td>
</tr>
<tr>
<td>$N(\text{trk} \in \text{jet})$</td>
<td>udsgc</td>
<td>$</td>
<td>Q(SV)</td>
</tr>
<tr>
<td>$\log(\chi^2_{\text{FD}}(SV))$</td>
<td>all</td>
<td>$\log(\chi^2_{\text{IP}}(SV))$</td>
<td>all</td>
</tr>
</tbody>
</table>

- $M_{\text{cor}}(SV)$
- $N(\text{trk})$
• fit 2-dimensional $\text{BDT}(bc|udsg)$ versus $\text{BDT}(b|c)$ distributions

udsg-jet

\begin{align*}
\text{BDT}(bc|udsg) & \quad \text{BDT}(b|c)
\end{align*}

LHCb simulation

$c$-jet

\begin{align*}
\text{BDT}(bc|udsg) & \quad \text{BDT}(b|c)
\end{align*}

LHCb simulation

$b$-jet

\begin{align*}
\text{BDT}(bc|udsg) & \quad \text{BDT}(b|c)
\end{align*}

LHCb simulation

• validate with four tag+probe data sub-samples
  • $B$ + jet: $b$-enhanced
  • $D$ + jet: $c$ and $b$-enhanced
  • displaced- $\mu$ + jet: $c$ and $b$-enhanced
  • $W$ + jet: use prompt isolated $\mu$, $udsg$-enhanced
• determine efficiency with:
\[ \frac{N_x(SV)}{N_x(\chi^2_{IP})}, \quad x \in udsg, c, b \]

| \( \chi^2_{IP} \) of hardest-\( p_T \) track (large initial \( udsg \)-background) |
|---|---|
| \( c \)-enhanced \( (D + \text{jet}) \) | \( b \)-enhanced \( (B + \text{jet}) \) |

| \( \chi^2_{IP} \) of hardest-\( p_T \) muon (only \( \mathcal{O}(10\%) \) of jets) |
Jet Tagging Run 1

\textit{udsg-jet}

- 

\textbf{LHCb simulation}\
\begin{tabular}{|c|c|c|}
\hline
$2.2 < \eta(\text{jet}) < 4.2$ & & \\
\hline
\end{tabular}

\begin{itemize}
\item mis-identification probability
\item $10^{-3}$
\item $10^{-4}$
\item $10^{-5}$
\item $10^{-6}$
\item $10^{-7}$
\end{itemize}

\begin{itemize}
\item light-jet SV-tagger
\item $p_T(\text{jet})$ [GeV]
\end{itemize}

\textbf{LHCb}\
\begin{tabular}{|c|c|c|}
\hline
& & \\
\hline
\end{tabular}

\begin{itemize}
\item mis-ID probability data/simulation
\item 20
\item 40
\item 60
\item 80
\item 100
\end{itemize}

\textbf{c-jet and b-jet}

- 

\textbf{LHCb simulation}\
\begin{tabular}{|c|c|c|}
\hline
$2.2 < \eta(\text{jet}) < 4.2$ & & \\
\hline
\end{tabular}

\begin{itemize}
\item efficiency
\item 0.5
\item 0.6
\item 0.7
\item 0.8
\item 0.9
\item 1
\end{itemize}

\begin{itemize}
\item b-jet SV-tagger
\item c-jet SV-tagger
\item $p_T(\text{jet})$ [GeV]
\end{itemize}

\textbf{LHCb}\
\begin{tabular}{|c|c|c|}
\hline
& & \\
\hline
\end{tabular}

\begin{itemize}
\item efficiency in data/simulation
\item 0.5
\item 0.6
\item 0.7
\item 0.8
\item 0.9
\item 1
\end{itemize}

\begin{itemize}
\item b-jet
\item c-jet
\item $p_T(\text{jet})$ [GeV]
\end{itemize}
isolation defined as $p_T(\mu)/p_T(j_\mu)$

- fit in bins of $\sqrt{s}$ and muon charge
  - di-jet template from $p_T$-balanced events, $p_T(j_\mu + j) < 10$ GeV
  - $Z + \text{jet}$ yield and template extrapolated from di-muon $Z + \text{jet}$ data
  - $W + \text{jet}$ template from di-muon $Z + \text{jet}$ data, corrected to $W + \text{jet}$ with simulation

LHCb Preliminary
W + j, b, c[µ] Run 1 (2)

- fit BDT($bc|udsg$) versus BDT($b|c$) distribution in each bin of $\sqrt{s}$, muon charge, and $p_T(\mu)/p_T(j_\mu)$ (bin of 0.9 – 1.0 below)
$W + j, b, c[\mu]$ Run 1  

### $\mu^+$, 8 TeV

- **data**
- **W+c**
- **Z+c**
- **di-jet**

### $\mu^-$, 8 TeV

- **LHCb**

**LHCb Preliminary**

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### $\mu^+$, 8 TeV

- **data**
- **W+b**
- **Z+b**
- **di-jet**

### $\mu^-$, 8 TeV

- **LHCb**

**LHCb Preliminary**