Electroweak physics and Exotics at LHCb
Run 1 results and prospects for Run 2

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CERN

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2nd NPKI workshop, Physics from Run 2 of the LHC, Jeju Island, Korea.
LHCb as a general purpose detector in the forward region

Detector configuration

Unique capabilities in the forward region:
- Muon and hadron identification.
- Tracking and vertexing
- b-jets identification.

Direct searches and production measurements:
- Luminosity penalty of a factor 8, \(3.2 \text{ fb}^{-1}\) up to now, \(\sim 5 \text{ fb}^{-1}\) for RunII.
- **Low pile-up condition** \(\mu \sim 2\) in Run I, even lower in Run II \(\mu \sim 1\).
- **Low** \(p_T, m\) triggers.
LHCb detector

2008 JINST 3 S08005

- Designed for CP violation studies in B,D decays and rare decays.
- **pp** collisions: $\sim 1.1 fb^{-1}$ at $\sqrt{s} = 7$ TeV, $\sim 2.2 fb^{-1}$ at $\sqrt{s} = 8$ TeV.
- **pA** collisions: $\sim 1.9 nb^{-1}$ at $\sqrt{s_{NN}} = 5$ TeV.
- Fully instrumented forward $2 < \eta < 4.5$, charged particle backward $-4 < \eta < -1.5$
Run I:

- Most of the triggers are optimised for B and D decays.
- Inclusive muons triggers down to low mass and $p_T$

<table>
<thead>
<tr>
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<tbody>
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<td>$p_T &gt; 1.3$ GeV ($IP &gt; 0.5$ mm,$IP\chi^2 &gt; 200$)</td>
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<tr>
<td>Double-$\mu$</td>
<td>$m_{\mu\mu} &gt; 4.8$ GeV</td>
<td>$m_{\mu\mu} &gt; 2.95$ GeV ($DLS &gt; 5$)</td>
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</tbody>
</table>

- No jet-based trigger, BUT an inclusive B hadron trigger:
  
  $\rightarrow$ **Act as a b-jet trigger.** $\epsilon_{b-jet} \sim 30 - 45\%$ for $p_T > 15$ GeV

Run II:

- Online detector calibration mechanism after first stage of triggering
  
  $\rightarrow$ **Offline-like reconstruction available (PID, tracking)**

- b-jet trigger under investigation.
- More flexibility $\rightarrow$ more complex signature.

  **Important to have some benchmark model of any ”non-standard” low $p_T$ signature**

- Storage rate: 5 kHz (Run I)$\rightarrow$ 12.5 kHz (Run II).
Electroweak and Exotic measurements @ LHCb

Electroweak bosons production in the forward region:

- Inclusive $W^\pm$ production in $pp$ at $\sqrt{s} = 7$ TeV [arXiv:1408.4354]
- Inclusive $Z$ production in $pp$ at $\sqrt{s} = 7$ TeV LHCb-CONF-2013-007.
- Inclusive $Z$ production in $pA$ at $\sqrt{s_{NN}} = 5$ TeV, arXiv:1406.2885.
- $Z + \text{jets}$ production in $pp$ at $\sqrt{s} = 7$ TeV JHEP01 (2014) 033.
- $Z + D$ meson production in $pp$ at $\sqrt{s} = 7$ TeV JHEP (2014) 091.

Exotic searches:

- $b\bar{b}$ Charge asymmetry PRL 113 (2014) 082003
- Neutral Higgs boson production in the forward region at $\sqrt{s} = 7$ TeV JHEP05 (2013) 132
- Pairs of long lived heavy charged particles in the forward region LHCb-CONF-2014-001
- Pairs of Long lived heavy neutral particles in the forward region LHCb-CONF-2012-013

Production with high rapidity gap:

- Exclusive $J/\psi$ and $\psi(2S)$ production in $pp$ at $\sqrt{s} = 7$ TeV JPG (2014) 055002
- Exclusive production of charmonium pair in $pp$ collision arXiv:1407.5973

Prospects

- EW bosons and heavy flavour
- Top production measurements
- Exotic long lived particles
Forward $W^{\pm}$ cross section at $\sqrt{s} = 7 \text{ TeV}$ with 1 fb$^{-1}$

- Probe the low-$x$ high-$Q^2$ PDFs.
- PDFs uncertainty for $W^{\pm}$ production in LHCb $O(1 – 8\%)$.
- $W$ yields from fit to the $p_T\mu$.
- Experimental uncertainty comparable to the theory uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta\sigma_{W^{+}\rightarrow\mu^+\mu^-}$ [%]</th>
<th>$\Delta\sigma_{W^{-}\rightarrow\mu^-\mu^+}$ [%]</th>
<th>$\Delta R_W$ [%]</th>
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<tbody>
<tr>
<td>Template shape</td>
<td>0.28</td>
<td>0.39</td>
<td>0.59</td>
</tr>
<tr>
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<td>0.10</td>
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<td>0.06</td>
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<tr>
<td>Reconstruction efficiency</td>
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<td>1.20</td>
<td>0.12</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>0.33</td>
<td>0.32</td>
<td>0.18</td>
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<tr>
<td>Acceptance and FSR</td>
<td>0.18</td>
<td>0.12</td>
<td>0.21</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.71</td>
<td>1.71</td>
<td>—</td>
</tr>
</tbody>
</table>

New precision luminosity measurement LHCb-PAPER-2014-047 to appear soon 1.16% at 8TeV
Forward $W^{\pm}$ cross section at $\sqrt{s} = 7$ TeV

Comparison to NNLO predictions with six different PDF sets.

Measured values for $W^+$ lower than prediction at low $\eta$ and higher at high $\eta$. 
Some systematic uncertainties cancels in the ratios:

- \( A_\mu(\eta) = \frac{\sigma(W^+(\eta)) - \sigma(W^-(\eta))}{\sigma(W^+(\eta)) + \sigma(W^-(\eta))} \)
- \( R_W(\eta) = \frac{\sigma(W^+(\eta))}{\sigma(W^-(\eta))} \)

Complementarity with ATLAS/CMS in the kinematic coverage at the LHC.
Prospects for SM measurements
EW bosons, jets and forward heavy flavour tagging

With Run I data:

- $Z + \text{jets}$ production in $pp$ at $\sqrt{s} = 7$ TeV [JHEP01 (2014) 033].
- $b$ and $c$ jet-tagging now available, based on a relaxed version of the inclusive B reconstruction and on jet information.
- $Z+b, W+j (l,c,b)$ production measurements should appear in the coming month(s).

- Update of those measurements at $\sqrt{s} = 8$ TeV.

- Single diffractive $W$ and $Z$ production can be investigated by looking at events with no tracks in the backward region ($-4 < \eta < -1.5$)
- With this rapidity gap: $\sim 1k$ $Z$ events and $\sim 10k$ $W$ events in $\sqrt{s} = 8$ TeV sample.
Prospects for SM measurements
EW bosons, jets and forward heavy flavour tagging

With Run II data:
- High $p_T$ lepton triggers will remain the same.
- $\sim 10$ times more $W$ with Run II dataset ($5 \text{ fb}^{-1}$) than in the 7 TeV measurement.
- Di-boson production reachable, hadronic modes to be investigated.
Prospects for SM measurements

**$t\bar{t}$ production in the forward region**


- With $p_T\ell > 4$ GeV, $p_T b,j > 20$ GeV and $2 < \eta_{\ell,b,j} < 4.5$:

<table>
<thead>
<tr>
<th>$d\sigma$(fb)</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell b$</td>
<td>285 ± 52</td>
<td>504 ± 94</td>
<td>4366 ± 663</td>
</tr>
<tr>
<td>$\ell bj$</td>
<td>97 ± 21</td>
<td>198 ± 35</td>
<td>2335 ± 323</td>
</tr>
<tr>
<td>$\ell bb$</td>
<td>32 ± 6</td>
<td>65 ± 12</td>
<td>870 ± 116</td>
</tr>
<tr>
<td>$\ell bbj$</td>
<td>10 ± 2</td>
<td>26 ± 4</td>
<td>487 ± 76</td>
</tr>
<tr>
<td>$\ell^+\ell^-$</td>
<td>44 ± 9</td>
<td>79 ± 15</td>
<td>635 ± 109</td>
</tr>
<tr>
<td>$\ell^+\ell^- b$</td>
<td>19 ± 4</td>
<td>39 ± 8</td>
<td>417 ± 79</td>
</tr>
</tbody>
</table>

- $\ell b$ and $\ell bj$ are the channel more suited for 7 and 8 TeV
Prospects for SM measurements
$t\bar{t}$ cross section in the forward region

[JHEP(2014)126, Gauld]

- large uncertainty on the high-$x$ gluon PDFs.
- Assume 4, 6 and 8% experimental uncertainty LHCb measurement at 14TeV.
- PDF re-weighting based on these pseudo-data.
- Up to 20% reduction of the PDF error.

Prospects for SM measurements
$\bar{t}t$ production in the forward region

[JHEP(2014)126, Gauld]

- Assuming realistic LHCb detection performance.
- $p_T \mu > 20\ GeV$, $p_T b > 60\ GeV$ to reduce the background.

- Background can be reduced further (good separation in $p_T \mu b$)
- Work on-going at $\sqrt{s} = 7, 8\ TeV$
Prospects for SM measurements
\( \bar{t}t \) asymmetry in the forward region

[\text{PRL}(2011)107, \text{Kagan et al.}]
[LHCb-PUB-2013-009]

- Quark initiated production relative contribution larger than in central region.
- Considering \( \ell b \) : 
  \[ A_\ell = \frac{N(\mu^+ b) - N(\mu^- b)}{N(\mu^+ b) + N(\mu^- b)} \]
- More pronounced at \( \sqrt{s} = 7 \text{ TeV} \) but statistical error \( 5 - 10\% \).
- With 5 \( fb \) at Run II, still to be evaluated.
Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Motivation

- Depending on new physics flavour structure, asymmetry could show up in the bottom sector.

\[ \text{[arXiv:1108.3301, Kahawala et al.]} \]

- At LHC access to the forward central asymmetry.
- Expected to be $O(1\%)$ from QCD with an extra $O(1\%)$ in the Z mass region.

- Analysis performed with 1 $fb^{-1}$
- Pairs of b-jets with $\Delta\phi(bb) > 2.6$ rad.
- One of the b-jets charge is tagged with a muon.
- Purity of the charge tagging $70.3 \pm 0.3\%$
Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Result with 1 $fb^{-1}$

$$A_{FC}^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},$$

$$\Delta y = |y_b| - |y_{\bar{b}}|$$

In different $m_{bb}$ bins:

- $A_{FC}^{b\bar{b}}(40, 75) = 0.4 \pm 0.4 \pm 0.3 \%$
- $A_{FC}^{b\bar{b}}(75, 105) = 2.0 \pm 0.9 \pm 0.6 \%$
- $A_{FC}^{b\bar{b}}(> 105) = 1.6 \pm 1.7 \pm 0.6 \%$

- No deviation from expectation with available statistics.
- Still 2 $fb^{-1}$ of the Run I data to be analysed.
- More efficient $b$-tagging available now.
Search for Higgs-like bosons decaying into neutral long lived particles

LHCb-CONF-2012-014

- LLP are features of several BSM models.
- In this analysis:
  \[ H \rightarrow \tilde{\chi}_0^1 \tilde{\chi}_0^1 \rightarrow 3q3\bar{q} \] from mSUGRA with BNV [PRL (2007) 99, Carpenter et al.].
- Experimental signature: pairs of high mass displaced vertices.
- \( N_{\text{tracks}} > 5, r > 0.4 \) \( mm, m > 6 \) GeV, no events seen.
- Search with 36 \( pb^{-1} \), update on full dataset soon available (\( \sim \times 80 \) more data).

- Single LLP search adding jet information to the displaced vertex to appear soon.

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- Trigger on all > 3 tracks vertices with \( r > 0.5(3) \) mm and \( m > 8(2.5) \) GeV
- LLP searches at low mass < 50 GeV, low lifetime \( c\tau \sim O(cm) \).
- In similar searches:
  - ATLAS covers low mass but longer lifetime, [PRL (2012) 108]
  - CMS covers low lifetime but higher masses, [CMS-PAS-EXO-12-038]
- Under 20 – 30 GeV need to move to merged jet strategy.
- Many other final states can be produced in BSM models:
  - Vertex with many tracks.
  - W or w/o tertiary vertices, w or w/o leptons
  - Several di-tracks vertices, clustered or not.
  - Multi lepton vertices.
  - ...
- Work needed to make sure Run II trigger covers most them

\[ \rightarrow \text{All suggestions welcome!} \]
Conclusion

- LHCb offers a unique way to probe the forward region of pp collisions at the LHC.
  - Low pile-up conditions.
  - Flexible and low threshold triggers.
  - Excellent tracking and secondary vertex capabilities.

- Several measurements probing pdfs in poorly constrained area.
  → Important input for precision physics.

- Jets reconstruction and heavy flavour jets tagging now available.
  → New series of measurements coming (EW bosons + heavy flavour jets, Top,...)

- Some searches/measurements complements ATLAS/CMS results in the forward region.
- Some others might be possible only at LHCb.
- We need to think of signatures we would miss in our trigger, any suggestions welcome for Run II at $\sqrt{s} = 13$ TeV!
Two $\mu$ and nothing else in the detector $\rightarrow$ Rapidity gap $\sim 5.2 [y]$

Exclusive contribution obtained from fit of $p_T^{2 \psi}$, purity $\sim 60\%$ for $p_{T\mu\mu} < 0.9$ GeV.


Rapidity gap will be extended in Run II with forward shower counters along the beam line (HERSCHEL)
Electroweak physics and Exotics at LHCb
Most of the trigger is optimised for B and D decays.

- 40 MHz → 1 MHz: High $p_T$ objects ($O(2 − 5\text{GeV})$)
- Down to $\sim 50$ kHz: Displaced tracks, di-$\mu$, higher $p_T$ leptons.
- Down to $\rightarrow \sim 5$ kHz: Inclusive selections for B, D, e, $\mu$ and exclusive selection.

Inclusive lepton triggers down to low mass and $p_T$:

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No jet-based trigger, BUT:

- 2, 3 or 4 displaced track vertices + MVA selection: efficient and pure on exclusive B decays [LHCb-PUB-2011-002].
- Act as a b-jet trigger. $\epsilon_{b-jet} \sim 30 − 45\%$ for $p_T > 15$ GeV.
40 MHz → 1 MHz: High $p_T$ objects ($O(2 - 5\text{GeV})$)

Down to $\sim 100$ kHz: Displaced tracks, di-$\mu$, high $p_T$ leptons.

Calibrated data available at this point.

Will allow PID usage, offline-like tracking resolution.

More flexibility → higher efficiency, more complex signature.

12.5 kHz storage rate (5 kHz during Run I) to cope with the increase in cross sections.
Exotics at LHCb
Search in the forward direction

Search for $\Phi_0 \rightarrow \tau \tau$, JHEP 05 (2013) 132
- Model independent search, limit on forward Higgs production.
- MSSM in $m_{h^0}^\text{max}$ scenario limits not as stringent as GPD.

Upper limits for the Drell-Yan production of $\tilde{\tau}$ pairs LHCb-CONF-2014-001
- Mass between to 124 GeV and 309 GeV.
- Limitation at low velocity due to the time window of the detector.
- For this model ATLAS/CMS exclude $m_{\tilde{\tau}} < 200$ GeV in the central region.
  Inclusive search in uncovered rapidity, could be interesting if some model predicts strong enhancement in the forward region.
Z+jet production in $pp$ at $\sqrt{s} = 7$ TeV

Jet reconstruction at LHCb

Inclusive Z production

- In pp collisions at $\sqrt{s} = 7$ TeV, LHCb-CONF-2013-007
- In pA collisions at $\sqrt{s_{NN}} = 5$ TeV, arXiv:1406.2885

First measurement with jets at LHCb, JHEP01 (2014) 033

- Fiducial volume of the measurement:
  - $2 < \eta_{\text{jet}} < 4.5$, $p_T \text{ jet} > 10(20)$ GeV
  - $60 < m_{\mu\mu} < 120$ GeV, $\eta_{\mu}$, $p_T \mu$.
  - $\Delta R(\mu, \text{jet}) > 0.4$

- Jet reconstruction:
  - Anti-$k_T$ with $R=0.5$.
  - Inputs from particle flow algorithm.
  - Jet energy correction determined from MC (range from 0.9 - 1.1)
  - Validated on data, JES data vs. MC within 3%.

- Dominant uncertainties of the measurement
  - Jet energy scale, resolution
  - Jet reconstruction efficiency
  - Work on-going to improve these points.
Z+jet production in \( pp \) at \( \sqrt{s} = 7 \) TeV

- Predictions from POWHEG+PYTHIA at \( O(\alpha_s) \) and \( O(\alpha_s^2) \) with different PDF sets.
- Predictions from FEWZ at \( O(\alpha_s^2) \) not corrected for hadronisation and underlying event.

- Not corrected for FSR
- Shapes in good agreement with NLO
Measurements with Z bosons
Inclusive production in pp and pA

in pp collisions at $\sqrt{s} = 7$ TeV, LHCb-CONF-2013-007
- Good agreement with NNLO predictions.
- Good agreement with ATLAS in overlap region.

- Poor nPDF data constraints in the high-x/low-x region.
- 11 Z events with p flying to LHCb (forward pA)
- 4 Z events with A flying to LHCb (backward pA)
- Good general agreement but more statistics needed.
Search for Higgs-like bosons decaying into long lived particles

Motivation

- Long lived neutral massive particles (LLP) arise from many new physics models.
- Pair production through Higgs-like boson accessible with early LHC data.
- mSUGRA with R parity and baryon number violation
  - $h^0 \rightarrow \tilde{\chi}_0^0 \tilde{\chi}_1^0 \rightarrow 3\text{jets} + 3\text{jets}$, $\sim 70\%$ of the decay have a b quark.
  - For $m_{h^0} = 125$ GeV, $m_{\tilde{\chi}_1^0} = 48$ GeV and $\tau_{\tilde{\chi}_1^0} = 10$ ps (BV48), $\sim 25\%$ of the events have a LLP in LHCb acceptance.
  - $\tilde{\chi}_1^0$ is the LLP, mass range $20 - 60$ GeV/$c^2$ and lifetime $3 - 25$ ps.

Similar topology in some Hidden Valley models

  - $h_0 \rightarrow \pi^0_\nu \pi^0_\nu \rightarrow b\bar{b}b\bar{b}$
  - $\pi^0_\nu$ is the LLP (HV10).

Add reference to ATLAS/CMS analyses
Search for Higgs-like bosons decaying into long lived particles

**Selections**

- Dataset: $36 \, pb^{-1}$ at $\sqrt{s} = 7 \, TeV$.
- Trigger and reconstruction of LLP based on an inclusive displaced vertex algorithm.
- $h^0 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$ candidates:
  - Vertex outside matter region.
  - $m_{\text{vertex}} > 4 \, GeV$, $R > 0.4 \, mm$ and $N_{\text{tr}} \geq 4$
  - back to back $\tilde{\chi}^0_1$ candidates pointing to the same PV
  - Shape and yields compatible with $b\bar{b}$ backgrounds:
    $(75 \pm 13)k \, b\bar{b}$ expected, $59k$ observed.
- Final selection to reject all $b\bar{b}$ MC:
  - $m_{\text{vertex}} > 6 \, GeV$, $N_{\text{tr}} \geq 6$
  - Good quality vertex.
- No candidate observed in data.
Overall selection efficiency on BV48: $0.384 \pm 0.017(\text{stat.}) \pm 0.085(\text{syst.})\%$.

Main systematic uncertainties on the detection efficiency: trigger efficiency (15%) and vertex reconstruction (12%)

$\sigma_{h_0} \times BR(h^0 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1)\,$ 95% CL upper limit: 32 pb.

A fast simulation of the analysis chain allow to extend the probed phase space.

<table>
<thead>
<tr>
<th>$m_{LLP}$</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>48</th>
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<tbody>
<tr>
<td>$m_{h^0}$</td>
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<tr>
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<td>179</td>
<td>90</td>
<td>61</td>
<td>41</td>
<td>29</td>
</tr>
</tbody>
</table>

Fixed LLP lifetime = 10 ps
Cross section calculations

Relation between photoproduction and exclusive $J/\psi$ production in $pp$ given by:

$$\frac{d\sigma}{dy_{pp \rightarrow pJ/\psi p}} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow J/\psi p}(W+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow J/\psi p}(W-)$$

- $\frac{dn}{dk_{\pm}}$ is the photon flux for photon of energy $k_{\pm} \approx (M_{J/\psi}/2)\exp(\pm|y|)$.
- $(W_{\pm}^2) = 2k_{\pm}\sqrt{s}$ and $r_{\pm}$ is absorptive corrections.
- Ambiguity between $W+$ and $W-$ solution, both are used.


Deviation from power law, can be explained both by higher order and saturation effects.

Can be explained both by higher order contributions and by saturation models.