LHCb Overview

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on behalf of the LHCb collaboration

LHCb Implications Workshop
28/10/2020
Outline

● The LHCb experiment
● Overview of new LHCb results in 2020
  ○ Spectroscopy
  ○ Rare decays
  ○ CPV
  ○ Exotica
● Future of LHCb
  ○ the renewed LHCb detector
  ○ physics prospects

Disclaimer: no time to cover everything, please check experimental talks in various streams for details
LHCb: Large Hadron Collider Beauty experiment

- Precision measurements heavy flavor physics
- Core physics: CPV and rare decays
- Much more: spectroscopy, QCD, heavy ions...

- > 900 authors and > 40 nationalities
- 87 institutes from 18 countries
LHCb detector at LHC

$\Delta p / p = 0.5 - 1.0\%$

$\Delta IP = (15 + 29/p_T[GeV]) \text{ } \mu m$

$\Delta E/E_{\text{ECAL}} = 1\% + 10\% / \sqrt{E[GeV]}$

Electron ID $\sim 90\%$ for $\sim 5\%$ $e \rightarrow h$ mis-id probability

Kaon ID $\sim 95\%$ for $\sim 5\%$ $\pi \rightarrow K$ mis-id probability

Muon ID $\sim 97\%$ for $1-3\%$ $\pi \rightarrow \mu$ mis-id probability
LHCb dataset

Total recorded luminosity $\sim$9 fb$^{-1}$:

- Run 1 (2010-2012) $\sim$ 3 fb$^{-1}$
- Run 2 (2015-2018) $\sim$ 6 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Integrated Recorded Luminosity (1/fb)</td>
</tr>
<tr>
<td>2010</td>
<td>0.04 fb</td>
</tr>
<tr>
<td>2011</td>
<td>0.04 fb</td>
</tr>
<tr>
<td>2012</td>
<td>0.04 fb</td>
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<tr>
<td>2013</td>
<td>0.04 fb</td>
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<tr>
<td>2016</td>
<td>0.04 fb</td>
</tr>
<tr>
<td>2017</td>
<td>0.04 fb</td>
</tr>
<tr>
<td>2018</td>
<td>0.04 fb</td>
</tr>
</tbody>
</table>

All b-hadron species!

- $B_s$: $\frac{f_d}{f_d + f_u} = 0.122 \pm 0.006$
- $\Lambda_b$: $\frac{f_{\Lambda_b}}{f_d + f_u} = 0.259 \pm 0.018$

average over $p_T \in [4, 25]$ GeV and $\eta \in [2, 5]$ in pp collisions at 13 TeV [PRD100(2019)031102] and more: $\Xi_b$, $\Omega_b$, $B_c$, $B^*$ ...

*combination of LHCb results ongoing

$\sigma^{13\text{TeV}}(pp\rightarrow B^\pm X)/\sigma^{7\text{TeV}}(pp\rightarrow B^\pm X) = 2.02 \pm 0.02 \pm 0.12$

[JHEP 1712 (2017) 026] → almost x4 b-hadrons in Run 2
LHCb results

- CPV
- RD
- SL
- Charm
- Spectroscopy
- QCD, EW & exotica
- Heavy ions
A b-hadron factory

**NEW 2020**

**Excited Ω⁻ᵇ states**

**New excited Λ^₀ᵇ state**

See talk by D. Craik for details and further studies
An exotic hadron factory!

Four-charm states in di-J/ψ spectrum?

Observation of $\Lambda_b \rightarrow \eta_c p K^-$ and search for $P_{c^+} \rightarrow \eta_c p$

See talk by M. Wang for details and further searches: X(2900), X(4740), $P_{cs}$
Multiplicity-dependent $\psi(2S)$ & $\chi_{c1}$ production

Production of $\psi(2S)$ and $\chi_{c1}(3872)$ studied in 8 TeV pp collisions, exploiting techniques from Heavy Ion physics

- decrease of prompt fraction and ratio $\chi_{c1}(3872)/\psi(2S)$ with multiplicity

See talk by J. Crkovska for details
Intriguing deviations in rare B decays

Differential BR and angular distributions

Lepton Universality tests
Angular analyses of $B \rightarrow K^*\ell\ell$

New $B^0 \rightarrow K^*\mu^+\mu^-$ results: tension with SM $3.3\sigma$

$B^0 \rightarrow K^*e^+e^-$ low $q^2$: strong constraints on $C'_7$

See talk by D. Gerich for new results in $B^+$!
1st observation of TD-CPV in $B_s$ decays

New Run 2 analysis using 2.1 fb$^{-1}$ and combination with Run 1 results

$$A_{CP}(t) = \frac{\Gamma_{B^0(s)\rightarrow f(t)} - \Gamma_{B^0(s)\rightarrow f(t)}}{\Gamma_{B^0(s)\rightarrow f(t)} + \Gamma_{B^0(s)\rightarrow f(t)}} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh \left( \frac{\Delta \Gamma_{d,s}}{2} t \right) + A_f \sinh \left( \frac{\Delta \Gamma_{d,s}}{2} t \right)}$$

See talk by M. Torres for details and more results
Direct CPV in $B_{(s)} \rightarrow K^+\pi^-$

Measurement of $A_{CP}$ in $B_{(s)} \rightarrow K\pi$ and relation as test of the SM

Most precise measurement from single experiment

$$A_{CP}^{B_0^0} = -0.0831 \pm 0.0034$$

$$A_{CP}^{B_0^0} = 0.225 \pm 0.012$$

$$\Delta = \frac{A_{CP}^{B_0^0}}{A_{CP}^{B_0^0}} + \frac{B(B_0^0 \rightarrow \pi^+K^-)}{B(B_0 \rightarrow K^+\pi^-)} \Gamma_s = 0$$

$$\Delta = -0.085 \pm 0.025 \pm 0.035$$

Comparable with 0 at 2σ

What about $B^+$ mode? See talk by W. Parker with new results!
New constraints on $\gamma$

Less well-known angle Unitarity Triangle ($\delta \gamma \sim 5^\circ$)

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$

$B^\pm \rightarrow D h^\pm$, $D \rightarrow K_s h^+ h^-$

See talk by P. d’Argent for details, more results and new LHCb combination
Suppressed decays

 Searches for suppressed counterparts of well known decays

 BR($B^0 \rightarrow J/\psi \phi$) < $1.1 \times 10^{-7}$ @90% CL

 $B(B^0_s \rightarrow D_s^{\mp} D^\mp) / B(B^0 \rightarrow D^{\mp} D^\mp) = 0.137 \pm 0.017$ (stat.) $\pm 0.002$ (syst.) $\pm 0.006 (f_s/f_d)$

 NEW 2020
Search for New Exotic states

Long-lived particles $X \rightarrow e\mu\nu$
- Run 2 data (5.1 fb$^{-1}$)
- $m \in [7, 50]$ GeV/c$^2$, $\tau \in [2, 50]$ ps

Heavy Neutral Leptons in $W \rightarrow \mu^+N(\mu^\pm\text{jet})$
- Run 1 LHCb data (3 fb$^{-1}$)
- Pompt LN and LNV cases considered
- $\mu\mu\text{jet}$ probed at $M_N < 20$ GeV/c$^2$ for 1st
LHCb prospects
LHCb Upgrade: a quasi-new detector
LHCb Upgrade

New VeloPix detector

New tracker detectors

New RICH detectors

Removal of SPD/PS, new electronics

Removal of M1, new electronics
LHCb Upgrade

New VeloPix detector

- 3.5mm to beam (5mm Run1/2)
- 52 modules with 41M pixels
- improved PV and IP resolutions
LHCb Upgrade

- Scintillating fibers 2.4m x 250μm
- higher granularity for higher occupancy

New tracker detectors
LHCb Upgrade

- Optimised optical system
- Higher photon yield and improved resolution

New RICH detectors
LHCb Upgrade II

To be installed in LS3+4: new sub-detectors and technology updates (timing)

Timing:
~50 collisions/bc

New detectors
Trigger in Run 3 and beyond

Remove limitations of hardware trigger:

- remove tight $p_T$ and $E_T$ requirements
- $x2$ yields for fully hadronic decays

First level software trigger in GPUs:

- increase complexity of tracking algorithms
- better performance at higher throughput
Prospects for LU tests in $b \rightarrow c \nu$ decays

$R(D) - R(D^*)$ ongoing with current dataset

Also measurements with other $b$ hadrons:

- $\sigma_{R(Ds)} < 6\%$ (2.5\%) and $R(D^{(*)*})$
- $\sigma_{R(\Lambda_c)} < 4\%$ (2.5\%) and $R(pp)$ ($b \rightarrow u\nu\nu$)
# Prospects for CKM measurements

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>ATLAS &amp; CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_s$, with $B_s^0 \to D_s^+ K^-$</td>
<td>$^{+17}_{-22}%$</td>
<td>136</td>
<td>4$%$</td>
<td>–</td>
<td>1$%$</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$^{+5.0}_{-5.8}%$</td>
<td>167</td>
<td>1.5$%$</td>
<td>1.5$%$</td>
<td>0.35$%$</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \to J/\psi K_s^0$</td>
<td>0.04</td>
<td>609</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>$\phi_s^0$, with $B_s^0 \to J/\psi \phi$</td>
<td>49 mrad</td>
<td>44</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \to D_s^+ D_s^-$</td>
<td>170 mrad</td>
<td>49</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
</tr>
<tr>
<td>$\phi_s^{S\bar{S}s}$, with $B_s^0 \to \phi \phi$</td>
<td>154 mrad</td>
<td>94</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad</td>
</tr>
<tr>
<td>$q_s^{\phi}$</td>
<td>$33 \times 10^{-4}$</td>
<td>211</td>
<td>$10 \times 10^{-4}$</td>
<td>–</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6$%$</td>
</tr>
</tbody>
</table>
Further measurement of $|v_{ub}|/|v_{cb}|$ from $B_s \rightarrow K^-\mu^+\nu$? See talk by B. Khanji!
Prospects for Charm physics

Large benefit from fully software trigger
Prospects for Rare Decays

See talk by M. Santimaria on Friday

<table>
<thead>
<tr>
<th></th>
<th>Run 3</th>
<th>Run 4</th>
<th>Upgrade II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_X$ precision</td>
<td>9 fb$^{-1}$</td>
<td>23 fb$^{-1}$</td>
<td>50 fb$^{-1}$</td>
</tr>
<tr>
<td>$R_K$</td>
<td>0.043</td>
<td>0.025</td>
<td>0.017</td>
</tr>
<tr>
<td>$R_{K^*0}$</td>
<td>0.052</td>
<td>0.031</td>
<td>0.020</td>
</tr>
<tr>
<td>$R_\phi$</td>
<td>0.130</td>
<td>0.076</td>
<td>0.050</td>
</tr>
<tr>
<td>$R_{pK}$</td>
<td>0.105</td>
<td>0.061</td>
<td>0.041</td>
</tr>
<tr>
<td>$R_\pi$</td>
<td>0.302</td>
<td>0.176</td>
<td>0.117</td>
</tr>
</tbody>
</table>

arXiv:1808.08865
Conclusions

LHCb is not only a **b-factory** (huge production of $B^{0/+}$, $B_s$, $\Lambda_b$...) but also a **general purpose detector** in the forward region.

Wealth of **new results this year** and fresh ones for this workshop → details and more exciting results in dedicated talks.

LHCb is being (will be) upgraded to **collect x30 larger dataset** in Run 3-5.

Theory input is critical for **interpretation** of our results and development of **new measurements** to fully exploit potential of our data.
Conclusions

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Looking forward to having lots of discussions in this workshop!
BACK-UP
Observation of excited $\Omega^{-}_b$ states

$\Omega^{-}_b \rightarrow \Xi^0_b K^-$ with $\Xi^0_b \rightarrow \Xi_c^+ \pi^-, \Xi_c \rightarrow pK\pi$

<table>
<thead>
<tr>
<th>Peak of $\delta M$ [MeV]</th>
<th>Width [MeV]</th>
<th>Signal yield</th>
<th>Significances [$\sigma$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>523.74 ± 0.31</td>
<td>0.00$^{+0.7}_{-0.0}$</td>
<td>15$^{+6}_{-5}$</td>
<td>3.6</td>
</tr>
<tr>
<td>538.40 ± 0.28</td>
<td>0.00$^{+0.4}_{-0.0}$</td>
<td>18$^{+6}_{-5}$</td>
<td>3.7</td>
</tr>
<tr>
<td>547.81 ± 0.26</td>
<td>0.47$^{+0.6}_{-0.5}$</td>
<td>47$^{+11}_{-10}$</td>
<td>7.2</td>
</tr>
<tr>
<td>557.98 ± 0.35</td>
<td>1.4$^{+1.0}_{-0.8}$</td>
<td>57$^{+14}_{-13}$</td>
<td>7.0</td>
</tr>
</tbody>
</table>
di-$J/\psi$ candidates
Potential $T_{cccc}$ candidates
Angular analysis of $B \rightarrow K^{*} \ell \ell$

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} \bigg|_p = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.
\]
\[
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l 
\]
\[
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi 
\]
\[
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi 
\]
\[
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi 
\]
\[
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \bigg] ,
\]
Exploiting $b \rightarrow se^+e^-$ at very low $q^2$

Angular coefficients $A_T^{(2)}$ and $A_T^{\text{Im}}$ give access to $C'_7$:

$$\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^4(\Gamma + \Gamma)}{dq^2 d\cos \theta_\ell d\cos \theta_K d\phi} =$$

$$= \frac{9}{16\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \left( \frac{1}{4} (1 - F_L) \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_\ell + \right.$$

$$\left. \frac{1}{2} (1 - F_L) A^{(2)}_T \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + (1 - F_L) A^\text{Re}_T \sin^2 \theta_K \cos \theta_\ell + \right.$$

$$\left. \frac{1}{2} (1 - F_L) A^{\text{Im}}_T \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right].$$

Pollution from $C_{9,10}$ when $q^2$ far from zero $\rightarrow$ analysis at very low $q^2$

- Run 1 analysis: $q^2 \in [0.002, 1.120]$ GeV$^2$/c$^4$
- Run 1+2: $q^2 \in [0.0008, 0.257]$ GeV$^2$/c$^4$

after folding $\Phi$ to reduce number of parameters
Exploiting $b \rightarrow s e^+ e^-$ at very low $q^2$

Much cleaner selection achieved in new analysis

Mass shape, angular acceptance and model validated with $B \rightarrow K^* \gamma (\rightarrow e^+ e^-)$

arXiv:2010.06011
Photon polarisation from $b \rightarrow s e^+ e^-$ low $q^2$

Angular analysis of $B \rightarrow K^* e^+ e^-$ at very low $q^2$ with full LHCb dataset

\begin{align*}
A_T^{(2)}(q^2 \rightarrow 0) &= \frac{2 \text{Re}(C_7 C_7^*)}{|C_7|^2 + |C_7'|^2}, \\
A_T^{\text{Im}}(q^2 \rightarrow 0) &= \frac{2 \text{Im}(C_7 C_7^*)}{|C_7|^2 + |C_7'|^2},
\end{align*}

\begin{align*}
F_L &= 0.044 \pm 0.026 \pm 0.014, \\
A_T^{\text{Re}} &= -0.06 \pm 0.08 \pm 0.02, \\
A_T^{(2)} &= +0.11 \pm 0.10 \pm 0.02, \\
A_T^{\text{Im}} &= +0.02 \pm 0.10 \pm 0.01,
\end{align*}

Word-best constraints on $C'_7$

Very good agreement with SM
Flavour tagging at LHCb
Search for $\text{B} \rightarrow \text{J}/\psi \phi$

significance of 2.3σ, world-best limit

$\text{BR} (\text{B} \rightarrow \text{J}/\psi \phi) < 1.1 \times 10^{-7} \text{ @90\% CL}$
LHCb schedule overview

- LHC:
  - 2021: Run 3
  - 2023: LS3

- HL-LHC:
  - 2024: LS3
  - 2026: Run 4
  - 2029: LS4
  - 2030: Run 5

- Belle II:
  - Upgrade I
  - Upgrade II
  - Upgrade Belle II?
Velopix performance

IP resolution

Average hit efficiency per track

Evaluated at $v = 7.6$, $\sqrt{s} = 14$ TeV
Sifi performance

LHCb simulation

- Non e⁻
- e⁻
Upgrade 2 new detectors

Magnet stations

Measurement of low momentum particles:

- strange and charm physics, $\gamma \rightarrow e^+e^-$
- multi-body b decays, near-threshold

Scintillating fibers + SiPMs technology developed for Upgrade I

TORCH

Time-of-flight system in downstream region:

- reduce ghost rate, improve $\Lambda^0$ efficiency
- provide PID below 10 GeV (RICH1 limit)

1 cm quartz radiator + Micro-Channel Plate PMTs $\rightarrow$ ~15 ps/track