Recent results from the LHCb

20th Planck Conference
physics beyond the Standard Model
22-27 May 2017
Warszawa, PL
LHCb experiment | The detector

- LHCb proved itself to be the Forward General-Purpose Detector at the LHC

- High cross-section of heavy-quark production
- Excellent particle identification
- Excellent decay time resolution
- Excellent momentum resolution
LHCb experiment | The physics program

- LHCb specialises (mostly) in the ‘indirect’ approach where precise measurements of low energy phenomena tells us about unknown physics at higher energies;

Heavy flavour production

CKM and CPV with b and c hadrons

Rare decays of b and c hadrons

EW, QCD + Exotica in forward region

Spectroscopy in pp collisions and B decays

Ions and Fixed Targen

> 378 papers! Public results link
  > 50 in 2016
  > 20 in 2017

PRL 118, 052002 (2017)

\[ \sigma(pp \rightarrow b\bar{b}X) \]
7TeV: \( \approx 295 \, \mu b \)
13TeV: \( \approx 600 \, \mu b \)

\[ \sigma(pp \rightarrow c\bar{c}X) \approx 20 \times \sigma_{bb} \]

- 0.36 fb\(^{-1}\) \( \sqrt{s} = 7 \, \text{TeV} \) (2010)
- 1 fb\(^{-1}\) \( \sqrt{s} = 7 \, \text{TeV} \) (2011)
- 2 fb\(^{-1}\) \( \sqrt{s} = 8 \, \text{TeV} \) (2012)
- 2 fb\(^{-1}\) \( \sqrt{s} = 13 \, \text{TeV} \) (2015&2016)
Heavy flavour production

CKM and CPV with b and c hadrons

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Spectroscopy in pp collisions and B decays

Ions and Fixed Target

- First $\phi_s$ measurement in $B_s \rightarrow J/\psi K K$  [arXiv:1704.08217]
- $B_{(s)}^0 \rightarrow \mu^+\mu^-$  [PRL 118 (2017) no.19, 191801]
- $B_{(s)}^0 \rightarrow \tau^+\tau^-$  [arXiv:1703.02508]
- $B^+ \rightarrow K^+\mu^+\mu^-$  [EPJ C77 (2017) no.3, 161]
- LU test with B decays: $R(K^{*0})$  [arXiv:1705.05802]
$CP$-violation
The Standard Model prediction of the CP-violating phase in $b \to c\bar{c}$ transitions:

$$\phi_s^{SM} \equiv -2 \arg \left( -\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) = -36.5^{+1.3}_{-1.2} \text{ mrad}$$


The average of previous measurements (D0, LHCb, ATLAS, CMS):

$$\phi_s = -30 \pm 33 \text{ mrad}$$

[arXiv:1612.07233]

The LHCb update:

- Full Run 1 dataset;
- The first measurement using $B_s \to J/\psi K^+K^-$ decays with $K^+K^-$ mass region above the $\phi(1020)$ meson;
- The CP-even and CP-odd components in the decay fitted as functions of the $B_s$ proper decay time and helicity angles.
Many resonances and a S-wave structure have been found:

- $\phi(1020)$
- $f_2(1270)$
- $f'_2(1525)$
- $\phi(1680)$
- $f_2(1750)$
- $f_2(1950)$

S-wave

Results

$\phi_s = 119 \pm 107 \pm 34 \text{ mrad}$

The LHCb combination

$\phi_s = -25 \pm 45 \pm 8 \text{ mrad}$
The measurement of the CP-violating phase $\phi_s$ is in agreement with the SM prediction:
- CP violation has never been measured in baryons before, despite predictions from the SM that CP violation also exists in the baryon sector.

- LHCb search for CP-violating asymmetries in the decay angle distributions of $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$ decays

- The $P$- and $CP$- violating observables define on asymmetries, $A_{\tilde{T}}$ built from scalar triple products

\[
a_{\tilde{T} \text{- odd}}^P = \frac{1}{2} (A_{\tilde{T}} + \overline{A}_{\tilde{T}}), \quad a_{\tilde{T} \text{- odd}}^{CP} = \frac{1}{2} (A_{\tilde{T}} - \overline{A}_{\tilde{T}})
\]
Signal yields obtained from fits to data:

\[ 6,646 \pm 105 \quad 1,030 \pm 56 \]

* For \( \Lambda_b^0 \to p\pi^-K^+K^- \) smaller purity and signal yield of the sample do not permit PV and CPV to be probed with the same precision as for \( \Lambda_b^0 \to p\pi^-\pi^+\pi^- \)
Searches for localized P or CP violation

Scheme A

To isolate regions of phase space according to their dominant resonant contributions:

$$\Delta(1232)^{++} \to p\pi^+$$

$$\rho(770)^0 \to \pi^+\pi^-$$

Scheme B

To exploits in more detail the interference of contributions visible as a function of the angle between the decay planes.
Results for $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$

Scheme A

$\alpha_{CP}$ odd

$\chi^2/\text{ndf} = 21.1/12$

Scheme B

$\alpha_{CP}$ odd

$\chi^2/\text{ndf} = 30.5/10$

An overall deviation from no-CPV hypothesis: 3.3 $\sigma$

First hints of CP violation in baryons!!!
Rare decays

- Strategy: measure with precision processes containing SM particles
- Very important to have SM predictions under theoretical control
- Some channels are very clean, only limiting factor is statistics
Rare decays $|B_{(s)}^0 \to \mu^+\mu^-|$

- Very accurate SM predictions [PRL 96 (2006) 241802]

$$B(B^0 \to \mu^+\mu^-)^{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$
$$B(B_s^0 \to \mu^+\mu^-)^{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9}$$

- Summary previous measurements / current situation
LHCb update

- 3 fb$^{-1}$ of Run1 + 1.4 fb$^{-1}$ of Run2
- new signal isolation
- new BDT: 50% better bgd rejection
- improved PID: 50% less $B \to h^+ h^-$
LHCb update

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- new signal isolation
- new BDT: 50% better bkgd rejection
- improved PID: 50% less $B \rightarrow h^+ h^-$

\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} \text{ at 95\% CL}
\]
\[
\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-9} \quad (7.8\sigma)
\]

First single-experiment observation of the $B_s$ mode !!!
Rare decays | $B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$  

$\Rightarrow$ New observable: effective lifetime

- Even if the BF is SM, the effective lifetime provides a probe to search for NP.

- The effective lifetime can be expressed in terms of $A_{\Delta \Gamma}^{\mu^{+}\mu^{-}}$  

$\Rightarrow$ For the first time, measurement of the effective lifetime

$\tau(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}) = 2.04 \pm 0.44 \text{ (stat) } \pm 0.05 \text{ (syst) ps}$

- The measurement consistency:
  
  SM: $A_{\Delta \Gamma}^{\mu^{+}\mu^{-}} = 1 \ (1\sigma)$  
  
  NP: $A_{\Delta \Gamma}^{\mu^{+}\mu^{-}} = -1 \ (1.4\sigma)$

- The first step for future analyses of this kind.
Rare decays | $B_{(s)}^0 \rightarrow \tau^+ \tau^-$

- Theoretically, as clean as the muonic mode
- Experimentally much more challenging
- More abundant than the muon mode [PRL 112 (2014) 101801]

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-)_{SM} = (2.22 \pm 0.19) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-)_{SM} = (7.73 \pm 0.49) \times 10^{-7}$$

- Will make for a very clean LFU test with muonic mode in the future
- Only existing limit on the $B^0$ mode from Babar [PRL 96 (2006) 241802]

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 4.1 \times 10^{-3} \quad @ \, 90\% \, C.L.$$
Rare decays | $B^0_{(s)} \rightarrow \tau^+\tau^-$

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\]

- Analysis of LHCb Run1 data, in hadronic tau decay via the resonances

\[
\tau^- \rightarrow a_1(1260)^-\nu_\tau, \quad a_1(1260)^- \rightarrow \rho(770)^0\pi^- \\
\mathcal{B}(\tau^\pm \rightarrow \pi^\pm\pi^\mp\pi^\pm\nu_\tau) = (9.31 \pm 0.05)\%
\]

- **World best limits** set for each mode (assuming no contributions from the other):

\[
\mathcal{B}(B^0_s \rightarrow \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at 95\% CL} \\
\mathcal{B}(B^0 \rightarrow \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at 95\% CL}
\]
The observed tensions in measurements where regions of dimuon mass around the $J/\psi$ and $\psi(2S)$ resonances were excluded [JHEP 06 (2014) 133]
The observed tensions in measurements where regions of dimuon mass around the $J/\psi$ and $\psi(2S)$ resonances were excluded.

Analyse the $m(\mu\mu)$ spectrum of $B^+ \rightarrow K^+ \mu^+ \mu^-$ modeling all resonances:
- Fits with different phase hypotheses for long-distance contributions

The observed BF is lower than the SM, in agreement with previous analysis (same data)

$$B(B^+ \rightarrow K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \text{ (stat)} \pm 0.23 \text{ (syst)}) \times 10^{-7}$$

Scan of Wilson coefficients disfavours the SM solution
Rare decays | angular anomalies

- Lepton Flavour Universality tests with B decays – tension in the data coming from $B \rightarrow K^* \mu^+ \mu^-$ angular observables

* Belle, ATLAS and CMS use angular folding, differences in observables, background treatment and control modes.
Lepton Flavour Universality tests with B decays – tension in the data coming from $B \to K^* \mu^+ \mu^-$ angular observables

Violation of lepton universality

$R(K)$ results

$LHCb : 0.745^{+0.090}_{-0.074} \pm 0.036$ in the $1 < q^2 < 6 \text{ GeV}^2/c^4$, tension with the SM at $2.6\sigma$
Lepton Flavour Universality tests with B decays – tension in the data coming from 
\( B \to K^* \mu^+ \mu^- \) angular observables

Violation of lepton universality

\( R(K) \) results

\( R(K^*) \) measurement
- Using full Run 1 data
- Double ratio to cancel systematics
- Measuring in two bins of \( q^2 \):
  - Low: 0.045-1.1 GeV/c2
  - Central: 1.1-6 GeV/c2
\( R(K^{*0}) \) measurement

\[
R_{K^{*0}} = \begin{cases} 
0.66 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4 \\
0.69 \pm 0.11 \text{ (stat)} \pm 0.05 \text{ (syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4
\end{cases}
\]

Results compatibility with the SM expectations:
- low\(-q^2\) bin 2.1 - 2.3 \(\sigma\)
- central\(-q^2\) bin 2.4 - 2.5 \(\sigma\)
- \( R(K^{*0}) \) measurement

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Results compatibility with the SM expectations:
- low-\( q^2 \) bin 2.1 - 2.3 \( \sigma \)
- central-\( q^2 \) bin 2.4 - 2.5 \( \sigma \)
Recent results from the LHCb

Conclusions

- LHCb has taken series of measurement in flavour physics
- CP violation results compatible with the SM
- First hints of CP violation in baryons
- Rare decays remain the source of tensions with the SM both in LFU tests and in global fits to Wilson coefficients
- First measurement of promising observable, the effective lifetime $B_s^0 \rightarrow \mu^+\mu^-$
- Many other recent results not covered here: [link]
Fit results of the resonant structure. The three possible polarizations of the $J/\psi$ generate longitudinal (0), parallel ($\parallel$) and perpendicular ($\perp$) transversity amplitudes.

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
<th>Transversity fraction (%)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
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<tr>
<td>$\phi(1020)$</td>
<td>70.5 ± 0.6 ± 1.2</td>
<td>50.9 ± 0.4</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>1.6 ± 0.3 ± 0.2</td>
<td>76.9 ± 5.5</td>
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<tr>
<td>$f_2'(1525)$</td>
<td>10.7 ± 0.7 ± 0.9</td>
<td>46.8 ± 1.9</td>
</tr>
<tr>
<td>$\phi(1680)$</td>
<td>4.0 ± 0.3 ± 0.3</td>
<td>44.0 ± 3.9</td>
</tr>
<tr>
<td>$f_2(1750)$</td>
<td>$0.59^{+0.23}_{-0.16}$ ± 0.21</td>
<td>58.2 ± 13.9</td>
</tr>
<tr>
<td>$f_2(1950)$</td>
<td>$0.44^{+0.15}_{-0.10}$ ± 0.14</td>
<td>2.2$^{+6.7}_{-1.5}$</td>
</tr>
<tr>
<td>S-wave</td>
<td>10.69 ± 0.12 ± 0.57</td>
<td>100</td>
</tr>
</tbody>
</table>
- Scalar triple products of final-state particle momenta in the $\Lambda_b^0$ centre-of-mass frame

\[
C_\tilde{T} = p_p \cdot (p_{h_1^-} \times p_{h_2^+}) \quad \overline{C_\tilde{T}} = p_\bar{p} \cdot (p_{h_1^+} \times p_{h_2^-}) \text{ for } \Lambda_b^0
\]

- Asymmetries definition

\[
A_{\tilde{T}}(C_\tilde{T}) = \frac{N(C_\tilde{T} > 0) - N(C_\tilde{T} < 0)}{N(C_\tilde{T} > 0) + N(C_\tilde{T} < 0)}
\]

\[
\overline{A_{\tilde{T}}}(\overline{C_\tilde{T}}) = \frac{\overline{N}(\overline{C_\tilde{T}} > 0) - \overline{N}(\overline{C_\tilde{T}} < 0)}{\overline{N}(\overline{C_\tilde{T}} > 0) + \overline{N}(\overline{C_\tilde{T}} < 0)}
\]

$N$ and $\overline{N}$ are the numbers of $\Lambda_b^0$ and $\Lambda_b^0$ decays

- The P- and CP-violating observables:

\[
a_{\tilde{T} \text{-odd}}^p = \frac{1}{2} \left( A_{\tilde{T}} + \overline{A_{\tilde{T}}} \right) \quad a_{\text{CP}}^{\tilde{T} \text{-odd}} = \frac{1}{2} \left( A_{\tilde{T}} - \overline{A_{\tilde{T}}} \right)
\]
Rare decays | $B^+ \rightarrow K^+ \mu^+ \mu^-$

EPJ C77 (2017) no.3, 161
Number of candidates for $B^0 \to K^*0 l^+ l^-$ final states with muons and electrons
Rare decays $| R(K^{*0}) |$

Submitted to JHEP last week!
☐ Systematic uncertainties

<table>
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<tr>
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<th>$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]</th>
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<td>low-$q^2$</td>
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<tr>
<td>$r_{\eta/\phi}$ ratio</td>
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<td>Total</td>
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