Review of recent results by LHCb at CERN

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On behalf of LHCb Collaboration

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Results by LHCb from Run 1 data at $\sqrt{s}=7$ and 8 TeV

Search for physics beyond SM

- Rare decays of heavy flavours
  \[ B_{(s)} \rightarrow \mu^+ \mu^- \quad B^0 \rightarrow K^* \mu^+ \mu^- \]
- Heavy quark couplings $V_{ub}, V_{cb}$
- Testing lepton universality
  \[ B^+ \rightarrow K^+ \ell^+ \ell^- \quad \bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell \]
- CKM and CP-violation parameters from $b$ (and $c$) decays

Hadron exotics

- Pentaquarks $P_c^+$ and tetraquarks XYZ
Long visible B decay path (~ 1 cm)

Vertex location ~10 μm

Large production rate of beauty mesons ($10^3$ e$^+e^-$ factories)

Excellent hadron identification

Covers $2<\eta<5$ for $10<\theta<300$ mrad

Trigger bandwidth 5 kHz

In Run 1, upgraded more than twice in Run 2

3 fb$^{-1}$ of data taken 2011-12

Rare decays $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

LO FCNC suppressed

Allowed at higher orders with possible contributions from new particles to loops

Standard Model

Possible contributions from New Physics
$B^0_{(s)} \rightarrow \mu^+ \mu^-$

Combined LHCb and CMS; BF determined normalizing numbers $B^0_{(s)} \rightarrow \mu \mu$ to total # decays (from measured $B^+ \rightarrow J/\Psi K^+$)

$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

Uncertainties statist. and syst. (35% and 18%) combined

$\frac{\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)} = 0.14^{+0.08}_{-0.06}$

$2\sigma$ compatibility with SM and BSM with minimum flavour violation
Semileptonic penguin processes with possible exotic contributions

\[ B^0 \rightarrow K^{*0} (892) \gamma \]
\[ \Downarrow K^+ \pi^- \quad \Downarrow \mu^+ \mu^- \]

\[ B^0 \rightarrow K^{*0} (892) \chi \]
\[ \Downarrow K^+ \pi^- \quad \Downarrow \mu^+ \mu^- \]
\( B^0 \to K^{*0}(892)\mu^+\mu^- \quad \text{Angular distributions' analysis} \)

Completely described by effective masses and angular distributions

\[
\frac{d^4 \Gamma}{dq^2 d\Omega} = \frac{9}{32\pi} \sum_{i=1}^{11} l_i(q^2) f_i(\Omega)
\]

Define observables

\[
S_i = (l_i + \bar{l}_i)/\left( \frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right) \quad A_i = (l_i - \bar{l}_i)/\left( \frac{d\Gamma}{dq^2} - \frac{d\bar{\Gamma}}{dq^2} \right)
\]

and determine from fits to data.
Optimized angular observables, where form-factor uncertainties cancel, to compare with SM predictions

\[ P_i' = \frac{S_i}{F_L(1 - F_L)}, \quad i = 4, \ldots, 8 \]

Fraction of longitudinal polarization of \( K^* \)
Comparison with SM predictions gives 3.4σ discrepancy; room for models, large hadronic effects are not excluded

$P'_5$ is the only parameter not fitting well to the data


SM predictions by S.Descotez-Henon et al., JHEP 12(2014)125

Last points discrepancy 2.8σ, 3σ
Penguin processes, e.g. $B_s \rightarrow \Phi \mu^+ \mu^-$

$\nabla \quad K^+ K^-$

Excluded charmonia resonances

Measured BFs $3\sigma$ below SM predictions for $q^2 < 6$ GeV$^2$

LHCb, JHEP 1509(2015)179
Tests of lepton universality

\[ \mathbf{B}^+ \rightarrow \mathbf{K}^+ \mathbf{\mu}^+ \mathbf{\mu}^- \]

Equality of E-W couplings of e and \( \mu \) in SM

\[ R_K = \frac{\mathcal{B}(\mathbf{B}^+ \rightarrow \mathbf{K}^+ \mu^+ \mu^-)}{\mathcal{B}(\mathbf{B}^+ \rightarrow \mathbf{K}^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-2}) \]

Sensitive to SME with new (pseudo)scalars

Measurement for dilepton mass range \( 1 < q^2 < 6 \text{ GeV}^2 \)

\[ R_K = 0.74^{+0.090}_{-0.074} \pm 0.036 \]

2.6 \( \sigma \) excursion from SM prediction
Lepton universality: ratio of semileptonic branching fractions

\[ R(D^*) = \frac{\mathcal{B}(\Bar{B}^0 \to D^* + \tau^- \Bar{\nu}_\tau)}{\mathcal{B}(\Bar{B}^0 \to D^* + \mu^- \Bar{\nu}_\mu)} \]

Identification of $\tau$ using

$\tau^- \to \mu^- \Bar{\nu}_\mu \nu_\tau$

All normalization and shape parameters at their best-fit values

Standard model: \( R(D^*) = 0.252 \pm 0.003 \)

LHCb: \( R(D^*) = 0.336 \pm 0.027 \text{ stat} \pm 0.030 \text{ syst} \)

2.1 \( \sigma \) away, (stat.+syst. combined)
CKM matrix elements, CP violation parameters, mixing, interference
Heavy flavour couplings

Measure strength of $b$ couplings to $u$ and $c$

\[
\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda^0_b \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda^0_b \to \Lambda^+_c\mu^-\bar{\nu}_\mu)} R_{ff} \]

Mass for determination signal candidates

$q^2 > 15 \text{ GeV}^2$ to reduce LQCD uncertainties

Corrected for $\Lambda^0_b \to N^*\mu\nu$ using MC
LHCb measurement for $q^2 > 15$ GeV$^2$

\[
\begin{align*}
|V_{ub}| &= 0.083 \pm 0.004 \pm 0.004 \\
|V_{cb}| &= (3.95 \pm 0.8) \times 10^{-3}
\end{align*}
\]

World average from exclusive measurements

Recentmost Belle result, full sample $B \rightarrow D\pi\nu$, arXiv:1510.03657

Normalization to $|V_{cb}|$
B and D decays used to determine CKM and CPV (incl. relevant hadronic parameters)

<table>
<thead>
<tr>
<th>Decay</th>
<th>Description</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to Dh$</td>
<td>$CP$-violating weak phase</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$\Gamma(B^- \to D^0 K^-)/\Gamma(B^- \to D^0 \pi^-)$</td>
<td>$R_{Cab.}$</td>
</tr>
<tr>
<td>$B^\pm \to D\pi^\pm$</td>
<td>$A(B^- \to \overline{D}^0 \pi^-)/A(B^- \to D^0 \pi^-) = r_{B}^{D\pi} e^{i(\delta_{B}^{D\pi}-\gamma)}$</td>
<td>$r_{B}^{D\pi}$, $\delta_{B}^{D\pi}$</td>
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<td>$B^\pm \to DK^\pm$</td>
<td>$A(B^- \to \overline{D}^0 K^-)/A(B^- \to D^0 K^-) = r_{B}^{DK} e^{i(\delta_{B}^{DK}-\gamma)}$</td>
<td>$r_{B}^{DK}$, $\delta_{B}^{DK}$</td>
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<td>$B^0 \to DK^{*0}$</td>
<td>amplitude ratio, effective strong phase difference, and coherence factor</td>
<td>$r_{B}^{DK^{*0}}$, $\delta_{B}^{DK^{*0}}$, $\kappa_{B}^{DK^{*0}}$</td>
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<tr>
<td>$B_s^0 \to D_s^\mp K^\mp$</td>
<td>$q/p \cdot A(B_s^0 \to D_s^- K^+)/A(B_s^0 \to D_s^+ K^-) = r_{B}^{D_s K} e^{i(\delta_{B}^{D_s K}-(\gamma-2\beta_s))}$</td>
<td>$r_{B}^{D_s K}$, $\delta_{B}^{D_s K}$</td>
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<td>$D^0 \to K^\pm \pi^\mp$</td>
<td>$A(D^0 \to \pi^- K^+)/A(D^0 \to K^- \pi^+) = r_{D}^{K\pi} e^{-i\delta_{D}^{K\pi}}$</td>
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<td>$D^0 \to K^+ K^-$</td>
<td>direct $CP$ asymmetry</td>
<td>$A_{CP}^{dir}(K K)$</td>
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<td>$D^0 - \overline{D}^0$</td>
<td>mixing parameters</td>
<td>$x_D$, $y_D$</td>
</tr>
<tr>
<td>$B_s^0 - \overline{B}_s^0$</td>
<td>mixing phase</td>
<td>$2\beta_s$</td>
</tr>
</tbody>
</table>

Plus other decays, more difficult to analyse (4h meson, beauty and charm baryon decays ..)
Determination of $\gamma$ CKM angle

$$\gamma = \arg \left( -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

LHCb, Phys.Rev. D90(2014)112002

Need to measure interference $b \rightarrow c, \ b \rightarrow u$

$$B^0 \rightarrow D^0 K^{*0}$$

Asymmetries between channels depend on $\gamma$ and amplitude-dependent hadronic parameters $\delta_B, r_B, \kappa$

Self-tagging channel (from kaon charge from $K^* \rightarrow K\pi$ decay), no need for time-dependent analysis

Interference term larger than in corresponding $B^+ \rightarrow K^+ \pi^0$ decay
LHCb, Phys.Rev. D90(2014)112002
Estimate based on tree-level processes measured by LHCb

LHCb, LHCb-CONF-2014-004, updates expected soon
\( \Phi_s \) interference phase

Small phase, precisely known
In theory

\[
\begin{align*}
\phi_M &= 2 \arg(V_{tb} V_{ts}^*) \\
\phi_D &= \arg(V_{cb} V_{cs}^*) \\
\phi_s &= \phi_M - 2\phi_D = -2 \arg\left(- \frac{V_{cb} V_{cs}^*}{V_{tb} V_{ts}^*}\right)
\end{align*}
\]
Golden channel: $B_s^0 \rightarrow J/\Psi \Phi$

Fit to decay time and helicity angles

Also contributions from other channels measured by LHCb, e.g. $J/\Psi \rightarrow e^+e^-$
Summary of $\Phi_s^{ccs}$ and $\Delta \Gamma_s$  

**Compatibility of world average with SM prediction:**

- $\Phi_s$ compatible with zero

**LHCb measurements**

- $J/\psi K^+ K^-$: $-0.058 \pm 0.049 \pm 0.006$  
- $J/\psi \pi^+ \pi^-$: $+0.070 \pm 0.068 \pm 0.008$  
  (LHCb, Phys.Rev. D89(2014)092006)
- $D_s^+ D_s^-$: $+0.02 \pm 0.17 \pm 0.02$  
  (LHCb, Phys.Rev.Lett. 113(2014)211801)
Recent result on CPV in charm decays; the most precise so far

\[ \Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-) \]

Detector and production asymmetries cancel

Preliminary result: LHCb-PAPER-2015-055

\[ \Delta A_{CP} = (-0.10 \pm 0.08_{\text{stat}} \pm 0.03_{\text{syst}})\% \]

No CPV observed
Pentaquark*) states

Decays of beauty hyperon

\[ \Lambda_b^0(5620) \rightarrow J/\Psi \ pK^- \]

Either usual \( \Lambda^* \rightarrow pK^- \) or (unusual) \( P_c^+ \rightarrow J/\Psi \ p \)

\[ J/\Psi \rightarrow \mu^+ \mu^- \]

\[ \Lambda(1520) \]

\[ m^2 = 19.5 \text{ GeV}^2 \]

*) treat the term with caution; true nature of states under debate
Amplitude analysis with all possible $\Lambda$ resonances (14 well-established)


Fit (■) with two additional states: masses 4380 and 4450 MeV widths 205 and 39 MeV parities (3/2)- and (5/2)+

No additional states: bad fit
Argand plot analysis; indication of resonant 4450 (not quite for 4380): rapid phase change counterclockwise


<table>
<thead>
<tr>
<th>State</th>
<th>mass (MeV)</th>
<th>width (MeV)</th>
<th>fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(3/2)^-</td>
<td>4380 ± 8 ± 29</td>
<td>205 ± 18 ± 86</td>
<td>8.4 ± 0.7 ± 4.2</td>
</tr>
<tr>
<td>P(5/2)^+</td>
<td>4449.8±1.7±2.5</td>
<td>39 ± 5 ± 19</td>
<td>4.1 ± 0.5 ± 1.1</td>
</tr>
</tbody>
</table>

Significance for 4380: 9σ, for 4450: 12σ
Combined: 15σ
Result compatible with pure charmonium or charmonium-molecular mixture interpretation; Does not support molecular DD* model (disfavoured at 4.4 \sigma)
**X(3872): determination of quantum numbers**

\[ B^+ \rightarrow X(3872) K^+ \]

- **LHCb, Phys.Rev. D92(2015)011102**

Only \( J^{PC}=1^{++} \) fits well \( \cos(\theta_X) \);

Decays dominantly S-wave, D-wave admixture 4%

Consistent with molecular, tetraquark or \( \chi_{c1}(2^3P_1) \), maybe mixed

![Graph showing LHCb data with different channels and results for different quantum numbers](image-url)
Tetraquarks*: evidence for Z(4430)

**B^0 \rightarrow \Psi' \pi^- K^+**

Unambiguously determined $J^P=1^+$ state at $m=4475$ MeV
(keep old Belle's name, however)

Originally found by Belle


Being charged, cannot be charmonium resonance

Adding another resonance, Z(4239) and 0^-, only slightly improves fit (26%); no claims

$m = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 173 \pm 13^{+37}_{-34}$ MeV

*) term to be treated cautiously
Recent LHCb results

- **Inclusive top production**: identified $t \to W^+(b\text{-jet})$ ($W \to \mu\nu$, $p_T^{\mu} > 25$ GeV, $p_T^b > 50$ GeV & requirements on $\eta$)

\[ \sigma_t(8 \text{ TeV}) = 289 \pm 43_{\text{stat}} \pm 40_{\text{syst}} \pm 29_{\text{th}} \text{ fb} \]

Agreement with NLO SM


- **Ridge** – 2-part. correlations in $p+Pb$ ($Pb+p$) (at 5 TeV)

LHCb, arXiv:1512.00439
earlier observed by other LHC experiments

Groups at $\Delta\Phi=0$ and $\Delta\Phi=\pi$ (different jets)
Other recent intriguing results by LHCb, but not covered in this talk

- Search for hidden sector bosons
- Search for lepton flavour violation
- More results on CP symmetry and CKM matrix elements
- Testing Lorentz and CPT symmetry
Conclusions

Search for New Physics by examination of SM predictions with 3 fb$^{-1}$ Run 1 data

- BF($B_{(s)} \rightarrow \mu^+ \mu^-$) consistent with SM (joint LHCb & CMS analysis)

- Search for exotic contributions to semileptonic penguin processes: $\sim 3.4 \sigma$ discrepancy but only in one angular observable

- Determination of $u_b$ and $c_b$ couplings from semileptonic $\Lambda_b$ decays: 3.5 $\sigma$ away from exclusive measurements
Conclusions, cont.

Search for New Physics by examination of SM predictions with 3 fb\(^{-1}\) Run 1 data, cont.

- Agreement 2.1 $\sigma$ with lepton universality in semileptonic B decays
- Determination of CKM $\gamma$ angle and $\Phi_s$ interference phase of mixing-induced CP violation: agreement with world data and SM; theoretical predictions still much more precise
- Search for CPV in charm decays consistent with no effect
Conclusions, cont.

Investigation of multiquark states containing c quarks and other hadron physics results

- Discovery of two pentaquark states $P_{c}^{+}(4450)$ and $P_{c}^{+}(4380)$; indication of resonant nature of $P_{c}^{+}(4450)$
- Determination of quantum numbers of state $X(3872)$
- Confirmation of tetraquark $Z(4430)$ and indication of its resonant nature
- Inclusive top quark production
- Ridge effect
Backup and additional material
LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger
- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

- 2 kHz Inclusive Topological
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon
Search for hidden-sector bosons

Lack of evidence for dark matter and observation of cosmic-ray anomalies

Possible candidates from hidden sector, coupling to both SM particles and WIMP

High sensitivity to hidden sector due to t-mediated b\rightarrow s transitions

\[ \mathbf{B}^0 \rightarrow \mathbf{K}^*{}^0(892) \chi \]
\[ \downarrow \mathbf{K}^+ \pi^- \quad \downarrow \mu^+ \mu^- \]

Taken whole sample with \( 1.1 < m_{\mu^+\mu^-} < 6 \text{ GeV}^2 \)

uBoost classifier used for sample selection, trained on sidebands to distinguish from background
All candidates' mass satisfying full selection: 506±33 signal

Mass regions excluded due to possible resonance contributions
Upper limits at 95% c.l., several $\tau(\chi)$

Measured by LHCb

$\mathcal{B}(B^0 \rightarrow K^* \mu^+ \mu^-) = (1.3 \pm 0.3) \times 10^{-7}$

$\mathcal{B}(B^0 \rightarrow K^* \chi(\mu^+ \mu^-))$

$B_s^0 \rightarrow J/\Psi \pi^+ \pi^-$

with resonant structure of $\pi^+\pi^-$

$B$ $B_s$

Other channels with $J/\Psi$, misreconstructed or lost hadrons

Signal fit

Background fit

LHCb, Phys.Rev. D89(2014)092006
\[ B_s^0 \rightarrow D_s^+ D_s^- \]
New measurement of CPV and estimate of $\gamma$ in $B^{\pm}\rightarrow Dh^{\pm}$, with $D\rightarrow \pi\pi\pi, K\pi\pi, KK\pi$

LHCb, Phys.Rev. D91(2015)112014

ADS decay modes: to flavour eigenstate, e.g. $D\rightarrow K\pi$
GLW modes: to CP eigenstate, e.g. $D\rightarrow KK$

Asymmetries sensitive to hadronic parameters and $\gamma$; hence new contribution to $\gamma$
Interpretations favour resonant \( P_c(4450) \): \( \Sigma_c^+ \bar{D}^0, \Lambda_c^+ \bar{D}^0 \)

Not so for \( P_c(4380) \), too deep binding of 80 MeV below threshold for \( \Sigma D = 4462 \) MeV

$B^+ \rightarrow X(3872) K^+$

$\gamma \rightarrow \psi \gamma$ \hspace{1cm} $\psi = J/\psi, \psi(2S)$

$\rightarrow \mu^+ \mu^-$

X(3872): determination of quantum numbers

\[ \text{B}^+ \rightarrow X(3872) \text{K}^+ \]

\[ \nabla \rho^0, J/\psi \rightarrow \mu^+ \mu^- \]

\[ \rightarrow \pi^+ \pi^- \]

Use 1011±38 decays and perform 5-dimensional helicity-dependent amplitude analysis without assumption on domination by lowest angular momentum \( L_{\text{min}} \).


Fit X(3872) signal

Background fit
Recent developments:
$P_c^+(4450)$ as $DΣ$ rescattering molecular resonance

$P_c^+(4450)$ is close to threshold for channels $Σ_c^+ D^0$, $Λ_c^+ D^0$

Same valence quark contents $(c\bar{c}uud)$ for systems $(J/ψ p)$, $(Σ_c^+ D^0)$, $(Λ_c^+ D^0)$
Amplitude for final-state $m(eson)$-$b(aryon)$ rescattering and resonance formation

\[
T^{(mb)}(M_{mb}) = V_b h_{K^-b} G_{mb}(M_{mb}) t_{mb \rightarrow J/\psi_p}(M_J/\psi_p)
\]

- Production weight
- Breit-Wigner
- Kinematics and CKM
- Intermediate regularized loop

This model naturally incorporates molecular-like picture