LHCb status and prospects

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LHCb collaboration
Flavour physics at colliders

### $e^+e^-$ machines

**Production of $b\bar{b}$ pairs at threshold.**

**Pros:**
- Clean environment
- Efficient reconstruction of neutral modes
- Efficient flavour tagging

**Contrasts:**
- Low production cross-section (especially $B^0_s$ and heavier)
- Small boost (artificially by asymmetric energies) $\Rightarrow$ low decay time resolution

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### Hadron machines

#### CDF

#### D0

#### LHCb

#### Atlas

#### CMS

**Production of $b\bar{b}$ pairs in $pp$ ($p\bar{p}$) collisions:**

**Pros:**
- Forward production, large boost
- All sorts of $b$ hadrons produced ($B^0, B^+, B^0_s, B^+_c, \Lambda^0_b, \Xi_b, B^*, \ldots$)
- Large production cross-section

**Contrasts:**
- Busy events, hard to reconstruct neutral modes.
- Lower flavour tagging power
One-arm spectrometer optimised for studies of beauty and charm decays at LHC

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- Good vertexing: measure $B^0$ and $B_s^0$ oscillations, reject prompt background

**Vertexing**

$B_s^0$ oscillations with $B_s^0 \rightarrow D_s \pi$

![Graph showing oscillations with decay time and tagged mixed, tagged unmixed, fit mixed, and fit unmixed data.](image)
One-arm spectrometer optimised for studies of beauty and charm decays at LHC

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- Particle identification: flavour tagging, misID background

PID

$K/\pi$ ID efficiency and misID rate

[EPJ C73 (2013) 2431]
One-arm spectrometer optimised for studies of beauty and charm decays at LHC

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- High-resolution tracking

[Image of spectrometer and mass spectrum from PRL 111 (2013) 101805]
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- Calorimetry: reconstruct neutrals ($\pi^0, \gamma$) in the final state

Calorimetry

$B^0_s \rightarrow \chi_{c1}\phi$, $\chi_{c1} \rightarrow J/\psi\gamma$

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- Calorimetry: reconstruct neutrals ($\pi^0$, $\gamma$) in the final state
- Efficient trigger, including fully hadronic modes
LHCb operation

3 fb\(^{-1}\) in 2011 and 2012 (Run 1, \(\sqrt{s} = 7, 8\) TeV): Most of results in this talk

2 fb\(^{-1}\) in 2015 and 2016 (Run 2, \(\sqrt{s} = 13\) TeV, higher \(b\) CS): Analyses ongoing

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LHCb trigger

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 $e/\gamma$

Defer 20% to disk

Software High Level Trigger

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

5 kHz Rate to storage
Trigger is a crucial element in experiments at hadron machines. Need to work in a very difficult environment with hundreds of tracks in each beam crossing.

- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm
- 2012: deferred trigger configuration: keep the trigger farm busy between fills
- Since 2015: split trigger
  - All 1st stage (HLT1) output stored on disk
  - Used for real-time calibration and alignment
  - 2nd stage (HLT2) uses offline-quality calibration
  - 5 kHz of 12 kHz to Turbo stream:
    - Candidates produced by trigger are stored
    - No raw event ⇒ smaller event size
    - Used for high-yield channels (charm, $J/\psi$, ...)
Analysis techniques

Time-dependent measurements
Measure lifetime based on vertex displacement from the primary vertex of $pp$ interaction.
Large boost provides excellent time resolution ($\sigma_t \simeq 45$ fs)

Flavor tagging
Need to identify $B$ flavour at production time (different from flavour at decay time due to oscillations).
Use decay products of the opposite-side $B$ (OS) and $\pi$, $K$ associated with same-side $B$ (SS).
Effective tagging power $\epsilon_{\text{tag}} D^2 = 3.7\%$.

Topological selections
Significant displacement of tracks from weakly-decaying particles.
Use of topological variables essential to reduce combinatorial background.
CKM measurements
Unitarity triangle measurements

$C\bar{P}$ violation in hadrons (difference of decay probabilities for particle and antiparticle) is described by Cabibbo-Kobayashi-Maskawa model

- Few parameters can explain a vast amount of experimental data
- A single weak phase responsible for $C\bar{P}$ violation
- Need interference of several amplitudes for $C\bar{P}$ violation to occur

Cabibbo-Kobayashi-Maskawa matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

($\lambda \simeq 0.22$ is a small parameter, $A, \rho, \eta \sim O(1)$)

Tree: SM only

Loop: possible NP

Tree-only quantities: $\gamma, |V_{ub}|$. SM references, compare with loop-based parameters.
Unitarity triangle measurements

$\mathcal{CP}$ violation in hadrons (difference of decay probabilities for particle and antiparticle) is described by Cabibbo-Kobayashi-Maskawa model

- Few parameters can explain a vast amount of experimental data
- A single weak phase responsible for $\mathcal{CP}$ violation
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Graphical CKM representation: Unitarity Triangle

Tree: SM only

Loop: possible NP

Tree-only quantities: $\gamma$, $|V_{ub}|$. SM references, compare with loop-based parameters.
**CP violation phenomenology**

*B* meson system as an example.

**Direct CP violation**

Asymmetry in decay amplitudes:

\[ |A_f / \bar{A}_f| \neq 1 \]

\[ A_\pm = \frac{\Gamma(B^- \rightarrow f^-) - \Gamma(B^+ \rightarrow f^+)}{\Gamma(B^- \rightarrow f^-) + \Gamma(B^+ \rightarrow f^+)} \]

The only possibility for charged mesons.

**Indirect CP violation (in interference)**

Interference between *B^0 \rightarrow f* and *B^0 \rightarrow \bar{B}^0 \rightarrow f*

Even if \(|A_f / \bar{A}_f| = 1\) and \(|q/p| = 1\), CP is violated if

\[ \Im \left( \frac{q \bar{A}_f}{p A_f} \right) \neq 0 \]

Can be measured in the time-dependent asymmetry:

\[ \frac{\Gamma(\bar{B}^0 \rightarrow f_{CP}) - \Gamma(B^0 \rightarrow f_{CP})}{\Gamma(B^0 \rightarrow f_{CP}) + \Gamma(B^0 \rightarrow f_{CP})} (\Delta t) = S_{f_{CP}} \sin(\Delta m_d \Delta t) + A_{f_{CP}} \cos(\Delta m_d \Delta t) \]

**CP violation in mixing**

If transitions *B^0 \leftrightarrow \bar{B}^0* are allowed:

\[ |B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \]

\[ |B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle \]

CP violation if \(|q/p| \neq 1\)

Can be observed in the asymmetry of “wrong-sign” decays \((\mu^\pm \mu^\pm)\)

\[ A_{SL} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \]
Direct $\mathcal{CP}$ violation in $B \to DK$

Measures CKM phase $\gamma$ at tree level, $\Rightarrow$ SM reference point.

\[
B^- \to D^0 K^-:
\]

\[
A \sim V_{cb} V_{us}^* \sim A \lambda^3
\]

\[
B^- \to \bar{D}^0 K^-:
\]

\[
A \sim V_{ub} V_{cs}^* \sim A \lambda^3 (\rho - i \eta)
\]

If $D^0$ and $\bar{D}^0$ decay into the same final state: $|\tilde{D}\rangle = |D^0\rangle + r_B e^{\pm i \gamma + i \delta_B} |\bar{D}^0\rangle$ for $B^\pm$

Ratio of two amplitudes:

\[
r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| = \left| \frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*} \right| \times [\text{Color supp}] \sim 0.1
\]

Measurement techniques:

- Measure asymmetry of rates with $D$ decaying to $\mathcal{CP}$-eigenstates ($D \to KK, \pi\pi$) or suppressed $D^0 \to K^+\pi^-$ states
- Measure asymmetry in kinematic distributions for multibody $D$ decays. “Golden mode”: $D \to K_S \pi^+ \pi^-$.

Extremely clean theoretically, limiting accuracy $< 10^{-7}$
Measure asymmetry of decay probabilities for $B^+$ and $B^-$
Direct $\mathcal{CP}$ violation in $B \to DK$: $D \to K_S^0 h^+ h^-$ modes

$B^\pm \to DK^\pm$, $D \to K_S^0 \pi^+ \pi^-$: amplitude analysis


Model-independent analysis: remove dependence on $A_D$ modelling (and hard-to-quantify model uncertainty) by binning the $D \to K_S^0 \pi^+ \pi^-$ phase space and counting events in bins.

$$N_i = h[K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(xc_i - ys_i)]$$

where $x = r_B \cos(\delta_B \pm \gamma)$, $y = r_B \sin(\delta_B \pm \gamma)$,

$c_i = \langle \cos \Delta \delta_D \rangle_i$, $s_i = \langle \sin \Delta \delta_D \rangle_i$ are obtained from $e^+ e^- \to D\bar{D}$

$K_i$ are yields in flavour $D^0$ decay, from $D^*$ tags

2D kinematic distribution of $D \to K_S^0 \pi^+ \pi^-$ from $B^\pm \to DK^\pm$

$$p_\pm(m_+^2, m_-^2) = |A_D + r_B e^{\pm i\gamma + i\delta} A_D|^2$$

where $A_D$ is known from flavour-specific $D^* \to D^0 \pi$ decays

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Direct $\mathcal{CP}$ violation in $B \rightarrow DK$: charm inputs

Measured asymmetries with ADS/GLW provide constraints on $\gamma$, e.g.:

Inputs related to $D$ decays are provided by external measurements:

- $r_D, \delta_D$ are ratio and phase difference between $A(D^0 \rightarrow K^+\pi^-)$ and $A(D^0 \rightarrow K^-\pi^+)$. Extracted from charm mixing analyses or from $e^+e^- \rightarrow D\overline{D}$ data.
- Multibody ADS modes e.g. $D \rightarrow K^-\pi^+\pi^-\pi^+$: additional coherence factor $\kappa$, from $e^+e^- \rightarrow D\overline{D}$.
- Quasi-$\mathcal{CP}$-eigenstates as $D \rightarrow \pi^+\pi^-\pi^+\pi^-$: $\mathcal{CP}$ content $F_+$, from $e^+e^- \rightarrow D\overline{D}$.

$D \rightarrow K^0_S\pi^+\pi^-$: average strong phase differences $c_i$, $s_i$ are external charm input.

- Currently from CLEO: contribution to $\sigma(\gamma) \sim 2^\circ$.
- BES-III: $\sim 4$ times more stats $\Rightarrow$ potentially $\sigma(\gamma) \sim 1^\circ$
- For $\gamma$ precision $< 1^\circ$ (LHCb upgrade) need more charm data.
- Alternatively, can constrain from charm mixing or other $B$ decays ($B^0 \rightarrow DK\pi$ with large $r_B$).

**Why $e^+e^- \rightarrow D\overline{D}$?** Because $D$ mesons are produced in quantum-correlated state $|A(D\overline{D})|^2 = |A(D_1)A(D_2) - A(\overline{D}_1)A(\overline{D}_2)|^2$.

Correlated densities provide relative phase information not observable otherwise.
Direct $CP$ violation in $B \rightarrow DK$

- Combination of many different modes sensitive to $\gamma$:
  - Time-integrated asymmetries in $B \rightarrow DK$, $B \rightarrow DK^*$, $B \rightarrow DK\pi$ with $D \rightarrow hh, hhhh$
  - Dalitz-plot analysis of $D^0 \rightarrow K_S^0 h^+ h^-$ from $B \rightarrow DK$, $B \rightarrow DK^*$
  - Time-dependent analysis of $B_s \rightarrow D_s K$

- Experimentally, just entering precision measurement regime ($< 10\%$)

```latex
\text{Combination of all LHCb results: $\gamma = (76.8^{+5.1}_{-5.7})^\circ$ (LHCb preliminary)}$
```

Indirect: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ [CKMFitter 2016]
SM reference CKM measurements: \(|V_{ub}|\) from semileptonic decays

- Use \(\Lambda^0_b\) sample for \(|V_{ub}|\) measurement, cleaner final state
- Measure \(|V_{ub}|/|V_{cb}|\) from \n\[
|V_{ub}/V_{cb}|^2 = \frac{\mathcal{B}(\Lambda^0_b \rightarrow p\mu\nu)}{\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c \mu\nu)} R_{FF}
\]
- Fit corrected mass \(M_{corr} = \sqrt{p_T^2 + M_{p\mu}^2} + p_T\)
- \(|V_{ub}| = [3.27 \pm 0.15 \pm 0.16(LQCD) \pm 0.06(V_{cb})] \times 10^{-3}\)
- Dominant uncertainty: absolute \(\mathcal{B}(\Lambda^+_c \rightarrow pK^-\pi^+).\) Potential \(c_T\) input.

[\text{LHCb, Nature Phys. 11 (2015) 743}]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{lhcbsignature}
\caption{LHCb signature for \(\Lambda^0_b \rightarrow p\mu\nu\) decays.}
\end{figure}
Rare decays
Rare decays and New Physics

What kinds of rare decays are we studying?

- **Flavour changing neutral currents.**
  In the SM, these are suppressed by weak loop:
  Typical signatures:
  - lepton pair (with $\gamma^*, Z^0 \rightarrow \mu^+ \mu^-$)
  - hard photon ($B \rightarrow K^* \gamma$)

  Search for deviations from SM expectation in probabilities, angular distributions etc.

- **Lepton flavour violating decays**
  E.g. $B \rightarrow e^\pm \mu^\mp$. Strongly forbidden in the SM.

- **Flavour (non-)universality**
  Lepton couplings in SM are the same for three generations of leptons ($e, \mu, \tau$).
  Possible NP if deviations e.g. in $B \rightarrow Ke^+e^-$ and $B \rightarrow K\mu^+\mu^-$. 
Angular observables in \( B^0 \rightarrow K^{*0}\rightarrow K^+\pi^- \mu^+\mu^- \)

- Decay fully described by three helicity angles \( \vec{\Omega} = (\theta_\ell, \theta_K, \phi) \) and \( q^2 = m_{\mu\mu}^2 \)

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \\
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- \( F_L, A_{FB}, S_i \) combinations of \( K^{*0} \) spin amplitudes depending on Wilson coefficients \( C_7^{(i)}, C_9^{(i)}, C_{10}^{(i)} \) and form factors

- Relative sign between \( B^0 \) and \( \bar{B}^0 \rightarrow \) access to \( CP \) asymmetries \( A_{3,\ldots,9} \)

- Alternative: ratios of angular observables where \textit{form factors} cancel at leading order, e.g. \( P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}} \) [S. Descotes-Genon \textit{et al.}, JHEP, 05 (2013) 137]
Measure angular observables \( F_L, A_{FB}, S_{3 ... 9} \) in bins of \( q^2 \).

- \( P'_5 \): 3.7\( \sigma \) tension in \( q^2 \in (4, 8) \text{ GeV}^2 \)
- \( A_{FB} \): mild tension in low-\( q^2 \) region
Global fits for $b \rightarrow s \mu \mu$ data

[Global fits to $b \rightarrow s$ data][W. Altmannshofer et al. EPJC 77 (2017) 377]

In general, consistent pattern: modified vector coupling $C^{NP}_9 \neq 0$ at 4-5$\sigma$ level.

- New tree-level contribution from e.g. $Z'$ with a mass of a few TeV
- Problem in our understanding of QCD contributions?

Could be understood by looking at $C_9$ trend as a function of $q^2$ $\Rightarrow$ need more data
Lepton universality in $b \to s\ell^+\ell^-$

**Lepton universality:** electroweak interaction is the same for all three generations of leptons.

$b \to s\ell^+\ell^-$ decays ($\ell = e, \mu$): good probe of lepton universality.

After a small phase space correction, $B$ to $\mu^+\mu^-$ and $e^+e^-$ should be equal in SM.

Measure double ratio to cancel systematic uncertainties:

$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)/\mathcal{B}(B^0 \to J/\psi(\mu^+\mu^-)K^*)}{\mathcal{B}(B^0 \to K^*e^+e^-)/\mathcal{B}(B^0 \to J/\psi(e^+e^-)K^*)}$$

as a function of $q^2 = m^2(\ell^+\ell^-)$.

This implies that $\mathcal{B}(J/\psi(\mu^+\mu^-)/\mathcal{B}(J/\psi(e^+e^-) = 1$, an assumption that is tested at $e^+e^-$ machines (in particular, KEDR).

$R(K^*) \neq 1$ could be generated by a contribution of new gauge bosons or leptoquarks.
Lepton universality in $b \to s\ell^+\ell^-$

$[arXiv:1705.05802]$
Lepton universality in $b \rightarrow s\ell^+\ell^-$

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Lepton universality in $b \rightarrow s\ell^+\ell^-$

$R_{K} = 0.745^{+0.090}_{-0.074}$ (stat) $\pm 0.036$ (syst) for $1 < q^2 < 6$ GeV$^2$/c$^4$ (2.6$\sigma$ from SM)

$R_{K^*0} = 0.66^{+0.11}_{-0.07}$ (stat) $\pm 0.03$ (syst) for $0.045 < q^2 < 1.1$ GeV$^2$/c$^4$

$R_{K^*0} = 0.69^{+0.11}_{-0.07}$ (stat) $\pm 0.05$ (syst) for $1.1 < q^2 < 6.0$ GeV$^2$/c$^4$ (2.5$\sigma$ from SM)

$R \simeq 0.8$ is predicted in some $Z'$ models, see e.g. [W. Altmannshofer et al., PRD 89 (2014) 095033]
Lepton universality in semileptonic $B$ decays

Another class of decays where hints of lepton non-universality is seen: $B \to D(\ast)\ell\bar{\nu}_\ell$ ($\ell = (\mu, \tau)$).

Previously studied by B factories and by LHCb with $\tau \to \mu\nu_\tau\bar{\nu}_\mu$.

SM contribution could be modified by charged Higgs or leptoquarks

Observables: yield, $q^2 = (p_B - p_D)^2$, angular distributions.

Now: measure $R(D^\ast) = \frac{\mathcal{B}(B^0 \to D^\ast + \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D^\ast + \mu^- \bar{\nu}_\mu)}$ with $\tau \to 3\pi(\pi^0)\bar{\nu}_\tau$ decays.

Technically, measure $K(D^\ast) = \frac{\mathcal{B}(B^0 \to D^\ast + \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D^\ast + 3\pi)}$

Employ decay topology for background suppression.

Multivariate discriminant (BDT) to suppress $B \to D^* D_s$
Lepton universality in semileptonic $B$ decays

3D fit in $\tau_B$, $q^2$, BDT response.

Fit results in $q^2$ and $\tau_B$ projections (4 BDT bins):

This analysis:

$$R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021 \, \text{(ext)}$$

External systematics from $\mathcal{B}(D_s^+)$ for backgrounds: potential $c\tau$ input

New WA: $R(D^*) = 0.304 \pm 0.015$

3.4$\sigma$ above SM prediction

Combined with $R(D)$: 4.1$\sigma$ from SM
Charm physics
Charm mixing with $D^0 \to K\pi$

$D^{*+} \to D^0\pi^+$ signals: favoured $D^0 \to K^-\pi^+$ (177M evt), suppressed $D^0 \to K^+\pi^-$ (722k evt)

\[
WS/RS \text{ ratio } R(t) = R_D + \sqrt{R_D} y^\prime \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2
\]

Measure $y'$ and $x'^2$, related to mixing parameters $x, y$ via rotation by strong phase difference $\delta_D$.

Additionally, fits allowing CP violation (direct and in mixing).

\[
x'^2 = (3.9 \pm 2.7) \times 10^{-5}, \quad y' = (5.28 \pm 0.52) \times 10^{-3}, \quad R_D = (3.454 \pm 0.031) \times 10^{-3}
\]
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Time-dependent $CP$ violation in charm

**Direct $CP$ violation in $D^0 \to hh$**

[PRL 116, 191601 (2016); PLB 767 (2017) 177-187]

\[
\Delta A_{CP}(K^+K^-, \pi^+\pi^-) = (-0.10 \pm 0.08 \pm 0.03)\% \\
A_{CP}(K^+K^-) = (+0.04 \pm 0.12 \pm 0.10)\% \\
A_{CP}(\pi^+\pi^-) = (+0.07 \pm 0.14 \pm 0.11)\%
\]

**Indirect $CP$ violation in $D^0 \to hh$**

[PRL 118 (2017) 261803]

\[
A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3} \\
A_\Gamma(D^0 \to \pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.16) \times 10^{-3}
\]
Can proceed via short- \((c \rightarrow u\mu^+\mu^-)\) or long-distance (via \(\rho^0, \omega\ etc.)\) contributions

Measured using \(D^0 \rightarrow K^-\pi^+(\mu^+\mu^-)\rho^0,\omega\) as normalisation

\[
\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51({\text{syst}}) \pm 0.97({\text{norm}})) \times 10^7
\]

\[
\mathcal{B}(D^0 \rightarrow K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09({\text{syst}}) \pm 0.16({\text{norm}})) \times 10^7
\]

Rarest charm decays ever observed. \(\mathcal{B}\)'s consistent with SM.
Hadron spectroscopy
“Conventional” spectroscopy at LHCb

Many discoveries in conventional spectroscopy ($b$ and $c$ states, baryons and mesons)

- Test theory approaches to low-energy QCD
- Hadronic input for NP-sensitive measurements
- Because it’s awesome!

![Excited $B_{s}^{*}$ states]

![Orbital $\Lambda_{b}^{0}$ excitations]

![$\Lambda_{c}^{+} (2860)$ baryon]

![$\chi_{c 1,2} \rightarrow J/\psi \mu^{+} \mu^{-}$]}
Observation of five new $\Omega_c$ states

Search for $\Omega_c^* \rightarrow \Xi^+_c K^-$

Large sample of $\Xi^+_c \rightarrow p K^- \pi^+$ decays, combine with a $K^-$

Two states extremely narrow (3050 and 3119), exotic?
Observation of doubly-charmed state

Search for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

[arXiv: 1707.01621]

10% of our $\Lambda_c \rightarrow pK^- \pi^+$ sample.

Combine it with $K^-$ and two $\pi^+$.

$$M = 3621.40 \pm 0.72 \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+) \text{ MeV}$$

Mass $\sim 100 \text{ MeV}$ away from SELEX, clearly not an isospin partner.

No lifetime measurement yet, but significant displacement $> 5\sigma_T \Rightarrow$ weakly decaying.
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

Most of charm and charmonium spectroscopy is done in decays of $b$ hadrons:

- Clean signal, small background due to well-separated vertex
- Well-defined initial state allows for determination of quantum numbers in amplitude analysis

$\Lambda_b^0 \rightarrow J/\psi (\mu^+ \mu^-) pK^-$ decay

Conventional contributions only in $pK^-$ spectrum ($\Lambda^*$ states).

Event yield: 26007 ± 166 events
Low background (5.4%)
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

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Event yield: $26007 \pm 166$ events
Low background (5.4%)

Dalitz distribution shows an unexpected narrow feature in $J/\psi p$ mass.
Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$

Two $J/\psi p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities

PRL 115, 072001 (2015),

Parameters of the pentaquark states

$P_c(4380)$:

$M = 4380 \pm 8 \pm 29$ MeV,
$\Gamma = 205 \pm 18 \pm 86$ MeV
$F = (8.4 \pm 0.7 \pm 4.2$ (syst))%

$P_c(4450)$:

$M = 4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV
$F = (4.1 \pm 0.5 \pm 1.1$ (syst))%

Significance (stat+syst) is overwhelming: 9$\sigma$ and 12$\sigma$
**LHCb: upgrade and future plans**

We are here

- **Run 2**
  - Install **Phase I** upgrade
  - \( \mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
  - 1.1 visible interactions / crossing
  - 8 fb\(^{-1}\) collected

- **LS2**

- **Run 3**
  - Potential **Phase Ib** upgrade projects in preparation for Phase II
  - \( \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
  - 5.5 visible interactions / crossing
  - 50 fb\(^{-1}\) collected

- **LS3**

- **Run 4**

- **LS4**
  - **Phase II** Upgrade
  - \( \mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  - 55 visible interactions / crossing
  - 300 fb\(^{-1}\) collected

- Run 5, 6, ...

Anton Poluektov
LHCb status and prospects
Super-charm-\(\tau\) factory workshop, 18–19 December 2017, BINP
Hardware L0 trigger becomes bottleneck at high luminosities
Readout at 40 MHz will allow to keep high efficiency for hadronic channels.
LHCb: flavour physics in proton-proton collisions. Extremely successful so far.

- Entering precision phase of $C\bar{P}$ violation measurements.
  - Looks SM-like yet.
- Interesting hints in rare decays. Stay cautiously optimistic, need more data.
  - Angular observables in $b \to s$ transitions.
  - Flavour universality.
- Broad charm physics programme
  - Thanks to innovations in trigger
- A flood of discoveries in charm and beauty spectroscopy.
  - Conventional and exotic
- Many interesting topics I could not cover: EW physics, soft QCD, fixed-target programme (gasous target), etc.
- Upgrade: Phase I approved and on track.
  - Start data taking in 2021, aim $50 \text{ fb}^{-1} \times 60 \text{ Run 1 stats for hadronic modes}$ by 2029
- Further upgrades being discussed
  - Up to $300 \text{ fb}^{-1}$, 2031 and beyond
Backup
Oscillations of neutral mesons

Weakly decaying neutral mesons ($K^0$, $D^0$, $B^0$, $B_s^0$) are known to oscillate.

Weak loop connects states of opposite flavour: mixing

For $B^0$ mesons, oscillation period is \( \sim \) lifetime.

Two mass eigenstates, mass difference \( \Delta M \)

\[
|B_L \rangle = |B^0 \rangle + |\overline{B}^0 \rangle \\
|B_H \rangle = |B^0 \rangle - |\overline{B}^0 \rangle
\]

In general, width difference \( \Delta \Gamma \)

Many CP violation measurements involve oscillations.
That’s why we want $B$ mesons to be boosted
\( (e^+e^- \text{ machines: artificial boost by asymmetric beam energies}) \)
Oscillations of neutral mesons

Weakly decaying neutral mesons \((K^0, D^0, B^0, B_s^0)\) are known to oscillate.

Weak loop connects states of opposite flavour: *mixing* \(\bar{t}, \bar{c}, \bar{u} \rightarrow \bar{b}, \bar{t}, \bar{c}, \bar{u}\)

\[ W \rightarrow B_s^0 \]

Two mass eigenstates, mass difference \(\Delta M\)

\[ |B_L\rangle = |B^0\rangle + |\bar{B}^0\rangle \]

\[ |B_H\rangle = |B^0\rangle - |\bar{B}^0\rangle \]

In general, width difference \(\Delta \Gamma\)

\[ B_s^0 \] mesons oscillate many times during their lifetime.

Many \(C\bar{P}\) violation measurements involve oscillations.

That’s why we want \(B\) mesons to be *boosted* \((e^+e^-\) machines: artificial boost by asymmetric beam energies)
Amplitude analyses

Another tool to measure phases: *amplitude analysis* technique.

Perform fits of the amplitude as a function of phase space variables

- Three-body decays $D \rightarrow ABC$: two kinematic variables $m_{AB}^2, m_{BC}^2$ (*Dalitz plot*)
- Add angular variables if initial/final state not scalar

![Diagram showing $m_{AB}^2$ vs. $m_{BC}^2$ with phase space dynamics and helicity structure.]

- Absolute phase not visible, but *relative* phases of components can be accessed through interference
- Typically, use *isobar model*. E.g. for a resonance in $AB$:
  - Line shape (*Breit-Wigner* etc.) in $m_{AB}^2$
  - Helicity structure (depending on spin of resonance) in $m_{BC}^2$

- In addition, there exist model-independent techniques for amplitude analyses.
Amplitude analyses

Another tool to measure phases: *amplitude analysis* technique.

Perform fits of the amplitude as a function of phase space variables:

- Three-body decays $D \rightarrow ABC$: two kinematic variables $m_{AB}^2, m_{BC}^2$ (*Dalitz plot*)
- Add angular variables if initial/final state not scalar

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**Diagram:**

- **Helicity in AB + line shape in BC**
- **Line shape in AB + helicity in BC**
- **Phase space**
- **Interference region**
- **Absolute phase not visible, but relative phases of components can be accessed through interference**
- **Typically, use isobar model. E.g. for a resonance in AB:**
  - Line shape (*Breit-Wigner* etc.) in $m_{AB}^2$
  - Helicity structure (depending on spin of resonance) in $m_{BC}^2$
- **In addition, there exist model-independent techniques for amplitude analyses.**
Direct $CP$ violation in charmless $B$ decays

Charmless $B$ decays, in principle, also give access to the value of $\gamma$, although they can be affected by the New Physics due to penguin contribution:

\[
B^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}, \quad B^{\pm} \rightarrow \pi^{\pm} K^{+} K^{-}
\]

Study integrated $CP$ asymmetries, as well as local asymmetries over the phase space.

\[
A_{CP} = \frac{\Gamma(B^{-}) - \Gamma(B^{+})}{\Gamma(B^{-}) + \Gamma(B^{+})}
\]

Huge asymmetries in certain regions of phase space. Amplitude analyses ongoing to understand their nature.
Use semileptonic $B_{(s)}^0 \to D_{(s)} \mu \bar{\nu}_\mu$ decays.

$$A_{CP} \equiv a_{sl} = \frac{\Gamma(\bar{B} \to B \to f) - \Gamma(B \to \bar{B} \to \bar{f})}{\Gamma(\bar{B} \to B \to f) + \Gamma(B \to \bar{B} \to \bar{f})}$$

Standard Model predictions: [A. Lenz, arXiv:1205.1444]

$$a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4}$$

$$a_{sl}^s = (+1.9 \pm 0.3) \times 10^{-5}$$

Production asymmetry can be $A_P \neq 0$ in $pp$ collisions.

- For $B_s^0$: smeared by fast $B_s^0$ oscillations, not an issue
- For $B^0$, can be accounted for by measuring time-dependent asymmetry:

$$A_{raw}(t) = A_D + \frac{a_{sl}}{2} - \left( A_P + \frac{a_{sl}}{2} \right) \cos \Delta mt$$

3.6σ tension with SM from $D0$, but not confirmed by LHCb measurements
Time-dependent $\mathcal{CP}$ violation in $B_s^0$ decays

Measure $\mathcal{CP}$ violation in the interference of decays with and w/o mixing

“Golden mode”: $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-)\phi(K^+ K^-)$

$\mathcal{CP}$ violating phase $\varphi_s = \varphi_M - 2 \varphi_D$; $\varphi_s^{SM} \simeq -2 \beta_s = 0.0376 \pm 0.0008 \text{ rad}$ [CKMFitter]

- Time-dependent flavor-tagged decay rate
- $K^+ K^-$ can be in $P$ wave ($\phi$) or $S$ wave
- 3 $P$ waves ($\mathcal{CP}$-odd or $\mathcal{CP}$-even), angular analysis to distinguish them

6D fit! ($m_{KK}$, $t$, mistag rate, 3 angles), bins in $m_{KK}$ and $B$ tag.

[PKL 114 (2015) 041801]
Time-dependent $CP$ violation in $B_s^0$ decays

Several different $B_s^0$ decay modes used by LHCb

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Analysis technique</th>
<th>$\varphi_s$ result</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \phi$</td>
<td>angular, bins in $m_{KK}$</td>
<td>$-0.068 \pm 0.049 \pm 0.006$</td>
<td>[PRL 114, 041801 (2015)]</td>
</tr>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>amplitude, angular</td>
<td>$+0.070 \pm 0.068 \pm 0.008$</td>
<td>[PLB 736 (2014) 186]</td>
</tr>
<tr>
<td>$D_s^+ D_s^-$</td>
<td>$CP$-even</td>
<td>$+0.02 \pm 0.17 \pm 0.02$</td>
<td>[PRL 113, 211801 (2014)]</td>
</tr>
<tr>
<td>$\psi(2S) \phi$</td>
<td>angular</td>
<td>$+0.23^{+0.29}_{-0.28} \pm 0.02$</td>
<td>[PLB 762 (2016) 253]</td>
</tr>
<tr>
<td>$J/\psi K^+ K^-$</td>
<td>amplitude, angular</td>
<td>$+0.119 \pm 0.107 \pm 0.034$</td>
<td>[arXiv:1704.08217]</td>
</tr>
</tbody>
</table>

Measurements are also performed by Atlas, CMS and Tevatron experiments

World-averaged value $\varphi_s(WA) = -0.030 \pm 0.033$ [HFLAV, arXiv:1612.07233]

In excellent agreement with the SM value $\varphi_s^{SM} = 0.0376 \pm 0.0008$
Mixing-induced CP violation in $B^0 \to J/\psi K^0_S$ decays

“Golden mode” at B-factories, but LHCb provides competitive measurement after recent flavour-tagging improvements.

Time-dependent asymmetry:

$$A(t) = \frac{S \sin(\Delta m t) + C \cos(\Delta m t)}{\cosh(\Delta \Gamma t/2) + A\Delta\Gamma \sinh(\Delta \Gamma t/2)}; S = \sin 2\beta$$

[LHCb, PRL 115, 031601 (2015)]

Effective tagging power

$$\varepsilon_{\text{tag}}(1 - 2\omega) = 3.02\%$$

$$\sin(2\beta) \equiv \sin(2\phi_1)$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar, PRD 79 (2009)</td>
<td>$0.69 \pm 0.03 \pm 0.01$</td>
</tr>
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<td>BaBar, PRD 80 (2009)</td>
<td>$0.69 \pm 0.52 \pm 0.04 \pm 0.07$</td>
</tr>
<tr>
<td>BaBar, PRD 69 (2004)</td>
<td>$1.56 \pm 0.42 \pm 0.21$</td>
</tr>
<tr>
<td>Belle, PRL 108 (2012)</td>
<td>$0.67 \pm 0.02 \pm 0.01$</td>
</tr>
<tr>
<td>ALEPH, PLB 492, 259 (2000)</td>
<td>$0.84 \pm 0.82 \pm 1.04 \pm 0.16$</td>
</tr>
<tr>
<td>OPAL, EPJ C5, 379 (1998)</td>
<td>$3.20 \pm 1.80 \pm 0.50$</td>
</tr>
<tr>
<td>CDF, PRD 61, 072005 (2000)</td>
<td>$0.79 \pm 0.41$</td>
</tr>
<tr>
<td>LHCb, PRL 115 (2015)</td>
<td>$0.73 \pm 0.04 \pm 0.02$</td>
</tr>
<tr>
<td>Belle5S, PRL 108 (2012)</td>
<td>$0.57 \pm 0.58 \pm 0.06$</td>
</tr>
<tr>
<td>Average, HFA, Moriond 2015</td>
<td>$0.69 \pm 0.02$</td>
</tr>
</tbody>
</table>

$$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$$
SM expectation: $B(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ [C. Bobeth, PRL 112, 101801 (2014)]
\[ B(s) \to \mu^+ \mu^- \text{ in LHC Run1} \]

- **Combination of CMS and LHCb:**
  
  - **Observation of** \( B_{s}^{0} \to \mu^+ \mu^- \):
    
    \[ B(B_{s}^{0} \to \mu^+ \mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9} \]
    
    6.2\( \sigma \) significance
    
    1.2\( \sigma \) compatibility with SM

  - **Evidence of** \( B^{0} \to \mu^+ \mu^- \):
    
    \[ B(B^{0} \to \mu^+ \mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10} \]
    
    3.0\( \sigma \) significance
    
    2.2\( \sigma \) compatibility with SM

- **Atlas**
  
  - \[ B(B_{s}^{0} \to \mu^+ \mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9} \]
  
  - \[ B(B^{0} \to \mu^+ \mu^-) < 4.2 \times 10^{-10} \]
    
    at 95\% CL
Effective lifetime of $B^0_s \rightarrow \mu^+\mu^-$

The two mass eigenstates of $B^0_s$ have significant width difference, $\Delta \Gamma = 0.082 \pm 0.007 \text{ ps}^{-1}$.

In SM, only heavier mass eigenstate decays to $\mu^+\mu^-$.

Can measure $B^0_s$ lifetime in $B^0_s \rightarrow \mu^+\mu^-$ decays (effective lifetime)

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B^0_s}}{1 - y_s^2} \frac{1 + 2A_{\Delta \Gamma} y_s + y_s^2}{1 + A_{\Delta \Gamma} y_s},$$

$$y_s = \tau_{B^0_s} \frac{\Gamma_s}{2}$$

In SM, $A_{\Delta \Gamma} = 1$, while in NP models it could be $A_{\Delta \Gamma} \in [-1, 1]$

New independent observable sensitive to NP

[\text{LHCb, PRL 118, 191801 (2017)}]

$\tau_{\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$

To be compared to $\tau_{B^0_s} = 1.520 \pm 0.004 \text{ ps}$
Model-independent description in effective theory:

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i + C'_i O'_i \]

Left-handed \quad Right-handed, \quad \frac{m_s}{m_b} \quad \text{suppressed}

Wilson coefficients \( C_{i}^{(t)} \) encode short-distance physics, \( O_{i}^{(t)} \) corr. operators

\( b \rightarrow s\gamma \quad B \rightarrow \mu\mu \quad b \rightarrow s\ell\ell \)

- \( O_{7}^{(t)} \) photon penguin \( \checkmark \quad \checkmark \)
- \( O_{9}^{(t)} \) vector coupling \( \checkmark \)
- \( O_{10}^{(t)} \) axialvector coupling \( \checkmark \quad \checkmark \)
- \( O_{S,P}^{(t)} \) (pseudo)scalar penguin \( \checkmark \)
$B(s) \rightarrow \mu^+ \mu^-$

Run 1 + part of Run2, 4.4 fb$^{-1}$ in total.

First observation of $B^0_s \rightarrow \mu^+ \mu^-$ in a single experiment

- Observation of $B^0_s \rightarrow \mu^+ \mu^-$:
  \[
  \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}
  \]
  7.8σ significance

- $B^0 \rightarrow \mu^+ \mu^-$ consistent with no signal:
  \[
  \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.5^{+1.2}_{-1.0}^{+0.2}_{-0.1}) \times 10^{-10}
  \]
  1.6σ significance

- First measurement of effective $B^0_s$ lifetime
  New independent observable sensitive to NP
  \[
  \tau_{\mu^+ \mu^-} = 2.04 \pm 0.44 \pm 0.05 \text{ ps}
  \]
  To be compared to $\tau_{B^0_s} = 1.520 \pm 0.004 \text{ ps}$

$[\text{LHCb, PRL 118, 191801 (2017)}]$
$B^0 \to K^{\ast 0} \mu^+ \mu^-$ selection

- BDT to suppress combinatorial background
  - Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto of $B^0 \to J/\psi K^{\ast 0}$ and $B^0 \to \psi(2S)K^{\ast 0}$ (important control decays)
  - and peaking backgrounds using kinematic variables and PID
- Signal clearly visible as vertical band after the full selection
Differential cross-sections in $b \rightarrow s \ell^+ \ell^-$ decays

Cross-sections consistently lower than SM in low-$q^2$ region.

New Physics or larger theory uncertainty?
Heavy flavour spectroscopy

- No free quarks, held together by strong interaction. Form colourless objects, most simple ones: mesons $(q\bar{q})$ and baryons $(qqq)$
- Angular, spin and radial excitations $\Rightarrow$ spectroscopy
- Perturbative QCD calculations have limited applicability: phenomenological models (non-relativistic potential), lattice QCD.

$SU(4)$ meson multiplets with $S = 1/2$  
$SU(4)$ baryon multiplets with $S = 1/2$

- Exotic spectroscopy: beyond 2- and 3-quark systems: tetraquarks $(qq\bar{q}\bar{q})$, pentaquarks $(qqqq\bar{q})$
Excited $\Omega_c$ states

Baryons with a single heavy quark:

- Heavy quark effective theory: heavy quark as a source of static potential
- Various spin and orbital excitations ($L, l, s_Q, s_1, s_2$)
- Ground states: $L = l = 0$, spin $S = 1/2$ or $3/2$

- No orbital excitations in $cSS$ system ($\Omega_c^0$) seen so far
- Expect many states above $\Xi_c K$ kinematic threshold
Searches for doubly-charmed states

- Double heavy quarks have only been seen in mesons: $\psi(c\bar{c})$, $\Upsilon(b\bar{b})$, $B^+_c(\bar{b}c)$.
- Expect three doubly-charmed states: $\Xi^{++}_{cc}(ccd)$, $\Xi^{++}_{cc}(ccu)$ and $\Omega^+_{cc}(ccs)$.
- A different system: $cc$ as a heavy diquark; similar to heavy mesons $Qq$.
- Many theoretical models (relativistic and non-relativistic QCD potential, triple harmonic oscillator, sum rules, bag model etc.), lattice results.

- $\Xi^+_{cc}$ and $\Xi^{++}_{cc}$ expected to have small mass difference.
- Lifetime $\tau(\Xi^{++}_{cc}) > \tau(\Xi^+_{cc})$ due to different interference pattern of spectator and exchange diagrams.
Searches for doubly-charmed states: “SELEX particle”

SELEX collaboration (Fermilab E781) seen a peak in $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$ spectra


Combined mass:

$M(\Xi_{cc}^+) = 3518.7 \pm 1.7$ MeV

Questions:

- Weakly decaying, but very short lifetime ($\tau(\Xi_{cc}^+) < 33$ fs 90% CL)
- Large production ratio (20% of $\Lambda_c^+$ rate through $\Xi_{cc}^+$)
Searches for doubly-charmed states: “SELEX particle”

Not confirmed by other experiments:

\[ \delta m \equiv m(\Lambda_c^+ K^+) - m(\Lambda_c^+) - m(K) - m(\pi) \]


LHCb, JHEP 12 (2013) 090 \( (0.65 \text{ fb}^{-1}) \)
Theorists have thought about exotic (beyond $q\bar{q}$, $qqq$) hadrons since the early days of quark model.

- Experimental evidence for 4-quark mesons started to appear only recently.
  - $X(3872)$ (Belle, BaBar, CDF)
  - $Z_b(10610)$ and $Z_b(10650)$ (Belle)
  - $Z(4430)$ (Belle, LHCb)
  - $Z_c(3900)$ (BES-III)

- Pentaquarks: discoveries and undiscoveries...

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R.A. Schumacher, nucl-ex/0512042
$Z(4430)$ in $B \to \psi(2S)K^+\pi^-$

- Decay $B^0 \to \psi(2S)K^+\pi^-$
- Signal yield: 25k events
- Combinatorial background: $\sim 4\%$
- 4D amplitude analysis:
  \[(m^2(K\pi), m^2(\psi(2S)\pi), \theta_{\psi'}, \phi_{\psi'})\]

![Graph showing the mass distribution of $m_{\psi'\pi}$]

![Plot showing the 4D amplitude analysis with $Z(4430)$ and $K^*(892)^0$]

[Ref: [PRL 112, 222002 (2014)]]
$Z(4430)$ in $B \rightarrow \psi(2S)K^+\pi^-$

Model-dependent fit prefers resonance-like state with $J^P = 1^+$

$\mathcal{F}(Z(4430)^+) = (5.9 \pm 0.9^{+1.5}_{-3.3} \text{(syst)})\%$

Quantum numbers (wrt. favoured $J^P = 1^+$)

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>9.7</td>
<td>3.4</td>
</tr>
<tr>
<td>$1^-$</td>
<td>15.8</td>
<td>3.7</td>
</tr>
<tr>
<td>$2^+$</td>
<td>16.1</td>
<td>5.1</td>
</tr>
<tr>
<td>$2^-$</td>
<td>14.6</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Belle</th>
</tr>
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<tbody>
<tr>
<td><strong>Mass, MeV</strong></td>
<td>$4475 \pm 7^{+15}_{-25}$</td>
<td>$4485 \pm 22^{+28}_{-11}$</td>
</tr>
<tr>
<td><strong>Width, MeV</strong></td>
<td>$172 \pm 13^{+27}_{-34}$</td>
<td>$200^{+41}<em>{-46}^{+26}</em>{-35}$</td>
</tr>
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</table>
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<tr>
<td>0$^-$</td>
<td>9.7</td>
<td>3.4</td>
</tr>
<tr>
<td>1$^-$</td>
<td>15.8</td>
<td>3.7</td>
</tr>
<tr>
<td>2$^+$</td>
<td>16.1</td>
<td>5.1</td>
</tr>
<tr>
<td>2$^-$</td>
<td>14.6</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV</td>
<td>4475 $^{+15}_{-25}$</td>
<td>4485 $^{+28}_{-11}$</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>172 $^{+27}_{-34}$</td>
<td>200 $^{+41}_{-46}$</td>
</tr>
</tbody>
</table>

[Refs: PRL 112, 222002 (2014)]
Model-independent test of phase rotation. Interference with $K^*$ states provides reference amplitude for phase motion measurement.

Split $M(\psi'\pi^-)$ (4277–4605 MeV) into 6 bins.

Fit magnitude and phase independently for each bin.

Clear phase rotation in counter clockwise direction: characteristic of a resonant behaviour.
Model-independent confirmation of a structure in $\psi'\pi^-$. Check that $K^-\pi^+$ amplitude only fails to describe the decay. $K^-\pi^+$ should contribute to reasonably low moments, while exotic $\psi'\pi^-$ contributes to all moments.

\[
\begin{align*}
J_{\text{max}} &= 2 \\
l_{\text{max}} &= 4 \\
(K^*, K_2^* \text{ etc.})
\end{align*}
\]

\[
\begin{align*}
J_{\text{max}} &= 3 \\
l_{\text{max}} &= 6 \\
(+K_3^*(1780) \text{ etc.})
\end{align*}
\]

\[
\begin{align*}
J_{\text{max}} &= 15 \\
l_{\text{max}} &= 30 \\
&\quad \ldots
\end{align*}
\]

$m(\psi(2S)\pi)$ distribution can only be described by an unreasonable number of Legendre moments.
Z(4430): model-independent confirmation

Test statistic:

\[-2\Delta NLL = -2 \sum_i W_i \frac{F_i(m_{\psi\pi})}{F_{30}(m_{\psi\pi})} \log \frac{F_i(m_{\psi\pi})}{F_{30}(m_{\psi\pi})}\]

Run toys with $K^+\pi^-$-only model to determine distribution, compare with $-2\Delta NLL$ in data.

Resonances with spin up to 3 cannot reproduce the features seen in data.

$l_{\text{max}} = 4$  

$l_{\text{max}} = 6$  

$l_{\text{max}} = 4 \ldots 6$ depending on $m(K^+\pi^-)$
Full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$

Admixture of all known $\Lambda^*$ states does not reproduce the peak observed at $m_{J/\psi p} = 4450$ MeV.
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi pK^-$

Full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$

Inclusion of the exotic $J/\psi p$ state improves the fit, best $J^P = 5/2^\pm$
Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_{\mu}, \phi_{\mu}, \theta_K, \phi_K)$

Two $J/\psi p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities
Pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$

Argand plots: model-independent confirmation of the resonant character of the exotic states.

Interference with $\Lambda^*$ states allows to extract the phase in bins of $m_{J/\psi p}$.

Clear phase rotation for $P_c(4450)$, direction consistent with Breit-Wigner amplitude

Not conclusive for $P_c(4380)$, need more statistics.
Model-independent approach: $\Lambda_0^0 \to J/\psi pK^-$

Checking that $\Lambda^*$ resonances only cannot describe the data.

Use Legendre moments in $\cos \theta_{\text{hel}}$ as a function of $m_{pK}$.

Allow $l_{\text{max}}$ depending on $m_{pK}$

Moments from model

Moments from data

[PLR 117 (2016) 082002]
Exotic contributions in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

[PRl 117 (2016) 082003]

Signal yield: $1885 \pm 50$ events
Background: $\sim 20\%$

$N^*$ states in $p\pi^-$

Possible exotic contributions:

- $P_c$ in $J/\psi p$
- $Z_c$ in $J/\psi \pi^-$ [Belle, PRD 90, 112009 (2014)]

$M = 4196^{+31}_{-29}^{+17}_{-13}$ MeV
$\Gamma = 370 \pm 70^{+70}_{-132}$ MeV
Exotic contributions in $\Lambda_b^0 \to J/\psi p\pi^-$

$N^* \to p\pi^-$ contributions:

- Baseline: isobar $p\pi^-$ with 7-14 states.
- Tried BW and Flatté for $N(1535)$ (opening of $n\eta$ threshold)
- Cross-check: $K$-matrix for $1/2^-$ wave using Bonn-Gatchina parametrisation [A. Anisovich et al., arXiv:0911.5277]

Exotic contributions:

- Considered $P_c(4380)$, $P_c(4450)$ (in $J/\psi p$) and $Z_c(4200)$ (in $J/\psi \pi^-$).
- Total significance of exotic contributions: $3.1\sigma$.
- Individual contributions are not significant
- Fit fractions:
  - $\mathcal{F}(P_c(4380)) = (5.1 \pm 1.5^{+2.6}_{-1.6})\%$
  - $\mathcal{F}(P_c(4450)) = (1.6^{+0.8+0.6}_{-0.5-0.6})\%$
  - $\mathcal{F}(Z_c(4200)) = (7.7 \pm 2.8^{+3.4}_{-4.0})\%$
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

Peaks in $J/\psi \phi$ around 4140 and 4274 MeV are found by CDF and confirmed by D0 and CMS

[CDF, PRL 102, 242002 (2009)]

Belle [PRL 104:112004 (2010)]:

no $X(4140)$, but $X(4350)$ in $\gamma \gamma \rightarrow J/\psi \phi$

no evidence from:

BaBar [PRD 91, 012003 (2015)],

LHCb (0.37 fb$^{-1}$) [PRD 85, 091103(R) (2012)]
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

Signal yield: $4289 \pm 151$ events
Background: $\sim 20\%$

Full 6D amplitude analysis
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]

Signal yield: $4289 \pm 151$ events
Background: $\sim 20\%$

Full 6D amplitude analysis
Exotic states in $B^+ \to J/\psi \phi K^+$

$K^*$ states only

$K^*$ plus 4(!) exotic states in $J/\psi \phi$

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$J^{PC}$</th>
<th>Significance</th>
<th>$M_0$ [MeV]</th>
<th>$\Gamma_0$ [MeV]</th>
<th>FF %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(4140)$</td>
<td>$1^{++}$</td>
<td>8.4σ</td>
<td>4146.5±4.5 $^{+4.6}_{-2.8}$</td>
<td>83±21 $^{+21}_{-14}$</td>
<td>13±3.2 $^{+4.8}_{-2.0}$</td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>$1^{++}$</td>
<td>6.0σ</td>
<td>4273.3±8.3 $^{+17.2}_{-3.6}$</td>
<td>56±11 $^{+8}_{-11}$</td>
<td>7.1±2.5 $^{+3.5}_{-2.4}$</td>
</tr>
<tr>
<td>$X(4500)$</td>
<td>$0^{++}$</td>
<td>6.1σ</td>
<td>4506±11 $^{+12}_{-15}$</td>
<td>92±21 $^{+21}_{-20}$</td>
<td>6.6±2.4 $^{+3.5}_{-2.3}$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td>$0^{++}$</td>
<td>5.6σ</td>
<td>4704±10 $^{+14}_{-24}$</td>
<td>120±31 $^{+42}_{-33}$</td>
<td>12±5 $^{+9}_{-5}$</td>
</tr>
</tbody>
</table>

Masses for $X(4140)$ and $X(4274)$ are consistent with previous measurements, but widths significantly larger.