(Exotic) Hadron physics at LHCb

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FSP meeting
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(Exotic) Hadron physics at LHCb

nPVs $\sim 2$
nTracks $\sim 200$
pT(B) $\sim 5$ GeV
pT(daughter) $\sim 1$ GeV

$\sigma_{bb}(7\,\text{TeV}) = 72.0 \pm 0.3 \pm 6.8 \mu\text{b}$
$\sigma_{bb}(13\,\text{TeV}) = 154.3 \pm 1.5 \pm 14.3 \mu\text{b}$

[PRL 118 (2017) 052002]
Recent news on charm baryons
Strange-charm baryons

The **css** system can be used to test HQET and Lattice, as many states expected

Heavy quark + light **ss** diquark

5 P-wave states predicted
Strange-charm baryons

$\Xi_c^+ \rightarrow pK^-\pi^+$

Cabibbo-suppressed weak decay

0.9 M events!

$\Xi_c^+$ detached from, but pointing back to, the primary pp vertex

LHCb-RICH system to identify particle type of daughter tracks

$[\text{PRL 118 (2017) 182001}]$

Add a kaon

Resolution 0.7-1.7 MeV/c$^2$

No peaks in same-sign data

Threshold enhancement consistent with $\Omega_c(3066)^0 \rightarrow \Xi_c^+K^-$. 
Strange-charm baryons

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yield</th>
<th>Nσ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ω_c(3000)^0$</td>
<td>3000.4 ± 0.2 ± 0.1 ±0.3</td>
<td>4.5 ± 0.6 ± 0.3</td>
<td>1300 ± 100 ± 80</td>
<td>20.4</td>
</tr>
<tr>
<td>$Ω_c(3050)^0$</td>
<td>3050.2 ± 0.1 ± 0.1 ±0.3</td>
<td>0.8 ± 0.2 ± 0.1</td>
<td>970 ± 60 ± 20</td>
<td>20.4</td>
</tr>
<tr>
<td>$Ω_c(3066)^0$</td>
<td>3065.6 ± 0.1 ± 0.3 ±0.3</td>
<td>&lt; 1.2 MeV, 95% CL</td>
<td>Very narrow</td>
<td></td>
</tr>
<tr>
<td>$Ω_c(3090)^0$</td>
<td>3090.2 ± 0.3 ± 0.5 ±0.3</td>
<td>3.5 ± 0.4 ± 0.2</td>
<td>1740 ± 100 ± 50</td>
<td>23.9</td>
</tr>
<tr>
<td>$Ω_c(3119)^0$</td>
<td>3119.1 ± 0.3 ± 0.9 ±0.3</td>
<td>8.7 ± 1.0 ± 0.8</td>
<td>2000 ± 140 ± 130</td>
<td>21.1</td>
</tr>
<tr>
<td>$Ω_c(3188)^0$</td>
<td>3188 ± 5 ± 13</td>
<td>1.1 ± 0.8 ± 0.4</td>
<td>480 ± 70 ± 30</td>
<td>10.4</td>
</tr>
</tbody>
</table>

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<tr>
<th>Resonance (Ed)</th>
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<th>Nσ</th>
</tr>
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<tr>
<td>$Ω_c(3066)^0$</td>
<td>700 ± 40 ± 140</td>
<td>220 ± 60 ± 90</td>
<td>190 ± 70 ± 20</td>
<td></td>
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What are the quantum numbers? Use $Ω_b^- \rightarrow (Ξ_c^+ K^-)π^-$. Why are they so narrow? Are the narrowest states pentaquark candidates? Which are orbital/radial excitations? Do they have isospin partners?

[Karliner, Rosner, PRD 95 (2017) 114012]
[Kim et al., PRD 96 (2017) 014009]
Doubly-charmed baryon

Full event reconstruction used in trigger (exploiting real-time alignment capabilities of LHCb in Run 2)

Write out events in ready-to-analyse format ⇒ no need for additional offline processing.

Only save part of the event that is needed ⇒ less disk space, crucial for states with large production cross-sections.
Doubly-charmed baryon

\[ \text{Beam: } u \rightarrow u \ | \ \Lambda_c^+ \rightarrow pK^+\pi^- \]

>12\sigma significant signal observed consistent with a weakly decaying state

\[ m(\Xi^{cc++}) = 3621.40 \pm 0.72 \text{ (stat)} \pm 0.27 \text{ (syst)} \pm 0.14 \text{ (}\Lambda_c^+\text{)} \text{ MeV} \]

consistent with many theory predictions

e.g. Lattice [Alexandrou PRD 96 (2017) 034511]

Novel online data processing \(\rightarrow\) Turbo!

Full event reconstruction used in trigger (exploiting real-time alignment capabilities of LHCb in Run 2)

Write out events in ready-to-analyse format \(\Rightarrow\) no need for additional offline processing.

Only save part of the event that is needed \(\rightarrow\) less disk space, crucial for states with large production cross-sections
Comparison with SELEX

Inconsistent with being isospin partners

SELEX reported signals of \( \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \), \( pD^+ K^- \) with very short lifetime [PRL 89 (2002) 112001, PLB 628 (2005) 18]

Next steps: measure lifetime, new decay modes and search for other double-heavies \( \Xi_{cc}^+ \), \( \Omega_{cc}^+ \), \( \Xi_{bc} \), \( \Omega_{bb} \) and \( \Xi_{bb} \)

[Brodsky at al., PLB 698 (2011) 251] [Karliner, Rosner, PRD 96 (2017) 033004]
Exotic mesons and baryons
The quark model

We then refer to the members $u_\frac{2}{3}$, $d_{-\frac{1}{3}}$, and $s_{-\frac{1}{3}}$ of the triplet as "quarks" [6] $q$ and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(qqq), (qqq\bar{q})$, etc., while mesons are made out of $(q\bar{q}), (qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

Quarks as the building blocks of mesons and baryons was first proposed in 1964 by Gell-Mann and Zweig
Charmonium spectroscopy

Classify using $J^{PC}$

$J = L \oplus S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

$n^{2S+1}L_J$

Low-lying states well measured and predicted by non-relativistic theory (lattice QCD, potential models)


[Lebed et al, arXiv:1610.04528]
Charmonium spectroscopy

Classify using $J^{PC}$

$J = L \oplus S$

$P = (-1)^{L+S}$

$C = (-1)^{L+S}$

Many new states observed above the open-charm threshold. No clear pattern.

Similar picture for bottomonium system

Recent review articles -
[Esposito et al, arXiv:1611.07920]
[Lebed et al, arXiv:1610.04528]
[Chen et al, arXiv:1601.02092]
The X(3872) revolution

Observation in 2003 by Belle has led to a revolution in exotic hadron spectroscopy [PRL 91 (2003) 262001 with >1100 citations!]

Many phenomenological models: $[c\bar{u}][\bar{c}u]$ tetraquark, $D^0D^{*0}$ molecule, $c\bar{c}g$ hybrid, hadro-charmonium…

$J^{PC} = 1^{++}$ from LHCb [PRD 92 (2015) 011102]

\[ B^+ \rightarrow \psi(2S)K^+ \quad \leftrightarrow \quad J/\psi \pi^+ \pi^- \]
\[ B^+ \rightarrow X(3872)K^+ \quad \leftrightarrow \quad J/\psi \pi^+ \pi^- \]
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$J^{PC} = 1^{++}$ from LHCb [PRD 92 (2015) 011102]

$B \to KKX(3872)$

$B \to \psi\phi, J/\psi \pi^+ \pi^-$

$J/\psi \phi(\to \pi^+ \pi^-)$

$D^0D^{*0}, D^0D^0\pi^0$

$\gamma J/\psi, \gamma \psi(3686)$

$\psi(2S) \to \chi_{c0}$, $J/\psi(2S) \to \psi(3686)$

Most studied state, but many open questions

$\Gamma_{X(3872)} < 1.2 \text{ MeV}/c^2$

$M_{X(3872)} = 3871.69 \pm 0.17 \text{ MeV}/c^2$

$M_{D^0} + M_{D^{*0}} = 3871.81 \pm 0.09 \text{ MeV}/c^2$

Loosely bound in the molecule scenario
Amplitude analyses

Both decay chains have the same particles in the final state.

Mass fit is sufficient to separate if state isolated and narrow, otherwise need an amplitude analysis to disentangle interfering contributions and to measure quantum numbers.

B hadrons provide well-defined state of known spin.

\[
B^0 \rightarrow \psi(2S)K^{+}\pi^- \quad \rightarrow J/\psi \pi^+ \pi^-
\]

\[
B^0 \rightarrow Z(4430)^- K^+ \quad \rightarrow \psi(2S)\pi^- \quad \rightarrow J/\psi \pi^+ \pi^-
\]
**X(4140) → J/ψϕ : some history**

**Seen** by CDF, D0 and CMS in $B^+ \rightarrow J/\psi \phi K^+$ decays
No evidence from LHCb, BaBar, BES-III, Belle.

Well above open-charm threshold but has **narrow width** ⏯ not conventional $c\bar{c}$.

Also second state at higher mass…

**Full amplitude analysis of decay is essential!**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$X(4140)$</th>
<th>$X(4274)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF [69]</td>
<td>$M = 4143.0 \pm 2.9 \pm 1.2$, $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$</td>
<td>–</td>
</tr>
<tr>
<td>CDF [100]</td>
<td>$M = 4143.4^{+2.9}<em>{-3.0} \pm 0.6$, $\Gamma = 15.3^{+10.4}</em>{-6.1} \pm 2.5$</td>
<td>$M = 4274.4^{+8.4}<em>{-6.7} \pm 1.9$, $\Gamma = 32.3^{+21.9}</em>{-15.3} \pm 7.6$</td>
</tr>
<tr>
<td>DØ [102]</td>
<td>$M = 4159.0 \pm 4.3 \pm 6.6$, $\Gamma = 19.9 \pm 12.6^{+1.0}_{-8.0}$</td>
<td>–</td>
</tr>
<tr>
<td>CMS [74]</td>
<td>$M = 4148.0 \pm 2.4 \pm 6.3$, $\Gamma = 28^{+15}_{-11} \pm 19$</td>
<td>$M = 4313.8 \pm 5.3 \pm 7.3$, $\Gamma = 38^{+30}_{-15} \pm 16$</td>
</tr>
</tbody>
</table>

[102] [D0 PRD 89, 012004]
[104] [Belle PRL 104, 112004]
[BES-III PRD 91 (2015) 032002]
$B^+ \rightarrow J/\psi\phi K^+ @ LHCb$

Are reflections from $K^*$ system causing structure in $J/\psi\phi$?

Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about $K^*$ contributions

$K^{*+} \rightarrow \phi K^+$ resonances expected to be broad (scattering expts)

$X(4140)\ ?$ ?

$X(4274)\ ?$

$X \rightarrow J/\psi\phi$ tetraquarks

[PRD 95, 012002 (2017)] [PRL 118, 022003 (2017)]
Are reflections from $K^*$ system causing structure in $J/\psi \phi$? Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about $K^*$ contributions

$K^{*+} \rightarrow \phi K^+$ resonances expected to be broad (scattering expts)

6D amplitude analysis to understand resonant structure

Three interfering decay chains (same particles in final state but different intermediate resonances):

1. $B^+ \rightarrow K^{*+}J/\psi$,  $K^{*+} \rightarrow \phi K^+$
2. $B^+ \rightarrow XK^+$,  $X \rightarrow J/\psi \phi$
3. $B^+ \rightarrow Z^+\phi$,  $Z^+ \rightarrow J/\psi K^+$

[$\text{PRD 95, 012002 (2017)}$, $\text{PRL 118, 022003 (2017)}$]
Which $K^*$ resonances to include?

Experimental measurements of **well-established** and **unconfirmed** $K^*$ resonances

Higher spin states expected to be suppressed in $B$ decays due to orbital angular momentum required to produce them

104 free parameters in fit

$p$-value $H_0$ (only $K^*$ resonances) < 10⁻⁴
Results including $X \to J/\psi \phi$ states

7 $K^*$ states, 4 exotic $X$ states and NR $J/\psi \phi$ and $\phi K^*$ components.

Inclusion of exotic $Z$ states does not improve fit.

98 free parameters in fit
p-value = 22%

[PRD 95, 012002 (2017)] [PRL 118, 022003 (2017)]
Exotic baryons
Pentaquark observation

Large production of b-baryons at LHC.
Many more Λ_b in LHCb than central detectors.

\[
\Lambda^0_b \rightarrow J/\psi p K^-
\]

26000 signal
5.4% background
in 2σ

LHCb

LHCb

[2015] 072001

[143] [HEP 08 (2014)]
Pentaquark observation

Can this be caused by reflections in $m(Kp)$, background or detector efficiency?

Interfering $\Lambda^* \rightarrow pK$ resonances

LHCb

[References: PRL 115 (2015) 072001]
Results without $P_c$ states

Using full set of $\Lambda^*$'s the $m(Kp)$ distribution looks good but not $m(J/\psi p)$.

Addition of non-resonant, extra $\Lambda^*$'s, all $\Sigma^*$ (isospin violating process) does not help.

**Also: model independent approach (Legendre moments) excludes the $\Lambda^*$-only hypothesis at 9σ**

[PRl 117 (2016) 082002]
Reduced model with two $P_c$'s

\[ \text{J}^P = (3/2^+, 5/2^-) \text{ and } (5/2^+, 3/2^-) \text{ also give good fits: need more data.} \]

No improvement with addition of other resonances
Significance evaluated using toy simulation
Need opposite parity to explain the data

\[ \text{LHCb} \]

\[ \begin{array}{ccc}
\text{Events/(15 MeV)} & \text{0} & \text{100} \\
\text{0} & \text{200} & \text{300} \\
\text{400} & \text{500} & \text{600} \\
\text{700} & \text{800} & \text{900} \\
\text{1000} & \text{1100} & \text{1200} \\
\text{1300} & \text{1400} & \text{1500} \\
\end{array} \]

\[ \begin{array}{ccc}
\text{m}_{Kp} \text{ [GeV]} & \text{1.4} & \text{1.6} \\
\text{1.8} & \text{2.0} & \text{2.2} \\
\text{2.4} & \text{2.6} & \text{2.8} \\
\end{array} \]

\[ \begin{array}{ccc}
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\text{1300} & \text{1400} & \text{1500} \\
\end{array} \]

\[ \begin{array}{ccc}
\text{m}_{J/\psi p} \text{ [GeV]} & \text{4} & \text{4.2} \\
\text{4.4} & \text{4.6} & \text{4.8} \\
\text{5} & \text{5.2} & \text{5.4} \\
\end{array} \]

\[ \begin{array}{ccc}
\text{J}^P & \text{P}_c(4380)^+ & \text{P}_c(4450)^+ \\
\text{Mass [MeV/c}^2] & 4380 \pm 8 \pm 29 & 4449.8 \pm 1.7 \pm 2.5 \\
\text{Width [MeV/c}^2] & 205 \pm 18 \pm 86 & 39 \pm 5 \pm 19 \\
\text{Fit fraction [%]} & 8.4 \pm 0.7 \pm 4.2 & 4.1 \pm 0.5 \pm 1.1 \\
\text{Significance} & 9\sigma & 12\sigma \\
\end{array} \]

\[ \text{uudc}\bar{c} \]

[\text{PRL 115 (2015) 072001}]
Resonant behaviour - a bound state?

Observe rapid change of phase near maximum of magnitude ⇒ resonance!

![Graph showing phase and magnitude changes](image)

**Simulation**

- $m_0$
- $\Gamma_0$
- 180°

**Argand diagram**

- $\text{Re } A^R$
- $\text{Im } A^R$
- $\text{BW amplitude}$

- $P_c(4450)$
- $P_c(4380)$

*[PRL 115 (2015) 072001]*
\[ \Lambda_b \rightarrow J/\psi p\pi^- \text{ pentaquark search} \]

\[ R_{\pi^-/K^-} \equiv \frac{B(\Lambda_b^0 \rightarrow \pi^- P_c^+)}{B(\Lambda_b^0 \rightarrow K^- P_c^-)} \approx 0.07 - 0.08 \]

\[ N_{\text{sig}} = 1885 \pm 50 \]

17% background

[Cheng et al. PRD 92, 096009 (2015)]

\[ R_{\pi^-/K^-} = 0.58 \pm 0.05 \]

[Hsiao, PLB 751, 572 (2015)]

MC histogram with calibrated PID

possible \( Z_c(4200)^\pm \rightarrow J/\psi \pi^\pm \) component

possible \( P_c^\pm \) components

[N\* \( \rightarrow p\pi \)]

[Cheng et al. PRD 92, 096009 (2015)]

[Hsiao, PLB 751, 572 (2015)]

[cc] from the sea

[PRL 117, 082003 (2016)]
$\Lambda_b \rightarrow J/\psi p\pi^-$ pentaquark search

**N*-only model** not a good fit

Good fit using 15 N* states + exotic components

3.1σ for (2 $P_c + Z_c$) or 3.3σ for 2 $P_c$ states

Main systematics from fixed $P_c/Z_c$ mass/width parameters, N* model and unknown $P_c$ spin

<table>
<thead>
<tr>
<th>States</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>$5.1 \pm 1.5^{+2.1}_{-1.6}$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$1.6^{+0.8}_{-0.6}$</td>
</tr>
<tr>
<td>$Z_c(4200)^-$</td>
<td>$7.7 \pm 2.8^{+3.4}_{-4.0}$</td>
</tr>
</tbody>
</table>

$P_c(4450)^+$

$m(p\pi) > 1.8$ GeV

w/ exotics

w/o exotics

$L(\text{PRL } 117, 082003 (2016))$

Largest syst. error from fit fraction of $P_c$ in the kaon mode

[PRL 117, 082003 (2016)]

[Hsiao, PLB 751, 572 (2015)]
Phenomenological models

Many phenomenological models on the market, e.g., $D^*\Sigma_c^-D^*_c\Sigma^+_c$ molecular state, tightly bound di-quarks, hadro-charmonium?

Not all of them can explain all of the observed exotic states, so may need several of them to explain observations.

[Maiani et al arXiv:1507.04980]
[Lebed arXiv:1507.05867]
[Zhu arXiv:1510.08693]
[Roca et al, PRD 92 (2015) 094003]
Another option - rescattering

$P_c(4450)^+$ has mass just above $\chi_{c1}p$ threshold so could be $J/\psi p \rightarrow \chi_{c1}p$ kinematic rescattering effect.

Reproduces phase motion of $P_c(4450)^+$, but what about $P_c(4380)^+$?

Rescattering would not explain narrow enhancement/deficit above $\chi_{c1}p$ threshold.

[Guo et al, PRD 92 (2015) 071502(R)]
[Bayar at al, PRD 94 (2016) 074039]
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Reproduces phase motion of $P_c(4450)^+$, but what about $P_c(4380)^+$?

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![Diagram](image)

\[ \frac{B(\Lambda_b^0 \rightarrow \chi_{c1}pK^-)}{B(\Lambda_b^0 \rightarrow J/\psi pK^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009 \]

\[ \frac{B(\Lambda_b^0 \rightarrow \chi_{c2}pK^-)}{B(\Lambda_b^0 \rightarrow J/\psi pK^-)} = B(\chi_{c2}) = 0.248 \pm 0.020 \pm 0.014 \pm 0.009 \]

[Guo et al, PRD 92 (2015) 071502(R)]
[Bayar at al, PRD 94 (2016) 074039]
Strange pentaquarks?

Strange pentaquark (udsc\overline{c}) predicted with mass \(\sim 4.65\) GeV and width \(\sim 10\) MeV.

First observation of the \(\Xi_{b}^{-} \rightarrow J/\psi \Lambda K^{-}\) decay.

**Next steps:**

Expect \(\sim 1500\) signal events after \(2018 \rightarrow\) amplitude analysis to look for exotics in \(m(J/\psi \Lambda)\)

Also look for \(\Lambda_{b} \rightarrow J/\psi \Lambda \phi\) decay

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[PLB 772 (2017) 265-273]

[PRC 93, 065203 (2016)]

[PLB 772 (2017) 265-273]

[N_{\text{sig}} = 308 \pm 21 (21\sigma)]
Future experimental programme

1. Observe states in different production mechanisms
e.g., prompt production of pentaquark direct from LHC pp collisions

2. Observe states in different decay modes
Search for $c\bar{c}$, open-charm and charm-less modes using all flavours of b-hadron

Transitions between exotic states (e.g., $Y(4260) \rightarrow X(3872)\gamma$)

Publish non-observations!

3. Look for isospin $(ccudd)$, strangeness $(ccuds)$, bottom $(bbuud)$ partners

4. Measure angular distributions and quantum numbers
Amplitude (partial wave) analyses are crucial, as are accounting for threshold effects

Publish experimental efficiencies to allow others to better use results

If exotic states are molecules then their open-charm decays may be dominant

[PRL 105, 232001 (2010)]
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\[
\begin{align*}
\Lambda_b^0 &\rightarrow \Sigma_c^+ D^- \\
\Lambda_b^0 &\rightarrow \Lambda_c^+ D^{*0} K
\end{align*}
\]

If exotic states are molecules then their open-charm decays may be dominant

\[
\Lambda_b^0 \rightarrow P_{cs}^0 \phi \rightarrow J/\psi \Lambda \phi
\]

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   **Amplitude (partial wave) analyses** are crucial, as are accounting for threshold effects
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---

LHC, Belle-II, BES-III, COMPASS, JLab and PANDA all have role to play!
LHCb provides ideal laboratory for (exotic) hadron spectroscopy due to large heavy quark production cross-sections, efficient triggers and low backgrounds. New conventional/exotic states now being discovered and their properties measured with unprecedented precision, allowing us to better understand non-perturbative QCD.

Crucial to confirm observations where possible and use state-of-the-art amplitude analyses and collaboration with theorists to understand observed states.


11-13th December 2017
Backup
The $X(5568)^\pm \rightarrow B_s \pi^\pm$?

3.9σ evidence for exotic state

Large $B_s$ production fraction: $\rho_X = (8.6 \pm 1.9 \pm 1.4)\%$

Not due to reflections from kaons/pions

$$M = 5567.8 \pm 2.9_{-1.9}^{+0.9}\text{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4_{-2.5}^{+5.0}\text{MeV}/c^2$$

Possible $\bar{b}s\bar{u}d$ tetraquark/molecule but difficult to explain when considering QCD chiral symmetry, heavy quark symmetry and threshold effects.

[ Burns, Swanson, arXiv:1603.04366 ]
[ Liu, Li, arXiv:1603.04366 ]

No sign on the lattice [Lang et al., arXiv:1607.03185]
LHC searches for $X(5568)^\pm$

LHCb use $>100k B_s$ mesons and combine with $\pi^\pm$. Sample 20x larger than D0 and much less background.

$B_s$ and $\pi^\pm$ required to come from same PV.

Fit signal using S-wave Breit-Wigner with mass and width of claimed D0 signal.

$\rho_{X}^{LHCb}(B_s^0, p_T > 10 \text{ GeV}/c) < 2.1 \ (2.4)\% \ @ \ 90 \ (95)\% \ CL$

Set limits as a function of $X$ mass and width.

How signal would look according to D0 result for $\rho_X$
Charmonium production in b-hadron decays

First observation of $\eta_c(2S) \rightarrow p\bar{p}$

No sign of $X(3872) \rightarrow p\bar{p}$

$B^+ \rightarrow ([c\bar{c}] \rightarrow p\bar{p}) K^+$ provides clean environment

$B(B^+ \rightarrow X(3872)K^+) \times B(X(3872) \rightarrow p\bar{p}) / B(B^+ \rightarrow J/\psi K^+) \times B(J/\psi \rightarrow p\bar{p}) < 0.20 (0.25) \times 10^{-2}$

No sign of $X(3872)$ or $X(3915) \rightarrow \phi\phi$

$b \rightarrow ([c\bar{c}] \rightarrow \phi\phi) X$

require separation between PV and secondary vertices

95% (90%) CL upper limit on BR relative to conventional $[c\bar{c}]$ with same $J^{PC}$
Pentaquark model-independent

Λ* spectrum is largest systematic uncertainty in observation of $P_c$ states.

**Model-independent approach**: do not assume anything about Λ*, Σ* or NR composition, spin, masses, widths or mass-shape.

Only restrict the maximal spin of allowed Λ* components at given $m(Kp)$.

---

Extension of [BaBar PRD 79 (2009) 112001]
Pentaquark model-independent

Maximal rank of the Legendre polynomial \( l_{\text{max}} \) cannot be higher than \( 2J_{\text{max}} \), where \( J_{\text{max}} \) is twice the highest (\( Kp \)) spin which is present in the data at a given \( m(Kp) \) value.

Null hypothesis (\( \Lambda^* \) only) rejected at 9\( \sigma \)

Working with JPAC to use better models of \( \Lambda^* \) resonances in future amplitude fits.
Meet the family

**Production mechanism**

- **b hadrons**
  - $X(3872)$
  - $Y(3940)$
  - $Z' (4430)$
  - $Z^- (4051)$
  - $Z^- (4248)$
  - $Y(4140)$
  - $Y(4274)$
  - $Z_c^+ (4200)$
  - $Z_c^+ (4240)$
  - $X(3823)$

- **ISR**
  - $Y(4260)$
  - $Y(4008)$
  - $X(3940)$
  - $X(4160)$

- **double charmonium**
  - $C=+$
  - $J^{PC}=1^{-+}$

- **$\gamma\gamma$ collisions**
  - $(e^+e^- \rightarrow e^+e^-X)$
  - $X(3915)$
  - $X(4350)$
  - $Z(3930)$

- **ISR $\rightarrow Y(4260)$**
  - $Z_c (3900)$
  - $Z_c (4025)$
  - $Z_c (4020)$
  - $Z_c (3885)$

---

Recent review articles -
- [Guo et al, arXiv:1705.00141]
- [Esposito et al, arXiv:1611.07920]
- [Lebed et al, arXiv:1610.04528]
- [Chen et al, arXiv:1601.02092]

---

$X(3872)$ also observed in prompt pp, $p\bar{p}$ collisions and ISR
Connections with “conventional” spectroscopy

Discovery of $\Omega_c^{**}$ and $\Xi_{cc}^{++}$ have spurred theoretical investigations, motivated by the calibration of the binding energy of their constituent diquarks.

Calibrating diquark model parameters from $\Omega_c^{**}$, treating them as [ss]c diquark-quark objects. Can then use this to make predictions about the Y states. [Ali et al., arXiv:1708.04650]

Not only are some of the $\Omega_c^{**}$ states now thought of as potential pentaquarks, but theorists are using these as a basis to propose other candidates. [Mehen arXiv:1708.05020] [Karliner and Rosner arXiv:1707.07666]

e.g., doubly-bottom tetraquark (~10.4 GeV) that is stable to EM/strong interactions, potentially narrow, with very interesting decay modes (B, D, double-J/ψ …)
X(3872) production

X(3872) seen in pp and and p\bar{p} collisions.

Compare cross-section with that of known molecules to understand X(3872) nature.

NLO NRQCD considers X(3872) to be a mixture of $\chi_{c1}(2P)$ and a D$^0$D$^{*0}$ molecular state, with the production dominated by the $\chi_{c1}(2P)$ part.

Supported by BR of $X(3872) \rightarrow [c\bar{c}]\gamma$ decays

[Artoisenet and Braaten, PRD 81 (2010) 114018]

[Esposito et al, PRD 92 (2015) 034028]

[Deuteron @ALICE]

[Helium-3 @ALICE (rescaled from Pb-Pb)]

[Hypertion @ALICE (rescaled from Pb-Pb)]

Need to bridge this gap

X(3872) @CMS

X(3872) @ALICE

[ATLAS, JHEP 01 (2017) 117]

[Artoisenet and Braaten, PRD 81 (2010) 114018]

[ATLAS, JHEP 01 (2017) 117]

[D0, PRL 103 (2009) 152001]

[CDF, PRL 103 (2009) 152001]

[CMS, JHEP 04 (2013) 154]

[LHCb, JHEP 04 (2013) 154]

[NPB 886 (2014) 665]
Baryon-number violation

BNV never been seen experimentally → strong constraints from proton lifetime.

BSM models with flavour-diagonal six fermion vertices allow BNV without violating constraints.  
[PRD 85, 036005 (2012), PLB 721 82 (2013)]

**Unambiguous experimental evidence:** baryon-antibaryon oscillations of hadrons that contain quarks of all three generations (usb).
Baryon-number violation @ LHCb

No evidence of BNV oscillations.

$$\omega < 0.08 \text{ ps}^{-1} \text{ @95\% CL (using likelihood ratio test and CL}_s\text{ method)}$$

$$\omega = 1/\tau^2_{\text{mix}} \rightarrow \text{mixing lifetime > 13 ps.}$$

Similar method for measuring charm mixing

$$R(t) = \frac{\Gamma(\Xi_b^0 \rightarrow \Xi_c^- \pi^+)}{\Gamma(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)} \approx \omega t^2$$
Future $X(3872)$ measurements

Charged partners of $X(3872)$ predicted by some tetraquark models \cite{Maiani et al}

Partners not observed in B decays and limits below what would be expected for isospin conservation \Rightarrow $X(3872)$ is iso-singlet?

Alternatively, the partners may be broad due to presence of thresholds, so may have evaded detection \Rightarrow amplitude analysis

Make more precise width and mass measurement

\[ \mathcal{B}(B^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 4.2 \times 10^{-6}, \]
\[ \mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 6.1 \times 10^{-6}, \]
Evidence for exotics in $\Lambda_b \to J/\psi p\pi^-$

$$\frac{B(\Lambda_b^0 \to J/\psi p\pi^-)}{B(\Lambda_b^0 \to J/\psi pK^-)} \approx 0.0824 \pm 0.0025 \text{ (stat)} \pm 0.0042 \text{ (syst)}$$

Observations of the $P_{c^+}^+$ states in another decay could imply they are genuine exotic baryonic states, other than kinematical effects, e.g. so-called triangle singularity. \[arXiv:1512.01959\]

$$R_{\pi^-/K^-} \equiv \frac{B(\Lambda_b^0 \to \pi^- P_{c^+}^+)}{B(\Lambda_b^0 \to K^- P_{c^+}^+)} \approx 0.07 - 0.08$$

$R_{\pi^-/K^-} = 0.58 \pm 0.05$

[LHCb JHEP 1407, 103 (2014)]

[Cheng et al. PRD 92, 096009 (2015)]

Λ_b → J/ψpπ⁻ pentaquark search

No prominent pentaquark-like peaks
Extended model with one $P_c$

Try all $\Lambda^*$'s with $J^P$ up to $7/2^\pm$

Best fit with a $J^P = 5/2^\pm$ pentaquark gives improvement, but $m(J/\psi p)$ still not good

$\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$
Pentaquark model-independent

\[ \frac{dN}{d \cos \theta_{A^*}} = \sum_{l=0}^{l_{\text{max}}} \langle P_l^U \rangle P_l(\cos \theta_{A^*}) \]

Maximal rank of the Legendre polynomial \( l_{\text{max}} \) cannot be higher than \( 2J_{\text{max}} \), where \( J_{\text{max}} \) is twice the highest \((Kp)\) spin which is present in the data at a given \( m(Kp) \) value.

Filter out maximum spin for each \( m(Kp) \).
Pentaquark model-independent

Simulate phase-space decays of $\Lambda_b^0 \rightarrow J/\psi pK^-$

Weight according to $m(Kp)$ and the moments (with $l_{\text{max}}$-filter applied)

Look at reflections of the $pK$ system into the $J/\psi p$ system $\rightarrow$ **pK reflections cannot explain narrow structure!**

Use likelihood ratio to test various hypotheses - **Null hypothesis ($\Lambda^*$ only) rejected at 9σ**
Angular distributions

Good fit to the angular observables

[PRL 115 (2015) 072001]
For the future: $B_s^0 \to J/\psi \phi \phi$

Possible threshold effects in $B_s^0 \to J/\psi \phi \phi$ and other modes  

Simplified phase-space simulation inadequate to describe structure

Looking forward to more data in Run-2 of LHCb

\[ \frac{B(B_s^0 \to J/\psi \phi \phi)}{B(B_s^0 \to J/\psi \phi)} = 0.0115 \pm 0.0012^{+0.0005}_{-0.0009} \]

Contamination from non-res decays

Background subtracted no efficiency correction

[Swanson PRD 91 (2015) 034009]

[JHEP 1603 (2016) 040]
**Z_c(3900)\(^{\pm}\) in e^+ e^- \rightarrow Y(4260) \rightarrow \pi^+ \pi^- J/\psi**

Observation of another possible **exotic charged state**.

Is Z(4430)\(^{\pm}\) a radial excitation of Z_c(3900)\(^{\pm}\)?

CLEO-c and BES-III have evidence/observation for neutral member of **isospin triplet** decaying to \(\pi^0 J/\psi\).

Also appears in D\(^{\pm}\)D\(^*\) decay mode (Z_c(3885)\(^{\pm}\))

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**[Maiani et al, NJP 10 (2008) 073004]**

**[Wang, arXiv:1405.3581]**

**[Agaev et al, arXiv:1706.01216]**

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\[ M = (3894.5 \pm 6.6 \pm 4.5) \text{ MeV/c}^2 \]
\[ \Gamma = (63 \pm 24 \pm 26) \text{ MeV} \]
Understanding the $Z_c(3900)^\pm$

Some lattice QCD calculations do not support existence of $Z_c(3900)^\pm$ 

No sign of $Z_c(3900)^\pm \rightarrow J/\psi\pi^\pm$ in B decays or photo-production ($\gamma p \rightarrow J/\psi\pi^\pm n$) 

Indicates that $Z_c(3900)^\pm$ (and $Z_c(4020)^\pm$) may not be dynamical in nature but some kinematic effect (e.g., threshold cusp)?

Or maybe not?
Open questions

We know a lot about some states as they have been seen in multiple production and decay modes by many experiments (i.e., $X(3872), Y(4260)$) but there are still things we don’t know, such as the natural width of the $X(3872)$ or if it is above or below the $D^0D^{*0}$ threshold, or phase motion of the $Y(4260)$ (although we now think it is two peaks!).

Lots of useful information from B meson decays (they act as an excellent filter and a well-defined initial state for spectroscopy), ISR but only a few states have been produced in pp, ppbar collisions.

Some states have only been seen by a single experiment in a single production/decay mode. Quantum numbers remain unknown and states need confirmation.

History of this field is one of surprises, driven by experimental results.

Experimentally, focussed on modes containing psi(‘), but now need to look at pairs of open-charm and open-beauty, which may reveal new surprises.

Why don’t we see evidence for $Z(3900)$ and $Y(4260)$ in B decays? Need larger data samples to investigate properly.
Future experimental programme

All LHCb results so far using Run 1.

Total Run 2 (ending in 2018) data will equal ~5/fb at 13 TeV, equivalent to x3 the Run 1 dataset, so prospects are good for more discoveries and more precise measurements.

Beyond this, the LHCb upgrade will run in 2021, when it is possible to accumulate even higher luminosities, leading to around 50/fb total lumi.

ATLAS/CMS will have even higher luminosity, so can contribute.

BES-III will study Y(4260) and Z(3900) in more detail.

Belle-II should have ~x50 larger dataset than Belle. Complementary strengths will be in modes with neutral particles. Look for isospin partners of many of the states that have been observed and useful for D(*)sD(*)s decay modes due to higher efficiency.

PANDA @ FAIR (2022) X(3872) line shape via energy scan (and width measurement at O(10) keV and D*s0(2317)

GlueX and CLAS12 photo-production for studies of hybrid mesons and Pc production
LHCb search for $X(5568)^\pm$

Use 112,000 $B_s$ mesons and combine with $\pi^\pm \rightarrow$ sample 20x that of D0, and much less background.

\[ N(B_s^0) = 65k \]
\[ \sigma = 15 \text{ MeV}/c^2 \]
\[ S/B = 10 \]

\[ N(B_s^0) = 45k \]
\[ \sigma = 6 \text{ MeV}/c^2 \]
\[ S/B = 50 \]
**Z(4430)$^{\pm}$ charged charmonium exotic**

- **[Belle, PRL 100 (2008) 142001]** 1D fit to $m(\psi'\pi^-)$ 6.5\(\sigma\)
- **[BaBar, PRD 79 (2009) 112001]** Not observed but does not contradict Belle!
- **[Belle, PRD 80 (2009) 031104]** 2D amplitude fit to $m(\psi'\pi^-)$ vs $m(K^+\pi^-)$ 6.4\(\sigma\)
- **[Belle, PRD 88 (2013) 074026]** 4D amplitude fit

---

$\mu^+\mu^-$, $J/\psi\pi^+\pi^-$

$B^{+,0} \rightarrow \psi(2S)\pi^- K^{+,0}$

$B^{+,0} \rightarrow Z(4430)^- K^{+,0} \mu^+\mu^-, J/\psi\pi^+\pi^-$

$\psi(2S)\pi^-$

$M = 4485^{+22+28}_{-22-11}$ MeV/c$^2$

$\Gamma = 200^{+41+26}_{-46-35}$ MeV/c$^2$

---

**K* veto region**

**With Z**

**Without Z**
Confirmation of the $Z(4430)^\pm$

LHCb has $>25k \, B^0 \rightarrow \psi(2S)K^+\pi^-$ candidates ($\times 10$ Belle/BaBar) with 3% background

Two analysis methods:

4D amplitude analysis used to measure resonance parameters and $J^P$.

Study angular moments in model-independent way (similar to what was done for pentaquark).
Resonant behaviour - a bound state?

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(Z)$ [MeV]</td>
<td>$4475 \pm 7^{+15}_{-25}$</td>
<td>$4485 \pm 22^{+28}_{-11}$</td>
</tr>
<tr>
<td>$\Gamma(Z)$ [MeV]</td>
<td>$172 \pm 13^{+37}_{-34}$</td>
<td>$200^{+41}<em>{-46}^{+26}</em>{-35}$</td>
</tr>
<tr>
<td>$f_Z$ [%]</td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$</td>
<td>$10.3^{+3.0}<em>{-3.5}^{+4.3}</em>{-2.3}$</td>
</tr>
<tr>
<td>$f_Z^I$ [%]</td>
<td>$16.7 \pm 1.6^{+2.6}_{-5.2}$</td>
<td>$-$</td>
</tr>
<tr>
<td>significance</td>
<td>$&gt; 13.9\sigma$</td>
<td>$&gt; 5.2\sigma$</td>
</tr>
<tr>
<td>$J^P$</td>
<td>$1^+$</td>
<td>$1^+$</td>
</tr>
</tbody>
</table>

Excellent agreement between LHCb and Belle.

Belle evidence for $Z(4430)^\pm \to J/\psi\pi^\pm$ and observation of a new resonant state $Z(4200)^\pm \to J/\psi\pi^\pm$ [PRD 90 (2014) 112009]
Z(4430) interpretations

Result confirms existence of the Z(4430), measures $J^P=1^+$ and, for the first time, demonstrates resonant behaviour.

Mass close to DD* thresholds - perhaps this is the organising principle of these exotic states?

Large width - unlikely to be molecule?

$P=+$ rules out interpretation in terms of $\bar{D}^*(2010)D^*(12420)$ molecule or threshold effect (cusp).


Rescattering effect proposed, but phase motion in wrong direction?

[Pakhov, Uglov PLB748 (2015) 183]

Diquark-antidiquark bound state is an explanation. [Maiani et al, PRD 89 114010]

Potential neutral isospin partner? $Z(4430)^0$ in $B^+ \rightarrow \psi(2S)\pi^0K^+$
Building the log-likelihood

Use Isobar approach - matrix element from coherent sum of two-body resonances.

\[
\frac{dP}{dm_{\phi K} d\Omega} \equiv P_{\text{sig}}(m_{\phi K}, \Omega|\tilde{\omega}) = \frac{1}{I(\tilde{\omega})} |\mathcal{M}(m_{\phi K}, \Omega|\tilde{\omega})|^2 \Phi(m_{\phi K})\epsilon(m_{\phi K}, \Omega)
\]

Masses, widths, helicity couplings

Phase space = pq

Efficiency

Integral from sum over fully simulated phase space MC

\[
I(\tilde{\omega}) \equiv \int P_{\text{sig}}(m_{\phi K}, \Omega) dm_{\phi K} d\Omega \propto \frac{\sum_j w_j^{MC} |\mathcal{M}(m_{K^0 j}, \Omega_j|\tilde{\omega})|^2}{\sum_j w_j^{MC}}
\]

MC correction weights

Background

\[
- \ln L(\tilde{\omega}) = -\Sigma_i \ln \left[ |\mathcal{M}(m_{\phi K_i}, \Omega_i|\tilde{\omega})|^2 \right] + \frac{\beta I(\tilde{\omega})}{(1-\beta)I_{\text{bkg}}} \frac{P_{\text{bkg}}^u(m_{\phi K_i}, \Omega_i)}{\Phi(m_{\phi K_i})\epsilon(m_{\phi K_i}, \Omega_i)} + N \ln I(\tilde{\omega})
\]

67
Matrix element for $K^{*+} \rightarrow \phi K^+$ contributions

Sum over $K^*$ resonances (usually BW)

\[ \mathcal{M}_{K^*}^{\Delta \lambda_\mu} = \sum_j R_j (m_{\phi K}) \sum_{\lambda_{J/\psi} = -1,0,1} \sum_{\lambda_\phi = -1,0,1} A_{\lambda_{J/\psi}}^{B \rightarrow J/\psi K^* \ j} A_{\lambda_\phi}^{K^* \rightarrow \phi K \ j} \]

Helicity couplings

\[ d_{\lambda_{J/\psi}, \lambda_\phi}^{J_{K^*} \ j} (\theta_{K^*}) \ d_{\lambda_\phi,0}^1 (\theta_{\phi}) e^{i\lambda_\phi \Delta \phi_{K^* \phi}} \]

Wigner d-matrices

In-coherent sum over difference between muon helictites

\[ |\mathcal{M}_{K^*}|^2 = \sum_{\Delta \lambda_\mu = \pm 1} |\mathcal{M}_{\Delta \lambda_\mu}|^2 \]

Parity conservation in strong decay of $K^*$ limits number of couplings

\[ A_{\lambda_\phi} = P_{K^*} (-1)^{J_{K^*} + 1} A_{-\lambda_\phi} \]
Now include the $X \rightarrow J/\psi \phi$ components

$$\mathcal{M}_{X}^{\Delta \lambda_{\mu}} \equiv \sum_{j} R_{j}(m_{J/\psi \phi}) \sum_{\lambda, \lambda_{J/\psi}, \lambda_{\phi} = -1,0,1} A_{\lambda, \lambda_{J/\psi}, \lambda_{\phi}}^{X \rightarrow J/\psi \phi j} \times$$

$$d_{0,\lambda_{J/\psi} - \lambda_{\phi}}^{J_{X}} (\theta_{X}) d_{\lambda_{\phi},0}^{1} (\theta^{X}_{\phi}) e^{i\lambda_{\phi} \Delta \phi_{X,\phi}} d_{\lambda_{J/\psi}, \Delta \lambda_{\mu}}^{1} (\theta^{X}_{J/\psi}) e^{i\lambda_{J/\psi} \Delta \phi_{X, J/\psi}}$$

### Table: Num independent $X$ helicity couplings

<table>
<thead>
<tr>
<th>$J^{P_{X}}$</th>
<th>Num independent $X$ helicity couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^{-}$</td>
<td>1</td>
</tr>
<tr>
<td>0$^{+}$</td>
<td>2</td>
</tr>
<tr>
<td>1$^{+}$</td>
<td>3</td>
</tr>
<tr>
<td>1$^{-}$, 2$^{-}$</td>
<td>4</td>
</tr>
<tr>
<td>2$^{+}$</td>
<td>5</td>
</tr>
</tbody>
</table>

from parity conservation

Angle to align coordinate axes in the $X$ and $K^{*}$ decay chains

$$|\mathcal{M}_{K^{*}+X}|^{2} = \sum_{\Delta \lambda_{\mu}=\pm1} |\mathcal{M}_{\Delta \lambda_{\mu}}^{K^{*}} + e^{i\alpha \lambda} \Delta \lambda_{\mu} \mathcal{M}_{\Delta \lambda_{\mu}}^{X}|^{2}$$

Similar matrix element for the $Z^{+} \rightarrow J/\psi K^{+}$ decay chain
Mass dependence

Sum of overlapping Breit-Wigners and mass-independent non-resonant components

\[ R(m|M_0, \Gamma_0) = B'_{LB}(p, p_0, d) \left( \frac{p}{p_0} \right)^{L_B} BW(m|M_0, \Gamma_0) B'_{LA}(q, q_0, d) \left( \frac{q}{q_0} \right)^{L_A} \]

- Orbital momentum of B meson
- Blatt-Weisskopf barrier factors
- Orbital momentum of resonance A

\[ BW(m|M_0, \Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)} \]

\[ \Gamma(m) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2L_A+1} \frac{M_0}{m} B'_{LA}(q, q_0, d)^2 \]

Use minimum allowed value of \( L_B \) and \( L_A \)

Systematic uncertainty to allow larger values
Assume efficiency factorises.

Fully simulated signal decay used to get parameterisation (bi-cubic interpolation between bin centres).

Simulation is weighted to match \( p(K) \), \( pT(B) \) and nTracks distributions in data.

Band in \( \varepsilon_2 \) from veto on double \( \varphi \rightarrow K^+K^- \).
Same factorisation method as for efficiency.
Use sidebands of the B mass to get distribution.
Amplitude model

Two interfering channels.

Use 5 angles and $m(Kp)$ as fit observables.

Resonance mass-shapes: Breit-Wigner or Flatté.

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
</tr>
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<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>$1/2^-$</td>
<td>$1405.1^{+1.3}_{-1.0}$</td>
<td>$50.5 \pm 2.0$</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>$1519.5 \pm 1.0$</td>
<td>$15.6 \pm 1.0$</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>$1/2^+$</td>
<td>$1600$</td>
<td>$150$</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>$1/2^-$</td>
<td>$1670$</td>
<td>$35$</td>
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<tr>
<td>$\Lambda(1690)$</td>
<td>$3/2^-$</td>
<td>$1690$</td>
<td>$60$</td>
</tr>
<tr>
<td>$\Lambda(1800)$</td>
<td>$1/2^-$</td>
<td>$1800$</td>
<td>$300$</td>
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<tr>
<td>$\Lambda(1810)$</td>
<td>$1/2^+$</td>
<td>$1810$</td>
<td>$150$</td>
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<tr>
<td>$\Lambda(1820)$</td>
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<td>$200$</td>
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<td>$\Lambda(2110)$</td>
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<td>$2110$</td>
<td>$200$</td>
</tr>
<tr>
<td>$\Lambda(2350)$</td>
<td>$9/2^+$</td>
<td>$2350$</td>
<td>$150$</td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>?</td>
<td>$\approx 2585$</td>
<td>$200$</td>
</tr>
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</tr>
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<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>$1519.5 \pm 1.0$</td>
<td>$15.6 \pm 1.0$</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>$1/2^+$</td>
<td>$1600$</td>
<td>$150$</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>$1/2^-$</td>
<td>$1670$</td>
<td>$35$</td>
</tr>
<tr>
<td>$\Lambda(1690)$</td>
<td>$3/2^-$</td>
<td>$1690$</td>
<td>$60$</td>
</tr>
<tr>
<td>$\Lambda(1800)$</td>
<td>$1/2^-$</td>
<td>$1800$</td>
<td>$300$</td>
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<td>$1820$</td>
<td>$80$</td>
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<td>$1830$</td>
<td>$95$</td>
</tr>
<tr>
<td>$\Lambda(1890)$</td>
<td>$3/2^+$</td>
<td>$1890$</td>
<td>$100$</td>
</tr>
<tr>
<td>$\Lambda(2100)$</td>
<td>$7/2^-$</td>
<td>$2100$</td>
<td>$200$</td>
</tr>
<tr>
<td>$\Lambda(2110)$</td>
<td>$5/2^+$</td>
<td>$2110$</td>
<td>$200$</td>
</tr>
<tr>
<td>$\Lambda(2350)$</td>
<td>$9/2^+$</td>
<td>$2350$</td>
<td>$150$</td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>?</td>
<td>$\approx 2585$</td>
<td>$200$</td>
</tr>
</tbody>
</table>

$\Lambda_b^0 \rightarrow J/\psi \Lambda^* \quad \Lambda^* \rightarrow pK^-$

$\Lambda_b$ rest frame

$\Lambda$ rest frame

$\psi$ rest frame

lab frame

$\Lambda_b$ rest frame

$P_c$ rest frame

lab frame

$\Lambda_b^0 \rightarrow P_c^+ K^- \quad P_c^+ \rightarrow J/\psi p$

[PRL 115 (2015) 072001]
Amplitude model

Consider three decay chains that mutually interfere:
\[
\Lambda_b^0 \rightarrow J/\psi N^*, N^* \rightarrow p\pi^-
\]
\[
\Lambda_b^0 \rightarrow P_c^+\pi^-, P_c^+ \rightarrow J/\psi p
\]
\[
\Lambda_b^0 \rightarrow Z_c^-p, Z_c^- \rightarrow J/\psi\pi^-
\]

**Additional angles** to align muon and proton helicity frames between each decay chain

\[
|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}=\pm \frac{1}{2}} \sum_{\lambda_p=\pm \frac{1}{2}} \sum_{\Delta \lambda_\mu=\pm 1} \left| \mathcal{M}_{\Lambda_b^0, \lambda_p, \Delta \lambda_\mu}^{N^*} + e^{i\Delta \lambda_\mu \alpha_\mu} \sum_{\lambda_{P_c}} d_{\lambda_p, \lambda_{P_c}}^{\frac{1}{2}} \mathcal{M}_{\Lambda_b^0, \lambda_{P_c}, \Delta \lambda_\mu}^{P_c} \right|^2
\]

\[
+ e^{i\Delta \lambda_\mu \alpha_\mu} \sum_{\lambda_{Z_c}} e^{i\lambda_{Z_c} \alpha_\mu} \sum_{\lambda_p} d_{\lambda_{P_c}, \lambda_p, \mathcal{P}}^{\frac{1}{2}} \mathcal{M}_{\Lambda_b^0, \lambda_{Z_c}, \Delta \lambda_\mu}^{Z_c} \left| \right|^2
\]

\[
B^0 \rightarrow J/\psi K^\pi \quad \text{[Belle, PRD 90 (2014) 112009]}
\]

\[
m_0 = 4196^{+31+17}_{-29-13} \text{ MeV}, \quad \Gamma_0 = 370 \pm 70^{+70}_{-132} \text{ MeV}
\]

\[
\Lambda_b \text{ rest frame} \quad \phi_\Lambda = 0
\]

\[
\Lambda \text{ rest frame}
\]

\[
\psi \text{ rest frame}
\]

\[
\text{lab frame}
\]

[Belle, PRD 90 (2014) 112009]

[LHCb-PAPER-2016-015]
Amplitude model [LHCb-PAPER-2016-015]

6D background subtracted using weighted fit. Integrate matrix element by summing over fully-simulated events (accounts for 6D efficiency automatically).
Limited statistics, so aim is to check that the data is consistent with that found in $\Lambda_b \rightarrow J/\psi pK$

Parameters of $P_c$ states fixed to those from $\Lambda_b \rightarrow J/\psi pK$

Different combinations of $N^*$ resonances considered for systematic uncertainties.

$Z_c(4430)$ is checked as systematic uncertainty.

Default fit: $3/2^- P_c(4380), 5/2^+ P_c(4450), 1^+ Z_c(4430)$

Well-established $N^*$ states
• Z(3900) most probably a threshold cusp

• Z(3900) been looked for on the lattice, but not found [Prevlosek]

• Candidates for the X(3872) has been seen by multiple groups on the lattice

• Exploratory studies of Z(4430) and Z(4025) (D1barD*)+- threshold but no conclusions yet. Positive parity of Z(4430) means that it can’t be D1barD* threshold
Observation of $B^+_c \rightarrow J/\psi D(\ast)K(\ast)$ decays

Make most precise $B_c^+$ mass measurement due to small Q-value in decay

$6274.28 \pm 1.40 \pm 0.32$ MeV
Observation of $B_c^+ \rightarrow J/\psi D^{(*)} K^{(*)}$ decays

Good candidates for exotics. Need more statistics.
Also useful for studying excited $D_{sJ}$ meson spectroscopy.

[Phys. Rev. D 95, 032005 (2017)]
C = +1 since \( X(3872) \to J/\psi \gamma \)

Pure DD* molecule interpretation disfavoured. \([\text{LHCb NPB 886 (2014) 665}]\)

Analyse 5D angular correlations

Amplitude model includes D-wave components (previously ignored)

Use likelihood ratio test to compare \( J^{PC} \) hypotheses

\[
|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta \lambda_\mu=-1,+1} \sum_{\lambda_{J/\psi}, \lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi}, \lambda_\rho} D_{\lambda_\rho - \lambda_\rho}^{J_X,0} (0, \theta_X, 0)^* D_{\lambda_{J/\psi}, \Delta \lambda_\mu}^1 (\Delta \phi_{X,J/\psi}, \theta_{J/\psi}, 0) |
\]

Previously studied by:
- \([\text{LHCb PRL 110 (2013) 222001}]\)
- \([\text{Belle PRD 84 (2011) 052004}]\)
- \([\text{CDF PRL 98 (2007) 132002}]\)
- \([\text{PRD 92 (2015) 011102}]\)
$X(3872)$ quantum numbers

$J^P C = 1^{++}$ confirmed!

3x larger sample than previous result

D-wave < 4% @ 95% CL

$\rho(770)$ dominates $\rightarrow$ decay violates isospin

so unlikely to be conventional $c\bar{c}$
Z_c(3900)^± amplitude analysis

I+ state preferred. [PRL 119, 072001 (2017)]

\[ M_{\text{pole}} = (3883.9 \pm 1.5 \text{ stat} \pm 4.2 \text{ syst}) \text{ MeV}/c^2, \Gamma_{\text{pole}} = (24.8 \pm 3.3 \text{ stat} \pm 11.0 \text{ syst}) \text{ MeV} \]

Original 1D fits from BES
3899.0 ± 3.6 ± 4.9 MeV
46 ± 10 ± 20 MeV

From Belle
\[ M = (3894.5\pm6.6\pm4.5) \text{ MeV}/c^2 \]
\[ \Gamma = (63\pm24\pm26) \text{ MeV}/c^2 \]

Large systematic from knowledge about \( \sigma \) and \( f_0(980) \) and \( f_0(1370) \) lineshapes

Does \( D^*D^0 \) analysis use full amplitude fit?
Other exotic states

$Z_c(3900)^+$ seen in $J/\psi\pi\pi^+$. Also have $Z_c(3885)^+$ in $(D\bar{D}^*)^+$, showing a dramatic near threshold peak. These could be the same state. Need partial wave analysis of $J/\psi\pi\pi\pi$ final state to determine this.

$Z_c(4020)^+$ seen in $h_c(1P)\pi^+$ by BESIII. Very narrow width. This could be charm-sector equivalent of $Z_b(10650)^+$. Isospin triplet?

$Z_c(4025)^+$ seen recently by BESIII just above $(D^*\bar{D}^*)^+$ threshold. $m(D^*\bar{D}^*)$ distribution not described by phase space. This could be same state as $Z_c(4020)^+$. 

![Diagram of $Z_c(3885)$](image1)

![Diagram of $Z_c(4020)$](image2)

![Diagram of $Z_c(4025)$](image3)
Exotic $Z_c$ states from BES-III

- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?

LHCb has evidence for $X(3872)$ in $B^+ \rightarrow \psi \gamma K^+$, $\psi \rightarrow \mu^+ \mu^-$
Efficiency($\psi(2S)\gamma$) / Efficiency($J/\psi\gamma$) $\sim 0.2$
Detecting soft photons at hadronic collider is hard.
Pure DD$^*$ molecule interpretation disfavoured.

$R_{\psi\gamma} = \frac{B(X(3872) \rightarrow \psi(2S)\gamma)}{B(X(3872) \rightarrow J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$

4.4$\sigma$
$J^{PC} = 1^{++}$ confirmed!

D-wave < 4% @ 95% CL (i.e., negligible)

$\rho(770)$ dominates $\rightarrow$ decay violates isospin so unlikely to be conventional ccbar

$\rho(770) \rightarrow \pi^+ \pi^-$

LHCb

[PRD 92 (2015) 011102]
Other exotic states in quarkonium spectra

Belle have evidence for $Z_1(4050)^-$ and $Z_2(4250)^-$ states in $B^0 \rightarrow Z^- K^+, Z^- \rightarrow \chi_{c1} \pi^-$. [PRD 78 (2008) 072004]

But only uses a simplified 2D Dalitz fit to the phase space. Quantum numbers undetermined.

BaBar have not confirmed. [PRD 85 (2012) 052003]

LHCb should be able to do something here in future

Expect x10 larger sample than Belle

Requires description of 6D phase space
**Z(4430)**$^{\pm}$ charged charmonium exotic

- **Belle** [PRL 100 (2008) 142001]
- **BaBar** [PRD 79 (2009) 112001]
- **Belle** [PRD 80 (2009) 031104]
- **Belle** [PRD 88 (2013) 074026]

1D fit to $m(\psi'\pi^-)$

Not observed but does not contradict Belle!

2D amplitude fit to $m(\psi'\pi^-)$ vs $m(K^+\pi^-)$

4D amplitude fit

$\mu^+\mu^-, J/\psi\pi^+\pi^-$

$B^{+,0} \rightarrow \psi(2S)\pi^- K^{+,0}$

$B^{+,0} \rightarrow Z(4430)^- K^{+,0} \mu^+\mu^-, J/\psi\pi^+\pi^-$

$\psi(2S)\pi^-$

$M = 4433 \pm 4 \pm 2$ MeV/c$^2$

$\Gamma = 45^{+18}_{-13}^{+30}_{-13}$ MeV/c$^2$

Not observed by BaBar!
History of the $Z(4430)^-$

- Belle [PRL 100 (2008) 142001] 1D fit to $m(\psi'\pi^-)$ $6.5\sigma$
- BaBar [PRD 79 (2009) 112001] Not observed but does not contradict Belle!
- Belle [PRD 80 (2009) 031104] 2D amplitude fit to $m(\psi'\pi^-)$ vs $m(K^+\pi^-)$ $6.4\sigma$
- Belle [PRD 88 (2013) 074026] 4D amplitude fit $6.4\sigma$

$\psi' = \psi(2S)$

$M = 4485^{+22+28}_{-22-11}$ MeV/$c^2$
$\Gamma = 200^{+41+26}_{-46-35}$ MeV/$c^2$
Model independent analysis

Does not make any assumption on the underlying $K^*$ resonances in the system, only restricts their maximal spin.

Weight phase space simulated $B^0 \rightarrow \psi' K^+ \pi^-$ events with data $m(K\pi\pi)$ and the spherical harmonic moments of $\cos \theta_K$.

Moments of $K^*$ resonances are unable to explain observed distribution.

Can reflection of the structures in $m(K\pi\pi)$ and $\cos \theta$ reproduce the $m(\psi'\pi)$ distribution? NO!


[PRD 92 (2015) 112009]
Z(4430) model independent
New decay mode of the $Z(4430)$

Belle 4D amplitude fit of $B^0 \rightarrow J/\psi \pi^- K^+$. 

$Z(4200)^+ \at 7.2\sigma$ with systematics ($J^P = 1^+$). Width $\sim 370\text{MeV}$. 

$Z(4430)^+ \at 4.0\sigma \rightarrow$ evidence for **new decay mode!**

Expect smaller BR if $Z$ has large radius, with larger overlap with $\psi(2S)$.

[PRD 90 (2014) 112009]
LHCb limits on the $\text{X}(5568)$

Well known excited B states found using same analysis techniques
Light meson exotics

BES-III observes number of light quark exotics.

$X(1835)$ threshold enhancement in $J/\Psi \rightarrow \gamma pp\bar{p}$.

ppbar bound state or glueball?

[PRL 95 (2003) 262001]
[PRL 108 (2012) 112003]
[PRL 106 (2011) 072002]
[PRL 115 (2010) 091803]
Reminder about Dalitz plots - 3 body decay

Configuration of decay depends on angular momentum of decay products.

All dynamical information contained in $|\mathcal{M}|^2$.

Density plot of $m_{12}^2$ vs. $m_{23}^2$ to infer information on $|\mathcal{M}|^2$.

Constraints | Degrees of freedom
--- | ---
3 four-vectors | +12
All decay in same plane ($p_{i,z} = 0$) | −3
$E_i^2 = m_i^2 + p_i^2$ | −3
Energy + momentum conservation | −3
Rotate system in plane | −1
Total | +2

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 \, dm_{12}^2 \, dm_{23}^2$$
Reminder about Dalitz plots

Peaks in distribution do not correspond to a real resonance - just a shadow/reflection

Modelled as product of Breit-Wigner, kinematic and dynamic factors

\[ d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 \; dm_{12}^2 \; dm_{23}^2 \]
Reminder about Dalitz plots

Use a model to disentangle interfering resonances and determine their properties.
Breit-Wigner amplitude

Often model resonances with pole mass \((m_0)\), width \((\Gamma_0)\) using a relativistic Breit-Wigner function.

\( q \) is daughter particle momentum in rest frame of resonance.

\( B_L \)' are Blatt-Weisskopf functions for the orbital angular momentum \((L)\) barrier factors.

Amplitude = \(|BW|^2\)

\[
BW(m|m_0, \Gamma_0) = \frac{1}{m_0^2 - m^2 - im_0\Gamma(m)}
\]

\[
\Gamma(m) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2L_{K^*}+1} \frac{m_0}{m} B_{L,K^*}'(q, q_0, d)^2
\]

Circular trajectory in complex plane is characteristic of resonance

Circle can be rotated by arbitrary phase

Phase change of 180° across the pole

size of the decaying particle (1.6/GeV)
4D “Dalitz plot” (scalar → vector scalar scalar)

\[ B^0 \rightarrow \psi' K^+ \pi^-, \quad \psi' \rightarrow \mu^+ \mu^- \]

Must use the angular information, in addition to \( m(\psi' \pi^-)^2 \) vs \( m(K^+ \pi^-)^2 \), to understand \(|M|^2\).
Amplitude model

Use the Isobar approach.

Build amplitude from sum of two-body decays: $B^0 \rightarrow \psi'\pi^- K^+$ and $B^0 \rightarrow Z(4430)^- K^+$

Overlapping and interfering Breit-Wigner resonances.

Sum over the $k$ resonances

$$|\mathcal{M}|^2 = \sum_{\Delta \lambda_{\mu} = -1,1} \left| \sum_{\lambda_{\psi} = -1,0,1} \sum_k A_{k,\lambda_{\psi}} (m_{K\pi}, \Omega | m_{0,k}; \Gamma_{0,k}) \right|^2$$

In 4D fit, $\mu^+\mu^-$ are final state particles so different dimuon helicity amplitudes are incoherent (cannot interfere)

Different $\psi'$ helicity amplitudes interfere

Complex amplitude that encodes the mass and angular dependence
Amplitude model - adding in the Z(4430)

Adding the Z(4430) component is more difficult since it has different helicity frame compared to $K^+\pi^-$ resonances.

It is has a BW shape in $m(\Psi'\pi^-)$ mass, but is basically flat in $m(K^+\pi^-)$.

Low Q-value in Z decay, so ignore D-wave contribution $\Rightarrow A_{Z,-1} = A_{Z,0} = A_{Z,+1}$

$$|\mathcal{M}|^2 = \sum_{\Delta\lambda_{\mu} = -1,1} \sum_{\lambda_\psi = -1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega|m_0 k, \Gamma_0 k)^2$$

$Z(4430)$ component interferes with the $K^+\pi^-$ sector

Rotation by $\alpha$ to different helicity frame
Which resonances should we add?

K⁺π⁻ spectrum contains many overlapping resonances. Each resonance has a complex amplitude for each helicity component. Measure all amplitudes relative to K*(892) helicity-0 component.

Default result includes all resonances up to K*₁(1680) (J ≤ 2).

Main systematic uncertainty comes from varying model to include higher K⁺π⁻ spin-states (J = 3, 4, 5).

[From PDG]

<table>
<thead>
<tr>
<th>Resonance</th>
<th>J⁰</th>
<th>Likely n²5⁻⁰⁻¹L_j</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>B(K⁺0 → K⁺π⁻⁻)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁺(800)⁺ (σ)</td>
<td>0⁺</td>
<td></td>
<td>682 ± 29</td>
<td>547 ± 24</td>
<td>~ 100%</td>
</tr>
<tr>
<td>K⁺(892)⁰</td>
<td>1⁻</td>
<td>1³S₁</td>
<td>895.94 ± 0.26</td>
<td>48.7 ± 0.7</td>
<td>~ 100%</td>
</tr>
<tr>
<td>K⁺(1430)⁰</td>
<td>0⁺</td>
<td>1³P₀</td>
<td>1425 ± 50</td>
<td>270 ± 80</td>
<td>(93 ± 10)%</td>
</tr>
<tr>
<td>K⁺(1410)⁰</td>
<td>1⁻</td>
<td>2³S₁</td>
<td>1414 ± 15</td>
<td>232 ± 21</td>
<td>(6.6 ± 1.3)%</td>
</tr>
<tr>
<td>K⁺(1430)⁰</td>
<td>2⁺</td>
<td>1³P₂</td>
<td>1432.4 ± 1.3</td>
<td>109 ± 5</td>
<td>(49.9 ± 1.2)%</td>
</tr>
</tbody>
</table>

B⁺⁻ → ψ(2S)K⁺π⁻⁻ phase space limit  1593

K⁺(1680)⁰         | 1⁻ | 1³D₁              | 1717 ± 27   | 322 ± 110   | (38.7 ± 2.5)% |
| K⁺(1780)⁰        | 3⁻ | 1³D₃              | 1776 ± 7    | 159 ± 21    | (18.8 ± 1.0)% |
| K⁺(1950)⁰        | 0⁺ | 2³P₀              | 1945 ± 22   | 201 ± 78    | (52 ± 14)%    |
| K⁺(2045)⁰        | 4⁺ | 1³F₄              | 2045 ± 9    | 198 ± 30    | (9.9 ± 1.2)%  |

B⁺⁻ → J/ψ K⁺π⁻⁻ phase space limit  2183

K⁺(2380)⁰         | 5⁻ | 1³G₀              | 2382 ± 9    | 178 ± 32    | (6.1 ± 1.2)%  |

Background from sidebands of B mass
S-wave parameterisation

$Z(4430)$ has largest effect $\sim 1.5\text{GeV}$

Important to understand the $K\pi$ S-wave in this region

**Isobar model** is default

$BW$ amplitude for $K^*(1430)+K^*(800)$

Non-resonant contribution

LASS model as cross-check

Does not violate unitarity

Sum of elastic scattering, destructively interfering with $K^*(1430)$

\[
\frac{1}{\cot \delta_B(m_{K\pi}) - i} + e^{2i\delta_B(m_{K\pi})} \frac{1}{\cot \delta_R(m_{K\pi}) - i}
\]

\[
\cot \delta_B(m_{K\pi}) = \frac{1}{a} + \frac{1}{2} r q \\
\cot \delta_R(m_{K\pi}) = \frac{m_0^2 - m_{K\pi}^2}{m_0 \Gamma(m_{K\pi})}
\]
Confirmation of the Z(4430)$^\pm$

LHCb has sample of >25k $B^0 \rightarrow \psi' K^+ \pi^-$ candidates (x10 Belle/BaBar).

Selection: most events come through dimuon trigger (eff~90%)

Typical $B^0 p_T \sim 6\text{GeV}$, $\mu^+ p_T \sim 2\text{GeV}$, $K^+ p_T \sim 1\text{GeV}$.

Use sidebands to build 4D model of combinatorial background.

Bkgs from mis-ID physics decays is small - excellent LHCb vertexing, PID!

Only 2 of the 4 dimensions…

![Candidates / 1 MeV](image1)

![4% combinatorial background in signal region](image2)

![psi' is mass constrained](image3)

![K*(892)$^0$](image4)

![Kj*(1430)$^0$](image5)

LHCb

$>25k$

$\psi'\rightarrow\mu^+\mu^-$

[PRL 112 (2014) 222002]
LHCb < 100% efficient at reconstructing the decay particles in 4D space.

Extract efficiency model from events simulated uniformly in phase space and passed through detector reconstruction.

Also, remove events (~12%) near edge of kinematic boundary since efficiency not well modelled there.

2D representation…

Caused by low momentum pions
Fitting the model to the data

\[- \ln L(\bar{\omega}) = - \sum_i^{N_{\text{data}}} \ln P_{\text{tot}}^u (\bar{v}_i | \bar{\omega}) = - \sum_i^{N_{\text{data}}} \ln \left( |\mathcal{M}(\bar{v}_i | \bar{\omega})|^2 \epsilon(\bar{v}_i) / I(\bar{\omega}) \right)\]

Likelihood fit to measure ~50 free parameters: amplitudes, phases, resonance mass/widths.

- In any amplitude fit, difficulty comes from \textbf{integrating} the matrix element.
- Solution: sum over fully simulated, reconstructed phase space MC.
  - This automatically \textbf{includes the efficiency} in the normalisation.
  - Alternative approach explicitly parameterises the 4D efficiency.

Try different models for $K^+\pi^-$ and $Z(4430)$, compare values of $L$. 
Z(4430)$^{\pm}$ parameters from amplitude fit

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(Z)$ [MeV]</td>
<td>$4475 \pm 7^{+15}_{-25}$</td>
<td>$4485 \pm 22^{+28}_{-11}$</td>
</tr>
<tr>
<td>$\Gamma(Z)$ [MeV]</td>
<td>$172 \pm 13^{+37}_{-34}$</td>
<td>$200^{+41+26}_{-46-35}$</td>
</tr>
<tr>
<td>$f_Z [%]$</td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$</td>
<td>$10.3^{+3.0+4.3}_{-3.5-2.3}$</td>
</tr>
<tr>
<td>$f_Z^L [%]$</td>
<td>$16.7 \pm 1.6^{+2.6}_{-5.2}$</td>
<td>-</td>
</tr>
<tr>
<td>significance</td>
<td>$&gt; 13.9\sigma$</td>
<td>$&gt; 5.2\sigma$</td>
</tr>
<tr>
<td>$J^P$</td>
<td>$1^+$</td>
<td>$1^+$</td>
</tr>
</tbody>
</table>

New (large) systematic included

- Excellent agreement between LHCb and Belle.
- Large width - unlikely to be molecule?

Amplitude fractions [%]

<table>
<thead>
<tr>
<th>Contribution</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$-wave total</td>
<td>$10.8 \pm 1.3$</td>
<td>$0.3 \pm 0.8$</td>
</tr>
<tr>
<td>$K^0_s(800)$</td>
<td>$3.2 \pm 2.2$</td>
<td>$5.8 \pm 2.1$</td>
</tr>
<tr>
<td>$K^*_0(1430)$</td>
<td>$3.6 \pm 1.1$</td>
<td>$1.1 \pm 1.4$</td>
</tr>
<tr>
<td>$K^*(892)$</td>
<td>$59.1 \pm 0.9$</td>
<td>$63.8 \pm 2.6$</td>
</tr>
<tr>
<td>$K^+_s(1430)$</td>
<td>$7.0 \pm 0.4$</td>
<td>$4.5 \pm 1.0$</td>
</tr>
<tr>
<td>$K^+_t(1410)$</td>
<td>$1.7 \pm 0.8$</td>
<td>$4.3 \pm 2.3$</td>
</tr>
<tr>
<td>$K^+_t(1680)$</td>
<td>$4.0 \pm 1.5$</td>
<td>$4.4 \pm 1.9$</td>
</tr>
<tr>
<td>$Z(4430)^-$</td>
<td>$5.9 \pm 0.9$</td>
<td>$10.3^{+3.0}_{-3.5}$</td>
</tr>
</tbody>
</table>

$$ f_i = \frac{\int |A_i(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}{\int |\sum_k A_k(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega} $$
Confirmation of the $Z(4430)^\pm$ [PRL 112 (2014) 222002]

Everything except the $Z \rightarrow$ large interference between $Z$ and $K^+\pi^-$ sector

$Z$ component $J^P = 1^+$

• LHCb has sample of $>25k \ B^0 \rightarrow \psi'K^+\pi^-$ candidates ($x10$ Belle/BaBar).

• 4D amplitude analysis performed.
Fit projections in slices of $m(K^+\pi^-)$

- $m_{K\pi}^2 < 0.7$ GeV$^2$
- $1.0 < m_{K\pi}^2 < 1.8$ GeV$^2$
- $m_{K\pi}^2 > 1.8$ GeV$^2$
Spin determination

- Build different $|M|^2$ corresponding to different $J^p$ values.
- $J^p=1^+$ is favoured (confirms Belle).
- Rule out other $J^p$ with large significance.
- Quote exclusion based on asymptotic formula (lower bound).
- Positive parity rules out $Z$ being $D^*(2007)D_1(2420)$ molecule.

<table>
<thead>
<tr>
<th>Disfavoured</th>
<th>Rejection level relative to $1^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^p$</td>
<td>LHCb</td>
</tr>
<tr>
<td>$0^-$</td>
<td>$9.7\sigma$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$15.8\sigma$</td>
</tr>
<tr>
<td>$2^+$</td>
<td>$16.1\sigma$</td>
</tr>
<tr>
<td>$2^-$</td>
<td>$14.6\sigma$</td>
</tr>
</tbody>
</table>

\[ \Delta(-2 \ln L) = [-2 \ln L(0^-)] - [-2 \ln L(1^+)] \]
Systematics: second exotic Z?

Fit confidence level increases to 26% with a second exotic (\( J^P=0^- \)) component, but...

No evidence for \( Z_0 \) in model independent approach.
Argand diagram for \( Z_0 \) is inconclusive.
Need larger samples to characterise this state.

Fitted parameters
\[
\begin{align*}
M_{Z_0} &= 4239 \pm 18 \quad ^{+45}_{-10} \; \text{MeV} \\
\Gamma_{Z_0} &= 220 \pm 47 \quad ^{+108}_{-74} \; \text{MeV} \\
f_{Z_0} &= (1.6 \pm 0.5) \quad ^{+1.9}_{-0.4}\% 
\end{align*}
\]

Same mass, width as \( Z^- \rightarrow \chi_{c1} \pi^- \) seen by Belle, but \( J^P=0^- \) can’t decay strongly to \( \chi_{c1} \pi^- \)

[PRD 78 (2008) 072004]

- Many checks performed to determine stability of the result and evaluate systematic errors on \( m_Z, \Gamma_Z, f_Z \).
- Main systematics come from assumption on \( K^* \pi^- \) Isobar model, efficiency and \( (q/m_{K^+\pi^-})^L \) vs. \( q^L \).
Bottomonium spectrum

[Olsen arXiv:1403.1254]
Bottomonium-like states

Belle has evidence for $Z_b(10610)^+$ and $Z_b(10650)^+$ resonances when looking at $\pi^+\pi^-\Upsilon(nS)$ and $\pi^+\pi^-h_b(mP)$.

$I^G(J^P) = 1^+(1^+)$, Virtual $B\overline{B}^*$ and $B^*\overline{B}^*$ S-wave molecule-like states?

Also first evidence for neutral isospin partners in $\pi^0\pi^0\Upsilon(2S)$ amplitude fit.

Projections of Dalitz plots

Use Breit-Wigner (without energy dependent width) to model resonances
Pentaquark models (tightly bound)

All models must explain JP of two states not just one. They also should predict properties of other states: masses, widths, JP. Many models: Let's start with tightly bound quarks ala' Jaffe

Two colored diquarks plus the anti-quark L. Maiani, et. al, [arXiv:1507.04980], ibid [PRD20(1979) 748]


Bag model, Jaffe; Strings, Rossi & Veneziano [Nucl. Phys. B123 (1977) 507]
Pentaquark models (molecular)


L. Ma et.al, [arXiv:1404.3450] for Z(4430)

T. Barnes et.al, [arXiv:1409.6651] for Z(4430)

π exchange models usually predict only one state, mainly JP=1/2+, but could also include ρ exchange...

Several authors consider Σc D(*) components (most of these are postdictions)
Many states appear to lie just above threshold which indicates experimental enhancements may be due to threshold cusp (the movement of resonant poles due to the proximity of multiparticle thresholds) effects rather than quark binding [Bugg, Swanson] [Blitz Lebed PRD91 (2015) 094025]

Zc(3900) DD*

Zc(4020) D*D*

Zb(10610) BB*

Zb(10650) B*B*

What are the degrees of freedom?