Confirmation of the exotic $Z(4430)^{\pm}$ resonance at LHCb

Greig Cowan (Edinburgh) on behalf of the LHCb collaboration

CERN, 3rd June 2014
Overview

1. Exotic spectroscopy: motivation
2. Introduction to the LHCb experiment
3. Reminder of Dalitz plots and amplitude analyses
4. The Z(4430)$^\pm$
   - History
   - Searching for the Z(4430)$^\pm$ in $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays
   - Determining quantum numbers (J$^P$)
5. Other exotic spectroscopy results
   - X(3872)
   - The scalar mesons, f$_0$(500) and f$_0$(980)

[arXiv:1404.1903, accepted by PRL]
“Three quarks for Muster Mark!”

- Bound states of quarks to form mesons and baryons were first proposed in 1964 by Gell-Mann and Zweig.
- $qqq\bar{q}$ states are not *a priori* excluded.
- Light quark spectroscopy used to understand structure of these states.
  - Difficult due to wide overlapping states, background.
  - Highly relativistic constituents (u, d and s quarks) make theoretical predictions difficult.
- What about heavier quarks?
Charmonium spectroscopy (c\bar{c})

- Simpler system to analyse since c quark is heavier
  - non-relativistic calculations
    - potential models
    - lattice QCD
  - narrow, non-overlapping states below $D\bar{D}$ threshold
  - no mixing of $c\bar{c}$ with lighter $q\bar{q}$ states.

Classify using $J^{PC}$
- $J = L \oplus S$
- $P = (-1)^{L+1}$
- $C = (-1)^{L+S}$

Predicted by theory

[Phys. Rev. D 81, 034508]
[Olsen arXiv:1403.1254]
Exotic charmonium spectroscopy

- Many different exotic (XYZ) states have been seen.
  - BESIII, Belle/BaBar, CDF/D0
  - mass/width, decay, $J^{PC}$

- Are these $[QQ][q\bar{q}]$ (tetraquarks), mesonic molecules, threshold effects, hybrids...?

- No clear pattern: need experimental, theoretical study to understand strong interaction dynamics that can cause their production and structure.

Lattice calculations begin to support existence of exotic charged states [arXiv:1405.7623v1]

The LHCb experiment

- ~900 physicists from 64 universities/labs in 16 countries.
- Running since 2010, 188 papers published.
- O(100k) $b\bar{b}$ pairs produced/sec.


- Rare B decays
- CP violation
- Charm physics
- (Exotic) spectroscopy
- QCD and electroweak
The LHCb detector

Vertex Finder
- \( \sigma(\text{IP}) \approx 20\mu m \)
- \( \delta p/p = 0.4 - 0.6\% \)
- \( \varepsilon_{\text{track}} > 96\% \)

Particle ID
- \( \varepsilon_{\text{PID}}(K) \approx 95\% \)
- \( \text{MisID}(K \rightarrow \pi) \approx 5\% \)

Calorimetry

Muon detection
- \( \varepsilon_{\text{PID}}(\mu) \approx 97\% \)
- \( \text{MisID}(\pi \rightarrow \mu) \approx 1 - 3\% \)

Covers 4% of solid angle but contains 25% of \( b \bar{b} \) pairs
A typical LHCb event

\[ \langle n_{PV}s \rangle \sim 2.0 \]
\[ \langle n_{Tracks} \rangle \sim 200 \]

\[ \sigma(p\bar{p} \to b\bar{b}X) \sim 80\mu b \]
\[ \sigma(c\bar{c}) \sim 1500\mu b \]

B hadrons fly \( \sim 1cm \) in the detector
Luminosity

- LHCb designed to run at lower luminosity than ATLAS/CMS.
  - LHCb tracking is sensitive to pile-up.
- LHC pp beams are displaced to reduce instantaneous luminosity.
  - Stable running conditions.

$\langle L \rangle_{2011} = 2.7 \times 10^{32} \text{ Hz/cm}^2$

$\langle L \rangle_{2012} = 4.0 \times 10^{32} \text{ Hz/cm}^2$
A well known exotic meson: X(3872)

- Observed by 6 experiments, first by Belle
  [PRL 91 (2003) 262001 - 894 citations!]

- $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

- Measured $J^{PC} = 1^{++}$ ⇒ unlikely to be conventional charmonium

- Exotic interpretation: $c\bar{c}u\bar{u}$ tetraquark, $D^0D^{*0} = (c\bar{u})(\bar{c}u)$ molecule, $c\bar{c}g$

$\Gamma_{X(3872)} < 1.2 \text{ MeV}$
$M_{X(3872)} = 3871.68 \pm 0.17 \text{ MeV}$
$M_{D^0} + M_{D^{*0}} = 3871.85 \pm 0.20 \text{ MeV}$

Calibrate using well-known $\psi(2S)$

$X(3872)$ seen in $B$ decays and $pp, p\bar{p}$ prompt production
A well known exotic meson: \( \text{X(3872)} \)

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

\[ R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi \gamma)} = 2.46 \pm 0.64 \pm 0.29. \]
History of the $Z(4430)^\pm$

- Belle observed $Z(4430)^\pm$ from sample of $\sim 2k$ $B^{+,0} \rightarrow \psi(2S)K^{+,0}\pi^-$
- Charged state $\Rightarrow$ minimal quark content of $c\bar{c}ud$

$M = 4433 \pm 4 \pm 2$ MeV/c$^2$
$\Gamma = 45^{+18}_{-13}^{+30}_{-13}$ MeV/c$^2$
History of the $Z(4430)^-$

- **Belle** [PRL 100 (2008) 142001] 1D fit to $m(\psi'\pi^-)$ $6.5\sigma$
- **Belle** [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 $6.4\sigma$

$M(D^*)+M(D^{**})=4472$ MeV

$K^*(892)^0$ $K_2^*(1430)$

**K**$^*$ veto region

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

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

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

\[
d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 \, dm_{12}^2 \, dm_{23}^2
\]

Constraints

<table>
<thead>
<tr>
<th>Degrees of freedom</th>
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</thead>
<tbody>
<tr>
<td>3 four-vectors</td>
</tr>
<tr>
<td>All decay in same plane ($p_{i,z} = 0$)</td>
</tr>
<tr>
<td>$E_i^2 = m_i^2 + p_i^2$</td>
</tr>
<tr>
<td>Energy + momentum conservation</td>
</tr>
<tr>
<td>Rotate system in plane</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>
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.

Spin-1 resonance

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

\[ d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 \, dm_{12}^2 \, dm_{23}^2 \]

**Spin-0 resonance**

**Spin-1 resonance**

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)

- $B^0 \rightarrow \psi' K^+ \pi^-$, $\psi' \rightarrow \mu^+ \mu^-$
- Must use the angular information, in addition to $m(\psi' \pi^-)^2$ vs $m(K^+ \pi^-)^2$, to understand $|M|^2$.

Constraints

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<tr>
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<tr>
<td>3 four-vectors</td>
<td>+12</td>
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<tr>
<td>All decay in same plane ($p_{i,z} = 0$)</td>
<td>-3</td>
</tr>
<tr>
<td>$E_i^2 = m_i^2 + p_i^2$</td>
<td>-3</td>
</tr>
<tr>
<td>Energy + momentum conservation</td>
<td>-3</td>
</tr>
<tr>
<td>Rotate system in plane</td>
<td>-1</td>
</tr>
<tr>
<td>Vector helicity</td>
<td>+2</td>
</tr>
<tr>
<td>Total</td>
<td>+4</td>
</tr>
</tbody>
</table>

Simulation
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%) $\psi'\rightarrow \mu^+\mu^-$
- 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!

![Graph showing $m_{\psi'\pi}$ distribution with signal and sideband regions marked.]

K*(892)$^0$    K$_J^*$*(1430)$^0$

Only 2 of the 4 dimensions…
Model independent analysis - qualitative check

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

- Does not make any assumption on the underlying $K^*$ resonances in the system, only restricts their maximal spin ($J \leq 2$).
- Weight phase space simulated $B^0 \rightarrow \psi'K^+\pi^-$ events with the spherical harmonic moments of $\cos\theta_K$.
- Moments of $K^*$ resonances are unable to explain observed distribution.

BaBar data for $B^0 \rightarrow \psi'(2S)K^\mp\pi^\pm$ [PRD 79 (2009) 112001]
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.

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

Sum over the $k$ resonances

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

\[
|M|^2 = \sum_{\Delta\lambda_\mu = -1,1} \sum_{\lambda_\psi = -1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega | m_{0k}, \Gamma_{0k})
\]

\[
+ \sum_{\lambda_\psi' = -1,0,1} A_{Z,\lambda_\psi'}(m_{\Psi\pi}, \Omega_Z | m_{0Z}, \Gamma_{0Z}) e^{i\Delta\lambda_\mu \alpha}
\]

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

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

- $K^+\pi^-$ 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 $K^*_1(1680)$ ($J \leq 2$).
- Main source of systematic uncertainties comes from varying model to include higher $K^+\pi^-$ spin-states ($J = 3, 4, 5$).

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$J^P$</th>
<th>Likely $n^{2S+1}L_J$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_0^*(800)^0$</td>
<td>0$^+$</td>
<td>—</td>
<td>682 ± 29</td>
<td>547 ± 24</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>1$^-$</td>
<td>$^1S_1$</td>
<td>895.94 ± 0.26</td>
<td>48.7 ± 0.7</td>
</tr>
<tr>
<td>$K_0^*(1430)^0$</td>
<td>0$^+$</td>
<td>$^3P_0$</td>
<td>1425 ± 50</td>
<td>270 ± 80</td>
</tr>
<tr>
<td>$K_1^*(1410)^0$</td>
<td>1$^-$</td>
<td>$^2S_1$</td>
<td>1414 ± 15</td>
<td>232 ± 21</td>
</tr>
<tr>
<td>$K_2^*(1430)^0$</td>
<td>2$^+$</td>
<td>$^3P_2$</td>
<td>1432.4 ± 1.3</td>
<td>109 ± 5</td>
</tr>
</tbody>
</table>

$B^0 \to \psi(2S)K^+\pi^-$ phase space limit: 1593

$B^0 \to J/\psi K^+\pi^-$ phase space limit: 2183

Background from sidebands of $B$ mass
**S-wave parameterisation**

- **Z(4430) has largest effect ~1.5GeV**
- Important to understand the **Kπ S-wave** in this region

- **Isobar model** is default
  - BW amplitude for K*0(1430)+K*0(800)
  - Non-resonant contribution

- **LASS model as cross-check**
  - Does not violate unitarity
  - Sum of elastic scattering, destructively interfering with K*(1430)

\[
\cot \delta_B(m_{K\pi}) = \frac{1}{a q + \frac{1}{2} \Delta q} \quad \cot \delta_R(m_{K\pi}) = \frac{m_0^2 - m_{K\pi}^2}{m_0 \Gamma(m_{K\pi})}
\]

Slowly varying NR contribution

BW amplitude for K(1430)

Reconstruction and selection efficiency

- 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

∈ High efficiency

Low efficiency
Fitting the model to the data

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

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

- In any amplitude fit, difficulty comes from integrating the matrix element.

- Solution: sum over fully simulated, reconstructed phase space MC.
  - This automatically includes the efficiency in the normalisation.
  - Alternative approach explicitly parameterises the 4D efficiency.

Efficiency drops out

Try different models for $K^+\pi^-$ and $Z(4430)$, compare values of $L$. 

\[I(\bar{\omega}) = \sum_{i}^{N_{\text{MC}}} |\mathcal{M}(\bar{\nu}_i|\bar{\omega})|^2\]
Projections of 4D amplitude fit without Z(4430)

- Determine goodness-of-fit from 4D $\chi^2$.
- The $\chi^2$ p-value < $2 \times 10^{-6}$.
- The data cannot be adequately described only using $J \leq 3$ $K^*$ contributions.
- Other 3 dimensions not shown.
Projections of 4D amplitude fit with $Z(4430)$

- The 4D $\chi^2$ p-value = 12%.
  - 4% with no $K_1^*(1410)$, 12% with $K_3^*(1780)$
- The data are well described when including a $J^P=1^+ Z(4430)$ in the fit.
Z(4430)$^\pm$ parameters from amplitude fit

### 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 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>NR</td>
<td>0.3 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>$K_0^*$ (800)</td>
<td>3.2 ± 2.2</td>
<td>5.8 ± 2.1</td>
</tr>
<tr>
<td>$K_0^*$ (1430)</td>
<td>3.6 ± 1.1</td>
<td>1.1 ± 1.4</td>
</tr>
<tr>
<td>$K^*$ (892)</td>
<td>59.1 ± 0.9</td>
<td>63.8 ± 2.6</td>
</tr>
<tr>
<td>$K_2^*$ (1430)</td>
<td>7.0 ± 0.4</td>
<td>4.5 ± 1.0</td>
</tr>
<tr>
<td>$K_1^*$ (1410)</td>
<td>1.7 ± 0.8</td>
<td>4.3 ± 2.3</td>
</tr>
<tr>
<td>$K_1^*$ (1680)</td>
<td>4.0 ± 1.5</td>
<td>4.4 ± 1.9</td>
</tr>
<tr>
<td>Z(4430)$^-,$</td>
<td>5.9 ± 0.9</td>
<td>10.3$^{+3.0}_{-3.5}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M(Z)$ [MeV]</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4475 \pm 7^{+15}_{-25}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$172 \pm 13^{+37}_{-34}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_f$ [%]</td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$</td>
<td>$10.3^{+3.0}_{-3.5}$</td>
</tr>
<tr>
<td>$f_f^I$ [%]</td>
<td>$16.7 \pm 1.6^{+2.6}_{-5.2}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

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

\[
 f_i = \frac{\int |A_i(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}{\int \sum_k |A_k(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}
\]
Fit projections in slices of $m(K^+\pi^-)$
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).

$$\Delta(-2 \ln L) = [-2 \ln L(0^-)] - [-2 \ln L(1^+)]$$

<table>
<thead>
<tr>
<th>Disfavoured $J^P$</th>
<th>Rejection level relative to $1^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>Belle</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>
Resonant behaviour - a bound state?

- Replace BW amplitude with 6 independent complex numbers in 6 bins of \(m(\psi'\pi)\) in region of \(Z(4430)\) mass peak.

- Allows \(Z(4430)\) shape to be constrained only by amplitudes in \(K\pi\) sector.

- Observe rapid change of phase near maximum of magnitude \(\Rightarrow\) resonance!

BW amplitude with default \(Z(4430)\) parameters

\[ 4277\text{MeV} \quad 4605\text{MeV} \]

Argand diagram
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**

\[ M_{Z_0} = 4239 \pm 18 ^{+45}_{-10} \text{ MeV} \]
\[ \Gamma_{Z_0} = 220 \pm 47 ^{+108}_{-74} \text{ MeV} \]
\[ f_{Z_0} = (1.6 \pm 0.5 ^{+1.9}_{-0.4})\% \]

Same mass, width as $Z^+ \rightarrow \chi_{c1}\pi^- \rightarrow \psi(3680) \rightarrow \pi^\pi$ 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. $q^L$.

Significance from $\Delta(-2\ln L) = 6\sigma$
Implications

- Result confirms existence of the $Z(4430)$, measures $J^P=1^+$ and, for the first time, demonstrates resonant behaviour.
- $P=+$ rules out interpretation in terms of $\bar{D}^*(2010)D^*(1240)$ molecule or threshold effect (cusp).
- Four-quark bound state is a remaining explanation. [Maiani et al, arXiv:1405.1551]
- Potential neutral isospin partner? $Z(4430)^0$ in $B^+ \rightarrow \psi\pi^0K^+$

- 2013: Observation of another exotic charged state: $Z_c(3900)^\pm$ in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$
- Is $Z(4430)^\pm$ a radial excitation of $Z_c(3900)^\pm$?

Major harvest of four-leaf clover

The LHCb Collaboration at CERN has just confirmed the unambiguous observation of a very exotic state, something that looks strangely like a particle being made of four quarks. As exotic as it might be, this particle is sternly called Z(4430)⁺, which gives its mass at 4430 MeV, roughly four times heavier than a proton, and indicates it is has a negative electric charge. The letter Z shows that it belongs to a strange series of particles that are referred to as XYZ states.

Quarks bonding differently at LHCb
The Large Hadron Collider beauty collaboration has confirmed the existence of exotic hadron with two quarks, two anti-quarks.

“The last time they fired it up, it was almost opening dimensional portals like a stargate! There were reports that people were seen coming in and out of different dimensions!” — Hagmann and Hagmann Report
Light quark spectroscopy using $B^0 \to J/\psi \pi^+ \pi^-$

- Study substructure of light mesons that decay to $\pi^+ \pi^-$.  
- Mass ordering is reversed between the scalar and vector mesons nonets.

<table>
<thead>
<tr>
<th>Isospin</th>
<th>$I = 0$</th>
<th>$I = 1/2$</th>
<th>$I = 0$</th>
<th>$I = 1$</th>
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</thead>
<tbody>
<tr>
<td>Scalar mesons</td>
<td>$f_0(500)$</td>
<td>$\kappa(800)$</td>
<td>$f_0(980)$</td>
<td>$a_0(980)$</td>
</tr>
<tr>
<td>Vector mesons</td>
<td>$\phi(1020)$</td>
<td>$K^*(892)^0$</td>
<td>$\omega(783)$</td>
<td>$\rho(776)$</td>
</tr>
</tbody>
</table>

- Are the scalar mesons ($f_0(500), f_0(980)$) $q\bar{q}$ or **tetraquarks** or some mixture?

Scalar meson mixing

\[
|f_0(980)\rangle = \cos \varphi_m |s\bar{s}\rangle + \sin \varphi_m |n\bar{n}\rangle \\
|f_0(500)\rangle = -\sin \varphi_m |s\bar{s}\rangle + \cos \varphi_m |n\bar{n}\rangle ,
\]

where $|n\bar{n}\rangle \equiv \frac{1}{\sqrt{2}} (|u\bar{u}\rangle + |d\bar{d}\rangle)$.

\[
\tan^2 \varphi_m \equiv r_f^\sigma = \frac{\mathcal{B} (\bar{B}^0 \to J/\psi f_0(980)) \Phi(500)}{\mathcal{B} (\bar{B}^0 \to J/\psi f_0(500)) \Phi(980)} = 1/2
\]
Amplitude analysis of $B^0 \rightarrow J/\psi \pi^+ \pi^-$

- Similar analysis to Z(4430)
- Build 4D matrix element from overlapping $\pi^+ \pi^-$ resonances.
- Correct for efficiency.
- No sign of exotic $J/\psi \pi^+$ resonances...

19k $B^0$ signal

Sidebands used for background modelling
Amplitude analysis of $B^0 \rightarrow J/\psi \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)$</td>
<td>$63.1 \pm 2.2^{+3.4}_{-2.2}$</td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>$22.2 \pm 1.2^{+2.6}_{-3.5}$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$7.5 \pm 0.6^{+0.4}_{-0.6}$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$0.68^{+0.20+0.17}_{-0.14-0.13}$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>$11.6 \pm 2.8 \pm 4.7$</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>$5.1 \pm 1.2 \pm 3.0$</td>
</tr>
</tbody>
</table>

- BW for $f_0(500)$: mass/width Gaussian constrained to CLEO values.
- Flatté for $f_0(980)$: parameters fixed to those from $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ [Phys. Rev. D 89, 092006 (2014)]
- Best fit model does **not** require $f_0(980)$ component $\Rightarrow$ upper limit for mixing angle:

$$\tan^2 \varphi_m \equiv r_f^f = (1.1^{+1.2+6.0}_{-0.7-0.7}) \times 10^{-2} < 0.098 \text{ at 90\% C.L}$$

**Different from tetraquark prediction (1/2) of this model by 8\sigma**
Summary

• LHCb has confirmed this existence and shown the resonant behaviour of the $Z(4430)^\pm$.

• Minimal quark content of $c\bar{c}u\bar{d}$.

• No clear picture of the complex system of charmonium-like exotic resonances.

• Further constraints will come from observing $Z(4430)^\pm$ and other exotics in alternative decay modes and/or production mechanisms.

• **Interesting times ahead…**
  • LHCb has large datasets of B decays containing $J/\psi$, $\psi(2S)$, $\chi_c$... where other exotics could live.
  • Look for synergies with the $s\bar{s}$ and $b\bar{b}$ sectors.
  • Data taking starts again in 2015, looking forward to collecting even higher statistics!

$Z(4430)$ in the media: [http://www.phy.syr.edu/~tomasz/z4430.html](http://www.phy.syr.edu/~tomasz/z4430.html)
BACKUP
**Vertex Locator (VELO)**

- 21 silicon strip detectors, 8mm from beam line.
- Operates in vacuum, separated from LHC vacuum by 300μm Al foil.
- Primary vertex resolution $\sim 13, 13, 69\mu m$ in $x, y, z$.
- IP resolution of tracks with $p_T > 2$ GeV/c$^2$ is $\sim 20\mu m$.
- Decay time resolution $\sim 45$ fs for many $B$ decay channels.
Particle ID

- Gas radiators ($C_4F_{10}, CF_4$) + aerogel.
- Photomultiplier tubes to detect Cerenkov light.
- Excellent for suppressing backgrounds.
- Muon-ID: $\varepsilon(\mu \to \mu) \sim 97\%$, $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
Tracking

- Silicon microstrip detectors closest to beam pipe.
- Straw tubes cover larger area.
- Aligned to $\sim 14\mu m$ using large samples of $J/\psi \rightarrow \mu\mu$, $D^0 \rightarrow K\pi$.
- $\Delta p/p \sim 0.5\%$.
- Mass resolution $\sim 8\text{MeV}/c^2$ for $b \rightarrow J/\psi X$ decays.

$\sigma \sim 15\text{MeV}/c^2$

Tag-and-probe $J/\psi$
**Trigger**

- Approach: try to maintain high efficiency for manageable data rates.

---

**40 MHz bunch crossing rate**

- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz $e/\gamma$

**Software High Level Trigger**

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

**5 kHz Rate to storage**

- 2 kHz Inclusive Topological
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon

---

**DiMuon trigger**

Lower efficiency for multi-body final states
An enigma... the X(4140)

$B^{±/0} \rightarrow XK^{±/0}$  $X \rightarrow J/\psi \phi$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$\sigma$</th>
<th>Published</th>
<th>Ref.</th>
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</thead>
<tbody>
<tr>
<td>CDF</td>
<td>4143.0±2.9±1.2</td>
<td>11.7</td>
<td>3.8</td>
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<td>Phys. Rev. Lett. 102, 242002</td>
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<tr>
<td>D0</td>
<td>4159.0±4.3±6.6</td>
<td>19.9±12.6</td>
<td>3.1</td>
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<tr>
<td>CMS</td>
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<td>28</td>
<td>&gt;5</td>
<td>N</td>
<td>arXiv: 1309.6920</td>
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<tr>
<td>Belle</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Y</td>
<td>Phys. Rev. Lett. 104, 112004</td>
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<td>LHCb</td>
<td>-</td>
<td>-</td>
<td>Y</td>
<td>Phys. Rev. D 85, 091103(R)</td>
<td></td>
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<tr>
<td>BaBar</td>
<td>-</td>
<td>-</td>
<td>N</td>
<td>Conference</td>
<td></td>
</tr>
</tbody>
</table>

Could be some hybrid state: $car{c}sar{s}$
An enigma... the X(4140)

- X(4140) seen by some experiments, not by others in m(J/ψΦ).
- Could be some hybrid state: $c\bar{c}s\bar{s}$
$Z_c(3900)^+ \text{ in } e^+e^- \rightarrow \pi^+\pi^-J/\psi$

- Other exotic **charged** state observed by BESIII, Belle at the Y(4260) and CLEO-c at Y(4160).
- CLEO-c also have evidence for neutral member of isospin triplet decaying to $\pi^0J/\psi$.

$$M = (3894.5\pm6.6\pm4.5) \text{ MeV/c}^2$$
$$\Gamma = (63\pm24\pm26) \text{ MeV/c}^2$$
Other exotic states

- $Z_c(3900)^+$ seen in $J/\psi\pi^+$. 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 $Z_c(4020)^+$. 

Other exotic states in quarkonium spectra

- Belle have evidence for $Z_1(4050)^-$ and $Z_2(4250)^-$ states in $B^0 \rightarrow Z^- K^+$, $Z^- \rightarrow \chi_{c1} \pi^-$. 
- BaBar have not confirmed... [Phys. Rev. D 85, 052003]

LHCb should be able to do something here in future
Do we see $Z(4430)$ in $B^0 \rightarrow J/\psi \pi^- K^+$ decays?

- 4D amplitude fit of $B^0 \rightarrow J/\psi \pi^- K^+$ shown by Belle @ Moriond QCD 2014.
- $Z(4200)^+$ at 7.2sigma with systematics ($J^P = 1^+$). Width $\sim 370\text{MeV}$.
- $Z(4430)^+$ at 4.0sigma: evidence for new decay mode.
  - Expect smaller BR if $Z$ has large radius, with larger overlap with $\psi'$. 

![Graphs showing $1.2 \text{GeV}^2/c^4 < M^2(K,\pi) < 1.432 \text{GeV}^2/c^4$ and $M^2(K,\pi) > 3.2 \text{GeV}^2/c^4$ distributions with event counts.](image)
Bottomonium spectrum
Other exotic states in quarkonium spectra

- $b\bar{b}$ spectrum
- Belle has claimed evidence for $Z_b(10610)^+$ and $Z_b(10650)^+$ resonances when looking at $\pi^+\pi^0\Upsilon(nS)$ and $\pi^+\pi^-h_b(mP)$.
- $I^G(J^P) = 1^+(1^+)$, Virtual $B\bar{B}^*$ and $B^*\bar{B}^*$ S-wave molecule-like states? [arXiv:1403.0992v1]
- Also first evidence for neutral isospin partners in $\pi^0\pi^0\Upsilon(2S)$ amplitude fit.
Cusps, threshold effects, rescattering

\[ K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \]

Expect \( \pi^+ \pi^- \) to be in an S-wave configuration.


[N Cabibbo, PRL 93:121801, 2004]
**Helicity formalism**

- Helicity ($\lambda$) is projection of $\bar{J}$ onto $\bar{p}$ ($\lambda = -|J| \ldots + |J|$)
- $a \rightarrow bc$

\[ |\mathcal{M}|^2 \propto \left| A_{\lambda_b,\lambda_c} d_{\lambda_a,\lambda_b-\lambda_c}^J (\theta) e^{i(\lambda_a-(\lambda_b-\lambda_c))\phi} \right|^2 \]

- $A$ is complex helicity coupling
- $d$ are Wigner d-matrices (see tables in PDG)
- $\theta$ is helicity angle
- $\phi$ is azimuthal angle defined by decay plane
  - Dependence drops out unless studying cascade decay like $a \rightarrow bc, b \rightarrow de$
Helicity formalism

- Cascade decays: $a \rightarrow bc, \ b \rightarrow de$
- In this case, need to **coherently sum over helicity of intermediate particle**...
- ...and **sum incoherently over final state particle helicities**.

\[
|M|^2 \propto \sum_{\lambda_c} \sum_{\lambda_d} \sum_{\lambda_e} \sum_{\lambda_b} A^a_{\lambda_b, \lambda_c} A^b_{\lambda_d, \lambda_e} \ldots \]

- For $B^0 \rightarrow \psi(2S)K^+\pi^-$
  - $B^0$ is spin-0, $\lambda_B = 0$
  - $\psi(2S) \rightarrow \mu^+\mu^-$ is EM decay, $\Delta \lambda_{\mu} = \pm 1$
Amplitude analysis of $B^0 \rightarrow J/\Psi \pi^+ \pi^-$

LHCb

$K_s^0$

$\rho$-$\omega$ interfere

[arXiv:1404.5673]