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

Classified states

Established $c\bar{c}$ states

[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 $[QQ][\bar{q}q]$ (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

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

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

The LHCb detector

- Vertex Finder
- Particle ID
- Calorimetry
- Muon detection

### Detector Characteristics

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

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

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

### Diagram Details

- Covers 4% of solid angle but contains 25% of $b\bar{b}$ pairs

[2008 JINST 3 S08005]
A typical LHCb event

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

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

B hadrons fly \(\sim 1\) cm 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, $c\bar{c}g$

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

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

$X(3872)$ seen in B decays and $pp, p\bar{p}$ prompt production
A well known exotic meson: 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($J/\psi\gamma$) $\sim 0.2$
- Detecting soft photons at hadronic collider is hard.
- Pure DD* molecule interpretation disfavoured.

$LHCb \ Preliminary$ [arXiv:1404.0275, NPB]

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

Probes of internal structure of X(3872)
**History of the Z(4430)**

- Belle observed Z(4430)± from sample of ~2k B+,0 → ψ(2S)K+,0π-
- Charged state ⇒ minimal quark content of c̅cud

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

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

- Belle  [PRL 100 (2008) 142001] 1D fit to $m(\psi'\pi^-)$  6.5σ
- 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 $m(K^+\pi^-)$  6.4σ
- Belle  [PRD 88 (2013) 074026] 4D amplitude fit  6.4σ

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

$M = 4485^{+22+28}_{-22-11}$ 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 $|\mathcal{M}|^2$.

Constraints

<table>
<thead>
<tr>
<th>Degrees of freedom</th>
</tr>
</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>

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

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

**Spin-1 resonance**

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

Modelled as product of Breit-Wigner, kinematic and dynamic factors
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 $180^\circ$ across the pole
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 $|\mathcal{M}|^2$.

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<tr>
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<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>
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<tr>
<td>Vector helicity</td>
<td>+2</td>
</tr>
<tr>
<td>Total</td>
<td>+4</td>
</tr>
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</table>
Confirmation of the $Z(4430)^\pm$

- LHCb has sample of $>25k$ $B^0 \rightarrow \psi'K^\pm\pi^-$ candidates ($x10$ Belle/BaBar).
- Selection: most events come through dimuon trigger (eff~90%) $\psi' \rightarrow \mu^+\mu^-$
- Typical $B^0$ pT $\sim 6$ GeV, $\mu^+$ pT $\sim 2$ GeV, $K^+$ pT $\sim 1$ GeV.
- Use sidebands to build 4D model of combinatorial background.
  - Bkgs from mis-ID physics decays is small - excellent LHCb vertexing, PID!

![Graph showing candidates and signal region]
Model independent analysis - qualitative check

Can reflection of the structures in \( m(K\pi) \) and \( \cos \theta \) reproduce the \( m(\psi'\pi) \) distribution?

- 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 \( B^0 \rightarrow \psi'(2S)K^+\pi^- \) events with the spherical harmonic moments of \( \cos \theta_K \).
- Moments of \( K^* \) resonances are unable to explain observed distribution.

![Graph showing BaBar data for \( B^0 \rightarrow \psi'(2S)K^+\pi^- \) events with LHCb data and Jmax ≤ 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 $\Rightarrow A_{Z,-1} = A_{Z,0} = A_{Z,+1}$

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

$Z(4430)$ 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 ($J = 3, 4, 5$).

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

- Z(4430) has largest effect \(\sim 1.5\text{GeV}\)
- Important to understand the \(K\pi\) \textbf{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 \(K^*(1430)\)

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

\[ BW \text{ amplitude for } K(1430) \]

- Slowly varying NR contribution

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

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
Fitting the model to the data

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

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

- 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

PDF

Observables (mass, angles)

Parameters

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

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

$J^P = 1^+$ Z component
Z(4430)$^{±}$ 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>$200^{+41}<em>{-46}^{+26}</em>{-35}$</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>$f'_Z [%]$</td>
<td>$16.7 \pm 1.6^{+2.6}_{-5.2}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

(with interference) significance

- $> 13.9\sigma$
- $> 5.2\sigma$

$J^P$

- $1^+$
- $1^+$

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>$5.8 \pm 2.1$</td>
</tr>
<tr>
<td>$K_0^*(800)$</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>$K_2^*(1430)$</td>
<td>$7.0 \pm 0.4$</td>
<td>$4.5 \pm 1.0$</td>
</tr>
<tr>
<td>$K_1^*(1410)$</td>
<td>$1.7 \pm 0.8$</td>
<td>$4.3 \pm 2.3$</td>
</tr>
<tr>
<td>$K_1^*(1680)$</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>

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

LHCb

Fit projections in slices of $m(K^+\pi^-)$

LHCb

Fit projections in slices of $m(K^+\pi^-)$

LHCb

Fit projections in slices of $m(K^+\pi^-)$

LHCb
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>$J^P$</th>
<th>Disfavoured $\Delta$</th>
<th>Rejection level relative to $1^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>9.7$\sigma$</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>15.8$\sigma$</td>
<td>3.7$\sigma$</td>
</tr>
<tr>
<td>$2^+$</td>
<td>16.1$\sigma$</td>
<td>5.1$\sigma$</td>
</tr>
<tr>
<td>$2^-$</td>
<td>14.6$\sigma$</td>
<td>4.7$\sigma$</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 \( \Rightarrow \text{resonance!} \)
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 $Z^- \rightarrow \chi_{c1}\pi^-$ 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 $\bar{D}^*(2010)D^*(2420)$ 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 $Z_c(3900)^{\pm}$?

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

1D fit to $m(\pi J/\Psi)$
Looking forward to amplitude analysis!
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 has a negative electric charge. The letter Z shows that it belongs to a strange series of particles that are referred to as ZZ states.

Quarks bonding differently at LHCb
Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers ‘Very Exotic Matter’ That Challenges Traditional Physics! (Must-See Videos)

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 $B^0 \rightarrow J/\psi \pi^+ \pi^-$

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

$\tan^2 \varphi_m \equiv r_f = \frac{\mathcal{B}(\overline{B}^0 \rightarrow J/\psi f_0(980)) \Phi(500)}{\mathcal{B}(\overline{B}^0 \rightarrow J/\psi f_0(500)) \Phi(980)} = 1/2$
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>
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<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
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<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>$7.5 \pm 0.6^{+0.4}_{-0.3}$</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 $B_s^0 \rightarrow J/\psi \pi^+ \pi^- \quad [\text{Phys. Rev. D 89, 092006 (2014)}]$.
- Best fit model does not require $f_0(980)$ component ⇒ upper limit for mixing angle:

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

Different from tetraquark prediction $1/2$ of this model by $8\sigma$

[arXiv:1404.5673, PRD]
[Stone, Zhang, PRL 111, 062001 (2013)]
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 \( p_T > 2 \text{ GeV}/c^2 \) is \( \sim 20 \mu m \).
- Decay time resolution \( \sim 45 \text{ fs} \) 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: $\varepsilon(\mu \rightarrow \mu) \sim 97\%$, $\varepsilon(\pi \rightarrow \mu) \sim 1 - 3\%$
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.

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 $\mu/\mu$
- 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
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon

DiMuon trigger

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

\[ B^{±/0} \rightarrow XXK^{±/0} \quad X \rightarrow J/\psi \phi \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>(\sigma)</th>
<th>Published</th>
<th>Ref.</th>
</tr>
</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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<td>CDF</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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<td>CMS</td>
<td>4148.0±2.4±6.3</td>
<td>28</td>
<td>&gt;5</td>
<td>N</td>
<td>arXiv: 1309.6920</td>
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<tr>
<td>Belle</td>
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<td>LHCb</td>
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<td>-</td>
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<td>Phys. Rev. D 85, 091103(R)</td>
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<tr>
<td>BaBar</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>N</td>
<td>Conference</td>
</tr>
</tbody>
</table>

Could be some hybrid state: \(c\bar{c}s\bar{s}\)

<table>
<thead>
<tr>
<th>(D\bar{O} \text{ Run II, 10.4 fb}^{-1} + \text{Data (C)})</th>
</tr>
</thead>
</table>

\[\text{N}(B^*) / 30 \text{ MeV}\]

\[\text{M}(J/\psi K^+K^-) \text{ (GeV)}\]

<table>
<thead>
<tr>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \rightarrow J/\psi \phi K^+)</td>
</tr>
</tbody>
</table>

\[\text{Candidates / 4 MeV}\]

\[\text{M}(J/\psi K^+K^-) \text{ (GeV)}\]
An enigma... the X(4140)

- X(4140) seen by some experiments, not by others in m(J/ψΦ).
- Could be some hybrid state: c̅c s̅s̅

\[ B^{±/0} \rightarrow X K^{±/0} \]
\[ X \rightarrow J/\psi \Phi \]
$Z_c(3900)^+ \text{ in } e^+e^- \rightarrow \pi^+\pi^- J/\psi$

- 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 $\pi^0 J/\psi$.

\[ M = (3894.5 \pm 6.6 \pm 4.5) \text{ MeV/c}^2 \]
\[ \Gamma = (63 \pm 24 \pm 26) \text{ MeV/c}^2 \]
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 $\sim 370$MeV.
- Z(4430)$^+$ at 4.0sigma: evidence for new decay mode.
  - Expect smaller BR if Z has large radius, with larger overlap with $\psi'$.
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 $\pi^+\pi^-\Upsilon(nS)$ 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

Expect $\pi^+\pi^-$ to be in an S-wave configuration
**Helicity formalism**

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

\[
|\mathcal{M}|^2 \propto |A_{\lambda_b, \lambda_c} d^{Ja}_{\lambda_a, \lambda_b - \lambda_c}(\theta) e^{i(\lambda_a - (\lambda_b - \lambda_c))\phi}|^2
\]

- $A$ 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**.

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

• 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

$\rho - \omega$ interfere

[arXiv:1404.5673]