LHCb Results on Exotic Meson Spectroscopy

Thomas Britton
On behalf of the LHCb collaboration
Recent Research

• Over the last few years there has been exciting research in exotic spectroscopy, more specifically charmonium and charmonium like states

• There are many new results from LHCb
  – Quantum number determination of X(3872)
  – Study of the resonant nature of Z(4430)
  – Discovery of pentaquarks

• This talk will focus mainly on the determination of X(3872) quantum numbers and the study of the resonant nature of Z(4430).
The LHCb Detector at the LHC

- Single-arm forward spectrometer designed for precision measurements of CP violating decays, specifically decays involving bottom or charm hadrons
  - Covering $2<\eta<5$
- Great particle identification
  - Muons: $\varepsilon \sim 97\%$ with 1-3% of $\mu \rightarrow \pi$ misidentification
  - Kaons: $\varepsilon \sim 95\%$ with 5% of $\pi \rightarrow K$ misidentification
- Good Impact parameter resolution: $\sigma = 20\mu m$
- Good momentum resolution: $\Delta p/p = 0.5\%$ at 20GeV to 0.8\% at 100GeV
Charmonium?  Tetraquark?  Molecule?

X(3872)
X(3872) Quantum Numbers

- X(3872) is a long-lived state ($\Gamma < 1.2 \text{ MeV}$) with the mass within the errors of $m(D^0) + m(D^{0*})$. Both conventional (charmonium) and exotic (D$^0$D$^{0*}$ molecule, tetraquark) interpretations have been proposed. Determination of its J$^P_C$ is important for narrowing down the possible interpretations.
- C=+ by observation of $X(3872) \rightarrow \gamma J/\psi$ (and $\psi(2S)\gamma$) decays
- Previous determinations of J$^P$:
  - **all assumed the lowest possible orbital angular momentum in** $X(3872) \rightarrow \rho J/\psi$, $\rho \rightarrow \pi^+\pi^-$ decays ($L_{min}$ value depends on J$^P$ hypothesis).
  - **CDF 2007**:
    - ruled out all but 1$^{++}$ and 2$^{--}$
  - **LHCb-PAPER-2013-001 (1 fb$^{-1}$)**:
    - ruled out 2$^{--}$
    - the data is consistent with 1$^{++}$ (and a pure S-wave decay)
- Significant $L > L_{min}$ could invalidate J$^P = 1^+$ assignment and hint at molecular structure of X(3872)
Data sample: Changes

- 2011 (1 fb\(^{-1}\)) → 2011+12 (3 fb\(^{-1}\))
- The same selection except for:
  - Now we cut on track ghost probability
  - \(p_T(\mu) > 0.9 \rightarrow 0.55 \text{ GeV} \); \(p_T(\pi,K) > 0.25 \rightarrow 0.2 \text{ GeV}\)
  - No cut on \(Q = M(\pi\pi J/\psi) - M(J/\psi) - M(\pi\pi) \rightarrow Q < 250 \text{ MeV}\)
  - \(J/\psi\) mass + \(\pi\pi J/\psi K\) vertex constraints → ... + B mass + B pointing to PV constraints

\(B^+ \rightarrow X(3872)K^+\) events:

1 fb\(^{-1}\)  

\[N_s = 313 \pm 26 \text{ signal events}\]
\[N_{es} = 171 \text{ equivalent bkg free signal events}\]

3 fb\(^{-1}\)

\[N_s = 1011 \pm 38 \text{ signal events}\]
\[N_{es} = 778 \text{ equiv.}\]

Statistical gain 4.5 in equivalent signal yield (2.1 in statistical errors)
L in X(3872)→ρ⁰J/ψ and Determinations of X(3872) J^P

• All previous determinations of J^P \((CDF \text{ PRL 98(2007)132002, LHCb-PAPER-2013-001 PRL 110 (2013) 222001 1fb}^{-1})\) assumed the lowest possible orbital angular momentum in X(3872)→π⁺π⁻J/ψ decays

Orbital angular momentum: \(L = r \cdot p\)

Conservation of parity: \(L = L_{\text{min}}, L_{\text{min}} + 2, \ldots\)

\((L_{\text{min}} \text{ value depends on } J^P)\)

• Significant \(L > L_{\text{min}}\) could:
  - invalidate the previous \(J^P=1^+\) assignment
  - hint at molecular structure of X(3872)
Determination of $X(3872) J^{PC}$: helicity formalism

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

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

$J/\psi \rightarrow \mu^+ \mu^-$

$\Omega$ – all 5 angles

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

Matrix element

Relation of the helicity couplings to LS amplitudes

Parity conservation

$LHCb$ 2015

Many more amplitudes to fit

$LHCb$ 2013

LS amplitudes to be determined from the data

$B^{+} \rightarrow X(3872) K^{+},$

$X(3872) \rightarrow J/\psi \pi^{+} \pi^{-},$

$J/\psi \rightarrow \mu^{+} \mu^{-}$

$\Delta \phi_{X,J/\psi}$

5 independent angles describing the decay in helicity formalism

$|\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} \times D_{0, \lambda_{J/\psi}, \rho}^1 (0, \theta_x, 0)^* \times D_{\lambda_{J/\psi}, \rho}^1 (\Delta \phi_{X,J/\psi}, \theta_\rho, 0)^* \times D_{\lambda_{J/\psi}, \rho}^1 (\Delta \phi_{X,J/\psi}, \theta_\rho, 0)^*$$

$LHCB$ 2015

Many more amplitudes to fit

$LHCB$ 2013

$LHCB$ 2015

Many more amplitudes to fit

$CDF$ 2007

$LHCb$ 2015

Many more amplitudes to fit

$CDF$ 2007

$LHCb$ 2013

LS amplitudes to be determined from the data
Determination of $X(3872)\ J^{PC}$

- Data unambiguously prefers $1^{++}$ hypothesis (new: no assumptions about $L$)
D-wave fraction in $X(3872) \rightarrow \rho^0 J/\psi$ for $J^{PC} = 1^{++}$

- Fit to the data:

$$\left| \frac{B_{21}}{B_{10}} \right|^2 = 0.0018 \pm 0.0042 \quad \left| \frac{B_{22}}{B_{10}} \right|^2 = 0.0066 \pm 0.0081$$

D-wave amplitudes are consistent with zero

D-wave significance using Wilks theorem applied to the likelihood ratio with/without D wave amplitudes: $0.8\sigma$

The likelihood was profiled as a function of the D-wave fraction:

$$f_D = \frac{\int |M(\Omega)_D|^2 d\Omega}{\int |M(\Omega)_{S+D}|^2 d\Omega}$$

$$f_D < 4\% \text{ at } 95\% \text{ CL}$$
Importance of Multidimensional Analysis

- $J^P_C$ sensitivity is in the multidimensional correlations!
- 1D fits to helicity angles lack discrimination power between certain $J^P$ assignments: see Belle analysis of $B \rightarrow X(3872)K$, $X(3872) \rightarrow \rho J/\psi$, $\rho \rightarrow \pi^+\pi^-$ PRD84, 052004 (2011)
- Our data and simulations show the larger the number of decay angles included in the likelihood, the larger $J^P$ separation.
- When using all decay angles, detector efficiency corrections become $J^P$ independent - the analysis becomes simpler when using all angles.
- The smaller the data statistics the more important to analyze all dimensions.
Radiative decays of $X(3872)$ in LHCb

**Measurement of**

$$R_{\psi\gamma} = \frac{\text{BR}(X(3872) \rightarrow \psi(2S)\gamma)}{\text{BR}(X(3872) \rightarrow J/\psi\gamma)}$$

a good probe for internal structure of $X(3872)$

- The results are not consistent with the expectations for a simple molecular model of $X(3872)$
- Mounting evidence that $X(3872)$ has a very significant $\chi_c(2^3P_{1+})$ component
Z(4430)
Z(4430)$^+$ previous measurements

B$\rightarrow\psi'\pi^+K$

[B$\rightarrow\psi'\pi^+K$]

[$\psi' \equiv \psi(2S)$]

Belle 2008

1D $M(\psi'\pi^-)$ mass fit

("K* veto region")

PRL 100, 142001 (2008)

Z(4430)$^+$

K$^*\rightarrow$K$\pi^+$
bkg.

non-B bkg

$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18}_{-13}^{+30}_{-13}$ MeV

significance 6.5$\sigma$

BaBar 2009

Harmonic moments of K*$s$ (2D) reflected to $M(\psi'\pi^+)$

Belle 1D 4D

PRD 79, 112001 (2009)

$M(\psi'\pi^+)\text{ GeV}$

Bkg. subtracted efficiency corrected

With Z(4430)$^+$

BaBar did not confirm Z(4430)$^+$ in B sample comparable to Belle.

Did not numerically contradict the Belle results.

Belle 2013

(2D amplitude fit in 2009)

4D amplitude fit (subsample with $\psi \rightarrow l^+l^-$)

$0.996 \text{ GeV/c}^2 < M(K,\pi) < 1.332 \text{ GeV/c}^2$

("K* veto region")

PRD 88, 074026 (2013)

$M(Z) = 4485_{-22}^{+22} \pm 28_{-11}^{+11}$ MeV

$\Gamma(Z) = 200_{-46}^{+41} \pm 26_{-35}^{+11}$ MeV

6.4$\sigma$ (5.6$\sigma$ with sys.)

$J^P=1^+$ preferred by $>3.4\sigma$

Made Ad hoc assumption about the K*$\rightarrow$K$\pi^+$

background shape.

Almost model independent approach to K*$\rightarrow$K$\pi^+$

backgrounds.

Model dependent approach to K*$\rightarrow$K$\pi^+$

backgrounds.

Higher statistical sensitivity.
Z(4430)$^+$ in LHCb: 4D amplitude analysis (a la Belle)

- The 2D model independent approach establishes the need for exotic hadron contributions, but cannot be used to characterize their properties:
  - The quantitative analysis does not formally distinguish between $\psi'\pi^+$ and $\psi'K^-$ exotics.
  - There is no way to fit Z(4430)$^+$ on top of the $K^*$ reflections in $m_{\psi'\pi^+}$ distribution because of the $Z$-$K^*$ interferences.
- The amplitude analysis is necessary!
- Use all dimensions of the decay kinematics (4D):
  - The best sensitivity to underlying physics
  - Avoids biases from non-uniform efficiency in averaged dimensions (for example the differences between Belle 4D vs 2D fits)

Z(4430)$^+ \rightarrow \psi'\pi^+$ amplitude parameterized in angles derivable from the angles in the $K^*$ decay chain.
Amplitude fits with $J^P=1^+ \ Z(4430)^+$

- The 4D $\chi^2$ p-value = 12\% ($< 2\times 10^{-6}$ when fitting without $Z(4430)^-$).

- The data are well described only when $J^P=1^+ \ Z(4430)^-$ is included in the fit.

- $Z(4430)^-$ significances from $\Delta(-2\ln L)$ is $18.7\sigma$ ($13.9\sigma$ with systematic variations e.g. allowing the tail of $K^*_{3}(1780)$).
Is $Z(4430)^+$ really a bound state?

- Does it follow resonant behavior if not forced by the amplitude model?
- Replace the Breit-Wigner amplitude for $Z(4430)^+$ by 6 independent amplitudes in $m_{\psi'\pi^+}^2$ bins in the peak region.

Rapid phase transition at the peak of the amplitude $\rightarrow$ resonance!

The first time the resonant character of a four-quark candidate was demonstrated this way!

Various models for $Z(4430)^+$ have been proposed: tightly bound tetraquark (e.g. diquark model)
Z(4430)- spin-parity analysis

- \( J^P = 1^+ \) now established beyond any doubt

Including systematic variations:

<table>
<thead>
<tr>
<th>Disfavored ( J^P )</th>
<th>Rejection level relative to ( 1^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td></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>

The only other confirmed charged four-quark candidate \( Z(3900) \) observed by BES-III and Belle in 2013 could be a \( \bar{D}D^* \) threshold effect.
Possibility of an additional $Z^+$


An additional $0^-$ state has $6\sigma$ significance. $0^-$ is preferred over $1^-, 2^+, 2^-$ by $8\sigma$. It could be $1^+$, however, $Z^+$ becomes unreasonably wide under that $J^P$ assumption.

- Argand diagram for this state is inconclusive, and there is no evidence for it in the model independent approach.
- More data is needed to clarify.
Z(4430) in LHCb: 2D model independent analysis

"Rectangular Dalitz plot"

Decompose into Legendre moments

Pass only moments with \( l \) not more than \( l_{\text{max}} = J_{\text{max}}/2 \)

Excess of events over the \( K^* J_{\text{max}} = 2 \) filtered distribution in the Z(4430) region is apparent!

This qualitative analysis was included in the 2014 paper
LHCb-PAPER-2014-014, PRL 112 (2014) 222002
Quantitative results from the model independent approach

LHCb-PAPER-2015-038 in preparation (preliminary results)

The outlined procedure from the previous slide is repeated for various $J_{\text{max}}$ ($l_{\text{max}}$)

- Allows for $K^*$ states up to $K^*_2(1430)$
- Allows for a tail of $K^*_3(1780)$
- Allows implausible $K^*$ contributions

Such high moments only contribute in the presence of $Z$
Quantitative results from the model independent approach
LHCb-PAPER-2015-038 in preparation (preliminary results)

Test significance of implausible $l_{\text{max}} < l < 30 \cos(\theta_{K^*})$ moments using the log-likelihood ratio:

$$\Delta(-2\text{NLL}) = -2 \log \frac{\mathcal{L}_{l_{\text{max}}}}{\mathcal{L}_{30}} = -2 \log \frac{\prod_i F_{l_{\text{max}}}(m_{\psi'\pi}^i)}{\prod_i F_{30}(m_{\psi'\pi}^i)}$$

Statistical simulations of pseudo-experiments were generated from the $l < l_{\text{max}}$ hypotheses, and $\Delta(-2\text{NLL})$ calculated:

- $K^*$ mass-dependent $J_{\text{max}} < 2$
- $J_{\text{max}} < 2$
- $J_{\text{max}} < 3$

Explanation of the data with plausible $K^*$ contributions is ruled out at high significance without assuming anything about $K^*$ resonance shapes or their interference patterns!
While not part of exotic meson spectroscopy I would be remiss if I did not at least mention LHCb’s discovery of pentaquarks as they, along with all other exotic candidates mentioned contain $c\bar{c}$

- See plenary talk tomorrow at 11:50: Observation of Pentaquark Resonances in $\Lambda_b \rightarrow J/\psi K_p$ Decay
  -- Zhenwei Yang

- Resonant nature clearly seen in $P_c(4450)$

Features in $J/\psi p$ unable to be described by $\Lambda^*$ alone

Best modeled by two $P_c$ states
Summary

- So far LHCb has contributed to the study of neutral candidates for exotic mesons (X(3872)) and the charged tetraquark candidate of Z(4430)
- X(3872):
  - With the full 3 fb\(^{-1}\) and after removing the assumption of X(3872)\(\rightarrow\rho J/\psi\) proceeding by the lowest angular momentum X(3872)’s J\(^P\) unambiguously determined to be 1\(^+\).
    - The quantum numbers are consistent with the molecular or tetraquark models or with the \(\chi_{c1}(2^3P_{1++})\) charmonium state, or their mixture. Inconsistent with the other interpretations e.g. \(\eta_c(1D_{2-})\) proposed previously.
    - An upper limit on D-wave fraction was set at 4% with a 95% CL:
      - Small D-wave fraction is expected in models in which X(3872) is a compact state (e.g. charmonium)
      - Since no quantitative predictions for D-wave fraction exist in any model, it is hard to draw any conclusions
      - The measurement \(\text{BR}(X(3872)\rightarrow\psi(2S)\gamma)/\text{BR}(X(3872)\rightarrow J/\psi\gamma)\) is pointing to the strong component of \(\chi_{c1}(2^3P_{1++})\) in X(3872), possibly mixing with the exotic form e.g. \(D^0D^{0*}\) molecule.
- Z(4430):
  - Amplitude analysis confirmed Z(4430)+ with overwhelming significance, together with J\(^P\)=1\(^+\). More precise mass, width measurements.
  - The first exotic hadron candidate for which a resonant nature has been demonstrated with an Argand diagram