Heavy Quark Spectroscopy

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On behalf of LHCb collaboration

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Outline of the talk

• The LHCb detector


• Tetra- and Penta-quarks:
  • HOT! Observation of $J/\psi p$ resonances consistent with pentaquark states PRL 115 (2015) 072001, 12 August
  • $Z_c(4430)^+$: charged four-quark candidate PRL 112 (2014) 222002
The LHCb detector

- **Efficient muon trigger:**
  \[ P_T(\mu_1) \times P_T(\mu_1) > 1.68 \text{ (GeV/c)}^2 \]
  - Ability to study low-p_T processes at large \( \eta \)
- **Very good muon identification:** \( \varepsilon \sim 97\% \)
  for \( \sim 1\% \pi \rightarrow \mu \) misidentification
- **Impact parameter resolution:** \( \sigma = 20\mu \text{m} \)
  \( \Rightarrow \) prompt/secondary separation
- **Rapidity coverage:** \( 2.0 < y < 4.5 \)
  - Covers just 4\% of the solid angle but captures 25\% of \( b \bar{b} \) heavy quark pairs produced at the LHC

Collected data:
- 1 fb\(^{-1}\) for \( \sqrt{s} = 7 \text{ TeV} \)
- 2 fb\(^{-1}\) for \( \sqrt{s} = 8 \text{ TeV} \)

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>ATLAS/CMS</th>
<th>LHCb</th>
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<tbody>
<tr>
<td>7 TeV</td>
<td>44%</td>
<td>25%</td>
</tr>
<tr>
<td>14 TeV</td>
<td>41%</td>
<td>24%</td>
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**$b\bar{b}$ bound states**

Since $\chi_b(3^3P)$ states are very near the open flavor threshold, it has been speculated that couplings to virtual $B^{(*)}\overline{B}^{(*)}$ pairs could drastically affect their masses and decay properties with respect to the expectations for pure $b\bar{b}$ states (see e.g. Ferretti, Galata, PRD90, 054010 (2014)).

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**Theoretical approaches:** potential models, NRQCD, lattice QCD
Masses of $\chi_b(3^3P_J)$ states

- Using all radiative transitions $\chi_b(3^3P_J)$ to $\Upsilon(1,2,3S)$ with converted photons (EPJC 74 (2014) 3092) and photons detected in calorimeter (JHEP 10 (2014) 088)

**Photons detected in calorimeter**

**Converted photons**

- First observation of $\chi_b(3^3P_J) \to \gamma \Upsilon(3S)$

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Masses of $\chi_b(3^3P_1)$ states

Most precise measurement of $\chi_b(3^3P_1)$ mass:
- Converted photons study: $10515.7^{+2.2}_{-3.9}$ (stat) $^{+1.5}_{-2.1}$ (syst) MeV/c$^2$
- Combined from two studies: $10512.1 \pm 2.1$ (experimental) $\pm 0.9$ (model) MeV/c$^2$, where experimental – stat and syst uncertainties, model uncertainty for varying $\chi_b(3^3P_1)$ and $\chi_b(3^3P_2)$ mass differences and relative rates

- The measured mass of the $\chi_b(3^3P_1)$ state is within a few MeV of the potential model predictions ($10516$ MeV/c$^2$) which are up to 26 years old!
  - It appears that coupled-channel corrections are either small or well absorbed into an effective potential adjusted to the experimental data on the other $bb$ states
  - The measured ratios of transition rates also consistent with the expectations
\( \chi_b(N^3P_J) \) mass splitting (N=1,2;J=1,2)

\[
m[\chi_b(1^3P_2)] - m [\chi_b(1^3P_1)] = \Delta m_{12}(1P) = 19.81 \pm 0.65(\text{stat}) \pm 0.20(\text{syst}) \text{ MeV/c}^2
\]
\[
m [\chi_b(2^3P_2)] - m [\chi_b(2^3P_1)] = \Delta m_{12}(2P) = 12.3 \pm 2.6(\text{stat}) \pm 0.6(\text{syst}) \text{ MeV/c}^2
\]

are in agreement with the world average values, \( \Delta m_{12}(1P) = 19.43 \pm 0.37 \) MeV/c\(^2\) and \( \Delta m_{12}(2P) = 13.5 \pm 0.6 \) MeV/c\(^2\) [PRD 86, 010001].

Relative production of \( \chi_b, \chi_c \) spin states:

- \( \chi_b \) and \( \chi_c \) results in agreement
- Ratio of cross-section ~ flat with \( p_T \)
- Increase predicted by LO NRQCD at low \( p_T \)
- \( p_T \) seems softer

- Better agreement with prediction from NLO NRQCD (arxiv:1410:8537) and CMS results (PLB 743 (2015) 383)
Exotic states

Tetra- and Penta-quarks states were predicted at the birth of Quark Model!

Searches for such states made out of the light quarks (u,d,s) are ~50 years old, but no undisputed experimental evidence have been found for them
Observation of $J/\psi p$ resonances consistent with pentaquark states (1/3)

$\Lambda_b \rightarrow J/\psi pK^-$: unexpected structure in $m(J/\psi p)$

• Unexpected, narrow peak in $m(J/\psi p)$
• Many checks done to ensure it is not an “artifact” of selection or reflection of other sources
• Proper amplitude analysis
Observation of $J/\psi p$ resonances consistent with pentaquark states (2/3)

- Check all possible known $\Lambda^*$ amplitudes
- Obtain good fits even with the reduced $\Lambda^*$ model

$P_c(4380)^+$:
- $m = 4380 \pm 8$ (stat) $\pm 29$ (syst) MeV/c$^2$
- $\Gamma = 205 \pm 18 \pm 86$ MeV/c$^2$
- Significance is 9$\sigma$

$P_c(4450)^+$:
- $m = 4449.8 \pm 1.7 \pm 2.5$ MeV/c$^2$
- $\Gamma = 39 \pm 5 \pm 19$ MeV/c$^2$
- Significance is 12$\sigma$

The preferred $J^P$ assignments are of opposite parity, with one state having spin 3/2 and the other 5/2
Observation of $J/\psi p$ resonances consistent with pentaquark states (3/3)

Variants for “internal mechanism” of quark interactions inside pentaquarks:

- Tightly bound
- Loosely bound in meson-baryon molecule

New field of research
$Z^+_c(4430)$: charged four-quark candidate

- The first observed state of that type [Belle PRL 100 (2008) 142001] Belle 2013 4D amplitude fit results [PRD 88 (2013) 074026]

4D amplitude fit to $B^0\rightarrow\psi'\pi^+K^-$
- $M(Z) = 4475 \pm 7_{-25}^{+15}$ MeV/c$^2$
- $\Gamma(Z) = 172 \pm 13_{-34}^{+37}$ MeV/c$^2$
- $J^P = 1^+$
- Significance is 13.9σ

- The minimal quark content is $c\bar{c}d\bar{u}$
- Confirming existence of this state and improving over Belle 2013 4D amplitude fit results (PR D88, 074026)
- LHCb-PAPER-2015-038 (preliminary) – it confirmed using a model independent method that $\psi'\pi^+$ distribution cannot be described by $K\pi$ reflections
Examples of other heavy quark spectroscopy studies at LHCb

• Orbital angular momentum in $X(3872) \rightarrow \rho^0 J/\psi$ and $X(3872) \ J^{PC}$
  arXiv:1504.06339 Apr. 2015

• Radiative decays of $X(3872)$ NPB 886 (2014) 665-680

• Results on $D_s^{**}$ states PRD 90 (2014) 072003 and PRL 113 (2014) 172001

• Results on $D^{**}$ states PRD 91 (2015) 092002 Mar. 2015

• Results on $B^{**}$ states JHEP 04 (2015) 024 Feb. 2015

• Results on $\Xi_b^*$ states PRL 114 (2015) 062004 Nov. 2014
Summary of LHCb results

• Studies of prompt production of radiatively decaying $\chi_b(3^3P_J)$ states:
  • These just below the $B\bar{B}$ threshold states have masses and photon transition rates consistent with the expectations for pure $bb$ states

• Two pentaquark candidates decaying to $J/\psi p$ observed by LHCb with overwhelming significance in a state of the art amplitude analysis. Loosely bound meson-baryon molecules or tightly bound? Need more statistics.

• Amplitude analysis of $Z(4430)^+$:
  • This state exists and its amplitude phase variation with the mass is consistent with an exotic four-quark bound state

• Many new results on heavy-light states: $D_s^{**}, D^{**}, B^{**}$ – Understanding of their mass spectra is important for meson pair contributions in theoretical models related to the exotic hadron candidates
Questions?