Spectroscopy

Yiming Li (Tsinghua University)
On behalf of LHCb collaboration
(Including results from ATLAS and CMS collaborations)
Content

- Heavy flavour spectroscopy at LHC
- Recent LHC results
  - Exotics
  - Heavy baryons
  - $B_c$ physics
- Summary
**Heavy flavour spectroscopy**

- Thanks to large $\sqrt{s}$ at LHC, $b\bar{b}/c\bar{c}$ are produced prolifically
  - $\sim 10^{11}$ $b\bar{b}$ pairs/yr in forward region
  - 20 times more for $c\bar{c}$
- Various theoretical models make predictions on the heavy hadron production and properties ($M$, $\tau$, $Br$…)
  - Need test by precise measurement
  - New states/decays provide inputs to theory
- In search of new physics (CP violation, rare decays…), these are SM background to be well understood
LHC experiments

- LHC detectors cover different acceptance and kinematic range ⇒ complementary on spectroscopy studies
  - ALICE: dedicated heavy-ion detector
  - ATLAS + CMS: general purpose (high $p_T$ low $\eta$)
  - LHCb: designed for heavy-flavour physics ($2 < \eta < 5$, low $p_T$)

Pseudo-rapidity coverage of detectors

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Exotic states

- Observation of $Z(4430)^+$
- Evidence of $X(3872) \rightarrow \psi(2S)\gamma$

Monica Pepe Altarelli
"Exotic charmonium-like spectroscopy at LHCb"
Belle observed $Z(4430)^+$ in $B^0 \to \psi(2S)\pi^-K^+$ in 2008

4D angular analysis favours $1^+$ over $0^-$, $1^-$, $2^-$ and $2^+$

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

$$\Gamma = 200^{+41+26}_{-46-35} \text{ MeV}.$$ 

BaBar could explain the enhancement by reflection of known $K^*$ states, but doesn’t rule out existence of $Z(4430)$
Observation of $Z(4430)^-$ at LHCb

- $B^0 \to \psi(2S)\pi^-K^+$, $\psi(2S) \to \mu^+\mu^-$
- $B$ signal yield $\sim 25k$, 10 times of Belle/BaBar yield
- Full amplitude analysis performed
  \[ \Rightarrow \text{Significance of } Z(4430)^- \text{ signal } > 13.9\,\sigma \]

- $J^P = 1^+$
  - by excluding $0^-, 1^-, 2^-, 2^+$ by at least $9.7\sigma$
- Minimum content is $c\bar{c}d\bar{u}$
  - Does not fit into traditional quark model

Fit with $Z(4430)$
Fit without $Z(4430)$
$X(3872)$ radiative decay

- $X(3872)$ discovered by Belle, the 1$\text{st}$ exotic particle observed
- Quantum numbers determined: $J^{PC} = 1^{++}$
  - But the nature still unclear…
  - Traditional $c\bar{c}$? Molecule? Tetraquark? Mixture?…
- Useful information from $R = Br(\psi(2S)\gamma)/Br(J/\psi\gamma)$
  - Charmonium $c\bar{c}(2^3P_1)$: $R = 1.2 \sim 15$
  - $D\bar{D}^*$ molecule: $R \sim (3 - 4) \times 10^{-3}$
  - Molecule-$c\bar{c}$ mixture: $R = 0.5 \sim 5$
- Evidence of $X(3872) \to \psi(2S)\gamma$ ($3.5\sigma$) by BaBar; not confirmed by Belle

CDF PRL 98 (2007) 132002
LHCb PRL 110 (2013) 222001
BaBar PRL 102 (2009) 132001
Belle PRL 107 (2011) 091803
Evidence (4.4σ) of $X(3872) \rightarrow \psi(2S)\gamma$ is found in $B^+ \rightarrow X(3872)K^+$ decay

Charmonium $c\bar{c}(2^3P_1) : 1.2 \sim 15$ (compatible)

$D\bar{D}^*$ molecule: $(3 - 4) \times 10^{-3}$ (not supported)

Molecule-$c\bar{c}$ mixture: 0.5 $\sim$ 5 (compatible)
Heavy baryons

- $\Lambda_b$ lifetime
- $\Xi_b$ and $\Omega_b$ lifetime
**$\Lambda_b$ lifetime**

- Heavy Quark Expansion (HQE) predicts b hadron lifetime are very close to $B \Rightarrow \tau(\Lambda_b^0)/\tau(B^0) \sim 1$ differ by only a few percent
  - LEP results indicates smaller value: $0.798 \pm 0.052$ or $0.786 \pm 0.034$
- ATLAS, CMS and CDF measured $\tau(\Lambda_b)$ lately:
  - ATLAS: $\tau = 1.449 \pm 0.036 \pm 0.017$ ps
    - Ref: ATLAS PRD 87 (2013) 032002
  - CMS: $\tau = 1.503 \pm 0.052 \pm 0.031$ ps
    - Ref: CMS JHEP (2013) 163
  - $\Rightarrow \tau(\Lambda_b)/\tau(B^0) \sim 1$, with large uncertainty
- LHCb 2011 1fb$^{-1}$ consistent with HQE:
  - $\tau(\Lambda_b)/\tau(B^0) = 0.976 \pm 0.012 \pm 0.006$
    - Ref: LHCb PRL 111 (2013) 102003
- Recently LHCb updated with 3 fb$^{-1}$
  - consistent with 2011 result and HQE
  - Most precise measurement of lifetime

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Yiming Li (Tsinghua University)
Another LHCb measurement using $\Lambda_b \rightarrow J/\psi \Lambda$ with 1 fb$^{-1}$

The results also include the most precise single measurement of $B^+$, $B^0$, $B_s$ (effective) lifetime

Combining two $\Lambda_b$ channels:

$$\tau_{\Lambda_b^0} = 1.468 \pm 0.009 \pm 0.008 \text{ ps}.$$
**Ξ_b and Ω_b lifetime**

- Unlike Λ_b^0 (udb), strange b baryons such as Ξ_b (dsb) or Ω_b^- (ssb) are less abundantly produced & less studied
  - the only τ measurement by CDF  PRD80 (2009)072003; PRD89 (2014)07014
- LHCb measure lifetimes, using Ξ_b^- → J/ψΞ^-, and Ω_b^- → J/ψΩ^-
  - J/ψ → μ^+μ^-, Ξ^- → Λπ^-, Ω^- → ΛK^-, Λ → pπ^-

\[ τ(Ξ_b^-) = 1.55 \pm 0.10 \pm 0.03 \text{ ps} \]
\[ τ(Ω_b^-) = 1.54 \pm 0.26 \pm 0.05 \text{ ps} \]

The most precise measurement, consistent with CDF result and theoretical prediction

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LHCb: arXiv:1405.1543

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Yiming Li (Tsinghua University)
$B_c$ physics

- Production
- Lifetime
- Decays
Production

- Full reconstruction using $B_c^+ \rightarrow J/\psi \pi^+$
- Ratio relative to $B^+ \rightarrow J/\psi K^+$

$$R_\sigma = \frac{\sigma(B_c^+) \times B(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \times B(B^+ \rightarrow J/\psi K^+)}$$

- LHCb 0.37 fb$^{-1}$
- $p_T > 4$ GeV, $2.5 < \eta < 4.5$

$$R_\sigma = (0.68 \pm 0.10 \pm 0.03 \pm 0.05(\tau_{B_c^+}))\%$$

LHCb PRL 109 (2012) 232001

- CMS 5.1 fb$^{-1}$
- $p_T > 15$ GeV, $|y| < 1.6$

$$R_\sigma = (0.48 \pm 0.05 \pm 0.04^{+0.05}_{-0.03}(\tau_{B_c^+}))\%$$

CMS CMS-PAS-BPH-12-011
Semileptonic decay $B_c^+ \rightarrow J/\psi \mu^+ \nu$

The most precise measurement

$\tau = 509 \pm 8 \pm 12 \text{ fs}$

Further improvement possible by combining with $B_c^+ \rightarrow J/\psi \pi^+$ result (uncertainties largely uncorrelated)

Benefit many other $B_c$ measurements (mass, production, Br...)
$B_c$ decays

- A large variety of decay modes expected

- Experimentally observed channels:
  - Tevatron: $J/\psi \ l\nu$, $J/\psi \ \pi^+$
  - LHCb: $J/\psi \ \pi^+\pi^-\pi^+$, $\psi(2S) \ \pi^+$, $J/\psi \ K^+$, $J/\psi \ D_s^*(*)^+$, $J/\psi \ K^+K^-\pi^+$, $J/\psi \ 3\pi^+ \ 2\pi^-$, $B_s\pi^+$...
\( B_c^+ \rightarrow B_s^0 \pi^+ \)

- The first observed \( c \) decay in \( B_c \)
- \( B_s^0 \rightarrow D_s^- \pi^+ \) or \( J/\psi \phi \)

**LHCb PRL 111(2013)181801**

\( B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+)\pi^+ \)

\( B_c^+ \rightarrow B_s^0(\rightarrow J/\psi \phi)\pi^+ \)

\[
\frac{\sigma(B_c^+) \times B(B_c^+ \rightarrow B_s^0 \pi^+)}{\sigma(B_s^0)} = (2.37 \pm 0.31\text{(stat)} \pm 0.11\text{(syst)})^{-0.13(\tau_{B_c^+})} \times 10^{-3}
\]

\( \mathcal{B}(B_c \rightarrow B_s \pi) \sim 10\% \), largest known 
Br of \( B \) meson weak decay
$b$ decay in $B_c$

- $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+ \ @ \ CMS$
  
  **CMS-BPH-12-011**

  $\frac{B(B_c^+ \to J/\psi \pi^+ \pi^- \pi^+)}{B(B_c^+ \to J/\psi \pi^+)} = 2.43 \pm 0.76^{+0.46}_{-0.44}$

  Consistent with LHCb result
  
  **LHCb PRL 108(2012)251802**

- $B_c^+ \to J/\psi K^+ K^- \pi^+ \ @ \ LHCb$
  
  **JHEP 1311 (2013) 094**

  $6.2 \sigma$
  
  $3 \text{ fb}^{-1}$

  $\frac{B(B_c^+ \to J/\psi K^+ K^- \pi^+)}{B(B_c^+ \to J/\psi \pi^+)} = 0.53 \pm 0.10 \pm 0.05$

- $B_c^+ \to J/\psi 3\pi^+ 2\pi^- \ @ \ LHCb$
  
  **arXiv: 1404.0287**

  $4.5 \sigma$
  
  $3 \text{ fb}^{-1}$

  $\frac{B(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)}{B(B_c^+ \to J/\psi \pi^+)} = 1.74 \pm 0.44 \pm 0.24$
Summary

- LHC experiments have been fruitful at spectroscopy studies
  - Observed charged exotic state $Z(4430)^-$
  - Further understanding on nature of $X(3872)$
  - Most precise measurement of $b$-baryon lifetime
  - Comprehensive study on $B_c$ meson
  - ...

- Many interesting results not covered
  - Quarkonium states, $D_J$, ...

- Analysis on LHC Run I data still ongoing, while Run II will bring more opportunities

- A lot more excitement to come!
Backup
Heavy quark production at LHCb

- LHCb measurement at 7 TeV:
  - $\sigma_{b\bar{b}} = 75.5 \pm 14.1 \mu b \ (2 < \eta < 6)$  
    \[ \text{PLB 694, 209} \]
  - $\sigma_{c\bar{c}} = 1419 \pm 134 \mu b \ (0 < p_T < 8 \text{ GeV}, 2.0 < y < 4.5)$  
    \[ \text{Nucl. Phys. B871, 1} \]
**X(4140) searches @ CMS & LHCb**

- CDF first reported evidence of $X(4140)$ in $B^+ \rightarrow J/\psi \phi K^+$; later confirm with $> 5\sigma$; Belle found no evidence in $\gamma\gamma \rightarrow J/\psi\phi$
- Search in : $X(4140) \rightarrow J/\psi\phi$

CDF PRL 102 (2009) 242002  
CDF PRL arXiv: 1101.6058  
Belle PRL 104 (2010) 112004

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**Graphs:**

LHCb PRD 85 (2012) 091103

CMS arXiv:1309.6920
\( \psi(4160) \) in \( B \rightarrow K\mu\mu \)

- LHCb observed a broad peaking structure in low recoil region (\( M(\mu^+\mu^-) > 3770 \text{ MeV} \))
- Consistent with interference between decay and a resonance (> 6\( \sigma \)).
- Compatible with \( \psi(4160) \) observed at BES [BES PLB 660 (2008) 315]
- First observation of \( B^+ \rightarrow \psi(4160)K^+ \) and \( \psi(4160) \rightarrow \mu^+\mu^- \)
- \( X(4260) \) resonance excluded with > 4\( \sigma \)
- Contribution in total low-recoil signal ~20%  
  - Higher than theoretical prediction (~10%) [EPJC 71 (2011) 1635]