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

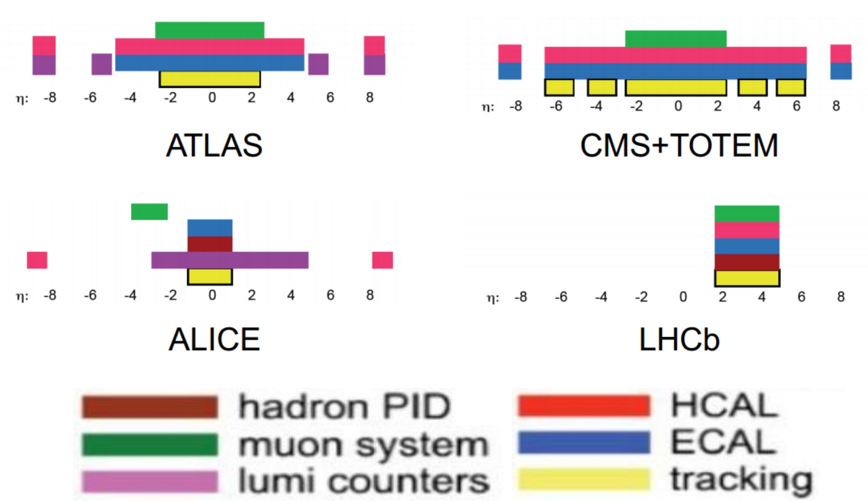
(Heavy flavour) spectroscopy

- 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, τ, 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

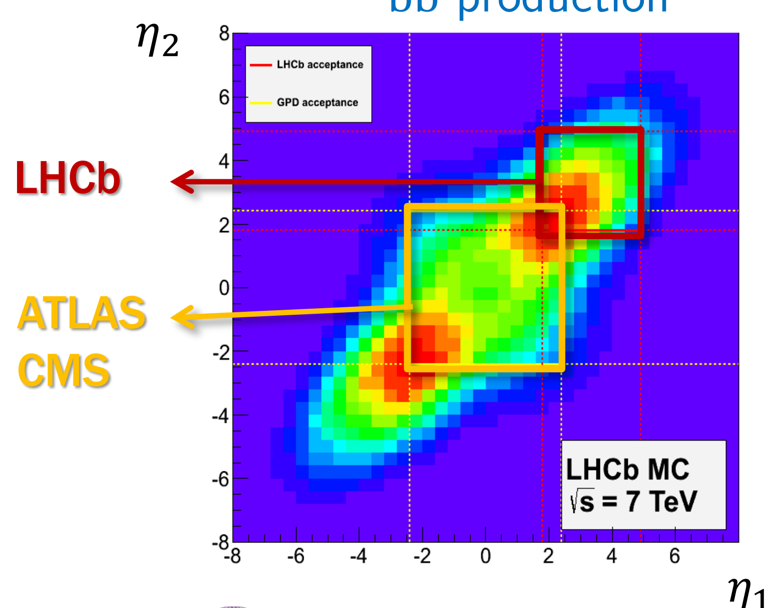
LHC experiments

- 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 η)
  - LHCb: designed for heavy-flavour physics ($2 < \eta < 5$, low p_T)

Pseudo-rapidity coverage of detectors



$b\bar{b}$ production



Exotic states

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

Monica Pepe Altarelli
"*Exotic charmonium-like spectroscopy at LHCb*"

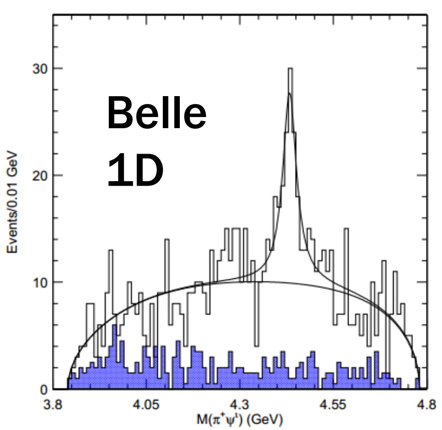
$Z(4430)^+$

- 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^+

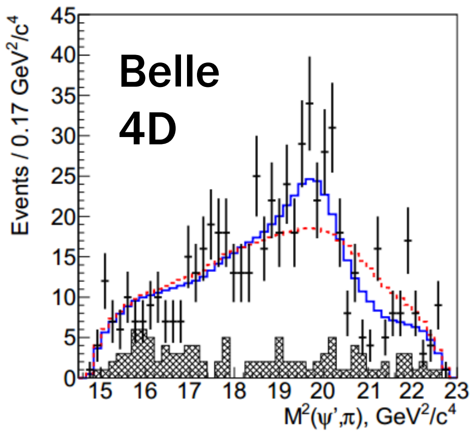
$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}/c^2,$$
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}.$$

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

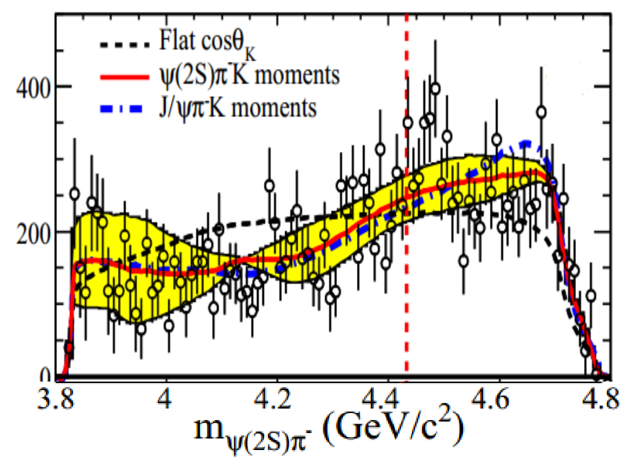
Belle PRL 100 (2008) 142001



Belle PRD 88 (2013) 074026



BaBar PRD 79 (2009) 112001



Observation of $Z(4430)^-$ at LHCb

LHCb arXiv: 1414.1908

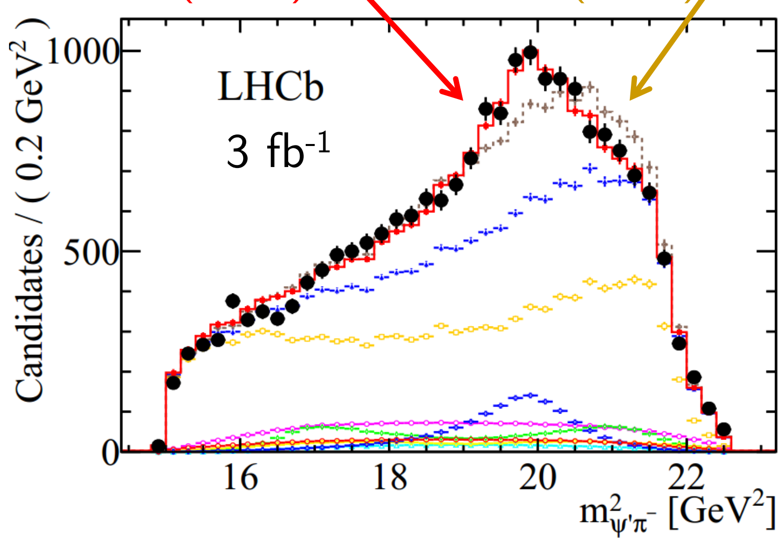
- $B^0 \to \psi(2S)\pi^- K^+$, $\psi(2S) \to \mu^+\mu^-$
- B signal yield ~25k, 10 times of Belle/BaBar yield
- Full amplitude analysis performed

  $\Rightarrow$ Significance of $Z(4430)^-$ signal $> 13.9\ \sigma$

- $J^P = 1^+$
  - by excluding 0^-, 1-, 2-, 2+ by at least 9.7σ
- 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

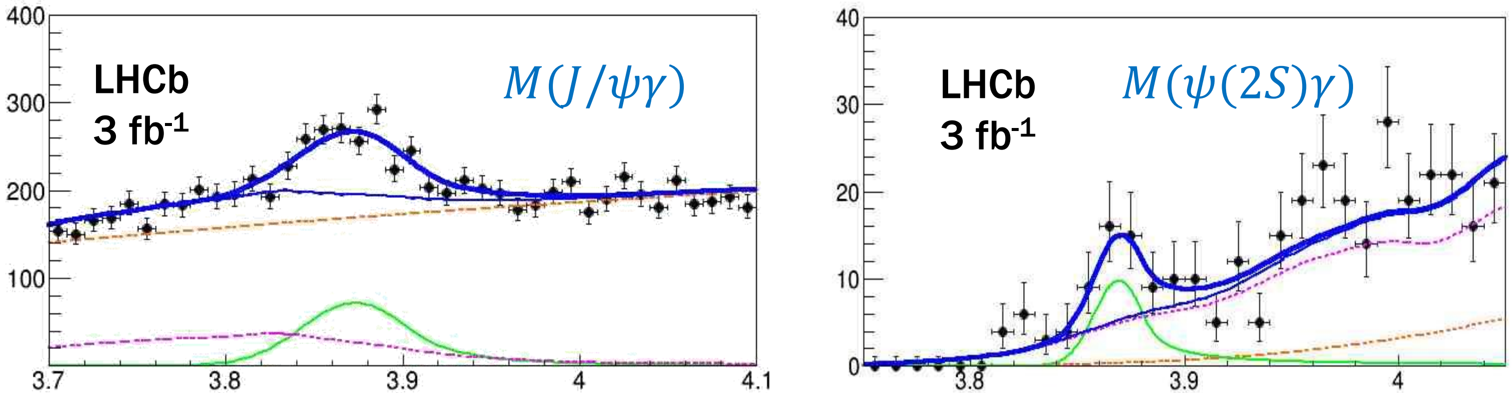
- X(3872) discovered by Belle, the 1st exotic particle observed
- Quantum numbers determined: $J^{PC} = 1^{++}$ CDF PRL 98 (2007) 132002 LHCb PRL 110 (2013) 222001
  - But the nature still unclear…
  - Traditional $c\bar{c}$? Molecule? Tetraquark? Mixture?...
- Useful information from $R = Br(\psi(2S)\gamma)/Br(J/\psi\gamma)$
  - 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 $X(3872) \to \psi(2S)\gamma$ (3.5σ) by BaBar; not confirmed by Belle

BaBar PRL 102 (2009) 132001
Belle PRL 107 (2011) 091803

$X(3872) \to \psi\gamma$ at LHCb

arXiv: 1404.0275

- Evidence (4.4σ) of $X(3872) \to \psi(2S)\gamma$ is found in $B^+ \to X(3872)K^+$ decay



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

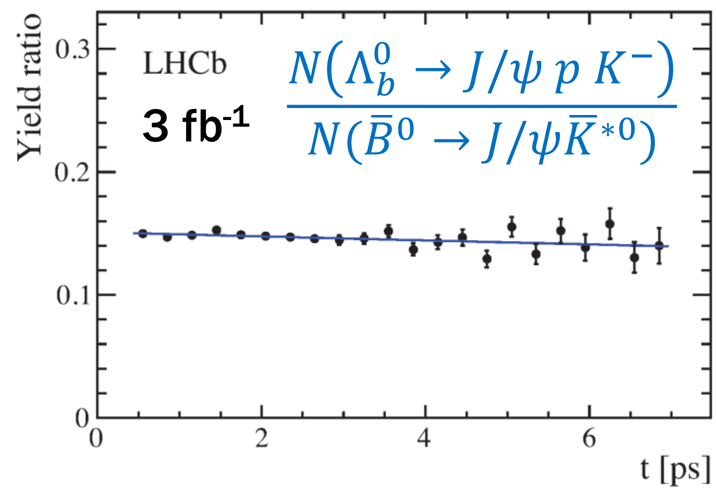
- Charmonium $c\bar{c}(2^3P_1)$: $1.2 \sim 15$ (compatible)
- $D\bar{D}^*$ molecule: $(3-4) \times 10^{-3}$ (not supported)
- Molecule-$c\bar{c}$ mixture: $0.5 \sim 5$ (compatible)

Heavy baryons

- Λ_b lifetime
- Ξ_b and Ω_b lifetime

Λ_b lifetime

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



$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.974 \pm 0.006 \pm 0.004$$

$$\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010 \text{ ps}$$

LHCb PLB 734(2014)122

Λ_b lifetime (cont.)

- Another LHCb measurement using $\Lambda_b \to J/\psi\Lambda$ with 1 fb^{-1}

arXiv:1402.2554

Lifetime	Value [ps]
$\tau_{B^+\to J/\psi K^+}$	$1.637 \pm 0.004 \pm 0.003$
$\tau_{B^0\to J/\psi K^{*0}}$	$1.524 \pm 0.006 \pm 0.004$
$\tau_{B^0\to J/\psi K^0_S}$	$1.499 \pm 0.013 \pm 0.005$
$\tau_{\Lambda_b^0\to J/\psi \Lambda}$	$1.415 \pm 0.027 \pm 0.006$
$\tau_{B_s^0\to J/\psi \phi}$	$1.480 \pm 0.011 \pm 0.005$

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

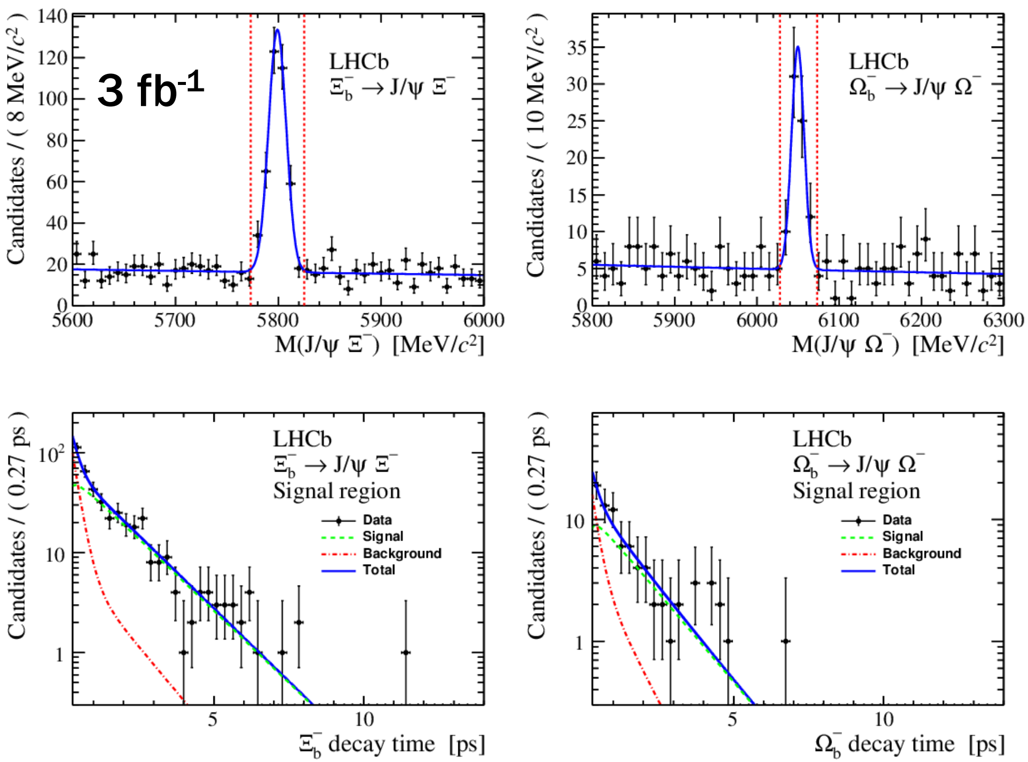
- Combining two Λ_b channels:

$$\tau_{\Lambda_b^0} = 1.468 \pm 0.009 \pm 0.008 \text{ ps}$$

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 $\Xi_b^- \to J/\psi\Xi^-$, and $\Omega_b^- \to J/\psi\Omega^-$
  - $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, $\Omega^- \to \Lambda K^-$, $\Lambda \to p\pi^-$

LHCb: arXiv:1405.1543



$$\tau(\Xi_b^-) = 1.55\,^{+0.10}_{-0.09} \pm 0.03\ \text{ps}$$

$$\tau(\Omega_b^-) = 1.54\,^{+0.26}_{-0.21} \pm 0.05\ \text{ps}$$

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

B_c physics

- Production
- Lifetime
- Decays

Production

- Full reconstruction using $B_c^+ \to J/\psi\pi^+$
- Ratio relative to $B^+ \to J/\psi K^+$ $R_\sigma = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi K^+)}$

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

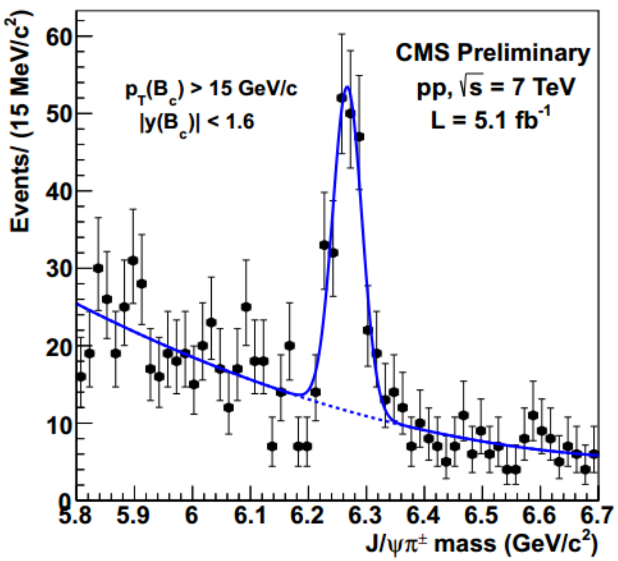
$$R_\sigma = (0.68 \pm 0.10 \pm 0.03 \pm 0.05(\tau_{B_c^+}))\%$$

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



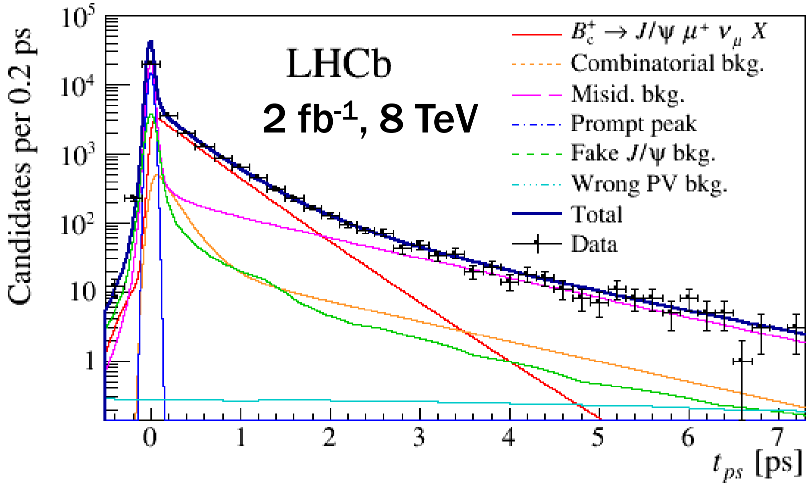
Lifetime

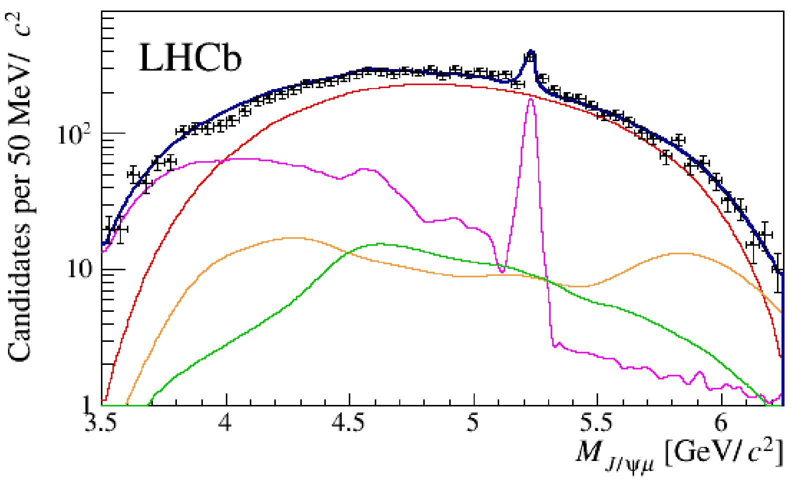
EPJC 74 (2014) 2839

- Semileptonic decay $B_c^+ \to J/\psi\mu^+\nu$
- The most precise measurement

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

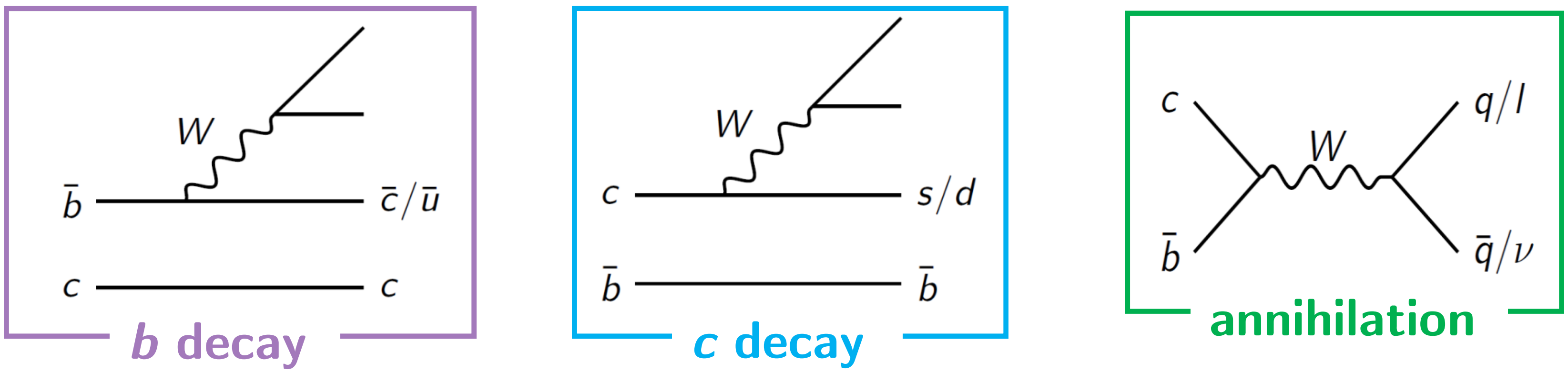
- Further improvement possible by combining with $B_c^+ \to J/\psi\pi^+$ result (uncertainties largely uncorrelated)
- Benefit many other B_c measurements (mass, production, Br...)





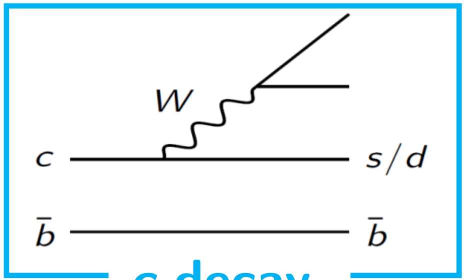
B_c decays

- A large variety of decay modes expected



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

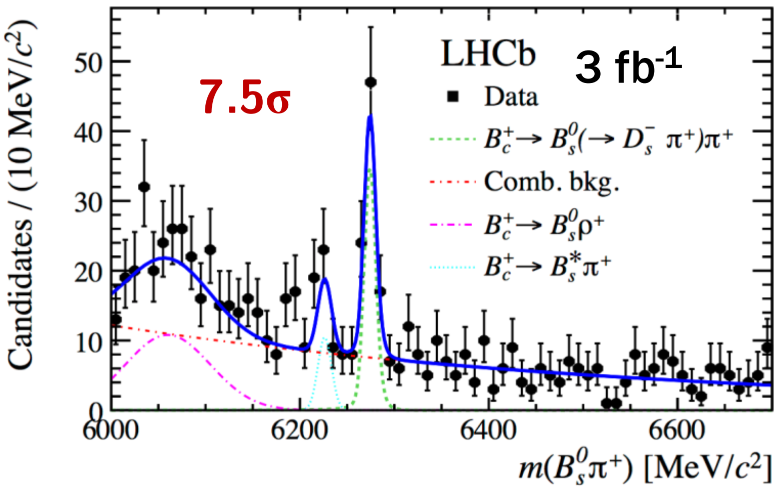
$B_c^+ \to B_s^0 \pi^+$



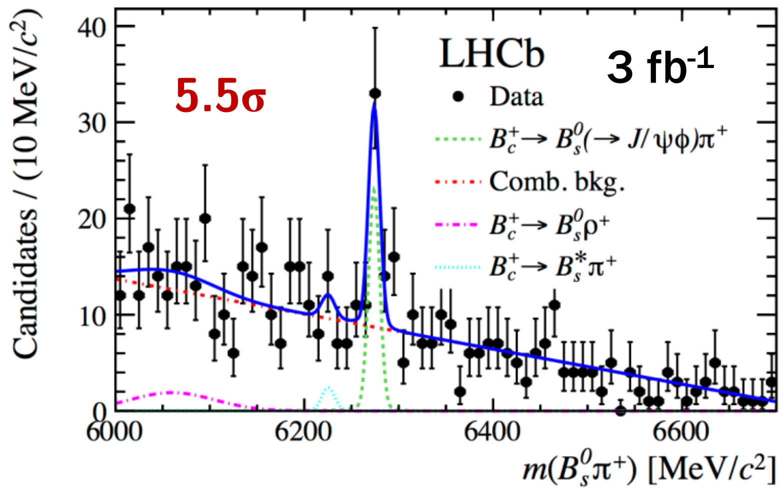
- The first observed c decay in B_c
- $B_s^0 \to D_s^- \pi^+$ or $J/\psi\ \phi$

LHCb PRL 111(2013)181801

$B_c^+ \to B_s^0(\to D_s^- \pi^+)\pi^+$



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



$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31(\text{stat}) \pm 0.11(\text{syst})^{+0.17}_{-0.13}(\tau_{B_c^+})\right) \times 10^{-3}$$

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

b decay in B_c

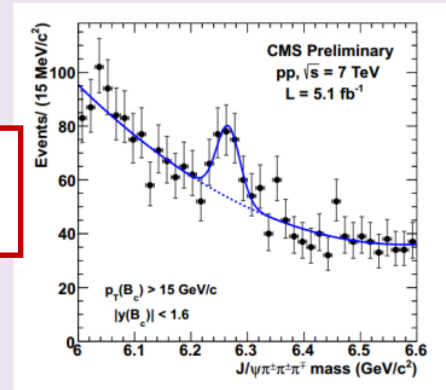
- $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ @ CMS

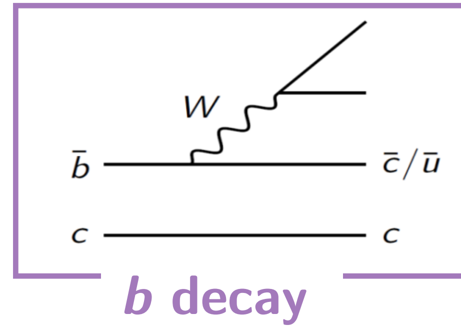
CMS-BPH-12-011

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

Consistent with LHCb result

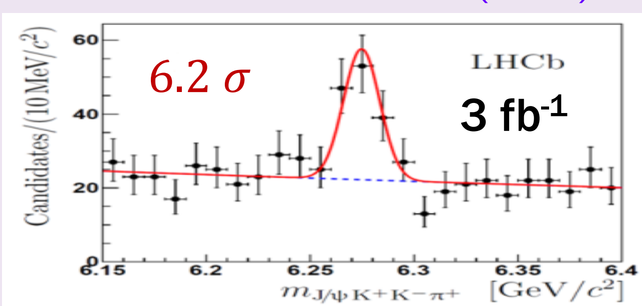
LHCb PRL 108(2012)251802





- $B_c^+ \to J/\psi K^+K^-\pi^+$ @ LHCb

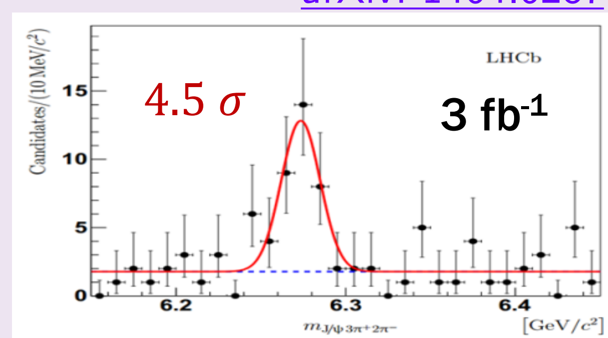
JHEP 1311 (2013) 094



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

- $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ @ LHCb

arXiv: 1404.0287



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

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

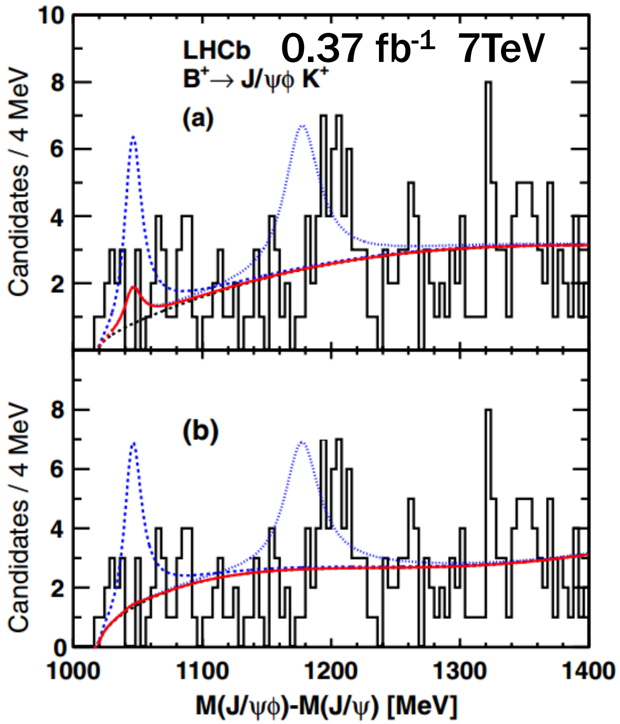
- LHCb measurement at 7 TeV:
- $\sigma_{b\bar{b}} = 75.5 \pm 14.1\ \mu b\ \ (2 < \eta < 6)$ PLB 694, 209
- $\sigma_{c\bar{c}} = 1419 \pm 134\ \mu b\ \ (0 < p_{\mathrm{T}} < 8\ \mathrm{GeV},\ 2.0 < y < 4.5)$

Nucl. Phys. B871, 1

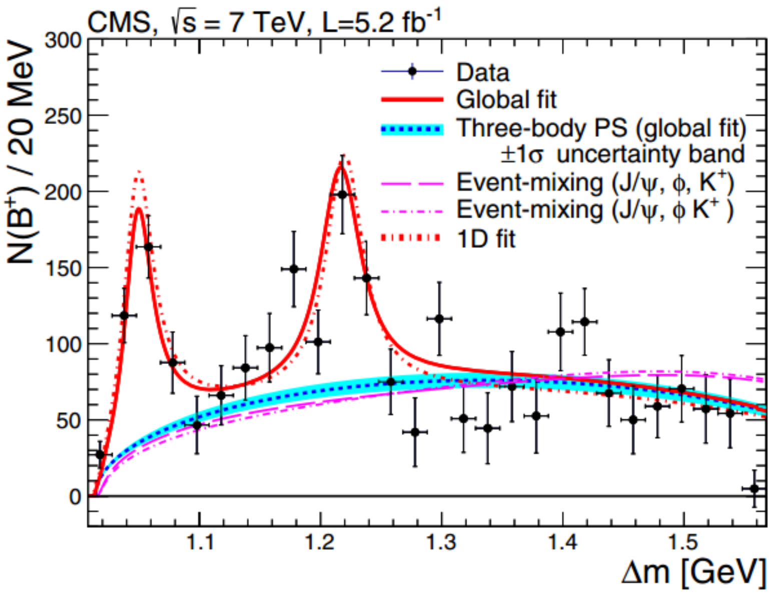
X(4140) searches @ CMS & LHCb

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

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



LHCb PRD 85 (2012) 091103



CMS arXiv:1309.6920

$\psi(4160)$ in $B \to K\mu\mu$

LHCb PRL 111 (2013) 112003

- LHCb observed a broad peaking structure in low recoil region ($M(\mu^+\mu^-)$>3770 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 $B^+ \to \psi(4160)K^+$ and $\psi(4160) \to \mu^+\mu^-$
- X(4260) resonance excluded with $> 4\sigma$
- Contribution in total low-recoil signal ~20%
  - Higher than theoretical prediction (~10%) EPJC 71 (2011) 1635