B decays to Charmonium at LHCb

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on behalf of the LHCb collaboration

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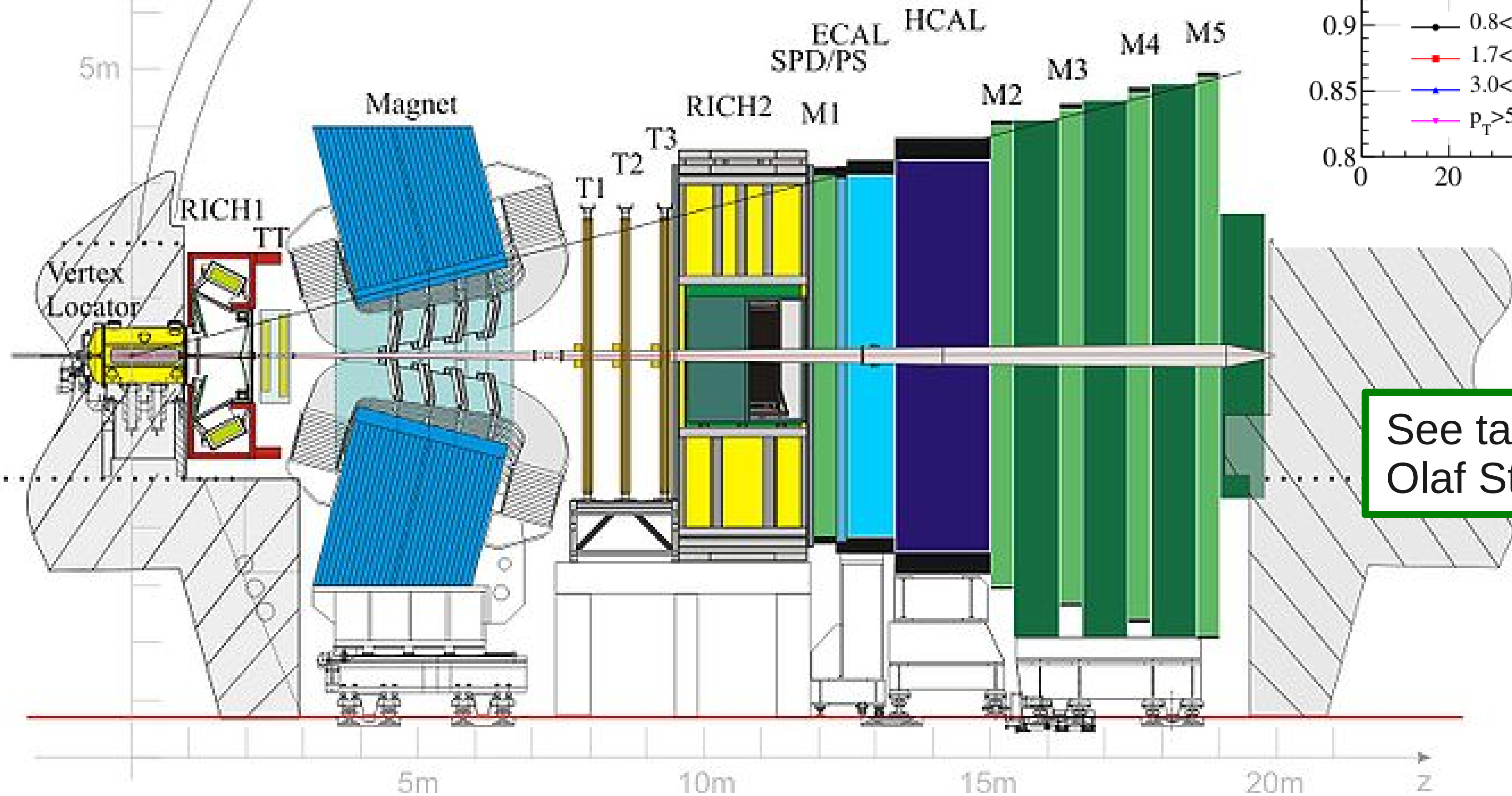
Outline

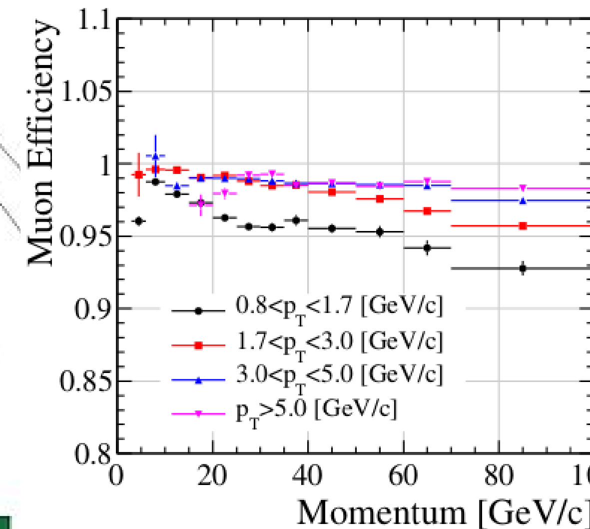
- LHCb detector + B selection
- $B^0 \to J/\psi K^{*0}$ angular analysis
- $B^0_{(s)}$ decays to higher charmonium states ($\psi(2S)$, χ_c) and neutrals
- X(3872) quantum numbers
- B_c^+ decays
- Summary

LHCb detector

Features relevant for $B \to J/\psi X$

- High efficiency single and di-muon trigger
- Good time resolution to select B candidates
- Good muon identification
- Good K/π separation by RICH detectors

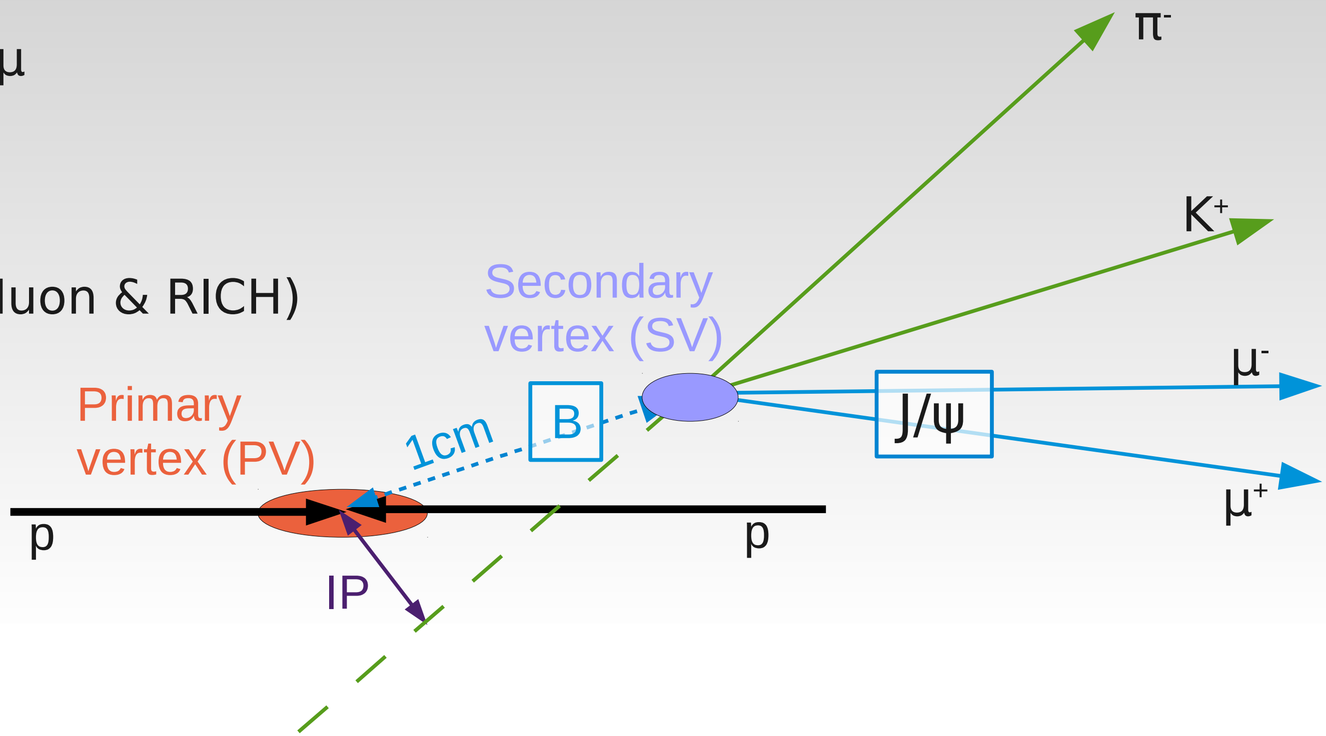




See talk by
Olaf Steinkamp

Selection

- Trigger on detached $\psi \to \mu\mu$
- Good quality tracks
- μ, K, π identification (Muon & RICH)
- Vertex quality
- PV and SV separation
  ($c\tau > x$)



- Daugther particles not from PV
  (cut on IP > 2σ, $p_T > x$)
- B-candidate from the PV
- Decay structure consistent

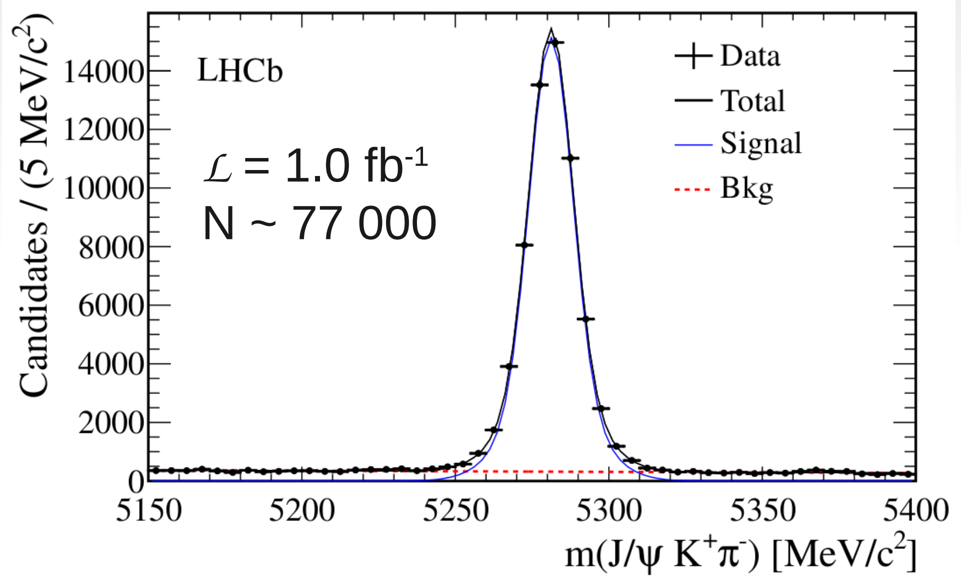
Efficiencies and background:

- Efficiencies from simulation
  (when possible from data – for PID, trigger)
- use sPlot technique to subtract backgound

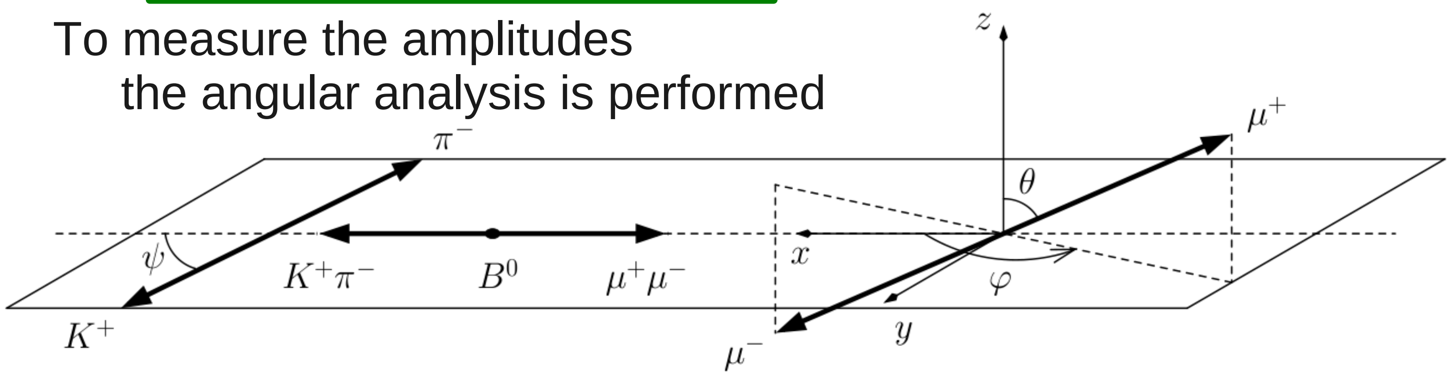
Angular analysis of $B^0 \to J/\psi K^{*0}$

- The decay ($S \to VV$) can be decomposed as
  - P-wave: A_0(longitudial), $A_{||}$(transverse-parallel), $A_{\perp}$(transverse-perpendicular)
  - S-wave: A_s(non-resonant $K\pi$)
  - Strong phases: $\delta_0=0$, $\delta_{||}$, $\delta_{\perp}$ and δ_s
  - Parity: even(A_0, $A_{||}$), odd($A_{\perp}$, A_s)
- Probe BSM contributions, which are approximately equal to those in $B_s \to J/\psi\varphi$ (golden mode for CPV in B_s)

  See talk by Olaf Steinkamp

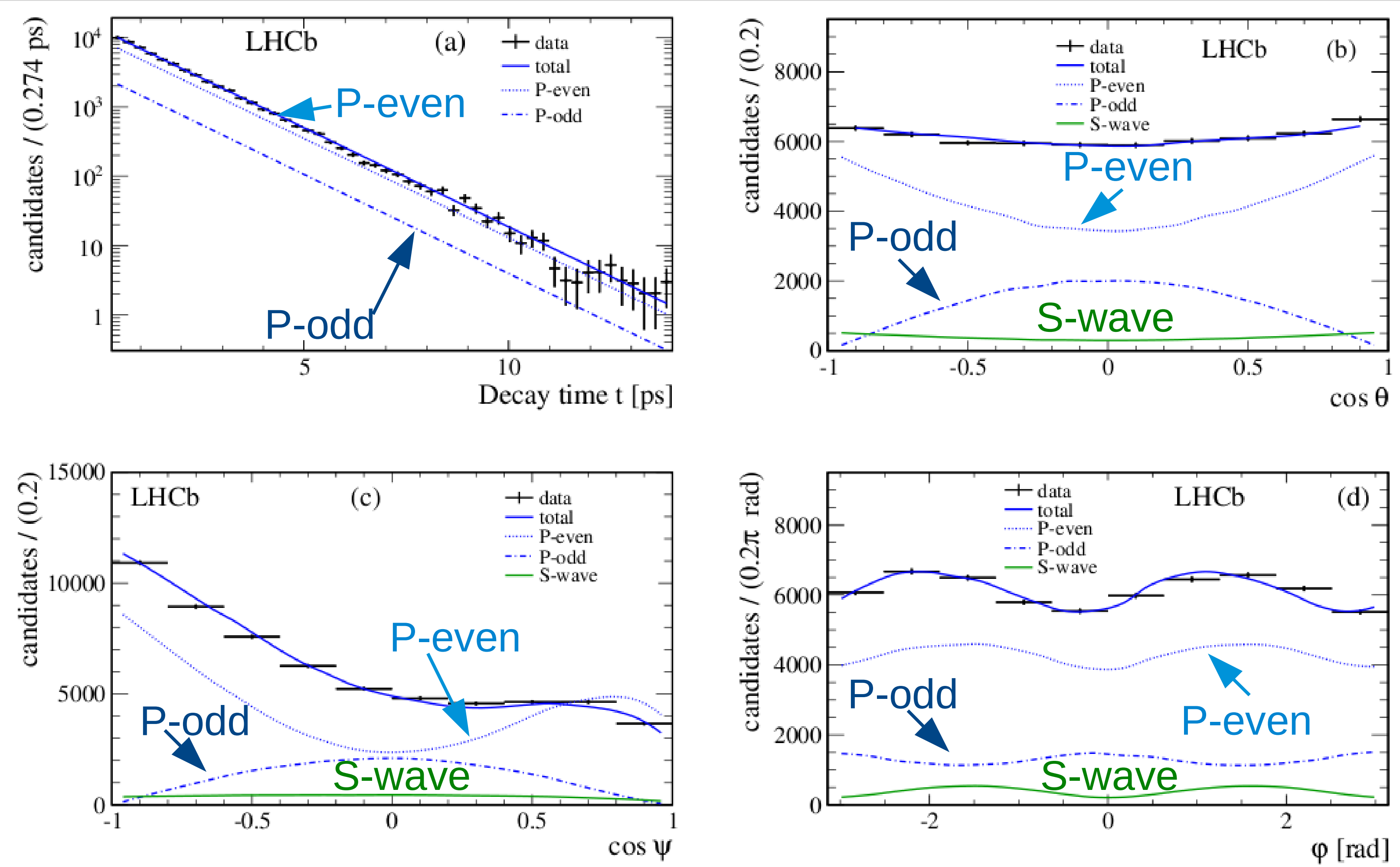


- To measure the amplitudes the angular analysis is performed



arXiv: 1307.2782

Angular analysis of $B^0 \to J/\psi K^{*0}$



Dominant systematic unc.
- acceptance
- contribution from other resonances in Kπ

$$|A_{||}|^2 = 0.227 \pm 0.004 \pm 0.011,$$
$$|A_{\perp}|^2 = 0.201 \pm 0.004 \pm 0.008,$$
$$\sigma_{||}[rad] = -2.94 \pm 0.02 \pm 0.03,$$
$$\sigma_{\perp}[rad] = 2.94 \pm 0.02 \pm 0.02$$

Consistent with previous measurements and SM predictions

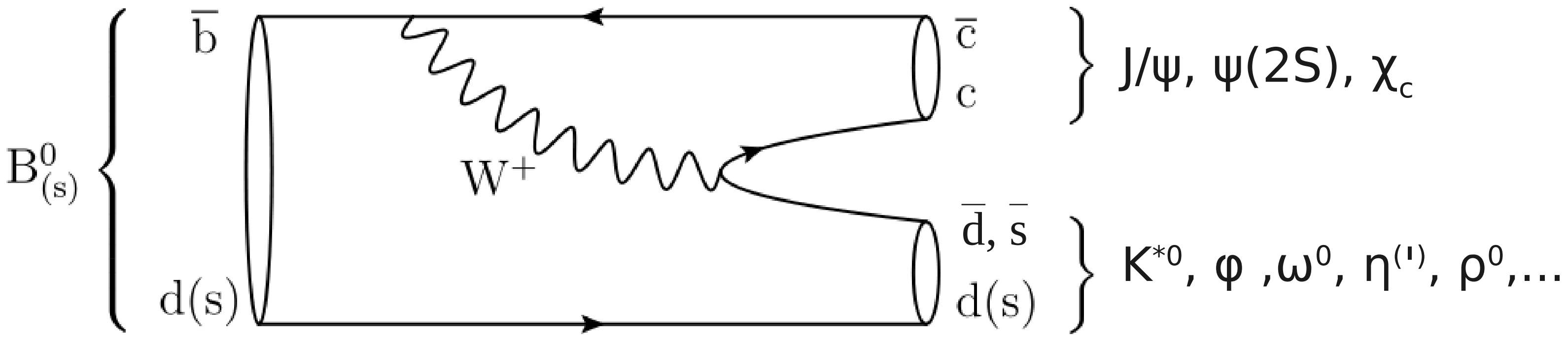
arXiv: 1307.2782

B decays to charmonium

- Crucial role in CP violation studies [see talk of Olaf Steinkamp]

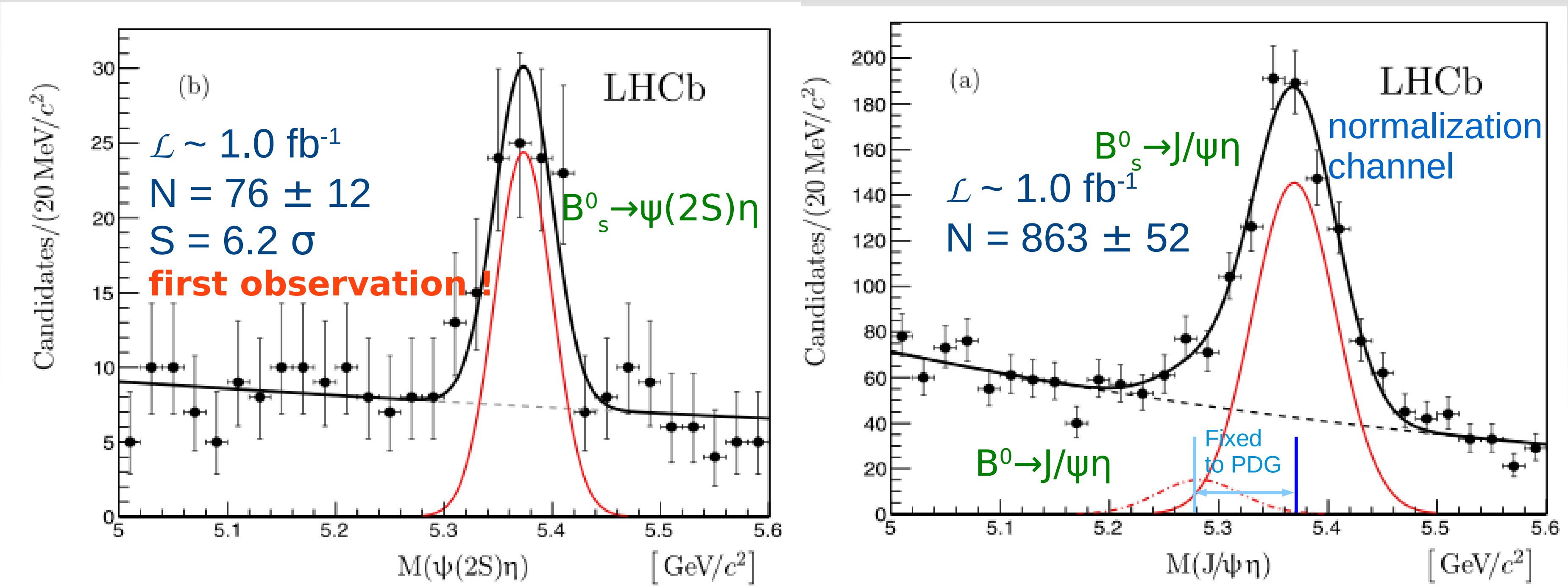
  & precise measurement of neutral B mixing parameters

  - new possible channels for CPV studies in B^0_s
- Sensitive labarotary for electro-weak transition studies
- Direct probe of charmonium properties
- Study light quarks



Observation of $B^0_s \to \psi(2S)\eta$

- $B^0_s \to J/\psi\eta$ has been previously seen by Belle [PRL 108 (2012) 181808] and LHCb [NPB 867 (2013) 547]



- Similar study for $B^0 \to \psi(2S)\pi\pi$ and $B^0_s \to \psi(2S)\pi\pi$
- Explore intermediate resonance structure with sPlot

Dominant systematics: efficiencies from simulation

$$\frac{BR(B^0_s \to \psi(2S)\eta)}{BR(B^0_s \to J/\psi\eta)} = 0.83 \pm 0.14\,(stat) \pm 0.12\,(syst) \pm 0.02\,(BR_{\psi\to\mu^+\mu^-})$$

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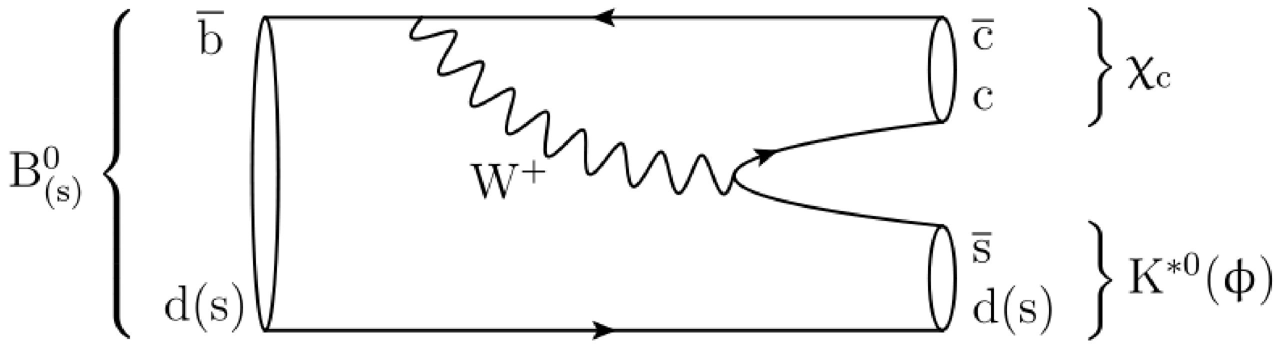
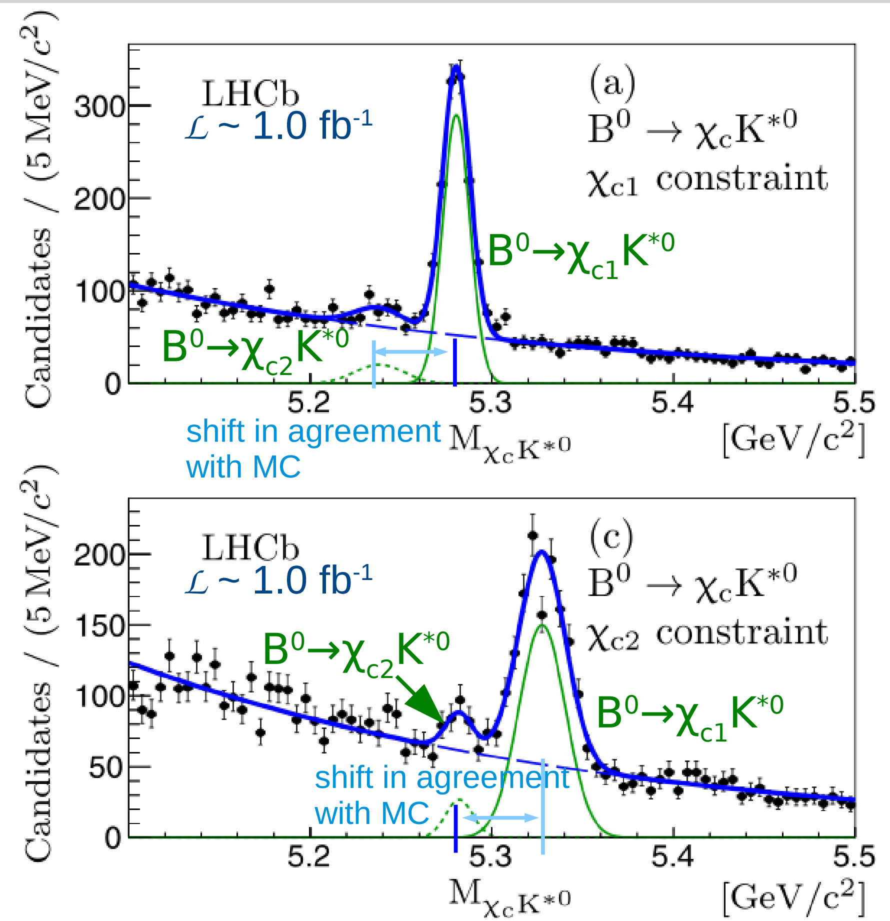
Study of $B^0_{(s)} \to \chi_{c1,2} K^{*0}(\varphi)$

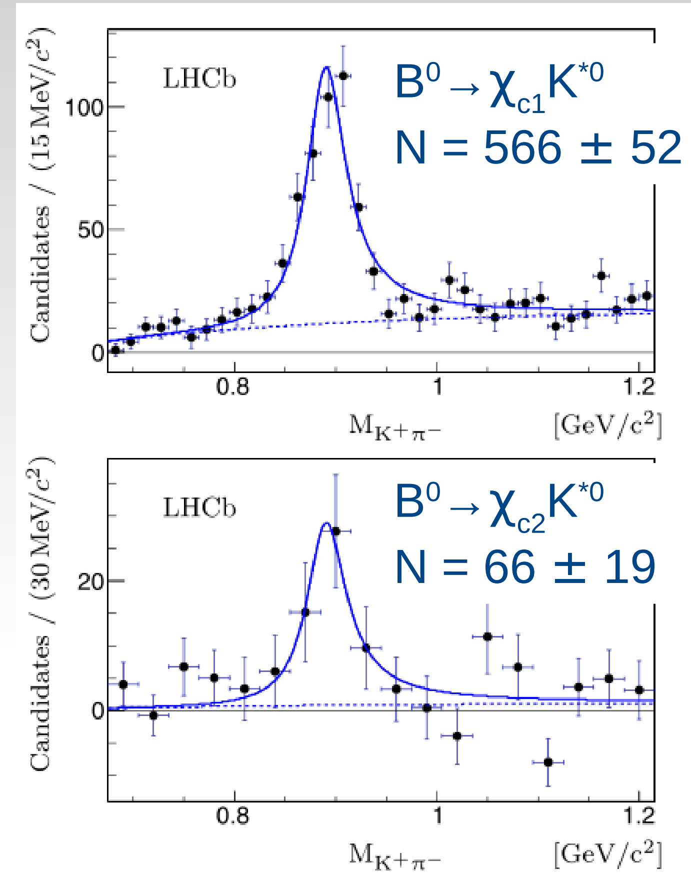
- In factorization approach $B \to \chi_{c0,2} K(\varphi)$ decay modes are expected to be suppressed with respect to $B \to \chi_{c1} K(\varphi)$
- But the measured $\mathcal{BR}(B^0 \to \chi_{c0} K^{*0}) = (1.7 \pm 0.3 \pm 0.2) \mathrm{x} 10^{-4}$ [BaBar, PR D78 (2008) 0911001]
  is compatible with $\mathcal{BR}(B^0 \to \chi_{c1} K^{*0}) = (2.5 \pm 0.2 \pm 0.2) \mathrm{x} 10^{-4}$ [BaBar, PRL 102 (2009) 132001]
  and $\mathcal{BR}(B^0 \to \chi_{c1} K^{*0}) = (1.73^{+0.15}_{-0.12}{}^{+0.34}_{-0.22}) \mathrm{x} 10^{-4}$ [Belle, PR D78 (2008) 072004]
- While $\mathcal{BR}(B^0 \to \chi_{c2} K^{*0}) = (6.6 \pm 1.8 \pm 0.5) \mathrm{x} 10^{-5}$ [BaBar, PRL 102 (2009) 132001] can still be explained in factorization approach
- The $B^0_s \to \chi_c \varphi$ have not been previously observed



Study of $B^0 \to \chi_{c1,2} K^{*0}$



Background subtraction (sPlot)



- Constraint $J/\psi\gamma$ mass to $\chi_{c1,2}$ to resolve two peaks
  → mass shift in agreement with simulation

$$\frac{BR(B^0 \to \chi_{c1} K^{*0})}{BR(B^0 \to J/\psi K^{*0})} = (19.8 \pm 1.1(stat) \pm 1.2(syst) \pm 0.9(BR_{\chi_c \to J/\psi\gamma})) \times 10^{-2}$$

$$\frac{BR(B^0 \to \chi_{c2} K^{*0})}{BR(B^0 \to \chi_{c1} K^{*0})} = (17.1 \pm 5.0(stat) \pm 1.7(syst) \pm 1.1(BR_{\chi_c \to J/\psi\gamma})) \times 10^{-2}$$

<u>Dominant systematic</u>:
- signal determination
- photon reconstruction

Compatible with previous measurements, but more precise

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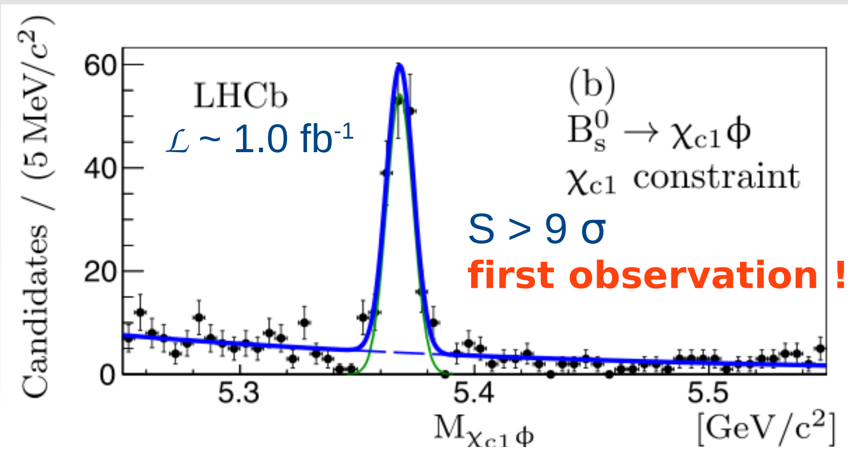
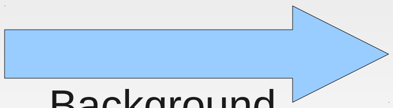
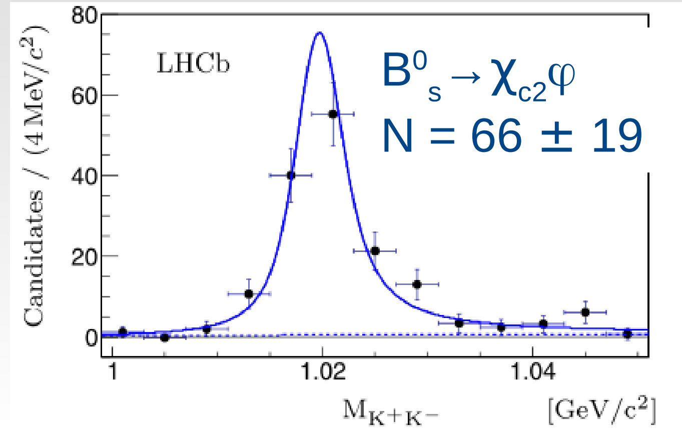
Study of $B^0_s \to \chi_{c1,2}\varphi$







- Measure branching ratio relatively to $B^0_s \to J/\psi\varphi$

<u>Dominant systematic</u>:
- signal determination
- photon reconstruction

$$\frac{BR(B^0_s \to \chi_{c1}\phi)}{BR(B^0_s \to J/\psi\phi)} = (18.9 \pm 1.8(stat) \pm 1.3(syst) \pm 0.8(BR_{\chi_c \to J/\psi\gamma})) \times 10^{-2}$$

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X(3872) quantum numbers

X(3872) was discovered by Belle in 2003 [PRL 91 (2003) 262001], but it's nature still unclear

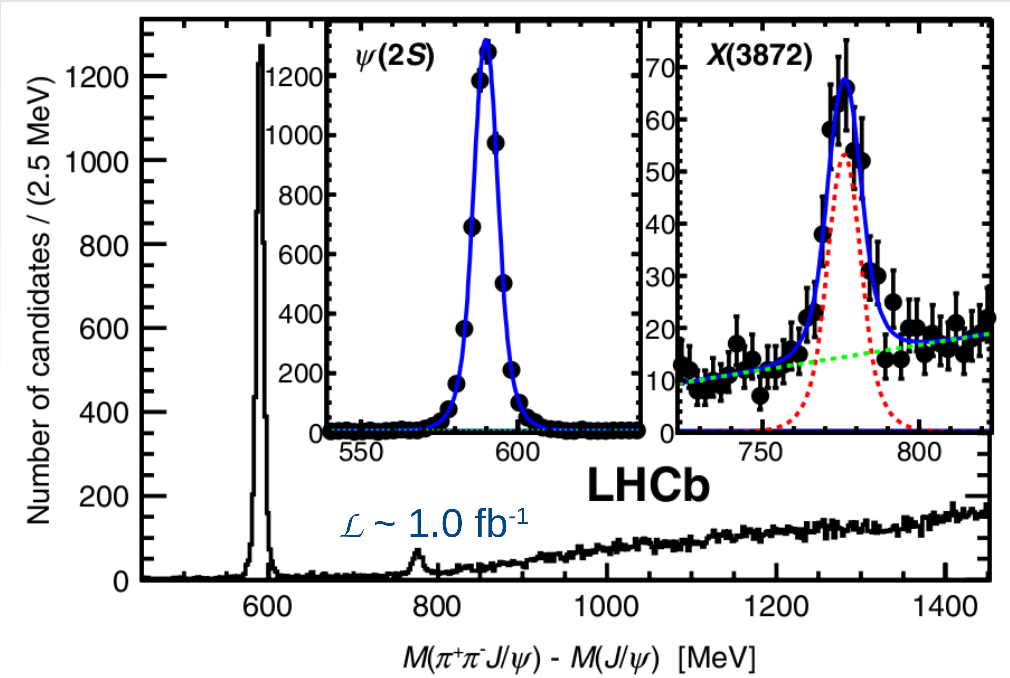
- C-parity = +1 since $X(3872) \to J/\psi\gamma$ is observed
- CDF excluded all J^{PC} combinations except 1^{++} and 2^{-+} [PRL 98 (2007) 132002]
- BaBar favoured 2^{-+} (68% CL) by studying $X(3872) \to J/\psi\omega^0$, but not ruled out 1^{++} (7% CL) [PRD 82 (2010) 011101]
- Belle couldn't distinguish 1^{++} and 2^{-+} by analysing 1D distributions [PRD 84 (2011) 052004]

Determination of quantum numbers is crucial for the interpretation of the state

- 1^{++}: molecular, tetraquark, $\chi_c(2^3P_1)$?
- 2^{-+}: $\eta_c(1^1D_2)$?

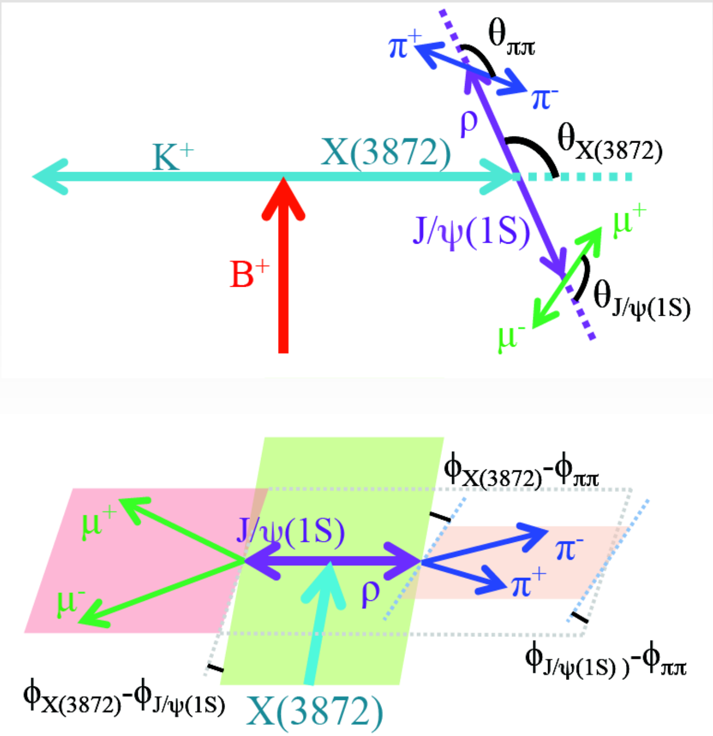
X(3872) quantum numbers

- 5-D angular analysis of $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$



$B^+ \to \psi(2S)K^+$, N = 5642±76
$B^+ \to X(3872)K^+$, N = 313±26

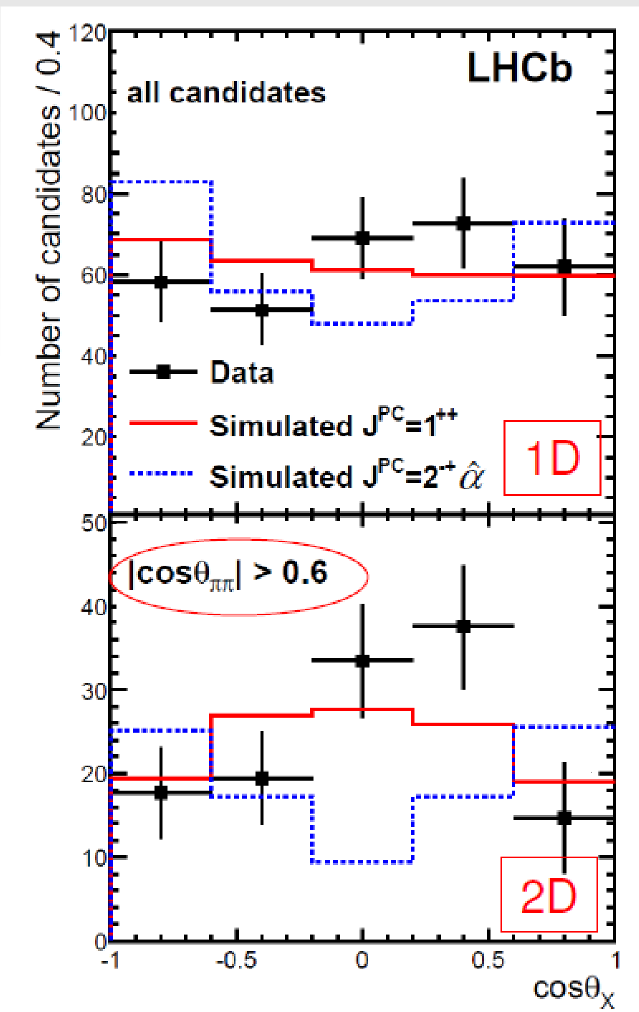
- Angular distributions carry information about J^{PC}



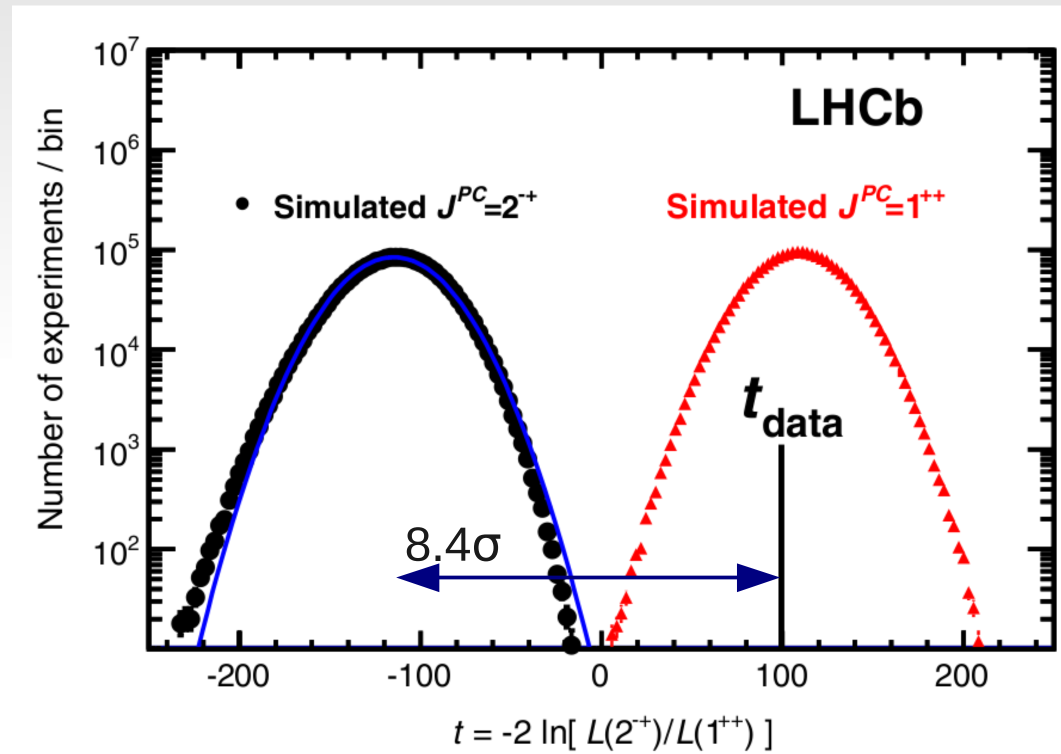
Phys. Rev. Let. 110, 222001 (2013)

X(3872) quantum numbers

- Angular correlations magnify differences between spin hypothesis:



- Likelihood-ratio test to discriminate between to hypothesis $t = -2\ln[\mathcal{L}(2^{-+})/\mathcal{L}(1^{++})]$
- Compare with simulated statistics



Result:
2^{-+} is rejected with 8.4σ,
with p-value for 1^{++} of 34%

Phys. Rev. Let. 110, 222001 (2013)

B_c decays

- The B_c meson, composed of two heavy quarks ($b\bar{c}$), is a unique, being the only weak decaying heavy quarkonium system

- Prior to LHCb only the $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$ decays were observed

- At LHCb $f(\bar{b} \to B_c^+) \sim 1/1000$

- LHCb has already observed new decay mode:
  $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ [PRL 108 (2012) 251802]

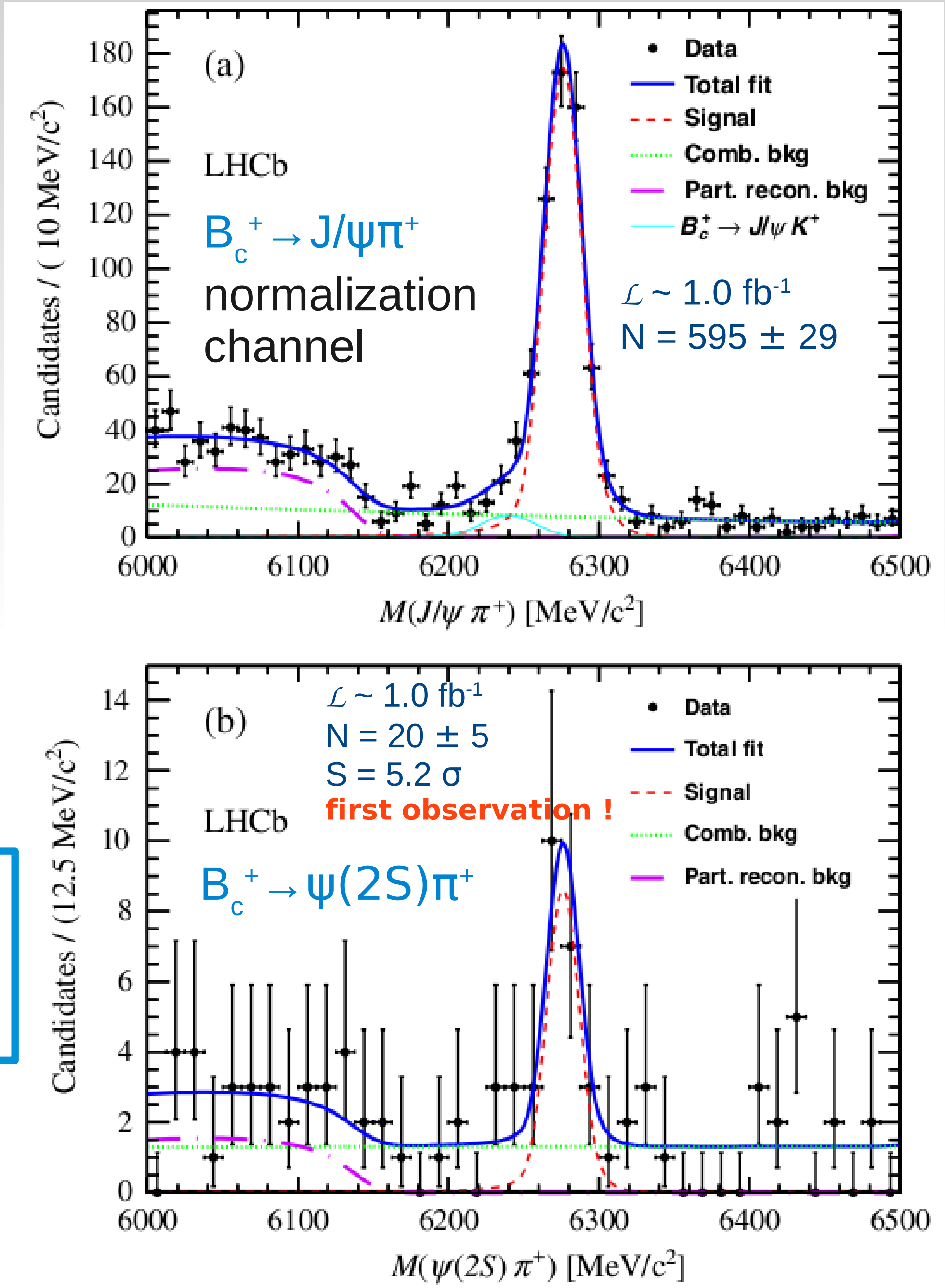
- Four more new decay modes in this summer → see next

$B_c^+ \to \psi(2S)\pi^+$

- Test different theoretical models for B_c^+ decays
- Analysis strategy:
  - multivariate selection (BDT) to supress background
  - $B_c^+ \to J/\psi\pi^+$ as normalization channel
- Dominant syst:
  - understanding of the BDT selection
  - background shape

$$BR(B_c^+ \to \psi(2S)\pi^+)/BR(B_c^+ \to J/\psi\pi^+) = 0.250 \pm 0.068(stat) \pm 0.014(syst) \pm 0.006(BR)$$

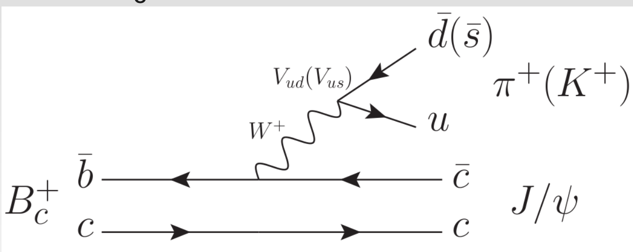
- The result favours relativistic quark model prediction with respect to the others



Phys. Rev. D 87, 071103(R) (2013)

$B_c^+ \to J/\psi K^+$

- The branching fraction relative to $B_c^+ \to J/\psi\pi^+$ is measured



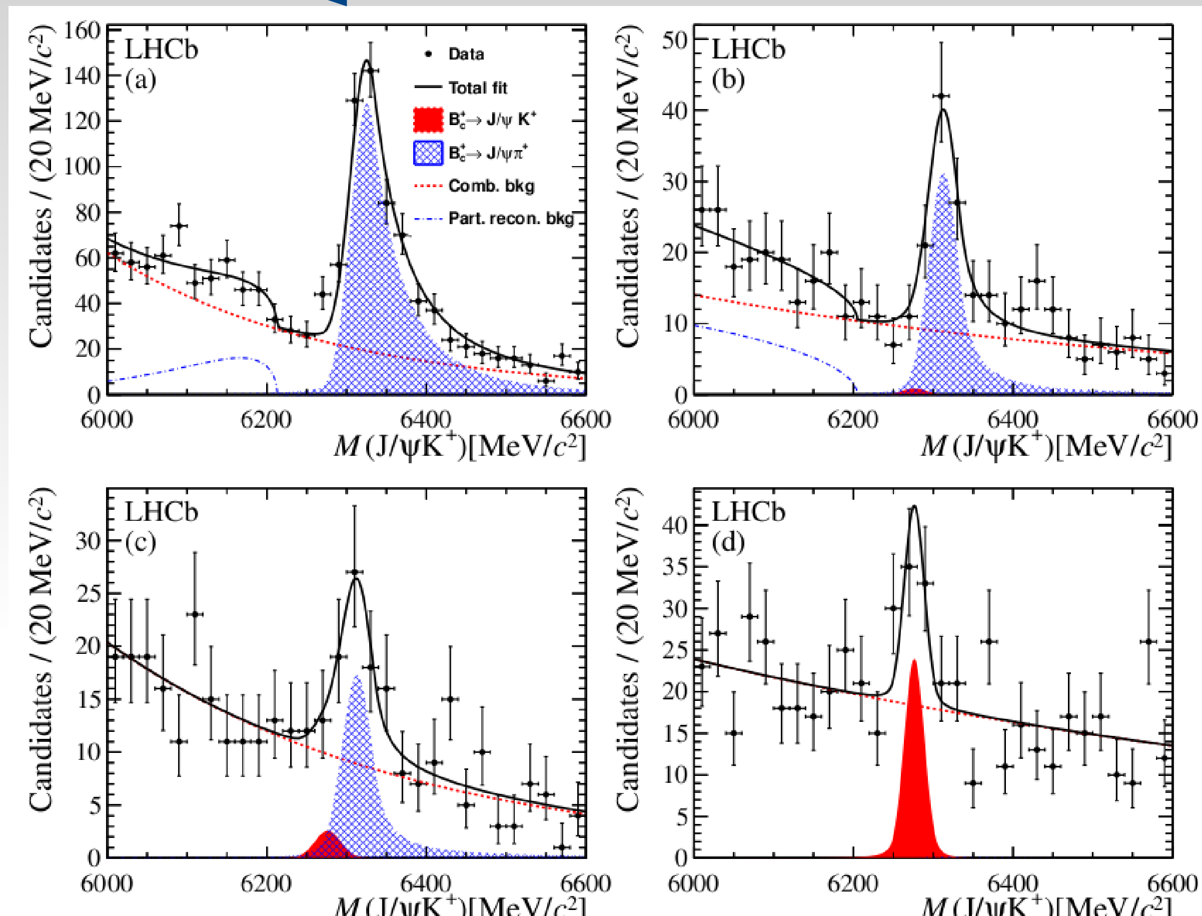
- Naive expectation:

$$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} \approx \left|\frac{V_{us} f_{K^+}}{V_{ud} f_{\pi^+}}\right|^2 = 0.077$$

- Theoretical predictions lie within 0.054 – 0.088 range → test hadronization model

- Analysis strategy:
  - Multivariate selection (BDT)
  - bins of discriminating K–π identification variable

pion-like



kaon-like

$\mathcal{L} \sim 1.0\ \mathrm{fb}^{-1}$
N = 46 ± 14
S = 5.0 σ
first observation !

$$\frac{BR(B_c^+ \to J/\psi K^+)}{BR(B_c^+ \to J/\psi \pi^+)} = 0.069 \pm 0.019 \pm 0.005$$

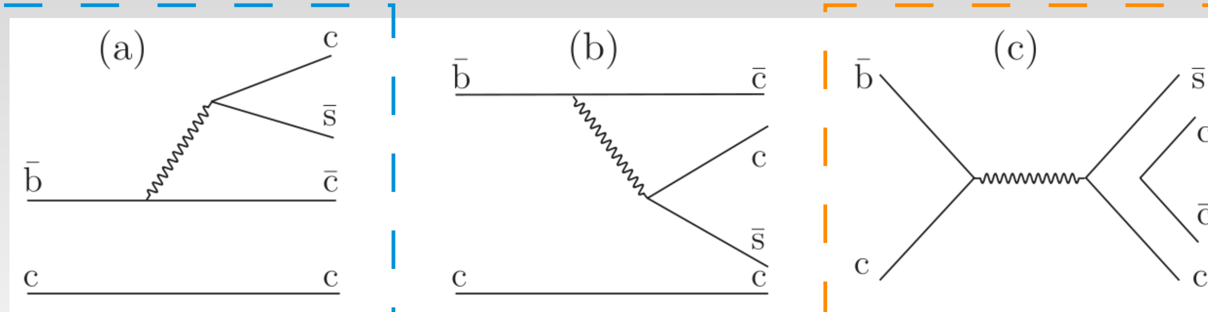
Dominant systematic:
- understanding of the BDT selection

arXiv:1306.6723

$B_c^+ \to J/\psi D_s^{+(*)}$

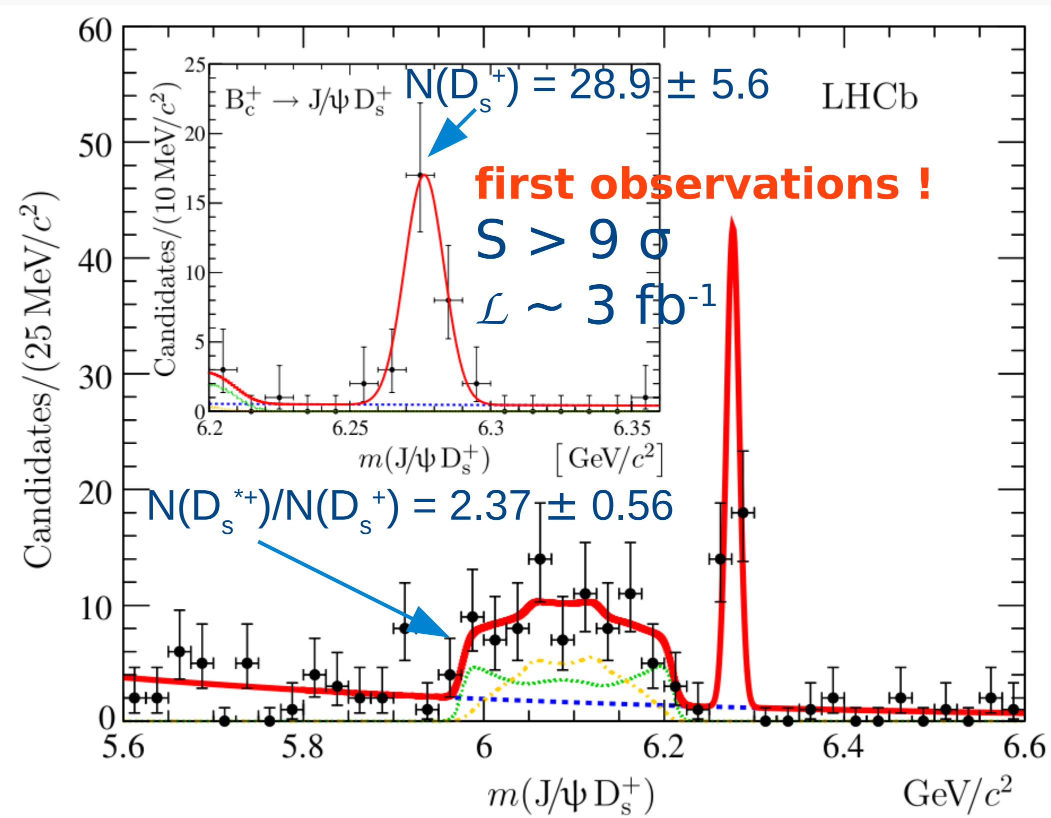
- The branching fraction relative to $B_c^+ \to J/\psi\pi^+$ is measured
- Three leading contributions
- Test assumption that spectator one dominates & factorization holds
- Low energy release allows precision mass measurement

can contribute in contrast to decays of other B mesons



$$\frac{BR(B_c^+ \to J/\psi D_s^+)}{BR(B_c^+ \to J/\psi \pi^+)} = 2.90 \pm 0.57(stat) \pm 0.24(syst)$$

$$\frac{BR(B_c^+ \to J/\psi D_s^{*+})}{BR(B_c^+ \to J/\psi D_s^+)} = 2.37 \pm 0.56(stat) \pm 0.10(syst)$$



- Compatible with naive expectations from $B \to D^* D_s^{(*)+}(\pi^+)$ decays

$$m_{B_c^+} = 6276.28 \pm 1.44(stat) \pm 0.36(syst)\ MeV/c^2$$

- In agreement with PDG (2013 update): $m(B_c^+) = 6274.5 \pm 1.8\ MeV/c^2$

Phys. Rev. D 87, 112012 (2013)

Conclusion

LHCb shows excellent performance in measuring B decays to charmonia

- Provide input for measurements of CPV and mixing in B mesons
- Explore charmonium properties

- Serie of new decays observed ($B^0_s \to \psi(2S)\eta$, $B^0_s \to \chi_{c1}\varphi$, $B_c^+ \to \ldots$)
- X(3872) quantum numbers determined to be 1^{++}
- Study of properties and observe new decays of the B_c^+ meson
  ($B_c^+ \to J/\psi K^+$, $B_c^+ \to J/\psi D_s^{(*)+}$)

- Plus many other analysis, for instance
  - Precision measurement of Λ_b lifetime [arXiv:1306.6723]
  - First upper limits on $\mathcal{BR}(B^0_s \to J/\psi p\bar{p})$ and $\mathcal{BR}(B^+ \to J/\psi p\bar{p}\pi^+)$ [arXiv: 1306.4489]
  - ...

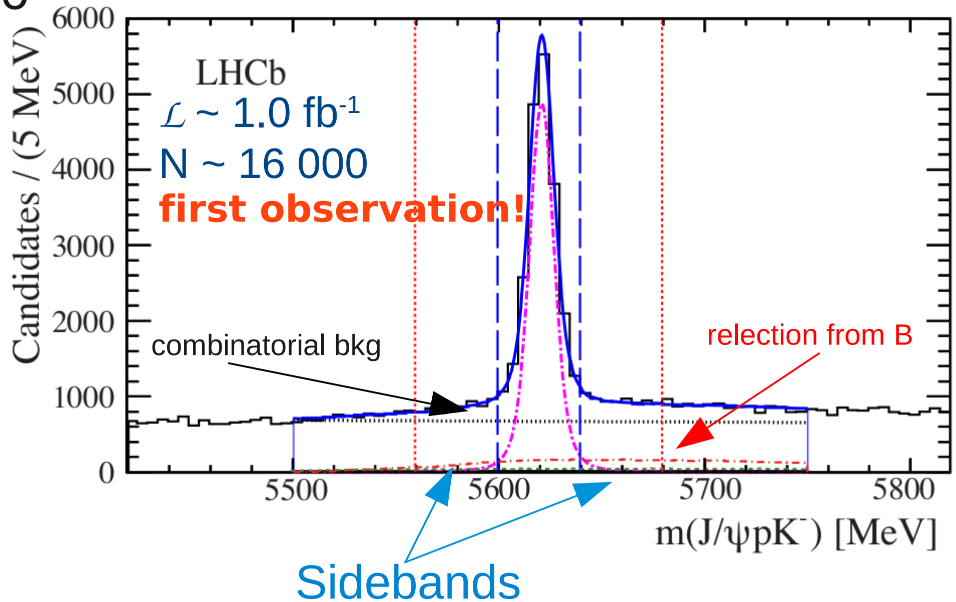
Thank you!

Backup

Λ_b lifetime

- According to Hevay Quark Expansion model $\tau(\Lambda_b)/\tau(B) \simeq 1$ with difference only a few persent expected
- Average experimental give 0.798 ± 0.052 [arXiv:hep-ph/0304132]
  0.786 ± 0.034 [arXiv:hep-ph/0310241, arXiv:hep-ph/0203089]
- Precision measurement is necessary

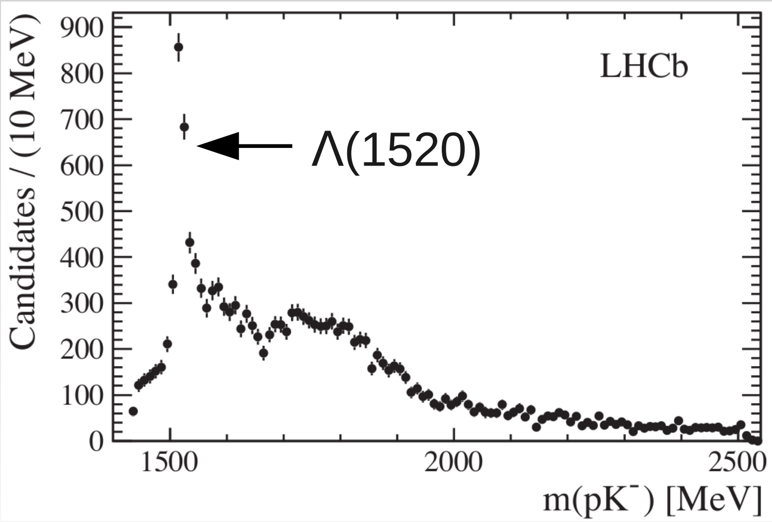
- Strategy:
  - Use similar decay modes $\Lambda_b \to J/\psi p K^-$ and $B \to J/\psi \pi^+ K^-$ → systematic uncertainty cancels in the ratio
  - BDT
  - Sideband to subtract background



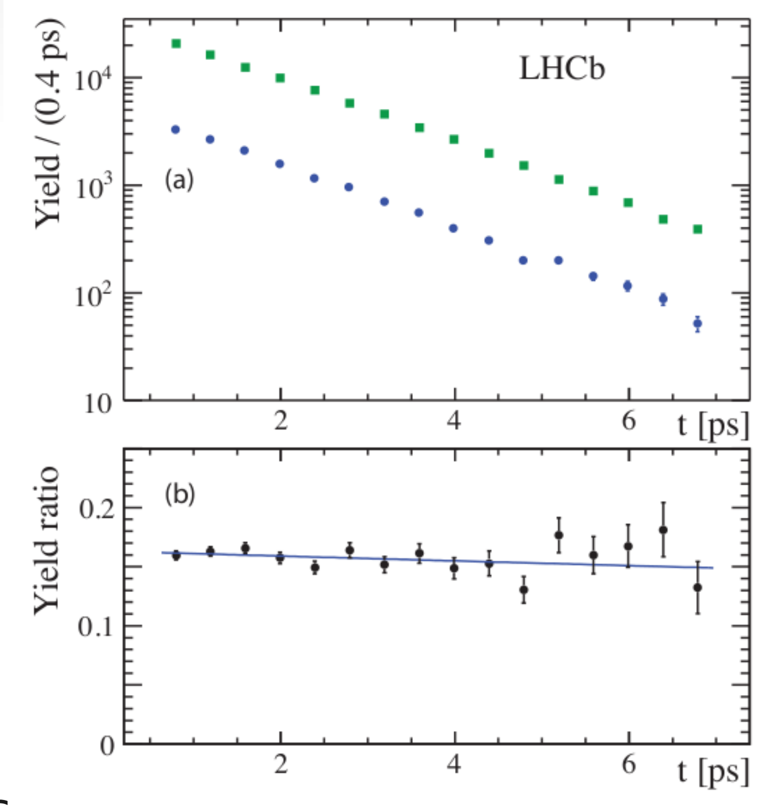
arXiv:1306.6723

Λ_b lifetime

- Use whole pK mass region
- Decay time acceptance from simulation
  weighted to match pK(πK) mass distribution
- Determine $\Delta_{\Lambda B} = \frac{1}{\tau_\Lambda} - \frac{1}{\tau_B}$ from ratio of yields



- Dominant uncertainty:
  – decay time fit range
  – acceptance slope



$$\frac{\tau_{\Lambda_b^0}}{\tau_{\overline{B}^0}} = \frac{1}{1+\tau_{\overline{B}^0}\Delta_{\Lambda B}} = 0.976 \pm 0.012 \pm 0.006$$

$$\tau_{\Lambda_b^0} = 1.482 \pm 0.018 \pm 0.012 \text{ ps}$$

- In agreement with HQE expectation of $\tau(\Lambda_b)/\tau(B) = 1$
- Consistent with, but more precise than,
  current world average: $\tau(\Lambda_b) = 1.429 \pm 0.024$ ps

arXiv:1306.6723

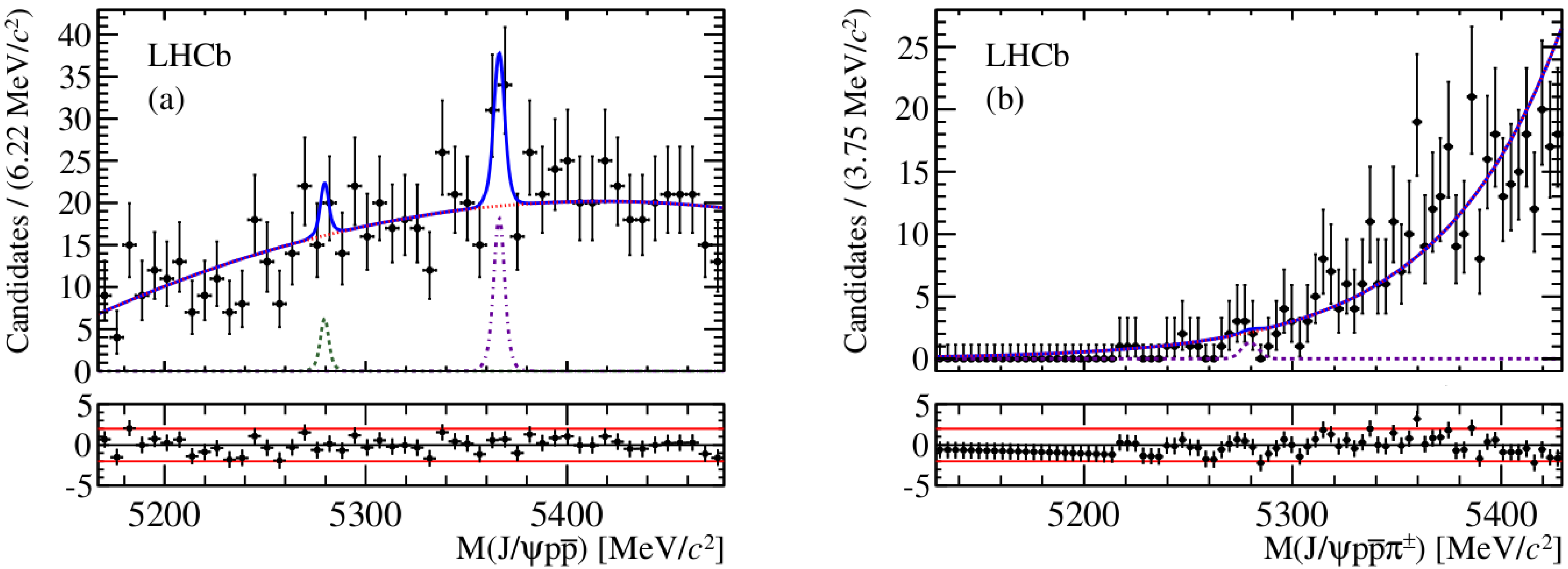
B decays to charmonia and dibaryons

- The study of such decays has not been extensively explored mainly due to the suppressed branching fractions of typically O(<10^{-5})
- Dibaryon production in B meson decays has been studied in decays $B^+ \to K^+ p\overline{p}$ or $B^0 \to \overline{D}^0 p\overline{p}$
- Branching fraction is ~10% that of the corresponding decay with pp replaced by $\pi^+\pi^-$
- In contrast

$$BR\left(B^0 \to J/\psi\,\pi^+\pi^-\right) = \left(4.6 \pm 0.9\right) \times 10^{-5}$$
$$BR\left(B^0 \to J/\psi\, p\overline{p}\right) < 8.3 \times 10^{-7}$$

~ 50 times difference

$B^0_{(s)} \to J/\psi p\bar{p}$ and $B^+ \to J/\psi p\bar{p}\pi^+$



No significant signals are seen

$$BR(B^0 \to J/\psi\, p\,\bar{p}) < 5.2(6.0) \times 10^{-7} \quad @90\%(95\%)\,CL$$

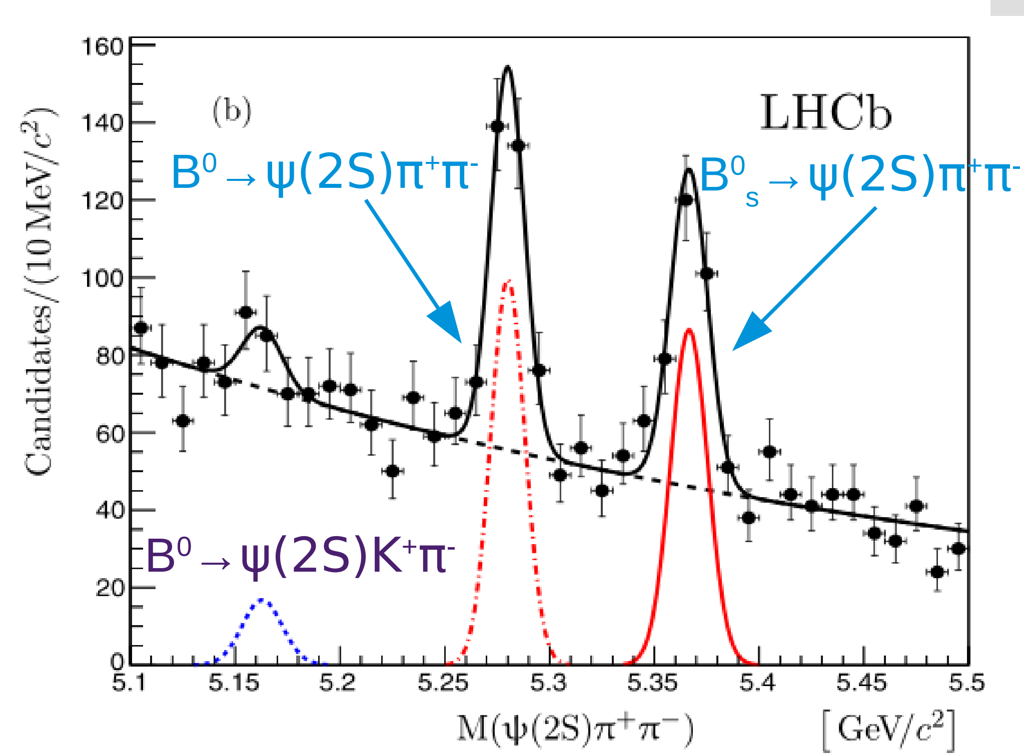
$$BR(B^0_s \to J/\psi\, p\,\bar{p}) < 4.8(5.3) \times 10^{-6} \quad @90\%(95\%)\,CL$$

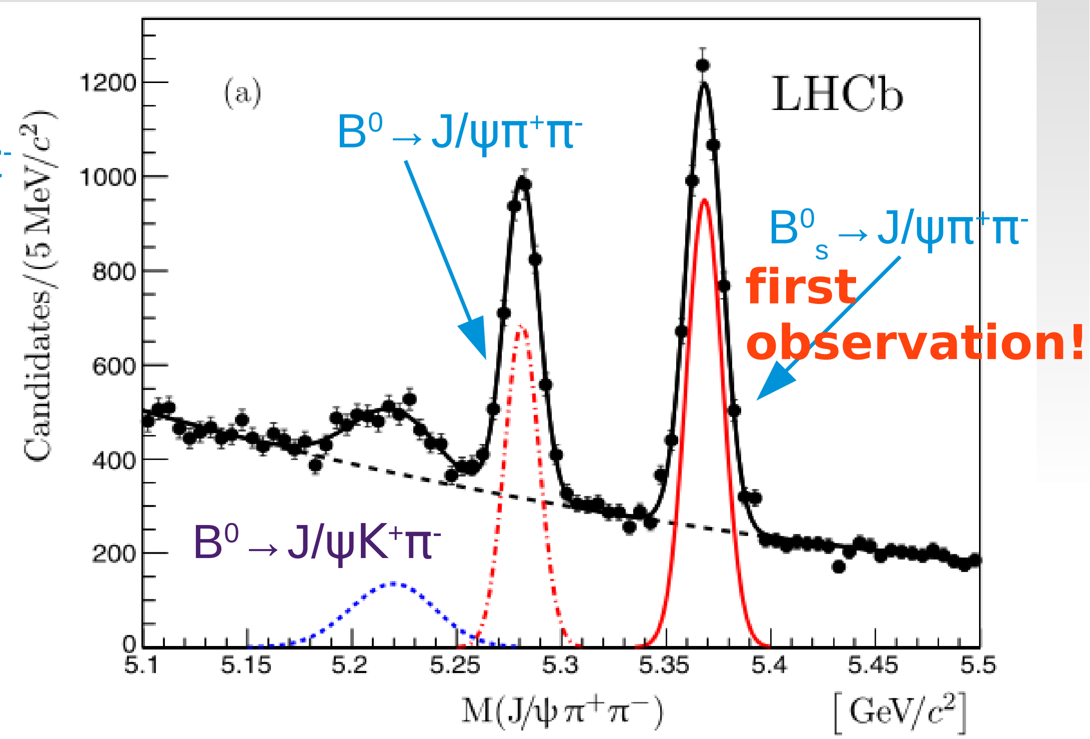
$$BR(B^+ \to J/\psi\, p\,\bar{p}\,\pi^+) < 5.0(6.1) \times 10^{-7} \quad @90\%(95\%)\,CL$$

first limits!

arXiv: 1306.4489

Observation of $B^0_{(s)} \to \psi(2S)\pi^+\pi^-$





$$\frac{BR(B^0 \to \psi(2S)\pi^+\pi^-)}{BR(B^0 \to J/\psi\pi^+\pi^-)} = 0.56 \pm 0.07(stat) \pm 0.05(syst) \pm 0.01(BR_{\psi \to \mu^+\mu^-})$$

$$\frac{BR(B^0_s \to \psi(2S)\pi^+\pi^-)}{BR(B^0_s \to J/\psi\pi^+\pi^-)} = 0.34 \pm 0.04(stat) \pm 0.03(syst) \pm 0.01(BR_{\psi \to \mu^+\mu^-})$$

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