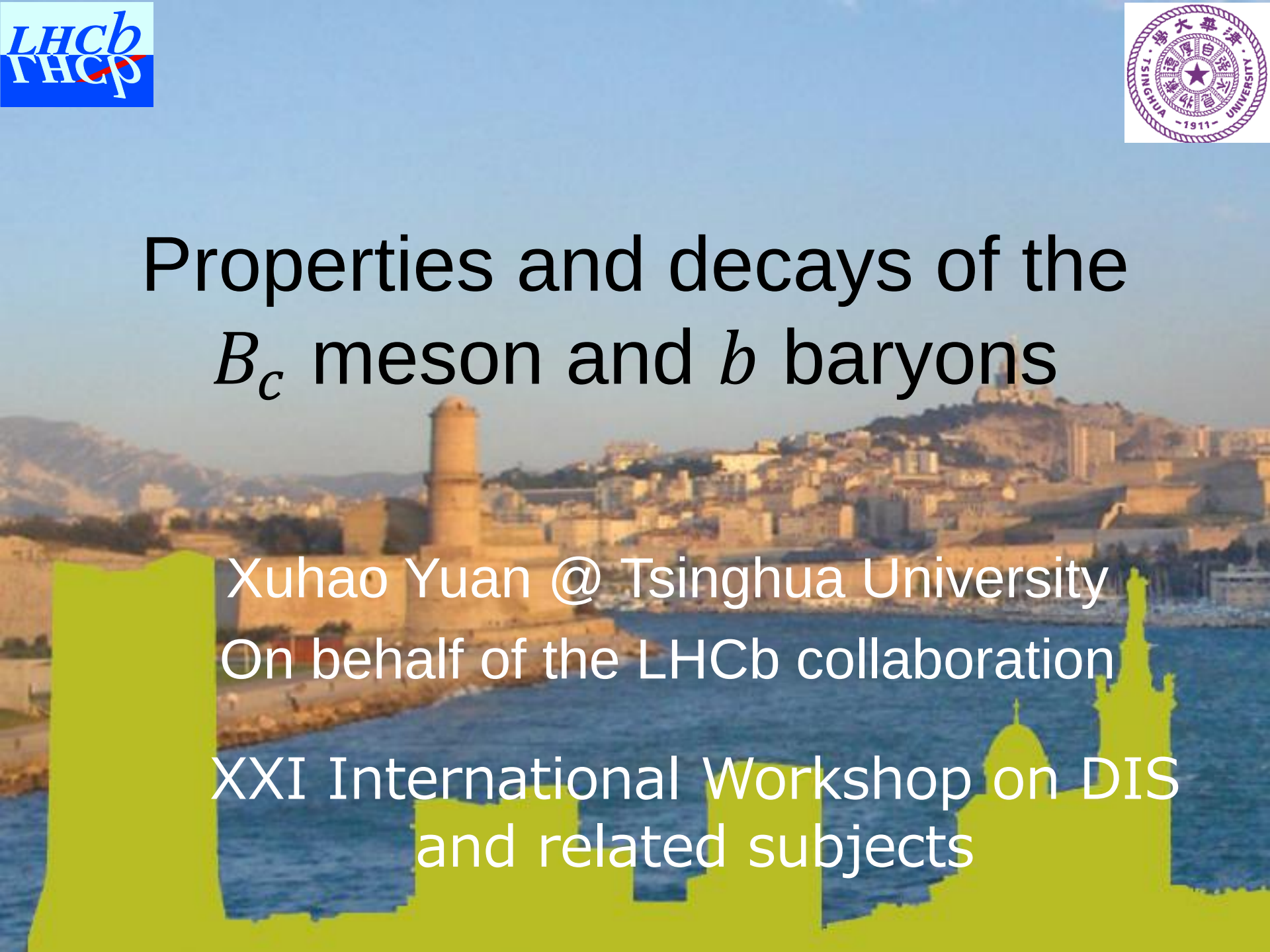


Properties and decays of the B_c meson and b baryons

Xuhao Yuan @ Tsinghua University

On behalf of the LHCb collaboration

XXI International Workshop on DIS and related subjects

Outline

- Introduction
- Observations of B_c^+ new decays
  - $B_c^+ \to \psi(2S)\pi^+$
  - $B_c^+ \to J/\psi D_s^{(*)+}$
- Mass measurements of B_c^+ meson and b baryons
- Polarization measurement of Λ_b^0 baryon
- Summary and prospects

B_c^+ meson

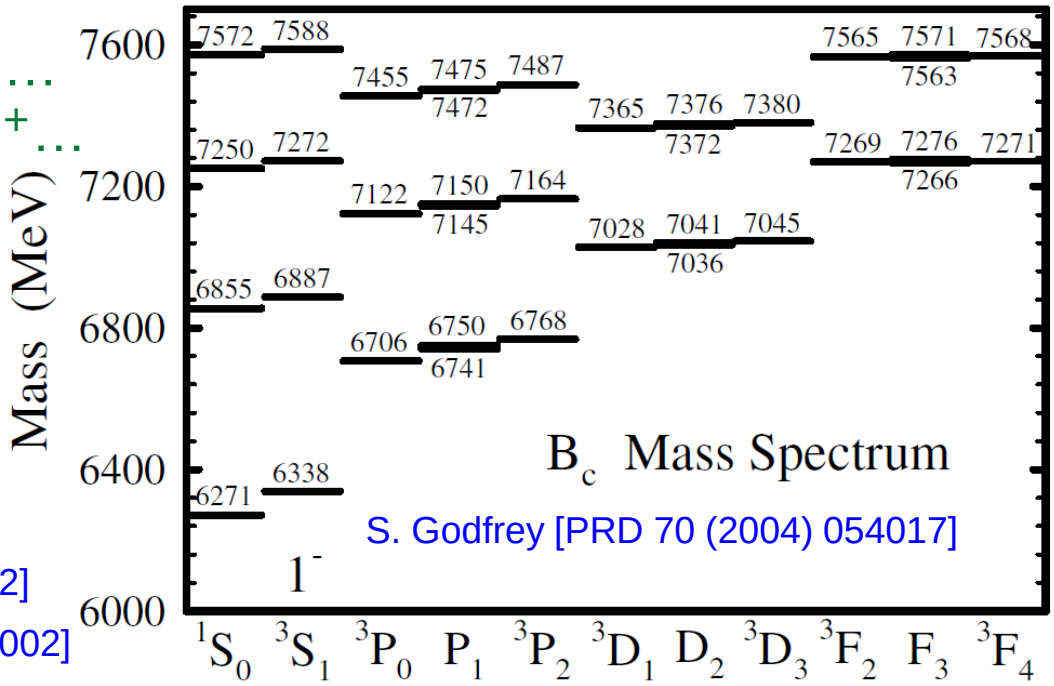
B_c^+ meson:

- Unique meson in SM with two open heavy flavors
- A wide range of decay modes
  - $c \to s$ transition: $B_c^+ \to B_s^0 \pi^+ \ldots$
  - $\bar{b} \to \bar{c}$ transition: $B_c^+ \to J/\psi \pi^+ \ldots$
  - $c\bar{b} \to W^+$ annihilation: $B_c^+ \to \tau^+ \nu_\tau \ldots$
- Rich spectroscopy

Experimental studies of B_c^+ before 2012:

- Few decay channels observed:
  - $B_c^+ \to J/\psi l^+ \nu$ [PRL 81 (1998) 2432]
  - $B_c^+ \to J/\psi \pi^+$ [PRL 96 (2006) 082002]
  - $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$ [PRL108 (2012) 251802]
- Ground state mass measured:

$m(B_c^+) = 6273.7 \pm 1.3(\text{stat.}) \pm 1.6(\text{syst.})\ MeV/c^2$ [PRL109 (2012) 232001]



b baryons

b baryons:

- SM predicts 16 ground states ($J = 1/2$ and $3/2$)

  ➔ to be tested by experiments

- Weakly decaying states:

  $\Lambda_b^0 \to J/\psi\Lambda$, [PLB 273 (1991) 540]

  $\Xi_b^- \to J/\psi\Xi$, [PRL 99 (2007) 052002]

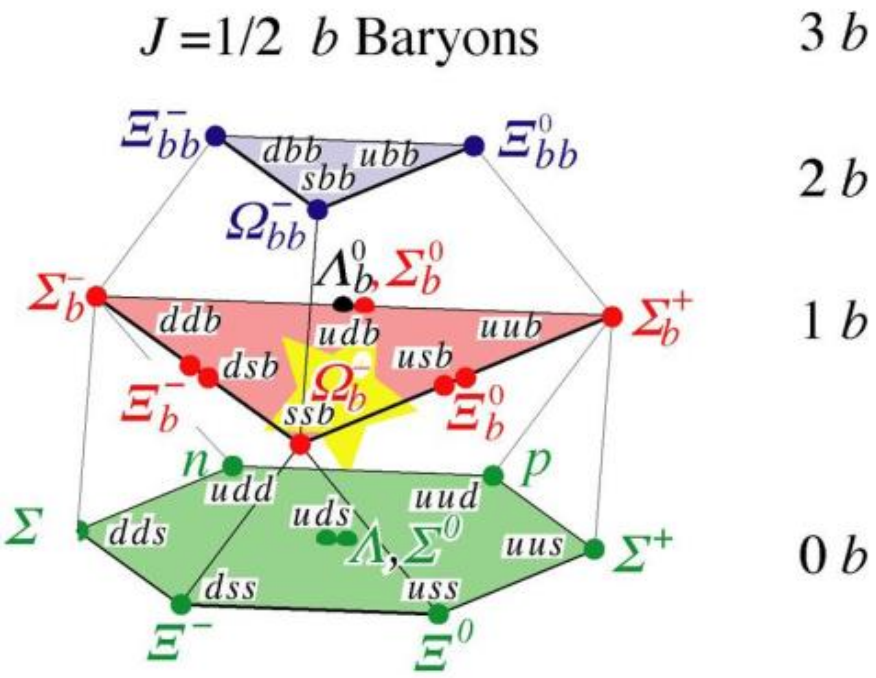
  $\Omega_b^- \to J/\psi\Omega$, [PRL 101 (2008) 232002, PRD 80 (2009) 072003]

- Strongly decaying states:

  $\Sigma_b^+ \to \Lambda_b^0\pi^+$, [PRL 99 (2007) 202001]

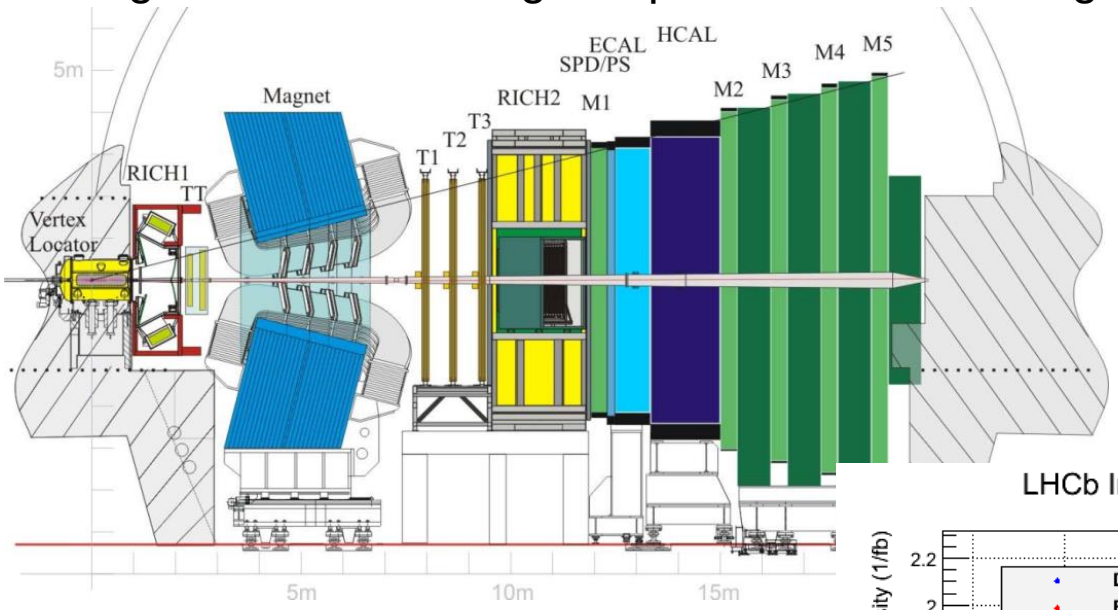
- Excited states: Λ_b^{*0} observed at LHCb

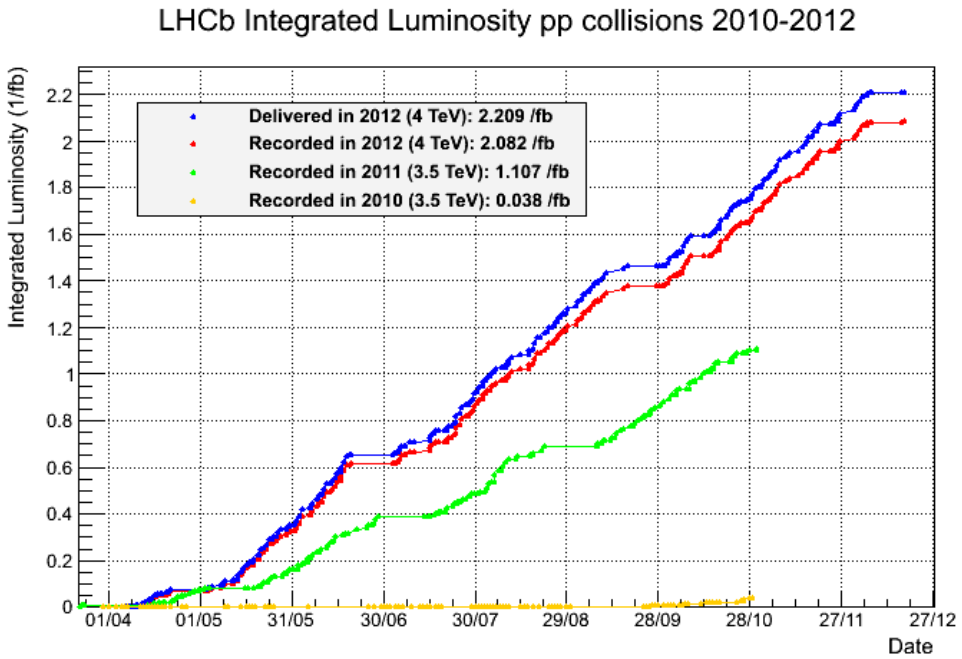
  $\Lambda_b^{*0}(5912) \to \Lambda_b^0\pi^+\pi^-$, $\Lambda_b^{*0}(5920) \to \Lambda_b^0\pi^+\pi^-$ PRL 109 (2012) 172003



LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$





- Data taking: stable & efficient
  - 2012: $\sim 2\ \mathrm{fb}^{-1}$@ 8TeV
  - 2011: $\sim 1\ \mathrm{fb}^{-1}$ @ 7TeV
  - 2010: $\sim 37\ \mathrm{pb}^{-1}$@ 7TeV

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

[arxiv:1303.1737, submitted to PRD]

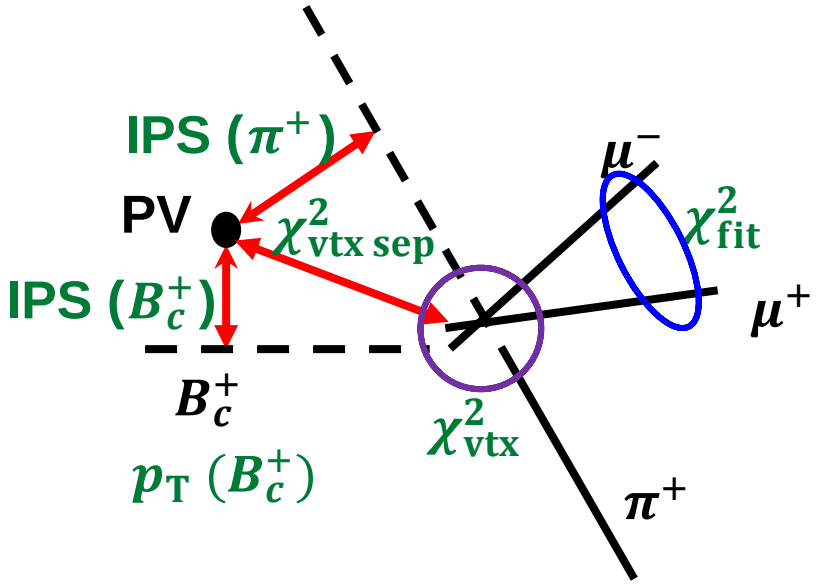
- Based on 1 fb^{-1} data collected in 2011

  The third observed hadronic decay mode of B_c^+ meson

- $\psi(2S)$ reconstructed in $\mu^+\mu^-$ channel
- Event selection with

  Boost Decision Tree (BDT)
- Control channel

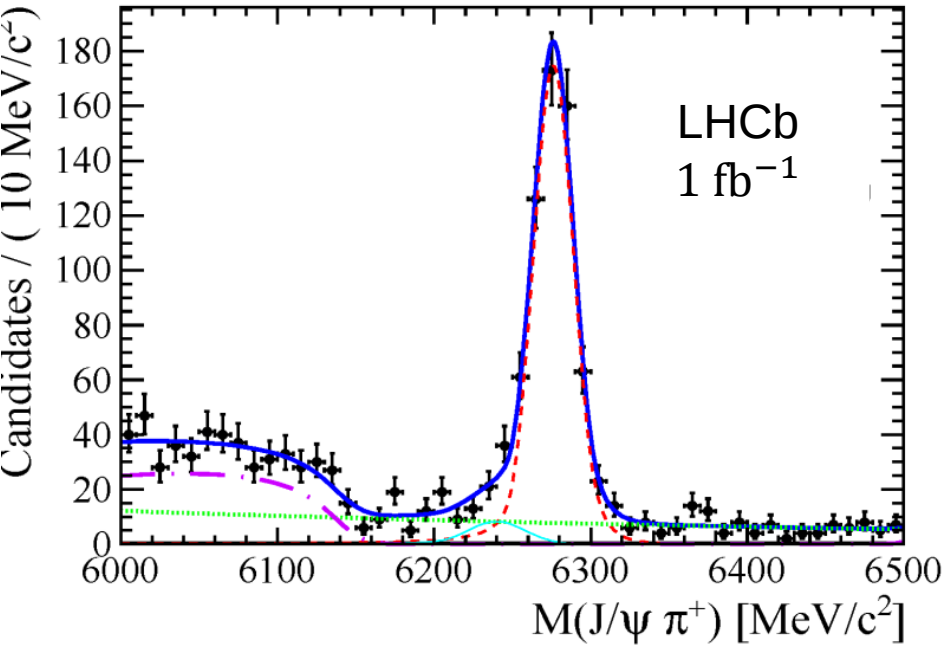
$$B_c^+ \to J/\psi(\to \mu^+\mu^-)\pi^+$$

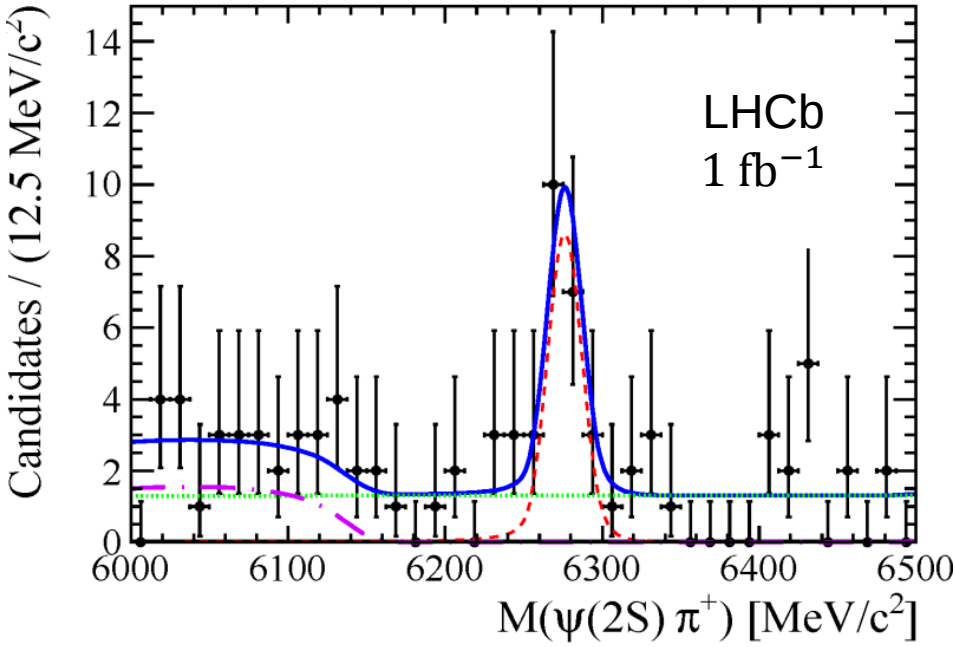


Fitting to $B_c^+ \to \psi(2S)\pi^+$

Signal: Crystal Ball $B_c^+ \to J/\psi K^+$: Crystal Ball

Partial reconstruction bkg: ARGUS ⊗ Gauss Combinatorial bkg: exponential





$N(B_c^+ \to J/\psi\pi^+) = 595 \pm 29$;
$\boldsymbol{N(B_c^+ \to \psi(2S)\pi^+) = 20 \pm 5}$ **with** $\boldsymbol{5.2\sigma}$

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

Ratio of branching fraction:

$$\frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = \epsilon_{rel} \times \frac{N(B_c^+ \to \psi(2S)\pi^+)}{N(B_c^+ \to J/\psi\pi^+)}$$

$$= 0.250 \pm 0.068(\text{stat.}) \pm 0.014(\text{syst.}) \pm 0.006(\mathcal{B})$$

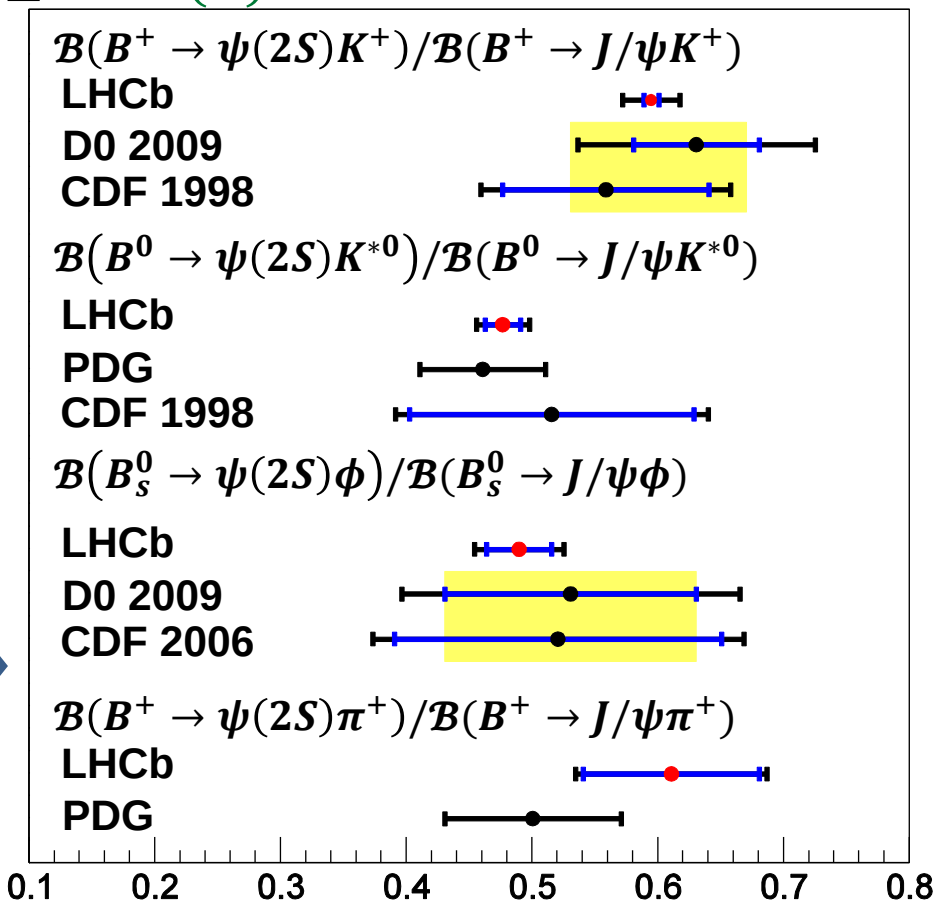
dominated by BDT selection

- Theoretical predictions
  - Relativistic quark model (RQM):

    $0.017/0.061 = 0.279$

    [PRD 68 (2003) 094020]

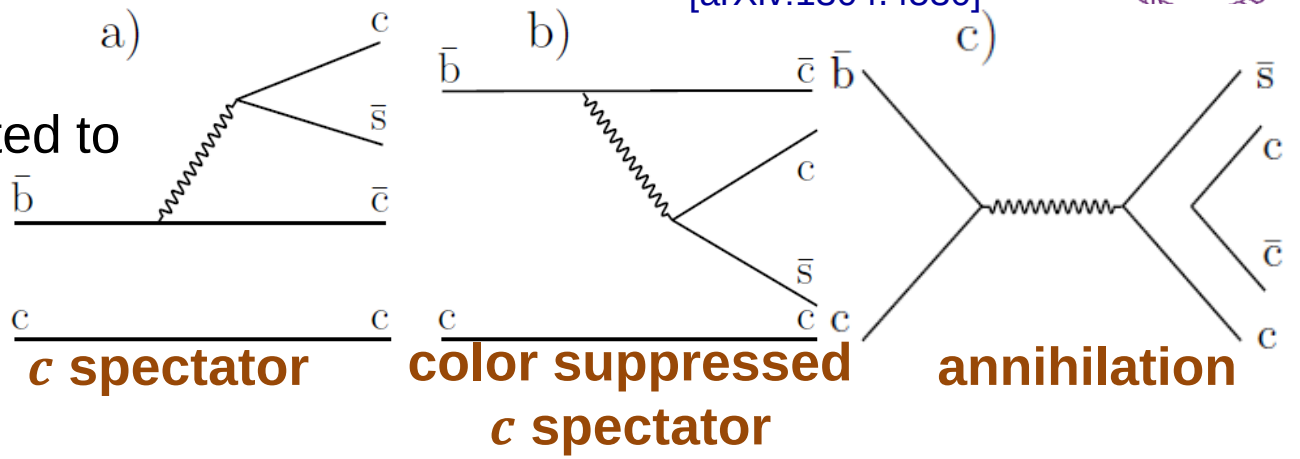
- Comparison with similar ratios for B-decays [EPJC 72 (2012) 2118]



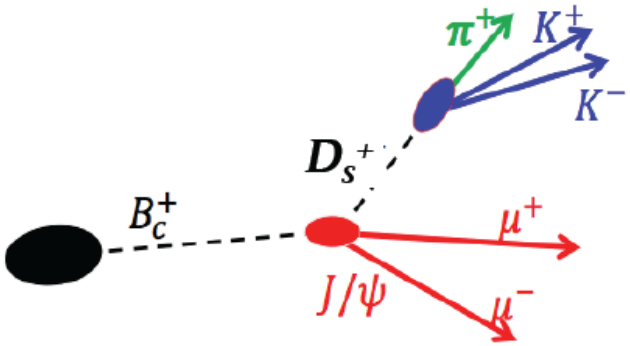
First observation of $B_c^+ \to J/\psi D_s^{(*)+}$

[arXiv:1304.4530]

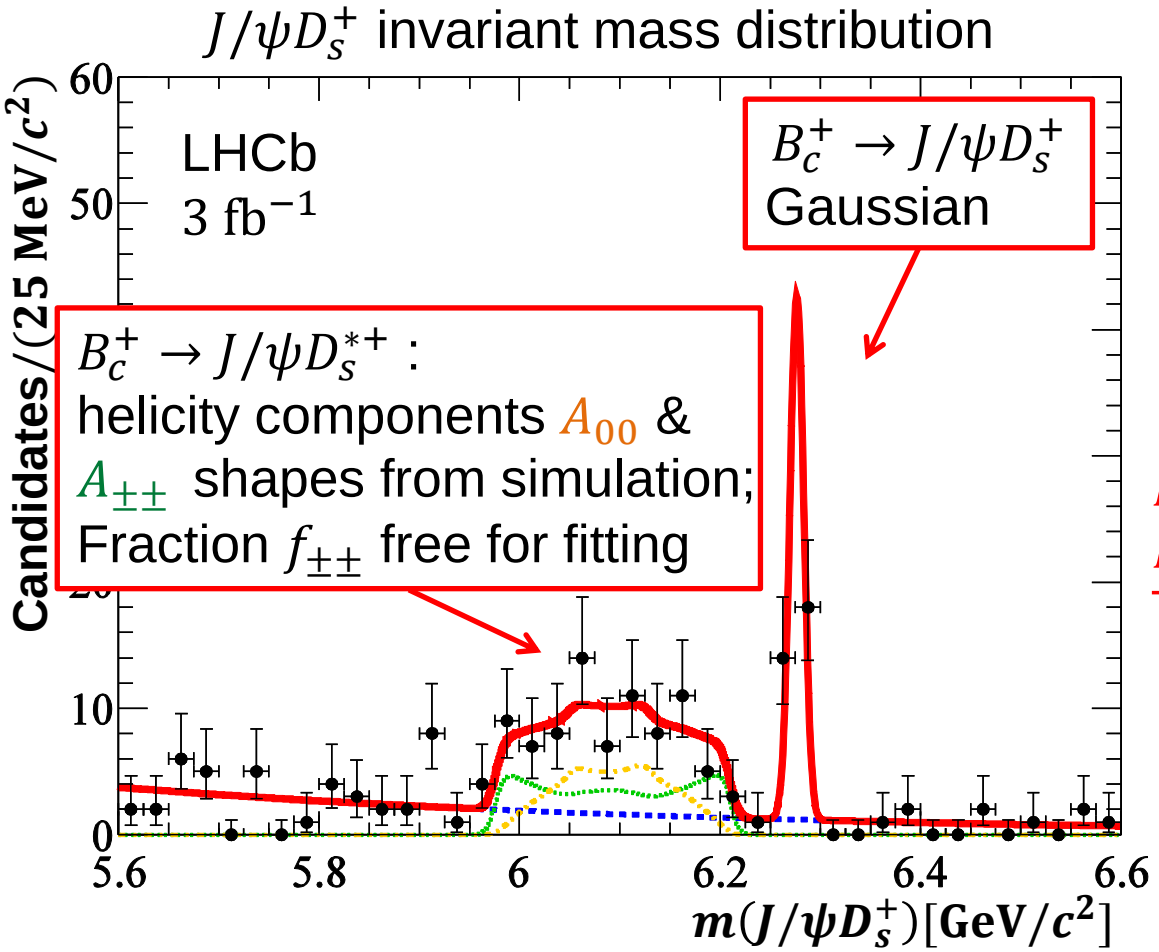
- $B_c^+ \to J/\psi D_s^{(*)+}$ expected to proceed through:



- $B_c^+ \to J/\psi D_s^{(*)+}$ searched with 3 fb^{-1} data collected in 2011 & 2012
- Event reconstructed in the decays:
  - $J/\psi \to \mu^+\mu^-, D_s^+ \to (K^+K^-)_\phi \pi^+$
  - D_s^{*+} partially reconstructed
    - ✓ followed by $D_s^{*+} \to D_s^+\gamma$ or $D_s^+\pi^0$
    - ✓ three helicity amplitudes: $\mathcal{A}_{++}$, $\mathcal{A}_{00}$ and $\mathcal{A}_{--}$



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



- First observations of these channels with $> 9\,\sigma$

$$N(B_c^+ \to J/\psi D_s^+) = 28.9 \pm 5.6$$

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

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

- Branching fraction:

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D_s^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{\epsilon_{\rm rel}}{\mathcal{B}_{D_s^+}} \times \frac{N(B_c^+ \to J/\psi D_s^+)}{N(B_c^+ \to J/\psi \pi^+)} = 2.96 \pm 0.67(\text{stat.}) \pm 0.25(\text{syst.})$$

dominated by $\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} = 2.36 \pm 0.56(\text{stat.}) \pm 0.10(\text{syst.})$$

[PRL 100 (2008) 161804]

dominated by selections

- Theoretical prediction

$\frac{\mathcal{B}(B_c^+ \to J/\psi D_s^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}$	$\frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)}$	
2.6	1.7	RQM [PRD 61 (2000) 034012]
1.3	3.9	QCDSR [arXiv:hep-ph/0308214]
2.90 ± 0.42	$2.20 \pm 0.35 \pm 0.62$	Naive factorization with B^0
1.58 ± 0.34	$2.07 \pm 0.52 \pm 0.52$	Naive factorization with B^+

$$\frac{\Gamma(B_c^+ \to J/\psi D_s^+)}{\Gamma(B_c^+ \to J/\psi \pi^+)} \approx \frac{\Gamma(B \to \bar{D}^* D_s^+)}{\Gamma(B \to \bar{D}^* \pi^+)}; \quad \frac{\Gamma(B_c^+ \to J/\psi D_s^{*+})}{\Gamma(B_c^+ \to J/\psi D_s^+)} \approx \frac{\Gamma(B \to \bar{D}^* D_s^{*+})}{\Gamma(B \to \bar{D}^* D_s^+)}$$

Results of fraction $f_{\pm\pm}$

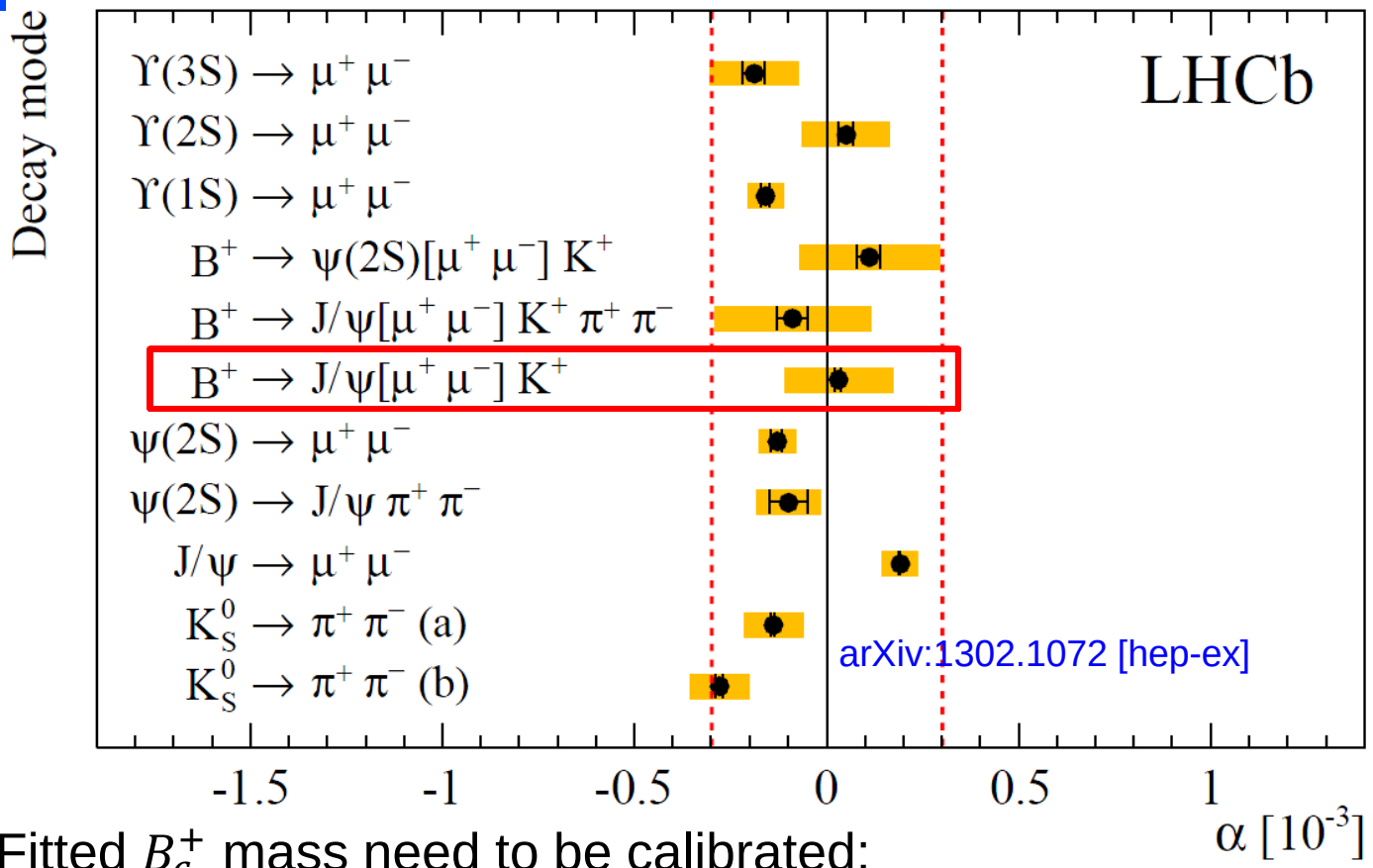
- Fraction $f_{\pm\pm}$:

$$f_{\pm\pm} = \frac{N_{\pm\pm}(B_c^+ \to J/\psi D_s^{*+})}{N_{\mathrm{tot}}(B_c^+ \to J/\psi D_s^{*+})} = 52 \pm 20\ \%$$

- Theoretical prediction

Simple estimation	$f_{\pm\pm} = \frac{2}{3}$	
Measurement of $B^0 \to D_s^{(*)+} D^{(*)-}$	$f_{\pm\pm} = (49.4 \pm 13.9 \pm 3.6)\ \%$	CLEO [PRD 62 (2000) 112003]
	$f_{\pm\pm} = (48.1 \pm 5.0 \pm 2.8)\ \%$	BaBar [PRD 67 (2003) 092003]
Factorization prediction for $B^0 \to D^{*-} D_s^{*+}$	$f_{\pm\pm} = 46.5 \pm 3.3\ \%$	[*"Probing the standard Model of particle interactions"*]
RQM prediction in $B_c^+ \to J/\psi l^+ \nu_l$ decays	$f_{\pm\pm} \approx 56\%$	[PRD 68 (2003) 094020]

B_c^+ mass determination

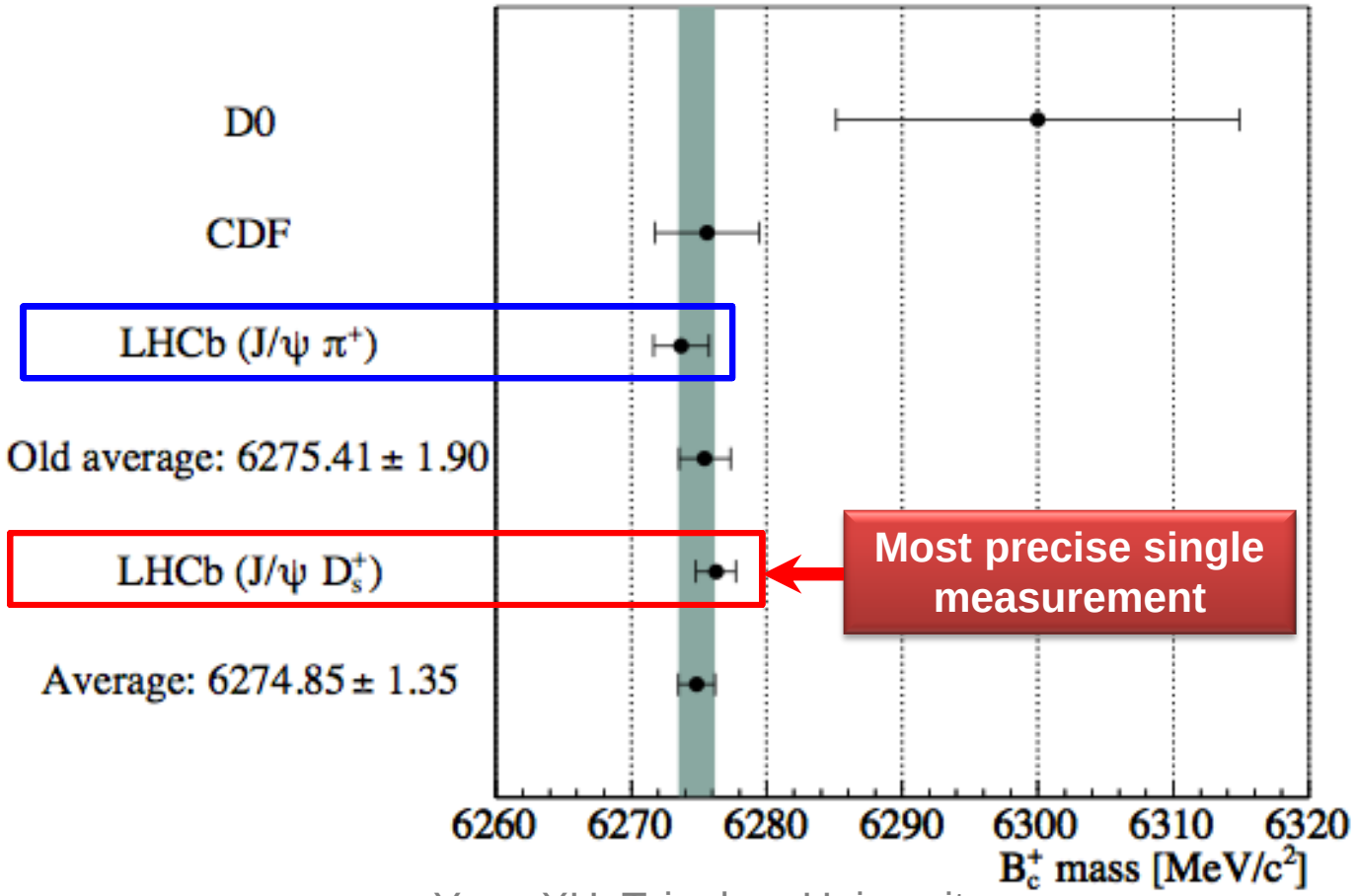


- Fitted B_c^+ mass need to be calibrated:
  - Scale on the track momentum
  - The scale α makes $B^+ \to J/\psi(\mu^+\mu^-)K^+$ mass to PDG 2012
  - Variation of scales studied with a variety of decays
    - ✓ 3×10^{-4}
    - ✓ Propagated to uncertainty of B_c^+ mass: $\pm 0.030\ \mathrm{MeV}/c^2$

Mass of B_c^+ meson

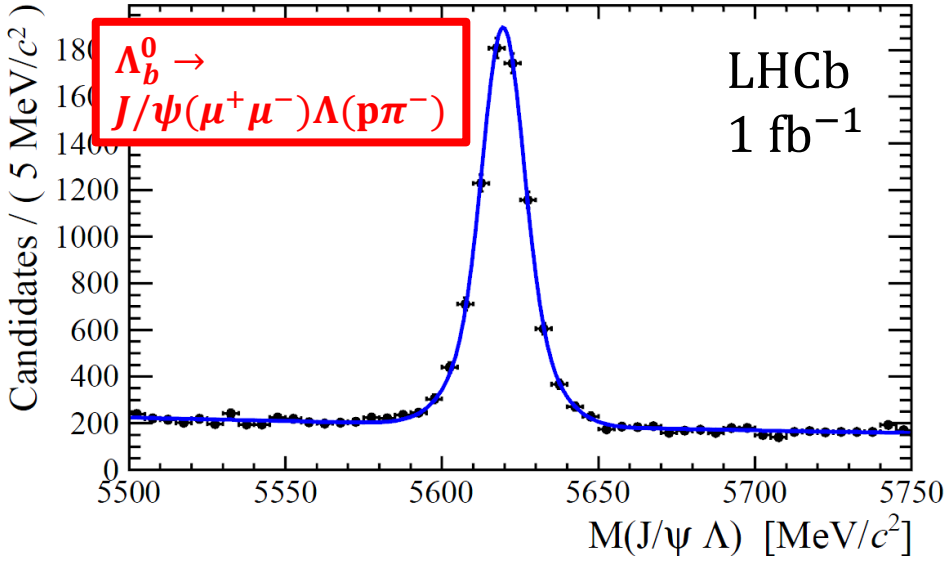
The low Q-value for the $B_c^+ \to J/\psi D_s^+$ decay mode allows the B_c^+ mass to be precisely measured

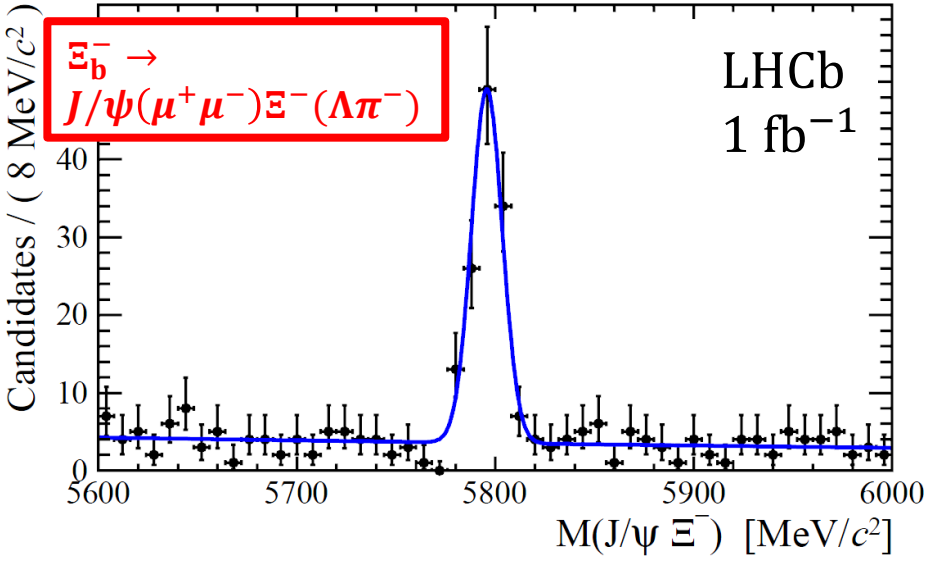
$$m(B_c^+) = 6276.28 \pm 1.44(\text{stat.}) \pm 0.36(\text{syst.})\ \text{MeV}/c^2$$
$$m(B_c^+) - m(D_s^+) = 4307.97 \pm 1.44(\text{stat.}) \pm 0.20(\text{syst.})\ \text{MeV}/c^2$$

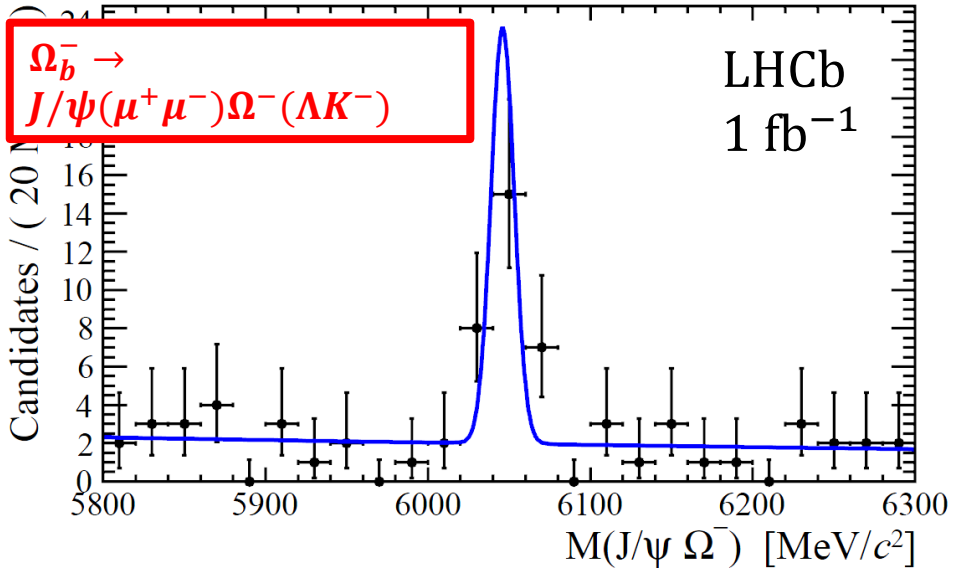


Mass measurement of b baryons

[arXiv: 1302.1072]







After calibration

$$m(\Lambda_b^0) = 5619.53 \pm 0.13 \pm 0.45\ \text{MeV}/c^2$$

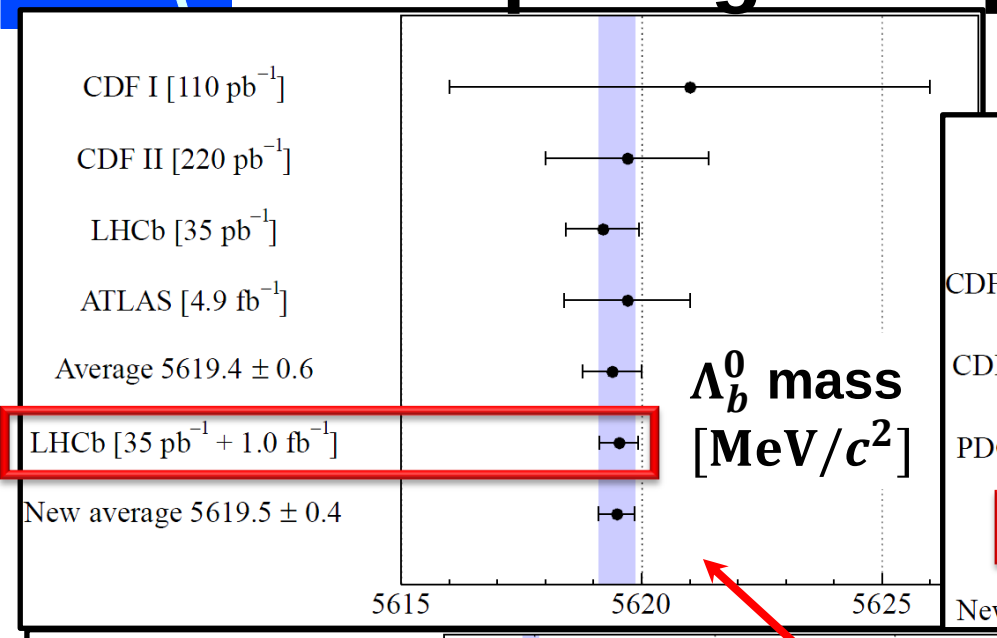
$$m(\Xi_b^-) = 5795.8 \pm 0.9 \pm 0.4\ \text{MeV}/c^2$$

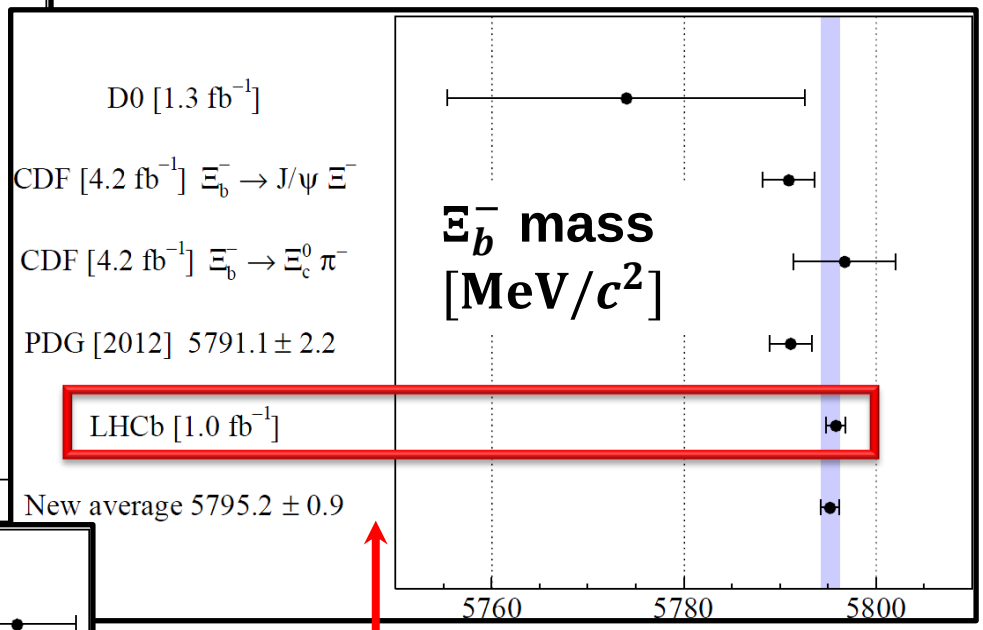
$$m(\Omega_b^-) = 6046.0 \pm 2.2 \pm 0.5\ \text{MeV}/c^2$$

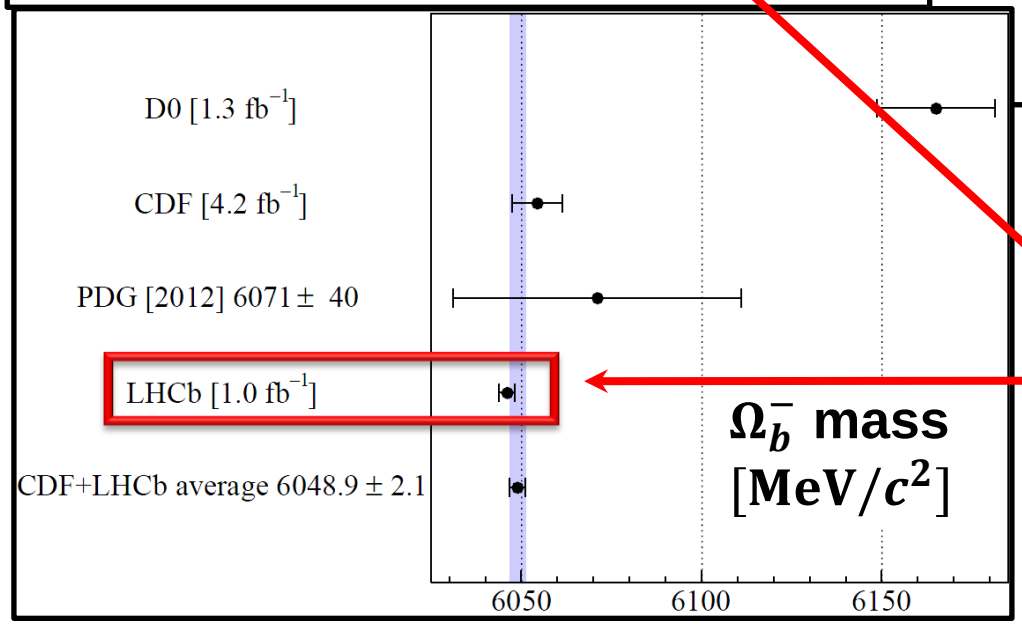
Combined with LHCb 2010 result

$$m(\Lambda_b^0) = 5619.44 \pm 0.13 \pm 0.38\ \text{MeV}/c^2$$

Comparing with previous results



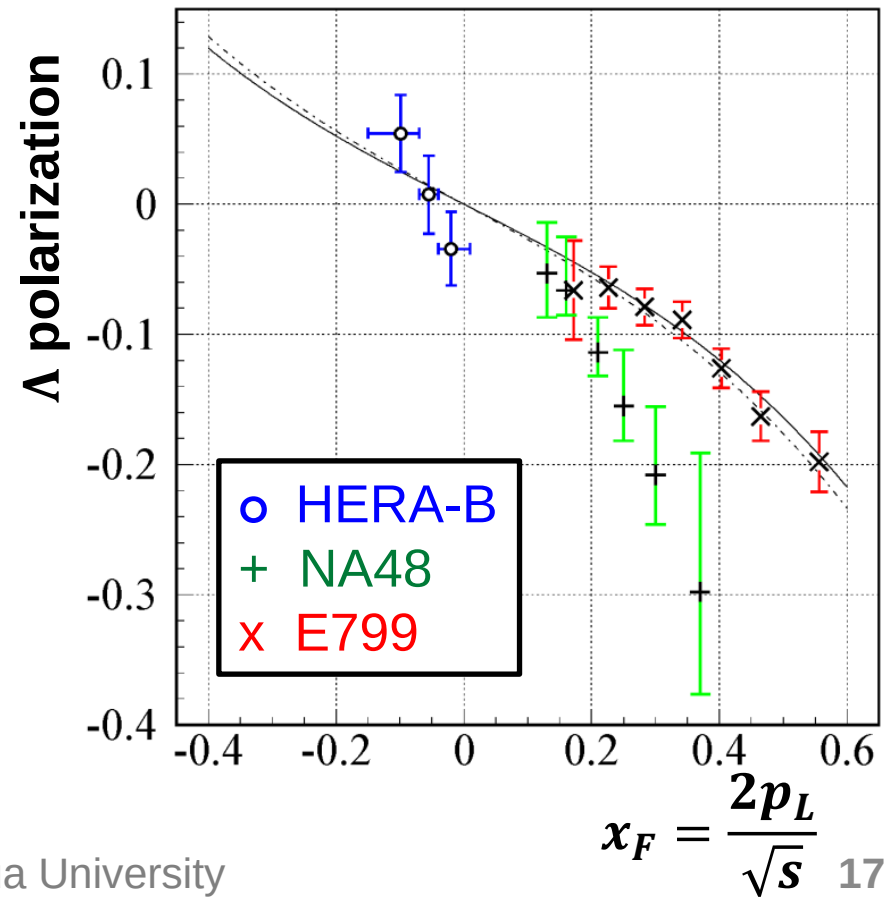




World's best measurements

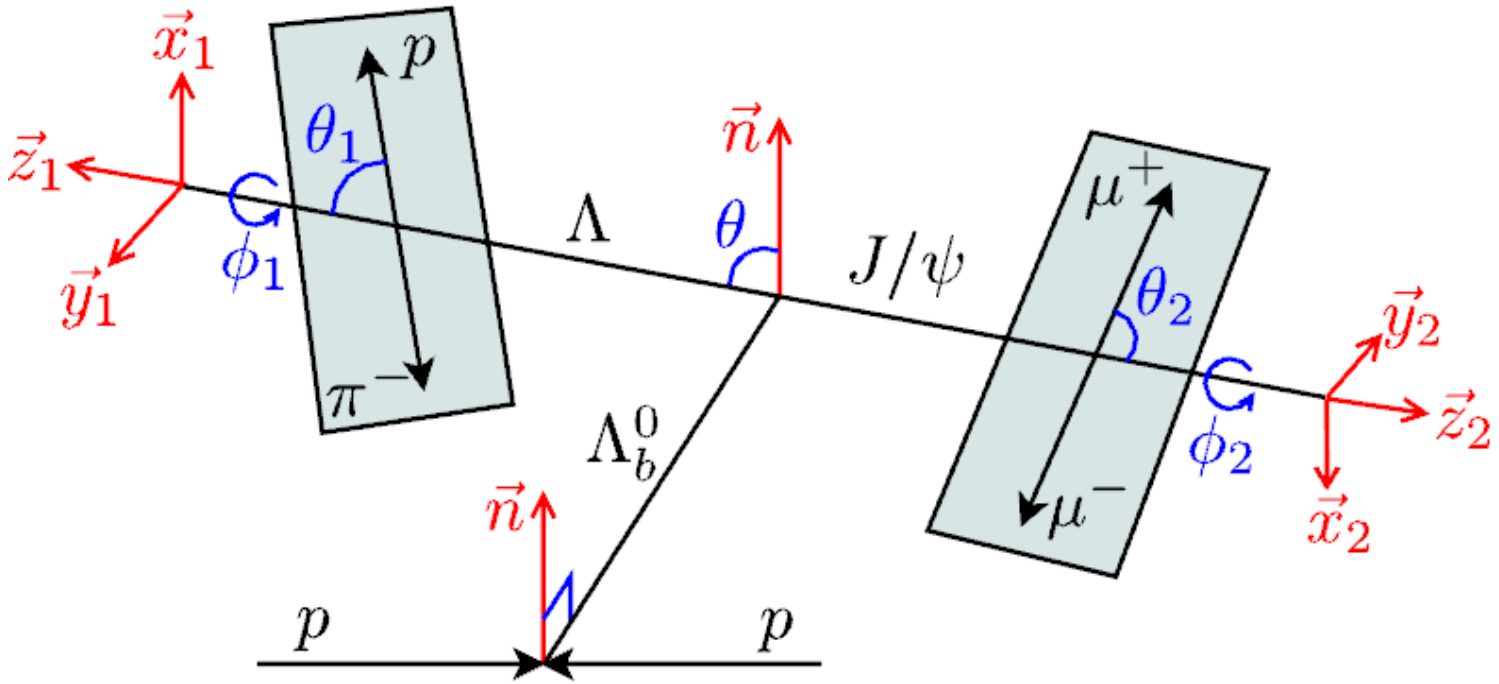
Λ_b polarization arXiv: 1302.5578

- Longitudinal polarization vanishes, but transverse polarization predicted large ($\sim 20\ \%$) [PLB 614 (2005) 165]
- Sufficient transverse polarization allows to measure the photon helicity in $\Lambda_b^0 \to \Lambda\gamma$ ➔ search for new physics [J. Phys. G 24 (1998) 979, PLB 645 (2007) 204]
- No polarization measurement for Λ_b^0 at hadron colliders before
- Hints from fixed target experiments
  - baryons polarization strongly depends on x_F
  - Vanishes at $x_F \to 0$
- Small Λ_b polarization ($< 10\ \%$) excepted at LHC ($x_F \approx 0.02$)



Angular analysis

- Decay chain: $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$



- 5 angles to describe the angular distribution
  - θ : polar angle of $\vec{p}_\Lambda$ wrt $\vec{n} = \vec{p}_{\Lambda_b^0} \times \vec{p}_{\rm beam}$ in Λ_b^0 rest frame
  - θ_1, ϕ_1: polar & azimuthal angle of $\vec{p}_p$ wrt $\vec{p}_{\Lambda_b^0}$ in Λ rest frame
  - θ_2, ϕ_2: polar & azimuthal angle of $\vec{p}_{\mu^+}$ wrt $\vec{p}_{\Lambda_b^0}$ in J/ψ rest frame

Angular distribution

Integrated over azimuthal, cross section parameterized as

$$\frac{d\Gamma}{d\Omega_3}(\cos\theta,\cos\theta_1,\cos\theta_2)=\frac{1}{16\pi}\sum_{i=0}^{7} f_i(\alpha_b,r_0,r_1)\, g_i(P_b,\alpha_\Lambda) h_i(\cos\theta,\cos\theta_1,\cos\theta_2)$$

Transverse polarization parameter

$$r_0 \equiv |\mathcal{M}_{+1/2,0}|^2 + |\mathcal{M}_{-1/2,0}|^2$$

$$r_1 \equiv |\mathcal{M}_{+1/2,0}|^2 - |\mathcal{M}_{-1/2,0}|^2$$

$$\alpha_b \equiv r_1 + |\mathcal{M}_{-1/2,-1}|^2 - |\mathcal{M}_{+1/2,+1}|^2$$

Helicity amplitude

P-violation asymmetry

i	$f_i(\alpha_b, r_0, r_1)$	$g_i(P_b, \alpha_\Lambda)$	$h_i(\cos\theta, \cos\theta_1, \cos\theta_2)$
0	1	1	1
1	α_b	P_b	$\cos\theta$
2	$2r_1 - \alpha_b$	α_Λ	$\cos\theta_1$
3	$2r_0 - 1$	$P_b\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$\frac{1}{2}(1-3r_0)$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
5	$\frac{1}{2}(\alpha_b - 3r_1)$	P_b	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta$
6	$-\frac{1}{2}(\alpha_b + r_1)$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta_1$
7	$-\frac{1}{2}(1+r_0)$	$P_b\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta\cos\theta_1$

Λ decay asymmetry parameter:

$\alpha_\Lambda = 0.642 \pm 0.013$ (PDG2012)

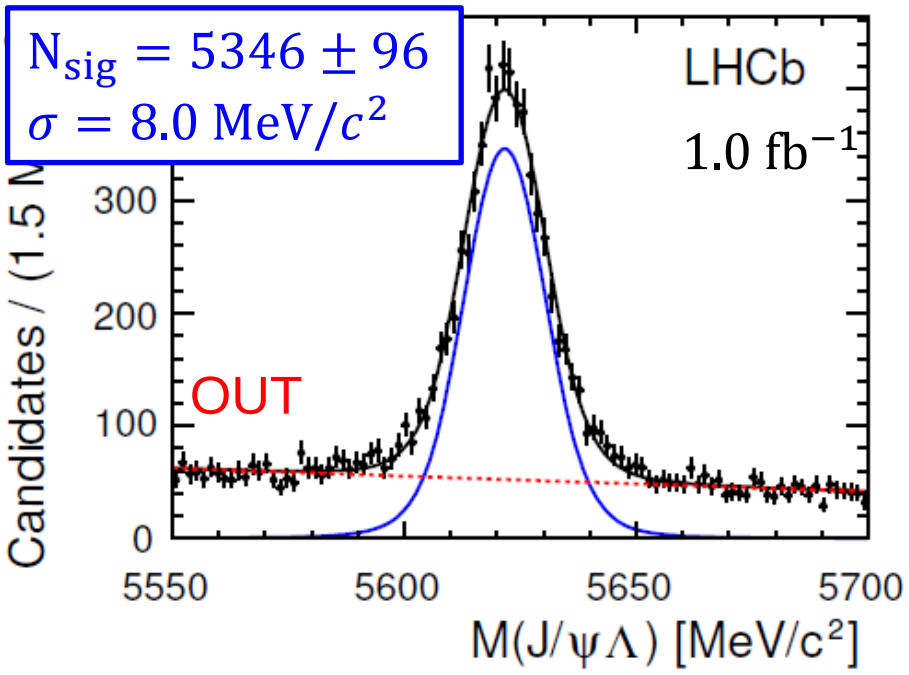
PRD 86 (2012) 010001

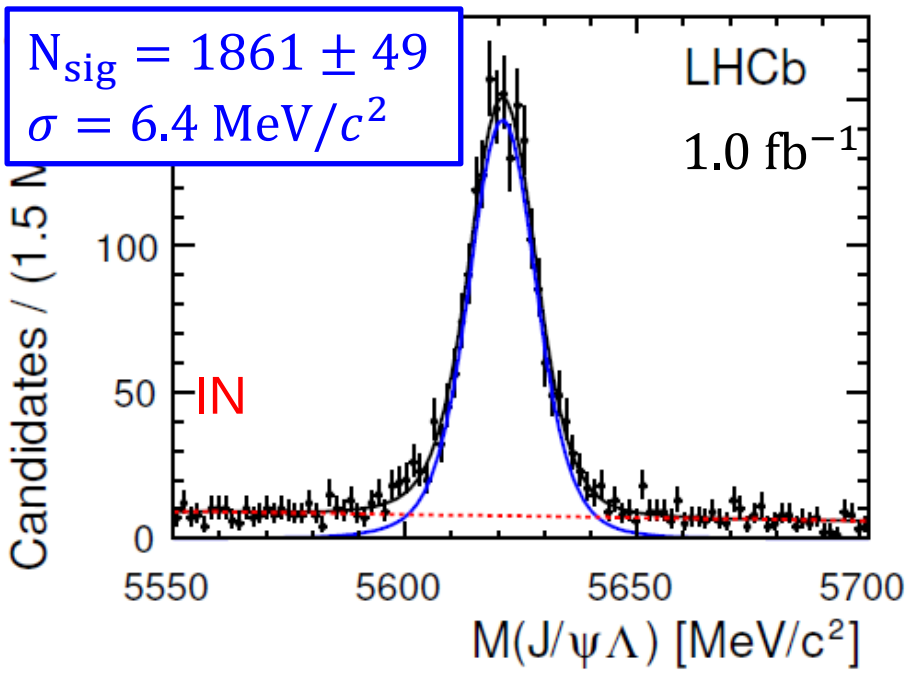
Four parameters $(P_b, \alpha_b, r_0, r_1)$ have to be measured simultaneously from the angular distribution

$\Lambda_b^0 \to J/\psi\Lambda$ signal

- Dataset: 1.0 fb^{-1} data in 2011
- Λ can decay outside (OUT) or inside (IN) of the vertex detector
- Event selection: BDT

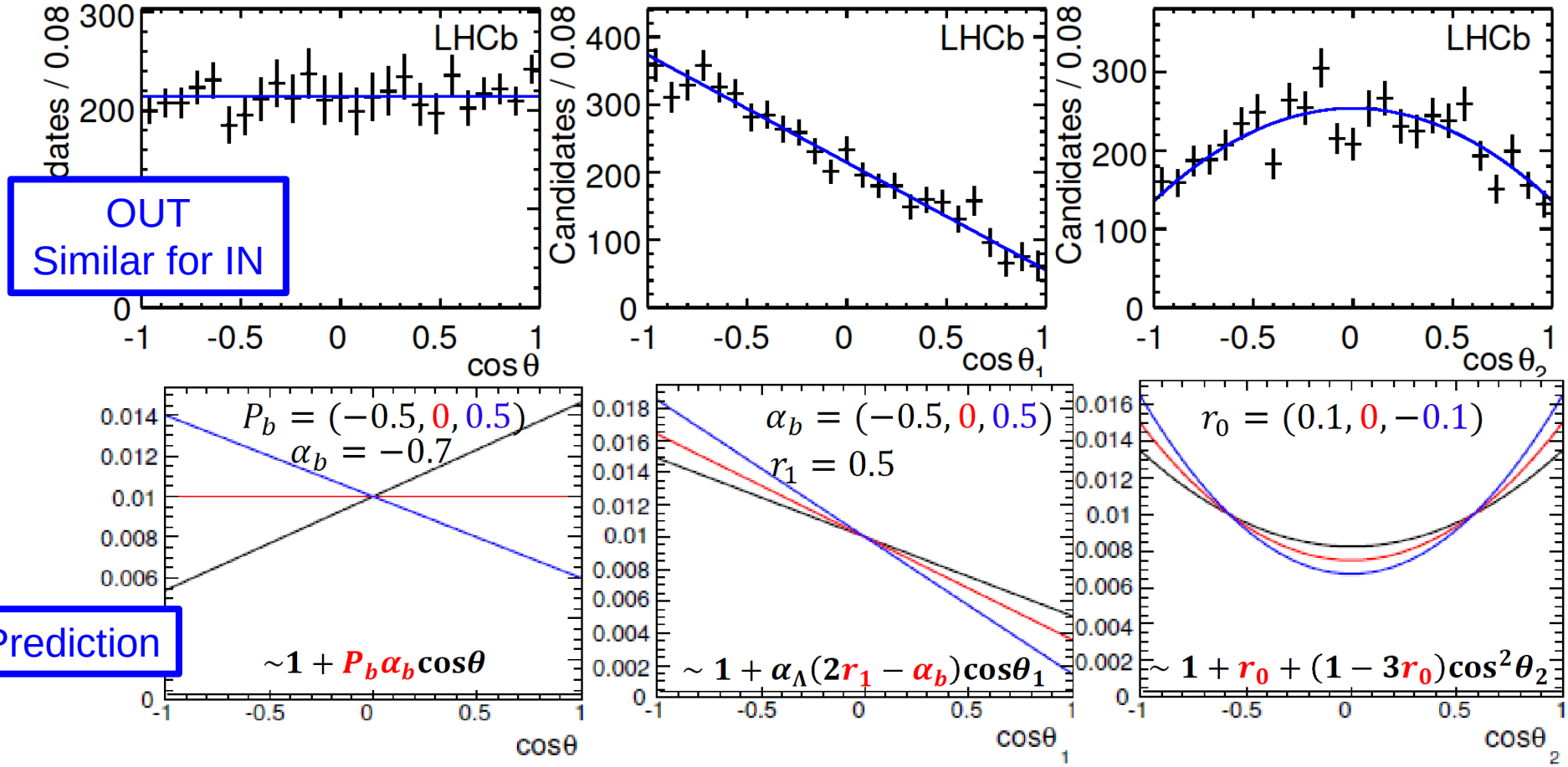
Signal: double Crystal Ball Background: first order polynomial





Fit of data

- Unbinned maximum likelihood fit to angular distribution (OUT + IN)
  - Background subtracted and acceptance corrected



Since distribution of cosθ is nearly flat, small polarization expected

Results of $\Lambda_b^0 \to J/\psi\Lambda$

- First measurements of Λ_b polarization

$$P_b = 0.05 \pm 0.07(\text{stat.}) \pm 0.02(\text{syst.})$$
$$\alpha_b = -0.04 \pm 0.17(\text{stat.}) \pm 0.07(\text{syst.})$$
$$r_0 = 0.57 \pm 0.02(\text{stat.}) \pm 0.01(\text{syst.})$$
$$r_1 = -0.59 \pm 0.10(\text{stat.}) \pm 0.05(\text{syst.})$$

- Comparison with theory
  - Polarization parameter P_b:
    - ✓ Dose not exclude QCD perturbative theory prediction of P_b to be $\mathcal{O}(10\%)$ [PLB 649 (2007) 152]
  - P-violation asymmetry parameters α_b:
    - ✓ Compatible with the predictions ranging from $-21\ \%$ to $-10\ \%$ [PRD 56 (1997) 2799, PRD 58 (1998) 014016, PTP 101 (1989) 959,PRD 65 (2002) 074030, PRD 80 (2009) 094016]
    - ✓ Disagrees with HQET prediction of 77.7% at $6.1\ \sigma$ [PLB 614 (2005) 165]

Summary

With $3\ \mathrm{fb}^{-1}$ data , LHCb provide good opportunities for B_c^+ meson and b baryon studies

B_c^+ studies at LHCb

- First observation of three decay modes
  - $B_c^+ \to \psi(2S)\pi^+$ $(5.2\ \sigma)$
  - $B_c^+ \to J/\psi D_s^+$ $(>9\ \sigma)$
  - $B_c^+ \to J/\psi D_s^{*+}$ $(>9\ \sigma)$
- World best determinations of B_c^+ mass

b baryons studies at LHCb

- World best determinations of Λ_b^0, Ξ_b^- and Ω_b^- masses
- First measurement of Λ_b^0 polarization in pp collisions with $1\ \mathrm{fb}^{-1}$ data

Prospects

B_c^+ meson

- More precise measurement of B_c^+ production with few thousands reconstructed $B_c^+ \to J/\psi\pi^+$
- New decay channels and excited states

b baryon

- New b baryons and excited states
- new decay modes

THANK you