Studies of *b* hadrons decays into final states containing charmonia

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on behalf of the LHCb Collaboration

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Stockholm

LHCb detector

LHCb,
JINST 3 (2008) S08005

Advantages of beauty physics at LHC:

✓high value of *bb* cross-section

✓access to all quasi-stable *b*-flavoured hadrons

RICH1 & RICH2:
$\varepsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

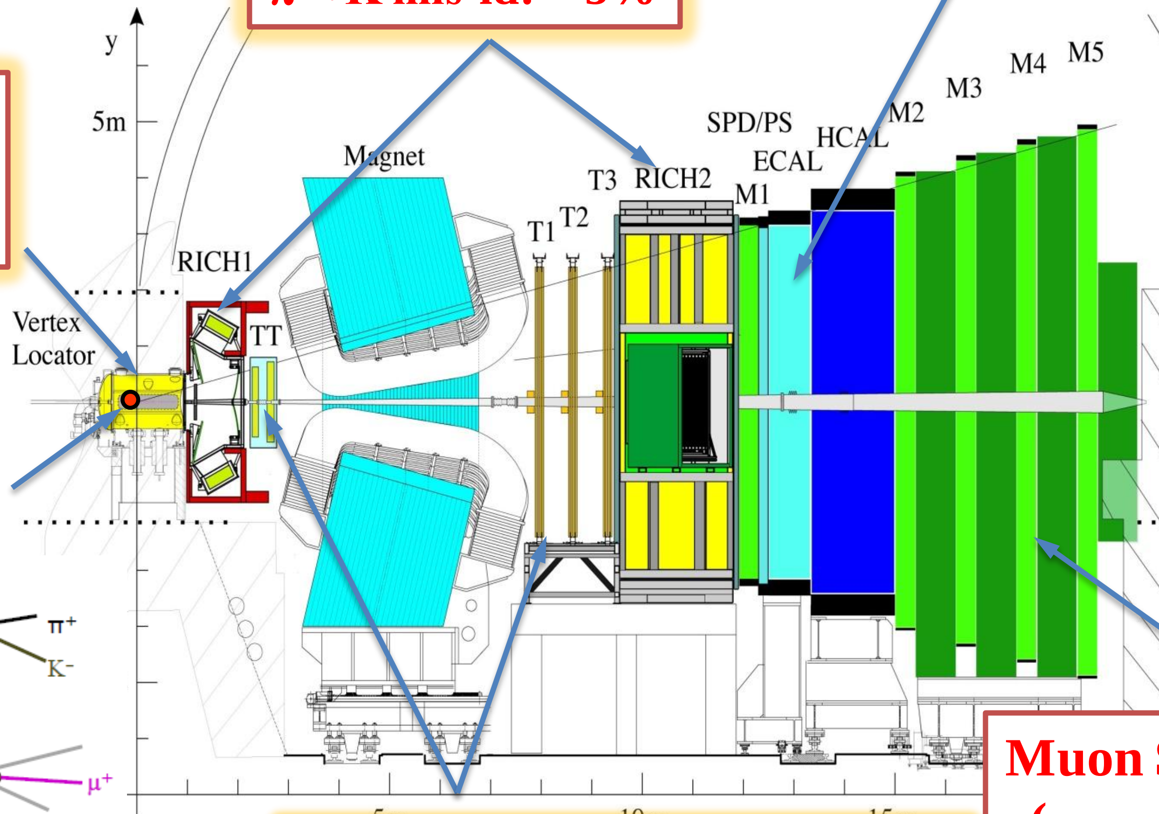
Calorimeters:
ECAL: $\sigma_E/E \sim 1\% \oplus 10\%/\sqrt{E(GeV)}$

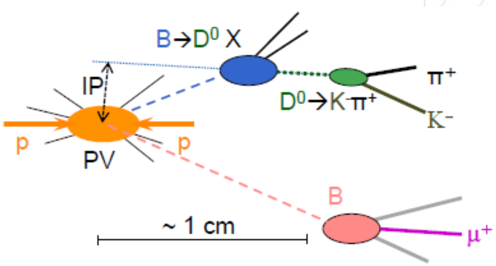
VELO:
$\sigma_{IP} \sim 20\ \mu m$ for high-p_T tracks

Beam 1

Interaction point

Beam 2





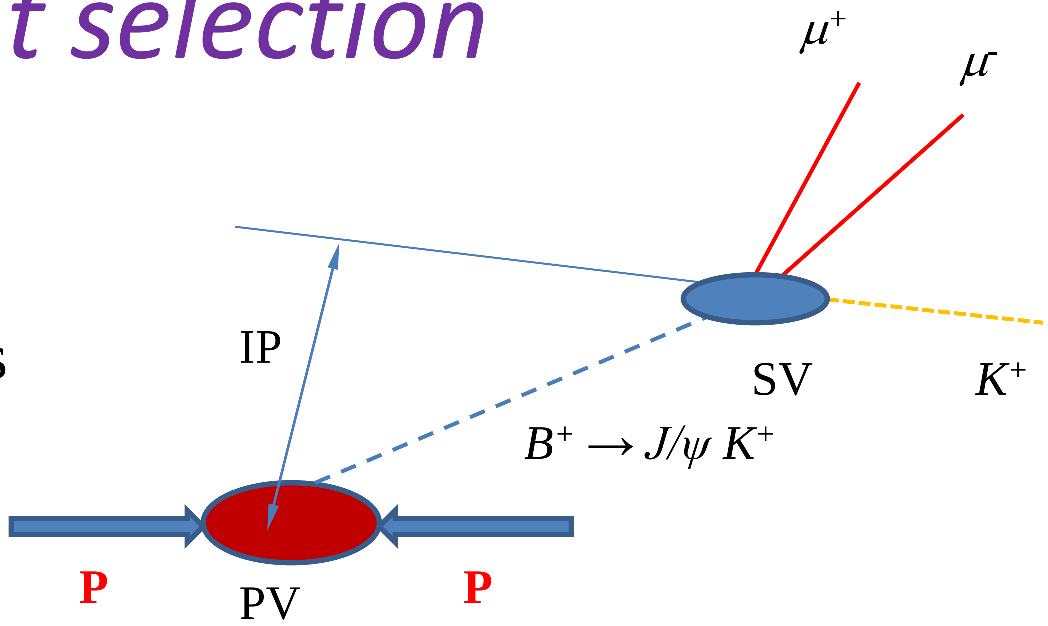
Muon System:
$\varepsilon(\mu \to \mu) \sim 97\%$
$\mu \to \pi$ mis-id: 1~ 3%

Pseudorapidity acceptance:
$2 < \eta < 5$

Tracking System:
$\Delta p/p = 0.4\%$ @5 GeV/c to 0.6% @ 100 GeV/c

Event selection

Detached vertex analysis:



- ✓ start from good quality tracks
- ✓ apply particle ID (μ,π,K,p)
- ✓ vertex quality cuts
- ✓ PV and SV separation:
    - daughter particles do not point to PV (>3σ)
    - mother particle does point to PV (<3σ)
    - mother has non-zero lifetime
    - the decay structure is self-consistent

Take care about background and keep track on efficiency determination

- use *sPlot* technique for background subtraction
- extract efficiencies from data (when possible)

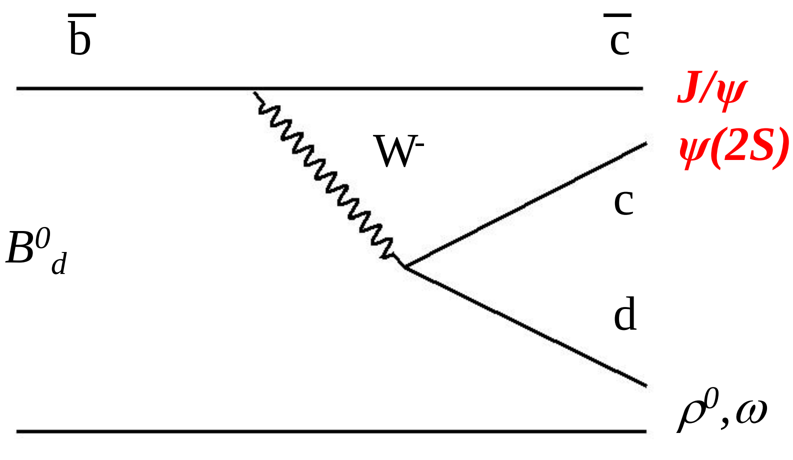
B decays to charmonium and neutrals

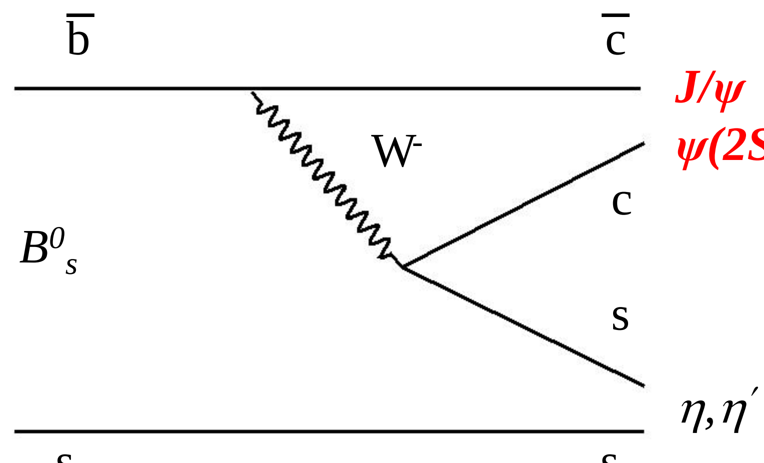
B meson decays containing charmonium in final state play a crucial role in *CP* violation study and in precise measurement of neutral *B* meson mixing parameter

see also talk

Measurement of ϕ_s at LHCb
Wandernoth, Sebastian

- sensitive for electroweak transition study
- direct probe of charmonium properties
- possible future measurement of B_s mixing phase ϕ_s *in* $B_s \to \psi(2S) f_0(980)$
- possible channel for *CP*-asymmetry measurements in $B_s \to J/\psi\eta$ or $B_s \to \psi(2S)\eta$



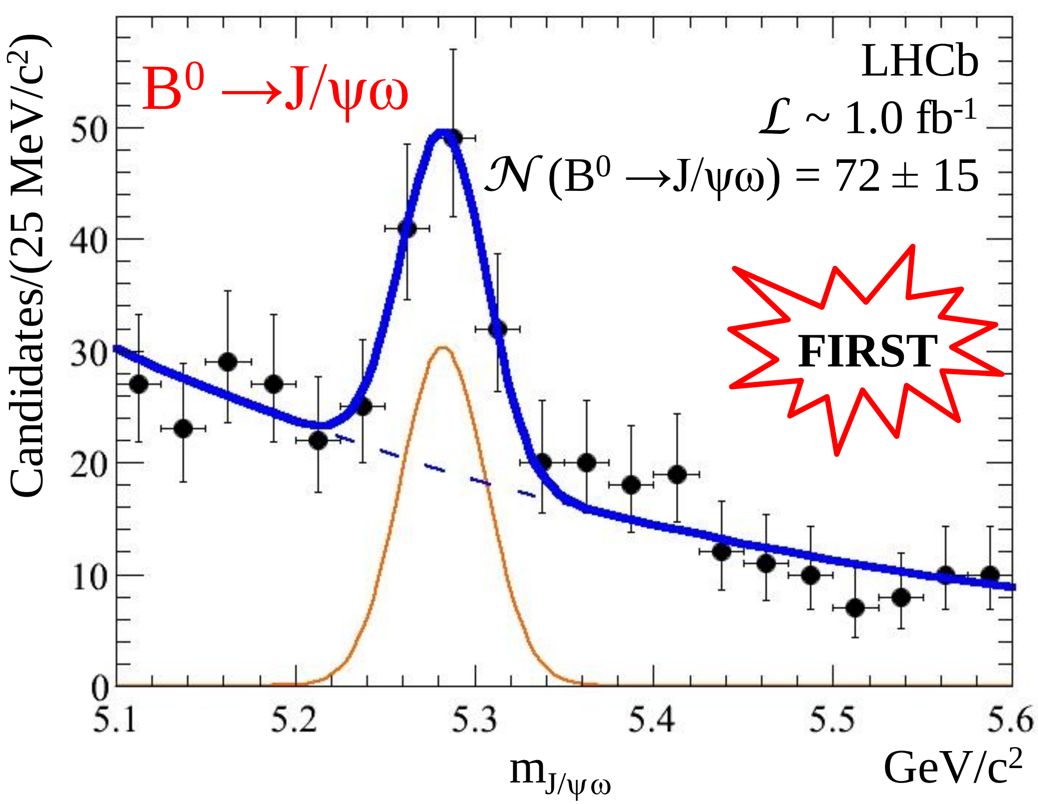


Evidence for $B^0 \to J/\psi\omega$

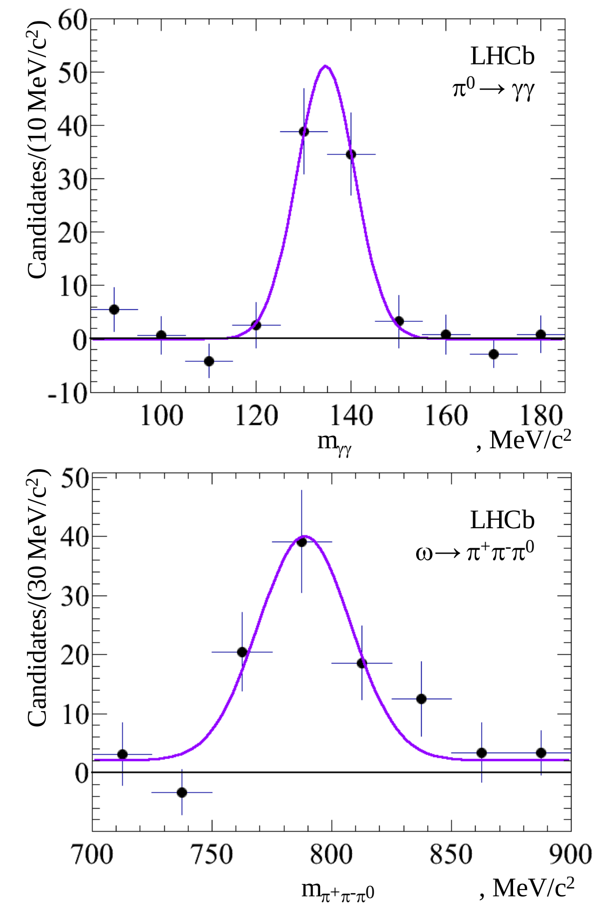
LHCb, Nucl Phys B867 (2013) 547

$\mathcal{BR}$ ($B^0 \to J/\psi\omega$) < 2.4 x 10^{-4} (90% CL), CLEO II, PL B369 (1996) 186

Signal: **Gaussian**; Background: **exponential**



Background-subtracted invariant mass distributions



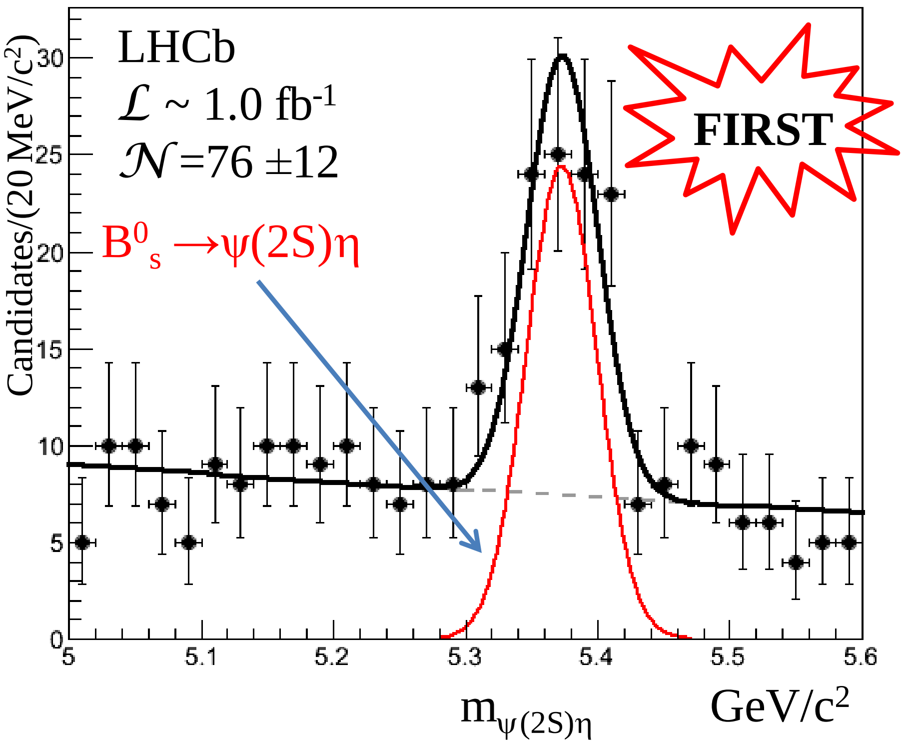
LHCb :

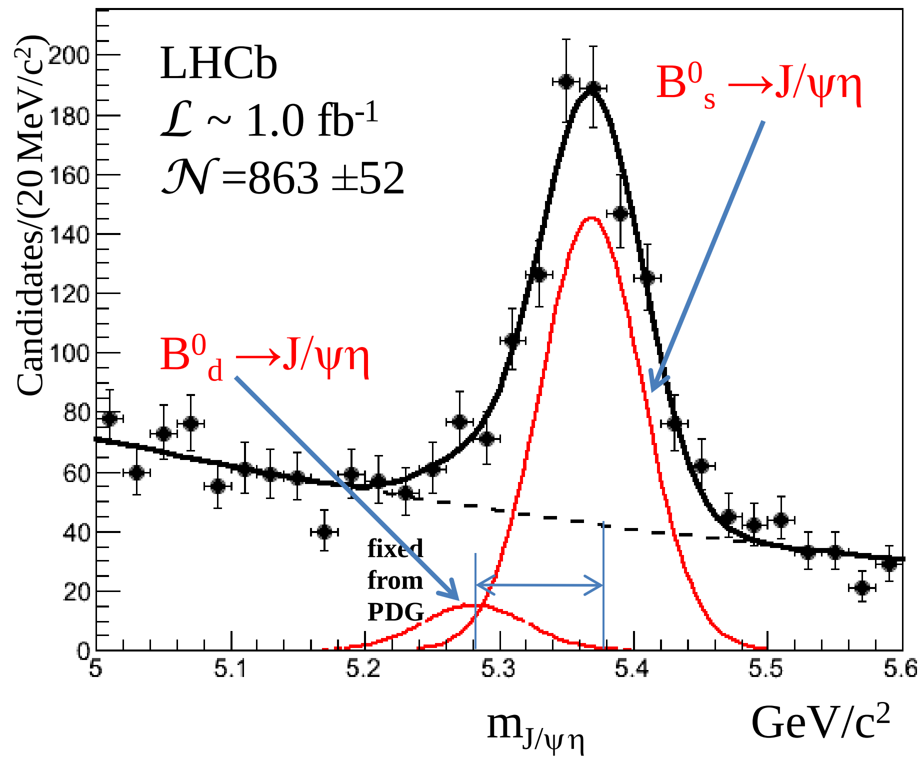
$\mathcal{BR}$ ($B^0 \to J/\psi\omega$) = (2.41 ± 0.52 (stat) $^{+0.19}_{-0.35}$ (syst) ± 0.36 $\mathcal{BR}$ ($B^0 \to J/\psi\rho^0(770)$)) x 10^{-5}

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

$B^0_s \rightarrow J/\psi\,\eta$ seen by
PRL 108 (2012) 181808 Belle
NPB 867 (2013) 547 LHCb

Signal: **Gaussian**; Background: **exponential**





LHCb :

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

LHCb, Nucl Phys B871 (2013) 403

Search for $B^0_{(d,s)} \rightarrow \chi_{c1,2} K^{*0}(\phi)$

Decays are expected to proceed predominantly via the color-suppressed tree diagram

Factorization hypothesis $\Rightarrow$ $\mathcal{BR}(B_d \rightarrow \chi_{c0,2}\, K^{*0})$ or $\mathcal{BR}(B_s \rightarrow \chi_{c0,2}\, \phi)$ are expected to be small (arXiv:hep-ex/0607221)

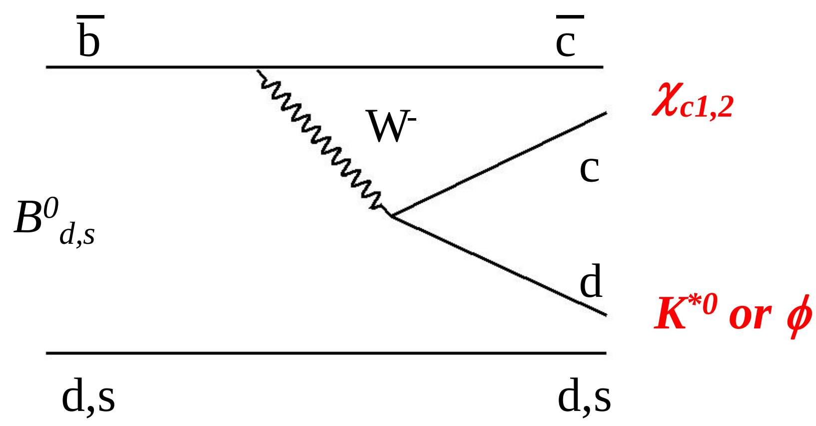
Experimental results

$\mathcal{BR}(B_d \rightarrow \chi_{c0}\, K^{*0}) = (1.7 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})\ )\ \text{x}10^{-4}$ BaBar, PR D78 (2008) 0911001

$\mathcal{BR}(B_d \rightarrow \chi_{c1}\, K^{*0}) = (2.5 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})\ )\ \text{x}10^{-4}$ BaBar, PRL 102 (2009) 132001

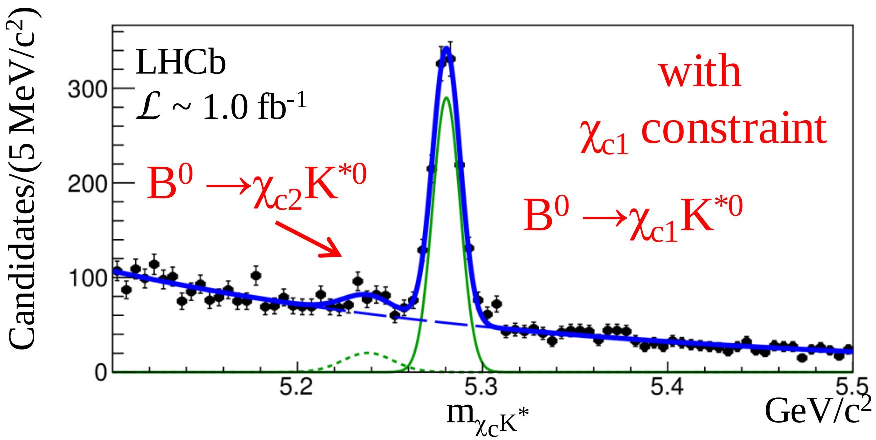
$\mathcal{BR}(B_d \rightarrow \chi_{c1}\, K^{*0}) = (1.73\ ^{+0.15}_{-0.12}(\text{stat})\ ^{+0.34}_{-0.22}(\text{syst})\ )\ \text{x}10^{-4}$ Belle, PR D78 (2008) 072004

$\mathcal{BR}(B_d \rightarrow \chi_{c2}\, K^{*0}) = (6.6 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})\ )\ \text{x}10^{-5}$ BaBar, PRL 102 (2009) 132001

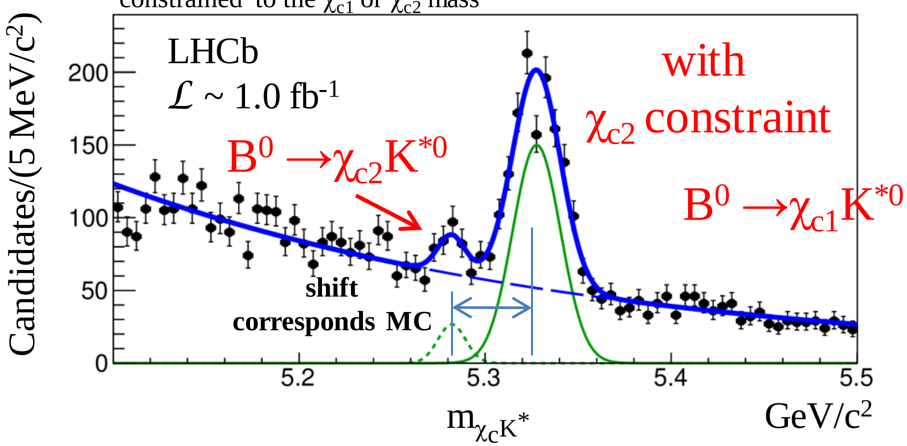


Search for $B^0 \to \chi_{c1,2} K^{*0}$

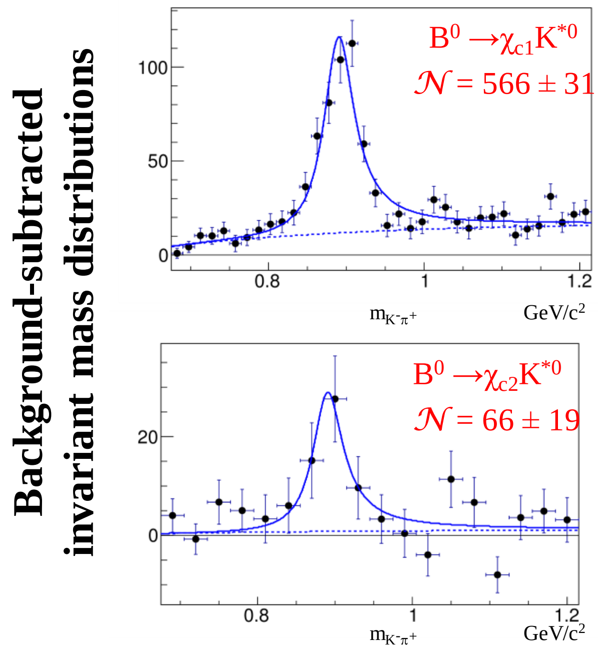
LHCb,
NPB 874 (2013) 663



Same B^0 candidate mass is calculated with the $J/\psi\gamma$ inv. mass constrained to the χ_{c1} or χ_{c2} mass



Signal: **Gaussian**;
Background: **exponential**;
Ratio of the mass resolutions are fixed to MC



Relativistic P-wave Breit-Wigner + LASS parameterization

LHCb :

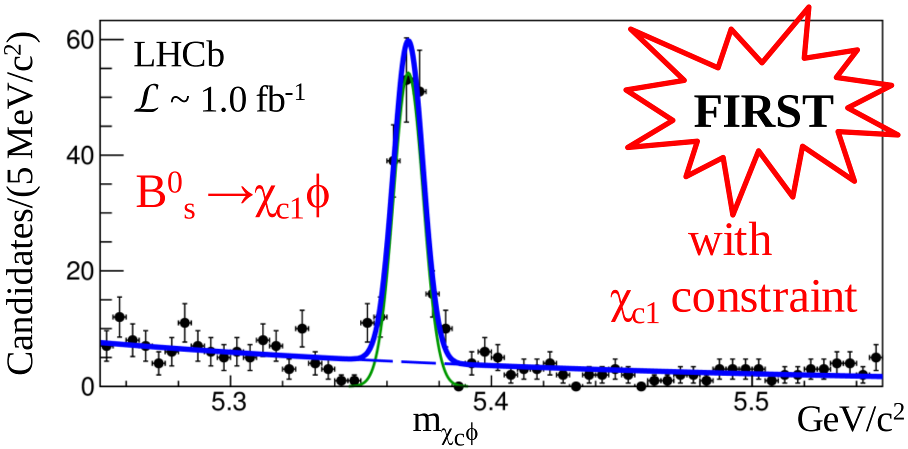
$$\frac{\mathcal{BR}(B^0 \to \chi_{c1} K^{*0})}{\mathcal{BR}(B^0 \to J/\psi K^{*0})} = (19.8 \pm 1.1(\text{stat}) \pm 1.2(\text{syst}) \pm 0.9\,(\mathcal{BR}(\chi_{c1} \to J/\psi\gamma))\ \text{x}10^{-2}$$

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

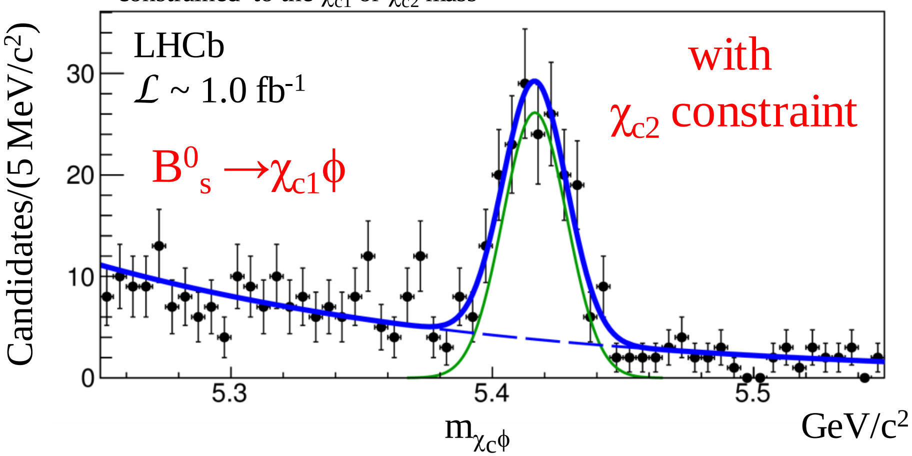
Compatible with previous, but more precise

Observation of $B^0_s \to \chi_{c1}\phi$

LHCb,
NPB 874 (2013) 663

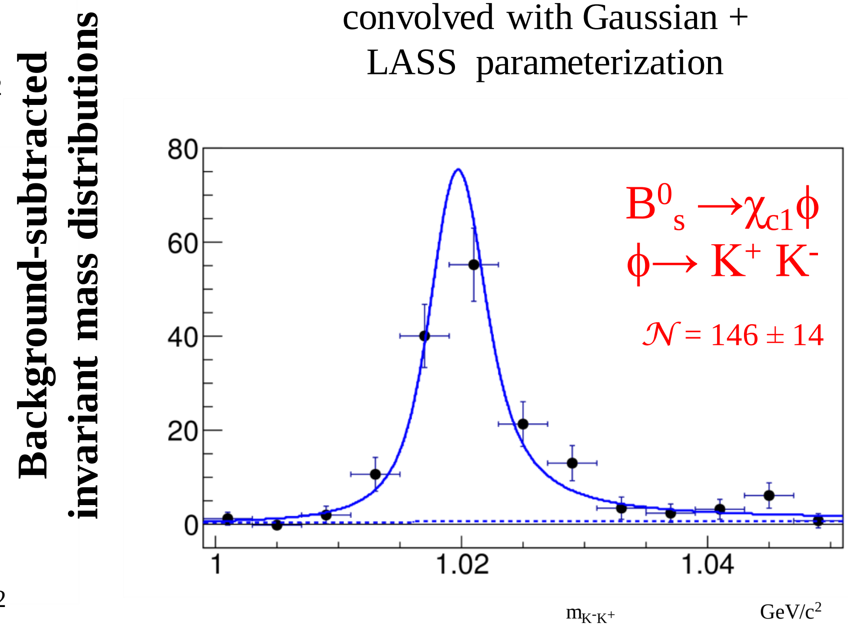


Same B^0_s candidate mass is calculated with the $J/\psi\gamma$ inv. mass constrained to the χ_{c1} or χ_{c2} mass



Signal: **Gaussian**
Background: **exponential**

Relativistic P-wave Breit-Wigner convolved with Gaussian + LASS parameterization



LHCb :

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

J^{PC} of X(3872) determination in B+ decay

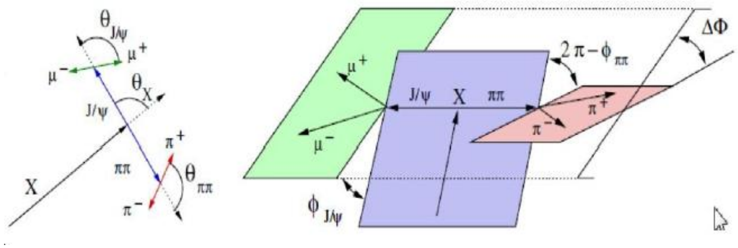
X(3872) discovered by Belle almost 10 years ago, but its nature still not clear

- ✓C-parity is positive since $X(3872) \rightarrow J/\psi\gamma$ observed
- ✓CDF: **excluded all** but cannot distinguish between **1^{++}** and **2^{-+}** PRL98 (2007) 132002
- ✓BaBar: the observed mass distribution of ω in $X(3872) \rightarrow J/\psi\omega\,(\omega \rightarrow \pi^+\pi^-\pi^0)$ favored **2^{-+}** (CL=68%) , but not ruled out **1^{++}** (CL=7%) PRD82 (2010) 011101
- ✓Belle: 1D analysis on polarized *X(3872)* could not distinguish between **1^{++}** and **2^{-+}** PRD84 (2011) 052004

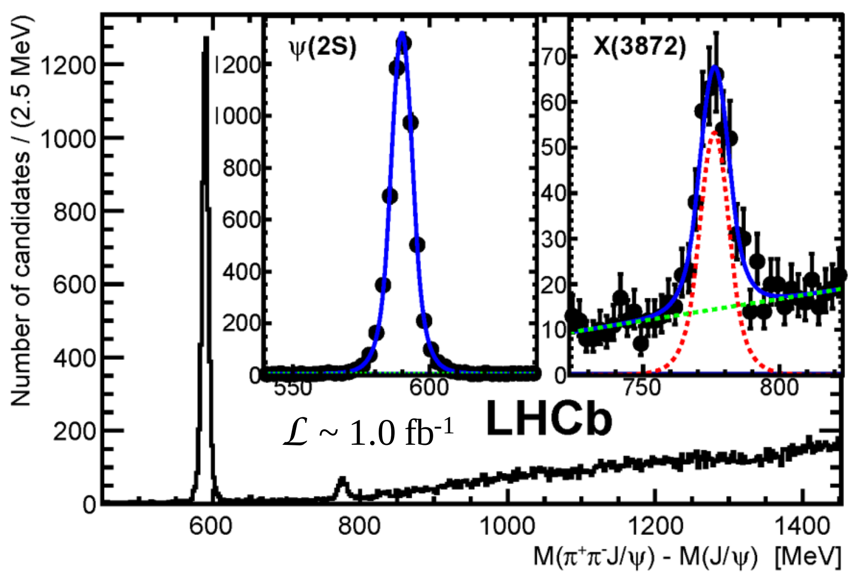
Determination of quantum numbers is crucial for theoretical interpretation of this state

- ✓ 1^{++}: molecule? tetra-quarks? $\chi_{c1}(2^3P_1)$?
- ✓ 2^{-+} : $\eta_{c2}(1^1D_2)$?

J^{PC} of X(3872) determination



Angular analysis of $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$
The angular correlation in the B^+ decay carry information about J^{PC} of the X(3872)
Complete 5-dimensional angular correlations

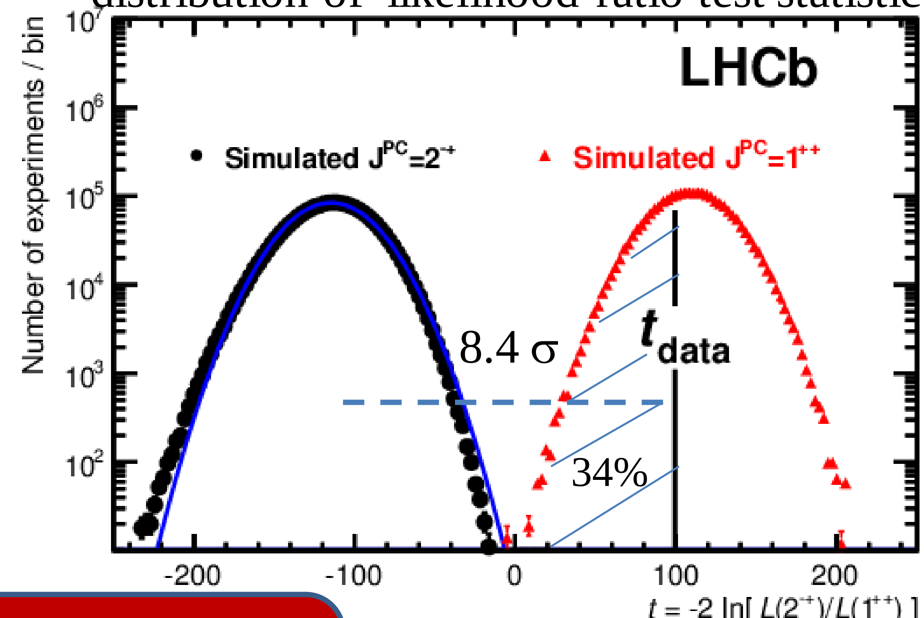


$B^+ \to X(3872)K^+$, $\mathcal{N} = 313 \pm 26$
$B^+ \to \psi(2S)K^+$, $\mathcal{N} = 5642 \pm 76$

Likelihood-ratio test to discriminate between 1^{++} and 2^{-+} hypotheses

$$t = -2 \ln[\mathcal{L}(2^{-+})/\mathcal{L}(1^{--})]$$
$t > 0$ implies 1^{++}
$t < 0$ implies 2^{-+}

Result of numerical simulation (2M experiments for each hypothesis) for the distribution of likelihood-ratio test statistic



LHCb:
$t_{data} = +99$ observed 1^{++} favored
2^{-+} rejected with a significance of 8.4σ
1^{++} *p*-value is high (34%)

LHCb, PRL 110 (2013) 222001

B decays to charmonium and dibaryons

The study of such B 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
$B^+ \to K^+ p \bar{p}$ or $B^0 \to \bar{D}^0 p \bar{p}$

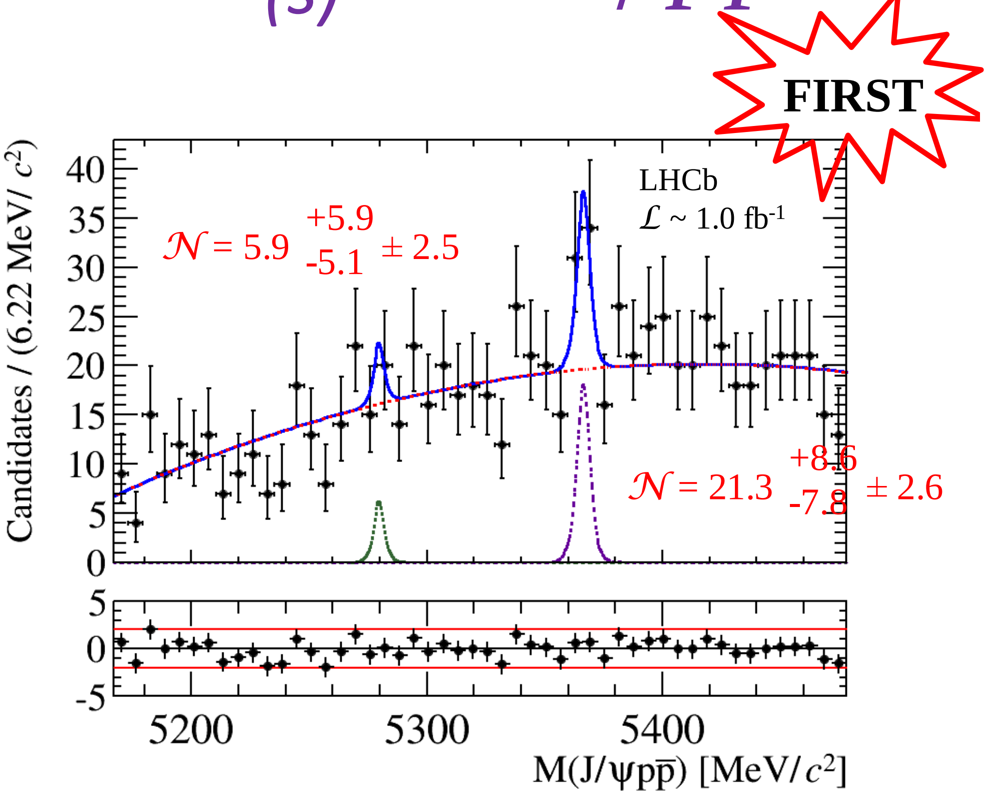
Branching fraction is ~10% that of the corresponding decay with $p\bar{p}$ replaced by $\pi^+ \pi^-$

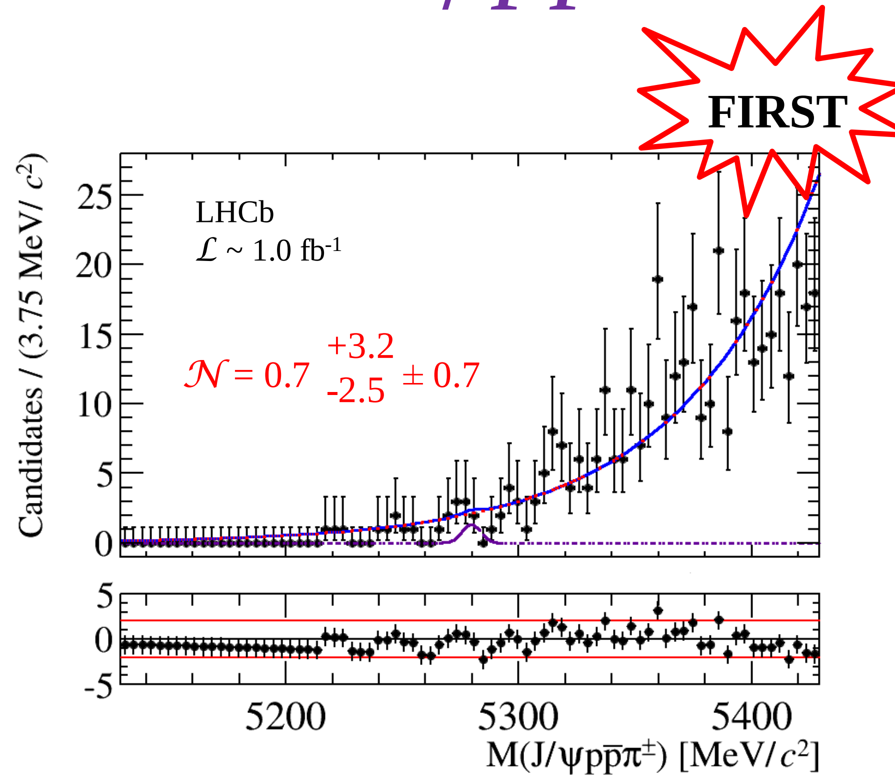
In contrast

$$\mathcal{BR}(B_d \to J/\psi \pi^+ \pi^-) = (4.6 \pm 0.9) \times 10^{-5}$$
$$\mathcal{BR}(B_d \to J/\psi\, p\bar{p}) < 8.3 \times 10^{-7} \text{ (90\% C.L.)}$$

~50 times low

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





LHCb, arXiv: 1306.4489

no significant signals are seen

LHCb :

$\mathcal{BR}$ ($B^0 \to J/\psi pp$) < 5.2 (6.0) x 10^{-7} @ 90% (95%) CL,

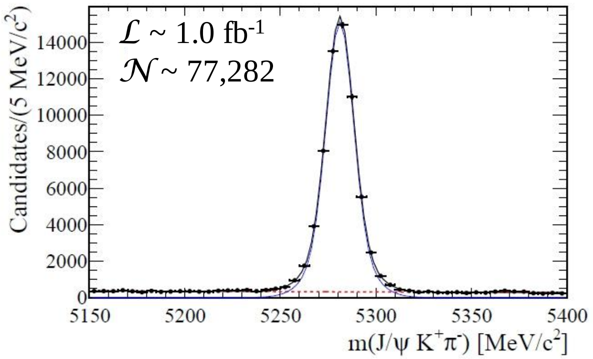
$\mathcal{BR}$ ($B^0_s \to J/\psi pp$) < 4.8 (5.3) x 10^{-6} @ 90% (95%) CL,

$\mathcal{BR}$ ($B^+ \to J/\psi pp\pi^+$) < 5.0 (6.1) x 10^{-7} @ 90% (95%) CL

Normalization channel $B^0_s \to J/\psi \pi^+ \pi^-$

Angular analysis of $B_d \to J/\psi K^{*0}(872)$

- $P \to VV$
- Angular acceptance from MC
- $K\pi$ final state can be decomposed in terms:



✓P-wave amplitudes:

A_0 (longitudinal), $A_\parallel$ (transverse-parallel), $A_\perp$ (transverse-perpendicular)

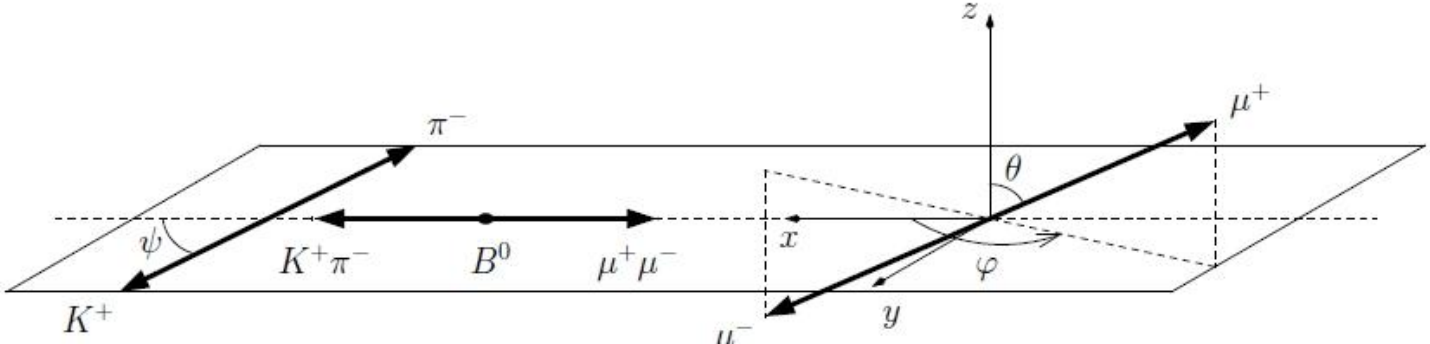
✓S-wave amplitude:

A_s (non-resonant $K\pi$ system)

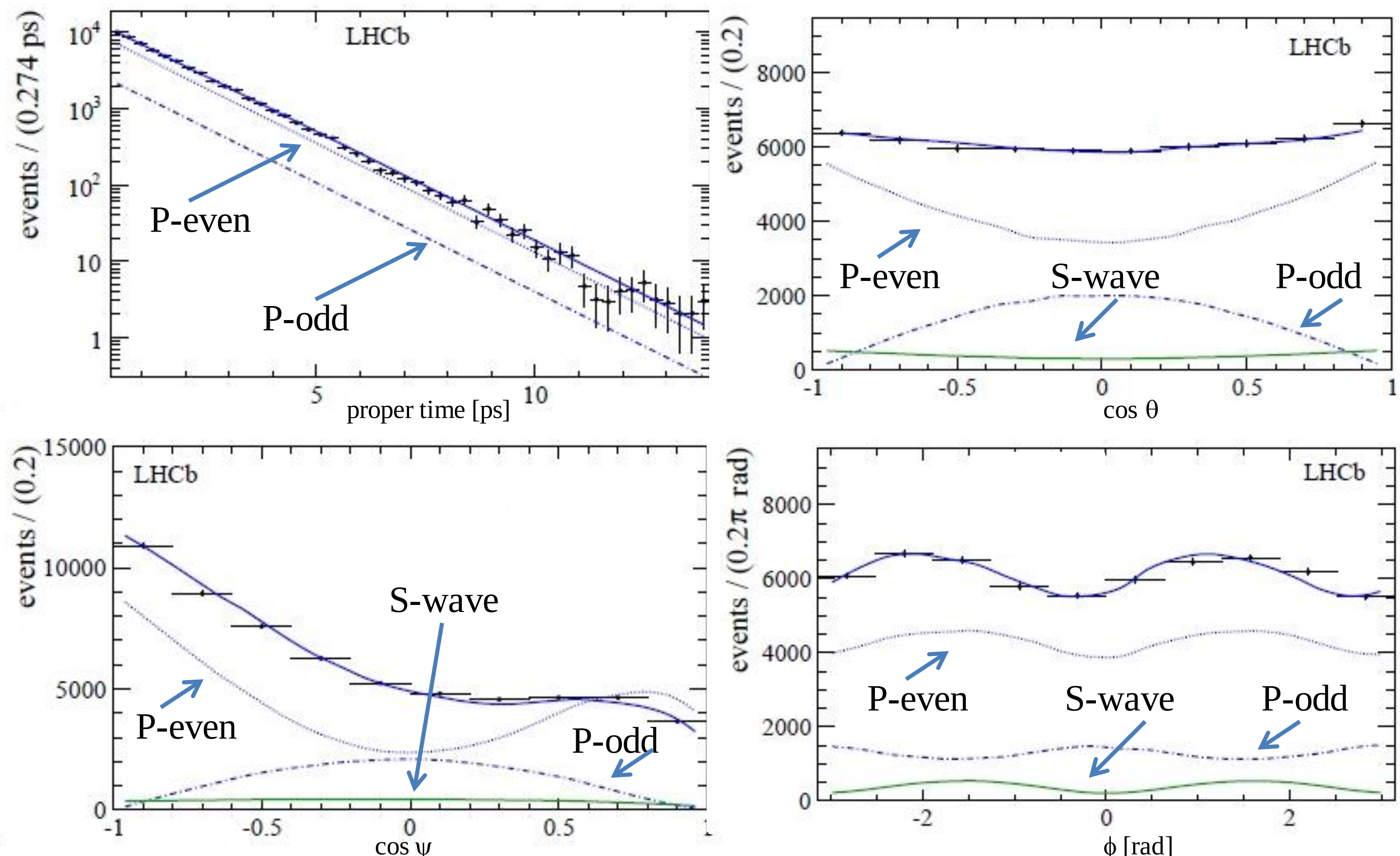
✓ strong phases of 4 amplitudes are denotes δ_0 , $\delta_\parallel$, $\delta_\perp$, δ_s

✓ parity: even for (A_0 , $A_\parallel$); odd for ($A_\perp$, A_s)

Individual polarization amplitudes (A_0 , $A_\parallel$, $A_\perp$, A_s) is analyzed in terms of the 3 transversity angles ($\cos\theta, \phi, \cos\psi$)



Angular analysis of $B_d \to J/\psi K^{*0}(872)$



Polarization amplitudes and their strong phases are measured

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

LHCb:
arXiv: 1307.2782

Conclusions

THANKS

First evidence for $\boldsymbol{B_d \to J/\psi\omega}$

✓measured relative branching ratio w.r.t $B_d \to J/\psi\, \rho0(770)$

First observation of $\boldsymbol{B_s \to \chi_{c1}\phi}$

✓measured relative branching ratios w.r.t J/ψ channels

J$^{\mathbf{PC}}$ of X(3872) determination

✓based on angular correlations in $B^+ \to X(3872)\, K^+$

First upper limits on $\boldsymbol{B_s \to J/\psi pp}$ and $\boldsymbol{B^+ \to J/\psi pp\pi^+}$

✓ measured w.r.t $B_s \to J/\psi\, \pi^+ \pi^-$

Measurement of the ***P-wave*** polarization amplitudes in $\boldsymbol{B_s \to J/\psi K^{*0}(892)}$

More results in

Measurement of ϕ_s at LHCb
Wandernoth, Sebastian

Measurements of b hadron lifetimes and effective lifetimes at LHCb
Eklund, Lars

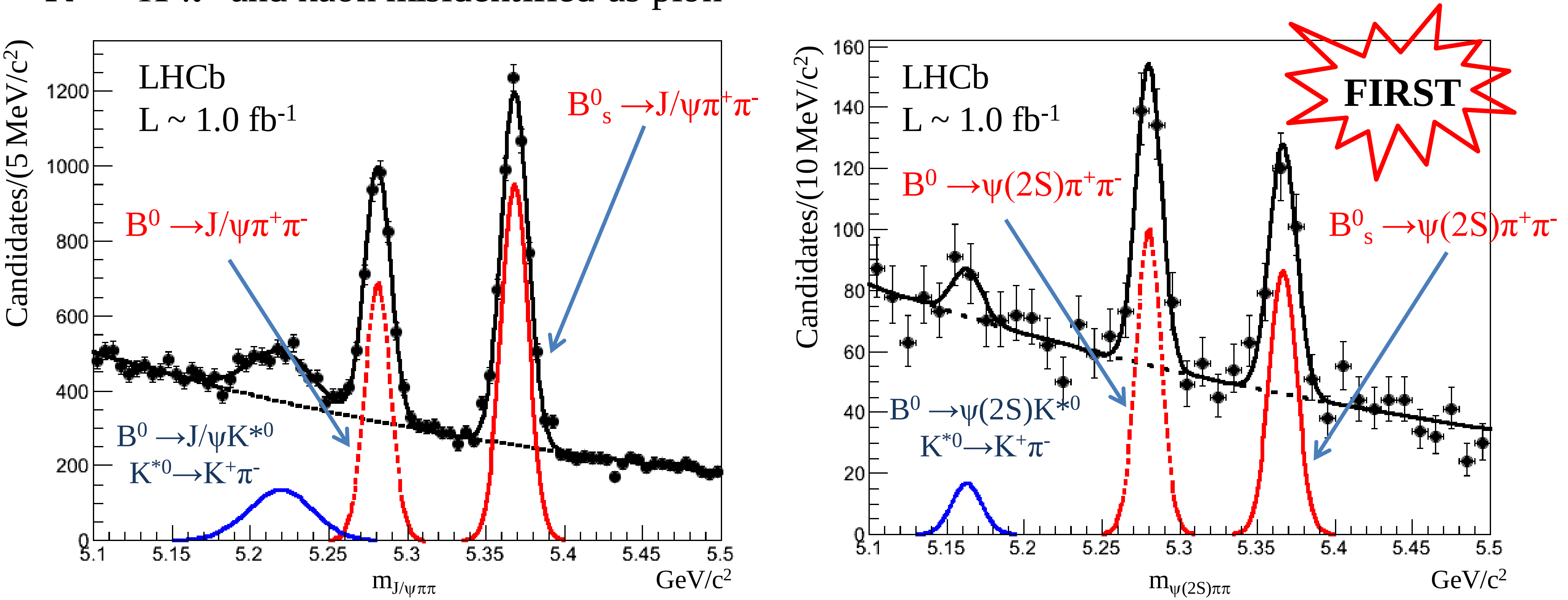
Studies of the properties and decays of the Bc meson at LHCb
Tuning, Niels

Backup

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

LHCb,
Nucl Phys B871 (2013) 403

Signal: **Gaussian**; Background: **exponential;**
Bifurcated Gaussian for contribution from $B^0 \to J/\psi K^{*0}$ or $B^0 \to \psi(2S)K^{*0}$, where $K^{*0} \to K^+\pi^-$ and kaon misidentified as pion

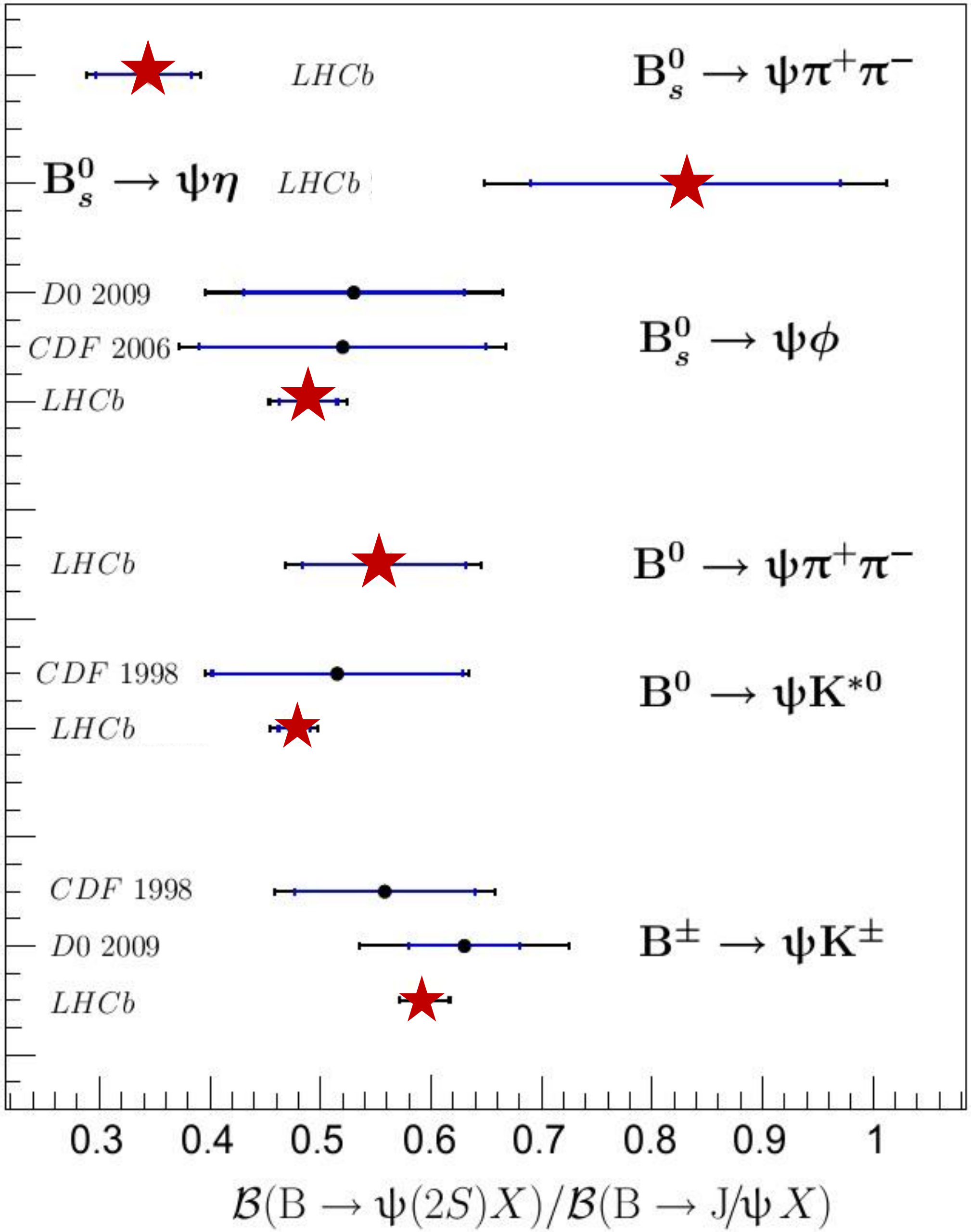


LHCb :

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

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

B decays to J/ψ or $\psi(2S)$ states



LHCb,
Nucl Phys B871 (2013) 403

LHCb,
Eur Phys J C72 (2012) 2118

$\Lambda_b \to J/\psi\Lambda$ decay amplitudes

For Λ_b baryons originating from energetic *b*-quarks, heavy-quark effective theory predicts:

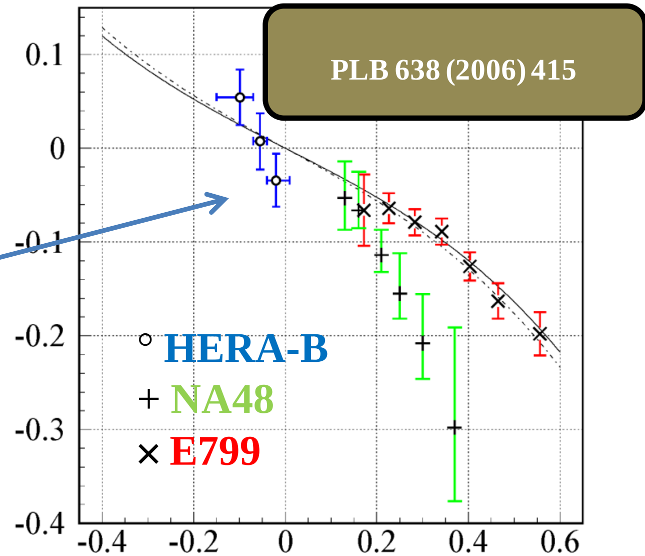
PLB 614 (2005) 165

- large fraction of the transverse *b*-quark polarization to be retained after hadronisation
- longitudinal polarization should vanish due to parity conservation in strong interactions

Measured in $e^+e^- \to Z^0 \to bb$ transition (at LEP), but not yet at any hadron machine

Hints from hadron machine:

- baryon polarization strongly depends on x_F
- vanishes at $x_F \sim 0$ (Λ^0)

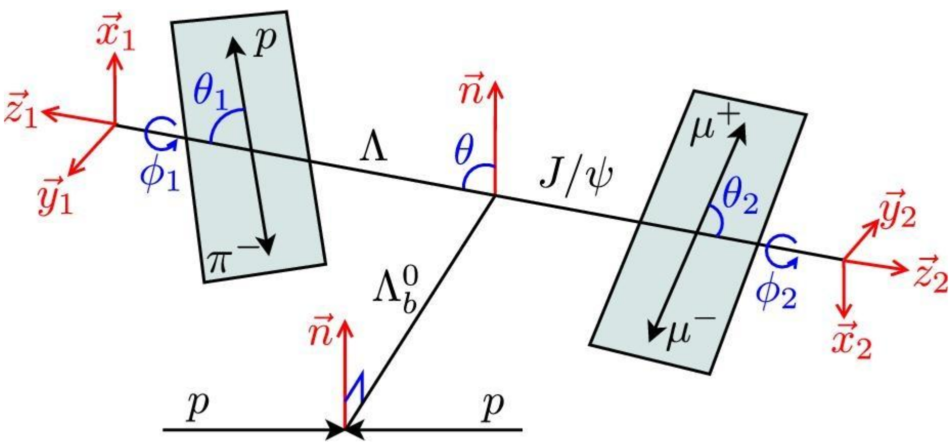


$$x_F = \frac{2p_L}{\sqrt{s}}$$

But with very small x_F~0.02 for Λ_b baryons at LHC polarization could be much smaller than 10%

$\Lambda_b \to J/\psi\Lambda$ decay amplitudes

	Λ_b	$\to$	J/ψ	+	Λ
J:	½	$\to$	1		½



The angular distribution depends on:

- ✓transverse polarization parameter P_b
- ✓$\Lambda \to p\pi^-$ decay asymmetry parameter α_b
- ✓4 helicity amplitudes $\mathcal{M}_{+½,0}$ $\mathcal{M}_{-½,0}$ $\mathcal{M}_{-½,-1}$ $\mathcal{M}_{+½,+1}$
- ✓5 angles $(\theta, \theta_1, \theta_2, \phi_1, \phi_2)$

Amplitudes parameterization:

$$r_0 = |\mathcal{M}_{+½,0}|^2 + |\mathcal{M}_{-½,0}|^2$$
$$r_1 = |\mathcal{M}_{+½,0}|^2 - |\mathcal{M}_{-½,0}|^2$$
$$\alpha_b = r_1 + |\mathcal{M}_{-½,-1}|^2 - |\mathcal{M}_{+½,+1}|^2$$

Parity violation asymmetry parameter of $\Lambda_b \to J/\psi\Lambda$

Functions used to describe the angular analysis

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	$-\frac{1}{2}(1+r_0)$	$P_b\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta\cos\theta_1$

Four parameters:

P_b, α_b, r_0 and r_1

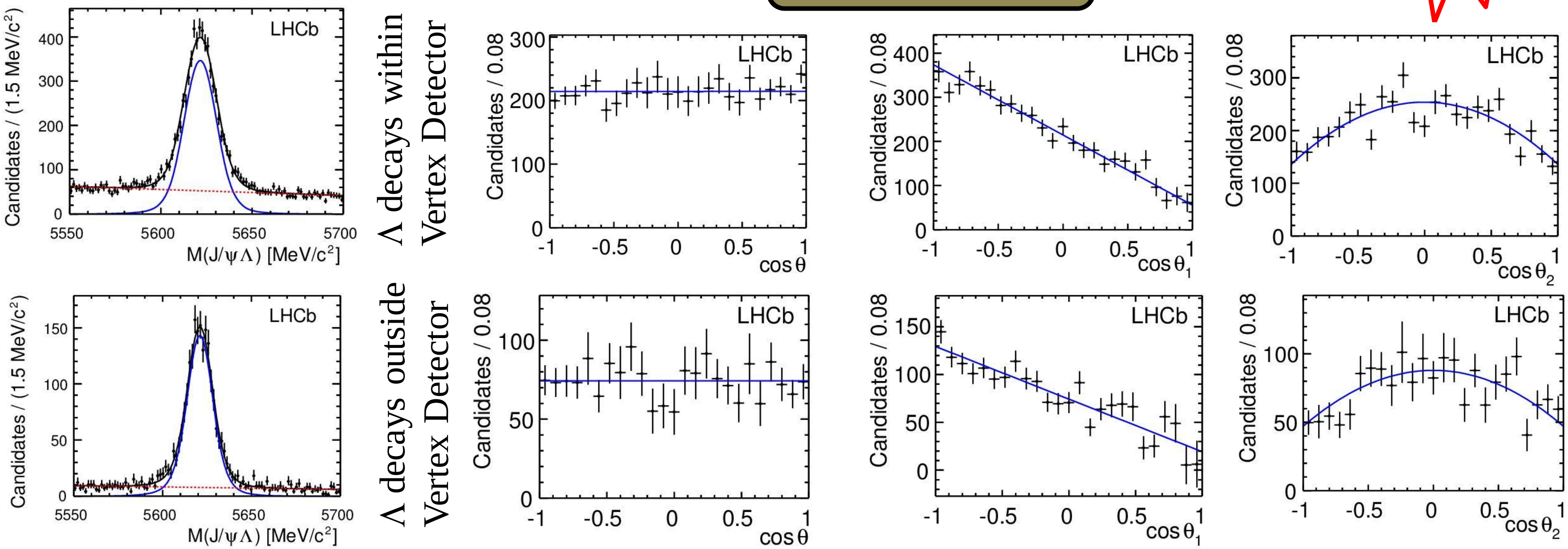
have to be measured simultaneously from the angular analysis

$\Lambda_b \to J/\psi\Lambda$ decay amplitudes

FIRST

$\mathcal{L} \sim 1.0\ \text{fb}^{-1}$, $\mathcal{N} \sim 7200$

LHCb, Phys Lett B724 (2013) 27



First measurement of the Λ_b polarization $\boldsymbol{P_b}$ in *pp* collisions and parity-violation asymmetry parameter $\boldsymbol{\alpha_b}$

LHCb :

$P_b = 0.06 \pm 0.07 \pm 0.02,$

$\alpha_b = 0.05 \pm 0.17 \pm 0.07,$

$r_0 = 0.58 \pm 0.02 \pm 0.01,$

$r_1 = 0.56 \pm 0.10 \pm 0.05$

Polarization parameter P_b :

- ✓**cannot exclude** order of 10% transverse polarization
- ✓but **disfavors** 20% at the level of 2.7σ

Parity-violation parameter

- ✓**compatible** with predictions ranging -21% to -10%
- ✓but **rejects** HQET prediction 77.7% at 6.1σ