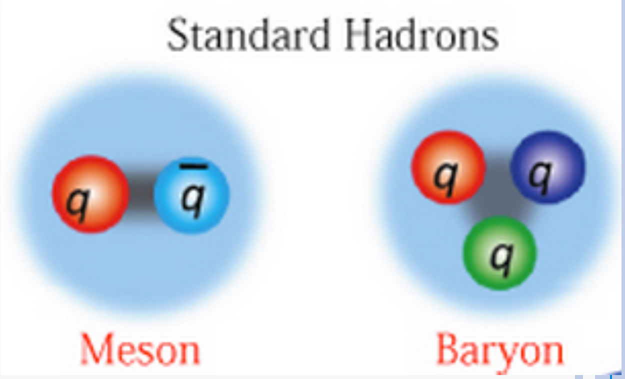
RESULTS AND PLANS FOR SPECTROSCOPY AT *LHCb*

Marco Pappagallo

B-Workshop
Neckarzimmern, 18-20 February 2015

DICTIONARY

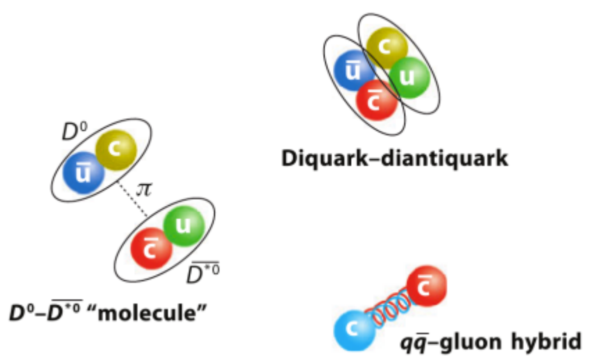
- ✓ Heavy quark = *charm* or *beauty*
- ✓ Heavy Meson = ***qq'*** state, where ***q***=*c*,*b*
- ✓ Heavy Baryons = ***qq'q"*** state, where ***q* = *c*,*b***
- ✓ Doubly Heavy baryons = ***qq'q"***, where ***q*** & ***q'* = *c*,*b***
- ✓ Quarkonia = Heavy Meson where ***q*=*q'*=*c*,*b***



Quarkonia-like state may be:

- ➢ Maybe conventional quarkonia
- ➢ Multiquark states:
  - Molecular state: loosely bound meson-meson state
  - Tetraquark: tightly bound four-quark state
- ➢ Hybrid meson
- ➢ Threshold effect

….in practice everything which doesn't fit in the standard quarkonia picture



arXiv:0801.3867

OUTLINE

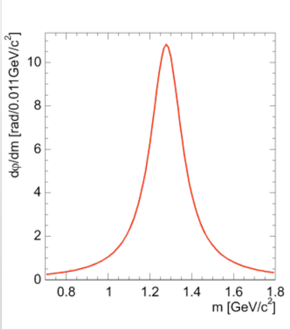
- ➢ Results
  - ✓ Heavy meson spectroscopy
  - ✓ Heavy baryon spectroscopy
  - ✓ Spectroscopy of charmonium-like states
- ➢ Plans

HOW TO DO SPECTROSCOPY?

“Inclusive Analysis”

(e.g. e^+e^- → D(→Dπ) + X or pp → B_s**(→BK) + X)**

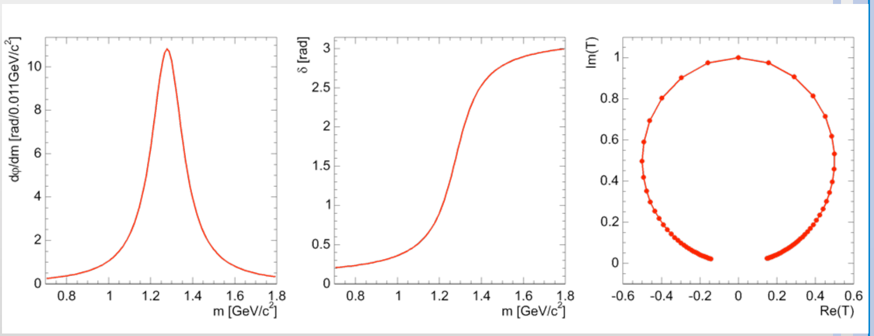
- Large cross sections 😄
- Large combinatorial background 😞
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization 😰



“Exclusive Analyses”

(e.g. B →D(→Dπ)π or B_c→B_s**(→BK)π)**

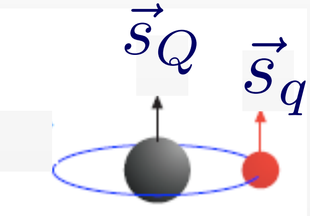
- Limited statistics 😞
- Small background 😄
- Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference) 😄
- Suitable to study broad resonances
- Spin-parity assignment by amplitude analysis 😰



Heavy Meson Spectroscopy

INTRODUCTION

- The heavy quark effective theories (HQET) predict the masses of the heavy mesons $D_{(s)}$ and $B_{(s)}$ by a perturbative expansion of $\Lambda_{QCD}/m_Q \sim 0$
- Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET



$\vec{L}$	Orbital angular momentum
$\vec{j}_q = \vec{L} + \vec{s}_{q=u,d,s}$	Angular momentum of the light quark
$\vec{J} = \vec{j}_q + \vec{s}_{Q=b,c}$	Total angular momentum of the heavy meson

Spectroscopy notation

Radial quantum number

$\boxed{n^{2S+1}L_J}$

Sum of quark spins

$L = 0,1,2\ldots$ → S, P, D

PDG notation

Natural spin-parity $J^P = 0^+, 1^-, 2^+, \ldots$

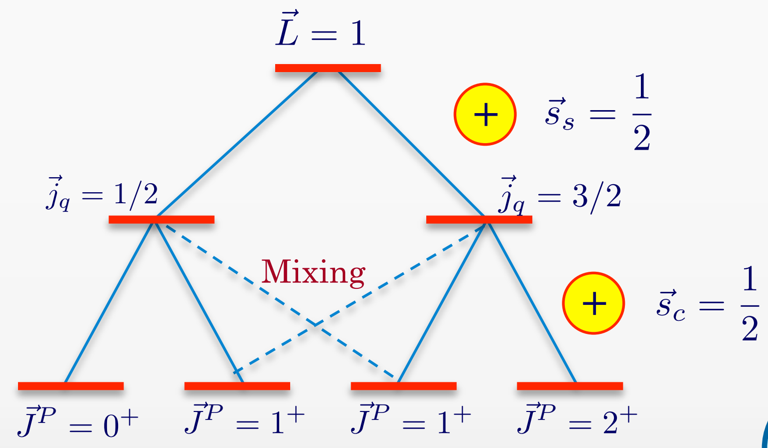
$\boxed{D^*_J(m)^{0/\pm} \text{ or } B^*_J(m)^{0/\pm}}$

Mass

EXCITED CHARMED AND BEAUTY STATES

For L>0, there are four different possible (J, j_q) combinations

E.g. Orbitally L=1 excited $D_s^{**} \rightarrow D^{(*)}K$



D_{s0}^* **D'_{s1}** **D_{s1}** **D_{s2}^***

Two Broad States decaying in S-wave (Γ~100 MeV)

j_q = 1/2 doublet

Two Narrow States decaying in D-wave (Γ~ 1÷10 MeV)

j_q = 3/2 doublet

	j_q	J^P	Allowed decay mode	
			DK	D^*K
$\mathbf{D_{s0}^*}$	1/2	0^+	yes	no
$\mathbf{D'_{s1}}$	1/2	1^+	no	yes
$\mathbf{D_{s1}}$	3/2	1^+	no	yes
$\mathbf{D_{s2}^*}$	3/2	2^+	yes	yes

The four states come in doublets and within each doublet :

- ✓ 1 natural state (D_{s2}^*) decaying to DK and D*K
- ✓ 1 unnatural state (D_{s1}) decaying to D*K

(Only exception is the (0^+,1^+) doublet above)

Similar picture for the excited $B^{**} \rightarrow B^{(*)}\pi$, $B_s^{**} \rightarrow B^{(*)}K$, $D^{**} \rightarrow D^{(*)}\pi$

HOW A DOUBLET LOOKS LIKE

Exclusive analysis

$B^- \rightarrow D^{(*)+} \pi^- \pi^-$

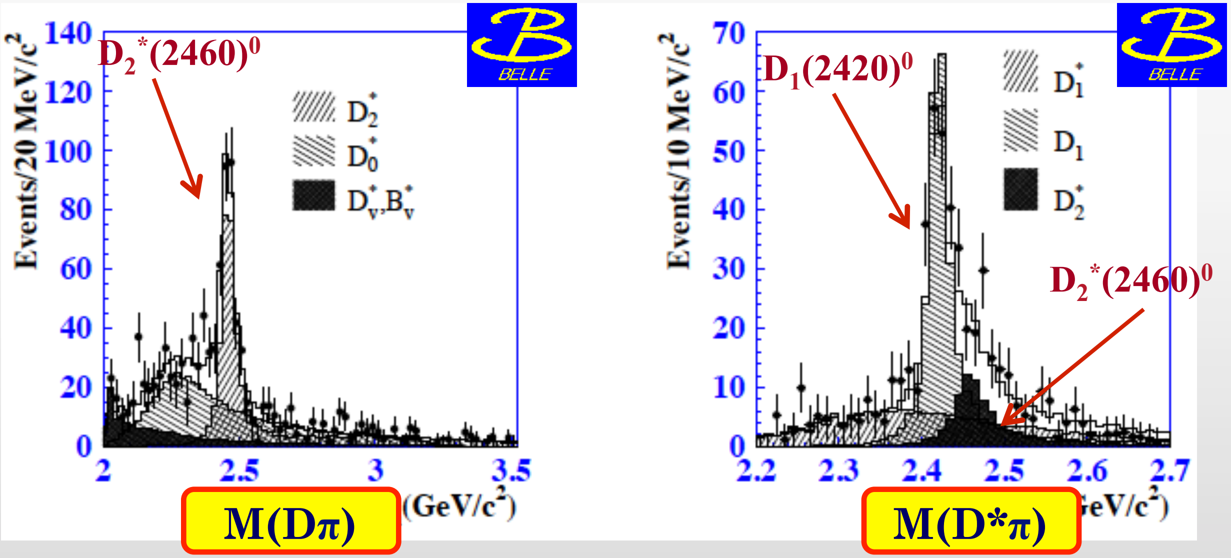
[Belle: Phys.Rev.D69 (2004) 112002]

j_q=3/2 doublet

- 1 peak in Dπ
- 2 peaks in D*π

} as expected

	j_q	J^P	Allowed decay mode $D\pi$	$D^*\pi$
D_0^*	$1/2$	0^+	yes	no
D_1'	$1/2$	1^+	no	yes
D_1	$3/2$	1^+	no	yes
D_2^*	$3/2$	2^+	yes	yes



Broad states of the j=1/2 doublets also revolved by an amplitude analysis

HOW A DOUBLET LOOKS LIKE

Inclusive analysis

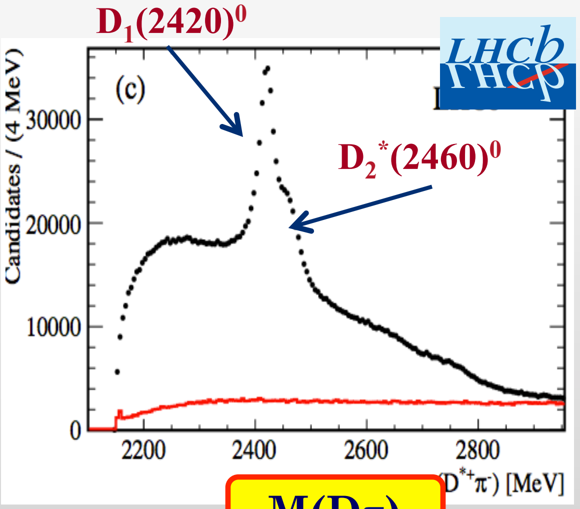
$pp \rightarrow D^{(*)+} \pi^- + X$

[LHCb: JHEP 09 (2013) 145]

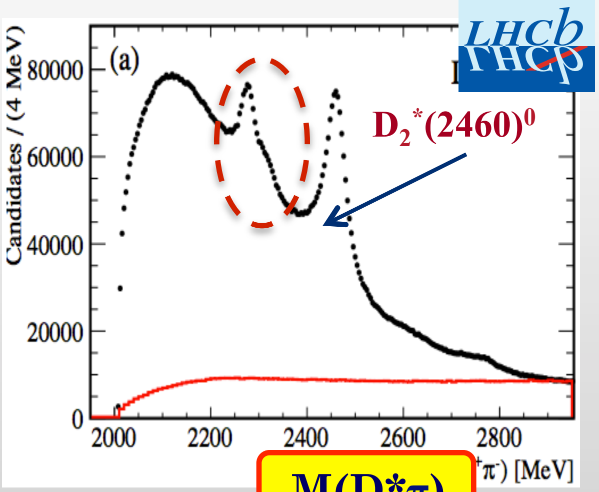
j_q=3/2 doublet

- ~~1 peak in Dπ~~ 3 peaks in Dπ?
- 2 peaks in D*π

	j_q	J^P	Allowed decay mode	
			$D\pi$	$D^*\pi$
D_0^*	1/2	0^+	yes	no
D_1'	1/2	1^+	no	yes
D_1	3/2	1^+	no	yes
D_2^*	3/2	2^+	yes	yes



M(Dπ)



M(D*π)

FEED-DOWNS OF $D_1/D_2^* \rightarrow D^*\pi$ DECAYS INTO $D\pi$ MASS SPECTRUM

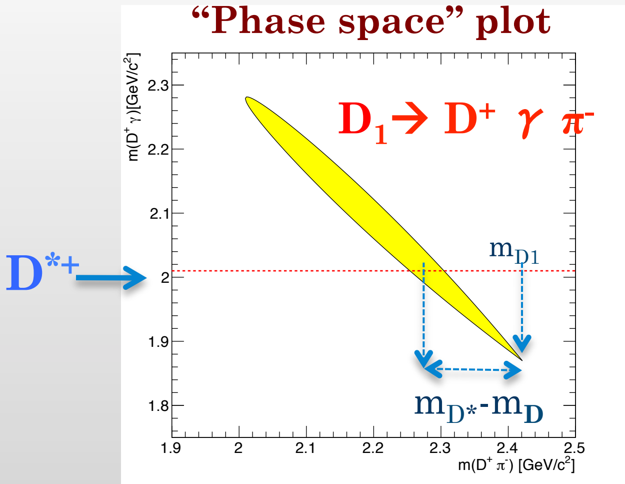
Inclusive analysis
$pp \rightarrow D^{(*)+} \pi^- + X$
[LHCb: JHEP 09 (2013) 145]

j_q=3/2 doublet

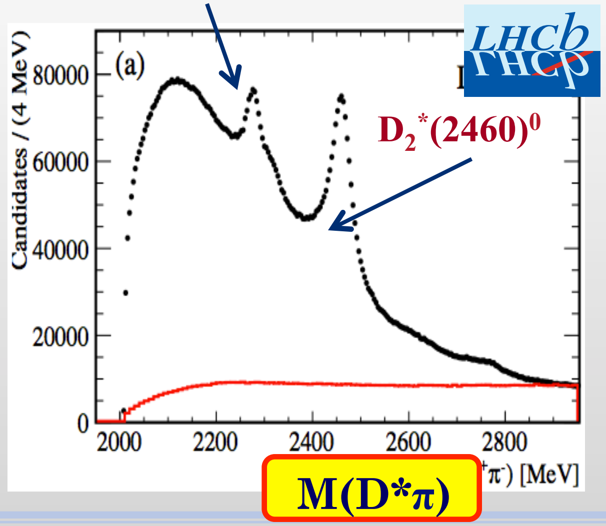
- 3 peaks in Dπ
  - ✓ $D_2^* \rightarrow D\pi$
  - ✓ $D_1 \rightarrow D^*\pi$ feed-down
  - ✓ $D_2^* \rightarrow D^*\pi$ feed-down
- 2 peaks in D*π

overlapped if Γ > m(D*)-m(D)

	j_q	J^P	Allowed decay mode $D\pi$	$D^*\pi$
D_0^*	1/2	0^+	yes	no
D_1'	1/2	1^+	no	yes
D_1	3/2	1^+	no	yes
D_2^*	3/2	2^+	yes	yes


"Phase space" plot

$D_1(2420)^0$ /$D_2^*(2460)^0$ feed-down
└▶ $D^{*+} \pi^-$
└▶ $D^+ \gamma/\cancel{\pi}^0$



THE EXCITED D$_{(s)}$ STATES

- The charmed excited states studied in inclusive analyses and into B decays
- The orbitally L=1 excited $D_{(s)}^{**}$ states observed first
- Masses and properties well predicted by theory

D** (L=1)

j_q = 1/2 doublet

j_q = 3/2 doublet

	Mass (MeV)	Width (MeV)
$D_0^*(2400)^0$	2318 ± 29	267 ± 40
$D_0^*(2400)^\pm$	2403 ± 40	283 ± 40
$D_1(2430)^0$	2427 ± 40	384^{+130}_{-110}
$D_1(2430)^\pm$	—	—
$D_1(2420)^0$	2421.4 ± 0.6	27.4 ± 2.5
$D_1(2420)^\pm$	2423.2 ± 2.4	25 ± 6
$D_2^*(2460)^0$	2462.6 ± 0.6	49.0 ± 1.3
$D_2^*(2460)^\pm$	2464.3 ± 1.6	37 ± 6

D_s** (L=1)

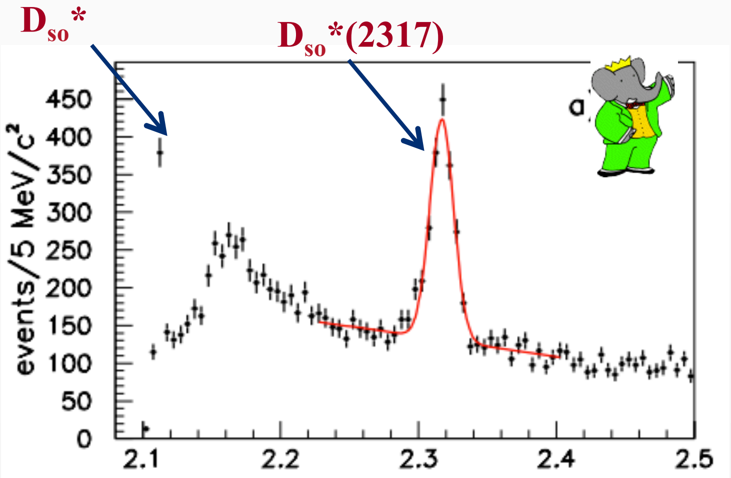
	Mass (MeV)	Width (MeV)
D_{s0}^*	—	—
D'_{s1}	—	—
$D_{s1}(2536)^\pm$	2535.10 ± 0.08	0.92 ± 0.05
$D_{s2}^*(2573)^\pm$	2571.9 ± 0.8	17 ± 4

j_q = 3/2 doublet

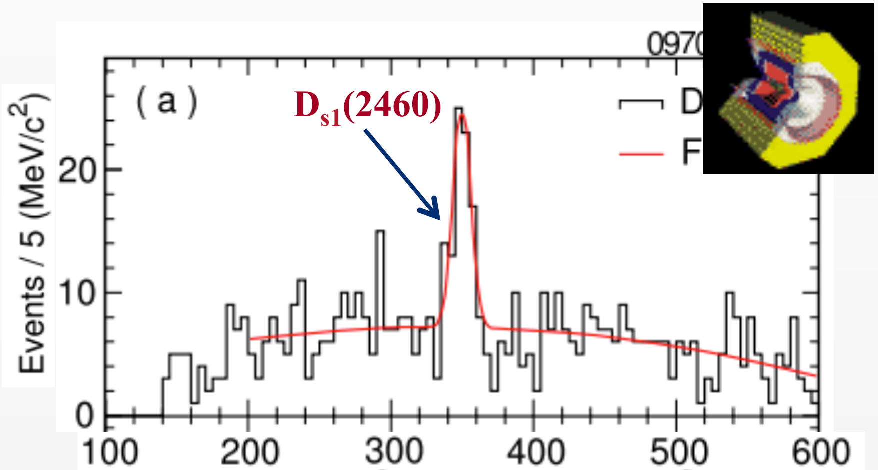
D_{s0}* and D_{s1}' states expected broad and to be studied in B_s decays…

Puzzle:
Excited D_s Mesons: L=1, j_q = 1/2(?)

Inclusive studies of $D_s^{(*)}\pi^0$
[BaBar, PRL90, 242001][CLEO, PRD68, 032002]



$M(D_s\pi^0)$

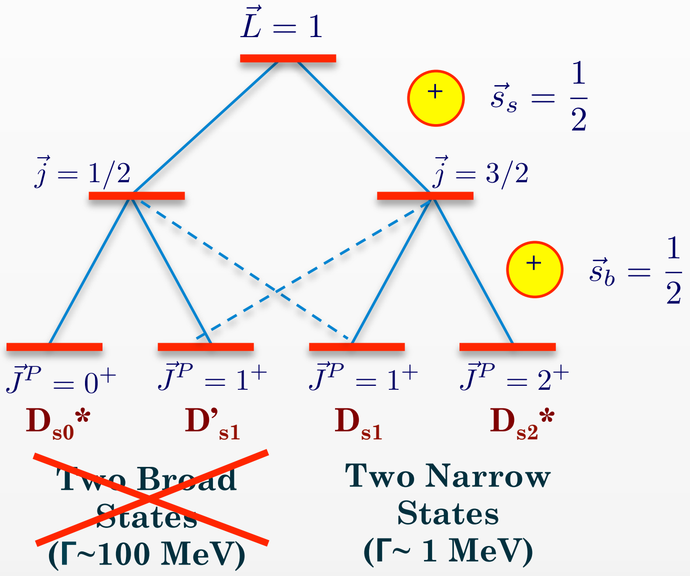


$M(D_s\gamma\pi^0)$-$M(D_s\gamma)$

PDG	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^\pm$	2317.7 ± 0.6	< 3.8
$D_{s1}(2460)^\pm$	2459.5 ± 0.6	< 3.5

Surprisingly narrow!

PUZZLE: EXCITED D_s MESONS: L=1, j_q = 1/2(?)



~~M(D_{s0}*) > m(D^0) + m(K^+)~~

~~M(D'$_{s1}$)~~
M(D_{s1})
M(D_{s2}*)
$\Big\}$> m(D^{*0}) + m(K^+)

	j_q	J^P	Allowed decay mode	
			D^0K^+	$D^{*0}K^+$
D^*_{s0}	1/2	0^+	no	no
D'_{s1}	1/2	1^+	no	no
D_{s1}	3/2	1^+	no	yes
D^*_{s2}	3/2	2^+	yes	yes

(1^+ → 0^- 0^- Forbidden)

- D_{s0}*/D_{s1}'→$D^{(*)}$K kinematically forbidden
- Isospin violation decays: D_{s0}* →D_s π^0 and D'$_{s1}$ →D_s* π^0

PUZZLE:
EXCITED D_s MESONS: L=1, j_q = 1/2(?)

- Spin-Parity $J^P = (0^+, 1^+)$ as expected for the L=1, j_q=1/2 states
- B→DD$_{s0}$* branching ratios below expectations (i.e. ~1) for a $q\bar{q}$ state **[PLB572, 164 (2003)][PRD69, 054002 (2004)]**

$$\frac{\mathcal{B}(B^+ \to \bar{D}^0 D_{s0}^{*+})}{\mathcal{B}(B^+ \to \bar{D}^0 D_s^+)} = 0.081^{+0.032}_{-0.025}$$

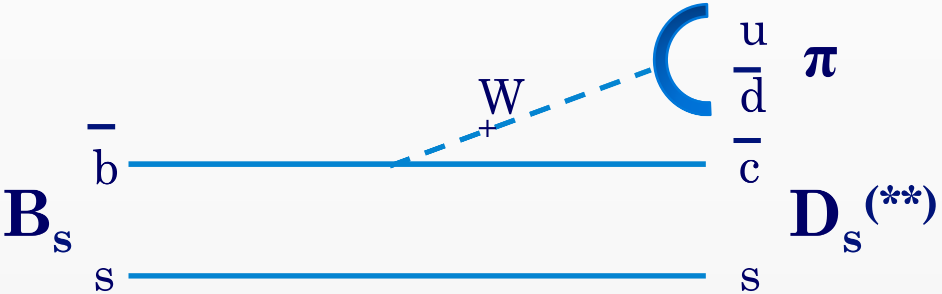
$$\frac{\mathcal{B}(B^0 \to D^- D_{s0}^{*+})}{\mathcal{B}(B^0 \to D^- D_s^+)} = 0.13 \pm 0.04$$

- Many alternative interpretations:
  DK or D_s π molecule, $q\bar{q}$ + tetraquark/DK mixing

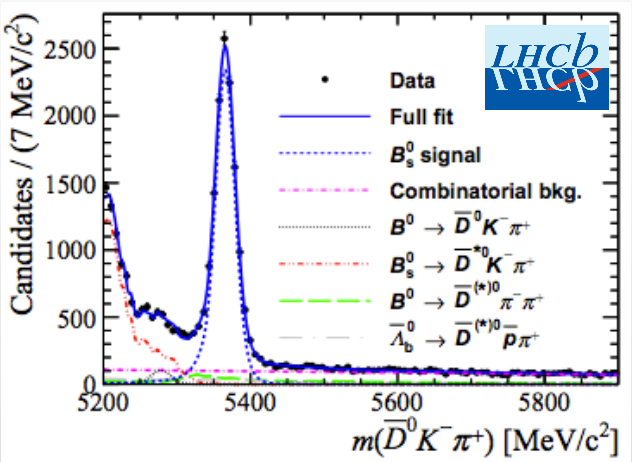
No $D_s^+\pi^\pm$ partners have been observed in inclusive studies **[BaBar: PRD74 (2006) 032007]** or in B decays **[Belle: R.Chistov@ EPS-HEP, Stockholm, Sweden (18 July 2013)]**

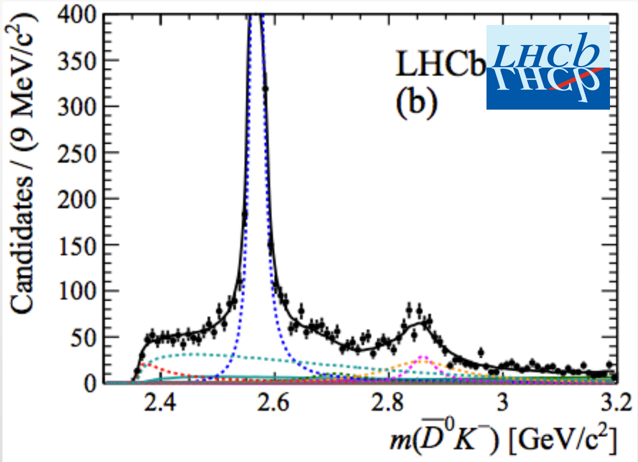
SEARCH FOR “D_{s0}*” IN B_s DECAYS

If the D_{s0}*(2317) is not the L=1, j_q=1/2 excited D_s state, then a broad D_{s0}* state above the DK threshold should appear in B_s decays

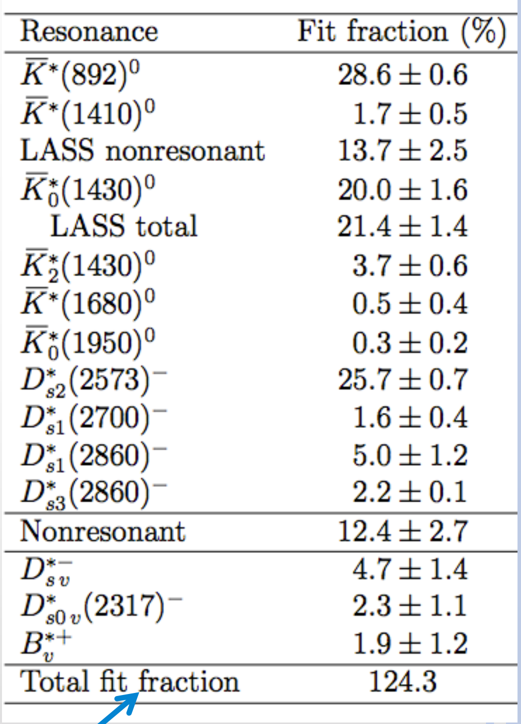


Amplitude analysis of $B_s \rightarrow D^0 K^- \pi^+$





[LHCb: PRL 113, 162001 (2014)]
[LHCb: PRD 90, 072003 (2014)]



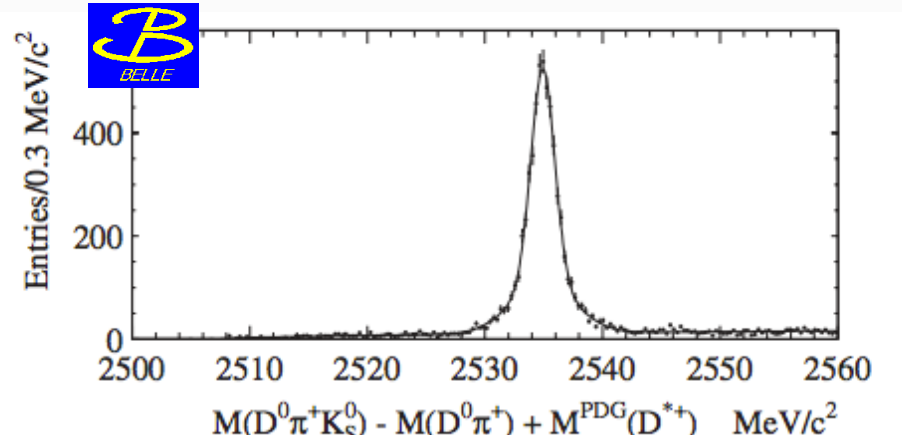
Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant	12.4 ± 2.7
$D_{s\,v}^{*-}$	4.7 ± 1.4
$D_{s0\,v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3

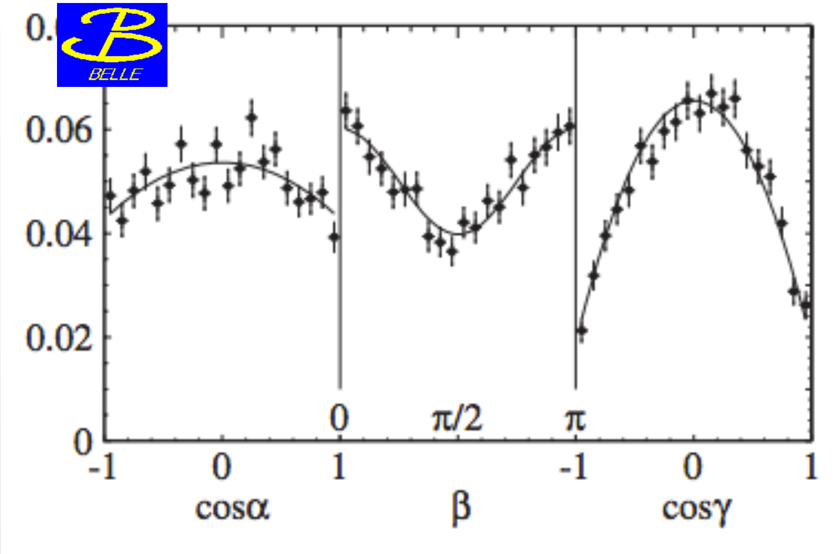
No evidence for such a broad D_{s0}* state

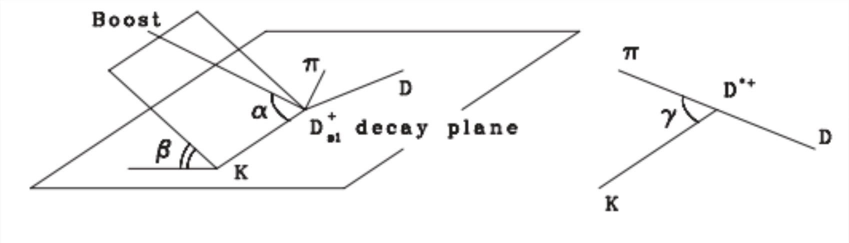
PUZZLE II:
IS $D_{s1}(2536)^+$ THE EXCITED L=1, j_q=3/2 STATE?

Angular analysis of $D_{s1}(2536)^+ \rightarrow D^{*+}K^0_S$ decay

[Belle: PRD77 (2008) 032001]







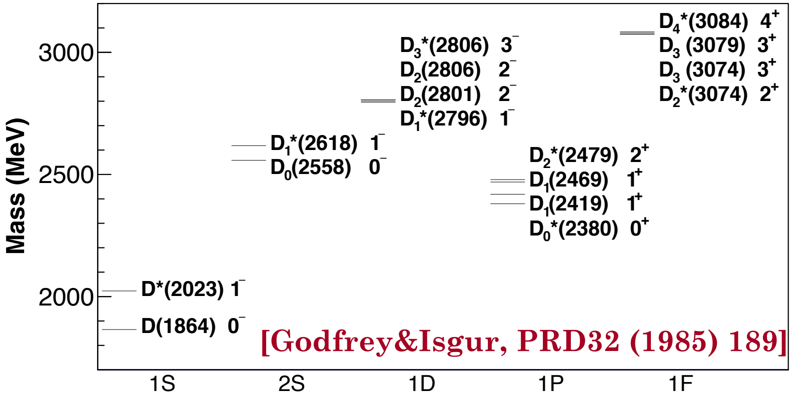
$$\frac{\Gamma_S}{\Gamma_{total}} = 0.72 \pm 0.05 \pm 0.01$$

Contrary of HQET expectations, the S-wave contribution dominates!

EXCITED D_J STATES

- The quark model predicts many excited states in limited mass regions
- Ground and 1P states well established
- BaBar collaboration has recently found 4 new states decaying to Dπ and/or D*π. Need to be confirmed. **[PRD82 (2010)111101]**

[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]



[Godfrey&Isgur, PRD32 (1985) 189]

LHCb: Inclusive study of $D^+(\rightarrow K\pi\pi)\pi^-$, $D^0(\rightarrow K\pi)\pi^+$ and $D^{*+}\pi^-$. Several millions of *D*'s in 1 fb^{-1}

- Natural spin-parity states ($J^P = 0^+, 1^-, 2^+, 3^- \ldots$) can decay to Dπ and D*π
- Unnatural spin-parity states ($J^P = 0^-, 1^+, 2^-, 3^+ \ldots$) can decay D*π

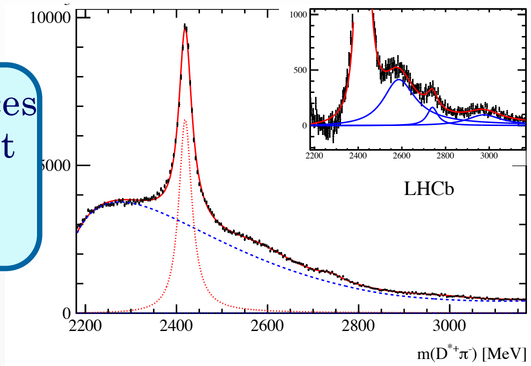
$\Downarrow$

- Dπ spectrum: natural spin-parity states + cross-feed of all states (expect 0^+)→D*π
- D*π spectrum: all states (expect 0^+). But different angular distribution ($\vartheta \equiv$ Helicity angle)
  - ✓ $\propto \sin^2\vartheta$ for natural spin-parity
  - ✓ $\propto 1 + h\cos^2\vartheta$ for unnatural spin-parity
  - ✓ Natural/Unnatural component can be enhanced with an ad hoc requirement on ϑ

D*π MASS SPECTRUM

[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]

① |cos ϑ| > 0.75 enhances unnatural component (residual natural component ~9%)

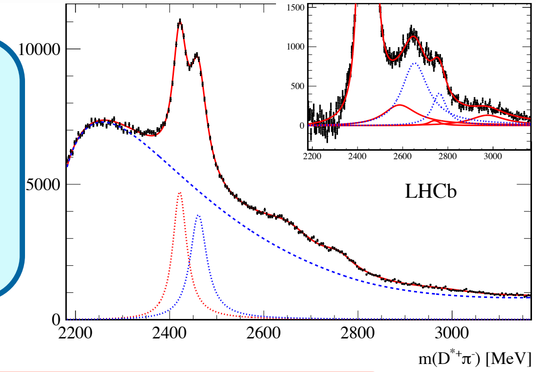


$D_1(2420)^0$ + 3 unnatural states:

$D_J(2580)$, $D_J(2740)$, $D_J(3000)$

②

- |cos ϑ|<0.5 enhances natural component
- Parameters of the unnatural states are fixed from Step 1



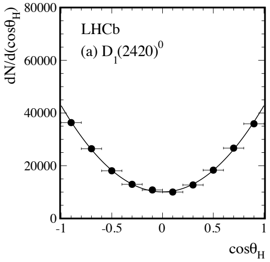
$D_2^*(2460)^0$ + unnatural states + 2 more natural states:

$D_J^*(2650)$, $D_J^*(2760)$

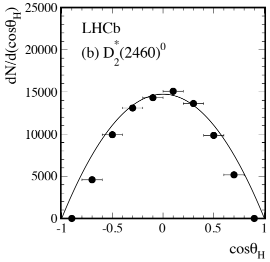
③

- Parameters of all states fixed from Step 1&2
- Fit performed in bins of cos ϑ to verify angular distributions

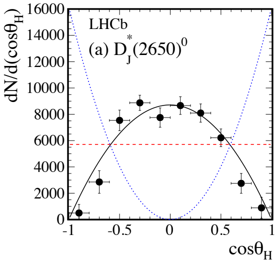
$D_1(2420)$ Unnatural



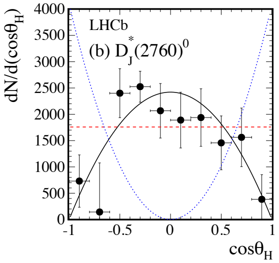
$D_2^*(2420)$ Natural



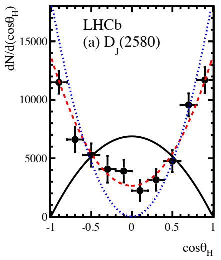
$D_2^*(2650)$ Natural



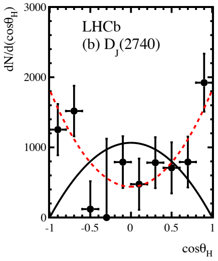
$D_2^*(2760)$ Natural



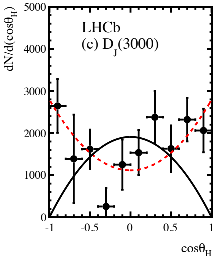
$D_J(2580)$ Unnatural



$D_J(2740)$ Unnatural



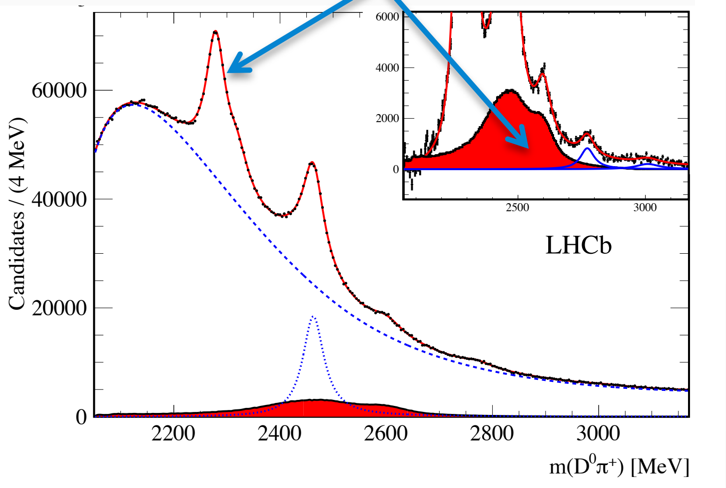
$D_J(3000)$ Unnatural

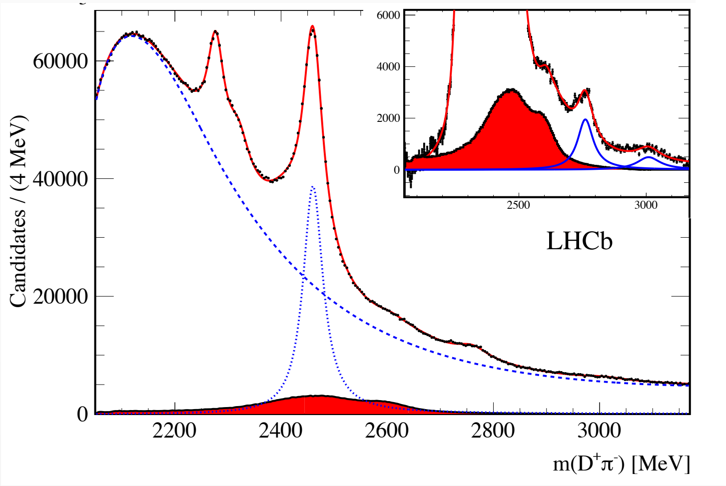


$D^0\pi^+/D^+\pi^-$ MASS SPECTRA

Cross-feeds estimated from states appearing in the $D^*\pi$ spectrum

[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]





2 more natural states:

$D_J^*(3000)^0$, $D_J^*(3000)^+$

Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Signif (σ)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50.7 \pm 2.2 \pm 2.3$	24.5
$D^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60.3 \pm 3.1 \pm 3.4$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7.7 \pm 1.1 \pm 1.2$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.5 ± 1.1	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675.0 \pm 9.0 \pm 1.3$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55.8 \pm 1.3 \pm 10.0$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	17.6 ± 1.1	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341.6 \pm 22.0 \pm 2.0$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20.1 \pm 2.2 \pm 1.0$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1(fixed)	110.5 (fixed)	7.6 ± 1.2	6.6

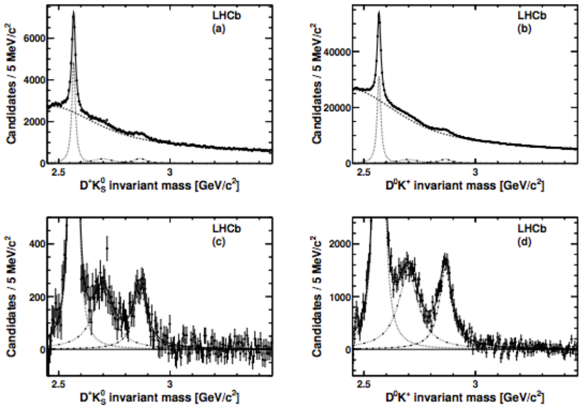
Study of $D^{(*)}\pi$ spectrum from B decays needed to establish spin-parity

EXCITED D_{sJ} STATES

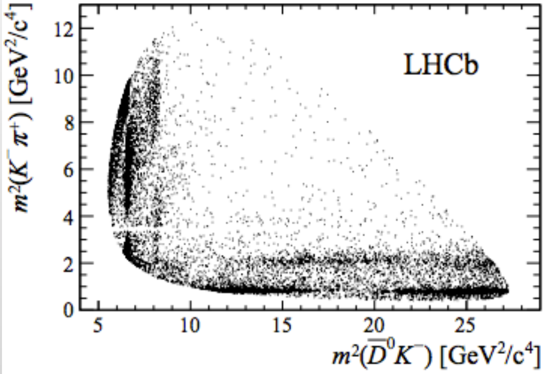
LHCb collaboration has recently confirmed 2 broad states decaying to DK:
$D_{s1}^*(2700)^+$ & $D_{sJ}^*(2860)^+$

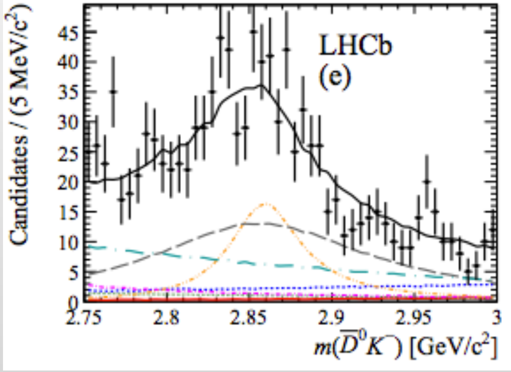
[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]

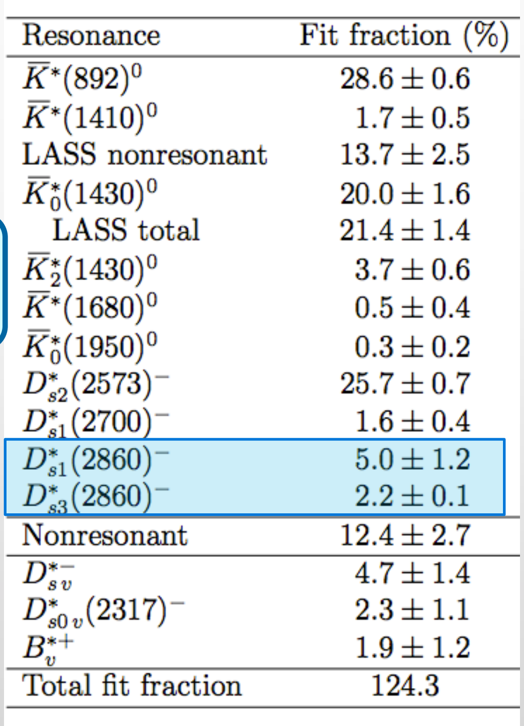
[LHCb, arXiv:1407.7574]
[LHCb, arXiv:1407.7712]



- LHCb has performed a Dalitz Plot analysis of $B_s \rightarrow D^0K\pi$
- $D_{sJ}^*(2860)^+$ consist of (at least) 2 overlapping states $J^P=1^-$ & 3^-



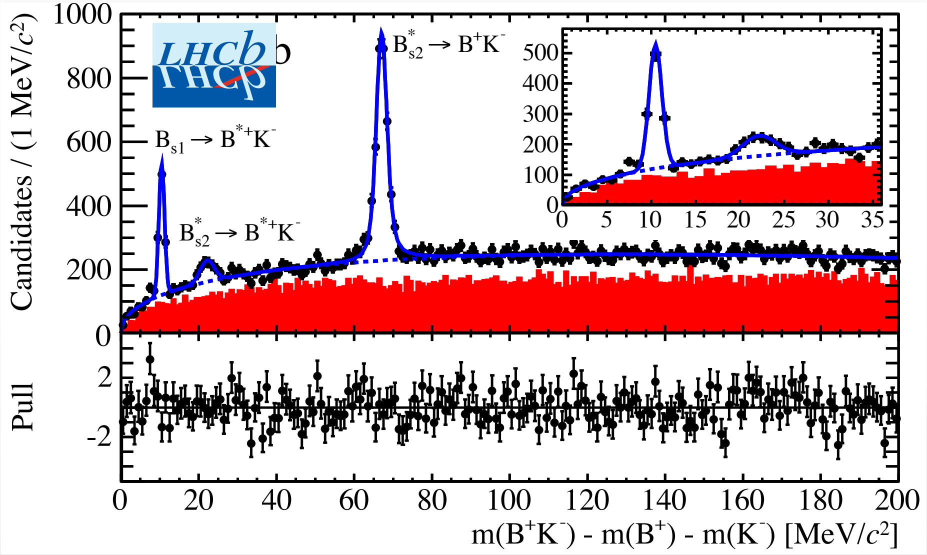




Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant	12.4 ± 2.7
$D_{s\,v}^{*-}$	4.7 ± 1.4
$D_{s0\,v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3

THE EXCITED B$_s$ STATES

- LHCb has reported the first observation of $B_{s2}^* \rightarrow B^*K$ decay ⇒(B_{s1}, B_{s2}^*) are the L=1 j_q=3/2 doublet
- Masses, widths, BR's well consistent with theory



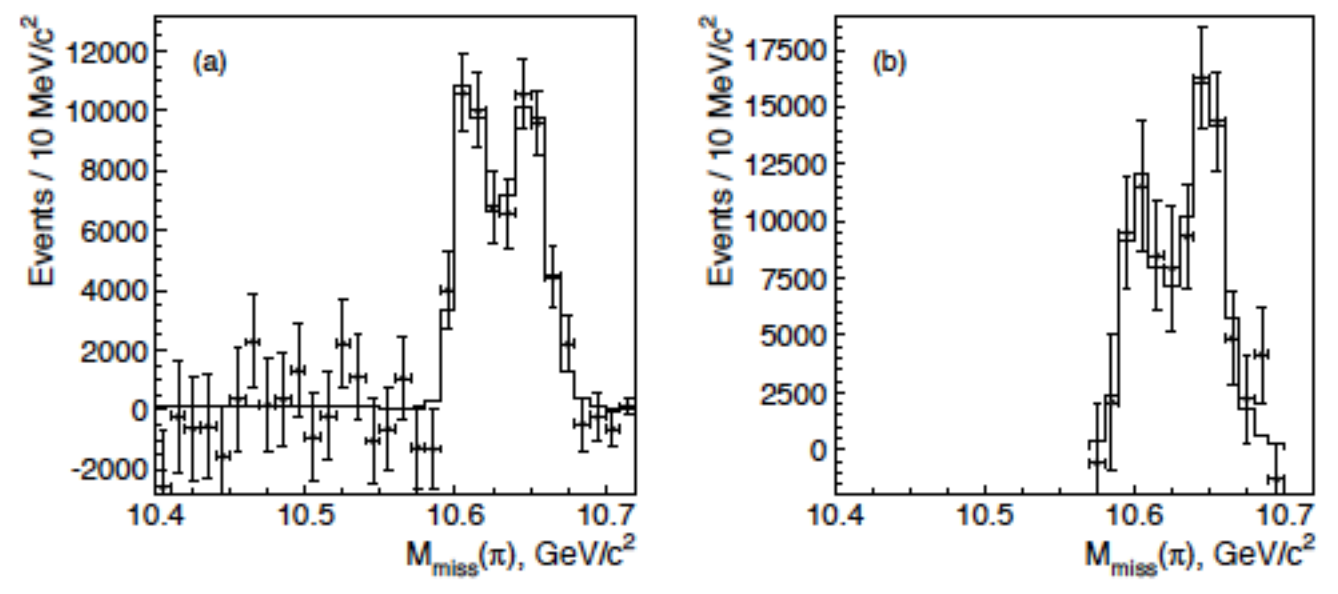
[LHCb: PRL 113, 162001 (2014)]

	j_q	J^P	Allowed decay mode B^+K^-	$B^{*+}K^-$
B_{s0}^*	1/2	0^+	yes	no
B'_{s1}	1/2	1^+	no	yes
B_{s1}	3/2	1^+	no	yes
B_{s2}^*	3/2	2^+	yes	yes

The two $B_{s1}/B_{s2}^* \rightarrow B^*K$ signals peak in the BK spectrum as well shifted by the B^{*+} - B^+ mass difference (~ 45 MeV) due to missing momentum of γ

THE B^{*+} MASS MEASUREMENT AND THE Z^{+}_{B}'S

- Observation of charged bottomonium-like $Z_b(10610)^+$ and $Z_b(10650)^+$ **(Belle collaboration, PRL 108 (2012) 122001)**
- $B\bar{B}^*$ and $B^*\bar{B}^*$ molecules? **(A. Bondar et al., PRD84 (2011) 054010)**

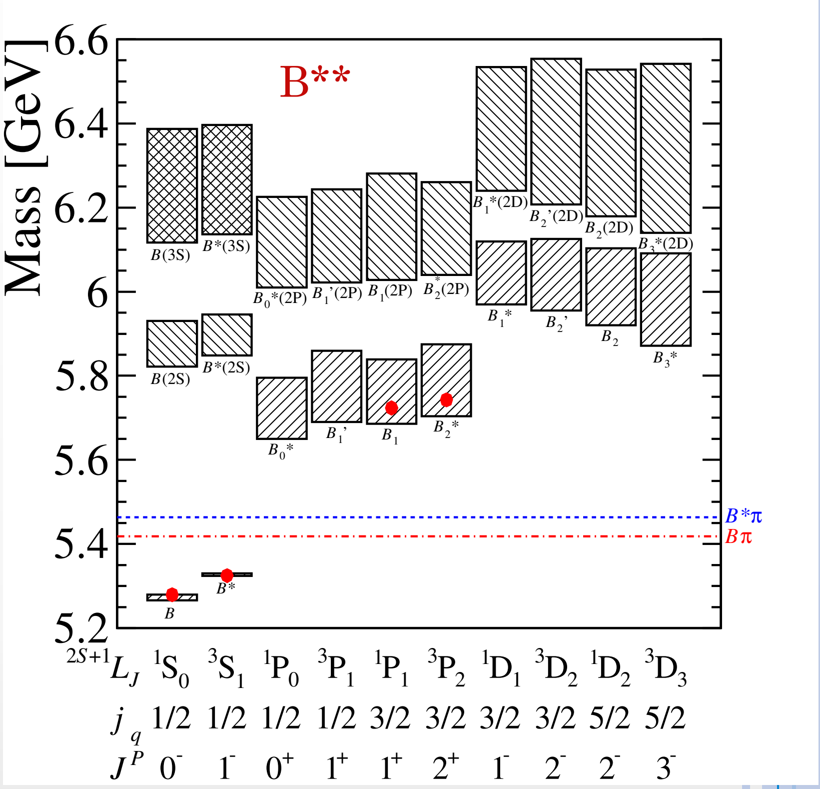


Using the B^{*+} mass measured in this analysis, we compute that the $Z_b(10610)^+$ and $Z_b(10650)^+$ masses are 3.69 ± 2.05 MeV/c^2 and 3.68 ± 1.71 MeV/c^2 above the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds respectively

THE EXCITED B STATES

- LEP experiments observed a single broad structure ($\Gamma >$ 100 MeV) in $B\pi$: $B_J^*(5732)$
- Tevatron experiments resolved it into 2 structures and interpreted the former as the overlap of $B_1^0/B_2^{*0} \rightarrow B^{*+}\pi^-$
- LHCb reported the first observation of the charged B_1^+ and B_2^{*+} **[LHCb-CONF-2011-053]**
- CDF reported the evidence of a broad state: $B(5970)^{0,+}$

	Mass (MeV)	Width (MeV)
$B(5970)^0$	$5978 \pm 5 \pm 12$	$70^{+30}_{-20} \pm 30$
$B(5970)^+$	$5961 \pm 5 \pm 12$	$60^{+30}_{-20} \pm 40$



In previous analyses, fit models made use of several external inputs:
m(B*)-m(B) (exp.), $Br(B_2^* \rightarrow B^*\pi)/Br(B_2^* \rightarrow B\pi)$ (theor.), $\Gamma(B_1)/\Gamma(B_2^*)$ (theor.)

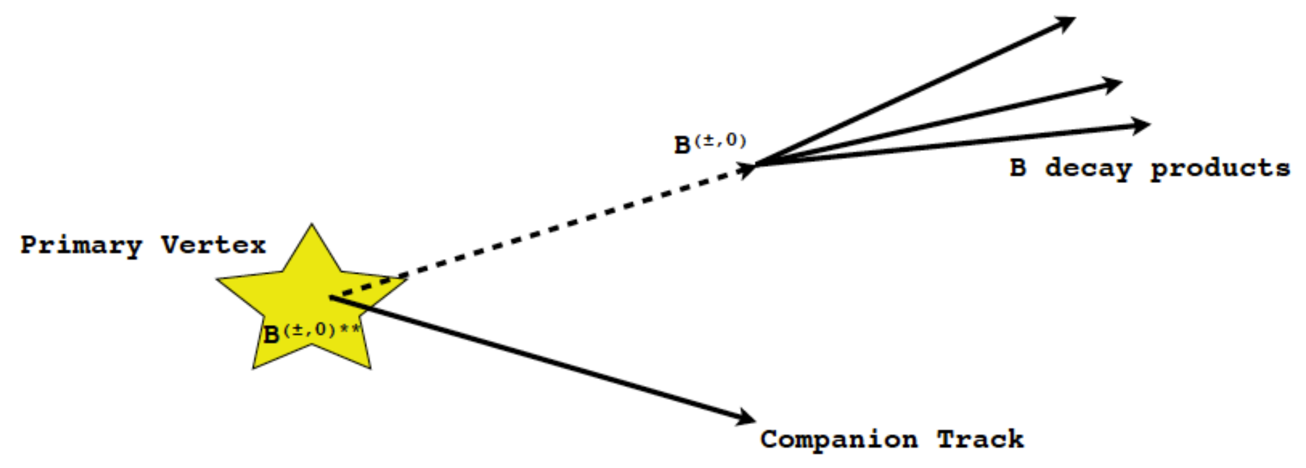
INCLUSIVE STUDY OF THE $B^+\pi^-$ AND $B^0\pi^+$ MASS SPECTRA

[LHCB-PAPER-2014-067; arXiv:1502.02638]

Analysis strategy

- 2011+2012 data sample corresponding to $\mathcal{L} = 3.0\ \text{fb}^{-1}$
- Selection of a high purity B^+ and B^0 samples
- The B^+ (B^0) candidates combined with π^-(π^+) originating from the interaction point
- Analysis carried out by fitting the Q distributions:

$$Q \equiv m(B\pi)\text{-}m(B)\text{-}m(\pi)$$



SELECTION OF THE B^+ CANDIDATES

[LHCB-PAPER-2014-067; arXiv:1502.02638]

B mesons are selected in several high-yield decay modes

B^+

- $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
- $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$
- $B^+ \to \bar{D}^0(\to K^+\pi^-\pi^+\pi^-)\pi^+$
- $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+\pi^-\pi^+$

B^0

- $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$
- $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$
- $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+\pi^-\pi^+$

$J/\psi/D^0/D^-$ masses constrained to their known values to improve signal resolutions

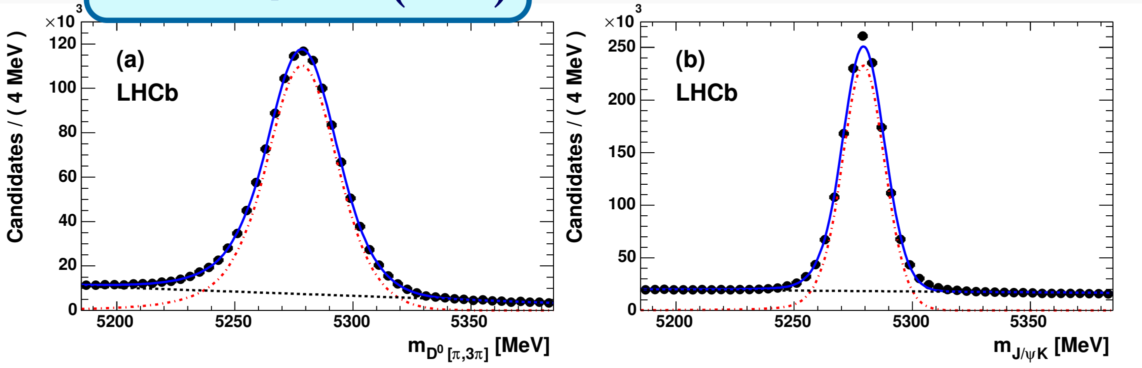
$B^{0,+}$ CANDIDATES

[LHCB-PAPER-2014-067; arXiv:1502.02638]

- Purity of B samples > 80%
- ~2.5M of B^+ candidates and 1.2M of B^0 candidates in 3.0 fb^{-1}

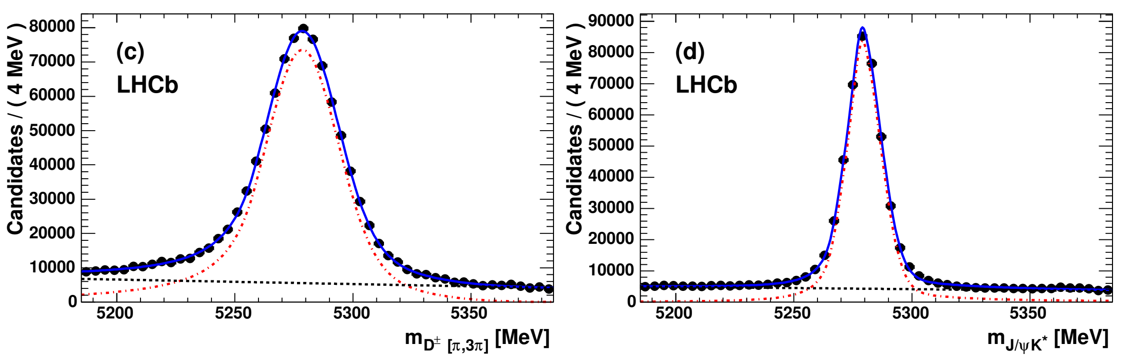
$B^+ \rightarrow \overline{D}^0 \pi^+(\pi^-\pi^+)$
$\rightarrow K^+\pi^-(\pi^+\pi^-)$

$B^+ \rightarrow J/\psi K^+$



$B^0 \rightarrow D^- \pi^+(\pi^-\pi^+)$
$\rightarrow K^-\pi^+\pi^+$

$B^0 \rightarrow J/\psi K^{*0}$



SELECTION OF THE Bπ CANDIDATES

[LHCB-PAPER-2014-067; arXiv:1502.02638]

- $B^+(B^0)$ candidates, within a ±25(50) MeV mass region, combined with $\pi^-(\pi^+)$
- The wrong sign (WS) combinations $B^+\pi^+$ and $B^0\,\pi^-$ are also selected for background studies
- $B^+\pi^-$ candidates refitted with
  - ✓ Primary vertex constraint (i.e. B and π are forced to originate from the primary vertex)
  - ✓ B^+ and $J/\psi/D^0/D^-$ mass constraints

- Selection tuning of companion pions:
  - ✓ $p_T > 0.5$ GeV (suppression of combinatorial background)
  - ✓ PID requirements (suppression of misidentified decays: e.g. $B_s^{**} \rightarrow BK$ where $K \rightleftarrows \pi$)
  - ✓ Small IP relative to the PV associated to the B candidates
- Selection tuning of the B candidates:
  - ✓ B^0 decay time < 0.2 ps (suppression of peaking signals in the WS due to the oscillations of the B^0's)

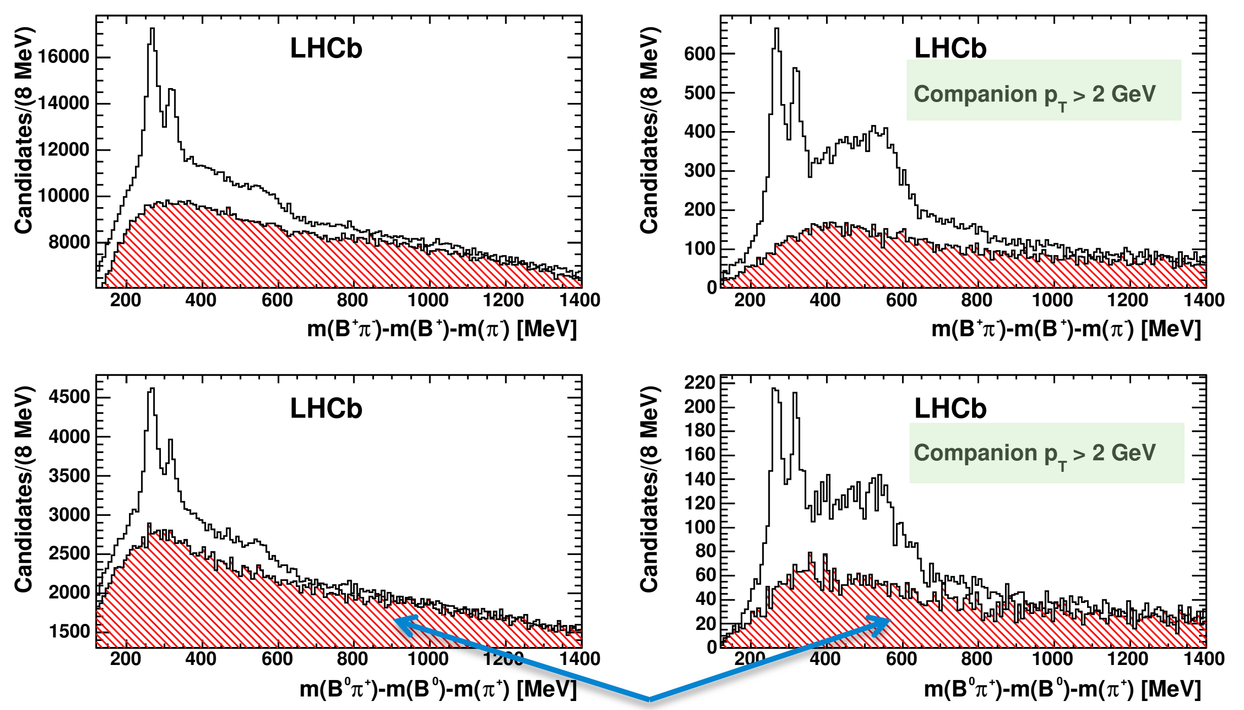
SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

[LHCB-PAPER-2014-067; arXiv:1502.02638]

- Two narrow peaks are seen in both $B^+\pi^-$ and $B^0\pi^+$ spectra interpreted as the decays of $B_1(5721)\rightarrow B^*\pi$ and $B_2^*(5747)\rightarrow B^{(*)}\pi$
- An excess of RS over WS combinations around Q ~ 500 MeV. Particularly prominent when p_T of companion pion > 2 GeV
- Furthermore a comparison with the WS shows a very broad excess of RS lying under the resonances (Associated Production)

$B^+\pi^-$

$B^0\pi^+$



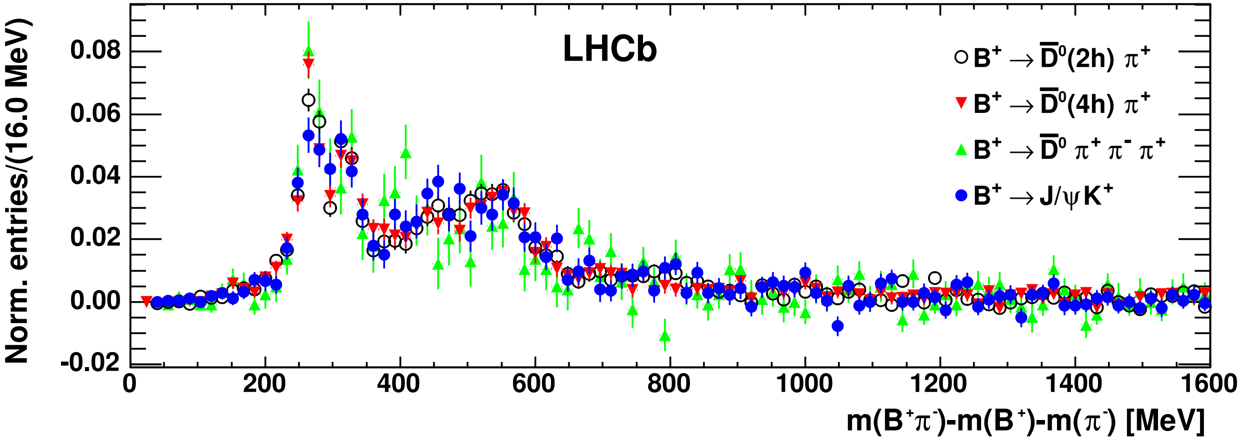
WS

SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

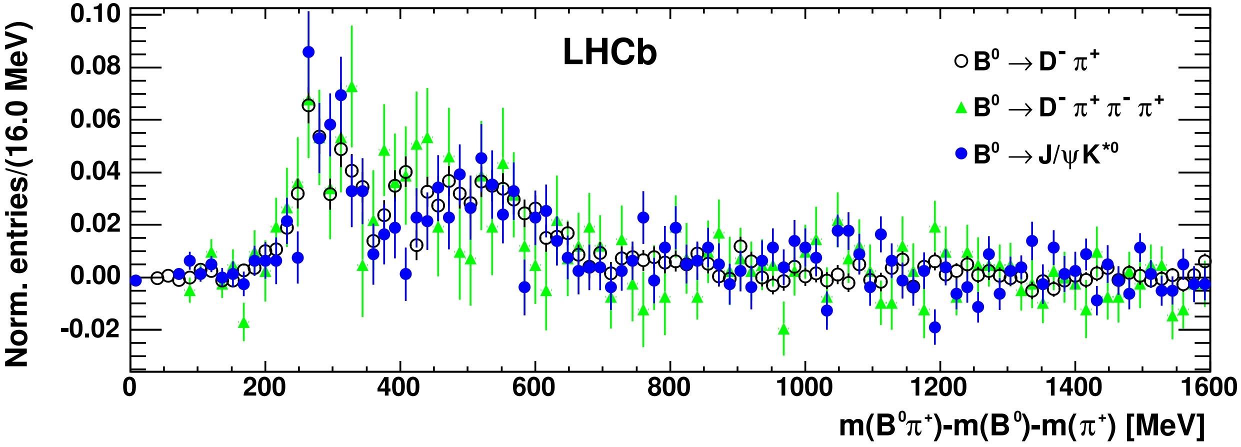
[LHCB-PAPER-2014-067; arXiv:1502.02638]

- Normalized WS subtracted Q value spectra
- Compatibility of the observed signals in all decay modes

$B^+\pi^-$



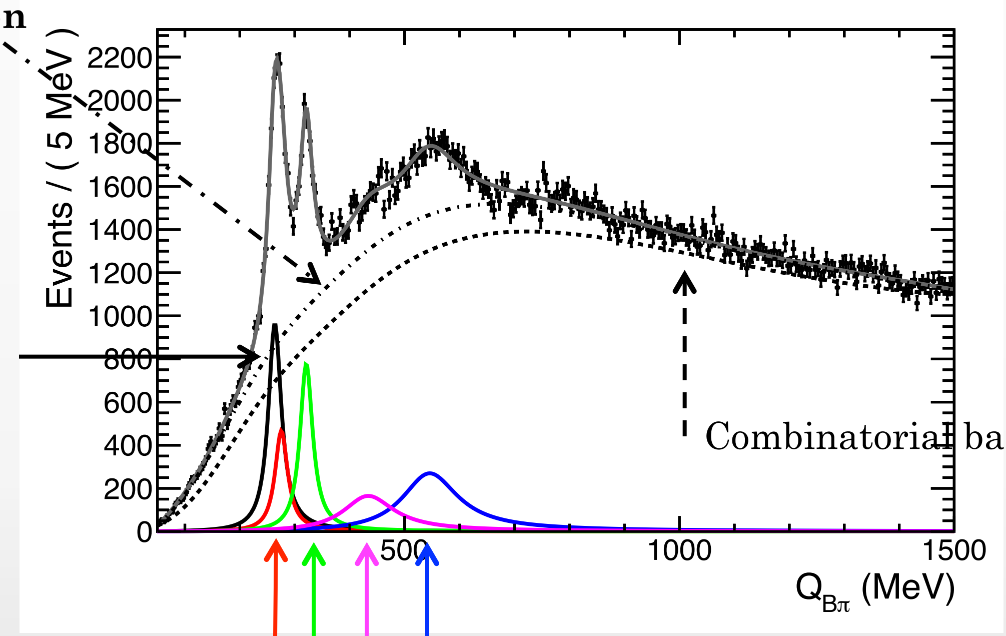
$B^0\pi^+$



FIT MODEL

[LHCB-PAPER-2014-067; arXiv:1502.02638]

Empirical Model ≡ Minimal choice



Associated Production
(Broad resonances
+
correlated nonresonant
production of B and π in the
fragmentation chain)

$B_1(5721) \rightarrow B^*\pi$
feed-down

Combinatorial background (i.e. WS)

$B_2^*(5747) \rightarrow B^*\pi$
feed-down

Broad structures $B_J(5840)$ and $B_J(5960)$

$B_2^*(5747) \rightarrow B\pi$

Alternative fit models (≡ Quark Model) consider the two broad states belonging to the same doublet. Then an extra fit function is added for the $B_J \rightarrow B^*\pi$ feed-down

FIT MODEL

[LHCB-PAPER-2014-067; arXiv:1502.02638]

	Fit function	Constraints
Signals	Relativistic Breit-Wigner (RBW) [Negligible resolutions ~ 2 MeV]	m(B*)-m(B) for B**→B*π feed-downs
Combinatorial Background	Linear combination of spline polynomials	From WS (event mixing as cross check)
Associated Production	Polynomial + Broad RBW shape	From simulation

- Binned χ^2 fit for $B^+\pi^-$ and $B^0\pi^+$ (Bin size = 1 MeV)
- Data samples split in 3 companion p_T bins [$0.5<p_T<1$ GeV; $1<p_T<2$ GeV, $p_T>2$ GeV]
- Fitting steps:
  - ✓ Fit the WS shapes
  - ✓ Simultaneous fit by fixing the combinatorial background from WS and the AP from simulation + broad RBW shape (varied appropriately for systematics)
- Signals parameters (masses and widths) shared between companion p_T bins
- No theoretical constraints

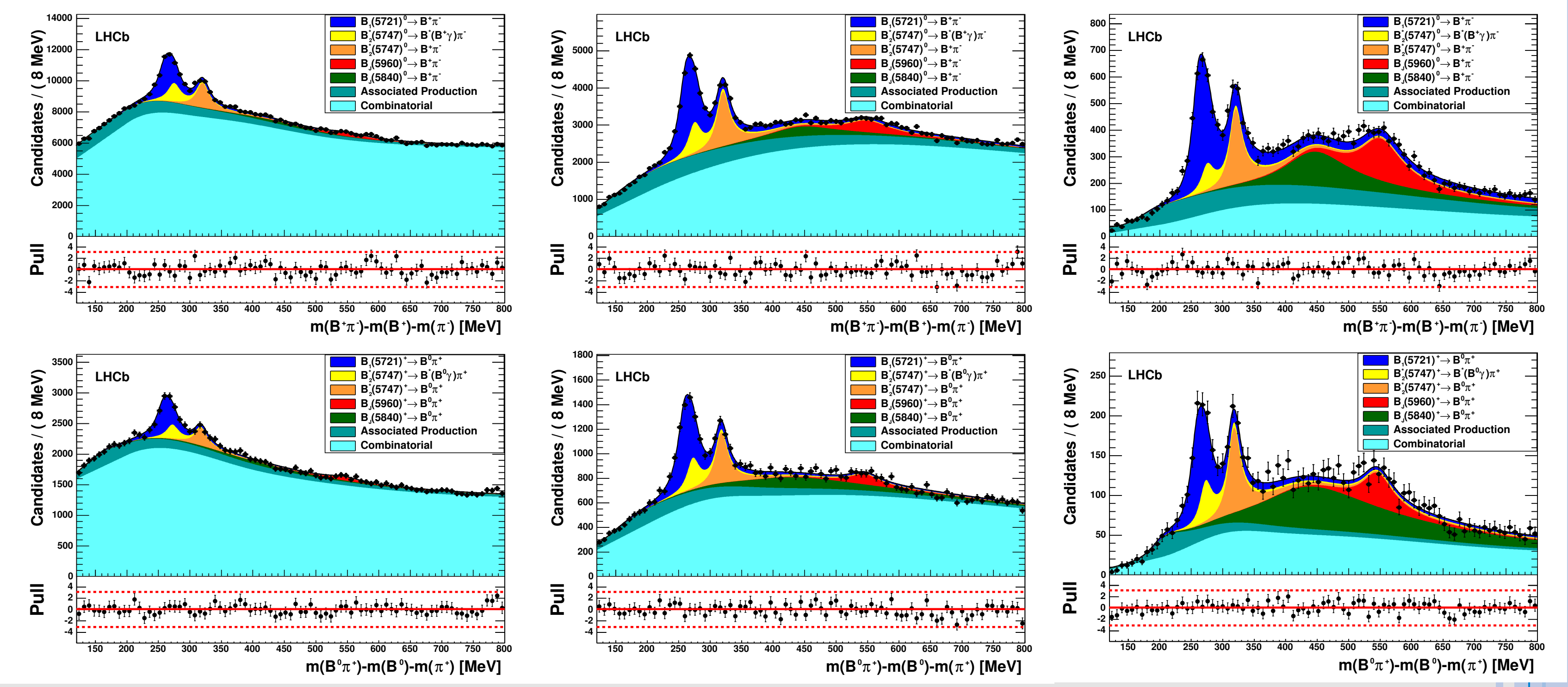
NOMINAL FIT RESULTS BY p_T BIN

[LHCB-PAPER-2014-067; arXiv:1502.02638]

$0.5 < p_T < 1$ GeV $\quad$ $1 < p_T < 2$ GeV $\quad$ $p_T > 2$ GeV

$B^+\pi^-$

$B^0\pi^+$



🟦 $B_1(5721)^0 \to B^{*+}(B^+\gamma)\pi^-$

🟨 $B_2^*(5747)^0 \to B^{*+}(B^+\gamma)\pi^-$

🟧 $B_2^*(5747)^0 \to B^+\pi^-$

🟥 $B_J(5960)^+ \to B^0\pi^+$

🟩 $B_J(5840)^+ \to B^0\pi^+$

▨ Associated Production

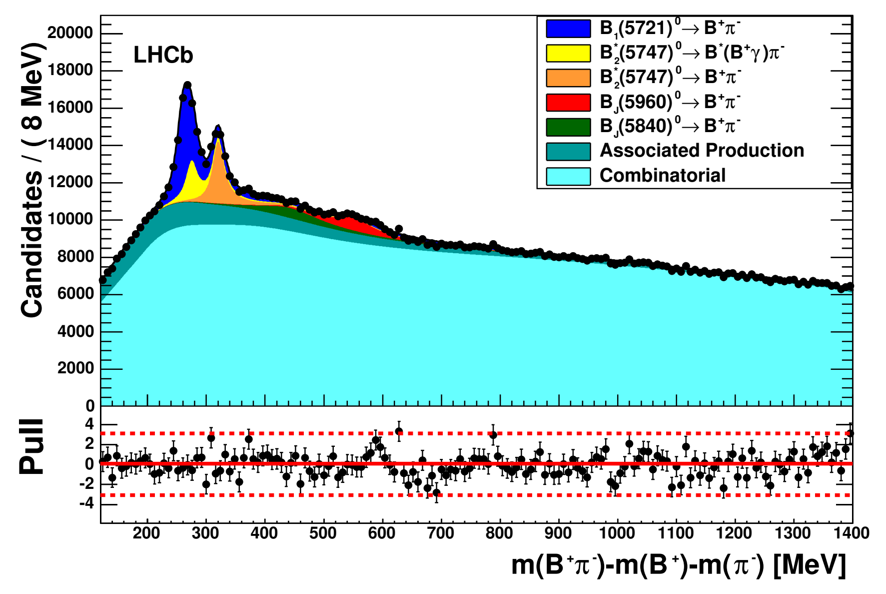
⬜ Combinatorial

NOMINAL FIT RESULTS

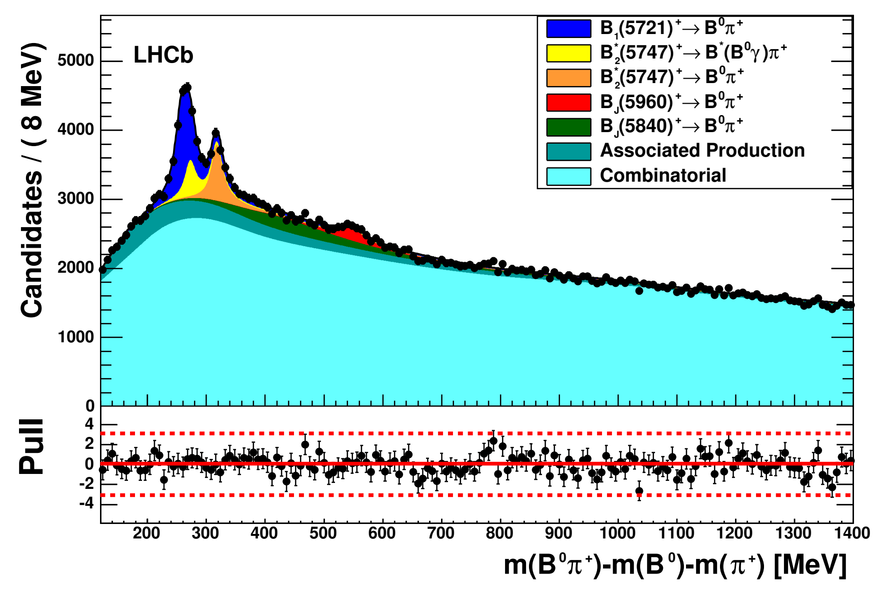
[LHCB-PAPER-2014-067; arXiv:1502.02638]

Candidates integrated over the 3 p_T bins

$B^+\pi^-$



$B^0\pi^+$



🟦 $B_1(5721)^0 \to B^{*+}(B^+\gamma)\pi^-$
🟨 $B_2^*(5747)^0 \to B^{*+}(B^+\gamma)\pi^-$
🟧 $B_2^*(5747)^0 \to B^+\pi^-$

🟥 $B_J(5960)^+ \to B^0\pi^+$
🟩 $B_J(5840)^+ \to B^0\pi^+$
▨ Associated Production
▢ Combinatorial

FINAL RESULTS: $B_1(5721)^{0,+}$ AND $B_2^*(5747)^{0,+}$

[LHCB-PAPER-2014-067; arXiv:1502.02638]

Q values converted into absolute masses by adding the known B, π and B-B* masses

			stat.	syst.	B mass	B*-B mass	
$m_{B_1(5721)^0}$	$=$	5727.7	$\pm\ 0.7$	$\pm\ 1.4$	$\pm\ 0.17$	$\pm\ 0.4$	MeV ,
$m_{B_2^*(5747)^0}$	$=$	5739.44	$\pm\ 0.37$	$\pm\ 0.33$	$\pm\ 0.17$		MeV ,
$m_{B_1(5721)^+}$	$=$	5725.1	$\pm\ 1.8$	$\pm\ 3.1$	$\pm\ 0.17$	$\pm\ 0.4$	MeV ,
$m_{B_2^*(5747)^+}$	$=$	5737.20	$\pm\ 0.72$	$\pm\ 0.40$	$\pm\ 0.17$		MeV ,
$\Gamma_{B_1(5721)^0}$	$=$	30.1	$\pm\ 1.5$	$\pm\ 3.5$			MeV ,
$\Gamma_{B_2^*(5747)^0}$	$=$	24.5	$\pm\ 1.0$	$\pm\ 1.5$			MeV ,
$\Gamma_{B_1(5721)^+}$	$=$	29.1	$\pm\ 3.6$	$\pm\ 4.3$			MeV ,
$\Gamma_{B_2^*(5747)^+}$	$=$	23.6	$\pm\ 2.0$	$\pm\ 2.1$			MeV .

Most precise measurements of the $B_1(5721)$ and $B_2^*(5747)$ masses and widths

$$\frac{\mathcal{B}\left(B_2^*(5747)^0 \to B^{*+}\pi^-\right)}{\mathcal{B}\left(B_2^*(5747)^0 \to B^+\pi^-\right)} = 0.71 \pm 0.14 \pm 0.30\,,$$

$$\frac{\mathcal{B}\left(B_2^*(5747)^+ \to B^{*0}\pi^+\right)}{\mathcal{B}\left(B_2^*(5747)^+ \to B^0\pi^+\right)} = 1.0 \pm 0.5 \pm 0.8\,,$$

First evidence of the $B_2^*(5747)^0 \rightarrow B^{*+}\pi^-$ (3.7σ)!

FINAL RESULTS: $B_J(5840)^{0,+}$ AND $B_J(5960)^{0,+}$

[LHCB-PAPER-2014-067; arXiv:1502.02638]

The properties of the $B_J(5960)^{0,+}$ states are consistent with and more precise than those obtained by the CDF collaboration when assuming decay only to Bπ

If the $B_J(5840)^{0,+}$ and $B_J(5960)^{0,+}$ states are considered under the quark model hypothesis, their properties are consistent with those expected for the B(2S) and B*(2S) radially excited states

		stat.	syst.	B mass	B*-B mass
	Empirical model				
$m_{B_J(5840)^0}$	5862.9	± 5.0	± 6.7	± 0.2	
$\Gamma_{B_J(5840)^0}$	127.4	± 16.7	± 34.2		
$m_{B_J(5960)^0}$	5969.2	± 2.9	± 5.1	± 0.2	
$\Gamma_{B_J(5960)^0}$	82.3	± 7.7	± 9.4		
$m_{B_J(5840)^+}$	5850.3	± 12.7	± 13.7	± 0.2	
$\Gamma_{B_J(5840)^+}$	224.4	± 23.9	± 79.8		
$m_{B_J(5960)^+}$	5964.9	± 4.1	± 2.5	± 0.2	
$\Gamma_{B_J(5960)^+}$	63.0	± 14.5	± 17.2		
	Quark model, $B_J(5840)^{0,+}$ natural				
$m_{B_J(5840)^0}$	5889.7	± 22.2	± 6.7	± 0.2	
$\Gamma_{B_J(5840)^0}$	107.0	± 19.6	± 34.2		
$m_{B_J(5960)^0}$	6015.9	± 3.7	± 5.1	± 0.2	± 0.4
$\Gamma_{B_J(5960)^0}$	81.6	± 9.9	± 9.4		
$m_{B_J(5840)^+}$	5874.5	± 25.7	± 13.7	± 0.2	
$\Gamma_{B_J(5840)^+}$	214.6	± 26.7	± 79.8		
$m_{B_J(5960)^+}$	6010.6	± 4.0	± 2.5	± 0.2	± 0.4
$\Gamma_{B_J(5960)^+}$	61.4	± 14.5	± 17.2		
	Quark model, $B_J(5960)^{0,+}$ natural				
$m_{B_J(5840)^0}$	5907.8	± 4.7	± 6.7	± 0.2	± 0.4
$\Gamma_{B_J(5840)^0}$	119.4	± 17.2	± 34.2		
$m_{B_J(5960)^0}$	5993.6	± 6.4	± 5.1	± 0.2	
$\Gamma_{B_J(5960)^0}$	55.9	± 6.6	± 9.4		
$m_{B_J(5840)^+}$	5889.3	± 15.0	± 13.7	± 0.2	± 0.4
$\Gamma_{B_J(5840)^+}$	229.3	± 26.9	± 79.8		
$m_{B_J(5960)^+}$	5966.4	± 4.5	± 2.5	± 0.2	
$\Gamma_{B_J(5960)^+}$	60.8	± 14.0	± 17.2		

SIGNIFICANCE DETERMINATION: $B_J(5840)^{0,+}$ AND $B_J(5960)^{0,+}$

[LHCB-PAPER-2014-067; arXiv:1502.02638]

Lack of knowledge of the AP shape ⇒Large systematic uncertainty on the yields

Are $B_J(5840)$ and $B_J(5960)$ an artefact of the non-resonant AP?

- Generation of pseudoexperiments without any high mass states included
- Fitting with and without an additional high mass state
- Comparing the χ^2 difference to that obtained from the corresponding fits to data
- Generation of pseudoexperiments with a single mass state to investigate the significance of a 2nd state

$B^+\pi$-: 9.6σ for at least one resonance, 7.5σ for two
$B^0\pi^+$: 4.8σ for at least one resonance, 4.6σ for two

Consistent with the interpretation of 4 states given the expected isospin symmetry

OBSERVATION OF $B_c^+ \rightarrow J/\psi K^+$

- Only few B_c decay modes observed before the LHC era:
  $B_c^+ \rightarrow J/\psi\, \pi^+$ and $B_c^+ \rightarrow J/\psi\, \mu^+\nu$
- LHCb is largely increasing the knowledge about the B_c^+ meson. New decays modes have been discovering:
  $B_c^+ \rightarrow J/\psi\, \pi^+\pi^-\pi^+$ and $B_c^+ \rightarrow \psi(2S)\, \pi^+$
- First observation of the decay $B_c^+ \rightarrow J/\psi\, K^+$ using 1 fb^{-1}

[LHCb, PRL 108, (2012) 251802]

[CMS, CMS-PAS-BPH-11-003]

[LHCb, PRL 109, (2012) 232001]

[ATLAS, ATLAS-CONF-2012-028]

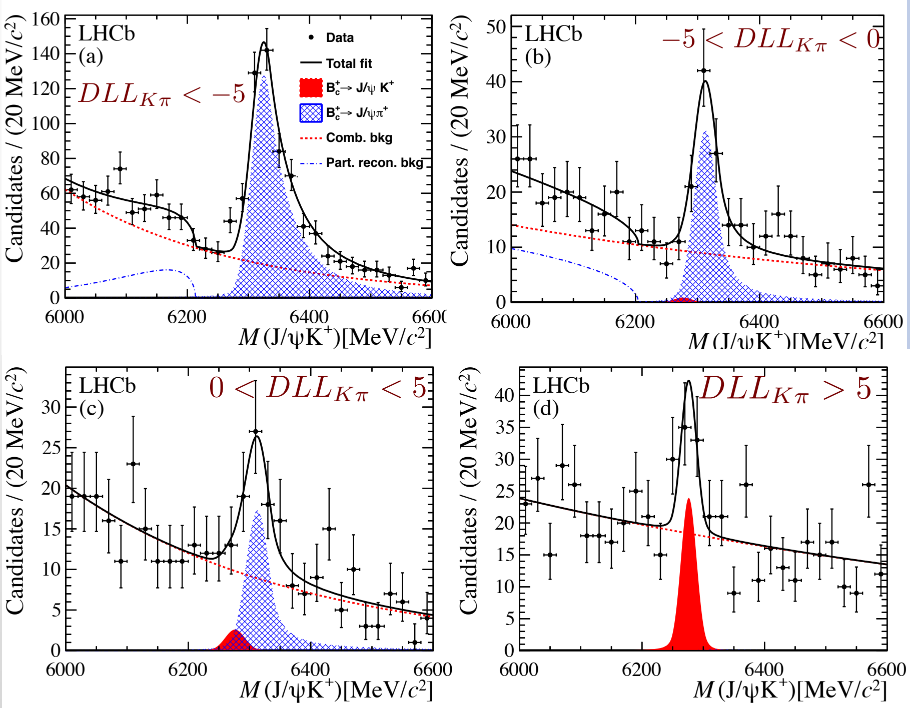
[LHCb, JHEP 09 (2013) 075]

$$DLL_{K\pi} = \ln\mathcal{L}(K) - \ln\mathcal{L}(\pi)$$

- Signal significance 5.0σ

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

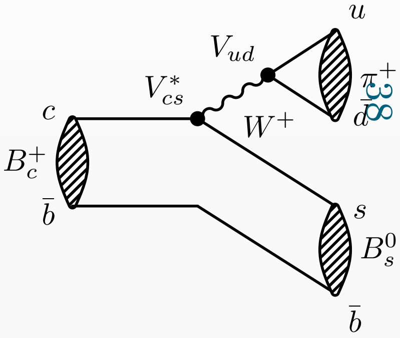
- Agreement with predictions

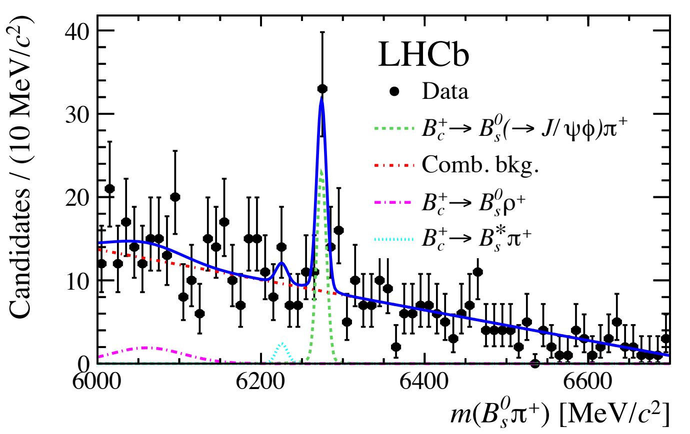


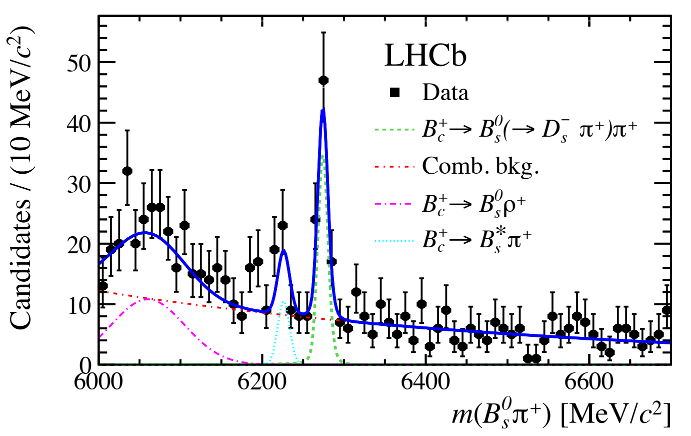
OBSERVATION OF $B_c^+ \rightarrow B_s^0\ \pi^+$

- Observed B_c decays to date are decays where the *b* quark decays weakly to a c quark but $B_c^+ \rightarrow B_{(s)}$ X decays are foreseen as well
- Experimental clarification is needed to shed light on the wide range of predictions
- LHCb performed a search based on 3 fb^{-1}. The B_s meson reconstructed in $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow D_s^-\ \pi^+$

[LHCb, arXiv 1308.4544]







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

$B_c^+ \rightarrow J/\psi\, D_s^{(*)+}$ AND MUCH MORE

- ➢ First observation of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$. The $B_c^+ \rightarrow J/\psi D_s^{*+}$ appears as a cross feed in the $J/\psi D_s^+$ mass spectrum
- ➢ Small Q value → Most precise measurement of B_c mass

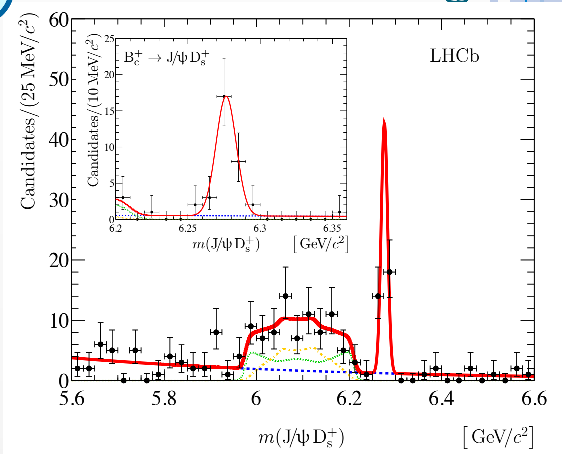
[LHCb, PRD 87 (2013) 112012]

[LHCb, arXiv:1309.0587]

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

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.90 \pm 0.57 \pm 0.24$$

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = 2.37 \pm 0.56 \pm 0.10$$

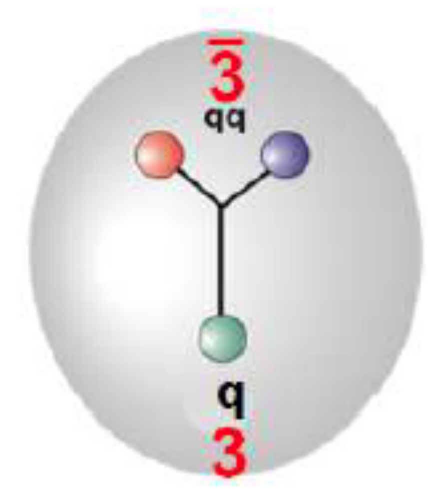


- ✓ Precise measurements of lifetime ($B_c \rightarrow J/\psi\ \mu\nu$ and $B_c \rightarrow J/\psi\ \pi$)
- ✓ Production studies

HEAVY BARYON SPECTROSCOPY

INTRODUCTION

The heavy quark effective theories (HQET) treat a heavy baryon as a system consisting of a static heavy quark Q ($m_Q >> \Lambda_{QCD}$) surrounded by a diquark system comprised of the two light quarks

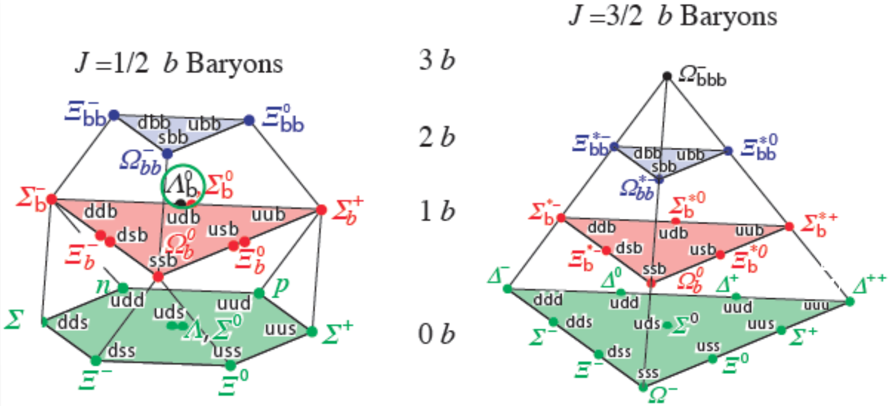


Credit: M. Pennington
AIP Conf.Proc. 1432 (2012) 176-184

INTRODUCTION

bqq (q=u,d,s) Baryons (B=1, C=0)

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	(0, 0)	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	(1/2, 1/2)	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	(1/2, -1/2)	-1	1
Σ_b^+	buu	$1/2^+$	6	(1, 1)	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	(1, 0)	0	1
Σ_b^-	bdd	$1/2^+$	6	(1, -1)	0	1
$\Xi_b^{0\prime}$	$b\{su\}$	$1/2^+$	6	(1/2, 1/2)	-1	1
$\Xi_b^{-\prime}$	$b\{sd\}$	$1/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^-	bss	$1/2^+$	6	(0, 0)	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	(1, 1)	0	1
Σ_b^{*0}	bud	$3/2^+$	6	(1, 0)	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	(1, -1)	0	1
Ξ_b^{*0}	bus	$3/2^+$	6	(1/2, 1/2)	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	(0, 0)	-2	1



The system of baryons containing a *b* quark remains largely unexplored.

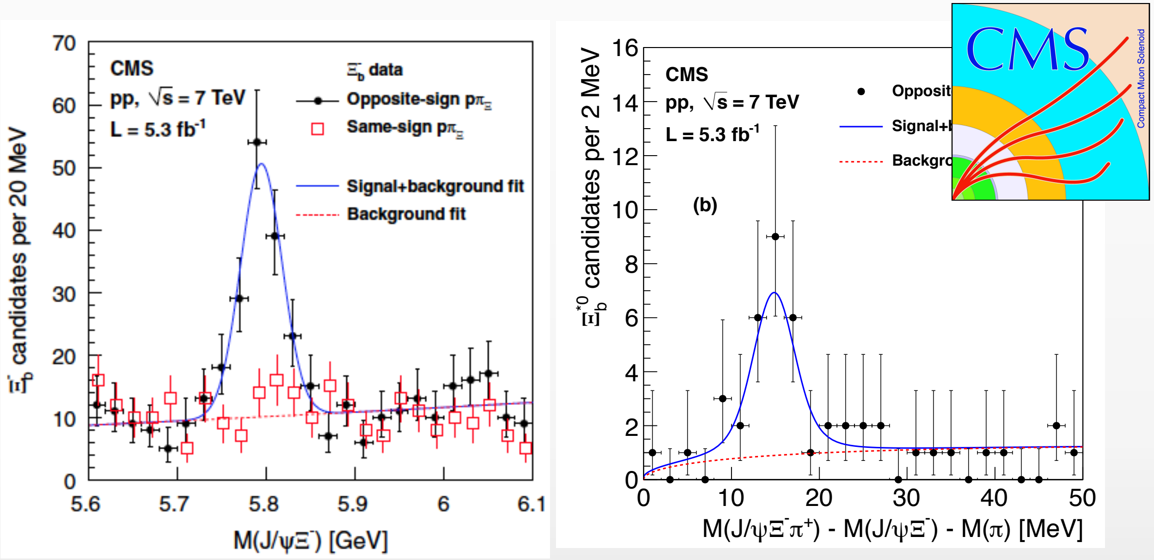
Missing states

“Spin excited states”

OBSERVATION OF $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$ AT CMS

[CMS, PRL 108 (2012) 252002]

In 2012 CMS collaboration claimed the observation of a new *b* baryon $\Xi_b(5945)^{*0}$ in the $\Xi_b^-\pi^+$ spectrum, where $\Xi_b^- \rightarrow J/\psi(\mu\mu)\ \Xi^-(\Lambda\pi)$



$N(\Xi_b^-) = 108 \pm 14$

$N(\Xi_b^{*0}) = 21$

- Theoretical models predict:
  - ✓ $\Xi_b'(J^P=1/2) \sim m(\Xi_b) + m(\pi)$
  - ✓ $\Xi_b^*(J^P=3/2) > m(\Xi_b) + m(\pi)$

SEARCH FOR $\Xi_b^{*-} \to \Xi_b^0\pi^-$

Significant isospin splitting measured in the Ξ_b sector:

$$m(\Xi_b^-) - m(\Xi_b^0) \simeq 6\,\mathrm{MeV} \qquad (1)$$

[LHCb: Phys.Lett.B736 (2014) 154]

Assuming the splitting is the same for all Ξ_b^{**}

$$m(\Xi_b^{*-}) - m(\Xi_b^{*0}) \simeq 6\,\mathrm{MeV} \qquad (2)$$

$$m(\Xi_b^{'-}) - m(\Xi_b^{'0}) \simeq 6\,\mathrm{MeV} \qquad (3)$$

Combining (1) and (2):

$$[m(\Xi_b^{*-}) - m(\Xi_b^0)] - [m(\Xi_b^{*0}) - m(\Xi_b^-)] \simeq 12\,\mathrm{MeV}$$

$$m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) \simeq 27\,\mathrm{MeV}$$

⬇

CMS: 15 MeV + $m(\pi^+)$

Similarly combining (1) and (3):

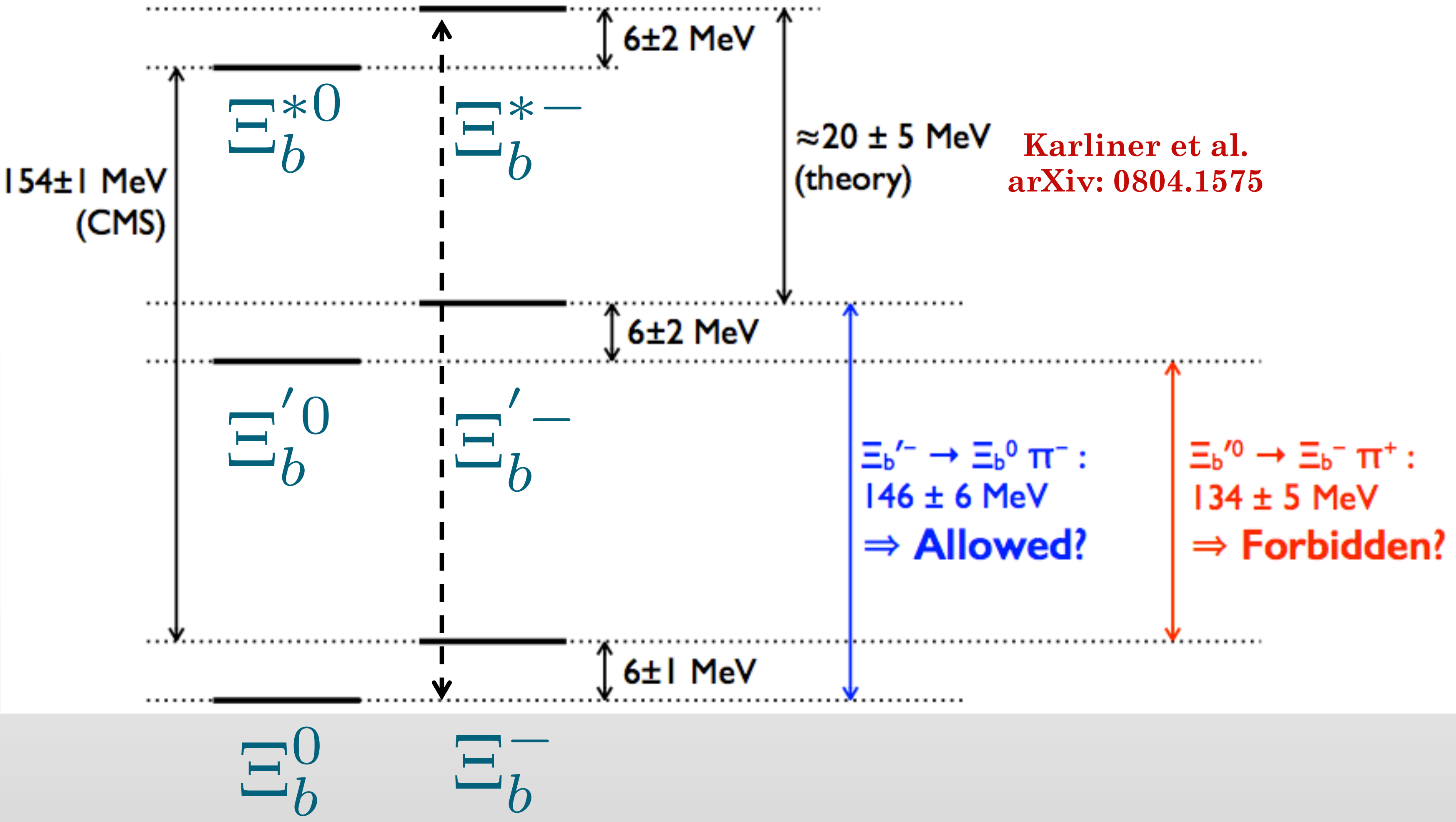
$$[m(\Xi_b^{'-}) - m(\Xi_b^0)] - [m(\Xi_b^{'0}) - m(\Xi_b^-)] \simeq 12\,\mathrm{MeV}$$

$$m(\Xi_b^{'-}) - m(\Xi_b^0) - m(\pi^-) < 12\,\mathrm{MeV}$$

⬇

$< m(\pi^+)$

SEARCH FOR $\Xi_b^{*-} \to \Xi_b^0\pi^-$

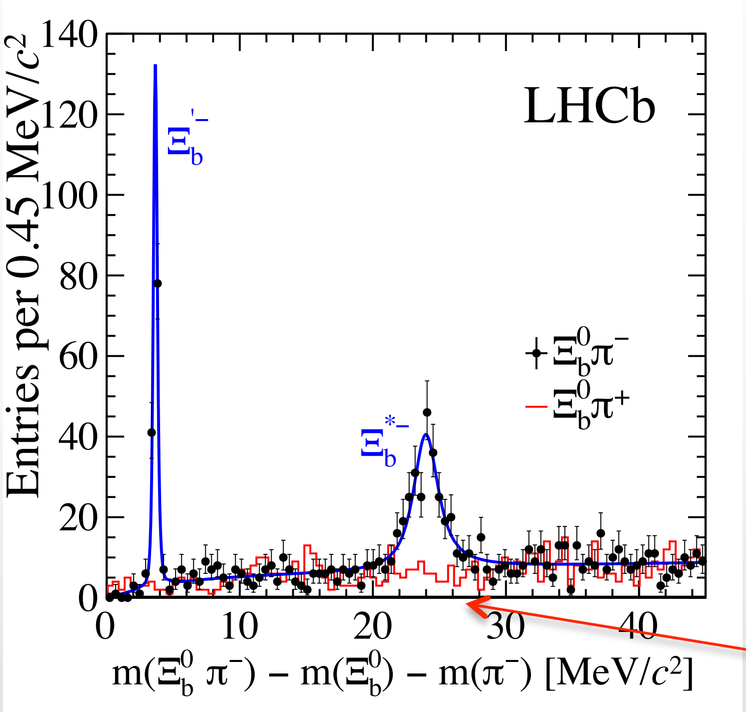


Karliner et al.
arXiv: 0804.1575

SEARCH FOR $\Xi_b^{*-} \rightarrow \Xi_b^0 \pi^-$ AT LHCb

[LHCB-PAPER-2014-061; arXiv:1411.4849]

- Integrated luminosity 3.0 fb^{-1}
- Sample of $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$, where $\Xi_c^+ \rightarrow pK^-\pi^+$ combined with a π^-



Wrong sign combinations

Fit Model

$\Xi_b^{'-}$: Resolution function

Ξ_b^{*-} : P-wave RBW $\otimes$ Resolution

Observation of two narrow peaks interpreted as $\Xi_b^{'-}$ and Ξ_b^{*-}

Very unlikely scenario: peak at ~3 MeV is a feed-down of $\Xi_b^{**-} \rightarrow \Xi_b^{'0} (\Xi_b^0 \pi^0) \pi^-$

FINAL RESULTS

[LHCB-PAPER-2014-061; arXiv:1411.4849]

The first peak is very narrow, so we put an upper limit on its width Γ, then fix it to 0 for the baseline fit

$$\Gamma(\Xi_{\rm b}'^{-}) < 0.08 \text{ MeV at } 95\% \text{ CL}$$

With this assumption, we measure:

$$\begin{aligned}
\delta m(\Xi_{\rm b}'^{-}) &= 3.653 \pm 0.018 \pm 0.006 \text{ MeV}\\
\delta m(\Xi_{\rm b}^{*-}) &= 23.96 \pm 0.12 \pm 0.06 \text{ MeV}\\
\Gamma(\Xi_{\rm b}^{*-}) &= 1.65 \pm 0.31 \pm 0.10 \text{ MeV}
\end{aligned}$$

Signal significances > 10σ

$$\begin{aligned}
m(\Xi_{\rm b}'^{-}) &= 5935.02 \pm 0.02 \pm 0.01 \pm 0.50 \text{ MeV}\\
m(\Xi_{\rm b}^{*-}) &= 5955.33 \pm 0.12 \pm 0.06 \pm 0.50 \text{ MeV}
\end{aligned}$$

FURTHER STUDIES

[LHCB-PAPER-2014-061; arXiv:1411.4849]

1) Angular analysis

The spin of the states investigated by studying the helicity angle θ

$$\begin{array}{cccccccc} \Xi_{\rm b}^{*-} & \to & \Xi_{\rm b}^0 & \pi^-, & \Xi_{\rm b}^0 & \to & \Xi_c^+ & \pi^- \\ J^P & \to & \frac{1}{2}^+ & 0^-, & \frac{1}{2}^+ & \to & \frac{1}{2}^+ & 0^- \end{array}$$

- ✓ J = ½ → Flat θ distribution
- ✓ J > ½ → θ distribution depends on the initial polarization

Flat θ distributions observed for both states consistent with the $\Xi_b'^-$ and Ξ_b^{*-} interpretation

2) Measurements of relative productions

$$\frac{\sigma(pp \to \Xi_{\rm b}'^- X)\mathcal{B}(\Xi_{\rm b}'^- \to \Xi_{\rm b}^0\pi^-)}{\sigma(pp \to \Xi_{\rm b}^0 X)} = 0.118 \pm 0.017 \pm 0.007$$

$$\frac{\sigma(pp \to \Xi_{\rm b}^{*-} X)\mathcal{B}(\Xi_{\rm b}^{*-} \to \Xi_{\rm b}^0\pi^-)}{\sigma(pp \to \Xi_{\rm b}^0 X)} = 0.207 \pm 0.032 \pm 0.015$$

$$\frac{\sigma(pp \to \Xi_{\rm b}^{*-} X)\mathcal{B}(\Xi_{\rm b}^{*-} \to \Xi_{\rm b}^0\pi^-)}{\sigma(pp \to \Xi_{\rm b}'^- X)\mathcal{B}(\Xi_{\rm b}'^- \to \Xi_{\rm b}^0\pi^-)} = 1.74 \pm 0.30 \pm 0.12$$

Given the isospin modes, large fraction of Ξ_b produced in the decays of Ξ_b resonances

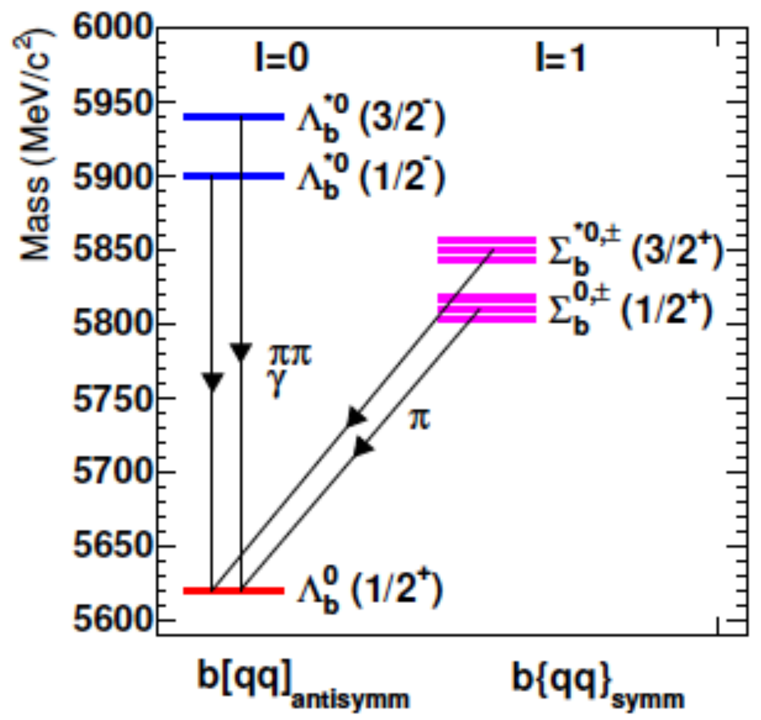
3) Search for $\Xi_b'^-$ and Ξ_b^{*-} in other Ξ_b^0 decay modes

Signals have been observed in

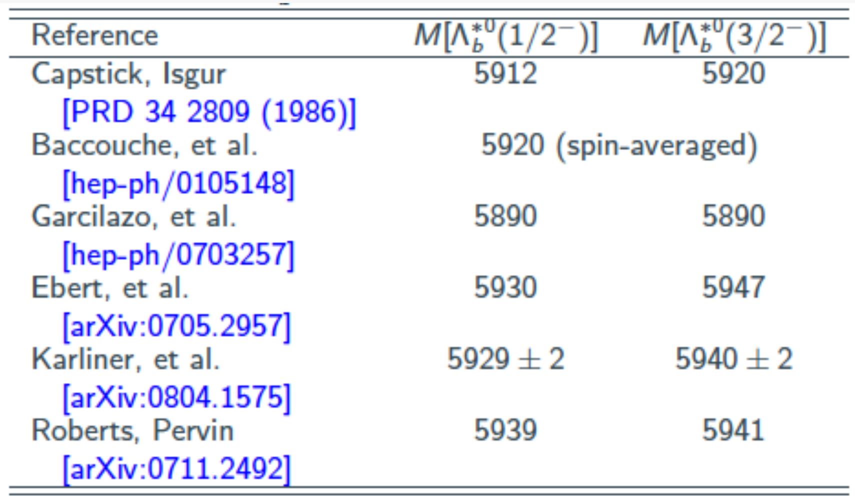
$\Xi_b^0 \to \Lambda_c^+(pK^-\pi^+)K^-\pi^+\pi^-, \Xi_b^0 \to D^0(K^-\pi^+)pK^-$ and $\Xi_{\rm b}^0 \to {\rm D}^+({\rm K}^-\pi^+\pi^+){\rm pK}^-\pi^+$

ORBITALLY EXCITED (L=1) Λ_b^0 BARYONS

- The ground state $\Lambda_b^0(J^P = 1/2^+)$: bud, where the ud diquark $J^P = 0^+$ and $L = 0$
- Orbital excitations with $L = 1$
- Excited Λ_b^0 states: two state with $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$
- Should decay to $\Lambda_b^0\pi^+\pi^-$ or $\Lambda_b^0\gamma$ (parity conservation) depending on mass



Predictions for Λ_b^{*0} masses

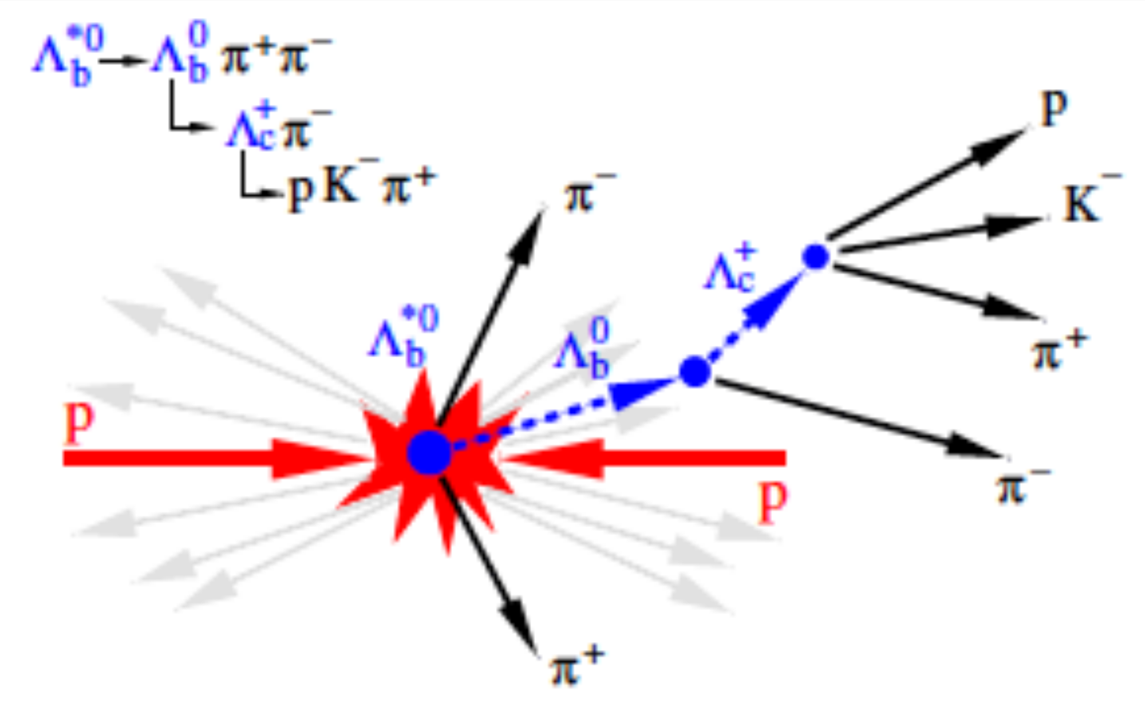


Reference	$M[\Lambda_b^{*0}(1/2^-)]$	$M[\Lambda_b^{*0}(3/2^-)]$
Capstick, Isgur [PRD 34 2809 (1986)]	5912	5920
Baccouche, et al. [hep-ph/0105148]	5920 (spin-averaged)	
Garcilazo, et al. [hep-ph/0703257]	5890	5890
Ebert, et al. [arXiv:0705.2957]	5930	5947
Karliner, et al. [arXiv:0804.1575]	5929 ± 2	5940 ± 2
Roberts, Pervin [arXiv:0711.2492]	5939	5941

Most predictions are above $\Lambda_b^0\pi\pi$ (5900 MeV/c^2) but below $\Sigma_b\pi$ (around 5950 MeV/c^2)

OBSERVATION OF EXCITED Λ_b^0 BARYONS

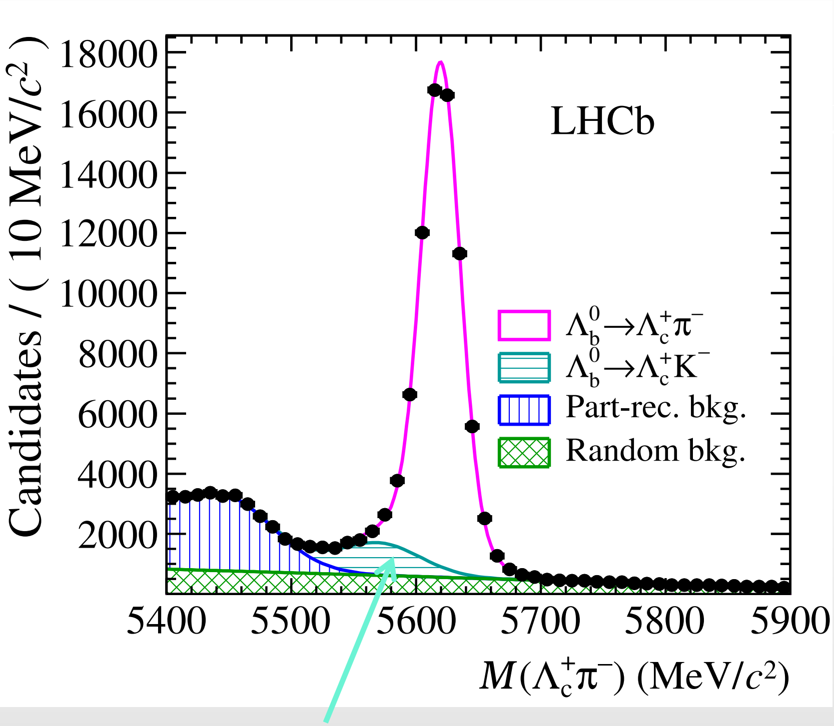
- ⊛ 1.0 fb^{-1} pp data sample, $\sqrt{s} = 7$ TeV
- ⊛ $\Lambda_b^0 \to \Lambda_c^+ \pi^-, \Lambda_c^+ \to pK^-\pi^+$ combined with a pair of pions from the primary vertex



SELECTION OF Λ_b^0 BARYONS

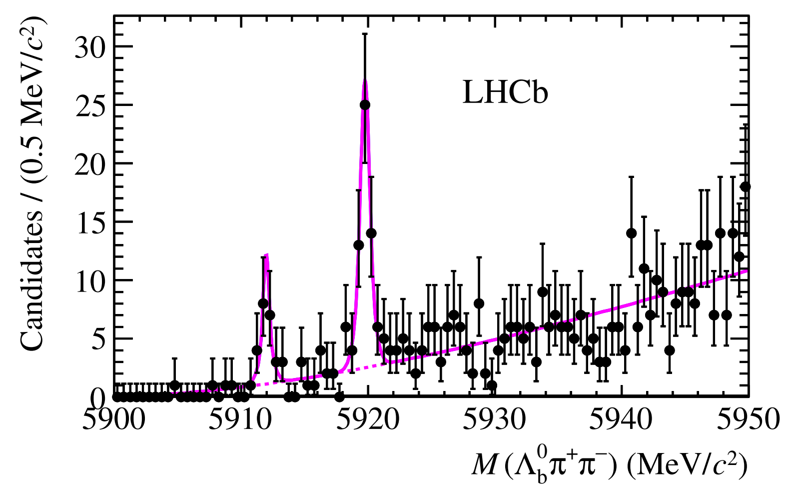
$N(\Lambda^0_b) = 70540 \pm 330$

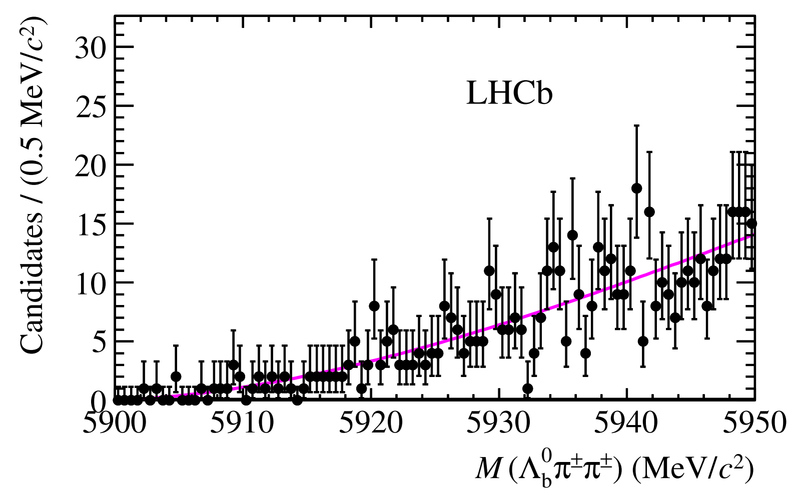
- Good quality tracks and well separated from any PV.
- PID for kaons and protons
- Kinematic fit which constrains:
  - the Λ^0_b to originate from the PV
  - Λ_c^+ mass to its PDG value



$\Lambda^0_b \rightarrow \Lambda_c^+ K^-$ decays (not yet reported in literature) where the kaon reconstructed under the pion mass hypothesis

FIT MODEL





Combined unbinned fit of $\Lambda_b^0\pi^+\pi^-$ and $\Lambda_b^0\pi^\pm\pi^\pm$

- ⊛ $\Lambda_b^{*0}(5912)$ and $\Lambda_b^{*0}(5920)$: sum of two Gaussians with same mean (signal shape fixed from the simulation)
- ⊛ Background: quadratic polynomial function

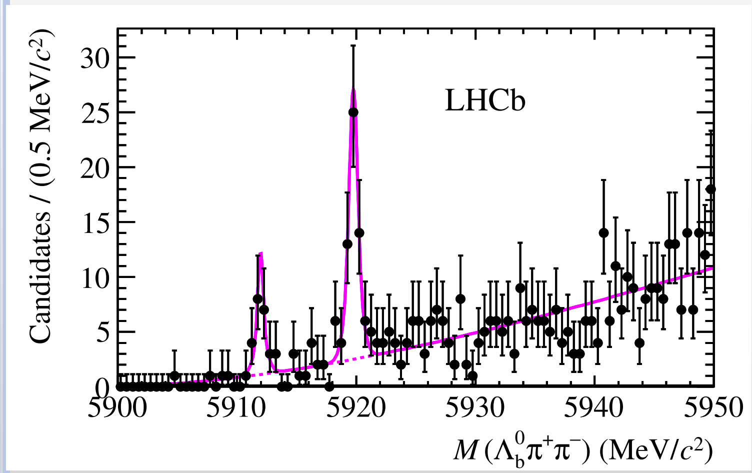
$$N_{\Lambda_b^{*0}(5912)} = 17.6 \pm 4.8 \Rightarrow 5.2\sigma$$
$$N_{\Lambda_b^{*0}(5920)} = 52.5 \pm 8.1 \Rightarrow 10.2\sigma$$

The two new peaks are interpreted as the orbitally excited Λ^0_b states

FIRST OBSERVATION OF ORBITALLY-EXCITED b BARYONS ($L>0$)

Masses are only slightly above $\Lambda_b^0\pi^+\pi^-$ threshold ($Q = 12$ and 20 MeV respectively) and below the $\Sigma_b^0\pi$ threshold

$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.66_{\Lambda_b^0\text{mass}}\ \text{MeV}/c^2$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.66_{\Lambda_b^0\text{mass}}\ \text{MeV}/c^2$$
$$\Delta M_{\Lambda_b^{*0}(5912)} = 292.60 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}\ \text{MeV}/c^2$$
$$\Delta M_{\Lambda_b^{*0}(5920)} = 300.40 \pm 0.08_{\text{stat}} \pm 0.04_{\text{syst}}\ \text{MeV}/c^2$$



Limits on natural widths (95% CL) obtained by an alternative fit

⊛ Signal PDF : 2 Gaussians $\otimes$ Breit-Wigner

$$\Gamma_{\Lambda_b^{*0}(5912)} < 0.83\ \text{MeV}$$
$$\Gamma_{\Lambda_b^{*0}(5920)} < 0.75\ \text{MeV}$$

CDF confirms $\Lambda_b^{*0}(5920)$ arXiv:1301.0949

SEARCH FOR Ξ_{cc}^{+}

[JHEP 12 (2013) 090]

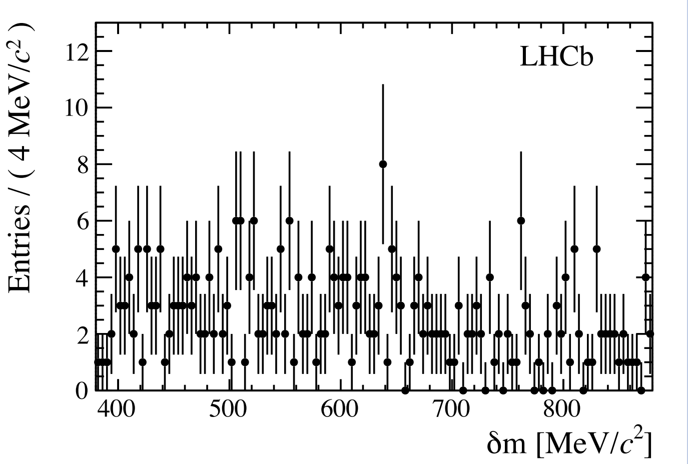
- All of the ground states with C=0 or C=1 have been discovered
- Three weakly decaying C=2 states expected: Ξ_{cc} isodoublet and Ω_{cc} isosinglet
- SELEX reported signals of $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$, $pD^{+}K^{-}$: [PRL 89 (2002) 112001, PLB 628 (2005) 18]
  - $M = 3519 \pm 2$ MeV and $\tau(\Xi_{cc}^{+}) < 33$ fs @ 90% C.L.
  - Large production (9% of Λ_c^{+} from Ξ_{cc}^{+})
  - No confirmation so far

- LHCb looks for $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ using 0.65 fb^{-1}
- The search is performed in wide ranges of mass and lifetime:
  $3300<M<3700$ MeV $100<\tau<400$ fs

- No signal found

$$\frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} < 1.5 \times 10^{-2} \text{ at the 95\% CL}$$

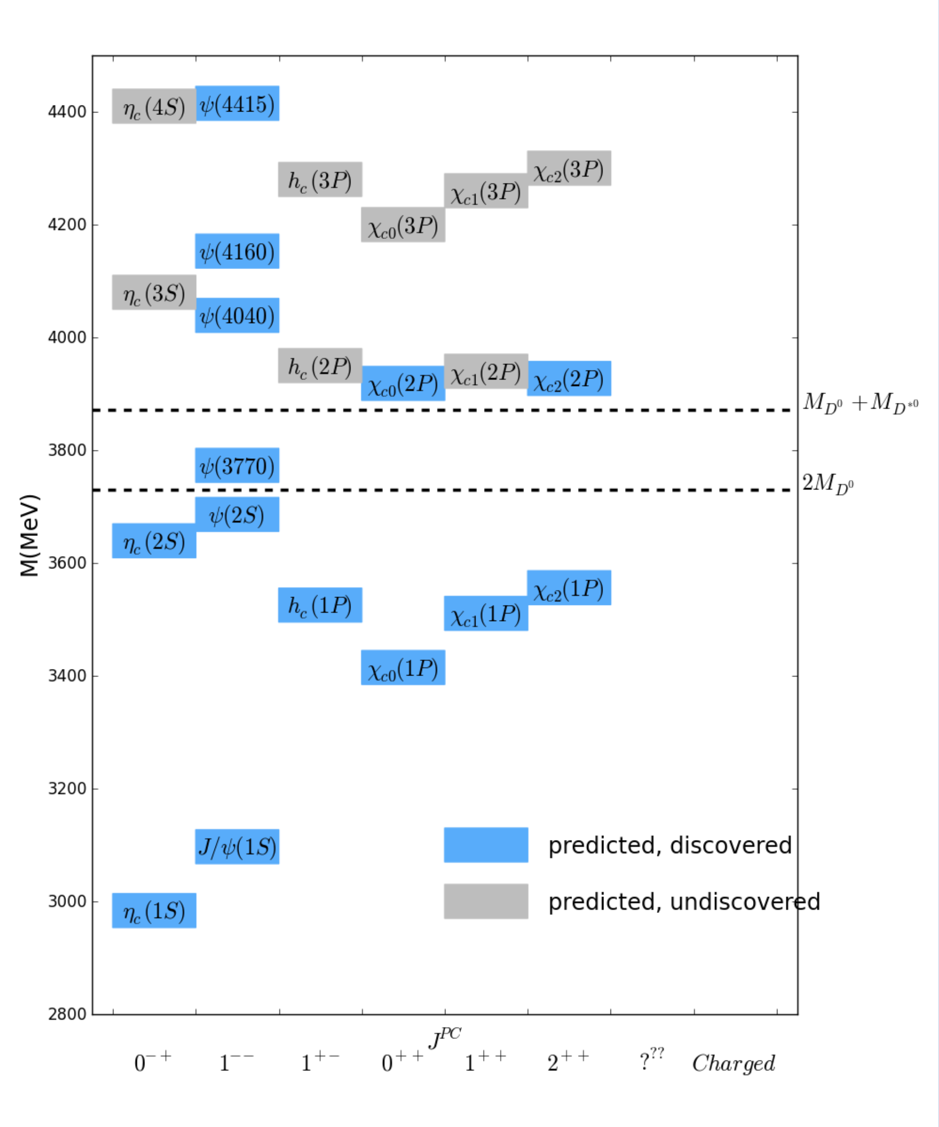
- The result doesn't confirm or disprove the SELEX signal



Quarkonium-like Spectroscopy

INTRODUCTION

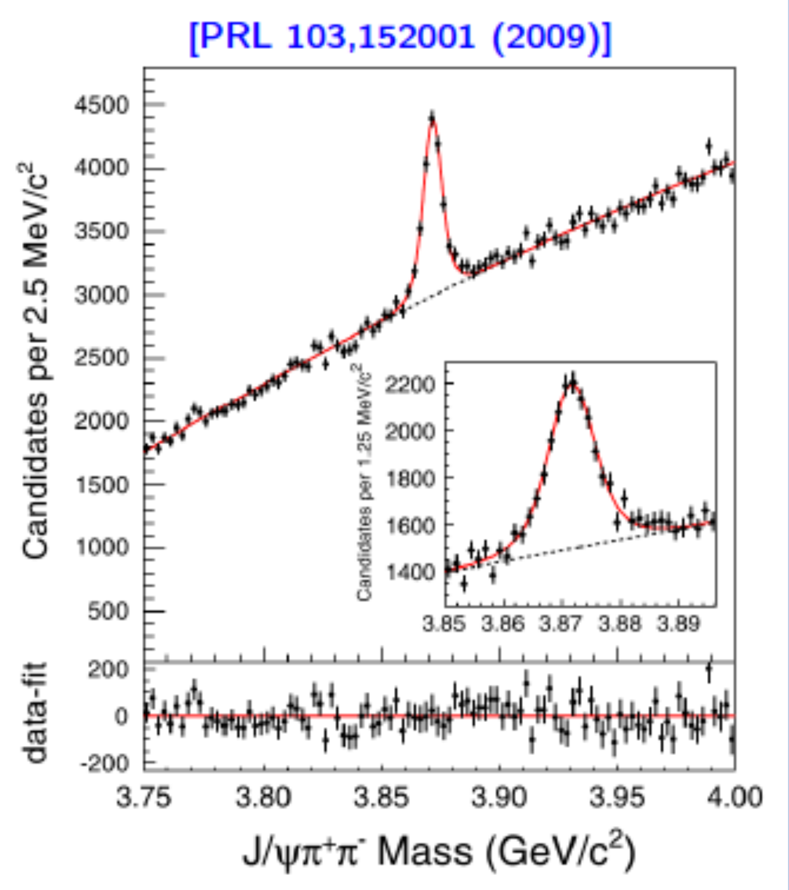
- All charmonium states below the $D\bar{D}$ threshold have been observed
- Charmonium states above the $D\bar{D}$ or $D\bar{D}^*$ threshold can decay into $D\bar{D}$ and $D\bar{D}^*$ final states
- Many predicted states still not observed
- Everything seemed understood and well established up to 2003…



X(3872)

The X(3872) exotic-meson was discovered in 2003 by the Belle collaboration in the $B \to KX(3872)$ with $X(3872) \to J/\psi\pi^+\pi^-$

- Promptly confirmed by BaBar, CDF, D0
- Observed also in $J/\psi\omega, \gamma J/\psi, \gamma\psi(2S), D^0\bar{D}^{*0}$
- Quantum number constrained to 1^{++} or 2^{-+} by CDF
- Width is surprisely narrow (< 1.2 MeV)
- Mass is not near to any of the predicted $c\bar{c}$ states
- Mass is roughly equal to $m(D^0) + m(D^{*0})$
- High production rate in $p\bar{p}$ collisions



[PRL 103,152001 (2009)]

After 10 years the nature of X(3872) remains uncertain:

- Conventional $c\bar{c}$ state? $\chi_{c1}(2^3P_1)$ $(J^{PC} = 1^{++})$?$\eta_{c2}(1^1D_2)$ $(J^{PC} = 2^{-+})$?
- $D^{*0}\bar{D}^0$ bound state or tetraquark state $(J^{PC} = 1^{++})$?

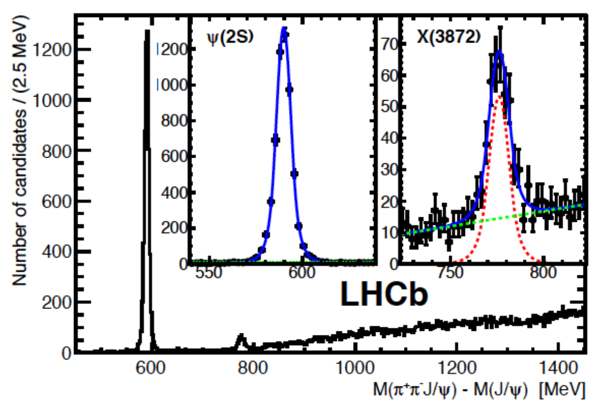
New experimental inputs requested: quantum numbers, precision measurement of mass and width, production mechanism

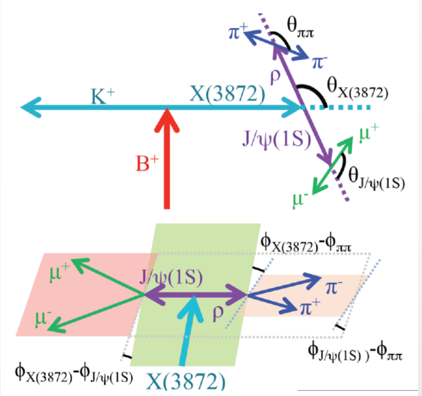
X(3872) QUANTUM NUMBERS

[PRL 110, 222001 (2013)]

Previously:

- B factories: Observation of the $X(3872) \to J/\psi\gamma$ decay $\Rightarrow$ **C=+**. [PRL 102 132001] [PRL 107 091803]
- CDF: 2292±113 $p\bar{p} \to X(3872)+anything$ events. Unknown X(3872) polarization (only 3 angles). Quantum numbers constrained to 1^{++} or 2^{-+}. [PRL 98, 132002 (2007)]
- Belle: 173±16 $B \to KX(3872)$ events. 1D analysis carried out (Not enough events to bin in 5D). 1^{++} or 2^{-+} could not be distinguished. [hep-ex/0505038]



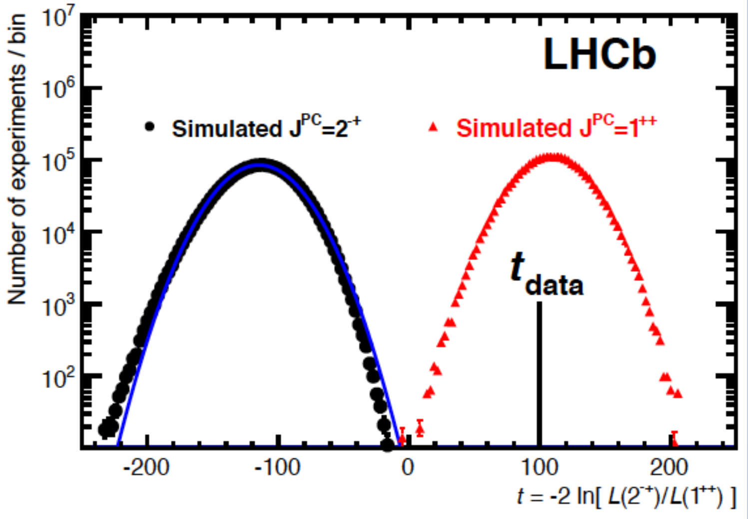


- 1.0 fb^{-1} dataset collected by LHCb in 2011
- 313 ± 26 $B^+ \to K^+ X(3872)$ with $X(3872) \to J/\psi\pi^+\pi^-$
- LHCb performs a 5D analysis which benefits of the angular correlations to disentangle the quantum number of the X(3872)

X(3872) QUANTUM NUMBERS: $J^{P} = 1^{++}$!

[PRL 110, 222001 (2013)]

- Likelihood-ratio test to discriminate between the 1^{++} and the 2^{-+} assignments
- Simulated experiments, each with the number of signals and background events as in the real experiment
- The two spin hypotheses are completely separated
  - $t > 0$ implies 1^{++} favoured
  - $t < 0$ implies 2^{-+} favoured
- Data favour the 1^{++} over the 2^{-+} hypothesis at 8.4σ

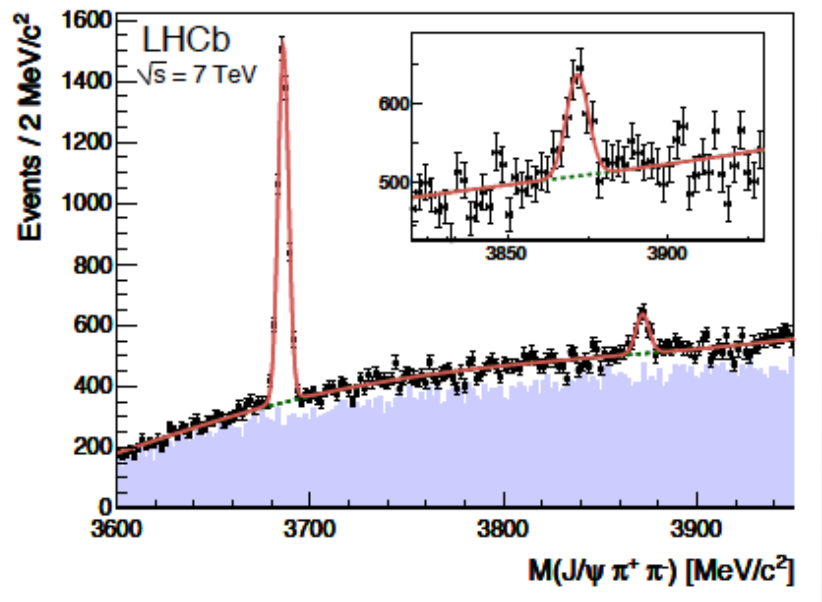


- $\eta_{c2}(1^1D_2)$ $(J^{PC} = 2^{-+})$ ruled out
- $\chi_{c1}(2^3P_1)$ disfavoured by the measured mass
- Conventional charmonium interpretation of the X(3872) seems fading in favour of an exotic scenario!

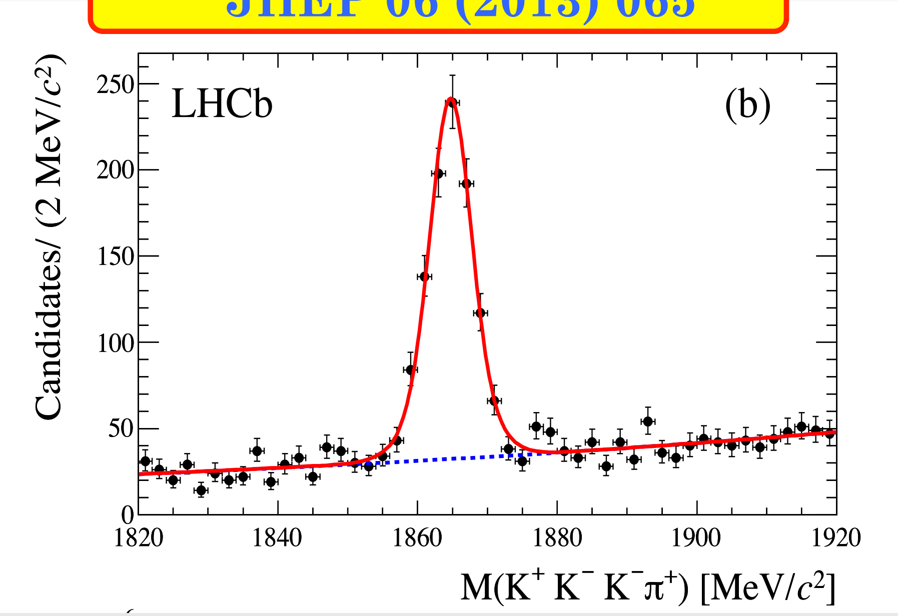
X(3872) AND D^0 MASS MEASUREMENTS

If X(3872) is a $\bar{D}^0 D^{*0}$ bound state $\Rightarrow m(X(3872)) < m(D^0) + m(D^{*0})$

Eur. Phys. J. C. 72 (2012) 1972



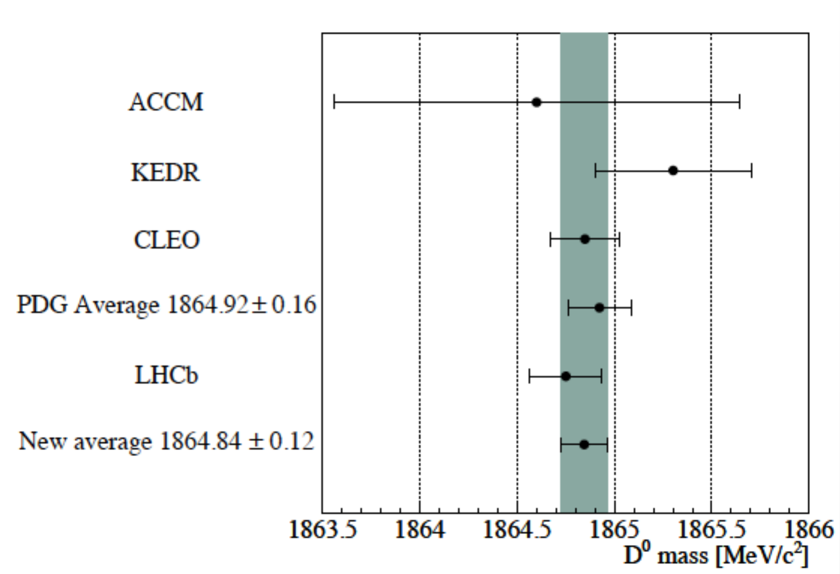
JHEP 06 (2013) 065

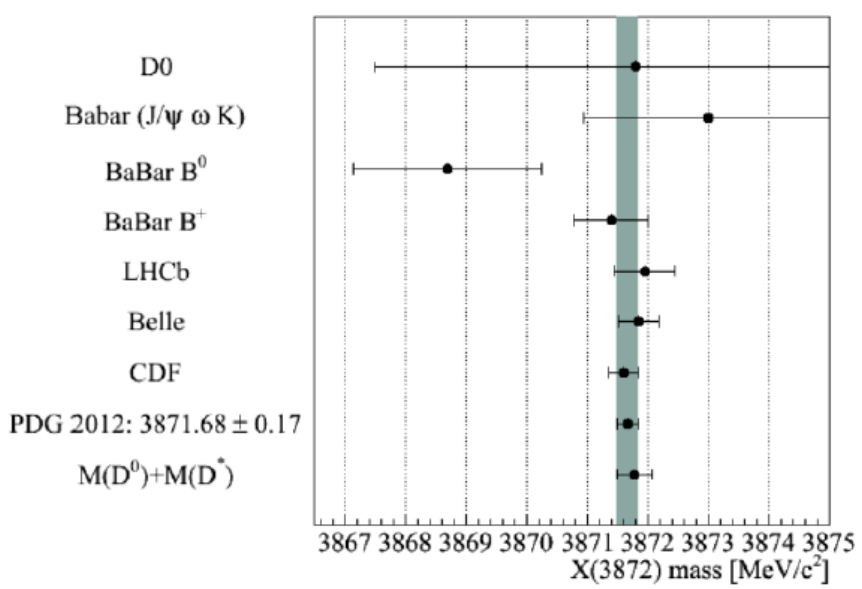


$m(X(3872)) = 3871.95 \pm 0.48 \pm 0.12\,\mathrm{MeV/c^2}$

$m(D^0) = 1864.75 \pm 0.15 \pm 0.11\,\mathrm{MeV/c^2}$

BINDING ENERGY



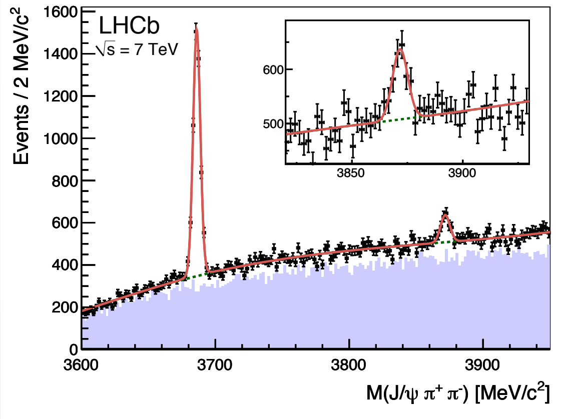


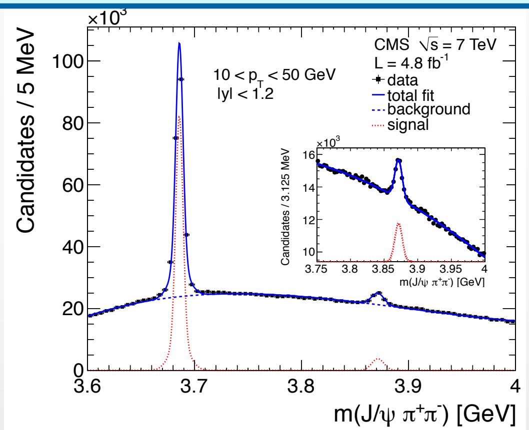
$$
\begin{aligned}
E_B &= m(D^0 D^{*0}) - m(X(3872)) \\
&= 2m(D^0) + \Delta m(D^{*0} - D^0) - m(X(3872)) \\
&= 0.09 \pm 0.28\,\mathrm{MeV/c^2}
\end{aligned}
$$

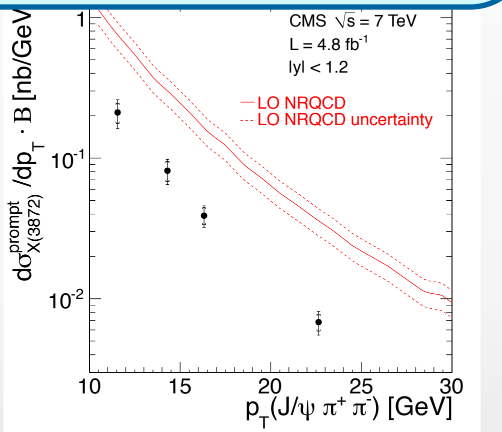
The result reinforces the conclusion that if the X(3872) state is a molecule, it is extremely loosely bound

X(3872) PRODUCTION

- ⊛ X(3872) production in hadron collisions reported by CDF [PRL93, 072001 (2004)], D0 [PRL93, 162002 (2004)], LHCb [EPJC72, 1972 (2012)] and CMS [JHEP 1304, 154 (2013)].
- ⊛ X(3872) reconstructed in the $J/\psi\pi^+\pi^-$ decay mode, in the central region (CMS, $|y| < 1.2$) or in the forward region (LHCb, $2.5 < y < 4.5$)







$$\text{LHCb}: \sigma_{X(3872)} \times BR(X(3972) \to J/\psi\pi^+\pi^-)^{[2.5<y<4.5, p_T>5\text{GeV}]} = 5.4 \pm 1.3 \pm 0.8\,\text{nb}$$

$$\text{CMS}: \sigma_{X(3872)} \times BR(X(3972) \to J/\psi\pi^+\pi^-)^{[|y|<1.2, p_T>10\text{GeV}]} = 1.06 \pm 0.11 \pm 0.15\,\text{nb}$$

CMS: Fraction of X(3872) from $B = (26.0 \pm 2.4 \pm 1.6)\%$

@ $\sqrt{s} = 7$ TeV

"Predictions" actually larger than the measured rate

EVIDENCE FOR X(3872)→ψ(2S)γ

[Nucl.Phys.B886 (2014) 665]

- ⊛ Observation of the $X(3872) \rightarrow J/\psi\gamma$ decay $\Rightarrow$ C=+ [PRL 102 132001] [PRL 107 091803]
- ⊛ Measurement of $R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J\psi\gamma)}$ to disentangle the nature of $X(3872)$
- ⊛ Predicitions of $R_{\psi\gamma}$ vary widely across different models:
  - → $\chi_{c1}(2^3P_1)$ interpretation: $R_{\psi\gamma} \sim 1.2 - 15$
  - → $D\bar{D}^*$ molecular picture: $R_{\psi\gamma} \sim (3-4) \times 10^{-3}$
  - → Mixture of $c\bar{c}$ and $D\bar{D}^*$: $R_{\psi\gamma} \sim 0.5 - 5$

Controversial experimental status:

- ➢ In 2009 BaBar: Evidence of X(3872)→ψ(2S)γ in B±→X(3872)K± decays:

$R_{\psi\gamma} = 3.4 \pm 1.4$ [PRL102 (2009) 132001]

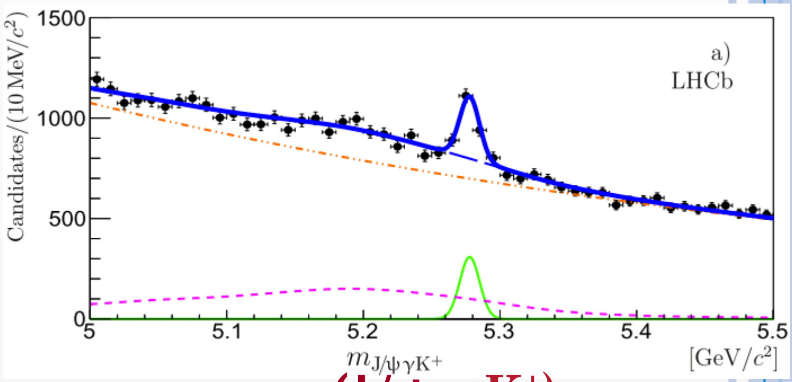
- ➢ In 2011 Belle: No evidence for X(3872)→ψ(2S)γ:

$R_{\psi\gamma} < 1.2$ @ 90 C.L. [PRL107 (2011) 091803]

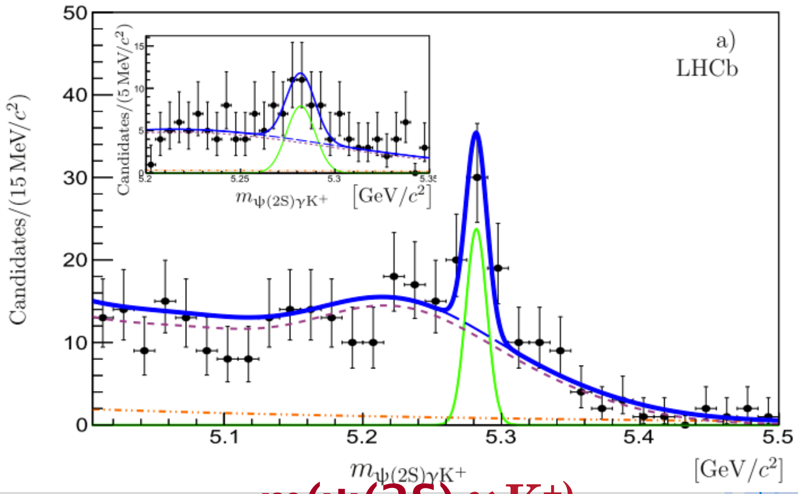
EVIDENCE FOR X(3872)→ψ(2S)γ

[Nucl.Phys.B886 (2014) 665]

- Integrated luminosity 3.0 fb^{-1}
- Reconstruction of $B^+ \to \psi(\to \mu\mu)\gamma K^+$, where $\psi = J/\psi$ or $\psi(2S)$
- π^0 veto
- $m(\psi\gamma) \in [3.7\text{-}4]$ GeV/c^2
- ψ mass and PV constrained to improve mass resolution



m(J/ψγK+)

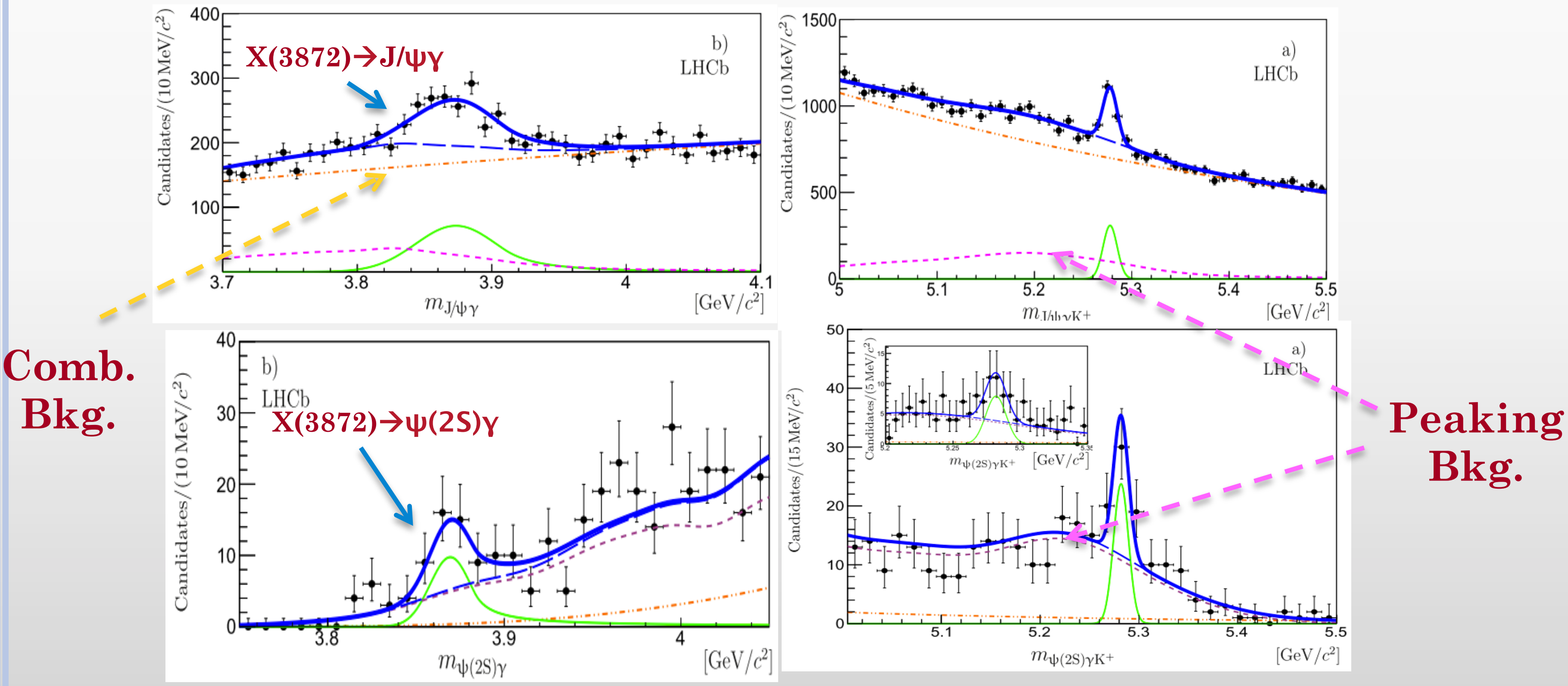


m(ψ(2S)γK+)

EVIDENCE FOR X(3872)→ψ(2S) γ

[Nucl.Phys.B886 (2014) 665]

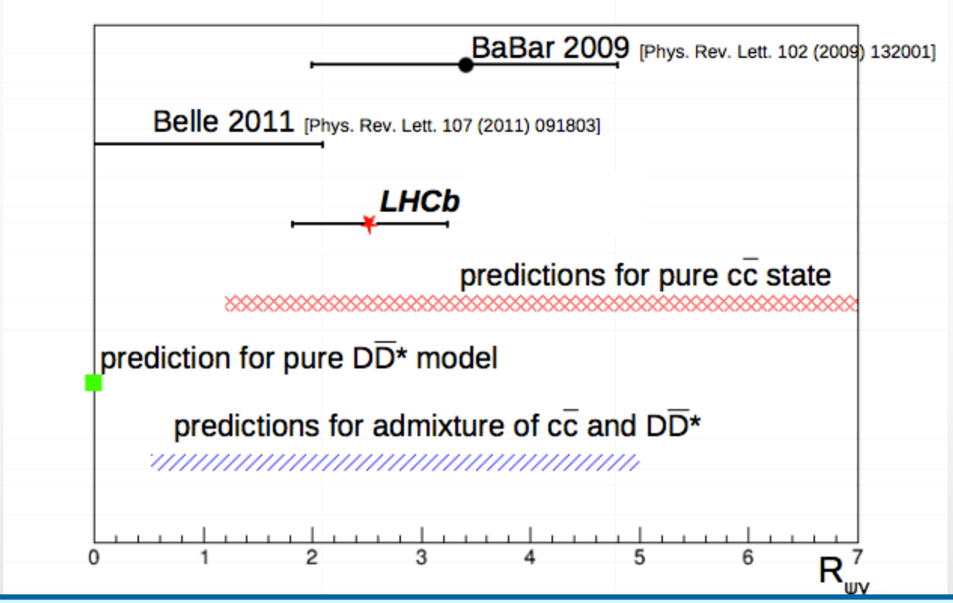
- 2D Fit: m($\psi\gamma$K) vs m($\psi\gamma$)
- Peaking backgrounds:
  - J/ψ mode: $B^+ \to J/\psi K^{*+}$, $K^{*+} \to K^+ \pi^0$ (→ γ~~γ~~)
  - ψ(2S) mode: b →J/ψ K⁺h + random γ



EVIDENCE FOR X(3872)→ψ(2S)γ

[Nucl.Phys.B886 (2014) 665]

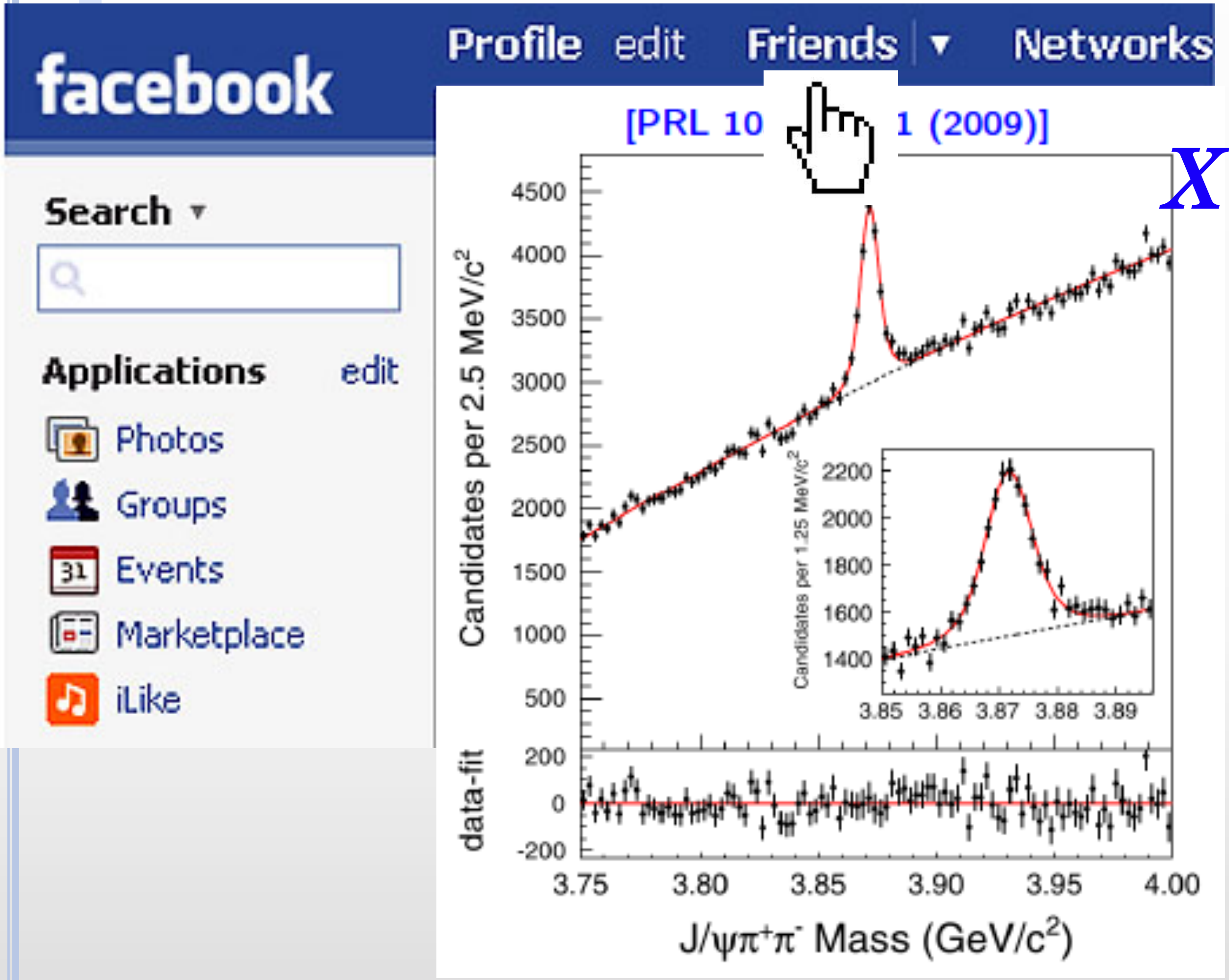
$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$



Does not support a <u>pure</u> DD* molecular interpretation.
Standard charmonium and other scenarios still compatible

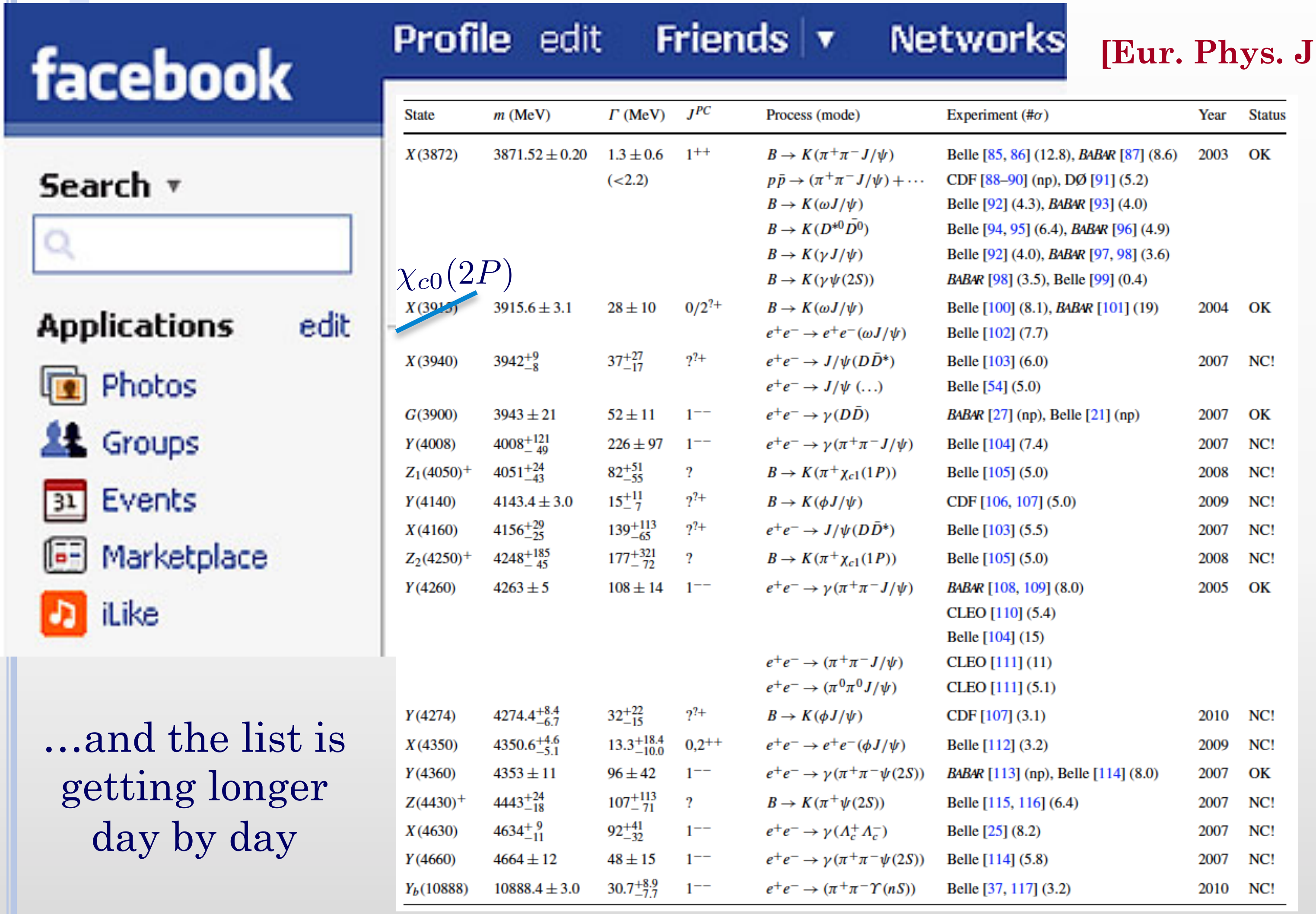
Can the radiative decays tell us more?
[F.Guo, C. Hanhart et al., arXiv:1410.6712]

…AND FRIENDS



X(3872)

…AND FRIENDS



[Eur. Phys. J. C71:1534, 2011]

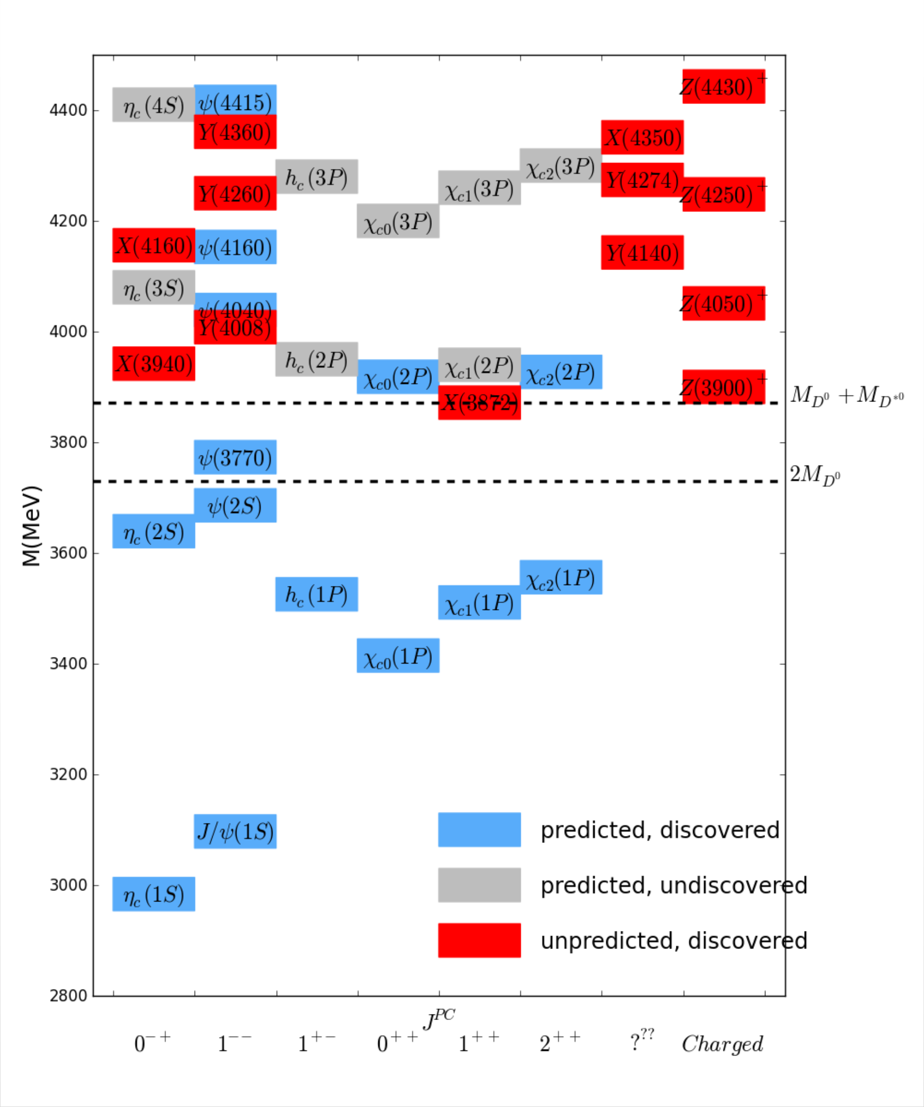
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma \psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
~~$X(3915)$~~ $\chi_{c0}(2P)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^- \Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

…and the list is getting longer day by day

N.B. Exotics are named X, Y, Z, G, ….currently all are X in PDG

THE EXOTIC PARTICLE ZOO

- The X(3872) has been the first unexpected quarkonia candidate
- Many other states observed in the years after
- Most of them need to be confirmed
- Large uncertainties on masses and width

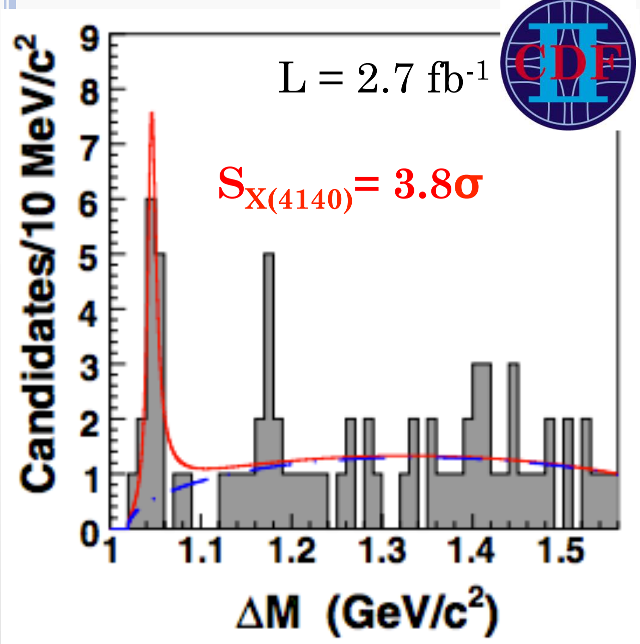


THE DAWN OF THE X(4140) & X(4274)

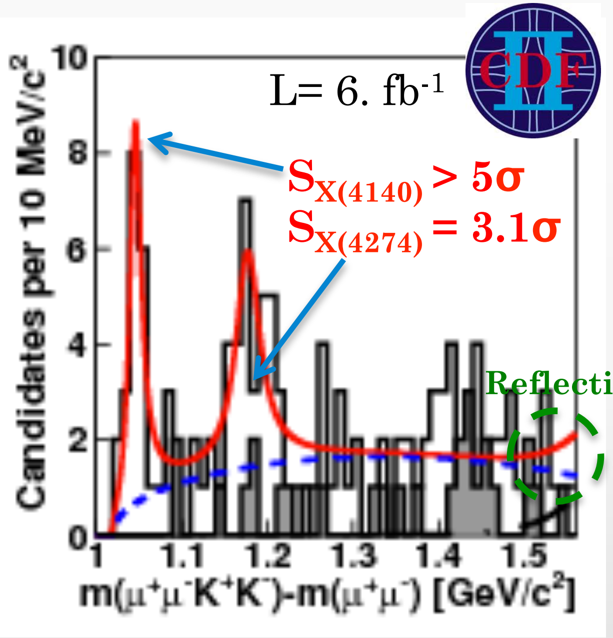
Evidence/“Observation” in $B^+ \rightarrow J/\psi\ \phi\ K^+$

PRL 102, 242002 (2009)

arXiv: 1101.6058 (2011)



$S_{X(4140)} = 3.8\sigma$



$S_{X(4140)} > 5\sigma$

$S_{X(4274)} = 3.1\sigma$

X(4140)

$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV

$\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV

X(4274)

$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV

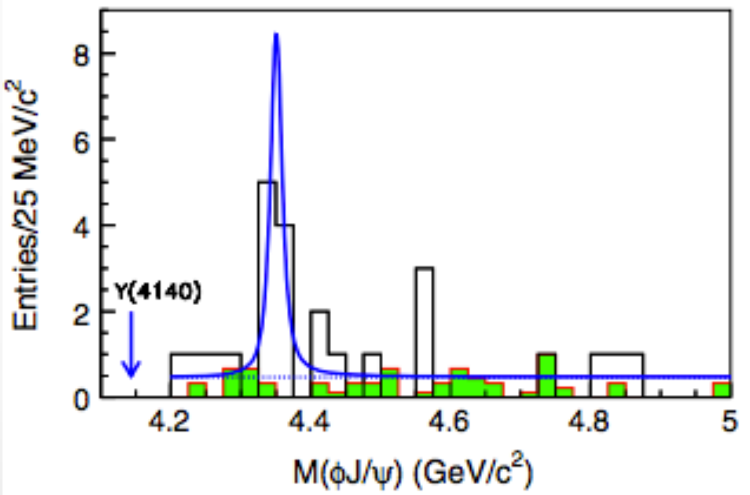
$\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV

Charmonium states with $m_X >> D_{(s)}^{(*)} D_{(s)}^{(*)}$ should decay easily into D mesons. The narrow widths hint that their nature is different: meson-meson, hybrid, tetraquark, etc..

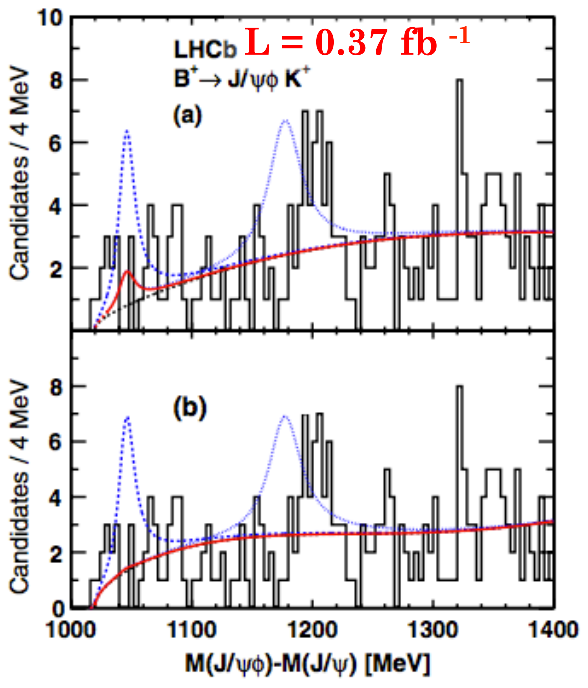
TWILIGHT OF THE GODS

$\gamma\gamma \rightarrow J/\psi\ \phi$

[Belle, PRL 104, 112004 (2010)]



[LHCb, PRD 85, 091103(R) (2012)]



- According to the CDF results, 35 ± 11 X(4140) signal candidates and 53 ± 19 X(4274) signal candidates expected
- No narrow structure is observed near the threshold
- The LHCb results disagree at 2.4σ level with the CDF measurement

LHCb(90%) C.L.

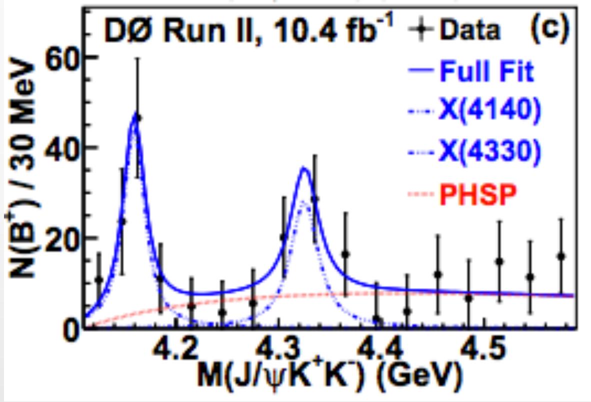
$$\frac{\mathcal{B}(B^+ \rightarrow X(4140)K^+) \times \mathcal{B}(X(4140) \rightarrow J/\psi\phi)}{\mathcal{B}(B^+ \rightarrow J/\psi\phi K^+)} < 0.07.$$

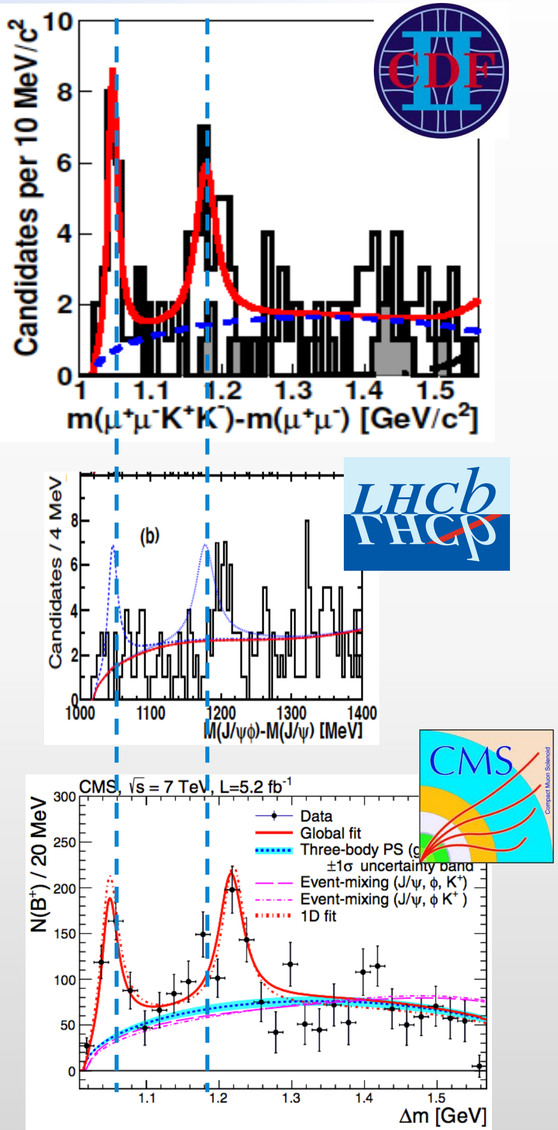
$$\frac{\mathcal{B}(B^+ \rightarrow X(4274)K^+) \times \mathcal{B}(X(4274) \rightarrow J/\psi\phi)}{\mathcal{B}(B^+ \rightarrow J/\psi\phi K^+)} < 0.08$$

RETURN OF THE LIVING DEAD

- CMS has reported observation/evidence of peaks in Jψ ϕ **[PLB 734 (2014) 261]**
- Some disagreement (3.8σ) for the mass of the X(4274)
- Similar structures seen by D0 collaboration

[D0, PRD89 012004 (2014)]



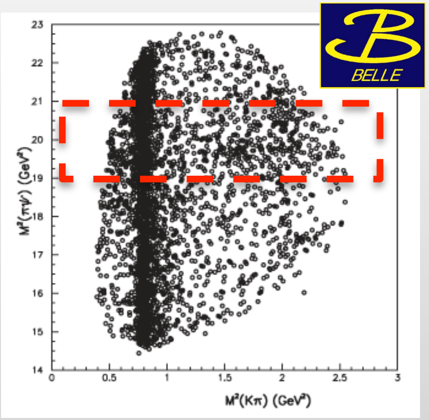


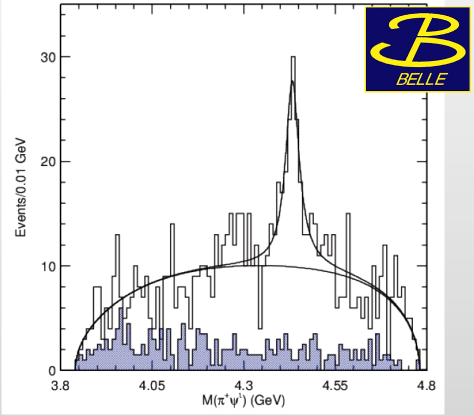
X(4140) and X(4274) still to be "confirmed"

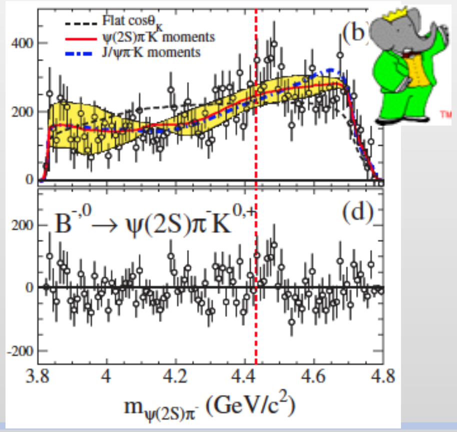
An amplitude analysis would help to investigate the resonance nature of these peaks

$Z(4430)^+$

- Observed in the $\psi(2S)\pi^+$ in $B^{0(+)} \to \psi(2S)\pi^+K^{-(0)}$ decays by Belle
  [Belle, PRL100, 142001 (2008)]
- Clear signature of exotic:
  Decay to charmonium $\to c\bar{c}$ pair content
  Electric charged $\to$ at least 2 more light quarks $N_{quarks} >= 4!$
  Tetraquark, D^*D_1 molecule $(J^P = 0^-, 1^-, 2^-)$?
- Later 2D "Dalitz" technique: $M^2(\psi(2S)\pi^+)$ vs $M^2(K^-\pi^+)$ **[Belle, PRD 80, 031104 (R) (2009)]**
- $Z(4430)^+$ not confirmed (nor excluded) by BaBar: Investigation the extent to which reflection of the $K\pi$ mass and angular structures are able to reproduce the $\psi(2S)\pi$ mass distributions **[BaBar, PRD 79, 112001 (2009)]**
- Belle presented results of a full 4D amplitude analysis. $J^P = 1^+$ favoured but $J^P = 0^-$ not excluded **[Belle, PRD 88 (2013) 074026]**



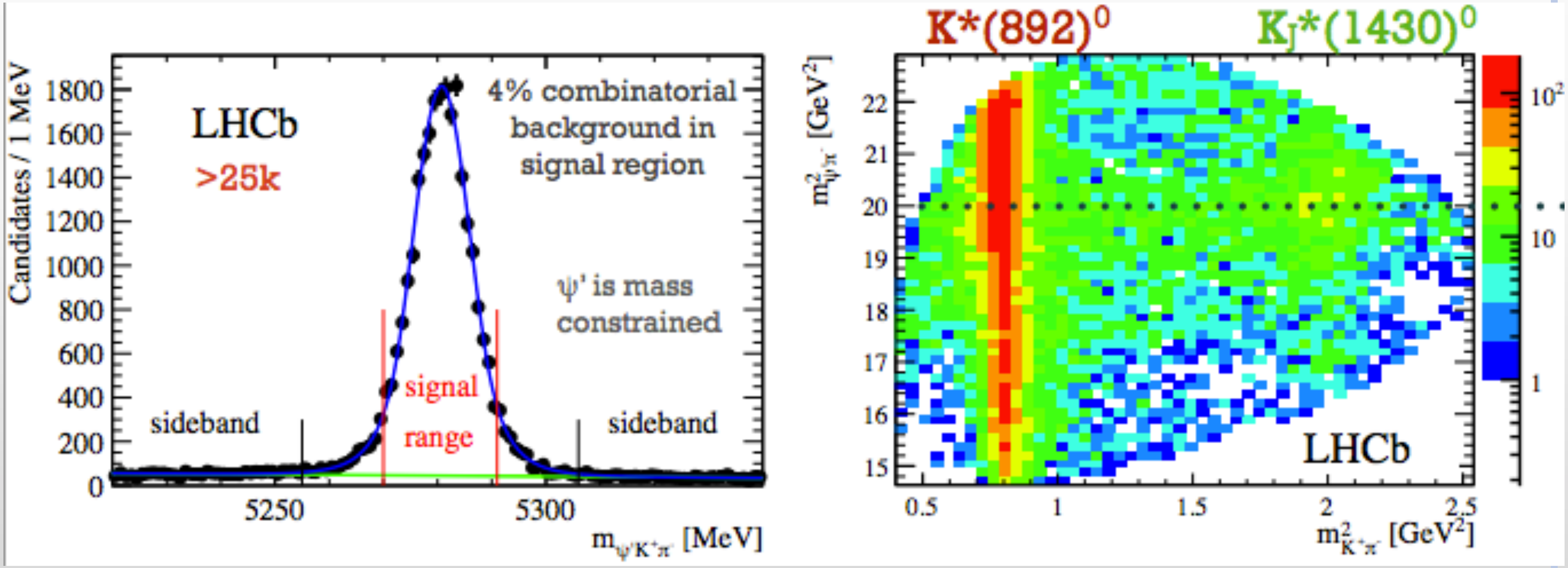




CONFIRMATION OF Z(4430)$^+$

[PRL 112, 222002 (2014)]

- Integrated luminosity of 3.0 fb^{-1}
- Sample of > 25k $B^0 \rightarrow \psi(2S)K^+\pi^-$ candidates (x10 Belle/BaBar)
- Backgrounds from mis-ID physics decay is small
- Sidebands are used to build 4D model of the combinatorial background

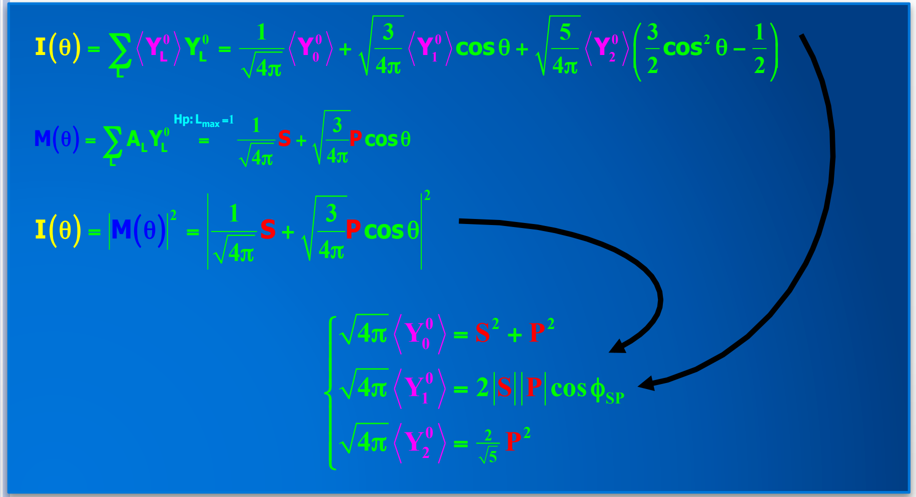


MODEL INDEPENDENT ANALYSIS

[PRL 112, 222002 (2014)]

Can reflection of the structures in m(Kπ) and cos θ reproduce the m(ψ'π) distribution?

[S.U.Chung, Phys. Rev. D56, 7299(1997)]

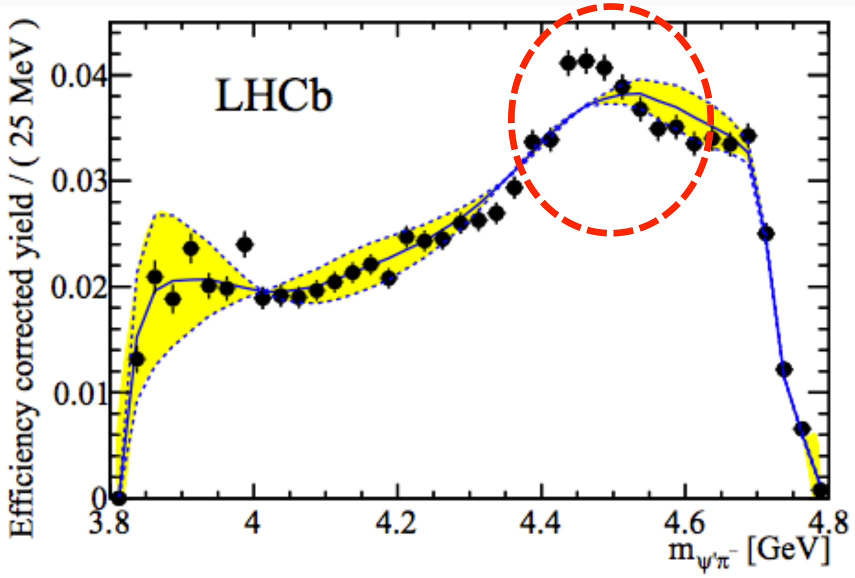


$$I(\theta) = \sum_L \langle Y_L^0 \rangle Y_L^0 = \frac{1}{\sqrt{4\pi}} \langle Y_0^0 \rangle + \sqrt{\frac{3}{4\pi}} \langle Y_1^0 \rangle \cos\theta + \sqrt{\frac{5}{4\pi}} \langle Y_2^0 \rangle \left(\frac{3}{2}\cos^2\theta - \frac{1}{2} \right)$$

$$M(\theta) = \sum_L A_L Y_L^0 \overset{Hp:\, L_{max}=1}{=} \frac{1}{\sqrt{4\pi}} S + \sqrt{\frac{3}{4\pi}} P \cos\theta$$

$$I(\theta) = |M(\theta)|^2 = \left| \frac{1}{\sqrt{4\pi}} S + \sqrt{\frac{3}{4\pi}} P \cos\theta \right|^2$$

$$\begin{cases} \sqrt{4\pi} \langle Y_0^0 \rangle = S^2 + P^2 \\ \sqrt{4\pi} \langle Y_1^0 \rangle = 2|S||P| \cos\phi_{SP} \\ \sqrt{4\pi} \langle Y_2^0 \rangle = \frac{2}{\sqrt{5}} P^2 \end{cases}$$



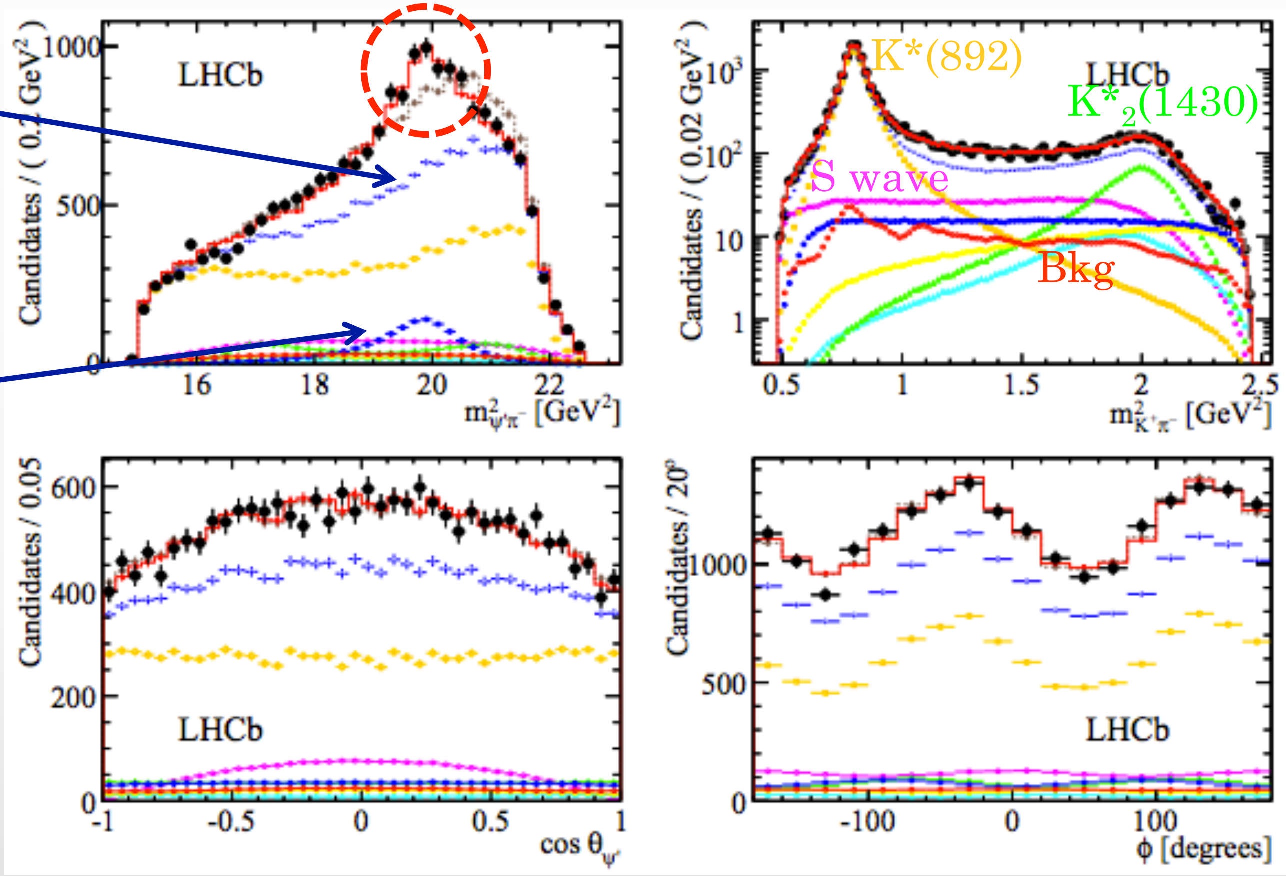
- Does not make any assumption on the underlying K* resonances in the system, only restricts their maximal spin (J ≤ 2).
- Weight phase space simulated $B^0 \longrightarrow \psi' K^+ \pi^-$ events with the spherical harmonic moments of cos θ_K .
- Moments of K* resonances are unable to explain observed distribution

PROJECTIONS OF 4D AMPLITUDE FIT WITH Z(4430)$^+$

[PRL 112, 222002 (2014)]

Everything except the Z →large interference between Z and Kπ sector

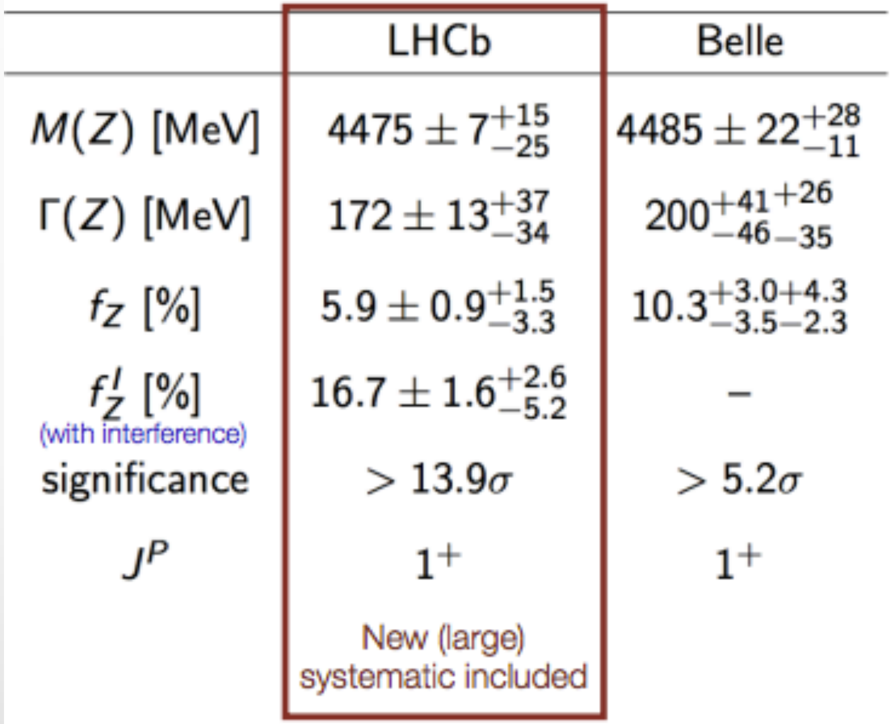
$J^P = 1^+$
Z component



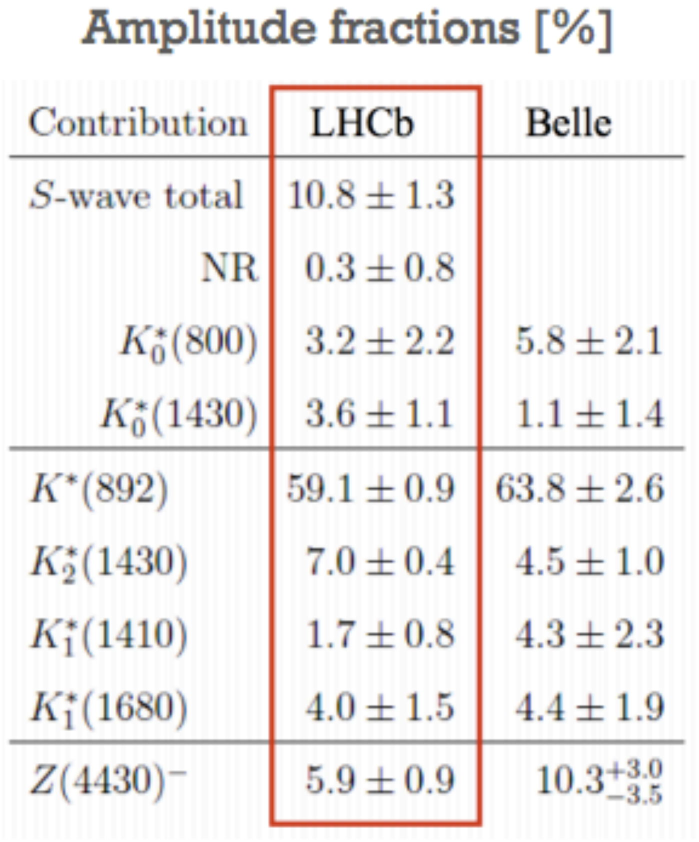
- ➢ The 4D χ^2 p-value = 12%.
- ➢ The data are well described when including a $J^P=1^+$ Z(4430) in the fit

Z(4430)$^+$ Parameters from Amplitude Fit

[PRL 112, 222002 (2014)]



	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interference)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+
	New (large) systematic included	



Amplitude fractions [%]

Contribution	LHCb	Belle
S-wave total	10.8 ± 1.3	
NR	0.3 ± 0.8	
$K_0^*(800)$	3.2 ± 2.2	5.8 ± 2.1
$K_0^*(1430)$	3.6 ± 1.1	1.1 ± 1.4
$K^*(892)$	59.1 ± 0.9	63.8 ± 2.6
$K_2^*(1430)$	7.0 ± 0.4	4.5 ± 1.0
$K_1^*(1410)$	1.7 ± 0.8	4.3 ± 2.3
$K_1^*(1680)$	4.0 ± 1.5	4.4 ± 1.9
$Z(4430)^-$	5.9 ± 0.9	$10.3^{+3.0}_{-3.5}$

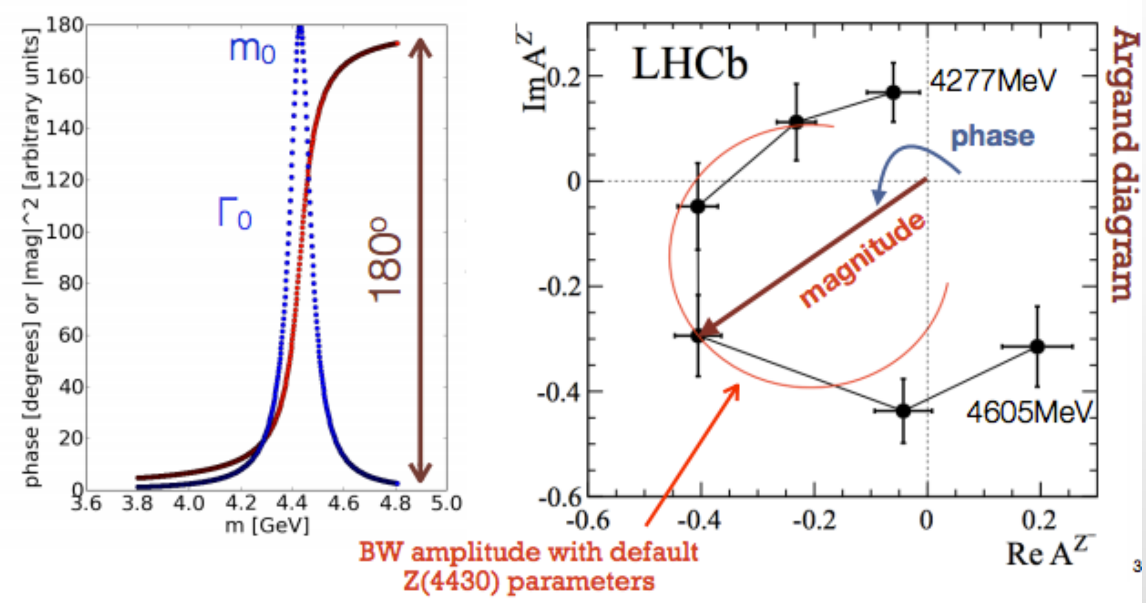
Very good agreement between LHCb/Belle results

RESONANT BEHAVIOUR – A BOUND STATE?

[PRL 112, 222002 (2014)]

Replace BW amplitude with 6 independent complex numbers in 6 bins of m(ψ'π) in region of Z(4430) mass peak.

- ➢ Allows Z(4430) shape to be constrained only by amplitudes in Kπ sector.
- ➢ Observe rapid change of phase near maximum of magnitude ⇒ resonance!



BW amplitude with default Z(4430) parameters

Still room for non-resonant interpretation?

[P.Pakhlov, T.Uglov, arXiv: 1408.5295]

SECOND EXOTIC Z^+?

[PRL 112, 222002 (2014)]

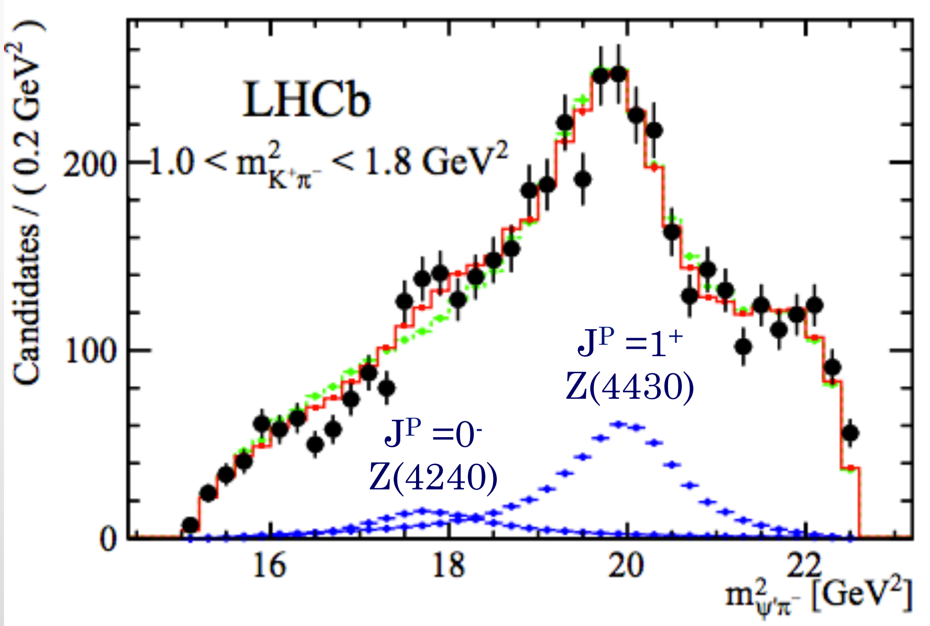
Fit confidence level increases with a second exotic ($J^P=0^-$) component, but…

- No evidence for Z_0 in model independent approach.
- Argand diagram for Z_0 is inconclusive.
- Need larger samples to characterize this state.

$$M_{Z_0} = 4239 \pm 18^{+45}_{-10}\mathrm{MeV}$$

$$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}\mathrm{MeV}$$

$$f_{Z_0} = (1.6 \pm 0.5^{+1.9}_{-0.4})\%$$



Mass and width consistent with other Z's observed by Belle:

- $Z^- \to \chi_{c1}\pi^-$ ($J^P \neq 0^-$) **[PRD 78 (2008) 072004]**
- $Z^- \to J/\psi\pi^-$ **[arXiv: 1408.6457]**