HEAVY HADRON SPECTROSCOPY
(MESONS & BARYONS)

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Hadron Physics and Non Perturbative QCD
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OUTLINE

- Introduction
- Standing(?) puzzles in heavy spectroscopy
- Experimental overview
  - Heavy Mesons
  - Heavy Baryons

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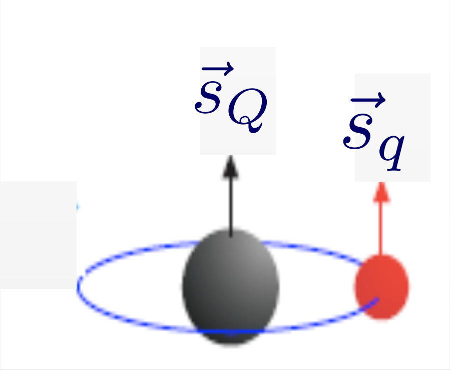
INTRODUCTION

- 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

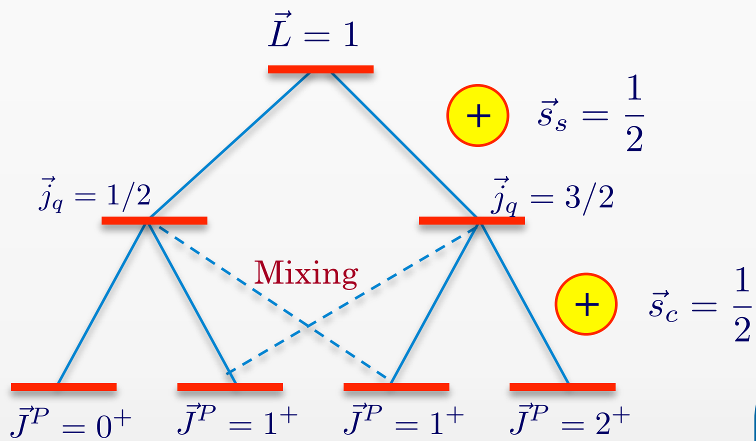


$\vec{L}$	Orbital angular momentum
$\vec{j}_q = \vec{L} + \vec{s}_{q=u,d,s}$	Angular momentum of the light quark
$\vec{J} = \vec{j}_q + \vec{s}_{Q=b,c}$	Total angular momentum of the heavy meson

Decays of Excited Heavy Mesons

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

E.g. Orbitally L=1 excited B→B$^{(*)}\pi$**



B_0* **B'$_1$** **B_1** **B_2***

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

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

j_q = 1/2 doublet

j_q = 3/2 doublet

	j_q	J^P	Allowed decay mode $B\pi$	Allowed decay mode $B^*\pi$
B_0^*	1/2	0^+	yes	no
B_1'	1/2	1^+	no	yes
B_1	3/2	1^+	no	yes
B_2^*	3/2	2^+	yes	yes

The four states come in doublets and within each doublet

- ✓ 1 natural state (B_2*) decaying to Bπ and B*π
- ✓ 1 unnatural state (B_1) decaying to B*π

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

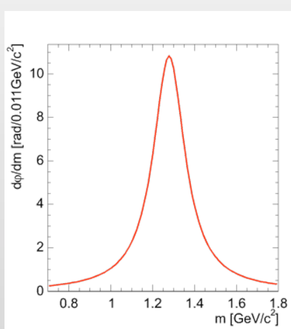
Similar scenario for the excited B_s→B$^{(*)}$K, D**→D$^{(*)}$ π, D_s**→D$^{(*)}$K**

How to do spectroscopy?

"Inclusive Analysis"

(e.g. $e^+e^- \to D^{**}(\to D\pi) + X$ or $pp \to B_s^{**}(\to BK) + X$)

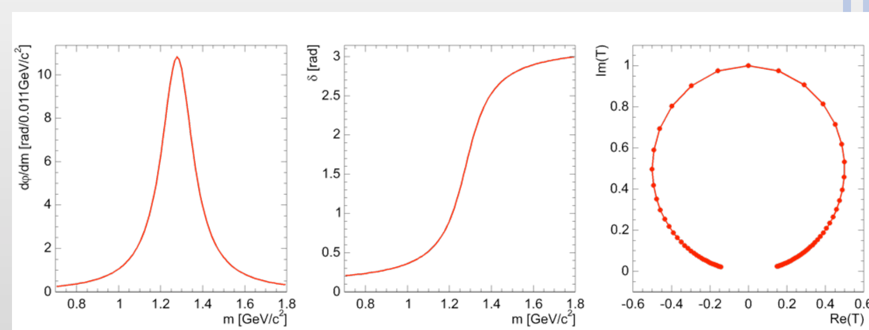
- Large cross sections
- Large combinatorial background
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization



"Exclusive Analyses"

(e.g. $B \to D^{**}(\to D\pi)\pi$ or $B_c \to B_s^{**}(\to BK)\pi$)

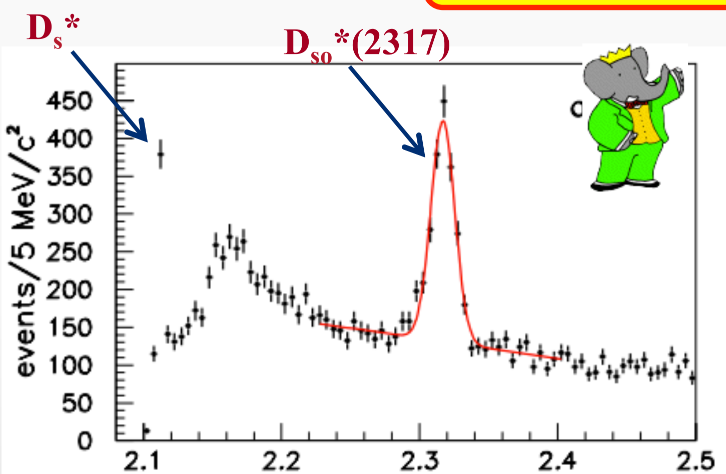
- Limited statistics
- Small background
- Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference)
- Suitable to study broad resonances
- Spin-parity assignment by amplitude analysis



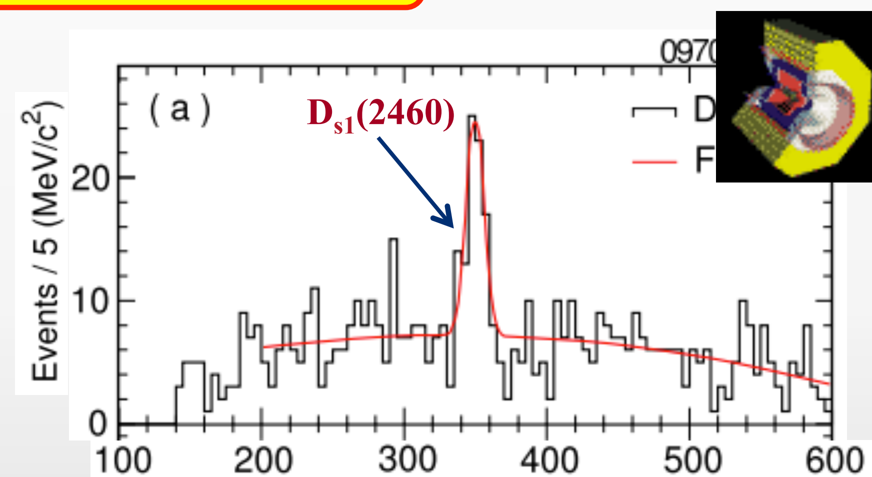
PUZZLE: EXCITED D_s MESONS: L=1, j_q = 1/2(?)

- Before 2003, HQET theories succeeded to predict masses and properties of the orbitally excited $D_{(s)}$ states
- But the (expected) broad D_{s0}^* and D_{s1}' states were still missing….

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(?)

- 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: arXiv:1504.02637]**

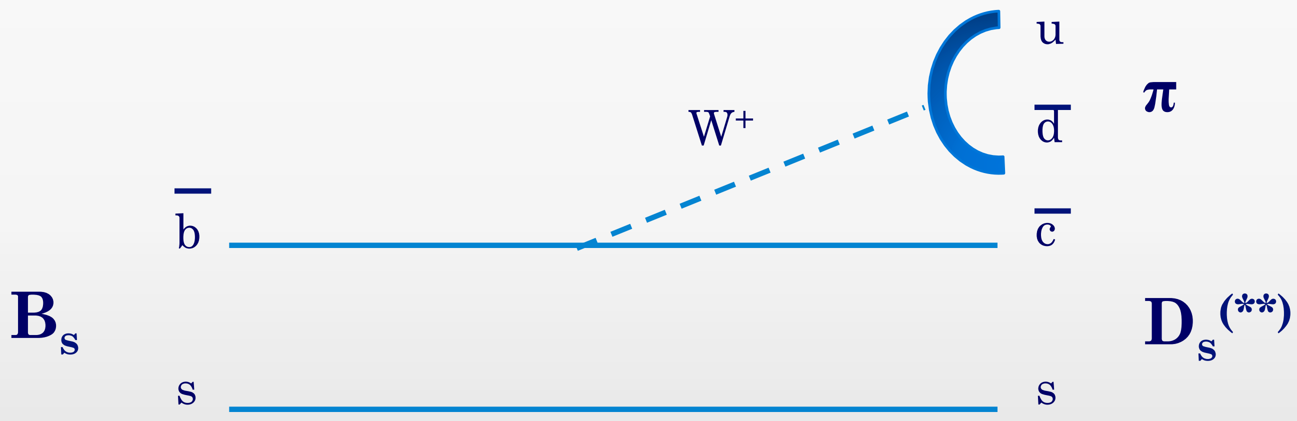
- Multiquark scenario→ Isospin partners of D_{s0}*

$$\mathcal{B}(B^0 \to D^- D_{s0}^{*+}) \simeq \mathcal{B}(B^0 \to D^0 D_{s0}^{*0}) \simeq \mathcal{B}(B^+ \to D^- D_{s0}^{*++})$$

- No signal observed. UL one order of magnitude lower than expected

SEARCH FOR "D_{s0}*" IN B_s DECAYS

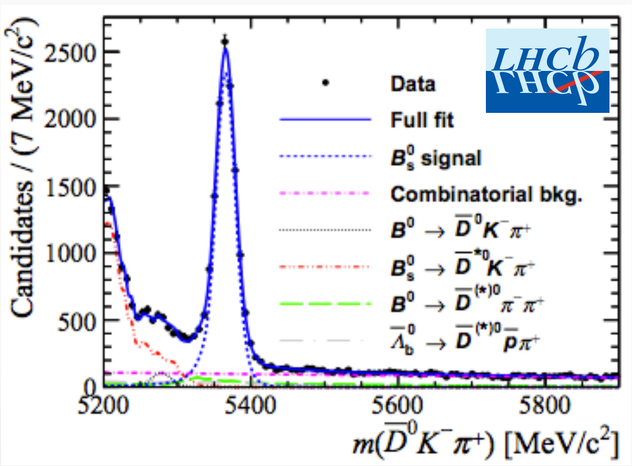
If the $D_{s0}^*(2317)$ is not the L=1, j_q=1/2 excited D_s state, then a broad D_{s0}^* state above the DK threshold should appear in B_s decays

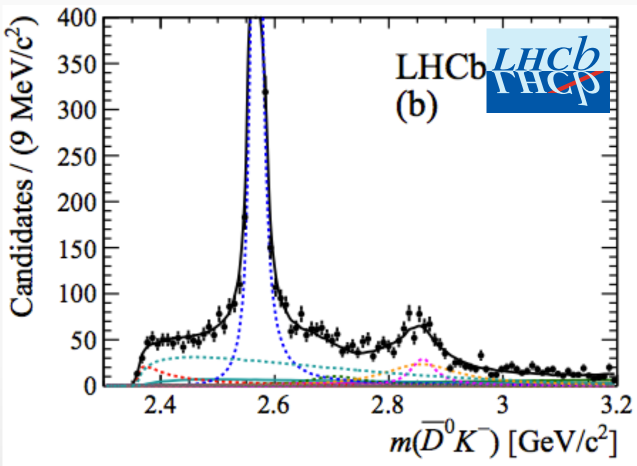


Search For "D_{s0}^*" in B_s Decays

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

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





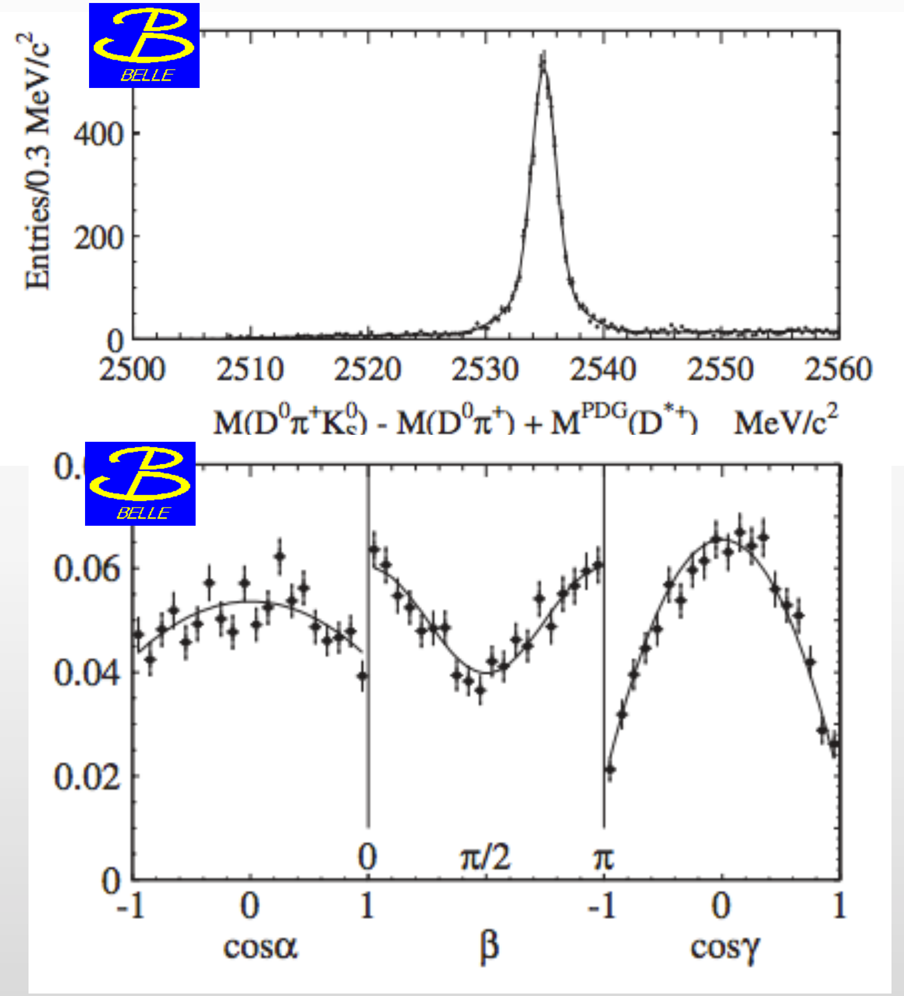
Resonance	Fit fraction (%)
$\overline{K}^*(892)^0$	28.6 ± 0.6
$\overline{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\overline{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\overline{K}_2^*(1430)^0$	3.7 ± 0.6
$\overline{K}^*(1680)^0$	0.5 ± 0.4
$\overline{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	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_{sv}^{*-}	4.7 ± 1.4
$D_{s0\,v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3

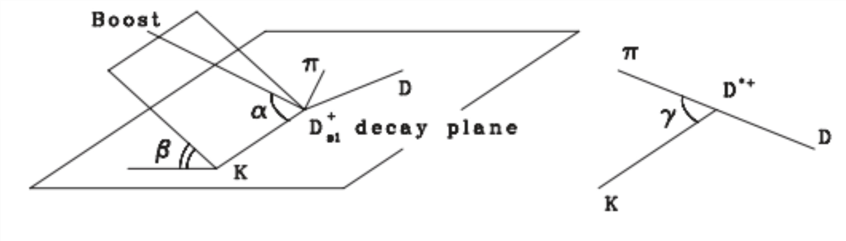
No evidence for such a broad D_{s0}^* state

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]





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

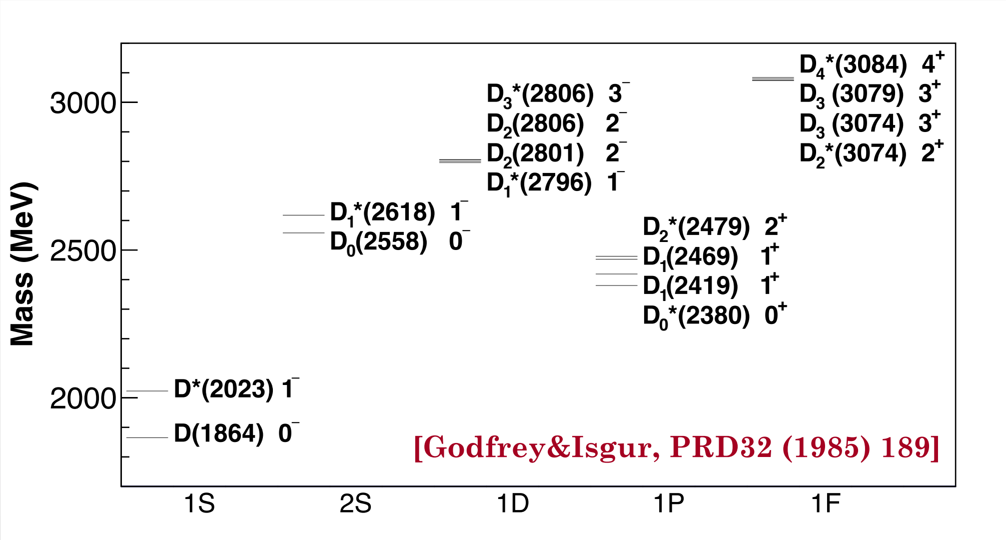
Contrary of HQET expectations, the S-wave contribution dominates!

Excited D mesons

EXCITED D_J STATES

[LHCb, JHEP 09 (2013) 145]

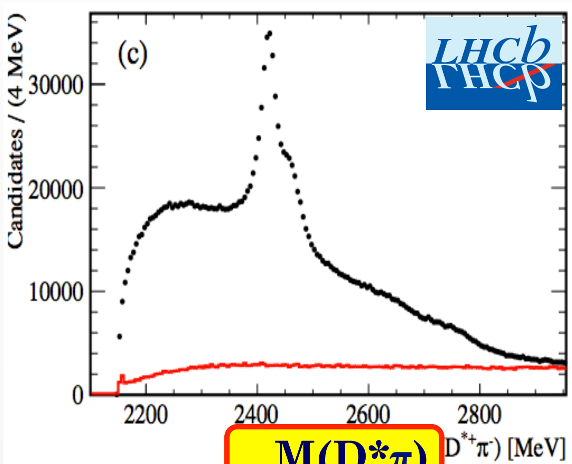
- The quark model predicts many excited states in limited mass regions
- Ground and 1P states well established
- BaBar collaboration found 4 new states decaying to Dπ and/or D*π. Need to be confirmed. [PRD82 (2010)111101]



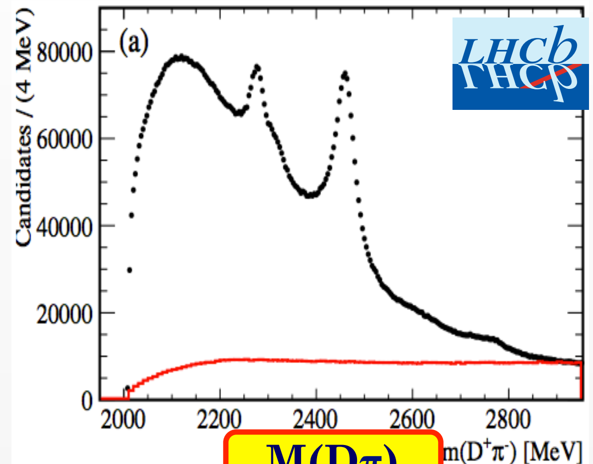
$D^{(*)}\pi$ Mass Spectra

[LHCb, JHEP 09 (2013) 145]

How to fit? How many resonances?



M(D*π)

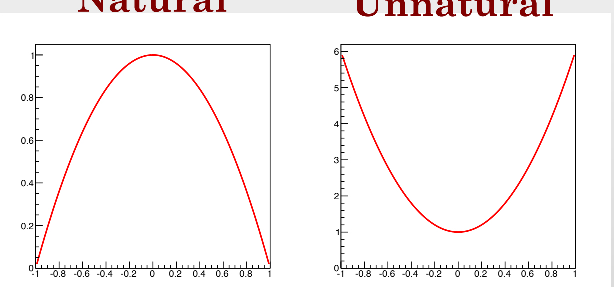


M(Dπ)

- D*π : Natural + Unnatural states
- Dπ : Natural states + Feed-down of states in D*π

- Fitting the D*π spectrum first
- Helicity angle ϑ used to study the natural/ unnatural component:
  - ✓ $\propto \sin^2\vartheta$ for natural spin-parity
  - ✓ $\propto 1+h\cos^2\vartheta$ for unnatural spin-parity

Natural **Unnatural**



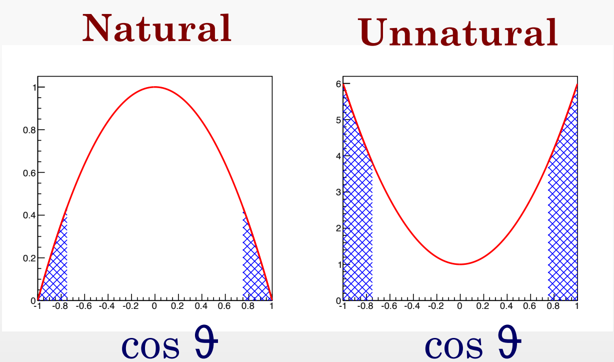
cos ϑ cos ϑ

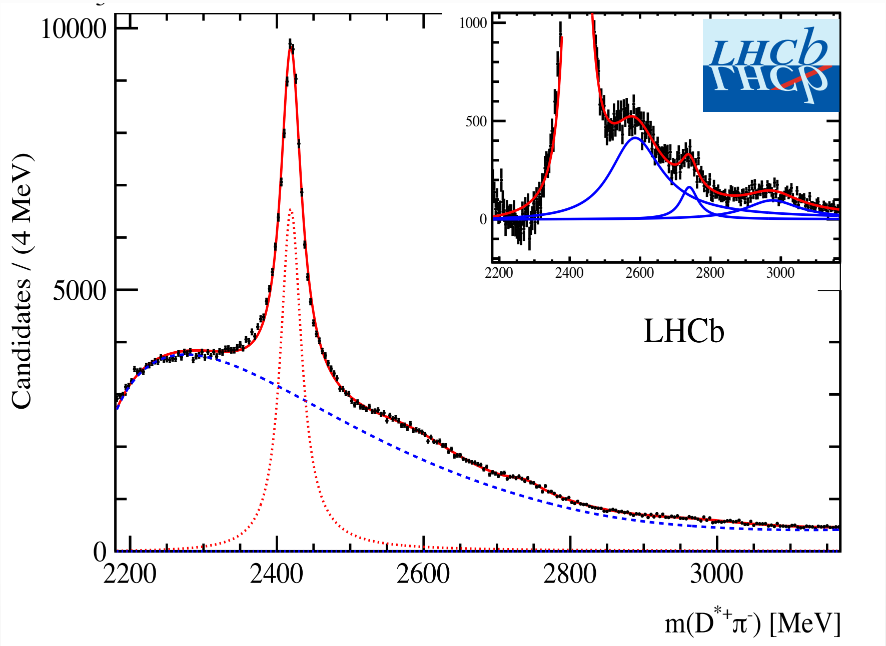
$D^{*+}\pi^-$ Mass Fit

[LHCb, JHEP 09 (2013) 145]

Step 1

$|\cos\vartheta| > 0.75$
enhances unnatural component
(residual natural component ~9%)





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

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

$D^{*+}\pi^-$ Mass Fit

[LHCb, JHEP 09 (2013) 145]

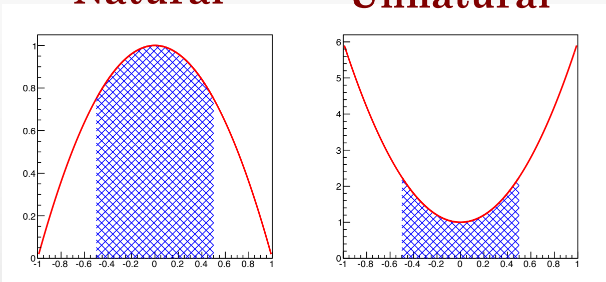
Step 2

$|\cos\vartheta| < 0.5$

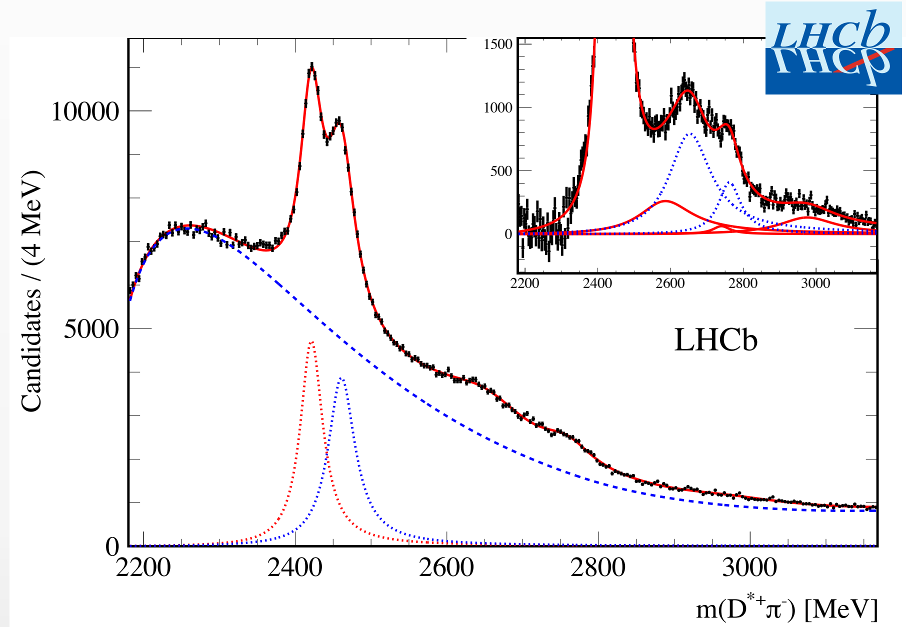
enhances natural component

Parameters of the unnatural states from Step 1

Natural Unnatural



cos ϑ cos ϑ



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

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

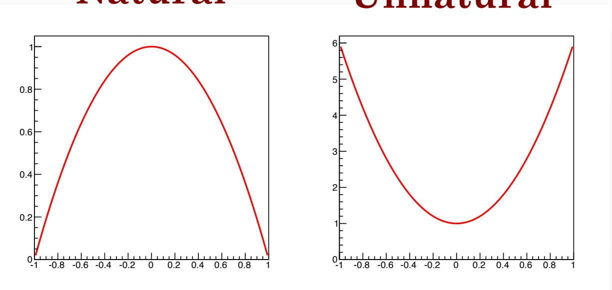
$D^{*+}\pi^-$ Mass Fit

[LHCb, JHEP 09 (2013) 145]

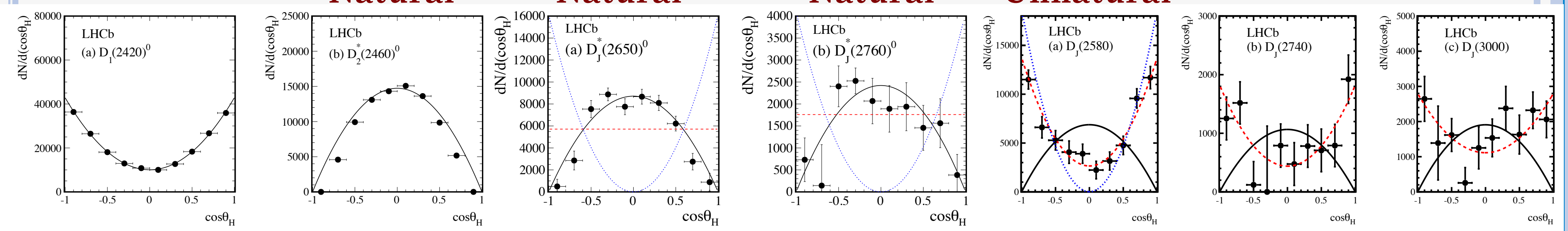
Step 3

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

Natural   Unnatural



$D_1(2420)$ Unnatural | $D_2^*(2460)$ Natural | $D_2^*(2650)$ Natural | $D_2^*(2760)$ Natural | $D_J(2580)$ Unnatural | $D_J(2740)$ Unnatural | $D_J(3000)$ Unnatural



$D_J(2580)$ could be identified with the D(2S) (e.g. $D_0(2558)$)
$D_J^*(2650)$ could be identified as the $J^P=1^-$ D*(2S) (i.e. $D_1^*(2618)$)

$D_J(2740)$ could be identified as the $J^P=2^-$ $D_2(1D)$ (i.e. $D_2(2801)$)
$D_J^*(2760)$ could be identified as the $J^P=1^-$ $D_1^*(1D)$ (i.e. $D_1^*(2796)$)

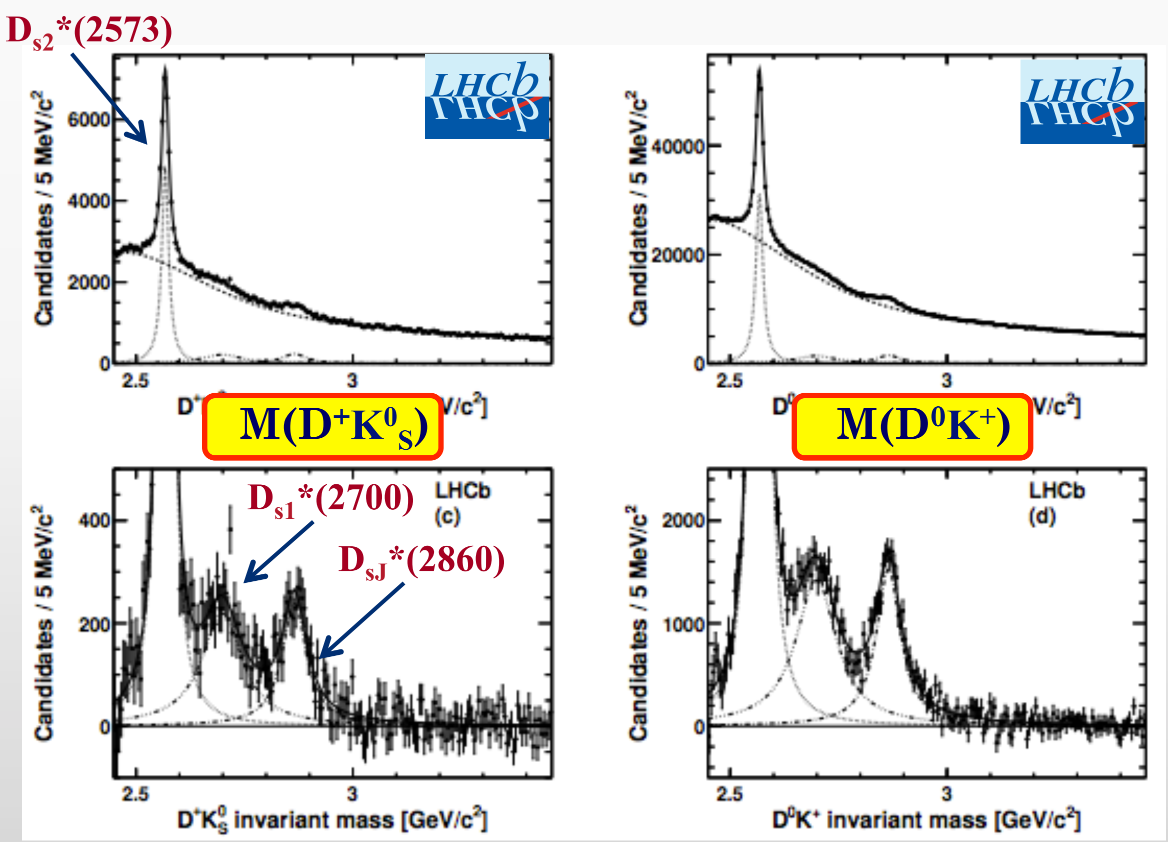
Study of $D^{(*)}\pi$ spectrum from B decays needed to establish spin-parity

Excited D_s mesons

EXCITED D_{sJ} STATES (INCLUSIVE ANALYSIS)

[LHCb, JHEP 10 (2012) 151]

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

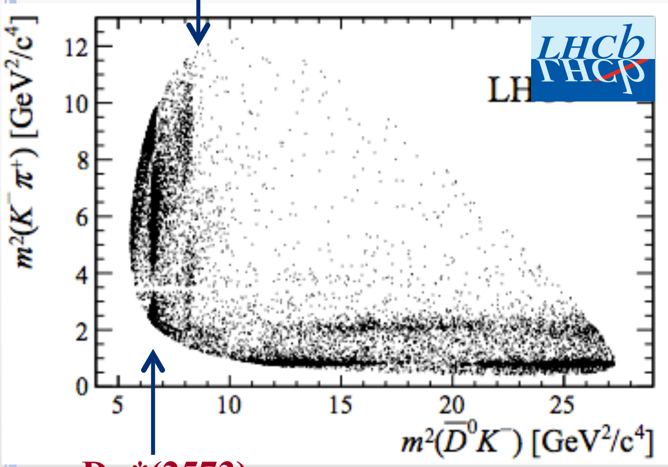


EXCITED D_{sJ} STATES FROM B DECAYS

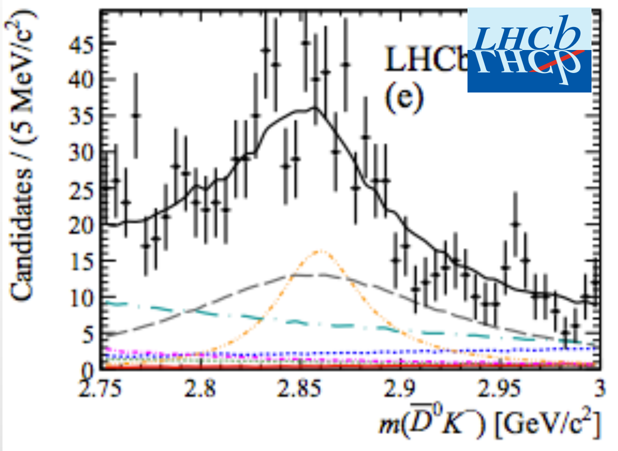
[LHCb: PRL 113, 162001 (2014)]
[LHCb: PRD 90, 072003 (2014)]

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

$D_{sJ}^*(2860)$



$D_{s2}^*(2573)$



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Total fit fraction	124.3

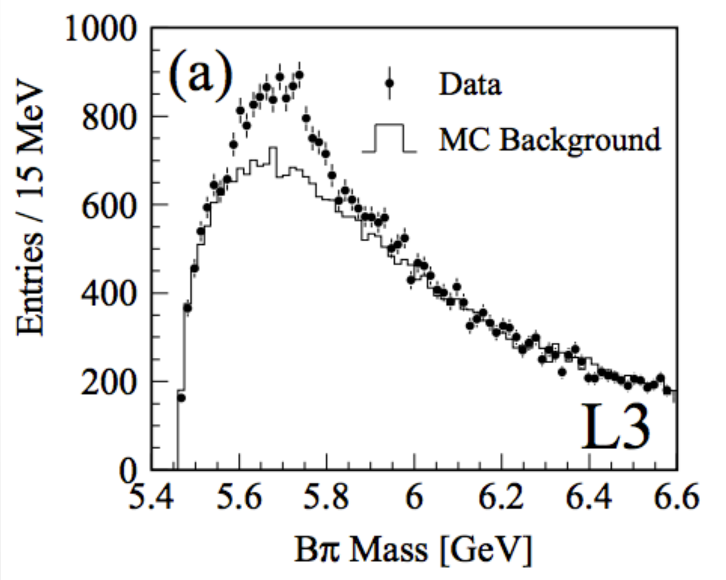
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)
$D_{s2}^*(2573)^-$	2568.39 ± 0.29	16.9 ± 0.5
$D_{s1}^*(2860)^-$	2859 ± 12	159 ± 23
$D_{s3}^*(2860)^-$	2860.5 ± 2.6	53 ± 7

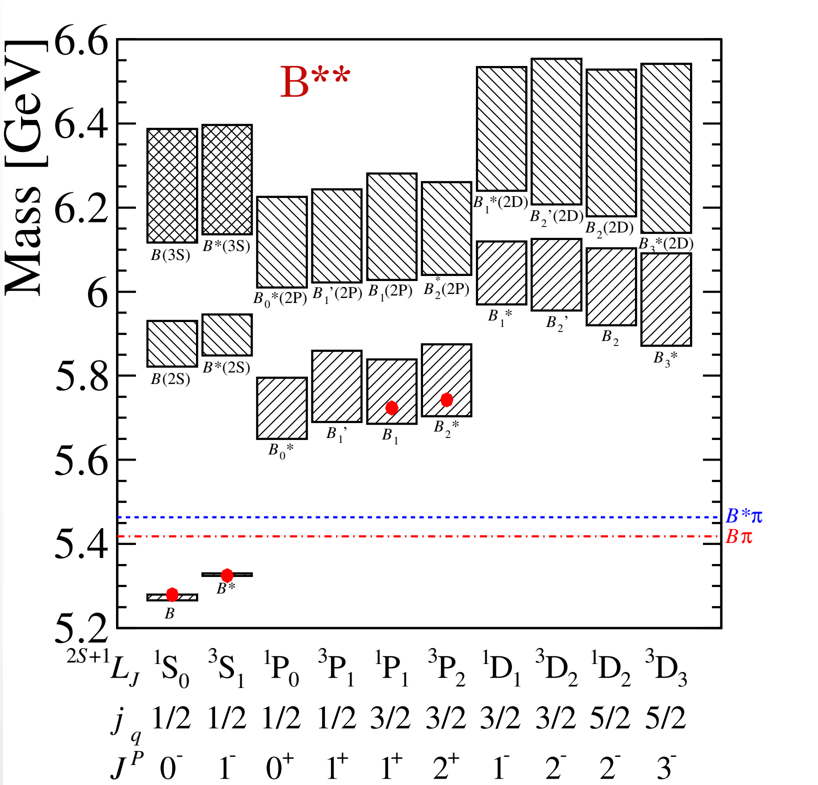
Likely they are the L=2 excited $D_{sJ}^*(1D)$ states

Excited B mesons

THE EXCITED B STATES

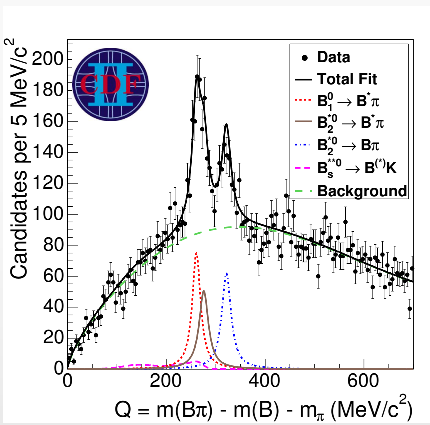
- LEP experiments observed a single broad structure (Γ > 100 MeV) in $B^+\pi^-$: $B_J^*(5732)$

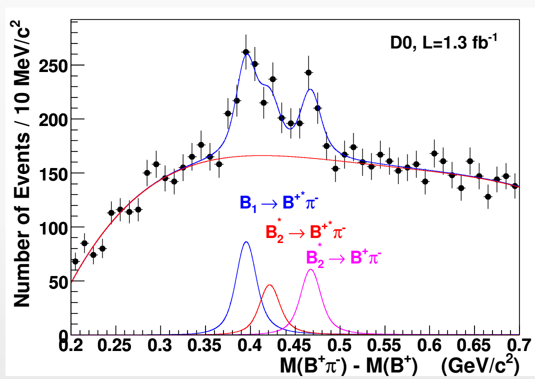


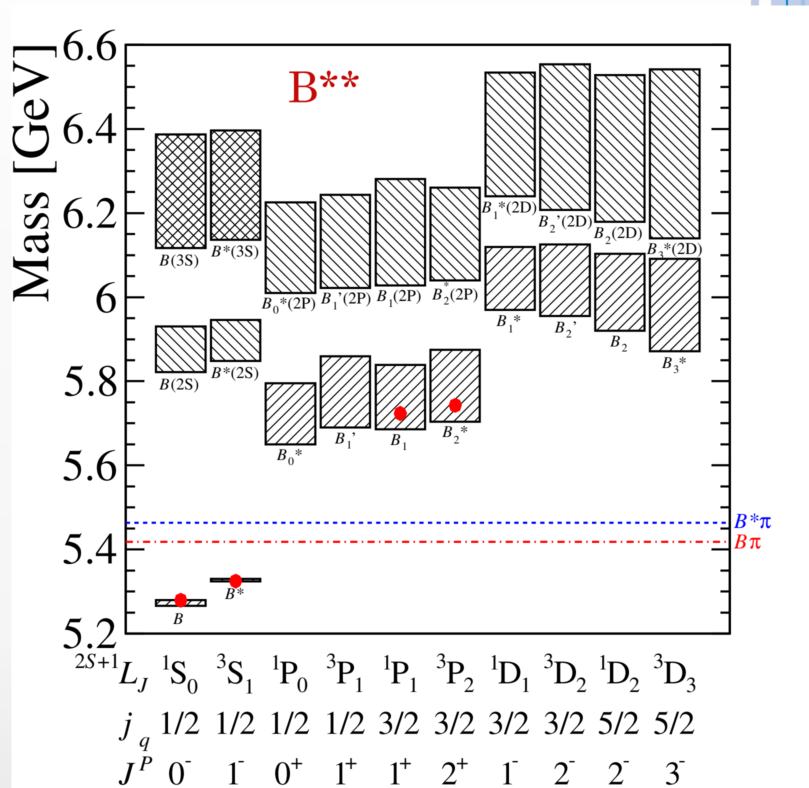


THE EXCITED B STATES

- 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 $B_1^0/B_2^{*0} \rightarrow B^{*+}\pi^-$







THE EXCITED B STATES

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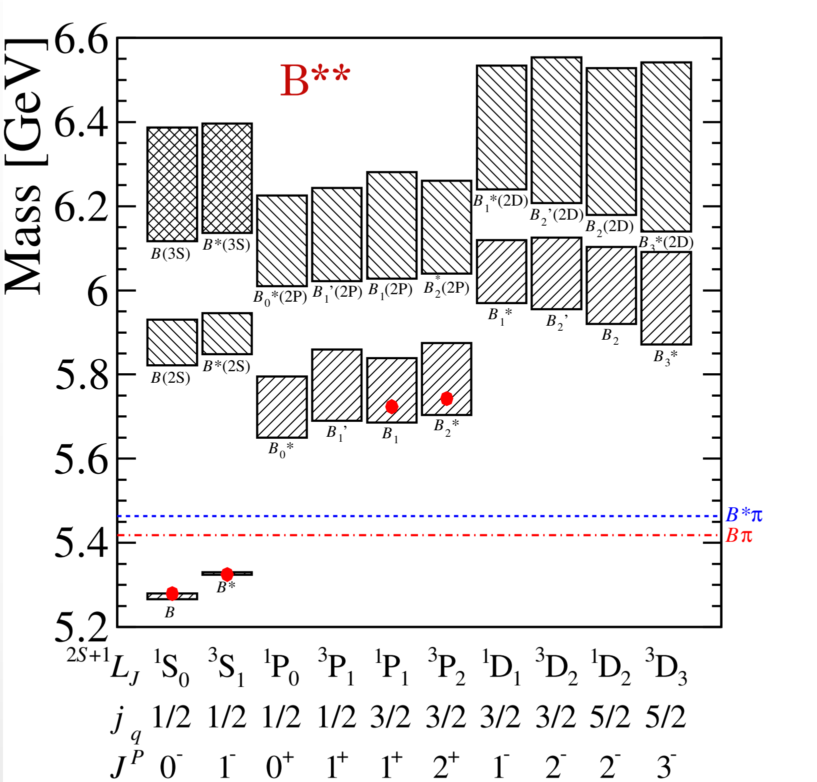
- Tevatron experiments resolved it into 2 structures and interpreted the former as the overlap of $B_1^0/B_2^{*0} \rightarrow B^{*+}\pi^-$
- LHCb reported the first observation of the charged B_1^+ and B_2^{*+} [LHCb-CONF-2011-053]
- CDF reported the evidence of a broad state: $B(5970)^{0,+}$

	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.)

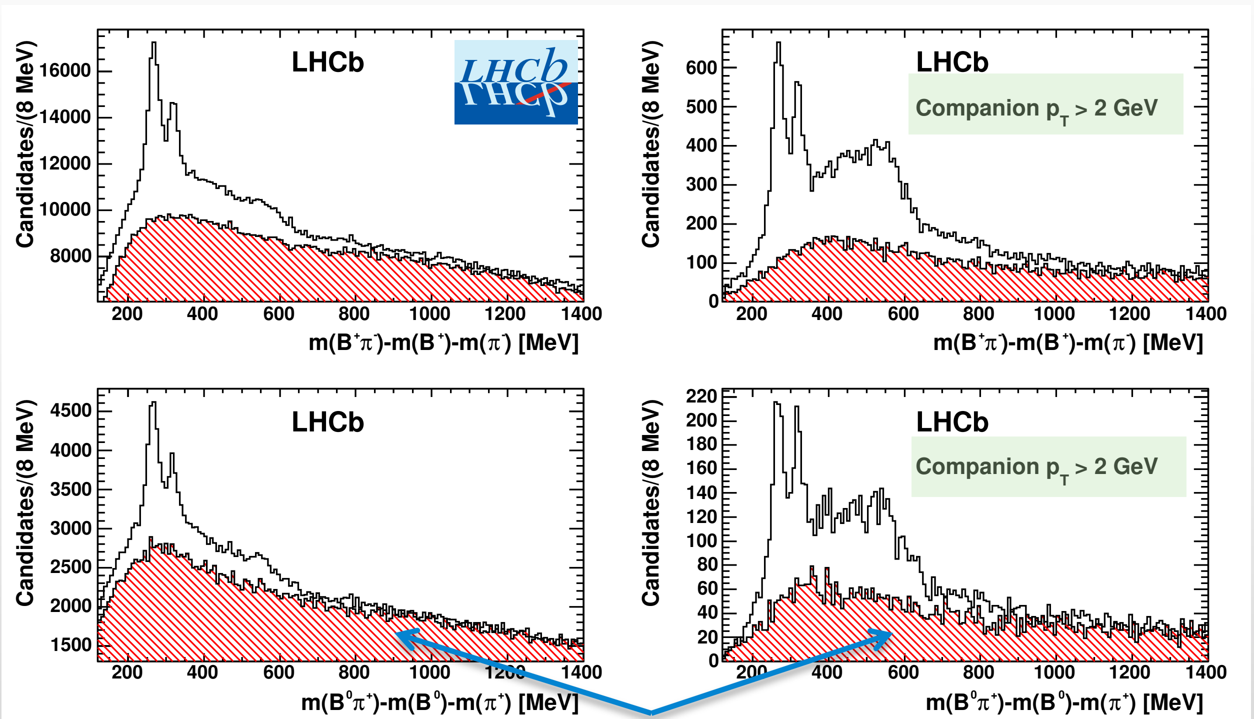
SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

[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)

$B^+\pi^-$

$B^0\pi^+$



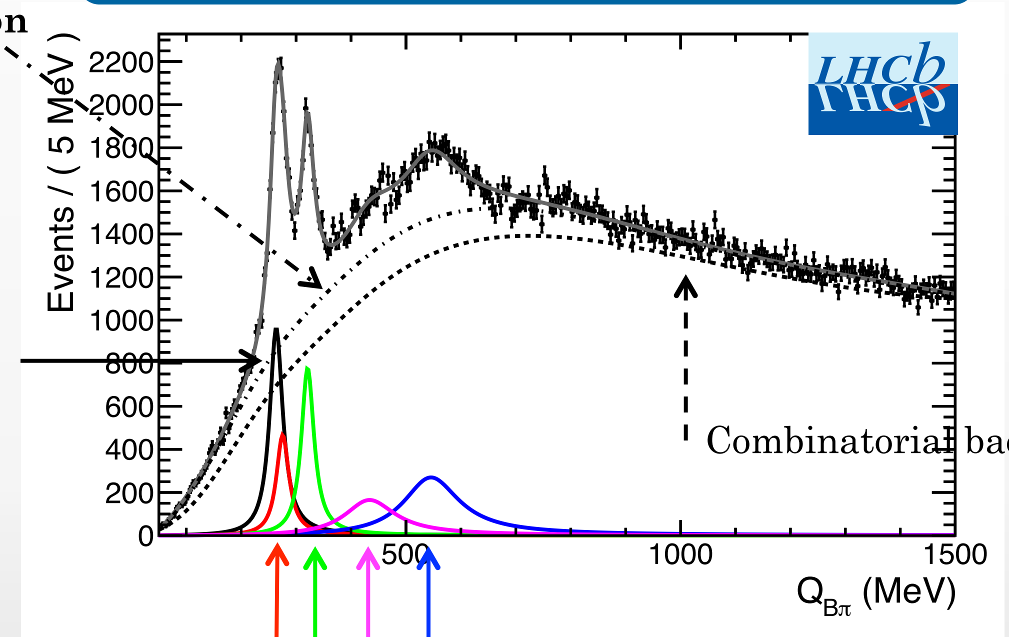
WS

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 $B_J(5960)$

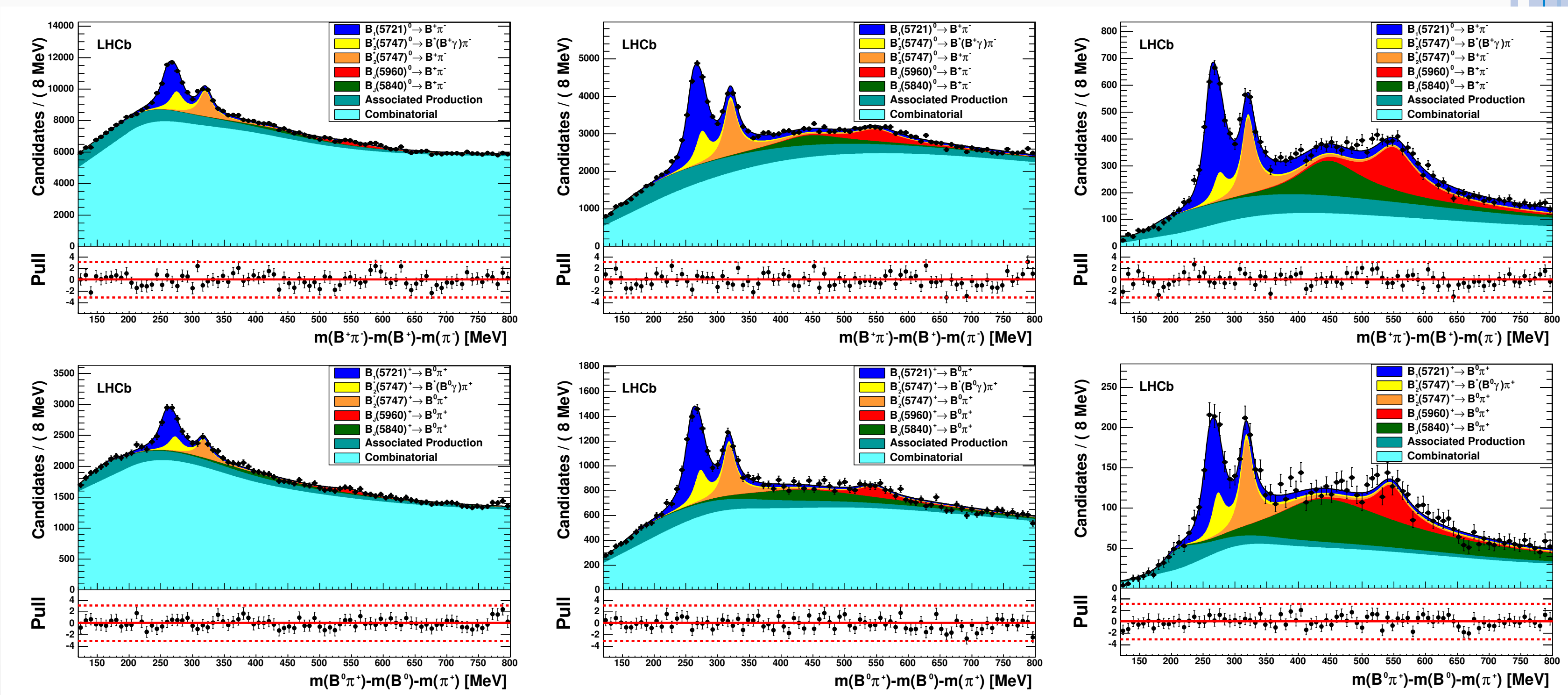
$B_2^*(5747) \rightarrow B\pi$

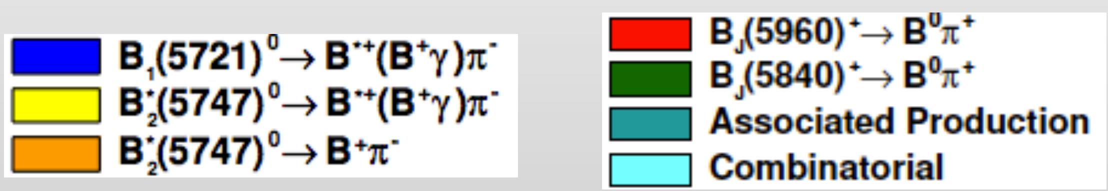
Alternative fit models (≡ Quark Model) consider the two broad states belonging to the same doublet. Then an extra fit function is added for the $B_J \rightarrow B^*\pi$ feed-down

NOMINAL FIT RESULTS BY p_T BIN

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

	$0.5 < p_T < 1$ GeV	$1 < p_T < 2$ GeV	$p_T > 2$ GeV
$B^+\pi^-$			
$B^0\pi^+$			

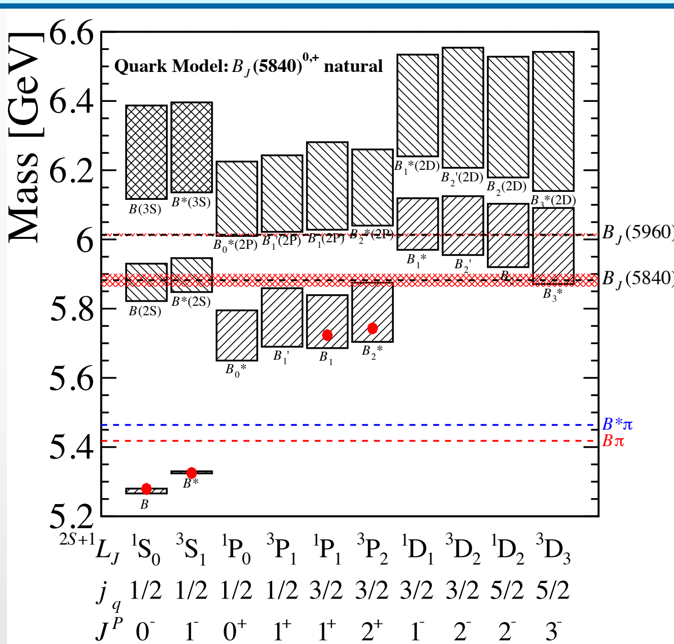


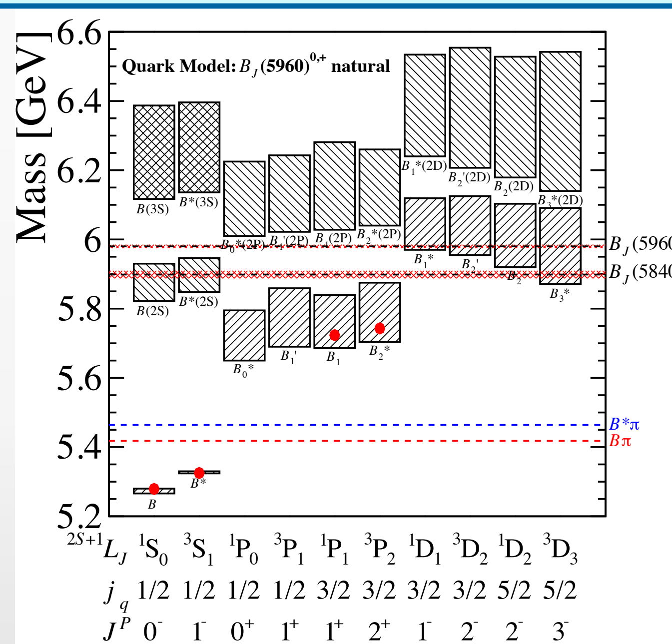


Final Results: $B_J(5840)^{0,+}$ and $B_J(5960)^{0,+}$

[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

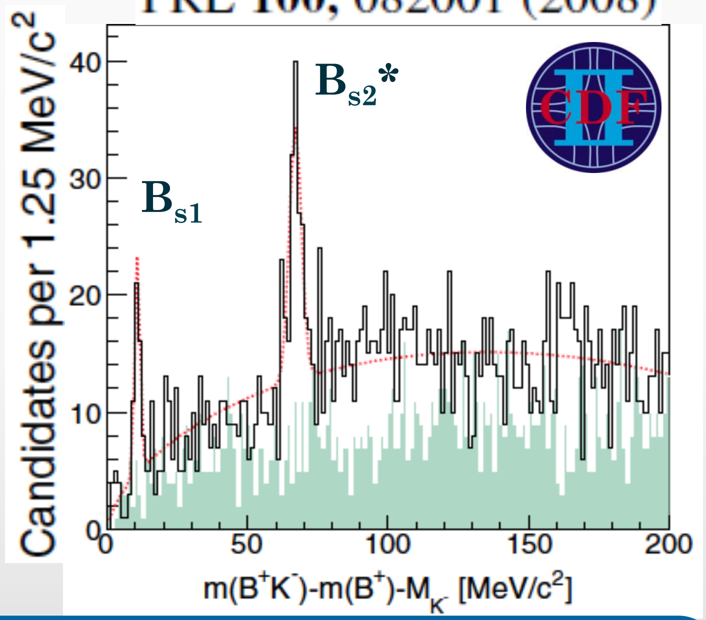
Excited B_s mesons

EXPERIMENTAL STATUS: $B_{s1}(5830)^0$ AND $B_{s2}^*(5840)^0$

- Two narrow peaks observed in the B^+K^- by CDF
- B_{s2}^* is the only narrow state expected. What is the nature of the second signal?

	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

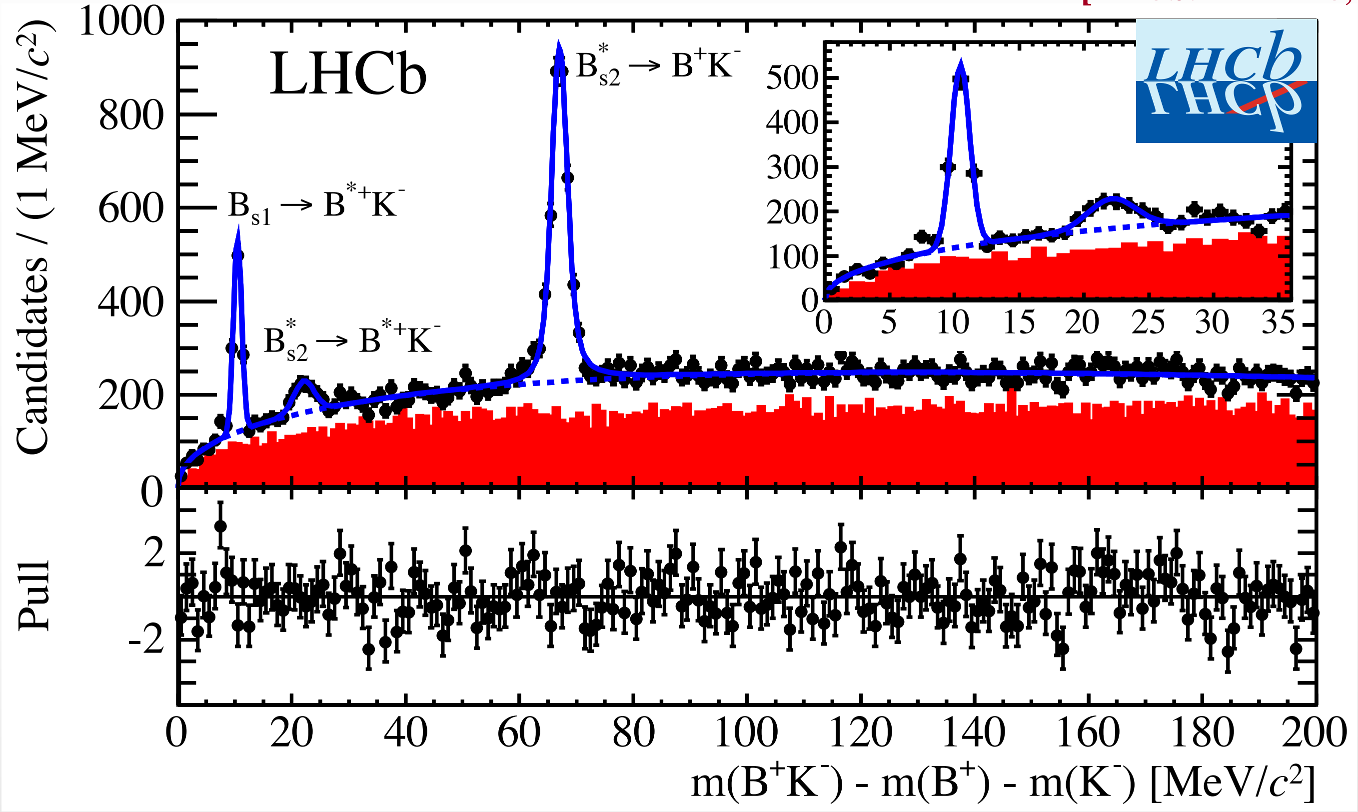
PRL 100, 082001 (2008)



- It is interpreted as a feed-down of the $B_{s1} \to B^{*+}K^-$ decay followed by $B^{*+} \to B^+ \gamma$, where the photon is not observed
- Swapping the identification would lead to a large mass splitting of the j=3/2 doublet
- The B_{s1} state was not confirmed by D0

FIRST OBSERVATION OF $B_{s2}^{*} \rightarrow B^{*}K$

[LHCb: PRL 113, 162001 (2014)]

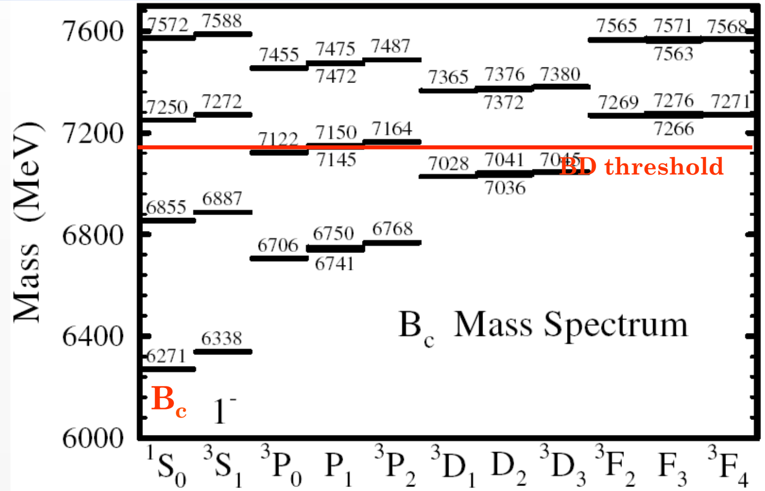


- The two narrow peaks corresponding to the $B_{s1} \rightarrow B^{*+}K^{-}$ and $B_{s2}^{*} \rightarrow B^{+}K^{-}$ signals are observed
- A new smaller structure seen around 20 MeV
- Most precise measurement of B*-B mass difference

EXCITED B_c MESON

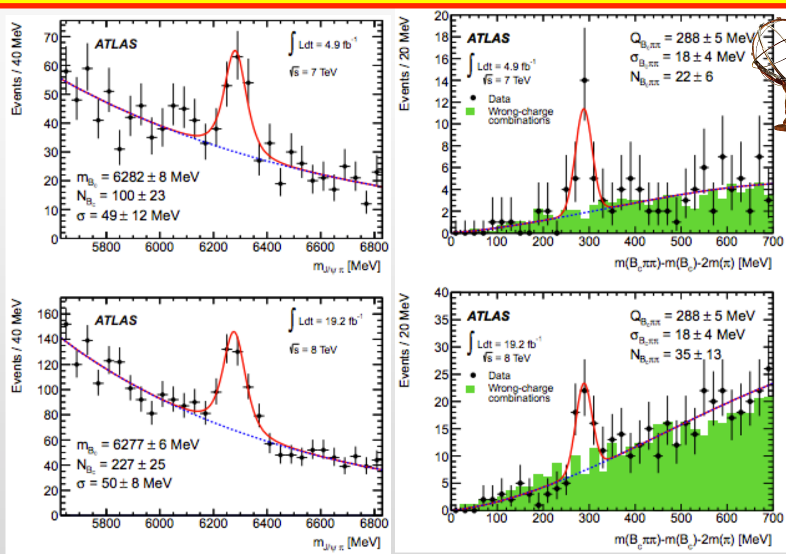
ORBITALLY EXCITED B_c

- B_c is the only meson is SM formed by two different heavy flavour quarks
- Many excited states predicted below the BD threshold
- $B_c^{**} \rightarrow B_c + X$ where $X = \gamma, \pi^+\pi^-, \ldots$



Phys.Rev.D70, 054017

Recently ATLAS found a peak in the $B_c\,\pi^+\pi^-$ mass spectrum identified as $B_c(2S)$



[ATLAS, PRL 113, 212004 (2014)]

M = 6842 ±4 ±5 MeV
Γ << resolution

- Large relative yield $N(B_c(2S))/N(B_c)$
- What about the the $B_c^*(2S) \rightarrow B_c^*\pi\pi$? $(\sigma(B_c^*(2S))/\sigma(B_c(2S))=3)$

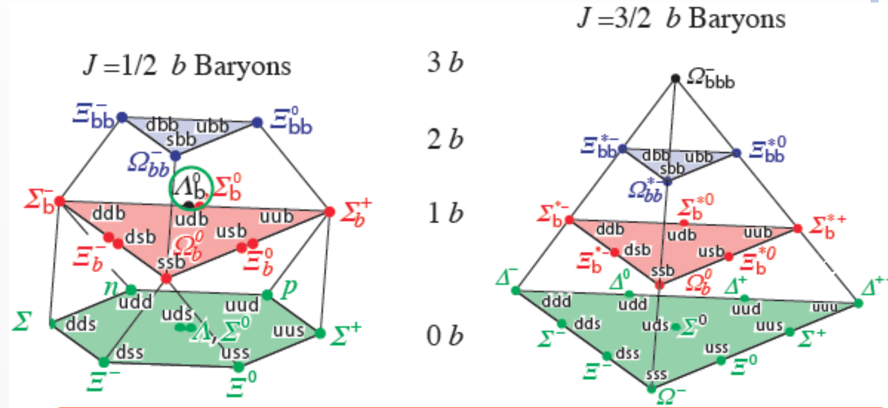
Beauty Baryons

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

Missing states

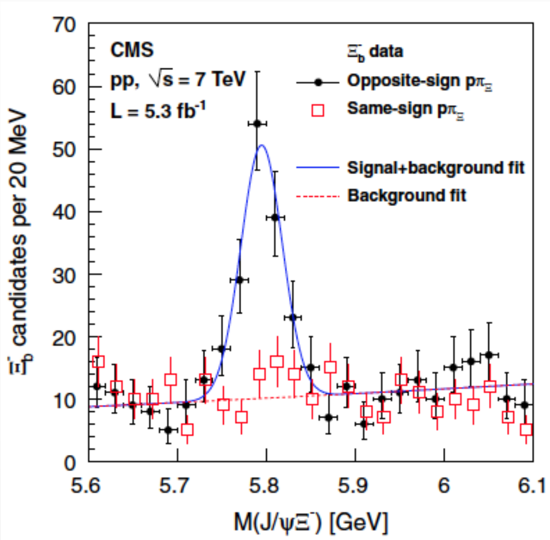


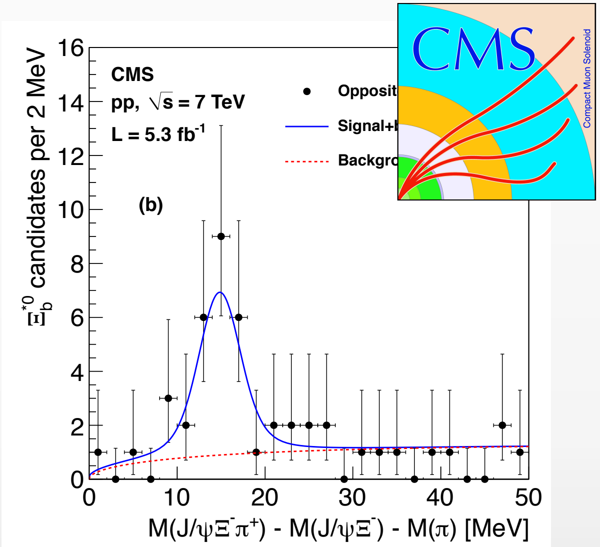
The system of baryons containing a *b* quark remains largely unexplored.

OBSERVATION OF $\Xi_b^{*0} \to \Xi_b^- \pi^+$ 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 $\Xi_b^- \to J/\psi(\mu\mu)\ \Xi^-(\Lambda\pi)$



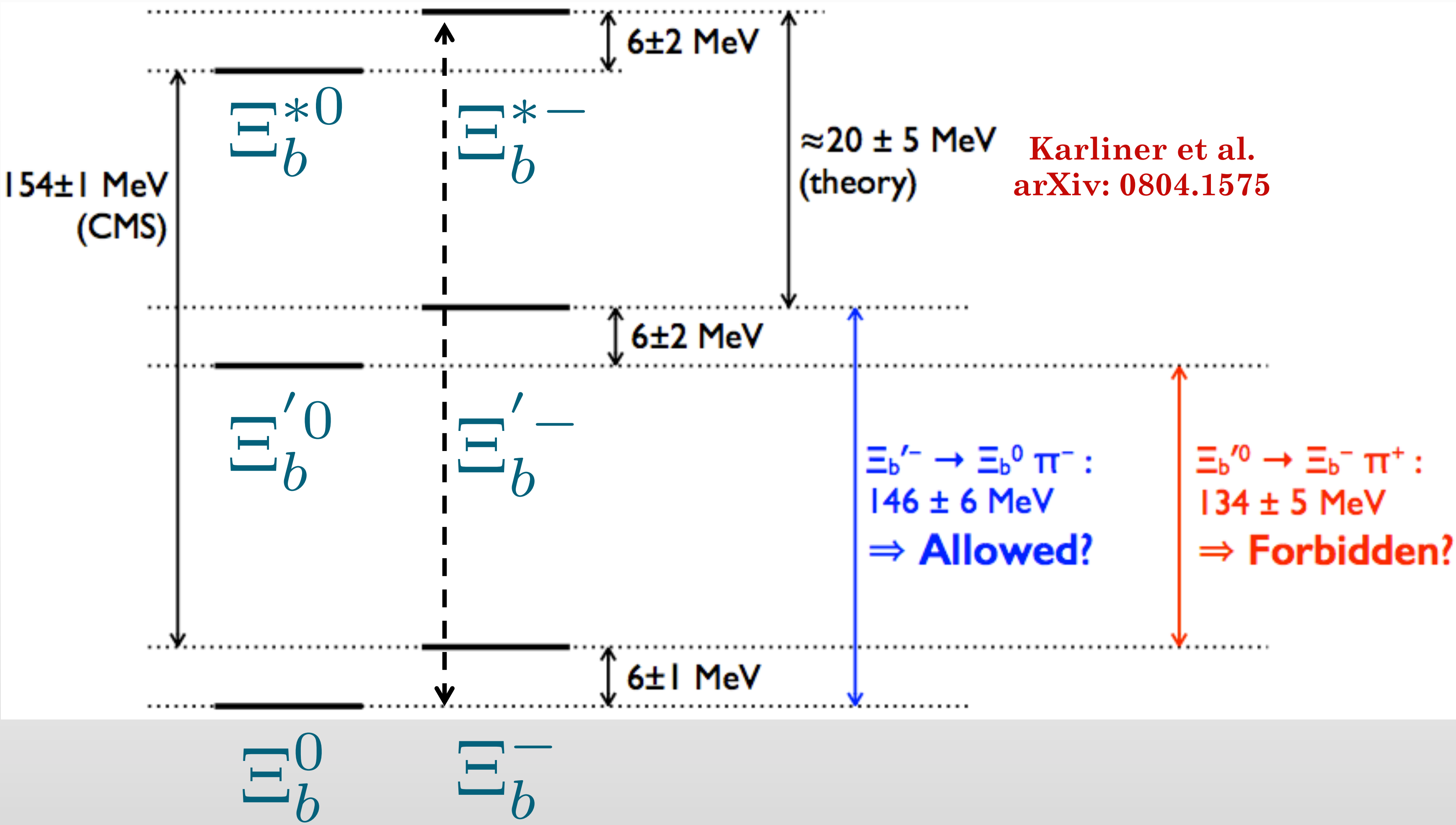


$N(\Xi_b^-) = 108 \pm 14$

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

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

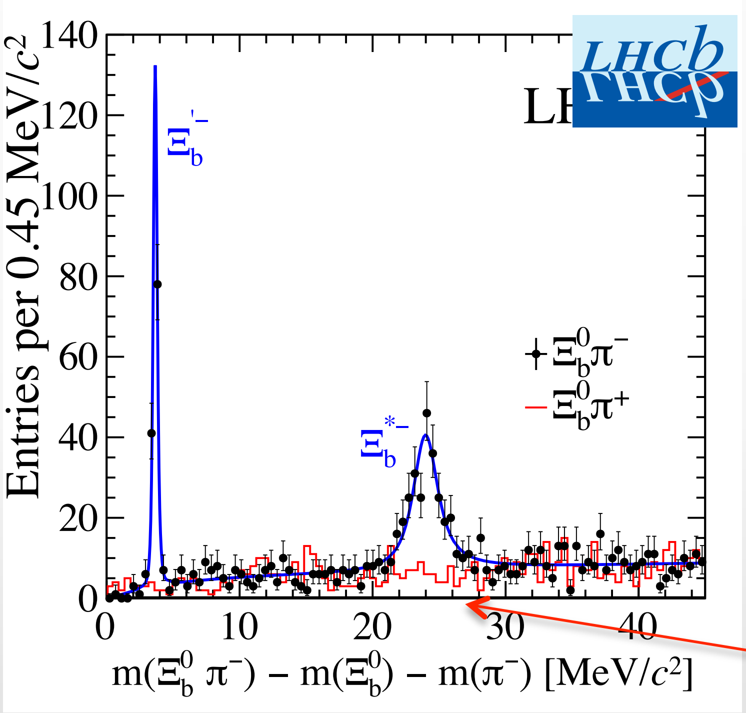
SEARCH FOR $\Xi_b^{*-} \to \Xi_b^0 \pi^-$



Search For $\Xi_b^{*-} \to \Xi_b^0 \pi^-$

[LHCb, PRL114, 062004 (2015)]

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



Wrong sign combinations

Fit Model

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

Ξ_b^{*-} : P-wave RBW ⊗ Resolution

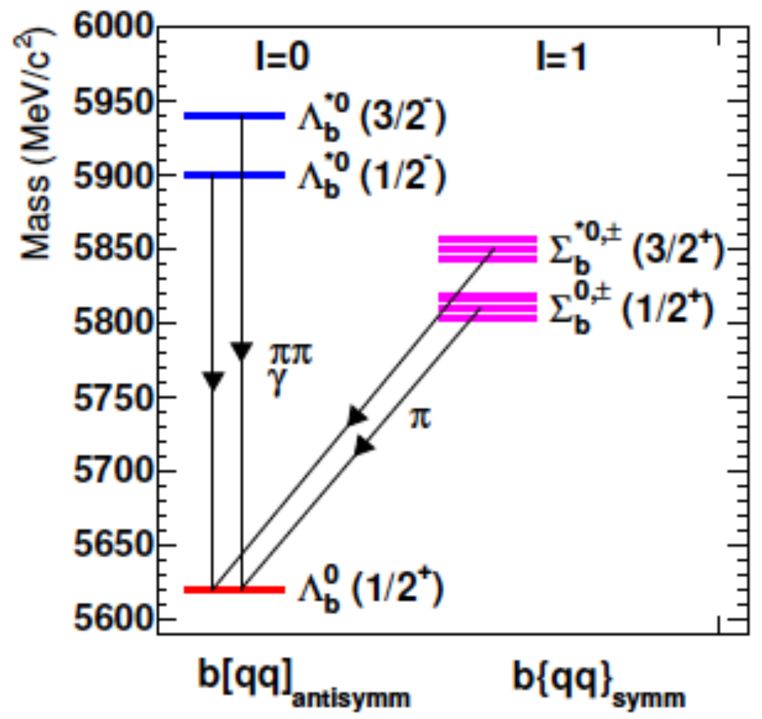
Observation of two narrow peaks interpreted as $\Xi_b^{'-}$ and Ξ_b^{*-}

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

Excited Beauty Baryons

Orbitally Excited (L=1) Λ_b^0 Baryons

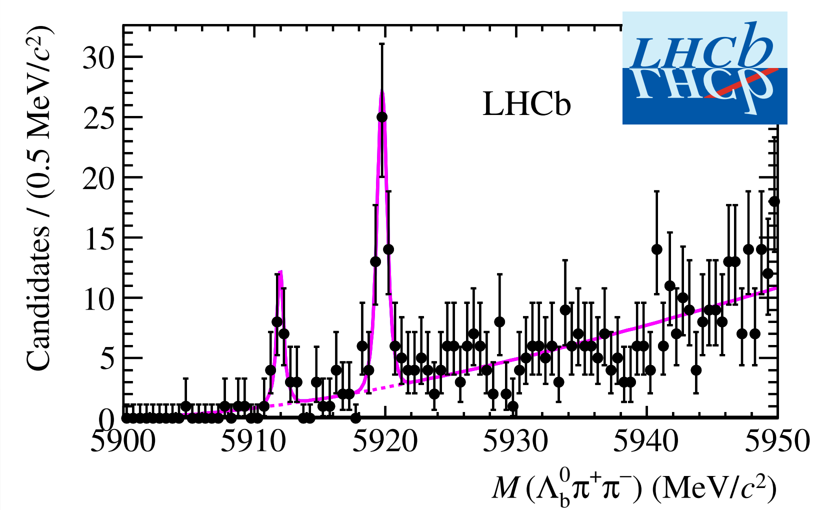
- The ground state $\Lambda_b^0(J^P = 1/2^+)$: *bud*, where the *ud* diquark $J^P = 0^+$ and $L = 0$
- Orbital excitations with $L = 1$
- Excited Λ_b^0 states: two state with $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$
- Should decay to $\Lambda_b^0\pi^+\pi^-$ or $\Lambda_b^0\gamma$ (parity conservation)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

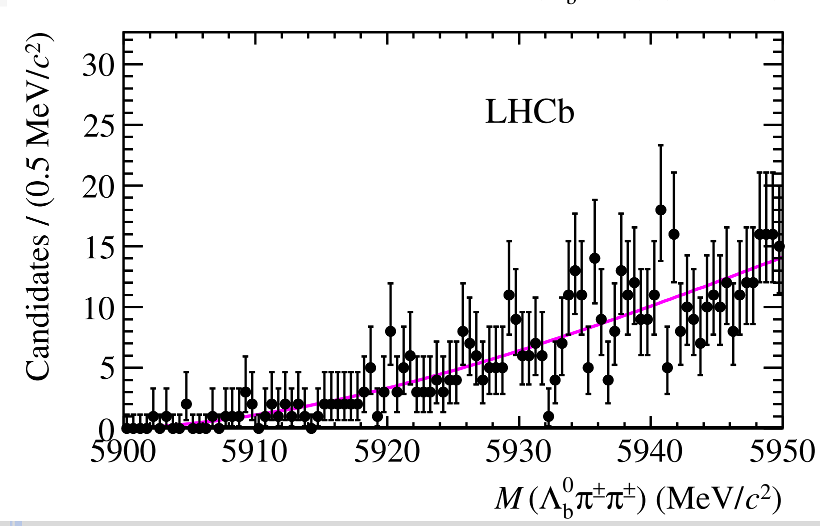


Most predictions are above $\Lambda_b^0\pi\pi$ (5900 MeV/c^2) but below $\Sigma_b\pi$ (around 5950 MeV/c^2)

First Observation of an Excited Λ_b^0 Baryons

[LHCb, PRL 109 (2012) 172003]





- Two peaks are observed with masses around 5912 MeV/c² and 5920 MeV/c²
- No corresponding structures in the same-sign pion combinations

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

- Signal width consistent with detector resolution
- Limits on natural widths

CDF confirms $\Lambda_b^{*0}(5920)$
PRD88, 071101 (2013)

Doubly Heavy Baryons

Search for Ξ_{cc}^+

[LHCb, JHEP 12 (2013) 090]

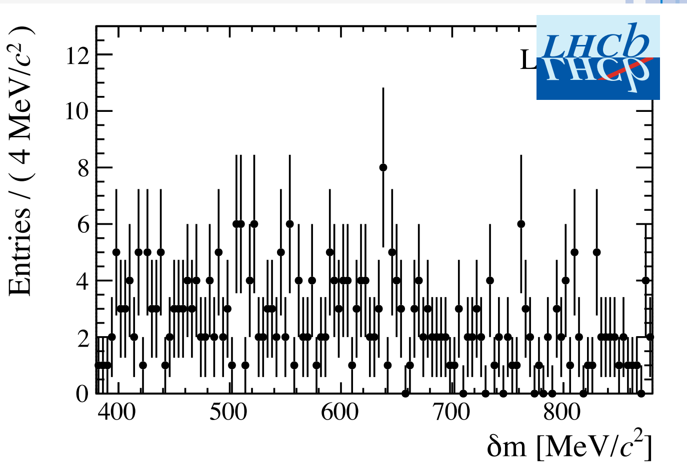
- All of the ground states with C=0 or C=1 have been discovered
- Three weakly decaying C=2 states expected: Ξ_{cc} isodoublet and Ω_{cc} isosinglet
- SELEX reported signals of $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, pD^+K^-: [PRL 89 (2002) 112001, PLB 628 (2005) 18]
  - $M = 3519 \pm 2$ MeV and $\tau(\Xi_{cc}^+)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

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

- No signal found

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

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

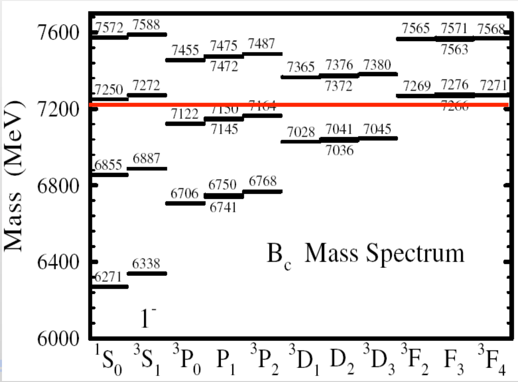


PROSPECTS I: (EXCITED) HEAVY MESONS

- Proliferation of excited $D_{(s)}$ states. Studies from B decays in order to establish spin parity. First observation of spin-3 state in B decays (higher spin states unlikely to be observed).
- Are all of them $q\bar{q}$ states? Investigation of the nature of D_{s0}* and D_{s1}' states: production studies, search for new decays modes (e.g. Σ BR(D_{s1}(2460) → D_s X)~ 70 ± 12%), measurements of BR's from B_s decays…

- Properties of B_{s1} and B_{s2}* states well predicted (as it was for D_{s1} and D_{s2}*)
- Further studies of $B_{(s)}$** states from decays are unlikely until we collect a large sample of B_c's
- Search for the missing B_{s0}* and B_{s1}' states. Same surprising low masses as D_{s0}* and D_{s1}'?
- (Orbitally) Excited B_s states in B^+K^-? $B^0K^0_S$?

- The hunting for the excited B_c has just started…



PROSPECTS II: (EXCITED) HEAVY BARYONS

- Charmed baryon spectroscopy:
  Any relation between the $c\bar{s}$ (D_s) and css (Ω_c) systems?

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
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$\Xi_b^{0\prime}$	$b\{su\}$	$1/2^+$	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

- $\Xi_b'^0$ and Ω_b^{*-} expected to decay radiatively (~100%) but $\Xi_b'^0 \rightarrow \Xi_b^0 \pi^0$ is not excluded. Unlikely to be observed.
- Search for the missing Σ_b^0 and Σ_b^{*0} into $\Sigma_b^0\pi^0$
- ….and excited baryons states of course
- Search for doubly-heavy baryons: the bcq baryons might be spot before the ccq baryons

Stay Tuned!

Back-up slides

Nomenclature

Spectroscopy notation

PDG notation

Radial quantum number

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

Sum of quark spins

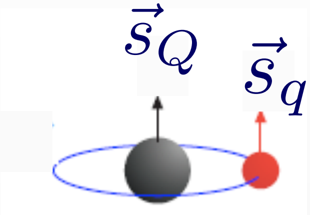
L = 0,1,2… → S, P, D

Natural spin-parity

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

Mass

Introduction



$\vec{L}$	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

$$\text{Parity } P = (-1)^{L+1}$$

Intrinsic parity of $q\bar{q}$

Mesons

Natural spin-parity

$$J^P = 0^+, 1^-, 2^+, 3^- ...., (-1)^J$$

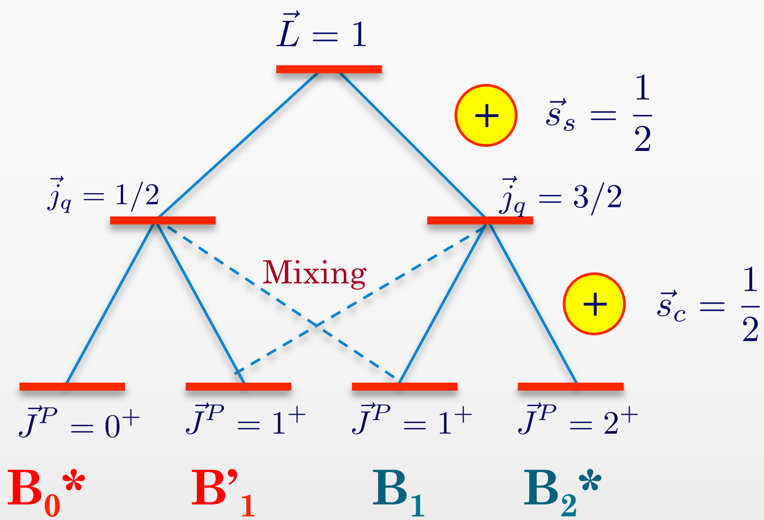
Unnatural spin-parity

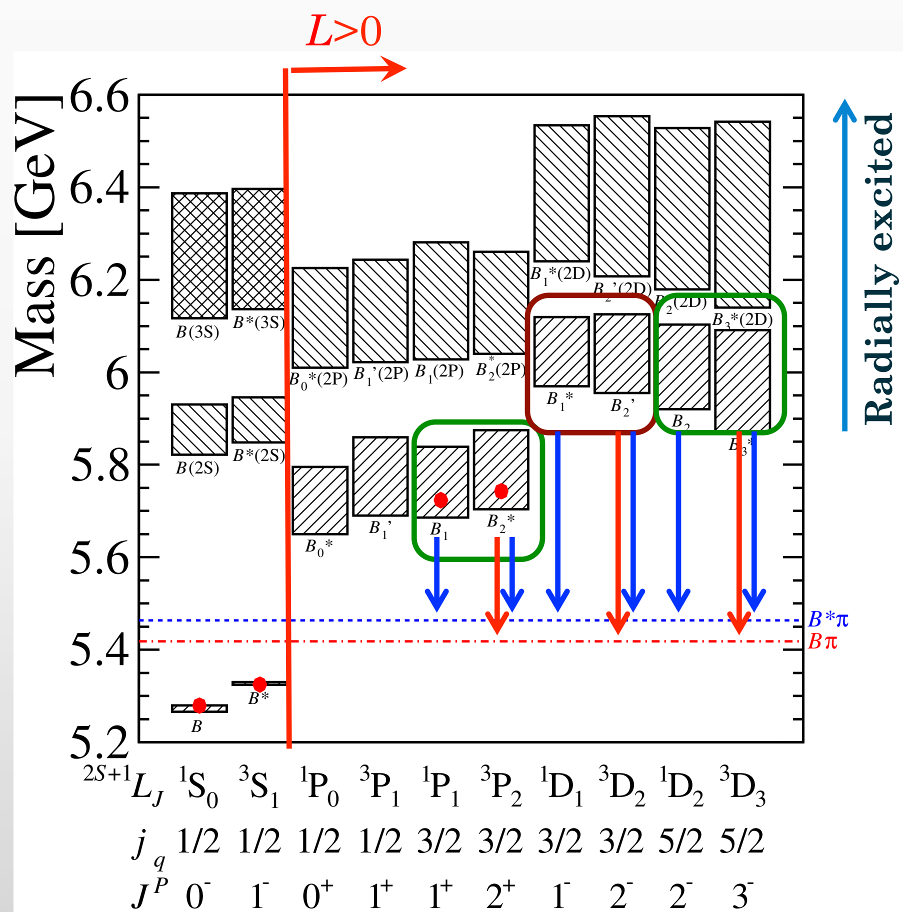
$$J^P = 0^-, 1^+, 2^-, 3^+ ...., (-1)^{J+1}$$

DECAYS OF EXCITED HEAVY MESONS

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

E.g. Orbitally L=1 excited B→B$^{(*)}\pi$**





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

Doublets in Inclusive Analyses

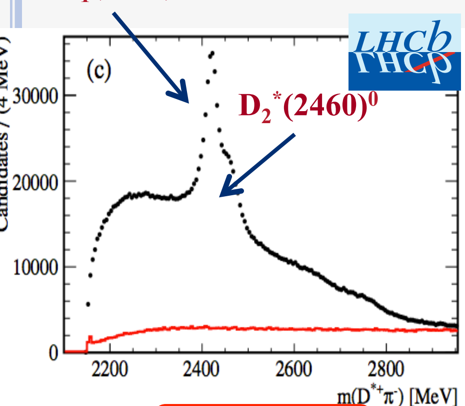
Inclusive analysis
pp → $D^{(*)+}\pi^- + X$
[LHCb: JHEP 09 (2013) 145]

(e.g) L=1, j_q=3/2 doublet
- ~~1 peak in Dπ~~ 3 peaks in Dπ?
- 2 peaks in D*π

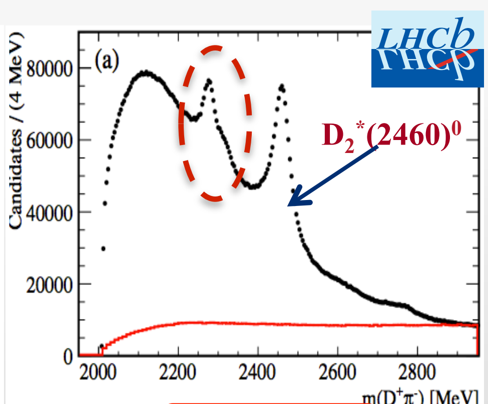
Exclusive analysis
$B^- \to D^{(*)+}\pi^-\pi^-$
[Belle: Phys.Rev.D69 (2004) 112002]

(e.g) L=1, j_q=3/2 doublet
- 1 peak in Dπ
- 2 peaks in D*π

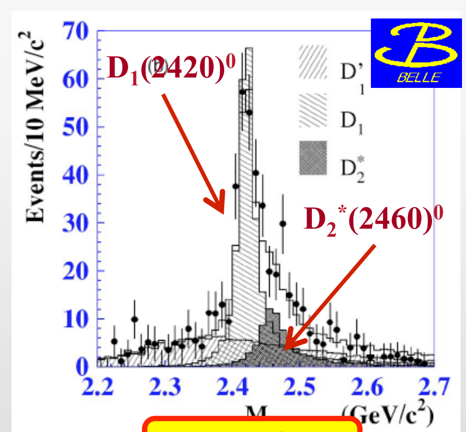
} as expected



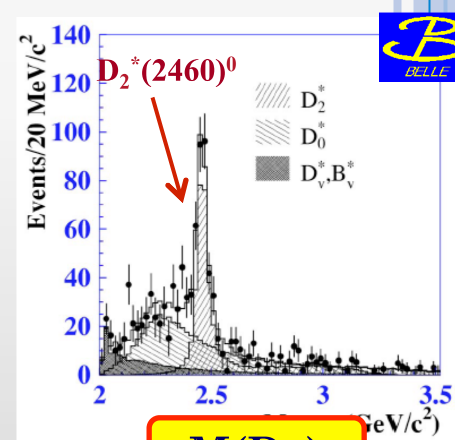
M(D*π)



M(Dπ)



M(D*π)



M(Dπ)

Broad states also revolved by an amplitude analysis

Doublets in Inclusive Analyses

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

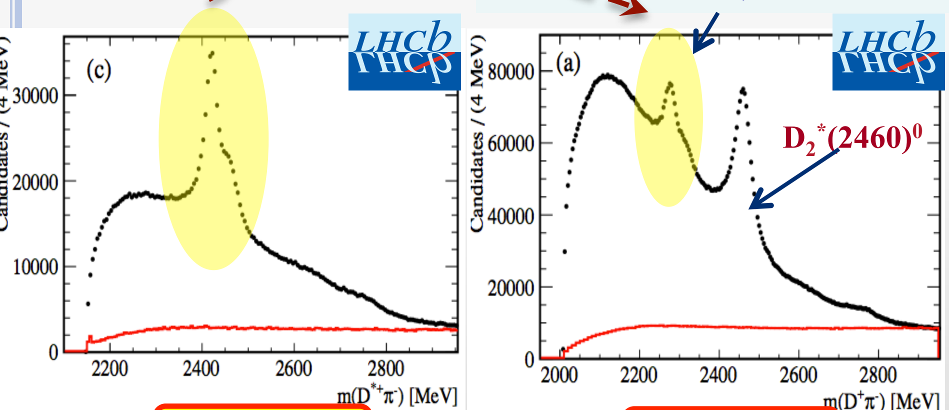
(e.g) L=1, j_q=3/2 doublet
- ~~1 peak in Dπ~~ 3 peaks in Dπ?
- 2 peaks in D*π

Exclusive analysis
$B^- \rightarrow D^{(*)+} \pi^- \pi^-$
[Belle: Phys.Rev.D69 (2004) 112002]

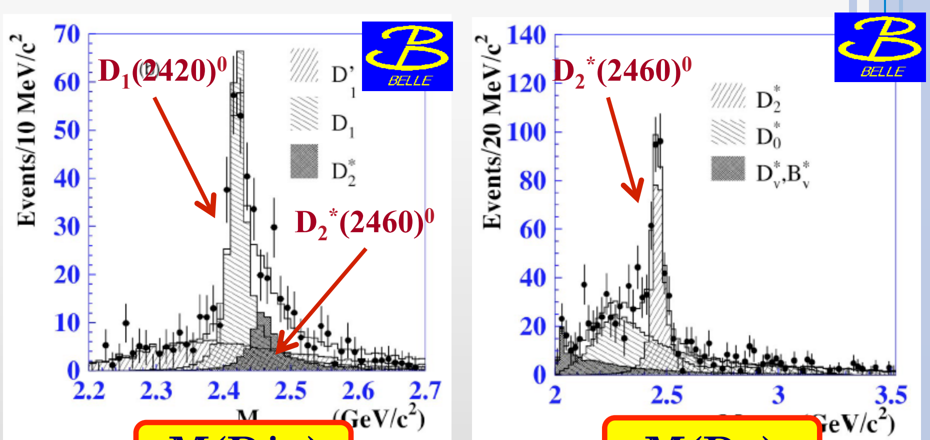
(e.g) L=1, j_q=3/2 doublet
- 1 peak in Dπ
- 2 peaks in D*π

} as expected

$D_1(2420)^0$ / $D_2^*(2460)^0$ feed-down
└► $D^{*+} \pi^-$
└► D^+ γ/~~π~~^{0}



M(D*π) M(Dπ)



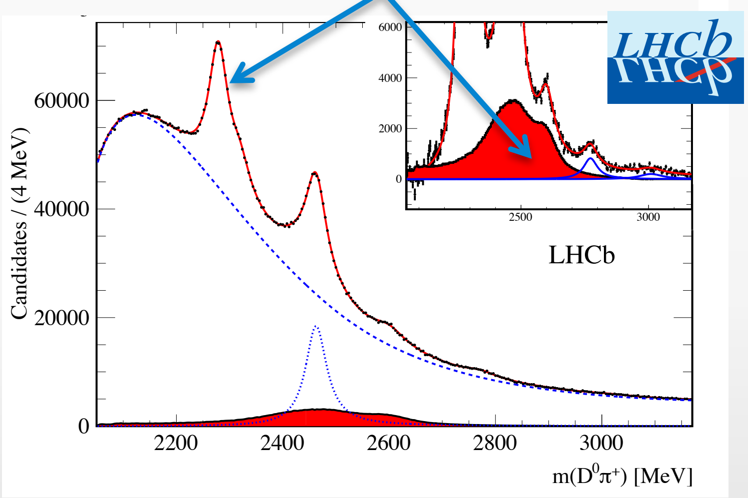
M(D*π) M(Dπ)

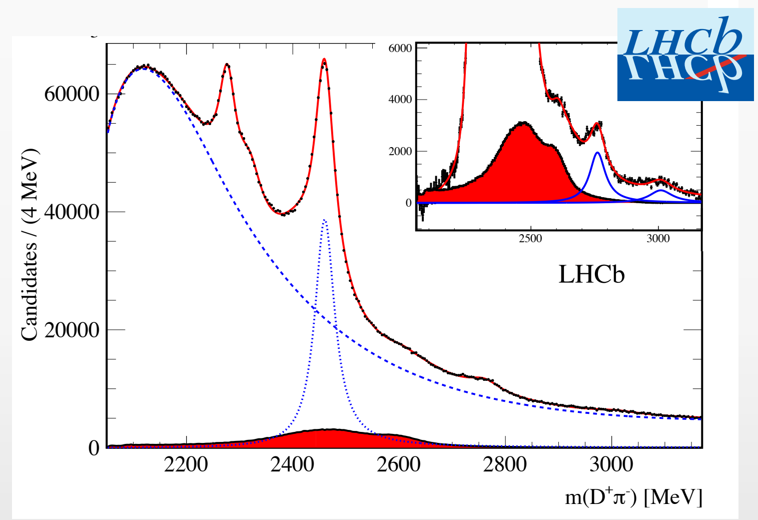
Broad states also revolved by an amplitude analysis

$D^0\pi^+/D^+\pi^-$ Mass Fits

[LHCb, JHEP 09 (2013) 145]

Cross-feeds estimated from states appearing in the D*π spectrum





2 more natural states:

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

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 $B^{**} \to B^{*}\pi$ 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

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	± 0.7		± 1.4		± 0.17		± 0.4	MeV ,
$m_{B_2^*(5747)^0}$	=	5739.44	± 0.37		± 0.33		± 0.17			MeV ,
$m_{B_1(5721)^+}$	=	5725.1	± 1.8		± 3.1		± 0.17		± 0.4	MeV ,
$m_{B_2^*(5747)^+}$	=	5737.20	± 0.72		± 0.40		± 0.17			MeV ,
$\Gamma_{B_1(5721)^0}$	=	30.1	± 1.5		± 3.5					MeV ,
$\Gamma_{B_2^*(5747)^0}$	=	24.5	± 1.0		± 1.5					MeV ,
$\Gamma_{B_1(5721)^+}$	=	29.1	± 3.6		± 4.3					MeV ,
$\Gamma_{B_2^*(5747)^+}$	=	23.6	± 2.0		± 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 $B_2^*(5747)^0 \to B^{*+}\pi^-$ (3.7σ)!

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 2^{nd} 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

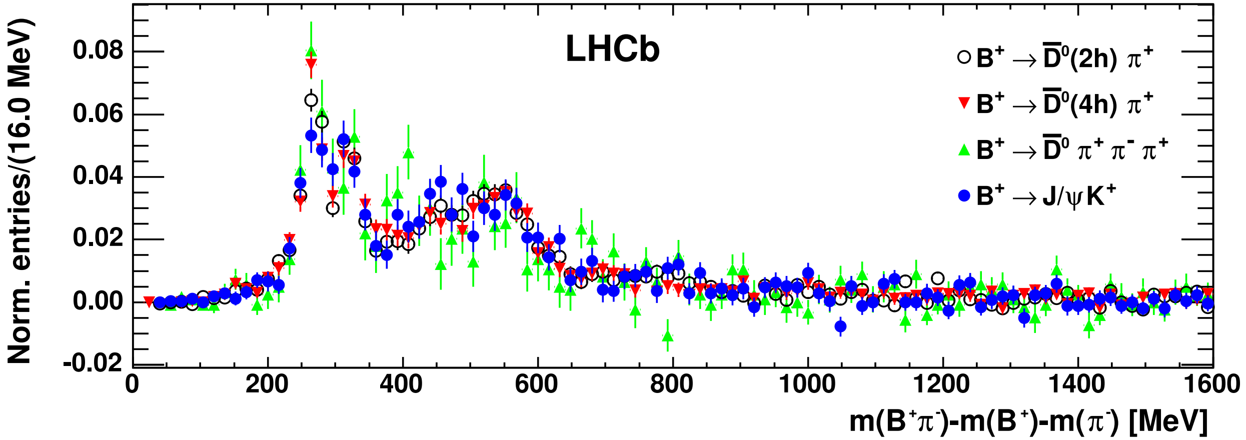
Consistent with the interpretation of 4 states given the expected isospin symmetry

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

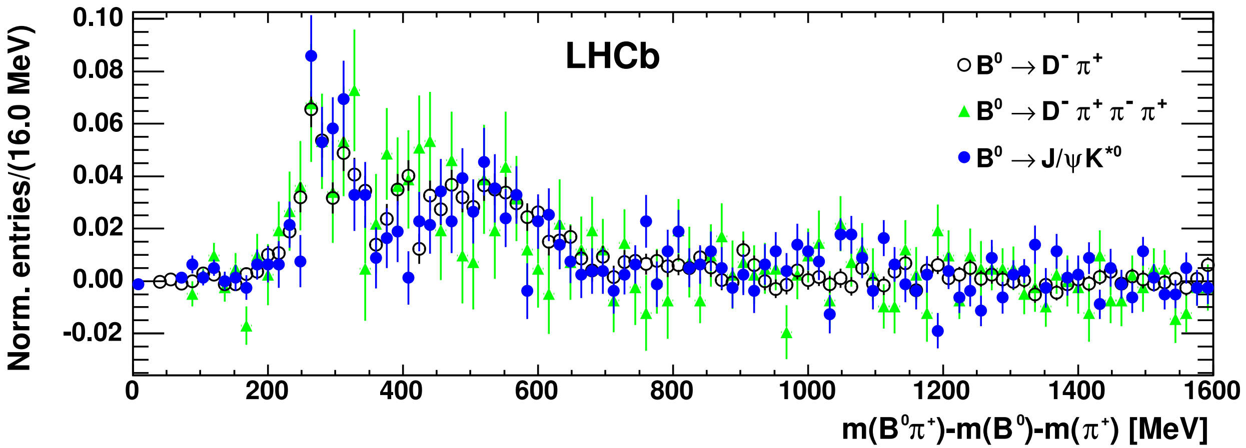
[LHCB-PAPER-2014-067; arXiv:1502.02638]

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

$B^+\pi^-$



$B^0\pi^+$

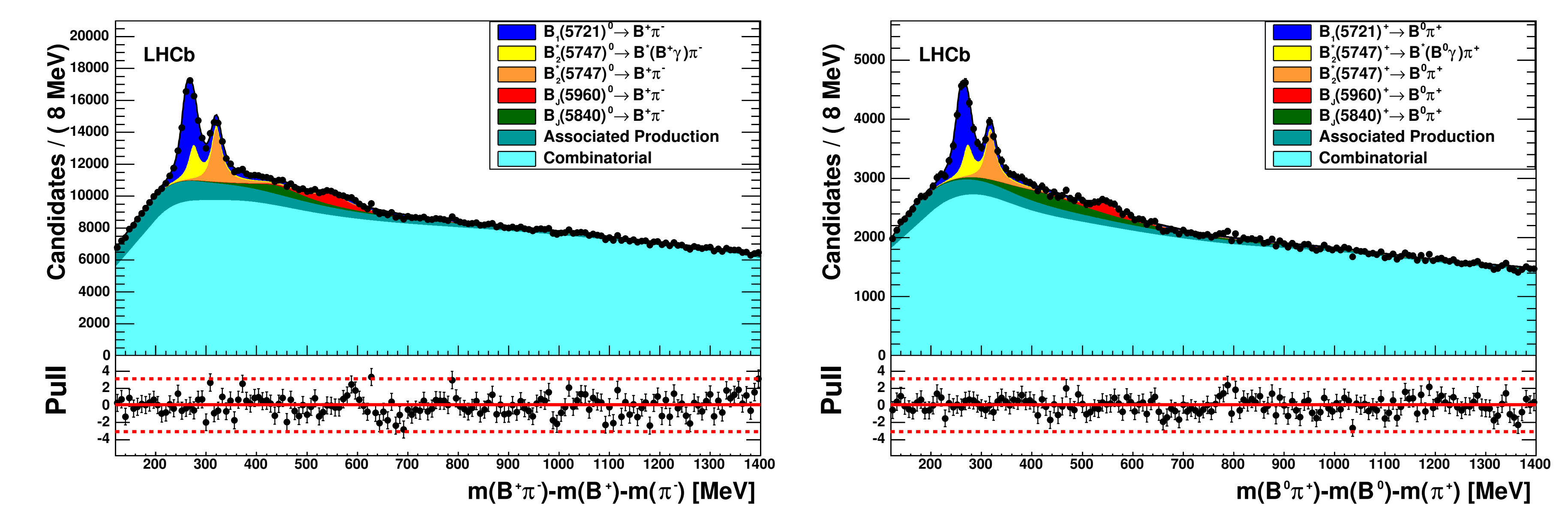


NOMINAL FIT RESULTS

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

Candidates integrated over the 3 p_T bins

$B^+\pi^-$ **$B^0\pi^+$**



FIT RESULTS

Parameter	Fit result	Best previous measurement
$m(B_{s1}) - m(B^{*+}) - m(K^-)$	$10.46 \pm 0.04_{stat} \pm 0.04_{syst}$ MeV/c^2	$10.73 \pm 0.21 \pm 0.14$ MeV/c^2
$m(B^*_{s2}) - m(B^+) - m(K^-)$	$67.06 \pm 0.05_{stat} \pm 0.11_{syst}$ MeV/c^2	$66.96 \pm 0.39 \pm 0.14$ MeV/c^2
$m(B^{*+}) - m(B^+)$	$45.01 \pm 0.30_{stat} \pm 0.23_{syst}$ MeV/c^2	45.6 ± 0.8 MeV/c^2
$\Gamma(B^*_{s2})$	$1.56 \pm 0.13_{stat} \pm 0.47_{syst}$ MeV/c^2	
$\frac{\mathcal{B}(B^*_{s2} \to B^{*+}K^-)}{\mathcal{B}(B^*_{s2} \to B^+K^+)}$	$(9.3 \pm 1.3_{stat} \pm 1.2_{syst})\%$	
$\frac{\sigma(pp \to B_{s1}X)\mathcal{B}(B_{s1} \to B^{*+}K^-)}{\sigma(pp \to B^*_{s2}X)\mathcal{B}(B^*_{s2} \to B^+K^-)}$	$(23.2 \pm 1.4_{stat} \pm 1.3_{syst})\%$	

- Confirmation of the B_{s1} state
- Most precise measurement of the B_{s1}, B_{s2}^* and B^* masses
- First observation of the $B_{s2}^* \to B^{*+}K^-$ decay (Significance = 8. σ)
- First measurement of the B_{s2}^* natural width

Comparison with theoretical predictions

$$\Gamma_{B^*_{s2}} = 1.56 \pm 0.13_{\rm stat} \pm 0.47_{\rm syst}\ \mathrm{MeV}$$

$$\frac{\mathcal{B}(B^*_{s2} \to B^{*+}K^-)}{\mathcal{B}(B^*_{s2} \to B^+K^-)} = (9.3 \pm 1.3_{\rm stat} \pm 1.2_{\rm syst})\%$$

Table 1: The strong decay widths of B_{s1} and B^*_{s2} in units of MeV.

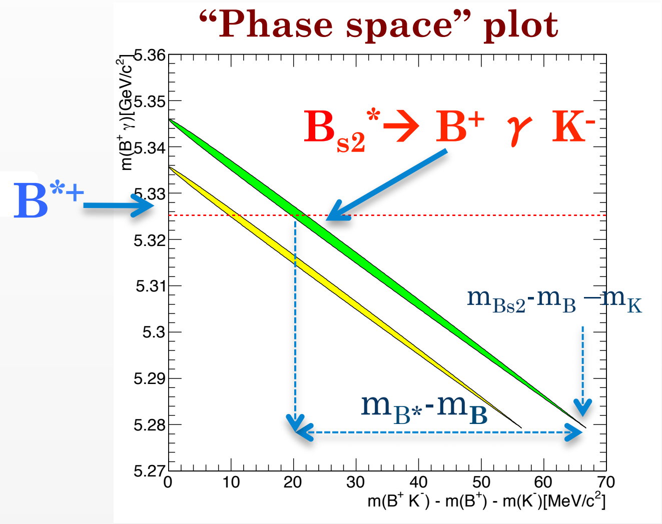
Mode	PLB706(2012)389	PRD43(1991)1679	PRD79(2009)074020	PRD86(2012)054024	PRD78(2008)014029
$B_{s1} \to B^*\bar{K}$	0.041 ± 0.011	—	0.098	0.016 ± 0.002	$0.4 \sim 1$
$B^*_{s2} \to B\bar{K}$	1.55 ± 0.43	2.6 (1.9)	4.6	—	2
$B^*_{s2} \to B^*\bar{K}$	0.148 ± 0.084	0.07 (0.05)	0.4	—	0.12
B^*_{s2}				0.9 ± 0.1	

$$\frac{\mathcal{B}(B^*_{s2} \to B^{*+}K^-)}{\mathcal{B}(B^*_{s2} \to B^+K^-)} = 0.070 \pm 0.005$$

SPECTRUM OF m(BK)-m(B)-M(K) MASS DIFFERENCE

	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

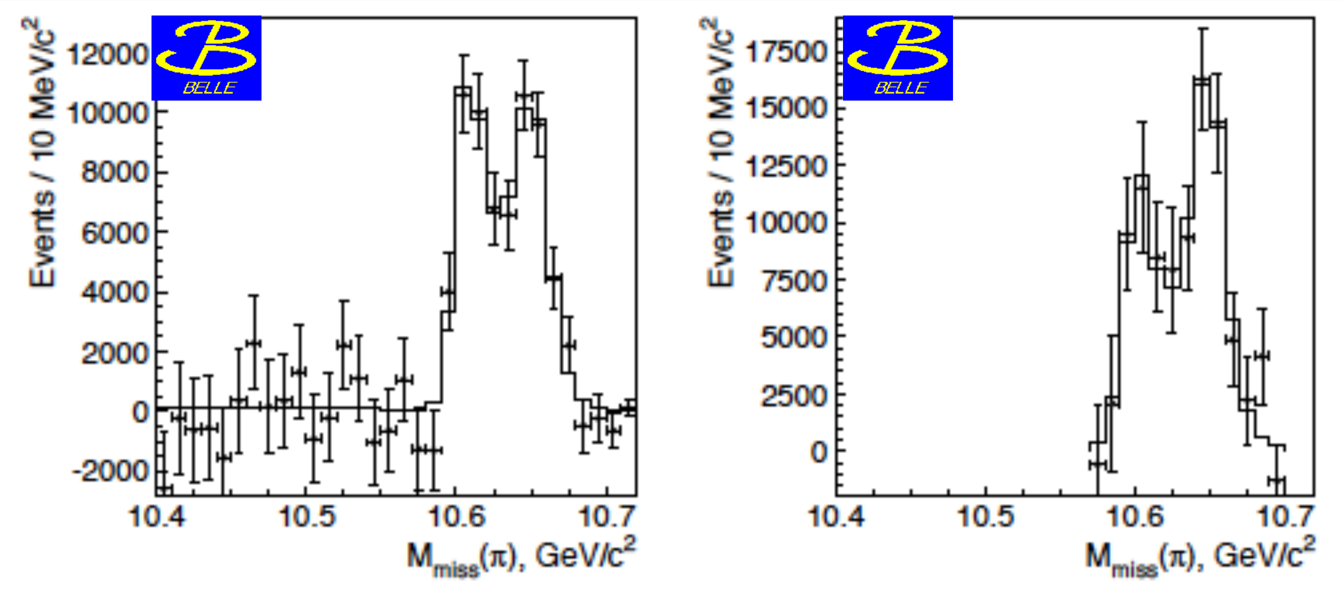
The $B_{s2}^* \rightarrow B^{*+}K^-$ decay could manifest itself in the B^+K^- mass spectrum in a similar fashion to the corresponding B_{s1} meson decay



- ✓ Distance between the two peaks returns $m(B^{*+})-m(B^+)$ (without detecting the photon → smaller systematic uncertainty)
- ✓ $B_{s2}^* \rightarrow BK$ and $B_{s2}^* \rightarrow B^*K \rightarrow B_{s2}^*$ is a natural state. $J^P = 2^+$ favored
- ✓ Likely (B_{s1}, B_{s2}^*) belong to the L=1 j_q=3/2 doublet

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

Search For $\Xi_b^{*-} \to \Xi_b^0 \pi^-$

Significant isospin splitting measured in the Ξ_b sector:

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

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

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

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

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

Combining (1) and (2):

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

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

CMS: 15 MeV + m(π^+)

Similarly combining (1) and (3):

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

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

< m(π^+)

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

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

With this assumption, we measure:

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

Signal significances > 10σ

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

FURTHER STUDIES

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

1) Angular analysis

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

$$\Xi_b^{*-} \to \Xi_b^0 \; \pi^-, \quad \Xi_b^0 \to \Xi_c^+ \; \pi^-$$

$$J^P \to \frac{1}{2}^+ \; 0^-, \quad \frac{1}{2}^+ \to \frac{1}{2}^+ \; 0^-$$

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

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

2) Measurements of relative productions

$$\frac{\sigma(pp \to \Xi_b^{\prime -} X)\mathcal{B}(\Xi_b^{\prime -} \to \Xi_b^0 \pi^-)}{\sigma(pp \to \Xi_b^0 X)} = 0.118 \pm 0.017 \pm 0.007$$

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

$$\frac{\sigma(pp \to \Xi_b^{*-} X)\mathcal{B}(\Xi_b^{*-} \to \Xi_b^0 \pi^-)}{\sigma(pp \to \Xi_b^{\prime -} X)\mathcal{B}(\Xi_b^{\prime -} \to \Xi_b^0 \pi^-)} = 1.74 \pm 0.30 \pm 0.12$$

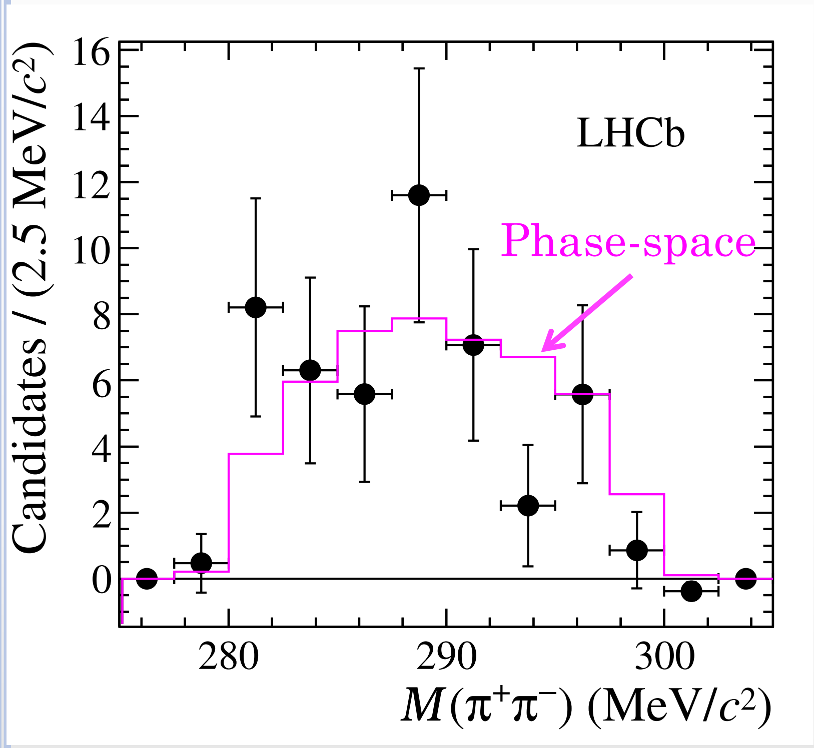
Given the isospin modes, large fraction of Ξ_b produced in the decays of Ξ_b resonances

3) Search for $\Xi_b^{\prime -}$ 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 $\Xi_b^0 \to \mathrm{D}^+(\mathrm{K}^-\pi^+\pi^+)\mathrm{p}\mathrm{K}^-\pi^+$

$\pi^+\pi^-$ Mass Distribution from $\Lambda_b^{*0}(5920)$



- Invariant mass of $\pi^+\pi^-$ from $\Lambda_b^{*0}(5920) \to \Lambda_b^0\pi^+\pi^-$
- Background subtracted by *sWeights* technique
- The invariant mass of $\Lambda_b^0\pi^+\pi^-$ used as discriminant variable
- No peaking structures are evident
- Consistent with phase-space decay