LATEST RESULTS ON HADRON SPECTROSCOPY AT *LHCb*

Marco Pappagallo

University of Glasgow

On behalf of the LHCb collaboration

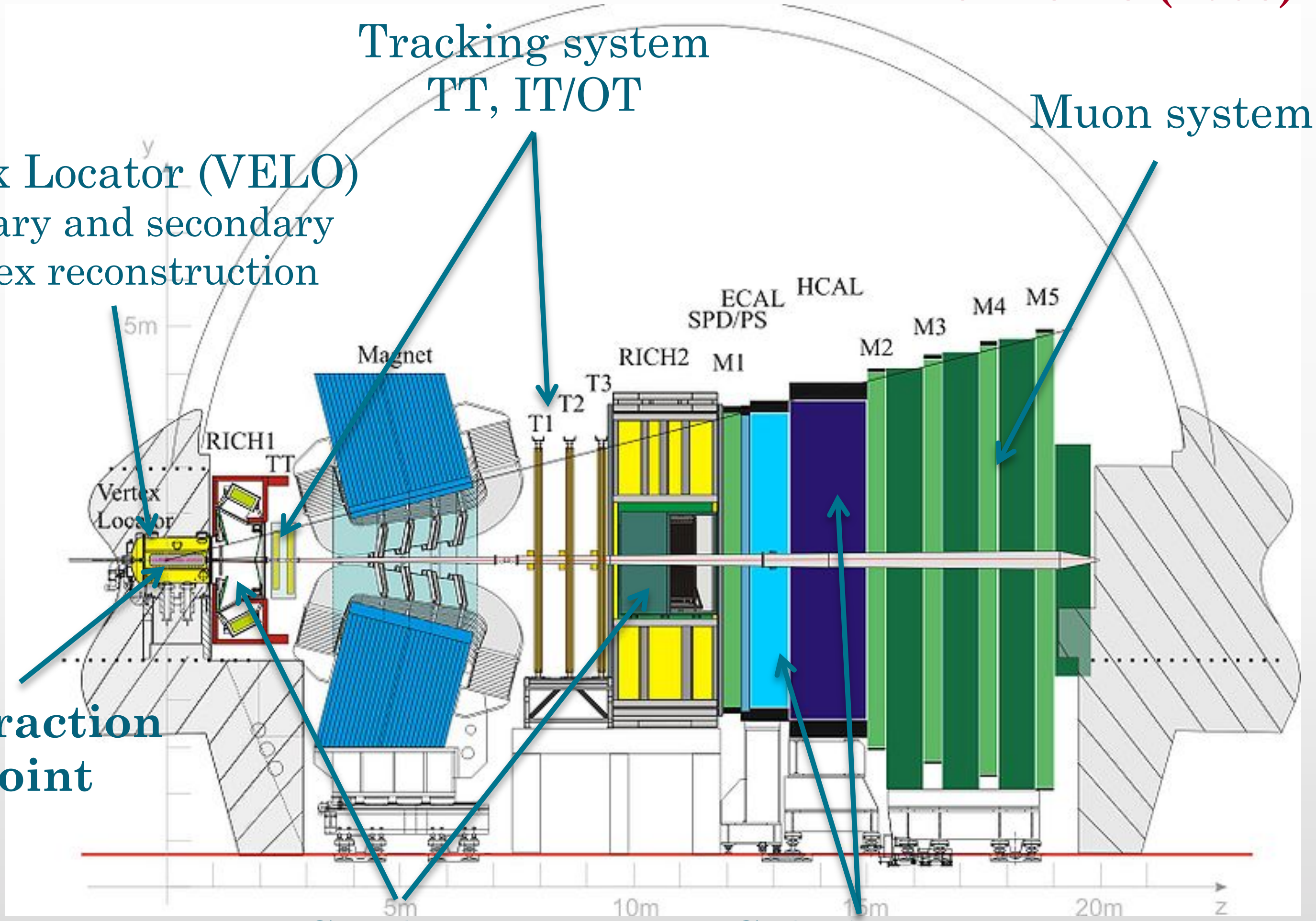
CERN, 10 February 2015

OUTLINE

- The LHCb detector
- Precise measurements of the properties of the $B_1(5721)^{0,+}$ and $B_2^*(5747)^{0,+}$ states and observation of $B^{+,0}\pi^{-,+}$ mass structures
  [LHCB-PAPER-2014-067; arXiv:1502.02638]
- Observation of two new Ξ^-_b baryon resonances
  [LHCB-PAPER-2014-061; arXiv:1411.4849; Accepted by PRL]

THE LHCb DETECTOR

JINST 3 (2008) S08005



Tracking system
TT, IT/OT

Muon system

Vertex Locator (VELO)
Primary and secondary
Vertex reconstruction

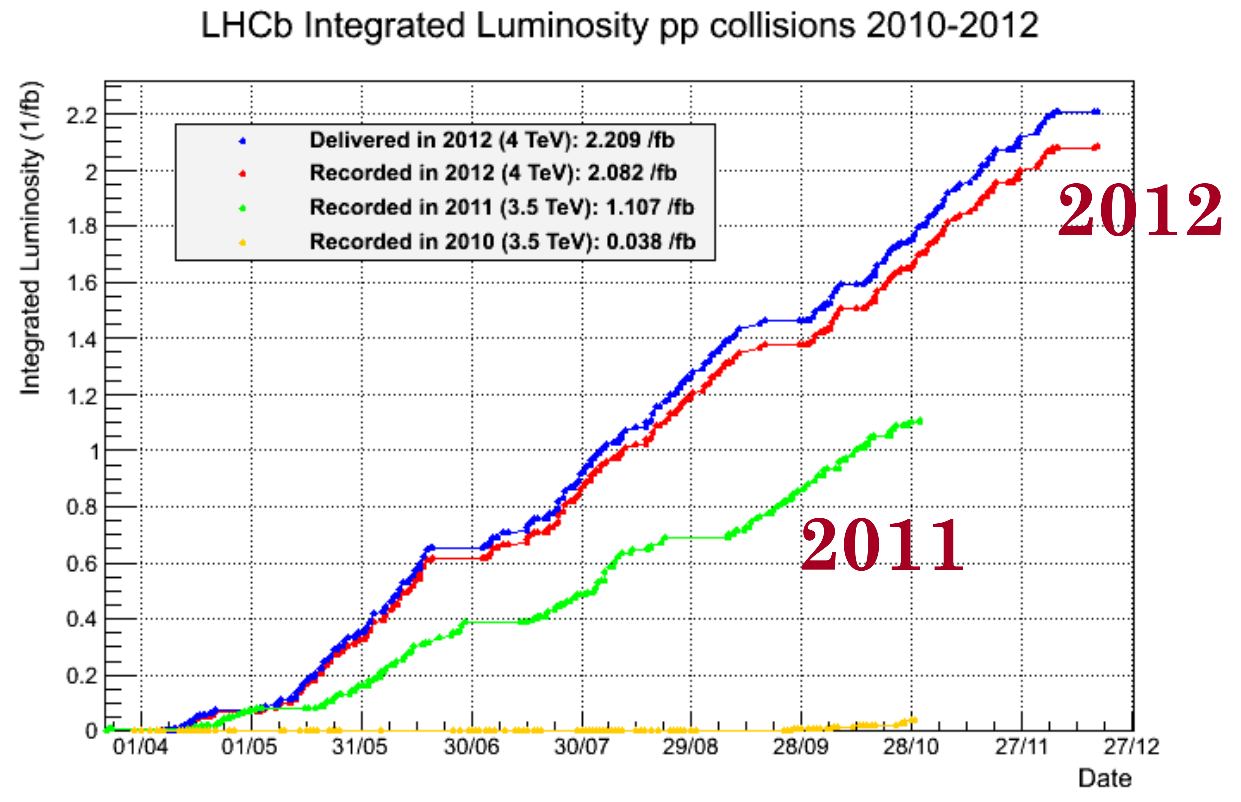
Interaction Point

RICH detector
PID K, π

Calorimeters
e, γ, π^0, n

DATASETS

LHCb collected 1. fb^{-1} at 7 TeV (2011) + 2. fb^{-1} at 8 TeV (2012)

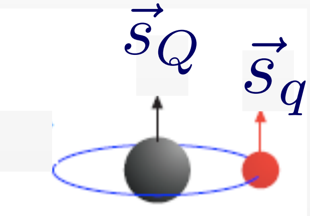


Precise measurements of the properties of the $B_1(5721)^{0,+}$ and $B_2^*(5747)^{0,+}$ states and observation of $B^{+,0}\ \pi^{-,+}$ mass structures

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

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

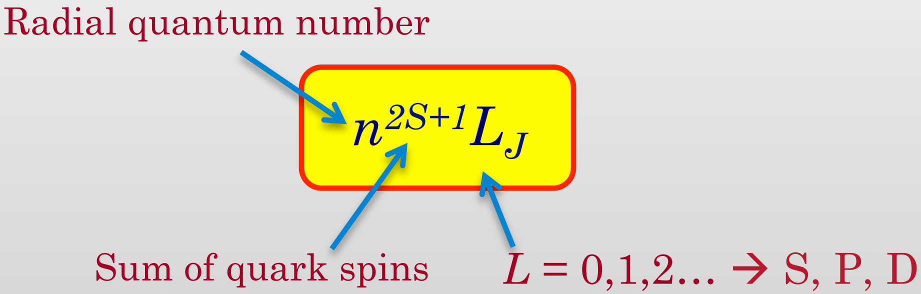


$\vec{L}$ Orbital angular momentum

$\vec{j}_q = \vec{L} + \vec{s}_{q=u,d,s}$ 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



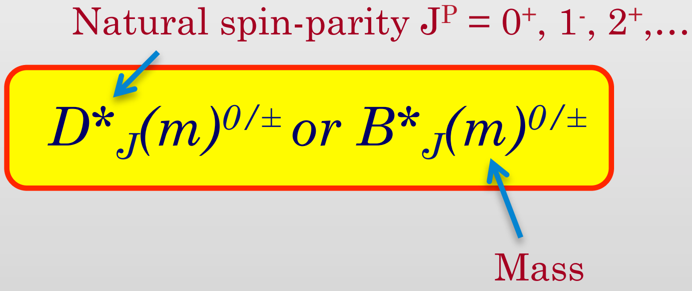
Radial quantum number

$n^{2S+1}L_J$

Sum of quark spins

$L = 0,1,2\ldots \rightarrow$ S, P, D

PDG notation



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

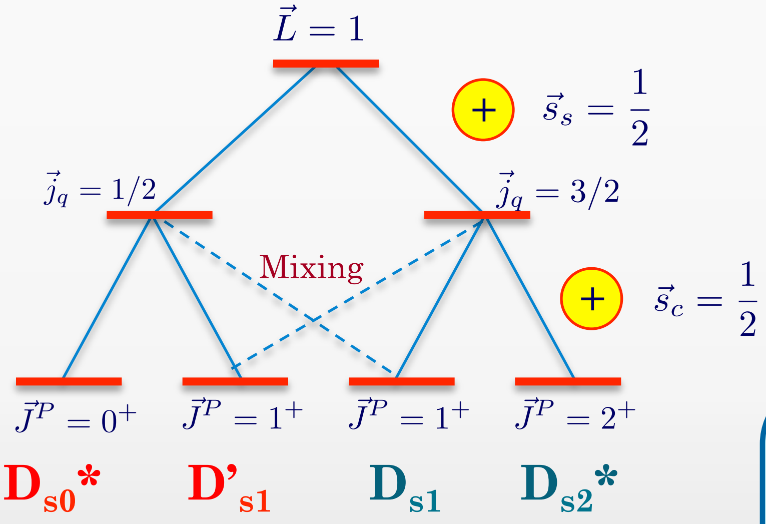
$D^*_J(m)^{0/\pm}$ or $B^*_J(m)^{0/\pm}$

Mass

EXCITED CHARMED AND BEAUTY STATES

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

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



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

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

$\underbrace{\hphantom{xxxxxxxx}}$ **j_q = 1/2 doublet**

$\underbrace{\hphantom{xxxxxxxx}}$ **j_q = 3/2 doublet**

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

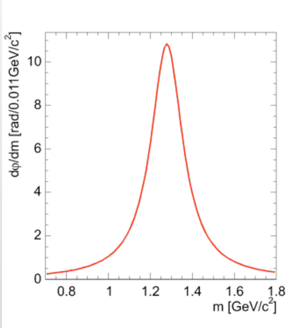
Similar picture for the excited $B^{**} \rightarrow B^{(*)}\pi$, $B_s^{**} \rightarrow B^{(*)}K$, $D^{**} \rightarrow D^{(*)}\pi$

HOW TO DO SPECTROSCOPY?

"Inclusive Analysis"

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

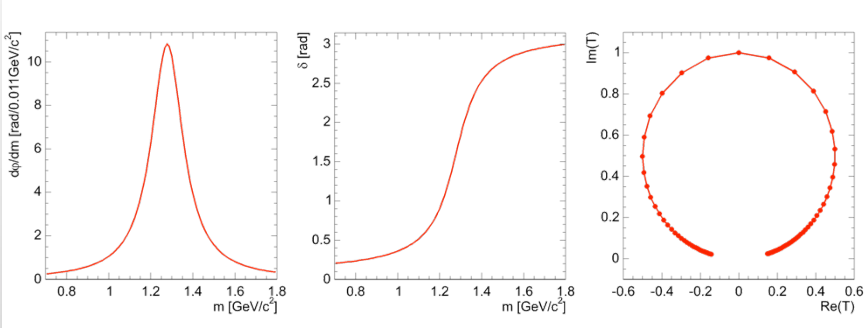
- ➢ Large cross sections
- ➢ Large combinatorial background
- ➢ Resonances appear as bumps
- ➢ Hard to disentangle broad structures
- ➢ Difficult to assess spin due to the unknown initial polarization



"Exclusive Analyses"

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

- ➢ 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



HOW A DOUBLET LOOKS LIKE

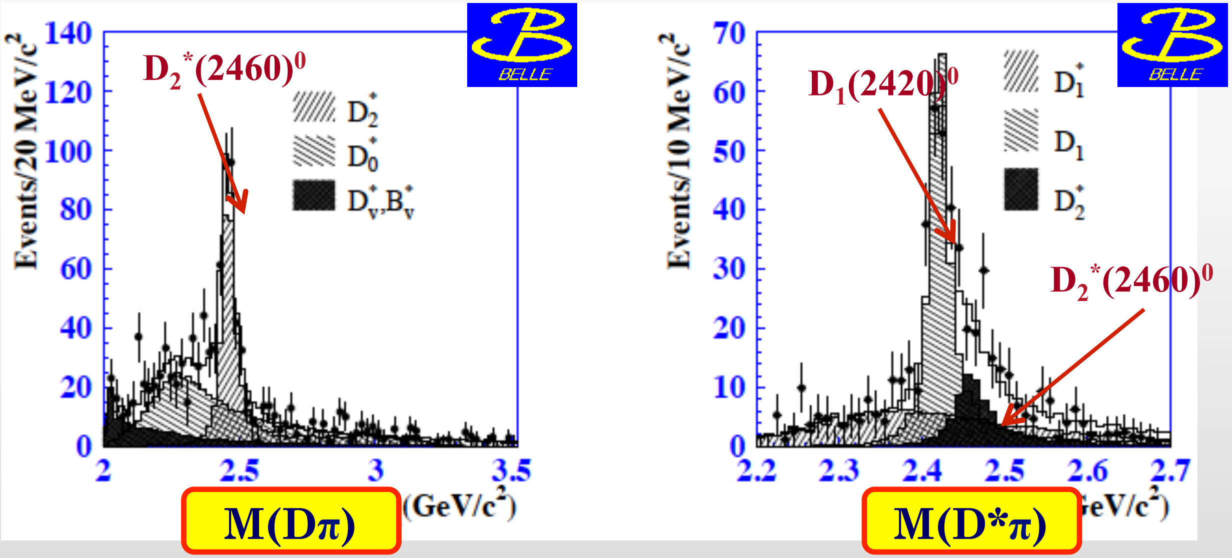
Exclusive analysis
$B^- \rightarrow D^{(*)+} \pi^- \pi^-$
[Belle: Phys.Rev.D69 (2004) 112002]

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

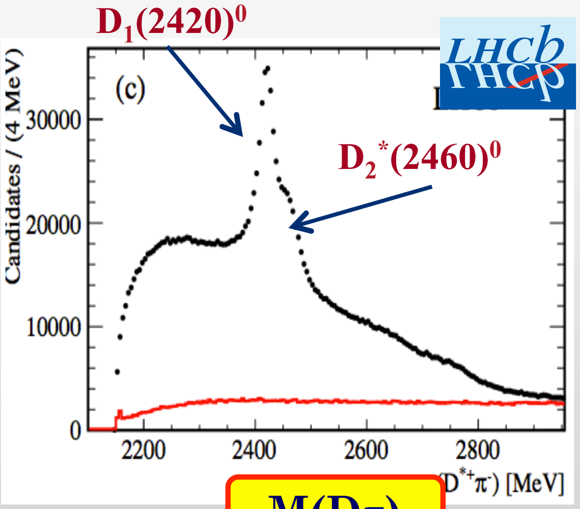
HOW A DOUBLET LOOKS LIKE

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

j_q=3/2 doublet

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

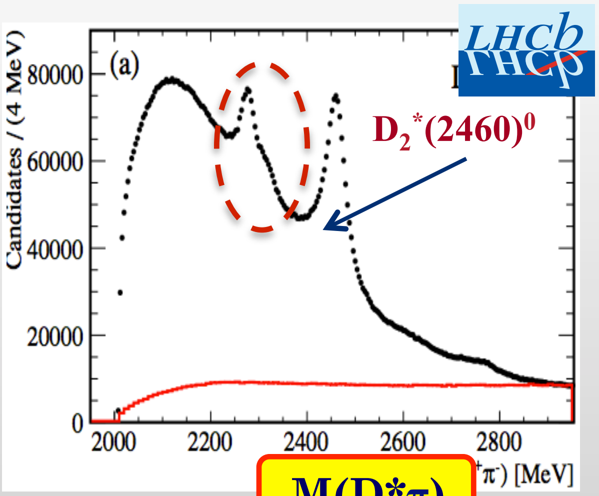
	j_q	J^P	Allowed decay mode	
			$D\pi$	$D^*\pi$
D_0^*	1/2	0^+	yes	no
D_1'	1/2	1^+	no	yes
D_1	3/2	1^+	no	yes
D_2^*	3/2	2^+	yes	yes



$D_1(2420)^0$

$D_2^*(2460)^0$

M(Dπ)



$D_2^*(2460)^0$

M(D*π)

FEED-DOWNS OF D_1/D_2^*→D*π DECAYS INTO Dπ MASS SPECTRUM

Inclusive analysis

pp → $D^{(*)+}\pi^- + X$

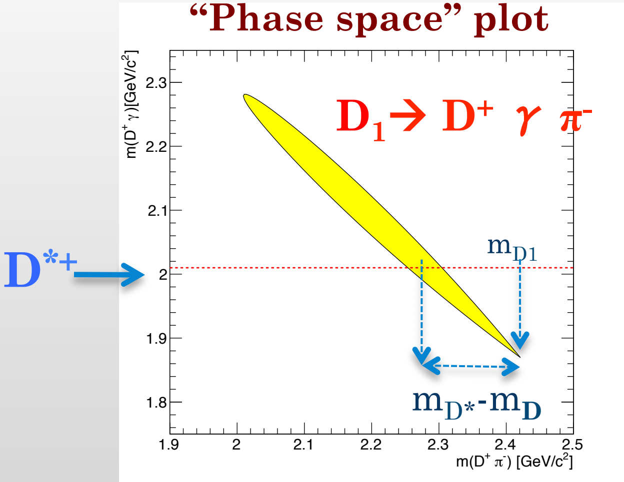
[LHCb: JHEP 09 (2013) 145]

j_q=3/2 doublet

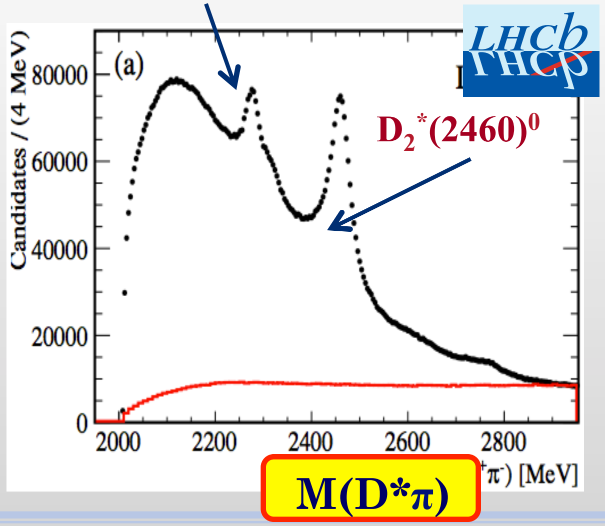
- 3 peaks in Dπ
  - ✓ D_2^*→Dπ
  - ✓ D_1 →D*π feed-down
  - ✓ D_2^*→D*π feed-down
- 2 peaks in D*π

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^+ γ/~~π^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)

		Mass (MeV)	Width (MeV)
j_q = 1/2 doublet	$D_0^*(2400)^0$	2318 ± 29	267 ± 40
	$D_0^*(2400)^\pm$	2403 ± 40	283 ± 40
	$D_1(2430)^0$	2427 ± 40	384^{+130}_{-110}
	$D_1(2430)^\pm$	—	—
j_q = 3/2 doublet	$D_1(2420)^0$	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)

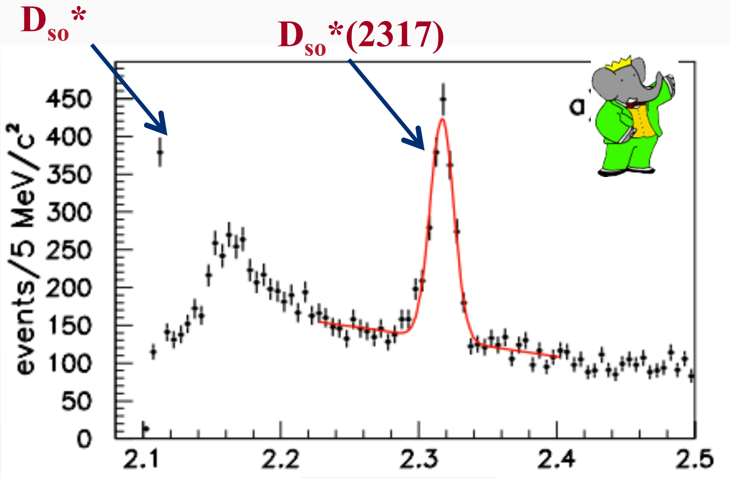
		Mass (MeV)	Width (MeV)
	D_{s0}^*	—	—
	D'_{s1}	—	—
j_q = 3/2 doublet	$D_{s1}(2536)^\pm$	2535.10 ± 0.08	0.92 ± 0.05
	$D_{s2}^*(2573)^\pm$	2571.9 ± 0.8	17 ± 4

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

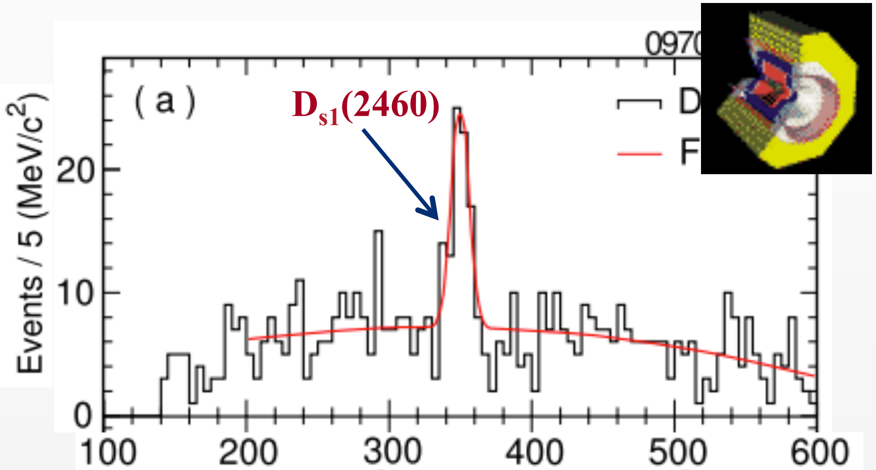
Puzzle:
Excited D_s Mesons: L=1, j_q = 1/2(?)

Inclusive studies of $D_s^{(*)}\pi^0$

[BaBar, PRL90, 242001][CLEO, PRD68, 032002]



$M(D_s\pi^0)$

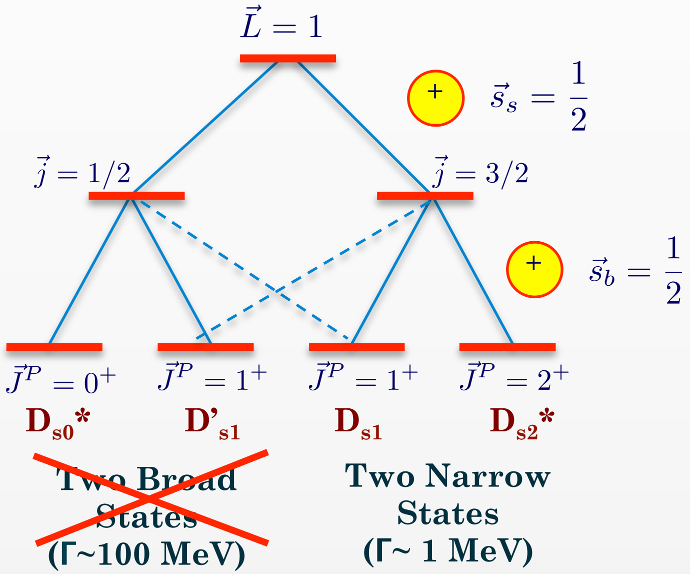


$M(D_s\gamma\pi^0)$-$M(D_s\gamma)$

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$_{s2}$*)
} > 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)]**

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

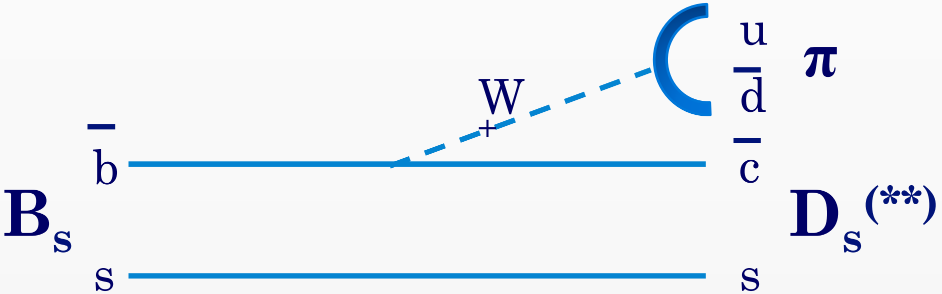
$$\frac{\mathcal{B}(B^0 \to D^- D_{s0}^{*+})}{\mathcal{B}(B^0 \to D^- D_s^+)} = 0.13 \pm 0.04$$

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

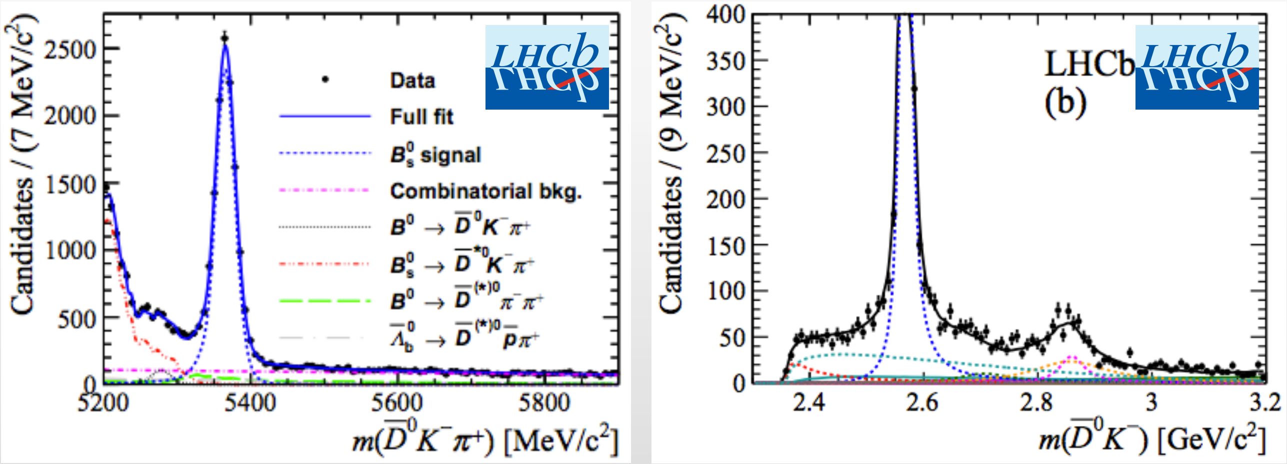
No $D_s^+\pi^\pm$ partners have been observed in inclusive studies **[BaBar: PRD74 (2006) 032007]** or in B decays **[Belle: R.Chistov@ EPS-HEP, Stockholm, Sweden (18 July 2013)]**

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)]

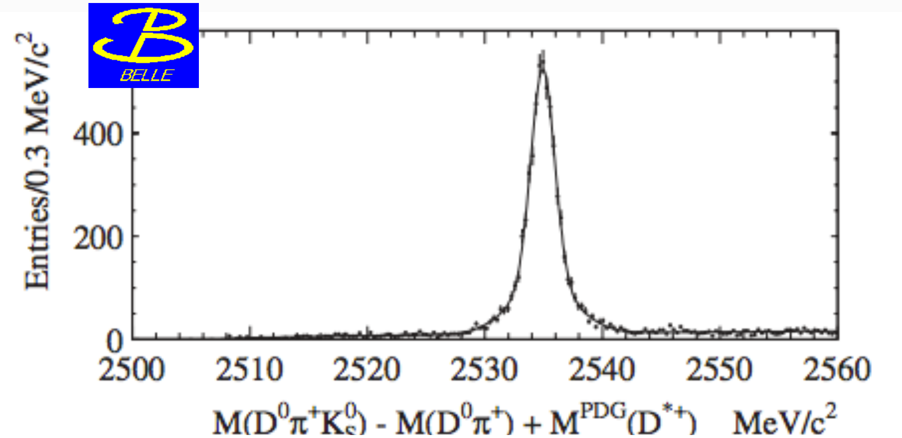
Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant	12.4 ± 2.7
D_{sv}^{*-}	4.7 ± 1.4
$D_{s0v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3

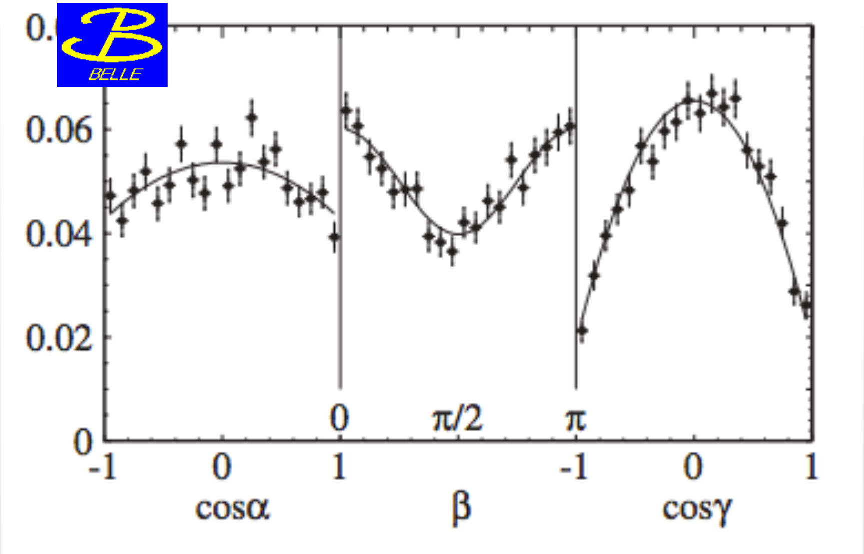
No evidence for such a broad D_{s0}^* state

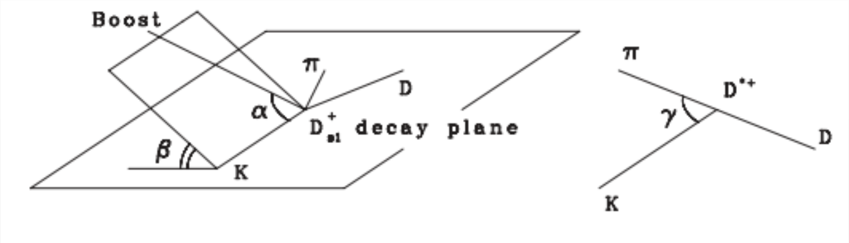
Puzzle II:
Is $D_{s1}(2536)^+$ the Excited L=1, j_q=3/2 State?

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

[Belle: PRD77 (2008) 032001]





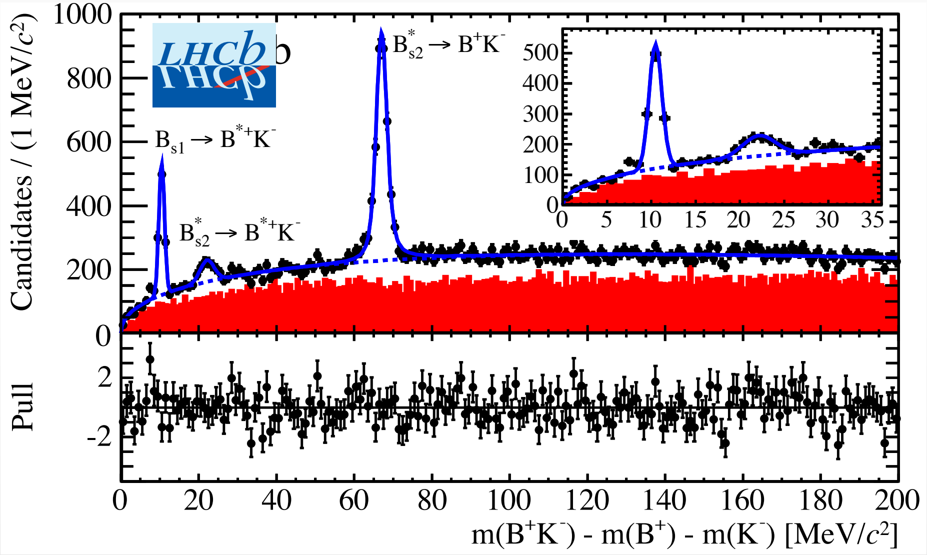


$$\frac{\Gamma_S}{\Gamma_{total}} = 0.72 \pm 0.05 \pm 0.01$$

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

THE EXCITED B$_s$ STATES

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



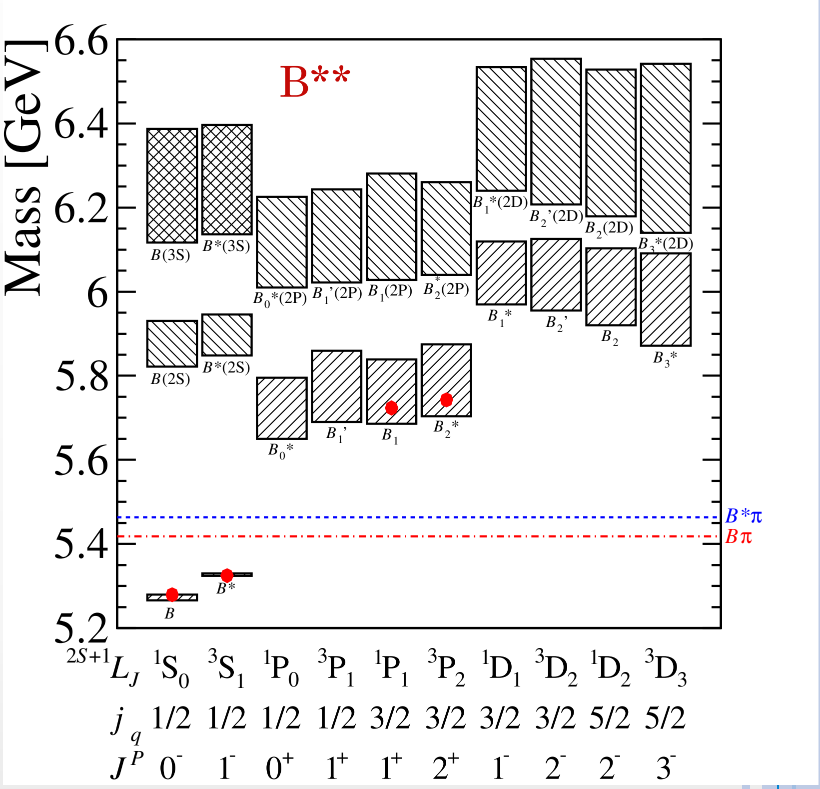
[LHCb: PRL 113, 162001 (2014)]

	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 EXCITED B STATES

- LEP experiments observed a single broad structure (Γ > 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.)

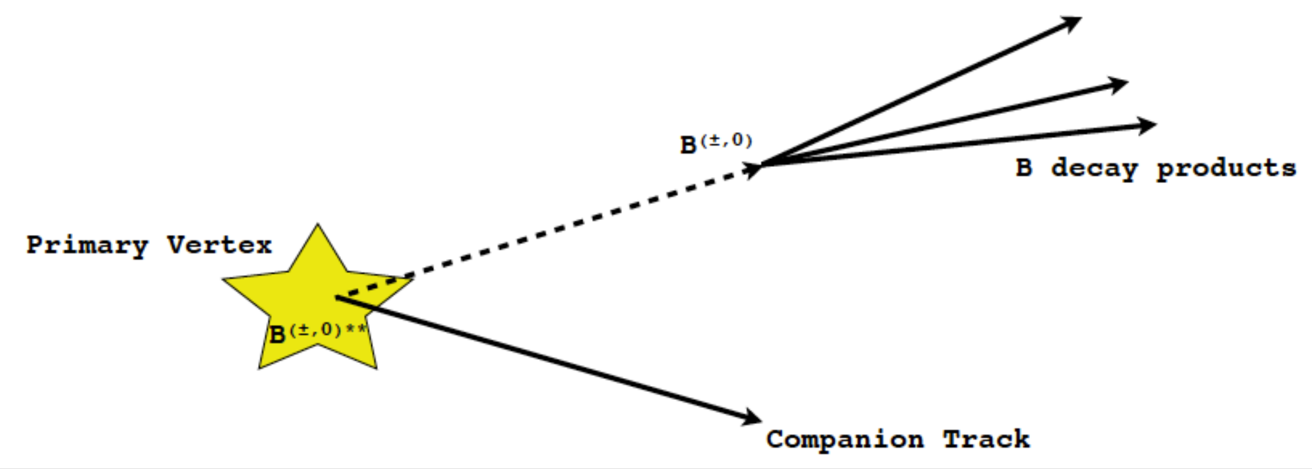
INCLUSIVE STUDY OF THE $B^+\pi^-$ AND $B^0\pi^+$ MASS SPECTRA

[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 $\pi^-(\pi^+)$ originating from the interaction point
- Analysis carried out by fitting the Q distributions:

$$Q \equiv m(B\pi)-m(B)-m(\pi)$$



SELECTION OF THE B⁺ CANDIDATES

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

B mesons are selected in several high-yield decay modes

B⁺

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

B⁰

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

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

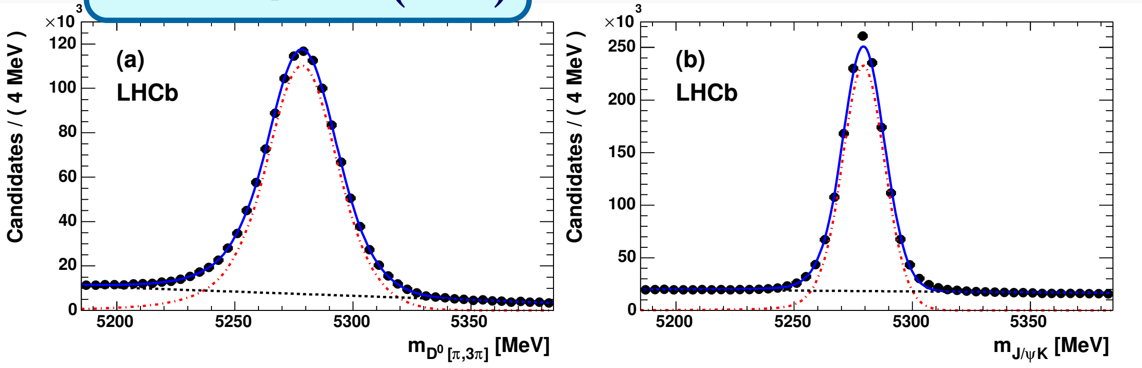
$B^{0,+}$ CANDIDATES

[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}

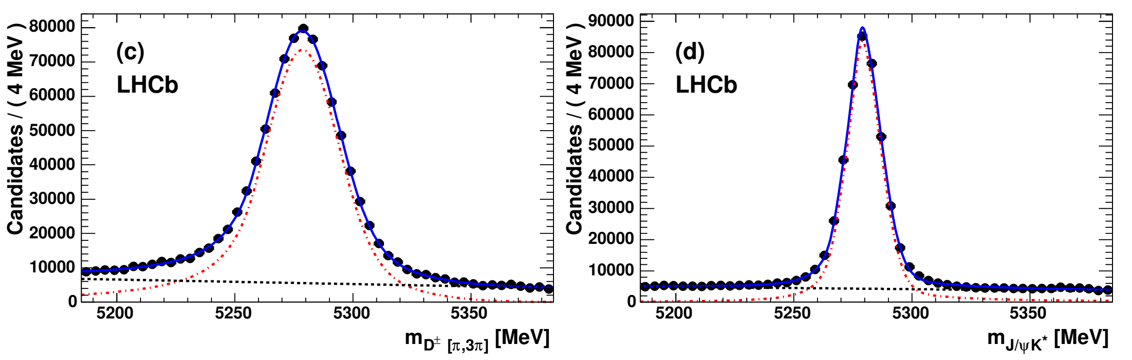
$B^+ \rightarrow \overline{D}^0 \pi^+(\pi^-\pi^+)$
$\rightarrow K^+\pi^-(\pi^+\pi^-)$

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



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

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



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)

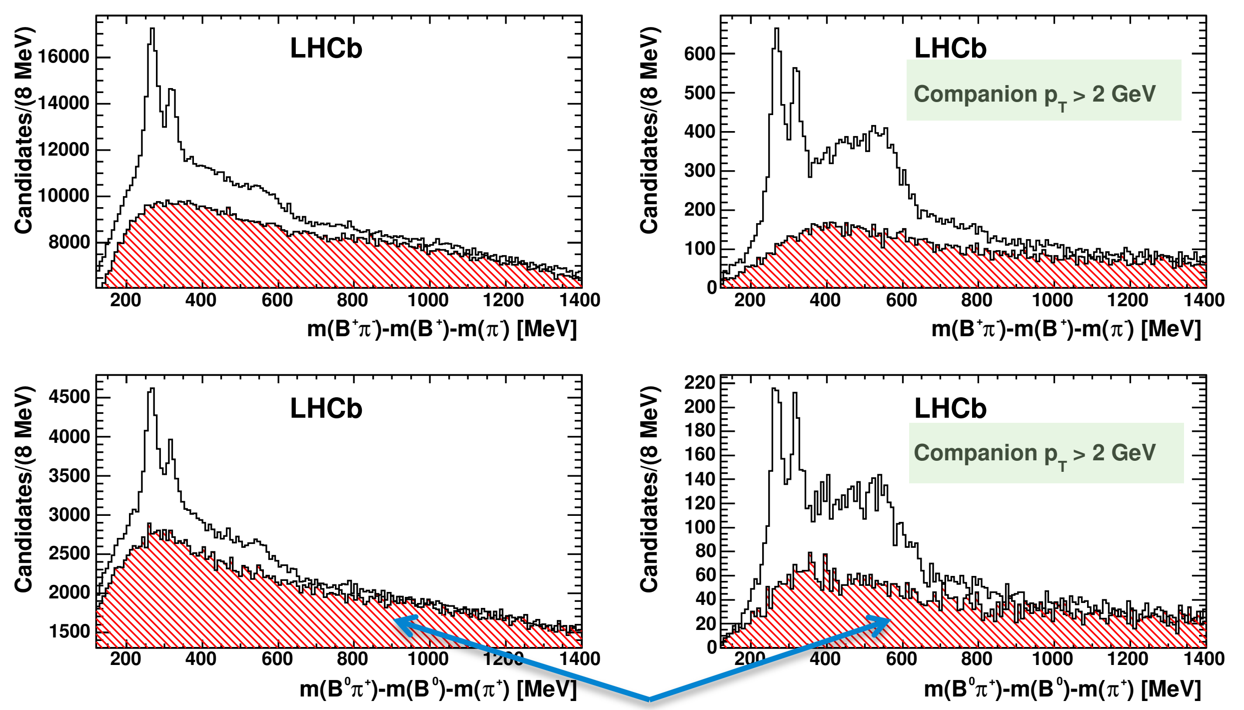
SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

[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

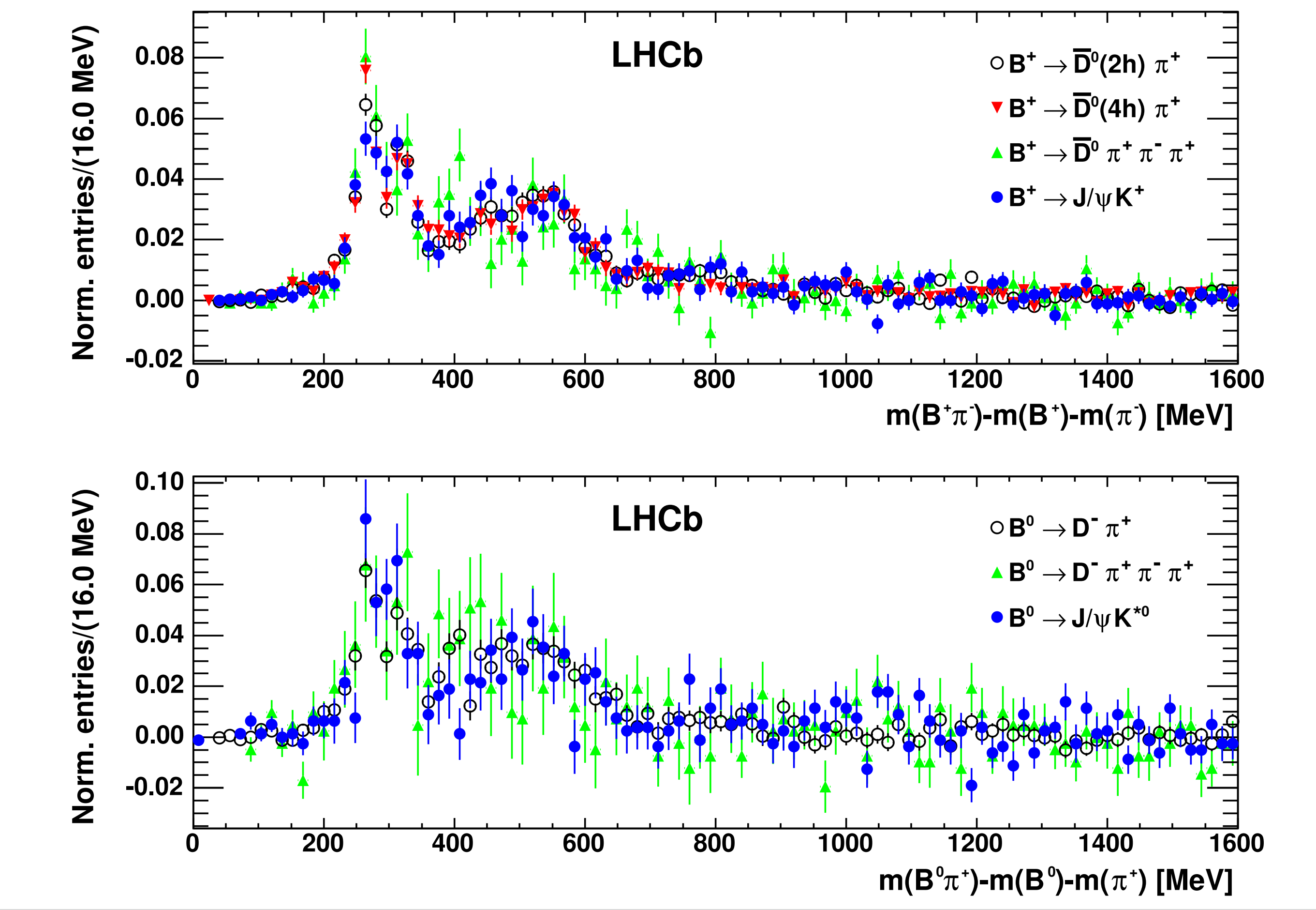
SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

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

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

$B^+\pi^-$

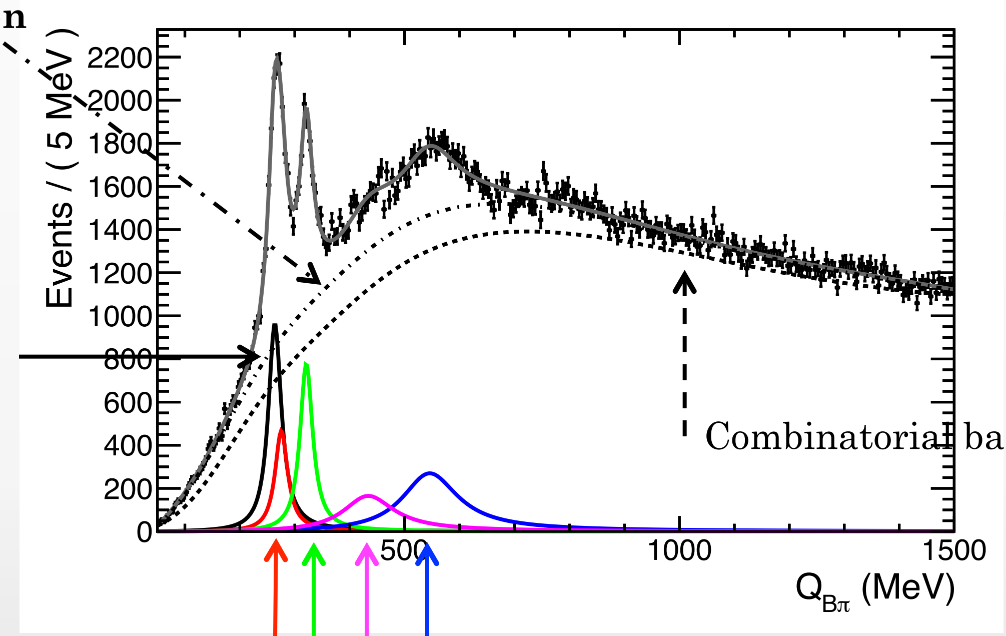
$B^0\pi^+$



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

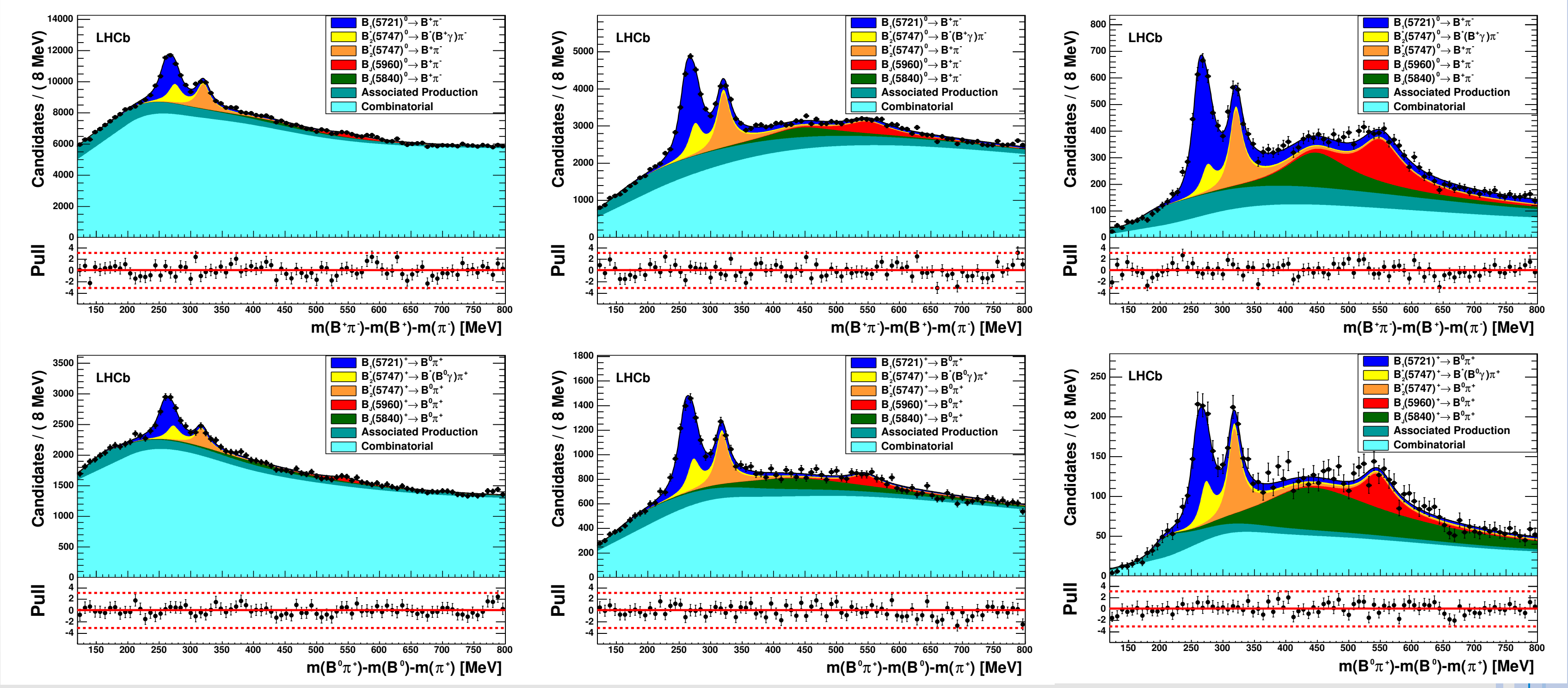
NOMINAL FIT RESULTS BY p_T BIN

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

$0.5 < p_T < 1$ GeV **$1 < p_T < 2$ GeV** **$p_T > 2$ GeV**

$B^+\pi^-$

$B^0\pi^+$



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

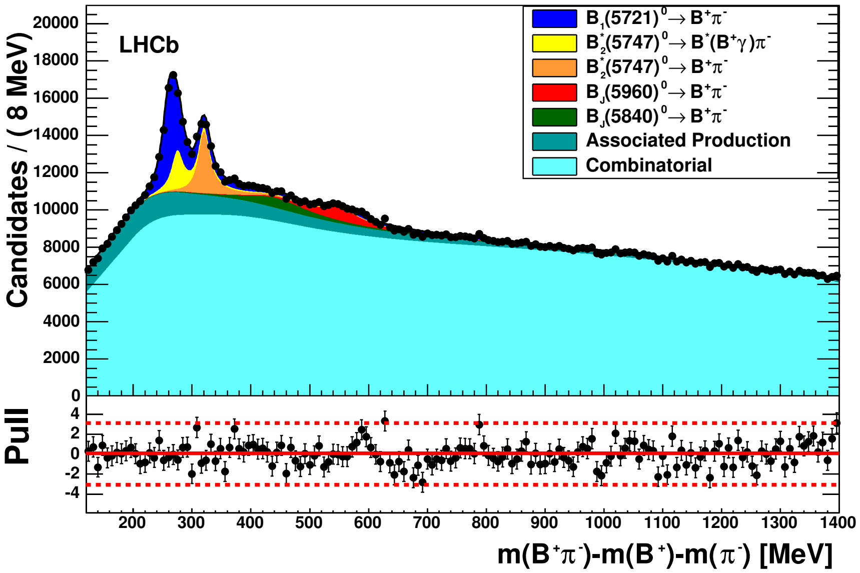
🟥 $B_J(5960)^+ \to B^0\pi^+$
🟩 $B_J(5840)^+ \to B^0\pi^+$
🟦 Associated Production
🟦 Combinatorial

NOMINAL FIT RESULTS

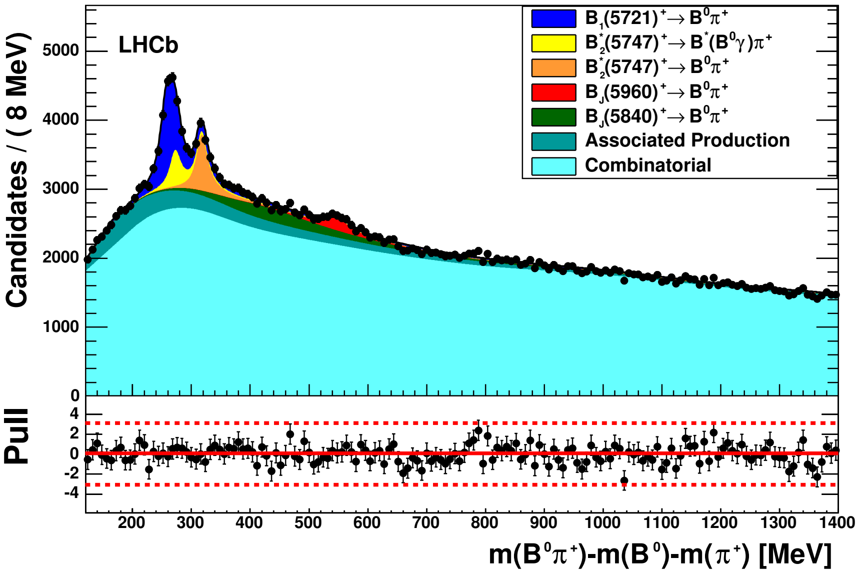
[LHCB-PAPER-2014-067; arXiv:1502.02638]

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

SYSTEMATICS UNCERTAINTIES

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

Source **(μ and Γ in MeV)**	$B_1(5721)^0$		$B_2^*(5747)^0$			$B_J(5840)^0$		$B_J(5960)^0$	
	μ	Γ	BF ratio	μ	Γ	μ	Γ	μ	Γ
Total statistical	0.72	1.52	0.14	0.37	1.01	4.95	16.70	2.88	7.71
Fit range (high)	0.33	1.30	0.06	0.08	0.37	2.20	2.90	0.52	0.26
Fit range (low)	0.04	0.11	0.01	0.02	0.39	0.04	8.22	0.69	2.83
2 MeV bins	0.02	0.14	0.00	0.04	0.07	1.09	0.50	0.08	1.00
Spline knots	0.11	0.01	0.02	0.02	0.26	1.75	0.04	0.45	1.44
Float AP	0.03	0.00	0.00	0.03	0.30	1.58	10.16	0.73	4.23
$B_2^*(5747)^0$ rel. eff., low p_T	0.56	0.91	0.15	0.08	0.16	0.07	0.23	0.00	0.18
$B_2^*(5747)^0$ rel. eff., mid p_T	0.64	1.01	0.05	0.09	0.18	0.08	0.26	0.00	0.16
$B_2^*(5747)^0$ rel. eff., high p_T	0.20	0.37	0.03	0.02	0.07	0.02	0.00	0.01	0.09
Eff. variation with Q value	0.13	0.33	0.02	0.04	0.07	0.45	2.46	0.19	0.70
Data-simulation reweighting	0.07	0.38	0.02	0.00	0.16	1.81	2.03	0.49	0.12
B p_T cut	0.02	0.20	0.01	0.24	0.72	3.98	3.67	1.30	4.29
p_T binning	0.90	2.45	0.24	0.06	0.39	1.49	27.77	4.20	1.47
Fit bias	0.06	0.17	0.01	0.00	0.16	0.45	5.34	0.40	2.24
Spin	0.02	0.06	0.01	0.06	0.46	1.95	3.32	0.62	3.74
Effective radius	0.33	1.44	0.02	0.12	0.76	2.17	9.68	1.24	3.81
$B^* - B$ mass	0.10	0.11	0.03	0.02	0.11	0.04	0.17	0.00	0.09
$B_J(5840)^0$ J^P	0.01	0.04	0.00	0.01	0.01	—	—	1.67	0.76
$B_J(5960)^0$ J^P	0.01	0.20	0.00	0.00	0.16	0.18	8.00	—	—
Extra state	0.00	0.26	0.00	0.04	0.34	1.67	0.99	0.12	2.08
Total systematic	1.36	3.49	0.30	0.33	1.48	6.68	34.24	5.10	9.41

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

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

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

$$\begin{array}{lcrlrlrl}
\dfrac{\mathcal{B}\left(B_2^*(5747)^0 \to B^{*+}\pi^-\right)}{\mathcal{B}\left(B_2^*(5747)^0 \to B^+\pi^-\right)} & = & 0.71 & \pm & 0.14 & \pm & 0.30\,, \\
\dfrac{\mathcal{B}\left(B_2^*(5747)^+ \to B^{*0}\pi^+\right)}{\mathcal{B}\left(B_2^*(5747)^+ \to B^0\pi^+\right)} & = & 1.0 & \pm & 0.5 & \pm & 0.8\,,
\end{array}$$

First evidence of the $B_2^*(5747)^0 \to B^{*+}\pi^-$ (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

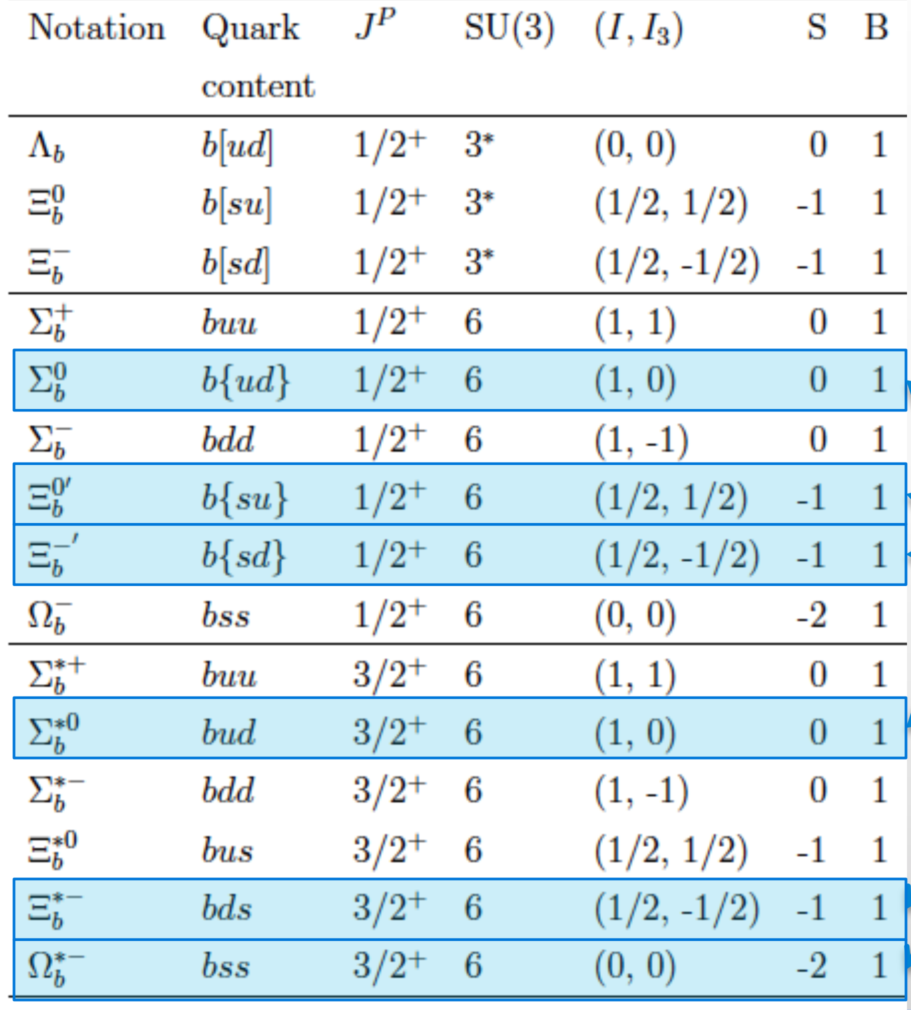
Consistent with the interpretation of 4 states given the expected isospin symmetry

OBSERVATION OF TWO NEW Ξ_b^- BARYONS RESONANCES

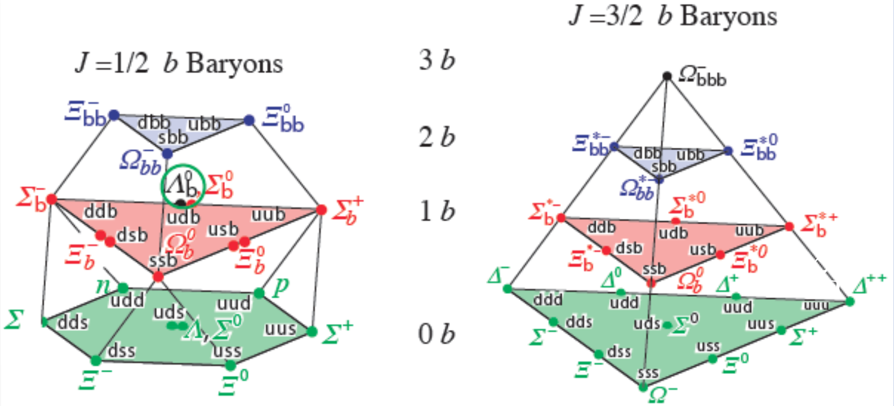
[LHCB-PAPER-2014-061; arXiv:1411.4849]

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



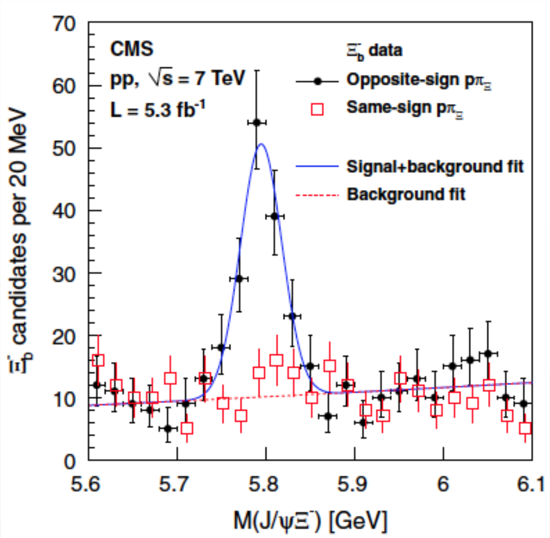
The system of baryons containing a *b* quark remains largely unexplored.

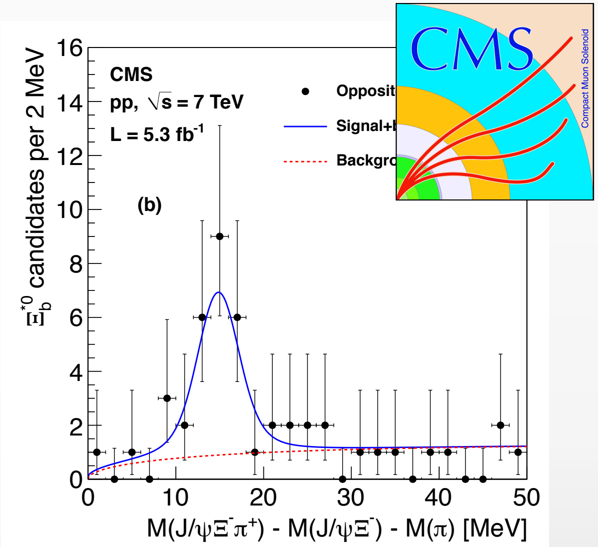
Missing states

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

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 + $m(\pi^+)$

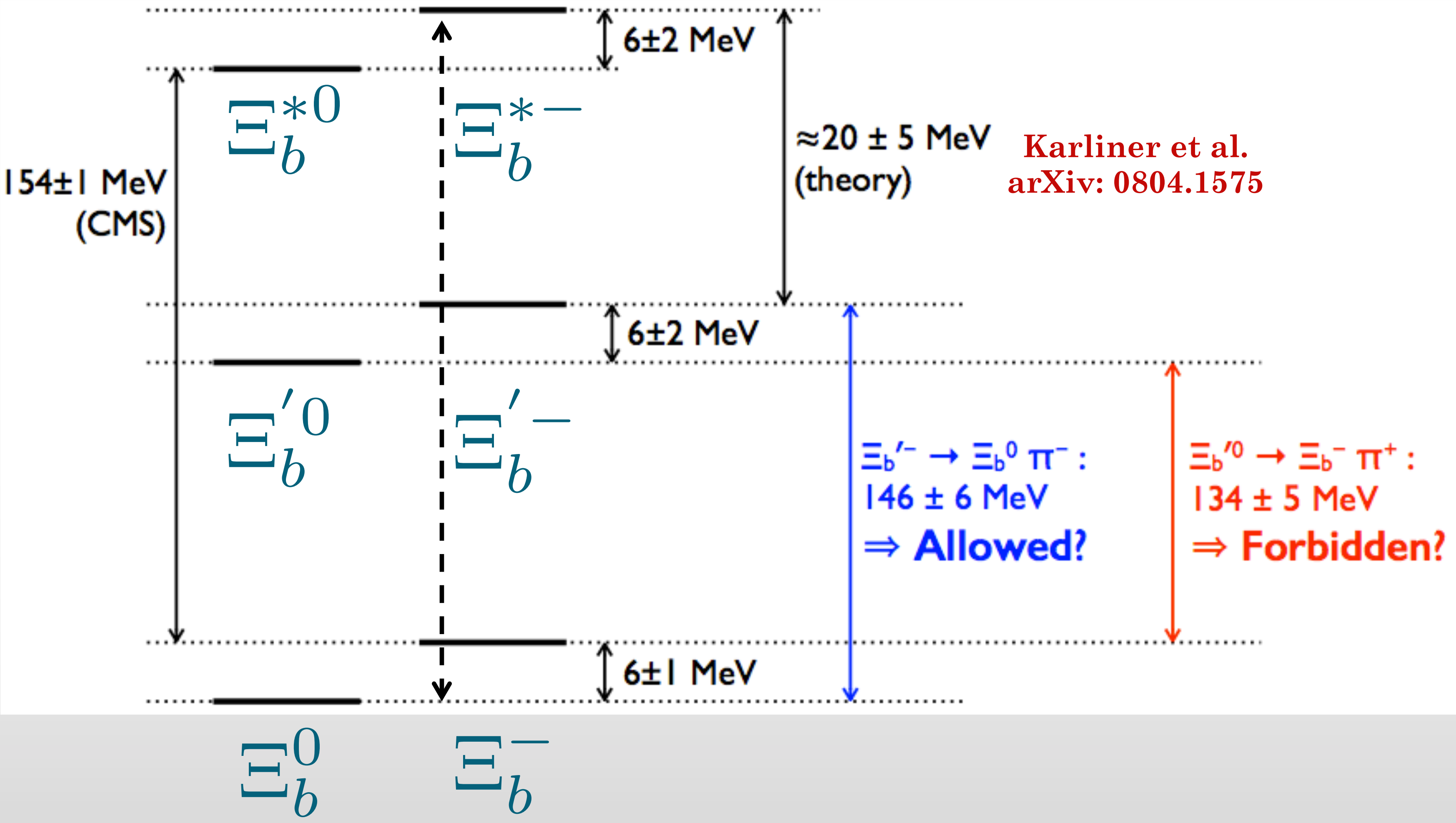
Similarly combining (1) and (3):

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

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

$< m(\pi^+)$

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

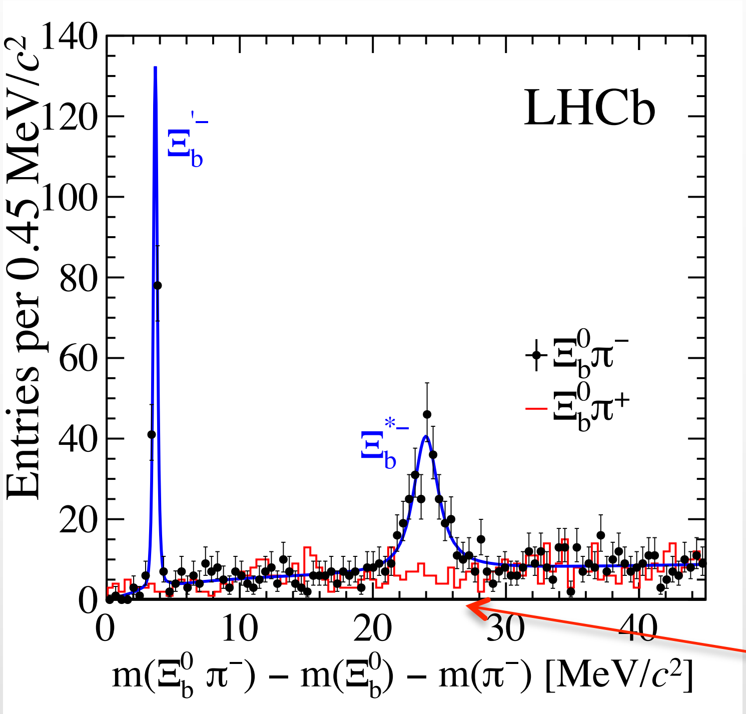


Karliner et al.
arXiv: 0804.1575

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 ⊗ 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 $\Xi_b^{**-} \rightarrow \Xi_b^{'0} (\Xi_b^0\pi^0) \pi^-$

SYSTEMATIC UNCERTAINTIES

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

Source **(All in MeV)**	$\delta m(\Xi_b'^{-})$	$\delta m(\Xi_b^{*-})$	$\Gamma(\Xi_b^{*-})$
Simulated sample size	0.002	0.005	
Multiple candidates	0.004	0.048	0.055
Resolution model	0.002	0.003	0.070
Background description	0.001	0.003	0.019
Momentum scale	0.003	0.014	0.003
RBW spin and radial parameter	0.000	0.023	0.028
Sum in quadrature	0.006	0.055	0.095
Statistical uncertainty	0.018	0.119	0.311

- Statistical uncertainties dominate
- Systematic uncertainty on δm(Ξ_b’) is only 6 keV (cross-checked using δm($D^{*+} \rightarrow D^0 \pi^+$) and comparing with a recent BABAR measurement)

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

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

With this assumption, we measure:

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

Signal significances > 10σ

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

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 $\Xi_b'^-$ and Ξ_b^{*-} interpretation

2) Measurements of relative productions

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

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

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

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

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

Signals have been observed in

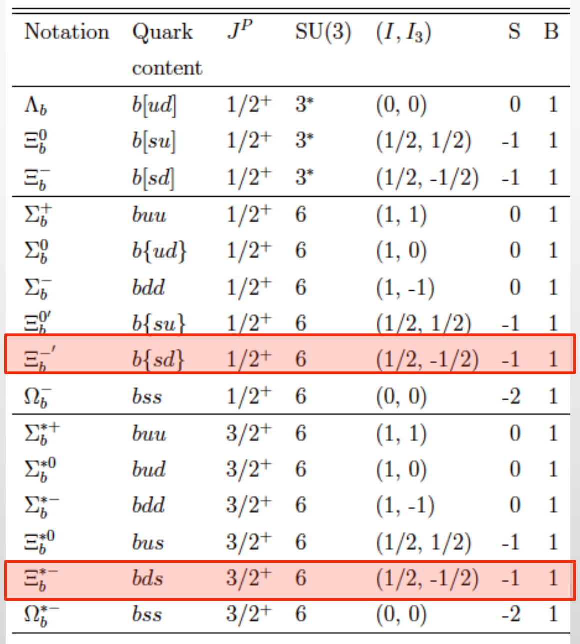
$\Xi_b^0 \to \Lambda_c^+(pK^-\pi^+)K^-\pi^+\pi^-, \Xi_b^0 \to D^0(K^-\pi^+)pK^-$ and $\Xi_b^0 \to \mathrm{D}^+(\mathrm{K}^-\pi^+\pi^+)\mathrm{pK}^-\pi^+$

SUMMARY: EXCITED HEAVY MESONS

- The excited B and D mesons extensively studied at LHCb
- In this talk we present the results of fitting the $B^+\pi^-$ and $B^0\pi^+$ spectra without any theoretical input:
  - ✓ The most precise measurements of the $B_1(5721)^{0,+}$ and $B_2^*(5747)^{0,+}$ masses and widths
  - ✓ First evidence of $B_2^*(5747) \to B^{*+}\pi^-$ decay
  - ✓ Observation of 4 broad structures $B_J(5840)^{0,+}$ and $B_J(5960)^{0,+}$ consistent with the B(2S) and B*(2S)

SUMMARY: BARYONS

- LHCb has shortened the list of the missing baryons
- In this talk the observation of two new baryons decaying into $\Xi_b^0\,\pi^-$:
  - One consistent with the isospin partner state observed by CMS and therefore interpreted as Ξ_b^{*-}
  - The second one likely to be the $\Xi_b^{\prime -}$ ($\Xi_b^{\prime 0}$ unobserved by CMS because under the $\Xi_b^-\,\pi^+$ threshold)
  - An angular analysis supports this scenario



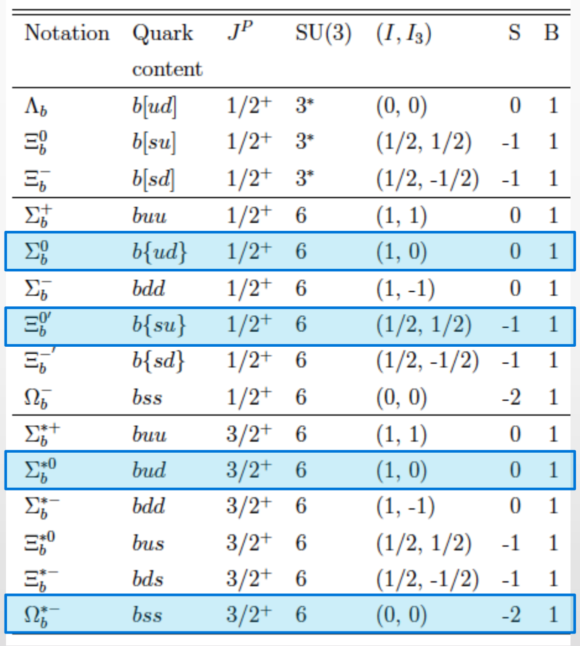
Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3^*	(0, 0)	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3^*	(1/2, 1/2)	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3^*	(1/2, -1/2)	-1	1
Σ_b^+	buu	$1/2^+$	6	(1, 1)	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	(1, 0)	0	1
Σ_b^-	bdd	$1/2^+$	6	(1, -1)	0	1
$\Xi_b^{0\prime}$	$b\{su\}$	$1/2^+$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

Artist's impression by Italic Pig

PROSPECTS

Excited Heavy Mesons

- 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}'?
- Investigation of the nature of D_{s0}* and D_{s1}' states: production studies, search for new decays modes, measurements of BR's from B_s decays…



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

Baryons

- $\Xi_b'^0$ 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 (e.g. $\Lambda_b^{**} \rightarrow \Lambda_b \pi^+ \pi^-$ [PRL 109 (2012) 172003])
- Search for doubly-heavy baryons [JHEP 1312 (2013) 090]

RUN I data not fully exploited so far. Many systems still unexplored and RUN II is ahead (expected 5-10 fb^{-1})

Stay Tuned!