HEAVY HADRON SPECTROSCOPY AT *LHCb*

Marco Pappagallo

University of Glasgow

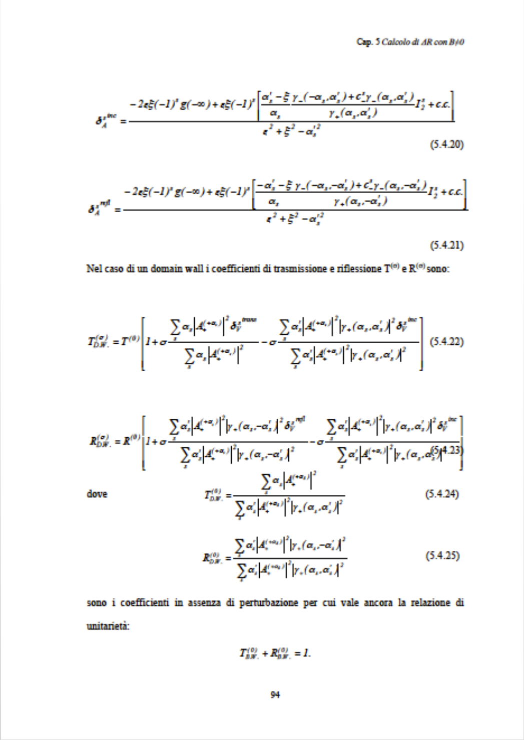
LPNHE, Paris, 9 March 2015

What about me?

Education

➢ ***Degree in Physics @ University of Bari***

Thesis: *Electroweak baryogenesis mediated by domain walls*



Cap. 5 Calcolo di ΔR con B≠0

(5.4.20)

(5.4.21)

Nel caso di un domain wall i coefficienti di trasmissione e riflessione $T^{(\sigma)}$ e $R^{(\sigma)}$ sono:

(5.4.22)

(5.4.23)

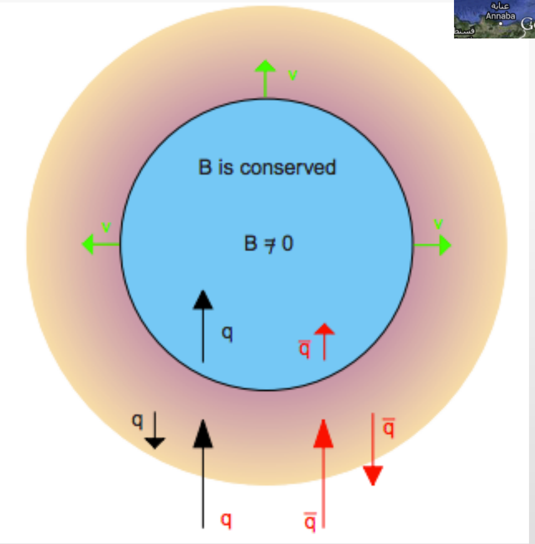
dove (5.4.24)

(5.4.25)

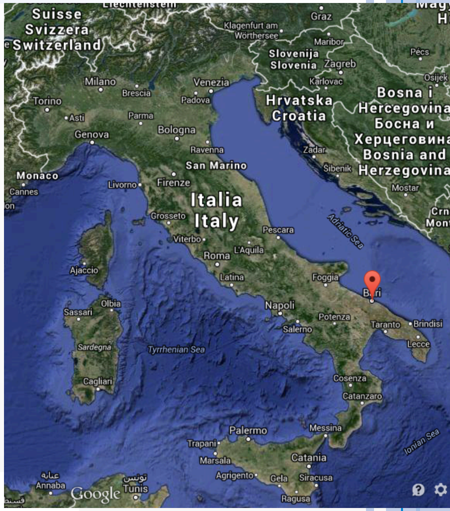
sono i coefficienti in assenza di perturbazione per cui vale ancora la relazione di unitarietà:

$$T^{(0)}_{D.W.} + R^{(0)}_{D.W.} = 1.$$

94



Credits: 2009 J. Phys. Conf. Series: 171 012005

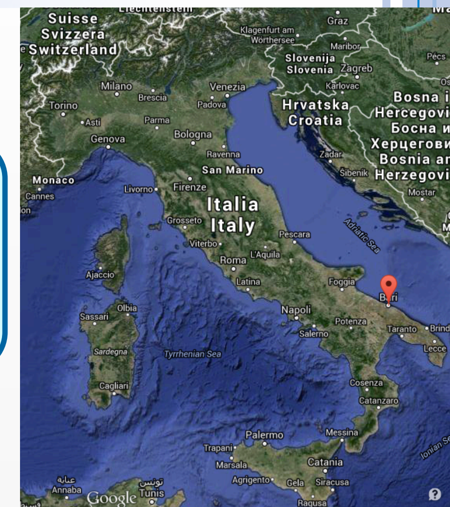


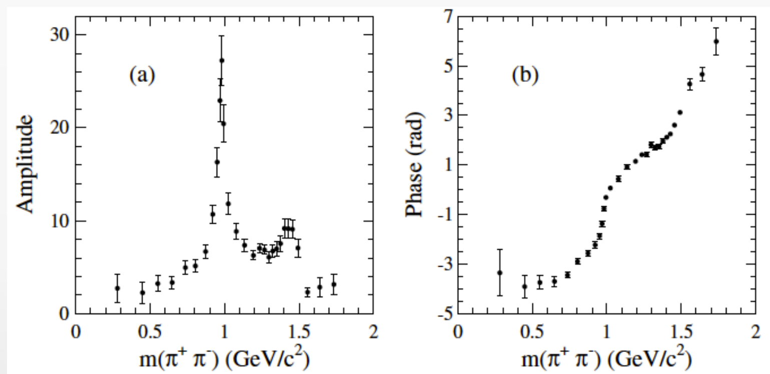
What about me?

Education

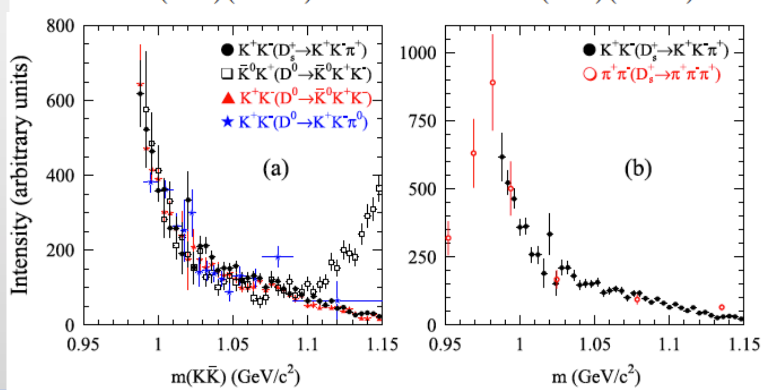
- Degree in Physics @ University of Bari
- ***PhD @ University of Bari***

Thesis: *"Dalitz plot analyses of $D_s \rightarrow KK\pi$ and $D_s \rightarrow \pi\pi\pi$ at BaBar"*





$D_s \rightarrow \pi\pi\pi$
[BaBar: PRD 79, 032003 (2009)]



$D_s \rightarrow KK\pi$
[BaBar: PRD 83, 052001 (2011)]

WHAT ABOUT ME?

Education

- Degree in Physics @ University of Bari
- PhD @ University of Bari

Jobs

- ***Post-doc @ Durham University** [Nov 2005 → Apr 2007]*

IPPP
(Institute for Particle Physics Phenomenology)

Search for rescattering effects by studying the $K^-\pi^+$ and K^+K^- S waves in the $D^+ \rightarrow K^-\pi^+\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$ decays

What about me?

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- Degree in Physics @ University of Bari
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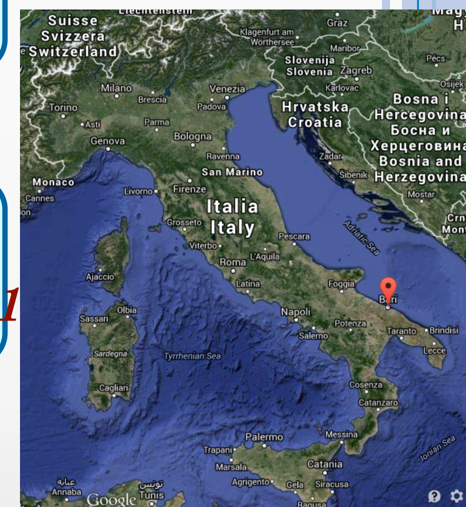
- ***Post-doc @ University of Bari [May 2007 → Jul 2011***



Charm and Beauty Spectroscopy

Scanning the geometry of the LHCb detector in simulation and looking for overlaps between volumes (> 3000)

WHAT ABOUT ME?

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- Post-doc @ University of Bari [May 2007 → Jul 2011]
- *Post-doc @ University of Glasgow[Nov 2011 → Present]*

Charm and Beauty Spectroscopy

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- ➢ Degree in Physics @ University of Bari
- ➢ PhD @ University of Bari

Jobs

- ➢ Post-doc @ Durham University [Nov 2005 → Apr 2007]
- ➢ Post-doc @ University of Bari [May 2007 → Jul 2011]
- ➢ Post-doc @ University of Glasgow[Nov 2011 → Present]

Responsibilities

- ➢ *Convener of the Exotic subgroup [Sep 2012 → Mar 2014]*

- ✓ Running weekly meetings
- ✓ Work coordination between several groups of analysts
- ✓ Reviewing the analyses at their first stages
- ✓ Taking care that the main analyses are covered
- ✓ Checking that analyses proceed smoothly to publication

Exotic Onia

What about me?

Education

- Degree in Physics @ University of Bari
- PhD @ University of Bari

Jobs

- Post-doc @ Durham University [Nov 2005 → Apr 2007]
- Post-doc @ University of Bari [May 2007 → Jul 2011]
- Post-doc @ University of Glasgow [Nov 2011 → Present]

Responsibilities

- Convener of the Exotic subgroup [Sep 2012 → Mar 2014]
- *Convener of the B-hadron&Quarkonia [Apr 2014 → Present]*

>20% Papers

Production & Polarization

b-hadron & B_c

Exotic Onia

LHCb

OUTLINE

- The LHCb detector
- Introduction
- Excited Charmed Mesons
- Excited Beauty Mesons

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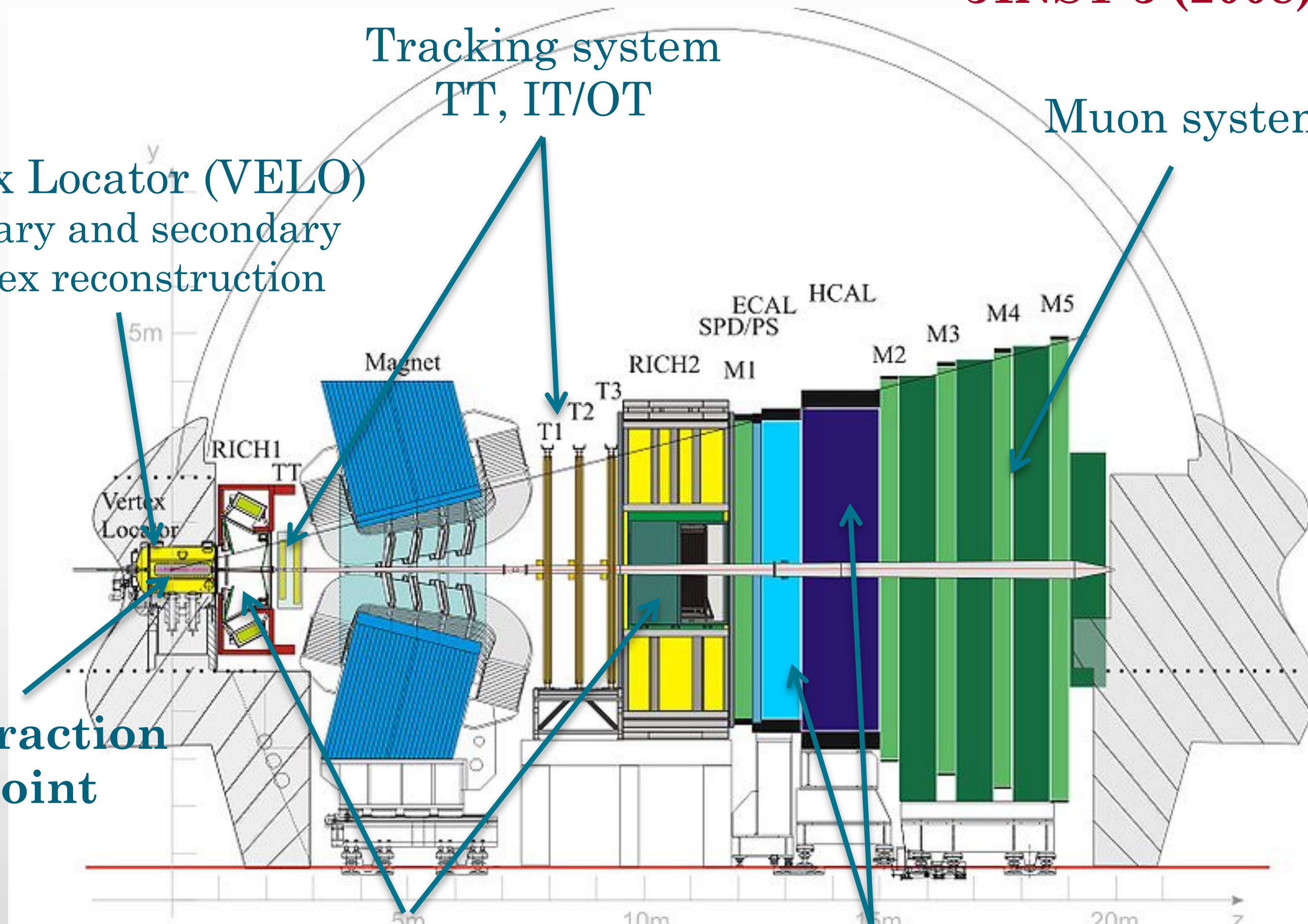
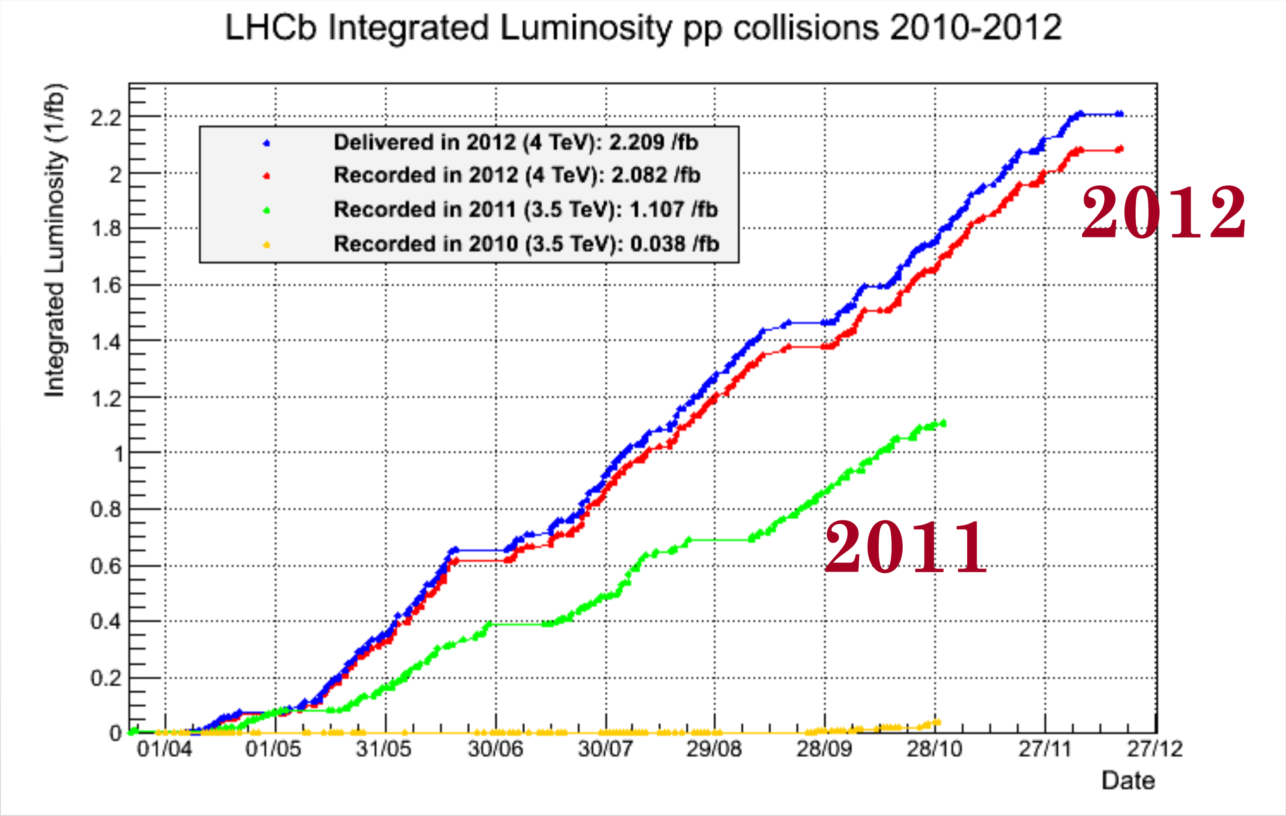
The LHCb detector

JINST 3 (2008) S08005



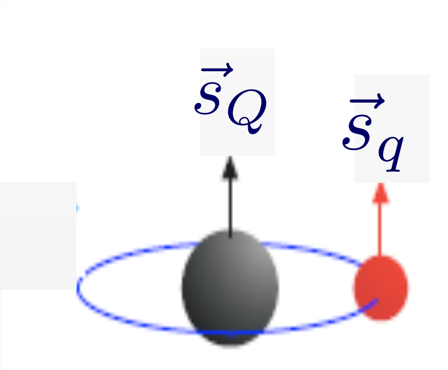
DATASETS

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



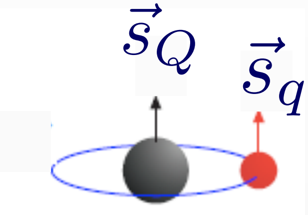
INTRODUCTION

- 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

Introduction



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

Intrinsic parity of $q\bar{q}$

Mesons

Natural spin-parity

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

Unnatural spin-parity

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

Nomenclature

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

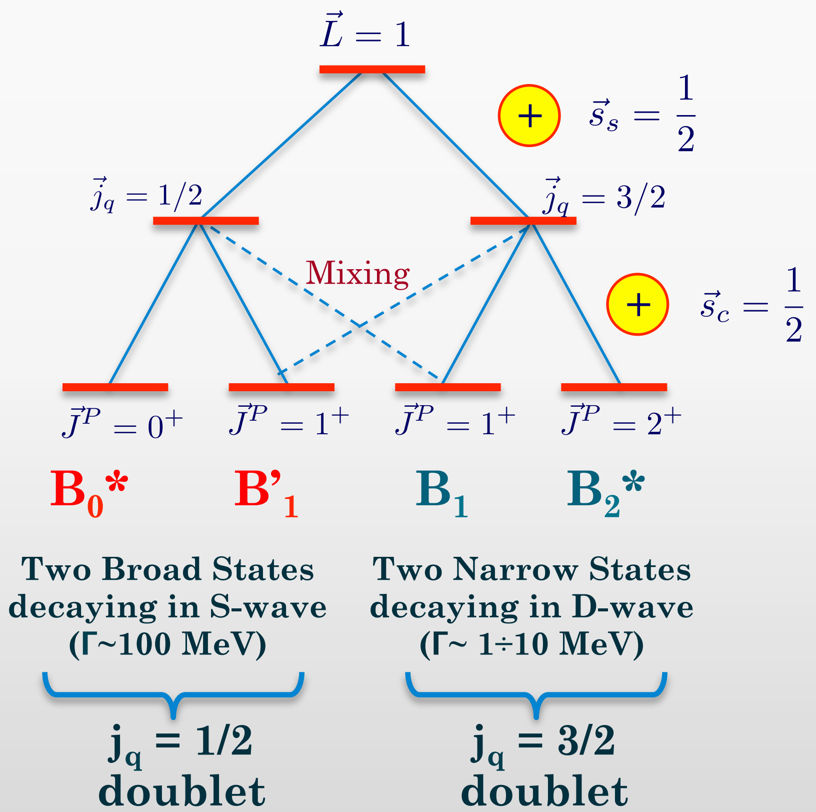
$$D^*_J(m)^{0/\pm} \text{ or } B^*_J(m)^{0/\pm}$$

Mass

Excited Heavy Mesons

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

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



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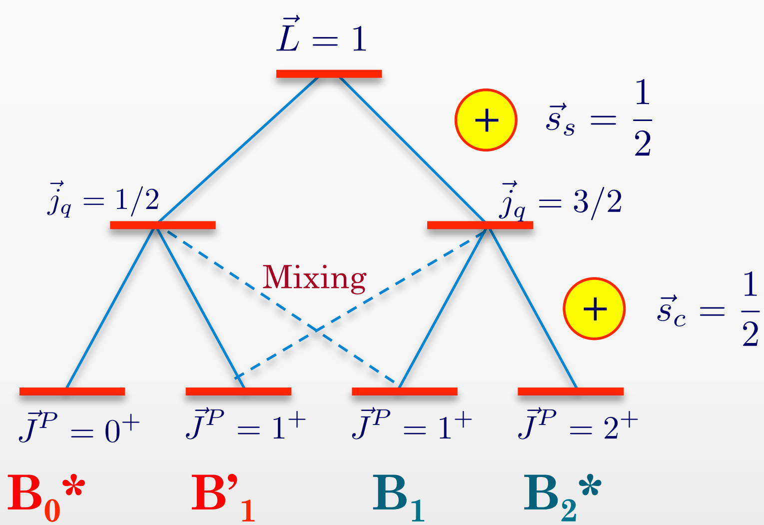

Two Broad States decaying in S-wave (Γ~100 MeV)

j_q = 1/2 doublet

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

j_q = 3/2 doublet

$\forall L > 0$ → Two j_q doublets → 4 states

Excited Heavy Mesons

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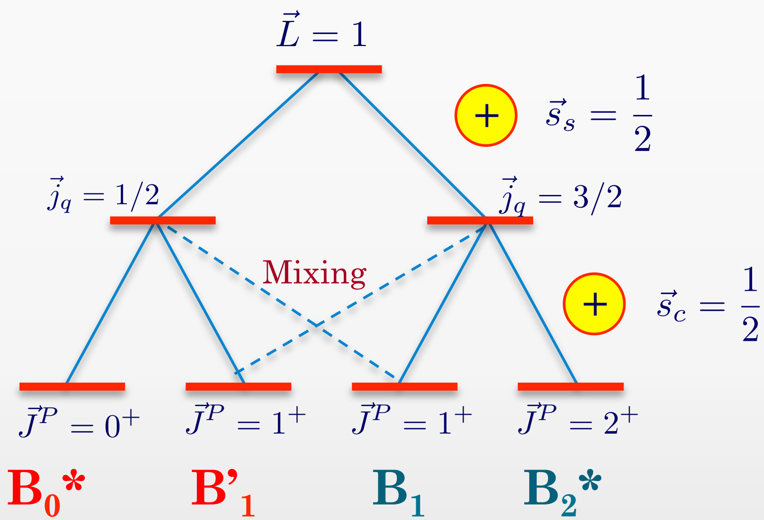
E.g. Orbitally L=1 excited $B^{**} \rightarrow B^{(*)}\pi$



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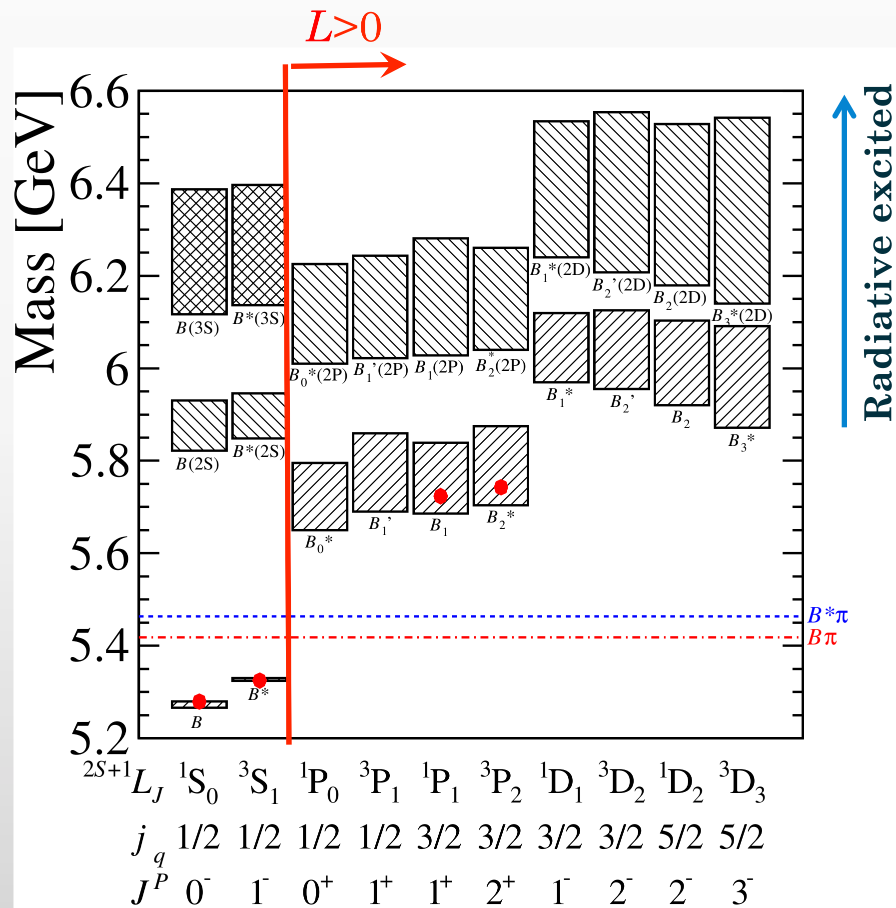
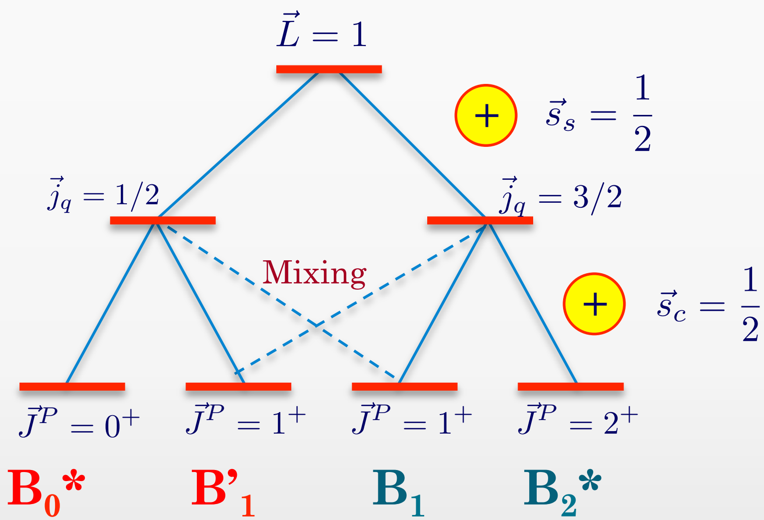


Excited Heavy Mesons

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

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



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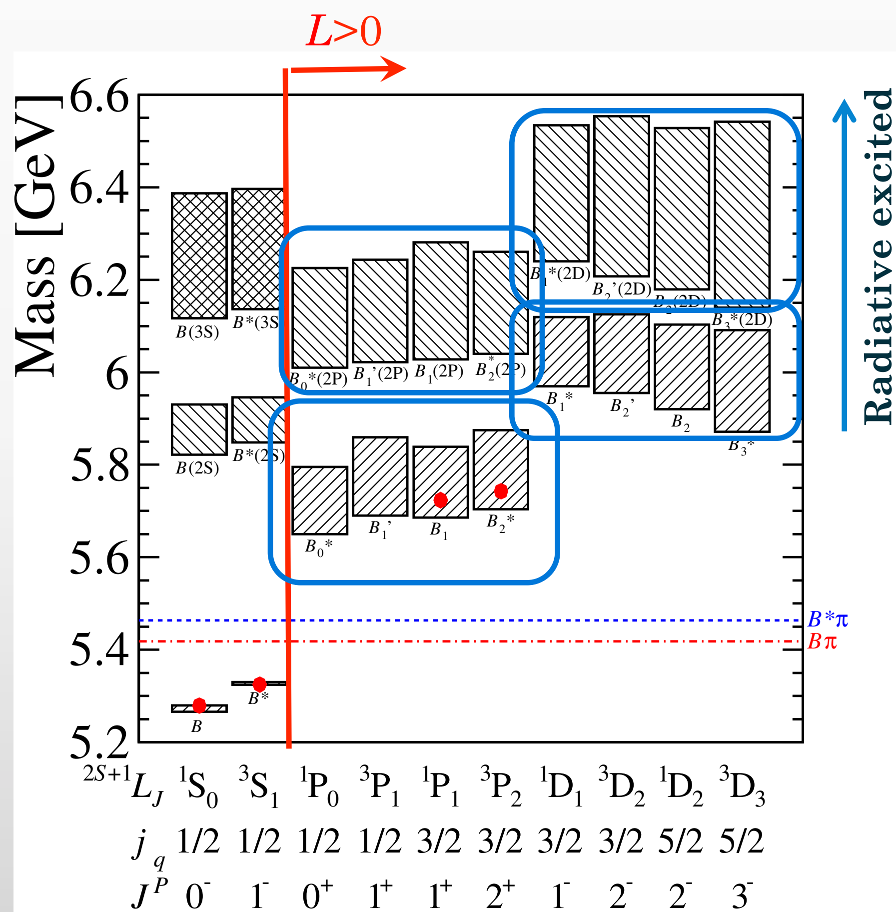

Excited Heavy Mesons

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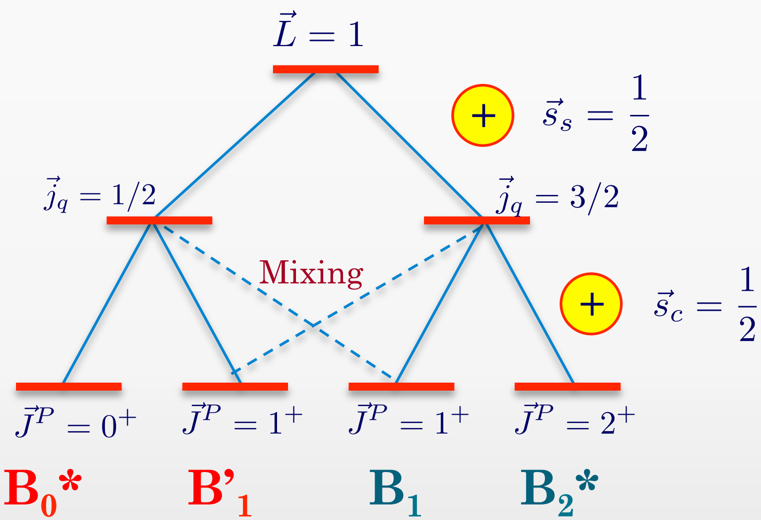
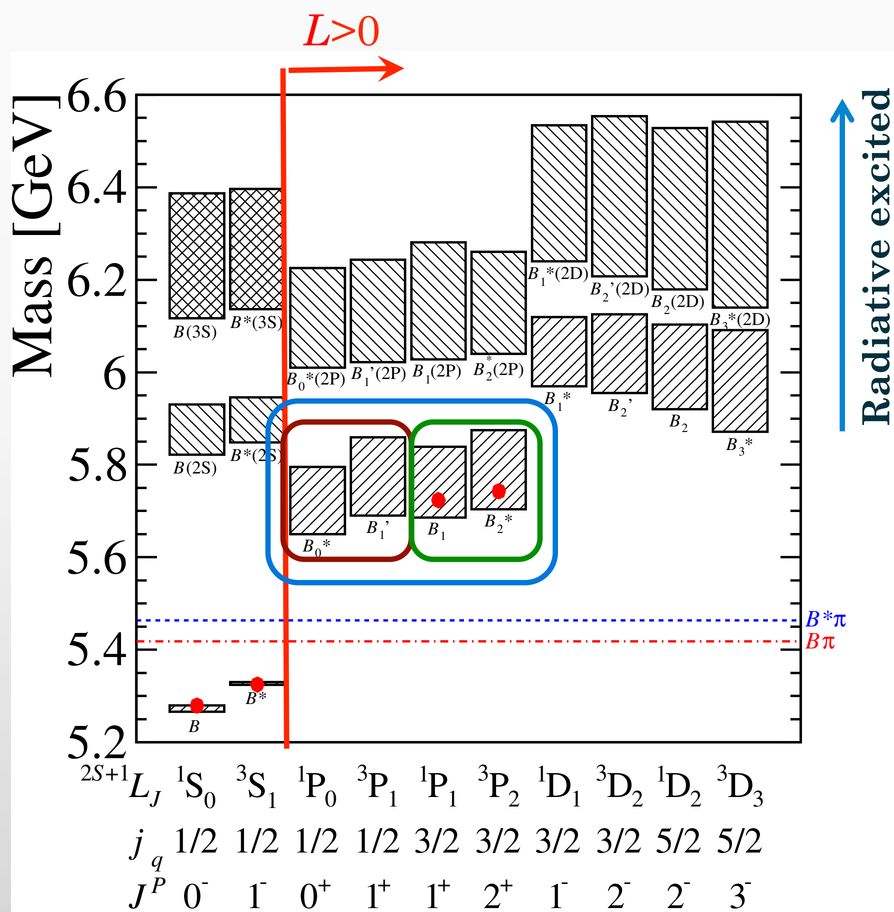




Two Broad States decaying in S-wave (Γ~100 MeV)

j_q = 1/2 doublet

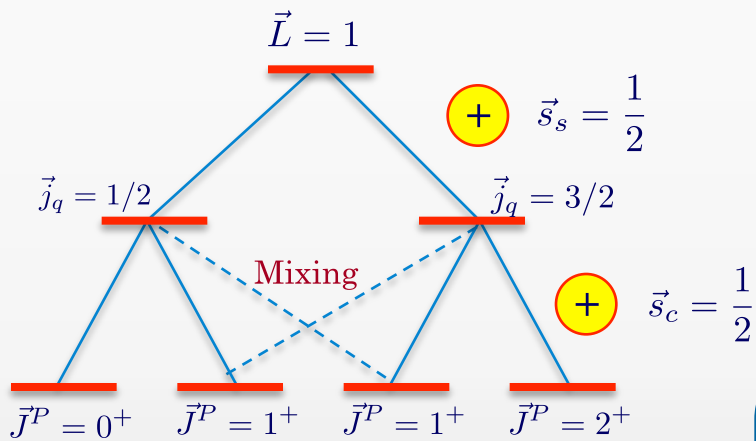
Two Narrow States decaying in D-wave (Γ~ 1÷10 MeV)

j_q = 3/2 doublet

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$^{(*)}\pi$**



	j_q	J^P	Allowed decay mode $B\pi$	$B^*\pi$
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

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

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

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

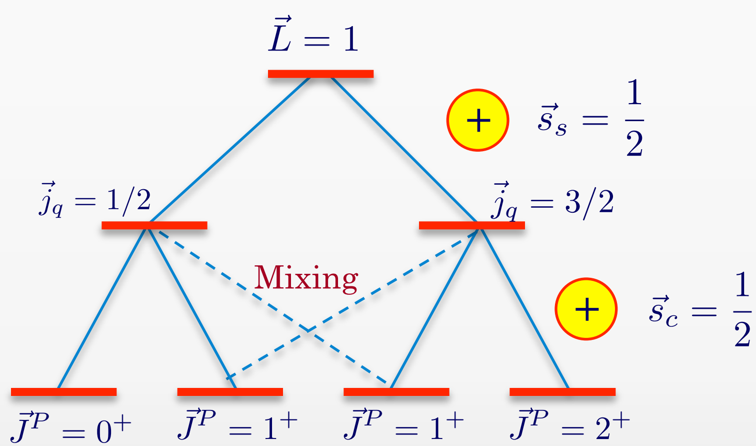
(Only exception is the (0^+,1^+) doublet above)

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

Decays of Excited Heavy Mesons

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

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



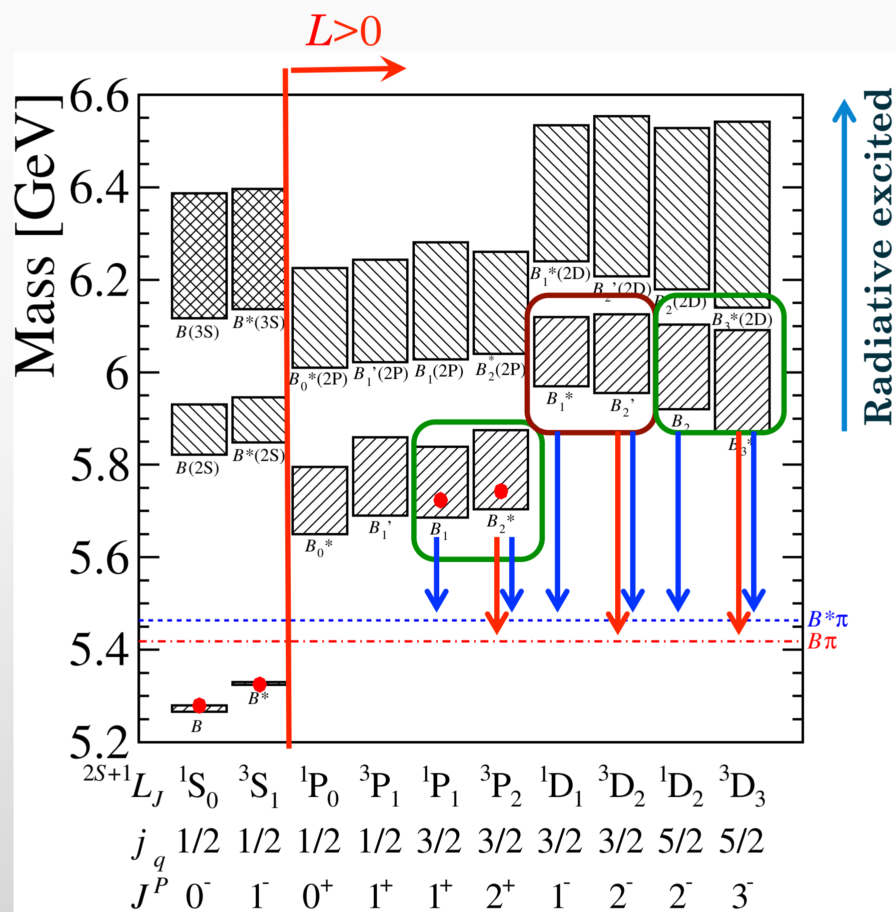
B_0^*	B'_1	B_1	B_2^*

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

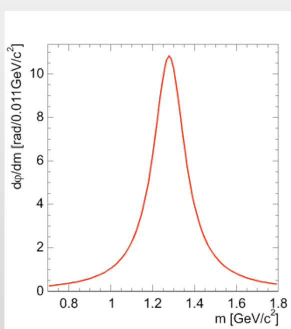


How to do spectroscopy?

"Inclusive Analysis"

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

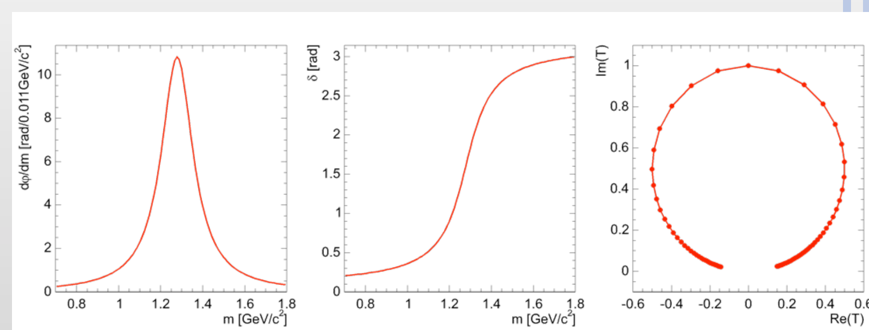
- Large cross sections
- Large combinatorial background
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization



"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



Doublets in Exclusive Analyses

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

	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

Doublets in Exclusive Analyses

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} as expected

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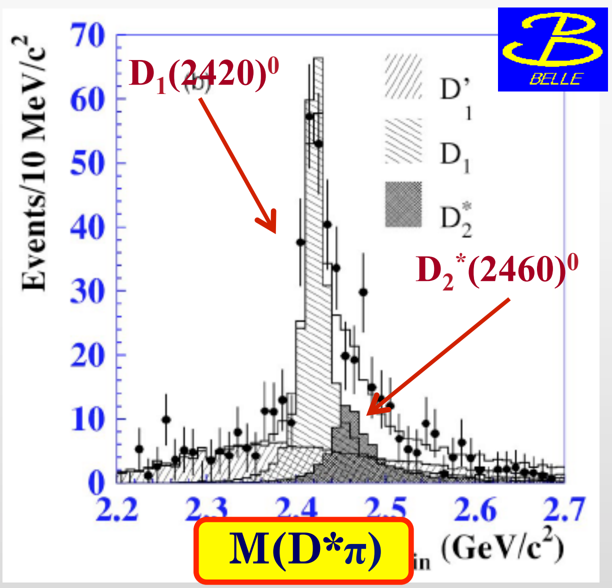

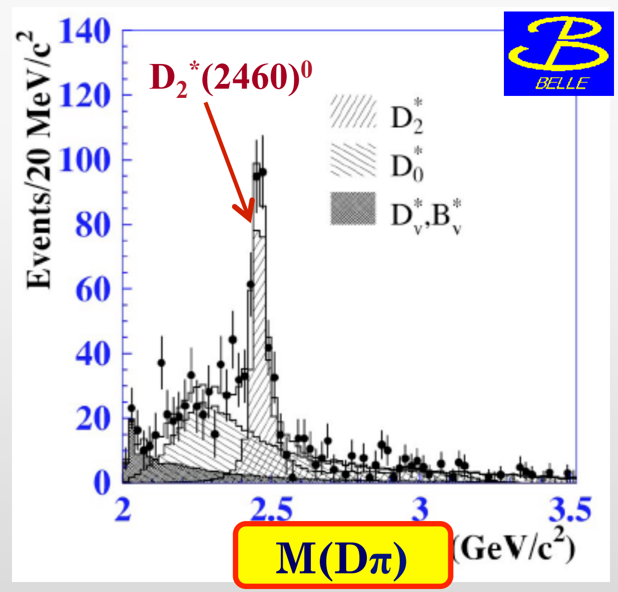

Broad states of the j=1/2 doublets also revolved by an amplitude analysis

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
- 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

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

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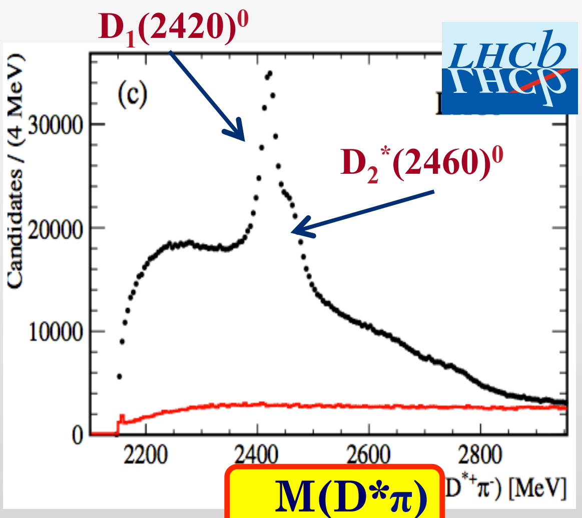
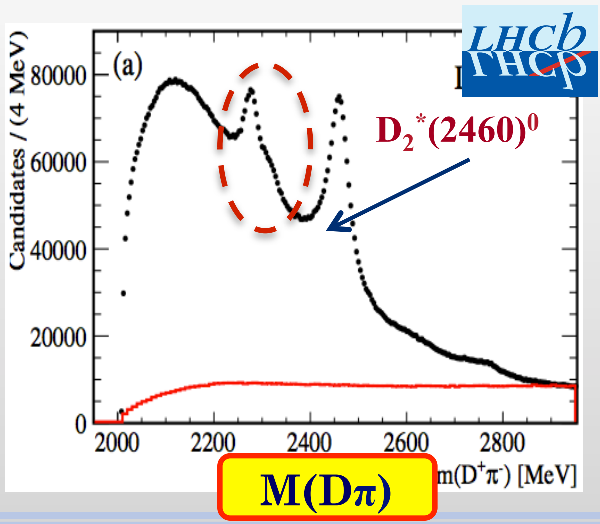




FEED-DOWNS OF $D_1/D_2^* \rightarrow D^*\pi$ DECAYS INTO $D\pi$ MASS SPECTRUM

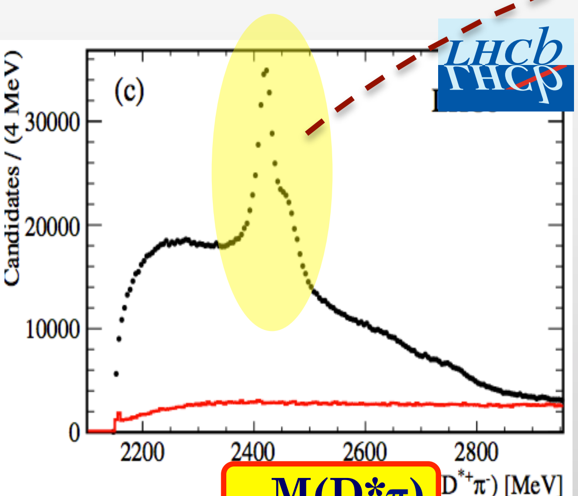
Inclusive analysis
$pp \rightarrow D^{(*)+}\pi^- + X$
[LHCb: JHEP 09 (2013) 145]

j_q=3/2 doublet

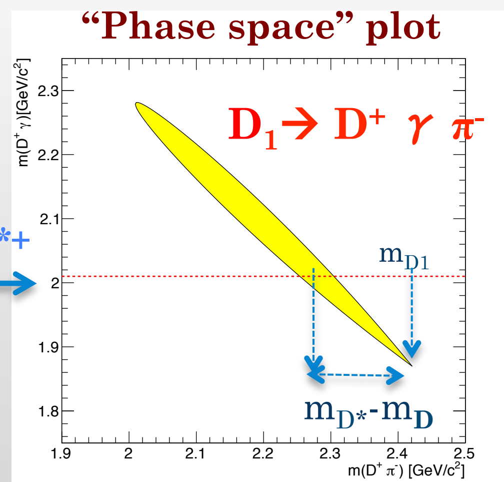
- 3 peaks in Dπ
  - ✓ $D_2^* \rightarrow D\pi$
  - ✓ $D_1 \rightarrow D^*\pi$ feed-down
  - ✓ $D_2^* \rightarrow D^*\pi$ feed-down
- 2 peaks in D*π

overlapped if $\Gamma > m(D^*)-m(D)$

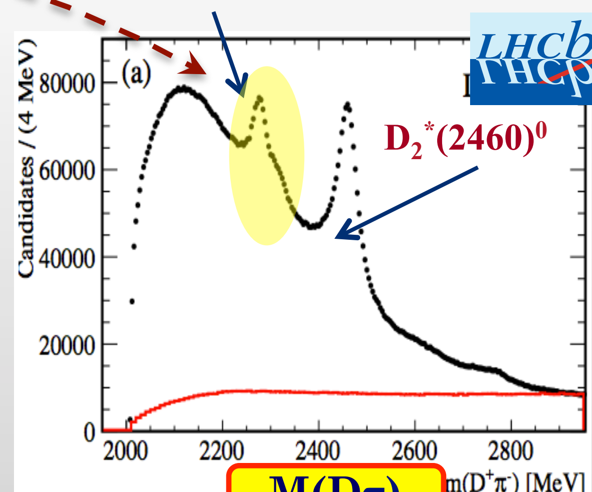
	j_q	J^P	Allowed decay mode $D\pi$	$D^*\pi$
D_0^*	1/2	0^+	yes	no
D_1'	1/2	1^+	no	yes
D_1	3/2	1^+	no	yes
D_2^*	3/2	2^+	yes	yes



M(D*π)



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



M(Dπ)

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 (before the states were observed)

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

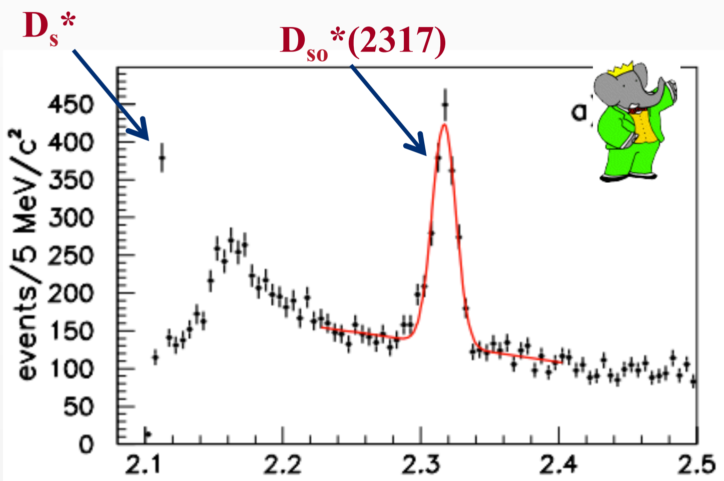
D_s** (L=1)

		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

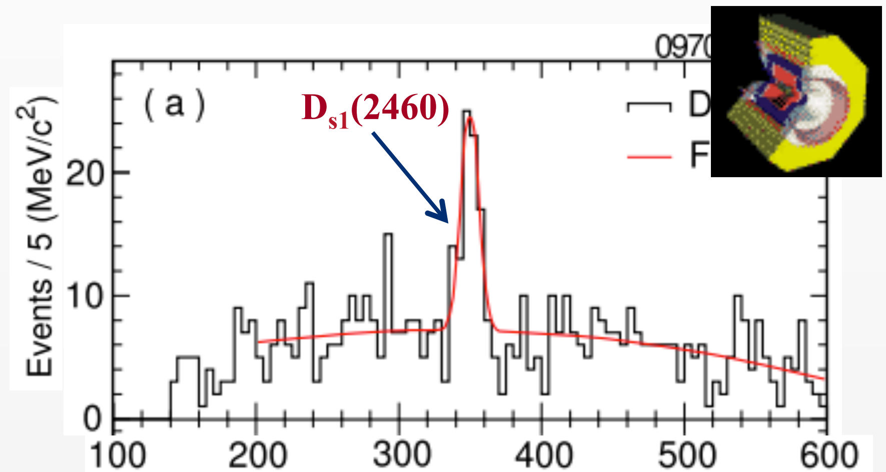
D_{s0}* and D_{s1}' states expected broad and to be studied in B_s decays…

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

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



$M(D_s\pi^0)$

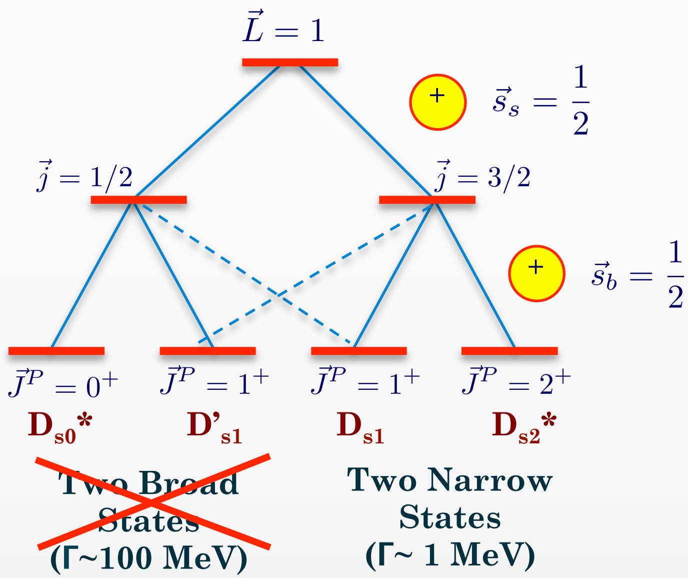


$M(D_s\gamma\pi^0)$-$M(D_s\gamma)$

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
- $B \rightarrow DD_{s0}^*$ branching ratios below expectations (i.e. ~1) for a $q\bar{q}$ state **[PLB572, 164 (2003)][PRD69, 054002 (2004)]**

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

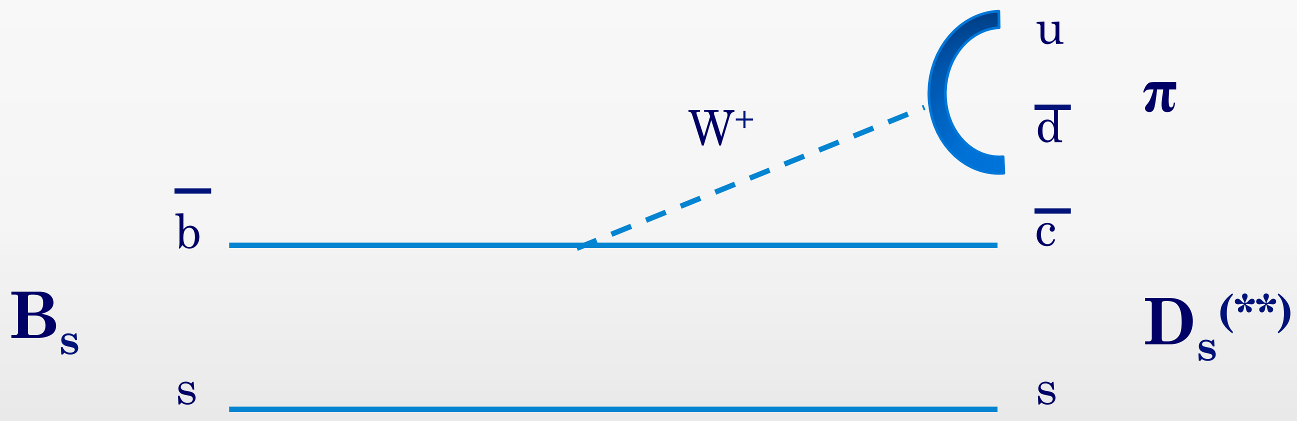
$$\frac{\mathcal{B}(B^0 \to D^- D_{s0}^{*+})}{\mathcal{B}(B^0 \to D^- D_s^+)} = 0.13 \pm 0.04$$

- 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

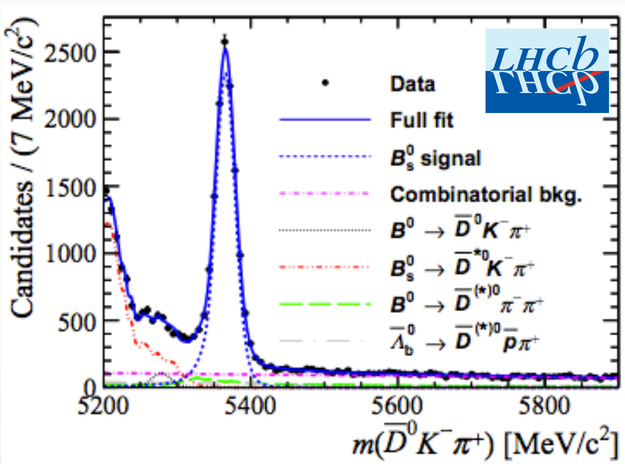
If the $D_{s0}^*(2317)$ is not the L=1, j_q=1/2 excited D_s state, then a broad D_{s0}^* state above the DK threshold should appear in B_s decays

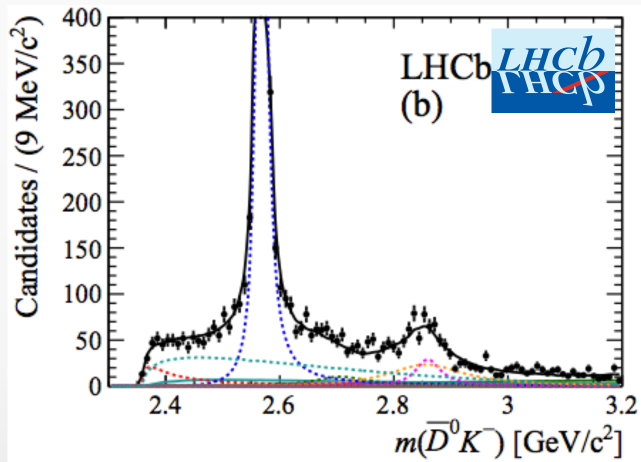


SEARCH FOR "D_{s0}*" IN B_s DECAYS

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

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





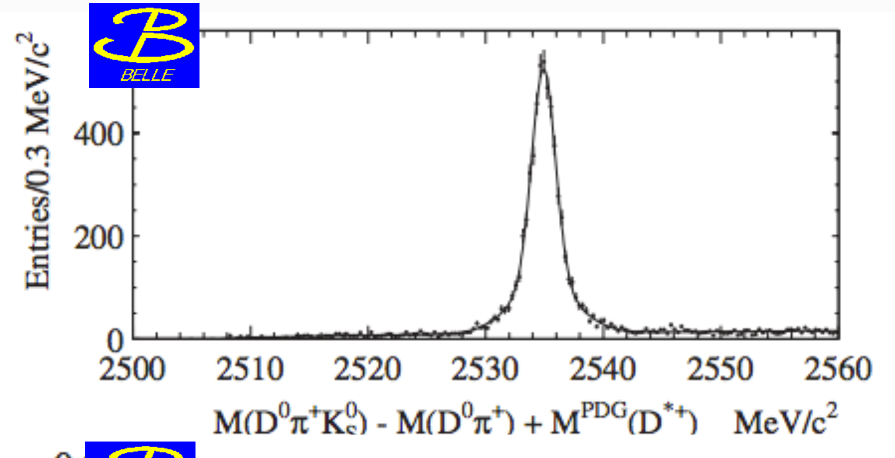
Resonance	Fit fraction (%)
$\overline{K}^*(892)^0$	28.6 ± 0.6
$\overline{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\overline{K}^*_0(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\overline{K}^*_2(1430)^0$	3.7 ± 0.6
$\overline{K}^*(1680)^0$	0.5 ± 0.4
$\overline{K}^*_0(1950)^0$	0.3 ± 0.2
$D^*_{s2}(2573)^-$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

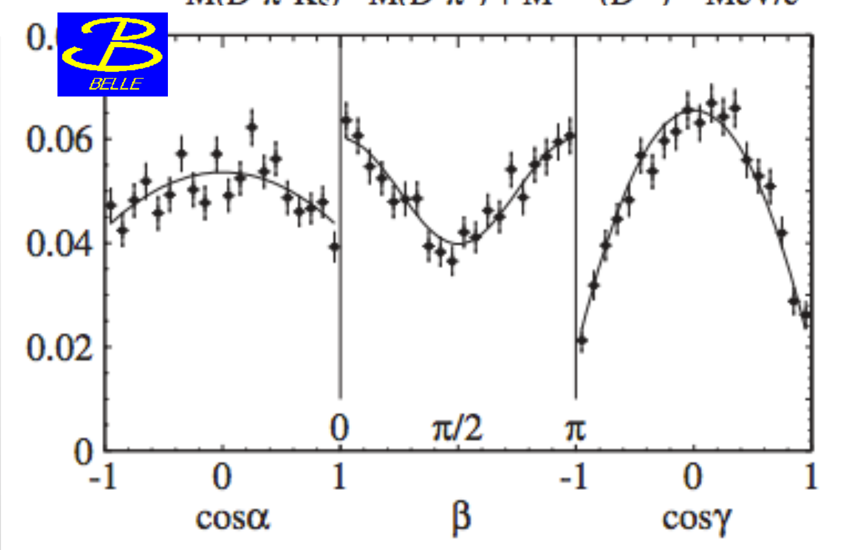
No evidence for such a broad D_{s0}* state

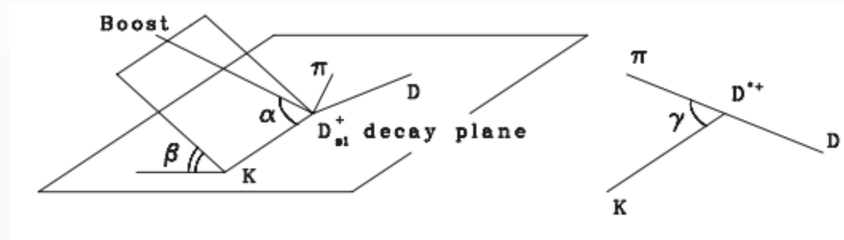
PUZZLE II:
IS $D_{s1}(2536)^+$ THE EXCITED L=1, j_q=3/2 STATE?

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

[Belle: PRD77 (2008) 032001]







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

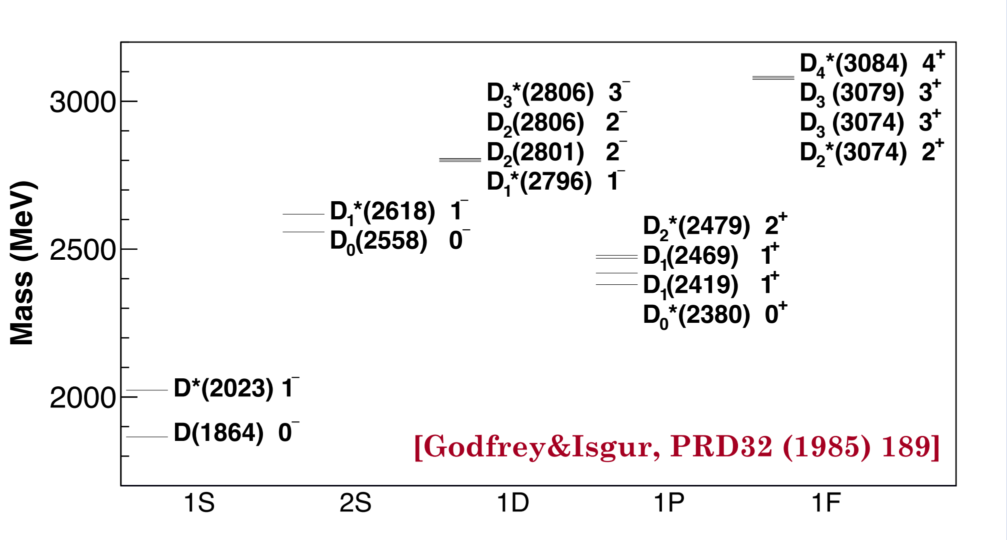
Contrary of HQET expectations, the S-wave contribution dominates!

Excited $D^{**} \rightarrow D^{(*)}\pi$ @ LHCb

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]**



EXCITED D_J STATES

[LHCb, JHEP 09 (2013) 145]

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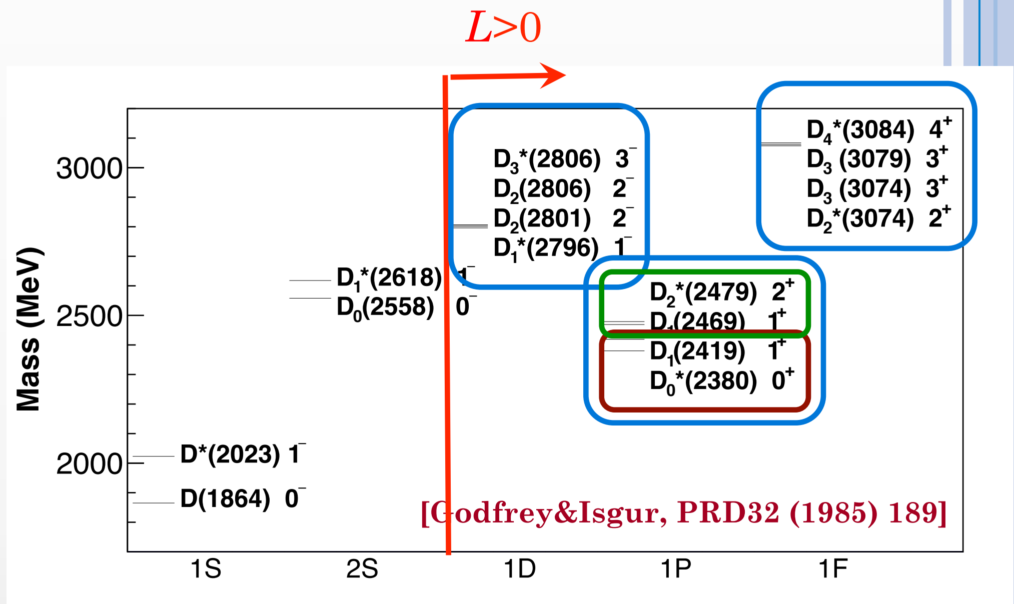
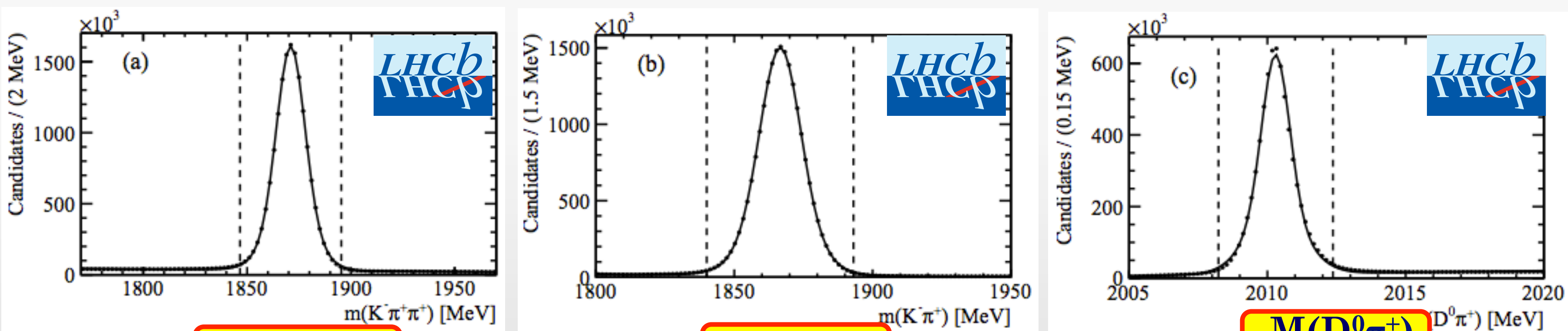


D$^+$, D^0, D^{*+} Samples

[LHCb, JHEP 09 (2013) 145]

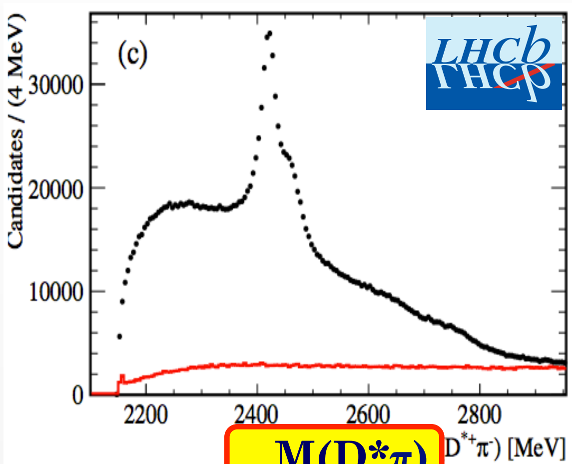
Inclusive study of $D^+(\rightarrow K\pi\pi)\pi^-$, $D^0(\rightarrow K\pi)\pi^+$ and $D^{*+}\pi^-$. Several millions of D's in 1 fb^{-1}



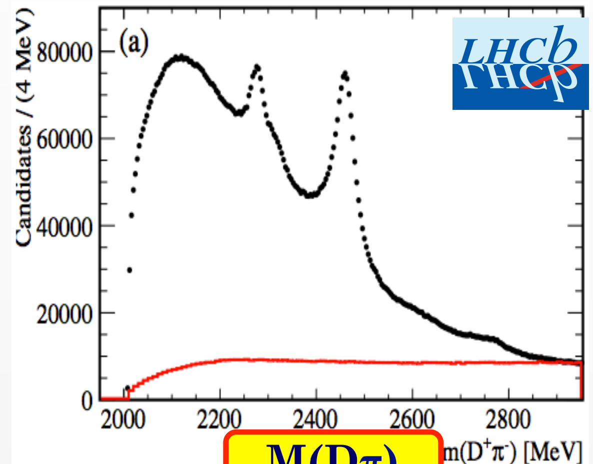
M(K$^-\pi^+\pi^+$) **M(K$^-\pi^+$)** **M(D$^0\pi^+$)**

$D^{(*)}\pi$ MASS SPECTRA

How to fit? How many resonances?



M(D*π)

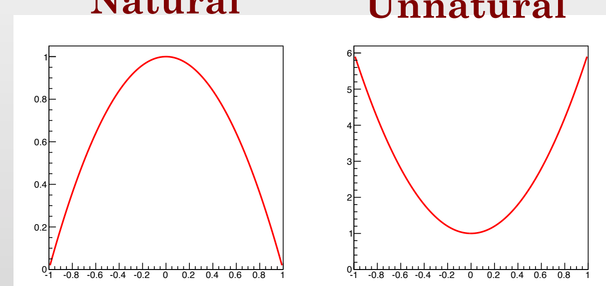


M(Dπ)

- 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**



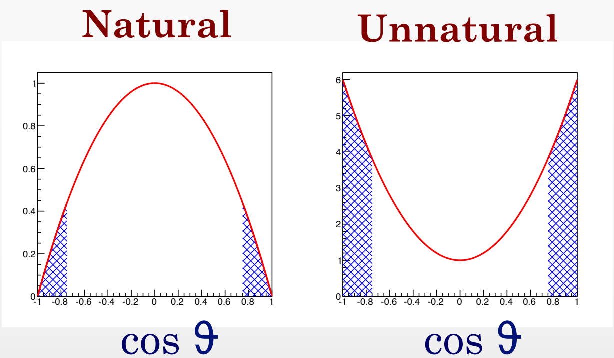
cos ϑ cos ϑ

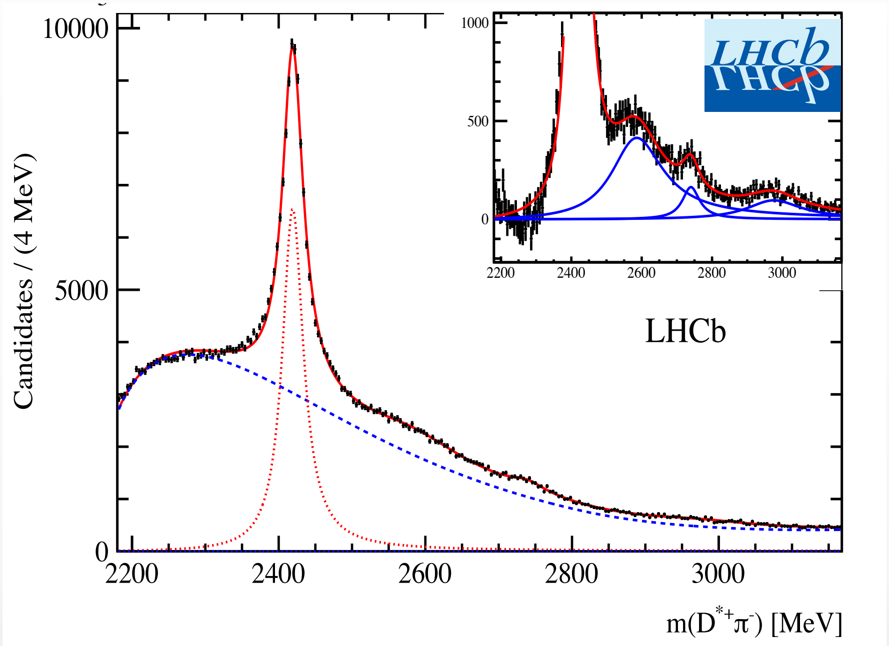
$D^{*+}\pi^-$ Mass Fit

[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

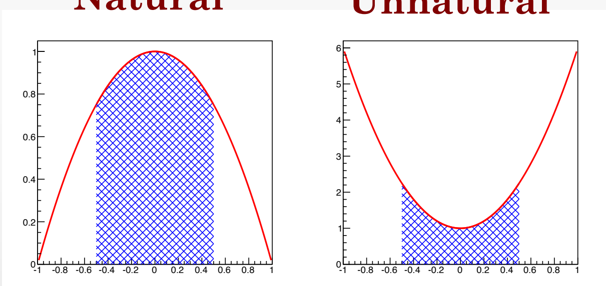
[LHCb, JHEP 09 (2013) 145]

Step 2

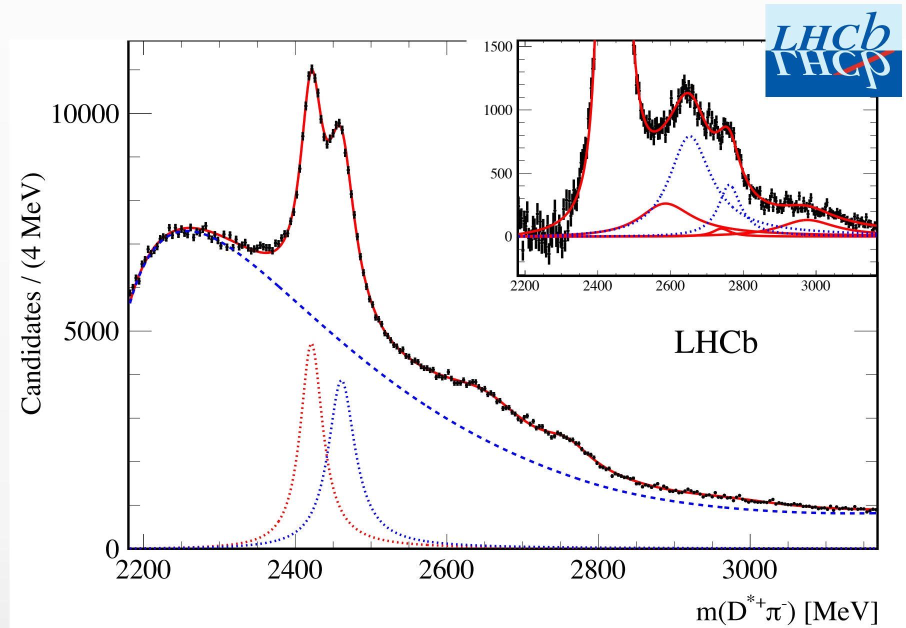
$|\cos\vartheta| < 0.5$
enhances natural component

Parameters of the unnatural states from Step 1

Natural **Unnatural**



cos ϑ cos ϑ



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

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

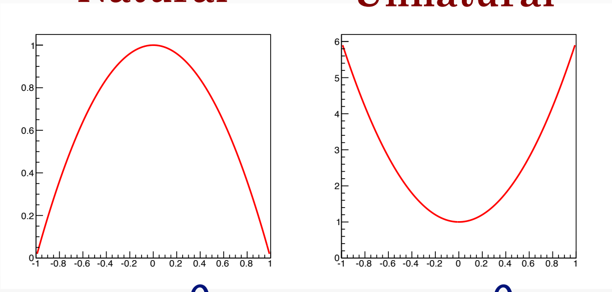
$D^{*+}\pi^-$ Mass Fit

[LHCb, JHEP 09 (2013) 145]

Step 3

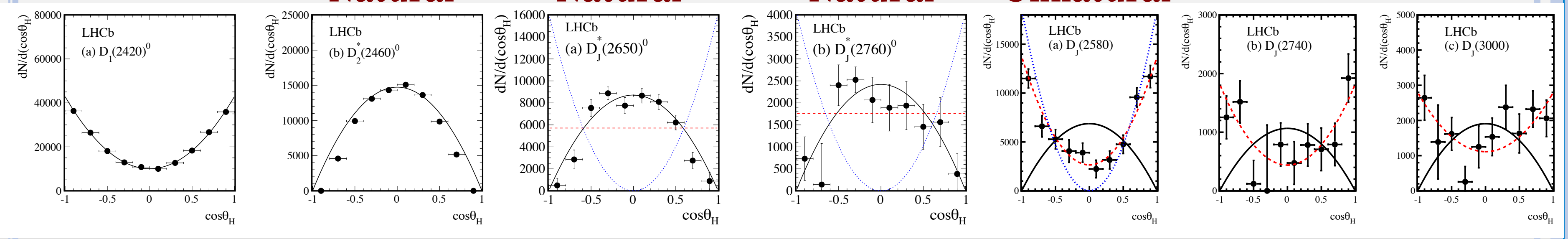
- Parameters of all states fixed from Step 1&2
- Fit performed in bins of cos ϑ to verify angular distributions

Natural | Unnatural



cos ϑ | cos ϑ

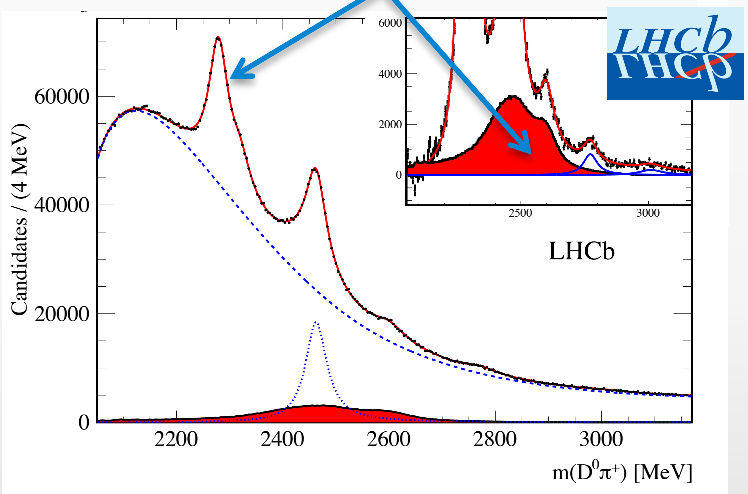
$D_1(2420)$ Unnatural | $D_2^*(2460)$ Natural | $D_2^*(2650)$ Natural | $D_2^*(2760)$ Natural | $D_J(2580)$ Unnatural | $D_J(2740)$ Unnatural | $D_J(3000)$ Unnatural

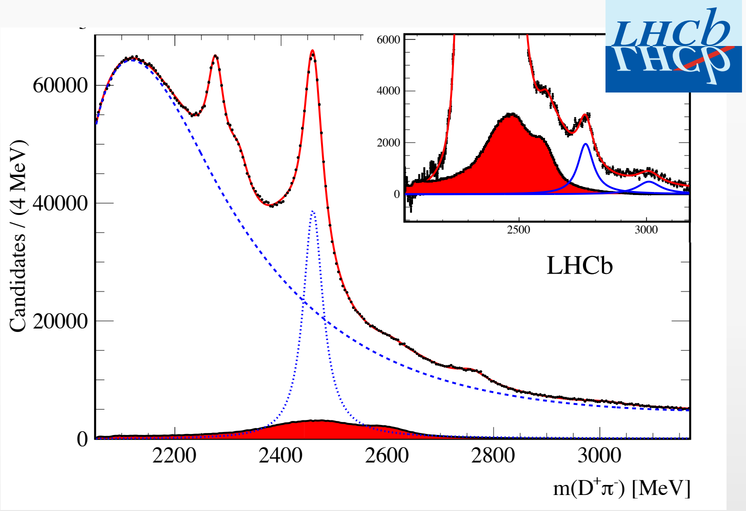


$D^0\pi^+/D^+\pi^-$ Mass Fits

[LHCb, JHEP 09 (2013) 145]

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





2 more natural states:

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

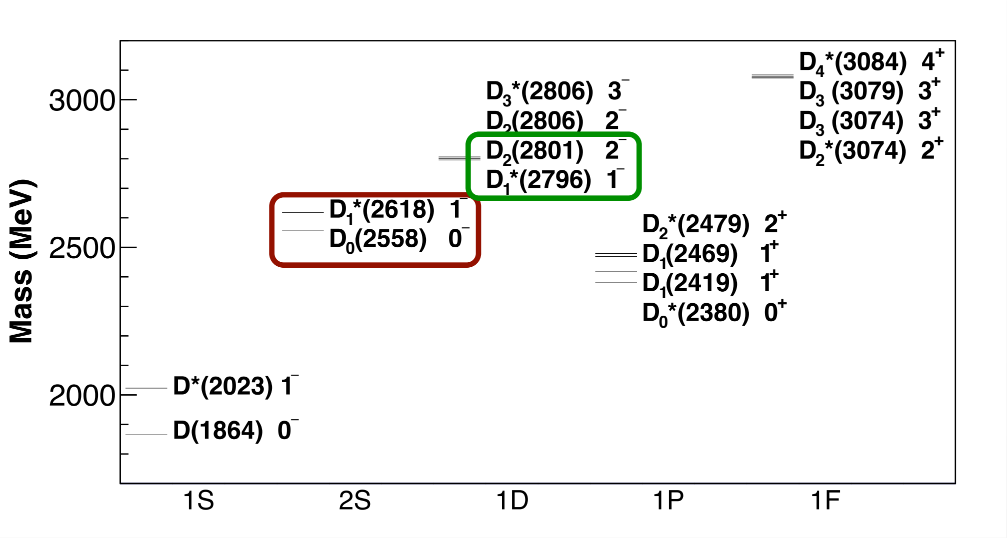
RESULTS

[LHCb, JHEP 09 (2013) 145]

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

INTERPRETATION

[LHCb, JHEP 09 (2013) 145]



$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))

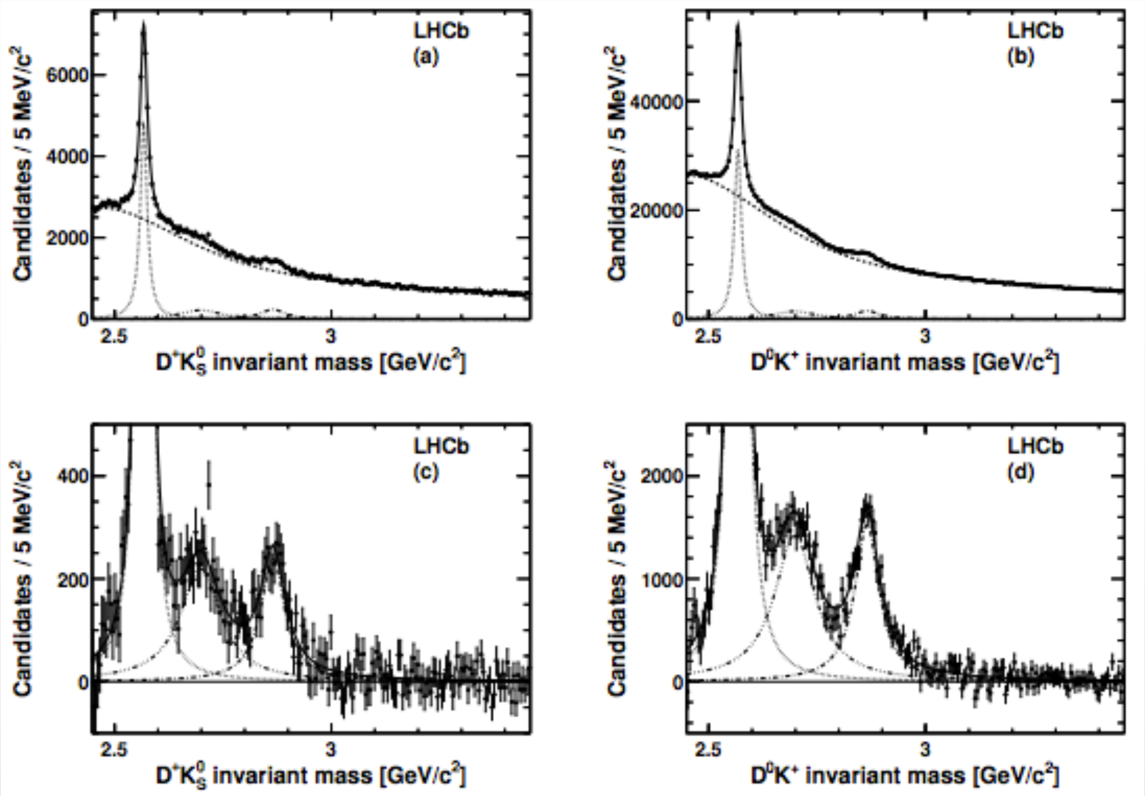
Study of $D^{(*)}\pi$ spectrum from B decays needed to establish spin-parity

Excited $D_s^{**} \rightarrow DK$ @ LHCb

Excited D_{sJ} States

[LHCb, JHEP 10 (2012) 151]

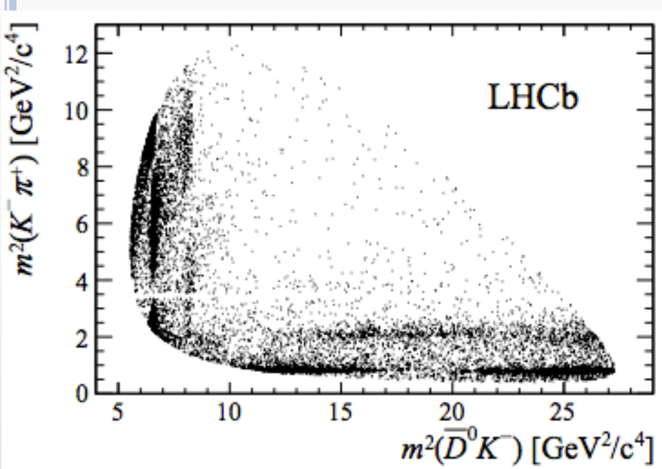
LHCb collaboration has recently confirmed 2 broad states decaying to DK:
$D_{s1}^*(2700)^+$ & $D_{sJ}^*(2860)^+$

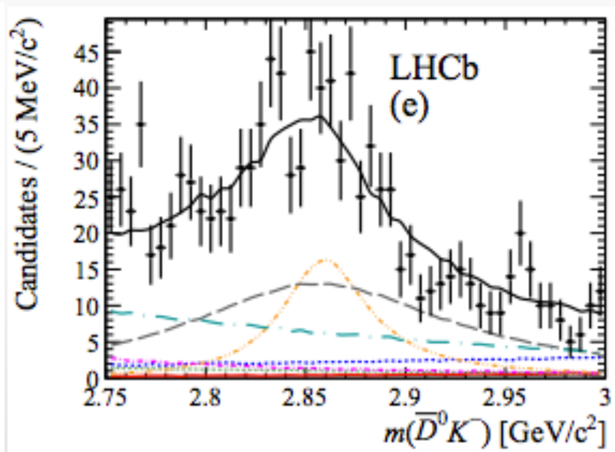


EXCITED D_{sJ} STATES

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

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





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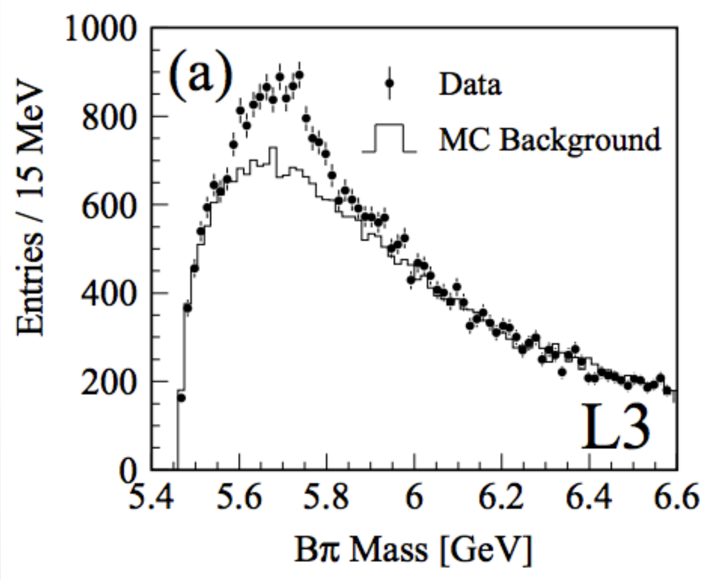
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant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

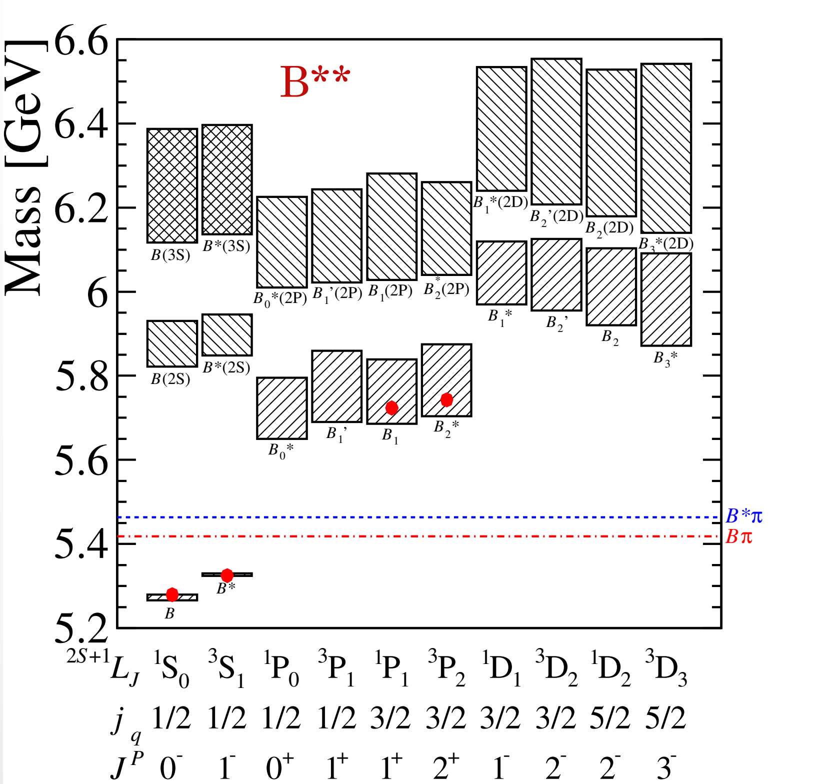
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)
$D_{s2}^*(2573)^-$	2568.39 ± 0.29	16.9 ± 0.5
$D_{s1}^*(2860)^-$	2859 ± 12	159 ± 23
$D_{s3}^*(2860)^-$	2860.5 ± 2.6	53 ± 7

Excited $B^{**} \rightarrow B\pi$ @ LHCb

THE EXCITED B STATES

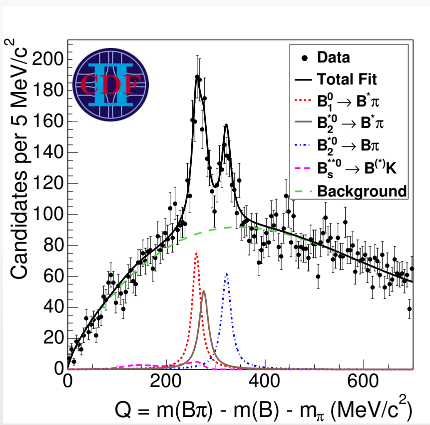
- LEP experiments observed a single broad structure (Γ > 100 MeV) in $B^+\pi^-$: $B_J^*(5732)$

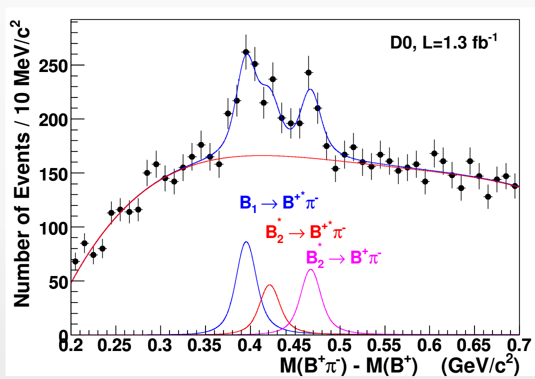


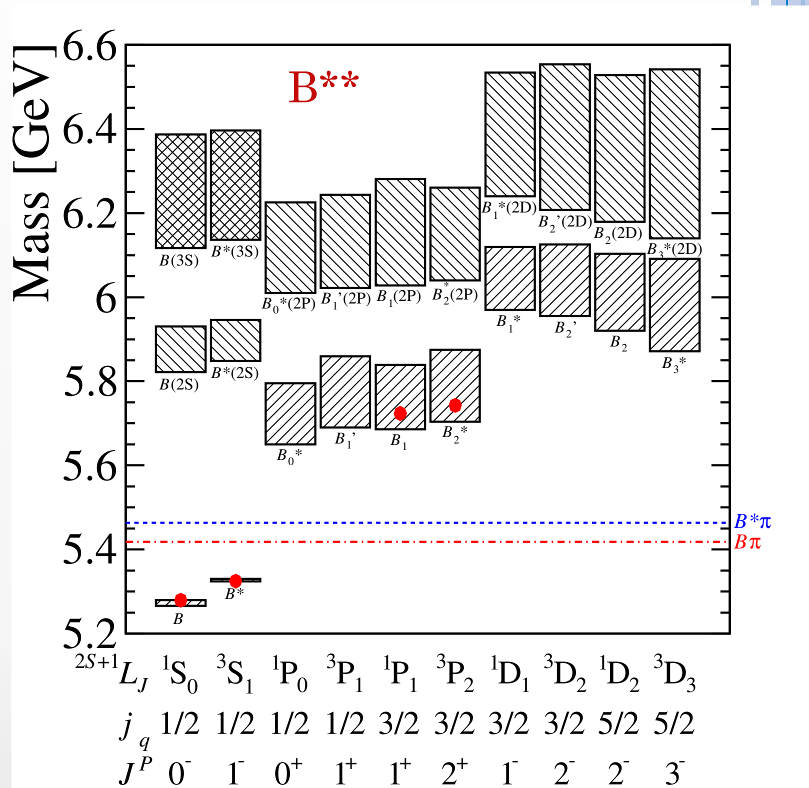


THE EXCITED B STATES

- LEP experiments observed a single broad structure (Γ > 100 MeV) in $B^+\pi^-$: $B_J^*(5732)$
- Tevatron experiments resolved it into 2 structures and interpreted the former as the overlap of $B_1^0/B_2^{*0} \rightarrow B^{*+}\pi^-$



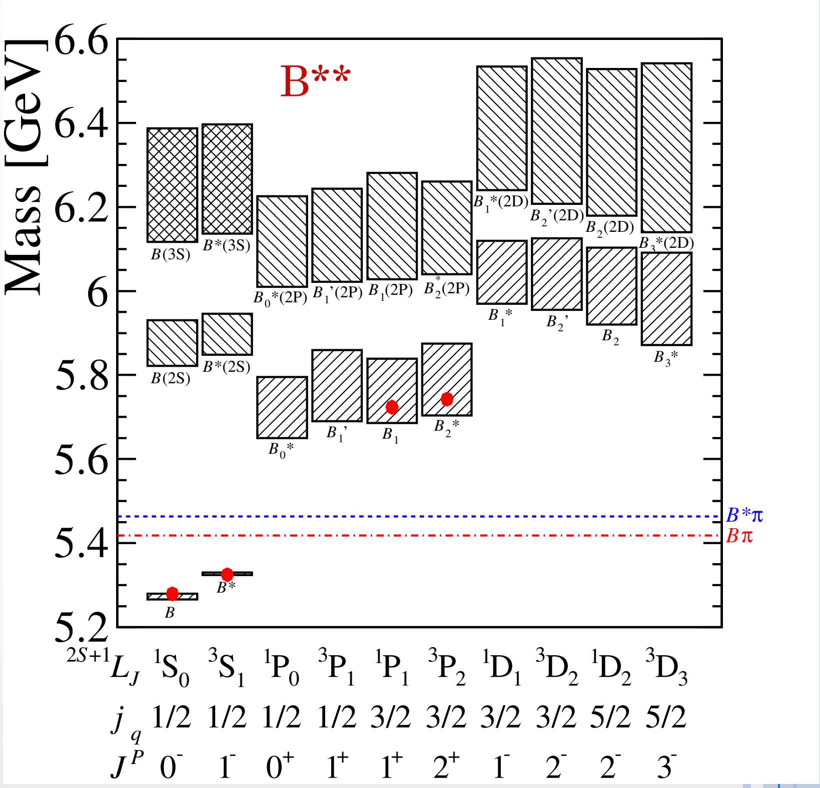




THE EXCITED B STATES

- 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.)

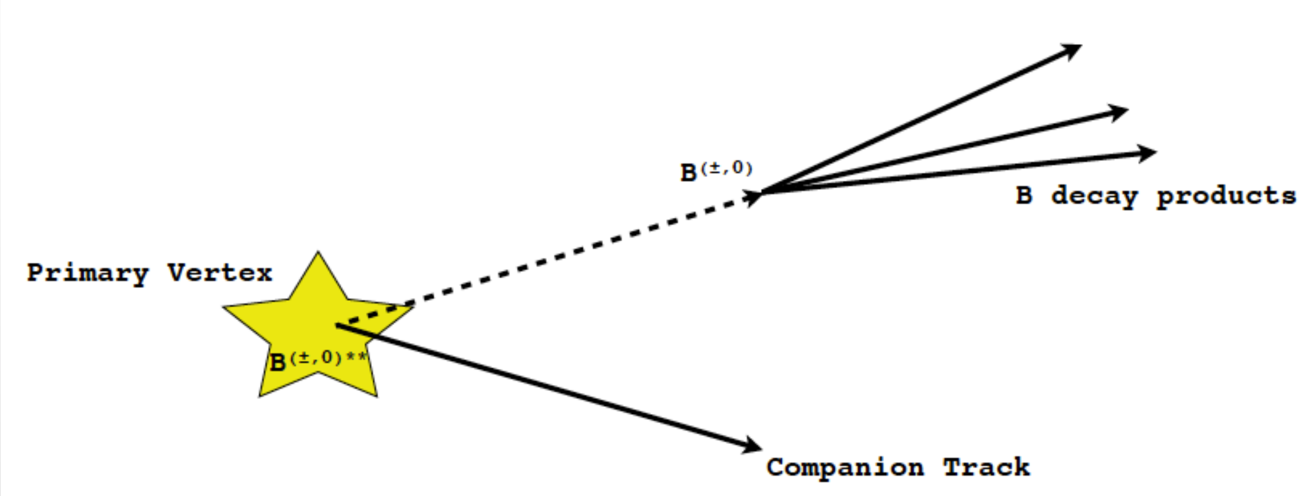
Inclusive Study of the $B^+\pi^-$ and $B^0\pi^+$ Mass Spectra

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

Analysis strategy

- 2011+2012 data sample corresponding to $\mathcal{L} = 3.0\ fb^{-1}$
- 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:

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



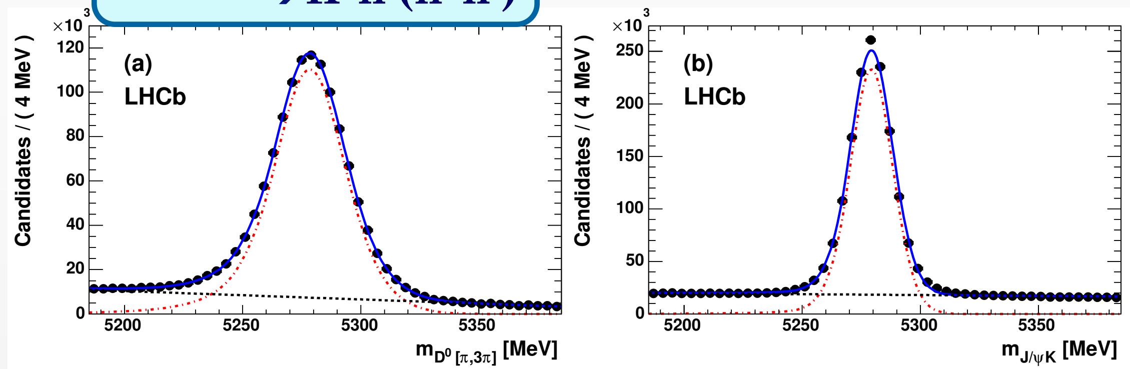
$B^{0,+}$ CANDIDATES

[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}

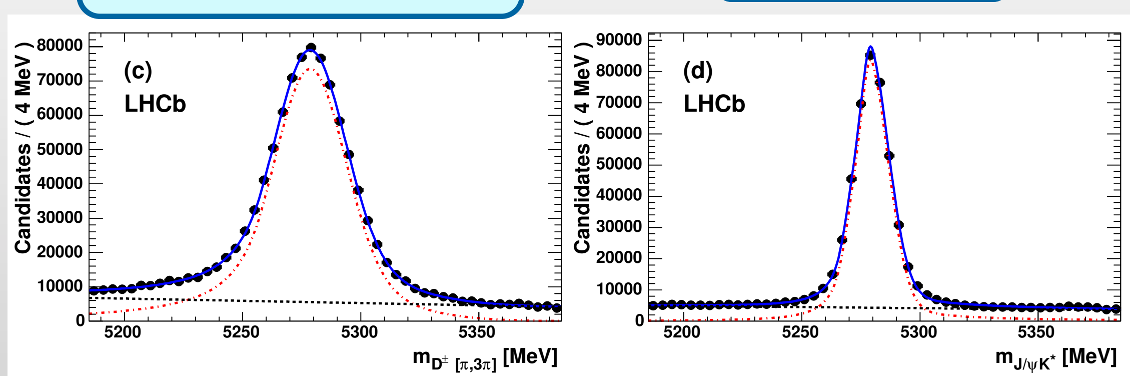
$B^+ \rightarrow \overline{D}^0 \pi^+(\pi^-\pi^+)$
$\rightarrow K^+\pi^-(\pi^+\pi^-)$

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



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

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



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

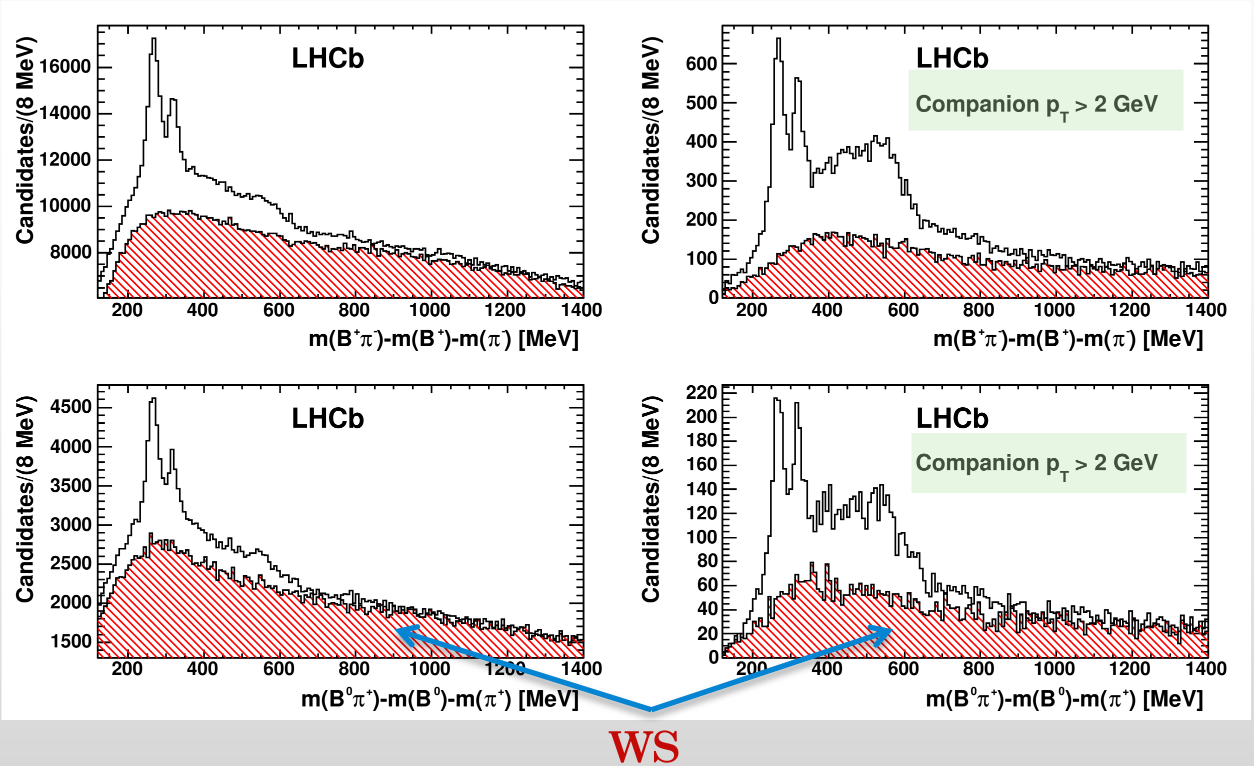
SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

[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)

$B^+\pi^-$

$B^0\pi^+$

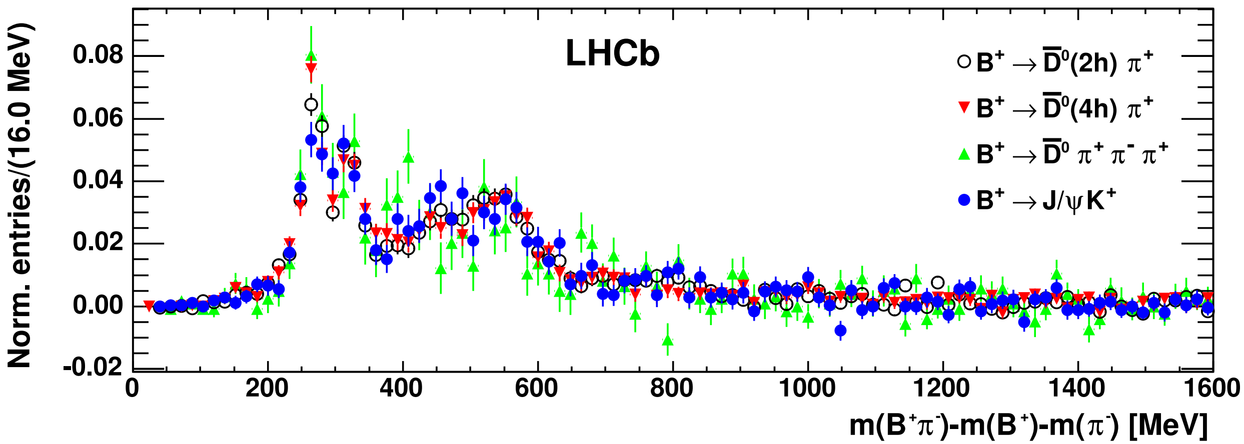


SPECTRUM OF m(Bπ)-m(B)-m(π) MASS DIFFERENCES

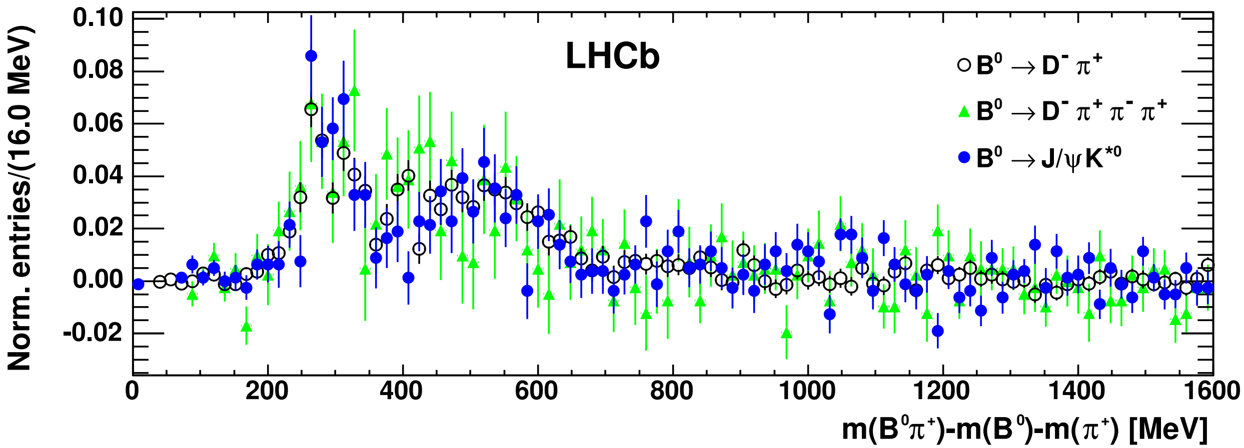
[LHCB-PAPER-2014-067; arXiv:1502.02638]

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

$B^+\pi^-$



$B^0\pi^+$



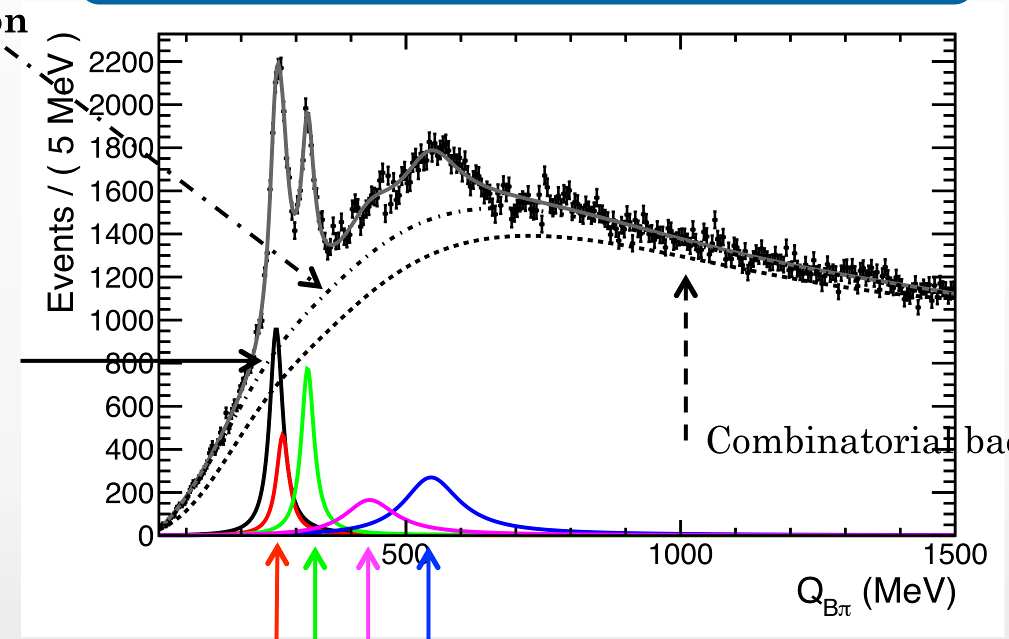
FIT MODEL

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

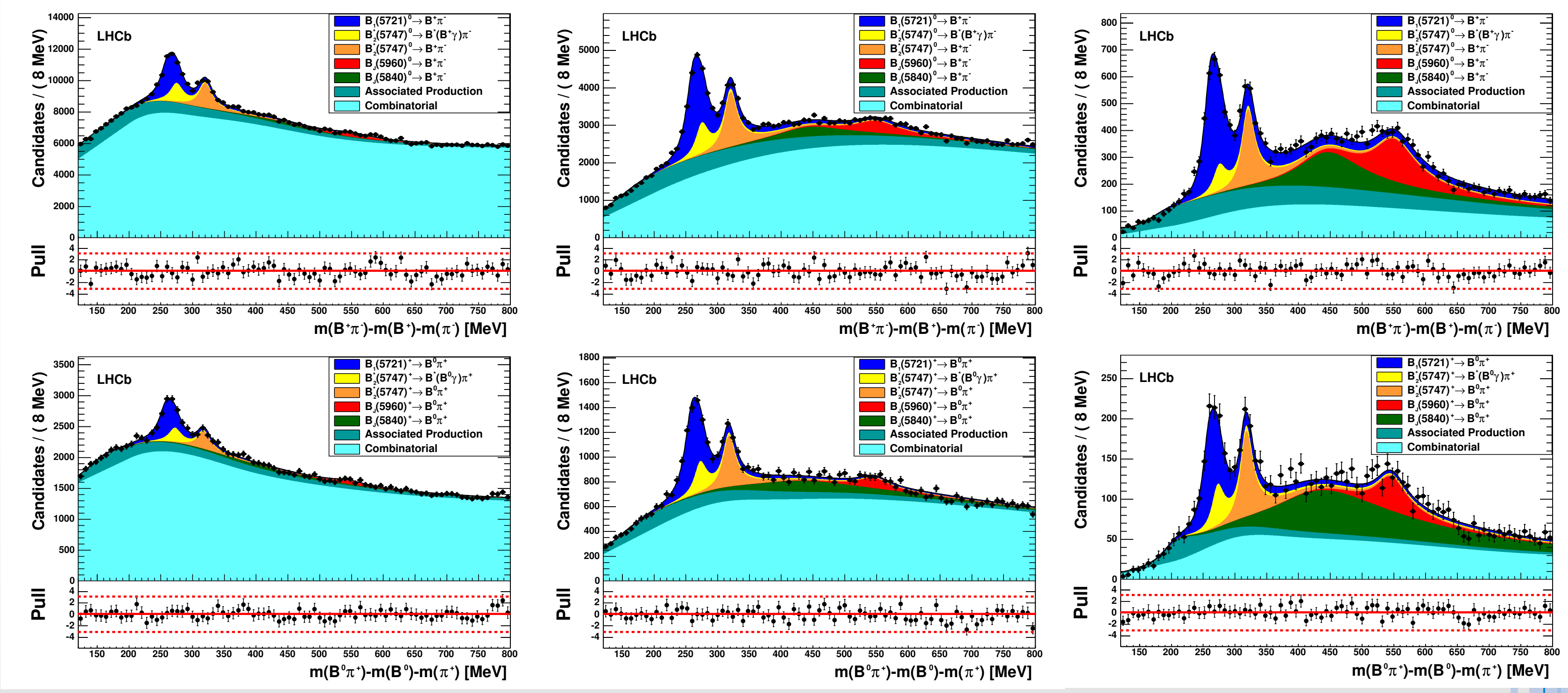
Nominal Fit Results by p_T Bin

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

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

$B^+\pi^-$

$B^0\pi^+$



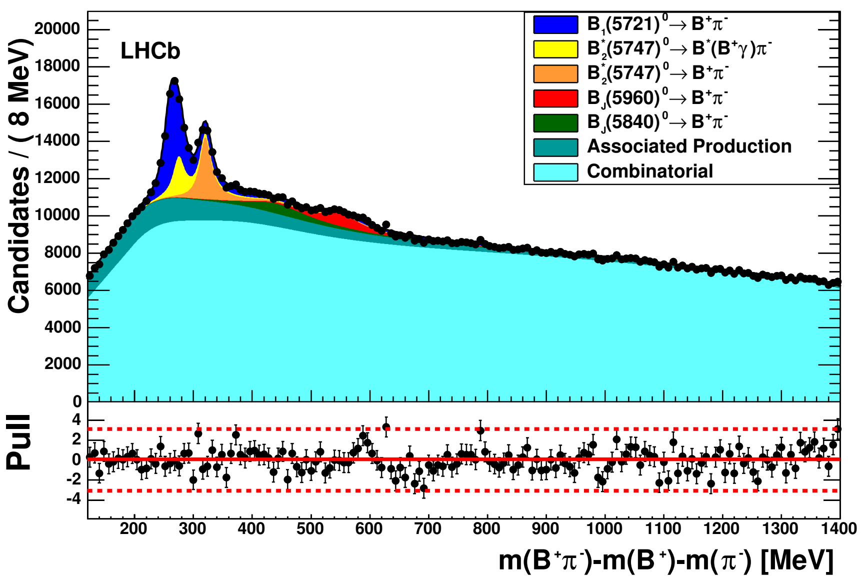
- $B_1(5721)^0 \to B^{*+}(B^+\gamma)\pi^-$
- $B_2^*(5747)^0 \to B^{*+}(B^+\gamma)\pi^-$
- $B_2^*(5747)^0 \to B^+\pi^-$
- $B_J(5960)^+ \to B^0\pi^+$
- $B_J(5840)^+ \to B^0\pi^+$
- Associated Production
- Combinatorial

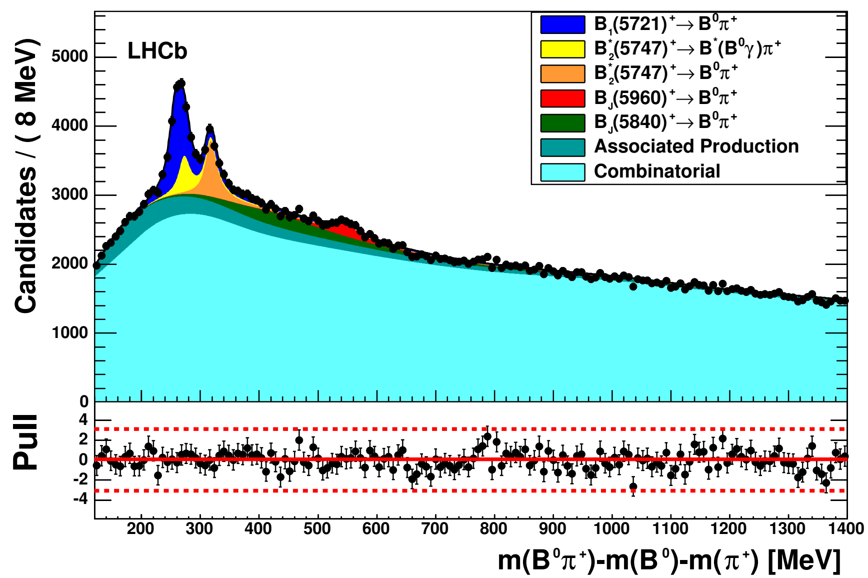
Nominal Fit results

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

Candidates integrated over the 3 p_T bins

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





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

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

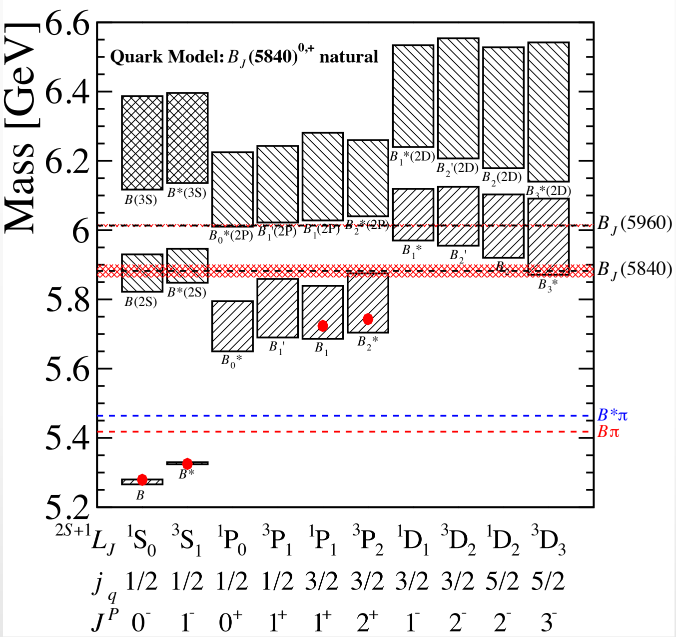
$$\frac{\mathcal{B}\left(B_2^*(5747)^+ \to B^{*0}\pi^+\right)}{\mathcal{B}\left(B_2^*(5747)^+ \to B^{0}\pi^+\right)} = 1.0 \pm 0.5 \pm 0.8\,,$$

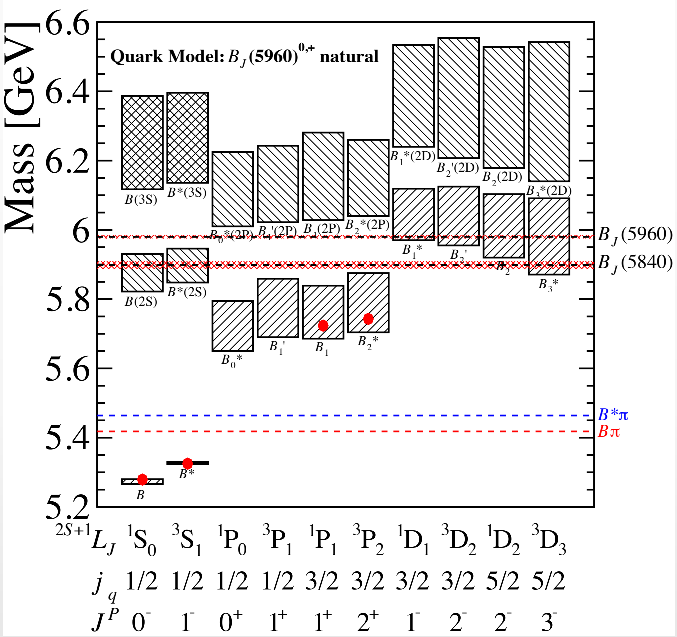
First evidence of the $B_2^*(5747)^0 \to B^{*+}\pi^-$ (3.7σ)!

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

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

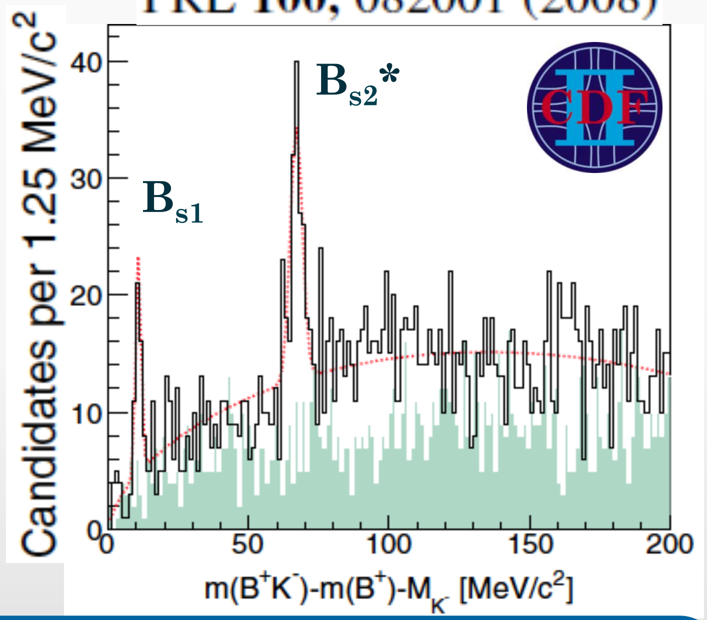
Excited $B_s^{**} \rightarrow BK$ @ LHCb

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 is not confirmed by D0

Search for B_{s1} and B_{s2}^* at LHCb

Analysis strategy

- 2011 data sample corresponding to $\mathcal{L} = 1.0\ fb^{-1}$
- Selection of a high purity B^+ sample
- The B^+ candidates are combined with a track of opposite charge that is identified as a kaon
- Optimization of the B_{s1} and B_{s2}^* in the B^+K^- mass spectrum

B$^+$ CANDIDATES

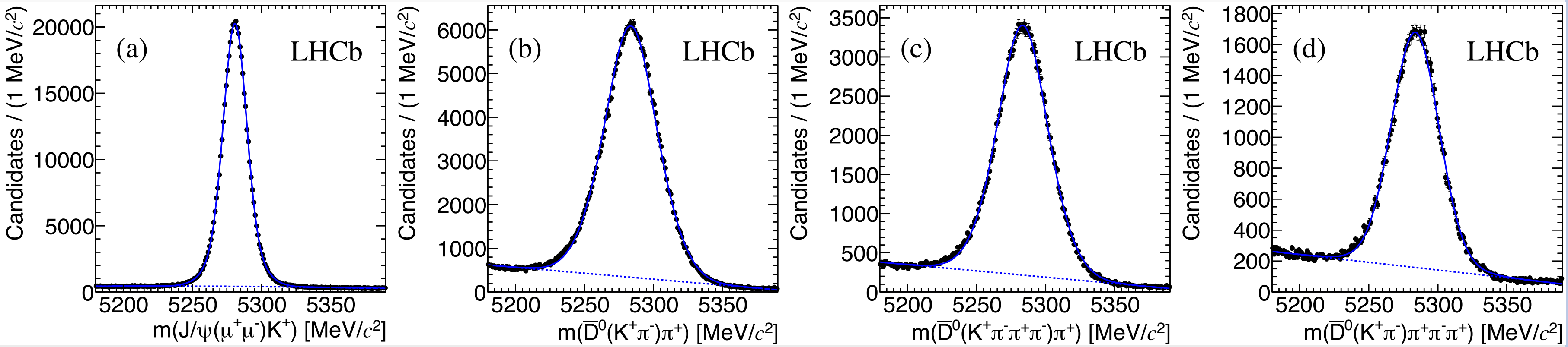
- B$^+$ samples with purity ~85% - 95%
- ~1M of B$^+$ candidates

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

$B^+ \to \overline{D}^0 \pi^+$, $\to K^+\pi^-$

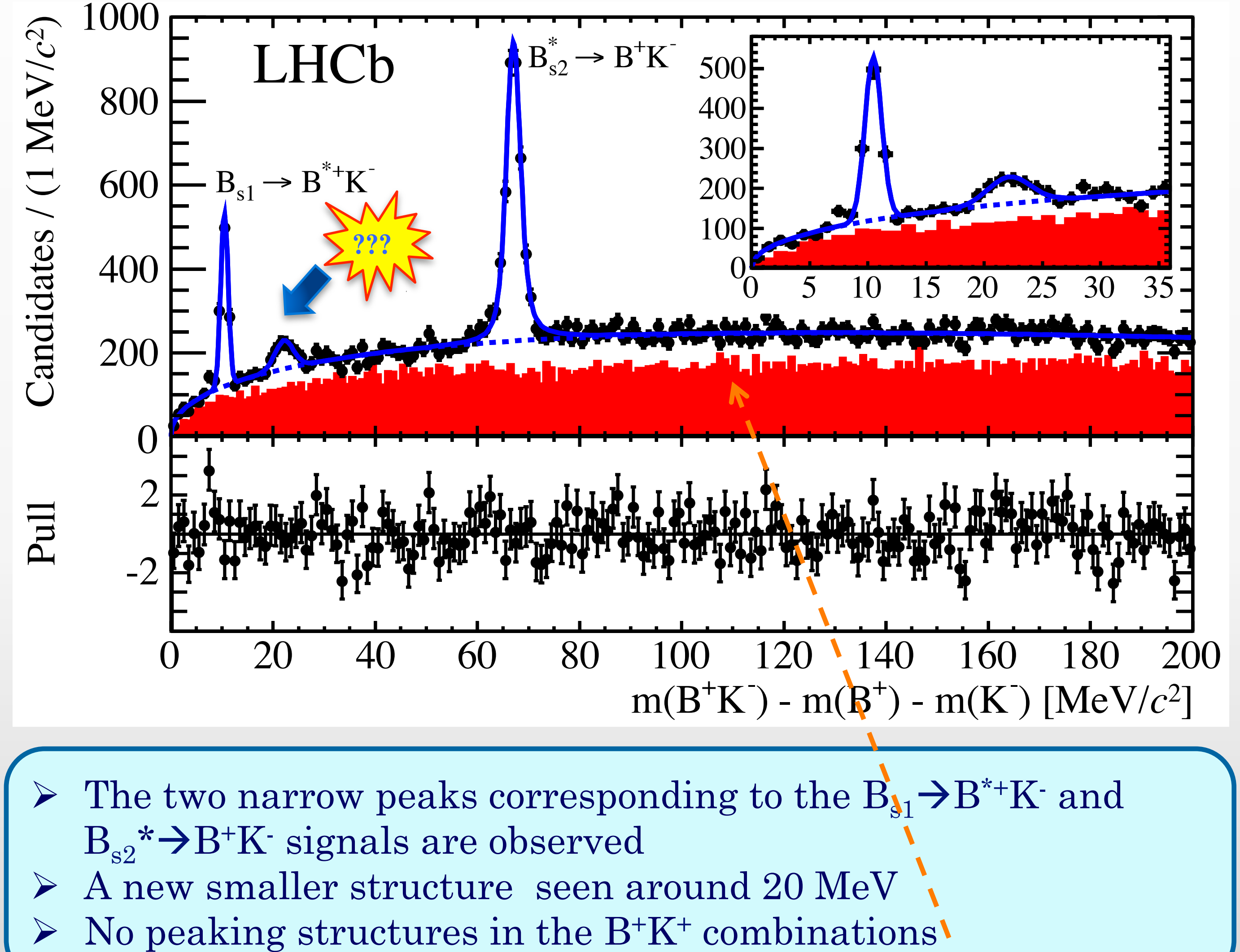
$B^+ \to \overline{D}^0 \pi^+$, $\to K^+\pi^-\pi^-\pi^+$

$B^+ \to \overline{D}^0 \pi^+\pi^-\pi^+$, $\to K^+\pi^-$



- B$^+$ candidates, within a $\pm 2\sigma$ mass region, combined with K$^-$
- The B$^+$K$^-$ candidates are refitted:
  - ✓ Primary vertex constraint (i.e. B$^+$ and K$^-$ are forced to come from the primary vertex)
  - ✓ B$^+$ and J/ψ (D^0) mass constraint

Spectrum of m(BK)-m(B)-M(K) mass difference

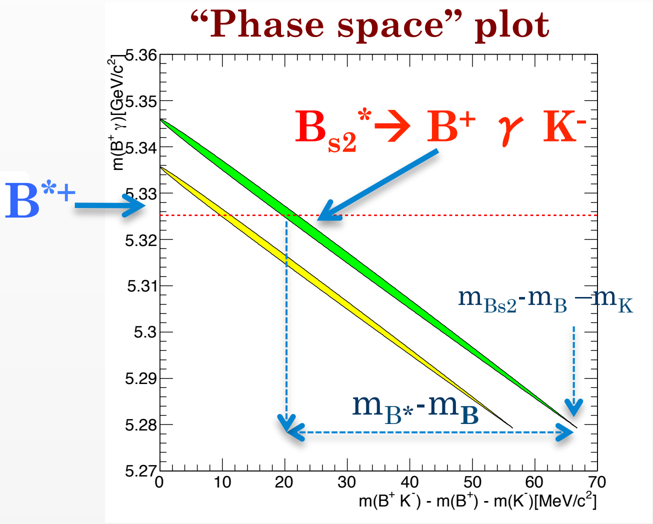


- The two narrow peaks corresponding to the $B_{s1} \rightarrow B^{*+}K^{-}$ and $B_{s2}^{*} \rightarrow B^{+}K^{-}$ signals are observed
- A new smaller structure seen around 20 MeV
- No peaking structures in the $B^{+}K^{+}$ combinations

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

Fit Results

Parameter	Fit result	Best previous measurement
$m(B_{s1})-m(B^{*+})-m(K^-)$	$10.46\pm0.04_{stat}\pm0.04_{syst}$ MeV/c^2	$10.73\pm0.21\pm0.14$ MeV/c^2
$m(B^*_{s2})-m(B^+)-m(K^-)$	$67.06\pm0.05_{stat}\pm0.11_{syst}$ MeV/c^2	$66.96\pm0.39\pm0.14$ MeV/c^2
$m(B^{*+})-m(B^+)$	$45.01\pm0.30_{stat}\pm0.23_{syst}$ MeV/c^2	45.6 ± 0.8 MeV/c^2
$\Gamma(B^*_{s2})$	$1.56\pm0.13_{stat}\pm0.47_{syst}$ MeV/c^2	
$\frac{\mathcal{B}(B^*_{s2}\to B^{*+}K^-)}{\mathcal{B}(B^*_{s2}\to B^+K^+)}$	$(9.3\pm1.3_{stat}\pm1.2_{syst})\%$	
$\frac{\sigma(pp\to B_{s1}X)\mathcal{B}(B_{s1}\to B^{*+}K^-)}{\sigma(pp\to B^*_{s2}X)\mathcal{B}(B^*_{s2}\to B^+K^-)}$	$(23.2\pm1.4_{stat}\pm1.3_{syst})\%$	

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

Comparison with theoretical predictions

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

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

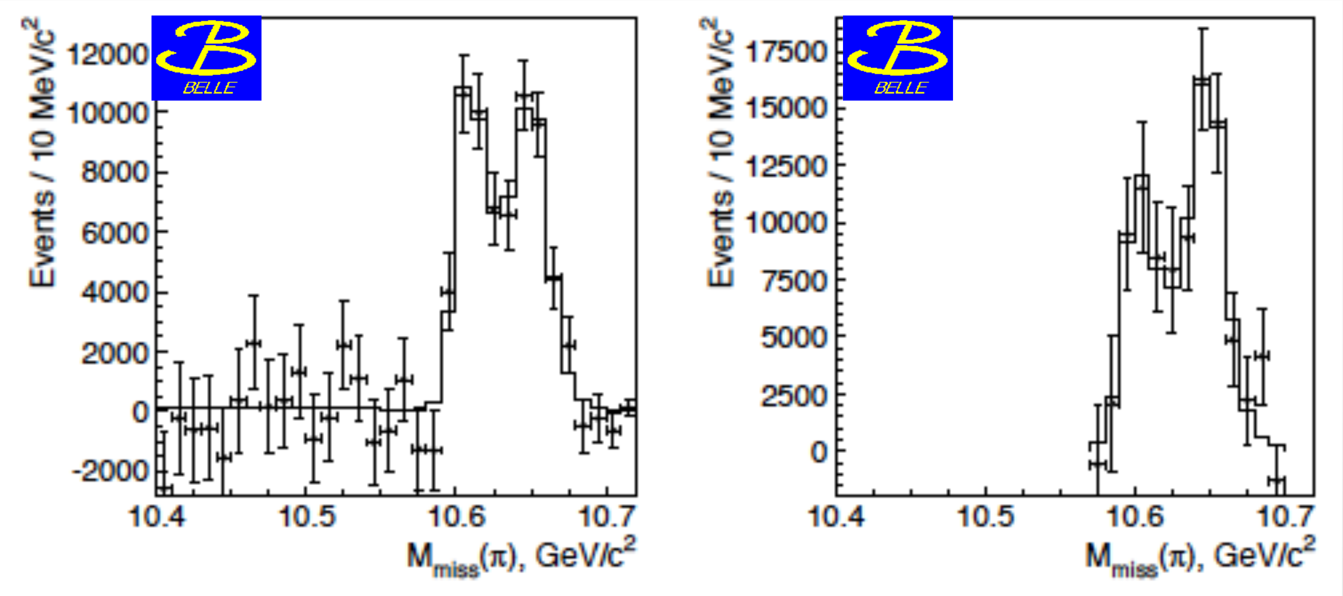
Table 1: The strong decay widths of B_{s1} and B^*_{s2} in units of MeV.

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	

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

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

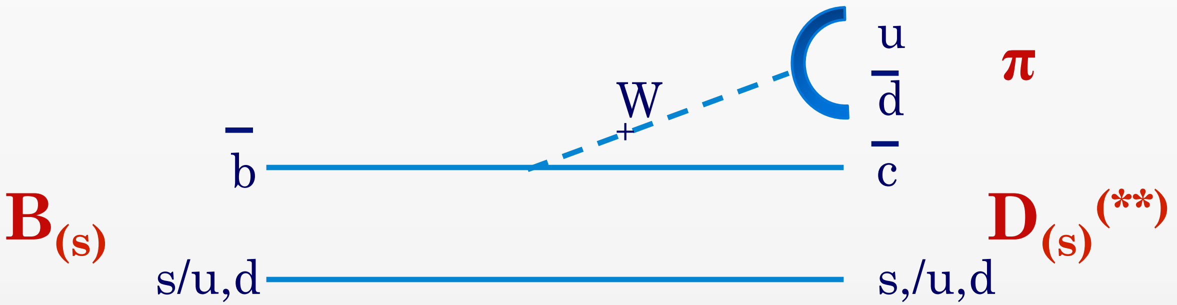
- Observation of charged bottomonium-like $Z_b(10610)^+$ and $Z_b(10650)^+$ **(Belle collaboration, PRL 108 (2012) 122001)**
- $B\bar{B}^*$ and $B^*\bar{B}^*$ molecules? **(A. Bondar et al., PRD84 (2011) 054010)**



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

PROSPECTS: EXCITED $D_{(s)}$ MESONS

Proliferation of excited charmed states observed in inclusive analyses. Determination of spin parity by amplitude analyses of B decays



✓ $B \rightarrow D\pi\pi$

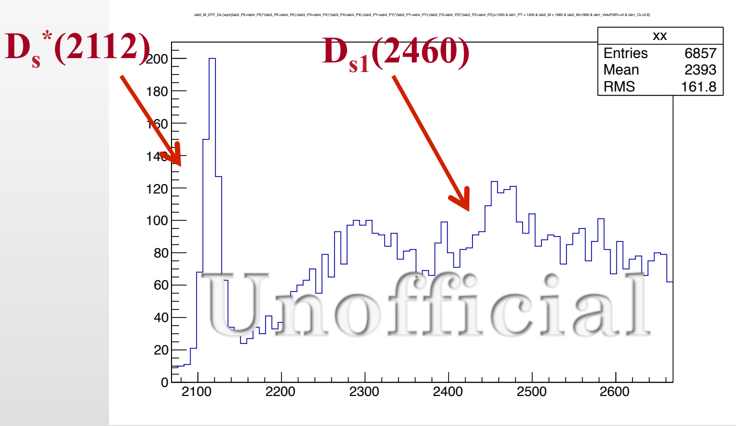
✓ $B_s \rightarrow DK\pi$

PROSPECTS: NATURE OF D_{s0}*(2317) AND D_{s1}(2460)

- Search for new decay modes (likely some D_{s1}(2460) decay modes are missing)
- Measurements of branching ratios in B_s decays (same suppression observed in B decays?)

✓ $B_s \rightarrow D_s \pi^0 \pi^+$
✓ $B_s \rightarrow D_s \gamma \pi^+$

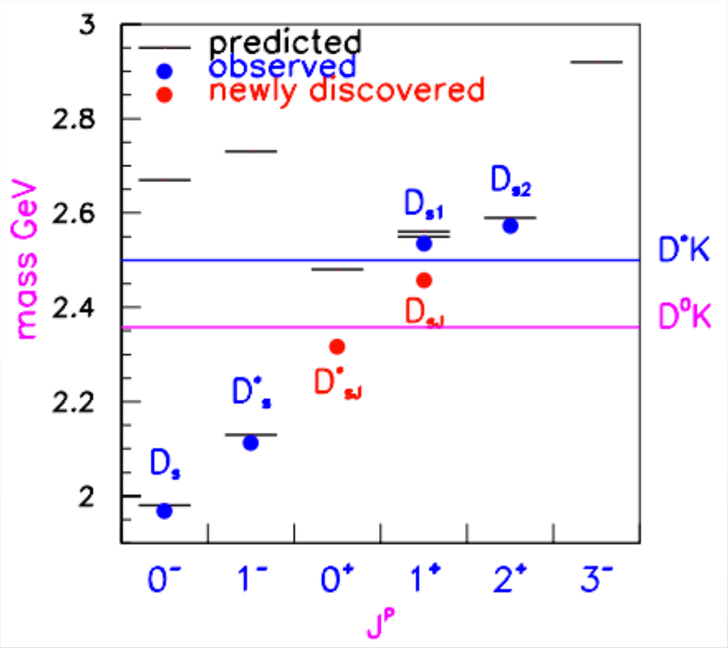
Measurements of the D_{s0}*/D_{s1}' production relative to D_s* (2112)



If the D_{s0}*/D_{s1}' are tetraquarks, the production should be highly suppressed

Prospect: Search for B_{s0}* and B_{s1}'

The D_{s0}*(2317) and D_{s1}(2460) should have "flavour partners": B_{s0}* and B_{s1}' . Same surprising low masses as D_{s0}* and D_{s1}"?

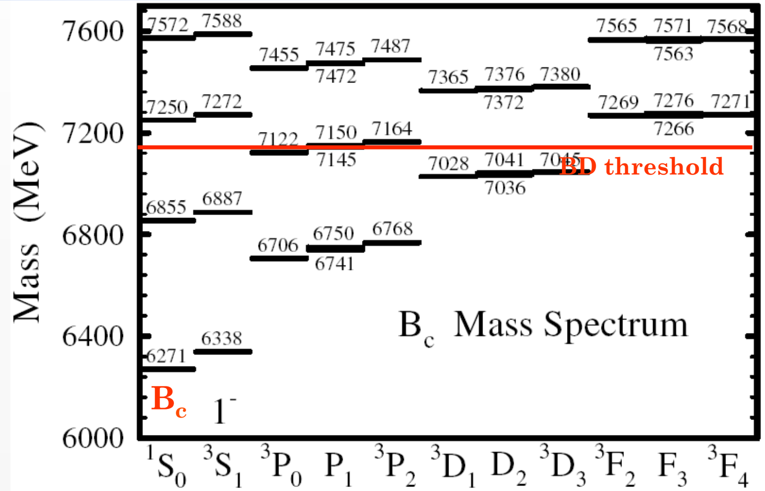


	j_q	J^P	Allowed decay mode B^+K^-	$B^{*+}K^-$
B^*_{s0}	$1/2$	0^+	yes	no
B'_{s1}	$1/2$	1^+	no	yes
B_{s1}	$3/2$	1^+	no	yes
B^*_{s2}	$3/2$	2^+	yes	yes

Broad structures are observed n Bπ. BK? $B^0K^0_S$?

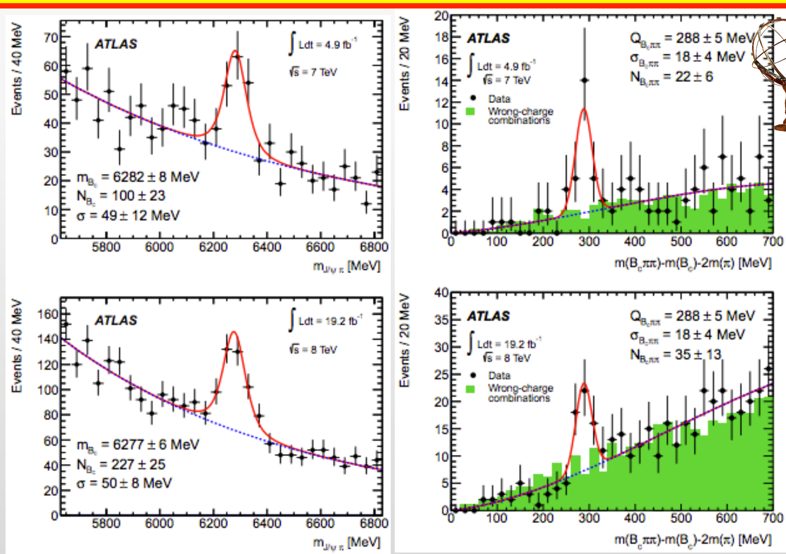
Prospect: Excited B_c

- 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 $B_c(2S)$

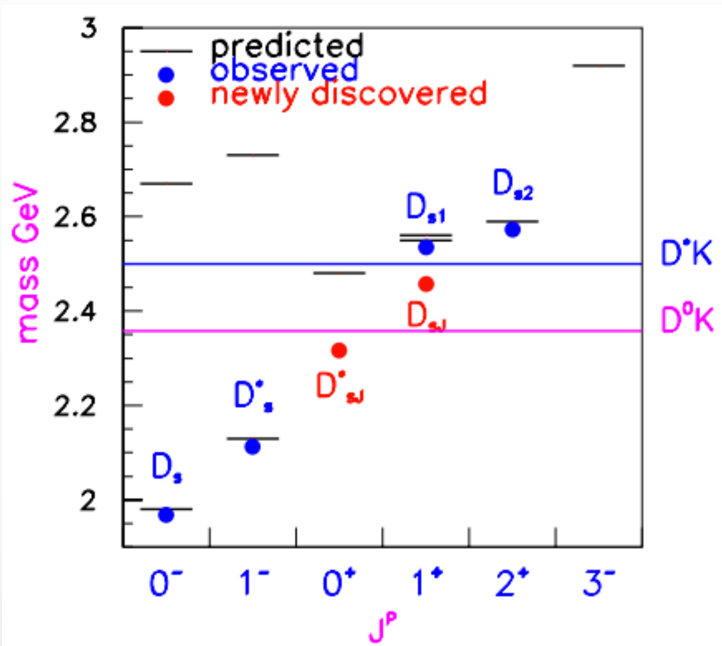


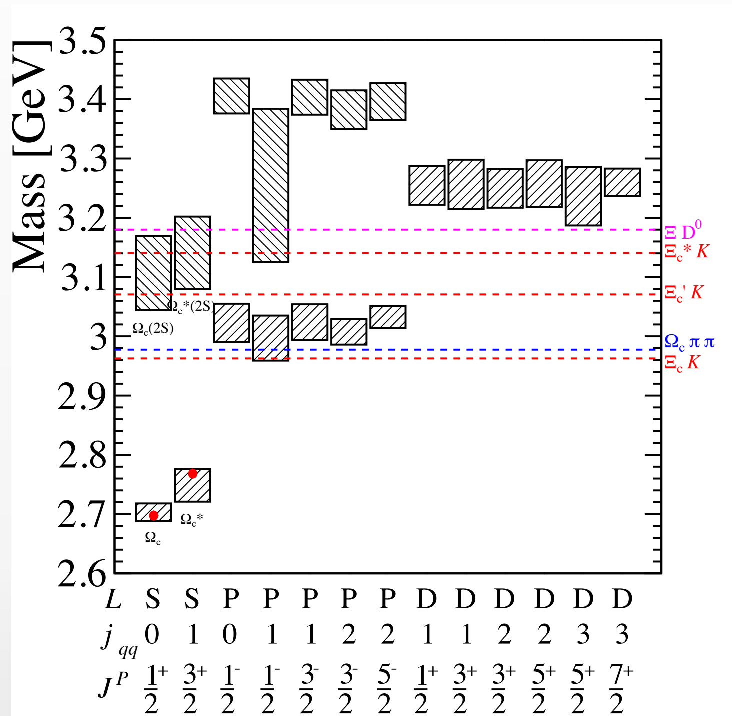
[ATLAS, arXiv:1407.1032]

$M = 6842 \pm 4 \pm 5$ MeV
$\Gamma \ll$ resolution

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

PROSPECT: Ω_c SPECTROSCOPY





Some surprising low mass Ω_c** states?

Summary

- LHCb is very active into studying excited heavy mesons
  - Inclusively: New states, new decay modes
  - Exclusively: New states, determination of quantum numbers
- 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}'?
- 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…
- Decays with neutral as decay products could be investigated

- ✓ Spectroscopy will play a more important role in the near future
- ✓ RUN I data not fully exploited so far. Many systems still unexplored…
- ✓ …and RUN II is ahead (expected 5-10 fb^{-1})

Stay Tuned!

Back-up slides

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)

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

SYSTEMATICS

Source	$Q(B_{s1})$ (MeV/c^2)	$Q(B^*_{s2})$ (MeV/c^2)	$m(B^{*+}) - m(B^+)$ (MeV/c^2)	$\Gamma(B^*_{s2})$ (MeV/c^2)	$R^{B^*_{s2}}$ (%)	$\sigma^{B_{s1}/B^*_{s2}} R^{B_{s1}/B^*_{s2}}$ (%)
Fit model	0.00	0.02	0.03	0.01	0.2	0.5
B^+ decay mode	0.01	0.01	0.02	0.01	0.1	0.1
Selection	**0.03**	0.02	**0.19**	0.05	**1.1**	0.6
B^+ signal region	0.01	0.03	0.11	0.07	0.2	0.4
Mass resolution	0.00	0.01	0.02	**0.46**	0.2	**0.9**
Momentum scale	0.02	**0.10**	0.03	-	-	-
Efficiency ratios	-	-	-	-	0.2	0.2
Missing photon	0.01	-	0.01	-	-	-
Total	0.04	0.11	0.23	0.47	1.2	1.3

- ✧ Variation of selection criteria
- ✧ Narrower B^+ signal region ($\pm 1\sigma$)
- ✧ Detector resolution varied by ± 20%
- ✧ Momentum scale calibration: ±0.15%
- ✧ Relative selection efficiency
- ✧ Mass shifts due to the missing photon