Heavy Quark Spectroscopy at LHCb

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(On behalf of LHCb Collaboration)

7th International Conference on Quarks and Nuclear Physics

Valparaiso, Chile, 2nd March 2015

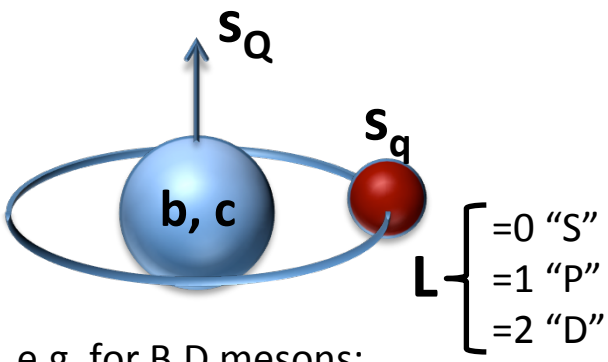
Introduction

Heavy-flavoured hadrons exhibit rich structure of excitations (intrinsic spin, orbital, radial)

Heavy Quark Effective Theories (HQET) predict properties by expanding in terms of Λ_{QCD}/m_b

Important quantum numbers are then:

- Orbital angular momentum, **L**, and radial excitation ***n***
- Total angular momentum of light quarks, $\mathbf{j_q}$
- Hadron angular momentum and parity, $\mathbf{J^P}$



e.g. for B,D mesons:

$$j_q = L + s_q$$
$$J = j_q + s_Q$$

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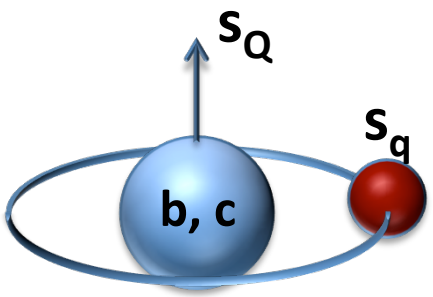


Many 'low lying' states still yet to be observed

Established states need confirmation of quantum numbers

⇒ Further study is essential to confirm quark-model state assignments, and refine HQET methods

LHCb ideally placed to search for new states, and measure their properties with high precision

⇒This talk: new and recent results in B, D**, and Ξ_b* searches**

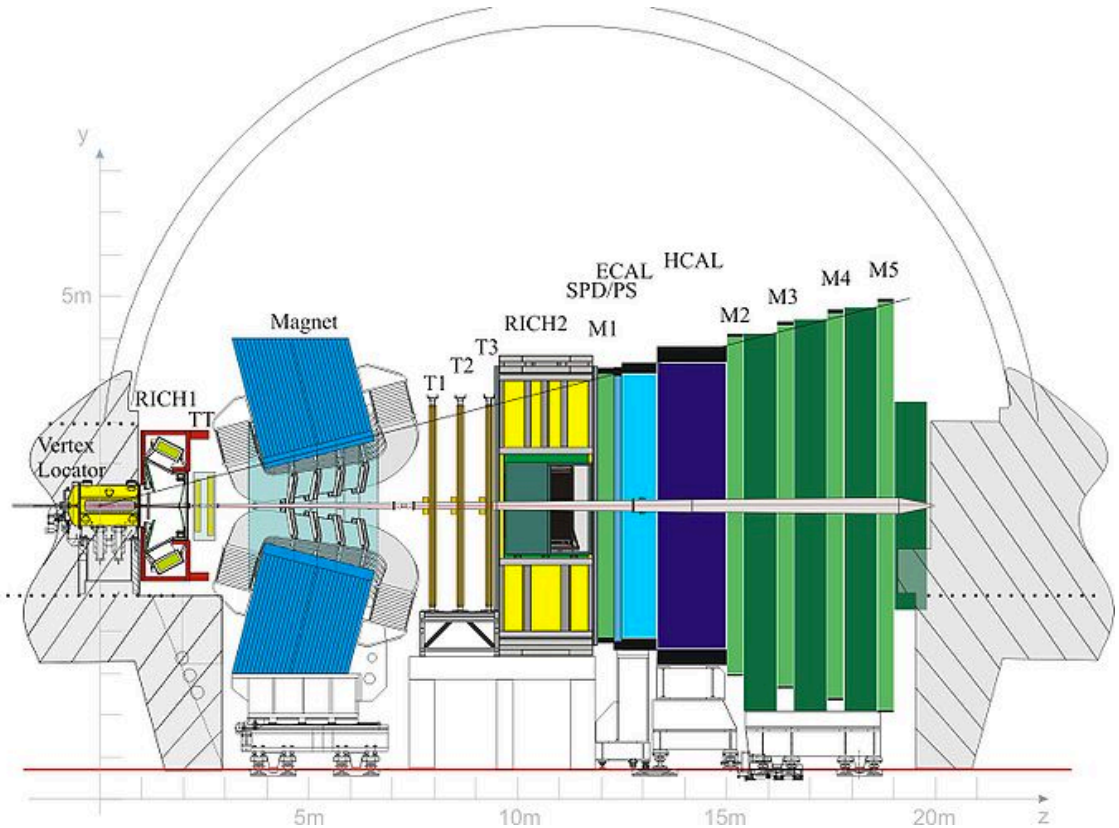
Spectroscopy @ LHCb

Proton-proton collider experiment

Single-arm forward spectrometer ($2 < \eta < 5$).

Analyses covered here rely on:

- Silicon Vertex Locator closest to interaction point: ***topological discrimination between signal and backgrounds***
- Si & straw tracking stations either side of 4 Tm magnet: ***excellent mass resolution***
- Particle Identification via 2 RICH detectors, calorimeter, and muon stations: ***remove backgrounds from mis-identified final-state hadrons***



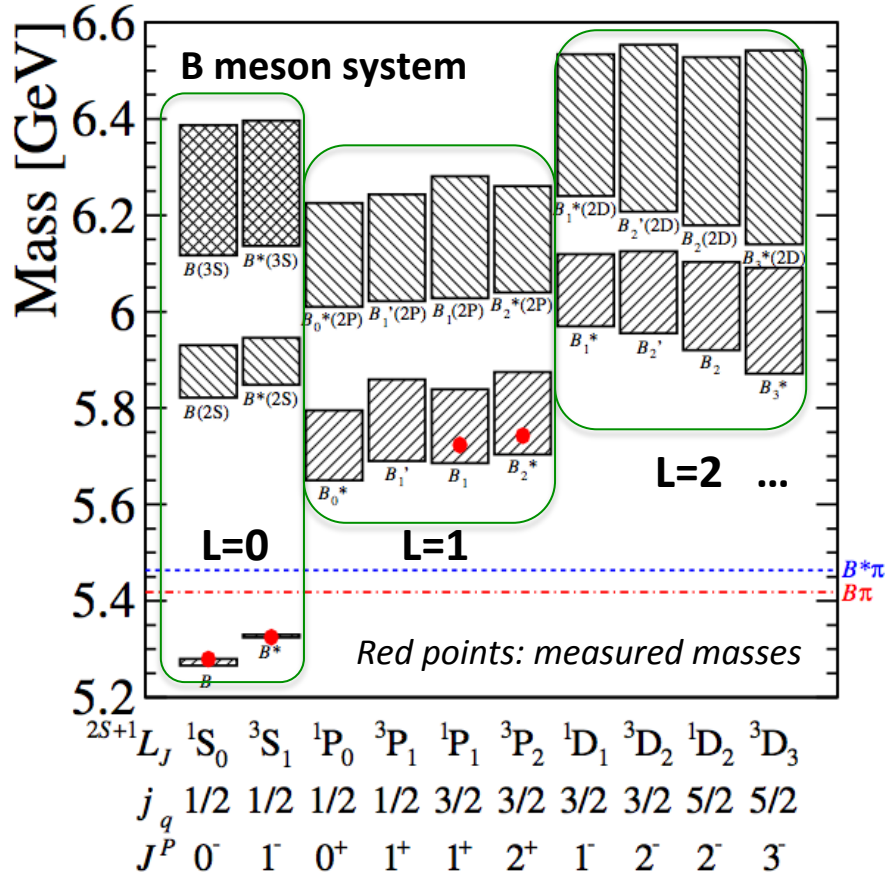
During Run I operations (2010-2012), collected ~1fb^{-1} (~2fb^{-1}) at $\sqrt{s}$ = 7 (8) TeV

Analyses presented here use full 3fb^{-1} sample

$B_{u,d}$** States: Properties and Observations

B mesons analogous to hydrogen atoms in QED – provide rich testing ground for HQET predictions

Higher orbital and radial states de-excite via strong interaction to low-lying states B or B* plus pions (or kaons for B_s**)



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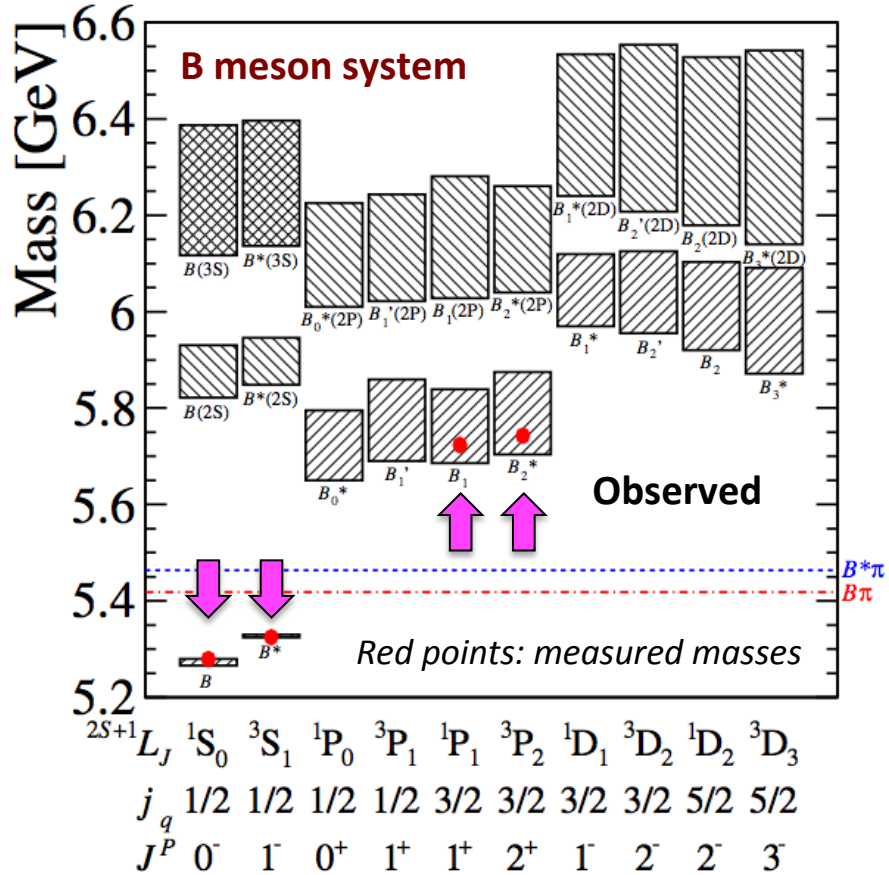

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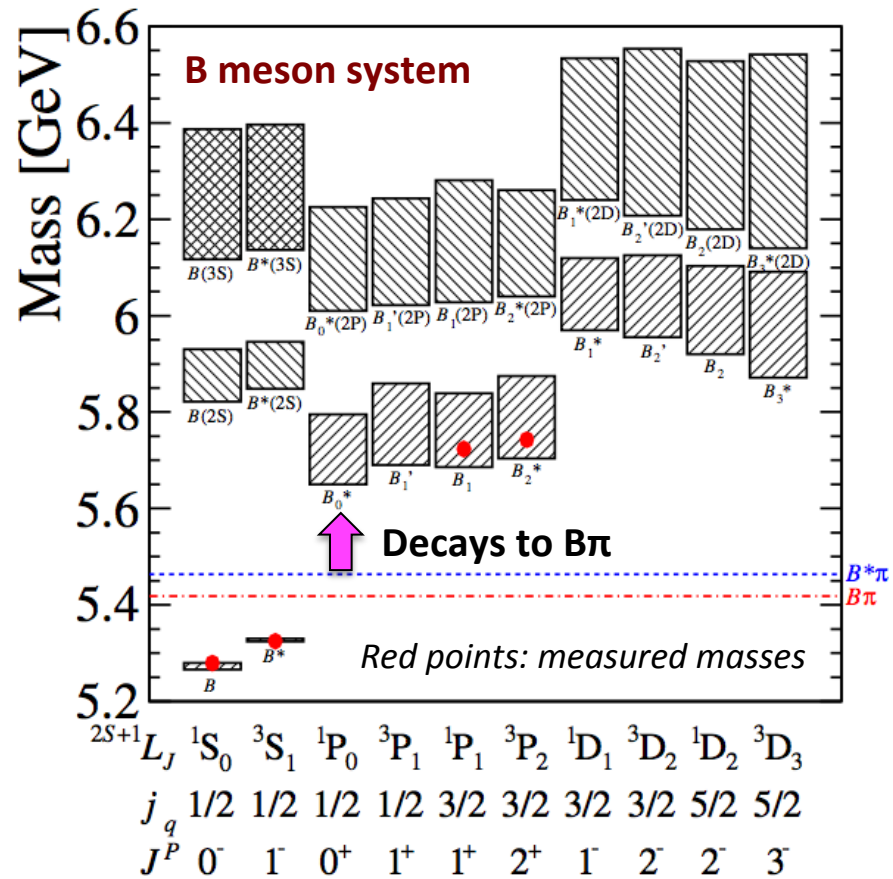
B*→Bγ ⇒ decays to B*π reconstructed as Bπ, with 45 MeV missing mass

Quantum numbers dictate allowed transitions



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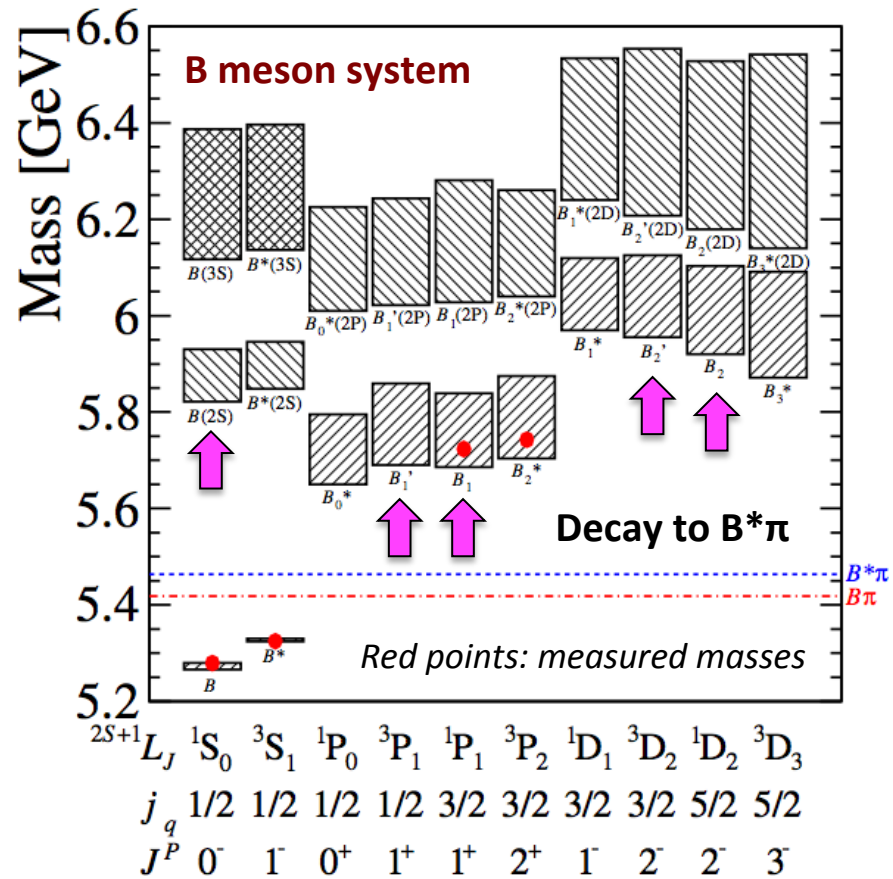

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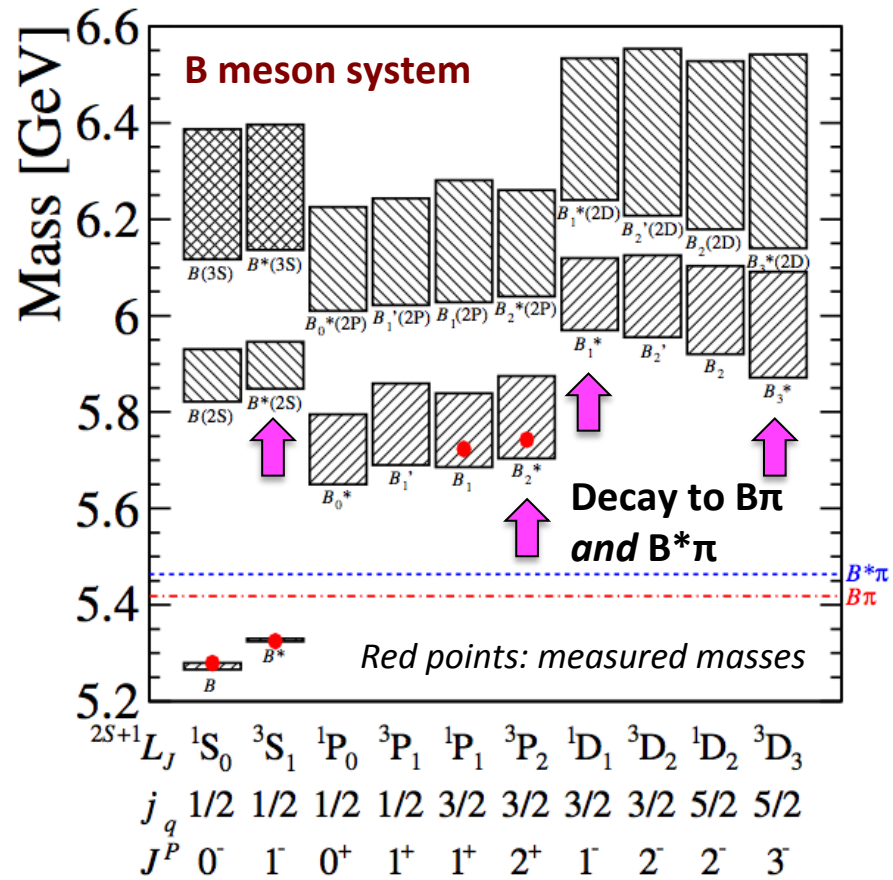
Quantum numbers dictate allowed transitions

States with both transitions allowed are reconstructed as two peaks in M(Bπ), separated by 45 MeV.

⇒ Spin doublets are reconstructed as three peaks



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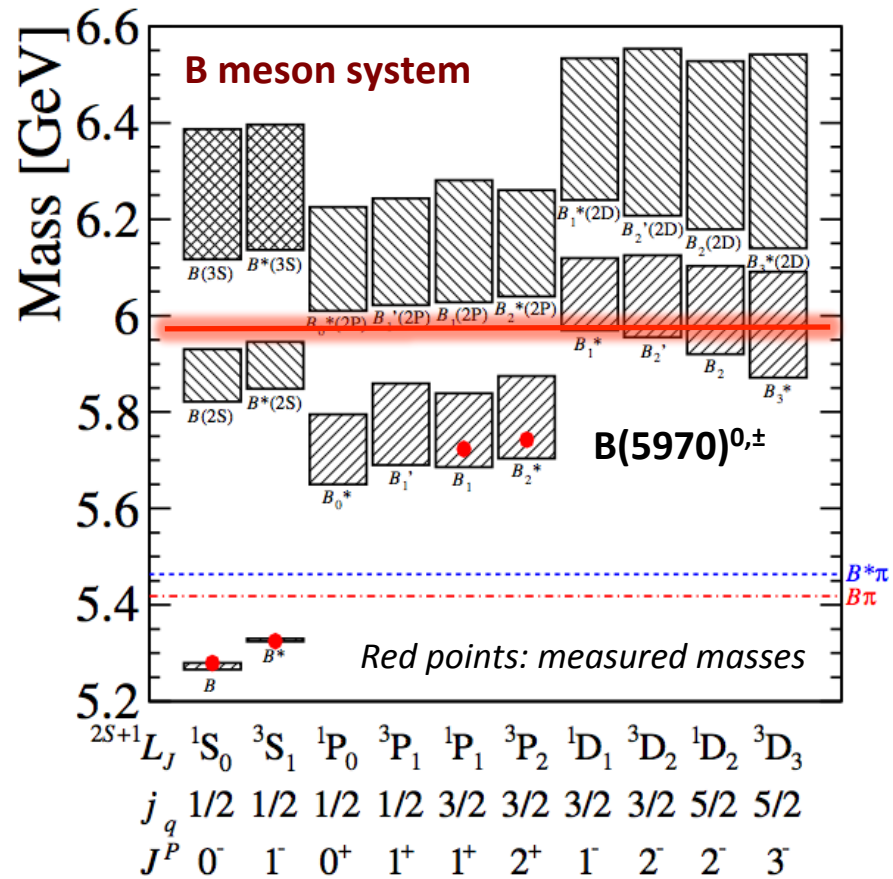
Currently only two narrow L=1 excitations established (in three systems: B^+, B^0, and B_s^0)

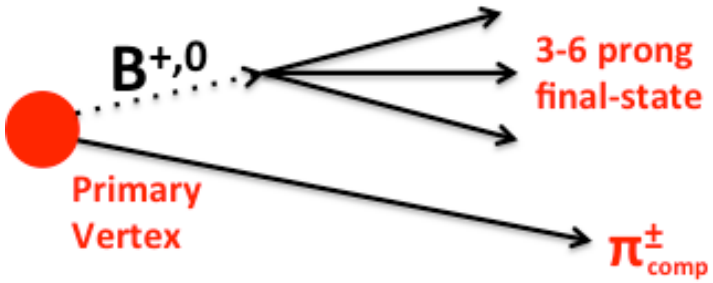
CDF recently reported evidence for a broad resonance $B(5970)^{0,\pm}$
Not clear which state(s) this corresponds to.



$B_{u,d}^{**}$ States: Properties and Observations

Select B^0 and B^+ mesons in several high-yield channels

Combine with companion pion track π_{comp} produced at the primary interaction, $B^+\pi^-$ and $B^0\pi^+$ (and C.C.)



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

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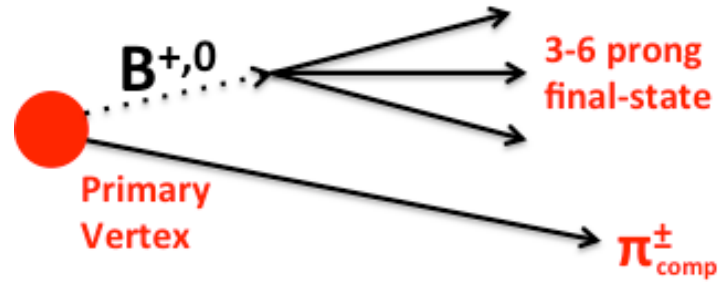


- Cut-based analysis
- Use all Bπ combinations that satisfy cuts (~1.4 per selected B meson)
- Large, pure samples of B^+ and B^0

$B^+ \to J/\psi(\mu\mu)K^+$

$\bar{D}^0(K^+\pi^-)\pi^+$

$\bar{D}^0(K^+\pi^-\pi^+\pi^-)\pi^+$

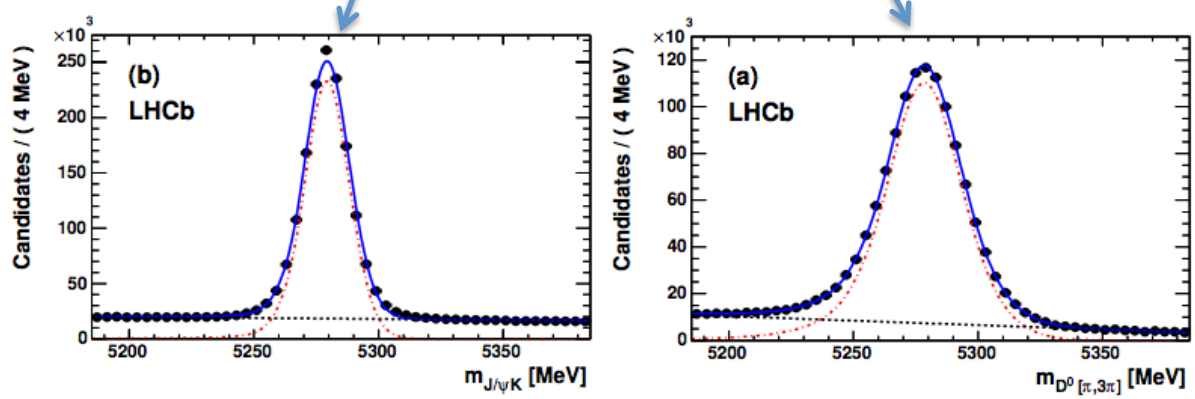
$\bar{D}^0(K^+\pi^-)\pi^+\pi^-\pi^+$

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

$D^-(K^+\pi^-\pi^-)\pi^+$

$D^-(K^+\pi^-\pi^-)\pi^+\pi^-\pi^+$

$N(B^0) \approx 1.2M$, $N(B^+) \approx 2.5M$,



$B_{u,d}^{**}$ States: Properties and Observations

Investigate and fit the Q distribution:

$$Q \equiv M_{cand}(B\pi) - M_{PDG}(B) - M_{PDG}(\pi)$$

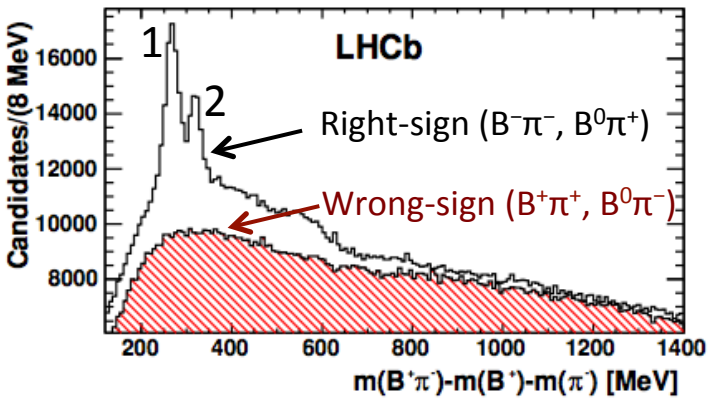
Right-sign ($B^-\pi^-$, $B^0\pi^+$) sample shows two narrow peaks above smooth trend seen in wrong-sign ($B^+\pi^+$, $B^0\pi^-$) sample.

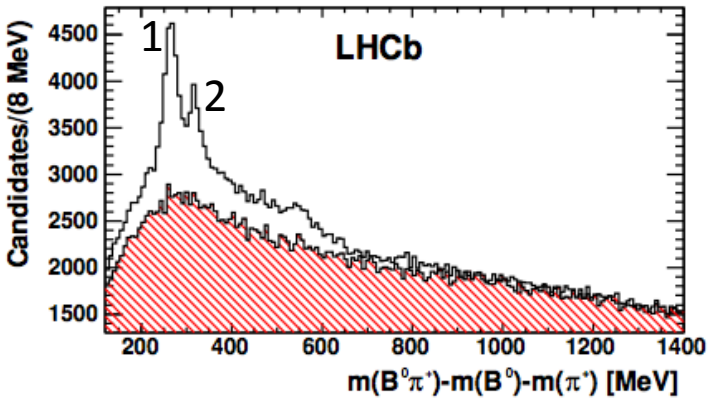
(1) Overlap of $B_1, B_2^* \rightarrow B^*\pi$

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

Broad excess of RS over WS indicates associated $B\pi$ production from wide resonances or non-resonant correlated production

Additional excess at Q ≈ 500 MeV…





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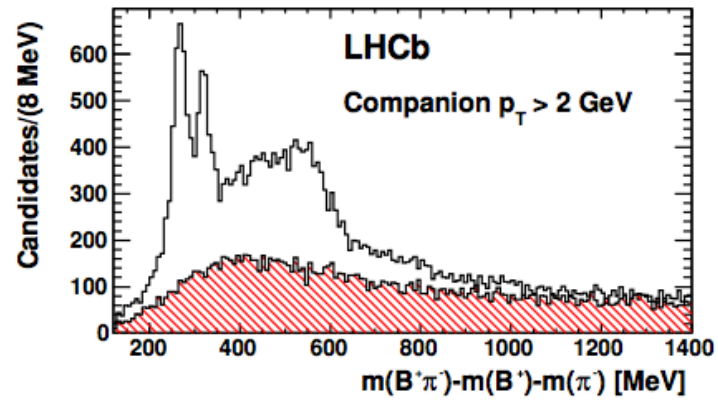
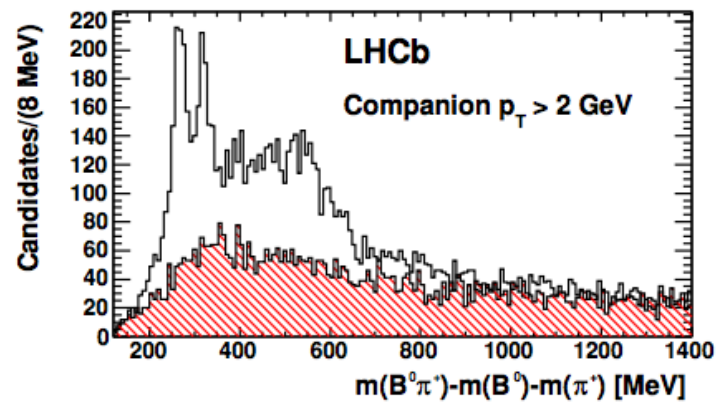
Additional excess at Q ≈ 500 MeV… becomes much more prominent at higher $p_T(\pi_{comp})$



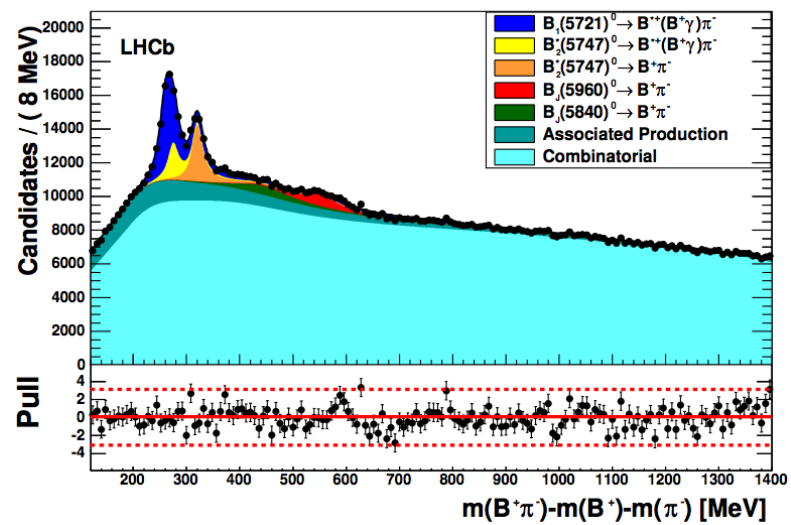


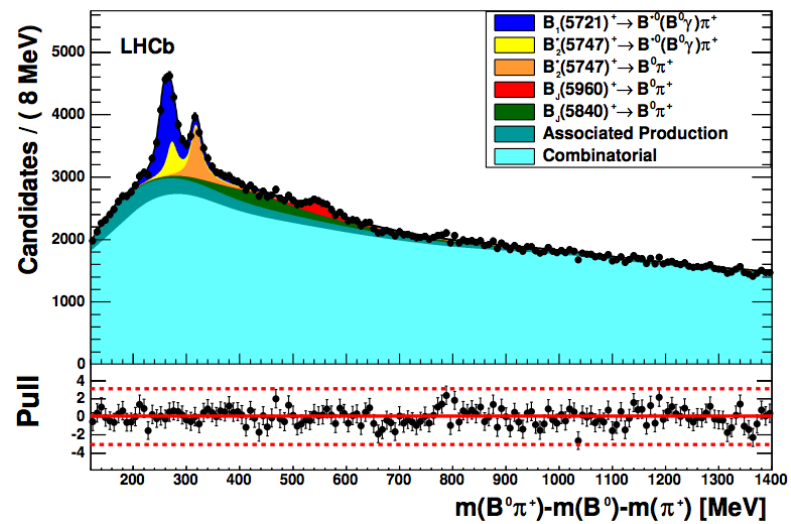
$B_{u,d}$** States: Properties and Observations

Fit $B^+\pi^-$ and $B^0\pi^+$ independently, in 3 bins of $p_T(\pi_{comp})$

- **Combinatorial BG**: smooth polynomial shape fixed from WS sample
- **Associated Production**: empirical description, using input from MC and data
- **Signal peaks**: Relativistic BW
  - $B_1 \rightarrow B^*\pi$
  - $B_2^* \rightarrow B\pi$
  - $B_2^* \rightarrow B^*\pi$

  Low-Q region: Established states
  - (Nominal) two peaks in high-Q region
  - (Alternative) three peaks





$B_{u,d}$** States: Properties and Observations

Nominal fit uses minimal empirical description for higher-Q region (two peaks)

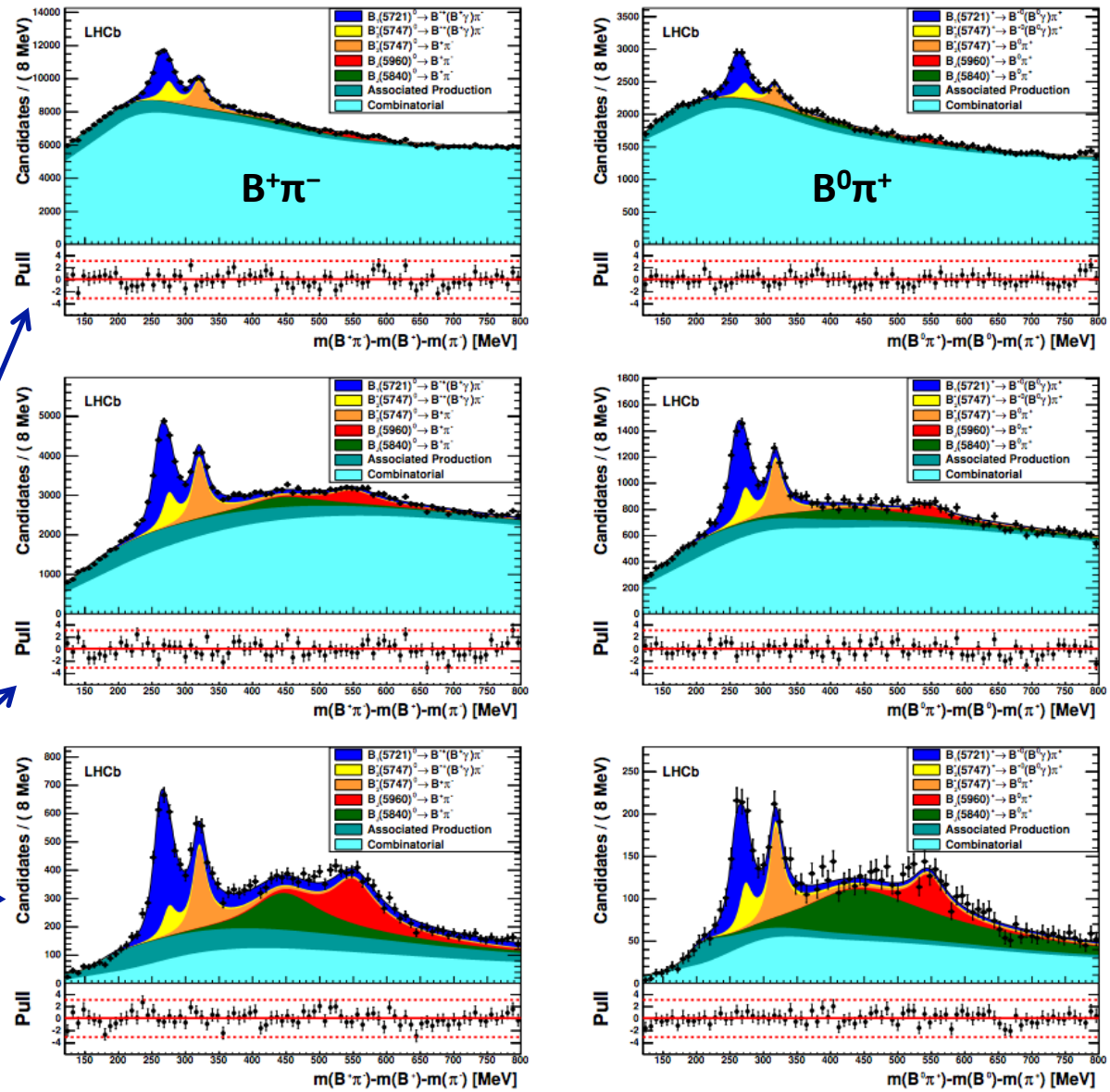
Adding a third peak to model feed-down from B* changes the mean masses – we quote values for all three hypotheses.

Share signal parameters between $p_T(\pi_{comp})$ bins

$0.5 < p_T(\pi_{comp}) < 1.0$ GeV/c

$1 < p_T(\pi_{comp}) < 2$ GeV/c

$p_T(\pi_{comp}) > 2$ GeV/c



Note: zoomed scale

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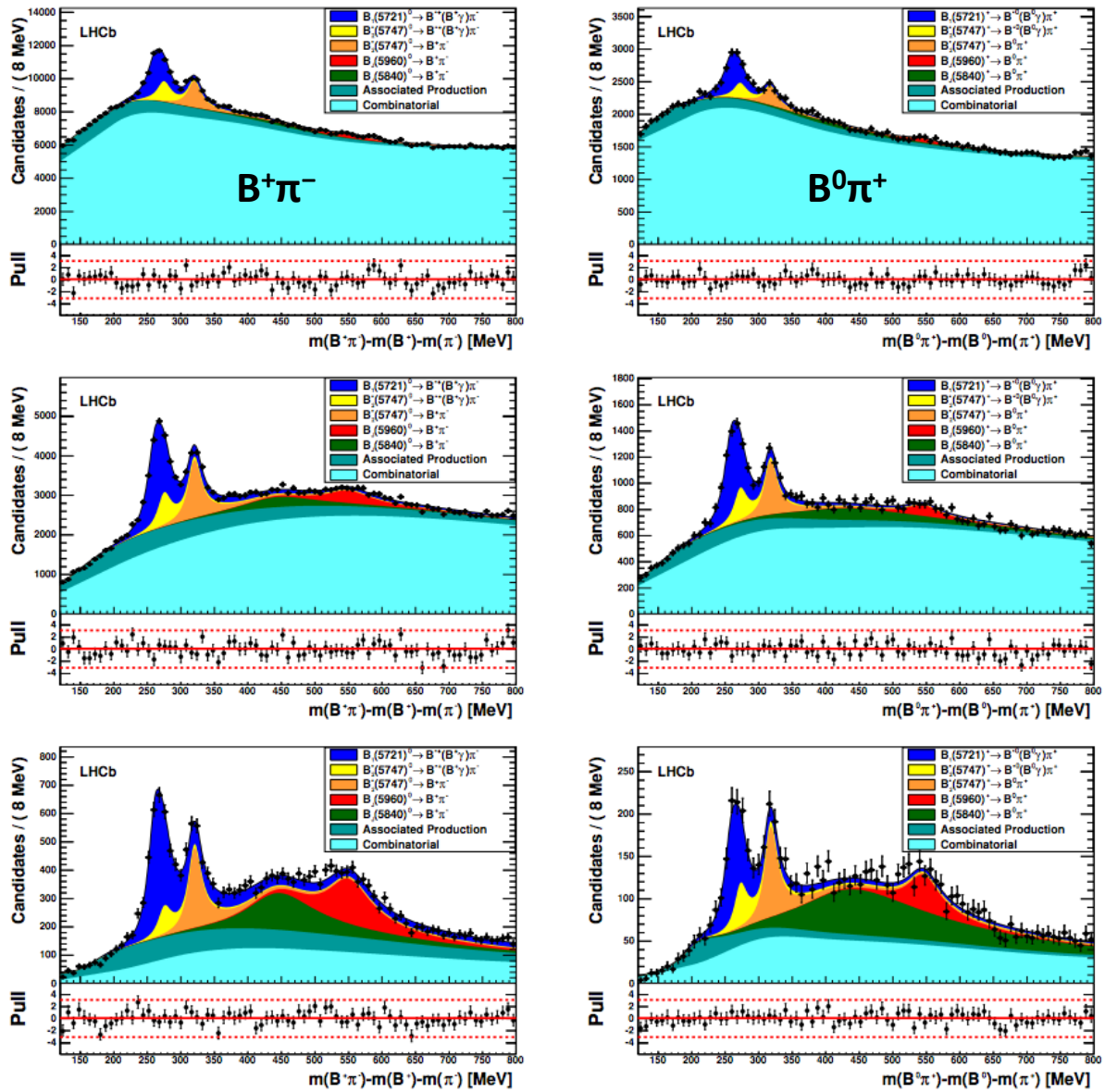
Comprehensive set of systematics to account for all assumptions and fit choices

Validated with ensembles of pseudoexperiments



Note: zoomed scale

$B_{u,d}$** States: Properties and Observations

Interpretation: Low-Q Peaks

Narrow low-Q peaks are identified with (established) L=1 $B_1(5721)^{0,\pm}$ and $B_2^*(5747)^{0,\pm}$ states.

First evidence (3.7σ) for $B_2^* \to B^*\pi$ feed-down transition

Masses and widths are measured:

				σ(stat)		σ(syst)		σ(B mass)		σ(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

Relative yields are converted to branching fractions, using efficiency input from simulation:

				σ(stat)		σ(syst)
$\frac{\mathcal{B}(B_2^*(5747)^0 \to B^{*+}\pi^-)}{\mathcal{B}(B_2^*(5747)^0 \to B^+\pi^-)}$	=	0.71	±	0.14	±	0.30
$\frac{\mathcal{B}(B_2^*(5747)^+ \to B^{*0}\pi^+)}{\mathcal{B}(B_2^*(5747)^+ \to B^0\pi^+)}$	=	1.0	±	0.5	±	0.8

$B_{u,d}$** States: Properties and Observations

Interpretation: High-Q region

Peak significances:

- One peak hypothesis:
  9.6σ (4.8σ) for $B^+\pi^-$ ($B^0\pi^+$)
- Two-peak hypothesis:
  7.5σ (4.6σ) for $B^+\pi^-$ ($B^0\pi^+$)

Assuming isospin invariance ⇒ first observations of two new pairs of states

Masses and widths under quark model hypothesis are consistent with expectations from radial excitations B(2S) and B*(2S)

	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					

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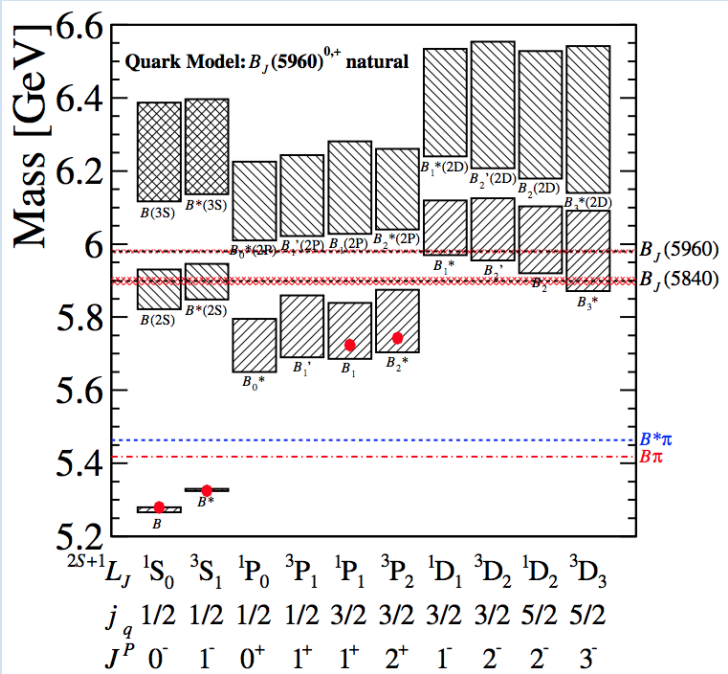
Masses and widths under quark model hypothesis are consistent with expectations from radial excitations B(2S) and B*(2S)

arXiv:1502.02638
Submitted to JHEP 9 Feb 2015



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Charm Meson Spectroscopy: New D_s^- States

Several interesting recent results in $D_s^\pm$ system, including observation of a number of higher-mass resonances:

$D_{s1}^*(2700)^-$ and $D_{sJ}^*(2860)^-$ seen by both BaBar and LHCb

Observed in DK and D*K decays

State	Mass	Width	Comment
		BaBar	
$D_{s1}^*(2700)^-$	$2710 \pm 2\,^{+12}_{-7}$	$149 \pm 7\,^{+39}_{-52}$	Seen in DK and D^*K
$D_{sJ}^*(2860)^-$	$2862 \pm 2\,^{+5}_{-2}$	$48 \pm 3 \pm 6$	Seen in DK and D^*K
$D_{sJ}(3040)^-$	$3044 \pm 8\,^{+30}_{-5}$	$239 \pm 35\,^{+46}_{-42}$	Seen in D^*K only
		LHCb	
$D_{s1}^*(2700)^-$	$2709.2 \pm 1.9 \pm 4.5$	$115.8 \pm 7.3 \pm 12.1$	Only DK studied
$D_{sJ}^*(2860)^-$	$2866.1 \pm 1.0 \pm 6.3$	$69.9 \pm 3.2 \pm 6.6$	

Multiple possible interpretations within the quark model, but D*K / DK doublet indicates natural spin-parity ($0^+,1^-,2^+,3^-$…)

Lowest-lying states are in 2S (1^-) or 1D (1^-, 3^-) families

⇒ Need further investigation to determine quantum numbers
(no J=3 heavy-flavour meson has yet been observed)

Charm Meson Spectroscopy: New D_s^- States

Spin structure of $D^{(*)}K$ resonances can be extracted by Dalitz analysis of decays $B_s^0 \to \bar{D}^0 K^- \pi^+$:

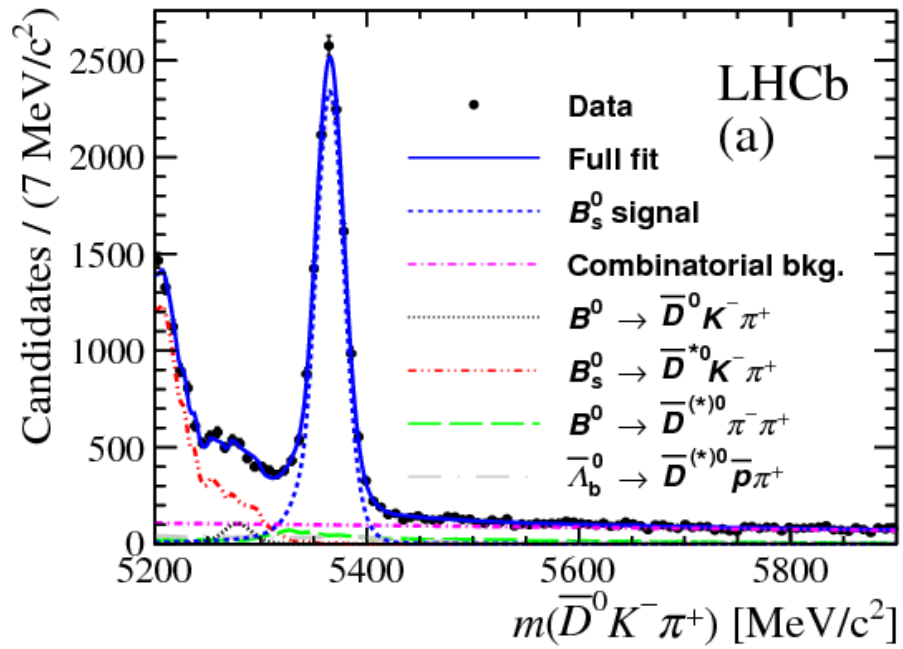
- Initial and final state spins are all known [$J^P(B_s^-) = 0^-$]
- Dalitz-plane behaviour allows separation of different spin hypotheses for intermediate resonances

Reconstruct $B_s^0 \to \bar{D}^0 K^- \pi^+$ candidates, selection optimised using multivariate techniques

Apply mass vetoes to remove problematic physics backgrounds ($B \to D^{*\pm}X$, $B_s \to D_s\pi$, $B_s \to D^0\bar{D}^0$, $B^0 \to J/\psi K^{*0}$)

Signal region: ±2.5σ around B_s^0 mass

- ~11,000 signal candidates
- ~1000 combinatorial BG
- ~700 physics BG (mainly $B^0 \to D^{(*)0}\pi^+\pi^-$, $\Lambda_b \to D^{(*)\pm}p\pi^-$)



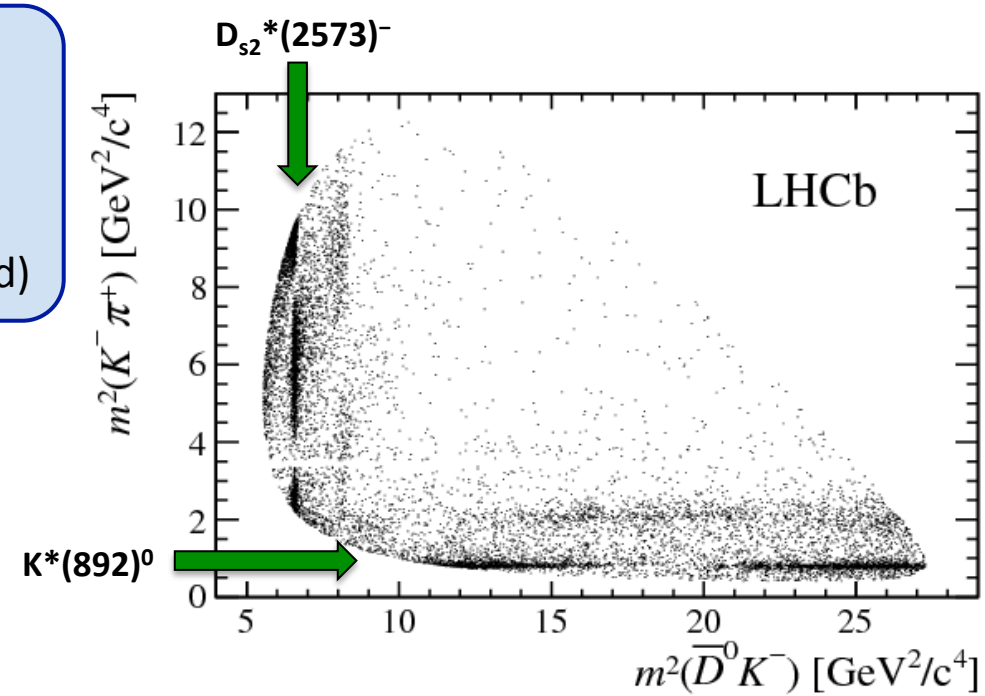
Charm Meson Spectroscopy: New D_s^- States

Efficiency variations and background components (from simulation and data-driven methods) taken into account in fit.

Parameterise using 6 resonances in $m^2(K^-\pi^+)$, plus 3 or 4 resonances in $m^2(\bar{D}^0K^-)$:

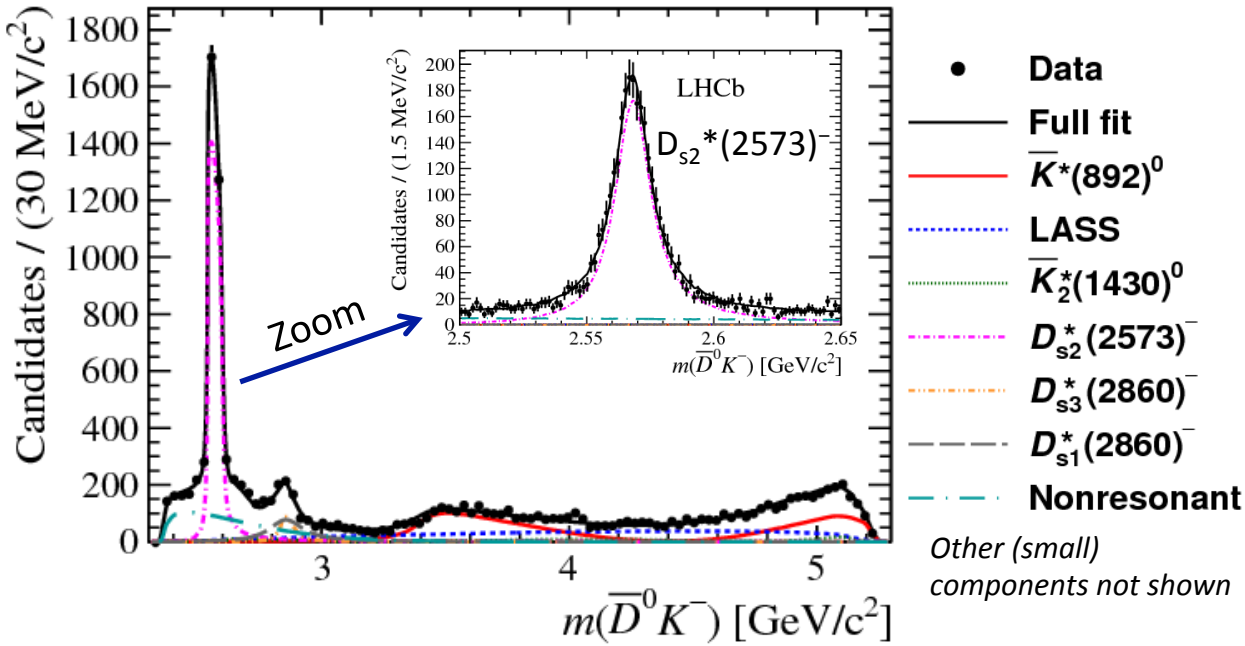
- $D_{s2}^*(2573)^-$ (spin 2)
- $D_{s1}^*(2700)^-$ (spin 1)
- $D_{sJ}^*(2860)^-$ (spin 1 and spin 3 components considered)

Also non-resonant $\bar{D}^0K^-$ and virtual contributions from D_s^{*-} and $D_{s0}^*(2317)^-$



Charm Meson Spectroscopy: New D_s^- States

Very clean $D_{s2}^*(2573)^-$ peak: gives most precise extraction of mass and width:



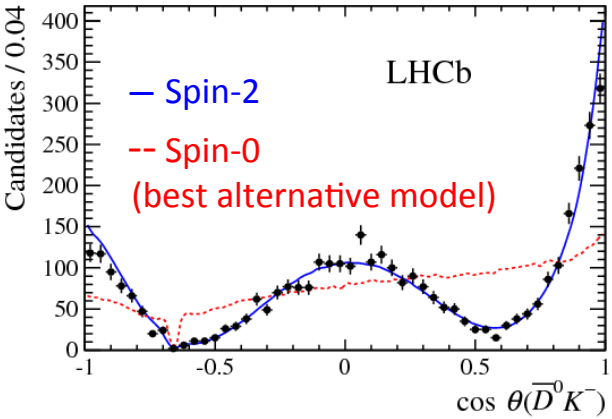
$M(D_{s2}^*(2573)^-) = 2568.39 \pm 0.29 \pm 0.19 \pm 0.18$ MeV/c²
$\Gamma(D_{s2}^*(2573)^-) = 16.9 \pm 0.5 \pm 0.4 \pm 0.4$ MeV/c²

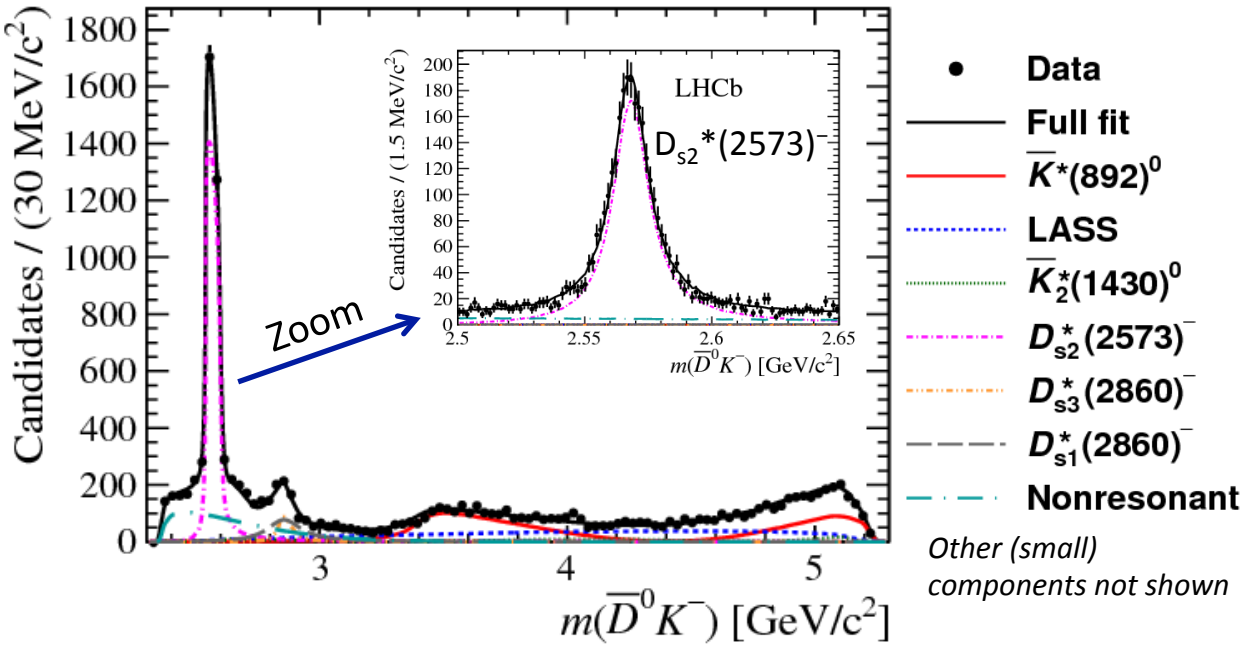
σ(stat) σ(syst) σ(model)

Charm Meson Spectroscopy: New D_s^- States

Very clean $D_{s2}^*(2573)^-$ peak: gives most precise extraction of mass and width:

Angular analysis confirms this state is spin-2





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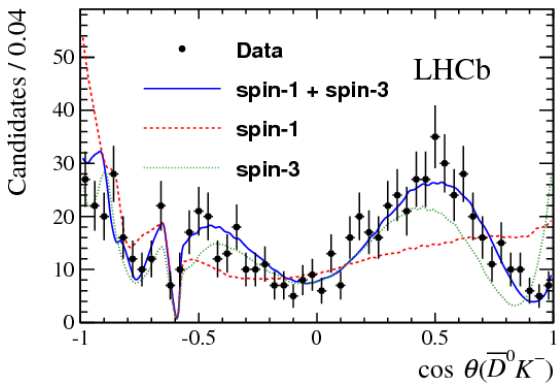
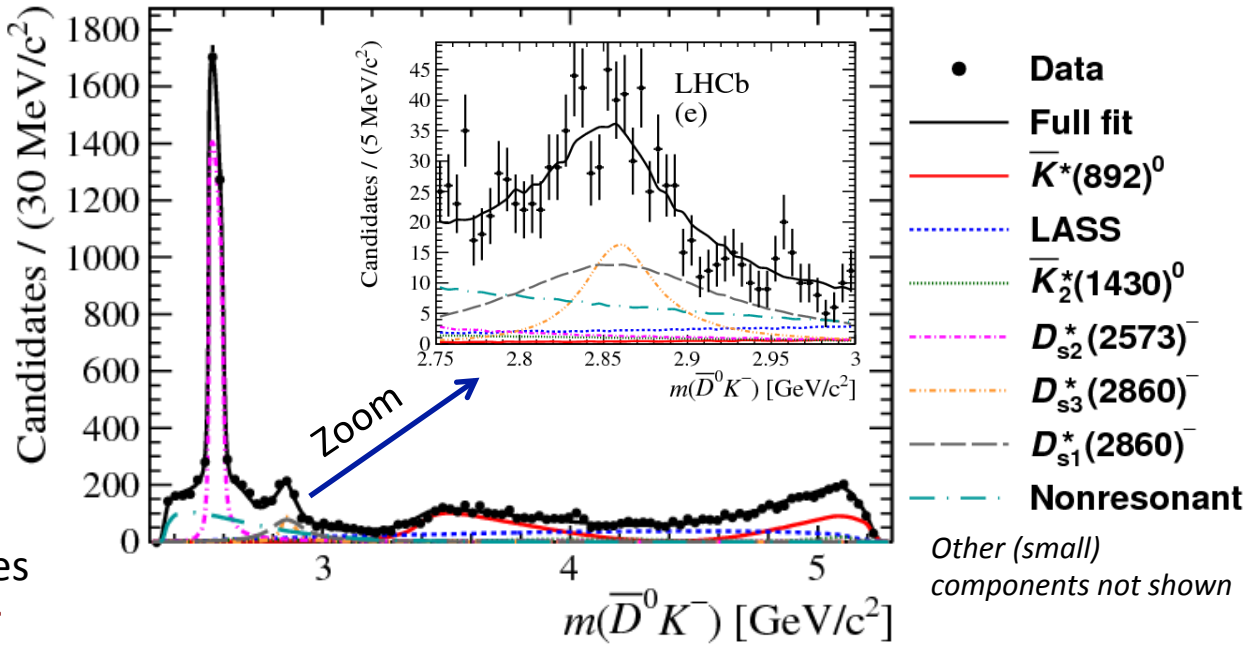
σ(stat) σ(syst) σ(model)

Charm Meson Spectroscopy: New D_s^- States

Fit significantly improved by allowing both spin-1 and spin-3 components for $D_{sJ}^*(2860)^-$

Confirmation from angular analysis





Separate statistical significances of both spin states exceed **10σ** including systematic and model uncertainties

$M(D_{s1}^*(2860)^-)$	= 2859	± 12	± 6	± 23	MeV/c²
$\Gamma(D_{s1}^*(2860)^-)$	= 159	± 23	± 27	± 72	MeV/c²
$M(D_{s3}^*(2860)^-)$	= 2860.5	± 2.6	± 2.5	± 6.0	MeV/c²
$\Gamma(D_{s3}^*(2860)^-)$	= 53	± 7	± 4	± 6	MeV/c²
		σ(stat)	*σ(syst)*	*σ(model)*	

Charm Meson Spectroscopy: New D_s^- States

Systematic uncertainties assigned from experimental effects and model choices

Experimental:

- Signal and BG yields from mass fit
- BG distributions over DP
- Signal efficiency over DP
- Possible fit biases
- Momentum calibration
- Input B_s^- and $\overline{D}^0$ masses used to define Dalitz plot boundaries

Model:

- Fixed parameters in model
- Inclusion/exclusion of (marginal) components
- Model choice for $K^-\pi^+$ S-wave
- Model choice for $\overline{D}^0K^-$ S- and P-waves

Charm Meson Spectroscopy: New D_s^- States

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Analysis reports fit fractions, complex amplitudes, and quasi-two-body branching fractions on all resonant components in the fit (including limits on marginal ones)

⇒ First confirmation that $D_{s2}^*(2573)^-$ is spin-2

⇒ First observation of spin-1 and spin-3 doublet in $D_{sJ}^*(2860)^-$

Favours interpretation as $J^P=1^-,3^-$ members of 1D family.

May be partial mixing from 2S 1^- state, producing physical $D_{s1}^*(2700)^-$ and $D_{s1}^*(2860)^-$ states

Charm Meson Spectroscopy: New D_s^- States

Systematic uncertainties assigned from experimental effects and model choices

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- Signal and BG yields from mass fit
- BG distributions over DP
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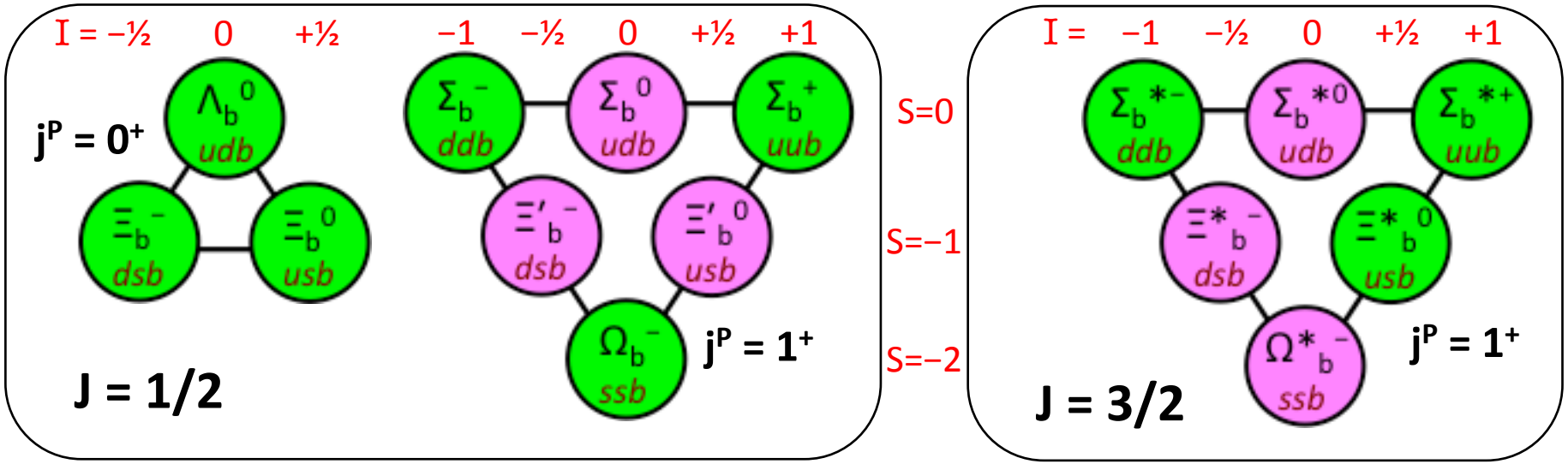
Phys. Rev. Lett. 113 (2014) 062001 ***(arXiv:1407.7574)***
Phys. Rev. D 90 (2014) 072003 ***(arXiv:1407.7712)***

New $\Xi_b^{\pm}$ Resonances

Still several L=0 b baryons yet to be observed

Green: experimentally confirmed
Magenta: Missing states



Quark model predicts three singly-strange iso-doublets, $\Xi_b^{0,-}$, only the lowest-lying doublet pair is established.

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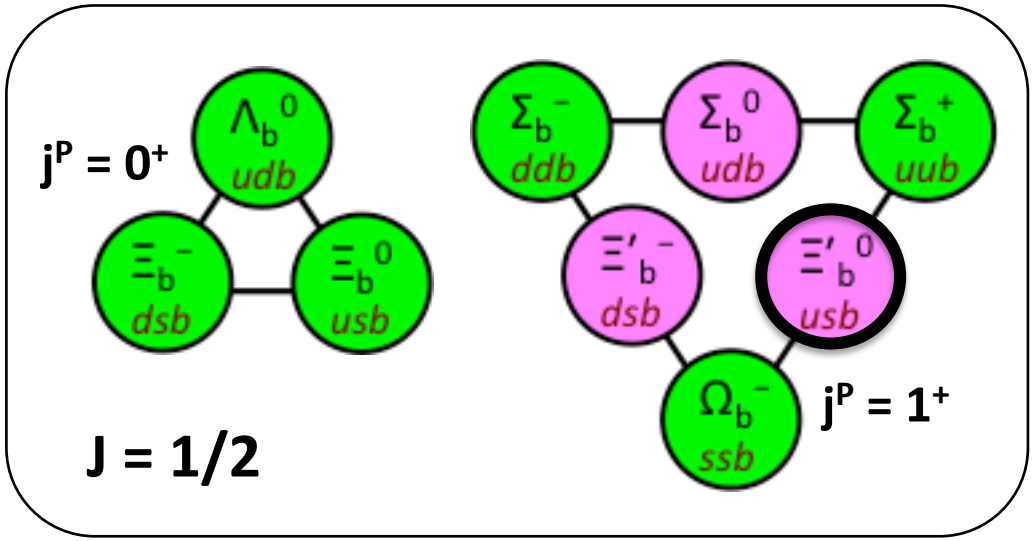

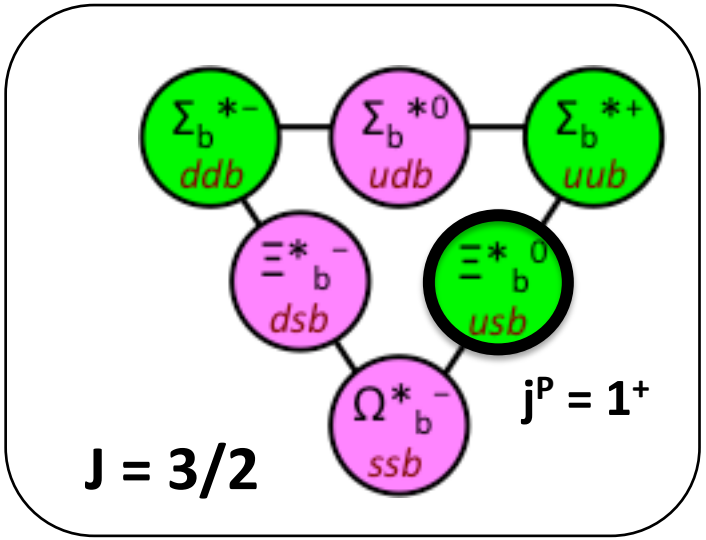

Last observation by CMS in 2012: $\Xi_b^{*0} \rightarrow \Xi_b^-(\rightarrow J/\psi \Xi^-)\pi^+$ but no sign of $j^P=1^+$ partner Ξ'^0_b, assumed to be below kinematic threshold, $M(\Xi_b'^0) - M(\Xi_b^-) < M(\pi^+)$.

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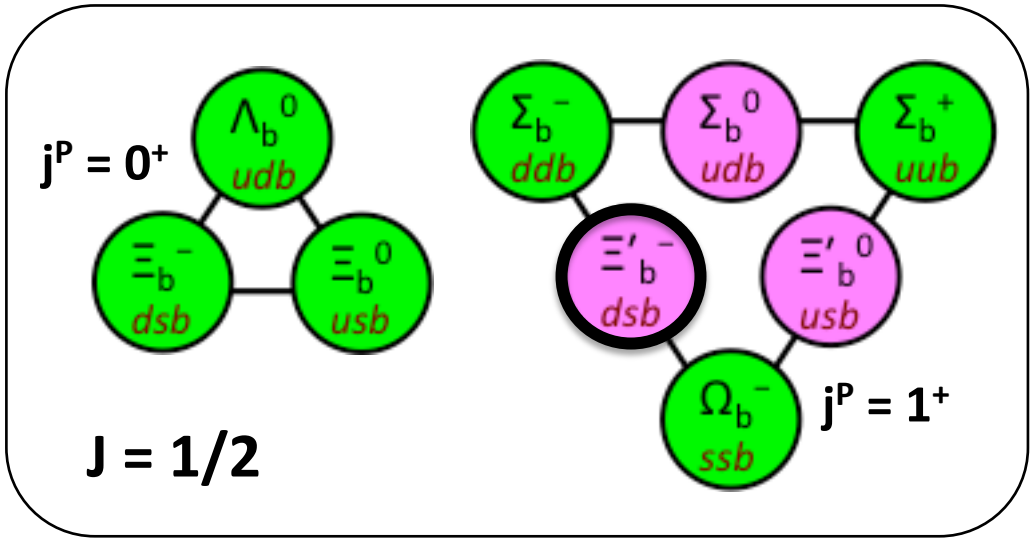

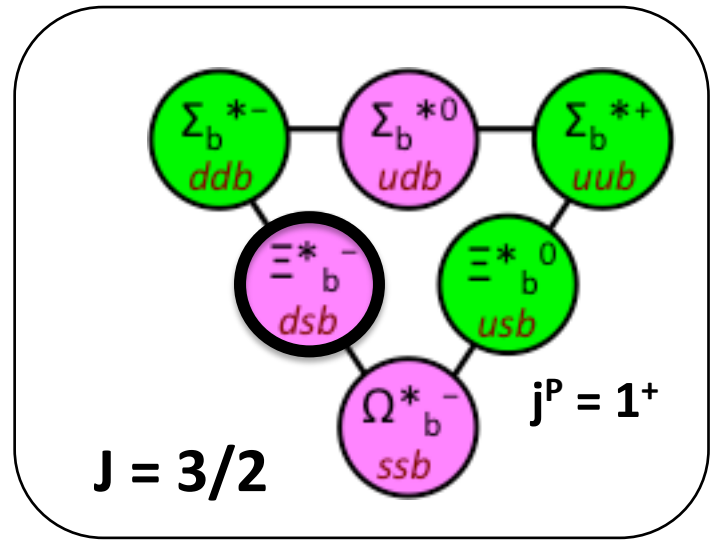

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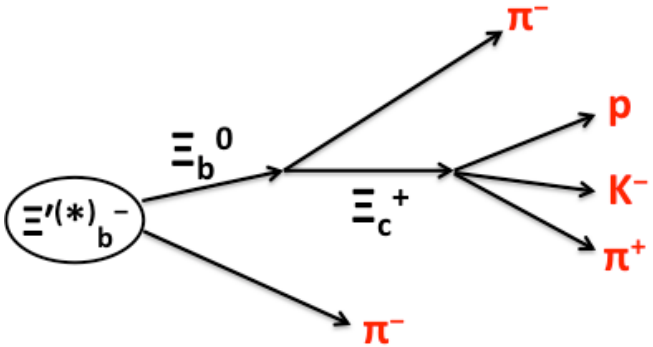
LHCb search for the charged isospin partners, $\Xi'^-_b, \Xi^{*-}_b \to \Xi_b^0\pi^-$.

Isospin splitting $O(10\ \mathrm{MeV}/c^2)$ may place both decays in kinematically-allowed region, in contrast to neutral case.

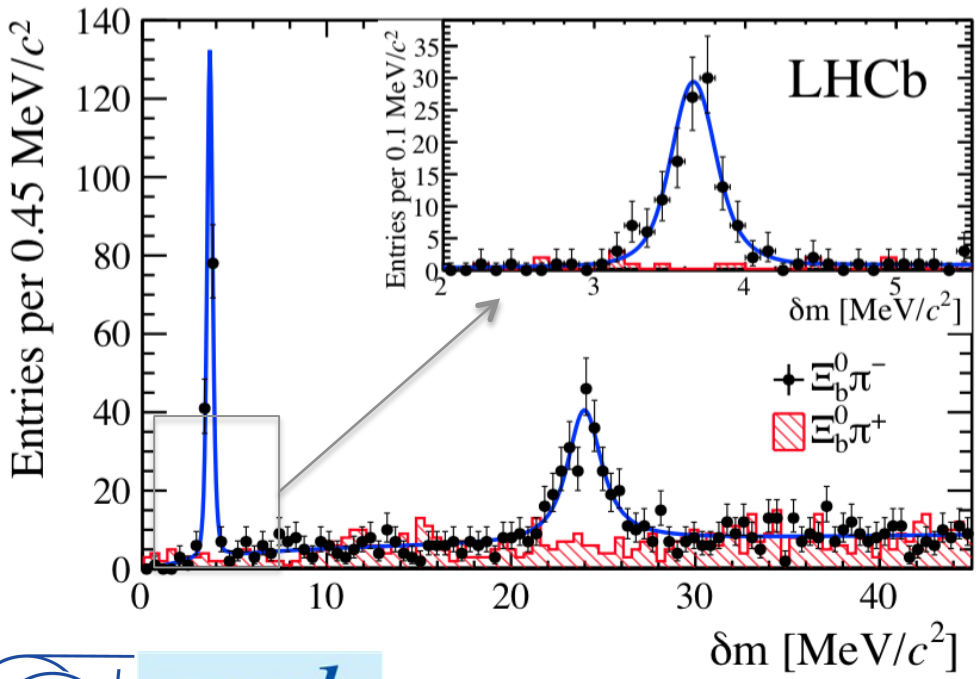
New $\Xi_b^{\pm}$ Resonances



Search for $\Xi_b'^{(*)-}$ states in fully-reconstructed hadronic decays:

Cut based analysis, using standard particle ID, kinematic, and topological selections

Two prominent peaks observed in $\delta m \equiv M_{cand}(\Xi_b^0\pi^-) - M_{cand}(\Xi_b^0) - M_{PDG}(\pi^-)$



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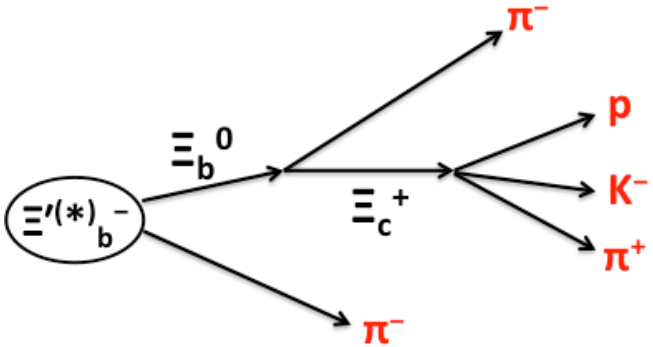

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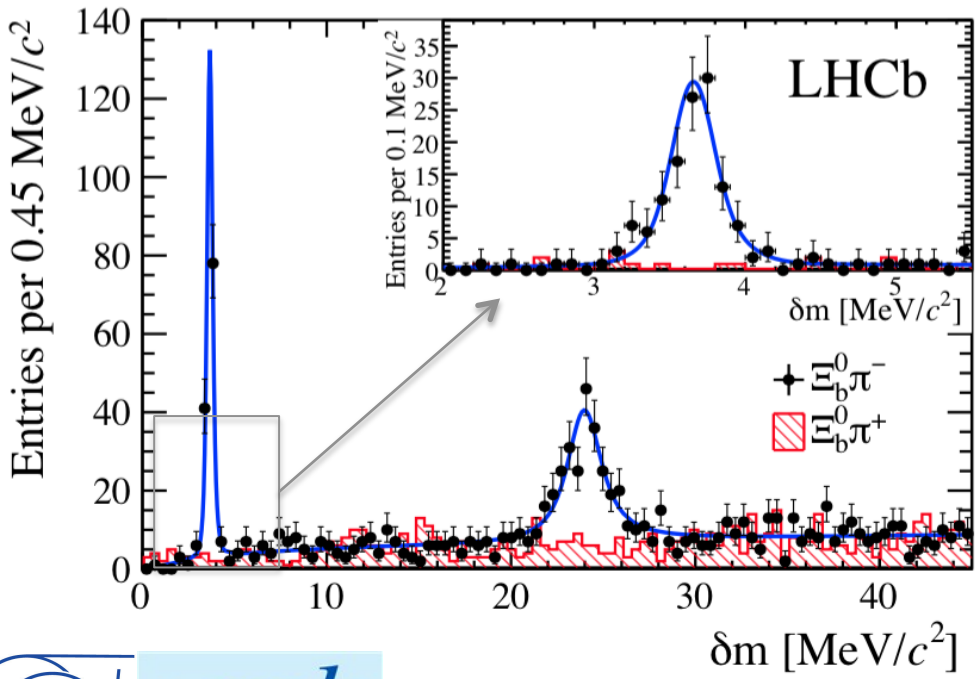
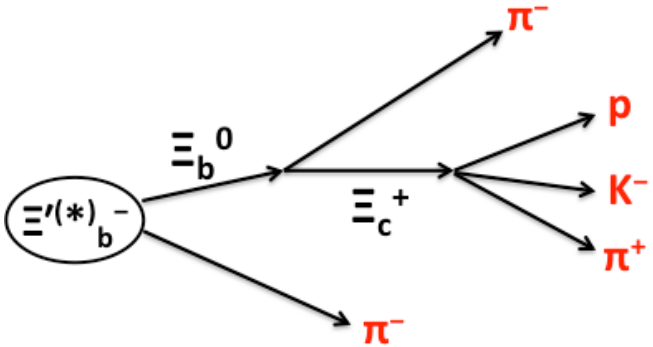


UML fit to the data, with two-peak hypothesis.

- Signal peaks: RBW convoluted with Resolution function
- For lower-mass peak, natural width consistent with zero – neglected in nominal fit.
- Combinatorial BG modelled by threshold function, validated on 'wrong sign' sample.

New $\Xi_b^{\pm}$ Resonances



Reconstruct $\Xi_b'^{(*)-}$ states in fully-reconstructed hadronic decays:

Cut based analysis, using standard particle ID, kinematic, and topological selections

Two prominent peaks observed in $\delta m \equiv M_{cand}(\Xi_b^0\pi^-) - M_{cand}(\Xi_b^0) - M_{PDG}(\pi^-)$

Both peaks have significance >10σ

Systematic uncertainties on masses and width much smaller than statistical

Source	$\delta m(\Xi_b')$	$\delta m(\Xi_b^*)$	$\Gamma(\Xi_b^*)$
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

New $\Xi_b^{\pm}$ Resonances

Upper limit on width of lower mass peak extracted from pseudoexperiments:

$\Gamma(\Xi'^{-}_b) < 0.08$ MeV @95% CL

Other mass parameters are measured:

$\delta m(\Xi'^{-}_b) = 3.653 \pm 0.018 \pm 0.006$ MeV/c^2

$\delta m(\Xi^{*-}_b) = 23.96 \pm 0.12 \pm 0.06$ MeV/c^2

$\Gamma(\Xi^{*-}_b) = 1.65 \pm 0.31 \pm 0.10$ MeV

Relative yields of excited and ground states used to extract production properties:

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

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

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

New $\Xi_b^{\pm}$ Resonances

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Angular analysis consistent with quark-model assignments, but cannot rule-out other options.

Signals also observed in cross-checks using alternative Ξ_b^0 channels:

- $\Xi_b^0 \to D^0(K^-\pi^+)pK^-$
- $\Xi_b^0 \to D^+(K^-\pi^+\pi^+)pK^-\pi^-$
- $\Xi_b^0 \to \Lambda_c^+(pK^-\pi^+)K^-\pi^+\pi^-$

Phys. Rev. Lett. 114 (2015) 062004
(arXiv:1411.4849)

Summary

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

arXiv:1502.02638
Submitted to JHEP 9 Feb 2015

(2) "Observation of overlapping spin-1 and spin-3 D^0K^- resonances at mass 2.86 GeV/c^2"

Phys. Rev. Lett. 113 (2014) 062001 ***(arXiv:1407.7574)***
Phys. Rev. D 90 (2014) 072003 ***(arXiv:1407.7712)***

(3) "Observation of two new Ξ_b^- baryon resonances"

Phys. Rev. Lett. 114 (2015) 062004
(arXiv:1411.4849)

Many more channels under investigation with the existing data

Upcoming run (~8fb^{-1}) will provide even greater discovery potential