Heavy Quark Spectroscopy at LHCb

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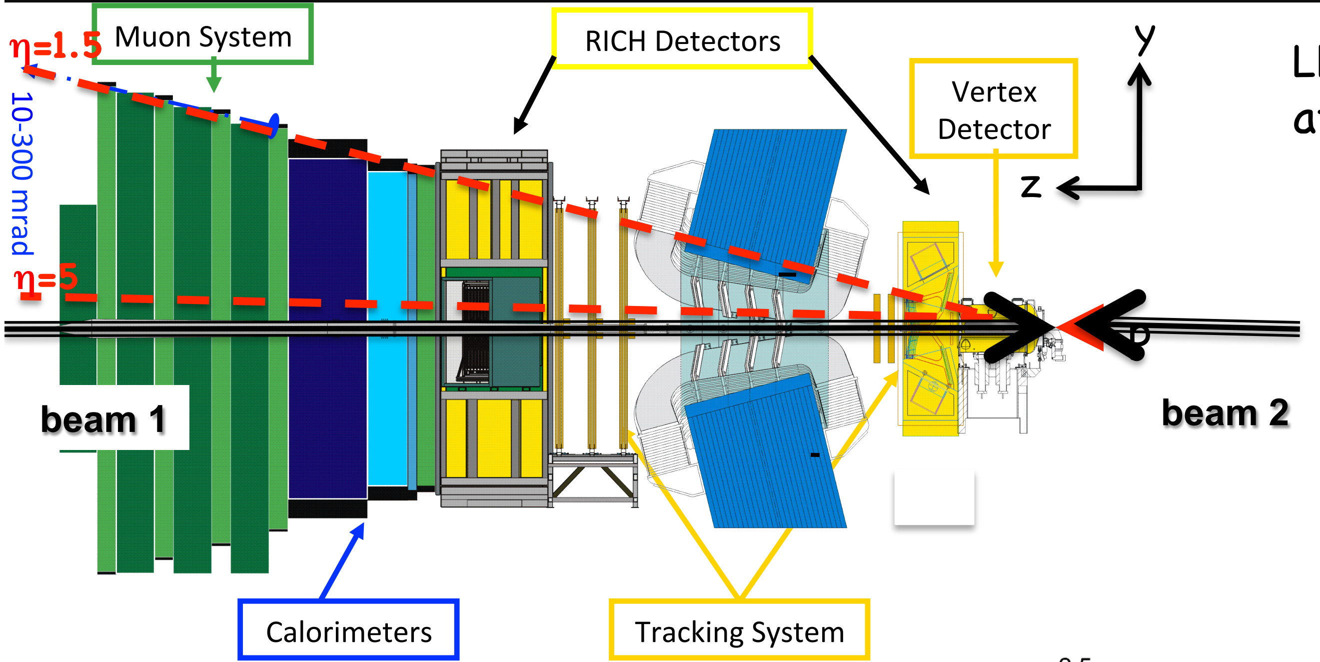
Outline

- Detector and accelerator: LHCb at the LHC
- Heavy baryon spectroscopy *VERY RECENT* results :
  - Observation of two new Ξ^-_b baryon resonances
    - [LHCB-PAPER-2014-061; arXiv:1411.4849;PRL 114 (2015) 062004]
  - 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, submitted to JHEP]
  - First Observation of the $B^- \rightarrow D^+ K^- \pi^-$ decay and study of its Dalitz plot structure
    - [LHCB-PAPER-2015-007; To be submitted to PRD]
- Conclusions and outlook

LHC and LHCb

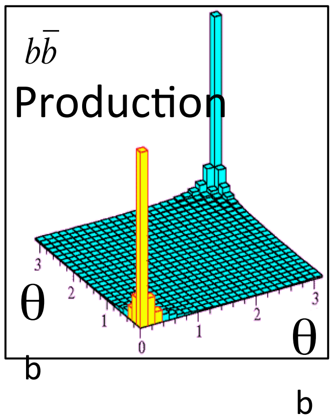
[JINST 3 (2008) S08005]



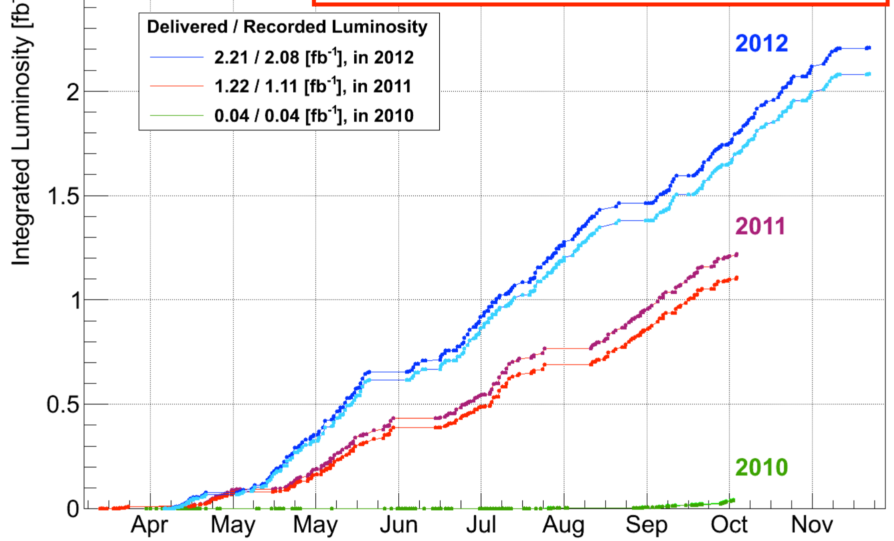
LHC pp collider : 2010-2013 at LHCb

- ➡ @ $\sqrt{s}$ = 2.76, 7, 8 TeV
- ➡ Tot L ≈3 fb^{-1}

In 2013 LHCb collected pA data -> Tot L ≈1.6 nb^{-1}



Uncertainty on Luminosity: 1.2% (J. Instrum. 9 (2014) P12005)



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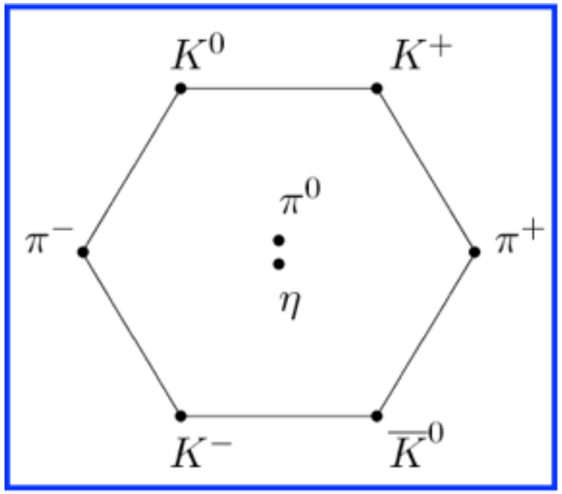
Introduction

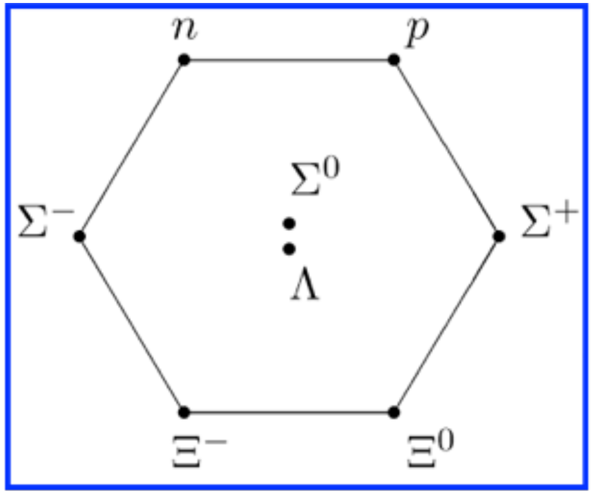
PRL 114 (2015) 062004

➡ Baryons in 2D



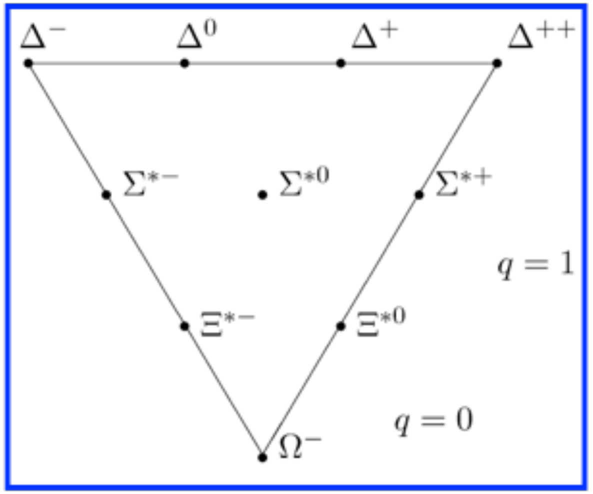
mesons ($J^P=0^-$)

(q-antiq)



baryons ($J^P={}^1/_2{}^+$)

(qq′q″)



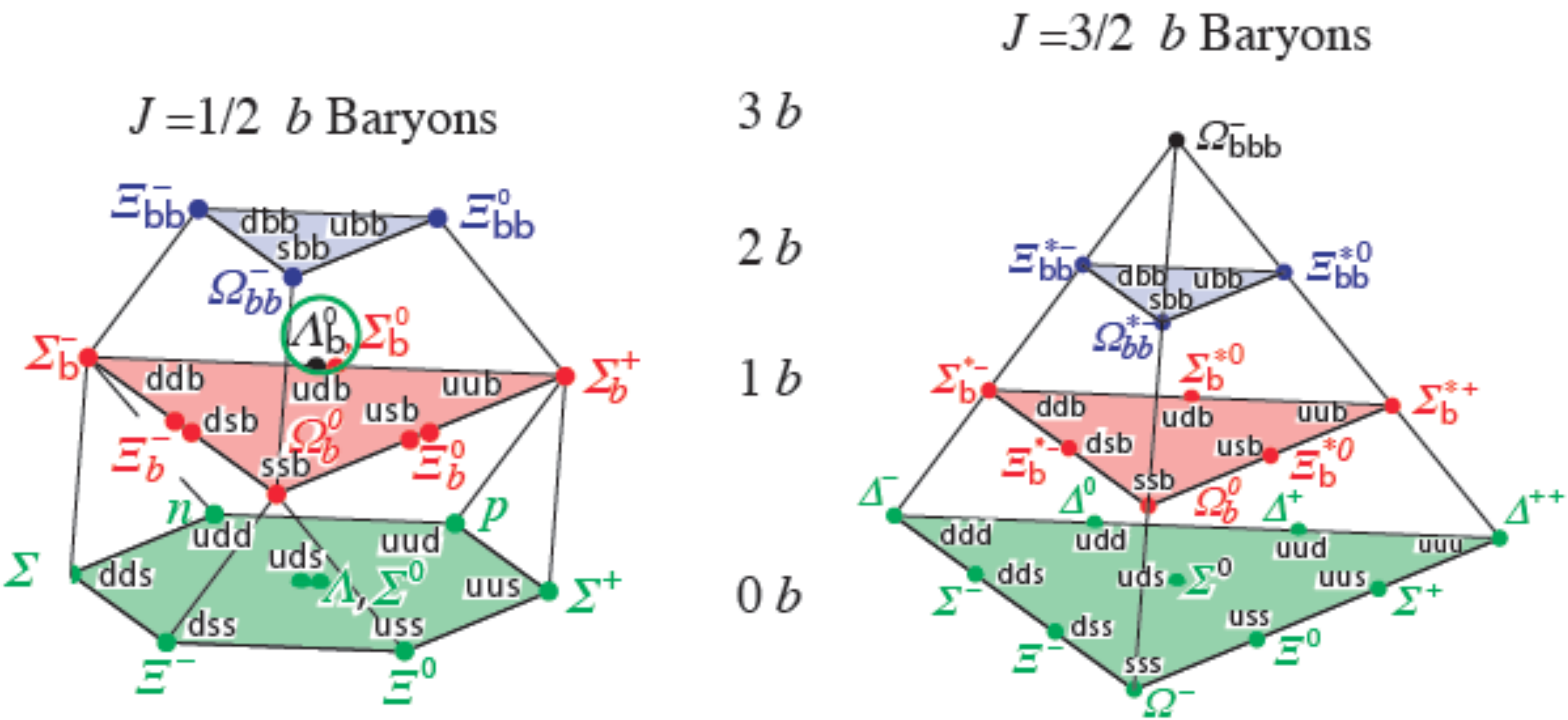
baryons ($J^P={}^3/_2{}^+$)

(qq′q″)

Introduction & Motivation

PRL 114 (2015) 062004

- ➡ Baryons in 3D
- ➡ The systems of baryons including a b are still largely unexplored



State of the art

PRL 114 (2015) 062004

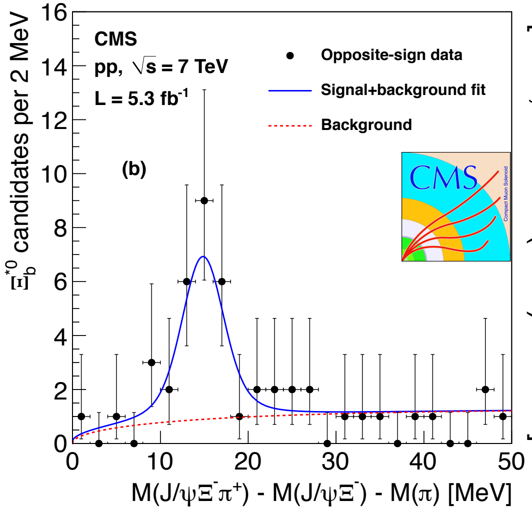
bqq (q=u,d,s) Baryons (B=1, C=0)

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

Missing states

State of the art

PRL 114 (2015) 062004



[CMS, PRL 108 (2012) 252002]

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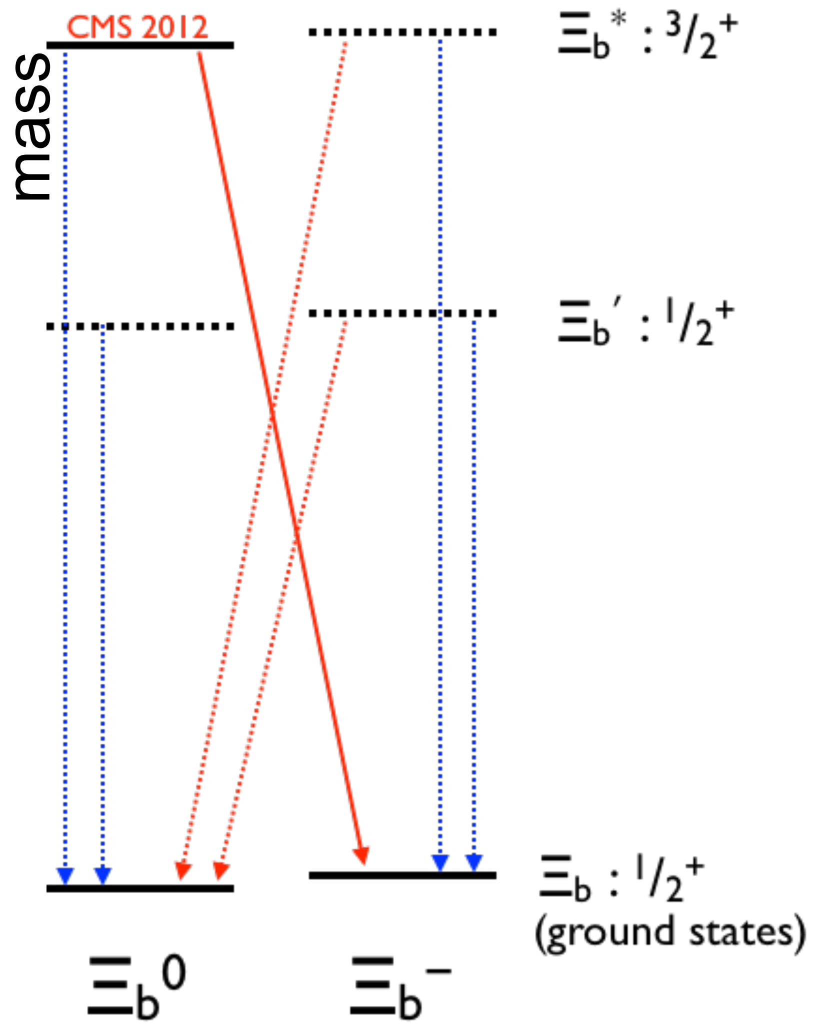
Missing states

Theory :

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

How to look for them?

PRL 114 (2015) 062004
[LHCB-PAPER-2014-061; arXiv:1411.4849]



Blue = neutral decay (π^0 or γ)

Red = charged decay ($\pi^{\pm}$)

Solid lines = already seen

Dotted lines = not **previously seen**

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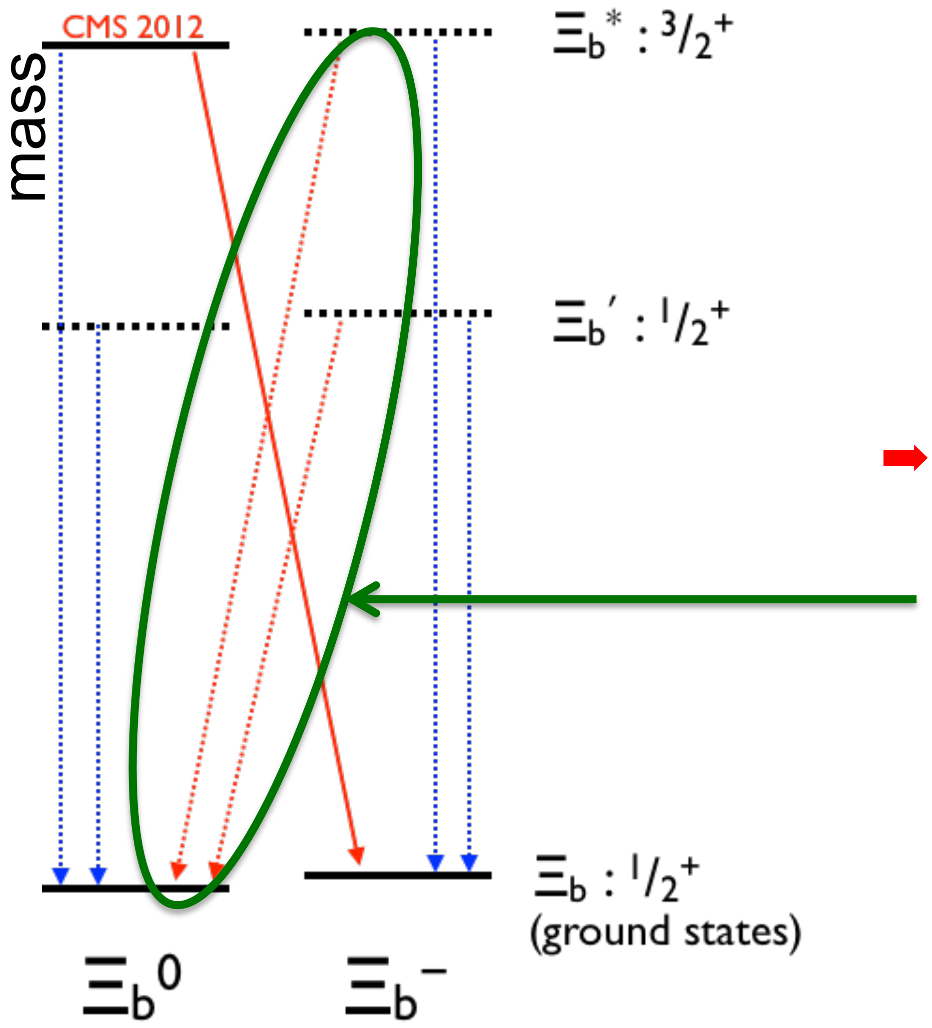
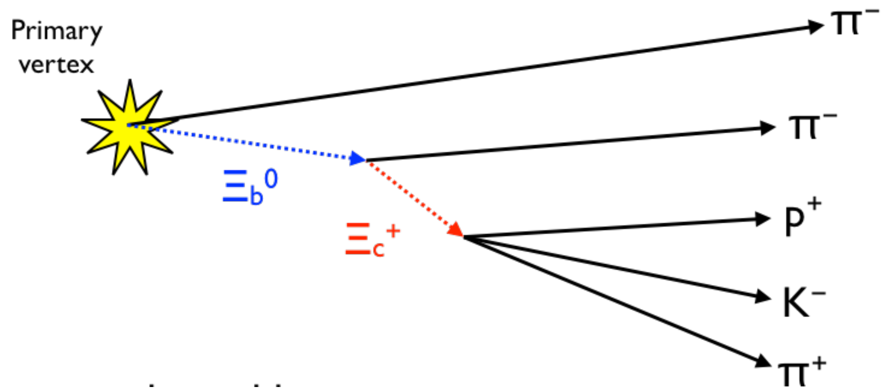


Blue = neutral decay (π^0 or γ)
Red = charged decay ($\pi^\pm$)
Solid lines = already seen
Dotted lines = not previously seen

➡ Search for these states in the $\Xi_b^0\,\pi^-$ final states (two dotted red lines), with $\Xi_b^0 \to \Xi_c^+(\to \pi^+ p^+ K^-)\pi^-$



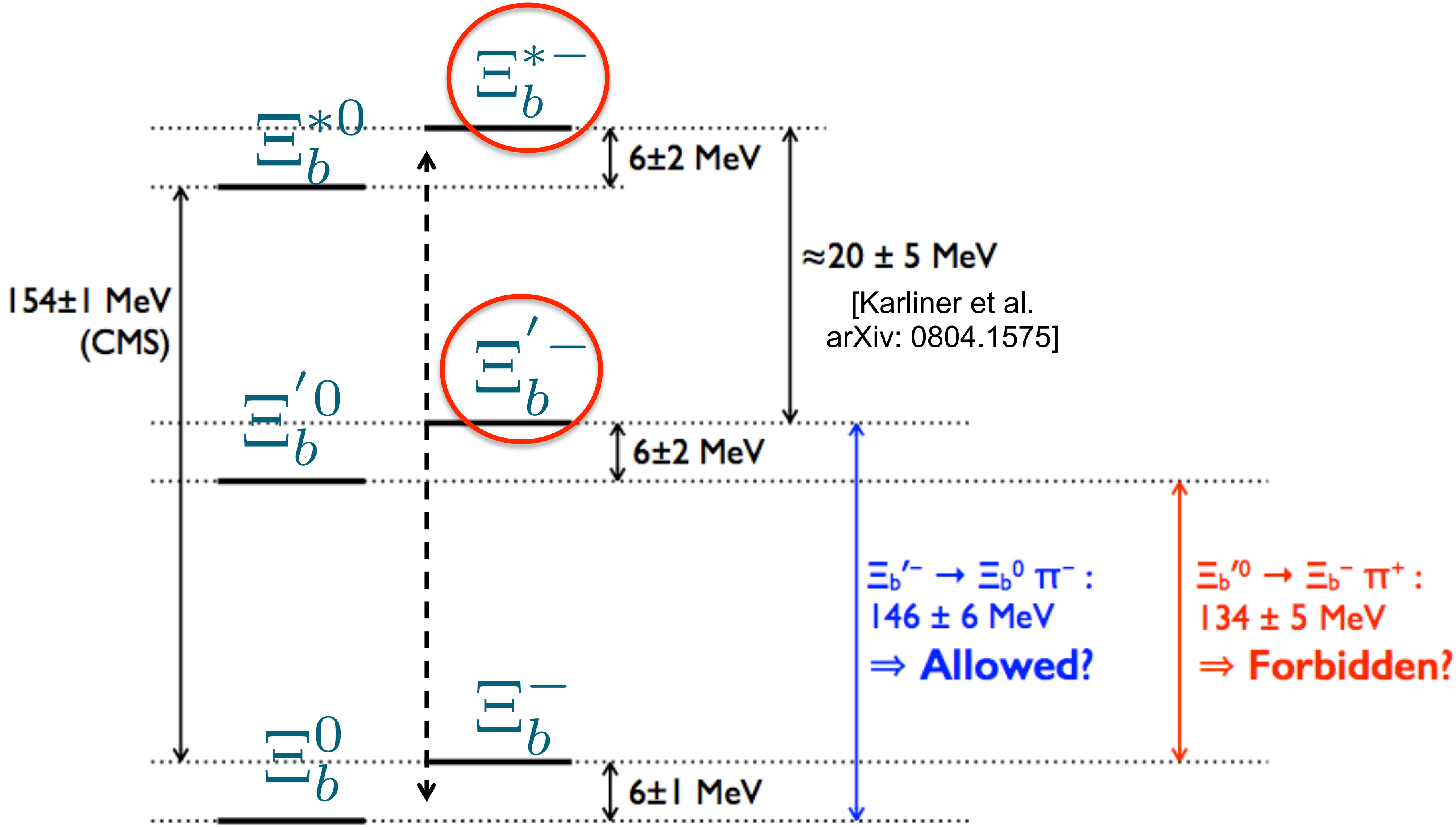
NB: This does not work for the Ξ_c' -> too light !

Mass Splittings

PRL 114 (2015) 062004

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

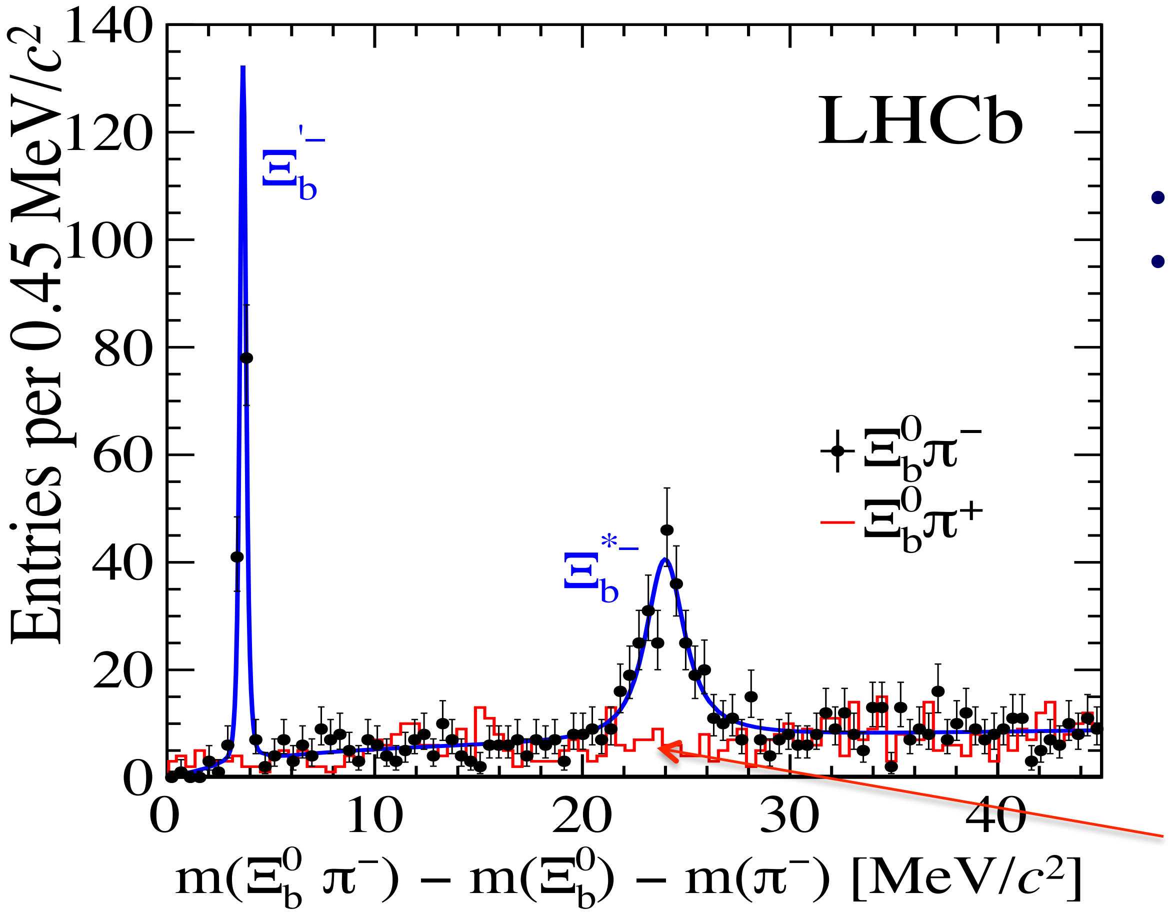
➡ Assuming isospin splitting~ 6 MeV measured in the Ξ_b sector is the same for all Ξ_b^*



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

PRL 114 (2015) 062004
[LHCB-PAPER-2014-061; arXiv:1411.4849]

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



Fit Model

- $\Xi_b'^-$: Resolution function
- Ξ_b^{*-} : P-wave Relativistic Breit-Wigner ⊗ Resolution

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

Signal significances > 10 σ

Probability peak at ~3 MeV is a feed-down of $\Xi_b^{**-} \to \Xi_b'^0 (\Xi_b^0 \pi^0) \pi^-$ very low

Results

PRL 114 (2015) 062004

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

- The first peak is very narrow -> upper limit on its width Γ, then fix it to zero for the baseline fit

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

- With this assumption :

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

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

- Further measurements of spin and relative production fractions (in the back-up) give further indication on the identity of these states

PRL 114 (2015) 062004

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B** Spectroscopy

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

- Heavy Quark Effective Theory (HQET) predicts spectrum of excited B states
  - Spectrum almost identical for charged and neutral B^{**} states
  - Higher excitations in $B/B* + \pi$
- States **largely unknown**
- **Predicted:** broad B^*_0/B^+_1 states,
- **Observed**: narrow B_1/B^*_2 states

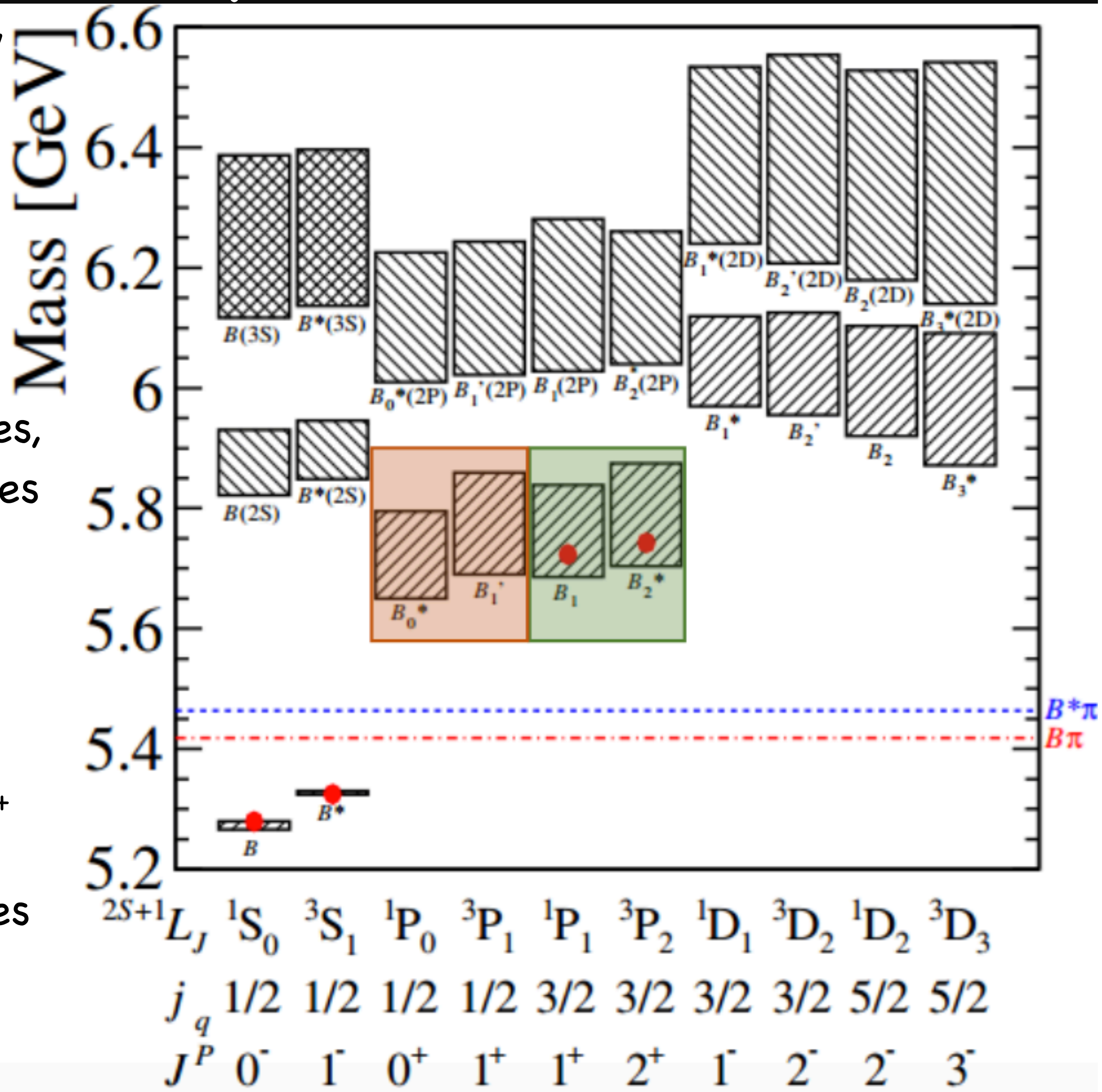
  interpreted as overlap of B_1^0 and $B_2^{*0} \rightarrow B^{*+}\pi^-$

  [CDF, Phys.Rev.Lett. 102 (2009) 102003]

  [D0, Phys.Rev.Lett. 99 (2007) 172001]
- LHCb reported the first observation of charged B_1^+, B_2^{*+}

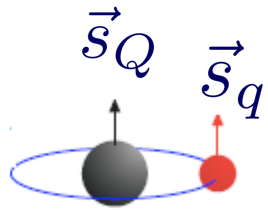
  [LHCb-CONF-2011-053]
- Evidence for higher mass states $B(5970)^{0,+}$ from CDF

  [Phys.Rev. D90 (2014) 1, 012013]



Motivation & Notation [LHCB-PAPER-2014-067; arXiv:1502.02638]

➡ 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… → S, P, D

PDG notation- USED HERE

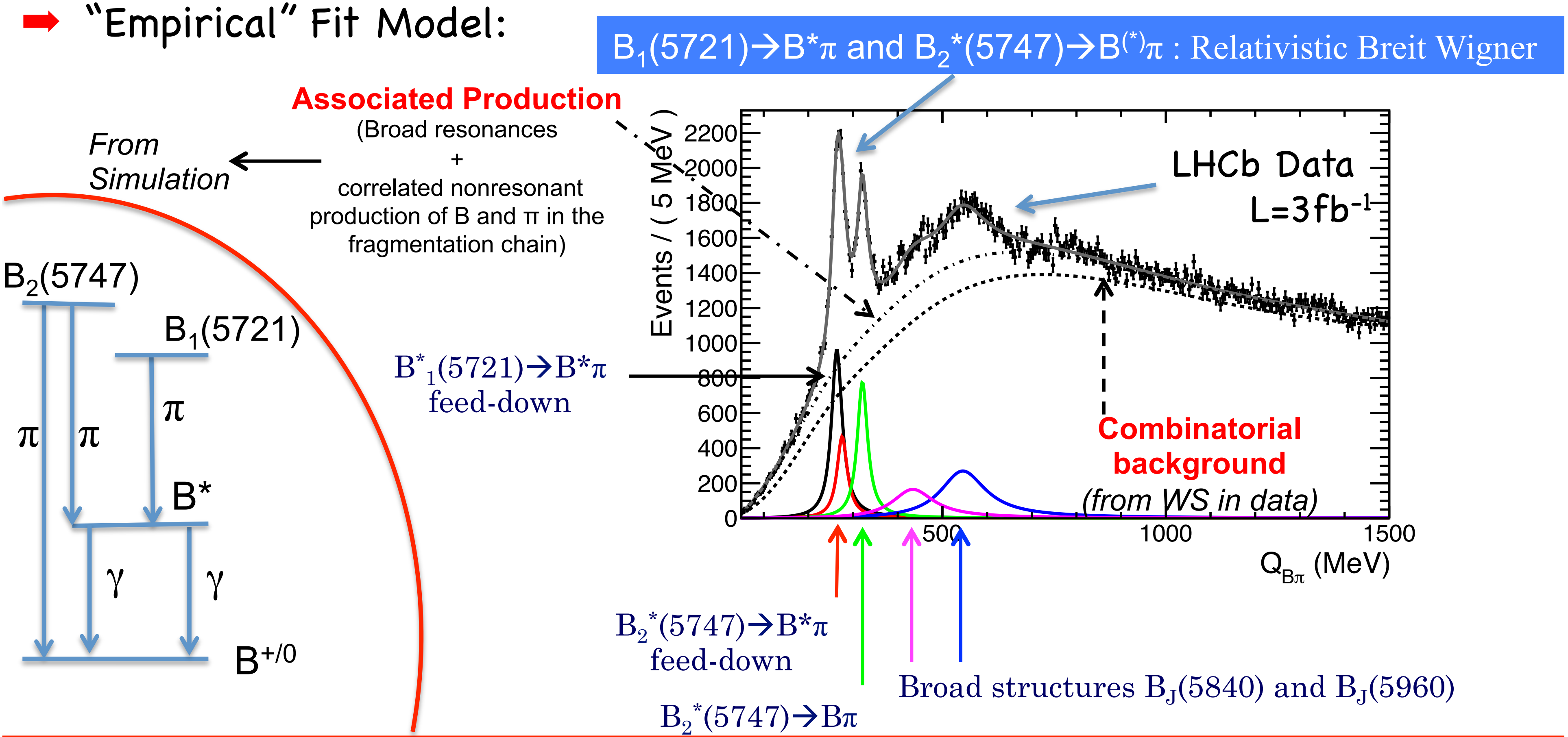
Natural spin-parity $J^P = 0^+, 1^-, 2^+, \ldots$

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

Mass

Search for B** in $B^{+/0}\pi^{-/+}$ [LHCB-PAPER-2014-067; arXiv:1502.02638]

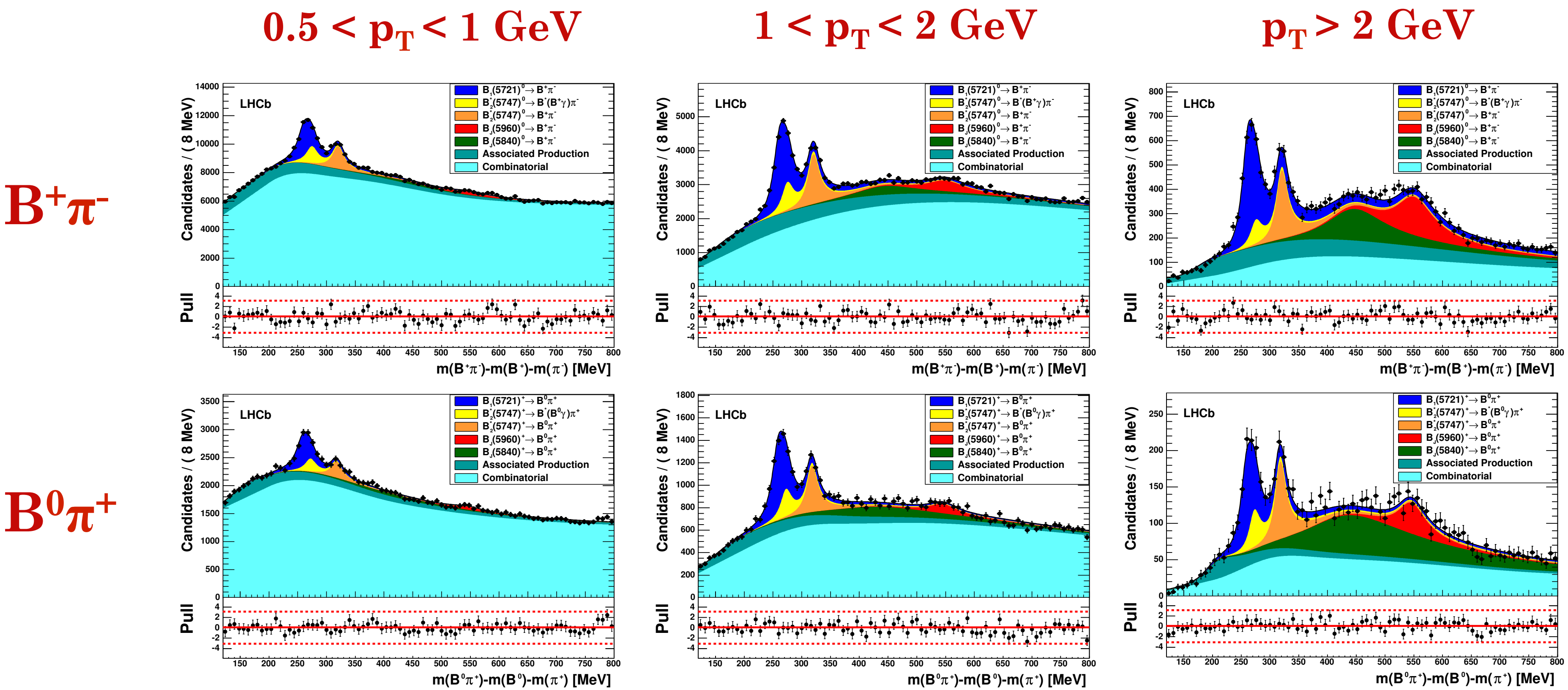
- Search for new structures in Bπ final states;
  - $B^+(B^0)$ candidates within ±25(50) MeV/c², decay time > 0.3 ps, combined with $\pi^-(\pi^+)$ (p_T>0.5 GeV/c, PID, small IP)
- Simultaneous fit to 3 bins for p_T of "companion" pion in $B^+\pi^-$, $B^0\pi^+$
- "Empirical" Fit Model:



Fit results

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

➡ In bins of p_T of the companion pion



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

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

$B_2^*(5747)^0 \to B^+\pi^-$

$B_J(5960)^+ \to B^0\pi^+$

$B_J(5840)^+ \to B^0\pi^+$

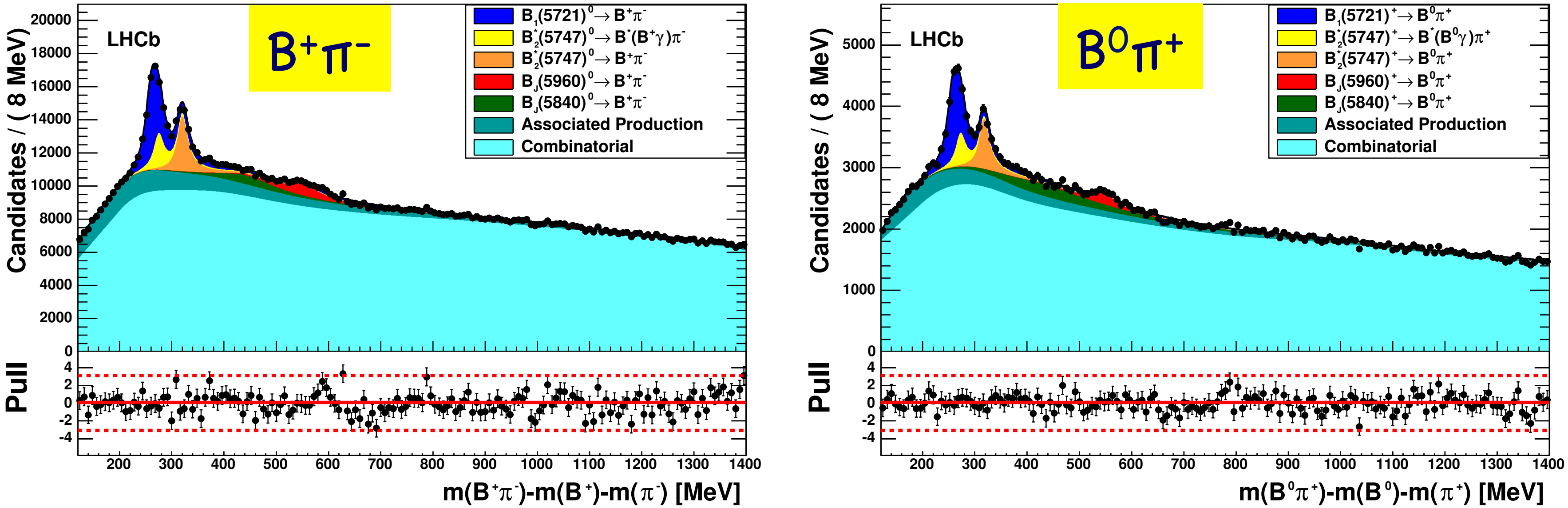
Associated Production

Combinatorial

Fit Results Integrated Over p_T

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

$p_T > 0.5$ GeV



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

Significances:

$B^+\pi^-$: 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

$B_1(5721)^{0,+}$ and $B_2^*(5747)^{0,+}$ Results [arXiv:1502.02638]

- Mass and width measurements presented for **narrow states**
  - Measurements agree with (but are more precise than) CDF results

		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

- Measured also relative productions :

stat. syst.

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

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

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

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

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

[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 $B\pi$

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

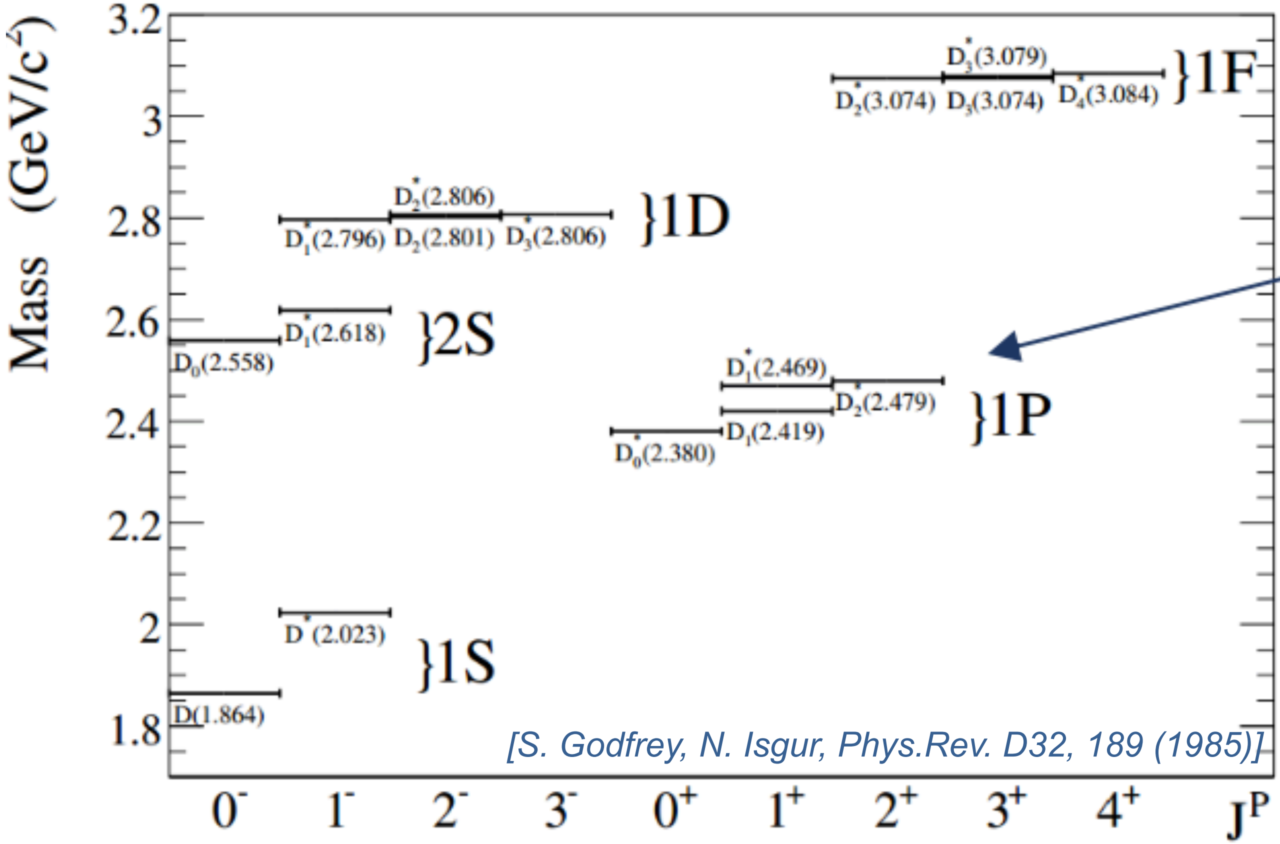
Structure at high mass clearly observed; measured parameters and interpretation depend on model assumptions

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

Outline

- ➡ Detector and accelerator: LHCb at the LHC
- ➡ Heavy baryon spectroscopy results :
  - Observation of two new Ξ^-_b baryon resonances
    - [LHCB-PAPER-2014-061; arXiv:1411.4849; PRL.114(2015) 062004]
  - 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, submitted to JHEP]
  - First Observation of the $B^- \to D^+K^-\pi^-$ decay and study of its Dalitz plot structure
    - [LHCB-PAPER-2015-007; To be submitted to PRD]
- ➡ Conclusions and outlook

D^{**} Spectroscopy : current

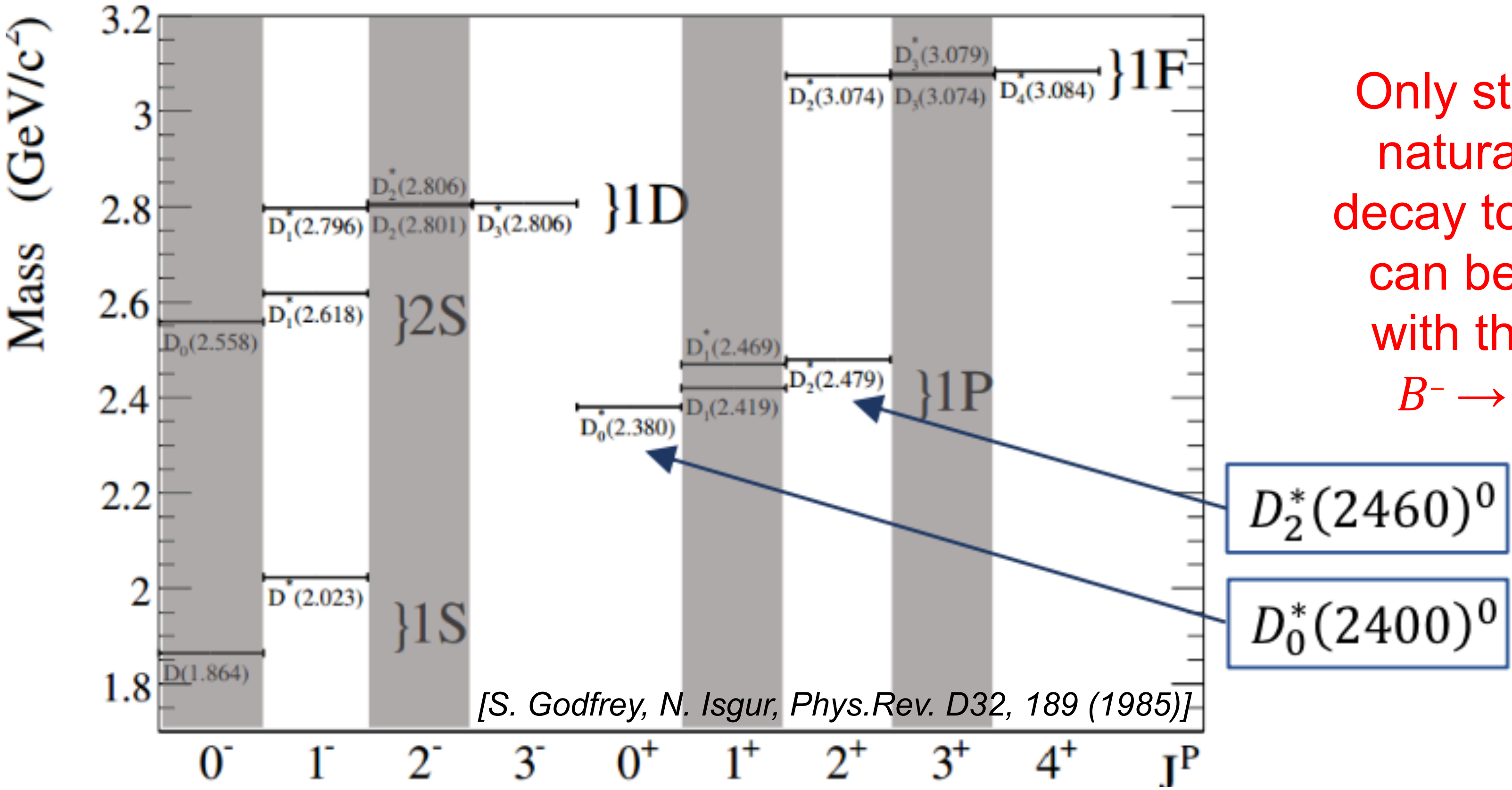


Parameters of orbitally excited (1P) states measured at B-factories and LHCb

Phys.Rev. D69 (2004) 112002
Phys.Rev. D79 (2009) 112004
Phys.Rev. D82 (2010) 111101
JHEP 1309 (2013) 145

➡ Charm spectrum predicted

D^{**} Spectroscopy : current



Only states with natural J^P can decay to $D^+\pi^-$ and can be studied with the decay $B^- \rightarrow D^+K^-\pi^-$

- ➡ Charm spectrum predicted
- ➡ Experimental results from Dalitz plot analyses [$D^*_0(2400)$] and prompt production[$D^*_2(2460)$] : discrepancies w.r.t. Theory
- ➡ Evidence for higher mass states, but not yet possible to assign quantum numbers->need amplitude analysis !

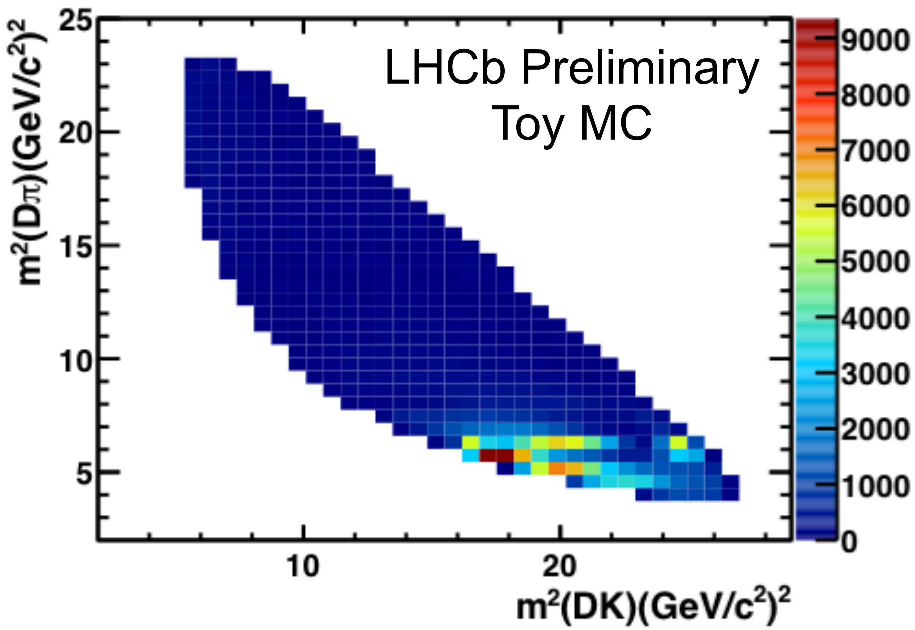
D^{**} Spectroscopy with $B^- \to D^+K^-\pi^-$

➡ $B^- \to D^+K^-\pi^-$ is an interesting mode to study D^{**} spectrum

- Decay previously unobserved -> first: measure branching fraction
- No resonances expected to decay to D^+K^- or $K^-\pi^-$ -> clean final state

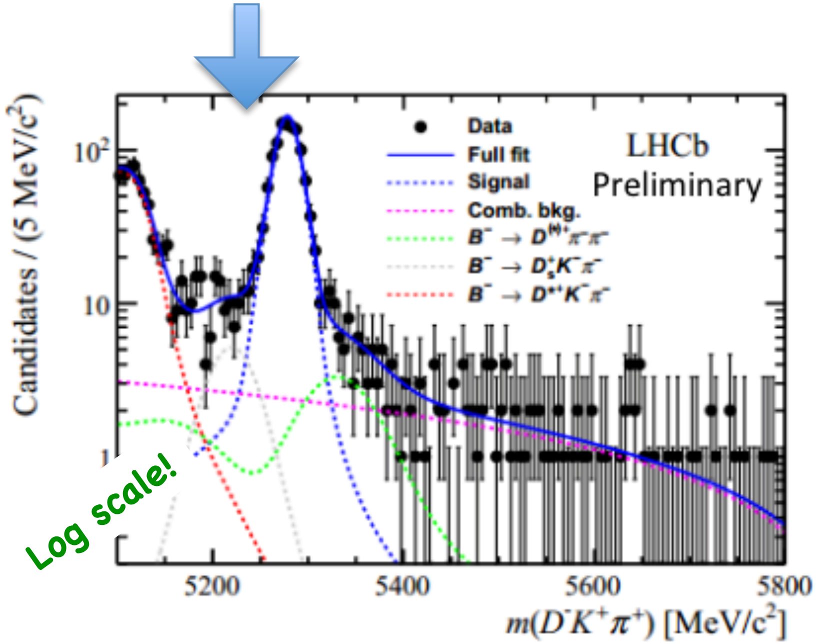
➡ Dalitz plot analysis of $B^- \to D^+K^-\pi^-$ can be very powerful !!

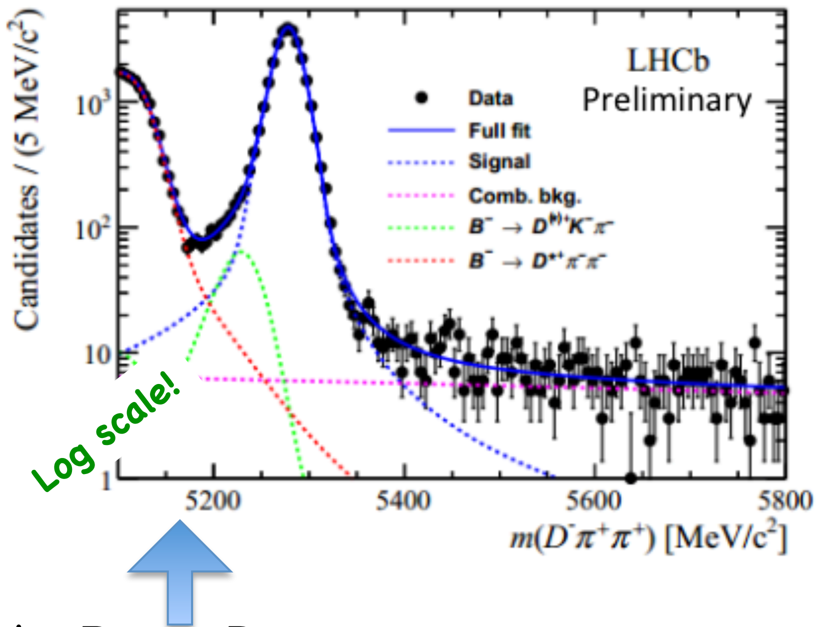
- Clean and constrained method compared to inclusive production studies
- Only states with natural spin-parity (J^P) can decay to $D^+\pi^-$
  ($D^*\ 2400^0$, $D^*\ 2460^0$ and higher mass states expected to contribute)
- Amplitude analysis techniques give spin-parity information



Branching Fraction measurement

- Events pre-selected with loose requirements and refined with neural network [M. Feindt and U.Kerzel, Nucl. Instrum. Meth. A559 (2006) 190]
- ~2000 $B^- \to D^+K^-\pi^-$ candidate events (> 60σ observation!)



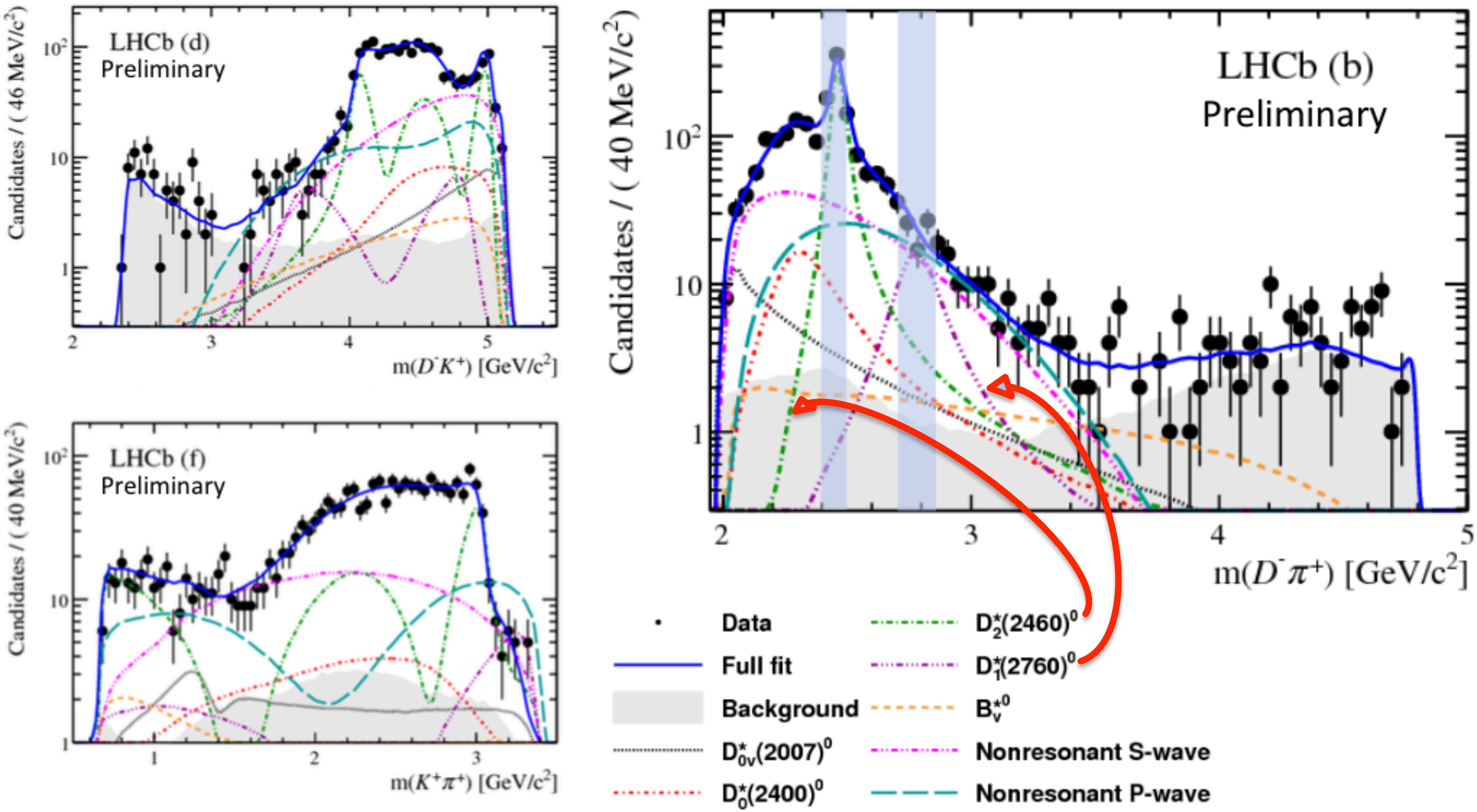


- Branching fraction measured relative to $B^- \to D^+\pi^-\pi^-$

$$\mathcal{B}(B^- \to D^+K^-\pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}$$

stat. syst. PDG uncertainty on B($B^- \to D^+\pi^-\pi^-$)

Dalitz Plot Fits



Dalitz Plot Analysis Results

- $D^*_1(2760)^0$ determined to have spin 1
  - Other hypotheses rejected with high significance
- Measured masses and widths of $D^*_2(2460)^0$ and $D^*_1(2760)^0$:

stat. syst. model

$$\begin{aligned} m(D_2^*(2460)^0) &= (2464.0 \pm 1.4 \pm 0.5 \pm 0.2)\,\mathrm{MeV}/c^2\,, \\ \Gamma(D_2^*(2460)^0) &= (43.8 \pm 2.9 \pm 1.7 \pm 0.6)\,\mathrm{MeV}\,, \\ m(D_1^*(2760)^0) &= (2781 \pm 18 \pm 11 \pm 6)\,\mathrm{MeV}/c^2\,, \\ \Gamma(D_1^*(2760)^0) &= (177 \pm 32 \pm 20 \pm 7)\,\mathrm{MeV}\,, \end{aligned}$$

- Measured product of branching fractions of resonances times $\mathcal{B}(B^- \to D^+K^-\pi^-)$:

Resonance	Branching fraction (x10^{-4})
$D_0^*(2400)^0$	$6.6 \pm 2.1 \pm 0.5 \pm 1.5 \pm 0.4$
$D_2^*(2460)^0$	$25.2 \pm 1.2 \pm 0.7 \pm 1.1 \pm 1.7$
$D_1^*(2760)^0$	$3.9 \pm 1.0 \pm 0.3 \pm 0.7 \pm 0.3$
S-wave nonresonant	$30.1 \pm 5.9 \pm 1.2 \pm 8.6 \pm 2.0$
P-wave nonresonant	$18.9 \pm 4.4 \pm 1.6 \pm 2.9 \pm 1.3$
$D_v^*(2007)^0$	$6.0 \pm 1.8 \pm 1.0 \pm 1.2 \pm 0.4$
B_v^*	$2.9 \pm 1.5 \pm 0.7 \pm 1.3 \pm 0.2$

stat. syst. model uncertainty on $\mathcal{B}(B^- \to D^+K^-\pi^-)$

Conclusions and Outlook

Several spectroscopy results produced by LHCb recently!

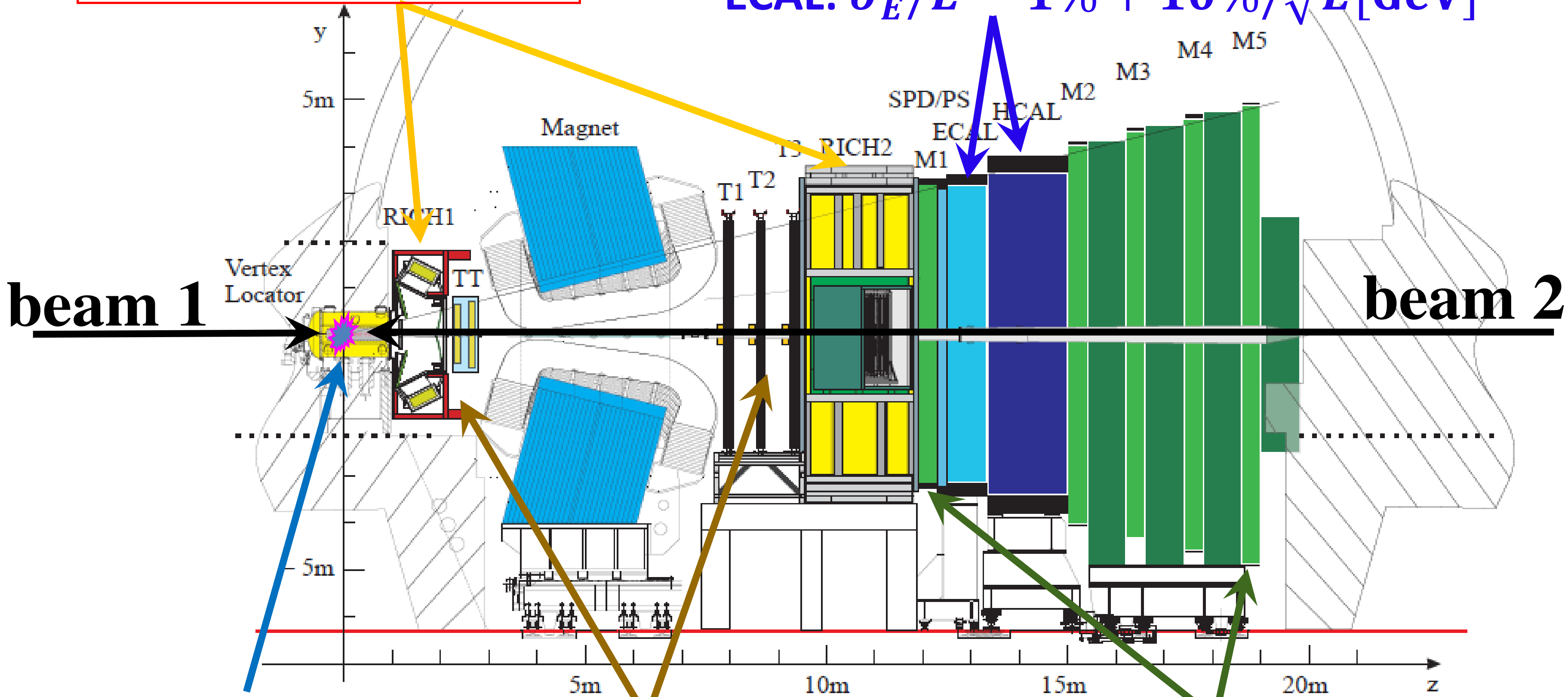
- Shown today:
  - Observation of new Ξ^- resonances [Phys. Rev. Lett. 114, 062004 (2015)]
  - New B^{**} results from studies of $B^0\pi^+$ and $B^+\pi^-$ mass distributions
    - First evidence of $B^*_2(5747)^0 \to B^{*+}\pi^-$ decay
    - Masses and widths of $B_1(5721)$ and $B^*_2(5747)$ states measured
    - Results for higher mass states depend on fit model used
  - New D** results from Dalitz plot analysis of $B^- \to D^+K^-\pi^-$ decays
    - First observation of $B^- \to D^+K^-\pi^-$ decay
    - $D^*_1(2760)^0$ determined to have spin 1
    - Masses and widths of $D^*_2(2460)$ and $D_1^*(2760)^0$ measured
    - Product branching fractions of resonances measured
- More soon !

Back up

LHCb

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\mathrm{GeV}]}$



VELO
$\sigma_{\mathrm{IP}} \sim 20\ \mu\mathrm{m}$
for high-p_{T} tracks

Tracking System
$\Delta p/p = 0.5\%$@ 5GeV/c
to 1%@200 GeV/c

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ mis-id: $1 \sim 3\%$

B** Systematic Uncertainties

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

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

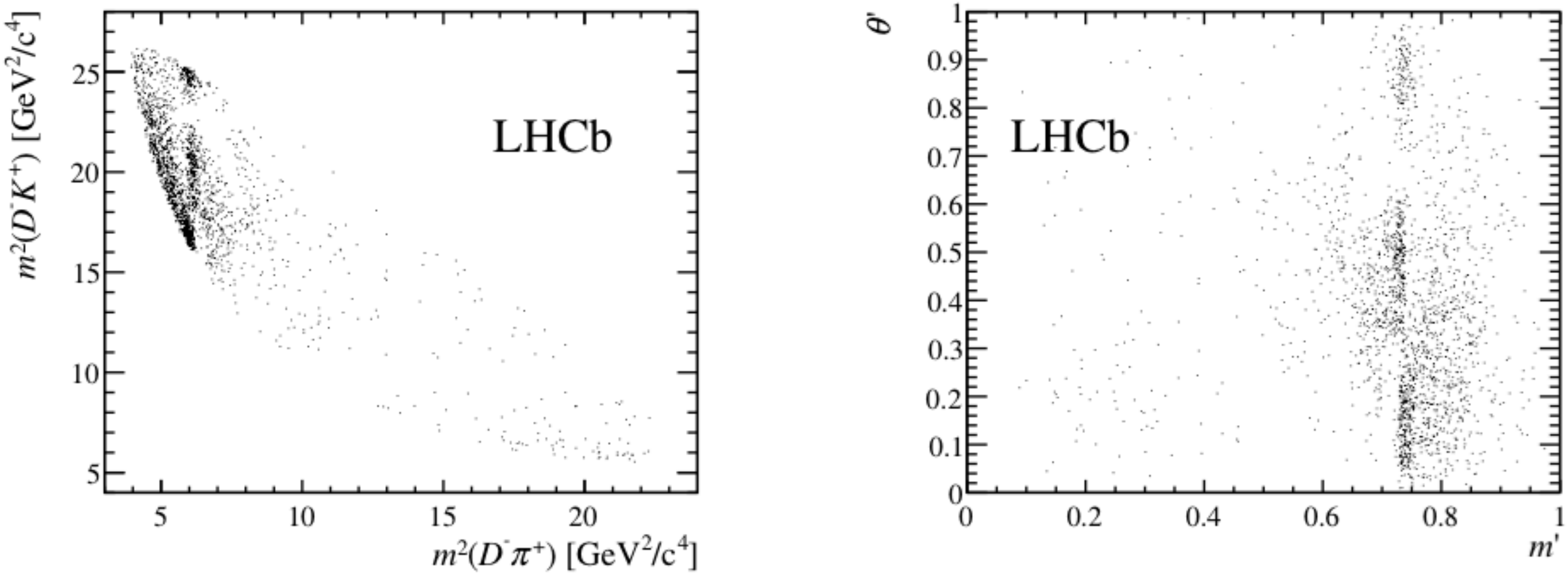
Signals have been observed in

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

LHCB-PAPER-2015-007

Actual Dalitz Plot

- DP=Dalitz Plot
- SDP = Squared Dalitz Plot



Distribution of $B^- \to D^+ K^- \pi^-$ candidates in the signal region over (a) the DP and (b) the SDP.