STUDY OF *b* HADRON PROPERTIES AT LHCb

Marco Pappagallo

University of Glasgow

On behalf of the LHCb collaboration

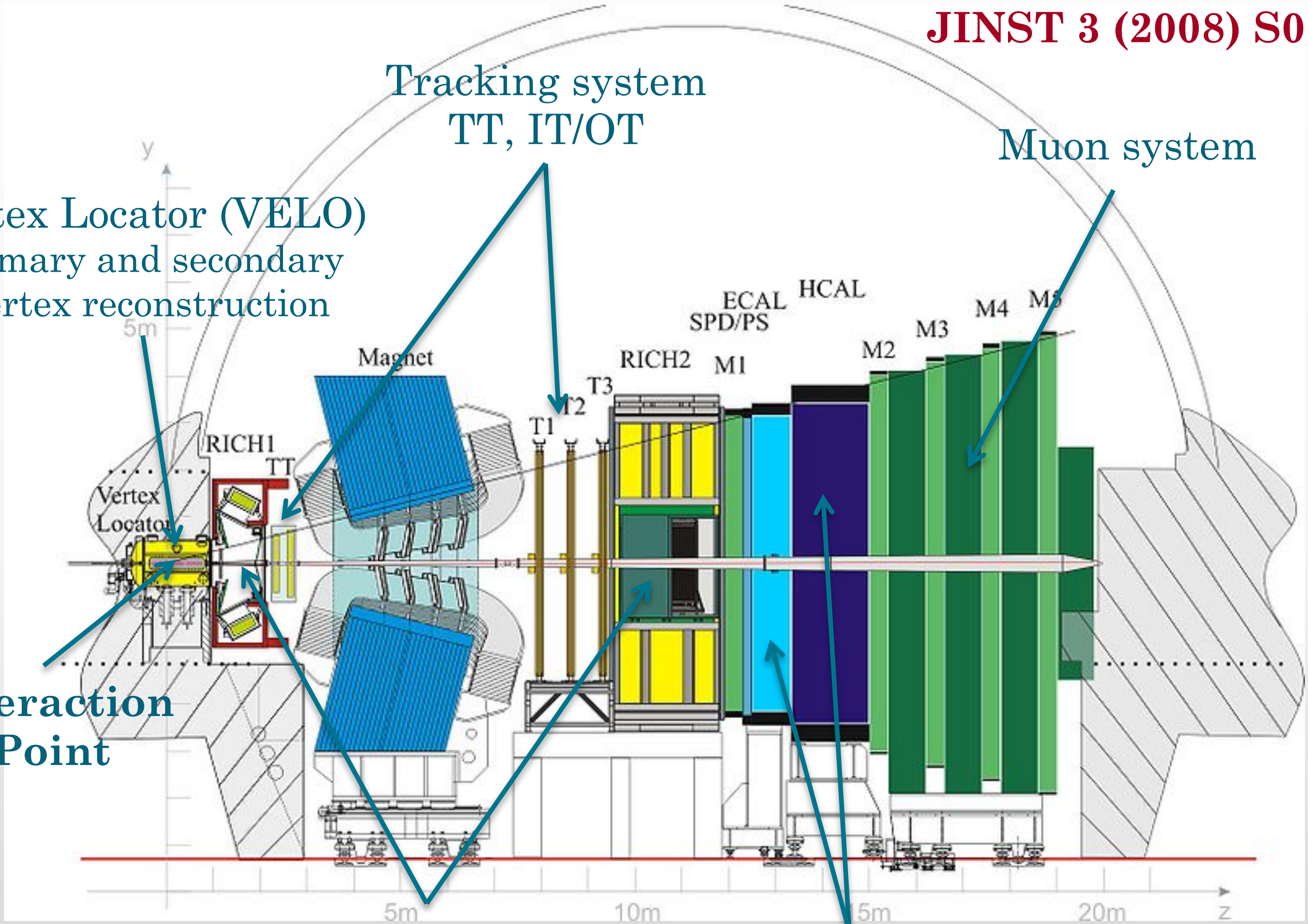
CERN, 5 February 2013

OUTLINE

- The LHCb detector
- First observation of the decay $B_{s2}^* \to B^{*+} K^-$ [LHCB-PAPER-2012-030; arXiv:1211.5994]
- Observation of excited Λ^0_b baryons [LHCB-PAPER-2012-012; PRL 109 (2012) 172003]
- Measurement of the Λ^0_b, Ω^-_b and Ξ^-_b baryon masses [LHCB-PAPER-2012-048 in preparation]
- Measurement of the Λ^0_b production polarisation [LHCB-PAPER-2012-057 in preparation]

THE LHCb DETECTOR

JINST 3 (2008) S08005



Tracking system
TT, IT/OT

Muon system

Vertex Locator (VELO)
Primary and secondary
Vertex reconstruction

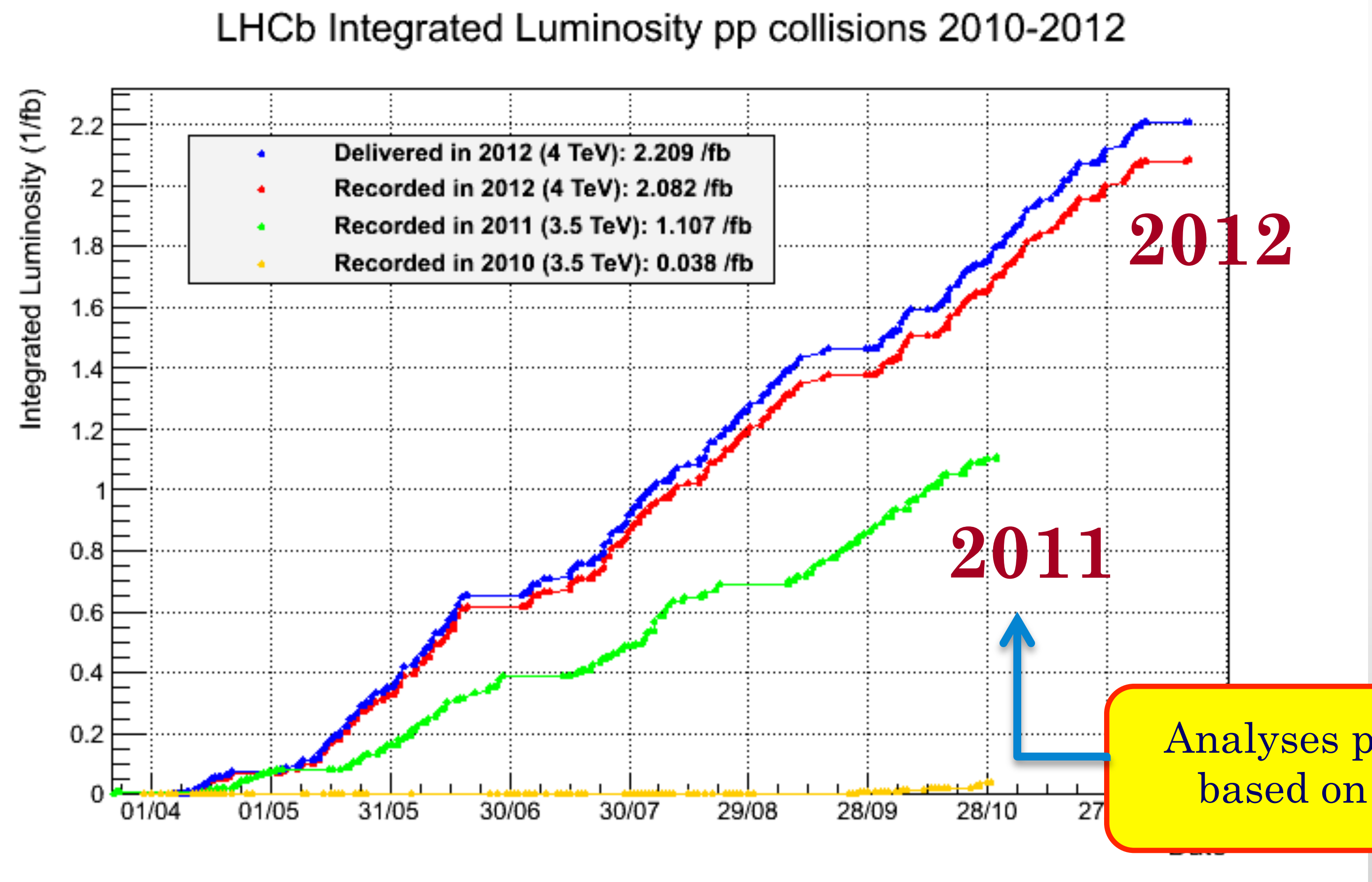
Interaction Point

RICH detector
PID K, π

Calorimeters
e, γ, π^0, n

DATASETS

LHCb collected 1.0 fb^{-1} at 7 TeV (2011) + 2.1 fb^{-1} at 8 TeV (2012)



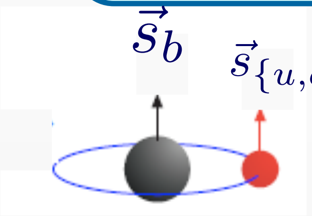
Analyses presented today are based on the 2011 dataset

First observation of the decay $B_{s2}^{*}(5840)^0 \rightarrow B^{*+}K^-$ and studies of excited B^0_s mesons

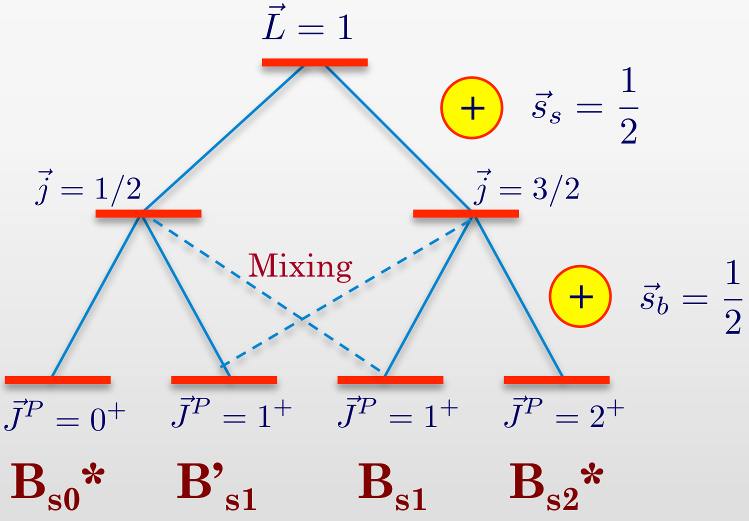
[LHCB-PAPER-2012-030; arXiv:1211.5994]

MOTIVATION

- The heavy quark effective theories (HQET) predict the masses of the $B_{(s)}$ mesons assuming $m_{\{u,d,s\}}/m_b \sim 0$
- Precise measurements of the excited B and B_s meson properties are a sensitive test of the validity of HQET



$\vec{L}$	Relative orbital angular momentum
$\vec{j} = \vec{L} + \vec{s}_{\{u,d,s\}}$	Angular momentum of the light quark
$\vec{J} = \vec{j} + \vec{s}_b$	Total angular momentum of the B meson



Two Broad States **(Γ~100 MeV)**

Two Narrow States **(Γ~ 1 MeV)**

Many models predict:

$m(B_{s0}^*) > m(B^+) + m(K^-)$

$$\left.\begin{array}{l} m(B'_{s1}) \\ m(B_{s1}) \\ m(B_{s2}^*) \end{array}\right\} > m(B^{*+}) + m(K^-)$$

	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

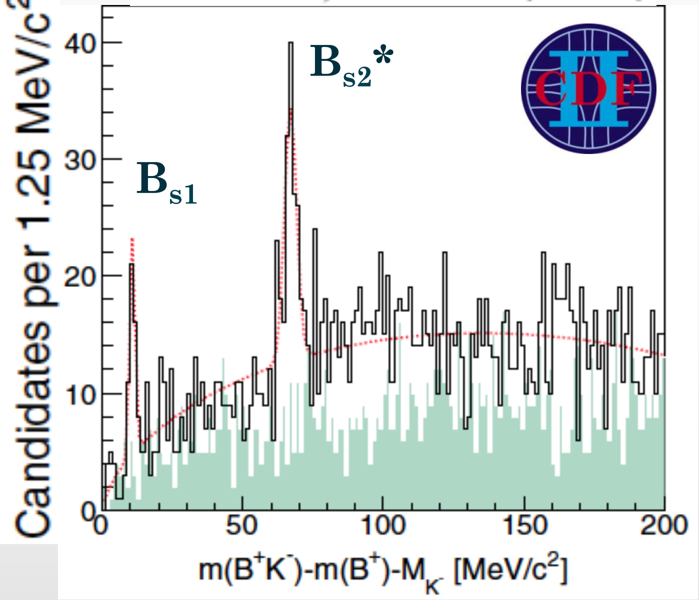
($1^+ \rightarrow 0^- 0^-$ Forbidden)

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?

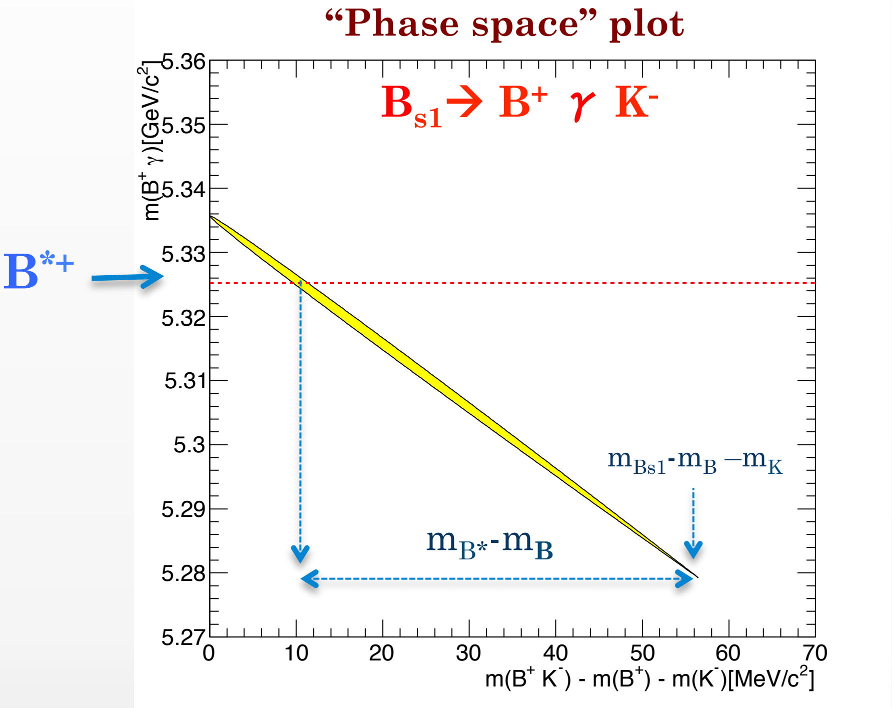
	j_q	J^P	Allowed decay mode	
			B^+K^-	$B^{*+}K^-$
B_{s0}^*	$1/2$	0^+	yes	no
B_{s1}'	$1/2$	1^+	no	yes
B_{s1}	$3/2$	1^+	no	yes
B_{s2}^*	$3/2$	2^+	yes	yes

PRL **100**, 082001 (2008)



It is interpreted as a feed-down of the $B_{s1} \rightarrow B^{*+}K^-$ decay followed by $B^{*+} \rightarrow B^+\gamma$, where the photon is not observed

$B_{s1}(5830)^0$ FEED-DOWN

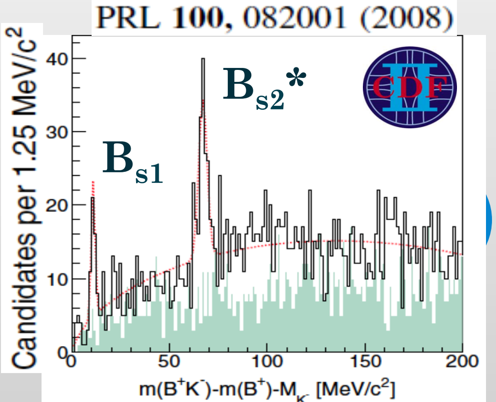


“Phase space” plot

$$\begin{aligned} B_{s1} &\to B^{*+} K^- \\ &\quad\ \to B^+ \gamma \end{aligned}$$

The peak is shifted by the B^{*+} - B^+ mass difference (~ 45 MeV) due to missing momentum of the photon

- ➢ 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



PRL **100**, 082001 (2008)

SEARCH FOR B_{s1} AND B_{s2}^* AT LHCb

Analysis strategy

- 2011 data sample corresponding to $\mathcal{L} = 1.0\ \mathrm{fb}^{-1}$
- 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

SELECTION OF THE B$^+$ CANDIDATES

- ⊛ B^+ mesons are selected in four decay modes:
  - ⊛ $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
  - ⊛ $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$
  - ⊛ $B^+ \to \bar{D}^0(\to K^+\pi^-\pi^+\pi^-)\pi^+$
  - ⊛ $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+\pi^-\pi^+$

- ➢ B$^+$ selection optimized by a boosted decision tree classifier trained on variables common to all four decay modes (e.g. P_T and IP of the final state tracks and of B$^+$ candidates, the detachment of the B$^+$ candidate from the primary interaction, etc…)

The classifier is trained on data using the *sWeights* technique, with the B$^+$ candidate mass as a discriminating variable, to unfold the signal and background distributions

B^+ CANDIDATES

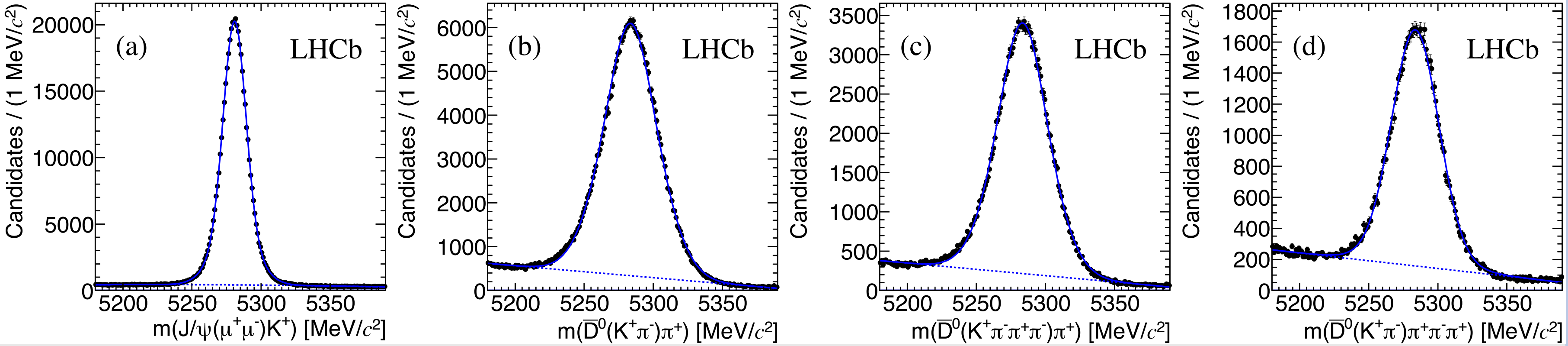
- ➢ The cut on the classifier response chosen by optimizing the significance of each B^+ signal.
- ➢ B^+ samples with purity ~85% - 95%
- ➢ ~1M of B^+ candidates

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

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

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

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



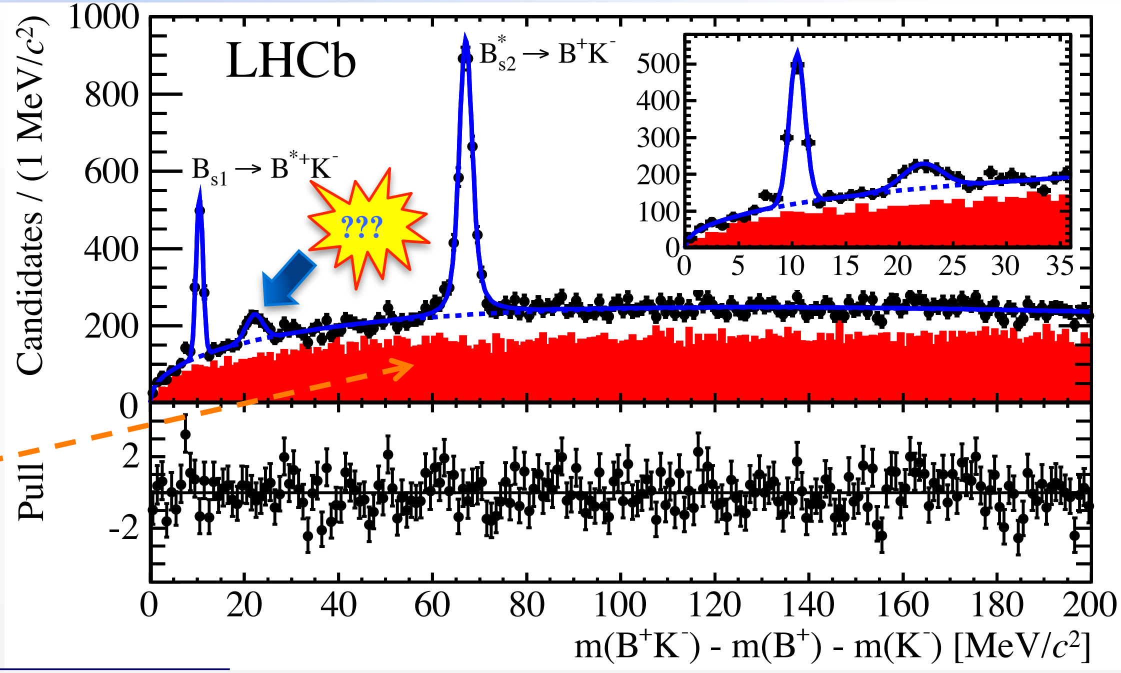
- ➢ B^+ candidates, within a ±2σ mass region, combined with K^-
- ➢ The B^+K^- candidates are refitted:
  - ✓ Primary vertex constraint (i.e. B^+ and K^- are forced to come from the primary vertex)
  - ✓ B^+ and J/ψ (D^0) mass constraint

SELECTION OF THE B^+K^- CANDIDATES

- Implementation of a Boosted Decision Tree classifier whose inputs are:
  - P_T of the B^+ and K^-
  - Kaon PID
  - Vertex χ^2
- The training is performed using simulated events for the signal and the like-charge B^+K^+ candidates in the data for the background, where $B^+ \rightarrow J/\psi K^+$
- The same selection is subsequently applied to all B^+ decay modes.
- The cut on the classifier response is chosen by optimizing the significance of the $B_{s2}^* \rightarrow B^+K^-$ signal. (N.B. Simulation shows that $B_{s1} \rightarrow B^{*+}K^-$ and $B_{s2}^* \rightarrow B^+K^-$ and $B_{s2}^* \rightarrow B^{*+}K^-$ decays are characterized by similar PDFs)

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

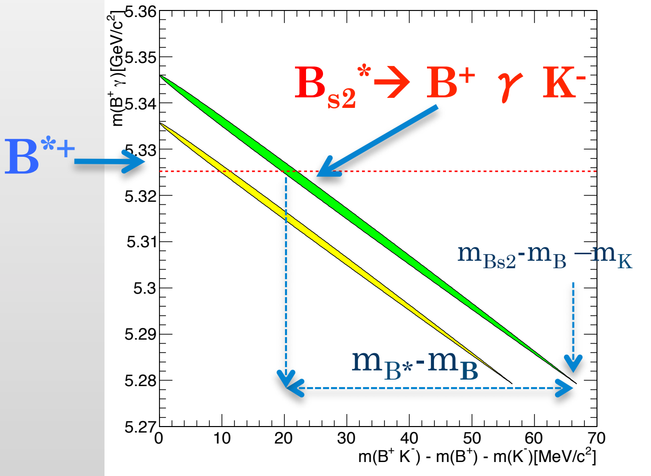
- The two narrow peaks corresponding to the $B_{s1} \rightarrow B^{*+}K^-$ and $B_{s2}^* \rightarrow B^+K^-$ signals are observed
- A new smaller structure seen around 20 MeV
- No peaking structures in the B^+K^+ combinations



	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

"Phase space" plot



FIT MODEL

$Q = m(B^{+}K^{-}) - M_{B+} - M_{K-}$

$B_{s2}^{*} \rightarrow B^{+}K^{-}$

- Relativistic Breit-Wigner convolved with a Gaussian.
- Gaussian width fixed to the expected MC resolution (~ 1 MeV)

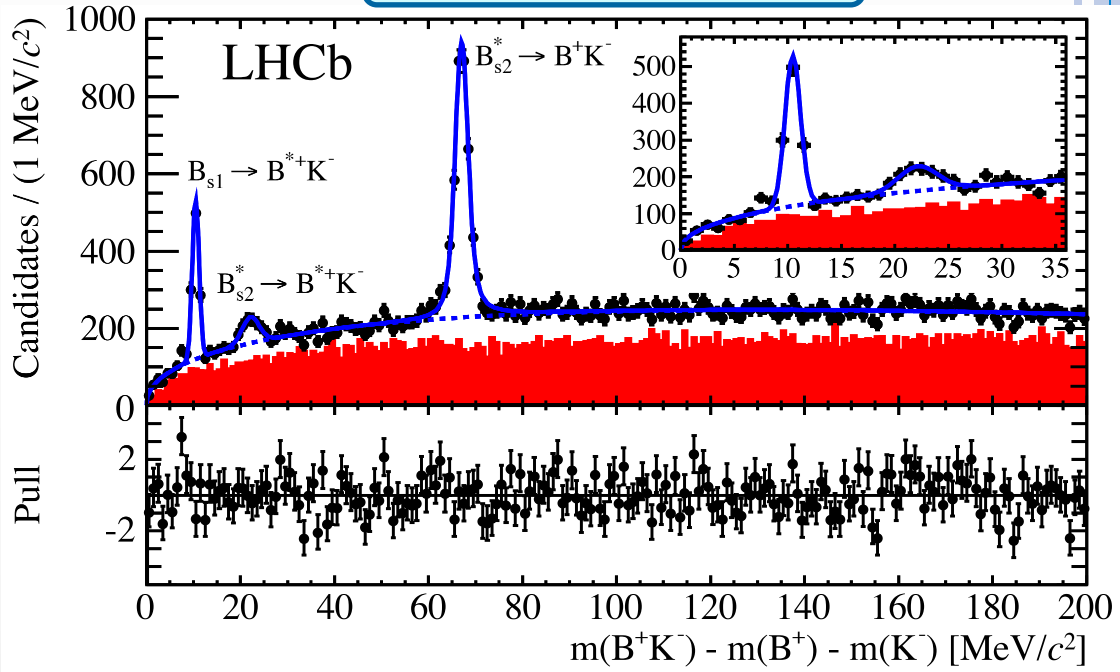
$B_{s1}/B_{s2}^{*} \rightarrow B^{*+}K^{-}$

- The shapes depend, in a non-trivial way, on the phase space and the angular distribution
- Gaussian function as effective parameterization

Background

Threshold function:

$$f(Q) = Q^{\alpha} \exp(\beta Q + \gamma)$$



FIT PARAMETERS

- ✧ Yield: $N(B_{s2}^{*} \rightarrow B^{+}K^{-})$
- ✧ Yield ratios relative to $B_{s2}^{*} \rightarrow B^{+}K^{-}$
- ✧ Q values
- ✧ $\Gamma(B_{s2}^{*})$
- ✧ $m(B^{*}) - m(B)$

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

FIT RESULTS

Parameter	Fit result	Best previous measurement
$m(B_{s1}) - m(B^{*+}) - m(K^-)$	$10.46 \pm 0.04_{stat} \pm 0.04_{syst}$ MeV/c^2	$10.73 \pm 0.21 \pm 0.14$ MeV/c^2
$m(B^*_{s2}) - m(B^+) - m(K^-)$	$67.06 \pm 0.05_{stat} \pm 0.11_{syst}$ MeV/c^2	$66.96 \pm 0.39 \pm 0.14$ MeV/c^2
$m(B^{*+}) - m(B^+)$	$45.01 \pm 0.30_{stat} \pm 0.23_{syst}$ MeV/c^2	45.6 ± 0.8 MeV/c^2
$\Gamma(B^*_{s2})$	$1.56 \pm 0.13_{stat} \pm 0.47_{syst}$ MeV/c^2	
$\frac{\mathcal{B}(B^*_{s2} \to B^{*+}K^-)}{\mathcal{B}(B^*_{s2} \to B^+K^+)}$	$(9.3 \pm 1.3_{stat} \pm 1.2_{syst})\%$	
$\frac{\sigma(pp \to B_{s1}X)\mathcal{B}(B_{s1} \to B^{*+}K^-)}{\sigma(pp \to B^*_{s2}X)\mathcal{B}(B^*_{s2} \to B^+K^-)}$	$(23.2 \pm 1.4_{stat} \pm 1.3_{syst})\%$	
$N_{B_{s1} \to B^{*+}K^-}$	$750 \pm 36_{stat}$	
$N_{B^*_{s2} \to B^{*+}K^-}$	$307 \pm 46_{stat}$	
$N_{B^*_{s2} \to B^+K^-}$	$3140 \pm 100_{stat}$	

The Q values are translated into absolute masses by adding the product masses

$$\begin{array}{rcl}
m(B^{*+}) &=& 5324.26 \pm 0.30_{stat} \pm 0.23_{syst} \pm 0.17_{B\ mass}\ \mathrm{MeV}/c^2 \\
m(B_{s1}) &=& 5828.40 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.41_{B^*\ mass}\ \mathrm{MeV}/c^2 \\
m(B^*_{s2}) &=& 5839.99 \pm 0.05_{stat} \pm 0.11_{syst} \pm 0.17_{B\ mass}\ \mathrm{MeV}/c^2
\end{array}$$

- 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

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

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

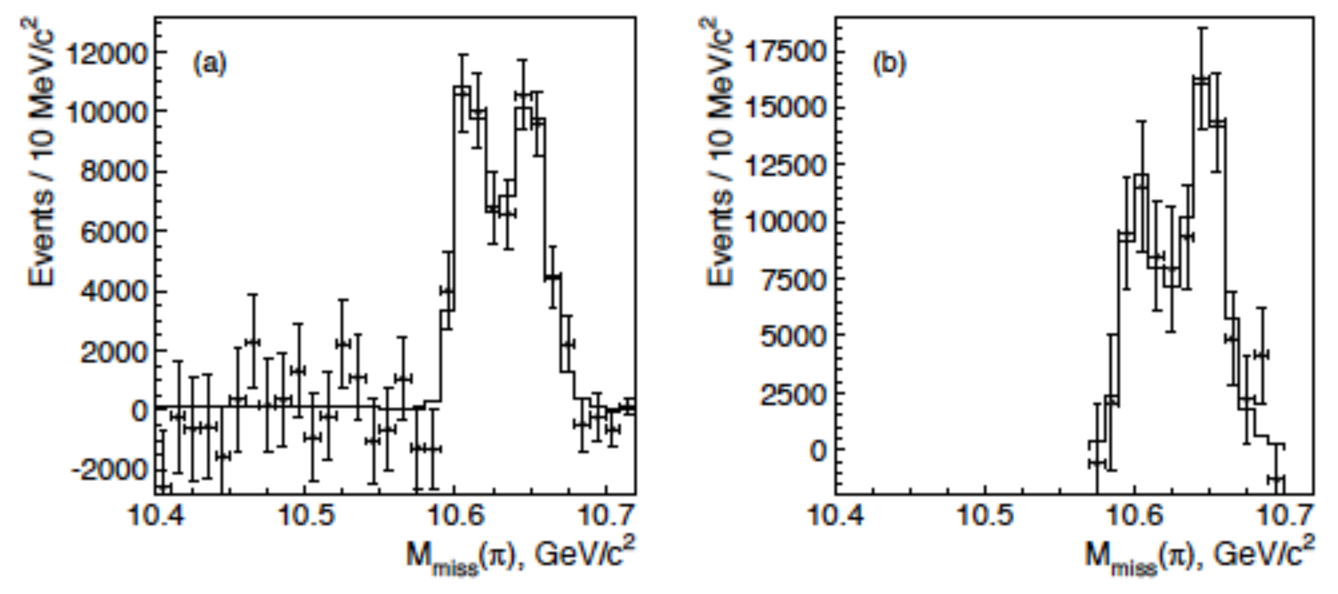
Table 1: The strong decay widths of B_{s1} and B^*_{s2} in units of MeV.

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)**
- $\mathbf{B\bar{B}^*}$ and $\mathbf{B^*\bar{B}^*}$ molecules? **(A. Bondar et al., PRD84 (2011) 054010)**



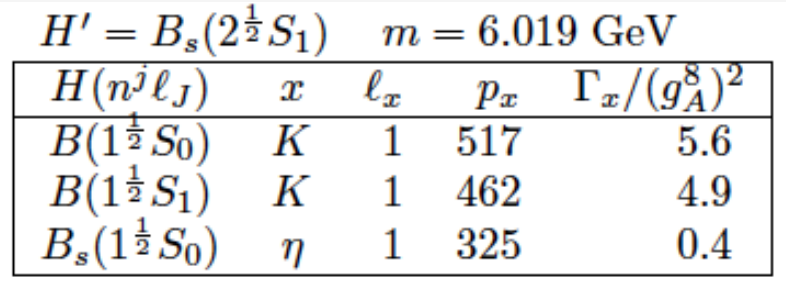
Using the B^{*+} mass measured in this analysis, we compute that the $Z_b(10610)^+$ and $Z_b(10650)^+$ masses are 3.69 ± 2.05 MeV/c^2 and 3.68 ± 1.71 MeV/c^2 above the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds respectively

SPIN-PARITY ASSIGNMENT TO B_{s2}*

- Spin-parity combinations for a state decaying into two scalar (B^+K^-) (natural spin-parity): 0^+, 1^-, 2^+, 3^-
- Spin-parity combinations for a state decaying into a vector and a scalar ($B^{*+}K^-$): 0^-, $1^\pm$, $2^\pm$, $3^\pm$
- Common combinations are 1^- and 2^+

Possible $J^P=1^-$ candidates

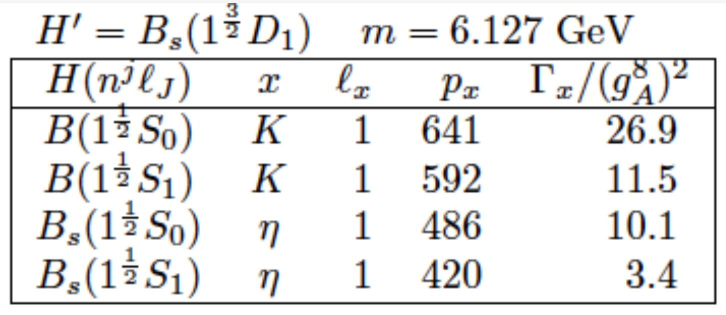
Radial excitation of B_s*



$H' = B_s(2\frac{1}{2}S_1)$ $m = 6.019$ GeV

$H(n^j\ell_J)$	x	ℓ_x	p_x	$\Gamma_x/(g_A^8)^2$
$B(1\frac{1}{2}S_0)$	K	1	517	5.6
$B(1\frac{1}{2}S_1)$	K	1	462	4.9
$B_s(1\frac{1}{2}S_0)$	η	1	325	0.4

Orbitally excitation L=2



$H' = B_s(1\frac{3}{2}D_1)$ $m = 6.127$ GeV

$H(n^j\ell_J)$	x	ℓ_x	p_x	$\Gamma_x/(g_A^8)^2$
$B(1\frac{1}{2}S_0)$	K	1	641	26.9
$B(1\frac{1}{2}S_1)$	K	1	592	11.5
$B_s(1\frac{1}{2}S_0)$	η	1	486	10.1
$B_s(1\frac{1}{2}S_1)$	η	1	420	3.4

The measured branching ratio and B_{s2}* width favour $J^P = 2^+$

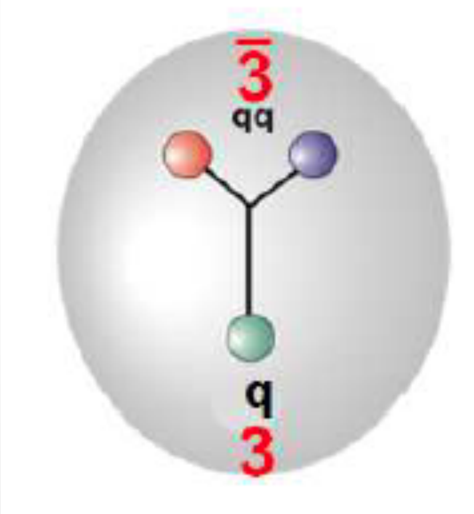
M. Di Pierro and E. Eichten
Phys.Rev.D64, 114004

OBSERVATION OF EXCITED Λ_b^0 BARYONS

[LHCB-PAPER-2012-012; PRL 109 (2012) 172003]

THE *bqq (q=u,d,s)* BARYONS

The heavy quark effective theories (HQET) treat a heavy baryon as a system consisting of a static heavy quark Q ($m_Q >> \Lambda_{QCD}$) surrounded by a diquark system comprised of the two light quarks



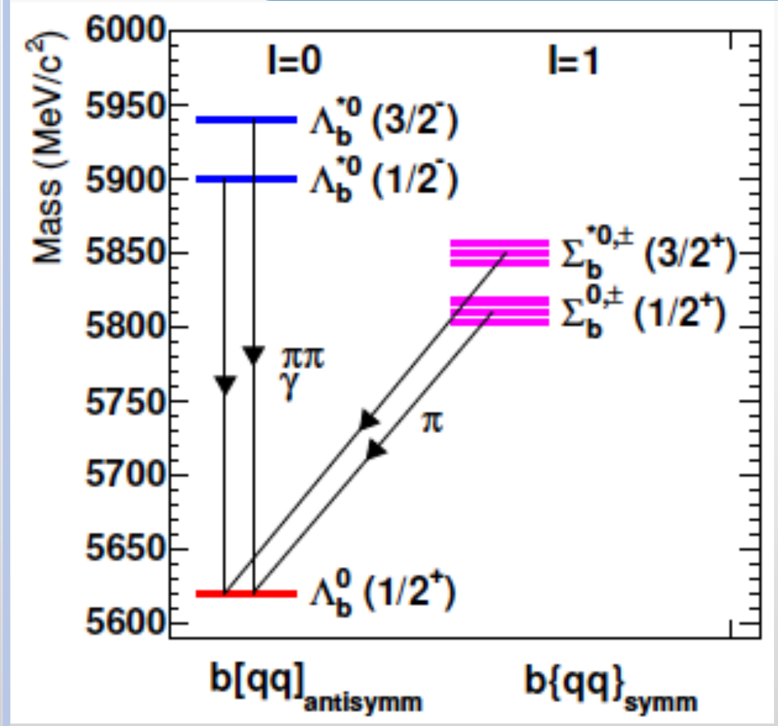
Credit: M. Pennington
AIP Conf.Proc. 1432 (2012) 176-184

Bottom baryons ($B = 1$)	$I(J^P)$
Λ_b^0	$0(1/2^+)$
Σ_b	$1(1/2^+)$
Σ_b^*	$1(3/2^+)$
$\Xi_b^0,\ \Xi_b^-$	$1/2(1/2^+)$
Ω_b^-	$0(1/2^+)$

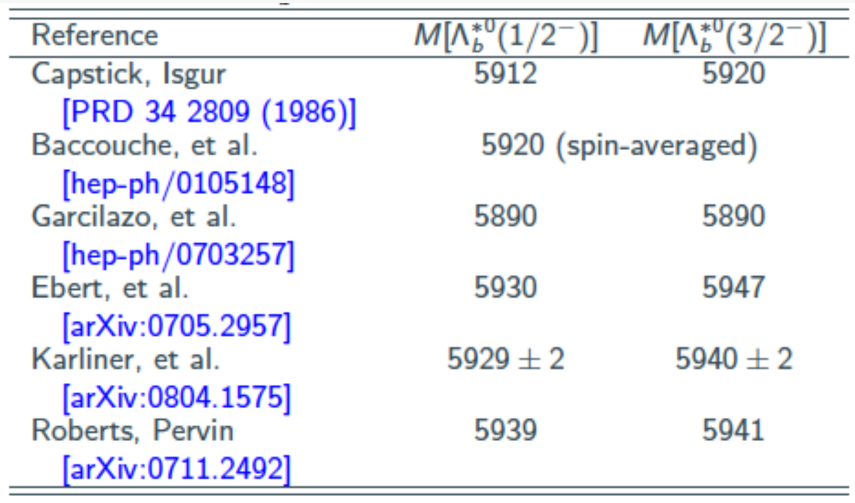
The system of baryons containing a b quark remains largely unexplored, despite recent progress made at the experiments at the Tevatron

Orbitally Excited (L=1) Λ_b^0 Baryons

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



Predictions for Λ_b^{*0} masses

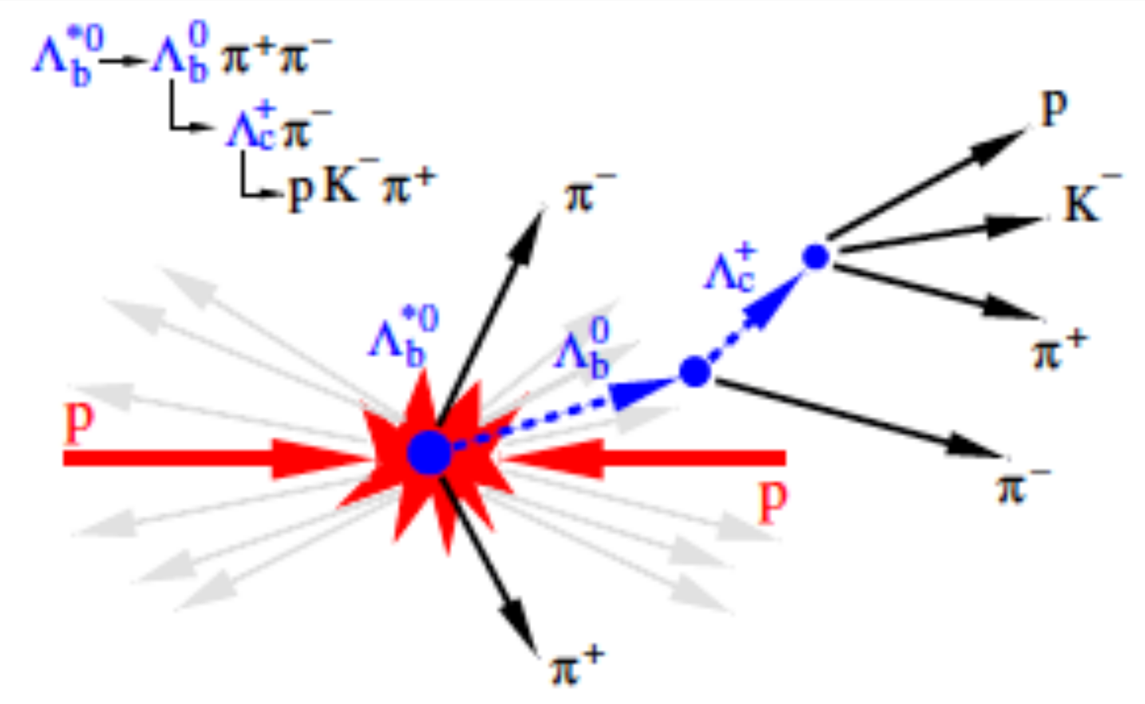


Reference	$M[\Lambda_b^{*0}(1/2^-)]$	$M[\Lambda_b^{*0}(3/2^-)]$
Capstick, Isgur [PRD 34 2809 (1986)]	5912	5920
Baccouche, et al. [hep-ph/0105148]	5920 (spin-averaged)	
Garcilazo, et al. [hep-ph/0703257]	5890	5890
Ebert, et al. [arXiv:0705.2957]	5930	5947
Karliner, et al. [arXiv:0804.1575]	5929 ± 2	5940 ± 2
Roberts, Pervin [arXiv:0711.2492]	5939	5941

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

OBSERVATION OF EXCITED Λ_b^0 BARYONS

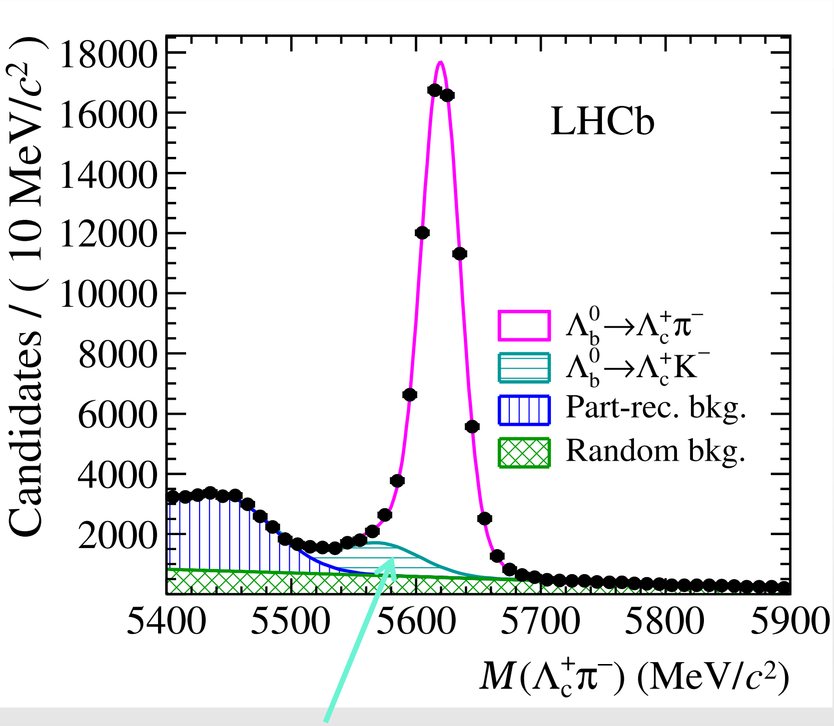
- $1.0\ \mathrm{fb}^{-1}$ pp data sample, $\sqrt{s} = 7$ TeV
- $\Lambda_b^0 \to \Lambda_c^+\pi^-, \Lambda_c^+ \to pK^-\pi^+$ combined with a pair of pions from the primary vertex



SELECTION OF Λ_b^0 BARYONS

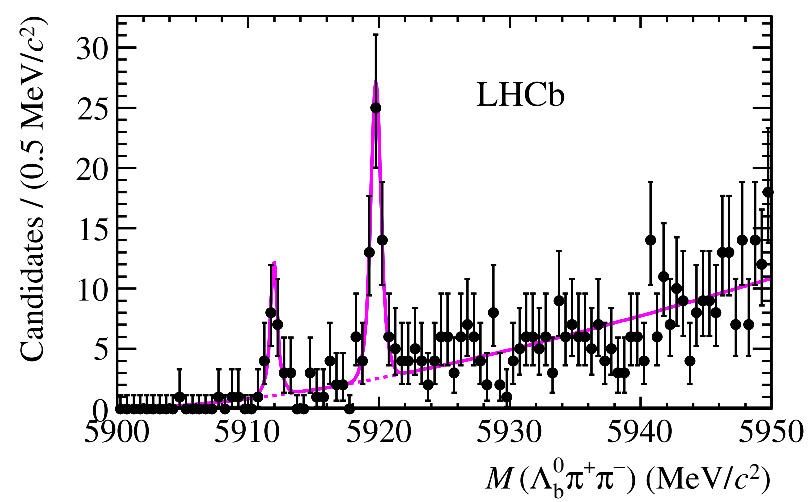
$N(\Lambda^0_b) = 70540 \pm 330$

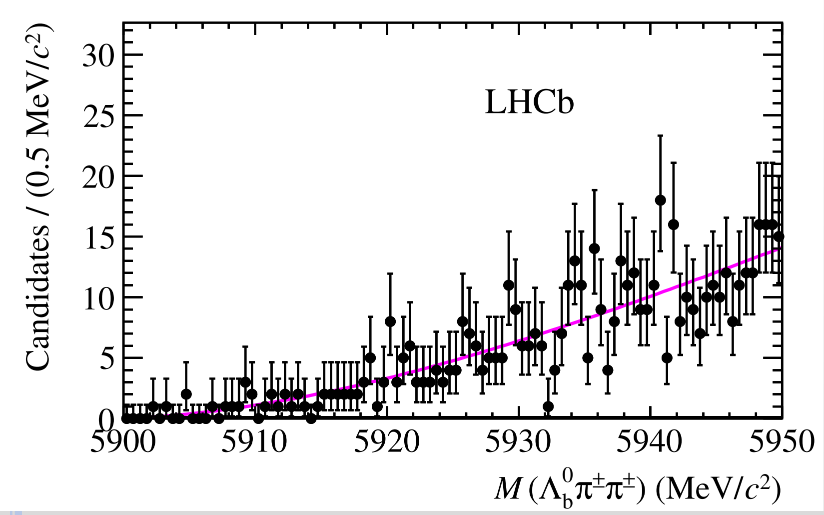
- Good quality tracks and well separated from any PV.
- PID for kaons and protons
- Kinematic fit which constrains:
  - the Λ^0_b to originate from the PV
  - Λ_c^+ mass to its PDG value



$\Lambda^0_b \to \Lambda_c^+ K^-$ decays (not yet reported in literature) where the kaon reconstructed under the pion mass hypothesis

SELECTION OF THE EXCITED Λ_b^0 BARYONS

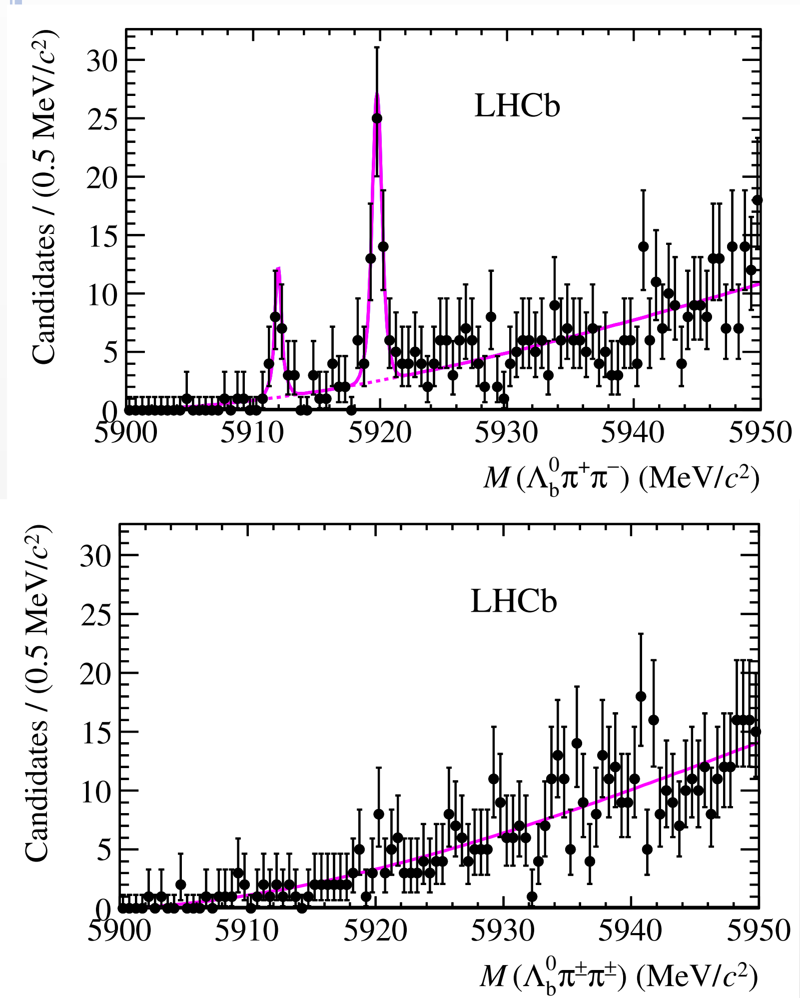




- The Λ_b^0 candidates combined with two pions:
  - $p_T > 150$ MeV/c^2
  - No PID
- Kinematic fit with vertex and mass constraints on Λ_b^0 and Λ_c^+

- Two peaks are evident with masses around 5912 MeV/c^2 and 5920 MeV/c^2
- No corresponding structures in the same-sign pion combinations

FIT MODEL



Combined unbinned fit of $\Lambda_b^0\pi^+\pi^-$ and $\Lambda_b^0\pi^\pm\pi^\pm$

- $\Lambda_b^{*0}(5912)$ and $\Lambda_b^{*0}(5920)$: sum of two Gaussians with same mean (signal shape fixed from the simulation)
- Background: quadratic polynomial function

$$N_{\Lambda_b^{*0}(5912)} = 17.6 \pm 4.8 \Rightarrow 5.2\sigma$$
$$N_{\Lambda_b^{*0}(5920)} = 52.5 \pm 8.1 \Rightarrow 10.2\sigma$$

The two new peaks are interpreted as the orbitally excited Λ^0_b states

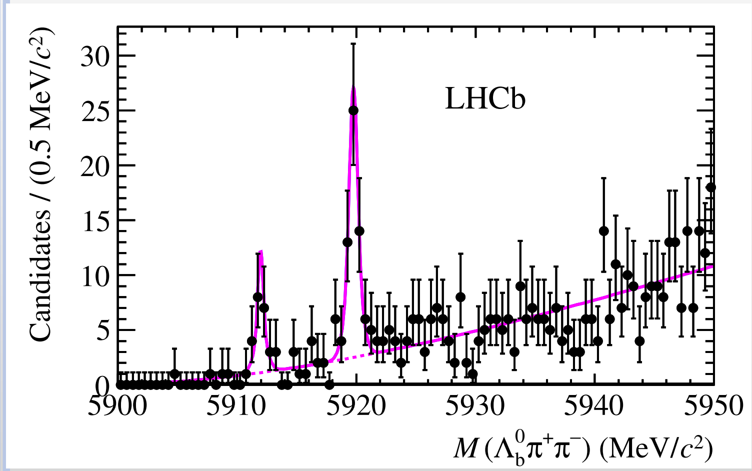
SYSTEMATICS TABLE

Source of uncertainty	Systematic bias, MeV/c^2 $\Delta M_{\Lambda_b^{*0}(5912)}$	Systematic bias, MeV/c^2 $\Delta M_{\Lambda_b^{*0}(5920)}$
Λ_b^0 mass	**0.034**	**0.035**
Signal PDF	0.021	0.011
Background PDF	0.002	0.002
Momentum scale	0.008	0.013
Total	0.041	0.039

FIRST OBSERVATION OF ORBITALLY-EXCITED b BARYONS ($L>0$)

Masses are only slightly above $\Lambda_b^0\pi^+\pi^-$ threshold ($Q = 12$ and 20 MeV respectively) and below the $\Sigma_b^0\pi$ threshold

$$
\begin{aligned}
M_{\Lambda_b^{*0}(5912)} &= 5911.97 \pm 0.12_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.66_{\Lambda_b^0\text{mass}}\ \text{MeV}/c^2\\
M_{\Lambda_b^{*0}(5920)} &= 5919.77 \pm 0.08_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.66_{\Lambda_b^0\text{mass}}\ \text{MeV}/c^2\\
\Delta M_{\Lambda_b^{*0}(5912)} &= 292.60 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}}\ \text{MeV}/c^2\\
\Delta M_{\Lambda_b^{*0}(5920)} &= 300.40 \pm 0.08_{\text{stat}} \pm 0.04_{\text{syst}}\ \text{MeV}/c^2
\end{aligned}
$$



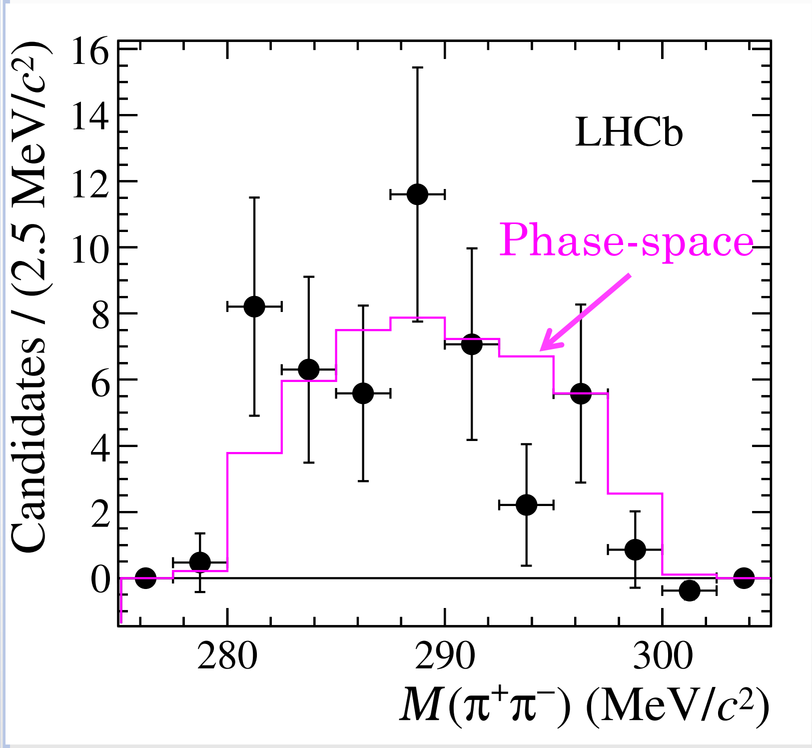
Limits on natural widths (95% CL) obtained by an alternative fit

- ⊛ Signal PDF : 2 Gaussians $\otimes$ Breit-Wigner

$$
\begin{aligned}
\Gamma_{\Lambda_b^{*0}(5912)} &< 0.83\ \text{MeV}\\
\Gamma_{\Lambda_b^{*0}(5920)} &< 0.75\ \text{MeV}
\end{aligned}
$$

CDF confirms $\Lambda_b^{*0}(5920)$
arXiv:1301.0949

$\pi^+\pi^-$ MASS DISTRIBUTION FROM $\Lambda_b^{*0}(5920)$



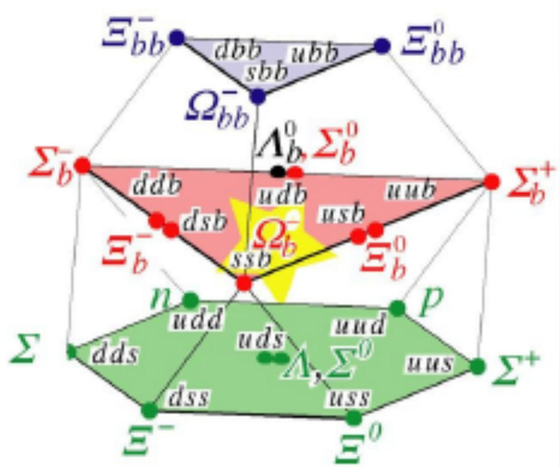
- ⊛ Invariant mass of $\pi^+\pi^-$ from $\Lambda_b^{*0}(5920) \to \Lambda_b^0\pi^+\pi^-$
- ⊛ Background subtracted by *sWeights* technique
- ⊛ The invariant mass of $\Lambda_b^0\pi^+\pi^-$ used as discriminant variable
- ⊛ No peaking structures are evident
- ⊛ Consistent with phase-space decay

MEASUREMENT OF THE Λ^0_B, Ω_B^- AND Ξ_B^- BARYON MASSES

[LHCB-PAPER-2012-048 in preparation]

INTRODUCTION

Quark model predicts several b-baryon ground states but only six have been observed so far, and a complete and reliable experimental mass spectrum would allow for precision tests of a variety of QCD models

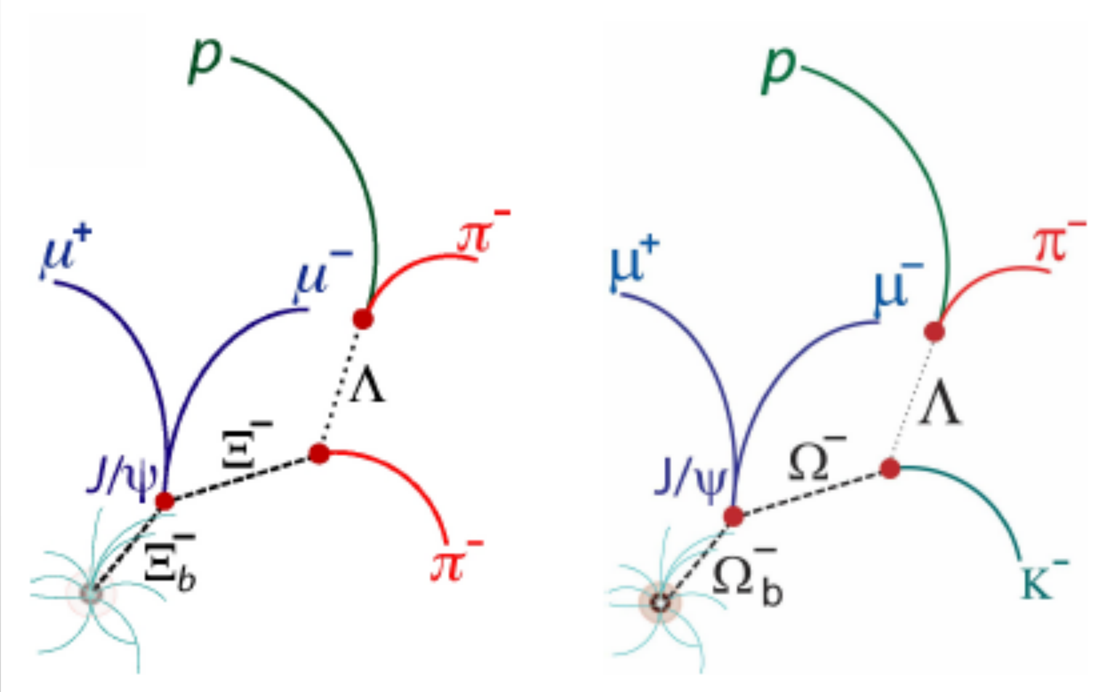


- D0 and CDF observed $\Omega_b^- \to J/\psi \Omega^-$ but obtained different mass measurement for Ω_b^-
  - D0: $M(\Omega_b^-) = 6165 \pm 10_{stat} \pm 13_{syst}$ MeV/c^2 **PRL101 (2008) 232002**
  - CDF: $M(\Omega_b^-) = 6054.4 \pm 6.8_{stat} \pm 0.9_{syst}$ MeV/c^2 **PRD80 (2009) 072003**
  - Difference above 6σ
  - Theoretical predictions for Ω_b^- mass: 5.94-6.12 GeV/c^2
- D0 and CDF observed $\Xi_b^- \to J/\psi \Xi^-$ and $\Xi_b^- \to \Xi_c^0 \pi^-$
  - Good agreement between Ξ_b^- mass measurements
  - $M(\Xi_b^-) = 5791.1 \pm 2.2$ MeV/c^2

MASS MEASUREMENTS OF Λ_b^0, Ξ_b^-, AND Ω_b^-

Mass measurements performed with the full 2011 data sample (1.0 fb^{-1})

- ⊛ $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi^-)$
- ⊛ $\Xi_b^- \to J/\psi(\to \mu^+\mu^-)\Xi^-(\to \Lambda\pi^-)$
- ⊛ $\Omega_b^- \to J/\psi(\to \mu^+\mu^-)\Omega^-(\to \Lambda K^-)$



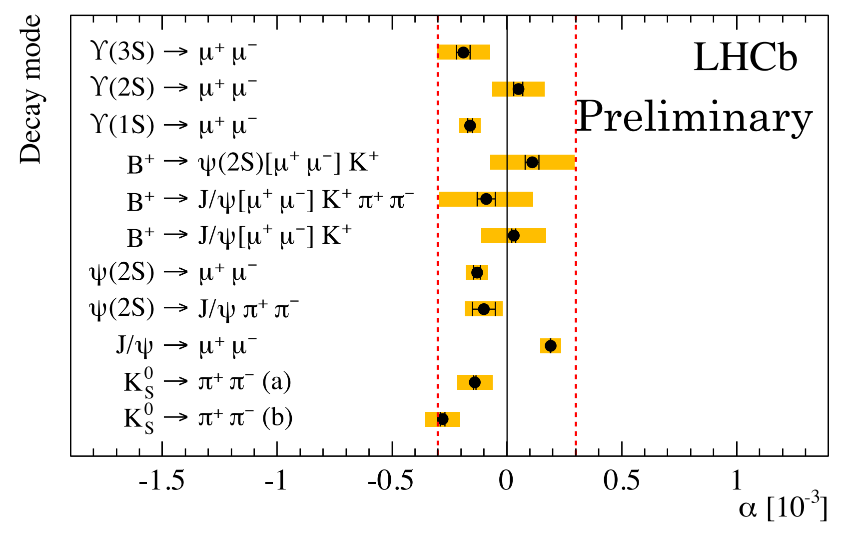
MOMENTUM SCALE

Precision mass measurements require the momenta of the final state particles to be determined accurately

Two-step momentum calibration procedure:

1. Inclusive $J/\psi \rightarrow \mu^+\mu^-$ decays used to account for the changes in the relative momentum scale between different data taking periods
2. The absolute scale derived from $B^+ \rightarrow J/\psi K^+$ decays (momentum scale determined as a function of the K^+ track kinematics)

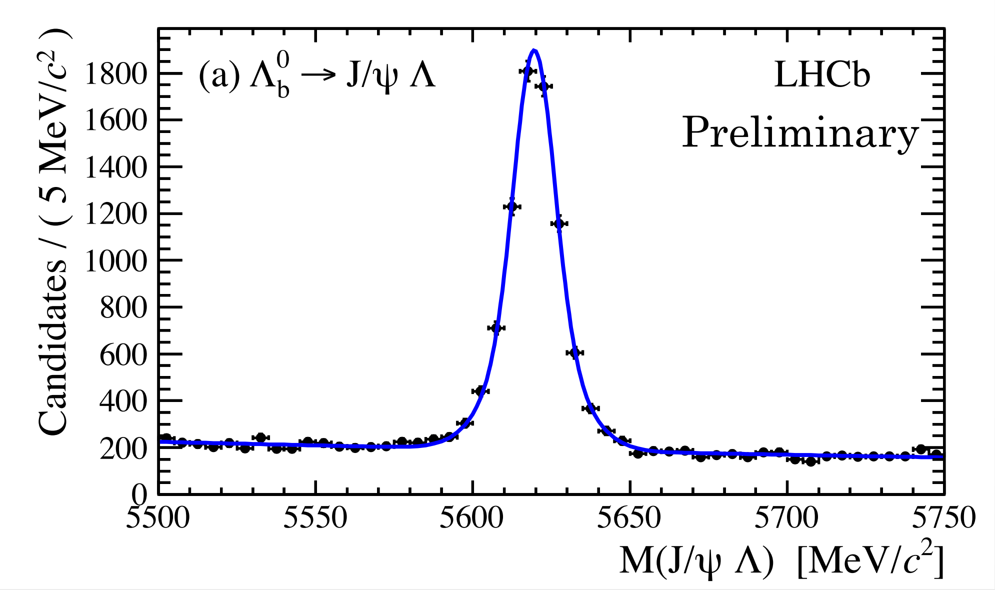
- Residual bias evaluated with a variety of decays
- $1-\alpha$ is the estimated momentum scale factor which shifts each state to its expected mass
- Systematic uncertainty on the calibrated momentum scale : 0.03%



SELECTION

- The topology of decays characterized by the long-lived particles in the decay chain
- 90% of the decays are not fully contained in the vertex detector. Tracks that have no hits in the vertex detector also considered
- PID requirement for the proton and the kaon
- Masses of intermediated state (J/ψ , Λ, Ω^-, Ξ^-) constrained
- Decay time >0.25 ps
- Vertex X^2/ndf

Λ_b^0 FIT

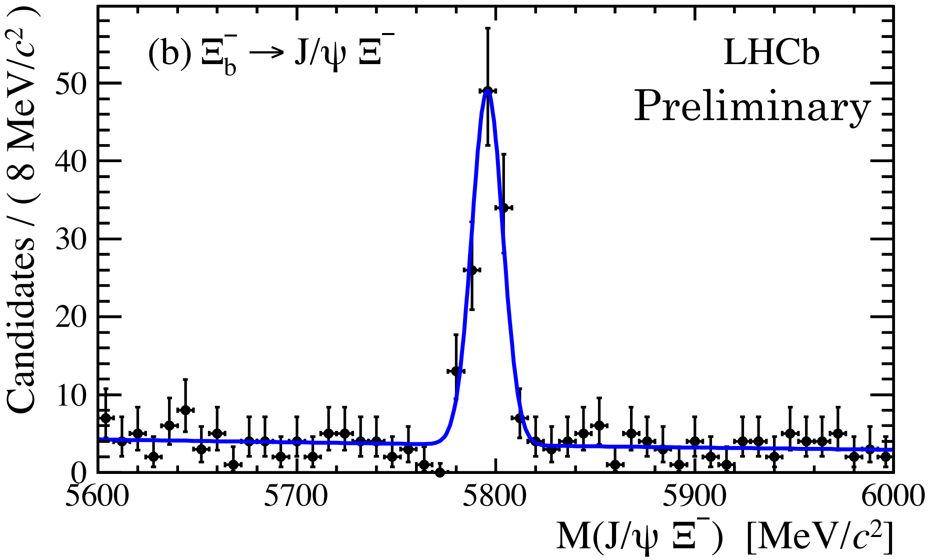


Unbinned maximum likelihood fit

- Double Gaussian
  - Free mean and widths
- Exponential background

$N(\Lambda_b^0) = 6870 \pm 110$ candidates

Ξ_b^- FIT

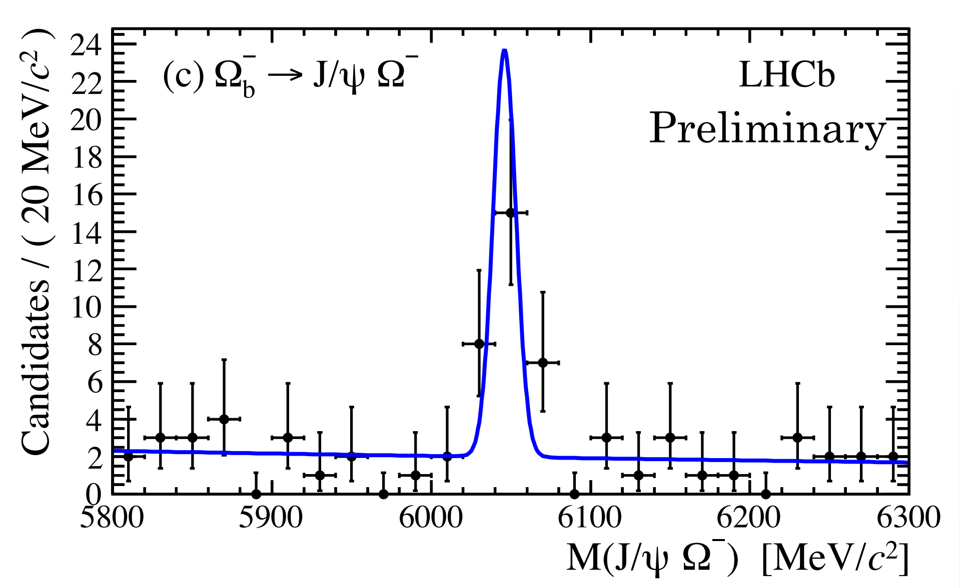


Unbinned maximum likelihood fit

- Single Gaussian
  - Free mean and width
- Exponential background

N(Ξ^-_b) = 111 ± 12 candidates

Ω_b^- FIT



Unbinned maximum likelihood fit

- Single Gaussian
  - Free mean
  - Width fixed to:

$$\sigma^{MC}_{\Omega_b^-} \times \sigma^{Data}_{\Xi_b^-} / \sigma^{MC}_{\Xi_b^-}$$

- Exponential background

N(Ω_b^-) = 19.1 ± 4.8 candidates
Signal significance = 6.2σ

SYSTEMATICS TABLE

Source	Λ_b^0	Ξ_b^-	Ω_b^-	Ξ_b^-–Λ_b^0	Ω_b^-–Λ_b^0
Momentum scale	**0.43**	**0.43**	**0.31**	0.01	0.12
dE/dx correction	0.09	0.09	0.09	0.01	0.01
Hyperon mass	0.01	0.07	0.25	**0.07**	**0.25**
Signal model	0.07	0.01	0.24	**0.07**	**0.25**
Background model	0.01	0.01	0.02	0.01	0.02
Total	0.45	0.45	0.47	0.10	0.37

FIT RESULTS

Most precise mass measurements of Λ_b^0, Ξ_b^- , Ω_b^- to date

$$M(\Lambda_b^0) = 5619.53 \pm 0.13_{stat} \pm 0.45_{syst} \ \mathrm{MeV}/c^2$$
$$M(\Xi_b^-) = 5795.8 \pm 0.9_{stat} \pm 0.4_{syst} \ \mathrm{MeV}/c^2$$
$$M(\Omega_b^-) = 6046.0 \pm 2.2_{stat} \pm 0.5_{syst} \ \mathrm{MeV}/c^2$$

Preliminary

Mass differences wrt the measured Λ_b^0 are reported as well.
The dominant systematic uncertainty partially cancels out

$$M(\Xi_b^-) - M(\Lambda_b^0) = 176.2 \pm 0.9_{stat} \pm 0.1_{syst} \ \mathrm{MeV}/c^2$$
$$M(\Omega_b^-) - M(\Lambda_b^0) = 426.4 \pm 2.2_{stat} \pm 0.4_{syst} \ \mathrm{MeV}/c^2$$

Preliminary

- Λ_b^0 and Ξ_b^- results are in good agreement with world average
- The Ω_b^- is in agreement with CDF but in disagreement with D0

MEASUREMENTS OF THE $\Lambda_b^0 \rightarrow \Lambda J/\psi$ DECAY AMPLITUDES AND THE Λ_b^0 BARYON PRODUCTION POLARISATION IN *pp* COLLISIONS AT $\sqrt{s} = 7$ TEV

[LHCB-PAPER-2012-057 in preparation]

Λ^0_b POLARISATION

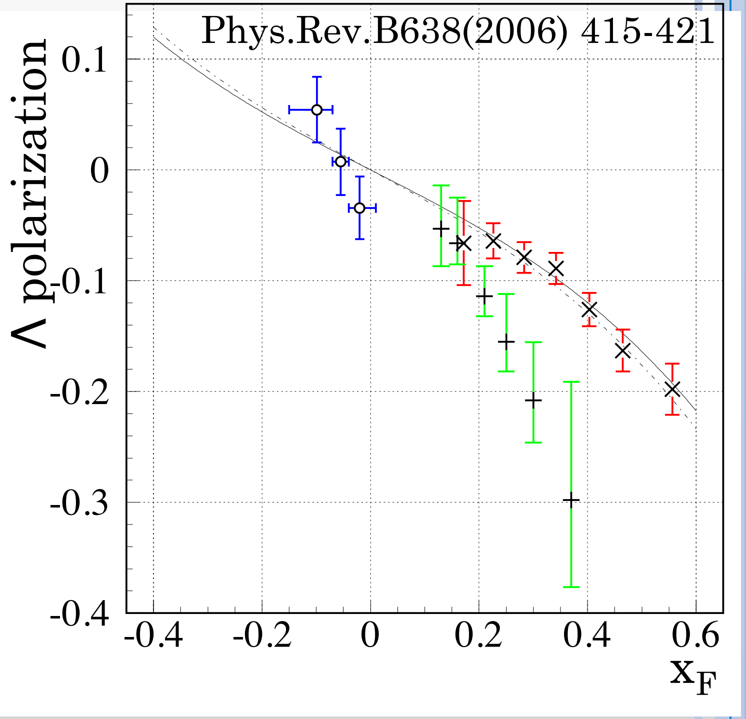
- Longitudinal polarisation vanishes due to parity conservation of strong interactions

$$P_{\parallel} = \langle \vec{\sigma} \cdot \vec{p}_{\Lambda^0_b} \rangle = 0 \qquad P_b = P_{\perp} = \langle \vec{\sigma} \cdot \vec{p}_{\Lambda^0_b} \times \vec{p}_p \rangle \neq 0$$

- Transverse polarisation predicted to be as large as 20% (PLB 614 (2005) 165)
- Sufficient polarisation would allow to measure the photon helicity in $\Lambda^0_b \rightarrow \Lambda\gamma$ ➔ Search for New Physics (J. Phys. G 24 (1998) 979, PLB 645 (2007) 204)

but…

- Polarisation of Λ depends strongly on $x_F = 2p_L/\sqrt{s}$ and vanishes for $x_F \sim 0$
- $x_F(\Lambda^0_b) \sim 0.02$ at LHC → small value?


Phys.Rev.B638(2006) 415-421

No polarisation measurement for Λ^0_b produced at hadron colliders so far

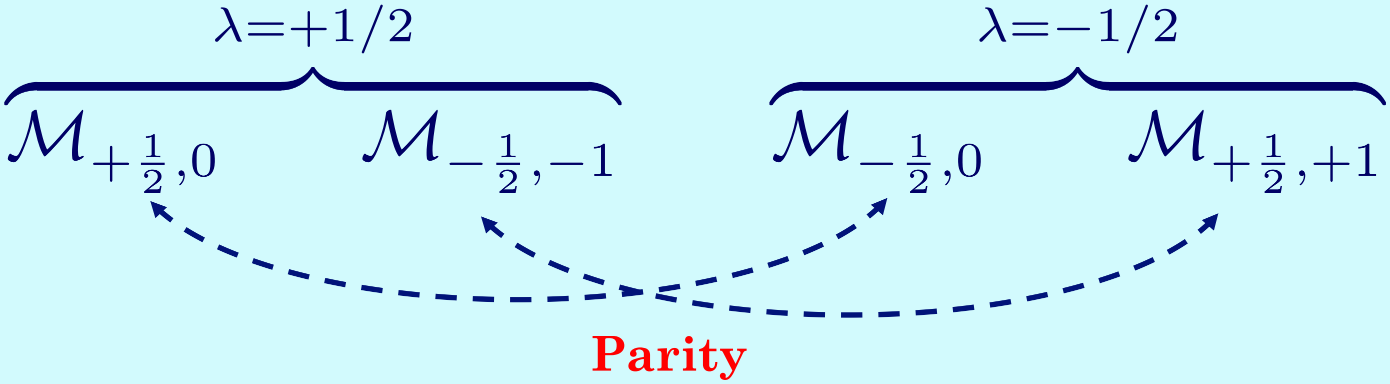
THE $\Lambda_b^0 \to \Lambda(\to p\pi^-)J/\psi(\to \mu^+\mu^-)$ DECAY

$J(\Lambda^0_b) = J(\Lambda) + J(J/\psi)$ i.e. **$\frac{1}{2} = \frac{1}{2} + 1$** spin decay

- 6 possible combinations but only 4 can return

$$\boldsymbol{\lambda = \lambda_1 - \lambda_2 = \pm \tfrac{1}{2}}$$

- Four amplitudes in the helicity basis



$$\overbrace{\mathcal{M}_{+\frac{1}{2},0} \qquad \mathcal{M}_{-\frac{1}{2},-1}}^{\lambda=+1/2} \qquad \overbrace{\mathcal{M}_{-\frac{1}{2},0} \qquad \mathcal{M}_{+\frac{1}{2},+1}}^{\lambda=-1/2}$$

Parity

- The decay asymmetry parameter α_Λ is well-measured
- Contains enough angular correlation to measure the polarization and the relative magnitudes of the amplitudes

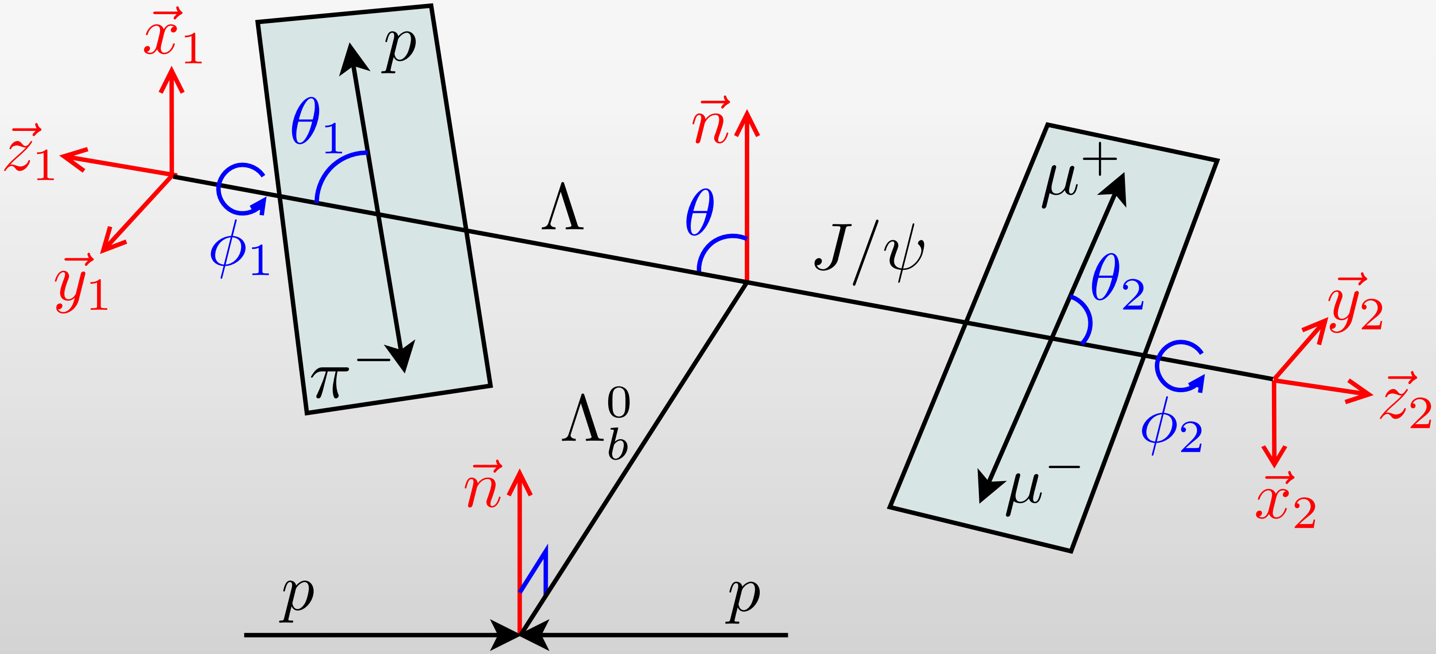
DEFINITIONS OF THE ANGLES

The angular distribution depends on P_b, α_Λ, the 4 helicity amplitudes and 5 angles

θ : polar angle of $\vec{p}_\Lambda$ wrt $\vec{n} = \vec{p}_{\Lambda_b^0} \times \vec{p}_{beam}$ in the Λ_b^0 rest-frame

θ_1, ϕ_1 : polar and azimuthal angle of $\vec{p}_p$ wrt $\vec{p}_{\Lambda_b^0}$ in the Λ rest-frame

θ_2, ϕ_2 : polar and azimuthal angle of $\vec{p}_{\mu^+}$ wrt $\vec{p}_{\Lambda_b^0}$ in the J/ψ rest-frame



ANGULAR DISTRIBUTIONS

Integration over the two ϕ angles

$$\omega_3(\cos\theta, \cos\theta_1, \cos\theta_2) = \frac{1}{16\pi}\sum_{i=0}^{7} f_i(|\mathcal{M}_{+\frac{1}{2},0}|^2, |\mathcal{M}_{-\frac{1}{2},0}|^2, |\mathcal{M}_{-\frac{1}{2},-1}|^2, |\mathcal{M}_{+\frac{1}{2},+1}|^2) g_i(P_b, \alpha_\Lambda)\, h_i(\cos\theta, \cos\theta_1, \cos\theta_2)$$

No more interference terms

R. Lednicky, Sov. J. Nucl. Phys. 43 (1986) 817

i	$f_i(\alpha_b, r_0, r_1)$	$g_i(P_b, \alpha_\Lambda)$	$h_i(\cos\theta, \cos\theta_1, \cos\theta_2)$
0	1	1	1
1	α_b	P_b	$\cos\theta$
2	$2r_1 - \alpha_b$	α_Λ	$\cos\theta_1$
3	$2r_0 - 1$	$P_b\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$\frac{1}{2}(1-3r_0)$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
5	$\frac{1}{2}(\alpha_b - 3r_1)$	P_b	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta$
6	$-\frac{1}{2}(\alpha_b + r_1)$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta_1$
7	$-\frac{1}{2}(1 + r_0)$	$P_b\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta\cos\theta_1$

- Amplitudes can be parametrised with:

$$\alpha_b \equiv |\mathcal{M}_{+\frac{1}{2},0}|^2 - |\mathcal{M}_{-\frac{1}{2},0}|^2 + |\mathcal{M}_{-\frac{1}{2},-1}|^2 - |\mathcal{M}_{+\frac{1}{2},+1}|^2$$

$$\equiv P\text{-violating asymmetry of the } \Lambda_b^0 \to \Lambda J/\psi \text{ decay}$$

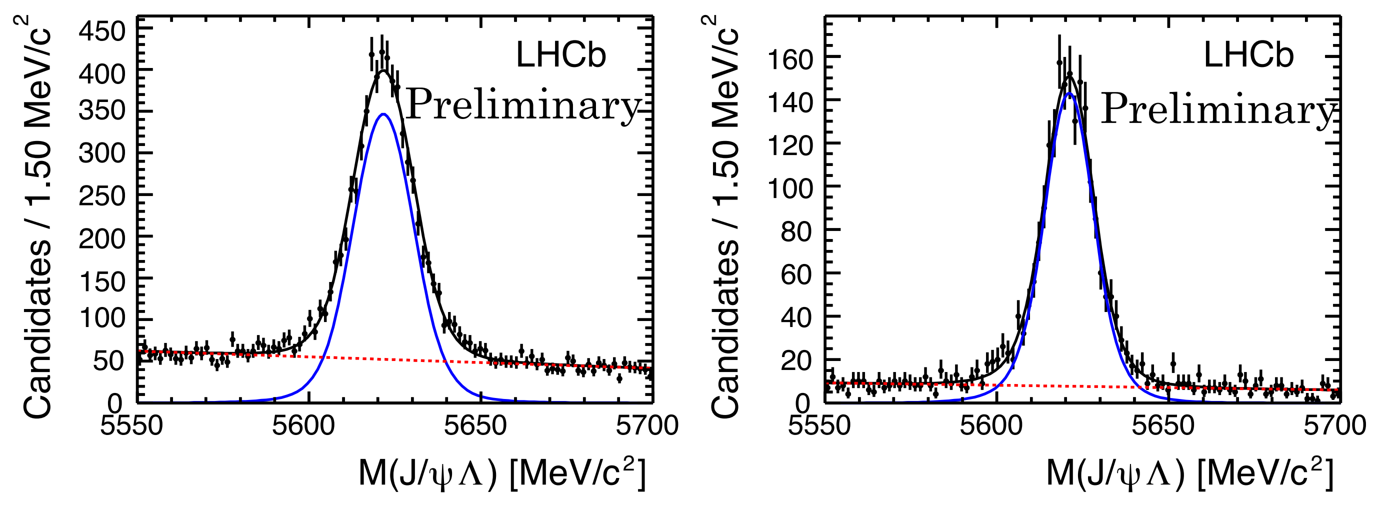
$$r_0 \equiv |\mathcal{M}_{+\frac{1}{2},0}|^2 + |\mathcal{M}_{-\frac{1}{2},0}|^2$$

$$r_1 \equiv |\mathcal{M}_{+\frac{1}{2},0}|^2 - |\mathcal{M}_{-\frac{1}{2},0}|^2$$

P_b, α_b, r_0, r_1 are the fit parameters of the analysis

$\Lambda_b^0 \to \Lambda J/\psi$ SIGNALS

- Λ can decay inside (IN) or outside (OUT) of the vertex detector
- OUT: slightly worse mass resolution and background level
- A boosted decision tree retains 90% of signal and removes (80%-90%) of background



Fit model
Signal: Crystal Ball
Bkg: 1st order polynomial

OUT: 5346 ± 96 signal candidates

IN: 1861 ± 49 signal candidates

sWeights technique to subtract the background in the angular distribution

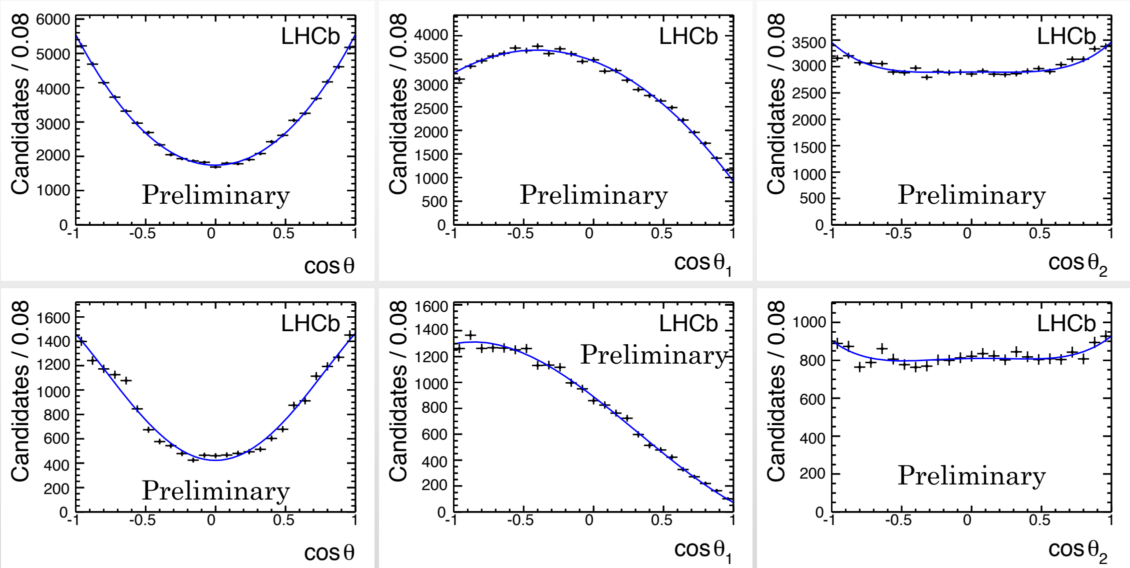
ACCEPTANCE

- Detector and selection create large acceptance effects
- Simulated events generated with flat angular distributions and passed through the data selection
- Differences for cos θ_1 between IN and OUT observed
- Acceptance modelled with a sum of products of Legendre polynomials

$$f_{acc} = \sum_{i,j,k} c_{ijk} L_i(cos\theta) L_j(cos\theta_1) L_k(cos\theta_2)$$

OUT

IN

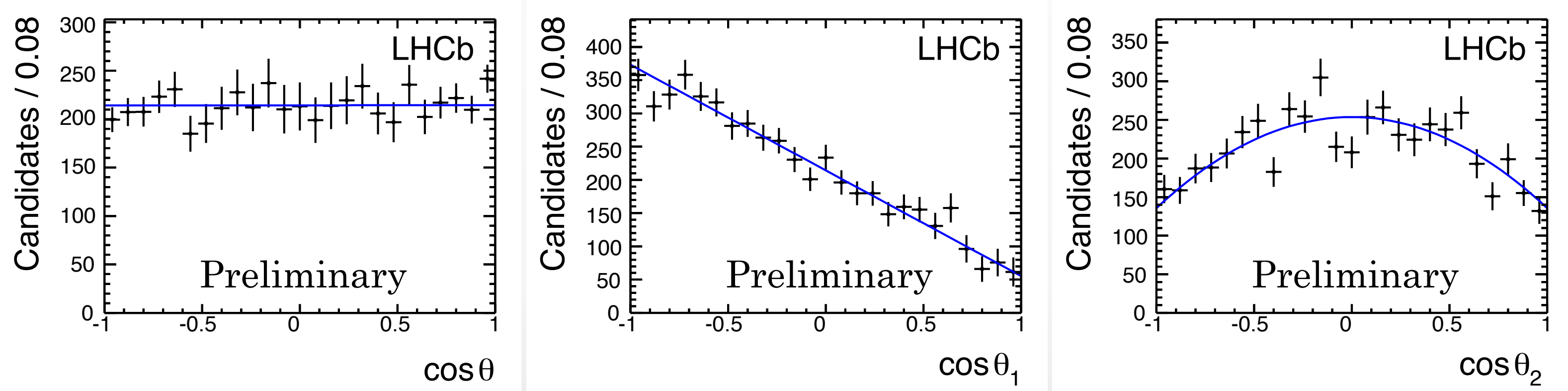


- Weights ($w = 1/f_{acc}$) obtained to correct the data

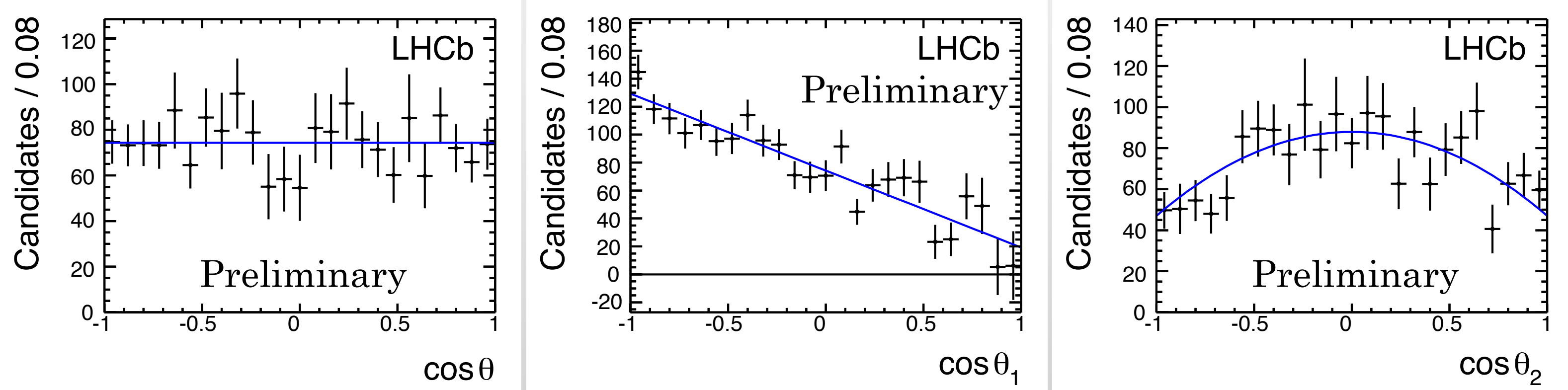
FIT OF THE DATA

- Simultaneous (OUT + IN) unbinned weighted likelihood fit
  - Weights subtract the background and correct for the acceptance $\Rightarrow$ only the signal PDF in the final fit

OUT



IN



SYSTEMATICS TABLE

Source	P_b	α_b	r_0	r_1
Background subtraction	0.001	0.006	0.001	0.005
Signal mass PDF		negl.		
Acceptance	**0.02**	**0.04**	**0.006**	**0.03**
Simulated data calibration	**0.01**	**0.04**	**0.006**	**0.03**
α_Λ	0.002	negl.	negl.	0.01
Fit bias	0.004	0.04	0.001	0.02
Angular resolution	0.002	0.01	negl.	0.005
Integration over ϕ_1 and ϕ_2		negl.		
Total (quadratic sum)	0.02	0.07	0.009	0.05

FIT RESULTS

First measurements of the Λ^0_b polarisation P_b (in *pp* collisions) and *P*-violation asymmetry parameter α_b

$$\begin{aligned} P_b &= 0.05 \pm 0.07_{stat} \pm 0.02_{syst} \\ \alpha_b &= -0.04 \pm 0.17_{stat} \pm 0.07_{syst} \\ r_0 &= 0.57 \pm 0.02_{stat} \pm 0.01_{syst} \\ r_1 &= -0.59 \pm 0.10_{stat} \pm 0.05_{syst} \end{aligned}$$

Preliminary

Method	Value	Reference
Factorization	−0.1	PRD56 (1997) 2799
Factorization	−0.18	PRD58 (1998) 014016
Covariant oscillator quark model	−0.208	Prog. Theor. Phys. 101 (1999) 959
Perturbative QCD	−0.17 to −0.14	PRD65 (2002) 074030
Factorization (HQET)	0.777 and 0.490	PLB614 (2005) 165 and LHCb-2008-005
Light front quark model	−0.204	PRD80 (2009) 094016

- ⊛ Polarisation P_b in agreement with extrapolation from Λ and in disagreement at 2.7σ with prediction of 20%
- ⊛ α_b in agreement with most predictions (-0.2 to -0.1); in disagreement with 0.78 and 0.49 at 6.1σ and 3.9σ

CONCLUSION

High precision measurements are most useful to test the reliability of several models and techniques into predicting the mass spectrum and the properties of the hadrons

- Observation of new excited states or decay modes:
  - $B_{s2}^{*} \to B^{*+}K^{-}$ [LHCB-PAPER-2012-030; arXiv:1211.5994]
  - $\Lambda_b^{0*}(5912)/\Lambda_b^{0*}(5920) \to \Lambda_b^0\pi^+\pi^-$ [LHCB-PAPER-2012-012; PRL 109 (2012) 172003]
- Most precise measurements of masses:
  - $m(B^{*+}) = 5324.26 \pm 0.30_{stat} \pm 0.23_{syst} \pm 0.17_{B\ mass}$ MeV/c^2
  - $m(B_{s1}) = 5828.40 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.41_{B^*mass}$ MeV/c^2
  - $m(B_{s2}^{*}) = 5839.99 \pm 0.05_{stat} \pm 0.11_{syst} \pm 0.17_{B\ mass}$ MeV/c^2
  - $m(\Lambda_b^0) = 5619.53 \pm 0.13_{stat} \pm 0.45_{syst}$ MeV/c^2
  - $m(\Xi_b^-) = 5795.8 \pm 0.9_{stat} \pm 0.4_{syst}$ MeV/c^2 [LHCB-PAPER-2012-048 in preparation]
  - $m(\Omega_b^-) = 6046.0 \pm 2.2_{stat} \pm 0.5_{syst}$ MeV/c^2
- Measurement of polarisation:
  - Λ_b^0: $P_b = 0.05 \pm 0.07_{stat} \pm 0.02_{syst}$
    $\alpha_b = -0.04 \pm 0.17_{stat} \pm 0.07_{syst}$ [LHCB-PAPER-2012-057 in preparation]

Preliminary

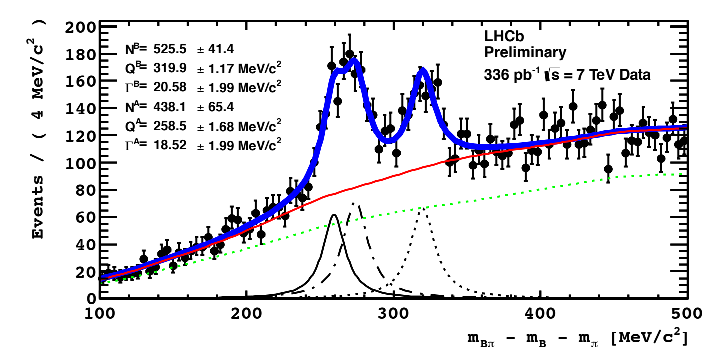
- ➢ The results presented in this talk used only 1/3 of the integrated luminosity recorded by the LHCb experiment
- ➢ You will surely hear more new results in the near future!

NEXT EPISODE TRAILER

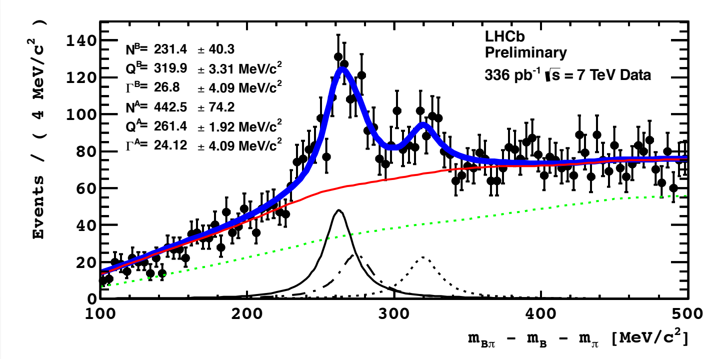
Observation of $B_1^{0,+}$ and B_2^{*0+}

LHCb-CONF-2011-053

$B^+ \pi^-$



$B^0 \pi^+$



Measurements of Λ^0_b production

LHCb-CONF-2012-031

$$\sigma(pp \to \Lambda_b^0 X)\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda) = 4.08 \pm 0.59_{stat} \pm 0.36_{syst}\ \text{nb}$$

$$\sigma(pp \to \bar{\Lambda}_b^0 X)\mathcal{B}(\bar{\Lambda}_b^0 \to J/\psi\bar{\Lambda}) = 2.60 \pm 0.46_{stat} \pm 0.26_{syst}\ \text{nb}$$

Preliminary