Heavy Quark Spectroscopy at LHCb

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Outline

1. X(3872)
2. $\psi(4160)$ in B decays
3. D and D_{sJ} mesons
4. Excited B_{sJ} mesons and $B_c^+ \to B_s^0\pi^+$
5. Summary

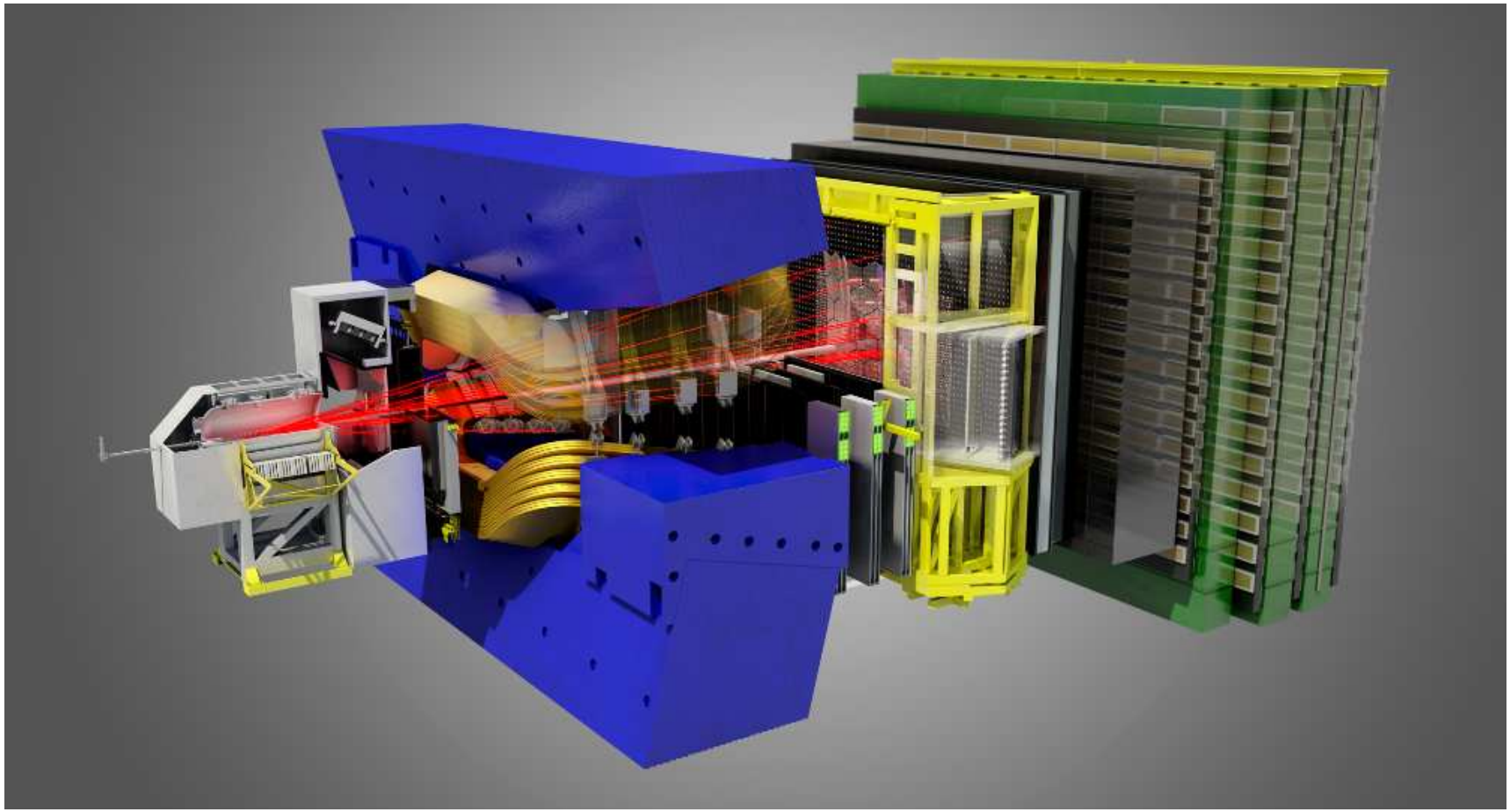
LHCb Experiment – I

- LHCb is a single-arm forward spectrometer at $2 < \eta < 5$ for a study of particles with b or c quarks
- 934 members, 65 Institutes from 17 countries
-

Year	$\sqrt{s}$, GeV	$\int Ldt$
2010	7	37 pb
2011	7	1.0 fb
2012	8	2 fb

- High-precision tracking (silicon strip, straw drift tubes), dipole magnet 4Tm
- Excellent PID based on two RICH detectors
- Muon system (alternating layers of Fe and MWPC)

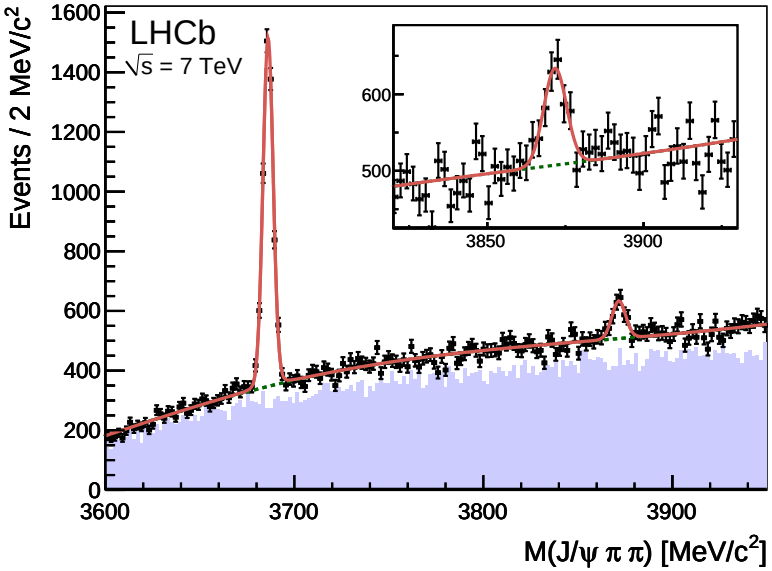
LHCb Experiment – II



Observation of X(3872) at LHCb

$\sigma(pp \to X + \text{anything})\,\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 5.4 \pm 1.3(\text{stat}) \pm 0.8(\text{syst})$ nb,

$2.5 < \eta < 4.5, 5 < p_T < 20$ GeV/c, $\int Ldt = 34.7$ pb^{-1} at $\sqrt{s} = 7$ TeV

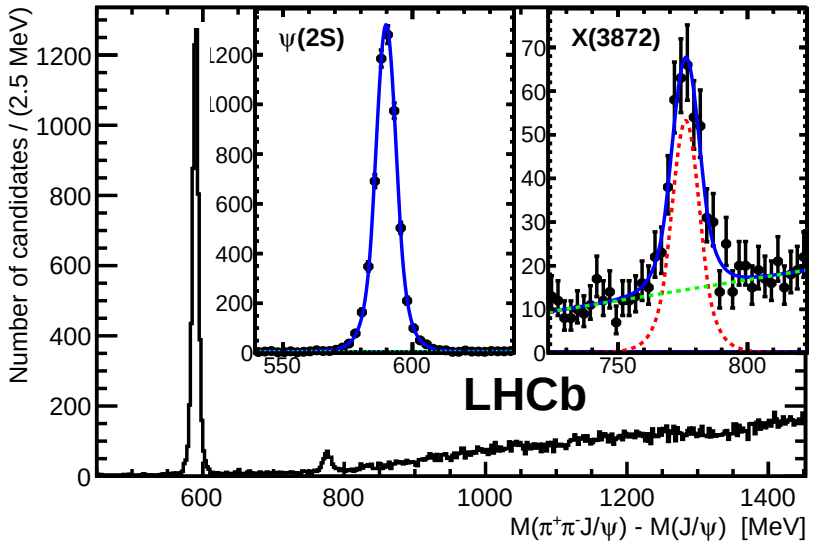


$\psi(2S)$	3998 ± 83	$3686.12 \pm 0.06 \pm 0.10$	$3686.114 \pm 0.007 \pm 0.016$ (KEDR)
X(3872)	565 ± 62	$3871.95 \pm 0.48 \pm 0.12$	$3871.61 \pm 0.16 \pm 0.19$ (CDF)

R. Aaij et al., Eur. Phys. J. C 72 (2012) 1972

Determination of X(3872) Quantum Numbers – I

A study of $B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\pi^+\pi^-,\ J/\psi \to \mu^+\mu^-$
produced in pp at $\sqrt{s} = 7$ TeV with $\int Ldt = 1$ fb^{-1}

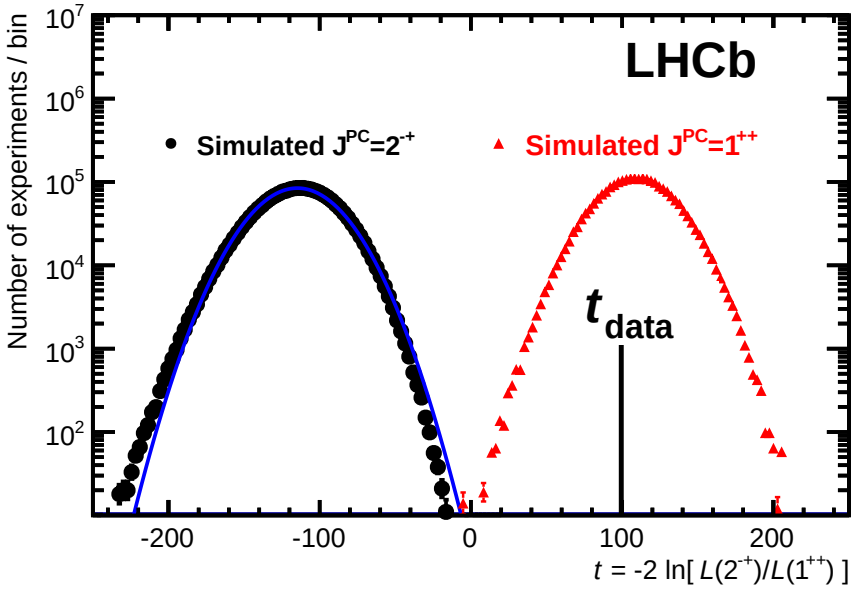


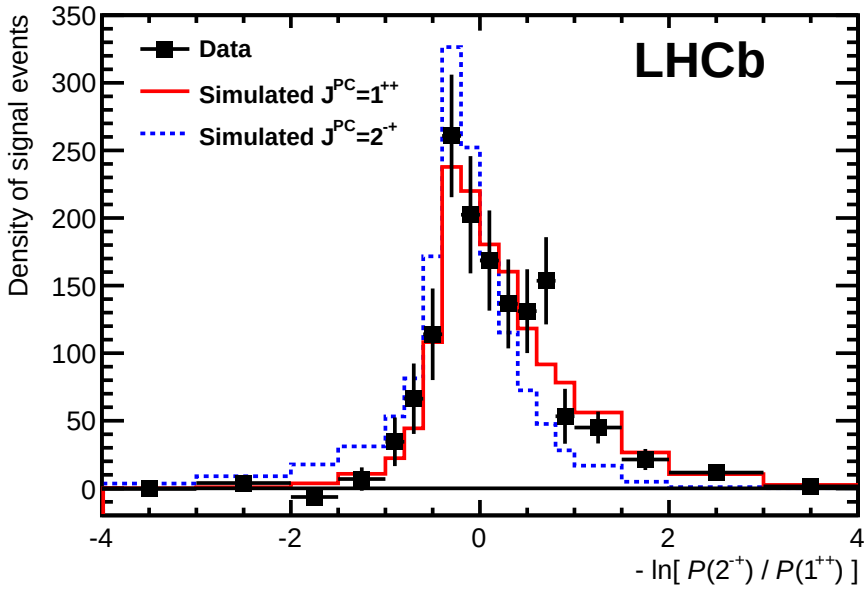
About 38000 B candidates selected in $M(J/\psi\pi^+\pi^-K^+)$ in a $\pm 2\sigma$ range,
a fit yields 5642 ± 76 $\psi(2S)$ events and 313 ± 26 $X(3872)$ (68% purity)

R. Aaij et al., Phys. Rev. Lett. 110 (2013) 222001

Determination of X(3872) Quantum Numbers – II

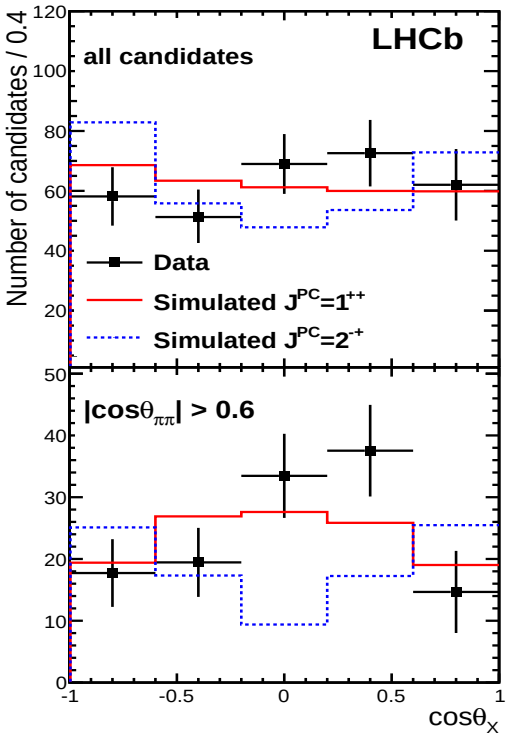
Analysis in $5D$ angular space $\Omega \equiv (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$





The 2^{-+} hypothesis is rejected with 8.4σ significance

Determination of X(3872) Quantum Numbers – III



- Projections onto five $1D$ and ten $2D$ binned distr. are all consistent with 1^{++}
- Correlations between $\cos\theta_X$ and $\cos\theta_{\pi\pi}$ increase the separation btw. 1^{++} and 2^{-+}

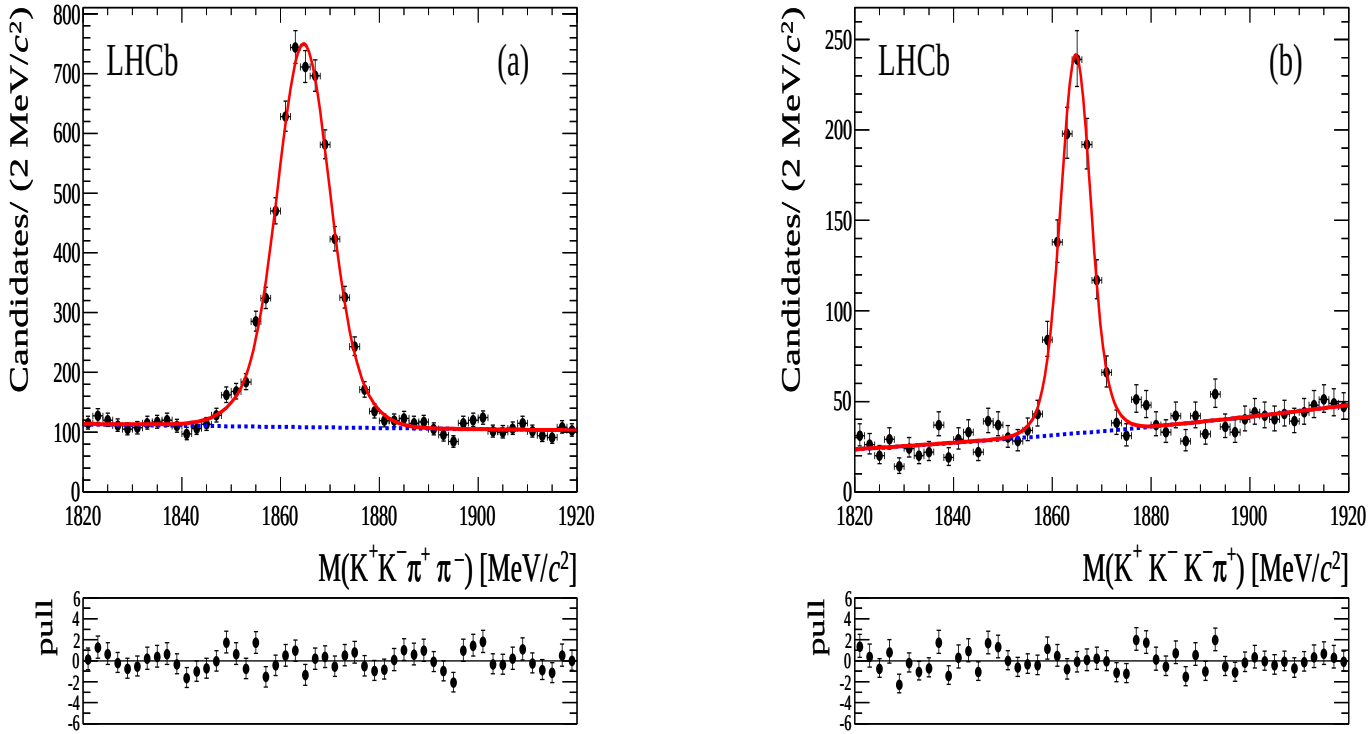
1^{++} rules out $X(3872)$ as a conventional $\eta_{c2}(1^1D_2)$ state,

$\chi_{c1}(2^3P_1)$ $c\bar{c}$ disfavored by $X(3872)$ mass,

Possible exotics: $D^{*0}\bar{D}^0$ molecule, 4-q state, $c\bar{c}$-molecule mixture

Precision Measurement of D Meson Mass Differences – I

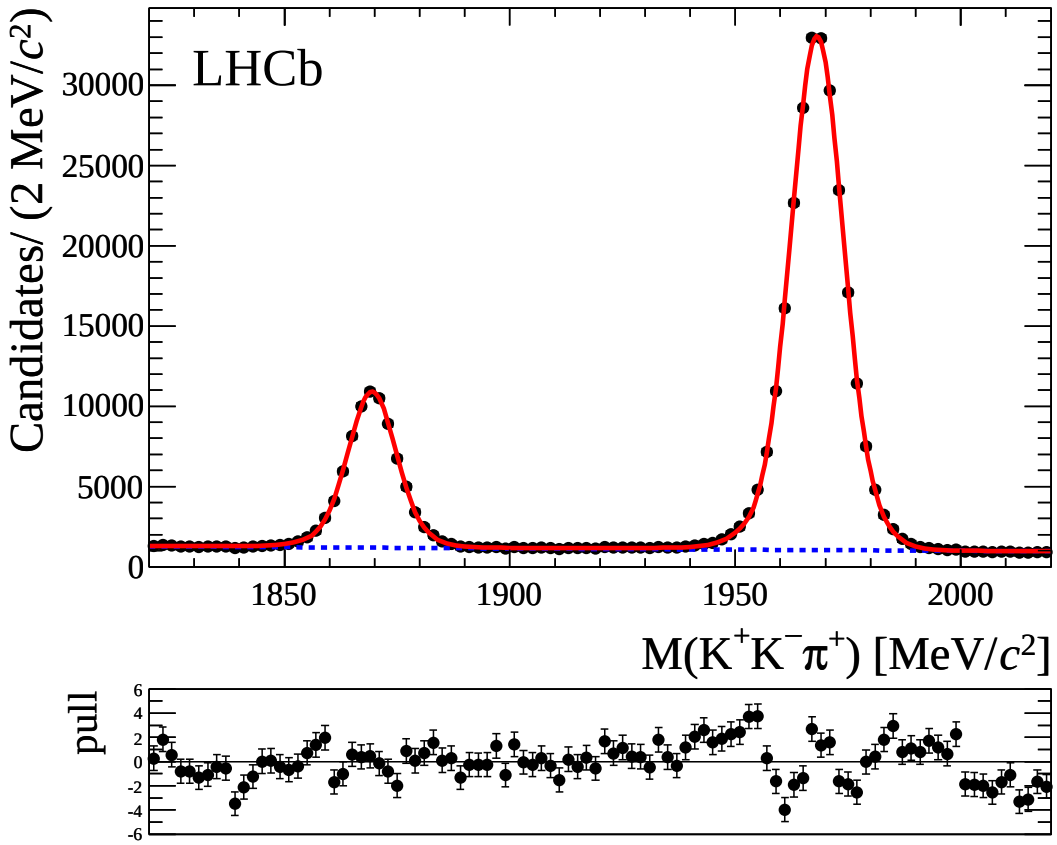
3- and 4-body decays of D mesons produced in semileptonic b-hadron decays, pp collisions at $\sqrt{s} = 7$ TeV with $\int Ldt = 1$ fb^{-1}



$M(D)$ measured in $D^0 \to K^+K^-\pi^+\pi^-$, small $Q = M(D) - \Sigma m_i$

R. Aaij et al., JHEP 1306 (2013) 065

Precision Measurement of D Meson Mass Differences – II



Precision Measurement of D Meson Mass Differences – III

Decay mode	Yield	Mass
$D^0 \to K^+K^-\pi^+\pi^-$	4608 ± 89	1864.74 ± 0.12
$D^0 \to K^+K^-K^-\pi^+$	849 ± 36	1864.75 ± 0.15
$D^+ \to K^+K^-\pi^+$	$68,787 \pm 321$	1869.50 ± 0.03
$D_s^+ \to K^+K^-\pi^+$	$248,694 \pm 540$	1968.19 ± 0.03

$$M(D^+) - M(D^0) = 4.76 \pm 0.12\,(\text{stat})\ \text{MeV}/c^2,$$
$$M(D_s^+) - M(D^+) = 98.68 \pm 0.03\,(\text{stat})\ \text{MeV}/c^2,$$

Modes 1,3,4 have large Q $\Rightarrow$ large systematics due to momentum scale (0.2-0.3 MeV) and are not used although the masses are consistent with PDG

Precision Measurement of D Meson Mass Differences – IV

$$
\begin{aligned}
M(D^0) &= 1864.75 \pm 0.15\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2,\\
M(D^+) - M(D^0) &= 4.76 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{MeV}/c^2,\\
M(D_s^+) - M(D^+) &= 98.68 \pm 0.03\,(\text{stat}) \pm 0.04\,(\text{syst})\ \text{MeV}/c^2.
\end{aligned}
$$

Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(D^0)$	1864.75 ± 0.19	1864.85 ± 0.18 CLEO	1864.86 ± 0.13
$M(D^+) - M(D^0)$	4.76 ± 0.14	4.7 ± 0.3 MARK2	4.76 ± 0.10
$M(D_s^+) - M(D^+)$	98.68 ± 0.05	98.4 ± 0.3 BaBar	98.88 ± 0.25

LHCb: $M(D_s^+) = 1968.19 \pm 0.20 \pm 0.14 \pm 0.08$ MeV,

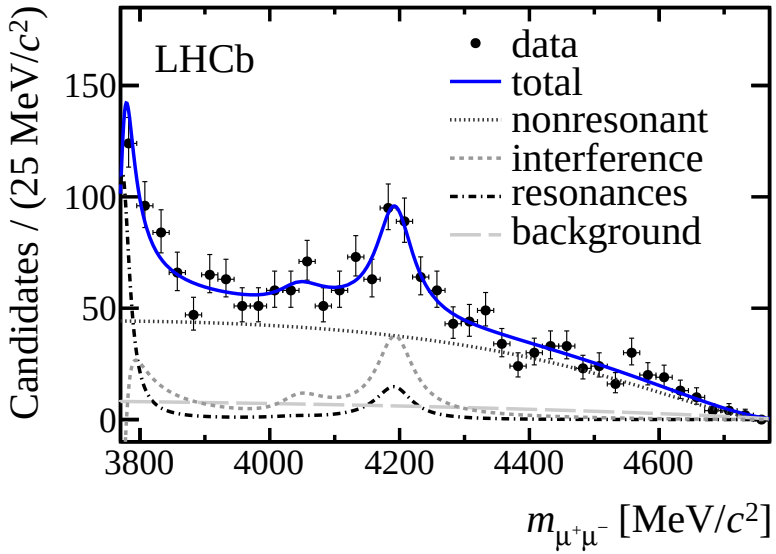
PDG: $M(D_s^+) = 1968.49 \pm 0.32$ MeV.

$E_B = M(D^0 D^{*0}) - M(X(3872)) = 0.09 \pm 0.28$ MeV,

so if $X(3872)$ is a molecule, it is extremely loosely bound.

Observation of a Resonance in $B^+ \to K^+\mu^+\mu^-$ – I

$B^+ \to K^+\mu^+\mu^-$ decay studied at $\sqrt{s}$ =7 and 8 TeV with $\int Ldt = 3$ fb^{-1}



1830 candidates in the low recoil region ($m_{\mu^+\mu^-} > 3770$ MeV)

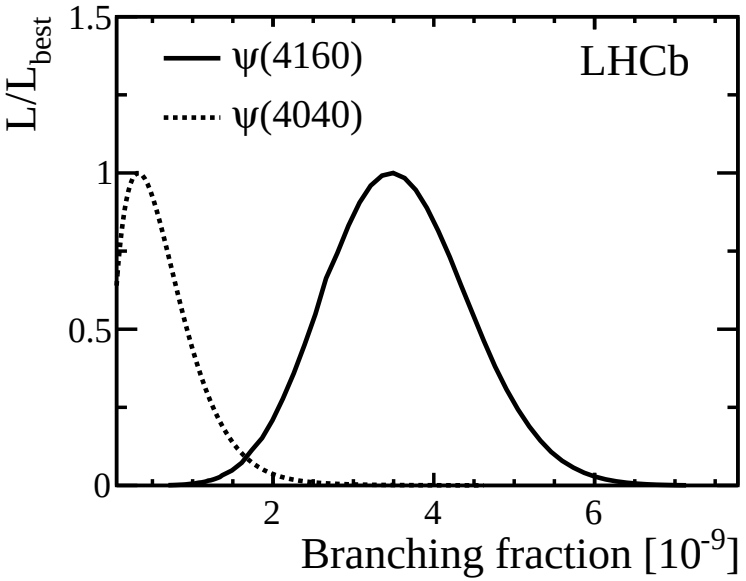
R. Aaij et al., Phys. Rev. Lett. 111 (2013) 112003.

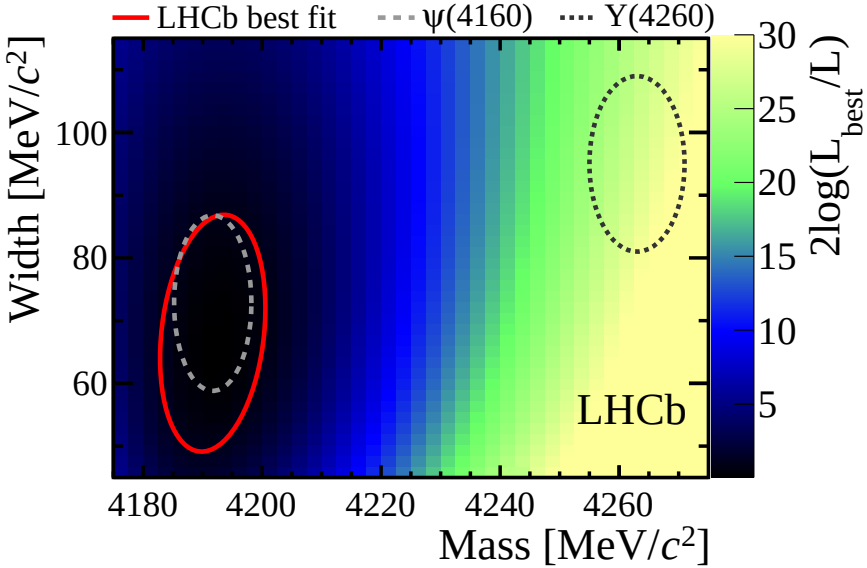
Observation of a Resonance in $B^+ \to K^+\mu^+\mu^-$ – II

	Unconstrained	$\psi(4160)$
B $[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$	$3.5\,^{+0.9}_{-0.8}$
Mass [MeV]	$4191\,^{+9}_{-8}$	4190 ± 5
Width [MeV]	$65\,^{+22}_{-16}$	66 ± 12
Phase [rad]	-1.7 ± 0.3	-1.8 ± 0.3

The structure has a significance exceeding 6σ,
its properties are consistent with the $\psi(4160)$

Observation of a Resonance in $B^+ \to K^+\mu^+\mu^-$ – III





$\mathcal{B}(B^+ \to \psi(4040)K^+)\mathcal{B}(\psi(4040) \to \mu^+\mu^-) < 1.3 \times 10^{-9}$ at 90% CL

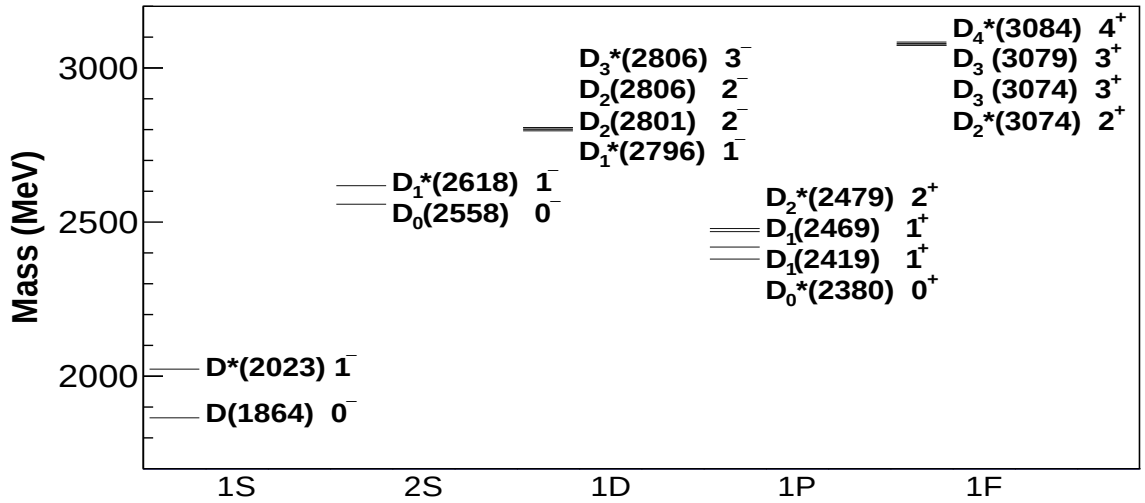
A hypothesis that the resonance is due to $Y(4260)$ is disfavored by more than 4σ

Using $\mathcal{B}(\psi(4160) \to e^+e^-) = (6.9 \pm 4.0) \times 10^{-6}$ and assuming lepton universality,

$\mathcal{B}(B^+ \to \psi(4160)K^+) = (5.1^{+1.3}_{-1.2} \pm 3.0) \times 10^{-4}$ while

$\mathcal{B}(B^+ \to \psi(4040)K^+) < 1.3 \times 10^{-4}$ at 90% CL

Study of D_J Mesons – I



J^P states with $P = (-1)^J$ $(0^+, 1^-, 2^+, \ldots)$ – natural parity states D^*,

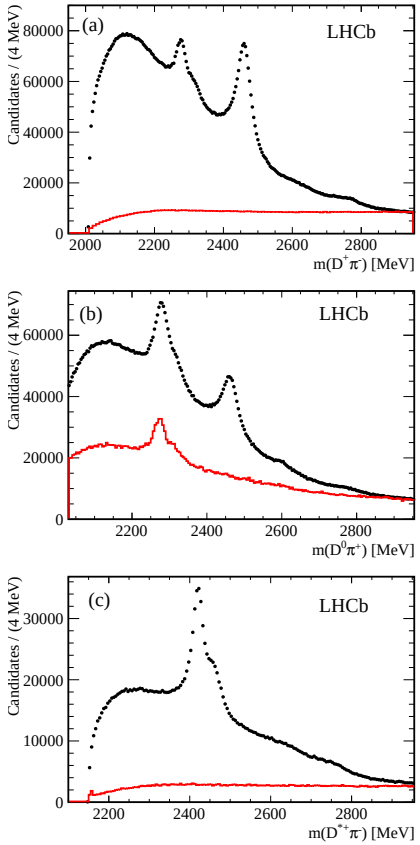
$J^P = 0^-, 1^+, 2^-, \ldots$ – unnatural parity states D,

2 narrow $1P$ states well known, $D_1(2420)$, $D_2^*(2460)$,

2 broad $L = 1$, $D_0^*(2400), D_1'(2430)$, found by Belle and BaBar

Study of D_J Mesons – II

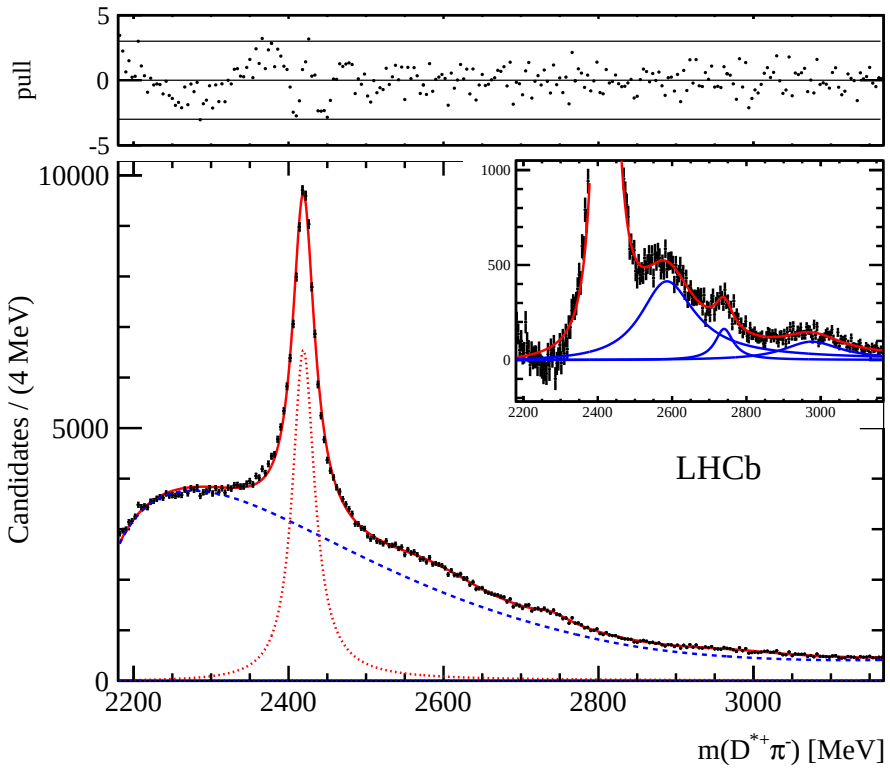
A study of $D^+\pi^-, D^0\pi^+, D^{*+}\pi^-$ states with 1.0 fb^{-1} at 7 TeV

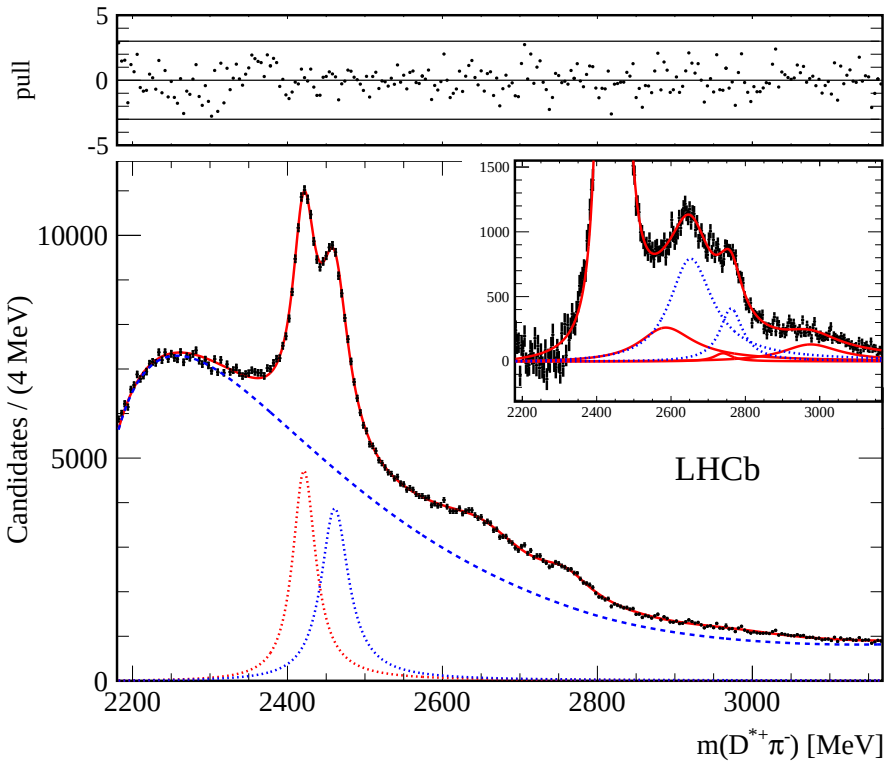


R. Aaij et al., arXiv:1307.4556, JHEP

Study of D_J Mesons – III

$D^{*+}\pi^-$ state

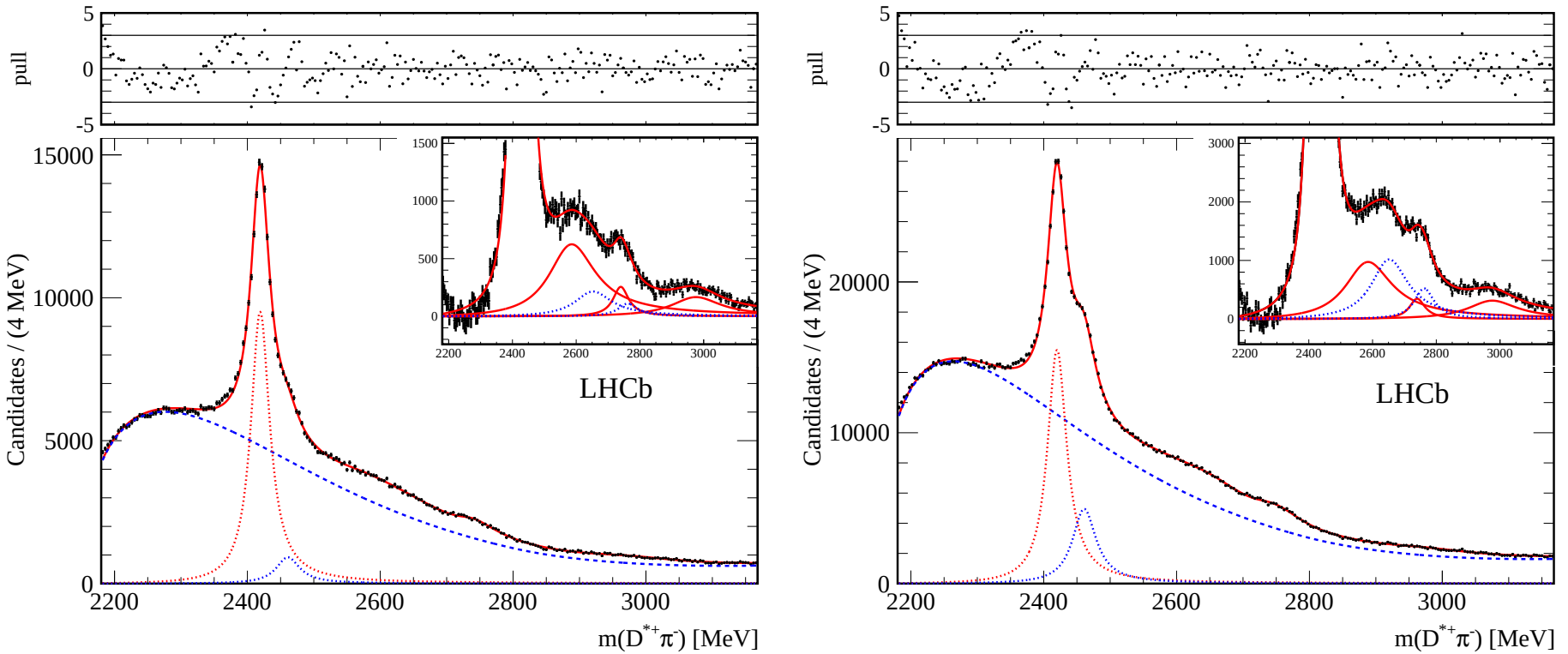




Enhanced unnatural ($|\cos\theta_{\rm H}| > 0.75$), natural ($|\cos\theta_{\rm H}| < 0.5$) parity

Study of D_J Mesons – IV

$D^{*+}\pi^-$ state

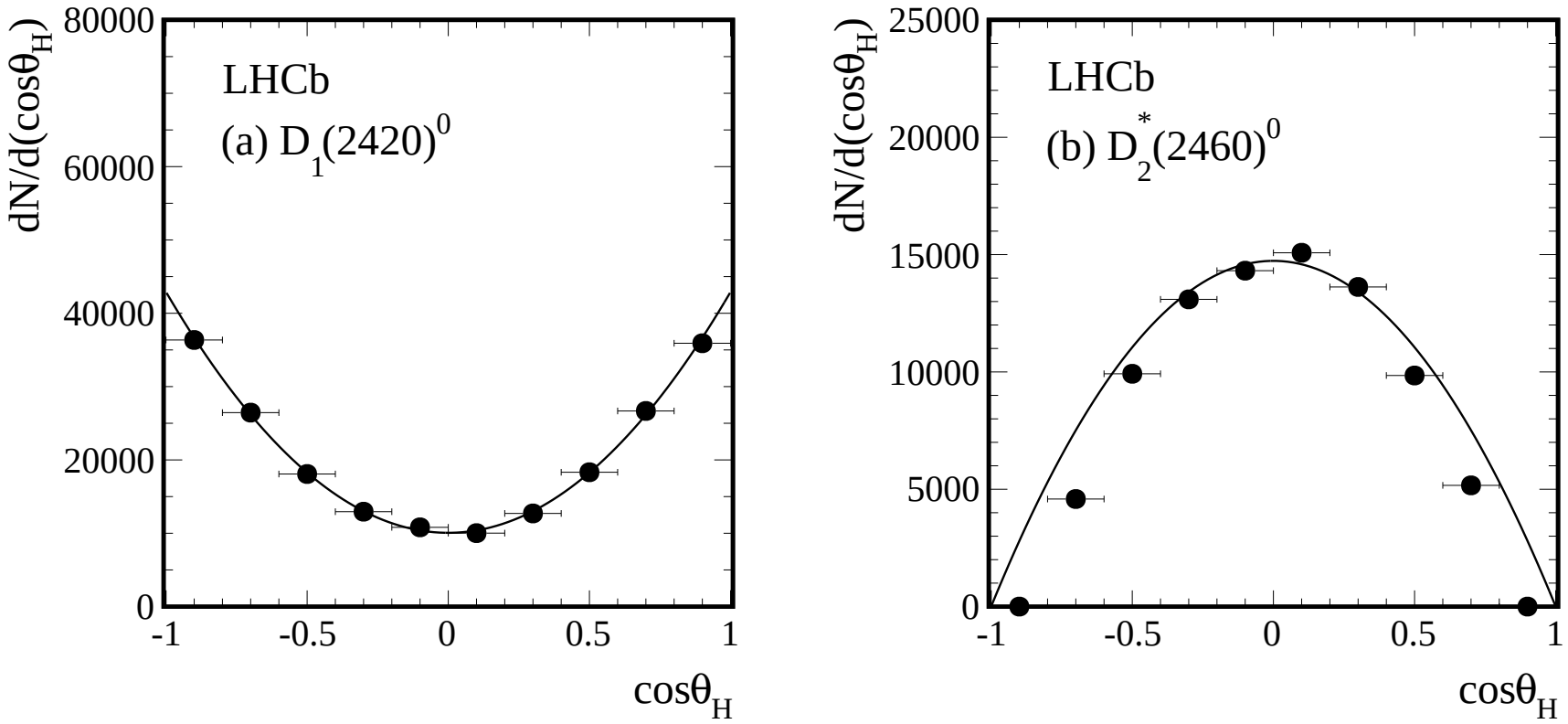


Unnatural parity ($|\cos\theta_{\rm H}| > 0.5$), total sample

Study of D_J Mesons – V

Resonance	Final state	Mass (MeV)	Width (MeV)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8

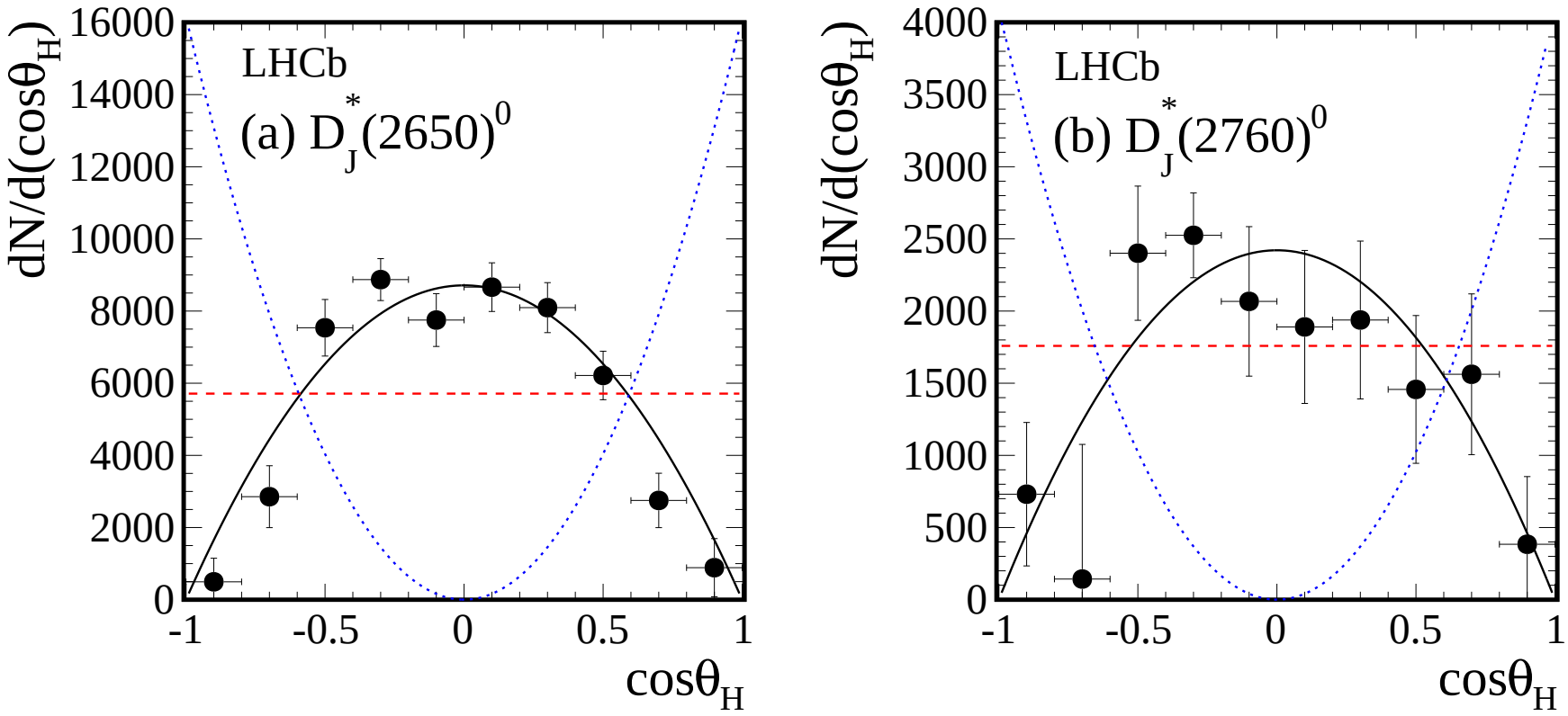
Study of D_J Mesons – VI



Helicity angle $\theta_{\rm H}$ is the angle btw. π^- and π^+ from the D^{*+} in the $D^{*+}\pi^-$ rest frame

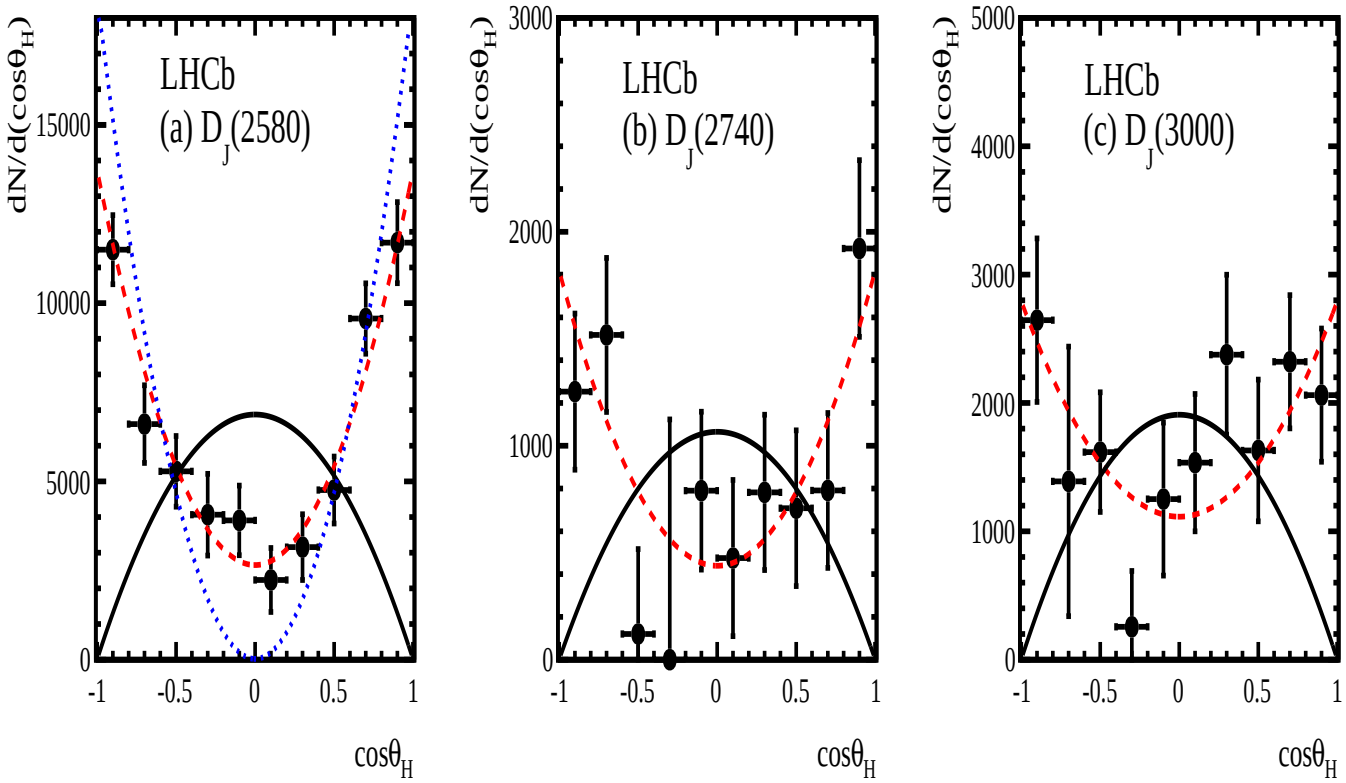
Good agreement with expectations for $D_1(2420)^0$ (1^+) and $D_2^*(2460)^0$ (2^+)

Study of D_J Mesons – VII



Parity: natural – black, unnatural – red, $J^P = 0^-$ - blue

Study of D_J Mesons – VIII



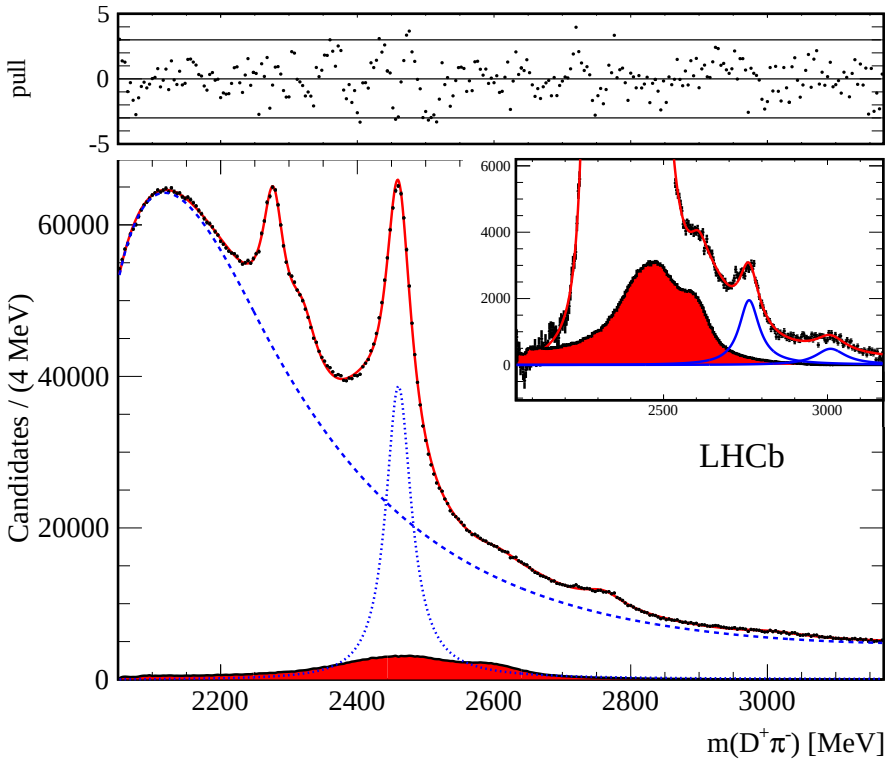
Parity: natural – black, unnatural – red, $J^P = 0^-$ - blue

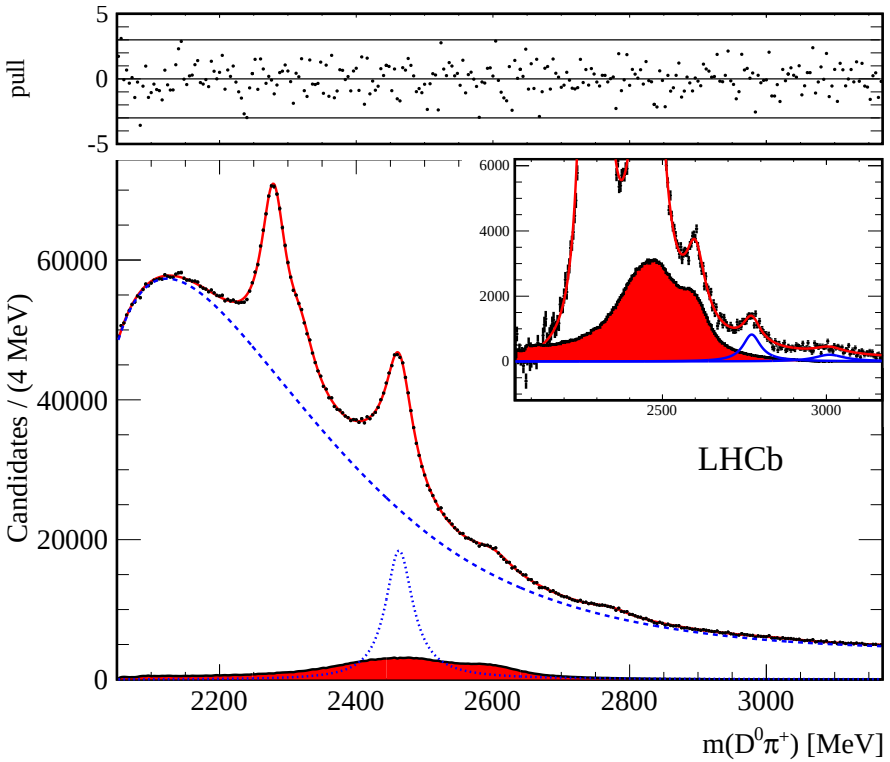
Study of D_J Mesons – IX

Resonance	J^P (Function)	h parameter
$D_1(2420)^0$	$1^+(1+h\cos^2\theta_{\rm H})$	3.30 ± 0.48
$D_2^*(2460)^0$	$2^+(\sin^2\theta_{\rm H})$	–
$D_J^*(2650)^0$	Nat. $(\sin^2\theta_{\rm H})$	–
$D_J^*(2760)^0$	Nat. $(\sin^2\theta_{\rm H})$	–
$D_J(2580)^0$	Unnat.$(1+h\cos^2\theta_{\rm H})$	4.2 ± 1.3
$D_J(2740)^0$	Unnat.$(1+h\cos^2\theta_{\rm H})$	3.1 ± 2.2
$D_J(3000)^0$	Unnat.$(1+h\cos^2\theta_{\rm H})$	1.5 ± 0.9

Study of D_J Mesons – X

$D^+\pi^-$ and $D^0\pi^+$ states





Substantial cross-feeds from $D^*\pi$ states

Study of D_J Mesons – XI

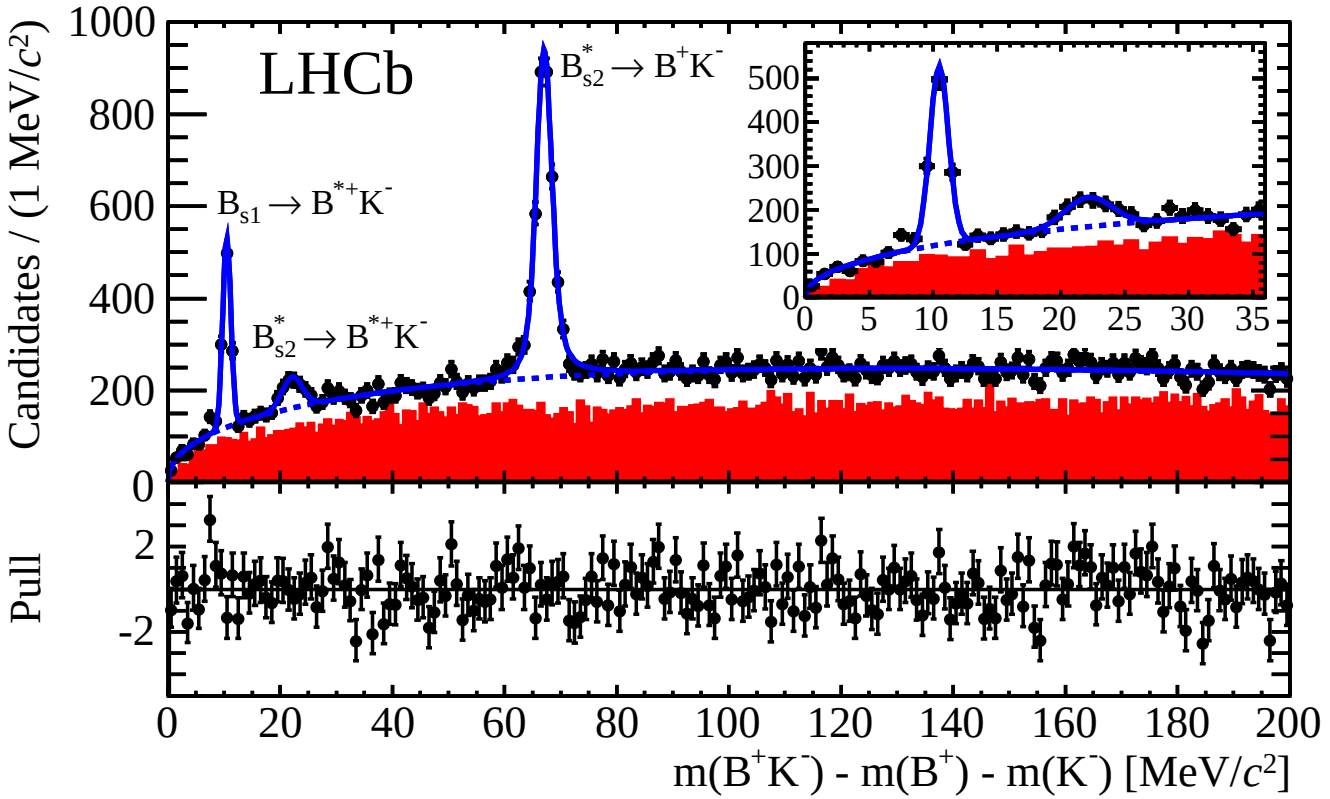
Resonance	Final state	Mass (MeV)	Width (MeV)
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm$
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)

Study of D_J Mesons – XII

- Parameters measured and J^P confirmed for the $D_1(2420)^0$ in the $D^{*+}\pi^-$ and the $D_2^*(2460)$ – in the $D^+\pi^-$, $D^0\pi^+$, $D^{*+}\pi^-$ final states
- Two natural parity states $D_J^*(2650)^0$ and $D_J^*(2760)^0$ observed in $D^{*+}\pi^-$
- In $D^+\pi^-$ and $D^0\pi^+$ the $D_J^*(2760)$ confirmed, but the $D_J^*(2650)$ region is inconclusive
- Two unnatural parity states $D_J(2580)^0$ and $D_J(2740)^0$ in $D^+\pi^-$
- $D_J(3000)^0$ with unnatural parity observed in $D^{*+}\pi^-$
- $D_J^*(3000)^0$ and $D_J^*(3000)^+$ observed in $D^+\pi^-$ and $D^0\pi^+$
- Partial agreement, although sometimes different parameters, with BaBar (P. del Amo Sanchez et al., Phys. Rev. D 82 (2010) 111101)
- Obtained results can be compared to quark model predictions

Excited B_s^0 Mesons – I

Orbitally excited ($L = 1$) B_s^0 states studied at 7 TeV with 1.0 fb^{-1}



R. Aaij et al., Phys. Rev. Lett. 110 (2013) 151803

Excited B_s^0 Mesons – II

Results of the fit to $m(B^+K^-) - m(B^+) - m(K^-)$

Parameter	Fit result, MeV	Best previous, MeV
$m(B_{s1}) - m(B^{*+}) - m(K^-)$	$10.46 \pm 0.04 \pm 0.04$	$10.73 \pm 0.21 \pm 0.14$
$m(B_{s2}) - m(B^+) - m(K^-)$	$67.06 \pm 0.05 \pm 0.11$	$66.96 \pm 0.39 \pm 0.14$
$m(B^{*+}) - m(B^+)$	$45.01 \pm 0.30 \pm 0.23$	45.6 ± 0.8
$\Gamma(B_{s2}^*)$	$1.56 \pm 0.13 \pm 0.47$ –	
$\frac{\mathcal{B}(B_{s2}^* \to B^{*+}K^-)}{\mathcal{B}(B_{s2}^* \to B^+K^-)}$	$(9.3 \pm 1.3 \pm 1.2)\%$	–

$N(B_{s1} \to B^{*+}K^-)$	$N(B_{s2}^* \to B^{*+}K^-)$	$N(B_{s2}^* \to B^+K^-)$
750 ± 36	307 ± 46	3140 ± 100

Excited B_s^0 Mesons – III

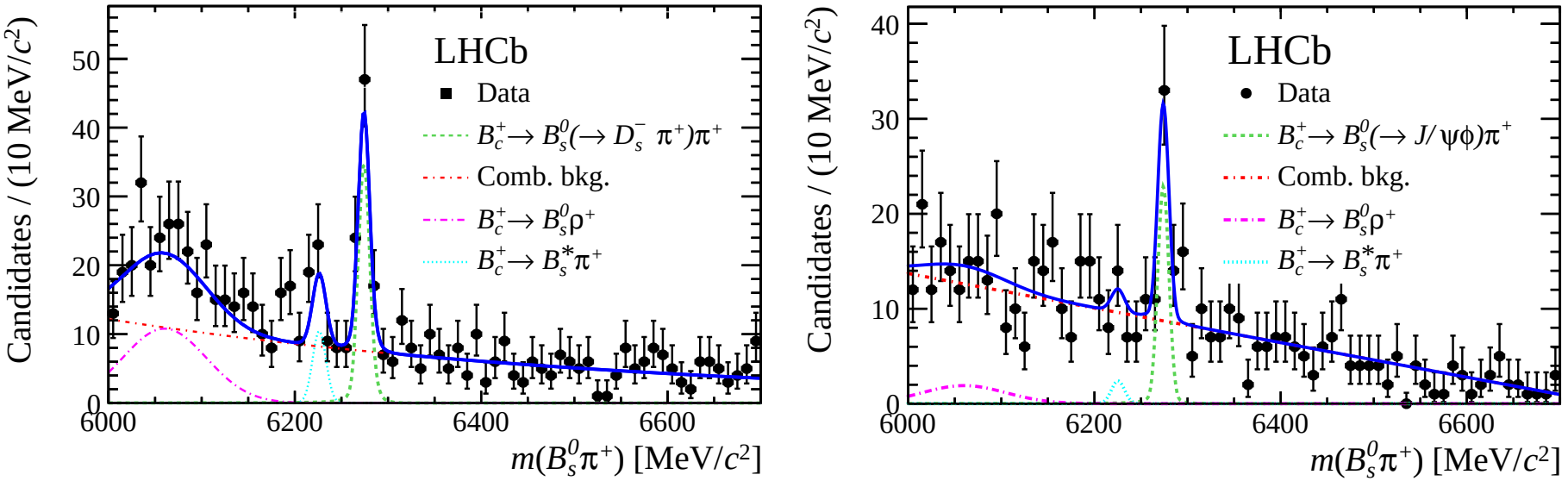
- Using $m(B^+)$, $m(B_{s1})$ and $m(B^{*+}) - m(B^+)$

$$m(B^*) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17\,\text{MeV},$$
$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41\,\text{MeV},$$
$$m(B_{s2}^*) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17\,\text{MeV}.$$

- Observation of $B_{s2}^* \to B^{*+}K^-$ and $B_{s2}^* \to B^+K^-$ favors $J^P = 2^+$
- First measurement of the B_{s2}^* width
- $m(Z_b(10610)^+)$ and $m(Z_b(10650)^+)$ are 3.69 ± 2.05 MeV and 3.68 ± 1.71 MeV above the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds

Observation of $B_c^+ \to B_s^0\pi^+$

Using 1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV, LHCb observes
$B_c^+ \to B_s^0\pi^+$, $B_s^0 \to D_s^-\pi^+$ and $B_s^0 \to J/\psi\phi$ with 7.7σ and 6.1σ significance



This is the first observation of the weak decay of a B meson decaying to another B, with the b quark acting as a spectator

R. Aaij et al., Arxiv:1308.4544, Phys. Rev. Lett.

Summary

- $X(3872)$ is clearly selected both in continuum and B decays
- $X(3872)$ quantum numbers are 1^+
- Precise determination of D meson masses
- Various D_J observed with J^P analysis
- Excited B_s states studied
- Decay $B_c^+ \to B_s^0 \pi^+$ observed
- Due to the high cross section, thus huge statistics, and excellent performance LHCb has a high potential for spectroscopy studies

Backup Slides

LHCb Resolution

- Momentum: $\Delta p/p$ =0.4% at 5 GeV/c to 0.6% at 100 GeV/c
- ECAL (nominal): $1\% + 10\%/\sqrt{E[\mathrm{GeV}]}$
- Impact parameter: 20 μm for high-p_T tracks
- Invariant mass:
  ~ 8 MeV/c^2 for $B \to J/\psi X$ with constraint on J/ψ mass,
  ~ 22 MeV/c^2 for two-body B decays,
  ~ 100 MeV/c^2 for $B_s \to \phi\gamma$, dominated by γ contribution
- Decay time: 45 fs for $B_s \to J/\psi\phi$ and for $B_s \to D_s\pi$

Results of the fit to the $J/\psi\pi^+\pi^-$ mass

Parameter	$\psi(2S)$	X(3872)
Signal events	3998 ± 83	565 ± 62
Mass, MeV	3686.10 ± 0.06	3871.88 ± 0.48
Resolution, MeV	2.54 ± 0.06	3.33 ± 0.08
Signal-to-noise ratio in $\pm 3\sigma$ window	1.5	0.15
Background events	73094 ± 282	

Systematic uncertainties on the $\psi(2S)$ and X(3872) masses

Category	Source of uncertainty	$\psi(2S)$	X(3872)
Mass fitting	Natural width	–	0.01
	Radiative tail	0.02	0.02
	Resolution	–	0.01
	Background model	0.02	0.02
Momentum calibration	Average momentum scale	0.08	0.10
	η dependence of momentum scale	0.02	0.03
Detector description	Energy loss correction	0.05	0.05
Detector alignment	Track slopes	0.01	0.01
Total		0.10	0.12

Determination of X(3872) Quantum Numbers

- About 38 000 candidates selected in a $\pm 2\sigma$ mass range around the B^+ peak in the $M(J/\psi K^+\pi^+\pi^-)$ distribution (signal purity of 89%)
- The $\psi(2S)$ fit in the 539.2–639.2 MeV range yields 5642 ± 76 signal (230 ± 21 background) candidates, $\sigma_{\Delta M} = 3.99 \pm 0.05$ MeV, signal purity of 99.2% in a $\pm 2.5\sigma_{\Delta M}$ region
- The $X(3872)$ fit in the 723–823 MeV range yields 313 ± 26 (568 ± 31 background) $X(3872)$ candidates, $\sigma_{\Delta M} = 5.5 \pm 0.5$ MeV, signal purity of 68% in a $\pm 2.5\sigma_{\Delta M}$ region
- The dominant background is from $B^+ \to J/\psi K_1(1270)^+$, $K_1(1270)^+ \to K^+\pi^+\pi^-$ decays (from a study of the $K^+\pi^+\pi^-$ mass)

Systematic uncertainties on the D meson masses

Source of uncertainty	$M(D^0)$	$M(D^+) - M(D^0)$	$M(D_s^+) - M(D^+)$
Momentum scale	0.09	0.04	0.04
Energy loss correction	0.03	0.06	<0.01
$K^\pm$ mass	0.05	<0.01	<0.01
Signal model	0.02	<0.01	<0.01
Background model	<0.01	<0.01	<0.01
Quadratic sum	0.11	0.07	0.04

Excited B_s^0 Mesons

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