



## Spectroscopy at LHCb

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PWA7  
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# Outline

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- The LHCb detector
- $B_c$  mesons
- Excited  $B$  and  $B_s$  mesons
- Excited  $D$  and  $D_s$  mesons
- Properties of the  $X(3872)$
- Search of  $X(4140)$  and  $X(4274)$

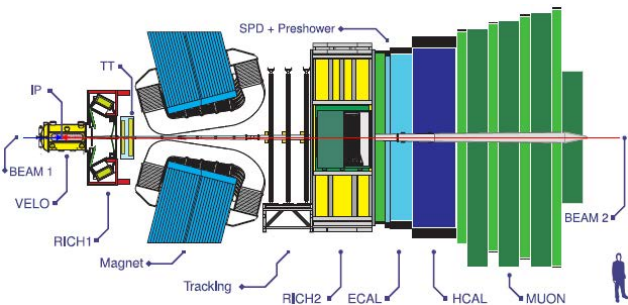
# Why spectroscopy?

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- Spectroscopy provides a test of QCD models
- Comparison of properties such as masses, lifetimes, decay properties
- Many predicted states not yet observed or poorly measured
- Searches for new/exotic states
- Shed light on the nature of some of the XYZ states

# The LHCb experiment

- LHC is the largest source of  $b$  (and  $c$ ) hadrons:  
 $\sigma_{b\bar{b}} \approx 284 \mu\text{b} @ 7 \text{ TeV} [\sim 10^6 b\bar{b}/s]$  [PLB 694, 209]  
 $\sigma_{c\bar{c}} \approx 20 \times \sigma_{b\bar{b}}$  [Nucl.Phys.B871(2013)1-20]
- LHCb designed to study rare decays and CP violation in  $b/c$ -hadrons  
ideal place also for spectroscopy
- Forward single-arm spectrometer (pseudorapidity region  $2 < \eta < 5$ )

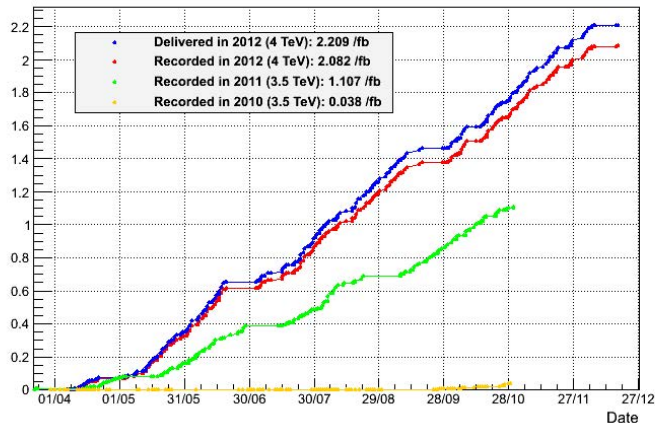


## Excellent performance:

- precise vertexing and momentum resolution
- Excellent particle ID performance
- Excellent trigger selecting high- $p_t$  lepton or hadron from displaced vertexes

# Data samples

## LHCb Integrated Luminosity pp collisions 2010-2012



LHCb is in very good shape:

- $37 \text{ pb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  recorded in 2010
- $1.1 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  in 2011
- $2 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$  in 2012

- Total statistics available on tape:  $\sim 3 \text{ fb}^{-1}$

# $B_c^+$ meson

- Unique meson composed of two heavy quarks decaying weakly

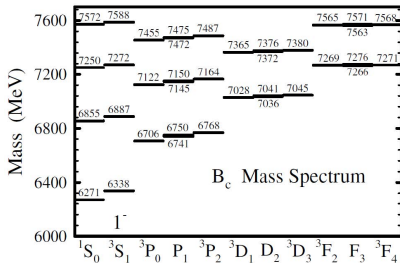
- Decays via

- $\bar{b} \rightarrow \bar{c}/\bar{u}$  transitions
- $c \rightarrow s/d$  transitions
- $\bar{b}c \rightarrow W$  annihilations

- Observed by CDF in  $J/\psi\ell\nu$  decays and  $J/\psi\pi^+$  [PRL 81,2432(1998); PRL 96,082002(2008)]

- Confirmed by LHCb in  $B_c^+ \rightarrow J/\psi\pi^+$  with  $0.37 \text{ fb}^{-1}$  measuring the mass and the production [PRL 109 232001 (2012)]

- Many other  $B_c$  decay modes observed at LHCb



- $B_c^+ \rightarrow J/\psi\pi^+\pi^-\pi^+$ ,  $1 \text{ fb}^{-1}$ , [PRL 108, 251802 (2012)]

- $B_c^+ \rightarrow \psi(2S)\pi^+$ ,  $1 \text{ fb}^{-1}$ , [PRD 87, 071103 (2013)]

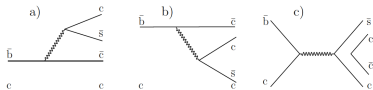
- $B_c^+ \rightarrow J/\psi K^+$ ,  $1 \text{ fb}^{-1}$ , [arXiv:1306.6723]

- $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+$ ,  $3 \text{ fb}^{-1}$ , [arXiv:1309.0587]

- $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ ,  $3 \text{ fb}^{-1}$ , [PRD 87 (2013) 112012]

- $B_c^+ \rightarrow B_s^0 \pi^+$ ,  $3 \text{ fb}^{-1}$ , [[arXiv:1308.4544]]

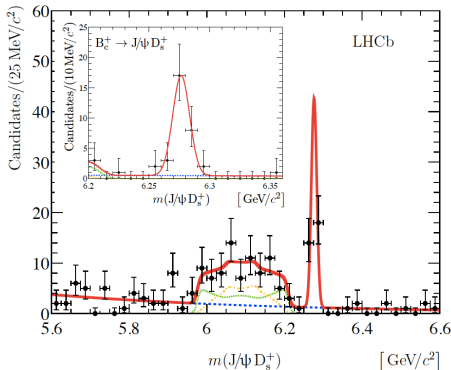
# Observation of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ [PRD 87 (2013) 112012]



- Spectator diagram dominant, possible contributions from colour suppressed spectator and annihilation
- Reconstruct  $J/\psi \rightarrow \mu\mu$  and  $D_s^+ \rightarrow \phi\pi^+ \rightarrow (K^+K^-)\pi^+$

Excess of more than  $9\sigma$  for both channels

- Partially reconstructed  $B_c^+ \rightarrow J/\psi D^{*+}$  where  $D_s^{*+} \rightarrow D_s^+(\gamma/\pi^0)$ : broad bump whose shape depends on  $A_{\pm\pm}$  and  $A_{00}$  helicity amplitudes (from simulation)



# Observation of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ [PRD 87 (2013) 112012]

Normalize to  $J/\psi\pi^+$ :  $\mathcal{R}_{D_s^{(*)+}/\pi^+} = \frac{1}{\mathcal{B}_{D_s^+}} \times \frac{\epsilon_{B_c^+ \rightarrow J/\psi\pi^+}}{\epsilon_{B_c^+ \rightarrow J/\psi D_s^{(*)+}}} \times \frac{N(B_c^+ \rightarrow J/\psi D_s^{(*)+})}{N(B_c^+ \rightarrow J/\psi\pi^+)}$

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)} = 2.96 \pm 0.67 \pm 0.25$$

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = 2.36 \pm 0.56 \pm 0.10$$

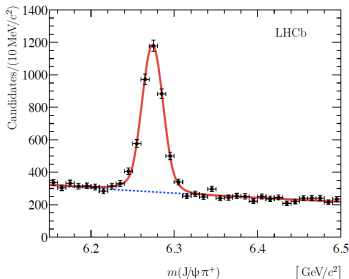
- Main systematics:

$$\mathcal{B}(D_s^+ \rightarrow \phi(\rightarrow K^+ K^-)\pi^+)$$

$$\mathcal{R}_{D_s^+/\pi^+} \equiv \frac{\Gamma(B_c^+ \rightarrow J/\psi D_s^+)}{\Gamma(B_c^+ \rightarrow J/\psi\pi^+)} \approx \frac{\Gamma(B \rightarrow \bar{D}^* D_s^+)}{\Gamma(B \rightarrow \bar{D}^* \pi^+)}$$

$$\mathcal{R}_{D_s^{*+}/D_s^+} \equiv \frac{\Gamma(B_c^+ \rightarrow J/\psi D_s^{*+})}{\Gamma(B_c^+ \rightarrow J/\psi D_s^+)} \approx \frac{\Gamma(B \rightarrow \bar{D}^* D_s^{*+})}{\Gamma(B \rightarrow \bar{D}^* D_s^+)}$$

- Results consistent with spectator dominance + naïve factorization (replace spectator  $c \rightarrow u/d$ )



The fraction of polarization amplitude  $\frac{\Gamma_{\pm\pm}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\Gamma_{tot}(B_c^+ \rightarrow J/\psi D_s^{*+})} = (52 \pm 20)\%$  also compatible with measurements in  $B^0 \rightarrow D^{*-} D_s^{*+}$  by CLEO and BaBar [PRD 62, 112003 (2000), PRD 67,092003 (2003)]



# $B_c^+$ mass @ LHCb [PRL 109 232001 (2012) - PRD 87 (2013) 112012]

- $B_c$  mass determined from  $J/\psi\pi^+$  decays
- Rather large  $Q$ -value  $\rightarrow$  large systematic uncertainty from momentum scale
- New measurement using  $B_c \rightarrow J/\psi D_s^+$  (low  $Q$ -value)

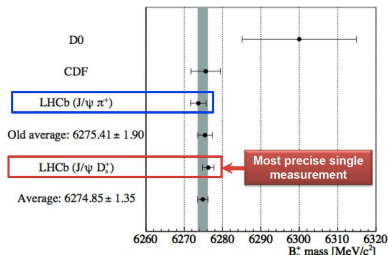
$$m_{B_c^+} - m_{D_s^+} = 4307.97 \pm 1.44_{stat} \pm 0.20_{syst} \text{ MeV}/c^2$$

- Dominant systematics from  $D_s$  mass largely cancels in the mass difference

- Using our latest  $D_s^+$  mass measurement [arXiv:1304.6865]

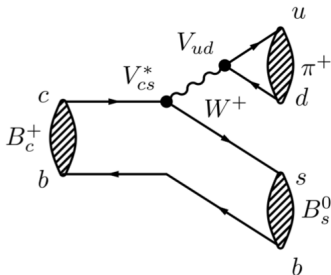
$$m_{B_c^+} = 6276.28 \pm 1.44_{stat} \pm 0.36_{syst} \text{ MeV}/c^2$$

- Single most precise measurement of  $B_c^+$  mass

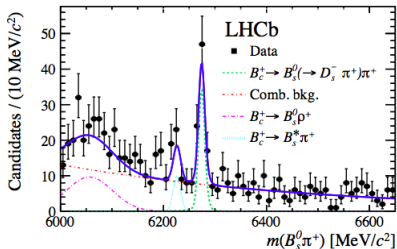


# Observation $B_c^+ \rightarrow B_s^0 \pi^+$ [arXiv:1308.4544]

- First decay where the  $b$  quark is acting as a spectator
- $b$ -quark decay should give larger rate
- Wide range of theoretical predictions for  $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$
- Experimental clarification needed
- Using both 2011 data ( $1 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$ ) and 2012 data ( $2 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ )
- Reconstructed either in  $B_s^0 \rightarrow J/\psi \phi$  or  $B_s^0 \rightarrow D_s^- \pi^+$  with  $\phi \rightarrow K^+ K^-$  and  $D_s^- \rightarrow K^+ K^- \pi^-$

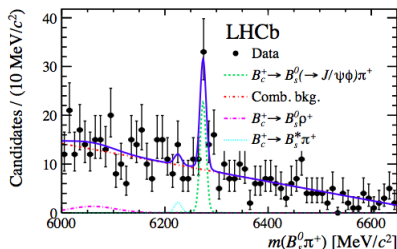


# $B_c^+ \rightarrow B_s^0 \pi^+$ [arXiv:1308.4544]



$$N(B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+) \pi^+) = 64 \pm 10$$

$$[7.7\sigma]$$



$$N(B_c^+ \rightarrow B_s^0(\rightarrow J/\psi \phi) \pi^+) = 35 \pm 8$$

$$[6.1\sigma]$$

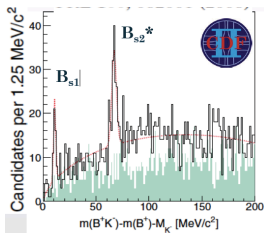
- First observation of a weak decay of a  $B$  meson to another  $B$  meson

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = (2.38 \pm 0.35(stat) \pm 0.11(syst)_{-0.12}^{+0.17}(\tau_{B_c^+})) \times 10^{-3}$$

- Using an estimate of  $\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \sim 0.02$ ,  $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) \approx 10\%$
- Largest exclusive branching fraction of any known weak  $B$  meson decay

## Excited $B_{sJ}$ mesons

- $B_{s2}^*$  first observed by CDF [PRL 100, 082002 (2008)] in  $BK$  invariant mass spectrum, confirmed by D0 [PRL 100, 082001 (2008)]
- Observation of a second peak identified as partially reconstructed  $B_{s1}$ , not confirmed by D0



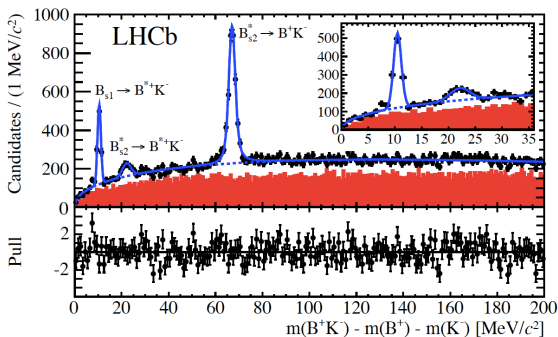
Search for excited  $B_{sJ}$  mesons at LHCb [ $1 \text{ fb}^{-1}$ ] [PRL 110, 151803 (2013)]

- Search for  $B_{sJ}$  mesons in  $B_{sJ} \rightarrow B^{+(*)}K^- \rightarrow (\gamma)B^+K^-$
- Select  $B^+$  candidates in four different final states
  - a)  $J/\psi K^+ \rightarrow (\mu^+\mu^-)K^+$
  - b)  $\bar{D}^0\pi^+ \rightarrow (K^+\pi^-)\pi^+$
  - c)  $\bar{D}^0\pi^+ \rightarrow (K^+\pi^-\pi^+\pi^-)\pi^+$
  - d)  $\bar{D}^0\pi^+\pi^-\pi^+ \rightarrow (K^+\pi^-)\pi^+\pi^-\pi^+$
- Combine the  $B^+$  with a  $K^-$

## $B^+K^-$ spectrum [PRL 110, 151803 (2013)]

The  $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$  spectrum shows 3 peaks:

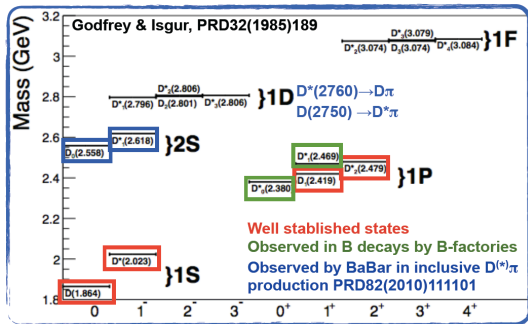
- partially reconstructed  
 $B_{s1} \rightarrow B^{*+}K^- \rightarrow B^+(\gamma)K^-$   
confirm CDF signal
- partially reconstructed  
 $B_{s2}^* \rightarrow B^{*+}K^- \rightarrow B^+(\gamma)K^-$   
first observation,  $8\sigma$
- fully reconstructed  
 $B_{s2}^* \rightarrow B^+K^-$  decays  
confirm CDF and D0 signal



## Results [PRL 110, 151803 (2013)]

- $\Gamma(B_{s2}^*) = 1.5 \pm 0.13 \pm 0.47 \text{ MeV}/c^2$  first measurement!
- Dominant systematics: invariant mass resolution
- The difference between the fully reconstructed and partially reconstructed  $B_{s2}^*$  is equal to
$$M(B^{*+}) - M(B^+) = 45.01 \pm 0.30 \pm 0.23 \text{ MeV}/c^2$$
- Best measurement: new method compared to earlier measurements, does not require  $\gamma$
- Absolute mass values are derived using the known  $B^+$  mass:
$$m(B^{*+}) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17 \text{ MeV}/c^2$$
$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41 \text{ MeV}/c^2$$
$$m(B_{s2}^*) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17 \text{ MeV}/c^2$$
- Precise  $B^{*+}$  mass measurement used to understand if the  $Z_b$  states reported by Belle could be  $B\bar{B}^*$  molecules:
  - the  $Z_b(10610)^+$  lies  $3.69 \pm 2.05 \text{ MeV}/c^2$  above the  $B\bar{B}^*$  threshold
  - the  $Z_b(10650)^+$  lies  $3.68 \pm 1.68 \text{ MeV}/c^2$  above the  $B^*\bar{B}^*$  threshold

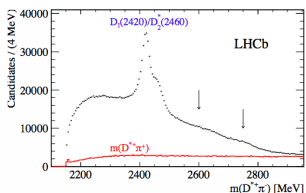
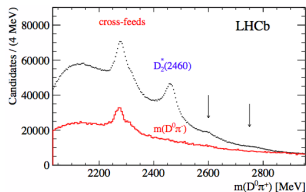
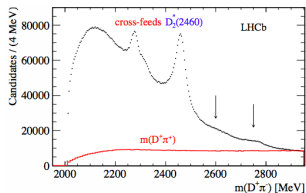
## Excited $D_J$ states



- Quark model predicts many states [Godfrey and Isgur, PRD 32 (1985) 82], not all observed
- Large mass discrepancies, up to  $50 \text{ MeV}/c^2$
- Most  $J^P$  needs confirmation
  - natural  $J^P = 0^+, 1^-, 2^+$
  - innatural  $J^P = 0^-, 1^+, 2^-$

- The ground states ( $D, D^*$ ), and two of the  $1P$  states,  $D_1(2420)$  and  $D_2^*(2460)$  are experimentally well established
- The broad  $L = 1$  states,  $D_0^*(2400)$  and  $D_1'(2430)$  have been observed by B-factories in exclusive  $B$  decays
- BaBar has found new states decaying to  $D\pi, D^*\pi$  [PRD 82,111101 (2010)]

# Excited $D_J$ states @ LHCb [arXiv.1307.4556]



Search for  $D_J$  states decaying to  $D^0\pi^+$ ,  $D^+\pi^-$ ,  $D^{*+}\pi^-$  by reconstructing  $D^0 \rightarrow K^-\pi^+$ ,  $D^+ \rightarrow K^-\pi\pi$  and  $D^{*+} \rightarrow D^0\pi^+$  using  $1\text{ fb}^{-1}$  of data

$D^+\pi^-$

- $D_2^*(2640)^0$  + weak structures (2600 and 2750 MeV)
- Cross-feed:  $D_1(2420)^0$  or  $D_2^*(2460)^0 \rightarrow \pi^- D^{*+} (\rightarrow D^+\pi^0/\gamma)$

$D^0\pi^+$

- $D_2^*(2640)^+$  + weak structures (2600 and 2750 MeV)
- Cross-feed:  $D_1(2420)^+$  or  $D_2^*(2460)^+ \rightarrow \pi^+ D^{*0} (\rightarrow D^0\pi^0/\gamma)$

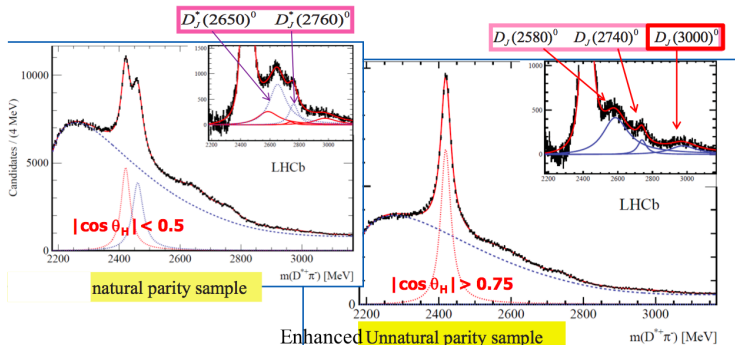
$D^{*+}\pi^-$

- $D_1(2420)^0$  and  $D_2^*(2460)^0$  + weak structures (2500 and 2800 MeV)



# Excited $D_J$ states @ LHCb [arXiv.1307.4556]

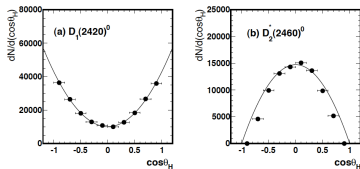
- The  $D^{*+}\pi^-$  final state gives information on the spin-parity assignment of a given resonance
- In the rest frame of the  $D^{*+}\pi^-$  we define the helicity angle  $\theta_H$  as the angle between the  $\pi^-$  and the  $\pi^+$  from the  $D^{*+}$  decay
- Exploit differences in  $\theta_H$  distribution for natural/unnatural spin-parity states to selectively enhance/suppress some of them in  $D^{*+}\pi^-$  spectrum to determine the needed signal components and initialize the final fit



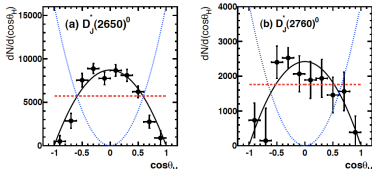
# Spin-parity analysis

Fit  $D^{*+}\pi^-$  mass spectrum in 10 bins of  $\cos\theta_H$  ( $\pi^-$  helicity angle) (resonance parameters fixed) to determine the angular distribution for each state

confirm spin-parity for  
 $D_1(2420)^0$   $J^P = 1^+$  and  
 $D_2^*(2460)^0$   $J^P = 2^+$

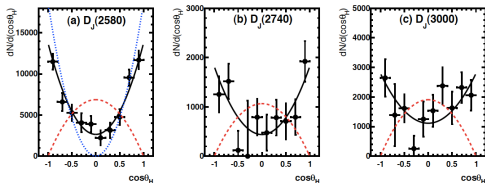


Natural spin-parity confirmed for  
 $D_J^*(2650)^0$  and  $D_J^*(2760)^0$



Unnatural spin-parity confirmed for  
 $D_J(2580)^0$  and  $D_J(2740)^0$

Unnatural spin-parity suggested for  $D_J(3000)^0$



- black=Natural Parity
- dashed red=Unnatural Parity
- dotted blue= $J^P = 0^-$

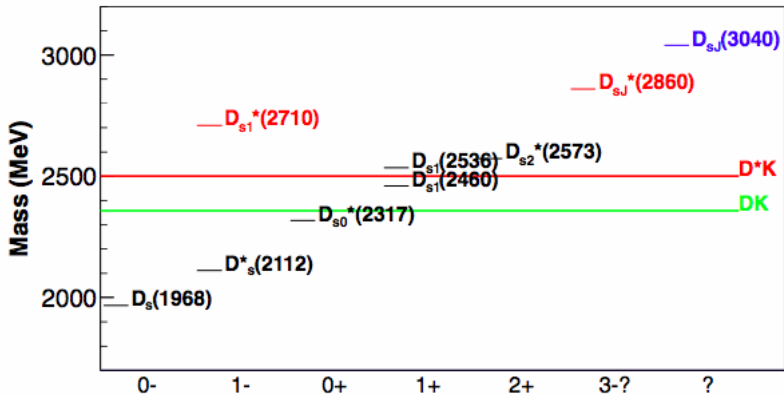
# Results

Final state	Mass (MeV)	Width (MeV)	Yields	Significance
$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210200 \pm 1900 \pm 700$	
$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81900 \pm 1200 \pm 900$	
$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50700 \pm 2200 \pm 2300$	24.5 (15.9)
$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14400 \pm 1700 \pm 1700$	10.2 (6.0)
$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60300 \pm 3100 \pm 3400$	18.8 (13.1)
$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7700 \pm 1100 \pm 1200$	7.2 (4.7)
$D^{*+}\pi^-$	$2971.8 \pm 8.7$	$188.1 \pm 44.8$	$9500 \pm 1100$	9.0 (3.7)
$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675000 \pm 9000 \pm 1300$	
$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55800 \pm 1300 \pm 10000$	17.3 (5.5)
$D^+\pi^-$	$3008.1 \pm 4.0$	$110.5 \pm 11.5$	$17600 \pm 1100$	21.2 (12.4)
$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341600 \pm 22000 \pm 2000$	
$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20100 \pm 2200 \pm 1000$	18.8 (8.3)
$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	$7600 \pm 1200$	6.6 (5.1)

- Confirmation of spin-parity of  $D_1(2420)$  and  $D_2^*(2460)^0$  resonances
- Observed two natural parity ( $D_J^*(2650)^0$  and  $D_J^*(2760)^0$ ) and two unnatural parity ( $D_J(2580)^0$  and  $D_J^*(2740)^0$ ) resonances
- Resonance parameters in reasonable agreement with BaBar
- Broad structures observed around  $3000 \text{ MeV}/c^2$ , could be superpositions of several states

$D_J^*(2650)^0$	$1^-$	$2S D_1^*(2618)$
$D_J^*(2760)^0$	$1^-$	$1D D_1^*(2796)$
$D_J(2580)^0$	$0^- ???$	$2S D_0(2558)$
$D_J(2740)^0$	$2^-$	$1D D_2(2801)$

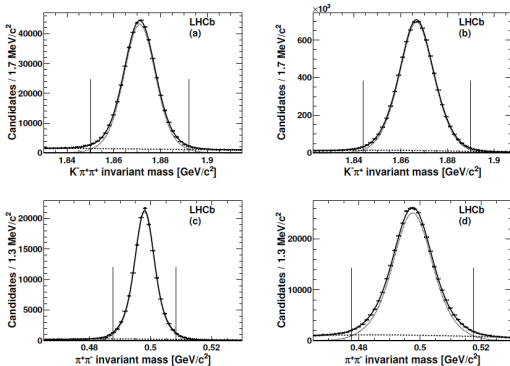
## Excited $D_{sJ}$ states



- Large discrepancy between predictions and experiment for  $D_{s0}^*(2317)$  and  $D_{s1}(2460)$ .
- $D_{s1}^*(2700)$  observed by BaBar (inclusive) and Belle (B decays).
- $D_{sJ}^*(2860)$  and  $D_{sJ}(3040)$  observed by BaBar.

# Excited $D_{sJ}$ states @ LHCb [JHEP 10.151 (2012)], $1 \text{ fb}^{-1}$

Search for states decaying to  $D^0 K^+$  and  $D^+ K_S^0$  by reconstructing  $D^0 \rightarrow K^- \pi^+$  (a),  $D^+ \rightarrow K^- \pi \pi$  (b), and  $K_S^0 \rightarrow \pi \pi$  decaying inside (c) or outside (d) the vertex detector



Reduce  $DK$  combinatorial background by requiring  $\cos \theta > 0$ , where  $\theta$  is the kaon helicity angle in the  $DK$  frame

# Excited $D_{sJ}$ states @ LHCb [JHEP 10.151 (2012)]

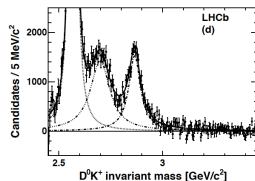
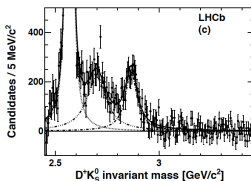
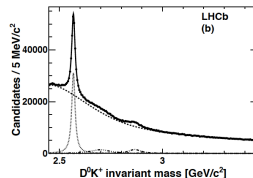
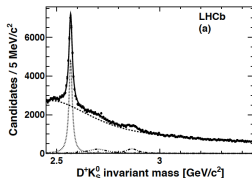
Observe the same structures in both final states, plus some feed-through from partially reconstructed  $D_{sJ} \rightarrow D^* K$  decays

Simultaneous fit to smooth background plus

- $D_{s2}^*(2573)^+$  — spin 2
- $D_{s1}^*(2700)^+$  — spin 1
- $D_{sJ}^*(2860)^+$  — spin 0?

constraining the resonance parameters to be the same in both spectra

No evidence for states above 3 GeV



$$\begin{aligned}
 m(D_{s1}^*(2700)^+) &= 2709.2 \pm 1.9(\text{stat}) \pm 4.5(\text{syst}) \text{ MeV}/c^2, \\
 \Gamma(D_{s1}^*(2700)^+) &= 115.8 \pm 7.3(\text{stat}) \pm 12.1(\text{syst}) \text{ MeV}/c^2, \\
 m(D_{sJ}^*(2860)^+) &= 2866.1 \pm 1.0(\text{stat}) \pm 6.3(\text{syst}) \text{ MeV}/c^2, \\
 \Gamma(D_{sJ}^*(2860)^+) &= 69.9 \pm 3.2(\text{stat}) \pm 6.6(\text{syst}) \text{ MeV}/c^2.
 \end{aligned}$$

First observation of these states in inclusive hadronic production  
Confirmation of the resonances observed at the B-factories, comparable precision

# The $X(3872)$

- New exotic mesons have been observed by different experiments:  
 $X(3872)$ ,  $X(4140)$ ,  $Z^\pm(4430)$
- First assigned to  $c\bar{c}$  charmonium states but they don't fit to diquark picture
- Many theoretical models to explain the nature of the XYZ states, with limited success
  - Tetraquark
  - Molecular state
  - Charmonium hybrids
  - Threshold effects
- The  $X(3872)$  is the first exotic meson observed
  - Discovered by Belle as a narrow peak in  $J/\psi\pi^+\pi^-$  invariant mass in  $B^+ \rightarrow (J/\psi\pi^+\pi^-)K^+$  decays [PRL 91 (2003) 262001].
  - Confirmed by BaBar, CDF and D0
  - Also LHCb studied it measuring production cross-section and mass with  $34.7 \text{ pb}^{-1}$  [EPJ C72, 1972 (2012)]

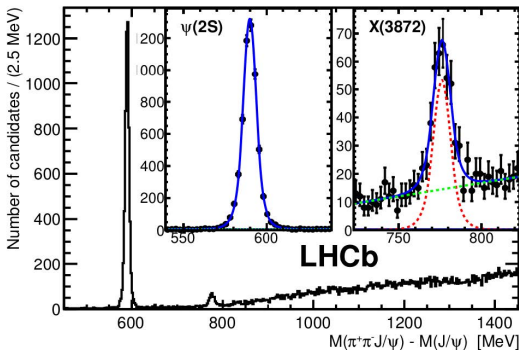
## The $X(3872)$ quantum numbers

- The existence of the  $X(3872)$  is beyond doubt but after 10 years the nature is still uncertain!
  - Extremely difficult to identify as a conventional charmonium state (Mass and decay mode disfavour  $c\bar{c}$  state)
  - C-parity known to be positive as  $X(3872) \rightarrow J/\psi\gamma$  observed by Belle [PRL 107 091803], BaBar [PRD 74 071101 (R)]
  - CDF helicity angle measurement [PRL 98 132002] excluded all  $J^{PC}$  except
    - $J^{PC} = 2^{-+}$ :  $\eta_{c2}(1^1D_2)$
    - $J^{PC} = 1^{++}$ :  $\chi_{c1}(2^3P_1)$  or exotic  $D^0D^*$  bound state or tetraquark
  - BaBar analysis of  $X(3872) \rightarrow \omega J/\psi$  prefers  $2^{++}$  but does not exclude  $1^{++}$  [PRD 82, 011101(R)]
  - Belle analysis of  $X(3872) \rightarrow J/\psi\pi^+\pi^-$  prefers  $1^{++}$  but does not exclude  $2^{-+}$  [PRD 84, 052004]



# $X(3872)$ quantum numbers @ LHCb [arXiv:1302.6269]

- $B^+ \rightarrow X(3872)K^+$  with  $X(3872) \rightarrow J/\psi(\rightarrow \mu\mu)\pi^+\pi^-$ ,  $1 \text{ fb}^{-1}$
- $B^+ \rightarrow \psi(2S)K^+$  control channel for systematic studies/signal shape determination
- Selection based on likelihood ratio classifier
- $313 \pm 26$   
 $B^+ \rightarrow X(3872)K^+$   
( $568 \pm 31$  background events)

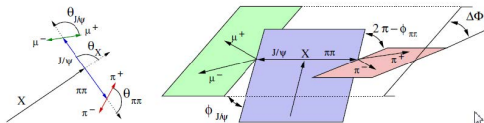


Angular correlations in the  $B^+$  decay chain carry information on the  $J^{PC}$  of the  $X(3872)$

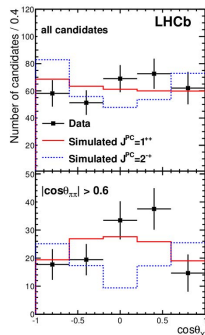
# The $X(3872)$ quantum numbers @ LHCb

- Analysis performed in 5D exploiting all angular correlations
- 3 helicity angles + 2 angles between the decay planes

$$\Omega = (\cos \theta_X, \cos \theta_{\pi\pi}, \Delta\phi_X, \pi\pi, \cos \theta_{J/\psi}, \Delta\phi_X, J/\psi)$$

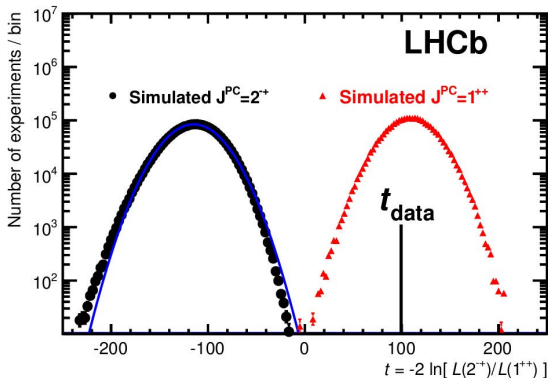


- Matrix elements in the helicity formalism
  - $1^{++}$ : no free parameter
  - $2^{-+}$ : one complex parameter  $\alpha$  which accounts for the different LS combinations (L is the orbital angular momentum between the  $\pi\pi$  and the  $J/\psi$ , S is the sum of their spins)



- Projections in  $\cos \theta_X$  for signal candidates
- Marginal differences in 1D distributions between  $J^{PC} = 1^{++}$  and  $J^{PC} = 2^{-+}$
- Discrimination relies on correlations in specific phase-space regions

# $X(3872)$ quantum numbers @ LHCb [arXiv:1302.6269]



Likelihood ratio test to discriminate between  $1^{++}$  and  $2^{++}$  hypotheses

$t > 0$  favors  $1^{++}$

$t < 0$  favors  $2^{++}$

test distribution for each hypothesis from simulated experiments

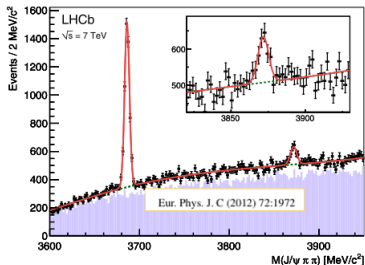
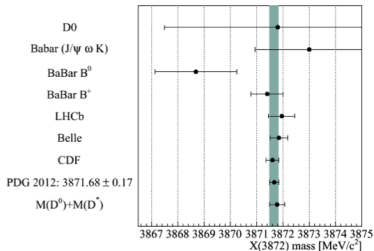
Data favors  $1^{++}$  over  $2^{++}$  at  $8.4 \sigma$

- Conventional charmonium fading: only  $c\bar{c}$  possibility:  $\chi_{c1}(2^3P_1)$  but mass is off
- non-conventional (exotic?) interpretation is favored
- More measurements are needed to elucidate nature of the  $X(3872)$ 
  - More precise mass measurement (+  $D$  masses)
  - Natural Width
  - Production properties and decay modes

# $X(3872)$ Mass Measurement @ LHCb

If  $X(3872)$  is a  $\bar{D}^0 D^{*0}$  bound state:  $m(X(3872)) < m(D^0) + m(D^{*0})$

- Using  $34.7 \text{ pb}^{-1}$ : inclusive selection of  $X(3872) \rightarrow J/\psi \pi^+ \pi^-$



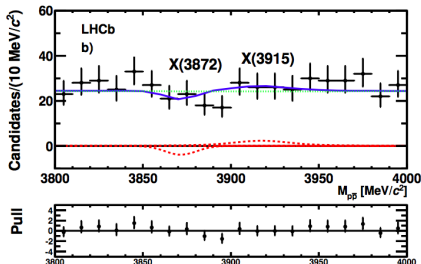
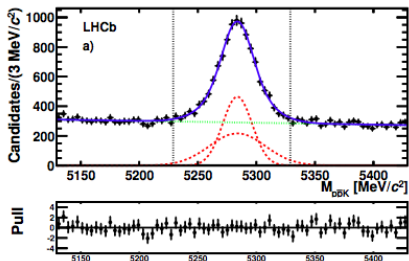
$$m(X(3872)) = 3871.95 \pm 0.48 \pm 0.12 \text{ MeV}/c^2$$

Statistically limited

- Using LHCb  $D^0$  mass measurement [JHEP 06 (2013) 065]:  
 $E_B = m(D^0 D^{*0}) - m(X(3872)) = 0.09 \pm 0.28 \text{ MeV}/c^2$
- The result reinforces the conclusion that if the  $X(3872)$  is a molecule, it is extremely loosely bound!

## Searching for new decay mode: $X(3872) \rightarrow p\bar{p}$

- Search for intermediate states decaying to  $p\bar{p}$  in the  $B^+ \rightarrow p\bar{p}K^+$
- With  $1 \text{ fb}^{-1}$  of data [EPJC 73, 2462 (2013)]
- $N(B^+ \rightarrow p\bar{p}K^+) = 6951 \pm 176$  and  $N(X(3872)) \rightarrow p\bar{p} = -9 \pm 8$



$$\frac{\mathcal{B}(X(3872) \rightarrow p\bar{p})}{\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)} < 2.0 \times 10^{-3}$$

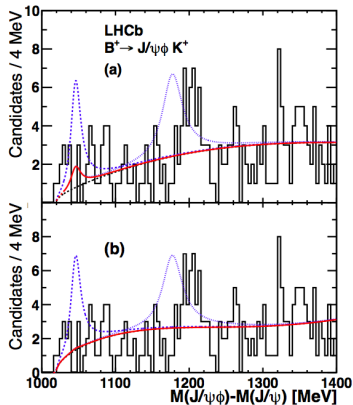
- Limit also on the never observed  $\eta_c(2S) \rightarrow p\bar{p}$  decay
- $$\frac{\mathcal{B}(\eta_c(2S) \rightarrow p\bar{p})}{\mathcal{B}(\eta_c(2S) \rightarrow KK\pi)} < 3.1 \times 10^{-2}$$

## $X(4140)$ and $X(4274)$

- $X(4140)$  observed by the CDF collaboration in  $B^+ \rightarrow J/\psi\phi K^+$  [PRL 102 (2009) 242002] +  $X(4274)$  [arXiv:1101.6058]: candidates for exotic bound state

LHCb,  $0.37 \text{ fb}^{-1}$ , [PRD 85, 091103 (R) (2012)]

- $N(B^+ \rightarrow J/\psi\phi K^+) = 382 \pm 22$  (6 times more than CDF)
- Fit to  $M(J/\psi\phi) - M(J/\psi)$  for candidates within  $M(B^\pm) = \pm 2.5\sigma$  and  $M(\phi) = \pm 15 \text{ MeV}/c^2$
- CDF fits overlaid scaled to  $0.37 \text{ fb}^{-1}$ :  
 $N(X(4140))_{exp} = 35 \pm 9 \pm 6$ ,  
 $N(X(4274))_{exp} = 53 \pm 19$
- Fit results:  
 $N(X(4140)) = 0.6 (< 7.1)$  [2.7 $\sigma$  disagreement],  $N(X(4274)) = 0 (< 10)$
- LHCb does not confirm the narrow structures near threshold



$$\mathcal{B}(B^\pm \rightarrow X(4140)K^\pm) \times \mathcal{B}(X(4140) \rightarrow J/\psi\phi) / \mathcal{B}(B^\pm \rightarrow J/\psi\phi K^\pm) < 0.07 \text{ @ } 90\% \text{ CL}$$

$$\mathcal{B}(B^\pm \rightarrow X(4274)K^\pm) \times \mathcal{B}(X(4274) \rightarrow J/\psi\phi) / \mathcal{B}(B^\pm \rightarrow J/\psi\phi K^\pm) < 0.08 \text{ @ } 90\% \text{ CL}$$

## Conclusions

- LHCb has observed many new  $B_c$  decay modes
- Mass of  $B_c$  known to  $< 1.5 \text{ MeV}/c^2$
- First observation of  $B_{s2}^*(5840)^0$  and measurement of its natural width by LHCb
- LHCb performs mass and width measurements of excited  $D_{sJ}$
- LHCb performs mass and width measurements of excited  $D_J$
- LHCb has established the  $X(3872)$  quantum numbers as  $J^{PC} = 1^{++}$
- No observation of  $X(4140)$  and  $X(4274)$  by LHCb
- Most of the analysis done not with the entire statistics available: new and updated results coming soon!

## Backup Slides



# Systematics $B_c^+ \rightarrow J/\psi D_s^{(*)+}$

Source	Uncertainty (%)
Simulated efficiencies	1.0
Trigger	1.1
Fit model	1.8
Track reconstruction	$2 \times 0.6$
Hadron interactions	$2 \times 2.0$
Track quality selection	$2 \times 0.4$
Kaon identification	3.0
$B_c^+$ lifetime	1.0
Stability for various data taking conditions	2.5
$\mathcal{B}(D_s^+ \rightarrow (K^- K^+)_{\phi} \pi^+)$	5.6
Total	8.4

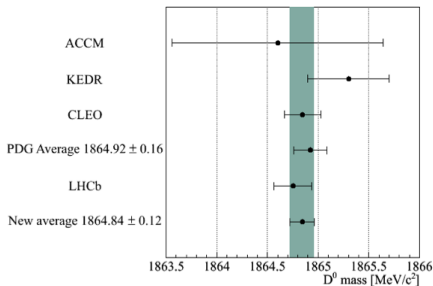
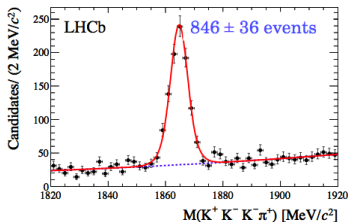
# Systematics $B_c^+ \rightarrow B_s^0 \pi^+$

Source	$D_s^- \pi^+$ (%)	$J/\psi \phi$ (%)
$B_s^0$ fit model	3.0	1.2
$B_c^+$ mean mass	—	2.0
$B_c^+$ mass resolution	—	5.2
$B_c^+$ signal model	1.5	1.7
Combinatorial background model	1.8	0.3
Partially reconstructed background	1.8	1.7
Data-simulation difference	3.7	3.7
$B_c^+$ lifetime	$+6.8$ $-3.5$	7.4
Total	$+9.2$ $-7.1$	10.4

# Exotic states

State	$m$ (MeV)	$\Gamma$ (MeV)	$J^{PC}$	Process (mode)	Experiment (# $\sigma$ )	Year	Status
X(3872)	3871.52±0.20	1.3±0.6 (<2.2)	1 <sup>++</sup> /2 <sup>-+</sup>	$B \rightarrow K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), BABAR [87] (8.6)	2003	OK
				$p\bar{p} \rightarrow (\pi^+\pi^- J/\psi) + \dots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \rightarrow K(\omega J/\psi)$	Belle [92] (4.3), BABAR [93] (4.0)		
				$B \rightarrow K(D^*0 \bar{D}^0)$	Belle [94, 95] (6.4), BABAR [96] (4.9)		
				$B \rightarrow K(\gamma J/\psi)$	Belle [92] (4.0), BABAR [97, 98] (3.6)		
				$B \rightarrow K(\gamma\psi(2S))$	BABAR [98] (3.5), Belle [99] (0.4)		
X(3915)	3915.6 ± 3.1	28±10	0/2 <sup>++</sup>	$B \rightarrow K(\omega J/\psi)$	Belle [100] (8.1), BABAR [101] (19)	2004	OK
				$e^+e^- \rightarrow e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
X(3940)	3942 <sup>+9</sup> <sub>-8</sub>	37 <sup>+27</sup> <sub>-17</sub>	2 <sup>++</sup>	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \rightarrow J/\psi(\dots)$	Belle [54] (5.0)		
G(3900)	3943 ± 21	52±11	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma(D\bar{D})$	BABAR [27] (np), Belle [21] (np)	2007	OK
Y(4008)	4008 <sup>+121</sup> <sub>-49</sub>	226±97	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
Z <sub>1</sub> (4050) <sup>+</sup>	4051 <sup>+24</sup> <sub>-43</sub>	82 <sup>+51</sup> <sub>-55</sub>	?	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
Y(4140)	4143.4 ± 3.0	15 <sup>+11</sup> <sub>-7</sub>	2 <sup>++</sup>	$B \rightarrow K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
X(4160)	4156 <sup>+29</sup> <sub>-25</sub>	139 <sup>+113</sup> <sub>-65</sub>	2 <sup>++</sup>	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
Z <sub>2</sub> (4250) <sup>+</sup>	4248 <sup>+185</sup> <sub>-45</sub>	177 <sup>+321</sup> <sub>-72</sub>	?	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
Y(4260)	4263 ± 5	108±14	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$	BABAR [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
					CLEO [111] (11)		
				$e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$	CLEO [111] (5.1)		
				$e^+e^- \rightarrow (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
Y(4274)	4274.4 <sup>+8.4</sup> <sub>-6.7</sub>	32 <sup>+22</sup> <sub>-15</sub>	2 <sup>++</sup>	$B \rightarrow K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
X(4350)	4350.6 <sup>+4.6</sup> <sub>-5.1</sub>	13.3 <sup>+18.4</sup> <sub>-10.6</sub>	0,2 <sup>++</sup>	$e^+e^- \rightarrow e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
Y(4360)	4353 ± 11	96±42	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma(\pi^+\pi^-\psi(2S))$	BABAR [113] (np), Belle [114] (8.0)	2007	OK
Z(4430) <sup>+</sup>	4443 <sup>+24</sup> <sub>-18</sub>	107 <sup>+113</sup> <sub>-71</sub>	?	$B \rightarrow K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
X(4630)	4634 <sup>+9</sup> <sub>-11</sub>	92 <sup>+41</sup> <sub>-32</sub>	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
Y(4660)	4664±12	48±15	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
Y <sub>s</sub> (10888)	10888.4±3.0	30.7 <sup>+8.9</sup> <sub>-7.7</sub>	1 <sup>--</sup>	$e^+e^- \rightarrow (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

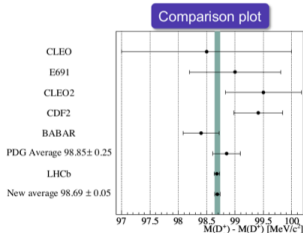
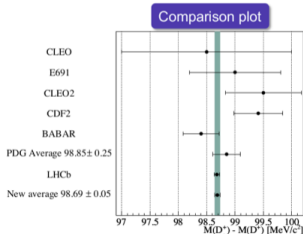
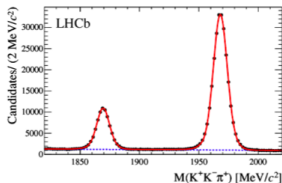
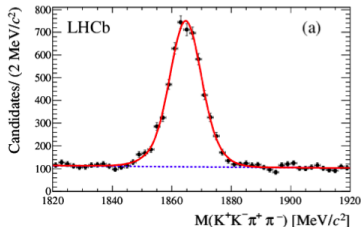
# $D^0$ mass measurement



$$m(D^0) = 1864.75 \pm 0.15_{stat} \pm 0.11_{syst} \text{ MeV}/c^2$$

- $D^0 \rightarrow K^+ K^- K^- \pi^+$  from B semileptonic decays
- Semileptonic decays: good background reduction and high trigger rate
- $D^0$  decay has low energy release: low systematic
- Main source of the systematic error is the calibration of the momentum scale of the detector

# D mass measurement



Using  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  and  $D_{(s)}^+ \rightarrow K^+ K^- \pi^+$ :

$$M(D^+) - M(D^0) = 4.76 \pm 0.12_{stat} \pm 0.07_{syst} \text{ MeV}/c^2$$

$$M(D_s^+) - M(D^+) = 98.68 \pm 0.03_{stat} \pm 0.04_{syst} \text{ MeV}/c^2$$

## X(3872) Angular Analysis

- Only  $\pi\pi$  P-wave contribution included
- Decay amplitude constructed in helicity formalism

$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \left| \sum_{\lambda_{J/\psi}, \lambda_{\pi\pi}=-1,0,+1} A_{\lambda_{J/\psi}, \lambda_{\pi\pi}} \times D_0^{J_X}{}_{\lambda_{J/\psi} - \lambda_{\pi\pi}}(\phi_X, \theta_X, -\phi_X) \times D_{\lambda_{\pi\pi}, 0}^1(\phi_{\pi\pi}, \theta_{\pi\pi}, -\phi_{\pi\pi}) \times D_{\lambda_{J/\psi}, \Delta\lambda_\mu}^1(\phi_{J/\psi}, \theta_{J/\psi}, -\phi_{J/\psi}) \right|^2$$

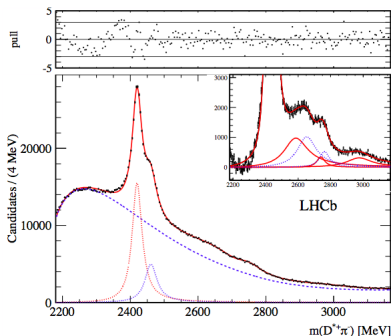
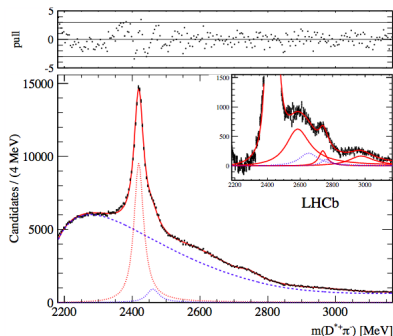
- Helicity coupling  $A_{\lambda_{j/\psi}, \lambda_{\pi\pi}}$  include one complex parameter  $\alpha$  for  $J^{PC} = 2^{-+}$ , No free parameter for  $J^{PC} = 1^{++}$ .

## X(3872) Angular Analysis

$$-2 \ln \mathcal{L}(J_X) = -2s_w \sum_{i=1}^{N_{data}} w_i \frac{|\mathcal{M}(\Omega|J_X)|^2 \epsilon(\Omega)}{I(J_X)}$$

- Normalization  $I(J_X) = \int d\Omega |\mathcal{M}(\Omega|J_X)|^2 \epsilon(\Omega)$
- MonteCarlo integration under the two hypothesis  $J_X^{PC} = 1^{++}/2^{-+}$  with detector acceptance/selection efficiency  $\epsilon(\Omega)$
- Background subtraction through sWeighting  $w_i$  (scale factor  $s_w$ )
- Fitting the  $2^{-+}$  hypothesis for helicity coupling:  
 $\alpha = (0.671 \pm 0.046, 0.280 \pm 0.046)$  compatible with Belle result [PRD 84, 052004]
- Test statistic to determine  $J^{PC}$ :  $-2 \ln[\mathcal{L}(2^{-+})/\mathcal{L}(1^{++})]$

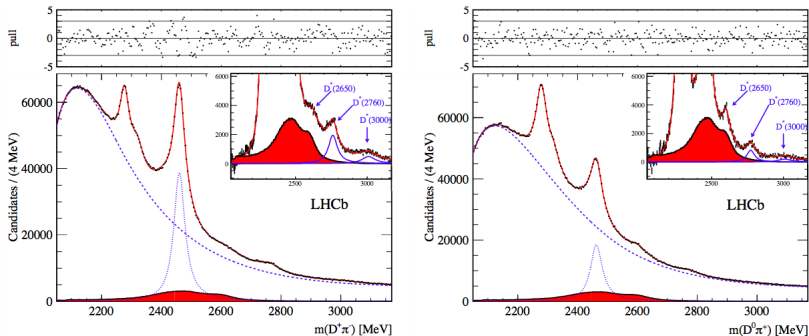
# Fit to the Unnatural Parity Sample and Total sample



- Unnatural Parity Sample: fix all resonances parameters except for  $D_1(2420)^0$
- Total: all resonances parameters fixed

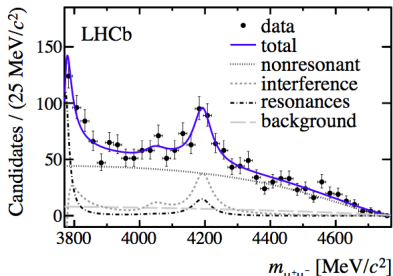


# Fit to the Unnatural Parity Sample and Total sample



- Cross-feeds (in red) produce a distortion of the  $D_2^*(2460)$  and  $D_J^*(2650)$  lineshapes

# A $\mu^+\mu^-$ resonance in $B^+ \rightarrow K^+\mu^-\mu^+$ at low recoil [arXiv:1307.7595]



- small recoil  $\rightarrow q^2 = m_{\mu\mu}^2$  above  $D\bar{D}$  threshold

- $\psi(3770)$  included with fixed parameters

- One additional resonance:  
 $M = 4191_{-8}^{+9}$ ,  $\Gamma = 65_{-16}^{+22}$  MeV/c<sup>2</sup>  
 compatible with  $\psi(4160)$

- $Y(4260)$  disfavoured by more than  $4\sigma$

$$\mathcal{B}(B^+ \rightarrow \psi(4160)K^+) \times \mathcal{B}(\psi(4160) \rightarrow \mu^+\mu^-) = (3.5_{-0.8}^{+0.9}) \times 10^{-9}$$

