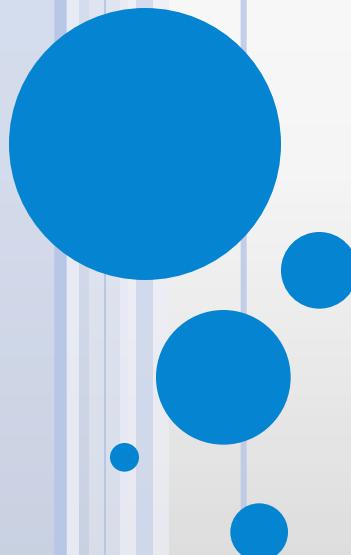


OPEN CHARM SPECTROSCOPY AT *LHCb*

Marco Pappagallo



EMMI: Resonances in QCD
GSI, Darmstadt, Germany, 12 October 2015

HEAVY HADRON SPECTROSCOPY

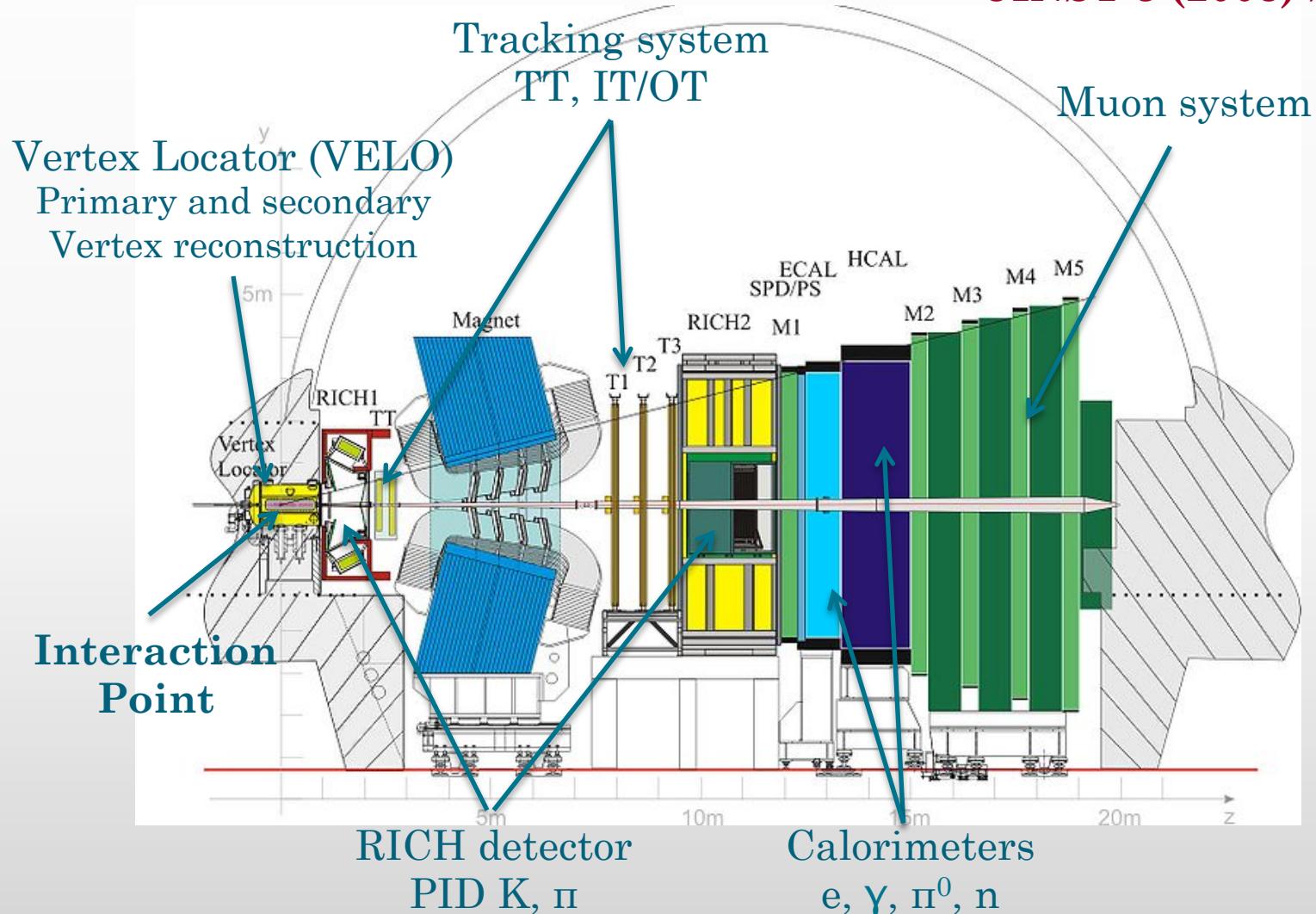


- The LHCb detector
- Introduction
- Spectroscopy of Charmed Mesons
 - Excited D Mesons at LHCb
 - Excited D_s Mesons at LHCb
- Prospect
- Summary

THE LHCb DETECTOR

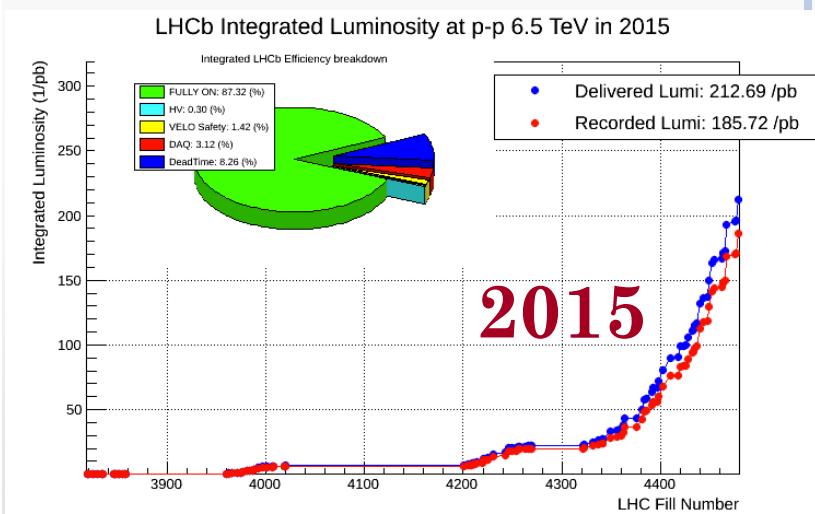
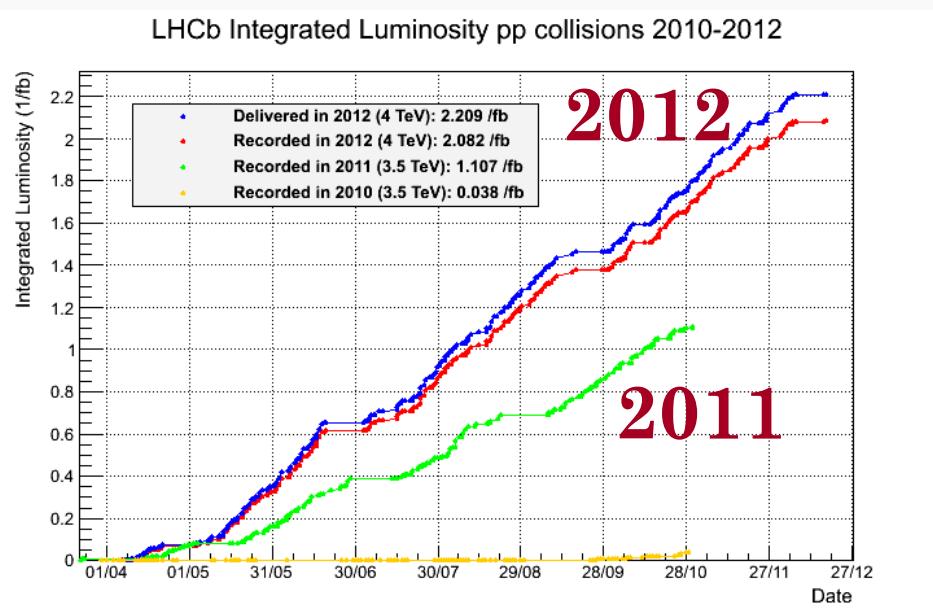


JINST 3 (2008) S08005



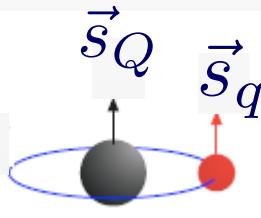
DATASETS

LHCb collected $1. \text{ fb}^{-1}$ at 7 TeV (2011) + $2. \text{ fb}^{-1}$ at 8 TeV (2012) +
 180 pb^{-1} at 13 TeV (2015)



INTRODUCTION

- The heavy quark effective theories (HQET) predict the masses of the heavy mesons $D_{(s)}$ and $B_{(s)}$ by a perturbative expansion of $\Lambda_{\text{QCD}}/m_Q \sim 0$
- Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET



$$\begin{aligned}\vec{L} \\ \vec{j}_q &= \vec{L} + \vec{s}_{q=u,d,s} \\ \vec{J} &= \vec{j}_q + \vec{s}_{Q=b,c}\end{aligned}$$

Orbital angular momentum

Angular momentum of the light quark

Total angular momentum of the heavy meson

Spectroscopy notation

Radial quantum number

$$n^{2S+1}L_J$$

Sum of quark spins

$L = 0, 1, 2, \dots \rightarrow S, P, D$

PDG notation

Natural spin-parity $J^P = 0^+, 1^-, 2^+, \dots, (-1)^J$

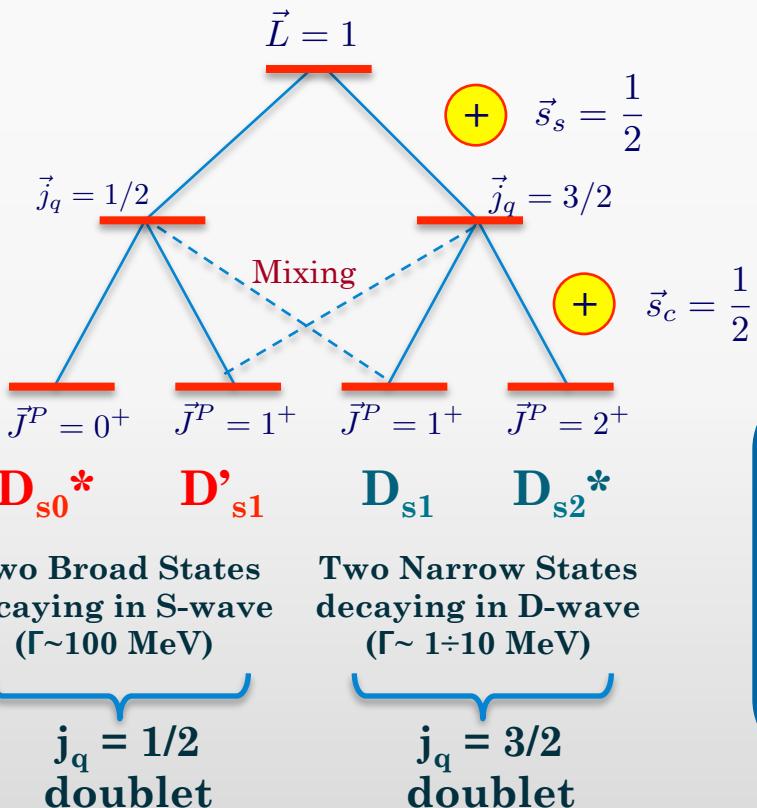
$$D^*_{-J}(m)^{0/\pm} \text{ or } B^*_{-J}(m)^{0/\pm}$$

Mass

EXCITED CHARMED AND BEAUTY STATES

For $L>0$, there are four different possible (J, j_q) combinations

E.g. Orbitally $L=1$ excited $D_s^{**} \rightarrow D^{(*)} K$



	j_q	J^P	Allowed decay mode	
			DK	$D^* K$
D_{s0}^*	$1/2$	0^+	yes	no
D'_{s1}	$1/2$	1^+	no	yes
D_{s1}	$3/2$	1^+	no	yes
D_{s2}^*	$3/2$	2^+	yes	yes

The four states come in doublets and within each doublet :

- ✓ 1 natural state (D_{s2}^*) decaying to DK and D^*K
- ✓ 1 unnatural state (D_{s1}) decaying to D^*K

(Only exception is the $(0^+, 1^+)$ doublet above)

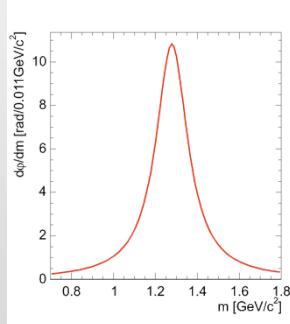
Similar picture for the excited $B^{**} \rightarrow B^{(*)}\pi$, $B_s^{**} \rightarrow B^{(*)}K$, $D^{**} \rightarrow D^{(*)}\pi$

HOW TO DO SPECTROSCOPY?

“Inclusive Analysis”

(e.g. $e^+e^- \rightarrow D^{**}(\rightarrow D\pi) + X$ or $pp \rightarrow B_s^{**}(\rightarrow BK) + X$)

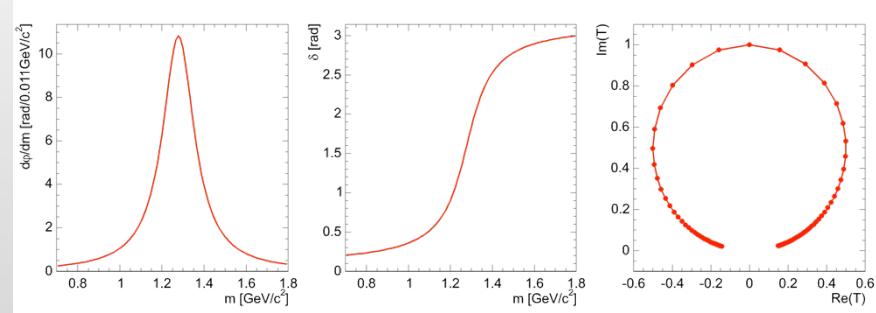
- Large cross sections 😊
- Large combinatorial background 😞
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization 😰



“Exclusive Analyses”

(e.g. $B \rightarrow D^{**}(\rightarrow D\pi)\pi$ or $B_c \rightarrow B_s^{**}(\rightarrow BK)\pi$)

- Limited statistics 😞
- Small background 😊
- Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference) 😊
- Suitable to study broad resonances
- Spin-parity assignment by amplitude analysis 😰

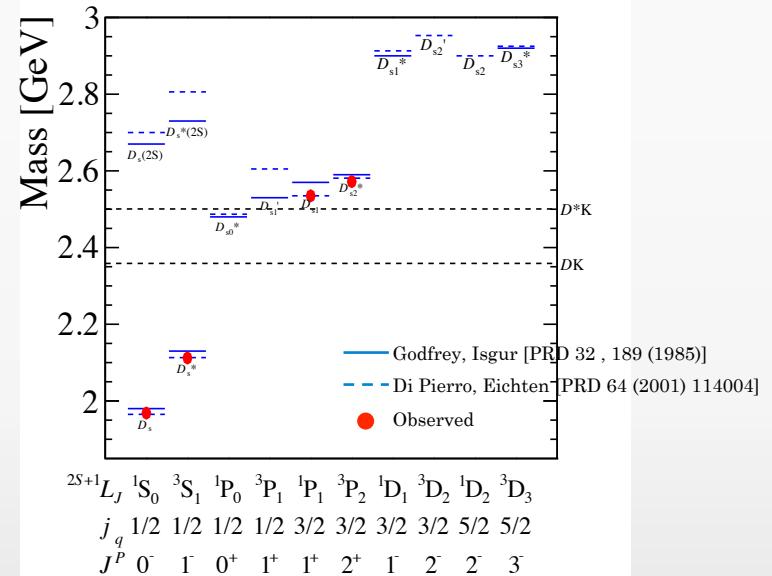
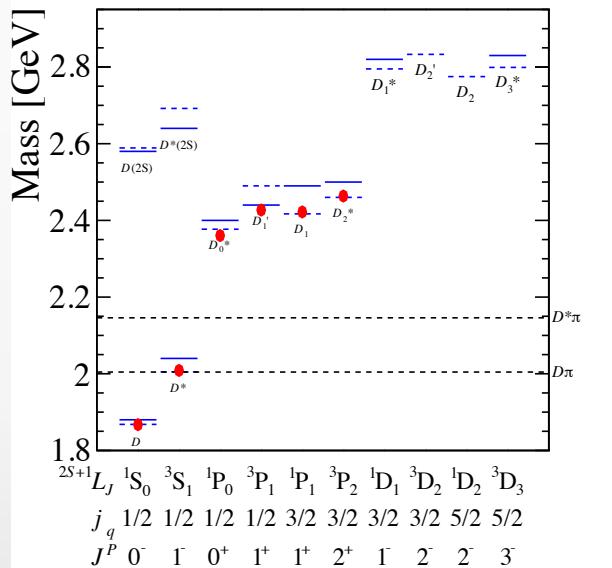




The Puzzle of the Excited D_s Mesons

STATUS OF $D_{(s)}$ SPECTROSCOPY (BEFORE 2003)

- The charmed excited states studied in inclusive analyses and into B decays
- The orbitally L=1 excited $D_{(s)}^{**}$ states observed first
- Four states expected: 2 narrow and 2 broad. Properties well predicted by theory

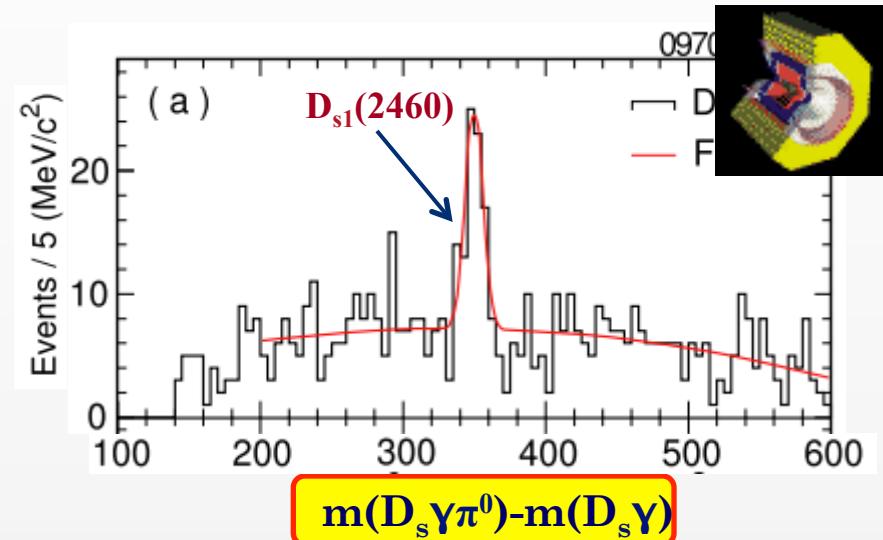
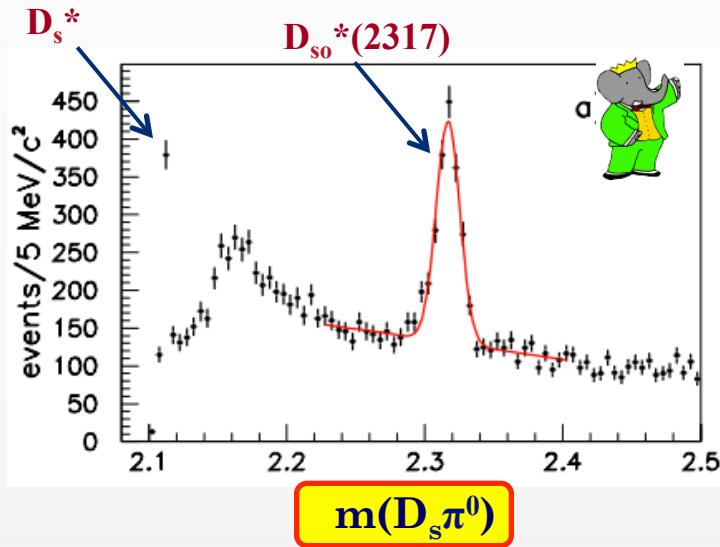


PDG	Mass (MeV)	Width (MeV)
$D_0^*(2400)^0$	2318 ± 29	267 ± 40
$D_0^*(2400)^\pm$	2403 ± 40	283 ± 40
$D_1(2430)^0$	2427 ± 40	384^{+130}_{-110}
$D_1(2430)^\pm$	—	—
$D_1(2420)^0$	2421.4 ± 0.6	27.4 ± 2.5
$D_1(2420)^\pm$	2423.2 ± 2.4	25 ± 6
$D_2^*(2460)^0$	2462.6 ± 0.6	49.0 ± 1.3
$D_2^*(2460)^\pm$	2464.3 ± 1.6	37 ± 6

PDG	Mass (MeV)	Width (MeV)
D_{s0}^*	—	—
D_{s1}'	—	—
$D_{s1}(2536)^\pm$	2535.10 ± 0.08	0.92 ± 0.05
$D_{s2}^*(2573)^\pm$	2571.9 ± 0.8	17 ± 4

PUZZLE: EXCITED D_s MESONS: $L=1$, $j_q = 1/2(?)$

Inclusive studies of $D_s^{(*)}\pi^0$
 [BaBar, PRL90, 242001][CLEO, PRD68, 032002]

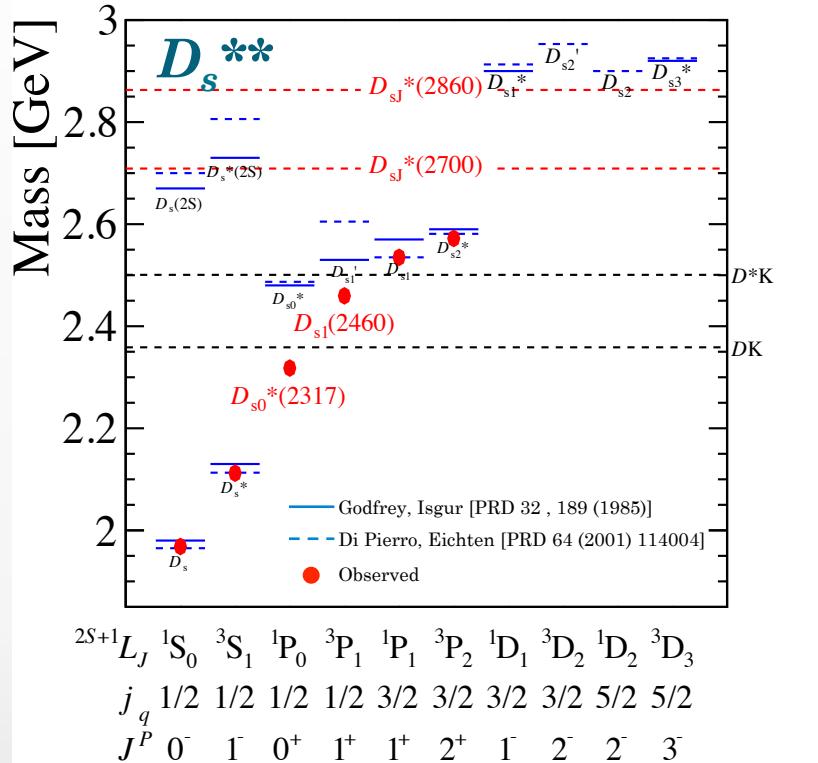
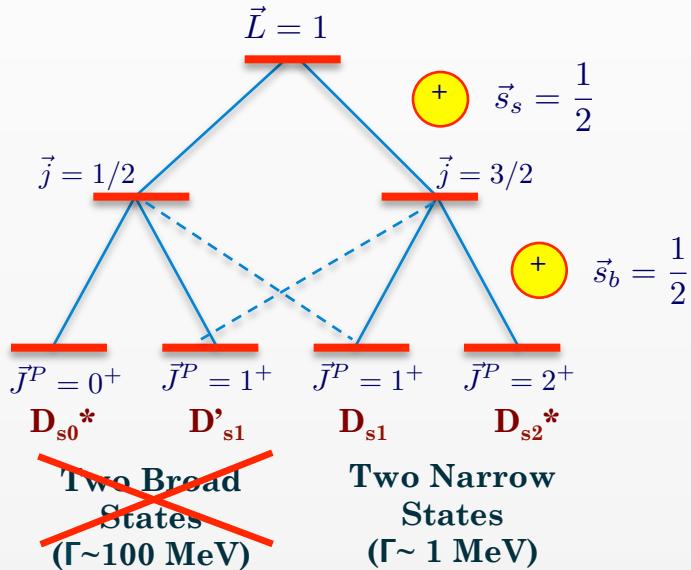


PDG	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^{\pm}$	2317.7 ± 0.6	< 3.8
$D_{s1}(2460)^{\pm}$	2459.5 ± 0.6	< 3.5

Surprisingly narrow!



PUZZLE: EXCITED D_s MESONS: L=1, j_q = 1/2(?)



- $D_{s0}^*/D_{s1} \rightarrow D^{(*)}K$ kinematically forbidden
- Isospin violation decays: $D_{s0}^* \rightarrow D_s \pi^0$ and $D'_{s1} \rightarrow D_s^* \pi^0$

PUZZLE:

EXCITED D_s MESONS: L=1, j_q = 1/2(?)

- Spin-Parity J^P = (0⁺, 1⁺) as expected for the L=1, j_q=1/2 states
- B → DD_{s0}* branching ratios below expectations (i.e. ~1) for a q⁻q state [PLB 572, 164 (2003)][PRD 69, 054002 (2004)]

$$\frac{\mathcal{B}(B^+ \rightarrow \bar{D}^0 D_{s0}^{*+})}{\mathcal{B}(B^+ \rightarrow \bar{D}^0 D_s^+)} = 0.081^{+0.032}_{-0.025}$$
$$\frac{\mathcal{B}(B^0 \rightarrow D^- D_{s0}^{*+})}{\mathcal{B}(B^0 \rightarrow D^- D_s^+)} = 0.13 \pm 0.04$$

- Many alternative interpretations:
DK or D_s π molecule, q⁻q + tetraquark/DK mixing

No D_s⁺π[±] partners have been observed in inclusive studies [BaBar: PRD 74 (2006) 032007] or in B decays [Belle: PRD 91 09211 (2015)]

IMPACT OF THE $D_{s0}(2317)$ MESON

1. The BaBar detector

(1892) BaBar Collaboration (Bernard Aubert (Annecy, LAPP) et al.). Apr 2001. 119 pp.

Published in **Nucl.Instrum.Meth. A479 (2002) 1-116**

SLAC-PUB-8569, BABAR-PUB-01-08

DOI: [10.1016/S0168-9002\(01\)02012-5](https://doi.org/10.1016/S0168-9002(01)02012-5)

e-Print: [hep-ex/0105044](https://arxiv.org/abs/hep-ex/0105044) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [BaBar Publications Database](#); [BaBar Password Protected Publications Data Server](#)

[Detailed record](#) - Cited by 1892 records 1000+

2. Observation of CP violation in the B^0 meson system

(728) BaBar Collaboration (Bernard Aubert (Annecy, LAPP) et al.). Jul 2001. 8 pp.

Published in **Phys.Rev.Lett. 87 (2001) 091801**

SLAC-PUB-8904, BABAR-PUB-01-18

DOI: [10.1103/PhysRevLett.87.091801](https://doi.org/10.1103/PhysRevLett.87.091801)

e-Print: [hep-ex/0107013](https://arxiv.org/abs/hep-ex/0107013) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#); [BaBar Publications Database](#); [BaBar Password Protected Publications Data Server](#)

[Detailed record](#) - Cited by 728 records 500+

3. Observation of a narrow meson decaying to $D_s^+ \pi^0$ at a mass of 2.32- GeV/c^2

(722) BaBar Collaboration (B. Aubert (Annecy, LAPP) et al.). Apr 2003. 7 pp.

Published in **Phys.Rev.Lett. 90 (2003) 242001**

SLAC-PUB-9711, BABAR-PUB-03-011

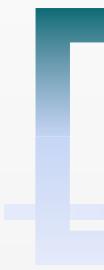
DOI: [10.1103/PhysRevLett.90.242001](https://doi.org/10.1103/PhysRevLett.90.242001)

e-Print: [hep-ex/0304021](https://arxiv.org/abs/hep-ex/0304021) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[CERN Document Server](#); [ADS Abstract Service](#); [BaBar Publications Database](#); [BaBar Password Server](#); [SLAC Document Server](#)

[Detailed record](#) - Cited by 722 records 500+



Excited D Mesons @ LHCb

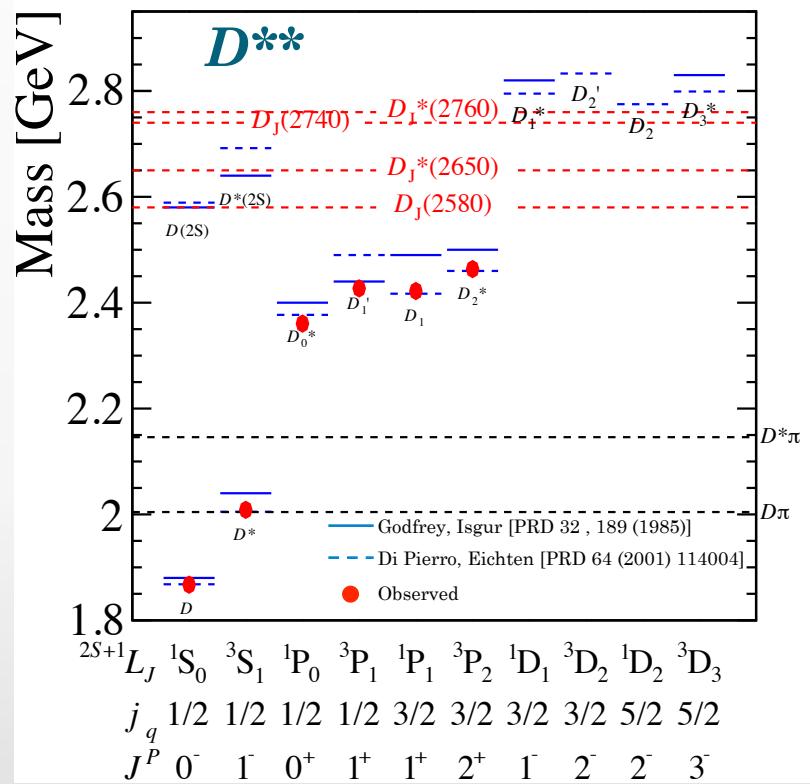
EXCITED D_J STATES

[LHCb, JHEP 09 (2013) 145]

- The quark model predicts many excited states in limited mass regions
- Ground and 1P states well established
- BaBar collaboration found 4 new states decaying to D π and/or D* π . Need to be confirmed. [PRD82 (2010) 111101]

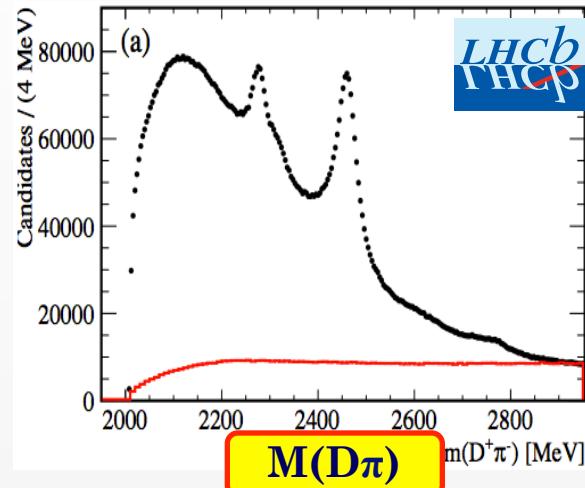
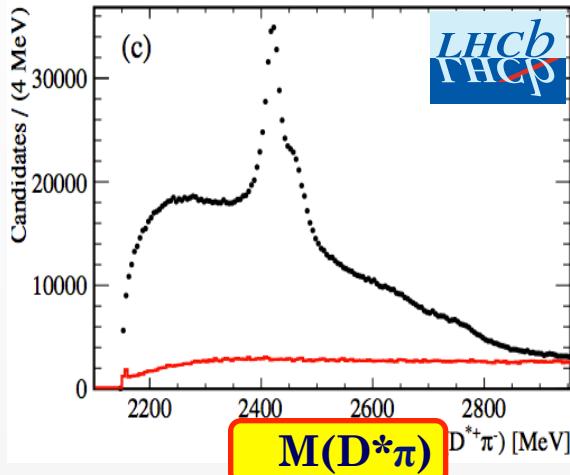
LHCb: Inclusive study of D⁺(\rightarrow K $\pi\pi$) π^- , D⁰(\rightarrow K π) π^+ and D*⁺ π^- . Several millions of D's in 1 fb⁻¹

- Natural spin-parity states ($J^P = 0^+, 1^-, 2^+, 3^- \dots$) can decay to D π and D* π
- Unnatural spin-parity states ($J^P = 0^-, 1^+, 2^-, 3^+ \dots$) can decay D* π



$D^{(*)}\pi$ MASS SPECTRA

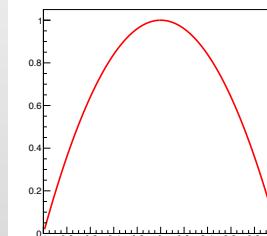
How to fit? How many resonances?



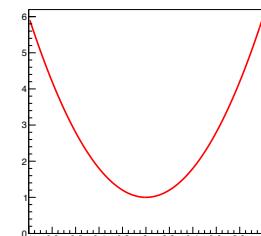
- $D^*\pi$: Natural + Unnatural states
- $D\pi$: Natural states + Feed-down of states in $D^*\pi$

- Fitting the $D^*\pi$ spectrum first
- Helicity angle θ used to study the natural/unnatural component:
 - ✓ $\propto \sin^2\theta$ for natural spin-parity
 - ✓ $\propto 1+h\cos^2\theta$ for unnatural spin-parity

Natural



Unnatural



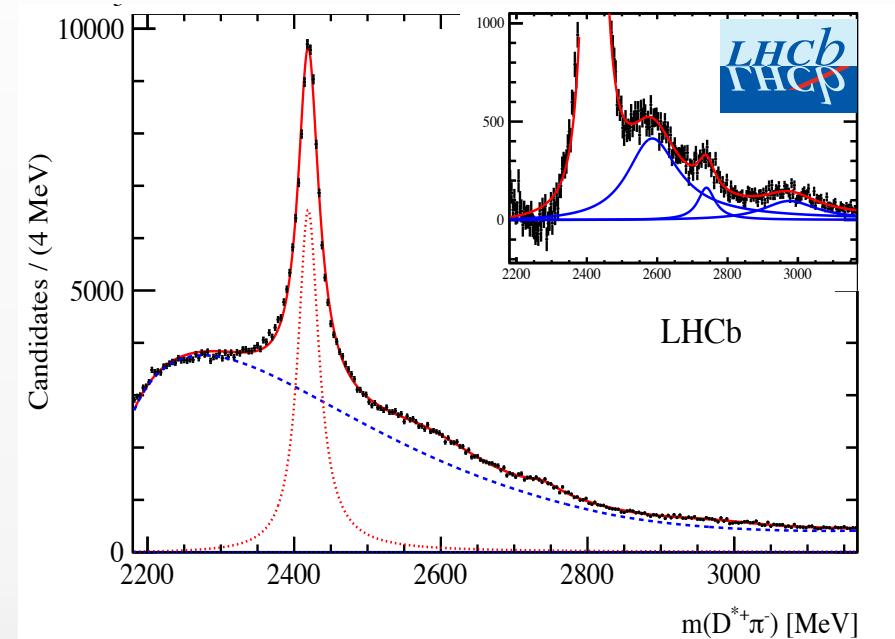
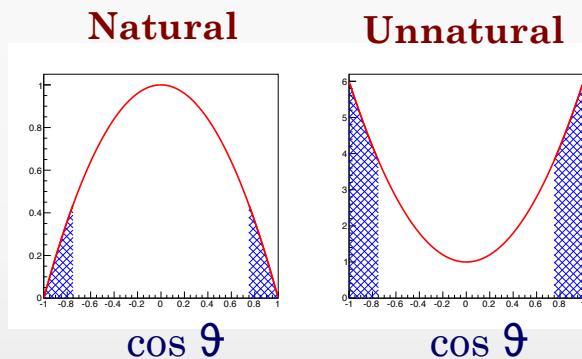
$D^{*+}\pi^-$ MASS FIT

[LHCb, JHEP 09 (2013) 145]

Step 1

$$|\cos \theta| > 0.75$$

enhances unnatural component
(residual natural component $\sim 9\%$)



$D_1(2420)^0 + 3$ unnatural states

$D_J(2580), D_J(2740), D_J(3000)$

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

[LHCb, JHEP 09 (2013) 145]

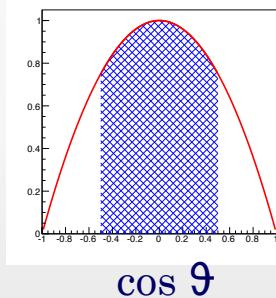
Step 2

$$|\cos \theta| < 0.5$$

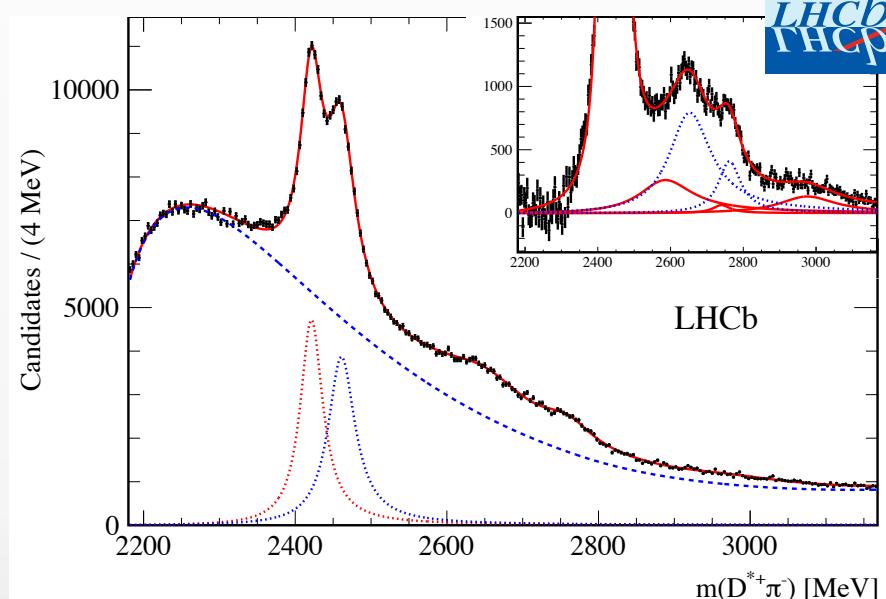
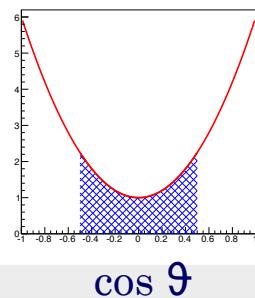
enhances natural component

Parameters of the unnatural states
from Step 1

Natural



Unnatural



$D_2^*(2460)^0 + \text{unnatural states} + 2 \text{ more natural states:}$

$D_J^*(2650), D_J^*(2760)$

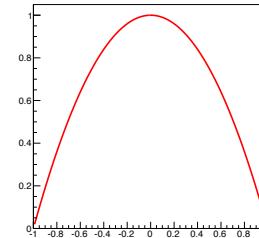
$D^{*+}\pi^-$ MASS FIT

[LHCb, JHEP 09 (2013) 145]

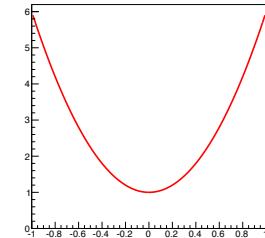
Step 3

- Parameters of all states fixed from Step 1&2
- Fit performed in bins of $\cos \theta$ to verify angular distributions

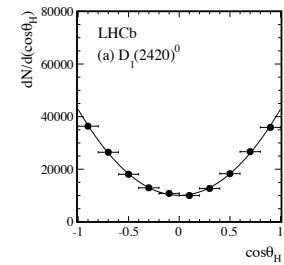
Natural



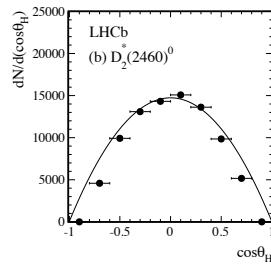
Unnatural



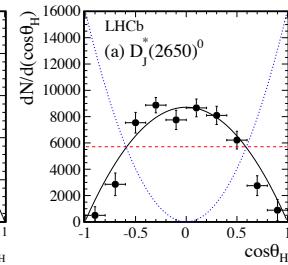
$D_1(2420)$
Unnatural



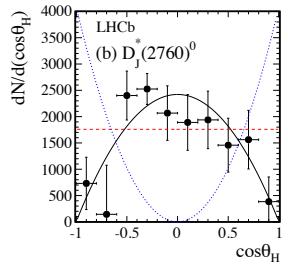
$D_2^*(2460)$
Natural



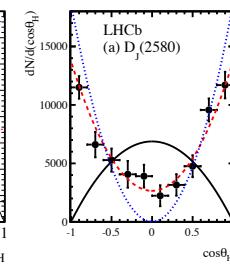
$D_2^*(2650)$
Natural



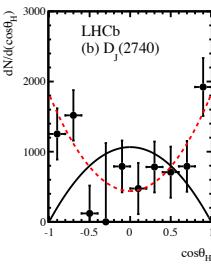
$D_2^*(2760)$
Natural



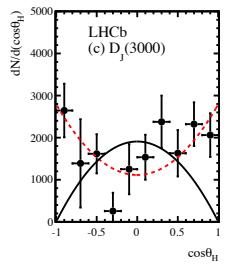
$D_J(2580)$
Unnatural



$D_J(2740)$
Unnatural



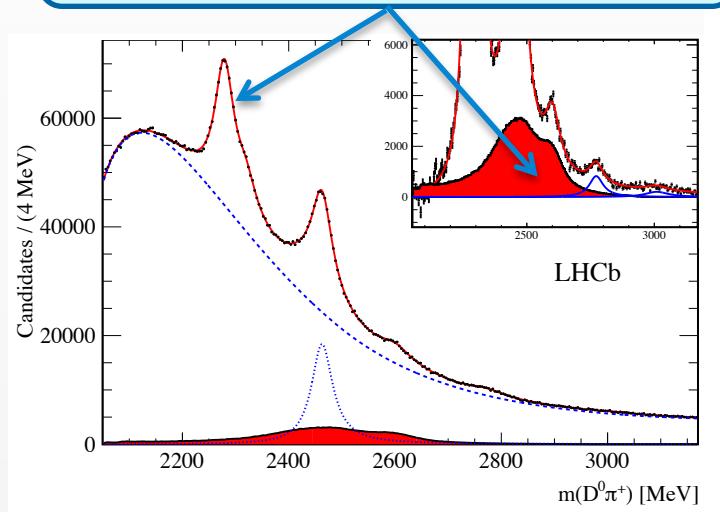
$D_J(3000)$
Unnatural



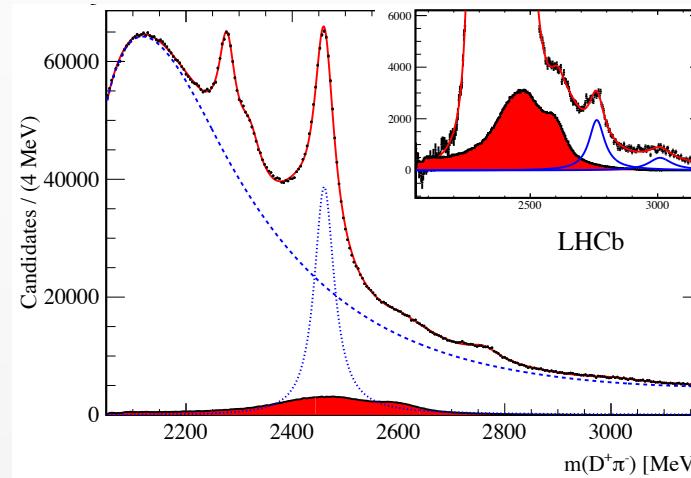
$D^0\pi^+ / D^+\pi^-$ MASS SPECTRA



Cross-feeds estimated from states appearing in the $D^*\pi$ spectrum



[LHCb, JHEP 09 (2013) 145]



2 more natural states:
 $D_J^*(3000)^0, D_J^*(3000)^+$

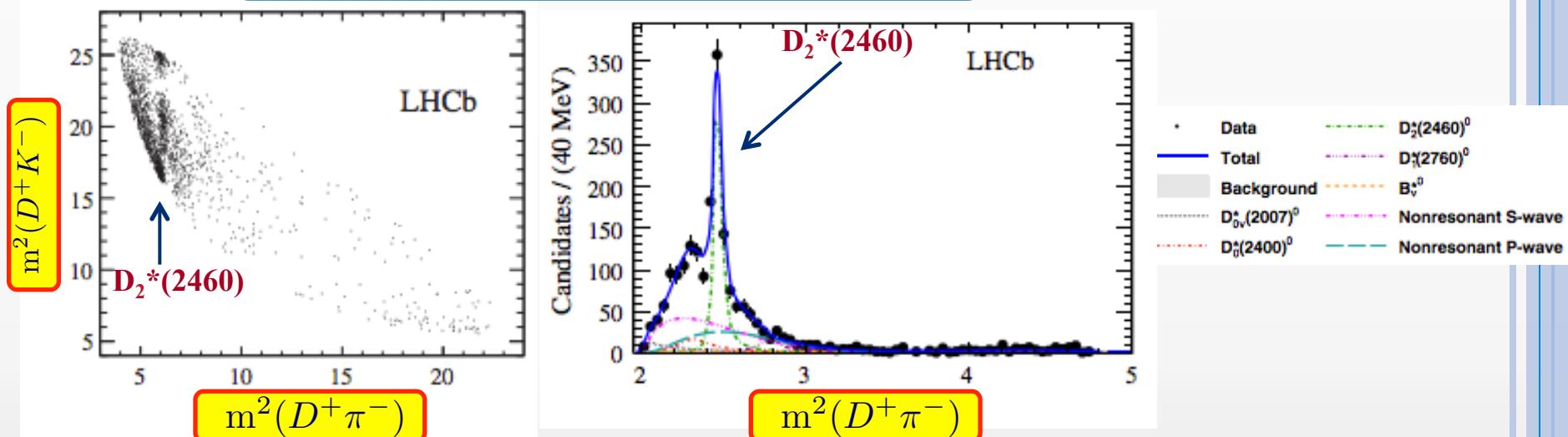
Study of $D^{(*)}\pi$ spectrum
from B decays required to
determine spin-parity

Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Signif (σ)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	$50.7 \pm 2.2 \pm 2.3$	24.5
$D^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	10.2
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	$60.3 \pm 3.1 \pm 3.4$	18.8
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	$7.7 \pm 1.1 \pm 1.2$	7.2
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.5 ± 1.1	9.0
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	$675.0 \pm 9.0 \pm 1.3$	
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	$55.8 \pm 1.3 \pm 10.0$	17.3
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	17.6 ± 1.1	21.2
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	$341.6 \pm 22.0 \pm 2.0$	
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	$20.1 \pm 2.2 \pm 1.0$	18.8
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1(fixed)	110.5 (fixed)	7.6 ± 1.2	6.6

SPECTROSCOPY OF D^{**} IN B DECAYS

First observation of $B^- \rightarrow D^+ K^- \pi^-$
 No resonances expected decaying
 in $D^+ K^-$ (quark content $csd\bar{u}$)

[LHCb: PRD 91 (2015) 092002]



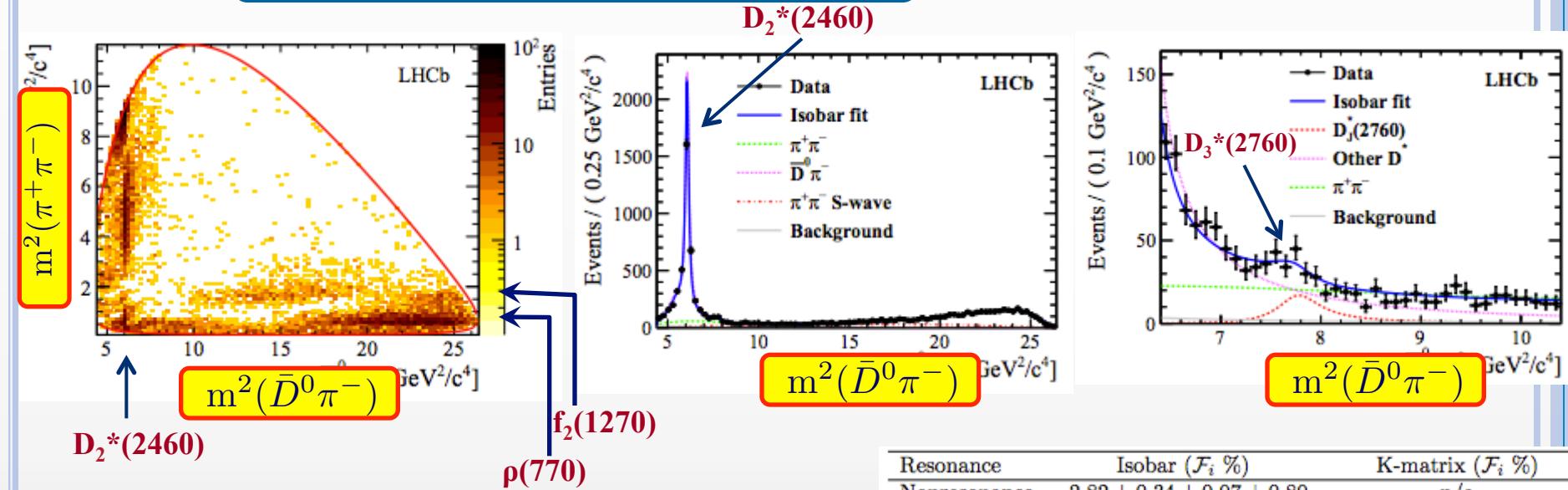
- Large NR component
- Observation of $D_1^*(2760)^0$:
 - Determination of mass and width
 - Determination of spin-parity $J^P=1^-$
 (further supporting the interpretation as $D_1^*(1D)$)

Resonance	Fit fraction
$D_0^*(2400)^0$	$8.3 \pm 2.6 \pm 0.6 \pm 1.9$
$D_2^*(2460)^0$	$31.8 \pm 1.5 \pm 0.9 \pm 1.4$
$D_1^*(2760)^0$	$4.9 \pm 1.2 \pm 0.3 \pm 0.9$
S-wave nonresonant	$38.0 \pm 7.4 \pm 1.5 \pm 10.8$
P-wave nonresonant	$23.8 \pm 5.6 \pm 2.1 \pm 3.7$
$D_v^*(2007)^0$	$7.6 \pm 2.3 \pm 1.3 \pm 1.5$
B_v^*	$3.6 \pm 1.9 \pm 0.9 \pm 1.6$

SPECTROSCOPY OF D^{**} IN B DECAYS (II)

Amplitude analysis of $B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-$

[LHCb: PRD 92 (2015) 032002]



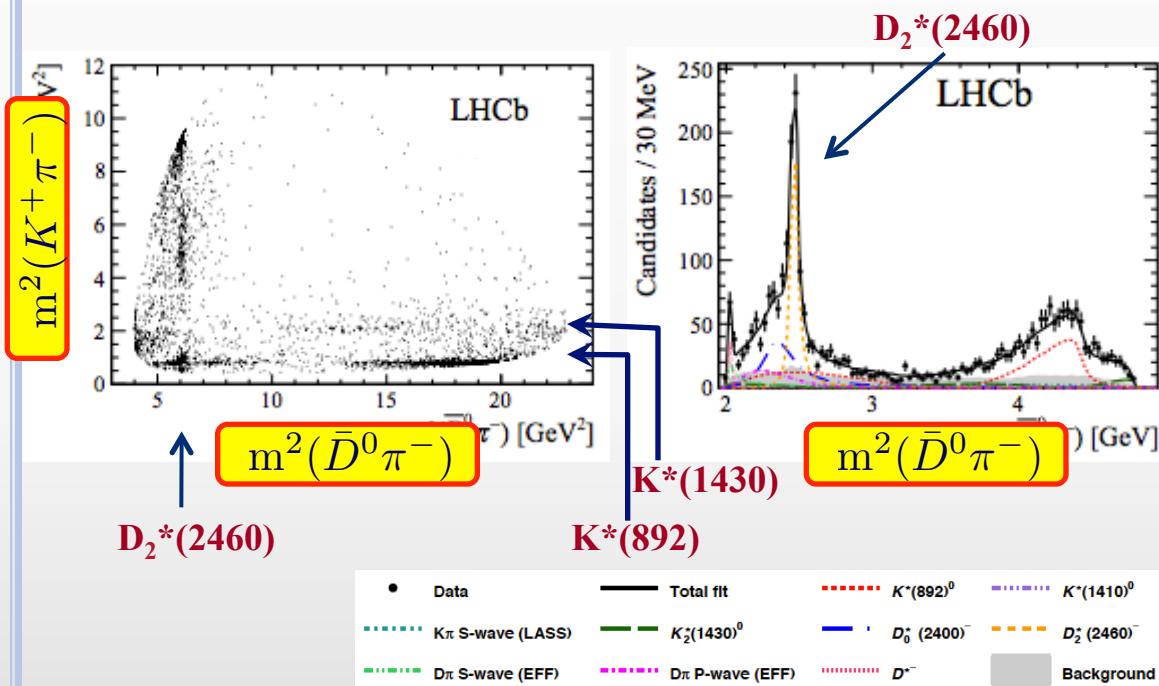
- Two models for $\pi^+ \pi^-$: sum of BW's and K-matrix
- $D_0^*(2400)^-$ spin-parity determined: $J^P=0^+$
- Observation of $D_3^*(2760)^-$:
 - Determination of mass and width
 - Determination of spin-parity $J^P=3^-$
(interpreted as orbitally $L=2$ excited state $D_3^*(1D)$)

Resonance	Isobar ($\mathcal{F}_i \%$)	K-matrix ($\mathcal{F}_i \%$)
Nonresonance	$2.82 \pm 0.34 \pm 0.07 \pm 0.80$	n/a
$f_0(500)$	$13.2 \pm 0.89 \pm 0.31 \pm 2.45$	n/a
$f_0(980)$	$1.56 \pm 0.29 \pm 0.11 \pm 0.54$	n/a
$f_0(2020)$	$1.58 \pm 0.36 \pm 0.15 \pm 1.00$	n/a
S-wave	$16.39 \pm 0.58 \pm 0.43 \pm 1.46$	$16.51 \pm 0.70 \pm 1.68 \pm 1.10$
$\rho(770)$	$37.54 \pm 1.00 \pm 0.61 \pm 0.98$	$36.15 \pm 1.00 \pm 2.13 \pm 0.79$
$\omega(782)$	$0.49 \pm 0.13 \pm 0.01 \pm 0.03$	$0.50 \pm 0.13 \pm 0.01 \pm 0.02$
$\rho(1450)$	$1.54 \pm 0.32 \pm 0.08 \pm 0.22$	$2.16 \pm 0.42 \pm 0.82 \pm 0.21$
$\rho(1700)$	$0.38^{+0.25}_{-0.12} \pm 0.07 \pm 0.06$	$0.83 \pm 0.21 \pm 0.61 \pm 0.12$
$f_2(1270)$	$10.28 \pm 0.49 \pm 0.31 \pm 1.10$	$9.88 \pm 0.58 \pm 0.83 \pm 0.58$
$\bar{D}^0 \pi^-$ P-wave	$9.21 \pm 0.56 \pm 0.24 \pm 1.73$	$9.22 \pm 0.58 \pm 0.67 \pm 0.75$
$D_0^*(2400)^-$	$9.00 \pm 0.60 \pm 0.20 \pm 0.35$	$9.27 \pm 0.60 \pm 0.86 \pm 0.52$
$D_2^*(2460)^-$	$28.83 \pm 0.69 \pm 0.74 \pm 0.50$	$28.13 \pm 0.72 \pm 1.06 \pm 0.54$
$D_3^*(2760)^-$	$1.22 \pm 0.19 \pm 0.07 \pm 0.09$	$1.58 \pm 0.22 \pm 0.18 \pm 0.07$

SPECTROSCOPY OF D^{**} IN B DECAYS (III)

[LHCb: PRD 92 (2015) 012012]

Amplitude analysis of $B^0 \rightarrow \bar{D}^0 K^+ \pi^-$



Resonance	Fit fraction	Upper limit
$K^*(892)^0$	$37.4 \pm 1.5 \pm 1.2 \pm 1.7$	
$K^*(1410)^0$	$0.7 \pm 0.3 \pm 0.8 \pm 0.8$	$< 3.2 \text{ (3.7)}$
$K_2^*(1430)^0$	$5.1 \pm 2.0 \pm 2.4 \pm 3.4$	
LASS nonresonant	$4.8 \pm 3.8 \pm 3.8 \pm 6.7$	
LASS total	$6.7 \pm 2.7 \pm 2.7 \pm 5.4$	
$K_2^*(1430)^0$	$7.4 \pm 1.7 \pm 1.1 \pm 2.0$	
$D_0^*(2400)^-$	$19.3 \pm 2.8 \pm 2.0 \pm 7.4$	
$D_2^*(2460)^-$	$23.1 \pm 1.2 \pm 1.1 \pm 1.2$	
$D_3^*(2760)^-$		$< 1.0 \text{ (1.1)}$
$D\pi$ S-wave (dabba)	$6.6 \pm 1.4 \pm 1.2 \pm 3.7$	
$D\pi$ P-wave (EFF)	$8.9 \pm 1.6 \pm 2.2 \pm 3.0$	

No evidence for $D_3^*(2760)^-$

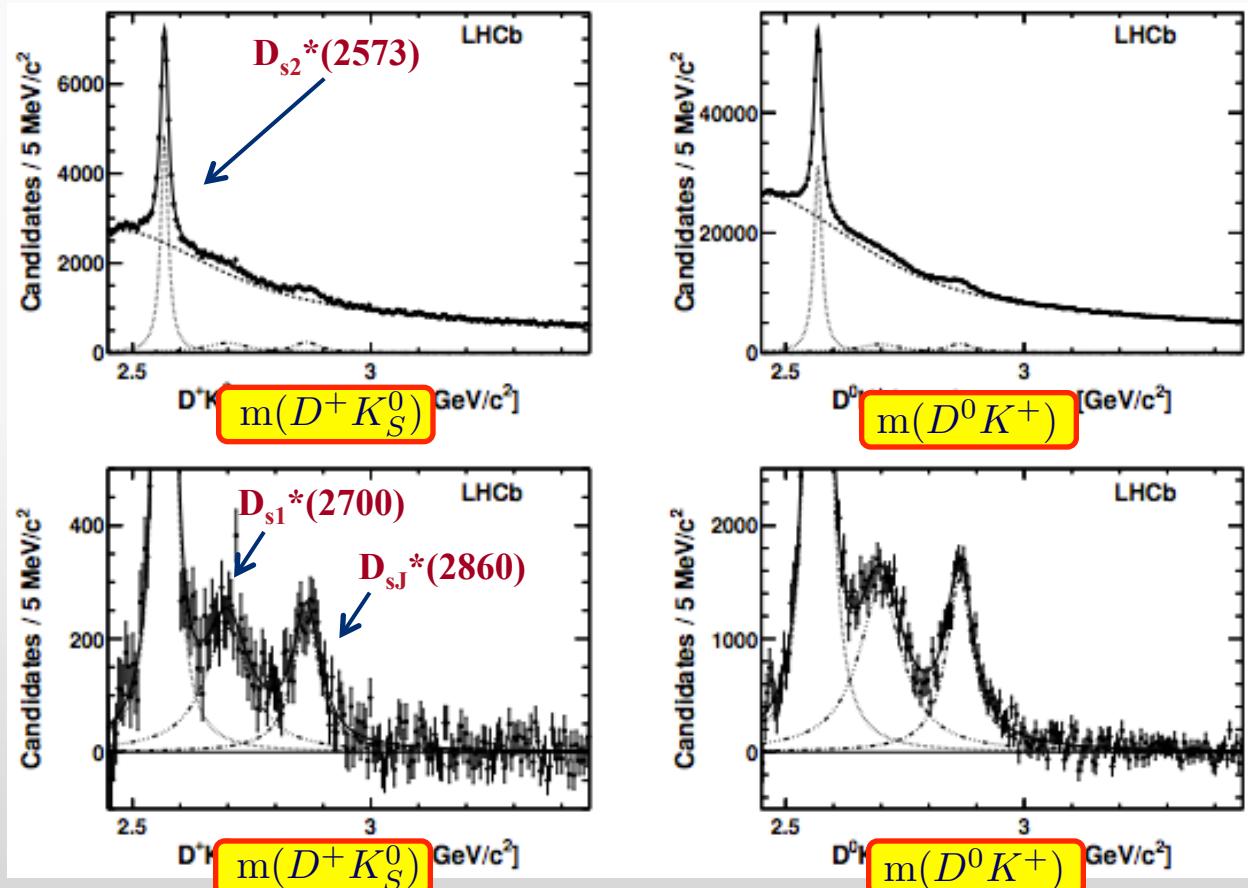


Excited D_s Mesons @ LHCb

EXCITED D_s STATES: INCLUSIVE ANALYSIS

[LHCb: JHEP 10 (2012) 151]

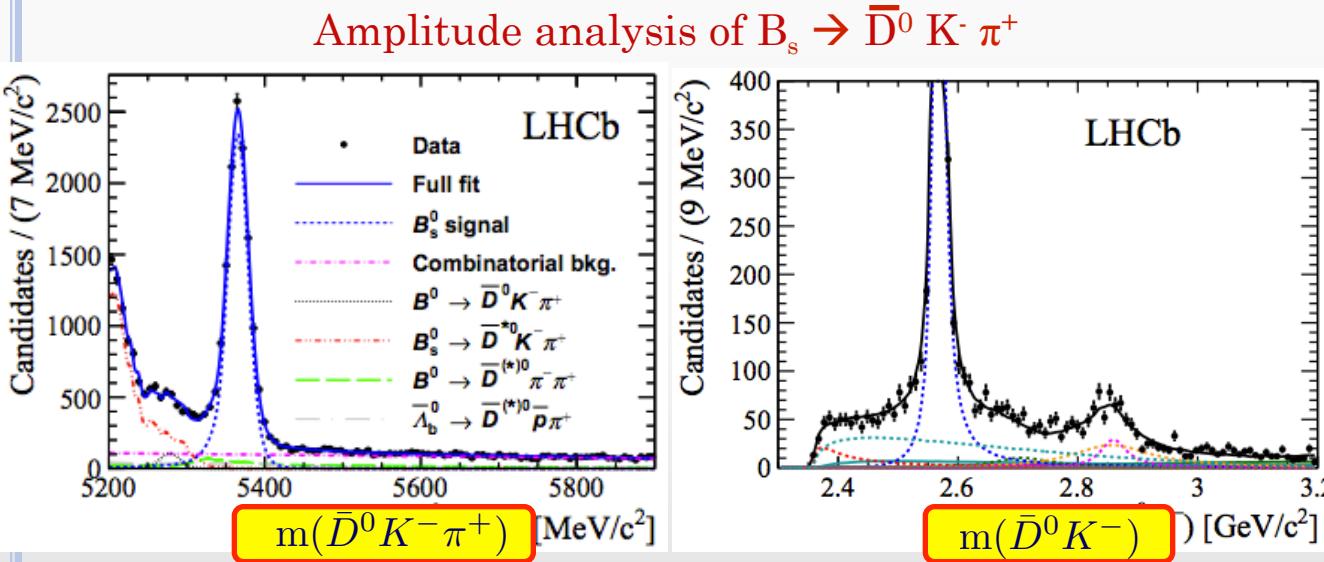
LHCb collaboration has confirmed 2 broad states decaying to DK:
 $D_{s1}^*(2700)^+$ & $D_{sJ}^*(2860)^+$



SEARCH FOR “ D_{s0}^* ” IN B_s DECAYS

[LHCb: PRL 113 (2014) 162001]
 [LHCb: PRD 90 (2014) 072003]

If the $D_{s0}^*(2317)$ is not the $L=1, j_q=1/2$ excited D_s state, then a broad D_{s0}^* state above the DK threshold should appear in B_s decays



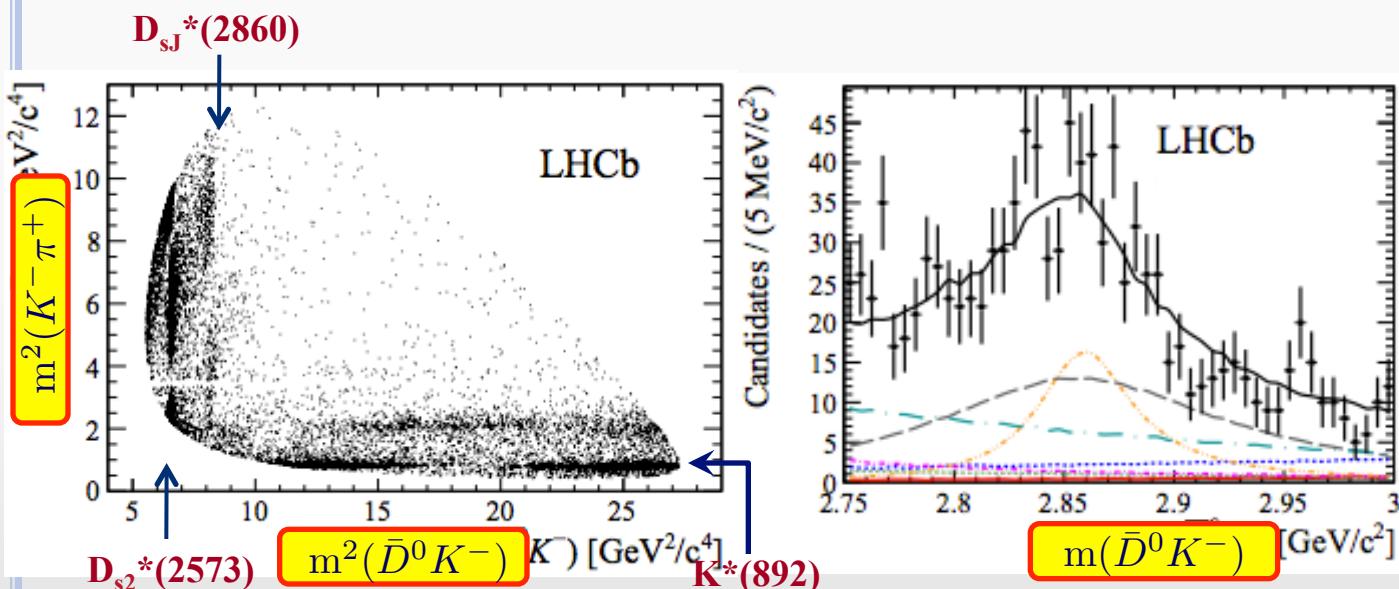
Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant	12.4 ± 2.7
D_{s2}^{*-}	4.7 ± 1.4
$D_{s0v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3

No evidence for such a broad D_{s0}^* state

EXCITED D_s STATES IN B_s DECAYS (II)

[LHCb: PRL 113 (2014) 162001]
 [LHCb: PRD 90 (2014) 072003]

- LHCb has performed a Dalitz Plot analysis of $B_s \rightarrow \bar{D}^0 K^- \pi^+$
- D_{sJ}^{*}(2860)⁺ consists of (at least) 2 overlapping states J^P=1⁻ & 3⁻



Resonance	Mass (MeV/c^2)	Width (MeV/c^2)
$D_{s2}^*(2573)^-$	2568.39 ± 0.29	16.9 ± 0.5
$D_{s1}^*(2860)^-$	2859 ± 12	159 ± 23
$D_{s3}^*(2860)^-$	2860.5 ± 2.6	53 ± 7

Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant	12.4 ± 2.7
D_{sv}^{*-}	4.7 ± 1.4
$D_{s0v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3



Plans & Prospects

WHAT'S NEXT?

RUN I not fully exploited so far!

- ✓ *Above $D^{(*)}$ π and $D^{(*)}$ K thresholds:*
 - ✓ *Most of spectra have been studied*
 - ✓ *Missing: $D^{*0} K^+$ and $D^{*+} K_S^0$ (Why?)*
- ✓ *Below $D^{(*)}$ π and $D^{(*)}$ K thresholds*
 - ✓ *Missing: $D^{(*)0} \gamma$, $D^{(*)0} \pi^0$, $D^{(*)}_s \gamma$, $D^{(*)}_s \pi^0$ (Why?)*

Calorimeter system not designed/optimized for the detection of “soft” photons and neutral pions (Only ~ 10 LHCb papers out of 280 deal with neutrals).

WHAT'S NEXT?

✓ **Prompt production:**

- ✓ *Low detection efficiency of neutrals balanced by the large production cross-section (larger than expected at 13 TeV [arXiv: 1510.01707])*
- ✓ *Trigger revisited to keep running the charm spectroscopy program*
- ✓ *Very large combinatorial background*

✓ **Production from $B_{(s)}$ decays:**

- ✓ *Selection optimized on the $B_{(s)}$ signals*
- ✓ *Production of high spin states disfavored*

PROSPECT

✓ ***Nature of $D_{s0}^*(2317)$ and $D_{s1}(2460)$:***

- *Search for new decays modes*

Decay Channel	$D_{sJ}^*(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+ \pi^0$	Seen	Forbidden
$D_s^+ \gamma$	Forbidden	Seen
$D_s^+ \pi^0 \gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+ \pi^0$	Forbidden	Seen
$D_{sJ}^*(2317)^+ \gamma$	—	Allowed
$D_s^+ \pi^0 \pi^0$	Forbidden	Allowed
$D_s^+ \gamma \gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+ \gamma$	Allowed	Allowed
$D_s^+ \pi^+ \pi^-$	Forbidden	Seen

- *Production studies (e.g. $D_{s1}(2460) \rightarrow D_s^- \gamma$ production cross-section)*
- *Studies from B_s decays (e.g. $B_s^0 \rightarrow D_s^- \pi^0 \pi^+$)*
 - *Determination of $D_s(2317)$ (and D_s^*) spin-parity*
 - *Measurement of BR*
 - *Search for $D_s(2317)^0 \rightarrow D_s^- \pi^+$*

SUMMARY

- ✓ ***What we achieved:***
 - ✓ Confirmation of many excited charmed states
 - ✓ Precise measurement of masses and widths
 - ✓ Determination of spin-parity by amplitude analysis of B decays
- ✓ ***Plans***
 - ✓ Studies of $D^*\pi$ and D^*K in B decays
 - ✓ Challenging studies of spectra with neutrals in the final state
 - ✓ Search for $D_{sJ}(2632) \rightarrow D_s \eta$
 - ✓ Search for the beauty partners of $D_{s0}(2317)$ and $D_{s1}(2460)$: B_{s0}^* and B_{s1}'

Exciting prospects ahead due to the ongoing data taking!

(RUN I + RUN II $\sim 8 \text{ fb}^{-1}$)



Back-up slides

DOUBLETS IN EXCLUSIVE ANALYSES

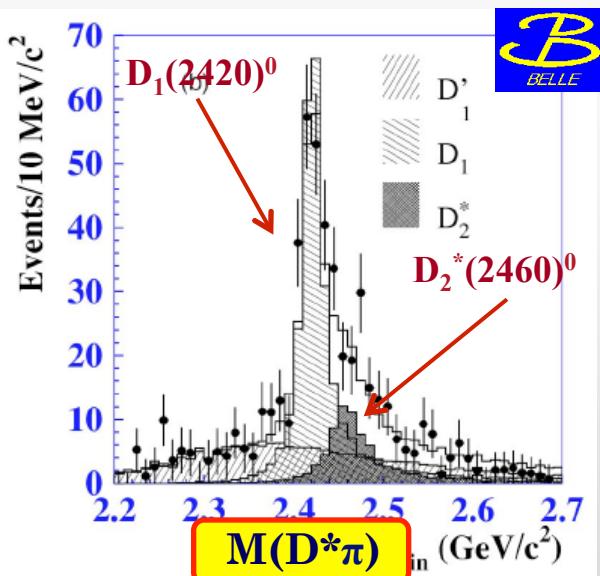
Exclusive analysis

$$B^- \rightarrow D^{(*)+} \pi^- \pi^-$$

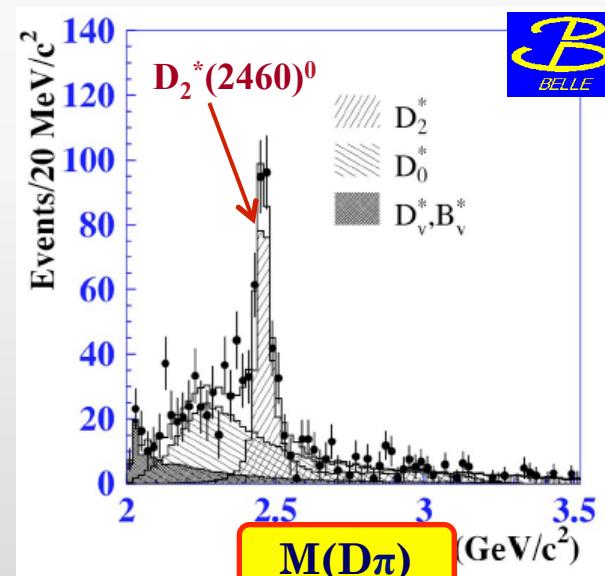
[Belle: Phys.Rev.D69 (2004) 112002]

(e.g) $L=1, j_q=3/2$ doublet

- 1 peak in $D\pi$
- 2 peaks in $D^*\pi$ } as expected



j_q	J^P	Allowed decay mode	
		$D\pi$	$D^*\pi$
D_0^*	$1/2$	0^+	yes
D_1'	$1/2$	1^+	no
D_1	$3/2$	1^+	no
D_2^*	$3/2$	2^+	yes



Broad states of the $j=1/2$ doublets also revolved by an amplitude analysis

DOUBLETS IN INCLUSIVE ANALYSES

Inclusive analysis



[LHCb: JHEP 09 (2013) 145]

(e.g) L=1, $j_q=3/2$ doublet

- 1 peak in $D\pi$
- 2 peaks in $D^*\pi$

j_q	J^P	Allowed decay mode	
		$D\pi$	$D^*\pi$
D_0^*	$1/2$	0^+	yes no
D_1'	$1/2$	1^+	no yes
D_1	$3/2$	1^+	no yes
D_2^*	$3/2$	2^+	yes yes

DOUBLETS IN INCLUSIVE ANALYSES

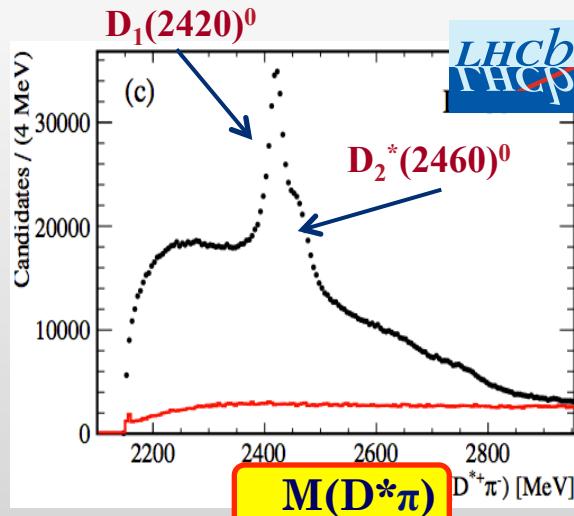
Inclusive analysis

$$pp \rightarrow D^{(*)+} \pi^- + X$$

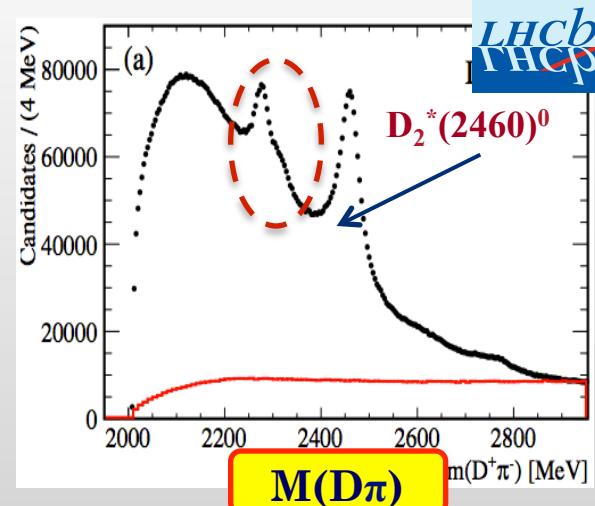
[LHCb: JHEP 09 (2013) 145]

(e.g) L=1, $j_q = 3/2$ doublet

- 1 peak in $D\pi$ 3 peaks in $D\pi$?
- 2 peaks in $D^*\pi$



j_q	J^P	Allowed decay mode	
		$D\pi$	$D^*\pi$
D_0^*	$1/2$	0^+	yes no
D_1'	$1/2$	1^+	no yes
D_1	$3/2$	1^+	no yes
D_2^*	$3/2$	2^+	yes yes



FEED-DOWNS OF $D_1/D_2^* \rightarrow D^*\pi$ DECAYS INTO $D\pi$ MASS SPECTRUM

Inclusive analysis

$$pp \rightarrow D^{(*)+} \pi^- + X$$

[LHCb: JHEP 09 (2013) 145]

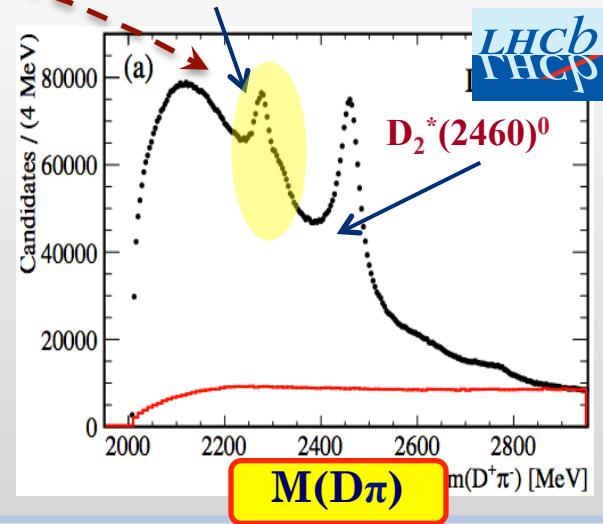
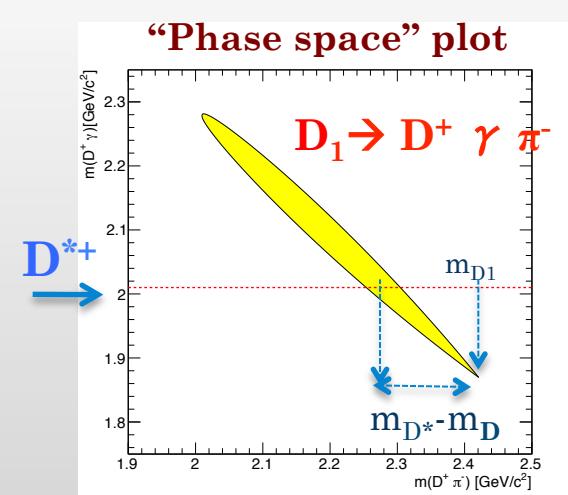
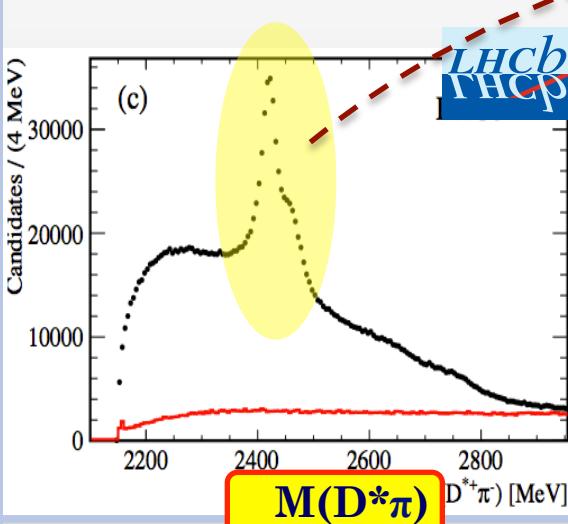
$j_q = 3/2$ doublet

- 3 peaks in $D\pi$
 - ✓ $D_2^* \rightarrow D\pi$
 - ✓ $D_1 \rightarrow D^*\pi$ feed-down } overlapped if $\Gamma > m(D^*) - m(D)$
 - ✓ $D_2^* \rightarrow D^*\pi$ feed-down }
- 2 peaks in $D^*\pi$

j_q	J^P	Allowed decay mode	
		$D\pi$	$D^*\pi$
D_0^*	$1/2$	0^+	yes
D_1'	$1/2$	1^+	no
D_1	$3/2$	1^+	no
D_2^*	$3/2$	2^+	yes

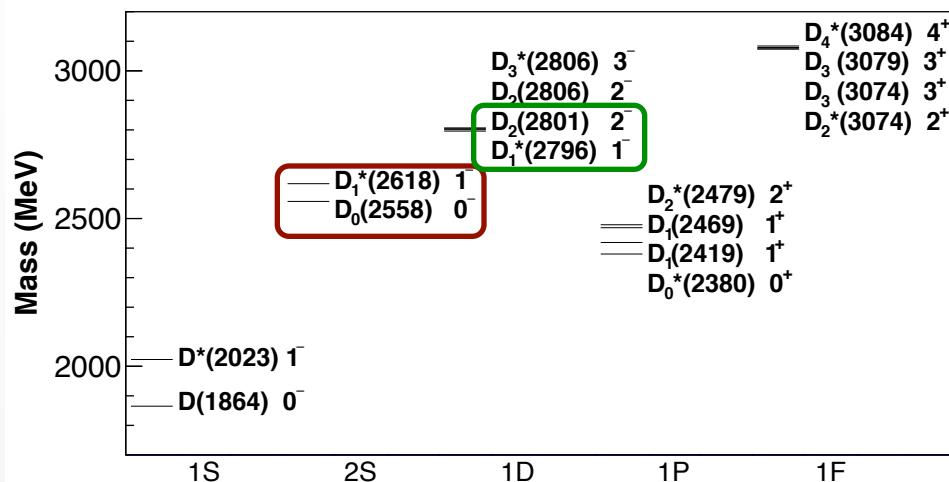
$D_1(2420)^0 / D_2^*(2460)^0$ feed-down

↳ $D^{*+} \pi^-$
 ↳ $D^+ \gamma/\pi^0$



INTERPRETATION

[LHCb, JHEP 09 (2013) 145]



$D_J(2580)$ could be identified with the $D(2S)$ (e.g. $D_0(2558)$)

$D_J^*(2650)$ could be identified as the $J^P=1^-$ $D^*(2S)$ (i.e. $D_1^*(2618)$)

$D_J(2740)$ could be identified as the $J^P=2^-$ $D_2(1D)$ (i.e. $D_2(2801)$)

$D_J^*(2760)$ could be identified as the $J^P=1^-$ $D_1^*(1D)$ (i.e. $D_1^*(2796)$)

Study of $D^{(*)}\pi$ spectrum from B decays
needed to establish spin-parity