Heavy Meson Spectroscopy

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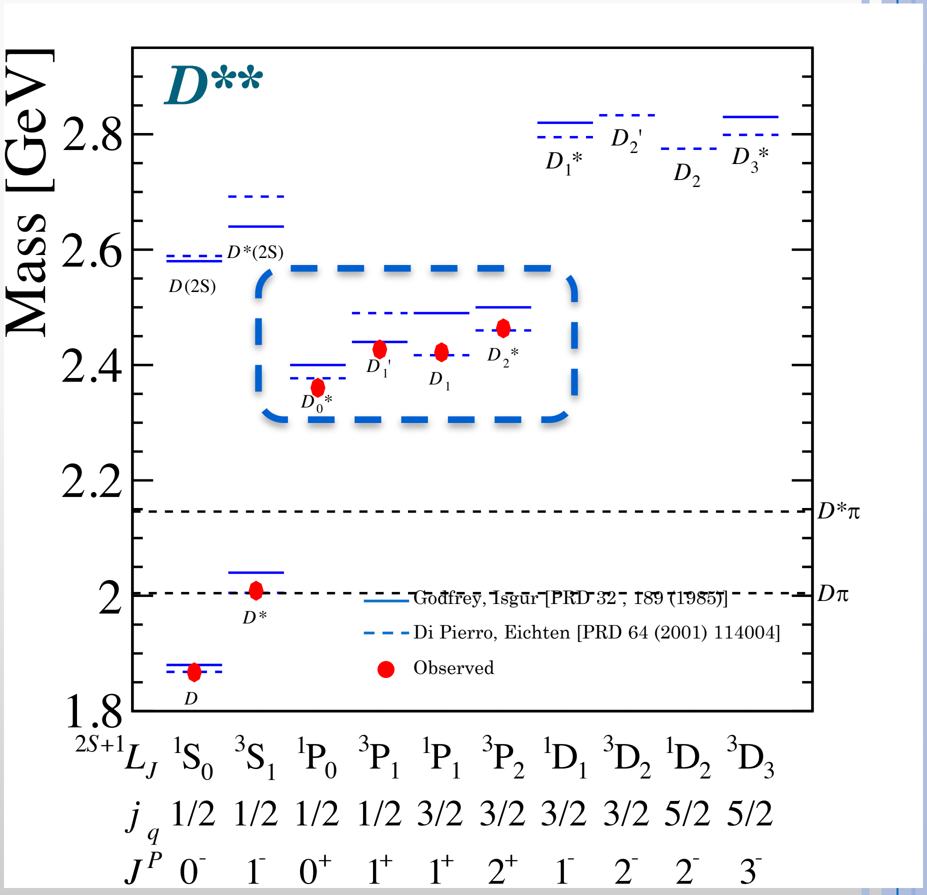
THE EXCITED *D* STATES

- The charmed excited states studied in inclusive analyses and into B decays
- The orbitally L=1 excited D** states observed first
- Masses and properties well predicted by theory

D** (L=1)

	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



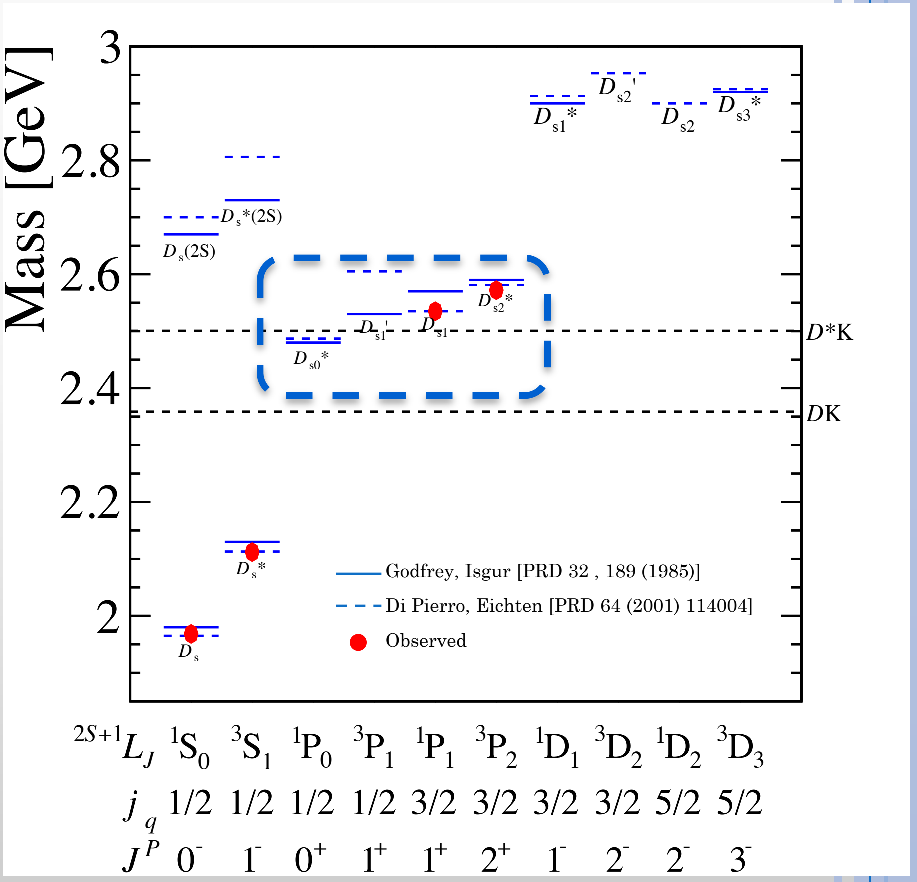
THE EXCITED D_S STATES

- The charmed excited states studied in inclusive analyses and into B decays
- The orbitally L=1 excited D_s^{**} states observed first
- Masses and properties well predicted by theory

D_s^{**} (L=1)

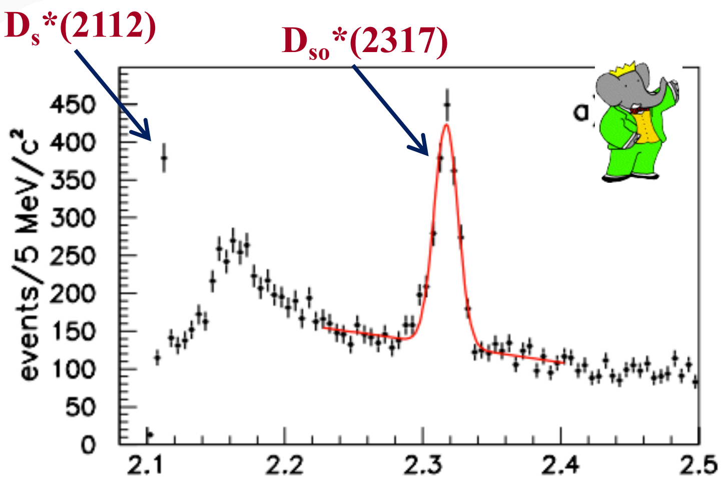
	Mass (MeV)	Width (MeV)
D^*_{s0}	—	—
D'_{s1}	—	—
$D_{s1}(2536)^{\pm}$	2535.10 ± 0.08	0.92 ± 0.05
$D^*_{s2}(2573)^{\pm}$	2571.9 ± 0.8	17 ± 4

D_{s0}^* and D_{s1}' states expected broad and to be observed in B_s decays…

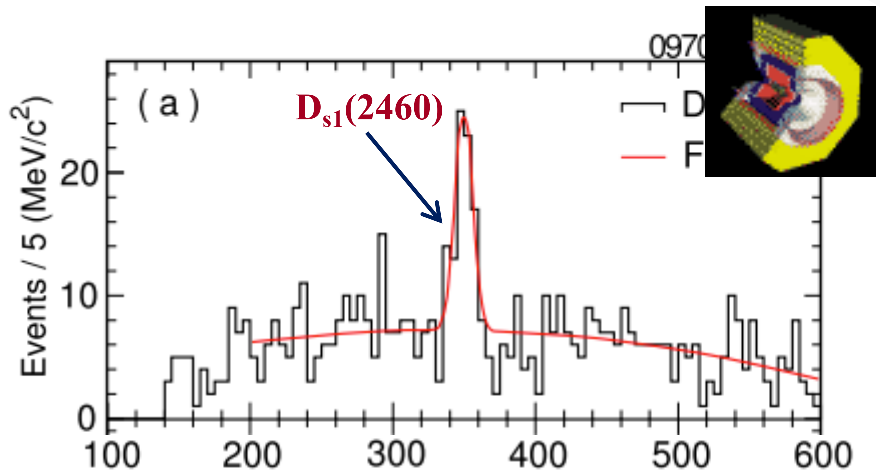


Puzzle: Excited D_S Mesons: L=1, j_q = 1/2(?)

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



M($D_s\pi^0$)



M($D_s\gamma\pi^0$)-M($D_s\gamma$)

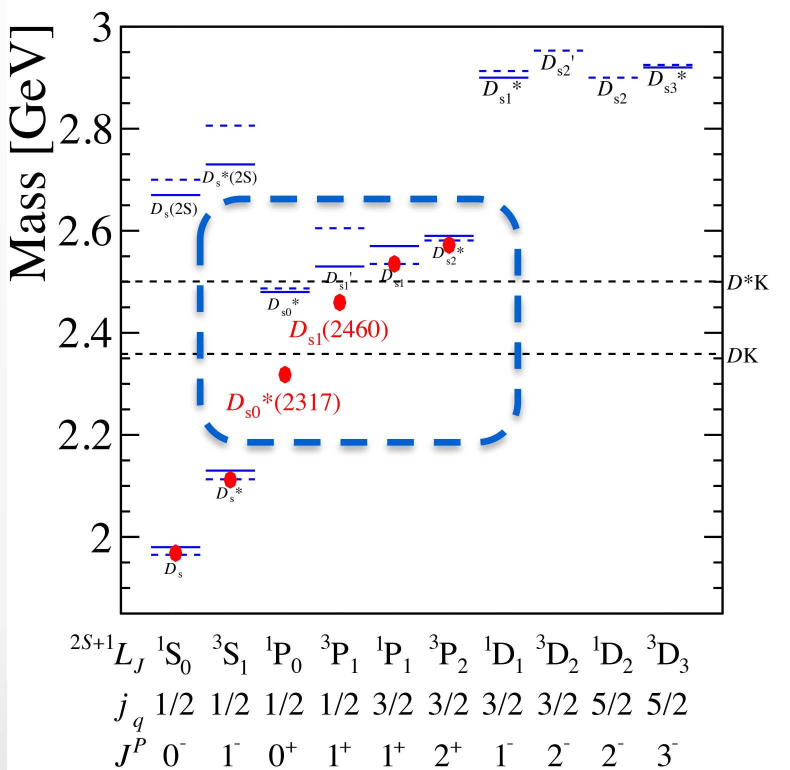
PDG	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^\pm$	2317.7 ± 0.6	< 3.8
$D_{s1}(2460)^\pm$	2459.5 ± 0.6	< 3.5

Surprisingly narrow!

Are They the Missing L=1 States?

- *Why are they so narrow?*
  Lack of an isospin-conserving strong decay channel since the decays to DK and $D^{(*)}K$ final states are kinematically forbidden

- *Why are the masses much lower (~100 MeV) than expected? Are they excited D_s states?*
  $J^P = (0^+, 1^+)$ as expected for the L=1, j_q=1/2 states. However many alternative interpretations proposed: DK or $D_s\,\pi$ molecule, $q\bar{q}$ + tetraquark/DK mixing



	Decay Mode	BR (%)
$D_s^*(2112)$	$D_s^+\pi^0$	5.8 ± 0.7
	$D_s^+\gamma$	93.5 ± 0.7
$D_{s0}^*(2317)$	$D_s^+\pi^0$	seen
	$D_s^+\gamma$	<5
	$D_s^{*+}\gamma$	<6
$D_{s1}(2460)$	$D_s^+\pi^0$	48 ± 11
	$D_s^+\gamma$	18 ± 4
	$D_s^{*+}\gamma$	<8

$$BR = 1.00^{+0.00}_{-0.14} \pm 0.14$$

[BES: PRD 97 (2018) 051103]

Are They the Missing L=1 States?

- Different mass splitting between the two doublets in a $q\bar{q}$ scenario:

$$M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \neq M_{D^*_{s2}(2573)} - M_{D_{s1}(2536)}$$

- B→DD_{s0}* branching ratios below expectations (i.e. ~1) for a $q\bar{q}$ state **[PLB572, 164 (2003)][PRD69, 054002 (2004)]**

$$\frac{\mathcal{B}(B^+ \to \bar{D}^0 D^{*+}_{s0})}{\mathcal{B}(B^+ \to \bar{D}^0 D^+_s)} = 0.081^{+0.032}_{-0.025}$$

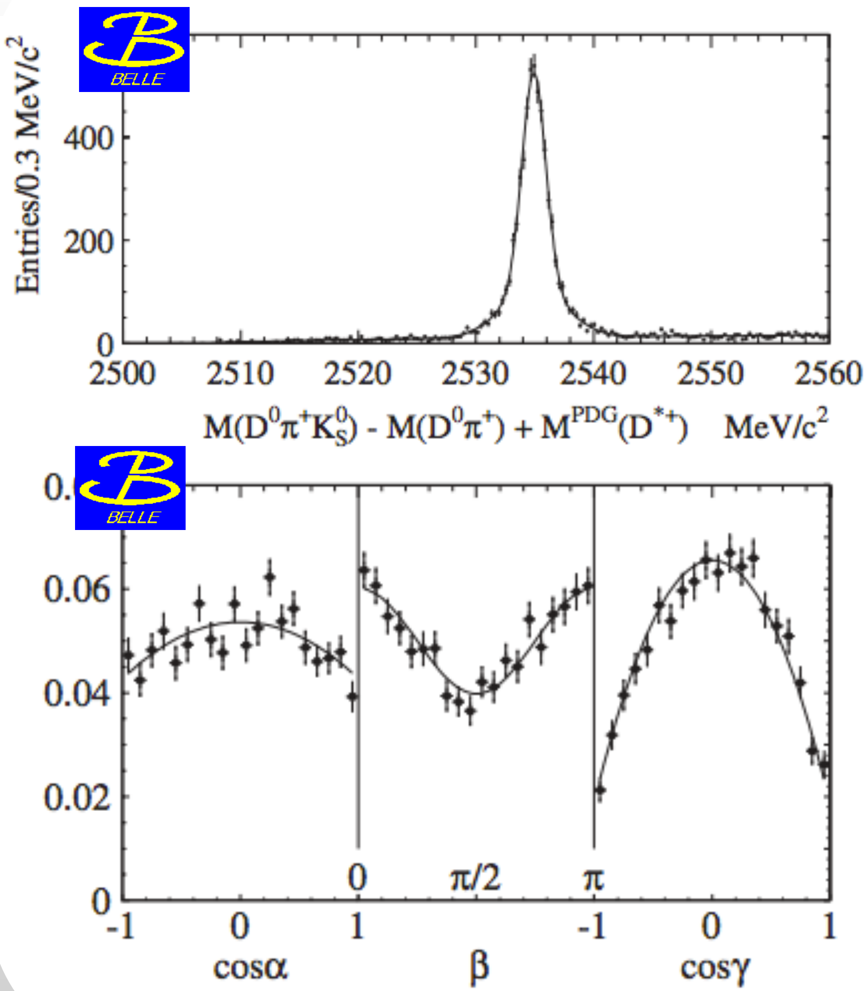
$$\frac{\mathcal{B}(B^0 \to D^- D^{*+}_{s0})}{\mathcal{B}(B^0 \to D^- D^+_s)} = 0.13 \pm 0.04$$

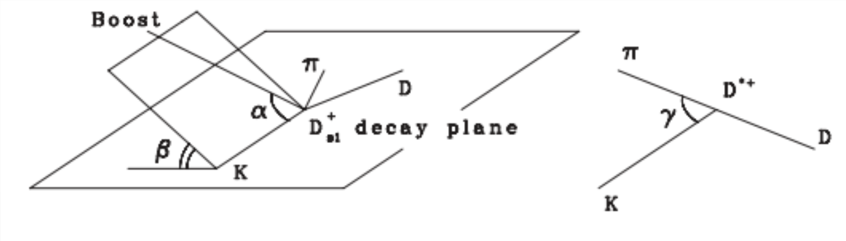
No $D_s^+\pi^\pm$ partners have been observed in inclusive studies **[BaBar: PRD74 (2006) 032007]** or in B decays **[Belle: PRD 91 (2015) 092011]** (upper limits more than an order of magnitude lower)

Puzzle II: Is $D_{S1}(2536)^+$ the Excited L=1, j_q=3/2 State?

Angular analysis of $D_{s1}(2536)^+ \to D^{*+}K^0_S$ decay

[Belle: PRD77 (2008) 032001]





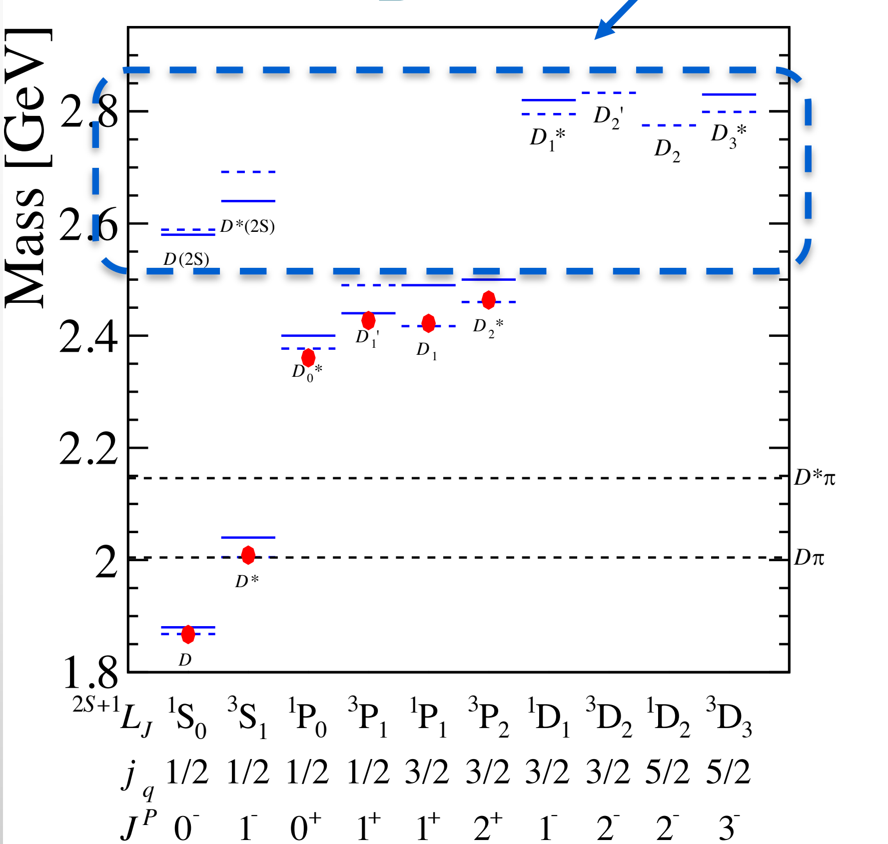
$$\frac{\Gamma_S}{\Gamma_{total}} = 0.72 \pm 0.05 \pm 0.01$$

Contrary of HQET expectations, the S-wave contribution dominates!

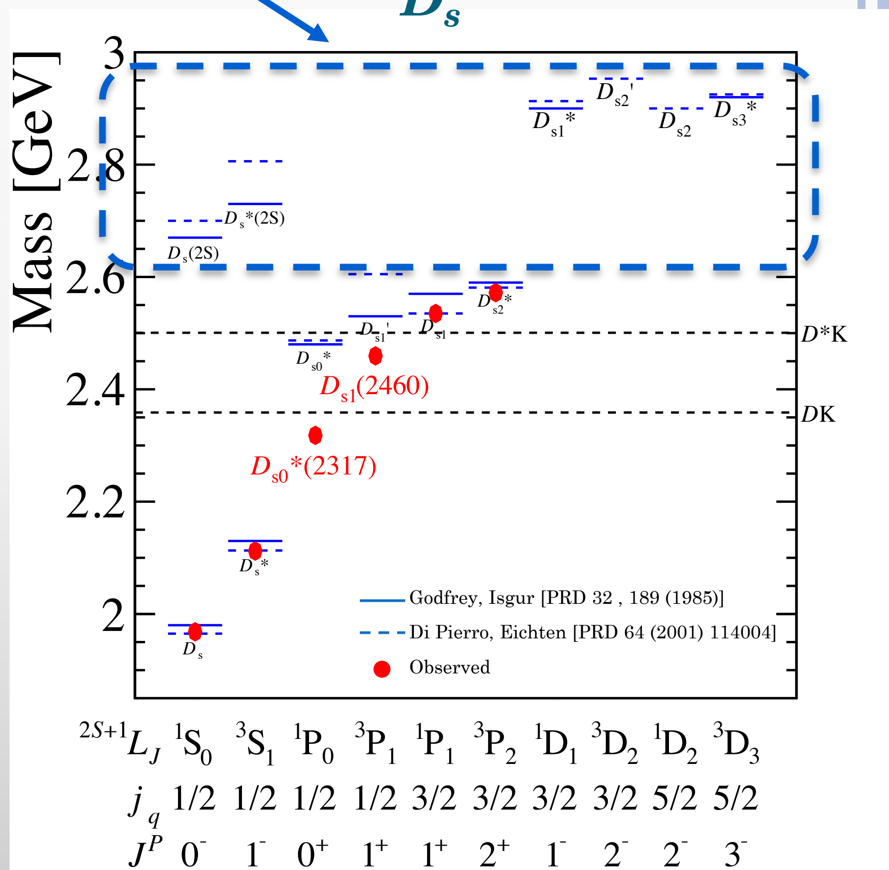
Highly Excited $D_{(s)}$ Mesons

Broad states are expected well above the $D^{(*)}\pi/K$ thresholds

D^{**}

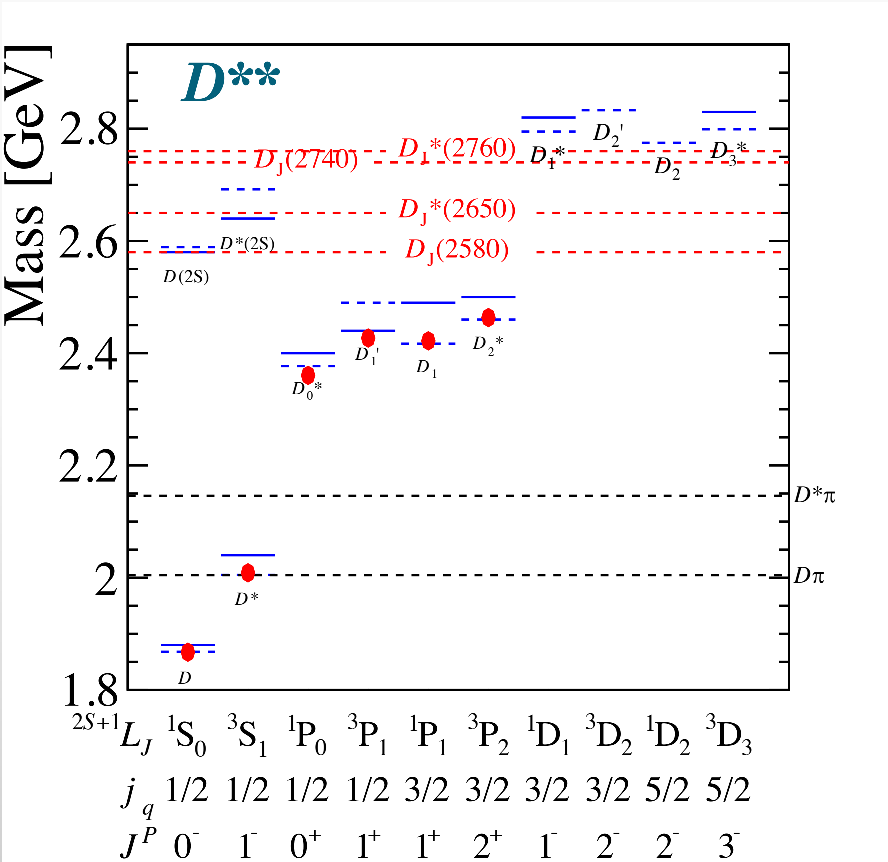


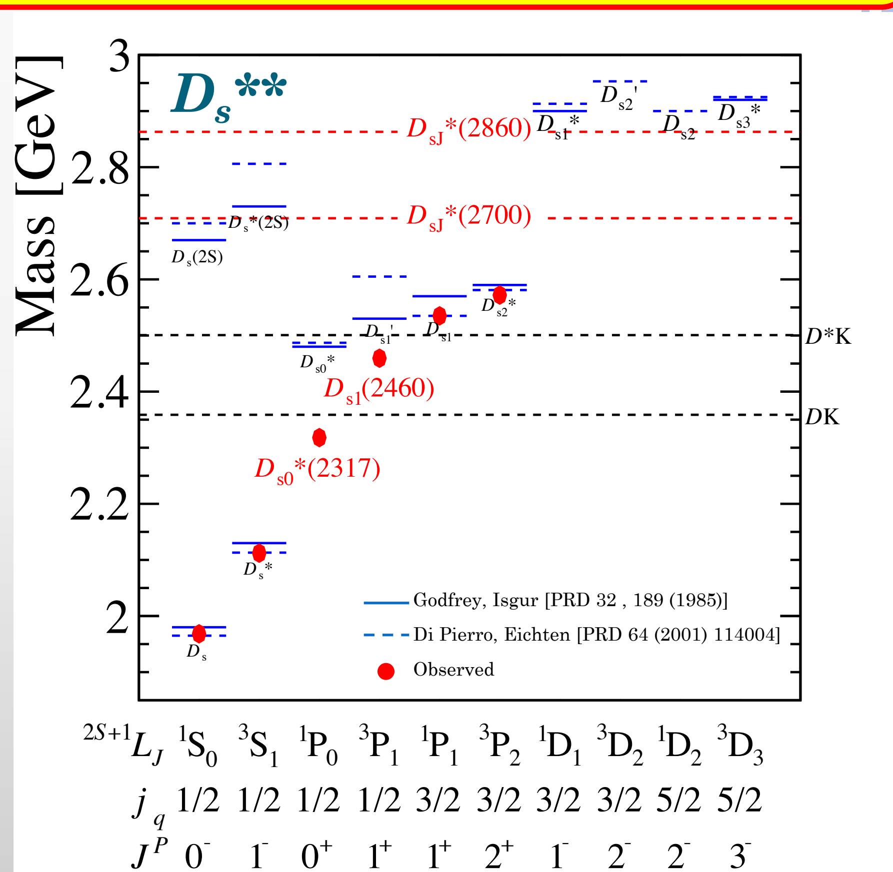
D_s^{**}



HIGHLY EXCITED D$_{(s)}$ MESONS

- Many broad states observed in prompt production and from B decays (Dalitz Analysis)
- First observation of a spin-3 meson
- Likely to be radially or L = 2 excitations





PROSPECTS: EXCITED $D_{(S)}$ MESONS

✓**$D^*_{s0}(2317)$ and $D_{s1}(2460)$:**

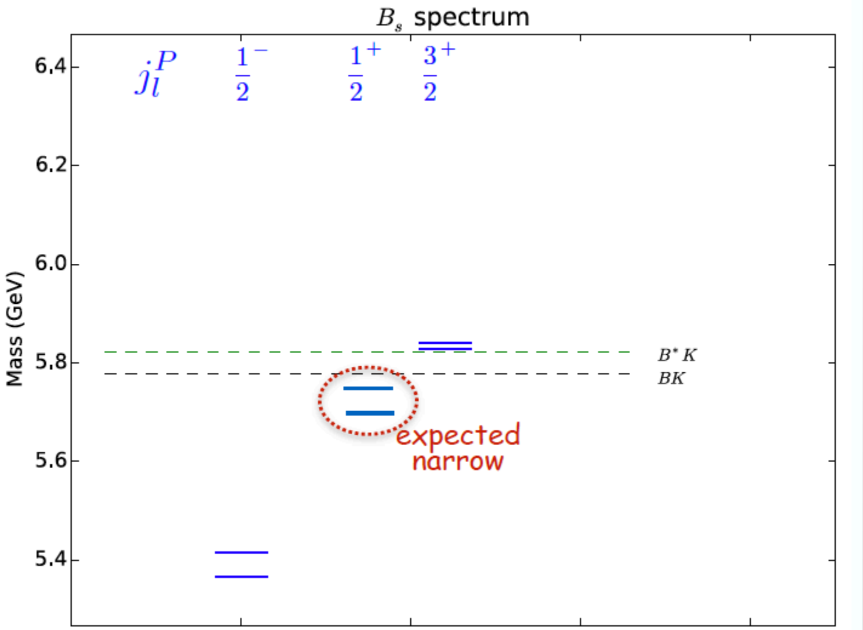
- Measurement of the natural widths (PANDA)
- Search for new decays modes (LHCb/Belle II/BES3)
- Production studies (e.g. $D_{s1}(2460) \rightarrow D_s \gamma$ production cross-section)
- Studies from $B_{(s)}$ decays (e.g. $B^0_s \rightarrow D_s^- \pi^0 \pi^+$)
  - Determination of $D^*_{s0}(2317)$ (and D_s^*) spin-parity
  - Measurement of BR

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

Excited B_S States

- Since $m_b > m_c$, the expansion terms should have a smaller effect
- After the discoveries of $D^*_{s0}(2317)$ and $D_{s1}(2460)$, many models predict 4 narrow states in the B_s sector as well

	J^P	Decay Modes
B^*_{s0}	0^+	$B_s^* \gamma$ $B_s \pi^0$
B_{s1}'	1^+	$B_s \gamma$ $B_s^* \gamma$ $B_s^* \pi^0$
$B_{s1}(2830)$	1^+	B^*K
$B^*_{s2}(2840)$	2^+	BK B^*K



E.J. Eichten, Quarkonium-Like States Near Threshold, LHCb Workshop 2016, Oct 2016

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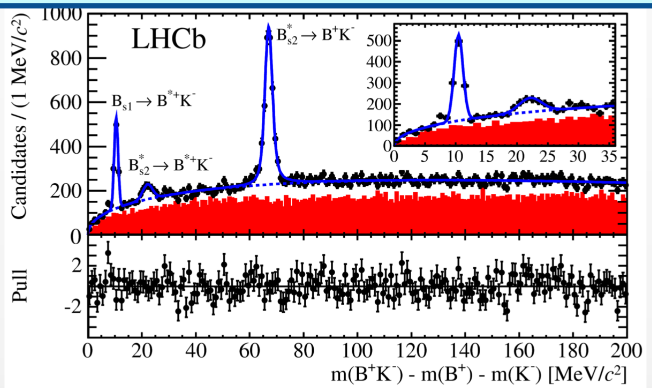
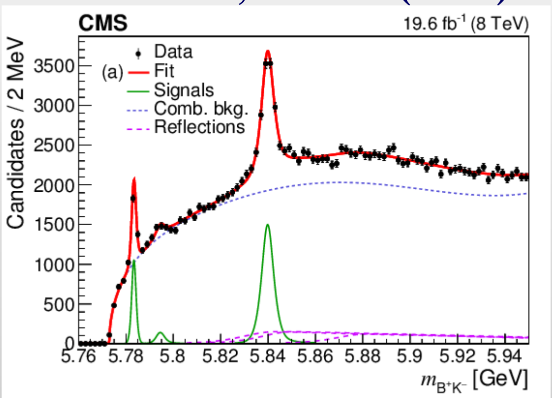


PRL 110, 151803 (2013)



EPJC 78 (2018) 11, 939

Where to look for the other two narrow states?

The isospin-violating decays are dominant in the D_s sector but radiative decays might be dominant in the B_s sector

$D_{s0}^*(2317)$

$D_{s1}(2460)$

system	transition	Q(keV)	overlap	dependence	Γ (keV)	exptl BR
$(c\bar{s})$	$0^+ \to 1^- + \gamma$	212	2.794	$r_{\bar{c}s}$	1.74	
	$0^+ \to 0^- + \pi^0$	297		$G_A\delta_{\eta\pi0}$	21.5	
	total				23.2	
$(c\bar{s})$	$1^+ \to 0^+ + \gamma$	138	0.992	$r'_{\bar{c}s}$	2.74	
	$1^+ \to 0^+ + \pi^0$	48		$g_A\delta_{\eta\pi0}$	0.0079	
	$1^+ \to 1^- + \gamma$	323	2.638	$r_{\bar{c}s}$	4.66	
	$1^+ \to 0^- + \gamma$	442	2.437	$r_{\bar{c}s}$	5.08	
	$1^+ \to 1^- + \pi^0$	298		$G_A\delta_{\eta\pi0}$	21.5	
	$1^+ \to 0^- + 2\pi$	221		$g_A\delta_{\sigma_1\sigma_3}$	4.2	
	total				38.2	
$(b\bar{s})$	$0^+ \to 1^- + \gamma$	293	2.536	$r_{\bar{b}s}$	58.3	
	$0^+ \to 0^- + \pi^0$	297		$G_A\delta_{\eta\pi0}$	21.5	
	total				79.8	
$(b\bar{s})$	$1^+ \to 0^+ + \gamma$	47	0.998	$r'_{\bar{b}s}$	0.061	
	$1^+ \to 1^- + \gamma$	335	2.483	$r_{\bar{b}s}$	56.9	
	$1^+ \to 0^- + \gamma$	381	2.423	$r_{\bar{b}s}$	39.1	
	$1^+ \to 1^- + \pi^0$	298		$G_A\delta_{\eta\pi0}$	21.5	
	$1^+ \to 0^- + 2\pi$	125		$g_A\delta_{\sigma_1\sigma_3}$	0.12	
	total				117.7	

	Decay Mode	BR (%)
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	$D_s^+\gamma$	93.5 ± 0.7
$D_{s0}^*(2317)$	$D_s^+\pi^0$	seen
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[Phys. Rev. D68:054024,2003]

Excited B_S States

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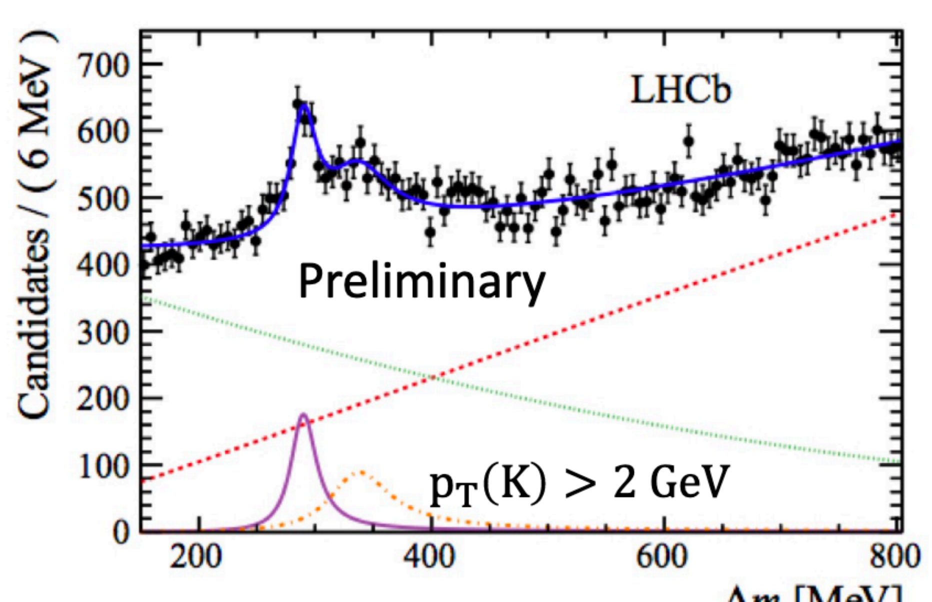
$B_{s1}(2830)$	1^+	B*K
$B^*_{s2}(2840)$	2^+	BK B*K

As for BK , 3 peaks could show up in the $B_s \gamma$ spectrum!

Highly Excited B_S States

- Excess observed in B+K- spectrum, ~300 MeV above threshold
  - Interpreted as two overlapping Bs** states
  - Likely L=2 orbitally excited mesons
  - Significance of two peak structure w.r.t. single peak = 7σ



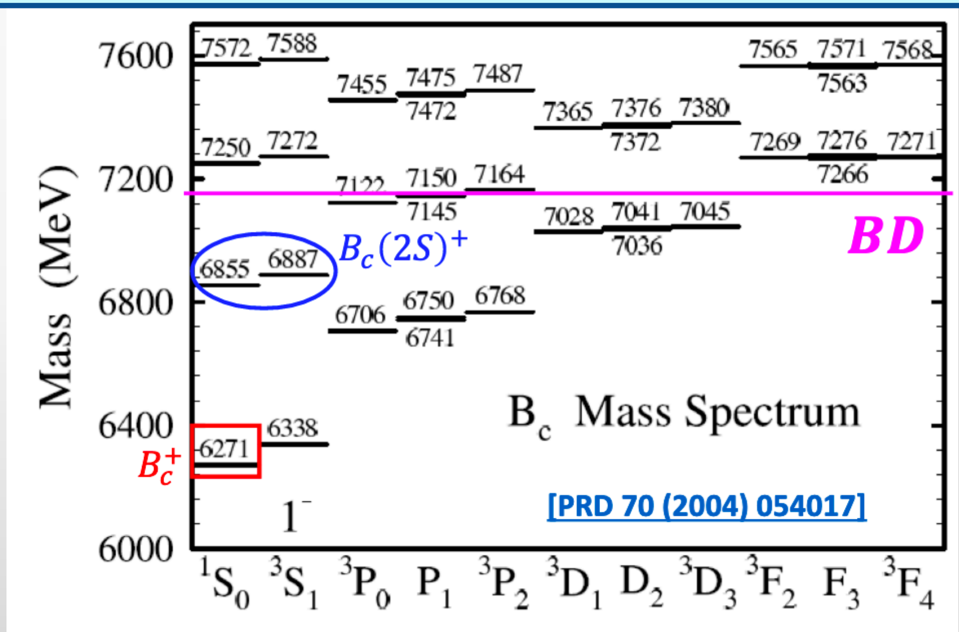
LHCb-PAPER-2020-026 in preparation

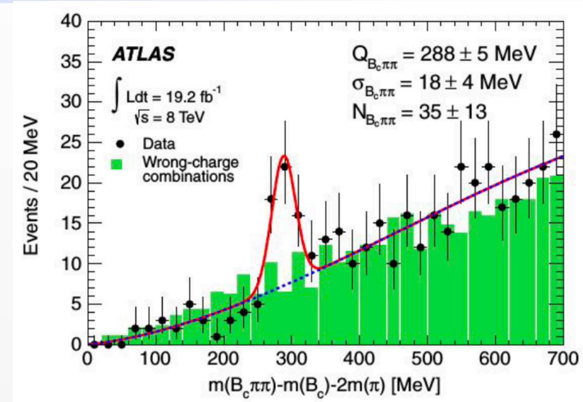
$$m_1 = 6063.5 \pm 1.2 \pm 0.8 \text{ MeV}, \Gamma_1 = 26 \pm 4 \pm 4 \text{ MeV}$$
$$m_2 = 6114 \pm 3 \pm 5 \text{ MeV}, \ \Gamma_2 = 66 \pm 18 \pm 21 \text{ MeV}$$

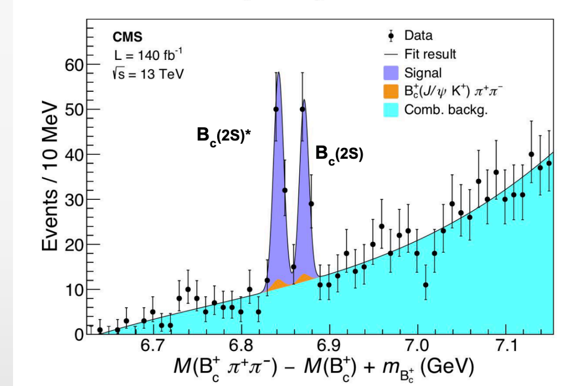
Spectroscopy of the B_C Meson

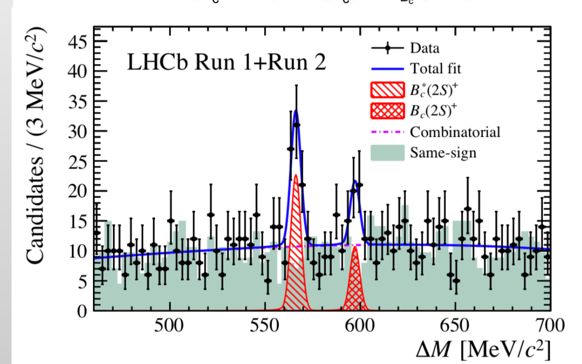
PRL 113, 212004 (2014)
PRL 122, 132001 (2019)
PRL 122, 232001 (2019)
arXiv:2008.08629

- B_c spectrum predicted by various models and Lattice QCD
- States below BD threshold can only undergo radiative or hadronic transitions to the ground state which decays weakly





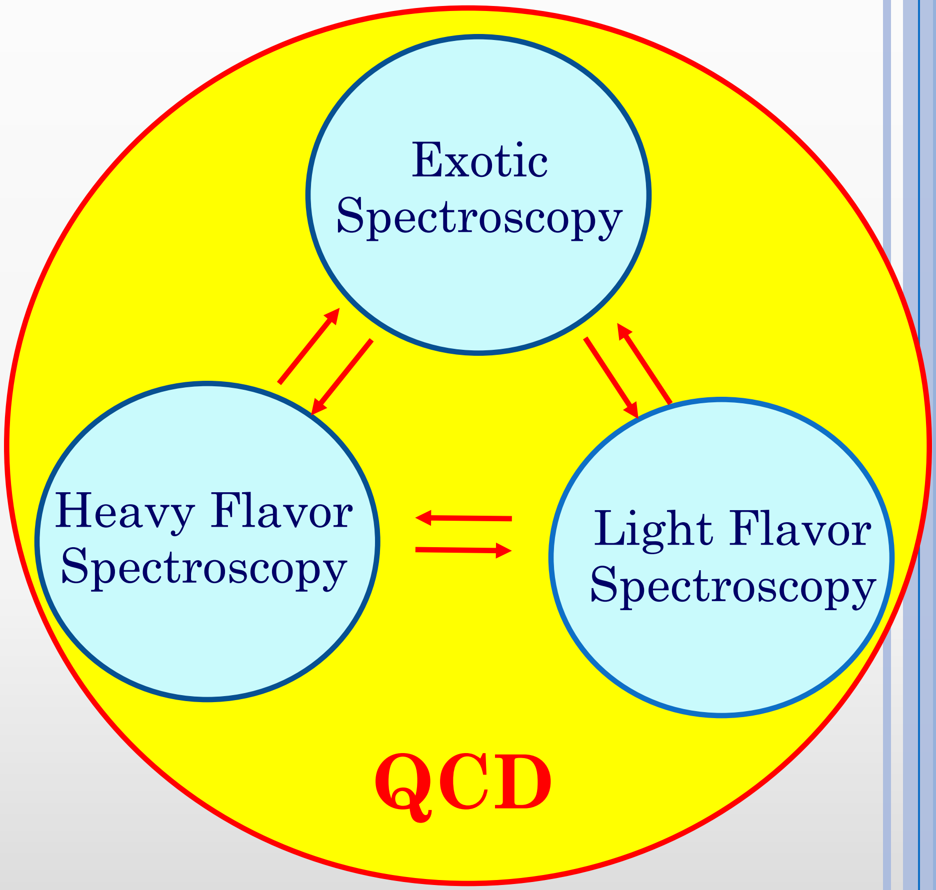




N.B. Dalitz plot analyses such as $B_c^+ \to B^+K^-\pi^+$ can shed new light on excited B_{sJ} states from the B^+K^- threshold to ~ 6135MeV

Summary

- Observations of new states challenge our current understanding of QCD and the validity of the HQET assumptions
- Interplay between light and heavy quark spectroscopy: (e.g.) the poor knowledge of N*, Λ* baryons has a large impact
- Sinergy with the theoretical community to improve models in amplitude analyses



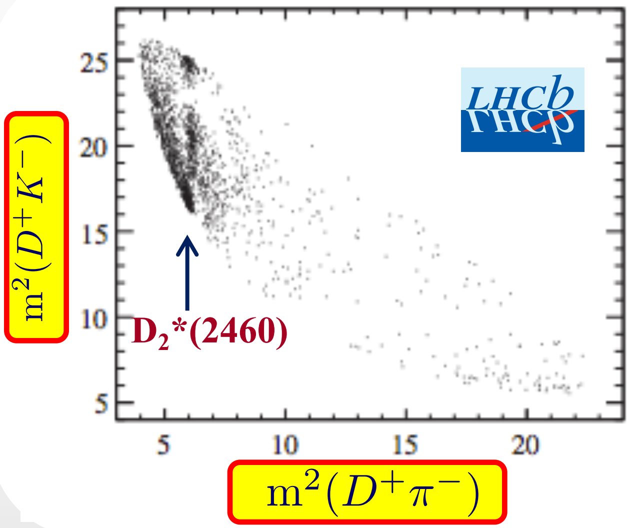
The LHC experiments will go under major upgrade in the next years, while Belle II has started taking data. PANDA, J-PARC, JLab and other hadron facilities will play an important role as well.

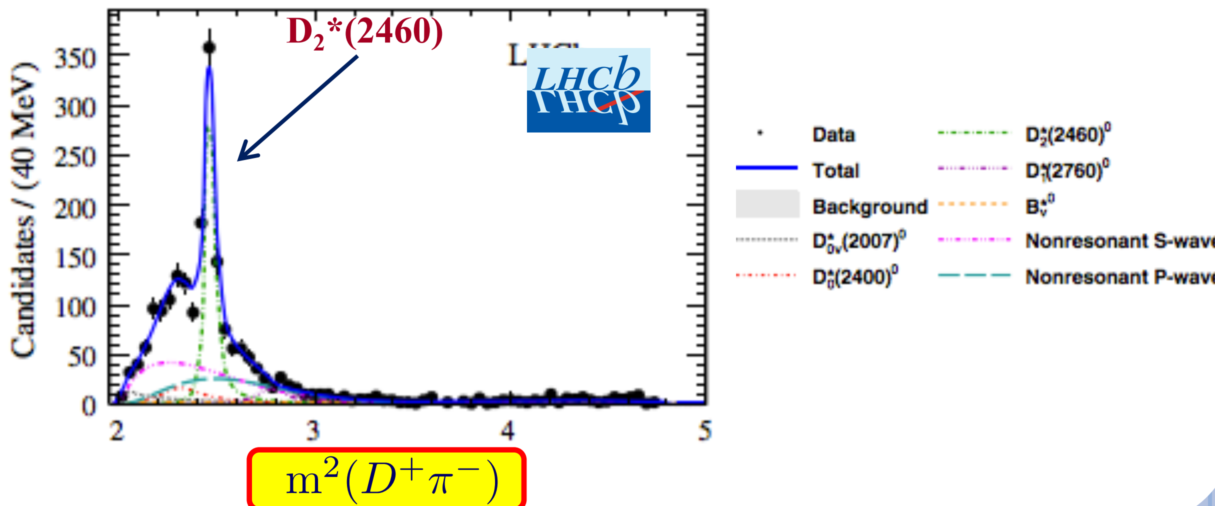
Back-up slides

Spectroscopy of D** in B decays

[LHCb: PRD 91 (2015) 092002]

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





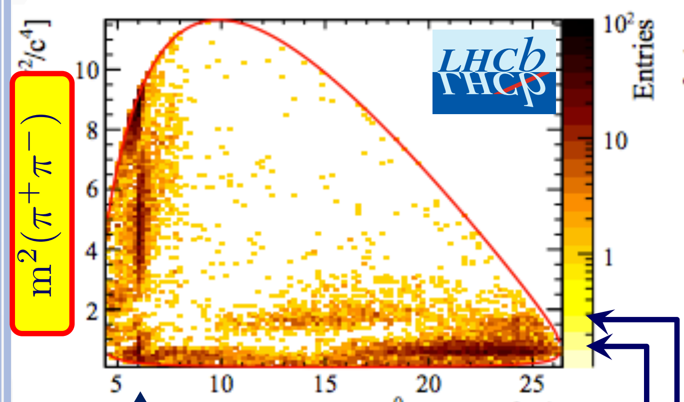
- Large NR component
- Observation of $D_1^*(2760)^0$:
  - Determination of mass and width
  - Determination of spin-parity $J^P=1^-$
    (further supporting the interpretation as $D_1^*(1D)$)

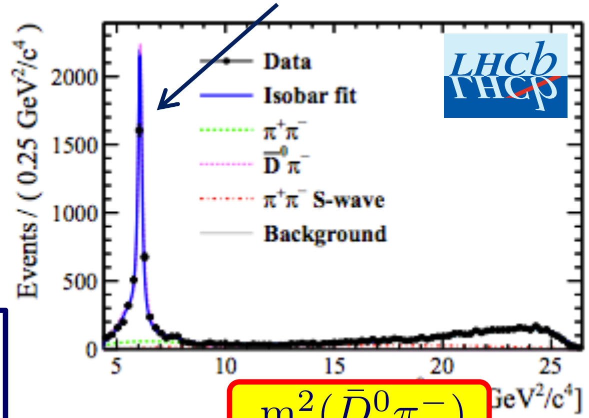
Resonance	Fit fraction
$D_0^*(2400)^0$	$8.3 \pm 2.6 \pm 0.6 \pm 1.9$
$D_2^*(2460)^0$	$31.8 \pm 1.5 \pm 0.9 \pm 1.4$
$D_1^*(2760)^0$	$4.9 \pm 1.2 \pm 0.3 \pm 0.9$
S-wave nonresonant	$38.0 \pm 7.4 \pm 1.5 \pm 10.8$
P-wave nonresonant	$23.8 \pm 5.6 \pm 2.1 \pm 3.7$
$D_v^*(2007)^0$	$7.6 \pm 2.3 \pm 1.3 \pm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

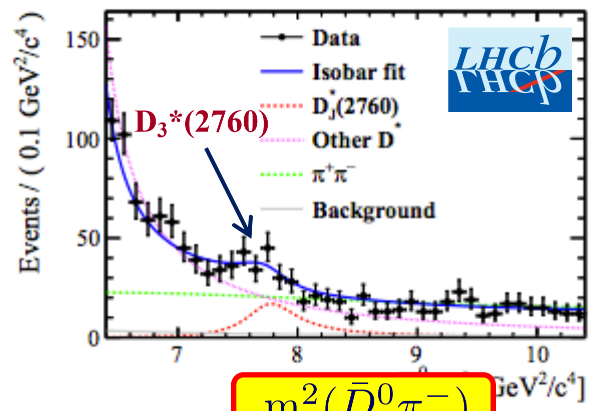
Spectroscopy of D** in B decays (II)

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

[LHCb: PRD 92 (2015) 032002]







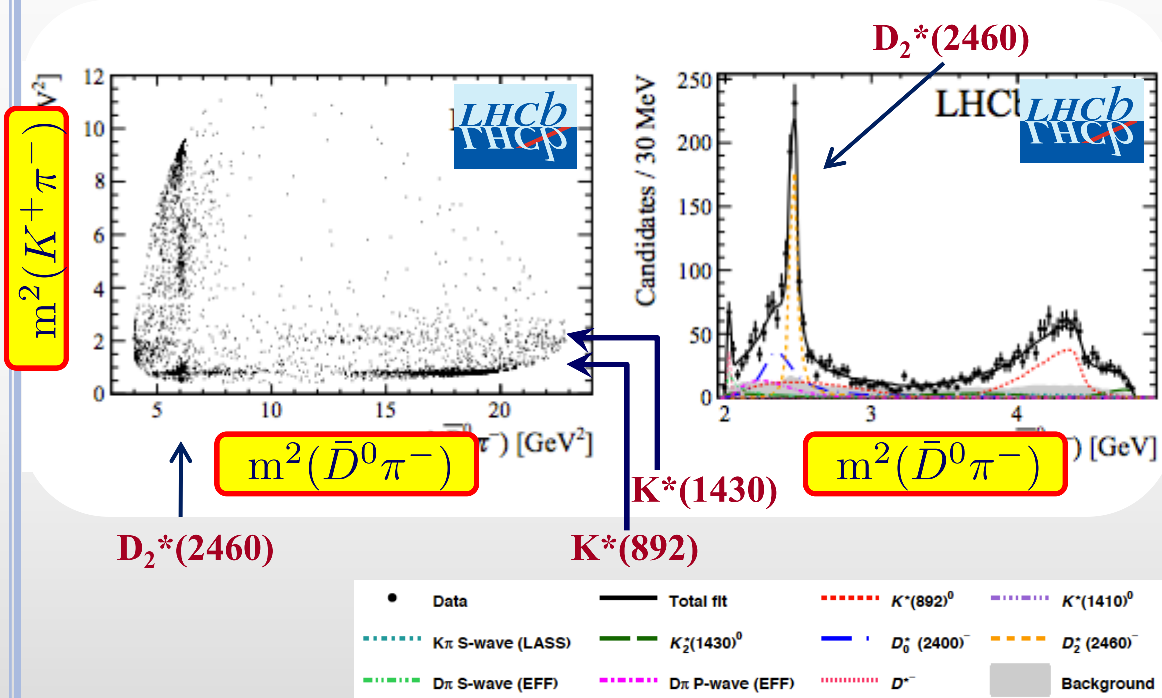
- Two models for $\pi^+\pi^-$: Isobar and K-matrix
- $D_0^*(2400)^-$ spin-parity determined: $J^P=0^+$
- Observation of $D_3^*(2760)^-$:
  - Determination of mass and width
  - Determination of spin-parity $J^P=3^-$ (interpreted as orbitally L=2 excited state *D_3*(1D)*)

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 $B^0 \rightarrow \overline{D}^0 K^+ \pi^-$



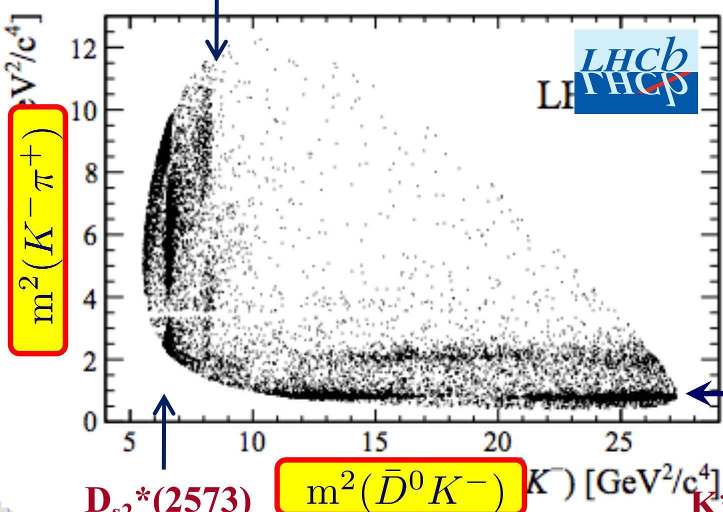
Resonance	Fit fraction	Upper limit
$K^*(892)^0$	$37.4 \pm 1.5 \pm 1.2 \pm 1.7$	
$K^*(1410)^0$	$0.7 \pm 0.3 \pm 0.8 \pm 0.8$	$< 3.2\ (3.7)$
$K_0^*(1430)^0$	$5.1 \pm 2.0 \pm 2.4 \pm 3.4$	
LASS nonresonant	$4.8 \pm 3.8 \pm 3.8 \pm 6.7$	
LASS total	$6.7 \pm 2.7 \pm 2.7 \pm 5.4$	
$K_2^*(1430)^0$	$7.4 \pm 1.7 \pm 1.1 \pm 2.0$	
$D_0^*(2400)^-$	$19.3 \pm 2.8 \pm 2.0 \pm 7.4$	
$D_2^*(2460)^-$	$23.1 \pm 1.2 \pm 1.1 \pm 1.2$	
$D_3^*(2760)^-$		$< 1.0\ (1.1)$
$D\pi$ S-wave (dabba)	$6.6 \pm 1.4 \pm 1.2 \pm 3.7$	
$D\pi$ P-wave (EFF)	$8.9 \pm 1.6 \pm 2.2 \pm 3.0$	

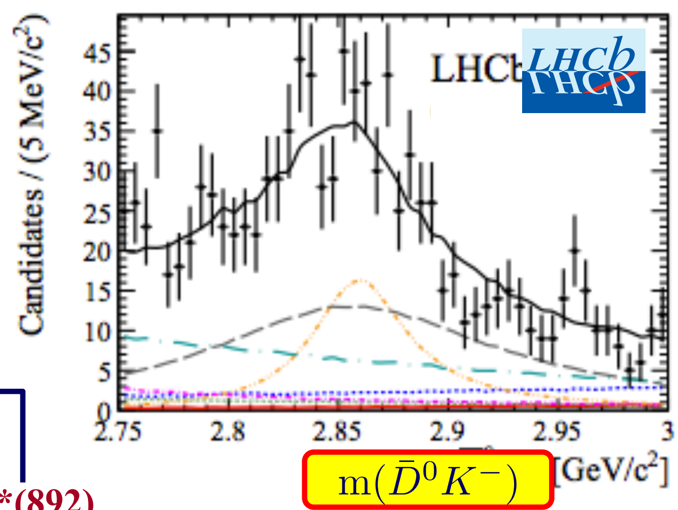
No evidence for $D_3^*(2760)^-$

Excited D_s States in B_s Decays

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

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





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

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

Relevance of the Width

- The width might be sensitive to the model and internal structure

		$\Gamma(D_{s1}(2460)^+ \to D_s^*\pi^0)$ (keV)
$c\bar{s}$	PRD 68 (2003) 054024	21.5
	PRD 69 (2004) 114008	32
	PRD 73 (2006) 034004	$35 - 51$
	PRD 73 (2006) 054012	35
	PLB 568 (2003) 254	$\simeq 10$
	EPJC 47 (2006) 445	$1.86 - 4.42$
	PLB 570 (2003) 180	7 ± 1
	arXiv:1406.5804	9.0 ± 2.1
Molecule	PRD 76 (2007) 014005/8	$50.1 - 79.2$
	EPJA (2014) 50	78 ± 14

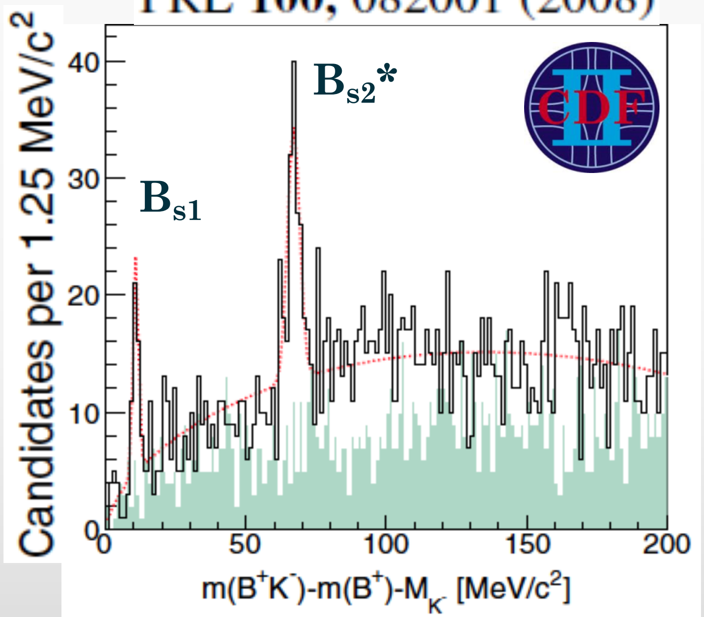
N.B. $\Gamma(D_{s1}(2460)^+ \to D_s^*\pi^0)/\Gamma_{TOT} = (48 \pm 11)\%$

$B_{S1}(5830)^0$ 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 $B_{s1} \to B^{*+}K^-$ decay followed by $B^{*+} \to B^+ \gamma$, where the photon is not observed