OPEN CHARM SPECTROSCOPY

Marco Pappagallo
University of Edinburgh

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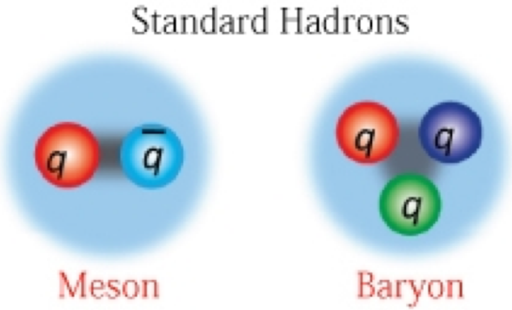
STRUCTURE OF HADRONS

Tetra- and Penta-quarks conceived at the birth of the quark model



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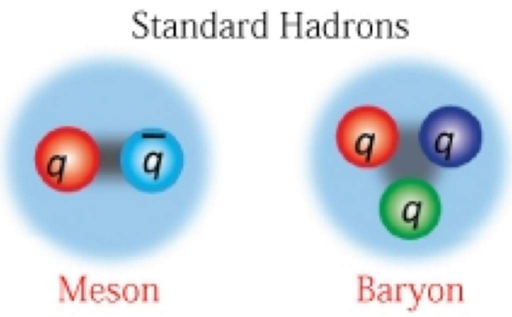
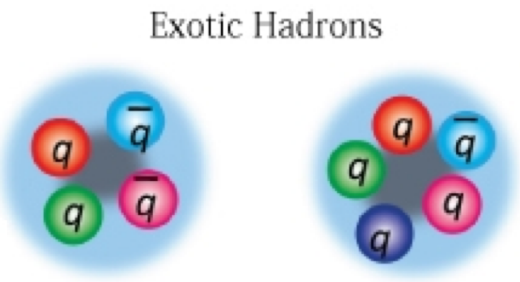
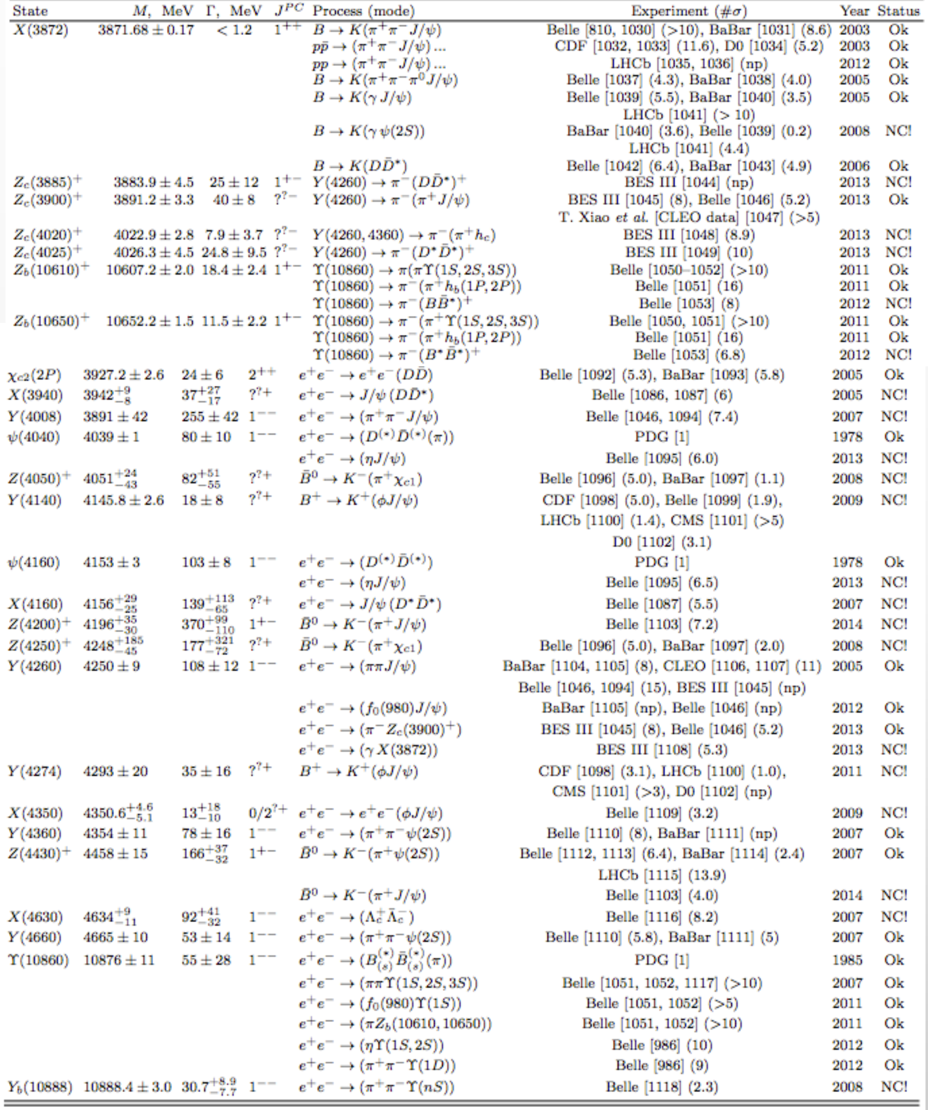

Standard Hadrons


Exotic Hadrons

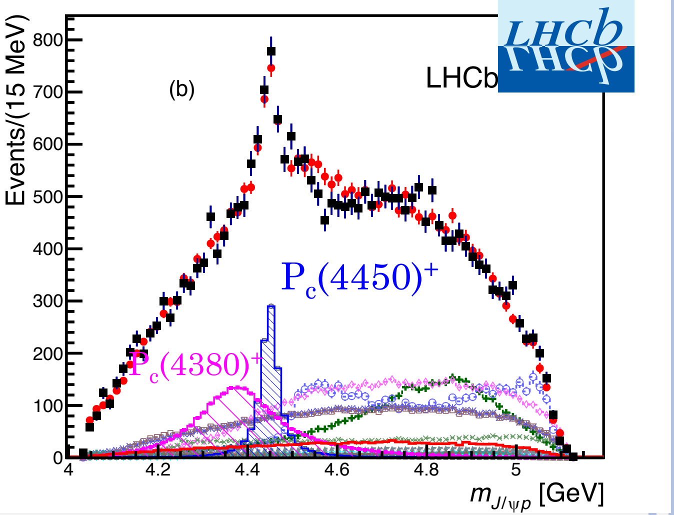
PLETHORA OF EXOTIC CANDIDATES

Eur.Phys.J. C74 (2014) 10, 2981

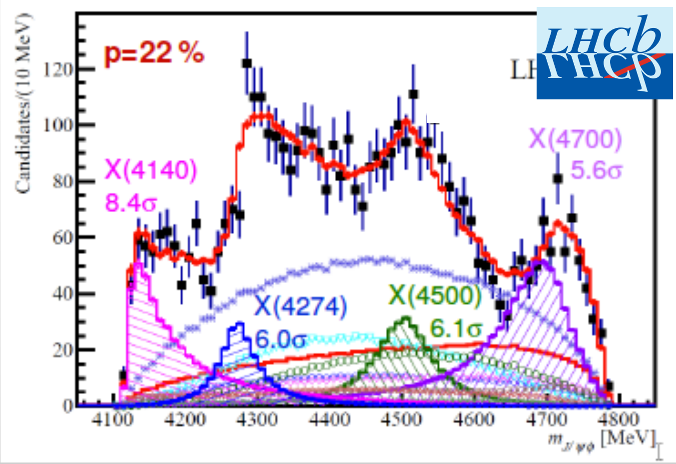


State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5) LHCb [1041] (> 10)	2005	Ok
				$B \to K(\gamma\,\psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2) LHCb [1041] (4.4)	2008	NC!
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2) T. Xiao *et al.* [CLEO data] [1047] (>5)	2013	Ok
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1050–1052] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1053] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1050, 1051] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1053] (6.8)	2012	NC!
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9), LHCb [1100] (1.4), CMS [1101] (>5) D0 [1102] (3.1)	2009	NC!
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11) Belle [1046, 1094] (15), BES III [1045] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma\,X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0), CMS [1101] (>3), D0 [1102] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4) LHCb [1115] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}(\pi))$	PDG [1]	1985	Ok
				$e^+e^- \to (\pi\pi\Upsilon(1S, 2S, 3S))$	Belle [1051, 1052, 1117] (>10)	2007	Ok
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [1051, 1052] (>5)	2011	Ok
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [1051, 1052] (>10)	2011	Ok
				$e^+e^- \to (\eta\Upsilon(1S, 2S))$	Belle [986] (10)	2012	Ok
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [986] (9)	2012	Ok
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [1118] (2.3)	2008	NC!

[PRL 115 (2015) 072001]



[PRL 118 (2017) 022003, PRD 95 (2017) 012002]



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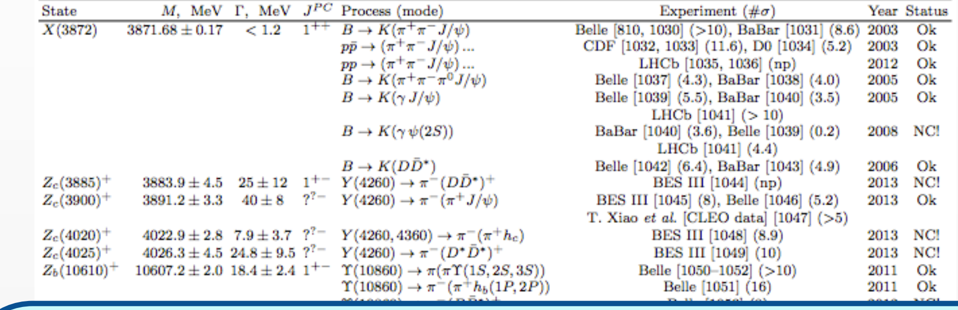

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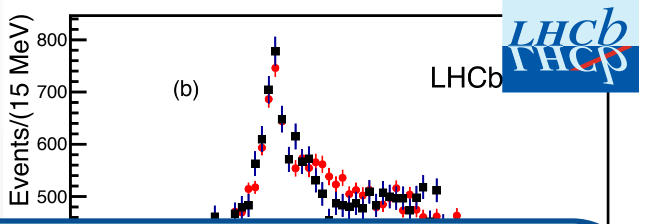
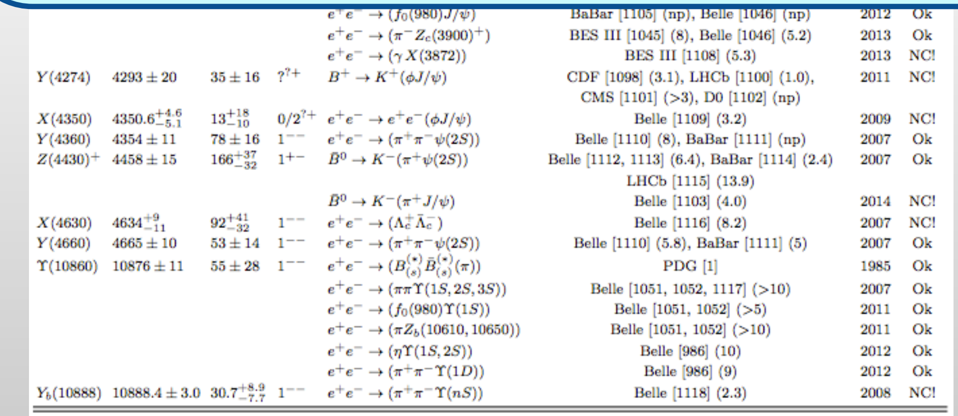


- All of them are charmonium/bottomonium-like states
- What about exotic candidates with a single *c* or *b* quark?
  - X(5568)$^\pm$ → $B_s^0\,\pi^\pm$ claimed by D0 but disproved by LHCb, CMS, ATLAS and CDF
  - $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ ← Today



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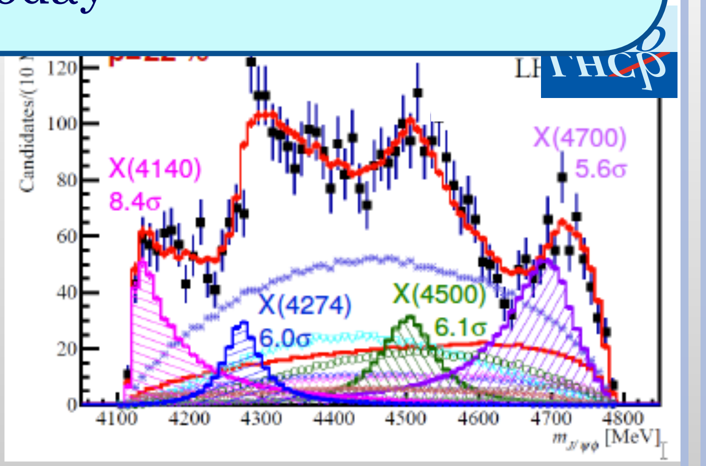


SPECTROSCOPY AND QCD

Standard Model

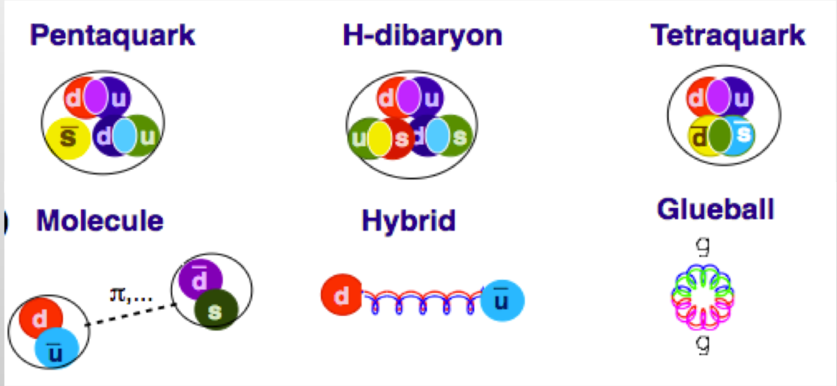
Colored quarks and gluons

Long-distance effects

Nature

Color-singlet mesons and baryons

- ➢ Long-distance regime of QCD is the least understood aspect of QCD
- ➢ Many models predict states beyond the standard $q\bar{q}$ and qqq



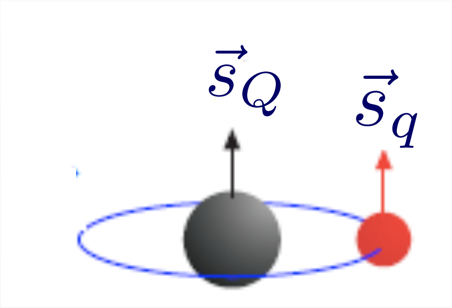
HEAVY QUARK EFFECTIVE THEORIES

The heavy quark effective theories (HQET) predict the masses of the heavy mesons $D_{(s)}$ and $B_{(s)}$ by a perturbative expansion of $\Lambda_{QCD}/m_Q \sim 0$

$$\mathrm{L}_{\mathrm{eff},1/\mathrm{m}} = \underbrace{\bar{h}_v \, iv\cdot D \, h_v}_{\text{HQET lagrangian}} + \underbrace{\frac{1}{2m_Q}\bar{h}_v \, (i \not{D}_\perp)^2 h_v}_{\text{Residual heavy quark kinetic energy}} + \underbrace{\frac{g}{4m_Q}\bar{h}_v \, \sigma_{\alpha\beta} \mathrm{G}^{\alpha\beta} h_v}_{\text{Chromagnetic operator}} + O\left(\frac{1}{m_Q^2}\right)$$

Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET

HEAVY MESONS IN HQET



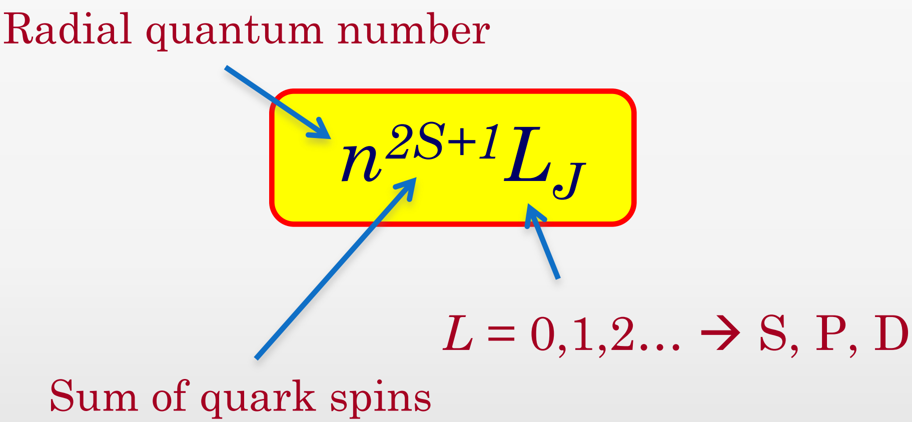
$\vec{L}$	Orbital angular momentum
$\vec{j}_q = \vec{L} + \vec{s}_{q=u,d,s}$	Angular momentum of the light quark
$\vec{J} = \vec{j}_q + \vec{s}_{Q=b,c}$	Total angular momentum of the heavy meson

The light quark quantum number (j_q) decouples and it is independent of the spin of heavy quark (s_Q)

Heavy Mesons		Atoms
Color magnetism vanishes No dependence on the mass (i.e. flavor)	⟺	Spin-orbit vanishes since $m_e/m_N \rightarrow 0$ Isopotes have same chemical properties

NAMING CONVENTION

Spectroscopy notation



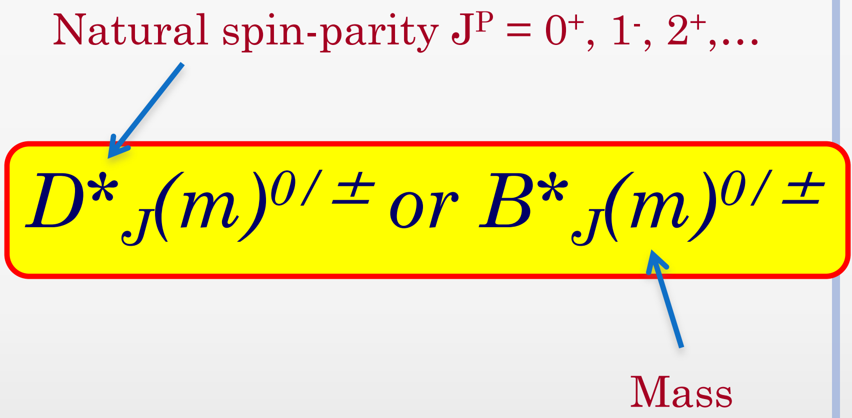
Radial quantum number

$n^{2S+1}L_J$

L = 0,1,2… → S, P, D

Sum of quark spins

PDG notation



Natural spin-parity $J^P = 0^+, 1^-, 2^+, \ldots$

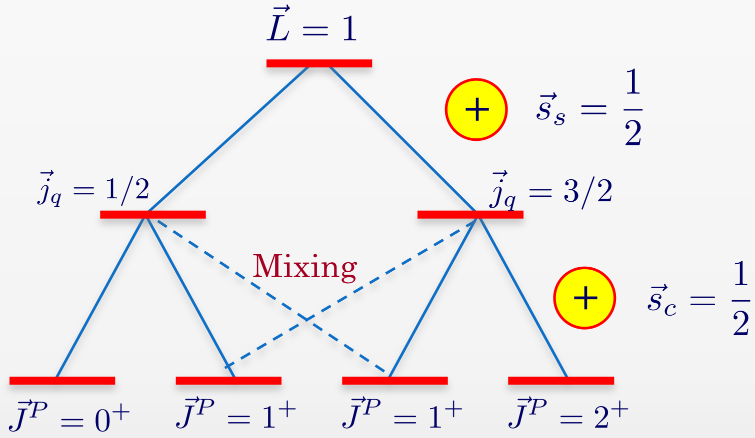
$D^*_J(m)^{0/\pm}$ or $B^*_J(m)^{0/\pm}$

Mass

L=1 EXCITED CHARMED MESONS IN HQET

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

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



D_{s0}^* **D'_{s1}** **D_{s1}** **D_{s2}^***

Two Broad States decaying in S-wave (Γ~100 MeV)

$\underbrace{\qquad\qquad}$

j_q = 1/2 doublet

Two Narrow States decaying in D-wave (Γ~ 1÷10 MeV)

$\underbrace{\qquad\qquad}$

j_q = 3/2 doublet

	j_q	J^P	Allowed decay mode DK	Allowed decay mode 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 4 states come in doublets. Within each doublet:

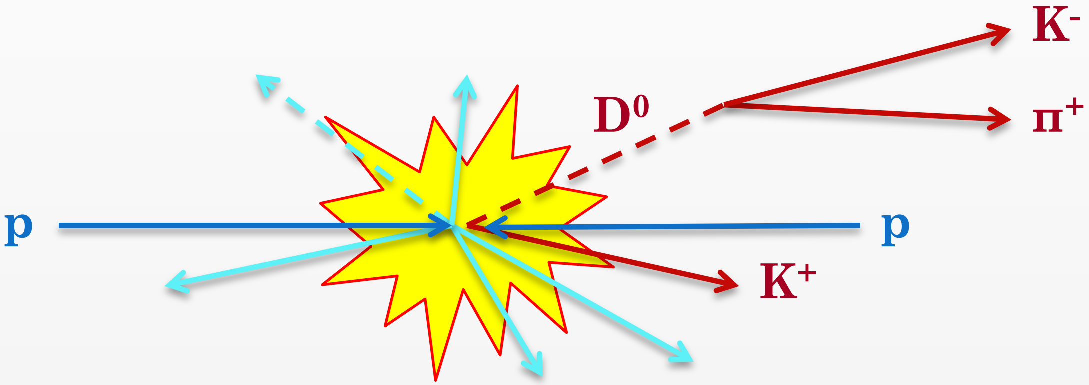
- ✓ 1 natural state (D_{s2}^*) decaying to DK and D*K
- ✓ 1 unnatural state (D_{s1}) decaying to D*K

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

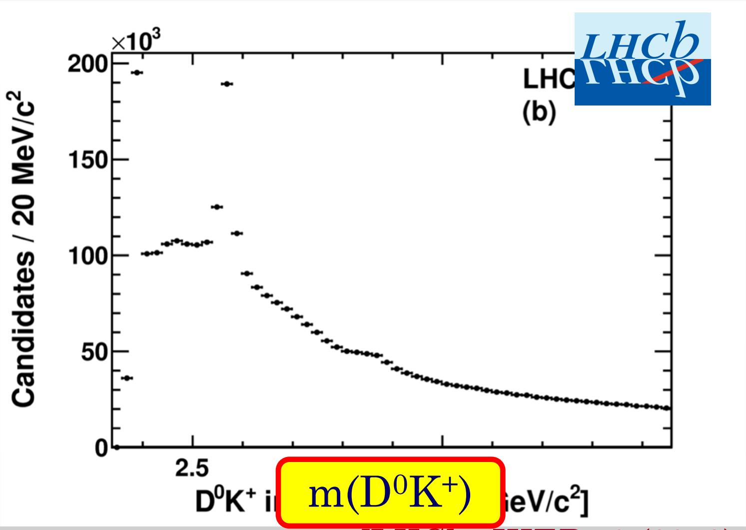
SPECTROSCOPY TECHNIQUE

“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
- Presence of “reflections”/“feed-downs”



[LHCb: JHEP 10 (2012) 151]

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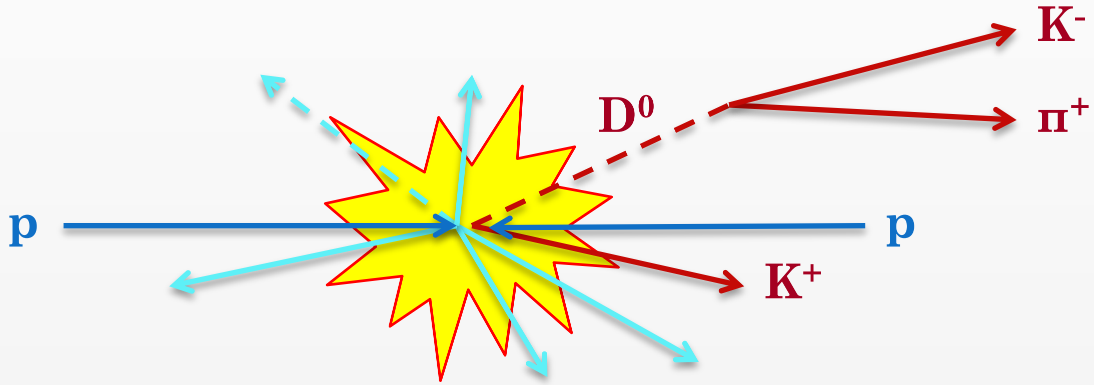

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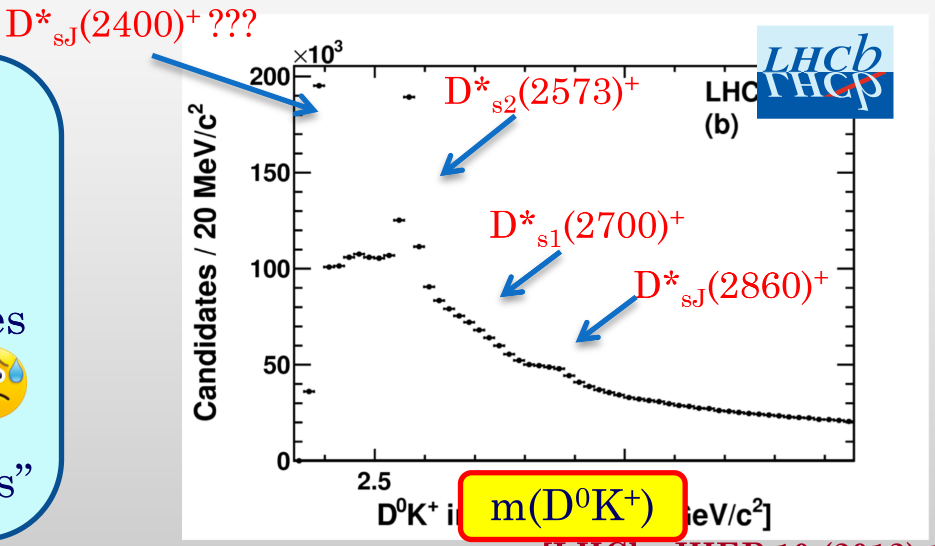

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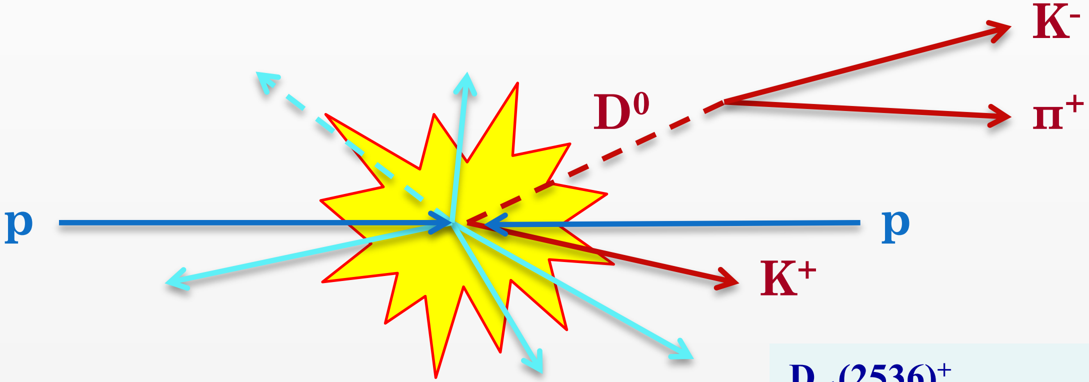
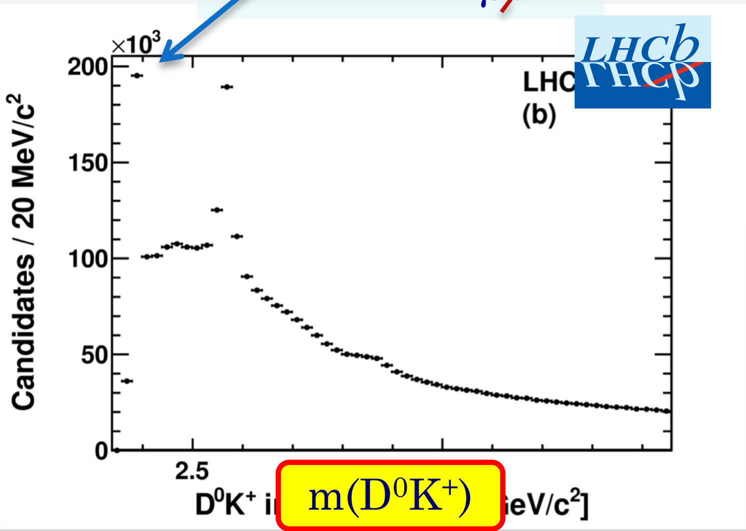
“Inclusive Analysis”

(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
- Presence of “reflections”/“feed-downs”

$D_{s1}(2536)^+$
↳ $D^{*0}\ K^+$
↳ $D^0\ \gamma/\cancel{\pi^0}$

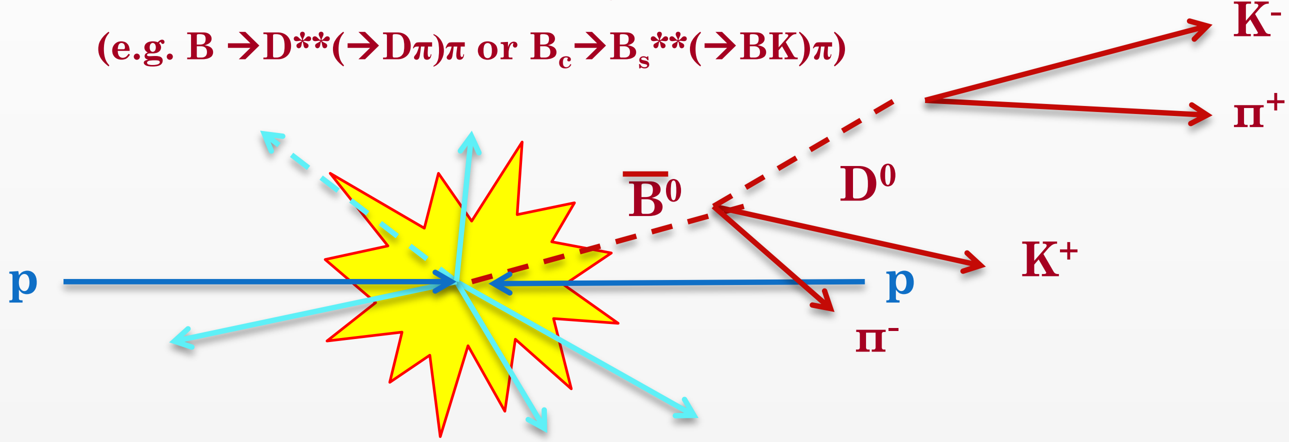


[LHCb: JHEP 10 (2012) 151]

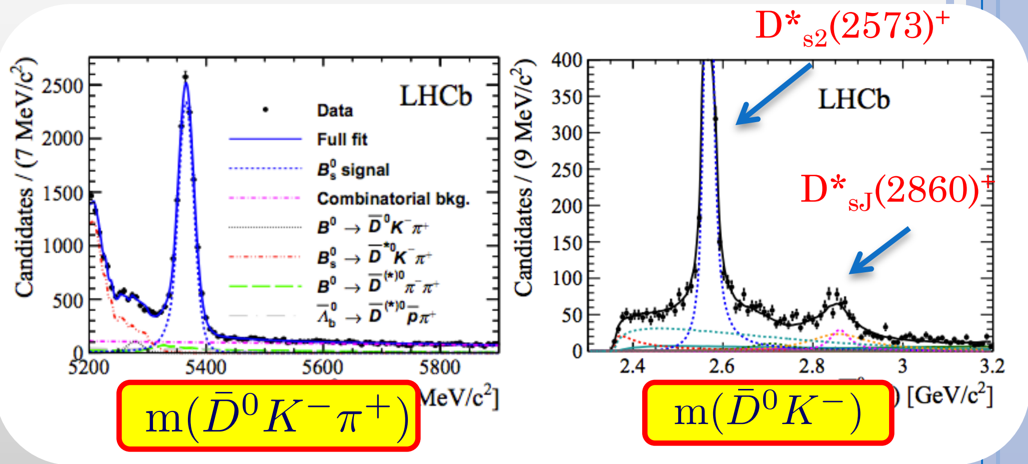
SPECTROSCOPY TECHNIQUE (II)

"Exclusive Analyses"

(e.g. B →D(→Dπ)π or B_c→B_s**(→BK)π)**

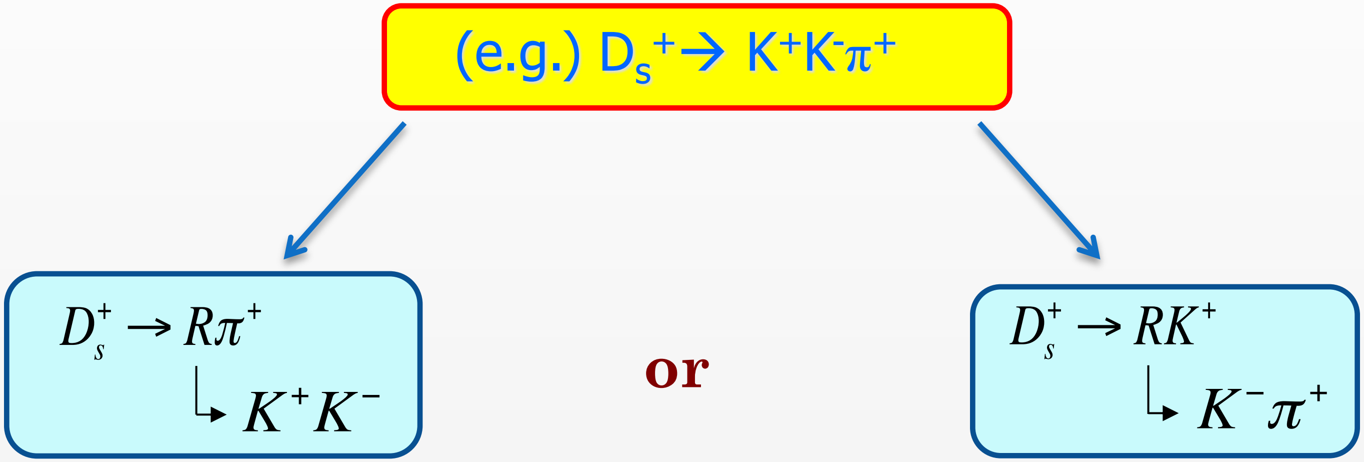


- ➢ Limited statistics
- ➢ Small background
- ➢ Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference)
- ➢ Suitable to study broad resonances
- ➢ Spin-parity assignment by amplitude analysis



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

KINEMATICAL REFLECTIONS/SHADOWS



(e.g.) $D_s^+ \to K^+K^-\pi^+$

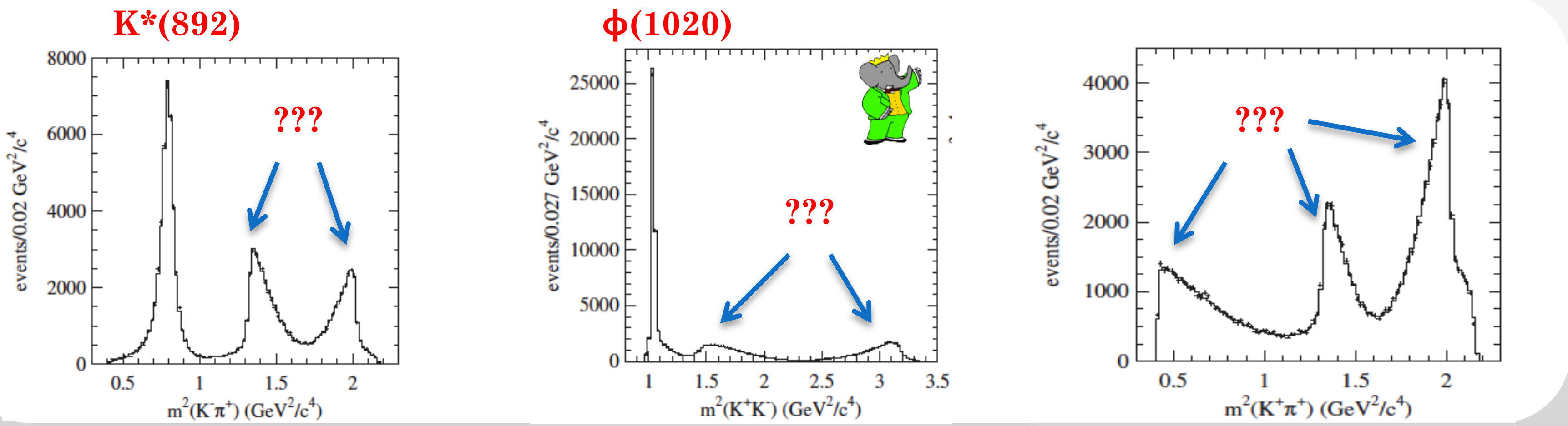
$D_s^+ \to R\pi^+$

$\hookrightarrow K^+K^-$

or

$D_s^+ \to RK^+$

$\hookrightarrow K^-\pi^+$

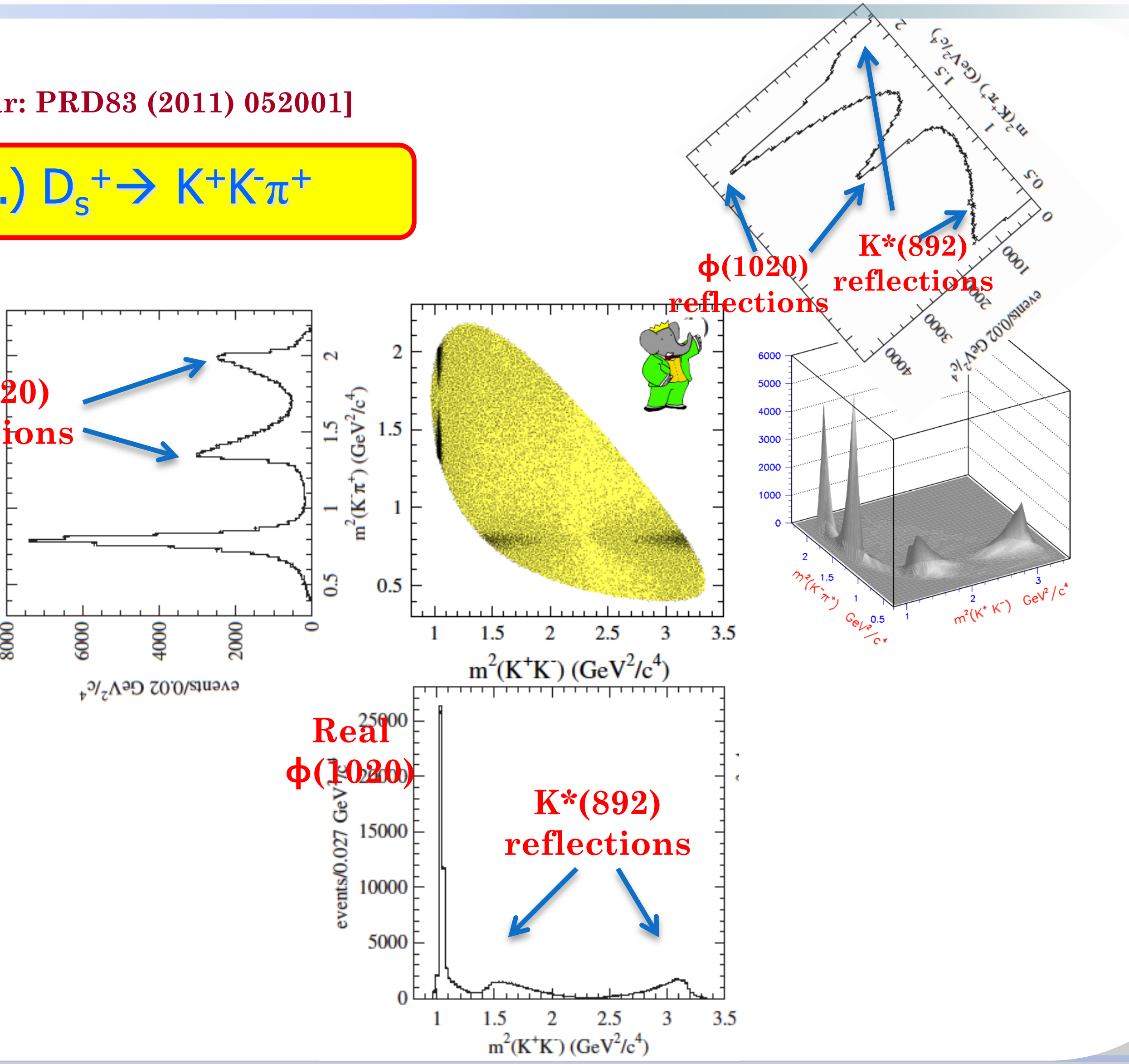


[BaBar: PRD83 (2011) 052001]

KINEMATICAL REFLECTIONS/SHADOWS

[BaBar: PRD83 (2011) 052001]

(e.g.) $D_s^+ \rightarrow K^+K^-\pi^+$



ϕ(1020) reflections

Real K*(892)

ϕ(1020) reflections

K*(892) reflections

Real ϕ(1020)

K*(892) reflections

THE EXCITED *D* STATES

Inclusive analysis

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

[LHCb: JHEP 09 (2013) 145]

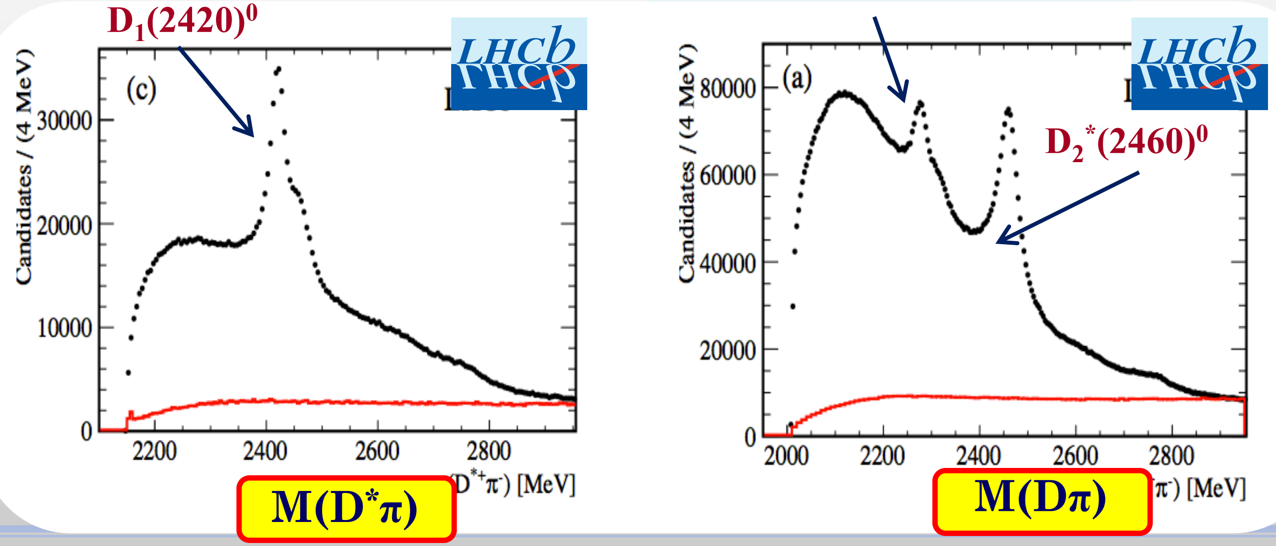
	j_q	J^P	Allowed decay mode $D\pi$	$D^*\pi$
D_0^*	1/2	0^+	yes	no
D_1'	1/2	1^+	no	yes
D_1	3/2	1^+	no	yes
D_2^*	3/2	2^+	yes	yes

j_q=3/2 doublet

- 3 peaks in Dπ
  - ✓ $D_2^* \rightarrow D\pi$
  - ✓ $D_1 \rightarrow D^*\pi$ feed-down
  - ✓ $D_2^* \rightarrow D^*\pi$ feed-down
- 2 peaks in D*π

overlapped if Γ > m(D*)-m(D)

$D_1(2420)^0$ / $D_2^*(2460)^0$ feed-down
↳ $D^{*+} \pi^-$
↳ $D^+ \gamma/\cancel{\pi^0}$



M(D*π)

M(Dπ)

THE EXCITED *D* STATES

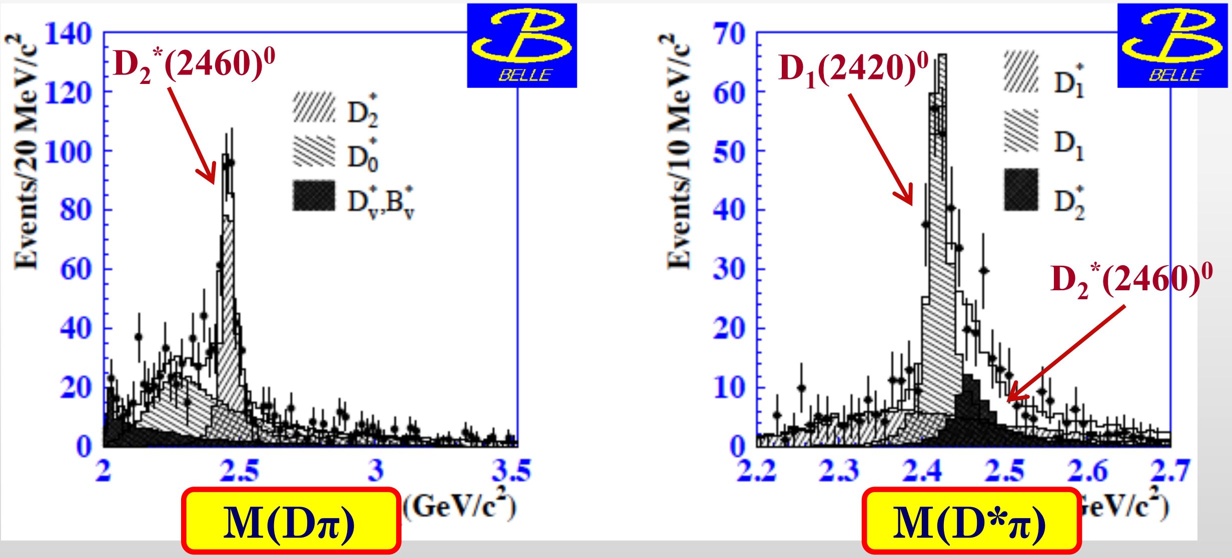
Exclusive analysis
$B^- \rightarrow D^{(*)+} \pi^- \pi^-$
[Belle: Phys.Rev.D69 (2004) 112002]

j_q=3/2 doublet

- 1 peak in Dπ
- 2 peaks in D*π

} as expected

	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



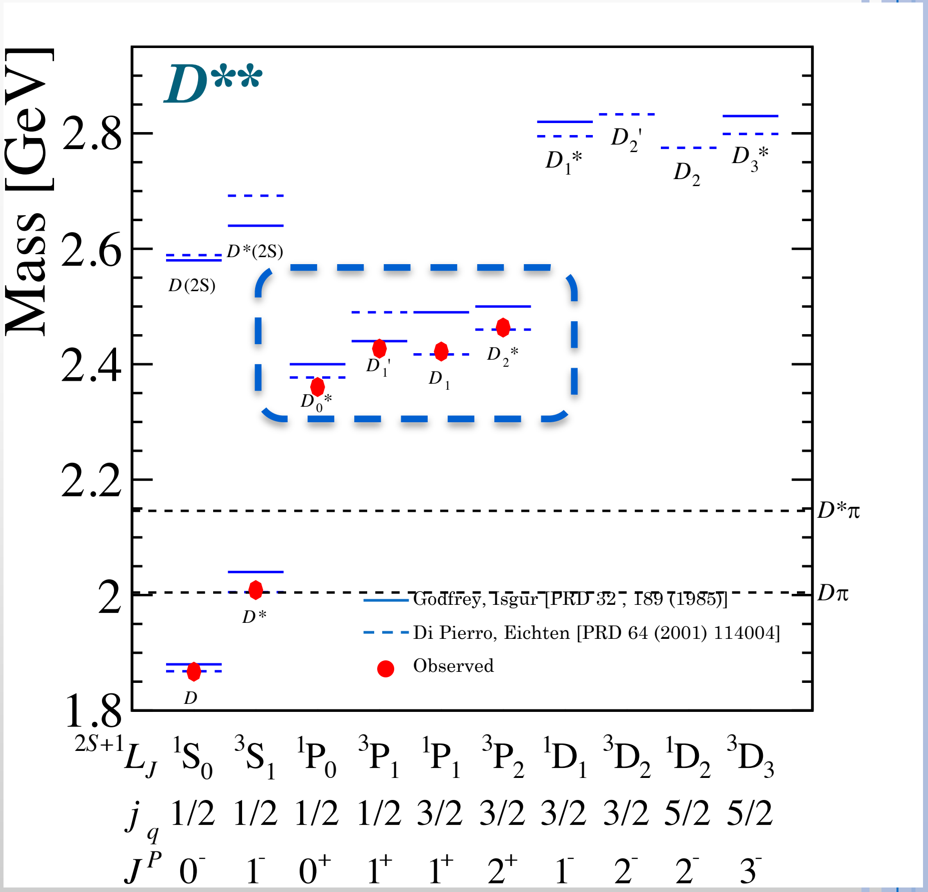
Broad states of the j=1/2 doublets also resolved by an amplitude analysis

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



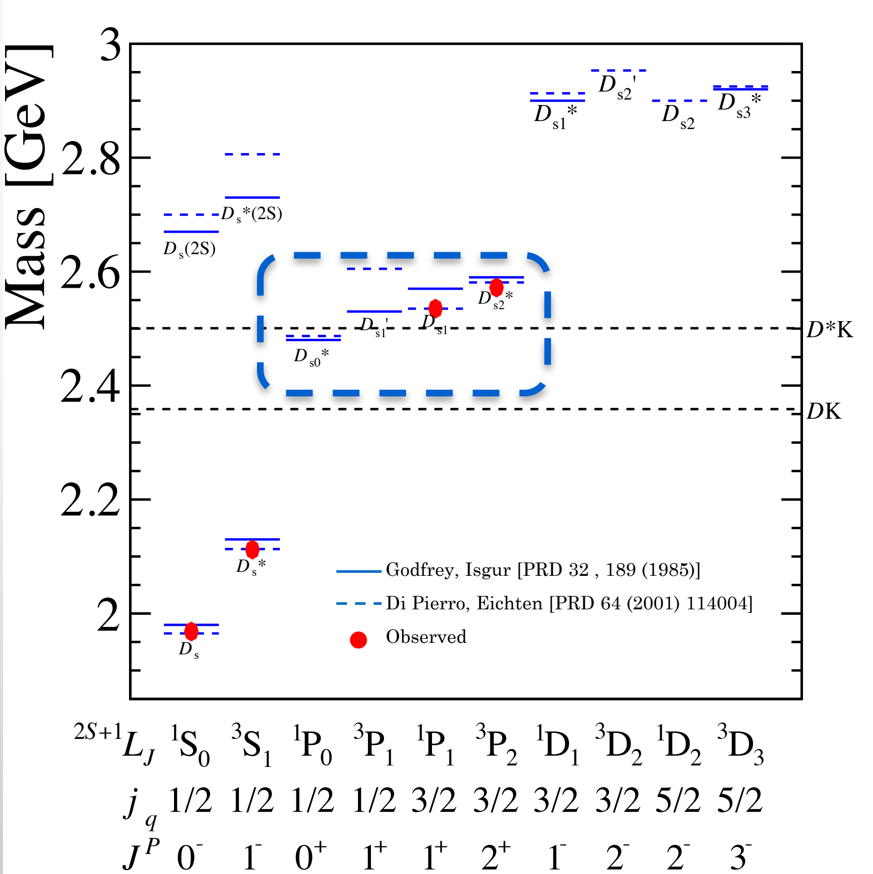
THE EXCITED D_S STATES

- 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)

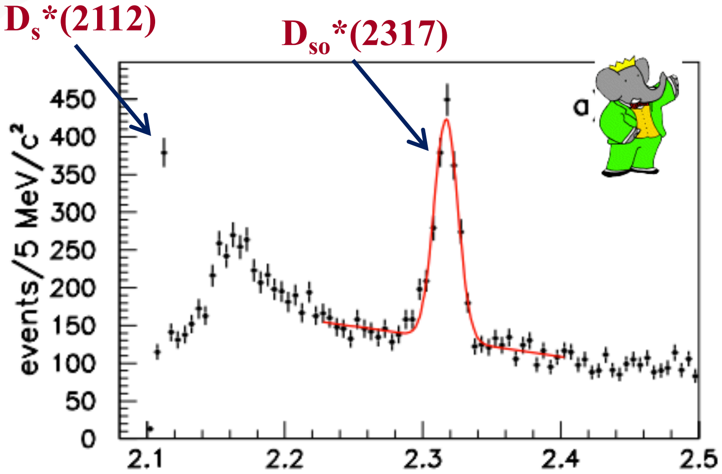
	Mass (MeV)	Width (MeV)
D^*_{s0}	—	—
D'_{s1}	—	—
$D_{s1}(2536)^\pm$	2535.10 ± 0.08	0.92 ± 0.05
$D^*_{s2}(2573)^\pm$	2571.9 ± 0.8	17 ± 4

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(?)

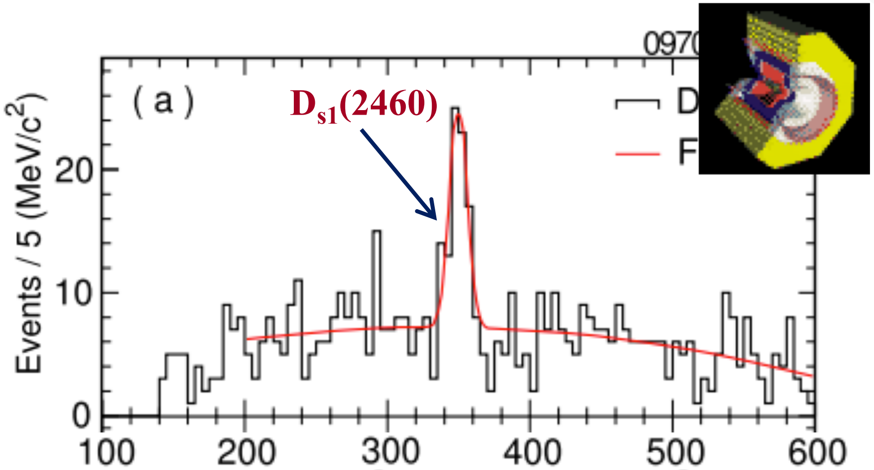
Inclusive studies of $D_s^{(*)}\pi^0$
[BaBar, PRL90, 242001][CLEO, PRD68, 032002]



D_s*(2112)

D_{so}*(2317)

$M(D_s\pi^0)$



D_{s1}(2460)

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

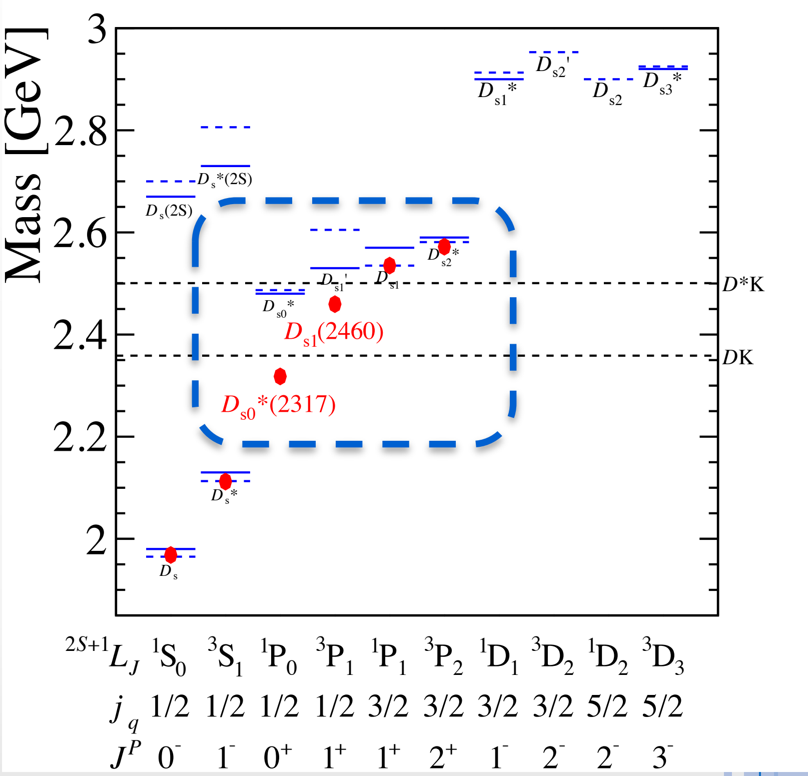
PDG	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^\pm$	2317.7 ± 0.6	< 3.8
$D_{s1}(2460)^\pm$	2459.5 ± 0.6	< 3.5

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 π 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)]**

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

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

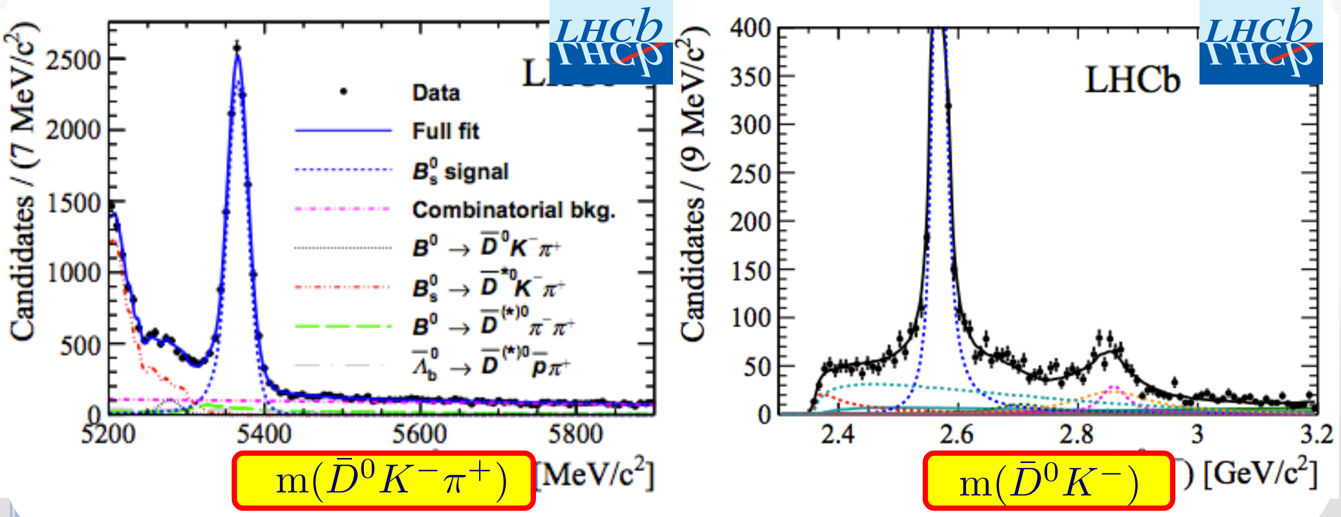
No $D_s^+\pi^\pm$ partners have been observed in inclusive studies **[BaBar: PRD74 (2006) 032007]** or in B decays **[Belle: PRD 91 (2015) 092011]** (upper limits more than an order of magnitude lower)

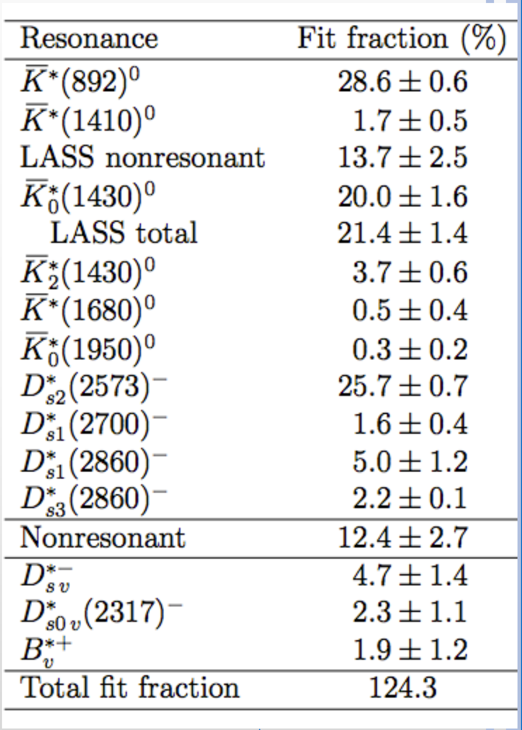
Search For "D_{s0}*" in B_s Decays

[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

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





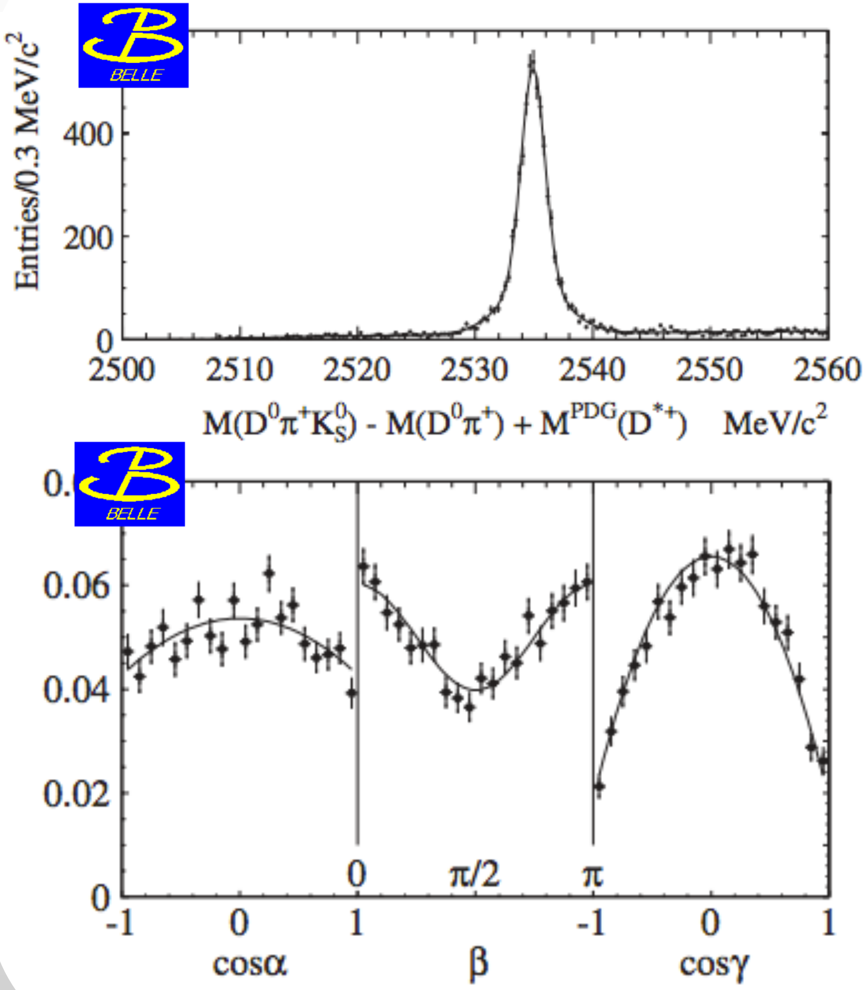
Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	1.6 ± 0.4
$D_{s1}^*(2860)^-$	5.0 ± 1.2
$D_{s3}^*(2860)^-$	2.2 ± 0.1
Nonresonant	12.4 ± 2.7
$D_{s\,v}^{*-}$	4.7 ± 1.4
$D_{s0\,v}^*(2317)^-$	2.3 ± 1.1
B_v^{*+}	1.9 ± 1.2
Total fit fraction	124.3

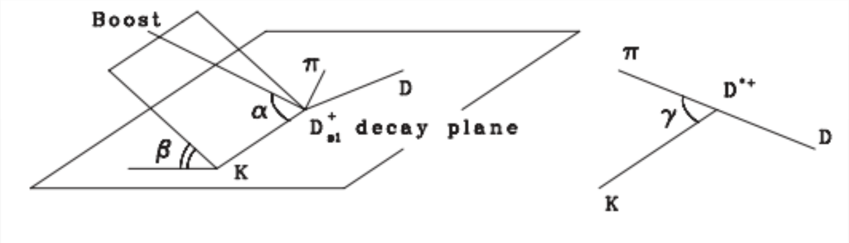
No evidence for such a broad D_{s0}^* state

PUZZLE II:
IS $D_{S1}(2536)^+$ THE EXCITED L=1, j_q=3/2 STATE?

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

[Belle: PRD77 (2008) 032001]



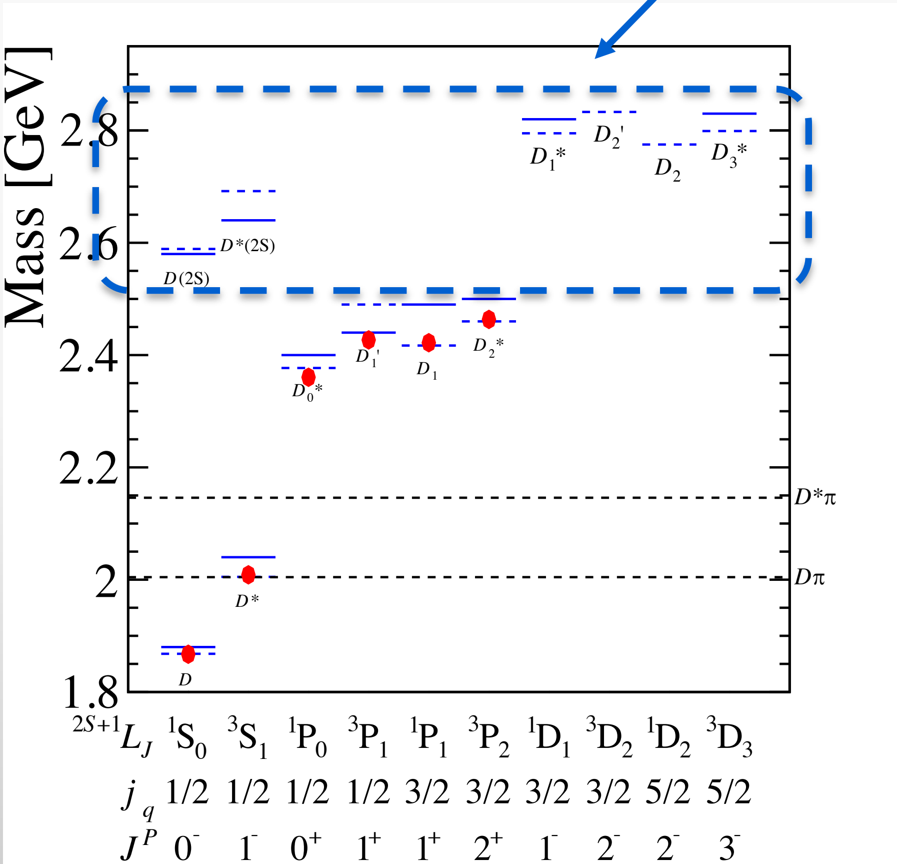


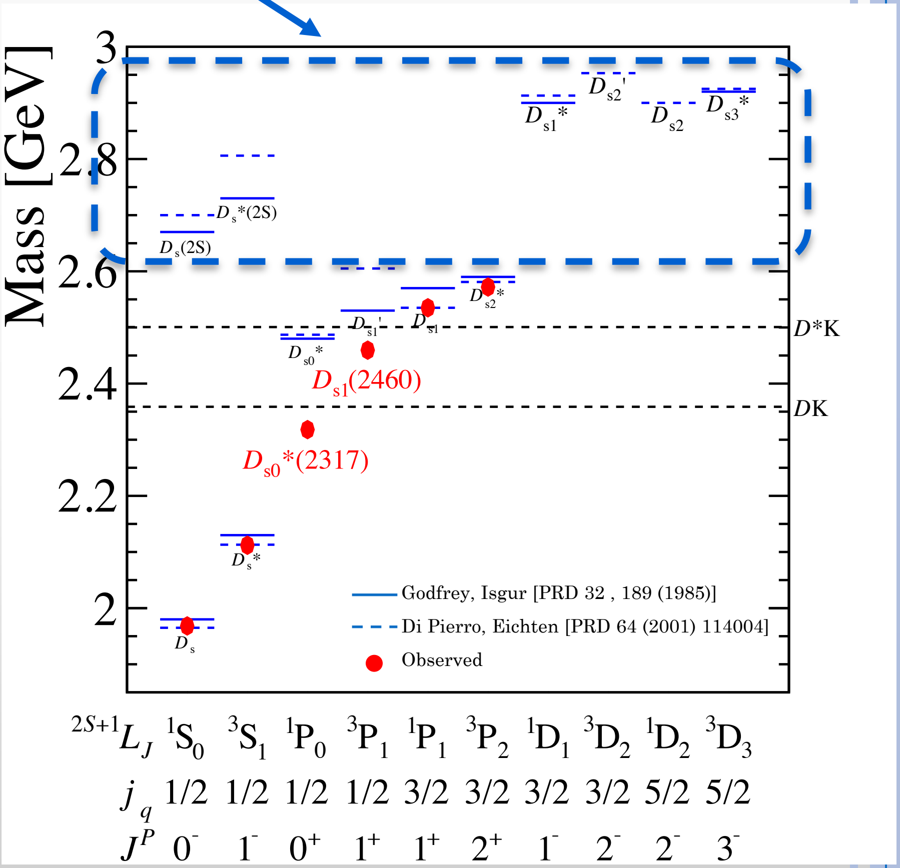
$$\frac{\Gamma_S}{\Gamma_{total}} = 0.72 \pm 0.05 \pm 0.01$$

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

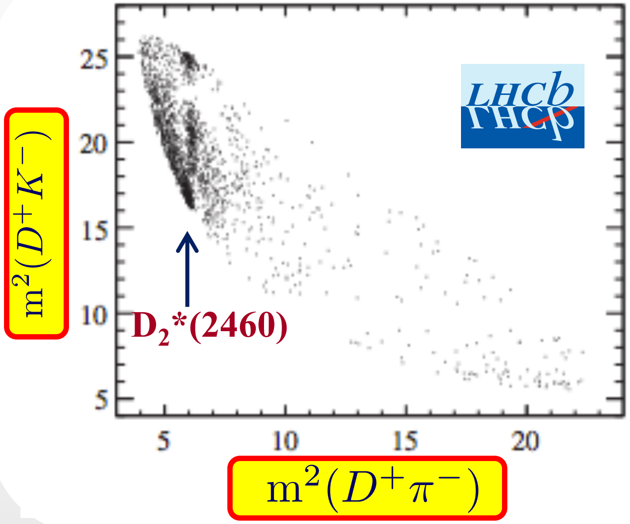


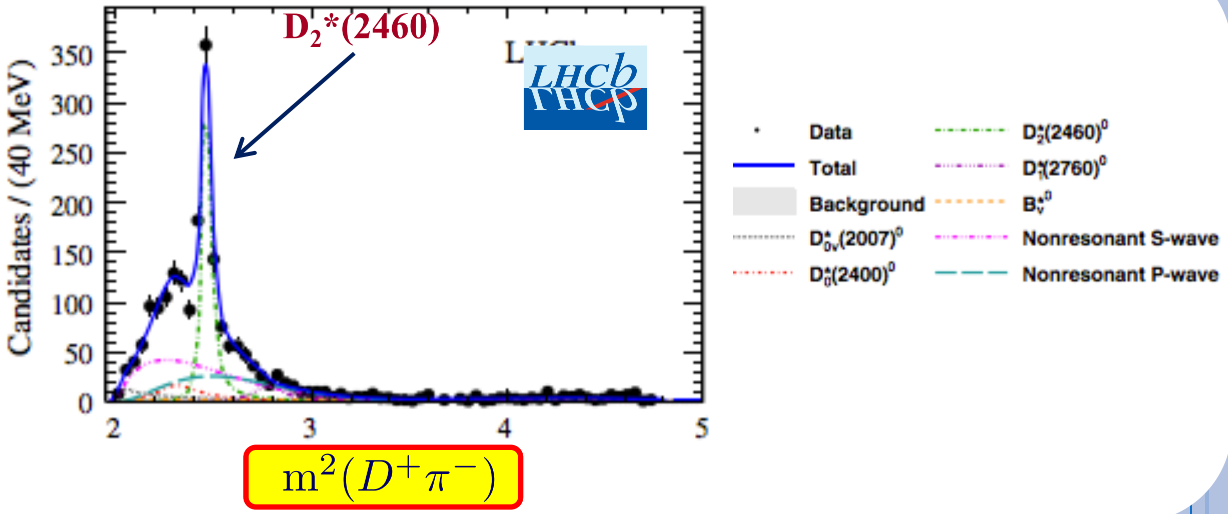


SPECTROSCOPY OF D** IN B DECAYS

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

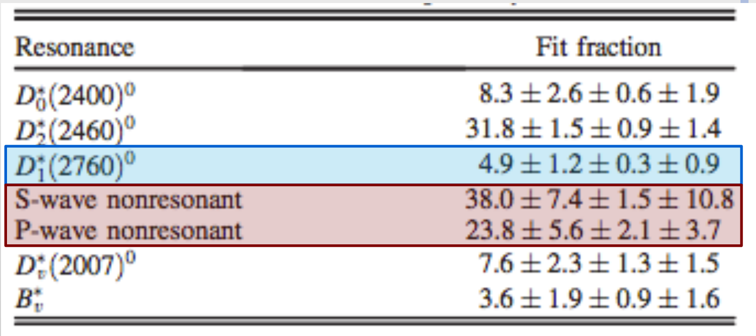
[LHCb: PRD 91 (2015) 092002]





- 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 $D_1^*(1D)$)

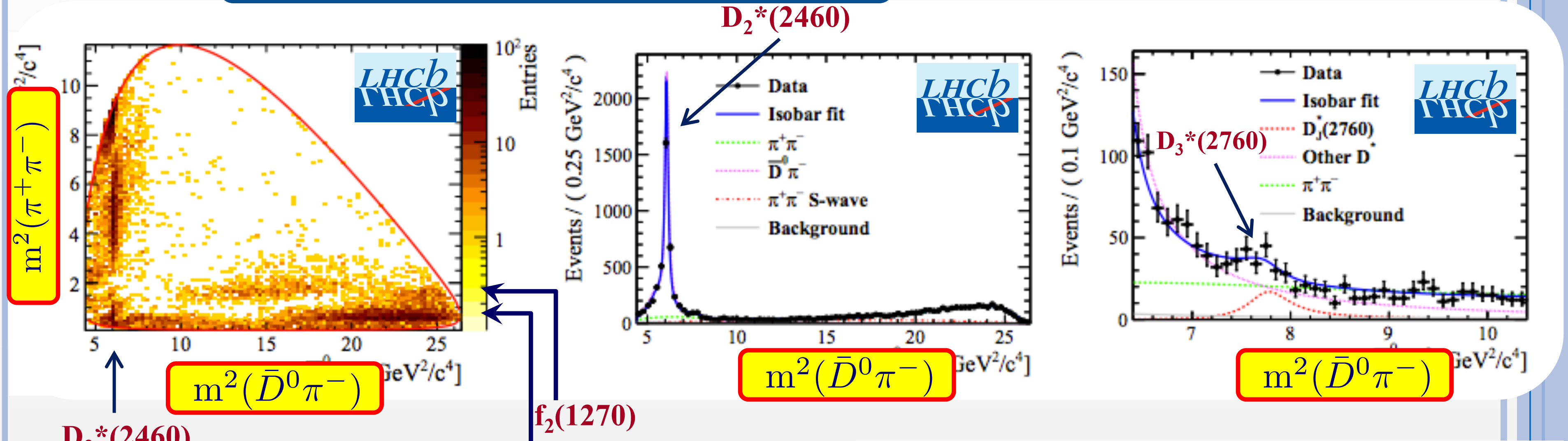


Resonance	Fit fraction
$D^*_0(2400)^0$	$8.3 \pm 2.6 \pm 0.6 \pm 1.9$
$D^*_2(2460)^0$	$31.8 \pm 1.5 \pm 0.9 \pm 1.4$
$D^*_1(2760)^0$	$4.9 \pm 1.2 \pm 0.3 \pm 0.9$
S-wave nonresonant	$38.0 \pm 7.4 \pm 1.5 \pm 10.8$
P-wave nonresonant	$23.8 \pm 5.6 \pm 2.1 \pm 3.7$
$D^*_v(2007)^0$	$7.6 \pm 2.3 \pm 1.3 \pm 1.5$
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]



$D_2^*(2460)$

$\rho(770)$

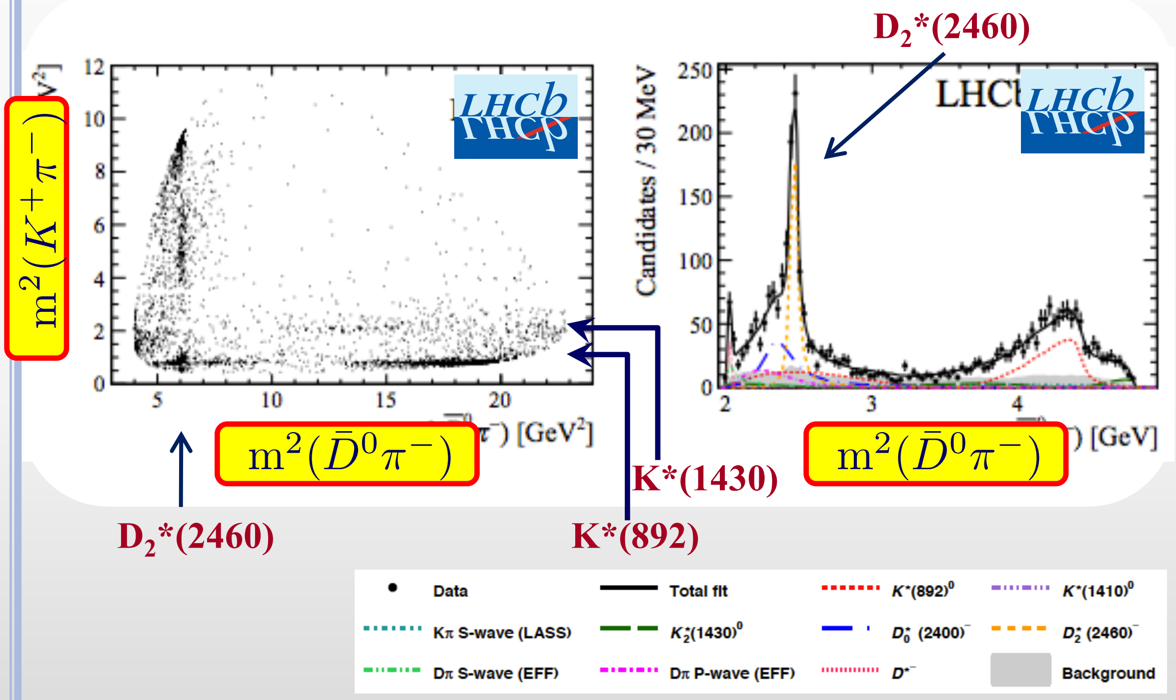
- Two models for $\pi^+\pi^-$: Isobar and K-matrix
- $D_0^*(2400)^-$ spin-parity determined: $J^P=0^+$
- Observation of $D_3^*(2760)^-$:
    - Determination of mass and width
    - Determination of spin-parity $J^P=3^-$ (interpreted as orbitally L=2 excited state $D_3^*(1D)$)

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



$m^2(K^+\pi^-)$

$m^2(\bar{D}^0\pi^-)$

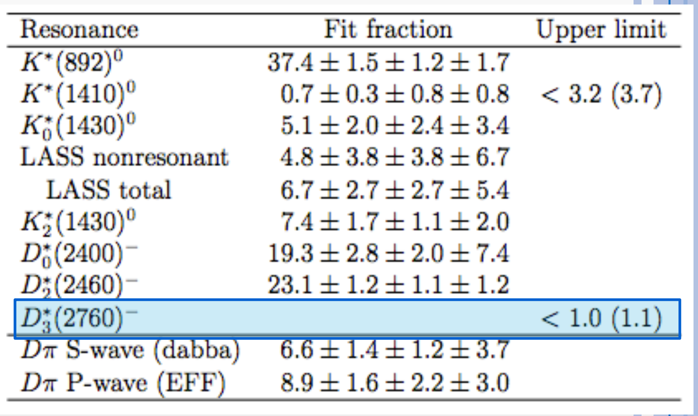
$m^2(\bar{D}^0\pi^-)$

$D_2^*(2460)$

$D_2^*(2460)$

$K^*(1430)$

$K^*(892)$



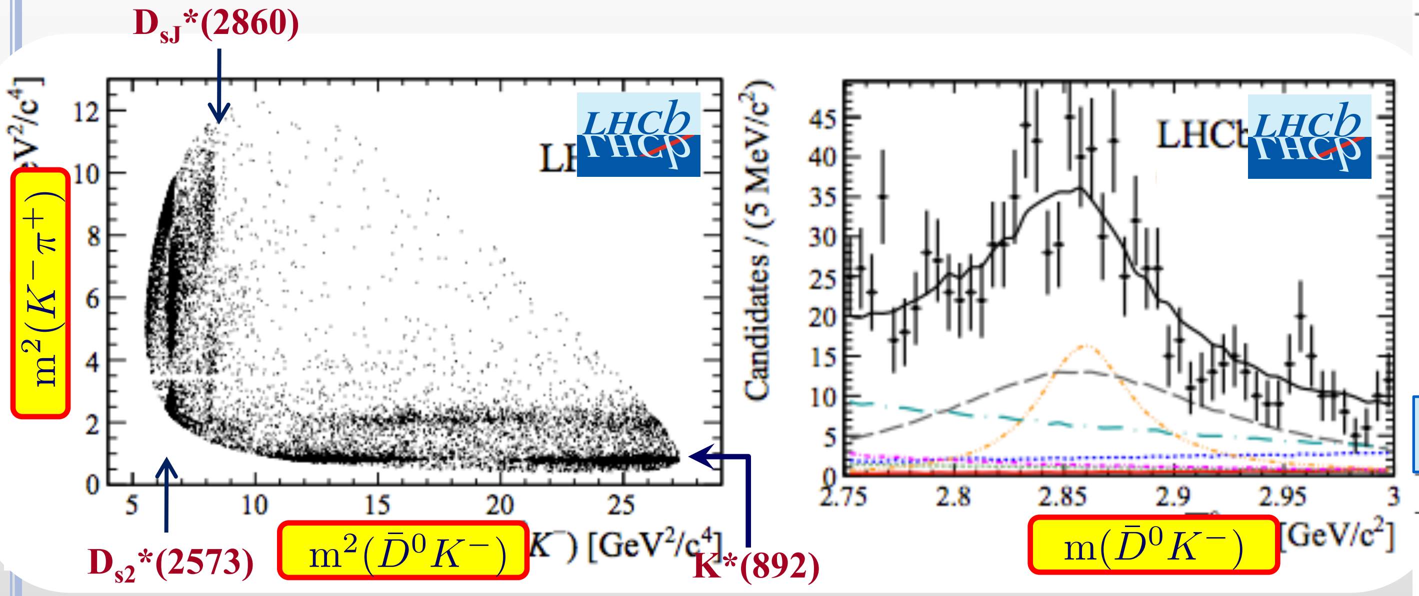
Resonance	Fit fraction	Upper limit
$K^*(892)^0$	$37.4 \pm 1.5 \pm 1.2 \pm 1.7$	
$K^*(1410)^0$	$0.7 \pm 0.3 \pm 0.8 \pm 0.8$	< 3.2 (3.7)
$K_0^*(1430)^0$	$5.1 \pm 2.0 \pm 2.4 \pm 3.4$	
LASS nonresonant	$4.8 \pm 3.8 \pm 3.8 \pm 6.7$	
LASS total	$6.7 \pm 2.7 \pm 2.7 \pm 5.4$	
$K_2^*(1430)^0$	$7.4 \pm 1.7 \pm 1.1 \pm 2.0$	
$D_0^*(2400)^-$	$19.3 \pm 2.8 \pm 2.0 \pm 7.4$	
$D_2^*(2460)^-$	$23.1 \pm 1.2 \pm 1.1 \pm 1.2$	
$D_3^*(2760)^-$		< 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]

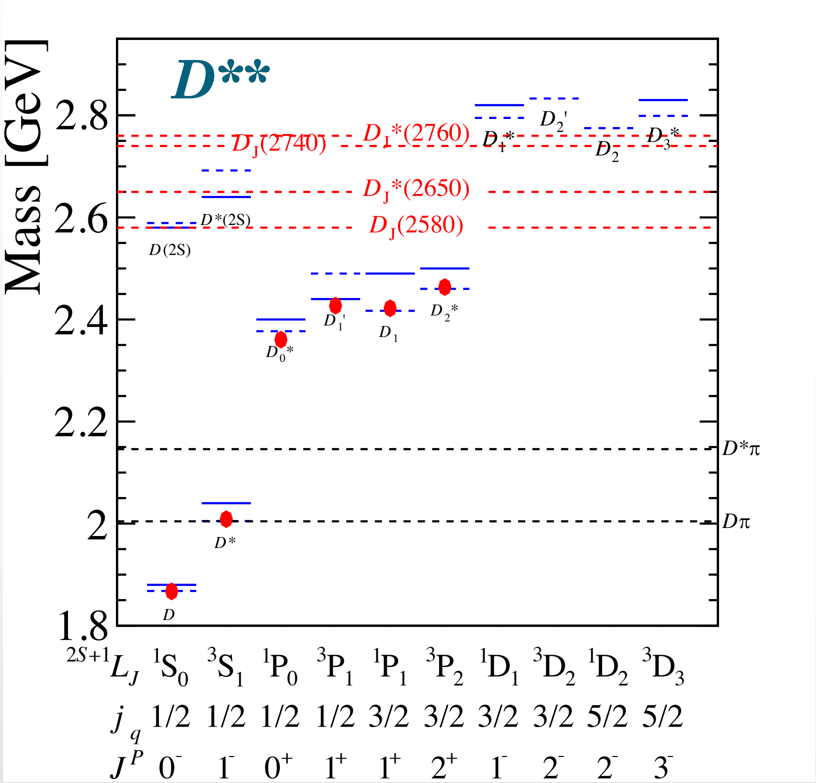
- ➢ LHCb has performed a Dalitz Plot analysis of $B_s \rightarrow \overline{D}^0 K^- \pi^+$
- ➢ $D_{sJ}^*(2860)^+$ consists of (at least) 2 overlapping states $J^P=1^-$ & 3^-

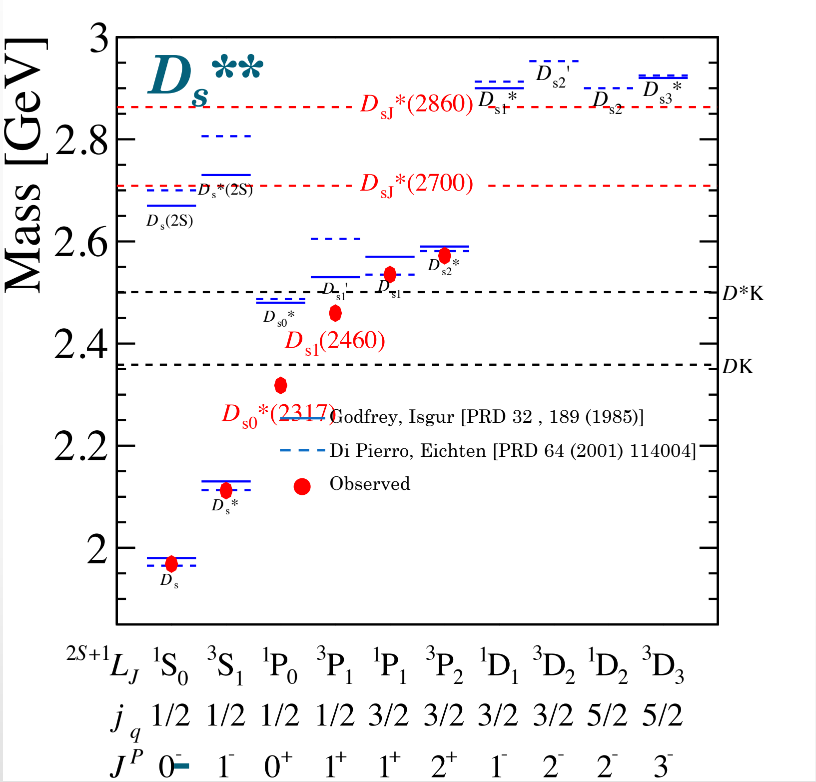


Resonance	Fit fraction (%)
$\bar{K}^*(892)^0$	28.6 ± 0.6
$\bar{K}^*(1410)^0$	1.7 ± 0.5
LASS nonresonant	13.7 ± 2.5
$\bar{K}_0^*(1430)^0$	20.0 ± 1.6
LASS total	21.4 ± 1.4
$\bar{K}_2^*(1430)^0$	3.7 ± 0.6
$\bar{K}^*(1680)^0$	0.5 ± 0.4
$\bar{K}_0^*(1950)^0$	0.3 ± 0.2
$D_{s2}^*(2573)^-$	25.7 ± 0.7
$D_{s1}^*(2700)^-$	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
$D_{s0\,v}^*(2317)^-$	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

EXCITED $D_{(S)}$ SPECTRA



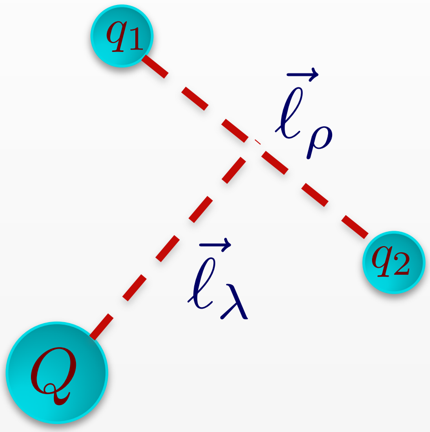


- Likely to be radially or L=2 excitations
- More studies requires: missing states, quantum numbers,…

Baryon Spectroscopy

HEAVY BARYONS IN HQET

Heavy baryon modeled as a system consisting of a static heavy quark Q surrounded by a diquark system comprised of the two light quarks



$\vec{\ell}_\rho$	Orbital angular momentum between the two light quarks
$\vec{\ell}_\lambda$	Orbital angular momentum between the heavy quark and the diquark system
$\vec{L} = \vec{\ell}_\rho + \vec{\ell}_\lambda$	Total orbital angular momentum
$\vec{s}_{qq} = \vec{s}_{q_1} + \vec{s}_{q_2}$	Sum of light quarks spins
$\vec{s}_{Q=b,c}$	Spin of the heavy quark
$\vec{j}_{qq} = \vec{L} + \vec{s}_{qq}$	Angular momentum of the diquark system
$\vec{J} = \vec{j}_{qq} + \vec{s}_Q$	Total angular momentum of the heavy meson

Parity $P = (-1)^{\ell_\rho + \ell_\lambda}$

INTRODUCTION

States can be classified according to their quantum numbers

Quark Model

$$\left|J^P, L, s_{qq}\right\rangle = \left|\left[\left(\ell_\rho \ell_\lambda\right)_L \left(s_{qq} s_Q\right)_S\right]_J\right\rangle$$

HQET

$$\left|J^P, j_{qq}\right\rangle = \left|\left\{\left[\left(\ell_\rho \ell_\lambda\right)_L s_{qq}\right]_{j_{qq}} s_Q\right\}_J\right\rangle$$

The states of one scheme are linear combinations of the states of the second

$$\left|\left\{\left[\left(\ell_\rho \ell_\lambda\right)_L s_{qq}\right]_{j_{qq}} s_Q\right\}_J\right\rangle = (-1)^{1/2+s_{qq}+L+J}\sqrt{2j_{qq}+1} \times \sum_S \sqrt{2S+1} \left\{ \begin{array}{ccc} 1/2 & s_{qq} & S \\ L & J & j_{qq} \end{array} \right\} \left|\left[\left(\ell_\rho \ell_\lambda\right)_L \left(s_{qq} s_Q\right)_S\right]_J\right\rangle$$

[W.Roberts, M.Pervin: Int.J.Mod.Phys. A23 (2008) 2817]

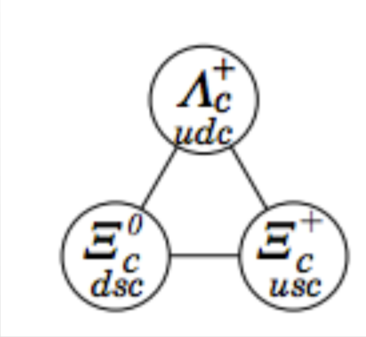
GROUND STATES

- Baryons made of 3 quarks (fermions)
- Wave function must be antisymmetric under interchange of any two equal-mass quarks

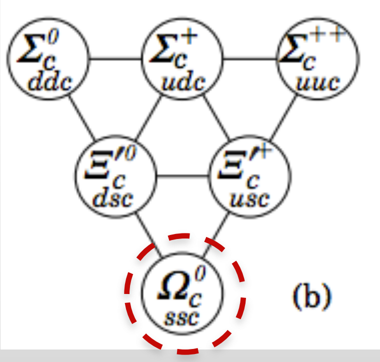
$$|qqq\rangle_A = |\text{color}\rangle_A \times |\text{space}, \text{spin}, \text{flavor}\rangle_S$$

SU(3) Multiplets

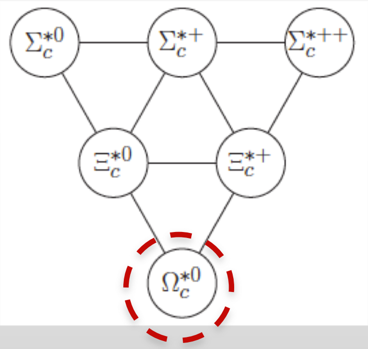
$j=0^+$ $J^P=1/2^+$



$j=1^+$ $J^P=1/2^+$



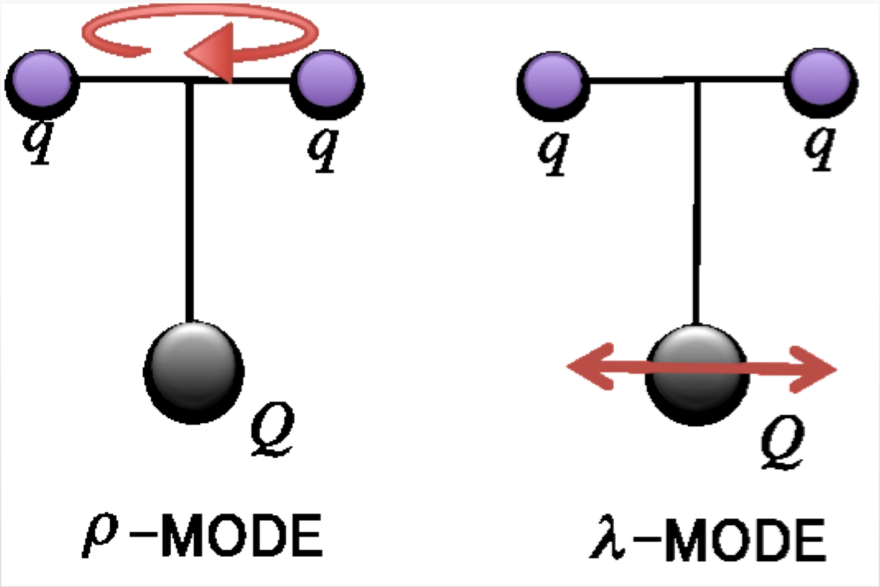
$j=1^+$ $J^P=3/2^+$



The baryon Ω_c^0 is made of 1 quark *charm* and two quarks *strange*

ORBITALLY EXCITED BARYONS

The ρ- and λ-mode excitations of the single-heavy baryon



[Phys.Rev. D92 (2015) 114029]

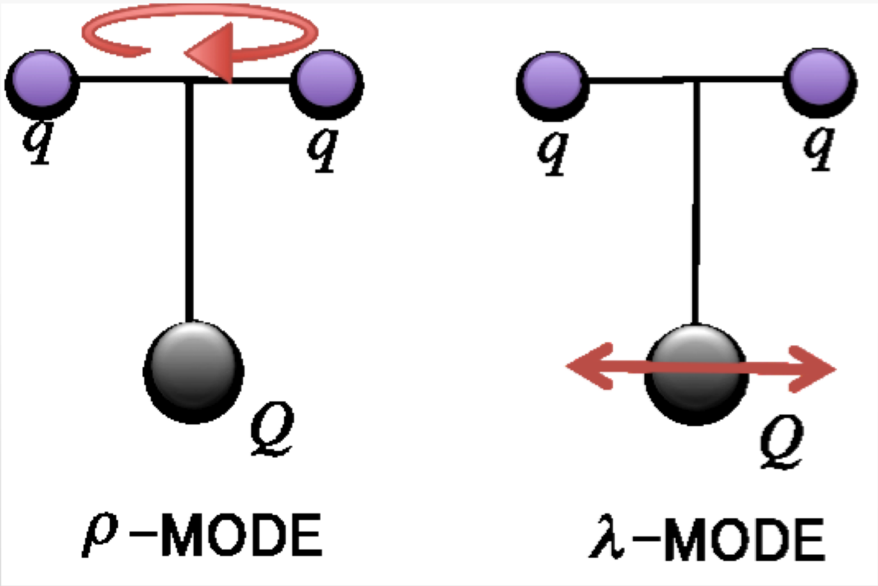
7 excited L = 1 Ω_c

5λ-modes

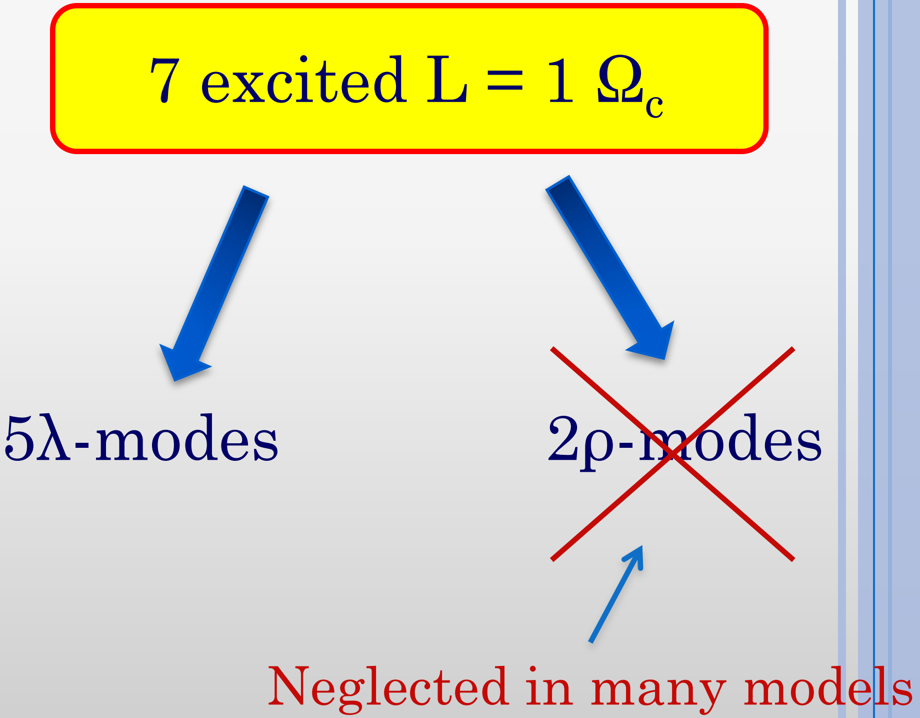
2ρ-modes

ORBITALLY EXCITED BARYONS

The ρ- and λ-mode excitations of the single-heavy baryon



[Phys.Rev. D92 (2015) 114029]



7 excited L = 1 Ω_c

5λ-modes

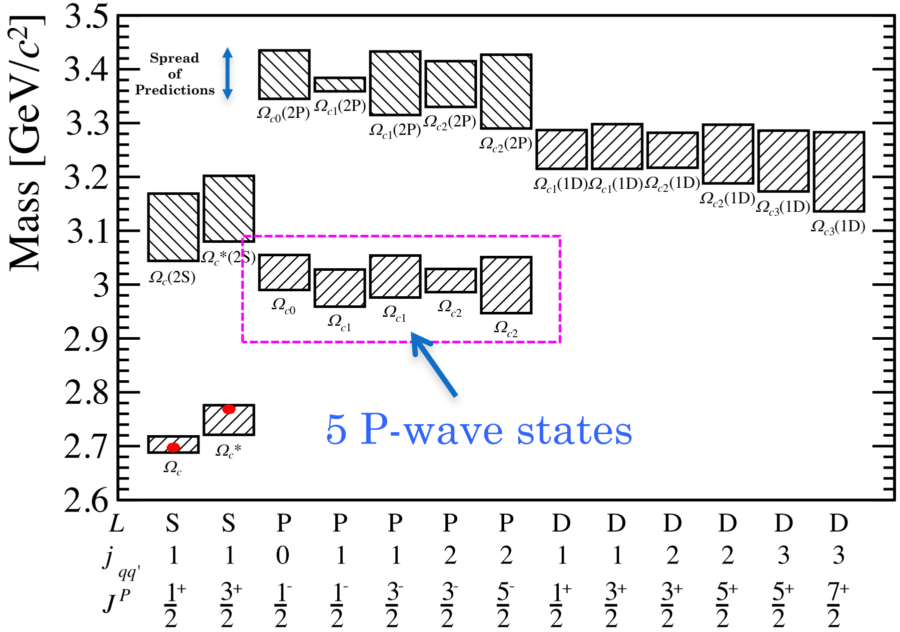
~~2ρ-modes~~

Neglected in many models

EXCITED Ω^0_c STATES

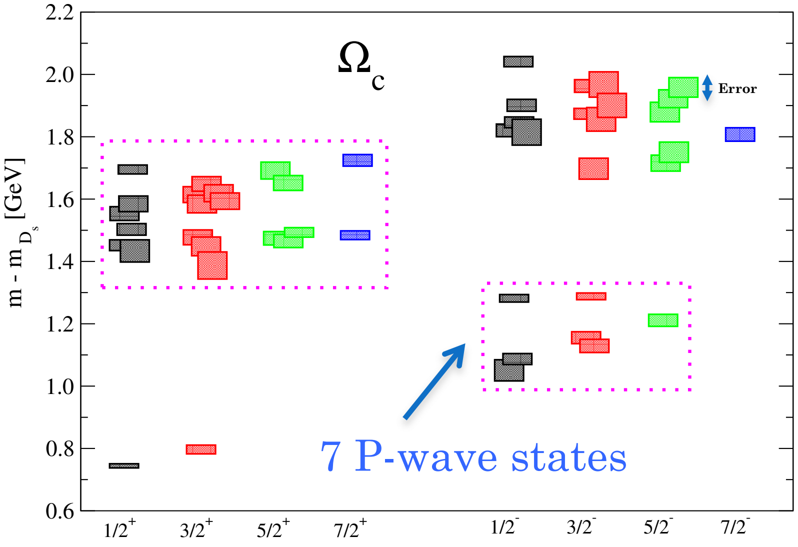
Only the ground states Ω^0_c ($J^P=1/2^+$) and Ω^{*0}_c($J^P=3/2^+$) are known so far

Excited modes between the two light quarks are not considered

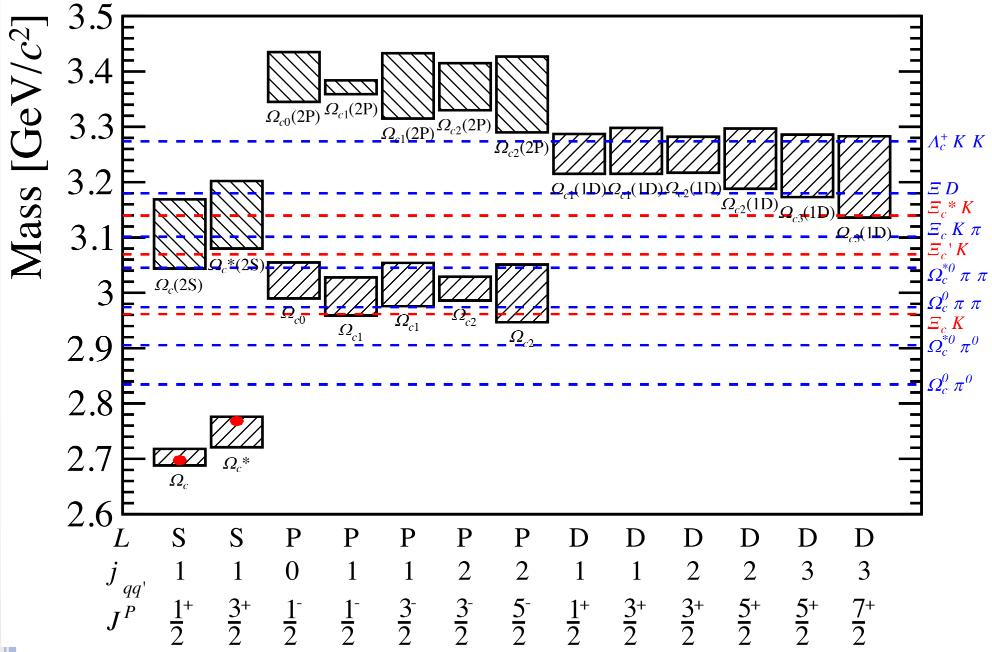


Lattice QCD:

[M. Padmanath *et al.* arXiv:1311.4806]



WHERE TO LOOK AT?

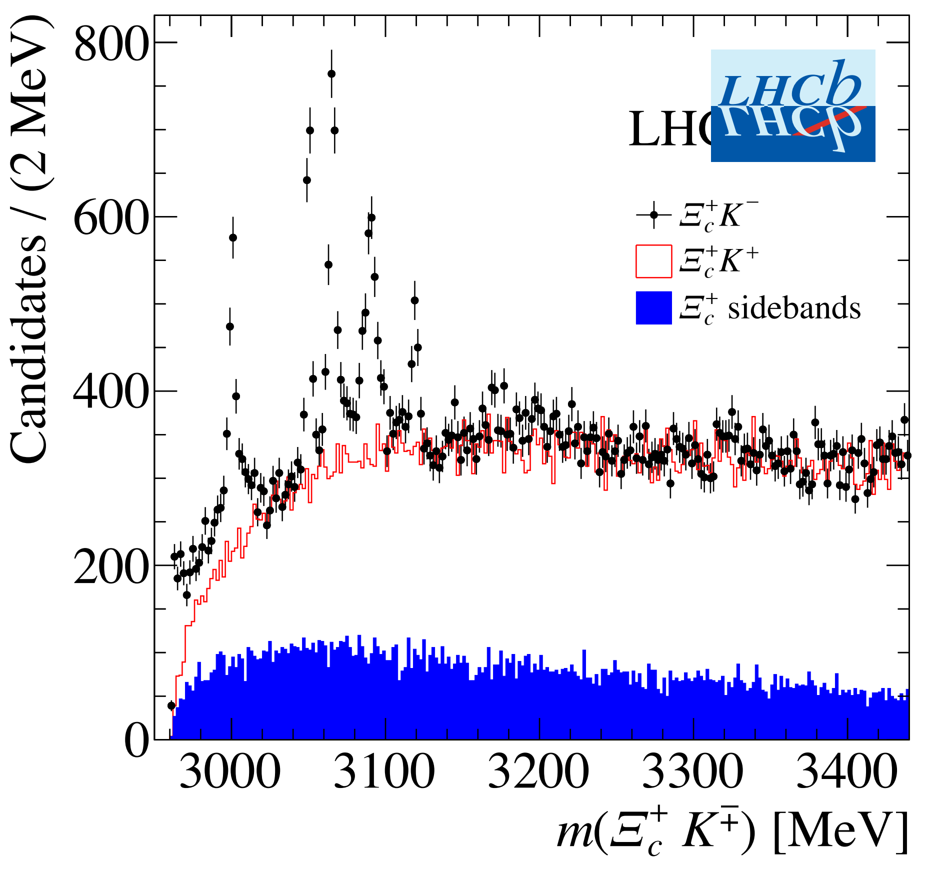


Decays to $\Omega^0_c\ \pi^0$ and $\Omega^{*0}_c\pi^0$ final states are suppressed by isospin-violation
Investigation of the decays to the $\Xi_c^+K^-$ final state

THE $\Xi_c^+K^-$ MASS SPECTRUM

[LHCb: PRL 118 (2017) 182001]

10^6 Ξ_c^+ candidates combined to kaons with opposite charge



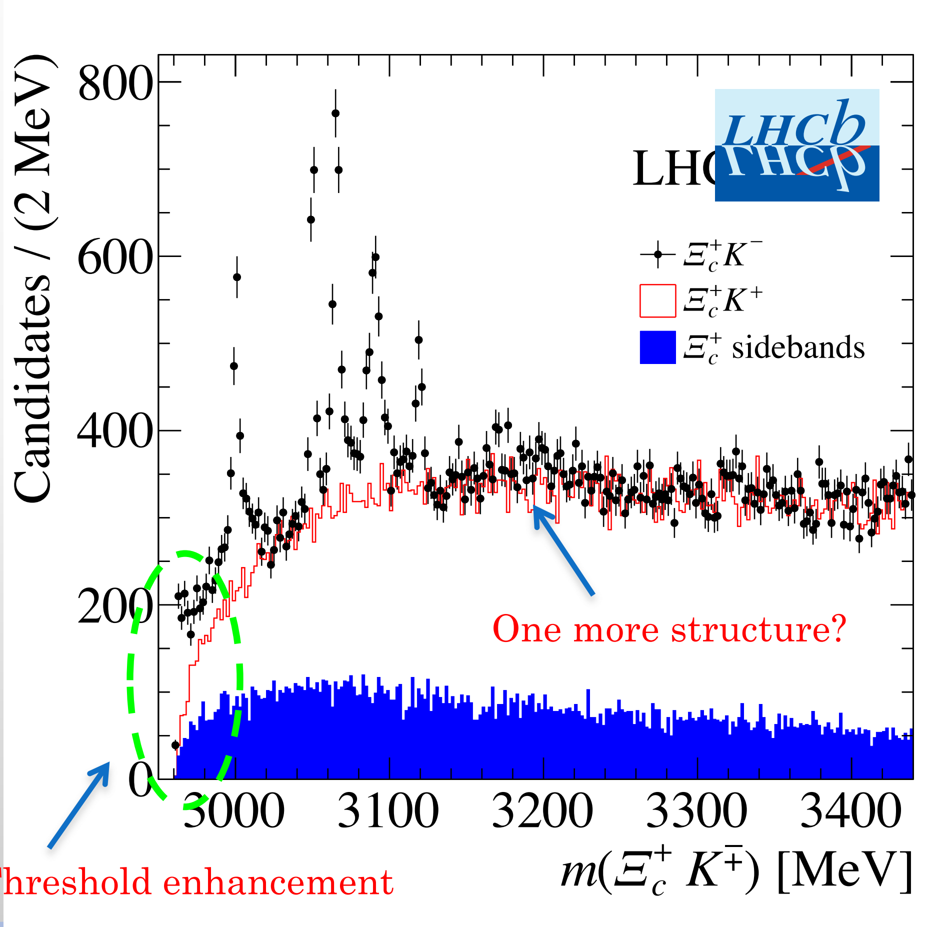
5 narrow peaks in $\Xi_c^+K^-$!

No peaks in the wrong sign sample $\Xi_c^+K^+$
No peaks in the Ξ_c^+ -sidebands K^- sample

The $\Xi_c^+K^-$ Mass Spectrum

[LHCb: PRL 118 (2017) 182001]

10^6 Ξ_c^+ candidates combined to kaons with opposite charge



One more structure?

Threshold enhancement

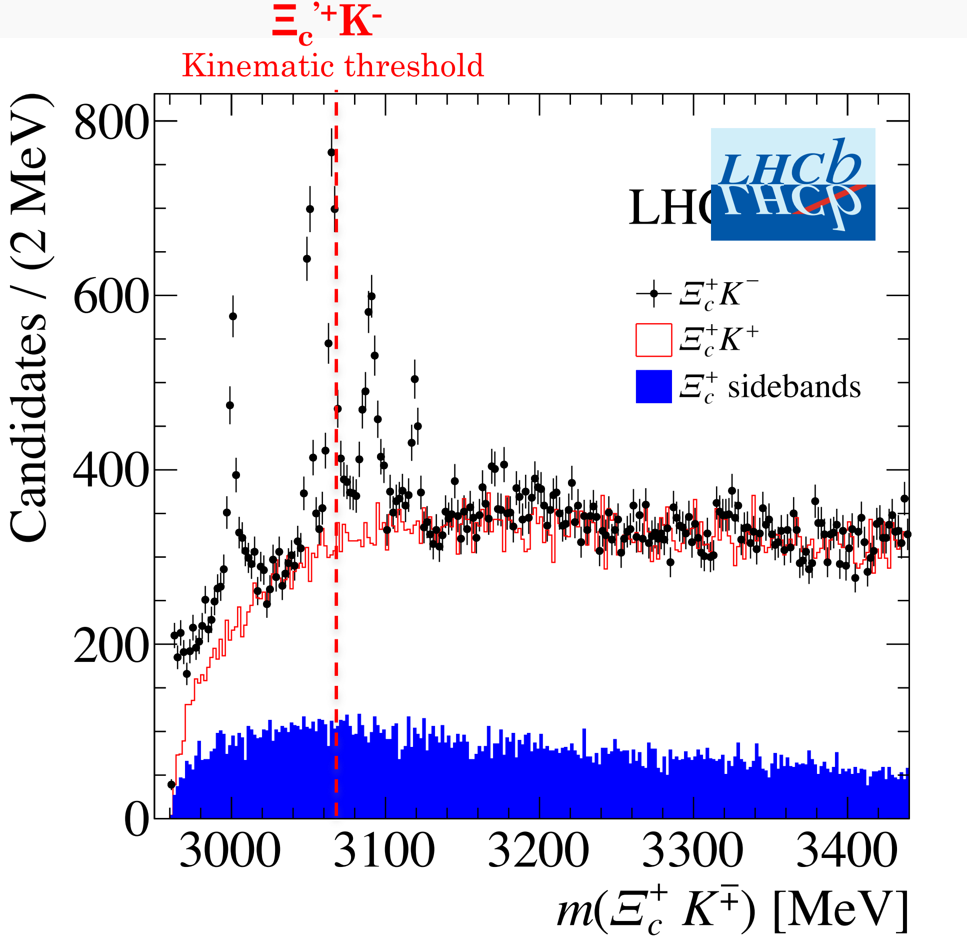
5 narrow peaks in $\Xi_c^+K^-$!

No peaks in the wrong sign sample $\Xi_c^+K^+$
No peaks in the Ξ_c^+ -sidebands K^- sample

THE $\Xi_c^+K^-$ MASS SPECTRUM

[LHCb: PRL 118 (2017) 182001]

10^6 Ξ_c^+ candidates combined to kaons with opposite charge



5 narrow peaks in $\Xi_c^+K^-$!

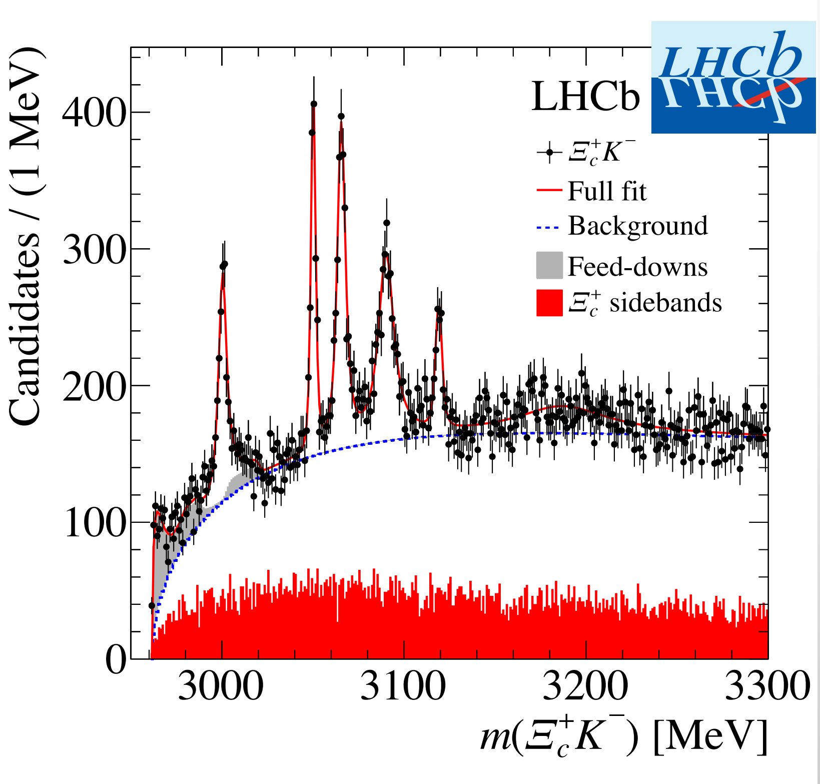
No peaks in the wrong sign sample $\Xi_c^+K^+$
No peaks in the Ξ_c^+ -sidebands K^- sample

States with masses $M > m(\Xi_c') + m(K)$ could decay to $\Xi_c'^+K^-$ as well and appear into Ξ_cK as partially reconstructed decays (i.e. feed-downs)

FIVE NEW EXCITED Ω^0_c STATES!

[LHCb: PRL 118 (2017) 182001]

- Observation of **5** new excited Ω_c states! Two of them extremely narrow
- First time so many states observed in a single mass spectrum
- Comprehensive explanation of all peaks challenges our current knowledge

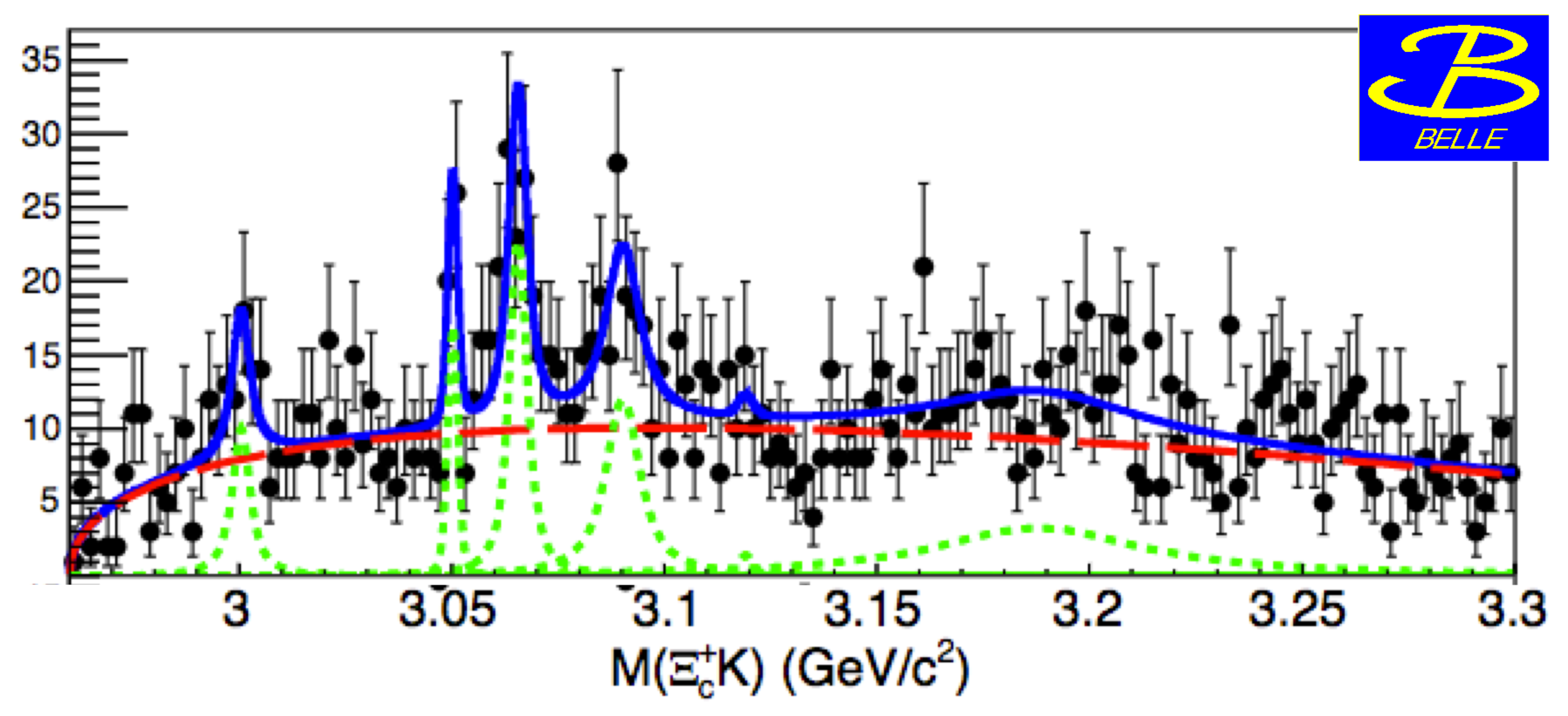


Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ $< 1.2\,\text{MeV}, 95\%\ \text{CL}$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ $< 2.6\,\text{MeV}, 95\%\ \text{CL}$
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

CONFIRMATION OF EXCITED Ω^0_c AT BELLE

[Belle: PRD 97(2018) 051102]

- 4 out of 5 states confirmed
- The narrow state at high mass is missing (not in disagreement with the LHCb observation)



WHAT ARE THEY? WHY ARE THEY SO NARROW?

Are they orbitally excited (L=1) states? Or radiatally excitations? Or…

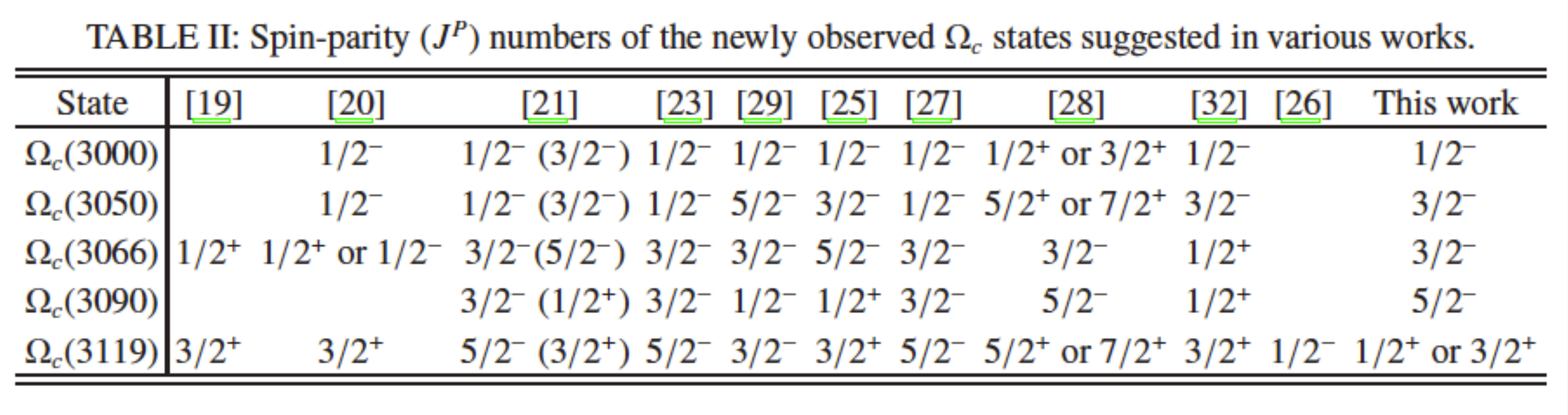


TABLE II: Spin-parity (J^P) numbers of the newly observed Ω_c states suggested in various works.

State	[19]	[20]	[21]	[23]	[29]	[25]	[27]	[28]	[32]	[26]	This work
$\Omega_c(3000)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^+$ or $3/2^+$	$1/2^-$		$1/2^-$
$\Omega_c(3050)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$5/2^+$ or $7/2^+$	$3/2^-$		$3/2^-$
$\Omega_c(3066)$	$1/2^+$	$1/2^+$ or $1/2^-$	$3/2^-(5/2^-)$	$3/2^-$	$3/2^-$	$5/2^-$	$3/2^-$	$3/2^-$	$1/2^+$		$3/2^-$
$\Omega_c(3090)$			$3/2^-$ $(1/2^+)$	$3/2^-$	$1/2^-$	$1/2^+$	$3/2^-$	$5/2^-$	$1/2^+$		$5/2^-$
$\Omega_c(3119)$	$3/2^+$	$3/2^+$	$5/2^-$ $(3/2^+)$	$5/2^-$	$3/2^-$	$3/2^+$	$5/2^-$	$5/2^+$ or $7/2^+$	$3/2^+$	$1/2^-$	$1/2^+$ or $3/2^+$

[K.-L. Wang, L.-Y. Xiao, X.-H. Zhong, Q. Zhao, Phys. Rev. D95 (2017) 116010]

…are they pentaquarks?

PENTAQUARK INTERPRETATION

The structure of pentaquarks Ω_c^0 in the chiral quark model

Gang Yang[1], Jialun Ping[1]
[1] *Department of Physics and Jiangsu Key Laboratory for Numerical Simulation of Large Scale Complex Systems, Nanjing Normal University, Nanjing 210023, P. R. China*

Recently, the experimental results of LHCb Collaboration suggested the existence of five new excited states of Ω_c^0, $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$, the quantum numbers of these new particles are not determined now. To understand the nature of the states, a dynamical calculation of 5-quark systems with quantum numbers $IJ^P = 0(\frac{1}{2})^-$, $0(\frac{3}{2})^-$ and $0(\frac{5}{2})^-$ is performed in the framework of chiral quark model with the help of gaussian expansion method. The results show the $\Xi\bar{D}$, $\Xi_c\bar{K}$ and $\Xi_c^*\bar{K}$ are possible the candidates of these new particles. The distances between quark pairs suggest that the nature of pentaquark states.

Narrow pentaquarks as diquark-diquark-antiquark systems

V.V. Anisovich[+], M.A. Matveev[+], J. Nyiri[*], A.N. Semenova[+],

June 6, 2017

[+] *Petersburg Nuclear Physics Institute of National Research Centre "Kurchatov Institute", Gatchina, 188300, Russia*

[*] *Institute for Particle and Nuclear Physics, Wigner RCP, Budapest 1121, Hungary*

Abstract

The diquark-diquark-antiquark model describes pentaquark states both in terms of quarks and hadrons. The latest LHCb data for pentaquarks with open charm emphasize the importance of hadron components in the structure of pentaquarks. We discuss pentaquark states with hidden charm $P(\bar{c}cuud)$ and those with open charm $P(\bar{u}ussc)$ which were discovered recently in LHCb data ($J/\Psi p$ and $\Xi_c^+ K^-$ spectra correspondingly). Considering the observed states as members of the lowest (s-wave) multiplet we discuss the mass splitting of states and the dumping of their widths.

The observed Ω_c^0 resonances as pentaquark states

C. S. An[*] and H. Chen[†]
School of Physical Science and Technology, Southwest University,
Chongqing 400715, People's Republic of China
(Dated: May 25, 2017)

Abstract

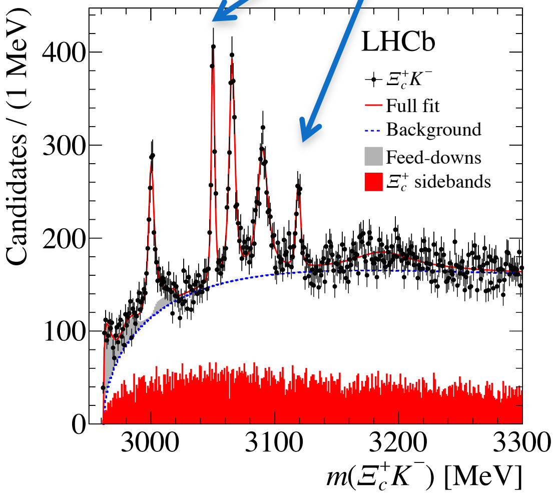
In present work, we investigate the spectrum of several low-lying $sscq\bar{q}$ pentaquark configurations employing the constituent quark model, within which the hyperfine interaction between quarks is taken to be mediated by Goldstone boson exchange. Our numerical results show that four $sscq\bar{q}$ configurations with $J^P = 1/2^-$ or $J^P = 3/2^-$ lie at energies very close to the recently observed five Ω_c^0 states by LHCb collaboration, this indicates that the $sscq\bar{q}$ pentaquark configurations may form sizable components of the observed Ω_c^0 resonances.

On a possibility of charmed exotica

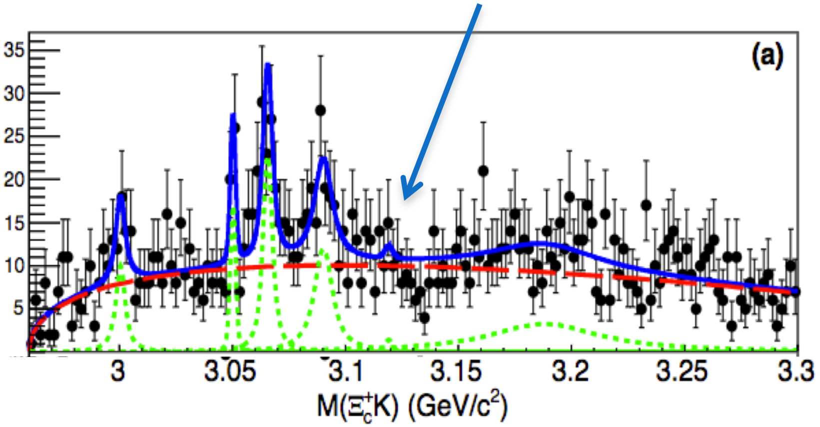
Hyun-Chul Kim,[1,2] Maxim V. Polyakov,[3,4] and Michał Praszałowicz[5]
[1] *Department of Physics, Inha University, Incheon 22212, Republic of Korea*[*]
[2] *School of Physics, Korea Institute for Advanced Study (KIAS), Seoul 02455, Republic of Korea*
[3] *Institut für Theoretische Physik II, Ruhr-Universität Bochum, D–44780, Bochum, Germany*[†]
[4] *Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188 300, Russia*
[5] *M. Smoluchowski Institute of Physics, Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland*[‡]

We employ the chiral quark-soliton model to describe excited baryons with one heavy quark. Identifying known charmed baryons with multiplets allowed by the model, we argue that apart from regular excitations of the ground state multiplets, some of recently reported by the LHCb collaboration narrow Ω_c^0 states, may correspond to the exotic pentaquarks. This interpretation can be easily verified experimentally, since exotic Ω_c^0 states – contrary to the regular excitations – form isospin triplets, rather than singlets.

Pentaquarks?



Suppressed due to the e$^+$e$^-$ production?

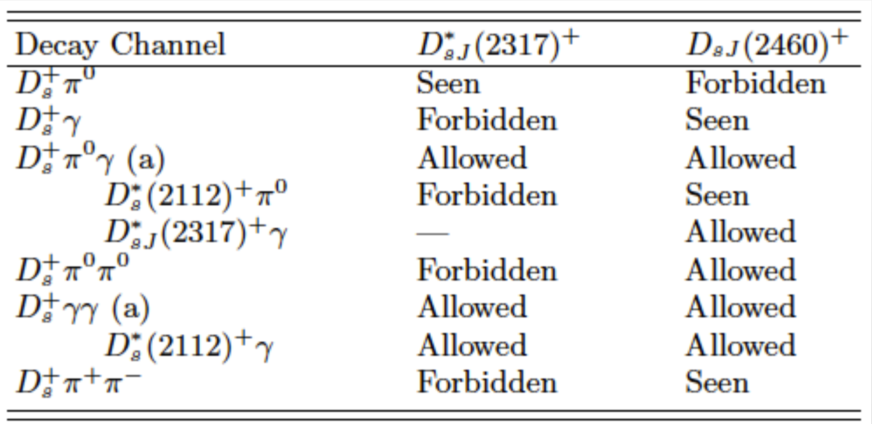


Plans & Prospects

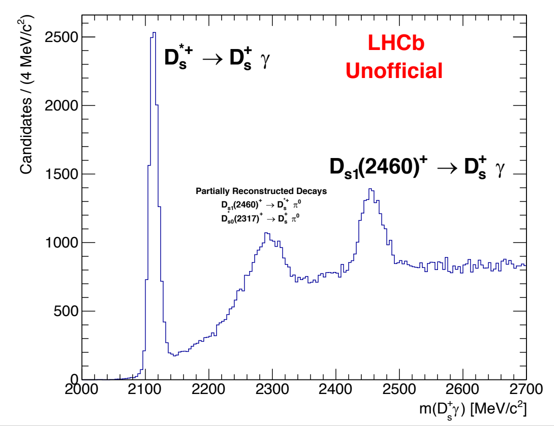
EXCITED $D_{(S)}$ MESONS

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

- Search for new decays modes
- Production studies (e.g. $D_{s1}(2460) \rightarrow D_s\,\gamma$ production cross-section)
- Studies from B^0_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
  - Search for $D^*_{s0}(2317)^0 \rightarrow D_s^-\,\pi^+$



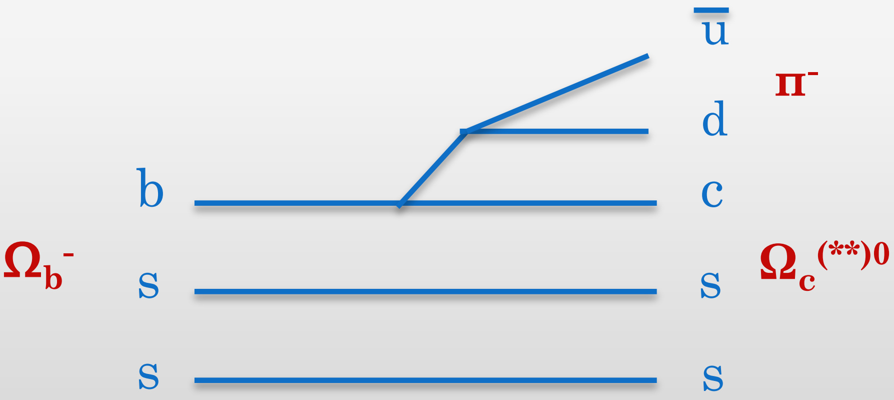
Decay Channel	$D^*_{sJ}(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+\pi^0$	Seen	Forbidden
$D_s^+\gamma$	Forbidden	Seen
$D_s^+\pi^0\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\pi^0$	Forbidden	Seen
$D^*_{sJ}(2317)^+\gamma$	—	Allowed
$D_s^+\pi^0\pi^0$	Forbidden	Allowed
$D_s^+\gamma\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\gamma$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



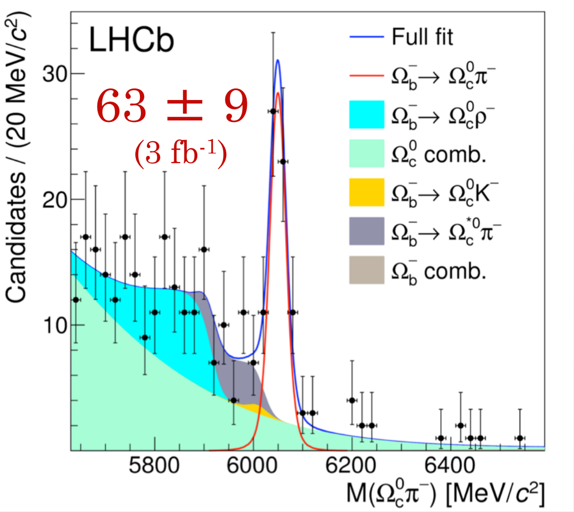
EXCITED Ω^0_c: DETERMINATION OF SPIN-PARITY J^P

Study of Ω_c^{**} in fully reconstructed decays: (e.g.) $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$

The decays $\Omega_b^- \rightarrow \Omega_c^0 (\rightarrow pKK\pi) \pi^-$ already observed.
Same number and type of tracks in the final state

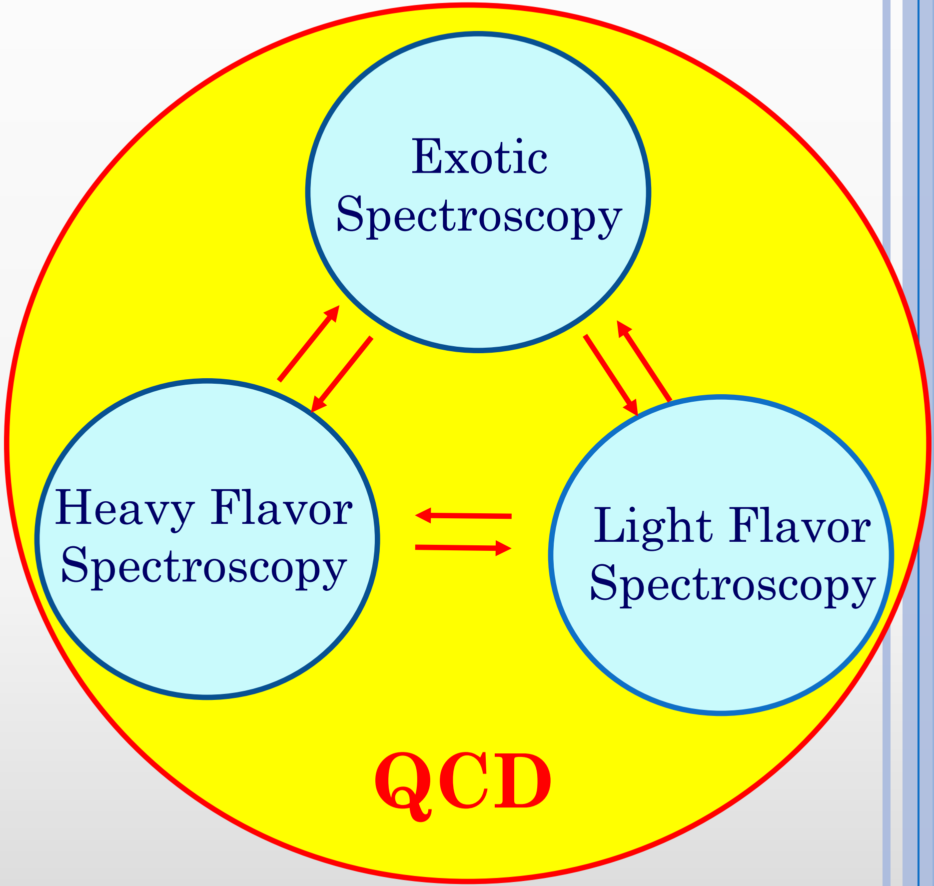


[Phys. Rev. D 93 (2016) 092007]



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 will be starting taking data. PANDA, J-PARC, JLab and other hadron facilities will play an importat role as well.

Back-up slides

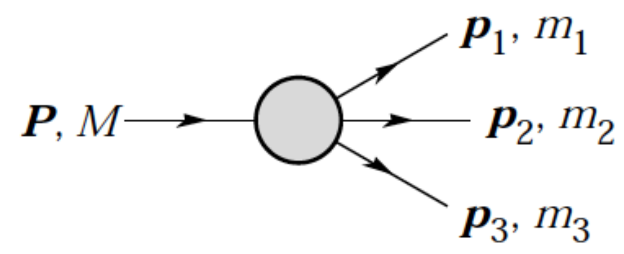
RELEVANCE OF THE WIDTH

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

3-BODY DECAY WITH SPINLESS DAUGHTERS



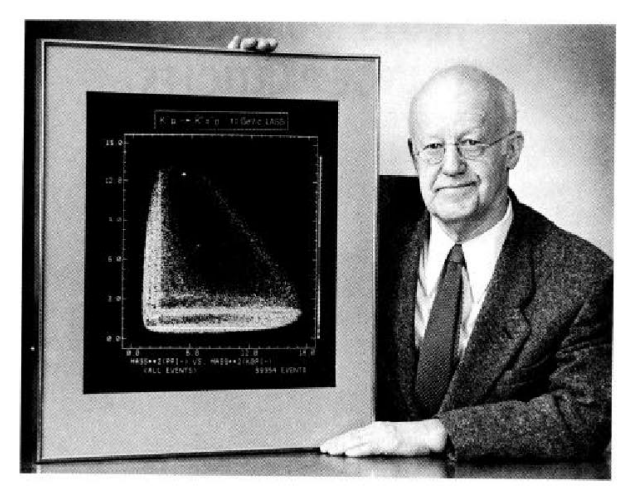
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2$$

Constraints	Degree of freedom
3 four-vectors	12
4-momentum conservation	-4
3 masses	-3
3 Euler angles	-3
TOT	2

DALITZ PLOT

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2dm_{23}^2$$

"I visualize geometry better than numbers."

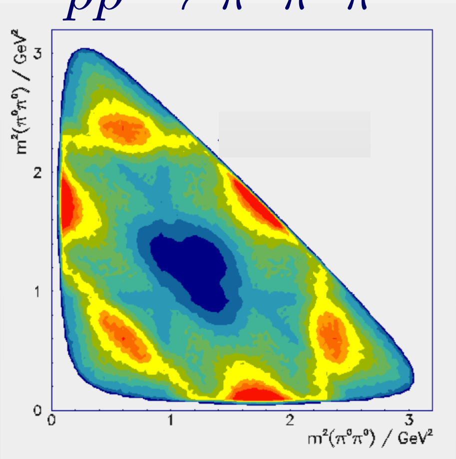


The scatter plot m_{12}^2 vs m_{23}^2 is usually called *Dalitz* plot

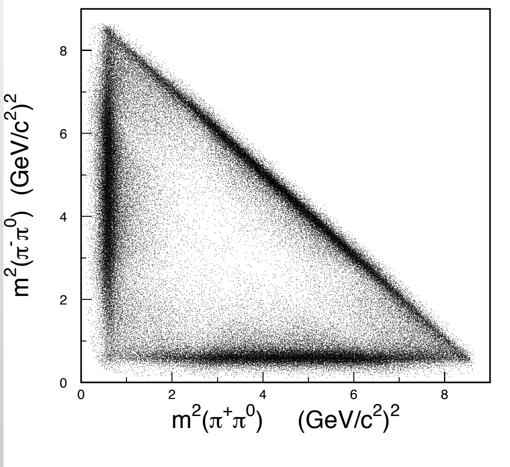
$\overline{|\mathcal{M}|^2} = Const \Rightarrow$ Dalitz uniformly populated

Nonuniformity $\Rightarrow$ Information on $\overline{|\mathcal{M}|^2}$

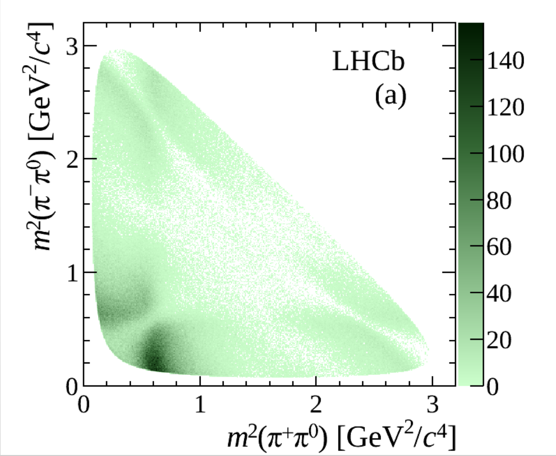
$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$



$J/\psi \rightarrow \pi^+\pi^-\pi^0$



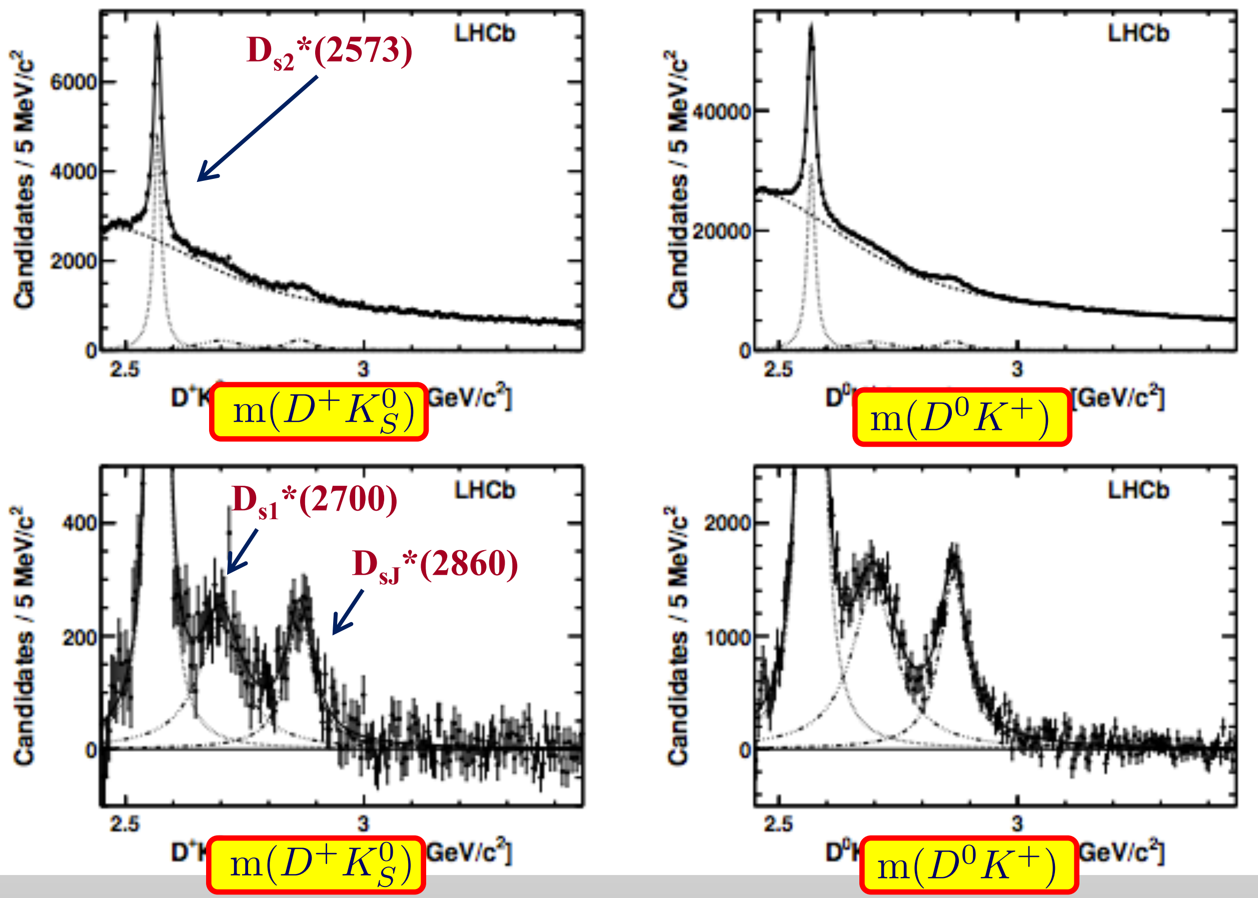
$D^0 \rightarrow \pi^+\pi^-\pi^0$



EXCITED D_S STATES: INCLUSIVE ANALYSIS

[LHCb: JHEP 10 (2012) 151]

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



$D_{s2}^*(2573)$

$D_{s1}^*(2700)$

$D_{sJ}^*(2860)$

$m(D^+K^0_S)$

$m(D^0K^+)$

$m(D^+K^0_S)$

$m(D^0K^+)$

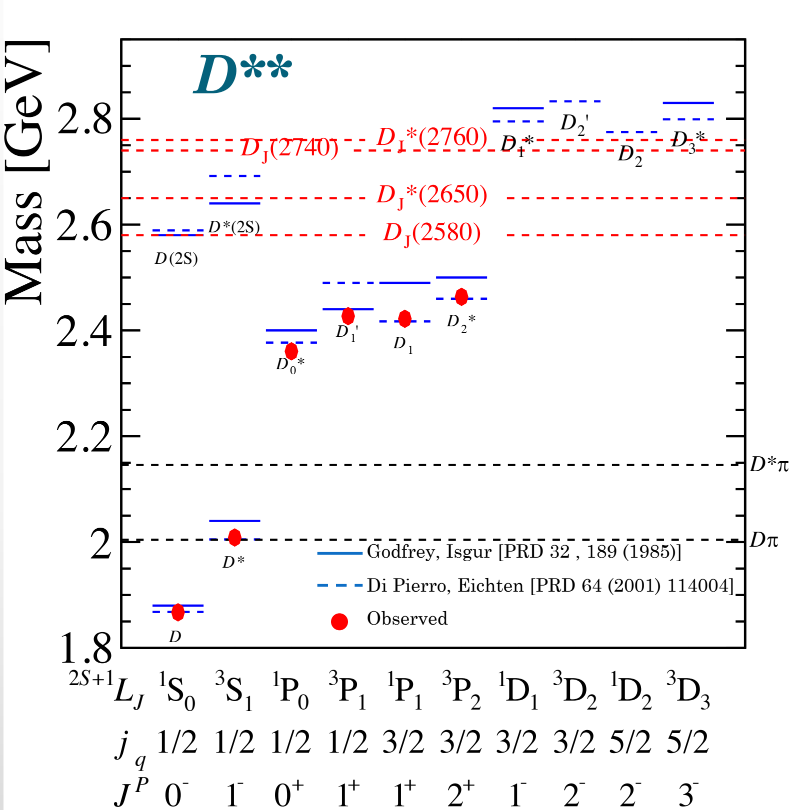
EXCITED D_J STATES

[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 Dπ and/or D*π. Need to be confirmed. **[PRD82 (2010)111101]**

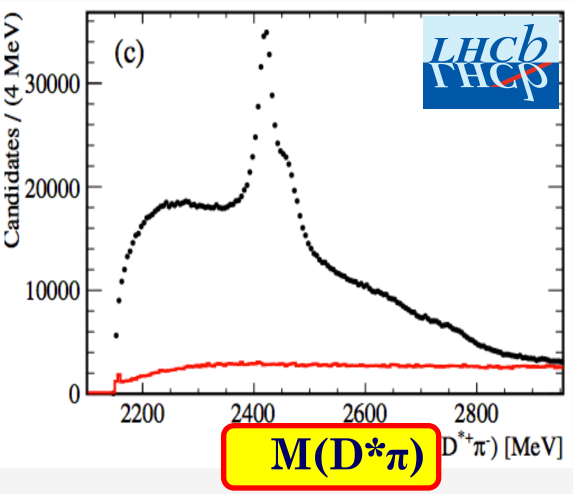
LHCb: Inclusive study of $D^+(\rightarrow K\pi\pi)\pi^-$, $D^0(\rightarrow K\pi)\pi^+$ and $D^{*+}\pi^-$. Several millions of *D*'s in 1 fb^{-1}

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

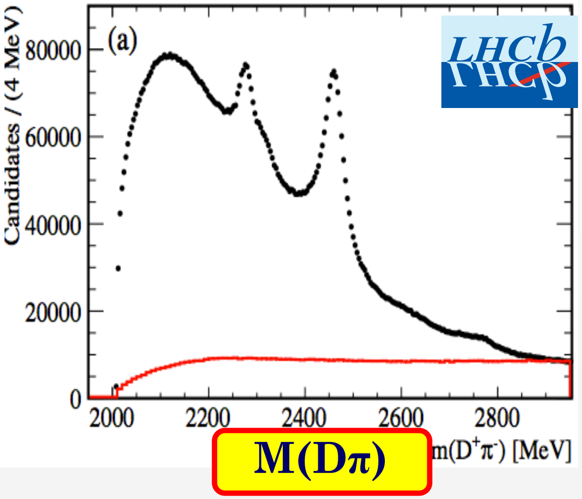


$D^{(*)}\pi$ Mass Spectra

How to fit? How many resonances?



M(D*π)

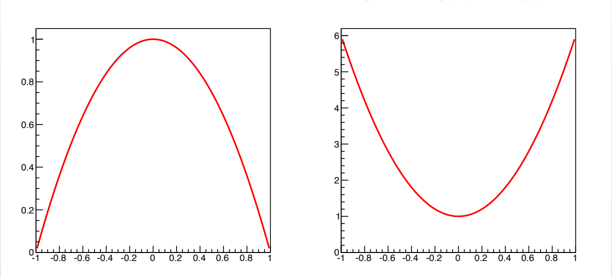


M(Dπ)

- ➢ D*π : Natural + Unnatural states
- ➢ Dπ : Natural states + Feed-down of states in D*π

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

Natural **Unnatural**



cos ϑ cos ϑ

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

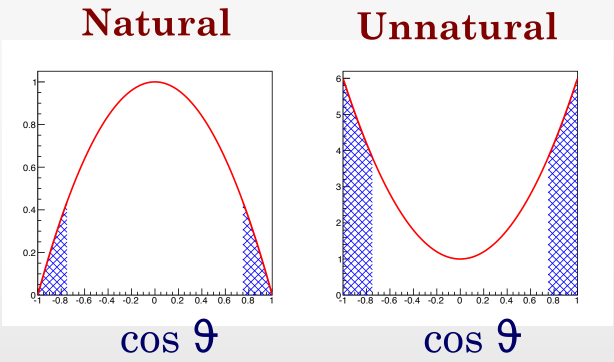
[LHCb, JHEP 09 (2013) 145]

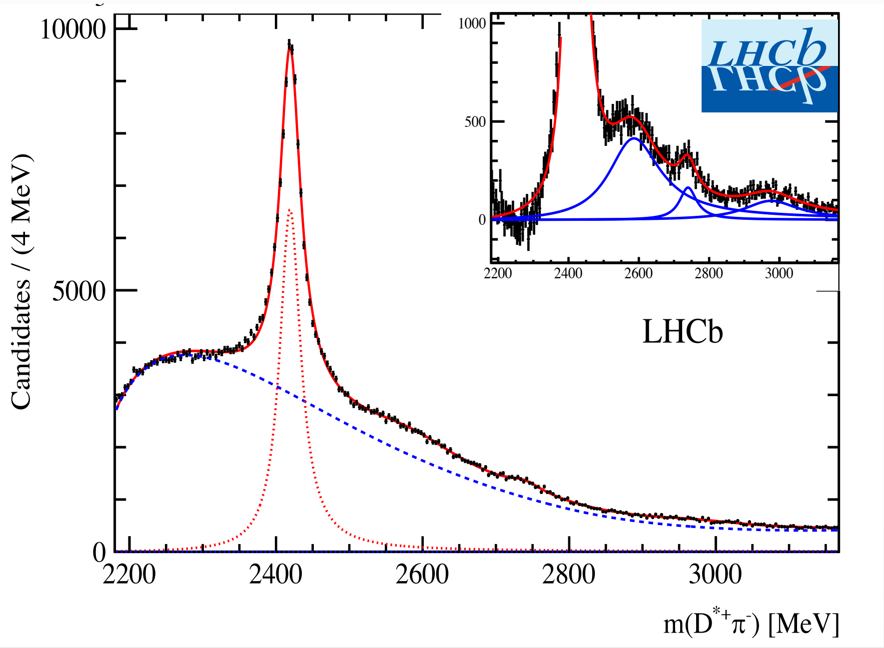
Step 1

$|\cos\vartheta| > 0.75$

enhances unnatural component

(residual natural component ~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]

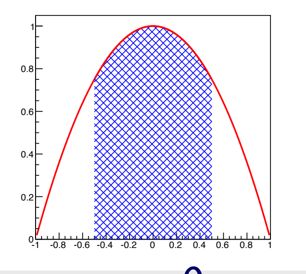
Step 2

$|\cos\vartheta| < 0.5$

enhances natural component

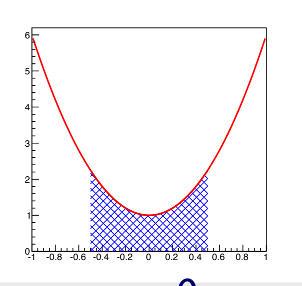
Parameters of the unnatural states
from Step 1

Natural

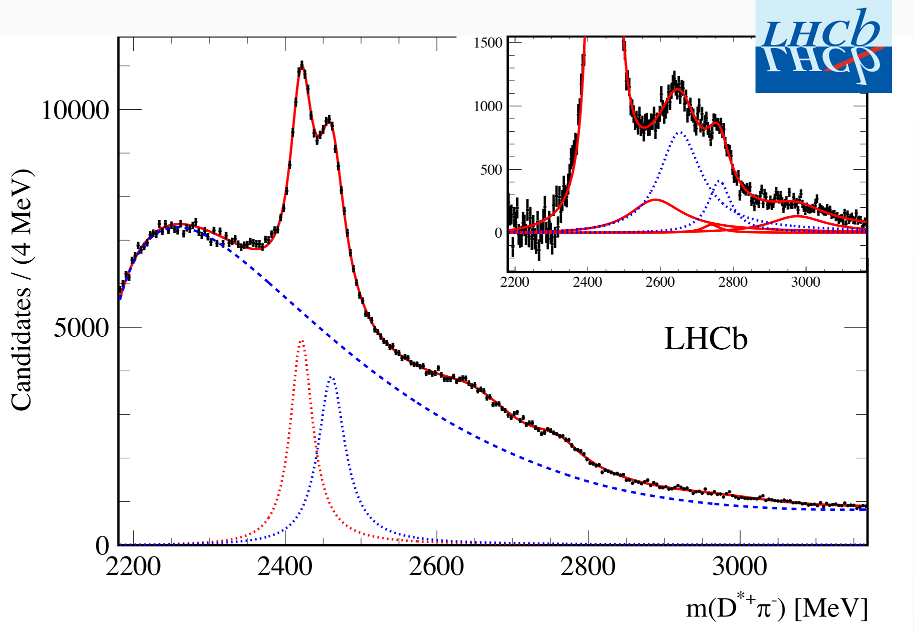


$\cos\vartheta$

Unnatural



$\cos\vartheta$



$D_2^*(2460)^0$ + unnatural states + 2 more natural states:

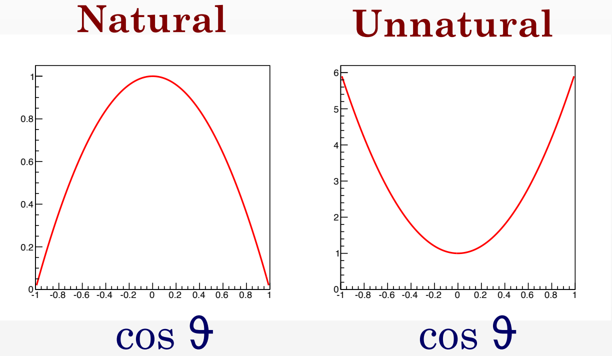
$D_J^*(2650)$, $D_J^*(2760)$

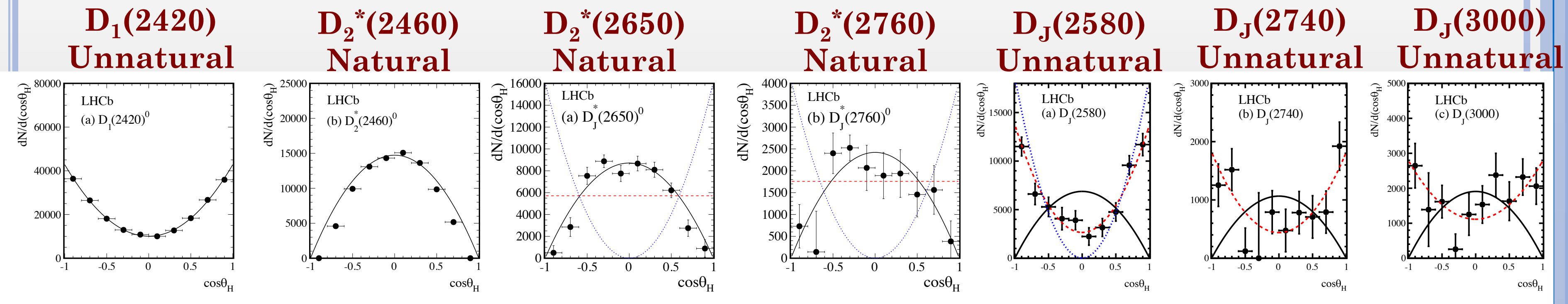
$D^{*+}\pi^-$ Mass Fit

[LHCb, JHEP 09 (2013) 145]

Step 3

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





$D_1(2420)$ Unnatural

$D_2^*(2460)$ Natural

$D_2^*(2650)$ Natural

$D_2^*(2760)$ Natural

$D_J(2580)$ Unnatural

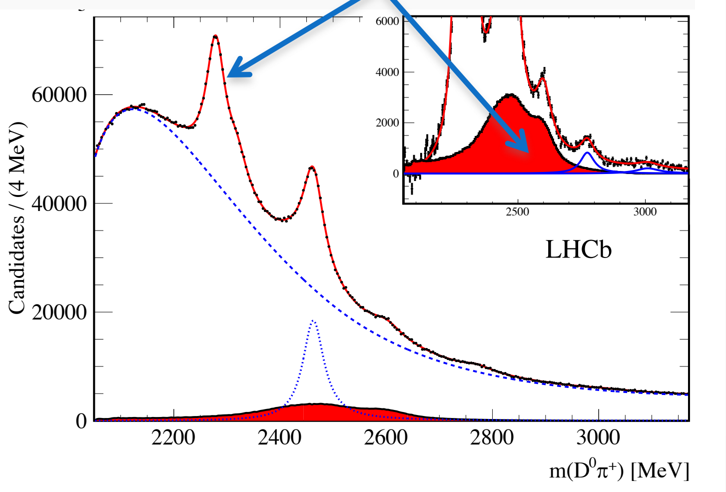
$D_J(2740)$ Unnatural

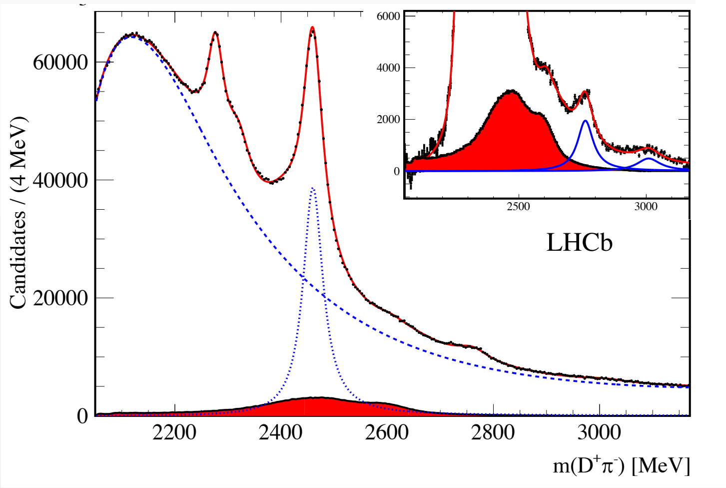
$D_J(3000)$ Unnatural

$D^0\pi^+/D^+\pi^-$ Mass Spectra

[LHCb, JHEP 09 (2013) 145]

Cross-feeds estimated from states appearing in the D*π spectrum





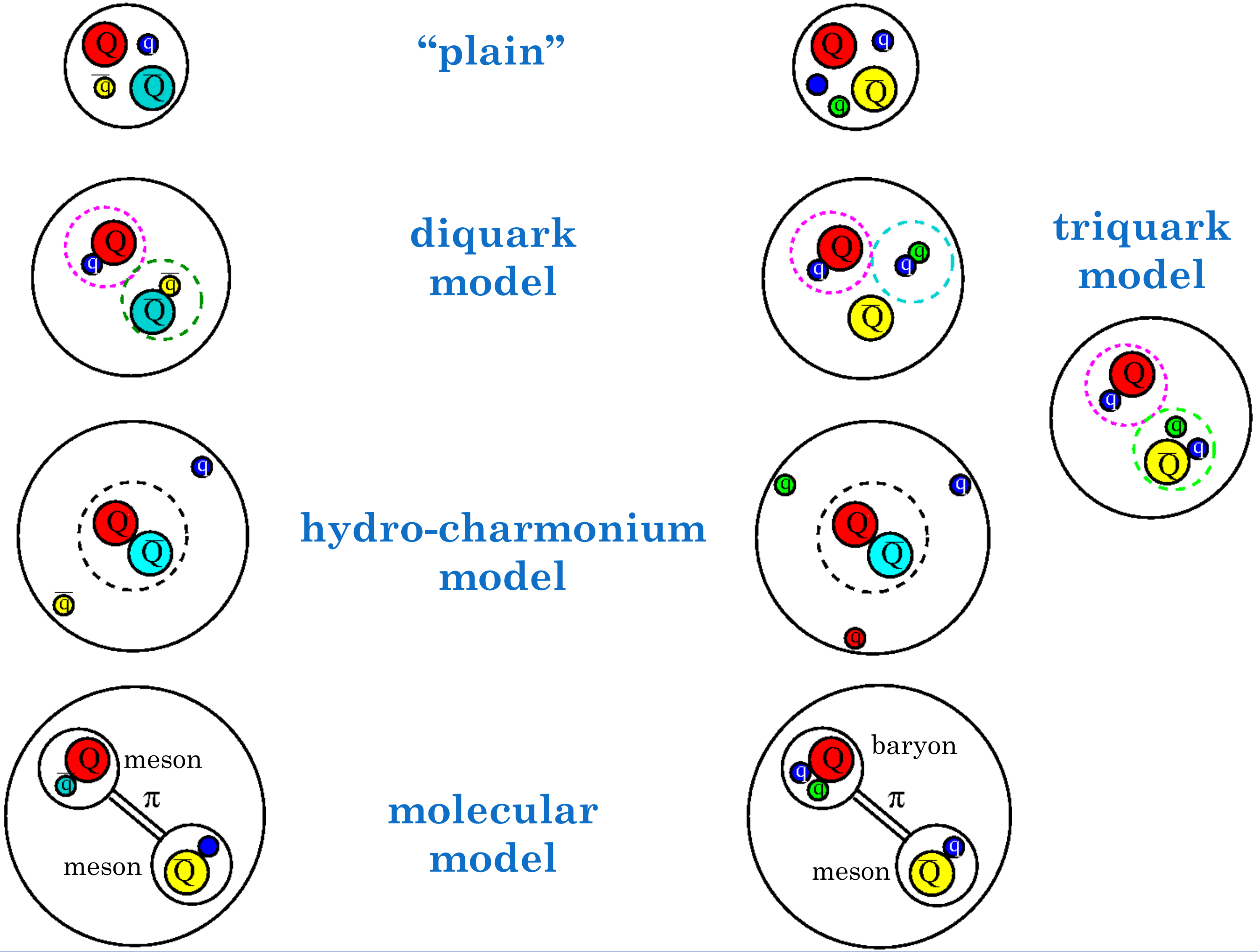
2 more natural states:

$D_J^*(3000)^0$, $D_J^*(3000)^+$

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

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

MODELS FOR TETRA- AND PENTA-QUARKS



“plain”

diquark model

triquark model

hydro-charmonium model

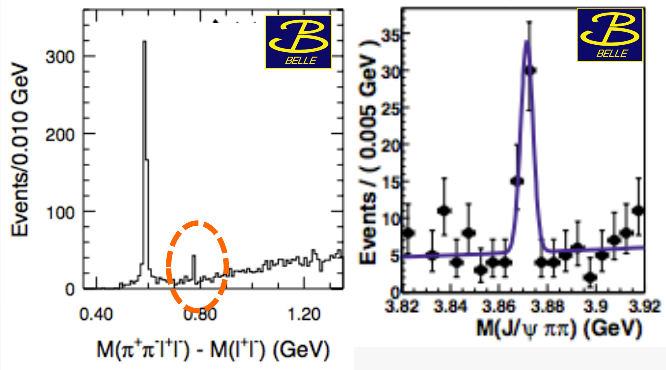
molecular model

THE X(3872) STATE

Discovered in 2003 by the Belle collaboration in the $B \to KX(3872)$ decay where $X(3872) \to J/\psi\pi^+\pi^-$

- ⊛ Mass is roughly equal to $m(D^0) + m(D^{*0})$
- ⊛ Width is surprisingly narrow (< 1.2 MeV)
- ⊛ Large production rate in $p\bar{p}$ collisions

[Belle: PRL 91, 262001 (2003)]



LHC experiments are largely contributing to shed light on the nature of the X(3872) state

- ➢ Determination of the quantum numbers $J^{PC} = 1^{++}$ **[PRL110 222001 (2013)][PRD92 011102 (2015)]**
- ➢ Measurement of B(X(3872)→ψ(2S) γ)/B(X(3872)→J/ψ γ) **[Nucl.Phys.B886 (2014) 665]**

$$\frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

➡ *Pure molecule scenario disfavored*

- ➢ Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

$$E_B = m(D^0) + m(D^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV}/c^2$$

➡ *Loosely bound in the molecule scenario*

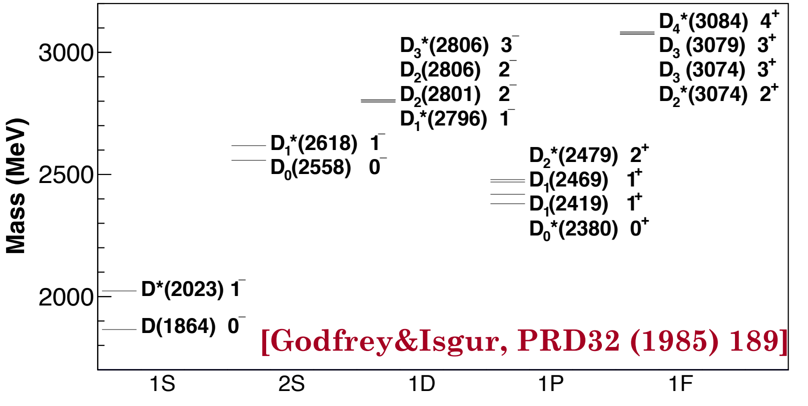
- ➢ Production cross-section in *pp* collisions at √s = 7 TeV **[EPJC 72 (2012) 1972,]**
- ➢ Search for new decay modes (e.g. X(3872) →$\bar{p}p$) **[arXiv: 1607.06446]**

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2}\,@\,95\%\,\mathrm{CL}$$

EXCITED D_J STATES

[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]

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



[Godfrey&Isgur, PRD32 (1985) 189]

LHCb: Inclusive study of $D^+(\rightarrow K\pi\pi)\pi^-$, $D^0(\rightarrow K\pi)\pi^+$ and $D^{*+}\pi^-$. Several millions of *D*'s in 1 fb^{-1}

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

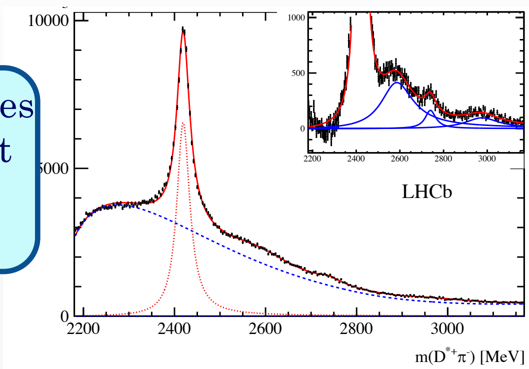
⇓

- Dπ spectrum: natural spin-parity states + cross-feed of all states (expect 0^+)→D*π
- D*π spectrum: all states (expect 0^+). But different angular distribution ($\vartheta \equiv$ Helicity angle)
  - ✓ $\propto \sin^2\vartheta$ for natural spin-parity
  - ✓ $\propto 1+h\cos^2\vartheta$ for unnatural spin-parity
  - ✓ Natural/Unnatural component can be enhanced with an ad hoc requirement on ϑ

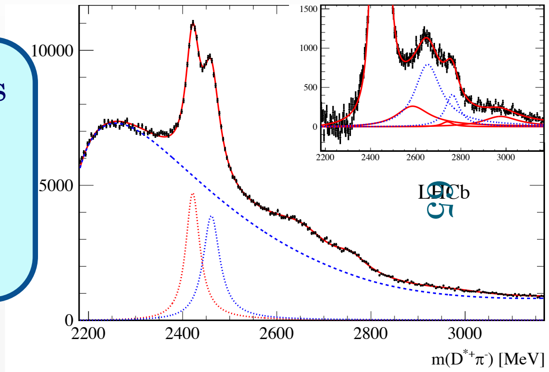
D*π Mass Spectrum

[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]

① |cos ϑ| > 0.75 enhances unnatural component (residual natural component ~9%)



②
- |cos ϑ|<0.5 enhances natural component
- Parameters of the unnatural states are fixed from Step 1



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

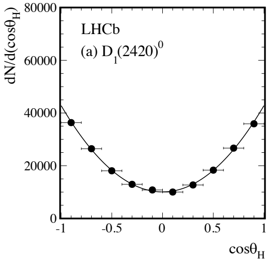
$D_J(2580)$, $D_J(2740)$, $D_J(3000)$

$D_2^*(2460)^0$ + unnatural states + 2 more natural states:

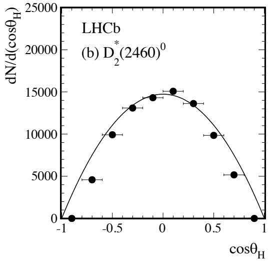
$D_J^*(2650)$, $D_J^*(2760)$

③
- Parameters of all states fixed from Step 1&2
- Fit performed in bins of cos ϑ to verify angular distributions

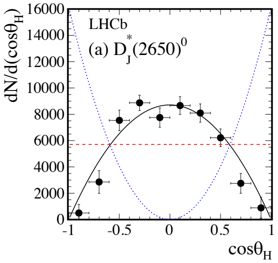
$D_1(2420)$ Unnatural



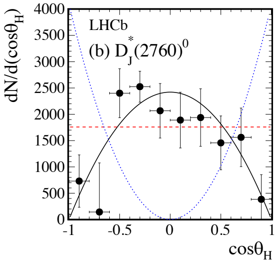
$D_2^*(2420)$ Natural



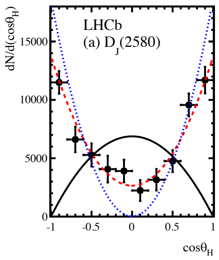
$D_2^*(2650)$ Natural



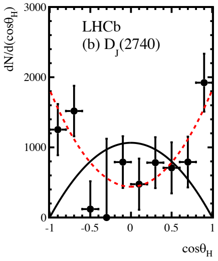
$D_2^*(2760)$ Natural



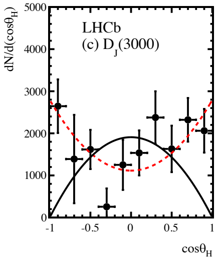
$D_J(2580)$ Unnatural



$D_J(2740)$ Unnatural



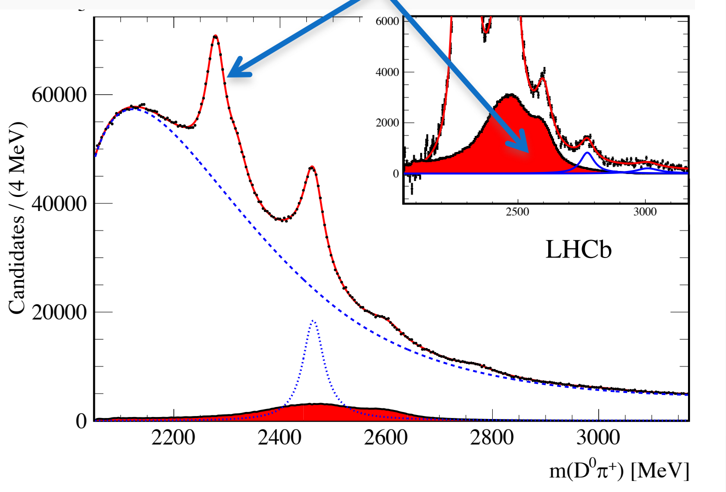
$D_J(3000)$ Unnatural

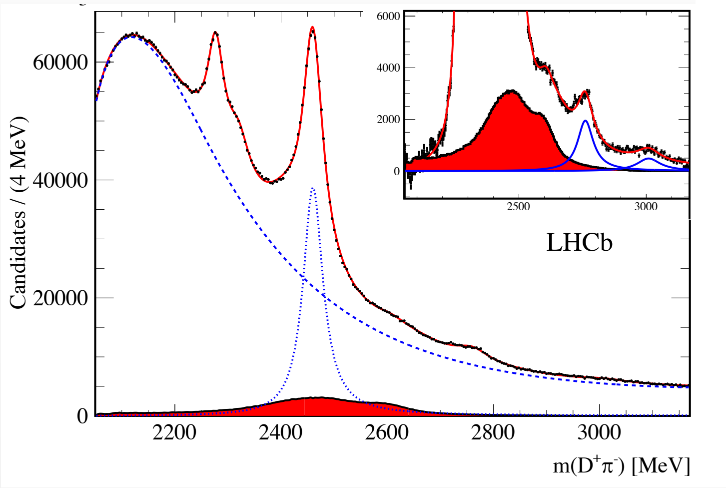


$D^0\pi^+/D^+\pi^-$ Mass Spectra

[LHCb, JHEP 09 (2013) 145] [LHCb, JHEP 10 (2012) 151]

Cross-feeds estimated from states appearing in the D*π spectrum





2 more natural states:

$D_J^*(3000)^0$, $D_J^*(3000)^+$

Resonance	Final state	Mass (MeV)	Width (MeV)	Yields $\times 10^3$	Signif (σ)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	$210.2 \pm 1.9 \pm 0.7$	
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	$81.9 \pm 1.2 \pm 0.9$	
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$D^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	$14.4 \pm 1.7 \pm 1.7$	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

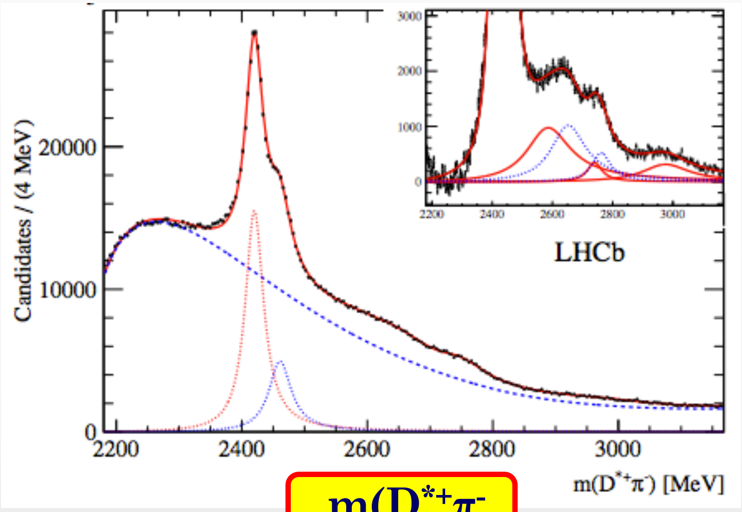
Study of $D^{(*)}\pi$ spectrum from B decays needed to establish spin-parity

SPECTROSCOPY OF D**: INCLUSIVE ANALYSES

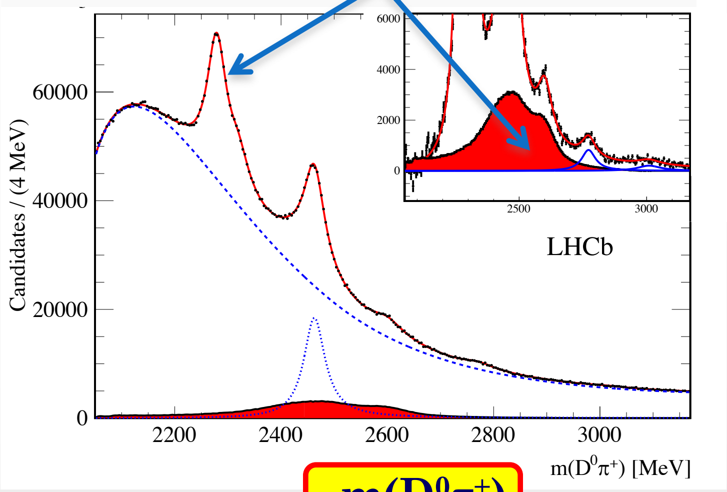
[LHCb: JHEP 09 (2013) 145]

Search for $D^{**} \rightarrow D^{(*)}\pi$

Cross-feeds estimated from states observed in the D*π spectrum



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

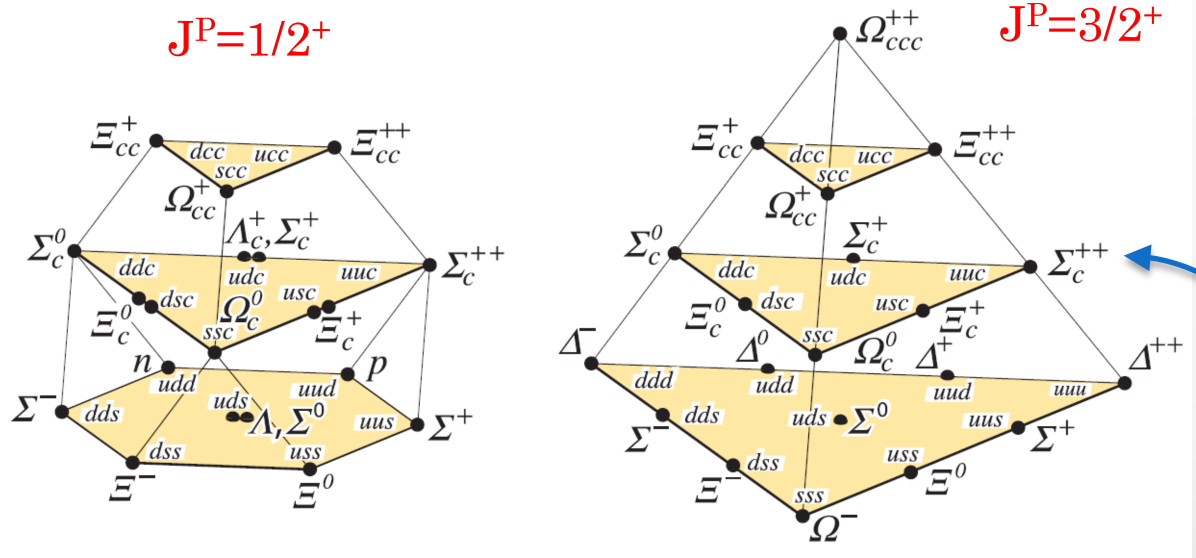


$m(D^0\pi^+)$

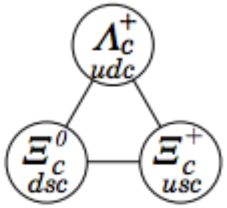
- Confirmation and observation of new excited states
- Precise measurement of masses and widths
- "Naturalness" determined by the distribution of helicity angle in the D*π
- New states can be interpreted as radial excitations (*D(2S)* and *D*(2S)*) and orbital L=2 excitations ($D_2(1D)$ and $D_1^*(1D)$)
- Studies in B decays required for determining spin-parity

GROUND STATES

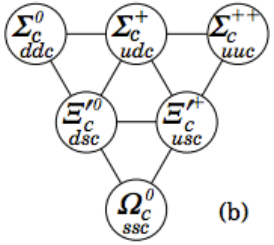
SU(4) Multiplets



j=0⁺ $J^P=1/2^+$

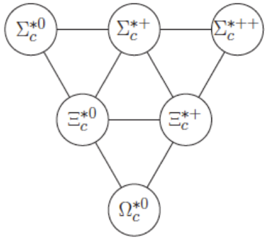


j=1⁺ $J^P=1/2^+$

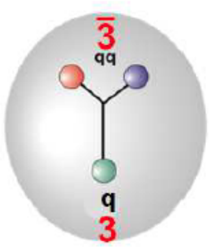


N.B. Ω_c^0 doesn't belong to the same multiplet of the well famous Ω^-

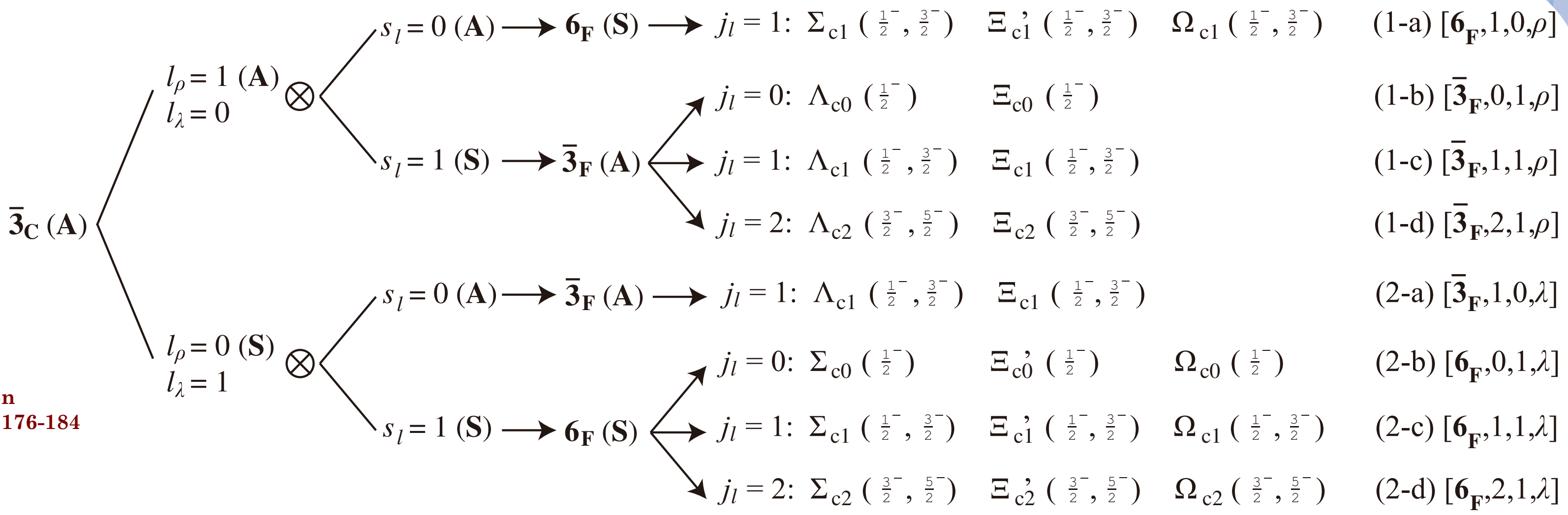
j=1⁺ $J^P=3/2^+$



P-WAVE STATES



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



$\bar{3}_C$ (A)

$l_\rho = 1$ (A), $l_\lambda = 0$ ⊗

- $s_l = 0$ (A) → 6_F (S) → $j_l = 1$: $\Sigma_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi'_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Omega_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ (1-a) $[\mathbf{6}_F,1,0,\rho]$
- $s_l = 1$ (S) → $\bar{3}_F$ (A) →
  - $j_l = 0$: $\Lambda_{c0}\,(\frac{1}{2}^-)$ $\Xi_{c0}\,(\frac{1}{2}^-)$ (1-b) $[\bar{\mathbf{3}}_F,0,1,\rho]$
  - $j_l = 1$: $\Lambda_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ (1-c) $[\bar{\mathbf{3}}_F,1,1,\rho]$
  - $j_l = 2$: $\Lambda_{c2}\,(\frac{3}{2}^-, \frac{5}{2}^-)$ $\Xi_{c2}\,(\frac{3}{2}^-, \frac{5}{2}^-)$ (1-d) $[\bar{\mathbf{3}}_F,2,1,\rho]$

$l_\rho = 0$ (S), $l_\lambda = 1$ ⊗

- $s_l = 0$ (A) → $\bar{3}_F$ (A) → $j_l = 1$: $\Lambda_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ (2-a) $[\bar{\mathbf{3}}_F,1,0,\lambda]$
- $s_l = 1$ (S) → 6_F (S) →
  - $j_l = 0$: $\Sigma_{c0}\,(\frac{1}{2}^-)$ $\Xi'_{c0}\,(\frac{1}{2}^-)$ $\Omega_{c0}\,(\frac{1}{2}^-)$ (2-b) $[\mathbf{6}_F,0,1,\lambda]$
  - $j_l = 1$: $\Sigma_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi'_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Omega_{c1}\,(\frac{1}{2}^-, \frac{3}{2}^-)$ (2-c) $[\mathbf{6}_F,1,1,\lambda]$
  - $j_l = 2$: $\Sigma_{c2}\,(\frac{3}{2}^-, \frac{5}{2}^-)$ $\Xi'_{c2}\,(\frac{3}{2}^-, \frac{5}{2}^-)$ $\Omega_{c2}\,(\frac{3}{2}^-, \frac{5}{2}^-)$ (2-d) $[\mathbf{6}_F,2,1,\lambda]$

[Phys. Rev. D91 (2015) 054034]

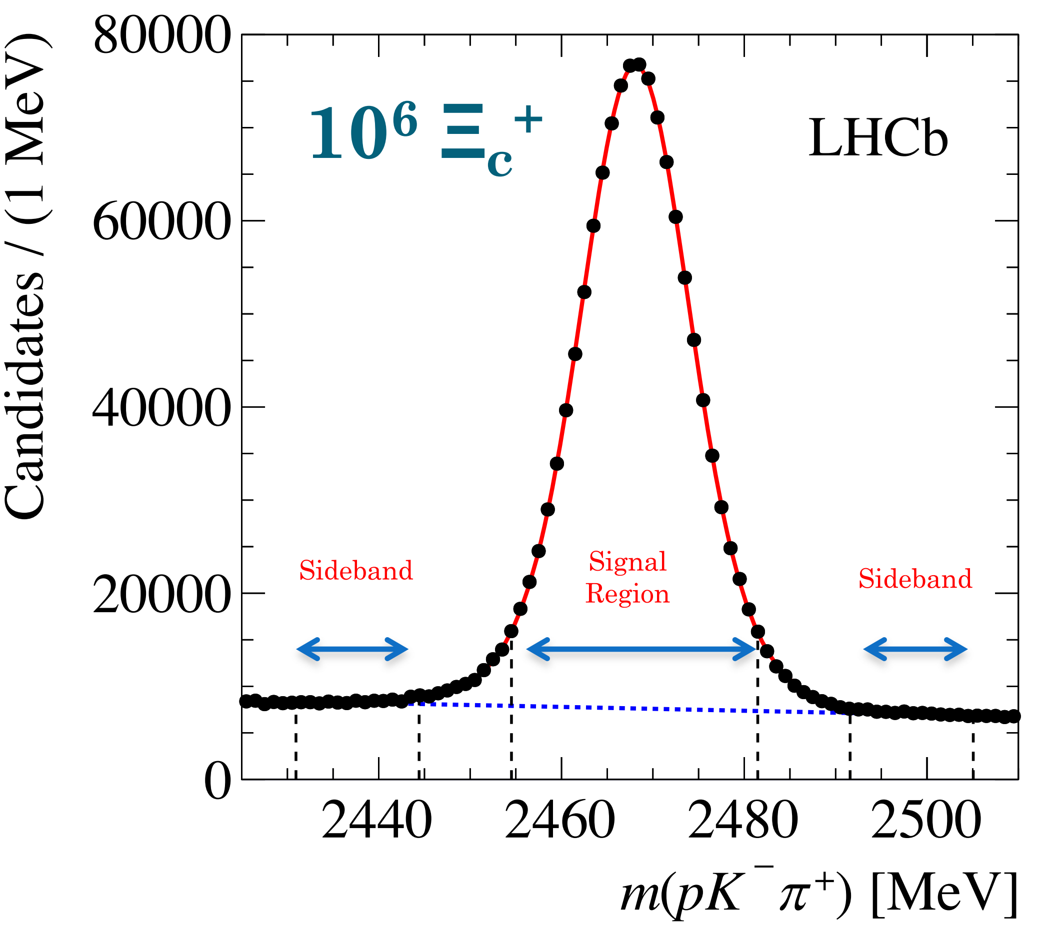
For each $j_{qq}>0$ → doublet $J^P = j_{qq} \pm 1/2$

7 excited $L = 1$ Ω_c → 5λ-mode excited states

D- wave: 14 excited $L = 2$ Ω_c → 6λ-mode excited states

The Inclusive Ξ_c^+ Sample

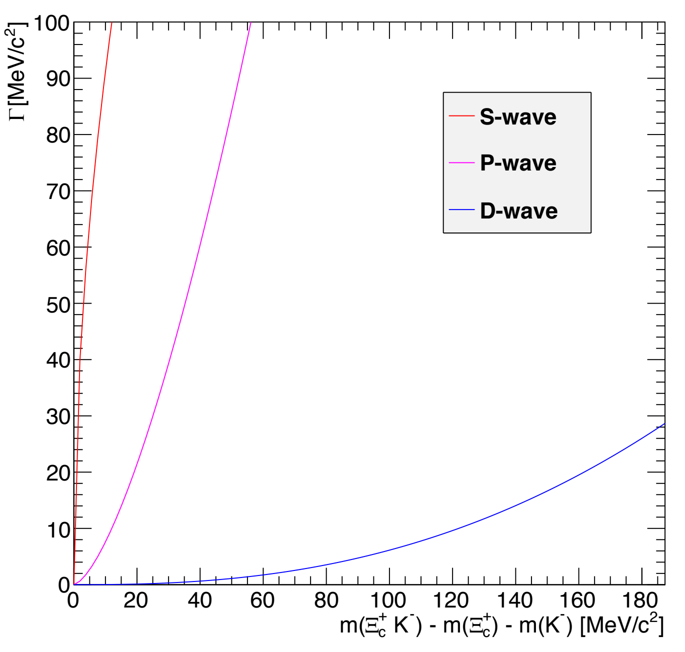
[arXiv:1703.04639]



Mass resolution: 6.8 MeV
Signal purity ~ 83%

WHAT ARE THEY?

We have already seen the mass predictions but what about the widths?

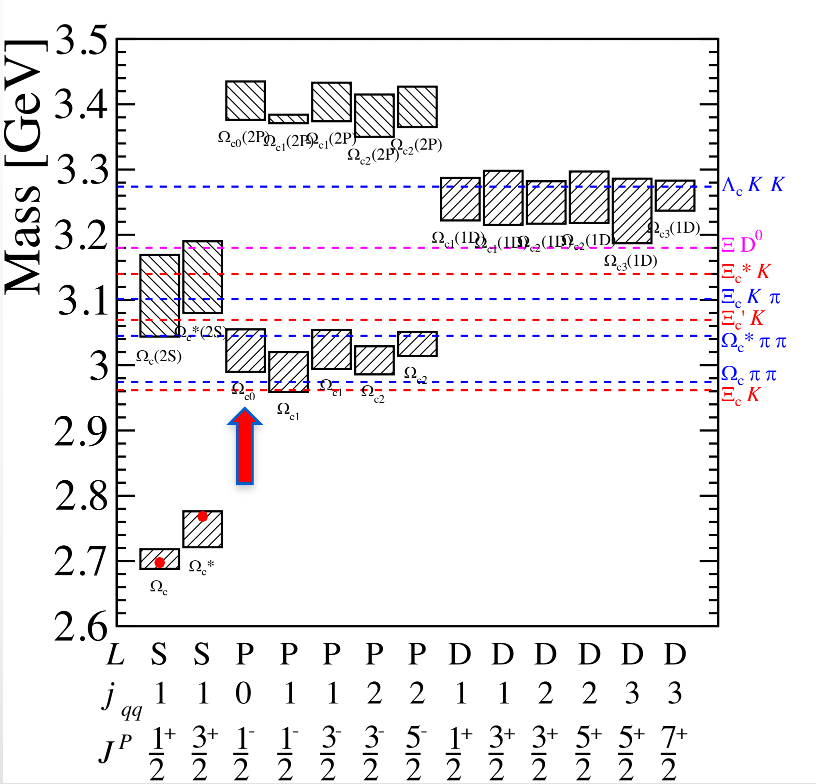


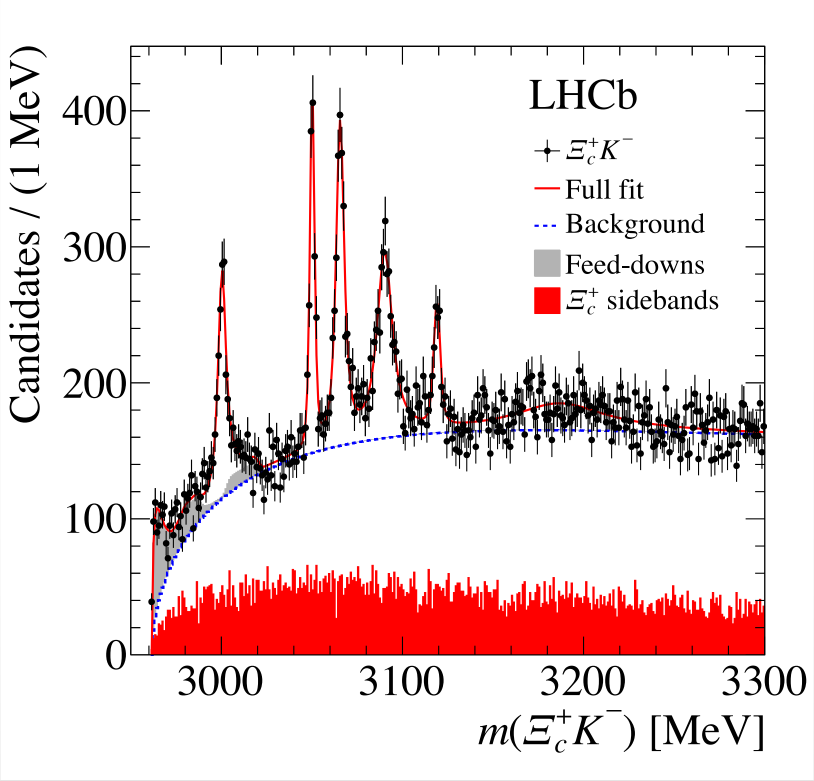
$$
\begin{aligned}
S\text{–wave}: \quad & \Gamma \sim 100\,\text{MeV} \times \left[\frac{E_K - m_K}{10\,\text{MeV}}\right]^{1/2}, \\
P\text{–wave}: \quad & \Gamma \sim 10\,\text{MeV} \times \left[\frac{E_K - m_K}{10\,\text{MeV}}\right]^{3/2}, \\
D\text{–wave}: \quad & \Gamma \sim 10\,\text{MeV} \times \left[\frac{E_K - m_K}{100\,\text{MeV}}\right]^{5/2}.
\end{aligned}
$$

[G. Chiladze, A. Falk: PRD 56 (1997) R6738]

Only D–wave transitions should return narrow states

WHAT ARE THEY?

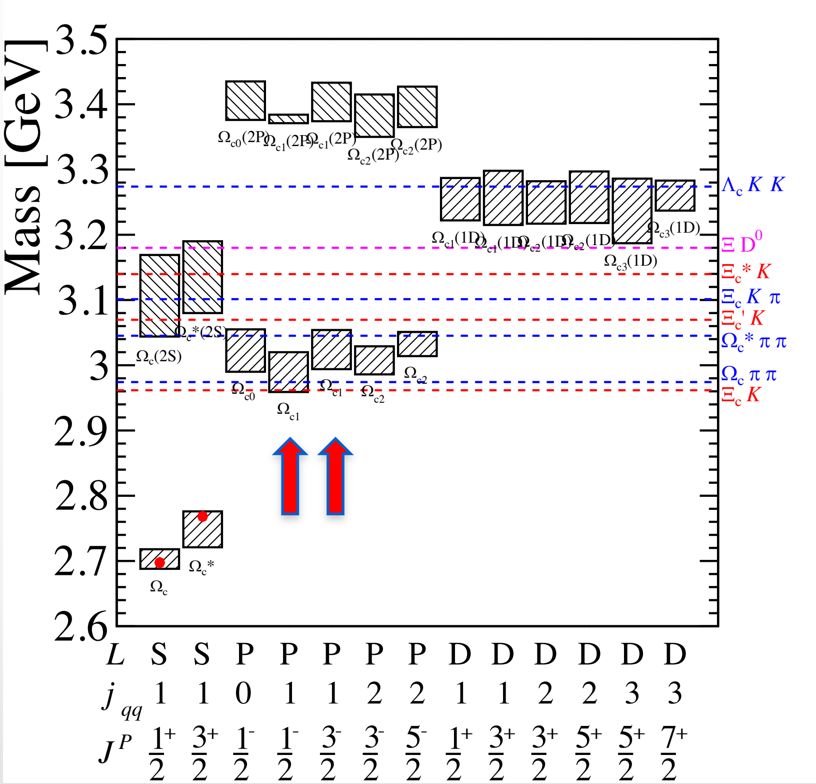


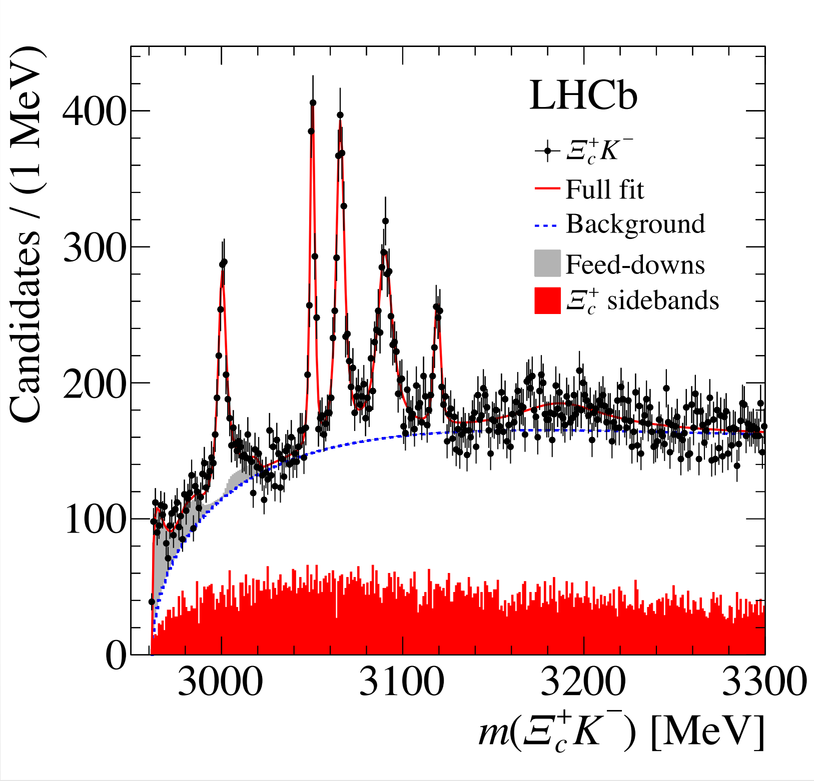


Ω_{c0} can decay to $\Xi_c K$ by S-wave→ Broad

In the framework of HQET, J^P and j_{qq} must be preserved during the strong decays of a state into another

WHAT ARE THEY?

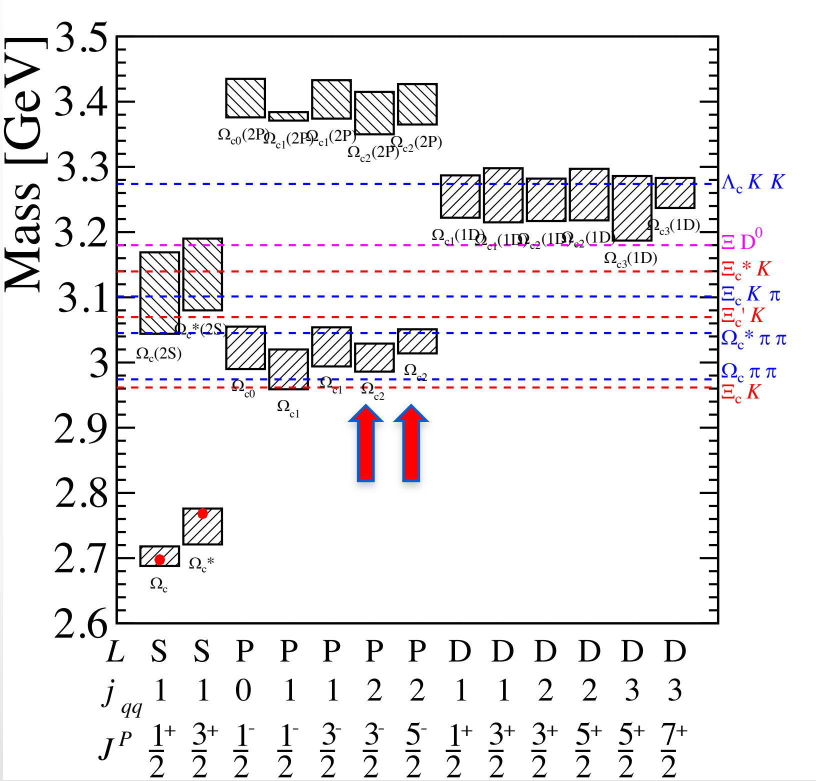


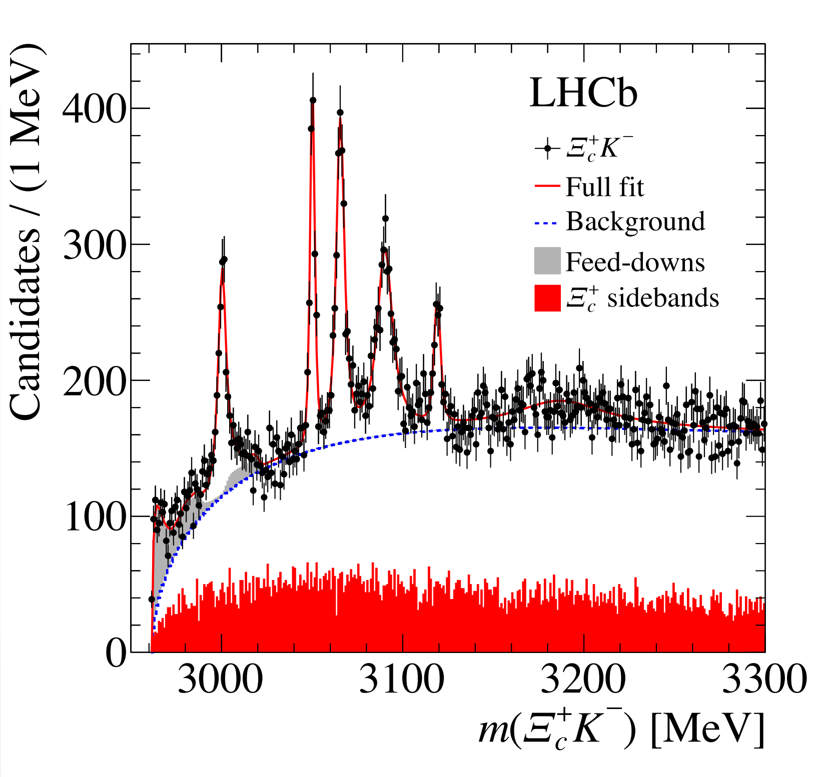


Ω_{c1}'s CAN'T decay to $\Xi_c K$

N.B. Ω_{c1}'s could decay to Ξ_c'K (if masses above the Ξ_c'K threshold)

WHAT ARE THEY?

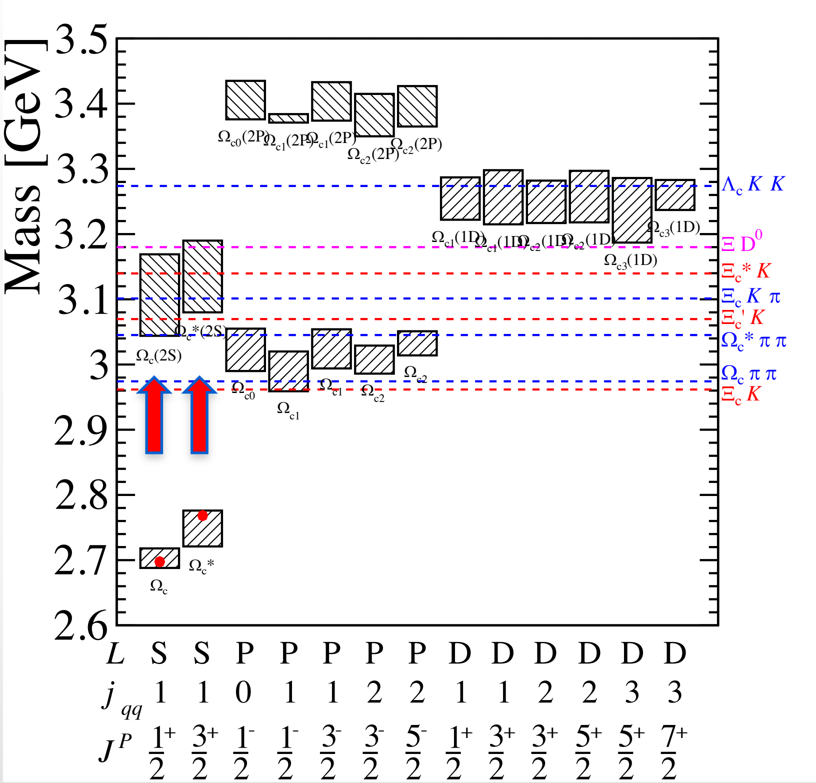


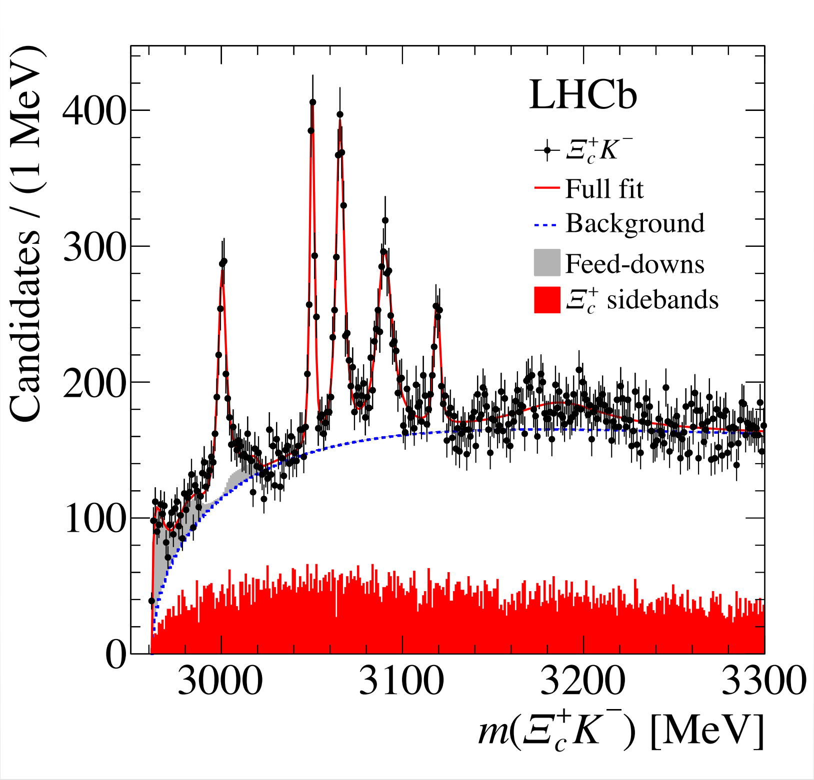


Ω_{c2}'s can decay to $\Xi_c K$ by D-wave → Narrow

In the framework of HQET, J^P and j_{qq} must be preserved during the strong decays of a state into another

WHAT ARE THEY?



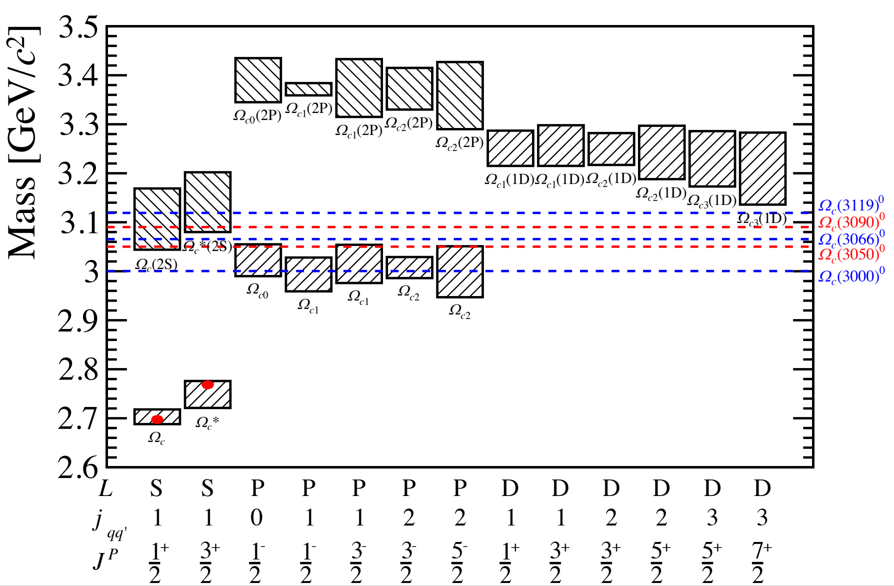


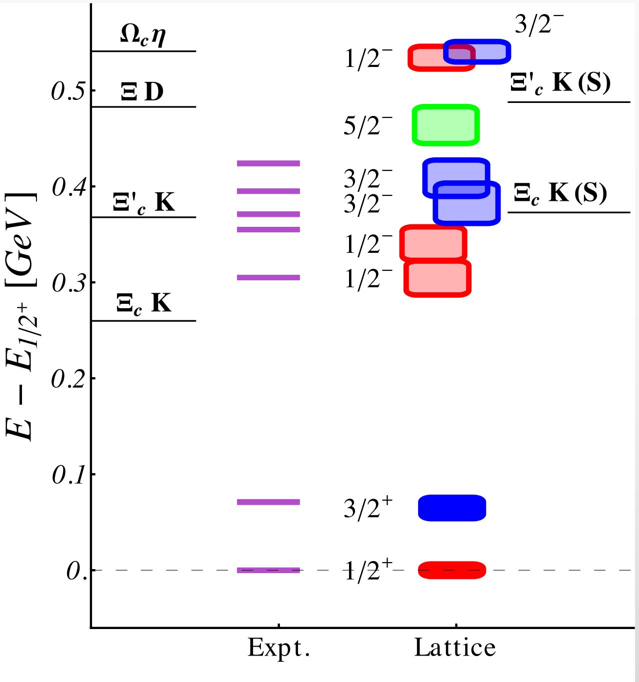
Ω_c(2S) and Ω_c^*(2S) can decay to Ξ_cK and Ξ_c'K by P-wave → ~Broad

In the framework of HQET, J^P and j_{qq} must be preserved during the strong decays of a state into another

WHAT ARE THEY?

Most of the authors identified these states as the orbitally or radially excitations of the Ω^0_c baryon though they struggle to explain their narrowness and decay pattern





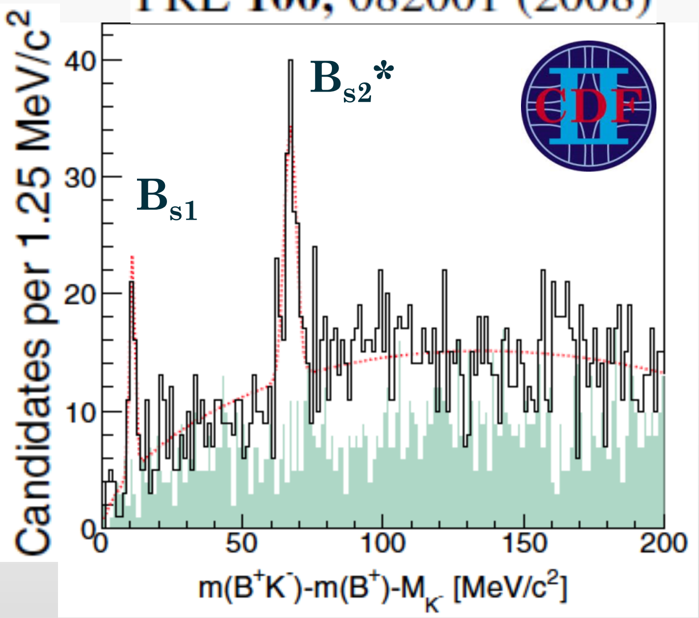
But there are some exceptions…..

$B_{S1}(5830)^0$ AND $B_{S2}^*(5840)^0$

- Two narrow peaks observed in the B^+K^- by CDF
- B_{s2}^* is the only narrow state expected. What is the nature of the second signal?

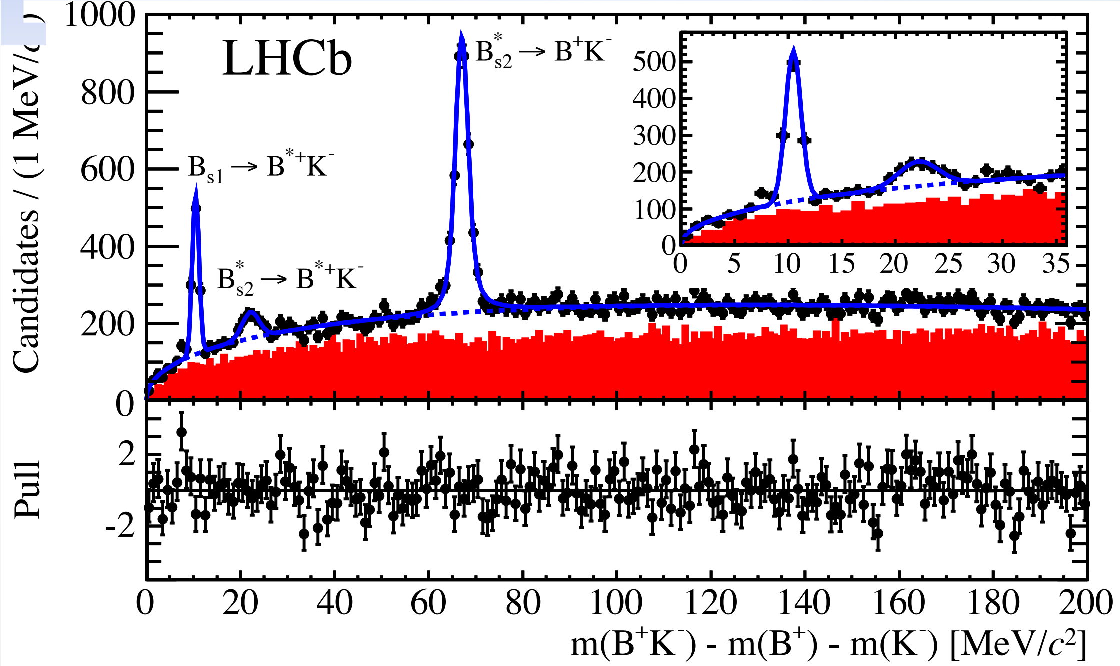
	j_q	J^P	Allowed decay mode	
			B^+K^-	$B^{*+}K^-$
B_{s0}^*	1/2	0^+	yes	no
B_{s1}'	1/2	1^+	no	yes
B_{s1}	3/2	1^+	no	yes
B_{s2}^*	3/2	2^+	yes	yes

PRL **100**, 082001 (2008)

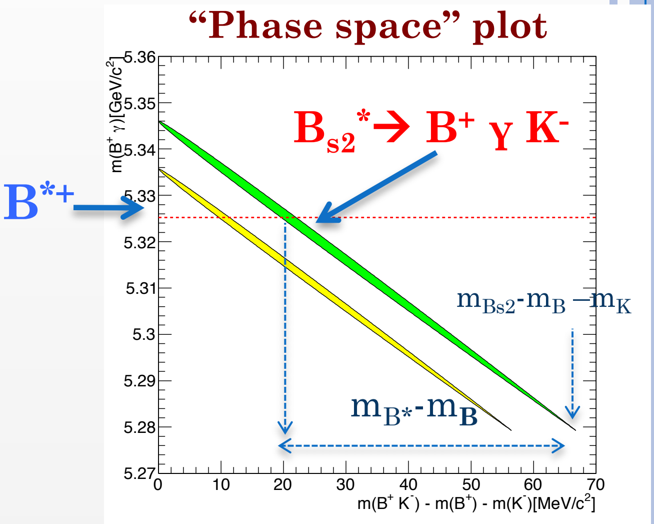


It is interpreted as a feed-down of the $B_{s1} \rightarrow B^{*+}K^-$ decay followed by $B^{*+} \rightarrow B^+ \gamma$, where the photon is not observed

$B_{S1}(5830)^0$ AND $B_{S2}^*(5840)^0$



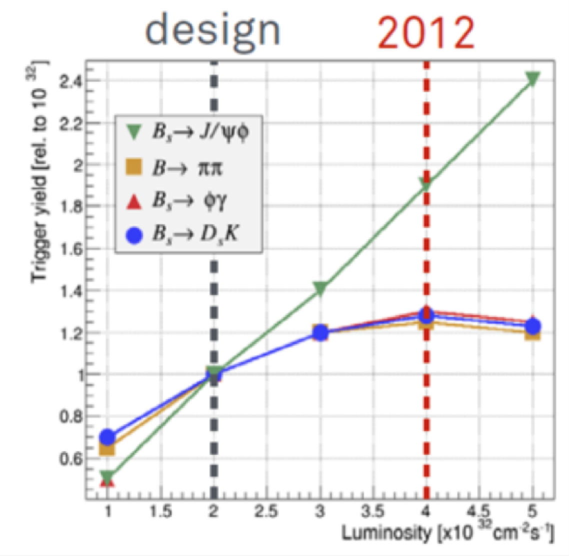
"Phase space" plot

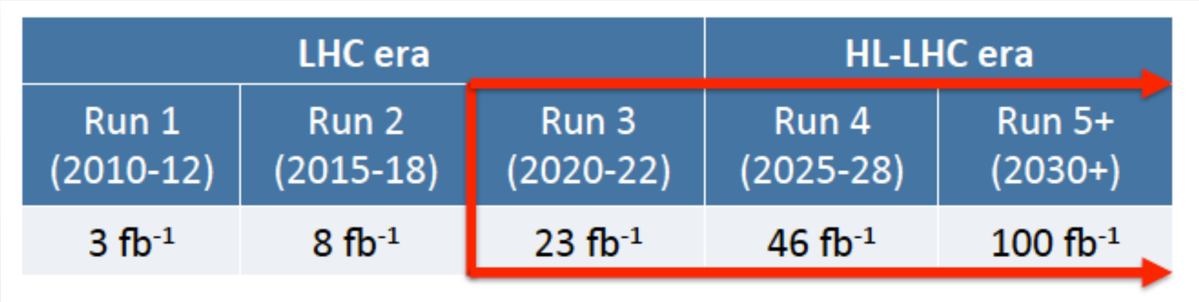


	j_q	J^P	Allowed decay mode B^+K^-	 $B^{*+}K^-$
B_{s0}^*	$1/2$	0^+	yes	no
B_{s1}'	$1/2$	1^+	no	yes
B_{s1}	$3/2$	1^+	no	yes
B_{s2}^*	$3/2$	2^+	yes	yes

LHCb GOING TO UPGRADE IN 2018

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
  - ✓ – Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- This is particularly problematic for hadronic final states





LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

LHCb upgrade
Running at 2×10^{33} cm^{-2} s^{-1} with full software trigger, running at 40 MHz and record 20 kHz