DK and related hadronic molecules

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Exotic Hadrons in LHCb, 18 Oct. 2022

L. Liu, K. Orginos, FKG, C. Hanhart, U.-G. Meißner, PRD87(2013)014508;

M. Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB767(2017)465;

M.-L. Du, M. Albaladejo, P. Fernandez-Soler, FKG, C. Hanhart, U.-G. Meißner, J. Nieves, D.-L. Yao, PRD98(2018)094018;

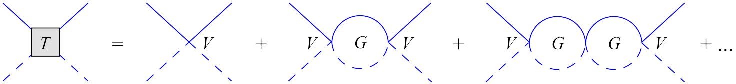
M.-L. Du, FKG, U.-G. Meißner, PRD99(2019)114002;

M.-L. Du, FKG, C. Hanhart, B. Kubis, U.-G. Meißner, PRL126(2021)192001; ...

Positive-parity charmed mesons (1)

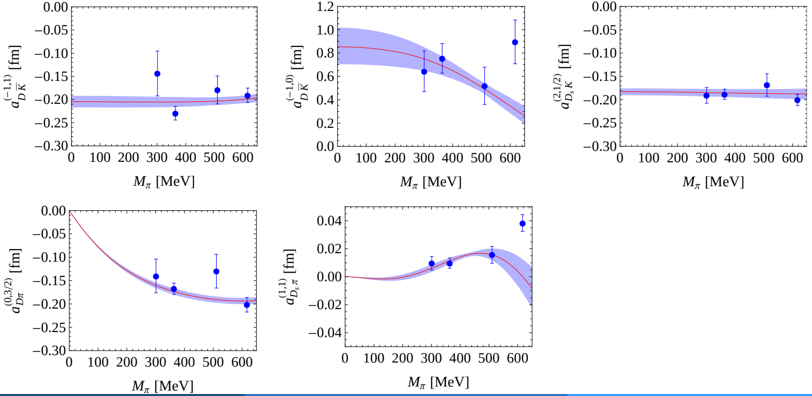
- Hadronic molecular model: $D_{s0}^*(2317)[DK]$, $D_{s1}(2460)[D^*K]$

  Barnes, Close, Lipkin(2003); van Beveren, Rupp(2003); Kolomeitsev, Lutz(2004); FKG et al.(2006); . . .

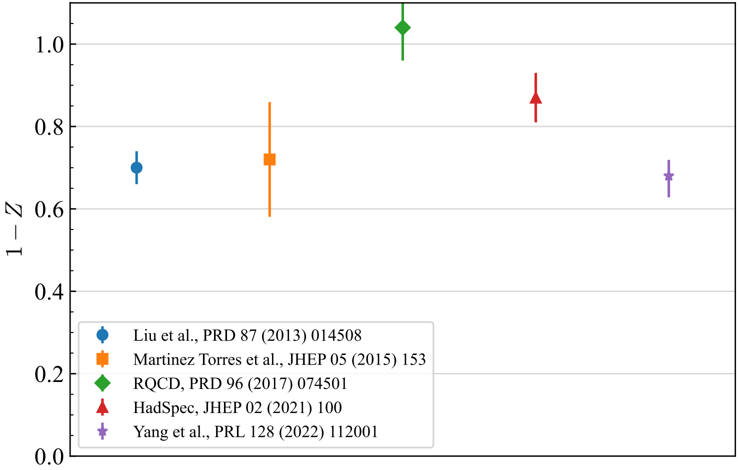


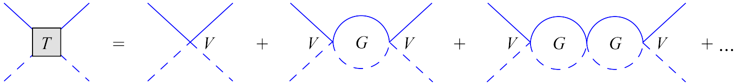
- Unitarized CHPT up to NLO

  L.Liu et al., PRD87(2013)014508



- Postdicted mass for $D_{s0}^*(2317)$: 2315^{+18}_{-28} MeV
- Compositeness (DK component) for $D_{s0}^*(2317)$ from (in)direct lattice calculations or analyses of lattice results





- Natural consequence of HQSS:

  similar binding energies $M_D + M_K - M_{D^*_{s0}} \simeq 45$ MeV

  $$M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \simeq M_{D^*} - M_D \text{ is understood}$$

- HQFS: predicting the bottom-partner masses (UCHPT Du et al., PRD98(2018)094018):

$$M_{B^*_{s0}} \simeq M_B + M_K - 45\,\text{MeV} \simeq 5730\text{ MeV} \quad \left(5720^{+16}_{-23}\text{ MeV}\right)$$
$$M_{B_{s1}} \simeq M_{B^*} + M_K - 45\,\text{MeV} \simeq 5776\text{ MeV} \quad \left(5772^{+15}_{-21}\text{ MeV}\right)$$

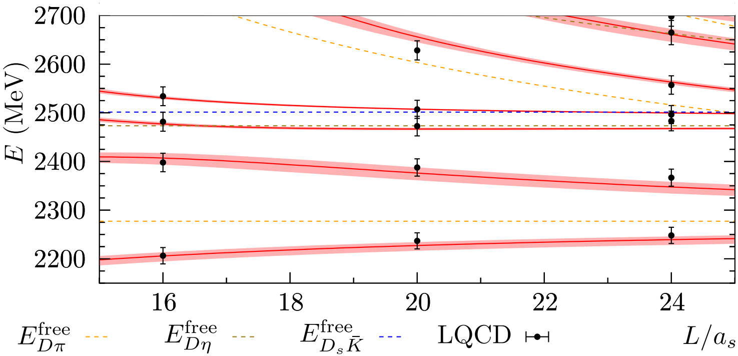
to be compared with lattice results for the lowest positive-parity bottom-strange mesons: Lang, Mohler, Prelovsek, Woloshyn, PLB750(2015)17

$$M^{\text{lat.}}_{B^*_{s0}} = (5.711 \pm 0.013 \pm 0.019)\text{ GeV}$$
$$M^{\text{lat.}}_{B_{s1}} = (5.750 \pm 0.017 \pm 0.019)\text{ GeV}$$

These B^*_{s0} and B_{s1} not found yet; for updated predictions on their radiative/pionic decays, see H.-L. Fu, Grießhammer, FKG, Hanhart, Meißner, EPJA58(2022)70

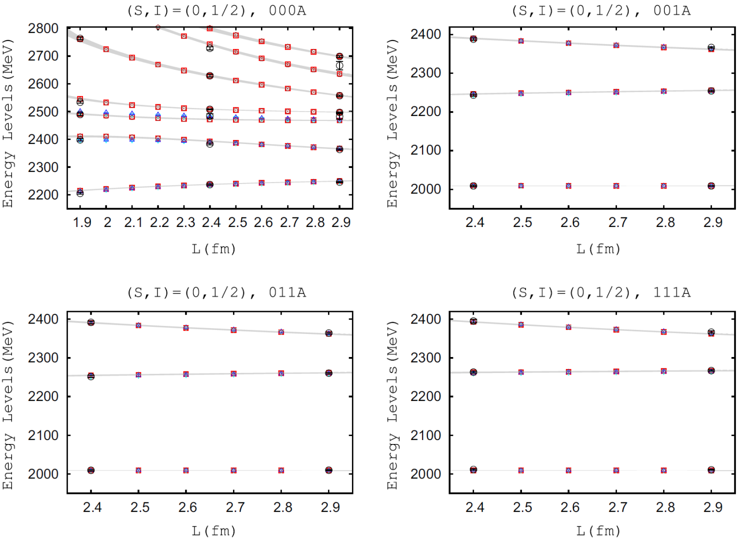
- In a finite volume: $\vec{q} = \frac{2\pi}{L}\vec{n}, \vec{n} \in \mathbb{Z}^3$; loop integral $G(s)$: $\int d^3\vec{q} \to \frac{1}{L^3}\sum_{\vec{q}}$
- Postdicted $I = 1/2\ D\pi, D\eta, D_s\bar{K}$ finite volume energy levels in the c.m. frame versus lattice QCD results by [G. Moir *et al.* [HadSpec], JHEP1610(2016)011]

NOT a fit ! M. Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB767(2017)465



consequence of SU(3) + chiral

A more recent fit to lattice data including the moving frame ones Z.-H. Guo et al., EPJC79(2019)13

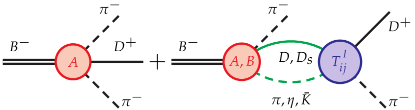


Positive-parity charmed mesons (6): $D_0^*(2300)$ contains TWO states!

- Heavy-nonstrange, two $I = 1/2$ states $(M, \Gamma/2)$ Du et al., PRD98(2018)094018

	Lower (MeV)	Higher (MeV)	PDG2022 (MeV)
D_0^*	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+36}_{-26}, 134^{+7}_{-8}\right)$	$(2343 \pm 10, 115 \pm 8)$
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$	$\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$(2412 \pm 9, 157 \pm 15)$
B_0^*	$\left(5535^{+9}_{-11}, 113^{+15}_{-17}\right)$	$\left(5852^{+16}_{-19}, 36 \pm 5\right)$	–
B_1	$\left(5584^{+9}_{-11}, 119^{+14}_{-17}\right)$	$\left(5912^{+15}_{-18}, 42^{+5}_{-4}\right)$	–

With the same LECs, the LHCb data for a set of B decays are well described



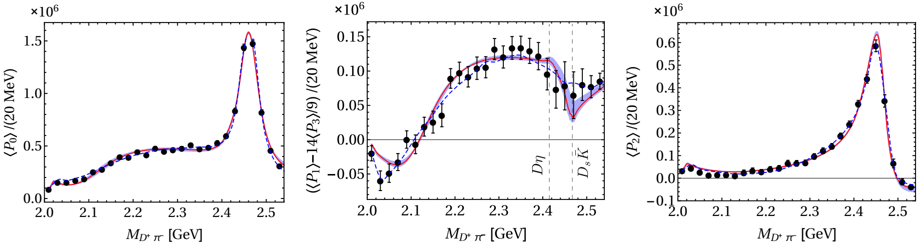
- S-wave: FSI, two new parameters
- P, D-wave: BWs from the LHCb fit

Angular moments for $B^- \to D^+\pi^-\pi^-$:

$$\langle P_0\rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2\,, \quad \langle P_2\rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_2 - \delta_0)\,,$$

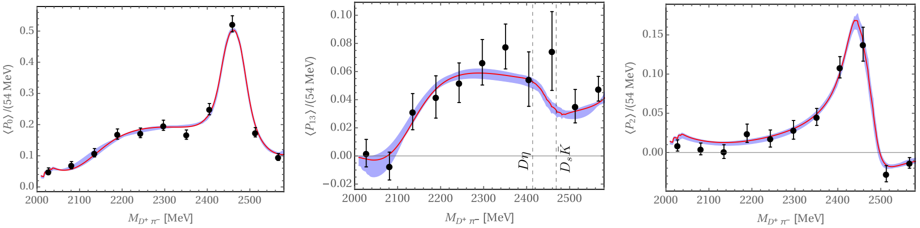
$$\langle P_{13}\rangle \equiv \langle P_1\rangle - \frac{14}{9}\langle P_3\rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1 - \delta_0)$$

Data: LHCb, PRD94(2016)072001



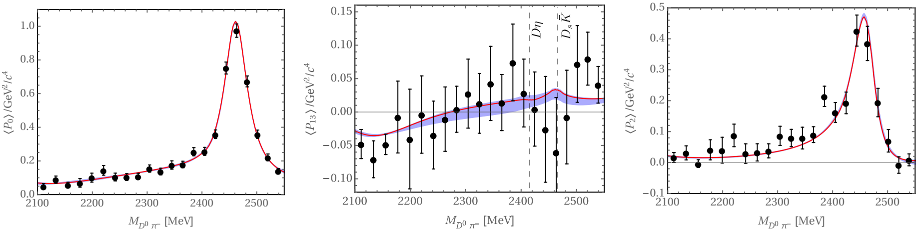
Fit to data of $B^- \to D^+\pi^- K^-$

Data: LHCb, PRD91(2015)092002



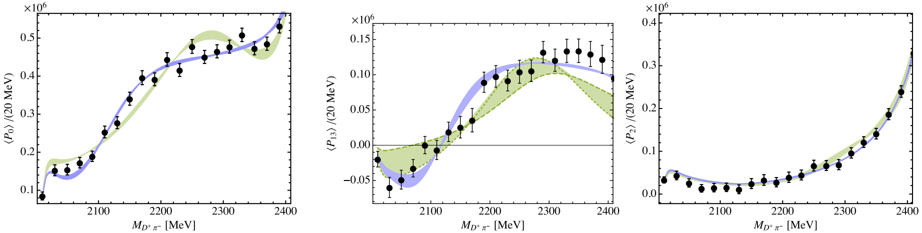
Fit to data of $B^0 \to \bar{D}^0\pi^-\pi^+$

Data: LHCb, PRD92(2015)032002



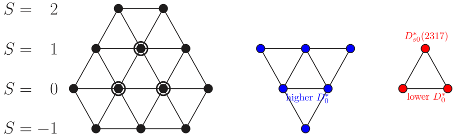
and also $B^0 \to \bar{D}^0\pi^- K^+$, $B_s^0 \to \bar{D}^0 K^-\pi^+$

- Fits with the Khuri-Treiman equation taking into account three-body unitarity: using S-wave $D\pi$ scattering phase from UCHPT (χ^2/d.o.f. $= 1.2$) and from BW (χ^2/d.o.f. $= 2.0$)



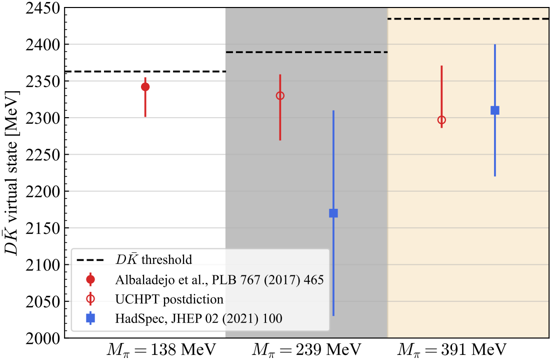
- The LHCb data are well described with UCHPT amplitude with two D_0^* states; the lower one has a mass about 2.1 GeV
- Support from lattice results:
  D_0^* with $M \approx 2.2$ GeV and $\Gamma \approx 0.4$ GeV obtained using $M_\pi \approx 239$ MeV L. Gayer et al. [HadSpec], JHEP07(2021)123
  $M = (2.12 \pm 0.03)$ MeV with $M_\pi \approx 266$ MeV Mohler, Prelovsek, Woloshyn, PRD87(2013)034501; pole given in J. Bulava et al., arXiv:2203.03230

- SU(3) irreps: $\bar{3} \otimes 8 = \overline{15} \oplus 6 \oplus \bar{3}$ Albaladejo et al., PLB767(2017)465



$(S, I) = (-1, 0)$: virtual state at 2342^{+13}_{-41} MeV at the physical mass

- HadSpec also found a virtual state HadSpec, arXiv:2008.06432



Summary and speculations

- Very strong evidence supporting $D^*_{s0}(2317)$ and $D_{s1}(2460)$ to be molecules

☞ By the same leading order interaction, there should be a whole family of kaonic bound states FKG, Meißner, PRD84(2012)014013

$D_{s1}(2860)$ as D_1K with $J^P = 1^-$; D_2K molecule with 2^-, $M \simeq 2.91$ GeV; $\Xi_{cc}\bar{K}$ molecule; $B_{1,2}\bar{K}$ molecules ($M \simeq$6.15, 6.17 GeV); ...

- Kaons are pseudo-Goldstone bosons, the interaction receives chiral suppression. If they form hadronic molecules, there must be many other molecules.

Du et al., PRD98(2018)094018

- $D^{(*)}\bar{K}$ form $I = 0$ virtual states (there should also be $D_{1,2}\bar{K}$ virtual states similarly); it's reasonable to expect $D^{(*)}\bar{K}^*$ would have bound states.

$D^*\bar{K}^*$ molecule: $X(2900)$ found by LHCb?

Then there must be partners:

spin partner $D\bar{K}^*$:~ 2760 MeV

bottom partners BK^* :~ 6175 MeV; B^*K^* :~ 6220 MeV

Then there might be deeper bound $D^{(*)}K^*/B^{(*)}\bar{K}^*$ isoscalar states.

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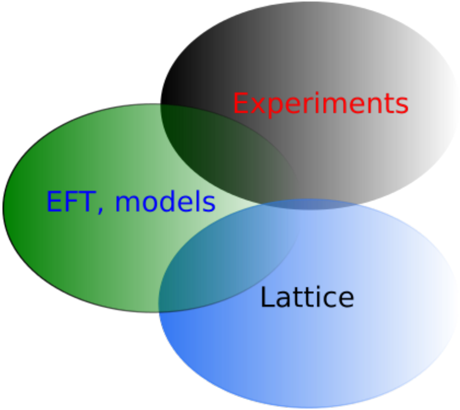


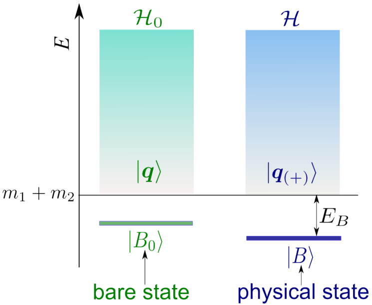
Thank you !

Backup slides

Weinberg, PR137(1965); Baru *et al.*, PLB586(2004); ...

see also, e.g., Weinberg's books: QFT Vol.I, Lectures on QM

Model-independent result for S-wave loosely bound composite states:



Consider a system with Hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + V$$

$\mathcal{H}_0$: free Hamiltonian, V: interaction potential

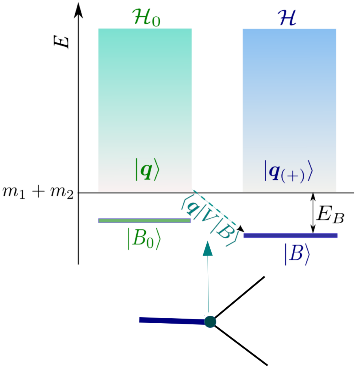
- Compositeness:

  the probability of finding the physical state $|B\rangle$ in the 2-body continuum $|\boldsymbol{q}\rangle$

$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$$

- $Z = \left|\langle B_0|B\rangle\right|^2, \qquad 0 \leq (1 - Z) \leq 1$
  - ☞ $Z = 0$: pure composite state
  - ☞ $Z = 1$: pure elementary state

Compositeness : $1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} |\langle \boldsymbol{q}|B\rangle|^2$



- Schrödinger equation

$$(\mathcal{H}_0 + V)|B\rangle = -E_B|B\rangle$$

multiplying by $\langle \boldsymbol{q}|$ and using $\mathcal{H}_0|\boldsymbol{q}\rangle = \frac{\boldsymbol{q}^2}{2\mu}|\boldsymbol{q}\rangle$

$$\langle \boldsymbol{q}|B\rangle = -\frac{\langle \boldsymbol{q}|V|B\rangle}{E_B + \boldsymbol{q}^2/(2\mu)}$$

- S-wave, small binding energy so that $R = 1/\sqrt{2\mu E_B} \gg r$, r: range of forces

$$\langle \boldsymbol{q}|V|B\rangle = g_{\rm NR}\left[1 + \mathcal{O}(r/R)\right]$$

- Compositeness:

$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \frac{g_{\rm NR}^2}{\left[E_B + \boldsymbol{q}^2/(2\mu)\right]^2}\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right] = \frac{\mu^2 g_{\rm NR}^2}{2\pi\sqrt{2\mu E_B}}\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right]$$

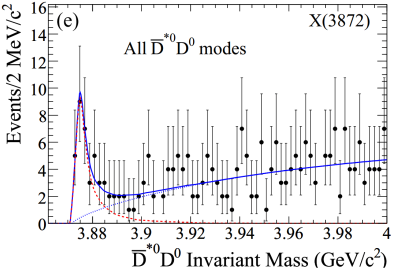
$X(3872)$ [$\chi_{c1}(3872)$]

- discovered in $B^\pm \to K^\pm J/\psi\pi\pi$ — Belle, PRL91(2003)262001

  $$M_{D^0} + M_{D^{*0}} - M_X = (0.00 \pm 0.18)\ \text{MeV}$$

- $\Gamma < 1.2$ MeV — Belle, PRD84(2011)052004
- $J^{PC} = 1^{++}$, S-wave coupling to $D\bar{D}^*$ — LHCb PRL110(2013)222001
- Observed in the $D^0\bar{D}^{*0}$ mode as well

  BaBar, PRD77(2008)011102



- Large coupling to $D^0\bar{D}^{*0}$:

  $\mathcal{B}(X \to D^0\bar{D}^{*0}) > 30\%$ — PDG2022

- Large isospin breaking:

  $$\frac{\mathcal{B}(X \to \omega J/\psi)}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$$

- 1^{++} $D\bar{D}^*$ bound state around 3.87 GeV predicted by Törnqvist — ZPC61(1994)525

- The large coupling to $D^0\bar{D}^{*0} + c.c.$ implies that $X(3872)$ must be an extended object with the longest-distance component given by $D^0\bar{D}^{*0} + c.c.$.

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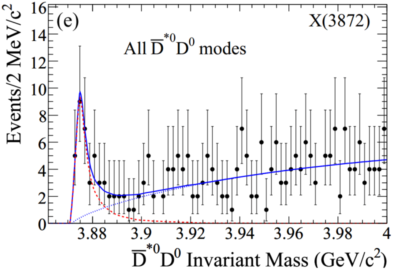

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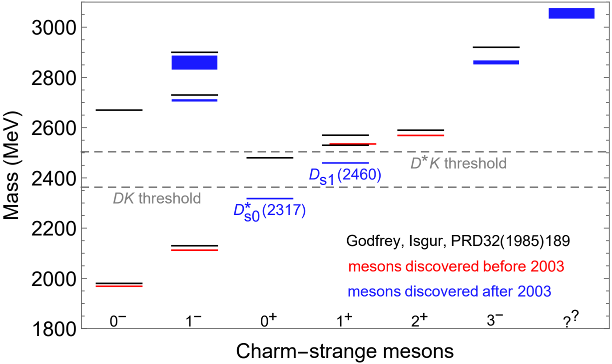
Charm-strange mesons: $D^*_{s0}(2317)$ and $D_{s1}(2460)$



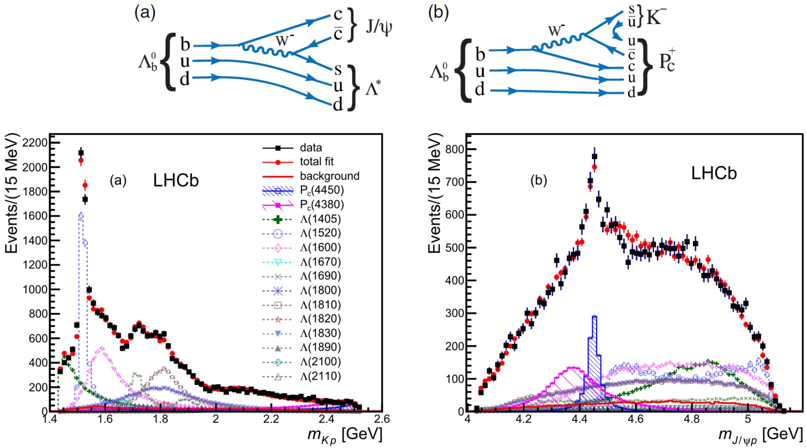
- $D^*_{s0}(2317)$: BaBar (2003)

  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$: CLEO (2003)

  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths $\Rightarrow I = 0$

- Mass problem: Why are $D^*_{s0}(2317)$ and $D_{s1}(2460)$ so light?
- Naturalness problem: Why $\underbrace{M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)}}_{(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{(140.67\pm0.08)\text{ MeV}}$?

Discovered in $\Lambda_b^0 \to J/\psi p K^-$ LHCb, PRL115(2015)072001 [arXiv:1507.03414]



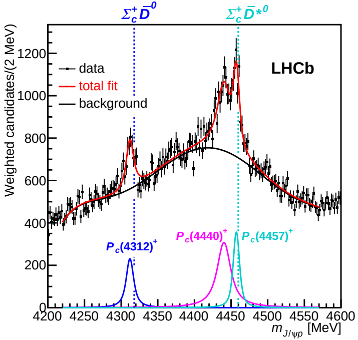
Two Breit–Wigner resonances, quantum numbers not fixed:

$$M_1 = (4380 \pm 8 \pm 29)\ \text{MeV}, \qquad \Gamma_1 = (205 \pm 18 \pm 86)\ \text{MeV},$$

$$M_2 = (4449.8 \pm 1.7 \pm 2.5)\ \text{MeV}, \qquad \Gamma_2 = (39 \pm 5 \pm 19)\ \text{MeV}.$$

The 2019 update of LHCb's P_c: three narrow states

LHCb, PRL122(2019)222001



State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

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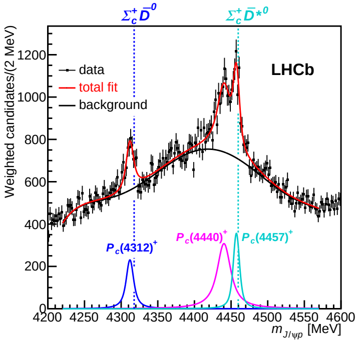

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$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

J^P	Λ	$\bar{D}\Sigma_c$ *PB* system	$\bar{D}^*\Sigma_c$ *VB* system
		$M - i\Gamma/2$	$M - i\Gamma/2$
$\frac{1}{2}^-$	650	–	–
	800	–	$4462.178 - 0.002i$
	1200	$4318.964 - 0.362i$	$4459.513 - 0.417i$
	1500	$4314.531 - 1.448i$	$4454.088 - 1.662i$
	2000	$4301.115 - 5.835i$	$4438.277 - 7.115i$
$\frac{3}{2}^-$	650	–	–
	800	–	$4462.178 - 0.002i$
	1200	–	$4459.507 - 0.420i$
	1500	–	$4454.057 - 1.681i$
	2000	–	$4438.039 - 7.268i$

$\bar{D}^{(*)}\Sigma_c$ molecules predicted:

prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV, J.-J. Wu, R. Molina, E. Oset, B.-S. Zou, PRL105(2010)232001

J.-J. Wu, T.-S. H. Lee, B.-S. Zou, PRC85(2012)044002

Other predictions: W.L.Wang et al.('11); Z.C.Yang et al.('12); Xiao, Nieves, Oset('13); Karliner, Rosner('15)