Hadronic molecules with heavy quarks

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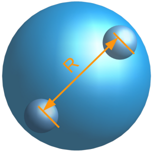
For a review of hadronic molecules, see:
FKG, C.Hanhart, U.-G.Meißner, Q.Wang, Q.Zhao, B.-S.Zou, Rev. Mod. Phys. **90** (2018) 015004

Hadronic molecules (1)

- Hadronic molecule: analogues of deuteron and other light nuclei
  dominant component is a composite state of 2 or more hadrons; extended

- Concept at large distances, so that can be approximated by system of multi-hadrons at low energies
  Consider a 2-body bound state with a mass $M = m_1 + m_2 - E_B$

  size: $R \sim \frac{1}{\sqrt{2\mu E_B}} \gg r_{\text{hadron}}$



  $\Rightarrow$ well-separated scales, nonrelativistic EFT

- Only narrow hadrons can be considered as components of hadronic molecules, $\Gamma_h \ll 1/r$, r: range of forces

FKG, Meißner, PRD84(2011)014013; see also Filin *et al.*, PRL105(2010)019101

- Defining property: large coupling to its constituents
- For S-wave shallow bound states, compositeness $(1-Z)$ related to measurable quantities

  compositeness: probability of the physical state being a 2-body composite state

  Weinberg, PR137(1965); Baru *et al.*, PLB586(2004); Hyodo, IJMPA28(2013)1330045; ...

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

  Coupling: $$|g_{\rm NR}|^2 \approx (1-Z)\frac{2\pi}{\mu^2}\sqrt{2\mu E_B} \leq \frac{2\pi}{\mu^2}\sqrt{2\mu E_B}$$

  ERE parameters: $$a \approx -\frac{2(1-Z)}{(2-Z)\sqrt{2\mu E_B}}, \quad r_e \approx -\frac{Z}{(1-Z)\sqrt{2\mu E_B}}$$

  Example: deuteron as pn. Exp.: $E_B = 2.2$ MeV, $a_{^3S_1} = -5.4$ fm;

  $$a_{Z=1} = 0 \text{ fm}, \qquad a_{Z=0} = (-4.3 \pm 1.4) \text{ fm}$$

- $X(3872)$; P_c; positive-parity charmed mesons

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$X(3872)$

L. Dai, FKG, T. Mehen, PRD101(2020)054024

FKG, PRL122(2019)202002

S. Sakai, H.-J. Jing, FKG, arXiv:2008.10829

New LHCb measurements:

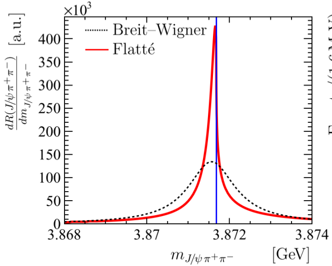
- from $B^+ \to J/\psi\pi^+\pi^-K^+$: LHCb, arXiv:2005.13422

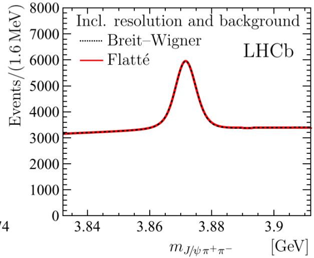
$$\text{Breit-Wigner width}: \quad \Gamma_{\text{BW}} = 0.96^{+0.19}_{-0.18} \pm 0.21 \text{ MeV}$$

- from b-hadron decays in the $J/\psi\pi^+\pi^-$ mode: LHCb, arXiv:2005.13419

$$\text{Breit-Wigner width}: \quad \Gamma_{\text{BW}} = 1.39 \pm 0.24 \pm 0.10 \text{ MeV}$$

$$\text{Flatté half-max. width}: \quad \Gamma_{\text{Flatté}} = 0.22^{+0.06+0.25}_{-0.08-0.17} \text{ MeV}$$

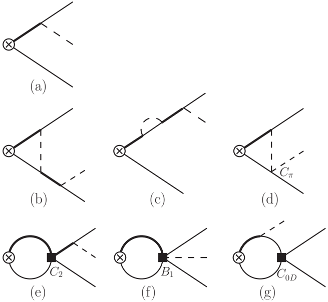


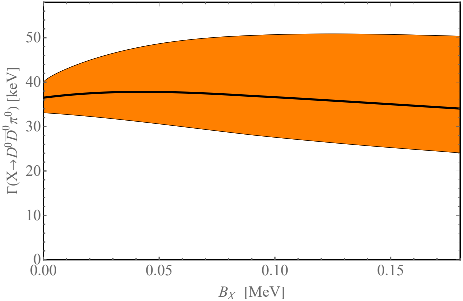


Do not use BW for near-threshold structures!

Width of the $X(3872)$ (2)

- $X(3872) \to D^0\bar{D}^0\pi^0$ in XEFT: Fleming et al., PRD76(2007)034006; L. Dai, FKG, Mehen, PRD101(2020)054024

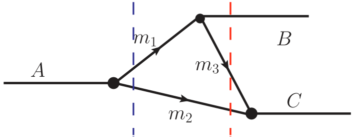




In the molecular picture: $\Gamma(X \to D^0\bar{D}^0\pi^0) = 36^{+14}_{-12}$ keV; would be smaller if $X(3872)$ is non-molecular

- $\mathcal{B}(X \to D^0\bar{D}^0\pi^0) > 40\%$ PDG2020
- Upper limit of the total width: $\Gamma(X) < 125$ keV see also, Mehen, PRD92(2015)034019
- can be precisely measured at PANDA, sensitivity ~ 100 keV PANDA, EPJA55(2019)42

Towards measuring the $X(3872)$ binding energy (1): triangle singularity



$$\frac{1}{2m_A}\sqrt{\lambda(m_A^2, m_1^2, m_2^2)} \equiv \boxed{p_{2,\text{left}} = p_{2,\text{right}}} \equiv \gamma\left(\beta\, E_2^* - p_2^*\right)$$

on-shell momentum of m_2 at the left and right cuts in the A rest frame

$\beta = |\vec{p}_{23}|/E_{23}, \gamma = 1/\sqrt{1-\beta^2}$ Bayar, Aceti, FKG, Oset, PRD94(2016)074039

- $p_2 > 0$, $p_3 = \gamma\left(\beta\, E_3^* + p_2^*\right) > 0 \Rightarrow m_2$ and m_3 move in the same direction
- velocities in the A rest frame: $v_3 > \beta > v_2$

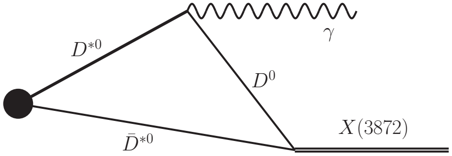
$$v_2 = \beta\, \frac{E_2^* - p_2^*/\beta}{E_2^* - \beta\, p_2^*} < \beta\,, \qquad v_3 = \beta\, \frac{E_3^* + p_2^*/\beta}{E_3^* + \beta\, p_2^*} > \beta$$

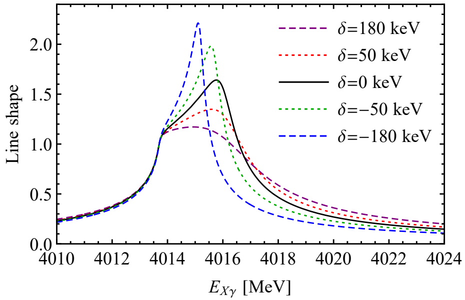
- Conditions (Coleman–Norton theorem): Coleman, Norton (1965); Bronzan (1964)
  - ☞ all three intermediate particles can go on shell simultaneously
  - ☞ $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)
- sensitive to the involved masses

Towards measuring the $X(3872)$ binding energy (2): $\gamma X(3872)$ line shape

Consider $\gamma X(3872)$ produced from S-wave $D^{*0}\bar{D}^{*0}$ at short-distances

FKG, PRL122(2019)202002





- For X blow $D^0\bar{D}^{*0}$ threshold, $\delta > 0$, TS is complex, smooth shape
- For X above $D^0\bar{D}^{*0}$ threshold, $\delta < 0$, TS is real $\Rightarrow$ logarithmic divergent peak if neglecting D^{*0} width
- Sharper peak when $\delta < 0$

$$E_{X\gamma}^{\text{TS}} \simeq 2M_{D^{*0}} + \frac{1}{2M_{D^0}}\left(M_{D^{*0}} - M_{D^0} - 2\sqrt{-M_{D^0}\delta} + \delta\right)^2$$

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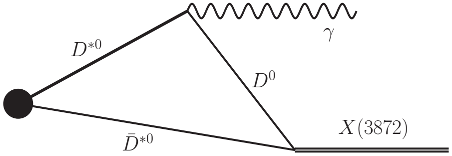
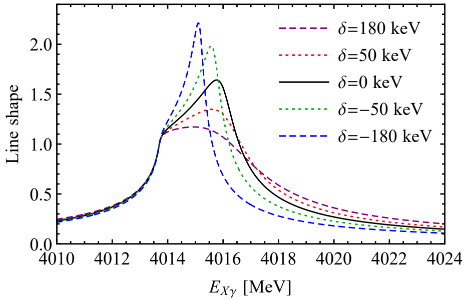




- Cusp fixed at the $D^{*0}\bar{D}^{*0}$ threshold
- Peak fixed at the TS energy:

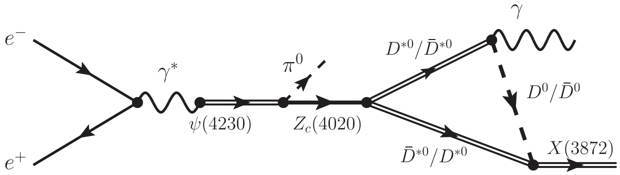
δ (keV)	$E^{\text{TS}}_{X\gamma}$ (MeV)
-180	$4015.2 - i0.1$
-50	$4015.7 - i0.2$
0	$4016.0 - i0.4$

$$E^{\text{TS}}_{X\gamma} \simeq 2M_{D^{*0}} + \frac{1}{2M_{D^0}}\left(M_{D^{*0}} - M_{D^0} - 2\sqrt{-M_{D^0}\delta} + \delta\right)^2$$

Towards measuring the $X(3872)$ binding energy (3): $e^+e^- \to \pi^0\gamma X(3872)$

Cross section estimate (not precise prediction): S. Sakai, H.-J. Jing, FKG, arXiv:2008.10829

- Consider $e^+e^- \to \psi(4230) \to \pi^0 Z_c(4020)^0 \to \pi^0\gamma X(3872)$,



- Consider $X(3872) \to J/\psi\pi^+\pi^-$ with a $X(3872)$ width of 100 keV
  take $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 4.1\%$ BABAR, PRL124(2020)152001

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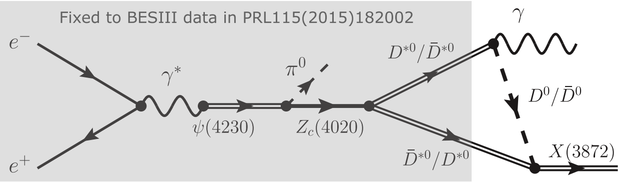

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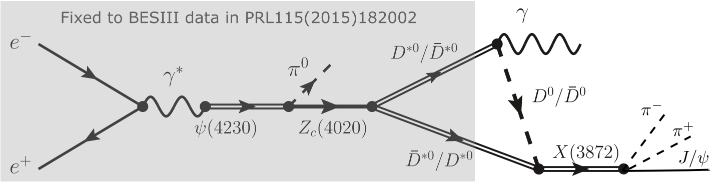

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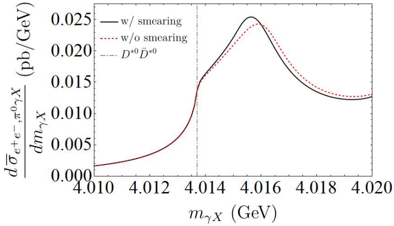

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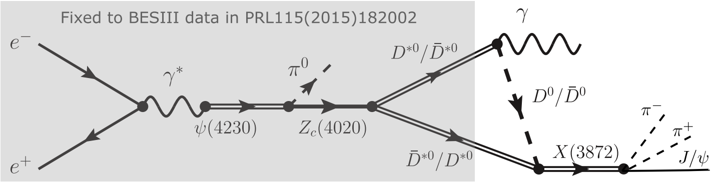

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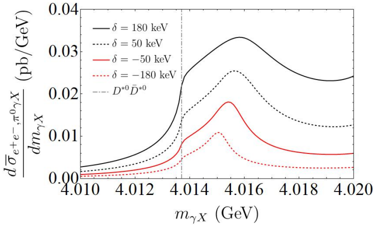
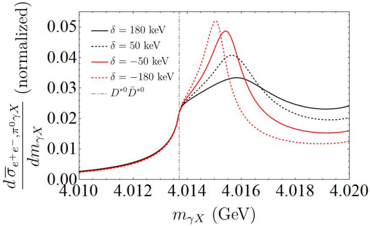
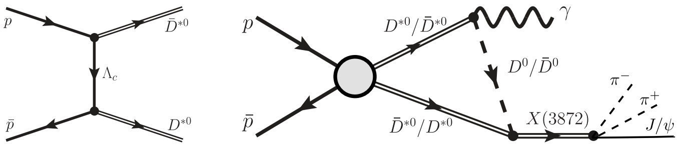
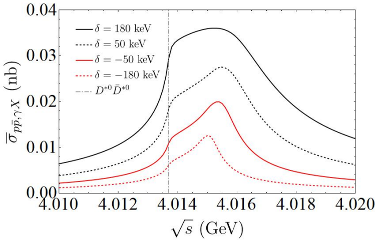


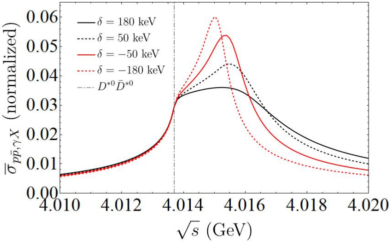


Cross section (order-of-magnitude) estimate: S. Sakai, H.-J. Jing, FKG, arXiv:2008.10829



- $\sigma(p\bar{p} \to \gamma X) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-) = \mathcal{O}(10\ \text{pb})$



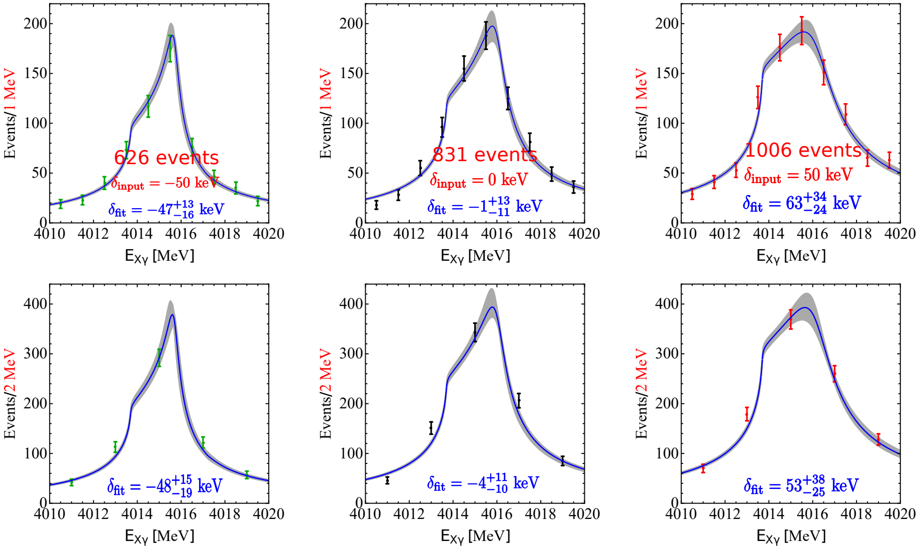


- $\mathcal{O}(2 \times 10^3)$ events taking into account $\mathcal{B}(J/\psi \to \ell^+\ell^-) \simeq 12\%$ for an integrated luminosity of 2 fb^{-1} at PANDA

PANDA, EPJA55(2019)42

- Directly probe δ, uncertainty can be smaller than that of the $D^{(*0)}$ masses

FKG, PRL122(2019)202002



P_c

M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, J. A. Oller, Q. Wang, PRL124(2020)072001

P_c states: $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecules, $P_c(4312) \sim \Sigma_c\bar{D}$, $P_c(4440, 4457) \sim \Sigma_c\bar{D}^*$?

Consider S-wave pairs of $\Sigma_c^{(*)}\bar{D}^{(*)}$ [$J_{\Sigma_c} = \frac{1}{2}, J_{\Sigma_c^*} = \frac{3}{2}$]:

$$J^P = \frac{1}{2}^- : \;\; \Sigma_c\bar{D},\; \Sigma_c\bar{D}^*,\; \Sigma_c^*\bar{D}^*$$
$$J^P = \frac{3}{2}^- : \;\; \Sigma_c^*\bar{D},\; \Sigma_c\bar{D}^*,\; \Sigma_c^*\bar{D}^*$$
$$J^P = \frac{5}{2}^- : \;\; \Sigma_c^*\bar{D}^*$$

Spin of the light degrees of freedom s_ℓ: $s_\ell(D^{(*)}) = \frac{1}{2}$, $s_\ell(\Sigma_c^{(*)}) = 1$. Thus, $s_L = \frac{1}{2}, \frac{3}{2}$

For each isospin, 2 independent terms

$$\left\langle 1, \frac{1}{2}, \frac{1}{2} \left| \hat{\mathcal{H}}_I \right| 1, \frac{1}{2}, \frac{1}{2} \right\rangle, \qquad \left\langle 1, \frac{1}{2}, \frac{3}{2} \left| \hat{\mathcal{H}}_I \right| 1, \frac{1}{2}, \frac{3}{2} \right\rangle$$

Thus, the 7 pairs are in two spin multiplets: 3 with $s_L = \frac{1}{2}$ and 4 with $s_L = \frac{3}{2}$

Seven P_c generally expected in this hadronic molecular model

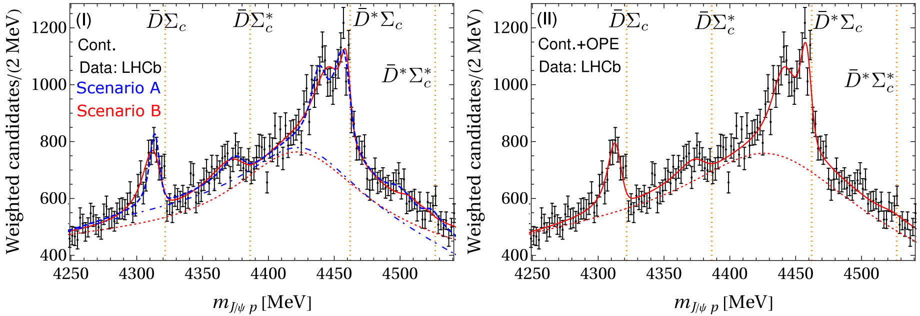
Xiao, Nieves, Oset, PRD88(2013)056012; Liu et al., PRD98(2018)114030, PRL122(2019)242001; Sakai, Jing, FKG, PRD100(2019)074007; . . .

predictions using the masses of $P_c(4440, 4457)$ as inputs   Liu et al., PRL122(2019)242001

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	13.1 – 14.5	4306.3 – 4307.7
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	13.6 – 14.8	4370.5 – 4371.7
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	3.1 – 3.5	4523.2 – 4523.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	10.1 – 10.2	4516.5 – 4516.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	25.7 – 26.5	4500.2 – 4501.0

Fit to the LHCb $J/\psi p$ data using hadronic molecular model with HQSS:
coupled channels ($\bar{D}^{(*)}\Sigma_c^{(*)}$, $J/\psi p$), complex (modeling $\Lambda_c\bar{D}^{(*)}$) contact terms + OPE

M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, J. A. Oller, Q. Wang, PRL124(2020)072001



- Scenario B is favored after considering the OPE ($\chi^2/\text{dof} = 1.0$ (B) v.s. 1.3 (A)).
- Existence of a narrow $P_c(4380)$ with a significance of about 1.7σ

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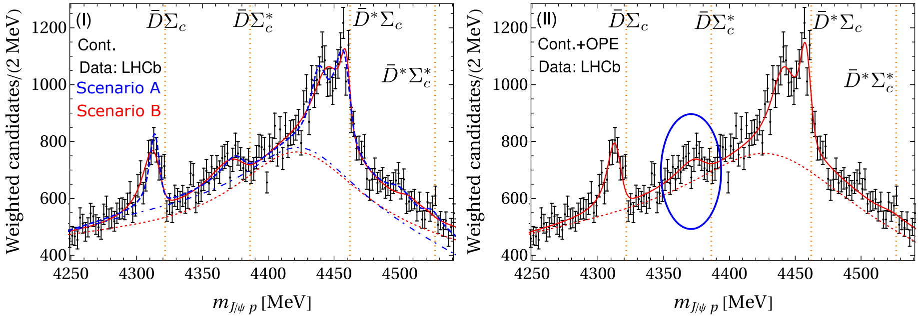

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HQSS for P_c (4)

Scheme II	J^P	Pole [MeV]	DC (threshold [MeV])	Production
$P_c(4312)$	$\frac{1}{2}^-$	$4314(2) - 5(2)i$	$\Sigma_c\bar{D}$ (4321.6)	$636(73) - 98(53)i$
$\mathbf{P_c(4380)}$	$\frac{3}{2}^-$	$4378(2) - 13(3)i$	$\Sigma_c^*\bar{D}$ (4386.2)	$618(373) - 181(95)i$
$P_c(4440)$	$\frac{3}{2}^-$	$4441(2) - 11(3)i$	$\Sigma_c\bar{D}^*$ (4462.1)	$999(140) - 15(18)i$
$P_c(4457)$	$\frac{1}{2}^-$	$4459(2) - 4(1)i$	$\Sigma_c\bar{D}^*$ (4462.1)	$-918(68) + 159(78)i$
P_c	$\frac{1}{2}^-$	$4524(2) - 9(1)i$	$\Sigma_c^*\bar{D}^*$ (4526.7)	$-228(384) + 22(23)i$
P_c	$\frac{3}{2}^-$	$4518(2) - 11(2)i$	$\Sigma_c^*\bar{D}^*$ (4526.7)	$-156(517) - 58(43)i$
P_c	$\frac{5}{2}^-$	$4498(5) - 35(17)i$	$\Sigma_c^*\bar{D}^*$ (4526.7)	$-393(620) - 2(26)i$

- Three additional P_c states $\gtrsim 4.5$ GeV: LHC Run-3, photoproduction?
- Production mechanism needs to be understood
- Different molecular model:
  $P_c(4440)$: $\frac{3}{2}^-\Sigma_c\bar{D}^*$; $P_c(4457)$: $\frac{1}{2}^+\Lambda_c(2595)\bar{D}$ Burns, Swanson, PRD100(2019)114033
- One way to distinguish the two models for $P_c(4457)$, isospin breaking decays into $J/\psi\Delta$: huge for $\Sigma_c\bar{D}^*$ FKG et al., PRD99(2019)091501; Burns, EPJA51(2015)152;
  tiny for $\Lambda_c(2595)\bar{D}$ Burns, Swanson, PRD100(2019)114033

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$P_c(4440)$	$\frac{3}{2}^-$	$4441(2) - 11(3)i$	$\Sigma_c \bar{D}^*$ (4462.1)	$999(140) - 15(18)i$
$P_c(4457)$	$\frac{1}{2}^-$	$4459(2) - 4(1)i$	$\Sigma_c \bar{D}^*$ (4462.1)	$-918(68) + 159(78)i$
P_c	$\frac{1}{2}^-$	$4524(2) - 9(1)i$	$\Sigma_c^* \bar{D}^*$ (4526.7)	$-228(384) + 22(23)i$
P_c	$\frac{3}{2}^-$	$4518(2) - 11(2)i$	$\Sigma_c^* \bar{D}^*$ (4526.7)	$-156(517) - 58(43)i$
P_c	$\frac{5}{2}^-$	$4498(5) - 35(17)i$	$\Sigma_c^* \bar{D}^*$ (4526.7)	$-393(620) - 2(26)i$

- Three additional P_c states $\gtrsim 4.5$ GeV: LHC Run-3, photoproduction?
- Production mechanism needs to be understood
- Different molecular model:
  $P_c(4440)$: $\frac{3}{2}^- \Sigma_c \bar{D}^*$; $P_c(4457)$: $\frac{1}{2}^+ \Lambda_c(2595)\bar{D}$ Burns, Swanson, PRD100(2019)114033
- One way to distinguish the two models for $P_c(4457)$, isospin breaking decays into
  $J/\psi\Delta$: huge for $\Sigma_c \bar{D}^*$ FKG et al., PRD99(2019)091501; Burns, EPJA51(2015)152;
  tiny for $\Lambda_c(2595)\bar{D}$ Burns, Swanson, PRD100(2019)114033

$$D_{s0}^*(2317), D_0^*(2300), D_{s1}(2460), D_1(2430)$$

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

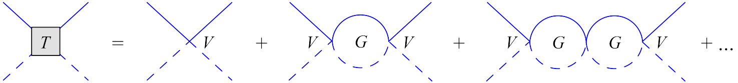
M. Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB767(2017)465

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

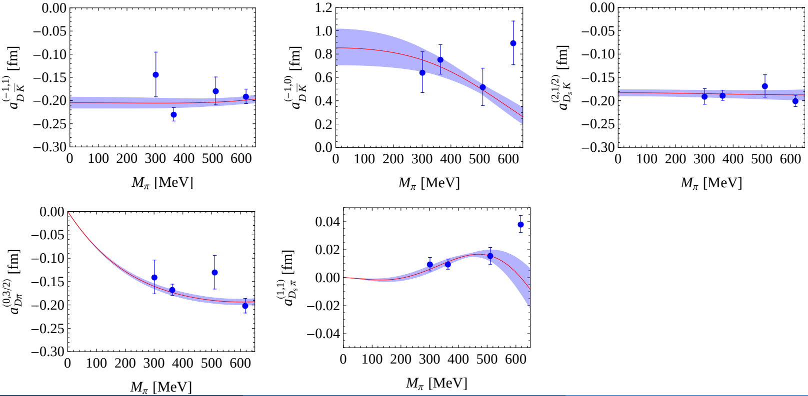
- Hadronic molecular model: $D_{s0}^*(2317)[DK]$, $D_{s1}(2460)[D^*K]$

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



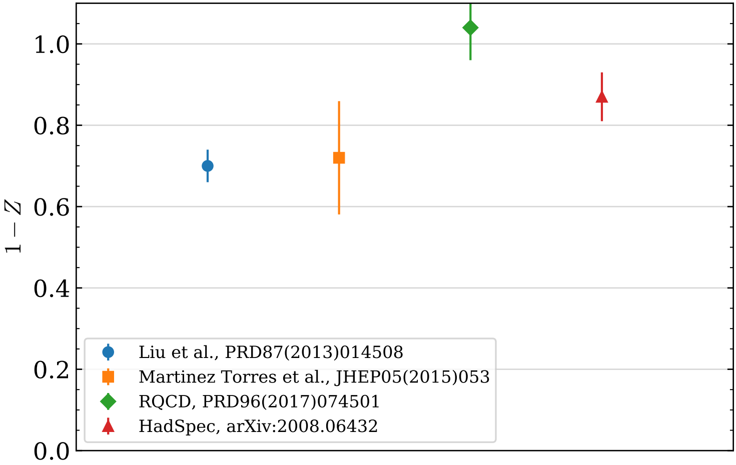
- Unitarized CHPT up to NLO

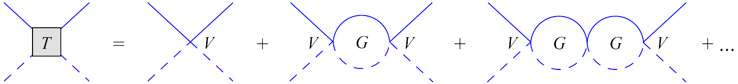
  L.Liu et al., PRD87(2013)014508



Positive-parity charmed mesons (2): compositeness

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





- 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

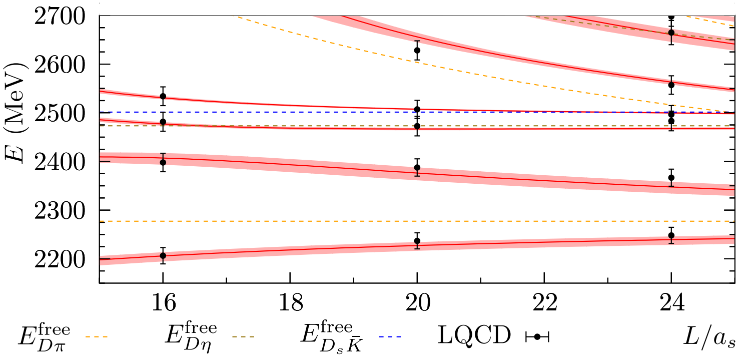
$$M_{B_{s0}^*}^{\text{lat.}} = (5.711 \pm 0.013 \pm 0.019)\text{ GeV}$$
$$M_{B_{s1}}^{\text{lat.}} = (5.750 \pm 0.017 \pm 0.019)\text{ GeV}$$

These B_{s0}^* and B_{s1} not found yet

Positive-parity charmed mesons (4): charm-nonstrange

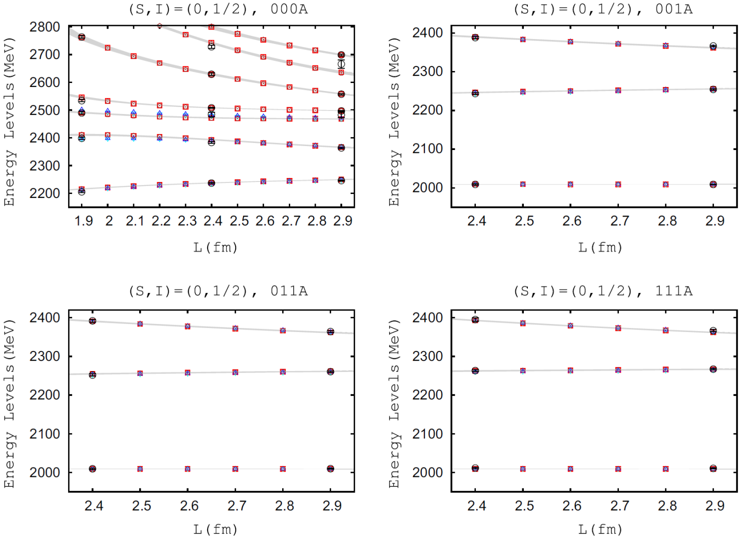
- In a finite volume: $\vec{q} = \frac{2\pi}{L}\vec{n}, \vec{n} \in \mathbb{Z}^3$; loop integral $G(s)$: $\int d^3\vec{q} \to \frac{1}{L^3}\sum_{\vec{q}}$
- Postdicted $I = 1/2\ D\pi, D\eta, D_s\bar{K}$ finite volume energy levels in the c.m. frame versus lattice QCD results by [G. Moir *et al.* [HadSpec],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

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



consequence of SU(3) + chiral

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



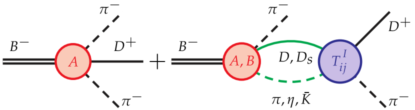
Determined parameters are similar

Lattice data: HadSpec, JHEP1610,011

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

	Lower (MeV)	Higher (MeV)	PDG2020 (MeV)
D_0^*	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+36}_{-26}, 134^{+7}_{-8}\right)$	$(2300 \pm 19, 137 \pm 20)$
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$	$\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$(2427 \pm 40, 192^{+65}_{-55})$
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



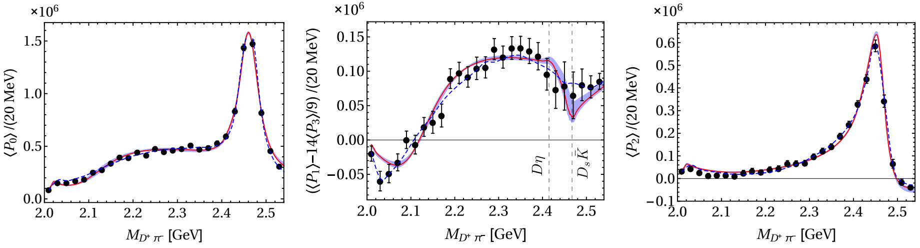
- S-wave: FSI, two new parameters
- P, D-wave: BWs from the LHCb fit

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

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

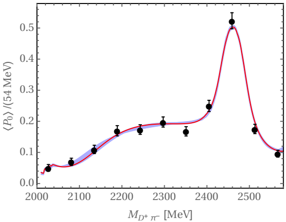
$$\langle P_{13} \rangle \equiv \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1 - \delta_0)$$

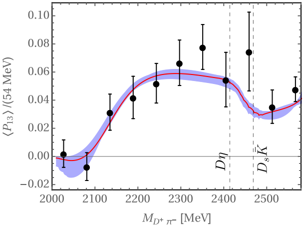
Data: LHCb, PRD94(2016)072001

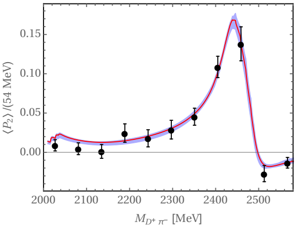


Fit to data of $B^- \to D^+\pi^-K^-$

Data: LHCb, PRD91(2015)092002

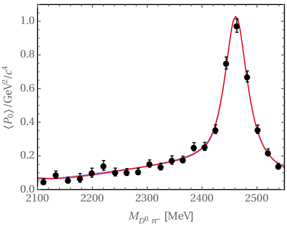


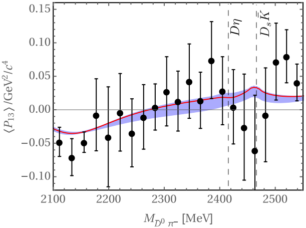


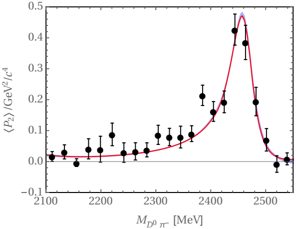


Fit to data of $B^0 \to \bar{D}^0\pi^-\pi^+$

Data: LHCb, PRD92(2015)032002

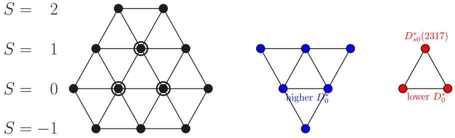






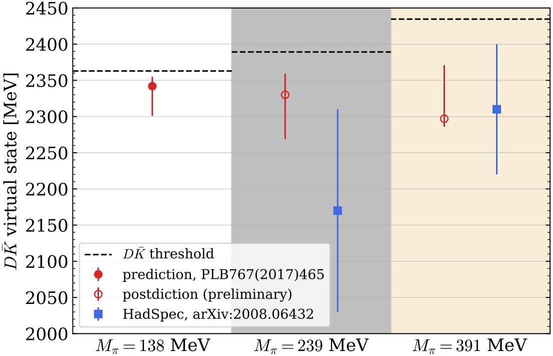
and also $B^0 \to \bar{D}^0\pi^-K^+$, $B_s^0 \to \bar{D}^0K^-\pi^+$

- SU(3) irreps: $\bar{\mathbf{3}} \otimes \mathbf{8} = \overline{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}$ 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; talk by C. Thomas last week



Summary and speculations

- HQS can provide interesting predictions/insights to hadronic molecules: seven P_c states in two spin multiplets; spin and bottom partners of $D^*_{s0}(2317)$
- Go beyond the mass spectrum: coupling strength and scattering length contain important structure information
- Very strong evidence supporting $D^*_{s0}(2317)$ and $D_{s1}(2460)$ to be molecules
- 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; it's reasonable to expect $D^{(*)}\bar{K}^*$ would have bound states.

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

  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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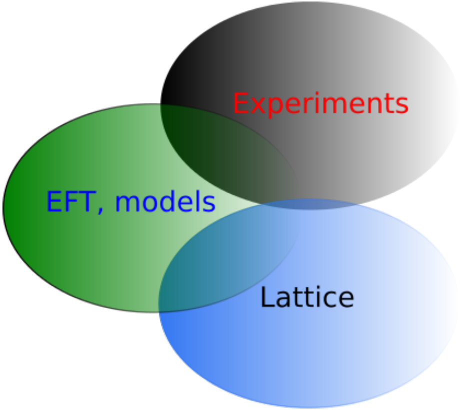


Thank you !

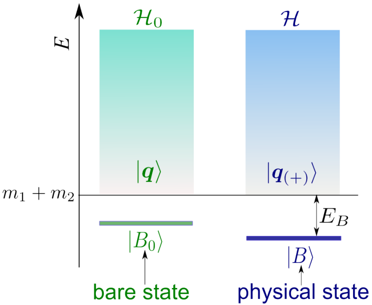
Backup slides

Compositeness (1)

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 $|\boldsymbol{q}\rangle$

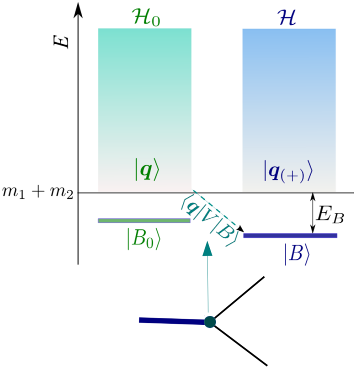
$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$$

- $Z = \left|\langle B_0|B\rangle\right|^2, \qquad 0 \leq (1 - Z) \leq 1$

  ☞ $Z = 0$: 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:

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

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

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

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

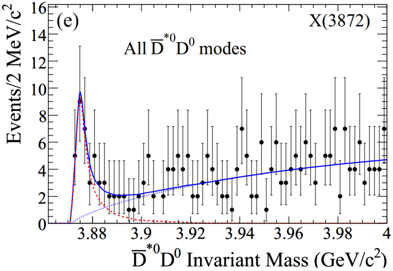
- Large coupling to $D^0\bar{D}^{*0}$:

  $\mathcal{B}(X \to D^0\bar{D}^{*0}) > 30\%$ — PDG2020

- 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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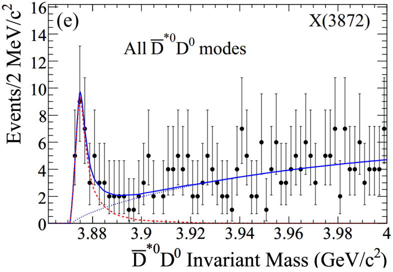

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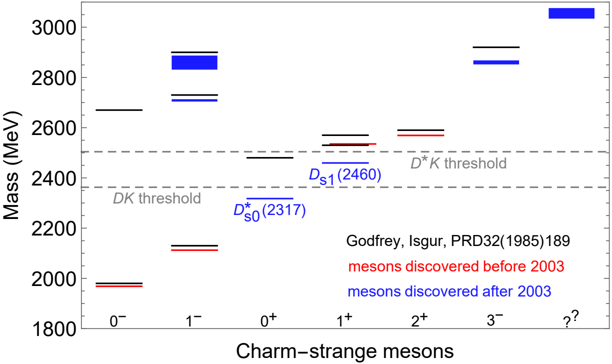
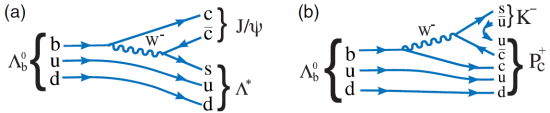
Charm-strange mesons: $D_{s0}^*(2317)$ and $D_{s1}(2460)$

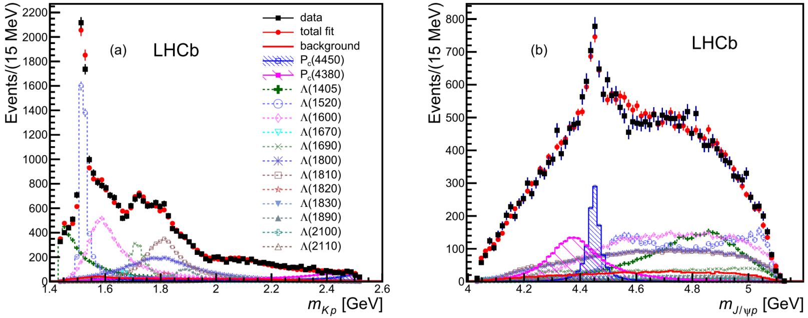


- $D_{s0}^*(2317)$: BaBar (2003)
  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$: CLEO (2003)
  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths
  $\Rightarrow I = 0$

- 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]





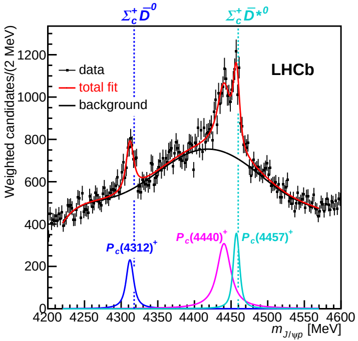
Two Breit–Wigner resonances, quantum numbers not fixed:

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

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

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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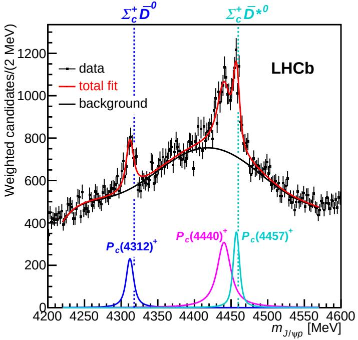
LHCb, PRL122(2019)222001



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

$\bar{D}^{(*)}\Sigma_c$ 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^P	Λ	$\bar{D}\Sigma_c$ *PB* system $M - i\Gamma/2$	$\bar{D}^*\Sigma_c$ *VB* system $M - i\Gamma/2$
$\frac{1}{2}^-$	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	–	$4438.039 - 7.268i$

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)