Hadronic molecules with heavy quarks

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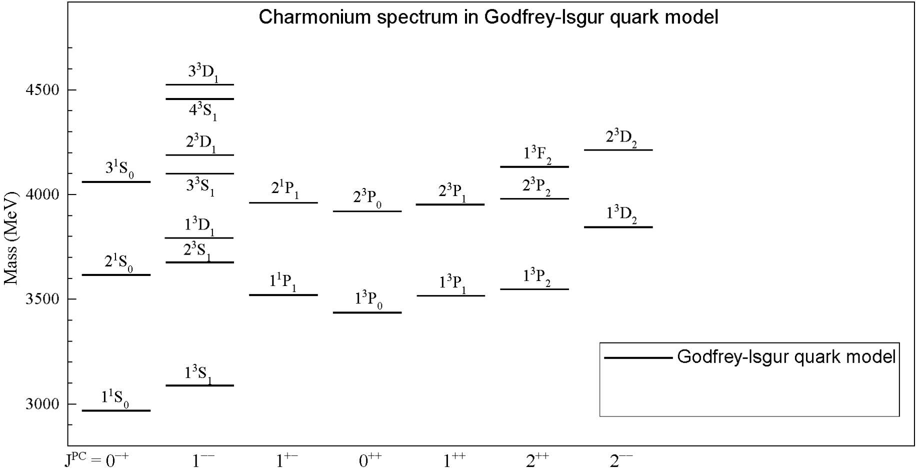
For a review of hadronic molecules, see:

FKG, C.Hanhart, U.-G.Meißner, Q.Wang, Q.Zhao, B.-S.Zou, Rev. Mod. Phys. **90** (2018) 015004

Charmonium spectrum



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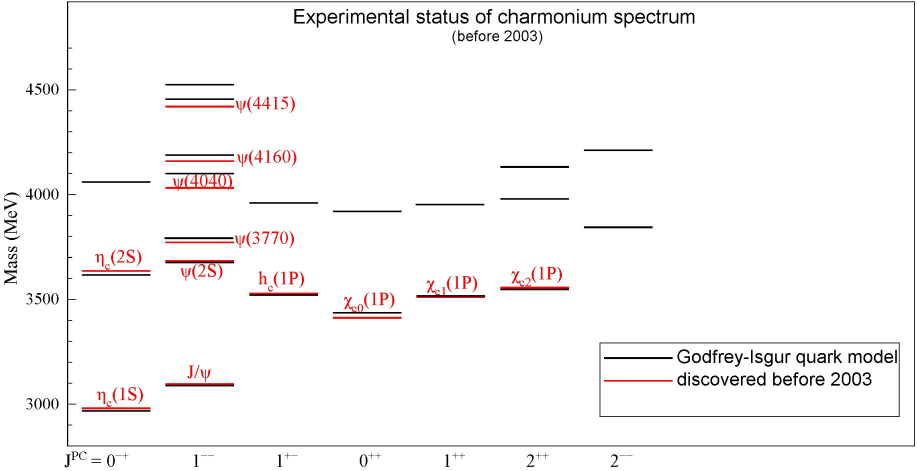

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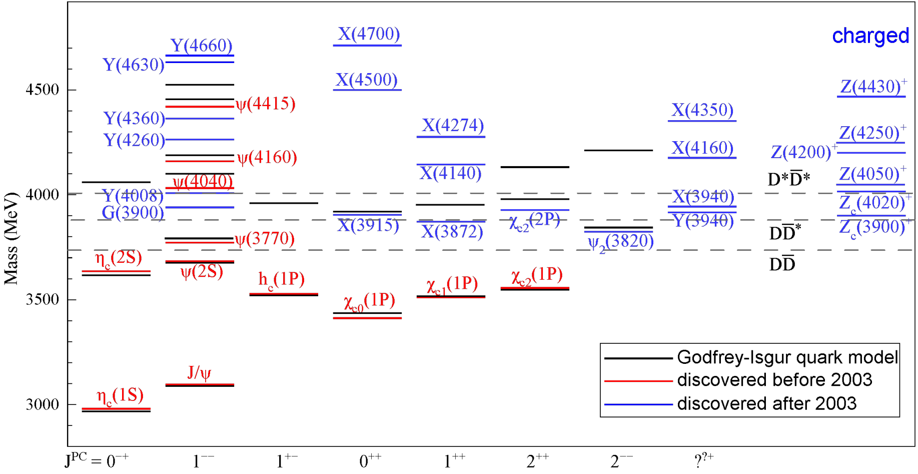

Note: the spin of $X(3915)$ has not been fixed: 0 or 2

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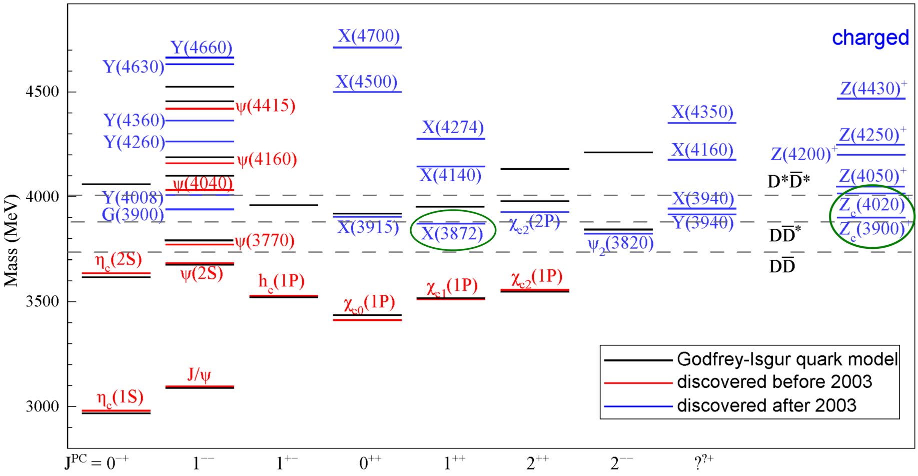

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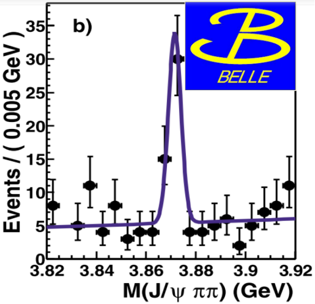
Beginning of the story in 2003: discovery of $X(3872)$

- $X(3872)$ Belle, PRL91(2003)262001



- Discovered in $B^\pm \to K^\pm J/\psi\pi\pi$

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

- $\Gamma < 1.2$ MeV Belle, PRD84(2011)052004
- $J^{PC} = 1^{++}$ LHCb PRL110(2013)222001

  $\chi_{c1}(3872)$; S-wave coupling to $D\bar{D}^*$

- 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

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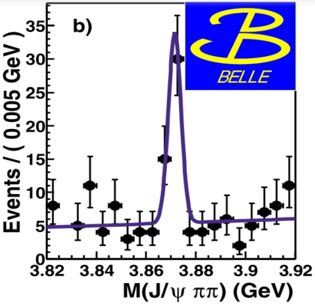

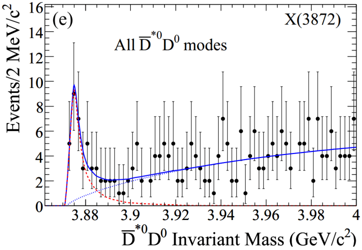

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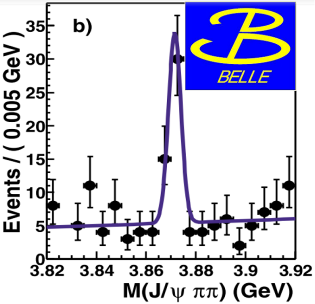

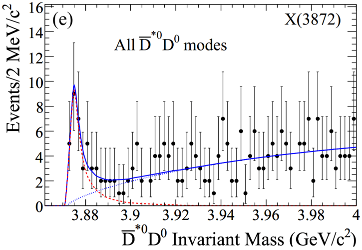

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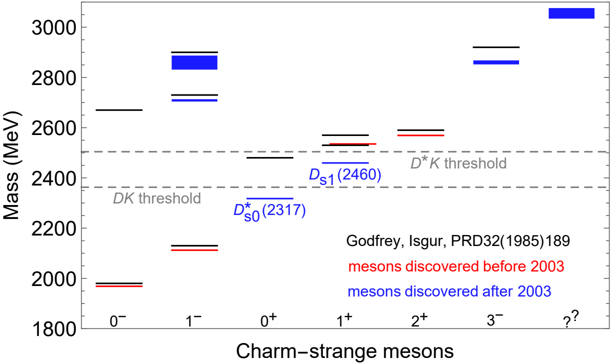
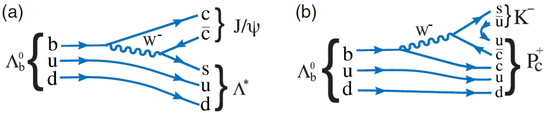
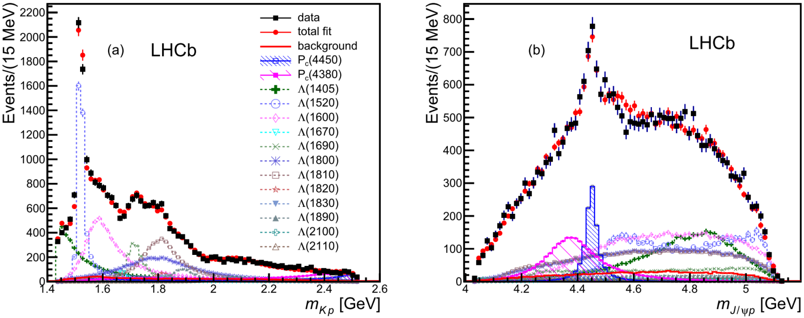


- $D^*_{s0}(2317)$: BaBar (2003)
  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$: CLEO (2003)
  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths
  $\Rightarrow I = 0$

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





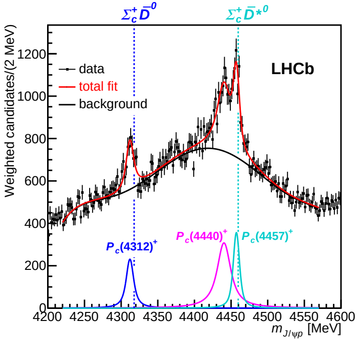
Two Breit–Wigner resonances, quantum numbers not fixed:

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

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

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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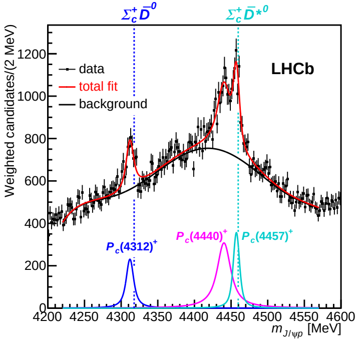

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$\bar{D}^{(*)}\Sigma_c$ molecules predicted:

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	$\bar{D}^*\Sigma_c$ *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	–	$4438.039 - 7.268i$

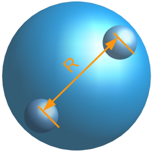
J.-J. Wu, T.-S. H. Lee, B.-S. Zou, PRC85(2012)044002

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

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
- EFT applicable; model-independent statements can be made 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;

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

Hadronic molecules (2)

- Defining property: large coupling to its constituents
- EFT applicable; model-independent statements can be made 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

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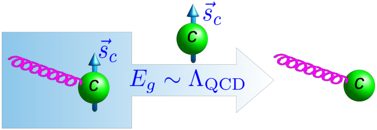
extension of compositeness to resonances:

Baru et al.(2004); Aceti, Oset (2012); Hyodo (2013); Z.-H. Guo, Oller (2015); Z. Xiao, Z.-Y. Zhou (2016); ...

Heavy quark symmetries

- For heavy quarks (charm, bottom) in a hadron, typical momentum transfer Λ_{QCD}
  - ☞ heavy quark spin symmetry (HQSS): chromomag. interaction $\propto \dfrac{\boldsymbol{\sigma}\cdot\boldsymbol{B}}{m_Q}$

    spin of the heavy quark decouples



  - ☞ heavy quark flavor symmetry (HQFS) for any hadron containing one heavy quark:

    velocity remains unchanged in the limit $m_Q \to \infty$: $\quad \Delta v = \dfrac{\Delta p}{m_Q} = \dfrac{\Lambda_{\text{QCD}}}{m_Q}$

    $\Rightarrow$ heavy quark is like a static color triplet source, m_Q is irrelevant

- Different models have distinct spectra for HQSS partners:

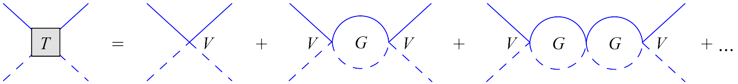
  Cleven, FKG, Hanhart, Wang, Zhao, PRD92(2015)014005

  hadronic molecular spin multiplets inherit the hyperfine splittings from their constituents

$D^*_{s0}(2317)$ and $D_{s1}(2460)$ as hadronic molecules (1)

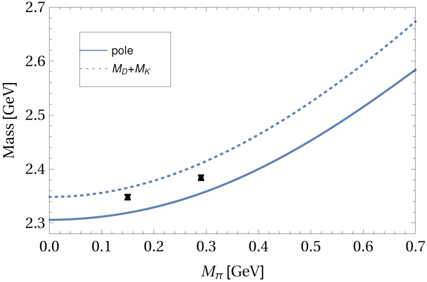
- in hadronic molecular model: $D^*_{s0}(2317)[DK]$, $D_{s1}(2460)[D^*K]$

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



- Compositeness extracted from analyzing lattice results: $\sim 70\%$ Liu, Orginos, FKG, Hanhart, Meißner PRD87(2013)014508; Martínez Torres et al., JHEP1505,053

- Latest lattice results in G. Bali et al., PRD96(2017)074501



$$1 - Z = 1.04(0.08)(+0.30)$$

M_π [MeV]	150	290
$M_{D^*_{s0}(2317)}$ [MeV]	2348 ± 4	2384 ± 3
M_{D_s} [MeV]	1977 ± 1	1980 ± 1

strong M_π dependence!

curves: prediction in Du et al., EPJC77(2017)728

$D^*_{s0}(2317)$ and $D_{s1}(2460)$ as hadronic molecules (2)

- Large coupling $\Rightarrow$ large width:

	$\Gamma(D^*_{s0}(2317) \to D_s\pi^0)$[keV]	$\Gamma(D^*_{s0}(2317) \to D^*_s\gamma)$[keV]
had. mol.	133 ± 22 [1]	9.4 [2]
chiral doublet [3]	21.5	1.74

[1] L. Liu, Orginos, FKG, Hanhart, Meißner, PRD87(2013)014508

[2] Cleven, Grießhammer, FKG, Hanhart, Meißner, EPJA50(2014)149

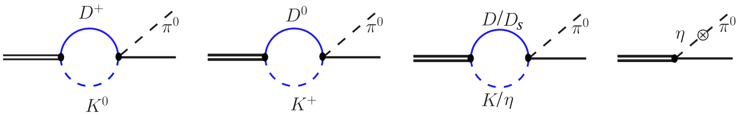
[3] Bardeen, Eichten, Hill, PRD68(2003)054024

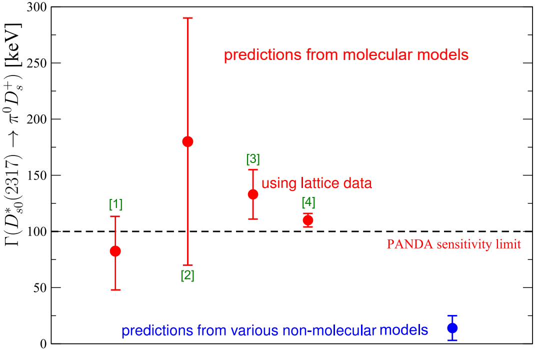
$\mathcal{B}(D^*_{s0}(2317) \to D_s\pi^0) \simeq 90\%$ in both models

- BESIII measurement: BESIII, PRD97(2018)051103

$$\mathcal{B}(D^*_{s0}(2317) \to D_s\pi^0) = 1.00^{+0.00}_{-0.14} \pm 0.14$$

$D_{s0}^*(2317)$ and $D_{s1}(2460)$ as hadronic molecules (3)





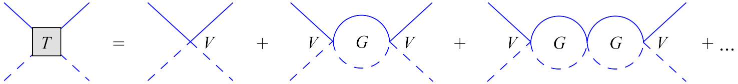
measurement planned at $\overline{\text{P}}$ANDA

molecular: [1] Faessler et al., PRD76(2007)014005; [2] FKG et al.,PLB666(2008)251;

[3] L. Liu et al.,PRD87(2013)014508; [4] X. Guo, Heo, Lutz,PRD98(2018)014510

non-molecular: e.g., Colangelo, De Fazio, PLB570(2003)180; Bardeen, Eichten, Hill, PRD68(2003)054024

$D_{s0}^*(2317)$ and $D_{s1}(2460)$ as hadronic molecules (4)



- 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:

$$M_{B_{s0}^*} \simeq M_B + M_K - 45\,\text{MeV} \simeq 5.730 \text{ GeV}$$
$$M_{B_{s1}} \simeq M_{B^*} + M_K - 45\,\text{MeV} \simeq 5.776 \text{ GeV}$$

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

HQSS for P_c (1)

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 $s_L = \frac{3}{2}$

HQSS for P_c (2)

Seven P_c generally expected in this hadronic molecular model

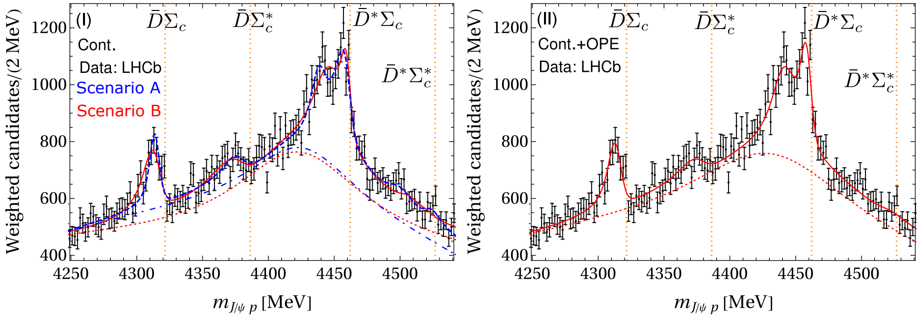
Xiao, Nieves, Oset, PRD88(2013)056012; Liu et al., PRD98(2018)114030, PRL122(2019)242001; Sakai, Jing, FKG, PRD100(2019)074007; . . .

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

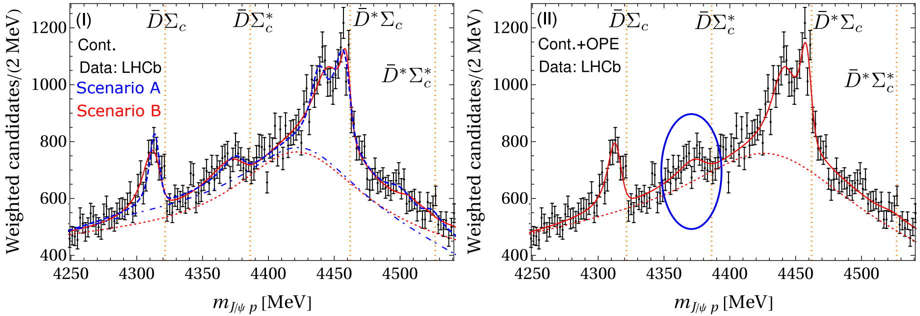
M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, J. A. Oller, Q. Wang, PRL124(2020)072001



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

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

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)	$-228(384) + 22(23)i$
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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;
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Width of the $X(3872)$ (1)

New LHCb measurements:

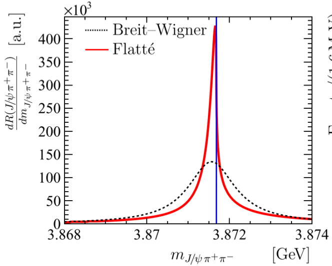
- from $B^+ \to J/\psi\pi^+\pi^-K^+$: LHCb, arXiv:2005.13422

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

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

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

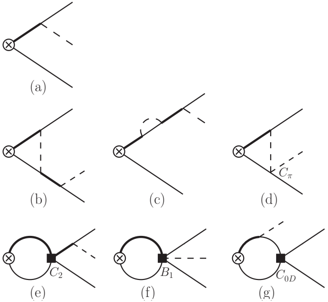
$$\text{Flatté half-max. width}: \quad \Gamma_{\rm Flatté} = 0.22^{+0.06+0.25}_{-0.08-0.17} \text{ MeV}$$

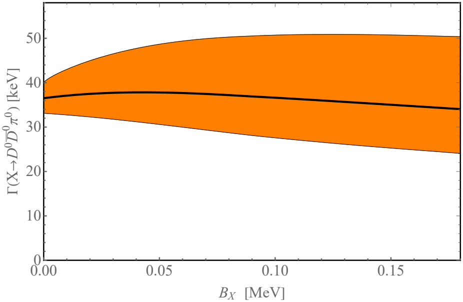


Do not use BW for near-threshold structures!

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

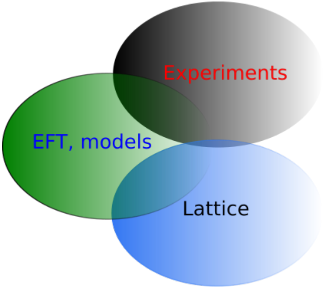
- $\mathcal{B}(X \to D^0 \bar{D}^0 \pi^0) > 40\%$ PDG2020
- Upper limit of the total width: $\Gamma(X) < 125$ keV see also, Mehen, PRD92(2015)034019

Summary

- heavy quark symmetry 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 because coupling strength contains important structure information:

  width of $D^*_{s0}(2317)$; width of $X(3872)$



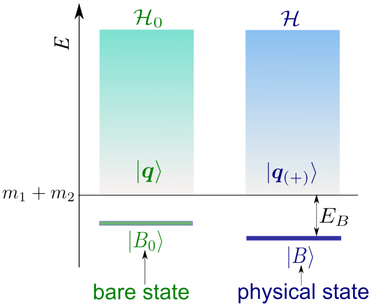
Thank you !

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 $|\boldsymbol{q}\rangle$

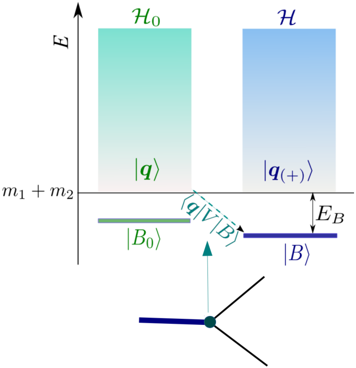
$$1 - Z = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left|\langle \boldsymbol{q}|B\rangle\right|^2$$

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

  ☞ $Z = 0$: 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:

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

Compositeness (3)

- Coupling constant measures the compositeness for an S-wave bound state with a small binding energy (model-independent)

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

- Z can be measured directly from observables, such as scattering length a and effective range r_e Weinberg (1965)

$$a = -\frac{2R(1-Z)}{2-Z}\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right], \quad r_e = \frac{RZ}{1-Z}\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right]$$

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

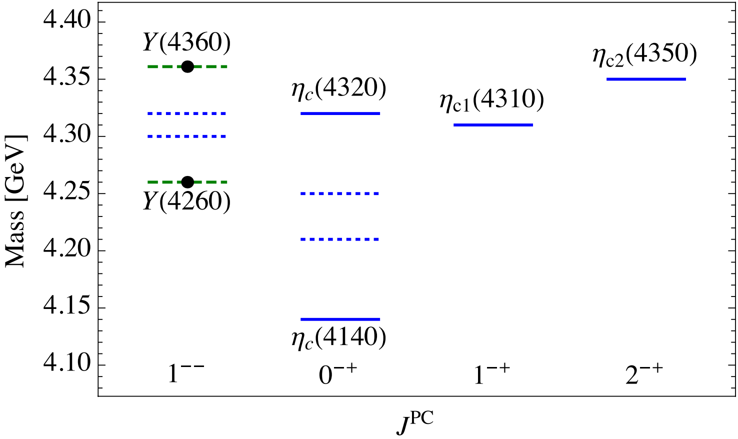
$$a_{Z=1} = 0 \text{ fm}, \qquad a_{Z=0} = (-4.3 \pm 1.4) \text{ fm}$$

If the $Y(4260)$ and $Y(4360)$ are mixed hadro-charmonia with h_c and ψ' core,

Li, Voloshin, MPLA29(2014)1450060

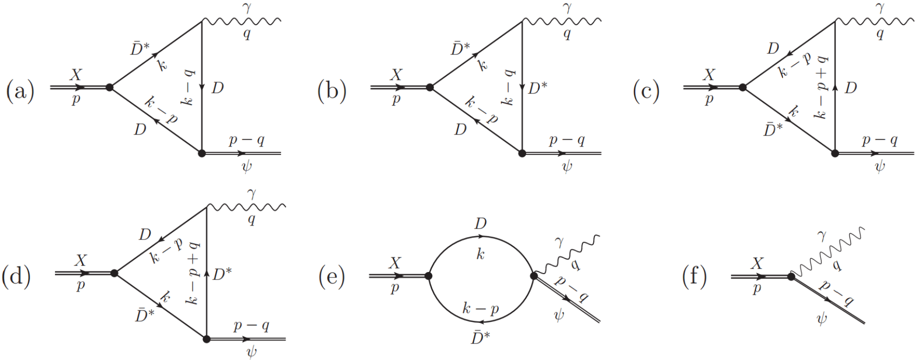
implications of HQSS for hadro-charmonia:

Cleven et al., PRD92(2015)014005



Decays: $X(3872) \to \psi\gamma$

FKG, Hanhart, Kalashnikova, Meißner, Nefediev, PLB742(2015)394



The ratio $$\frac{\mathcal{B}(X(3872) \to \psi'\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$ LHCb, NPB886(2014)665

is insensitive to the molecular component of the $X(3872)$:

- loops are sensitive to unknown couplings $g_{\psi DD}/g_{\psi' DD}$
- loops are divergent, needs a counterterm (short-distance physics)!

see also Mehen, Springer, PRD83(2011)094009; Molnar et al., arXiv:1601.03366