Emergence of near-threshold structures in heavy hadron spectrum

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General model-independent analysis on threshold structures:

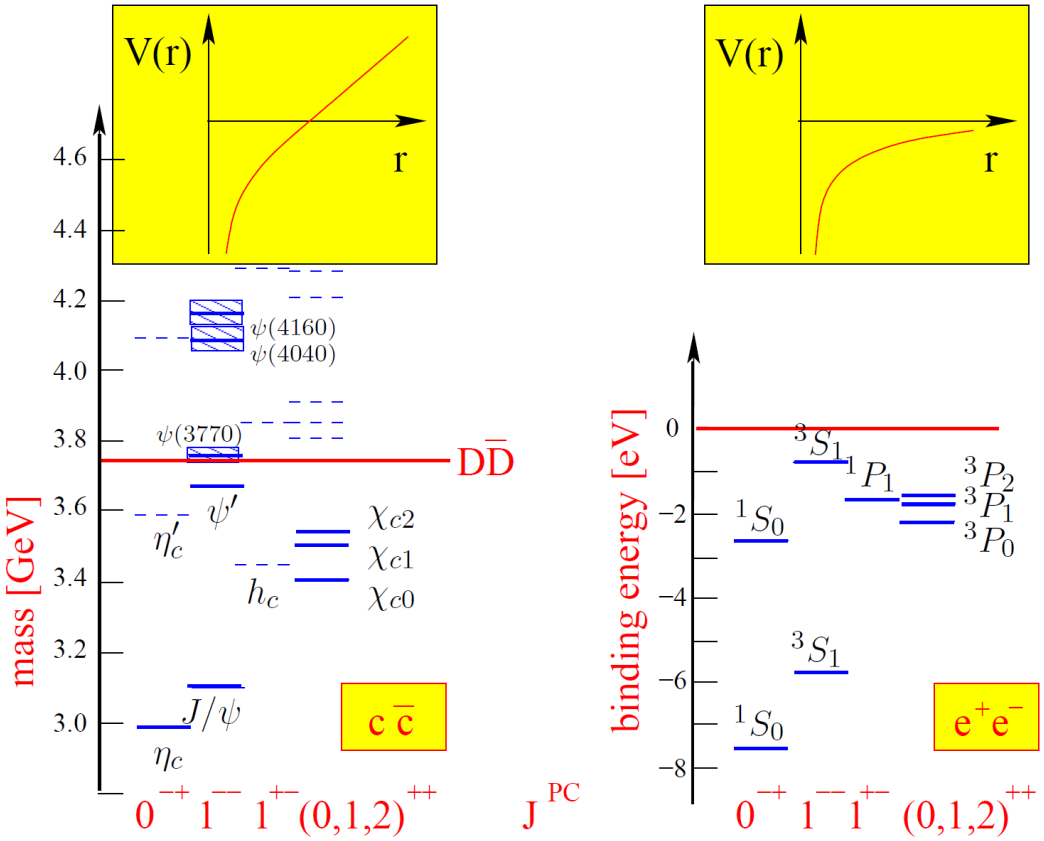
X.-K. Dong, FKG, B.-S. Zou, Phys. Rev. Lett. 126 (2021) 152001 [arXiv:2011.14517]

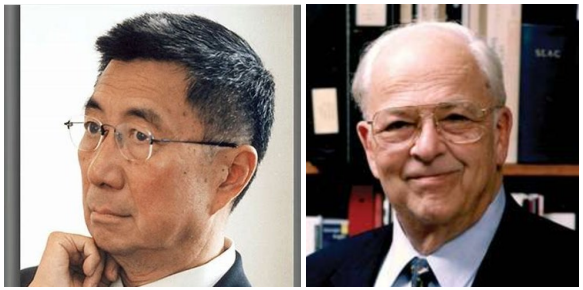
Systematic spectrum of hadronic molecules:

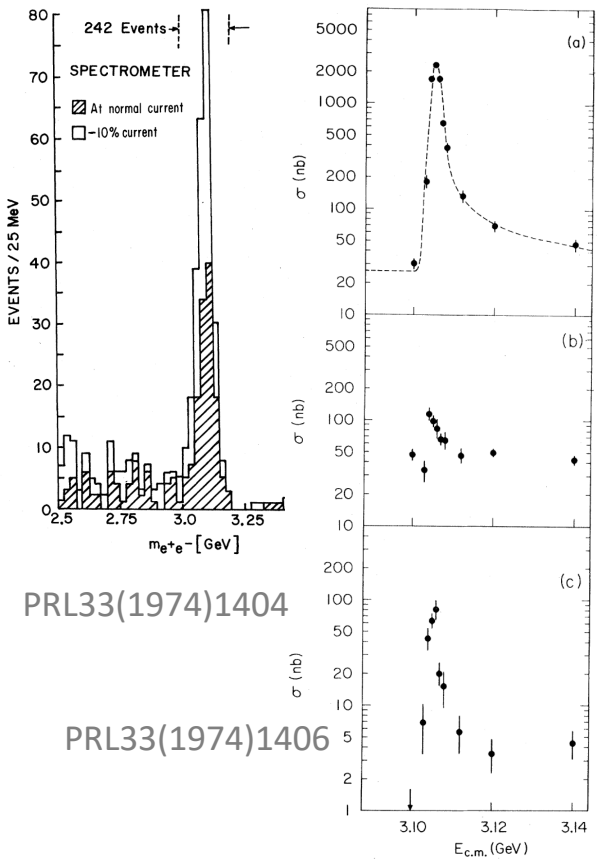
X.-K. Dong, FKG, B.-S. Zou, 《物理学进展》41 (2021) 65 [arXiv:2101.01021]; Commun. Theor. Phys.73 (2021) 125201 [arXiv:2108.02673]

Charmonium

- Meson consisting of a charm quark and an anticharm quark
  - The first charmonium: J/ψ
  - Probing both perturbative and nonperturbative QCD







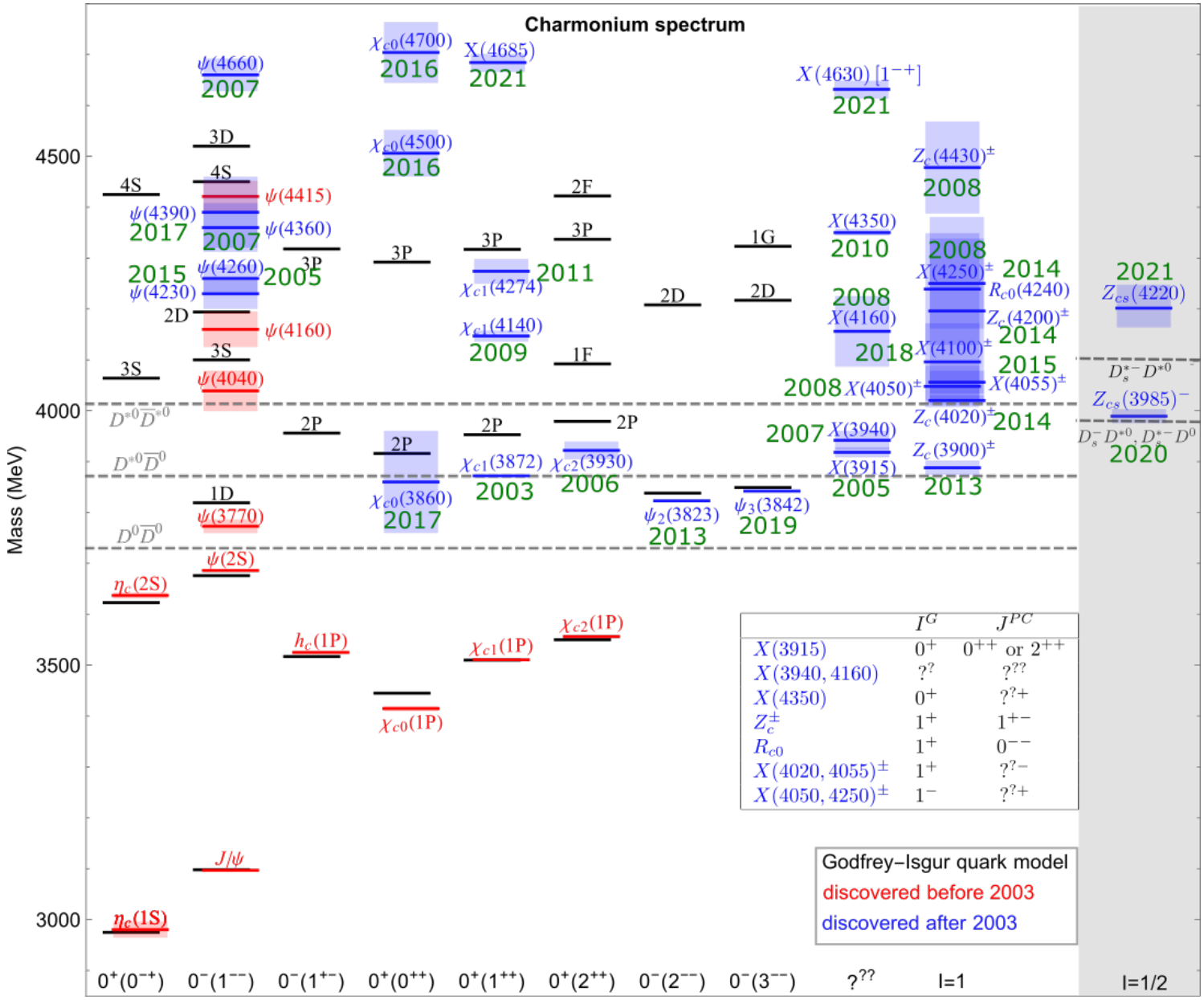
PRL33(1974)1404

PRL33(1974)1406

From talk by Hanhart at APS2018

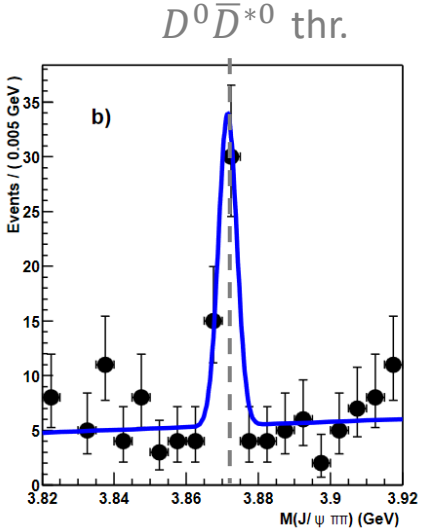
Cornell potential model:
Eichten et al., PRD17(1978)3090

Charmonium(-like) structures

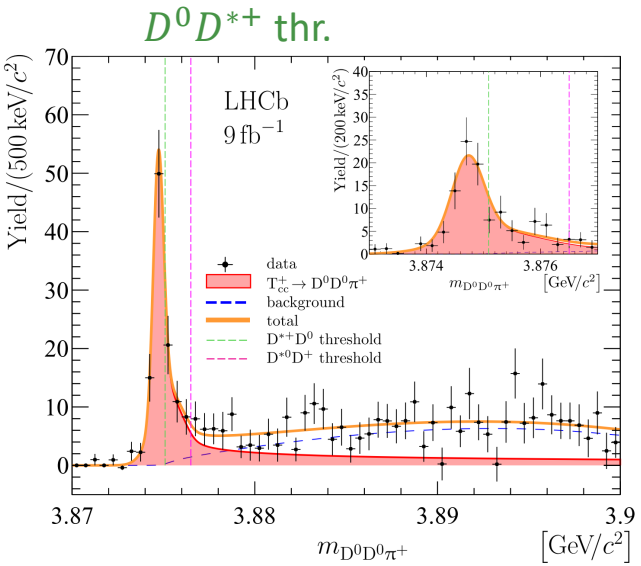


Charmonium-like structures

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

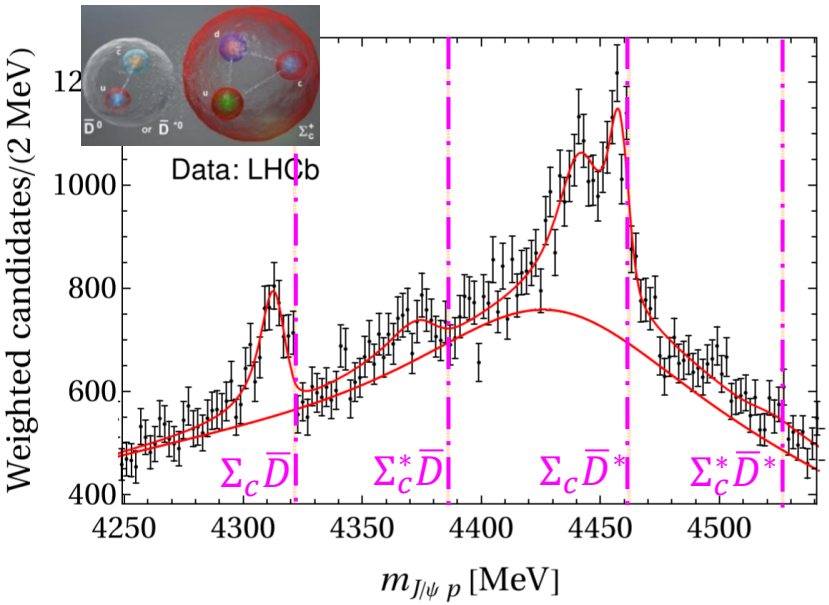


- T_{cc}^+

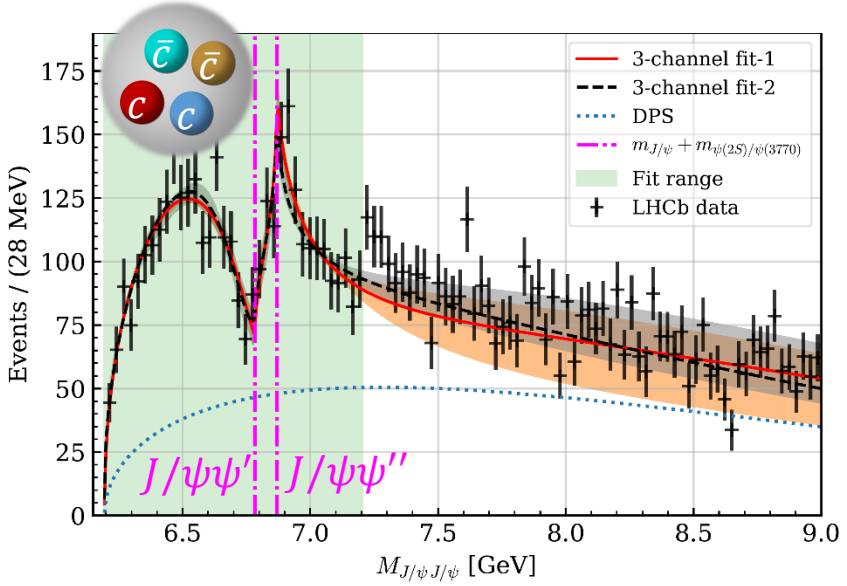


LHCb, arXiv:2109.01038; arXiv:2109.01056

P_c and double-J/ψ structures



data from LHCb, PRL122 (2019) 222001;
fit from
M.-L. Du, Baru, FKG, Hanhart, Meißner, Oller, Q. Wang,
PRL124 (2020) 072001



data from LHCb, Sci.Bull.65 (2020) 1983;
fit from
X.-K. Dong, Baru, FKG, Hanhart, Nedefiev,
PRL126 (2021) 132001

Many new structures are near thresholds of a pair of heavy hadrons.

Why are there so many (near-)threshold structures in heavy-hadron spectrum?
Is there any rule?

Effective range expansion

$$f_0^{-1}(k) = \frac{1}{a_0} + \frac{1}{2} r_0 k^2 - ik + \mathcal{O}\left(\frac{k^4}{\beta^4}\right)$$

a_0: S-wave scattering length; negative for repulsion or attraction w/ a bound state

positive for attraction w/o bound state

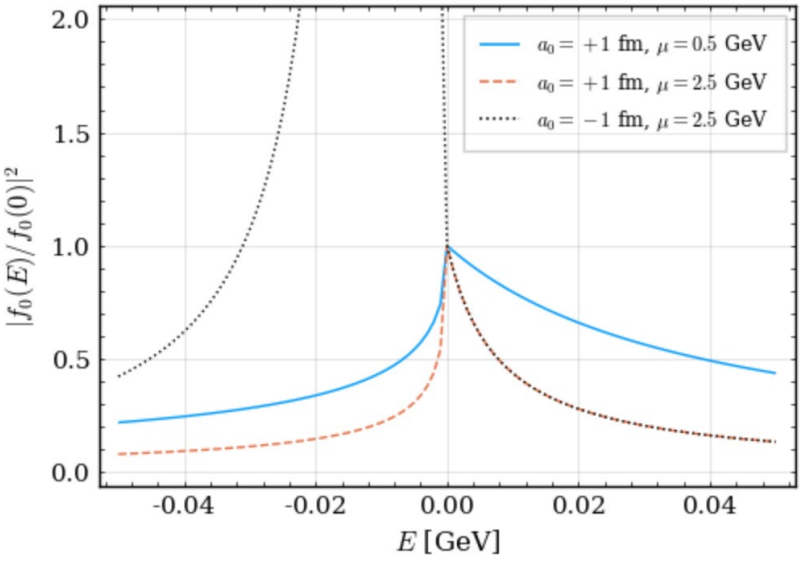
Very close to threshold, then scattering length approximation: $f_0^{-1}(E) = \frac{1}{a_0} - i\sqrt{2\mu E}$

$$|f_0(E)|^2 = \begin{cases} \dfrac{1}{1/a_0^2 + 2\mu E} & \text{for } E \geq 0 \\ \dfrac{1}{\left(1/a_0 + \sqrt{-2\mu E}\right)^2} & \text{for } E < 0 \end{cases}$$

- Cusp at threshold (E=0)
- Maximal at threshold for positive a_0 (attraction)
- Half-maximum width: $\frac{2}{\mu a_0^2}$;

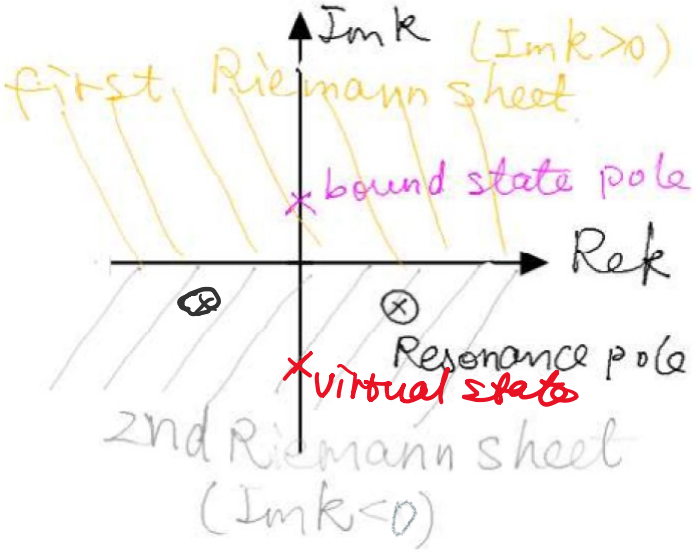
  virtual state pole at $E_{\text{virtual}} = -1/(2\mu a_0^2)$
- Strong interaction, a_0 becomes negative, pole below threshold, peak below threshold

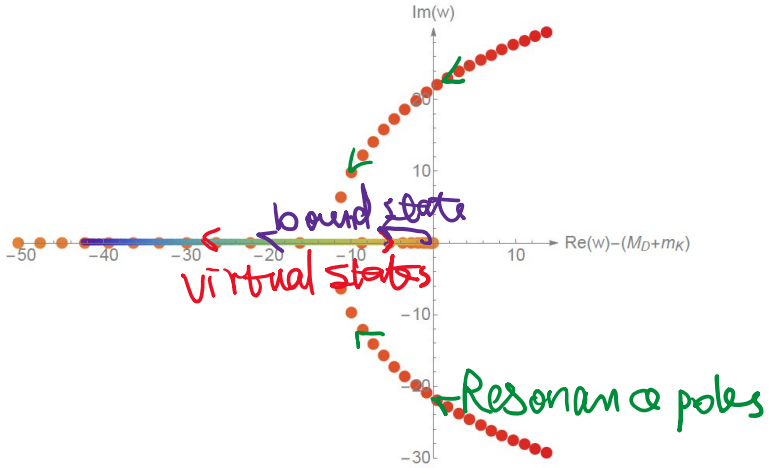
see also, e.g., Brambilla et al. Phys. Rept. 873, 1 (2020)



Bound state, virtual state and resonance

- Bound state: pole below threshold on real axis of the first Riemann sheet of complex energy plane
- Virtual state: pole below threshold on real axis of the second Riemann sheet
- Resonance: pole in the complex plane on the second Riemann sheet



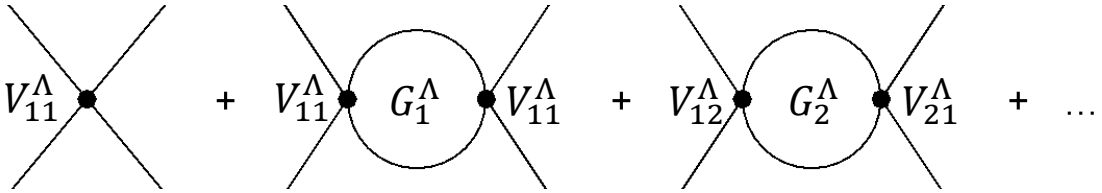


Plot from Matuschek, Baru, FKG, Hanhart, EPJA57(2021)101

For $\frac{1}{1/a_0 - i\,k}$, only bound or virtual state poles are possible

Coupled channels

- Full threshold structure needs to be measured in a lower channel ⇨ coupled channels
- Consider a two-channel system, construct a nonrelativistic effective field theory (NREFT)
  - Energy region around the higher threshold, Σ_2
  - Expansion in powers of $E = \sqrt{s} - \Sigma_2$
  - Momentum in the lower channel can also be expanded



$$T(E) = V + VG(E)V + VG(E)VG(E)V + \cdots = \frac{1}{V^{-1} - G(E)}$$

$$G_1^{\Lambda}(E) = i\int^{\Lambda_1} \frac{d^4q}{(2\pi)^2} \frac{1}{(q^2 - m_{1,1}^2 + i\epsilon)[(P-q)^2 - m_{1,2}^2 + i\epsilon]} = R(\Lambda_1) - i\frac{k_1}{8\pi\sqrt{s}}$$

$$G_2^{\Lambda}(E) = -\frac{1}{4m_{2,1}m_{2,2}} \int^{\Lambda_2} \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{2\mu_2}{\mathbf{q}^2 - 2\mu_2 E - i\epsilon} = \frac{1}{8\pi\Sigma_2}\left[-\frac{2\Lambda_2}{\pi} + \sqrt{-2\mu_2 E - i\epsilon} + \mathcal{O}\left(\frac{k_2^2}{\Lambda_2}\right)\right]$$

- Λ dependence absorbed by V^{-1}

Nonanalyticity only from here

NREFT at LO

- Very close to the higher threshold, LO:

$$T(E) = 8\pi\Sigma_2 \begin{pmatrix} -\frac{1}{a_{11}} + ik_1 & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & -\frac{1}{a_{22}} - \sqrt{-2\mu_2 E - i\epsilon} \end{pmatrix}^{-1}$$

$$= -\frac{8\pi\Sigma_2}{\det} \begin{pmatrix} \frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon} & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & \frac{1}{a_{11}} - ik_1 \end{pmatrix},$$

$$\det = \left(\frac{1}{a_{11}} - i\,k_1\right)\left(\frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon}\right) - \frac{1}{a_{12}^2}$$

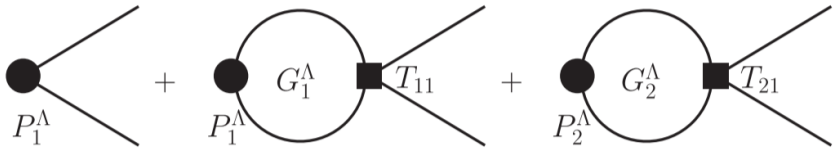
Effective scattering length with open-channel effects becomes complex, $\mathrm{Im}\frac{1}{a_{22,\mathrm{eff}}} \leq 0$

$$T_{22}(E) = -\frac{8\pi}{\Sigma_2}\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}$$

$$\frac{1}{a_{22,\mathrm{eff}}} = \frac{1}{a_{22}} - \frac{a_{11}}{a_{12}^2(1+a_{11}^2k_1^2)} - i\frac{a_{11}^2k_1}{a_{12}^2(1+a_{11}^2k_1^2)}.$$

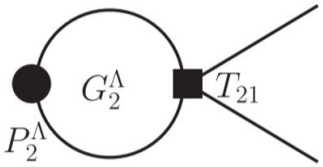
NREFT at LO

- Consider a production process, must go through final-state interaction (unitarity)



$$\begin{aligned} &P_1^\Lambda[1+G_1^\Lambda T_{11}(E)]+P_2^\Lambda G_2^\Lambda(E)T_{21}(E) \\ &=P_1^\Lambda(V_{11}^\Lambda)^{-1}T_{11}(E)+\left[P_1^\Lambda(V_{11}^\Lambda)^{-1}V_{12}^\Lambda+P_2^\Lambda\right]G_2^\Lambda T_{21}(E) \\ &\equiv P_1 T_{11}(E)+P_2 T_{21}(E) \end{aligned}$$

- All nontrivial energy dependence are contained in $T_{11}(E)$ and $T_{21}(E)$
- Case-1: dominated by $T_{21}(E)$,

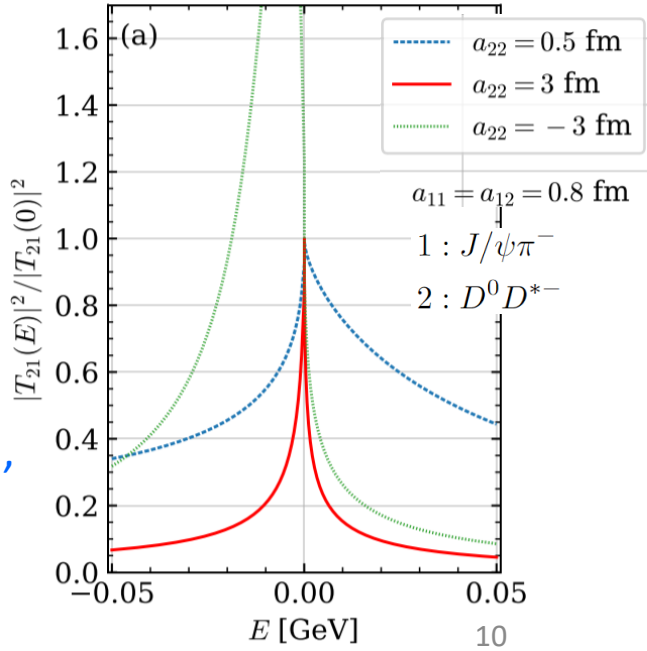


$$T_{21}(E)=\frac{-8\pi\Sigma_2}{a_{12}(1/a_{11}-ik_1)}\left[\frac{1}{a_{22,\text{eff}}}-i\sqrt{2\mu_2 E}+\mathcal{O}(E)\right]^{-1}.$$

$$|T_{21}(E)|^2\propto|T_{22}(E)|^2\propto$$

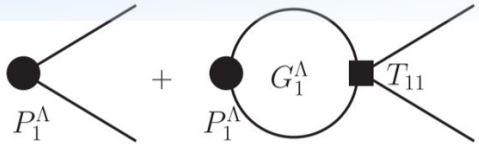
$$\begin{cases}\left[\left(\text{Re}\,\frac{1}{a_{22,\text{eff}}}\right)^2+\left(\text{Im}\,\frac{1}{a_{22,\text{eff}}}-\sqrt{2\mu E}\right)^2\right]^{-1} & \text{for } E\geq 0\\ \left[\left(\text{Im}\,\frac{1}{a_{22,\text{eff}}}\right)^2+\left(\text{Re}\,\frac{1}{a_{22,\text{eff}}}+\sqrt{-2\mu E}\right)^2\right]^{-1} & \text{for } E<0\end{cases}$$

- ➢ Maximal at threshold for positive $\text{Re}(a_{22,\text{eff}})$ (attraction), FWHM $\propto 1/\mu$
- ➢ Peaking at pole for negative $\text{Re}(a_{22,\text{eff}})$

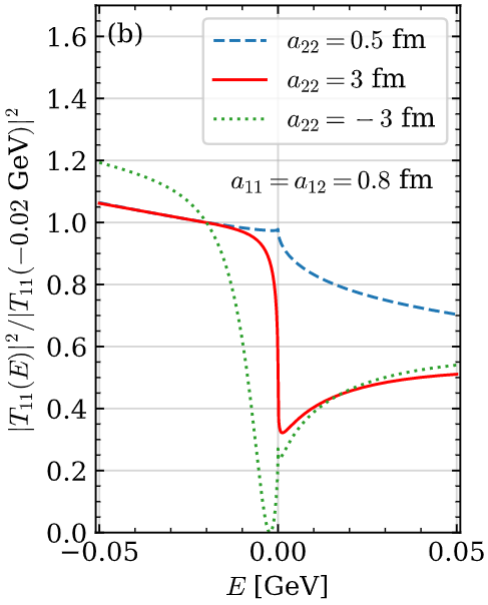


NREFT at LO

- Case-2: dominated by $T_{11}(E)$



$$T_{11}(E) = \frac{-8\pi\Sigma_2\left(\frac{1}{a_{22}} - i\sqrt{2\mu_2 E}\right)}{\left(\frac{1}{a_{11}} - i\,k_1\right)\left[\frac{1}{a_{22,\text{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]}$$



Poles in complex momentum plane:

$(0.37 - i0.08)\text{GeV}$

$(0.04 - i0.08)\text{GeV}$

$(-0.09 - i0.08)\text{GeV}$

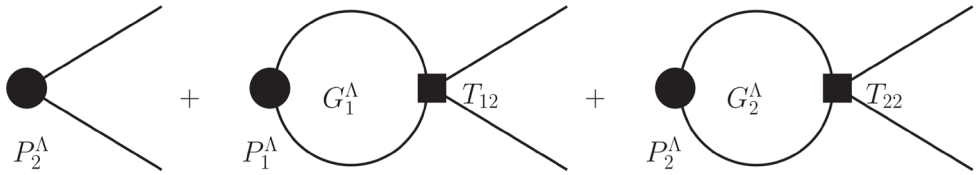
- One pole and one zero
- For strongly interacting channel-2 (large a_{22}), there must be a dip around threshold (zero close to threshold)

$$\frac{1}{a_{22,\text{eff}}} = \frac{1}{a_{22}} - \frac{a_{11}}{a_{12}^2(1+a_{11}^2k_1^2)} - i\frac{a_{11}^2k_1}{a_{12}^2(1+a_{11}^2k_1^2)}.$$

- More complicated line shape if both channels are important for the production

NREFT at LO

- Case-3: final states in channel-2



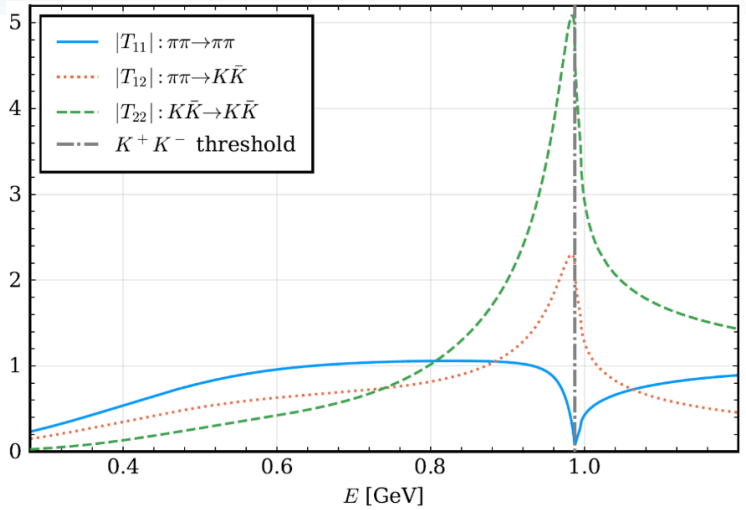
$$P_1 T_{12}(E) + P_2 T_{22}(E) \propto \left[\frac{1}{a_{22,\text{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E) \right]^{-1}$$

- Suppression due to phase space
- Peak just above threshold would require the pole to be nearby

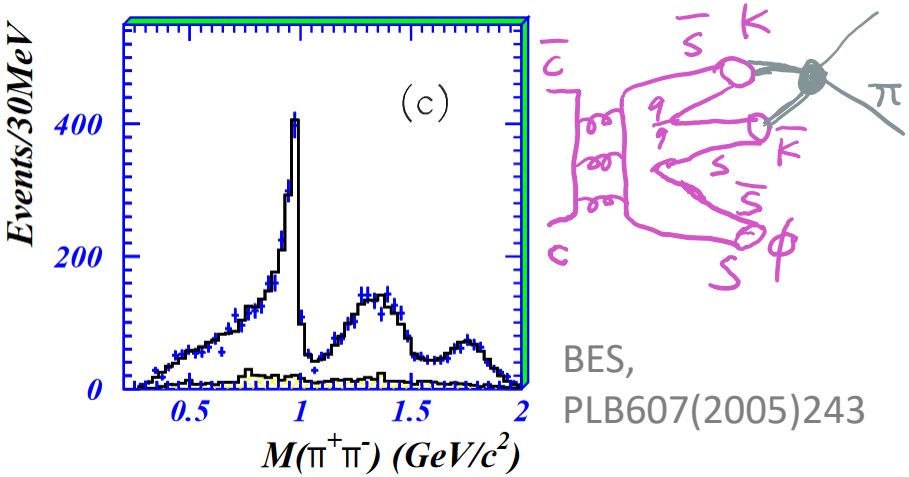
Phenomenology

- T-matrix for $\pi\pi$ and $K\bar{K}$ coupled channels

  with the T-matrix from
  L.-Y. Dai, M. R. Pennington, PRD90(2014)036004



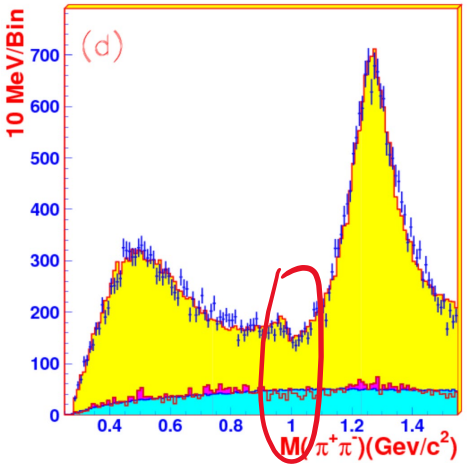
- $f_0(980)$ in $J/\psi \to \phi\pi^+\pi^-$ and $J/\psi \to \omega\pi^+\pi^-$ Channels: $\pi\pi$ and $K\bar{K}$

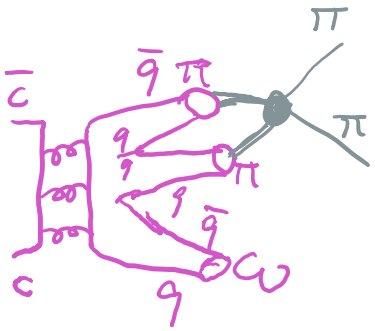


BES, PLB607(2005)243

Driving channel: $K\bar{K}$

$J/\psi \to \phi K\bar{K} \to \phi\pi^+\pi^-$





BES, PLB598(2004)149

Driving channel: $\pi\pi$

$J/\psi \to \omega\pi\pi \to \omega\pi^+\pi^-$

Phenomenology

- Production of states with hidden-charm and hidden-bottom: open-flavor much easier than $Q\bar{Q}$ + light hadrons, generally peaks around threshold of a pair of open-flavor hadrons for attractive interaction
- Complications due to more channels
- Threshold structures should be more pronounced in bottom-bottom and bottom-charm than in charm-charm
  - Either threshold cusp or below-threshold peak
  - peak width $\propto 1/m_Q$ for fixed a
  - Perturbative estimate of scattering length: $a \propto m_Q$ [potential independent of m_Q]; nonperturbative for strong attraction, near-threshold pole

Model estimate of near-th. interactions

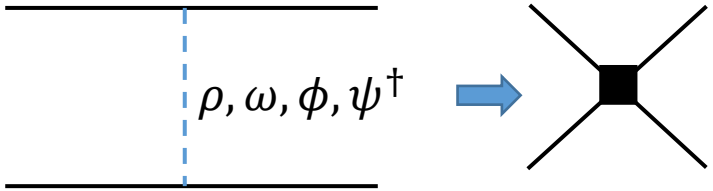
- Constant contact terms saturated by light-vector-meson exchange, similar to VMD in the resonance saturation of the low-energy constants in CHPT

V, A, S, S_1 and η_1 contributions to the coupling constants L_i^r in units of 10^{-3}.

	$L_i^r(M_\rho)$	V	A	S	S_1	η_1	Total
L_1^r	0.7 ± 0.3	0.6	0	-0.2	0.2[b]	0	0.6
L_2^r	1.3 ± 0.7	1.2	0	0	0	0	1.2
L_3	-4.4 ± 2.5	-3.6	0	0.6	0	0	-3.0
L_4^r	-0.3 ± 0.5	0	0	-0.5	0.5[b]	0	0.0
L_5^r	1.4 ± 0.5	0	0	1.4[a]	0	0	1.4
L_6^r	-0.2 ± 0.3	0	0	-0.3	0.3[b]	0	0.0
L_7	-0.4 ± 0.15	0	0	0	0	-0.3	-0.3
L_8^r	0.9 ± 0.3	0	0	0.9[a]	0	0	0.9
L_9^r	6.9 ± 0.7	6.9[a]	0	0	0	0	6.9
L_{10}^r	-5.2 ± 0.3	-10.0	4.0	0	0	0	-6.0

[a] Input.
[b] Large-N_C estimate.

Ecker, Gasser, Pich, de Rafael, NPB321(1989)311



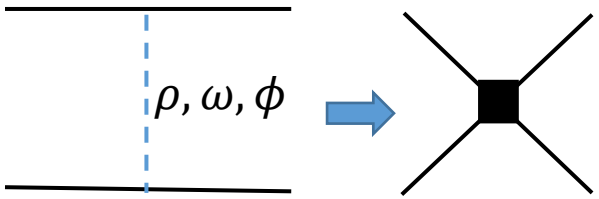
- List of attractive pairs of charm-anticharm hadron pairs

$H\bar{H}$	$D^{(*)}\bar{D}^{(*)}[0, 1^\dagger]$;	$D_s^{(*)}\bar{D}^{(*)}$ $[\frac{1}{2}^\dagger]$;	$D_s^{(*)}\bar{D}_s^{(*)}$ $[0]$
	$X(3872), Z_c(3900, 4020)$	$Z_{cs}(3985)$	$X(4140)$
	$Z_b(10610, 10650)$		
$\bar{H}T$	$\bar{D}^{(*)}\Xi_c$ $[0]$;	$\bar{D}_s^{(*)}\Lambda_c$ $[0^\dagger]$	
	$P_{cs}(4459)$		
$\bar{H}S$	$\bar{D}^{(*)}\Sigma_c^{(*)}$ $[\frac{1}{2}]$;	$\bar{D}_s^{(*)}\Sigma_c^{(*)}$ $[1^\dagger]$;	$\bar{D}^{(*)}\Xi_c^{\prime(*)}$ $[0]$;
	$P_c(4312, 4440, 4457)$		
	$\bar{D}^{(*)}\Omega_c^{(*)}$ $[\frac{1}{2}^\dagger]$		
$T\bar{T}$	$\Lambda_c\bar{\Lambda}_c$ $[0]$;	$\Lambda_c\bar{\Xi}_c$ $[\frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c$ $[0, 1]$
$T\bar{S}$	$\Lambda_c\bar{\Sigma}_c^{(*)}$ $[1]$;	$\Lambda_c\bar{\Xi}_c^{\prime(*)}$ $[\frac{1}{2}]$;	$\Lambda_c\bar{\Omega}_c^{(*)}$ $[0^\dagger]$;
	$\Xi_c\bar{\Sigma}_c^{(*)}$ $[\frac{3}{2}^\dagger, \frac{1}{2}]$;	$\Xi_c\bar{\Xi}_c^{\prime(*)}$ $[1, 0]$;	$\Xi_c\bar{\Omega}_c^{(*)}$ $[\frac{1}{2}]$
$S\bar{S}$	$\Sigma_c^{(*)}\bar{\Sigma}_c^{(*)}$ $[2^\dagger, 1, 0]$;	$\Sigma_c^{(*)}\bar{\Xi}_c^{\prime(*)}$ $[\frac{3}{2}^\dagger, \frac{1}{2}]$;	$\Sigma_c^{(*)}\bar{\Omega}_c^{(*)}$ $[0^\dagger]$;
	$\Xi_c^{\prime(*)}\bar{\Xi}_c^{\prime(*)}$ $[1, 0]$;	$\Xi_c^{\prime(*)}\bar{\Omega}_c^{(*)}$ $[\frac{1}{2}]$;	$\Omega_c^{(*)}\bar{\Omega}_c^{(*)}$ $[0]$

Hadronic molecules from VMD interactions

- Approximations:
  - Constant contact terms (V) saturated by light-vector-meson exchange, similar to the vector-meson dominance in the resonance saturation of the low-energy constants in CHPT

    G. Ecker, J. Gasser, A. Pich, E. de Rafael, NPB321(1989)311
  - Single channels
  - Neglecting mixing with normal charmonia

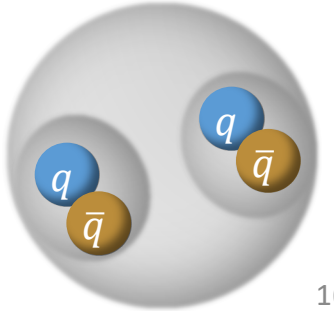


- The T-matrix:

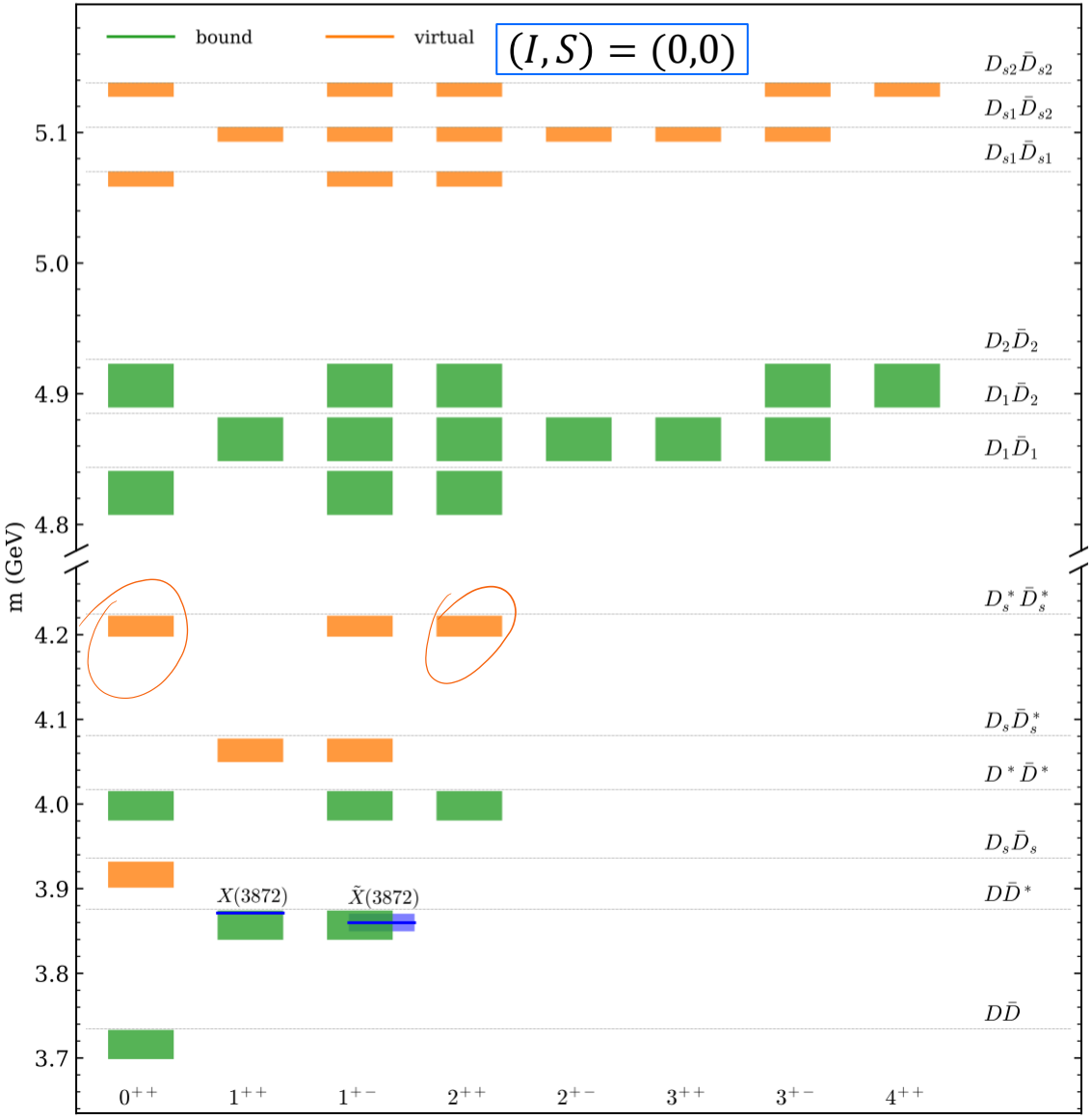
$$T = \frac{V}{1 - VG}$$

G: two-point scalar loop integral regularized using dim.reg. with a subtraction constant matched to a Gaussian regularized G at threshold, with cutoff $\Lambda \in [0.5, 1.0]$ GeV

- Hadronic molecules appear as bound or virtual state poles of the T matrix

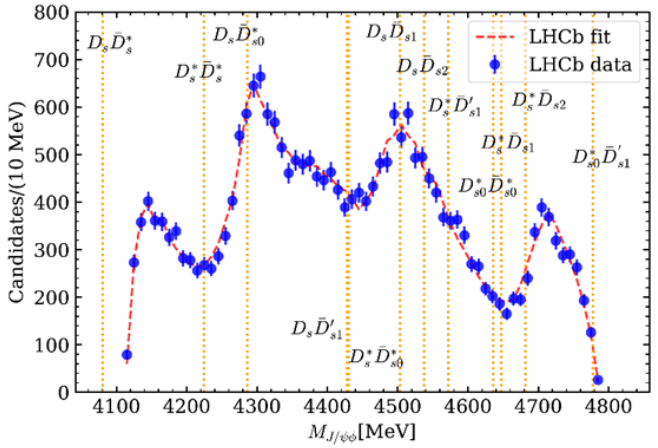


X(3872) and related states



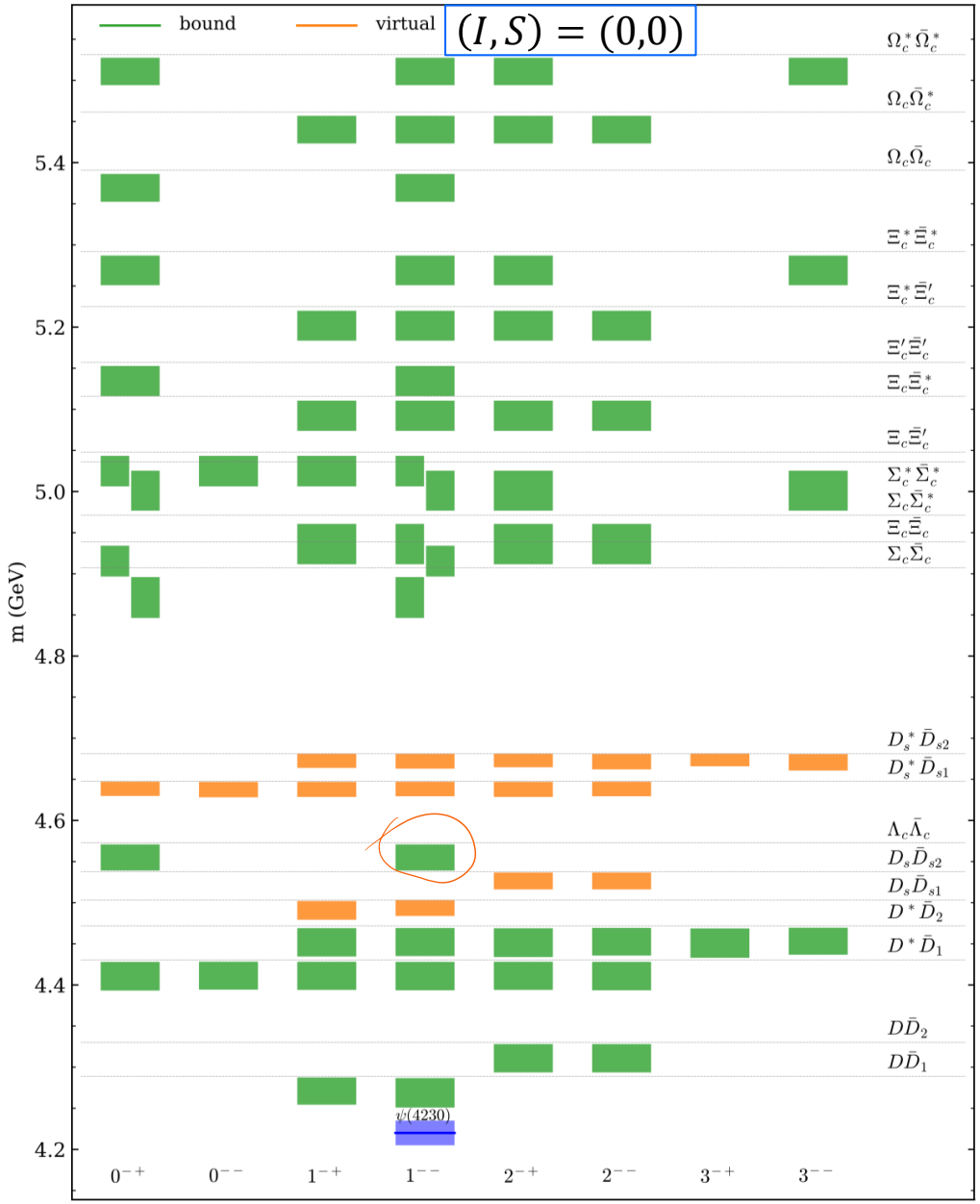
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys. 41 (2021) 65

- ✓ $X(3872)$ as a $\bar{D}D^*$ bound state
- ✓ Negative-C parity partner observed by COMPASS PLB783(2018)334
- ✓ $\bar{D}D$ bound state predicted with lattice Prelovsek et al., JHEP2106,035 and other models
  e.g., Wong, PRC69, 055202; Zhang et al., PRD74, 014013; Gamermann et al., PRD76, 074016; Nieves et al., PRD86, 056004; …
- ✓ Evidence for a $D_s^*\bar{D}_s^*$ virtual state in LHCb data?

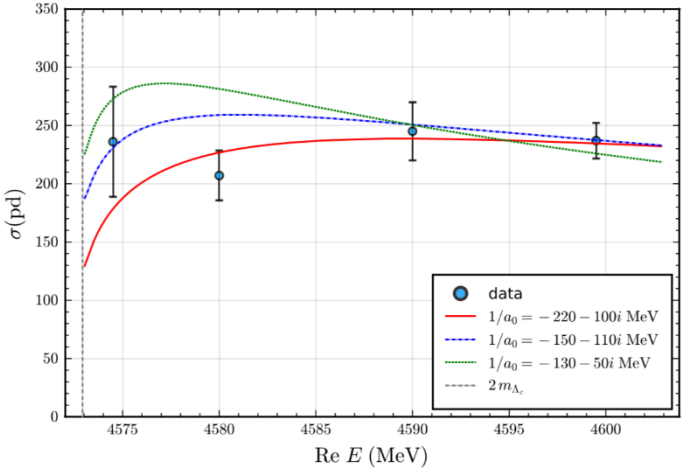


LHCb data: PRL127, 082001

Isoscalar vectors and related states



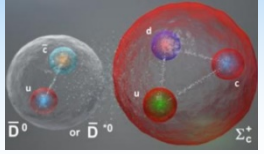
- ✓ $Y(4260)/\psi(4230)$ as a $\bar{D}D_1$ bound state
- ✓ Vector charmonia around 4.4 GeV unclear
- ✓ Evidence for 1^{--} $\Lambda_c\bar{\Lambda}_c$ bound state in BESIII data
  - Sommerfeld factor
  - Near-threshold pole
  - Different from $Y(4630/4660)$

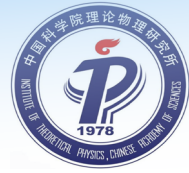


Data taken from BESIII, PRL120(2018)132001

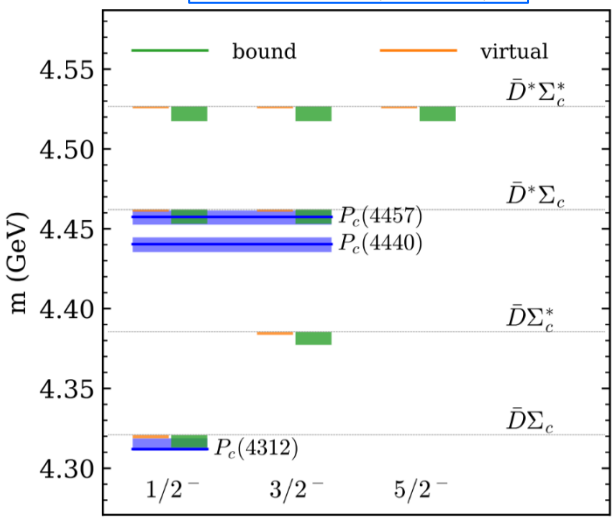
- ✓ Many 1^{--} states above 4.8 GeV: Belle-II, BEPC-II-Upgrade, STCF

Hidden-charm pentaquarks

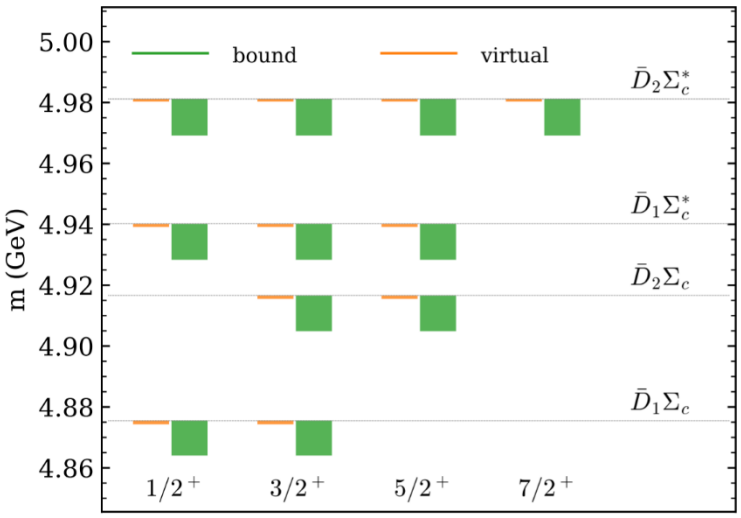




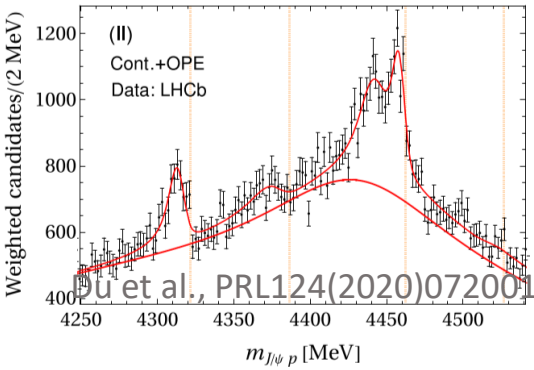
$(I,S) = (1/2,0)$



$(I,S) = (1/2,0)$

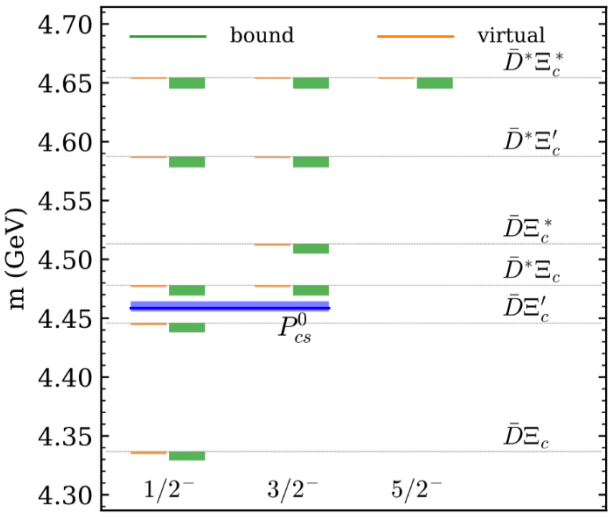


- ✓ The LHCb P_c states as $\bar{D}^{(*)}\Sigma_c$ molecules
- ✓ $\bar{D}\Sigma_c^*$ molecule: hint in the LHCb data

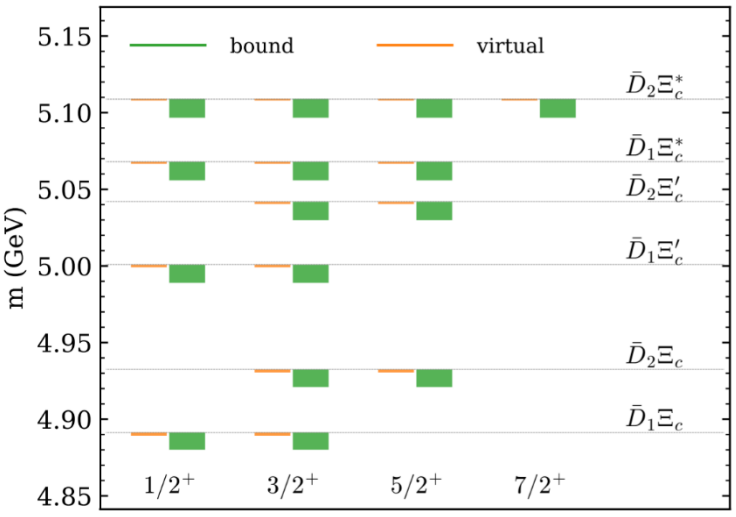


Pu et al., PRL124(2020)072001

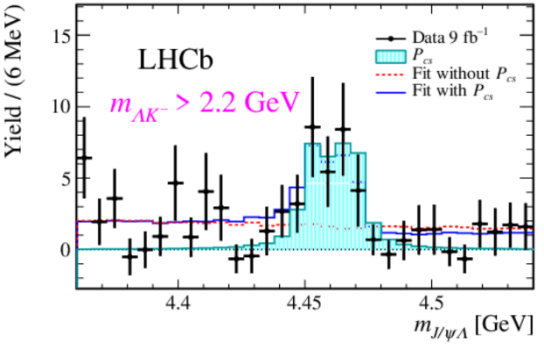
$(I,S) = (0,1)$



$(I,S) = (0,1)$



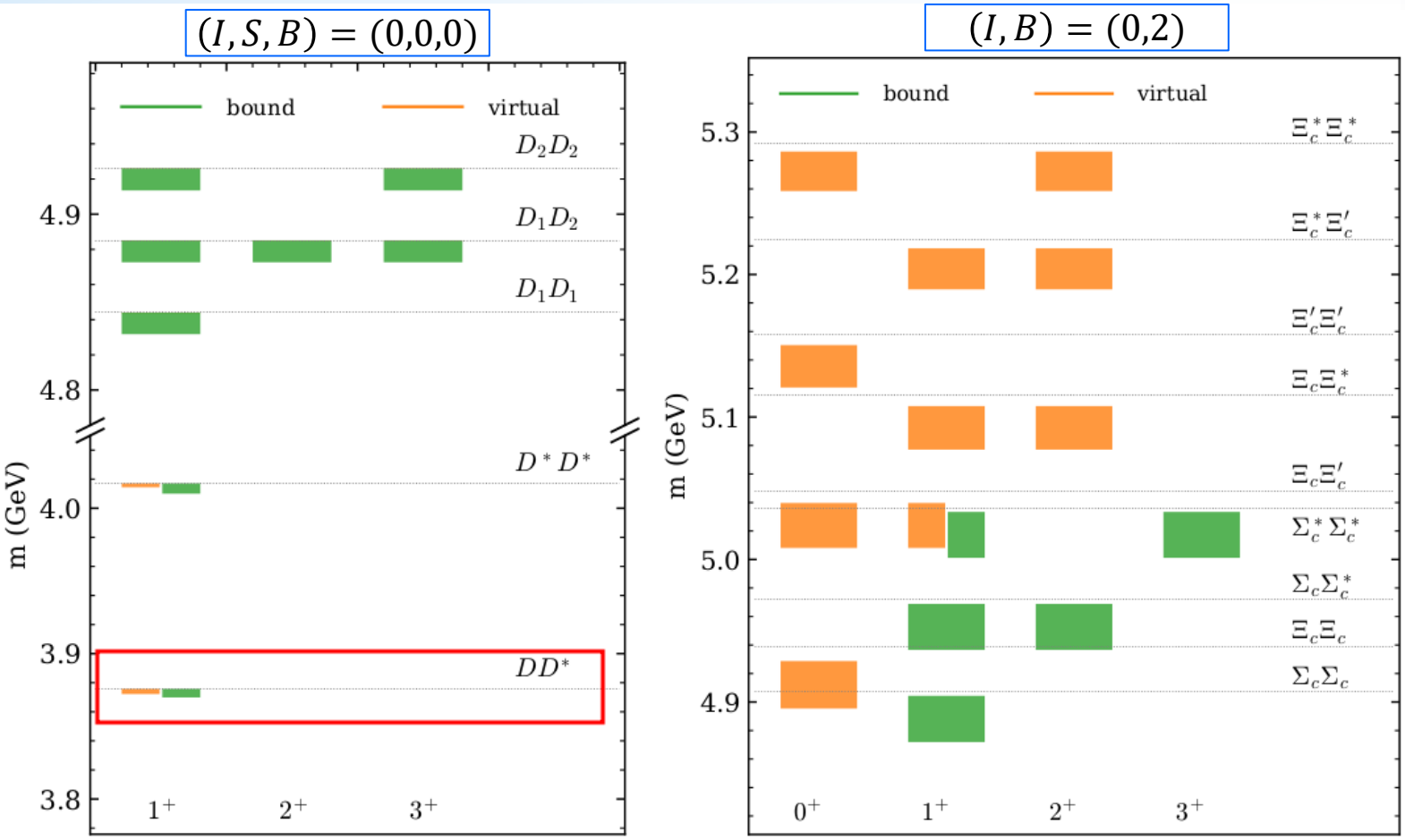
- ✓ The $P_{cs}(4459)$ could be two $\bar{D}^*\Xi_c$ molecules



LHCb, Sci.Bull.66,1278

- ✓ Many more baryon-antibaryon molecular states above 4.7 GeV

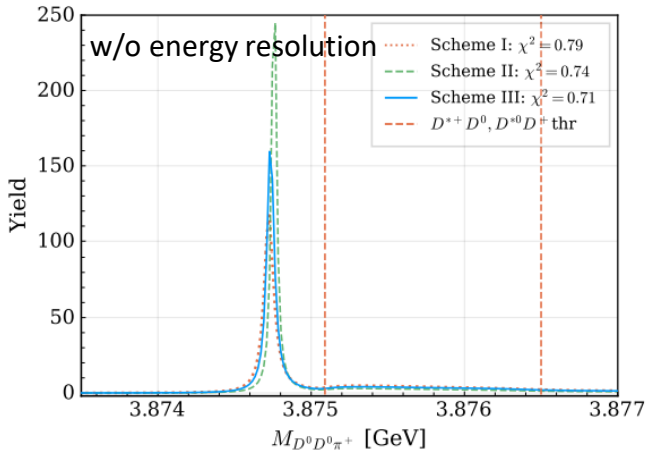
Double-charm

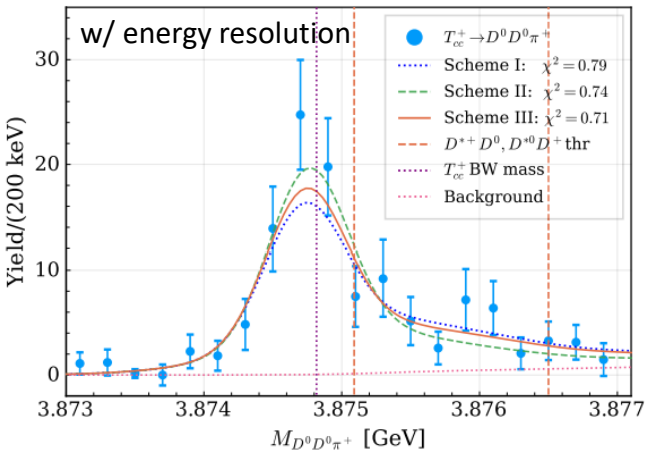


- ✓ There is an isoscalar DD^* molecular state
- ✓ It has a spin partner 1^+ D^*D^* state
- ✓ Many other similar double-charm molecular states in other sectors

X.-K. Dong, FKG, B.-S. Zou, CTP73(2021)125201

- Description of the LHCb data in the hadronic molecular picture M.-L. Du et al., arXiv:2110.13765



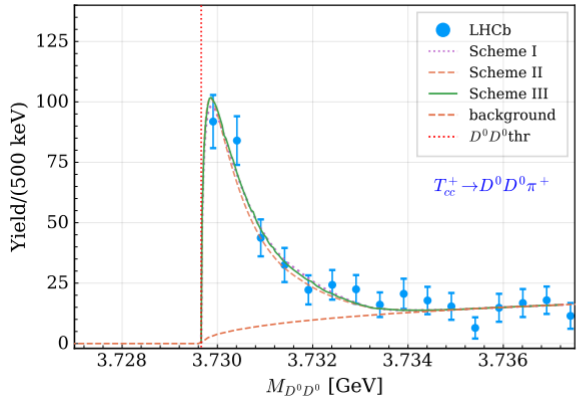


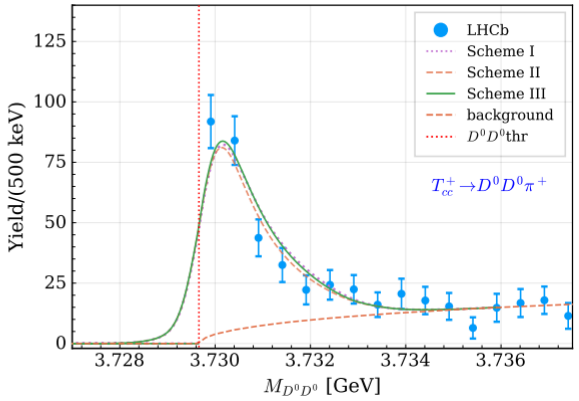
Isoscalar D^*D molecule, components:

- $D^{*+}D^0$: ~73%
- $D^{*0}D^+$: ~27%

Scheme	I	II	III
Pole [keV]	$-368^{+43}_{-42} - i(37 \pm 0)$ (RS-I)	$-333^{+41}_{-36} - i(18 \pm 1)$ (RS-II)	$-356^{+39}_{-38} - i(28 \pm 1)$ (RS-II)
	Contact term + const. Γ_{D^*}	Contact term + dynamical Γ_{D^*}	Contact term + OPE + dynamical Γ_{D^*}

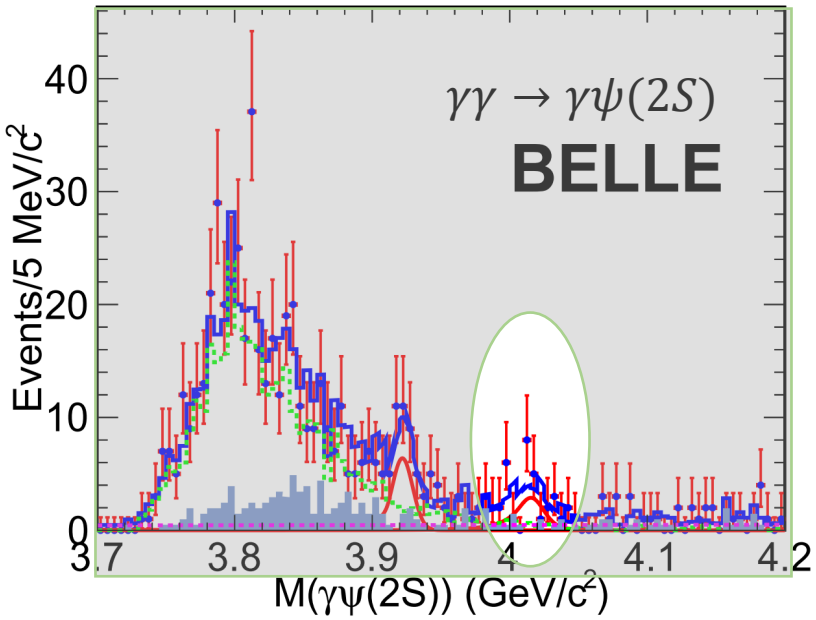
- Predicted DD spectra versus LHCb data





Spin partners

- Structure observed in $\gamma\gamma \to \gamma\psi(2S)$: evidence for X_2, the spin partner of $X(3872)$?



$M = 4014.4 \pm 4.1 \pm 0.5$ MeV,

$\Gamma = 6 \pm 16 \pm 6$ MeV

significance: 3.0σ

Belle, arXiv:2105.06605

- Width of $X_2 \to D\bar{D}, \bar{D}D^* + c.c.$ predicted in molecular model:

  $\sim 2 - 8$ MeV M. Albaladejo, FKG, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama, EPJC75(2015)547

  ~ 50 MeV V. Baru, E. Epelbaum, A.A. Filin, C. Hanhart, U.-G. Meißner, A.V. Nefediev, PLB763(2016)20

- 1^{+-} $D\bar{D}^*$ molecule: $\tilde{X}(3872)$ by COMPASS ? COMPASS, PLB783(2018)334

- Spin partner of T_{cc}^+: T_{cc}^{*+} $[D^{*0}D^{*+}]$ with 1^+, decay modes: $DD\pi, DD\pi\pi, DD\gamma, DD\gamma\,\gamma$

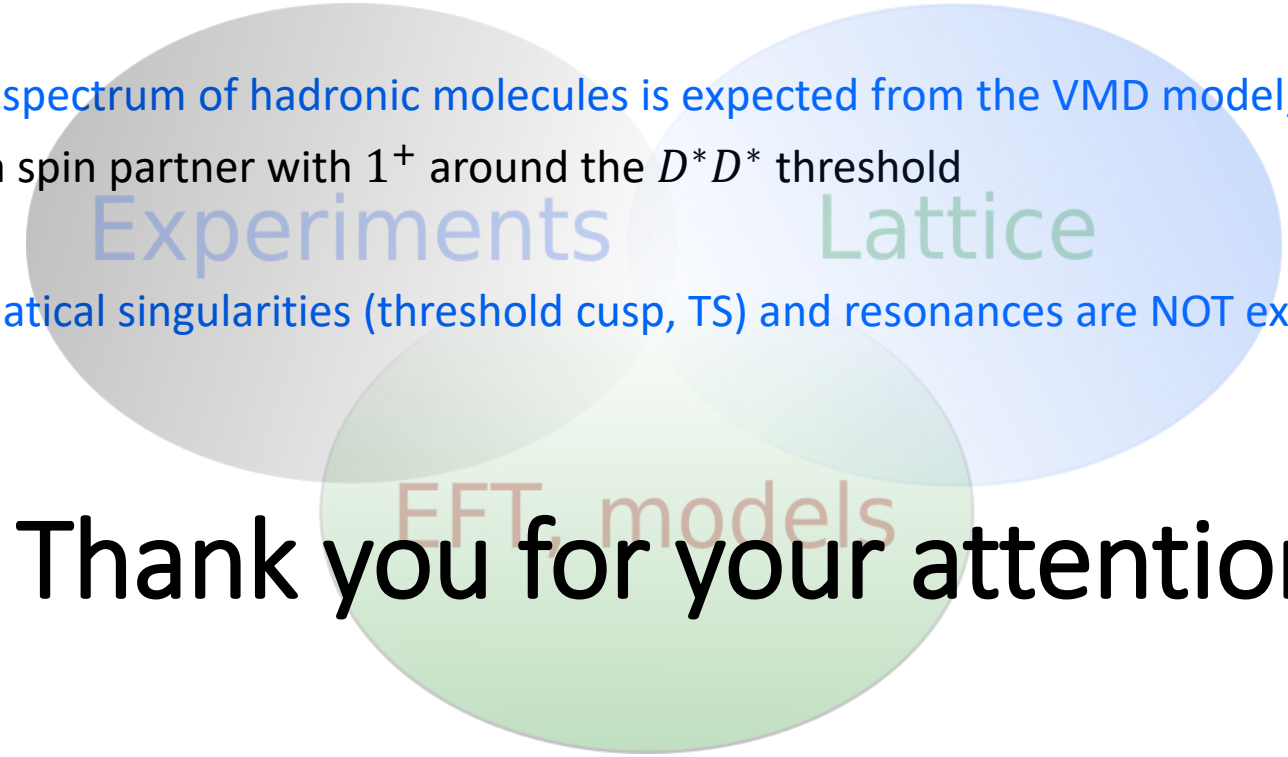
Conclusion

- General rule for (near-)threshold structures: S-wave attraction, more prominent for heavier particles and stronger attraction
- Strong attraction, then hadronic molecules below threshold, otherwise threshold cusps (and virtual state poles)

- Structures should be more prominent in bottom than in charm

- A rich spectrum of hadronic molecules is expected from the VMD model; T_{cc}^{+} would have a spin partner with 1^{+} around the $D^{*}D^{*}$ threshold

- Kinematical singularities (threshold cusp, TS) and resonances are NOT exclusive



Thank you for your attention!

Threshold cusp

- Unitarity of the S-matrix: $S\,S^\dagger = S^\dagger S = \mathbb{1},\ S_{fi} = \delta_{fi} - i(2\pi)^4\delta^4(p_f - p_i)T_{fi}$

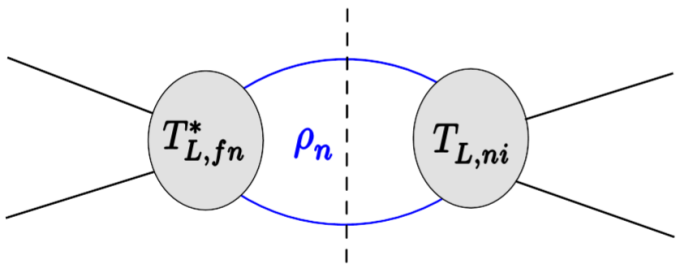
  T-matrix: $T_{fi} - T^\dagger_{fi} = -i(2\pi)^4 \underbrace{\sum_n}_{\text{all physically accesible states}} \delta(p_n - p_i)T^\dagger_{fn}T_{ni}$

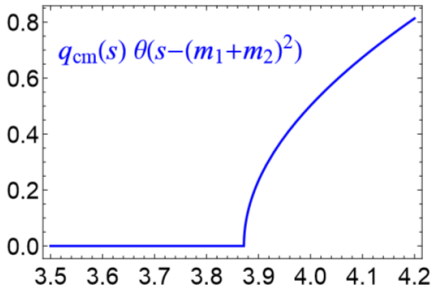
  assuming all intermediate states are two-body, partial-wave unitarity relation:

$$\boxed{\text{Im}\, T_{L,fi}(s) = -\sum_n T^*_{L,fn}\,\rho_n(s)\,T_{L,ni}}$$

  2-body phase space factor: $\rho_n(s) = q_{\text{cm},n}(s)/(2\sqrt{s})\theta(\sqrt{s} - m_{n1} - m_{n2})$,

  $q_{\text{cm},n}(s) = \sqrt{[s-(m_{n1}+m_{n2})^2][s-(m_{n1}-m_{n2})^2]}/(2\sqrt{s})$



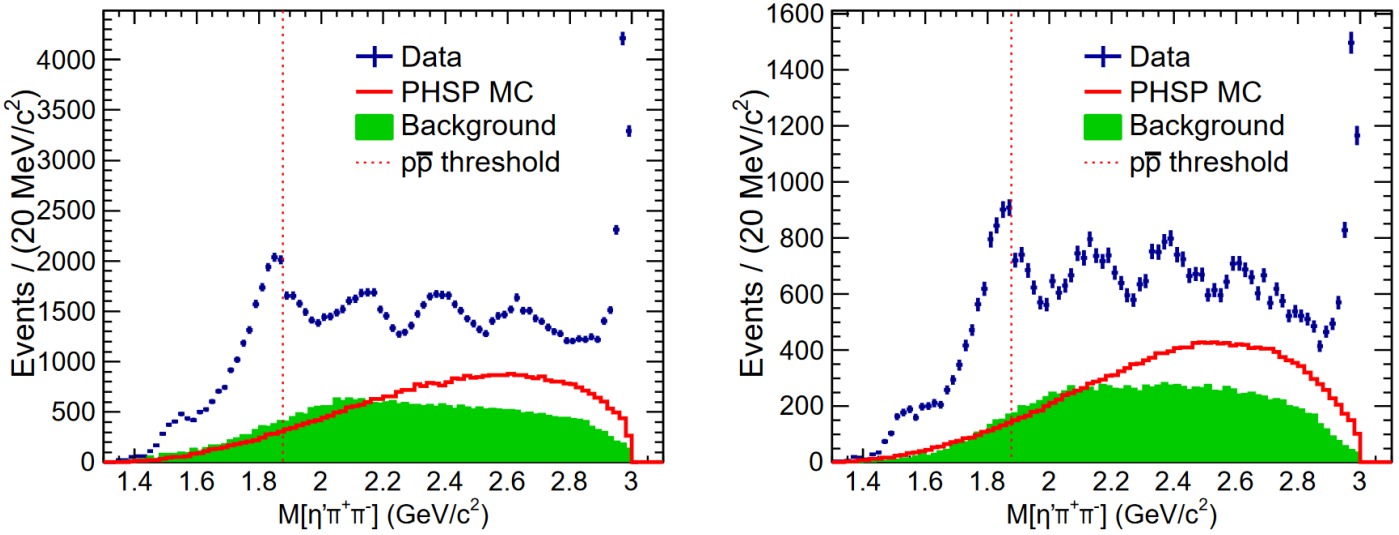


- There is always a cusp at an S-wave threshold

Phenomenology

- $p\bar{p}$ threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII, PRL117(2016)042002



Drastic drop:

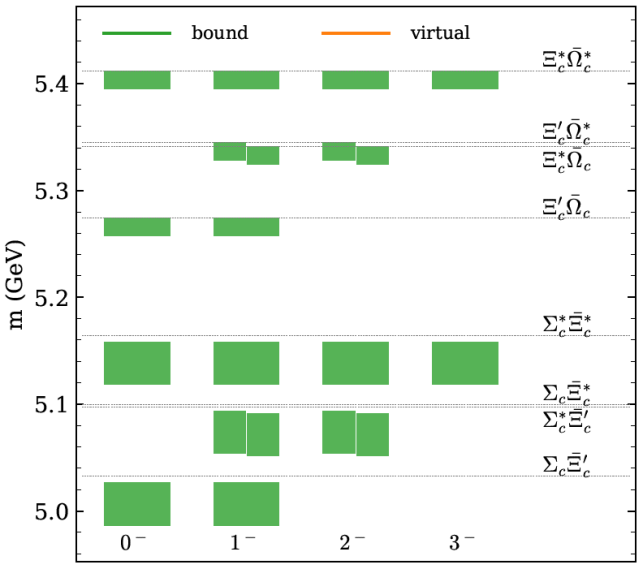
- there should be a pole near the $p\bar{p}$ threshold
- $p\bar{p}$ is not the driving channel

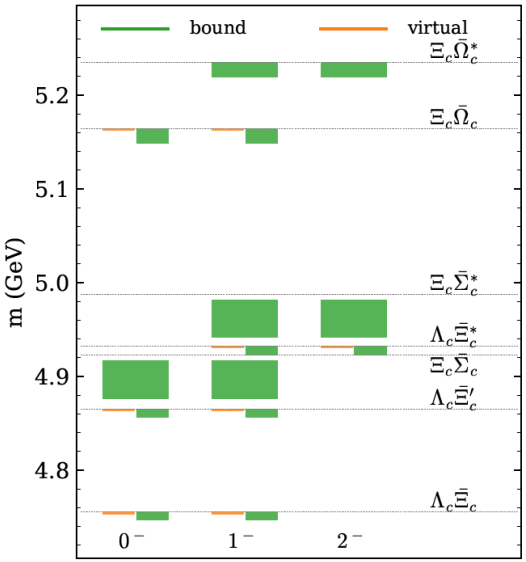
- $D^{(*)}\bar{D}^{(*)}$ should be the driving channels for $X(3872), Z_c(3900), Z_c(4020)$

More states with exotic quantum numbers

$(I,S) = (1,0)$

$(I,S) = (1/2,1)$

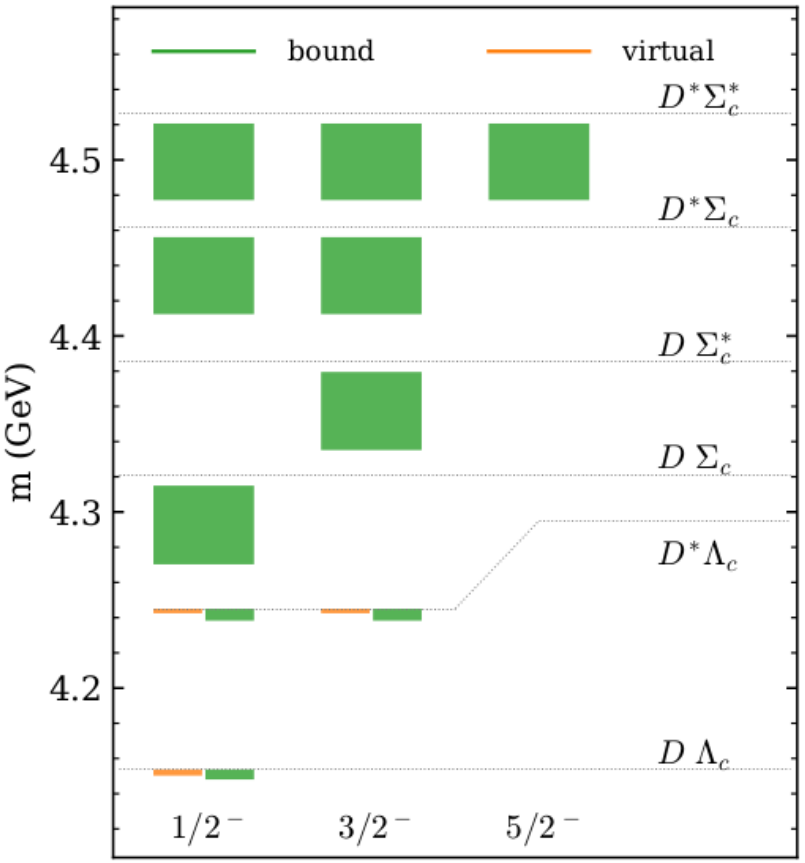




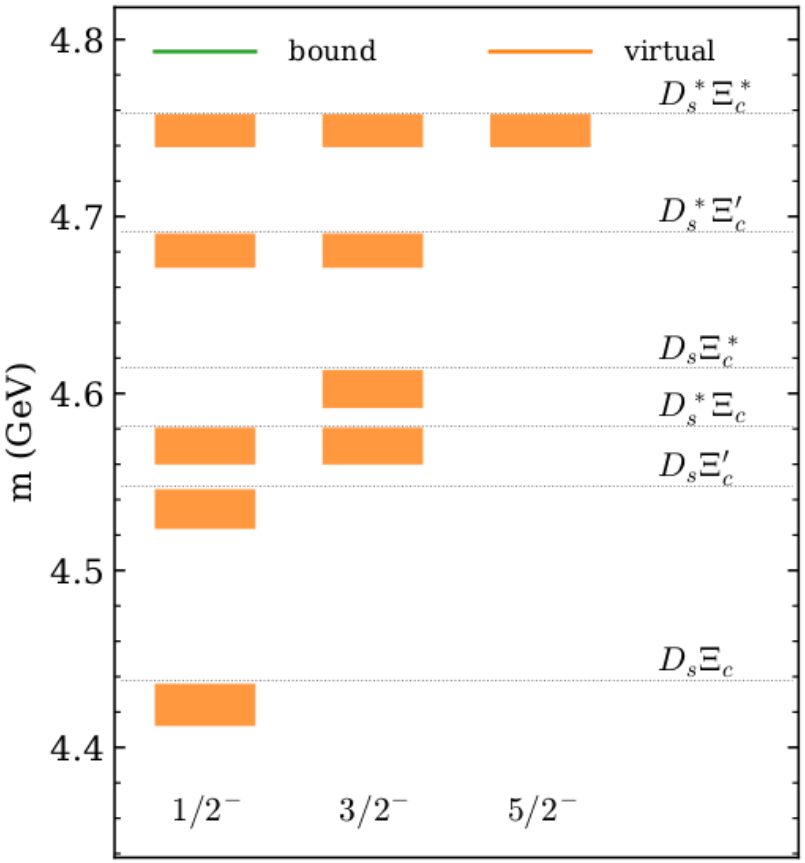
- ✓ Many baryon-antibaryon molecular states above 4.7 GeV, beyond the current exp. region

Double-charm

$(I,S,B) = (1/2,-1,1)$



$(I,S,B) = (0,0,1)$



- ✓ The attractions for $D^{(*)}\Sigma_c^{(*)}$ are stronger than those for $\bar{D}^{(*)}\Sigma_c^{(*)}$
- ✓ However, the $D^{(*)}\Sigma_c^{(*)}$ states mix with normal double-charm baryons

X.-K. Dong, FKG, B.-S. Zou, arXiv:2108.02673

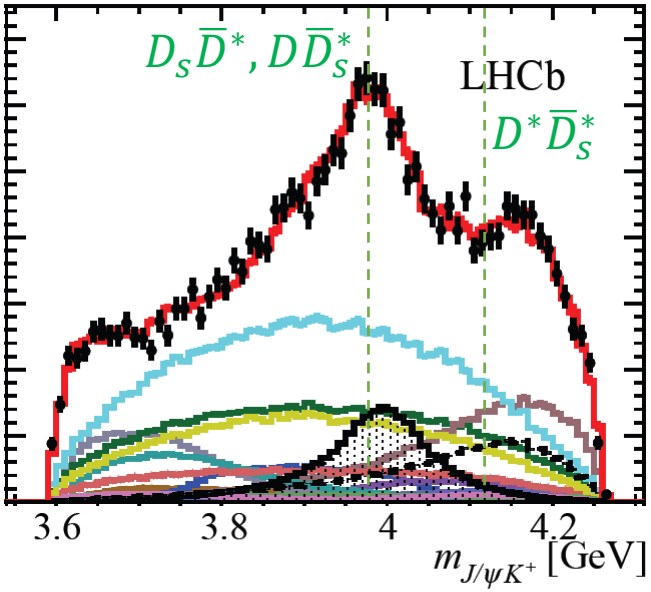
Comments on Z_c and Z_{cs}

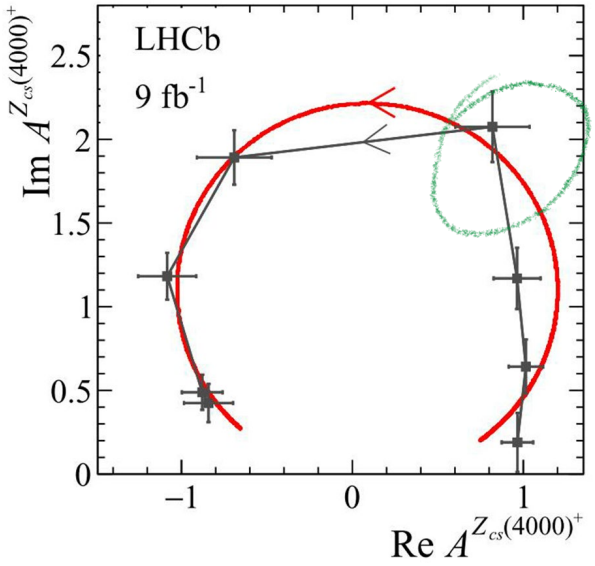
- ✓ Isovector interaction between $D^{(*)}\bar{D}^{(*)}$ from light vector exchange vanishes
- ✓ Charmonia exchange might be important here: F.Aceti, M.Bayar, E.Oset et al., PRD90(2014)016003

  no mass hierarchy, a series of charmonia can be exchanged Dong, FKG, Zou, arXiv:2101.01021

  axial-vector meson exchange considered in Yan, Peng, Sanchez Sanchez, Pavon Valderrama 2102.13058
- ✓ $Z_c(3900,4020)$ as $\bar{D}^{(*)}D^*$ virtual states
- ✓ $Z_{cs}(3985)$ as $D_s\bar{D}^*, D\bar{D}_s^*$ virtual state; there should also be a $D^*\bar{D}_s^*$ state around 4.1 GeV

  Z. Yang, X. Cao, FKG, J. Nieves, M. Pavon Valderrama, PRD103(2021)074029





Threshold behavior with a strong coupling

LHCb, arXiv: 2103.01803

Comments on Z_c and Z_{cs}

✓ Simultaneous fit to the BESIII and LHCb Z_{cs} data: Z_{cs} as virtual states

Ortega, Entem, Fernandez, 2103.07781