Overview of Hadronic Molecules

Feng-Kun Guo

Institute of Theoretical Physics, Chinese Academy of Sciences

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Hadronic molecules

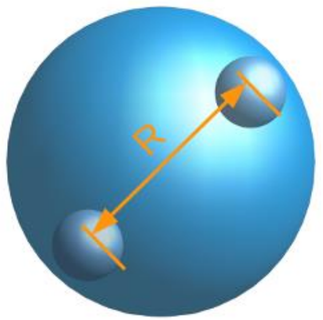
- Hadronic molecule: analogue of light nuclei;

  dominant component is a composite state of 2 or more hadrons; extended object

- Concept at large distances, so that can be approximated by a composite system of multi-hadrons at low energies

  Consider a 2-body bound state with a mass $M = m_1 + m_2 - E_B$

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



- Well-separated scales: effective field theories (EFTs)
- Only narrow hadrons can be considered as components of hadronic molecules, $\Gamma_h \ll 1/r$, r: range of forces

FKG, Meißner, PRD 84 (2011) 014013; see also Filin et al., PRL 105 (2010) 019101

Hadronic molecules

- How is energy excited inside a hadron:
  - Radial excitations?
  - Excitation of light quark-antiquark pairs ⇒ compact multiquarks?
  - Hadron-hadron pairs? In the form of hadronic molecules
    - Implication of confinement (large-size systems in favor of color-singlet clusters)?
    - More and more molecular candidates have been observed (see below)
      - If compact multiquarks exist too, why are the extended molecules so easily produced?

Different confinement pictures

- Crucial quantity: compositeness $1 - Z$, well-defined for S-wave loosely bound state; can be expressed in terms of low-energy observables

S. Weinberg (1965); V. Baru et al. (2004); T. Hyodo et al. (2012); F. Aceti, E. Oset (2012); Z.-H. Guo, J. Oller (2016); I. Matuschek et al. (2021); J. Song et al. (2022); M. Albaladejo, J. Nieves (2022) ; Y. Li, FKG, J.-Y. Pang, J.-J. Wu, PRD 105 (2022) L071502 …

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;

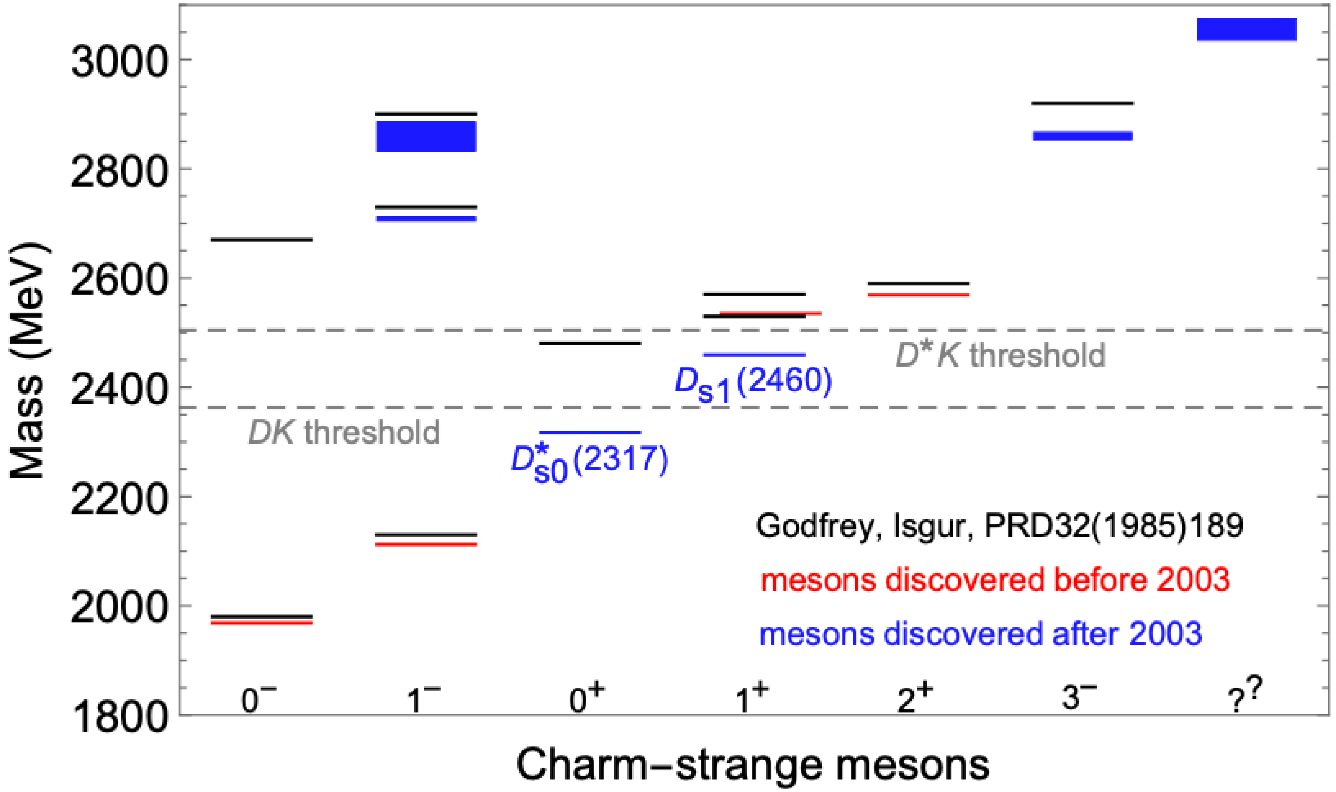
$a_{Z=1} = 0$ fm, $\quad a_{Z=0} = (-4.3 \pm 1.4)$ fm

After range corrections (for ERE up to NLO):

hold for $a \in \left[-\frac{1}{\sqrt{2\mu E_B}}, 0\right], r_e < 0$;

$Z = 0$ with $a < -\frac{1}{\sqrt{2\mu E_B}}, r_e > 0$

Charm-strange mesons

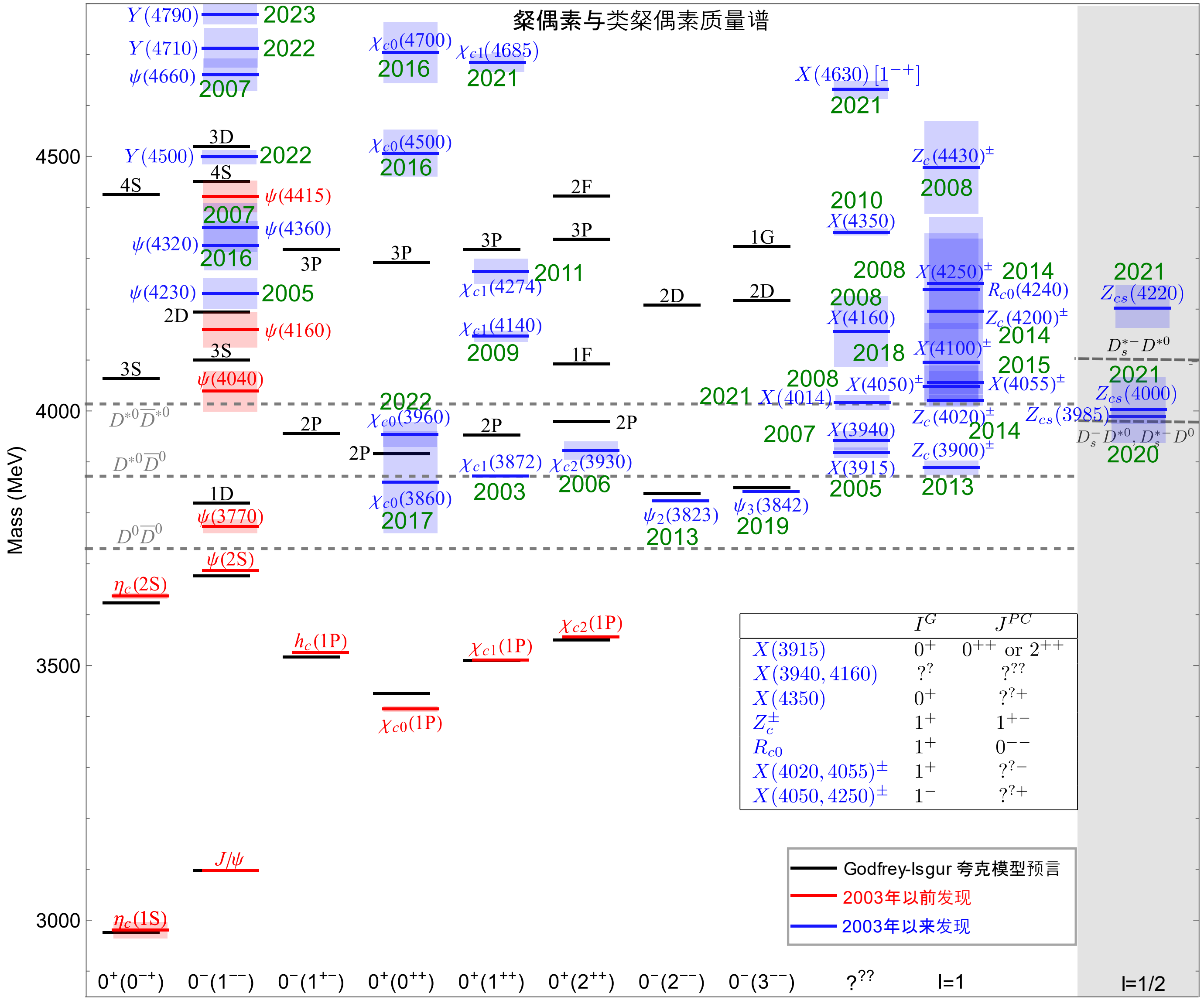


- $D^*_{s0}(2317)$: BaBar (2003)
  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$: CLEO (2003)
  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths $\Rightarrow I = 0$

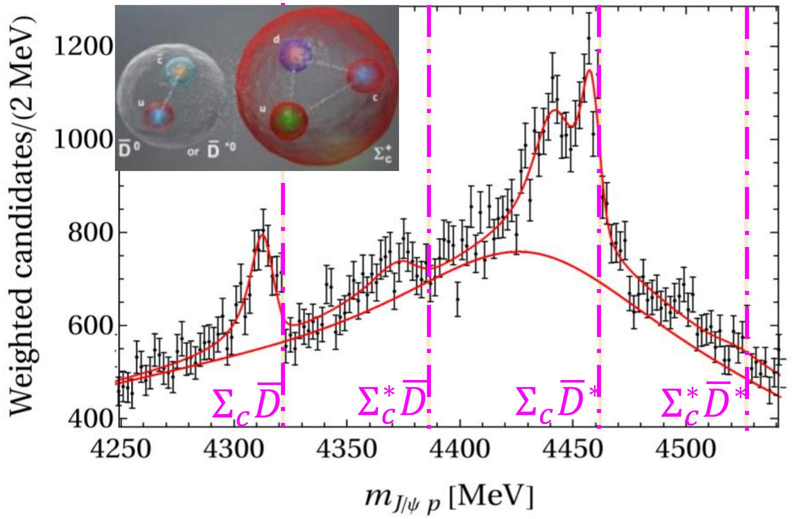
- Mass problem: Why are $D^*_{s0}(2317)$ and $D_{s1}(2460)$ so light?
- Naturalness problem: Why $\underbrace{M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)}}_{(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^{\pm}}}_{(140.67\pm0.08)\text{ MeV}}$?

Hidden-charm and double-charm exotic hadrons

- Charmonium-like states



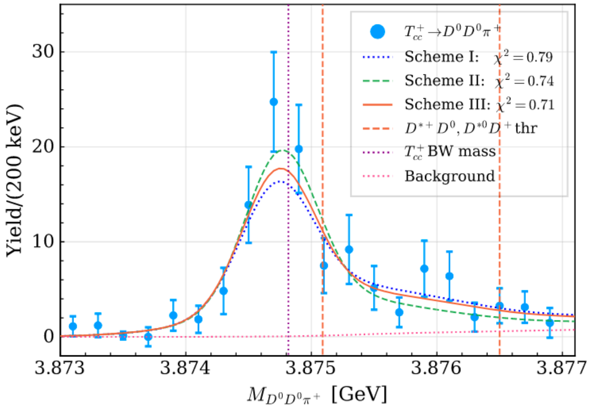
- Hidden-charm pentaquarks

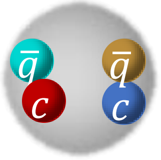


Data: LHCb, PRL122 (2019) 222001;

Fit: M.-L. Du, et al., PRL 124 (2020) 072001

- Double-charm tetraquarks





Data: LHCb, Nature Phys. 18 (2022) 751;

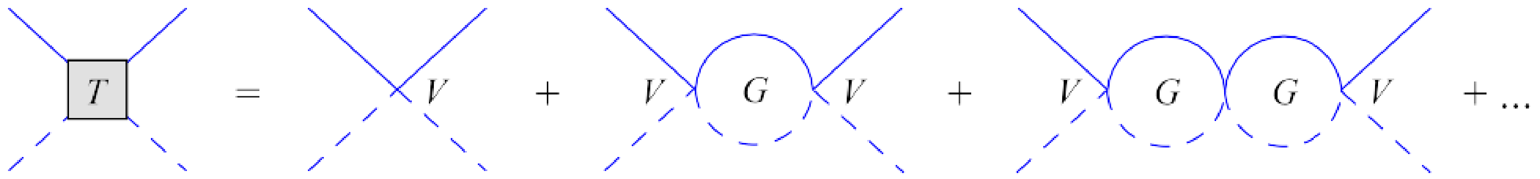
Fit: M.-L. Du et al., PRD 105 (2022) 014024

Charm-strange mesons from chiral EFT and lattice QCD

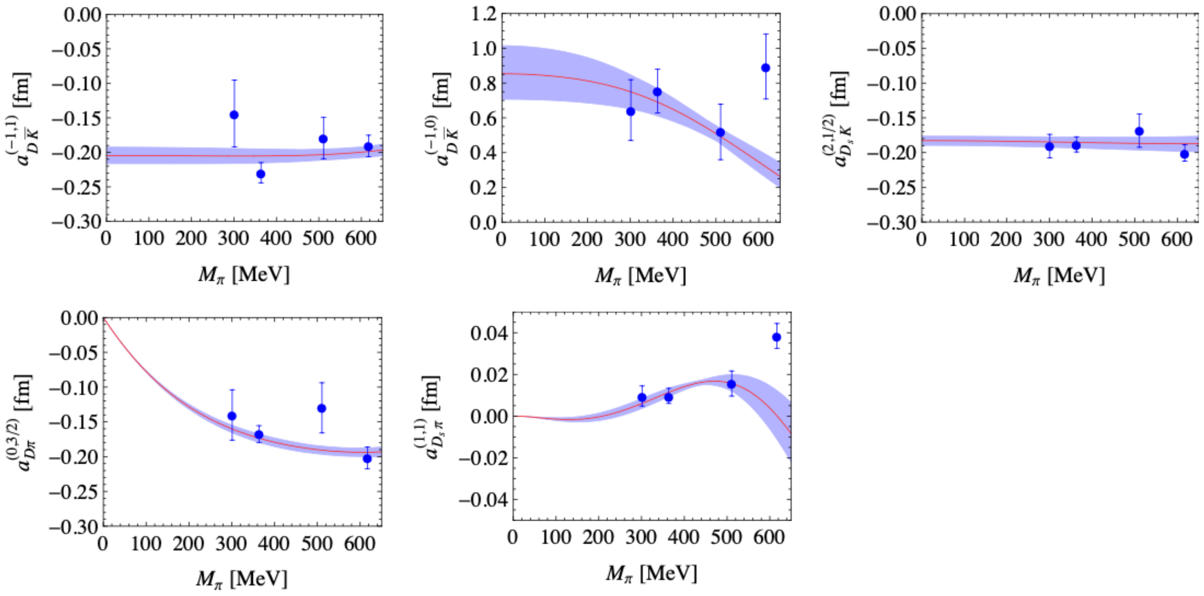
- In hadronic molecular model: $D_s^{*0}(2317)[DK], D_{s1}(2460)[D^*K]$

  Barnes, Close, Lipkin (2003); van Beveren, Rupp (2003); Y.-Q. Chen, X.-Q. Li (2004); Kolomeitsev, Lutz (2004); FKG et al. (2006); Gamermann et al. (2007); …

- Chiral EFT for the sncattering between charmed mesons and light pseudoscalar mesons

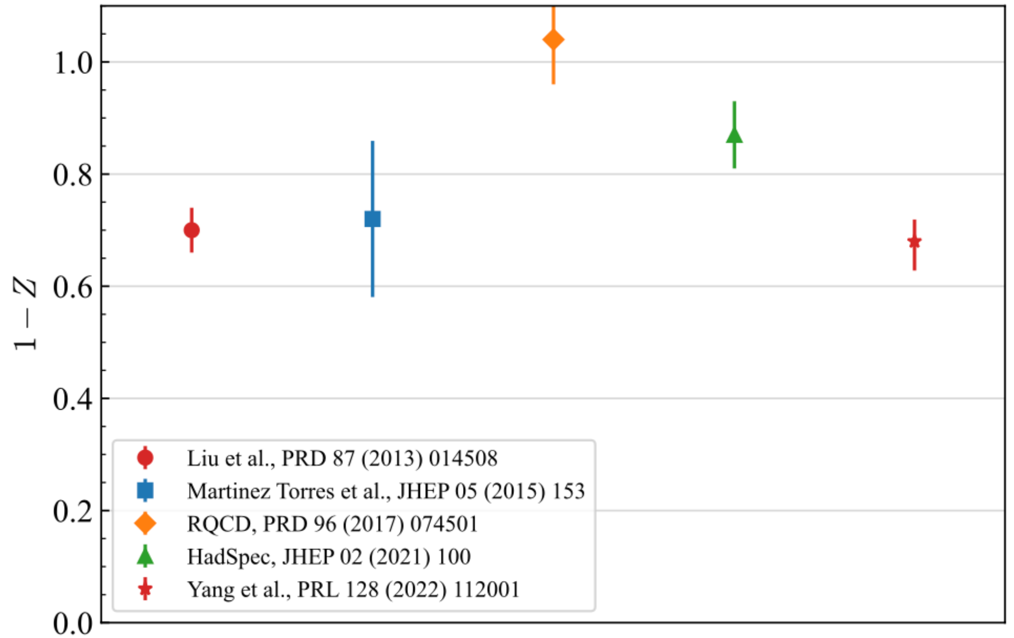


➢ Parameters fixed from fitting to lattice QCD results



L. Liu, Orginos, FKG, Hanhart, Meißner, PRD86(2013)014508

➢ DK compositeness of $D_s^{*0}(2317)$ from lattice QCD

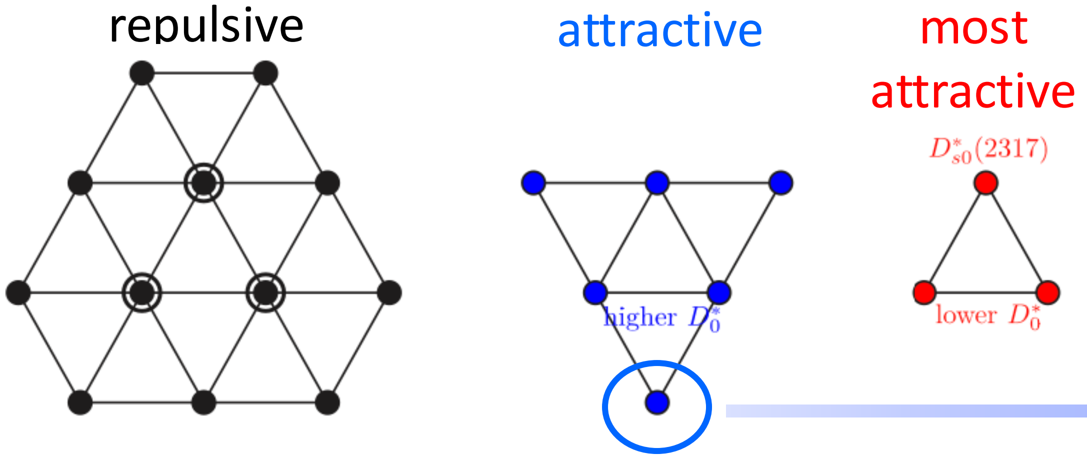


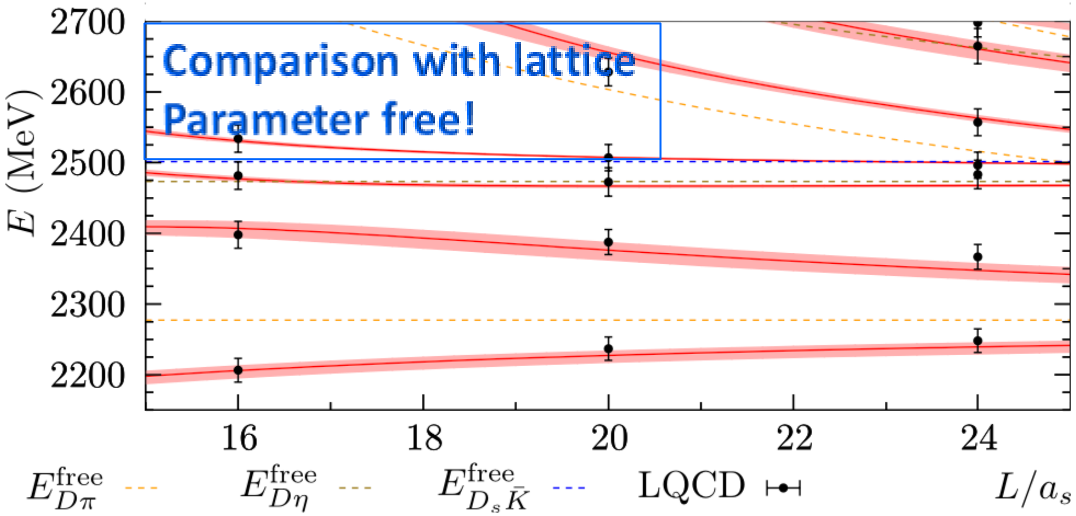
Charm-strange mesons from chiral EFT and lattice QCD

- SU(3) structures differ from quark model!

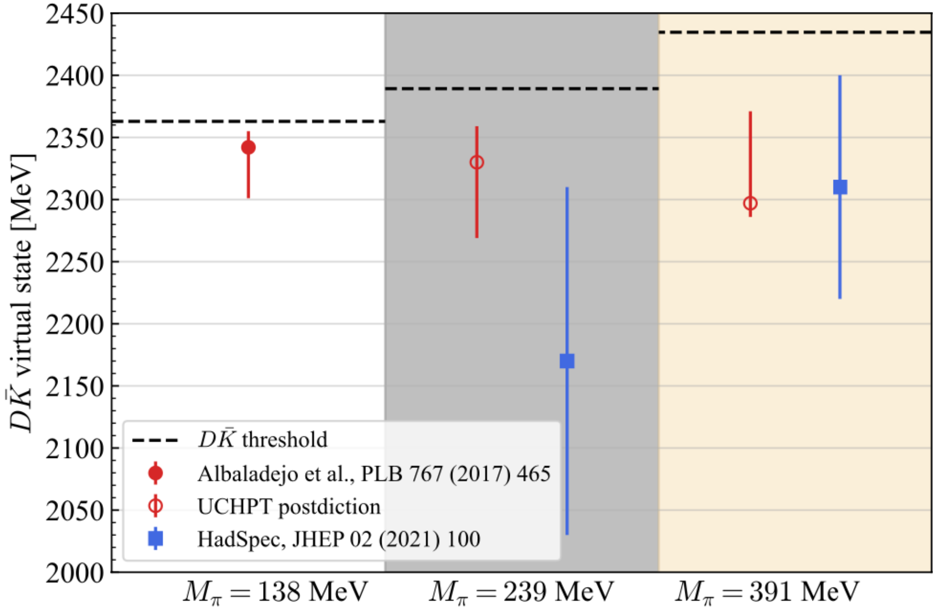
More exotic states: $\bar{3} \otimes 8 = \overline{15} \oplus 6 \oplus \bar{3}$

M. Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB 767 (2017) 465





- Prediction of $I = 0, D\bar{K}$ virtual state confirmed by lattice QCD



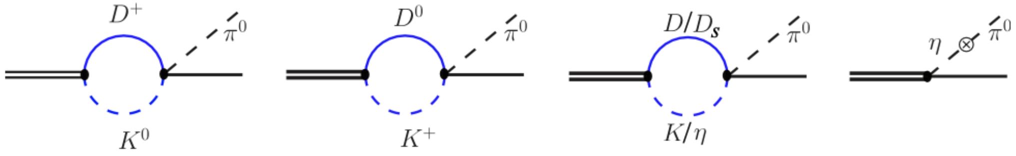
- More supports from lattice & exp. not shown

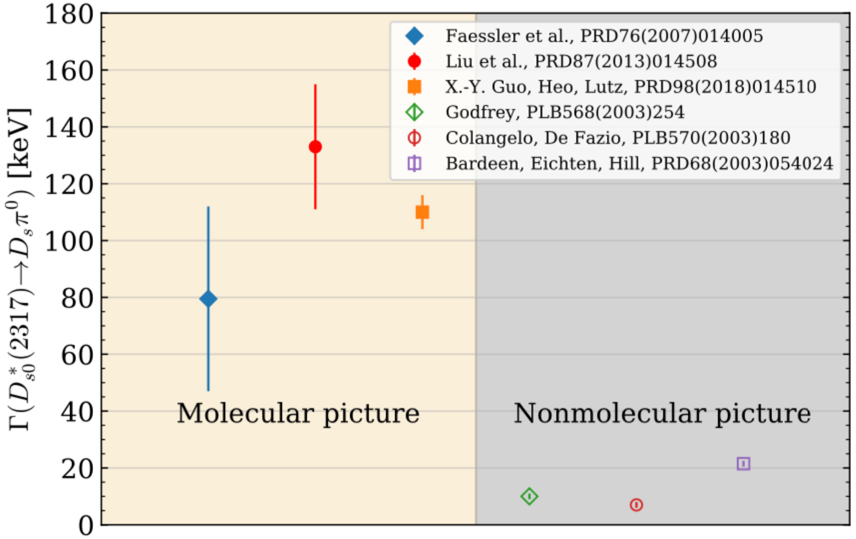
M.-L. Du, FKG, Hanhart, Kubis, Meißner, PRL 126 (2021) 192001; …

- Solutions to the two problems:
  - ➢ DK and D^*K molecular states
  - ➢ Consequence of heavy quark spin symmetry

Charm-strange mesons: smoking guns of molecular structure

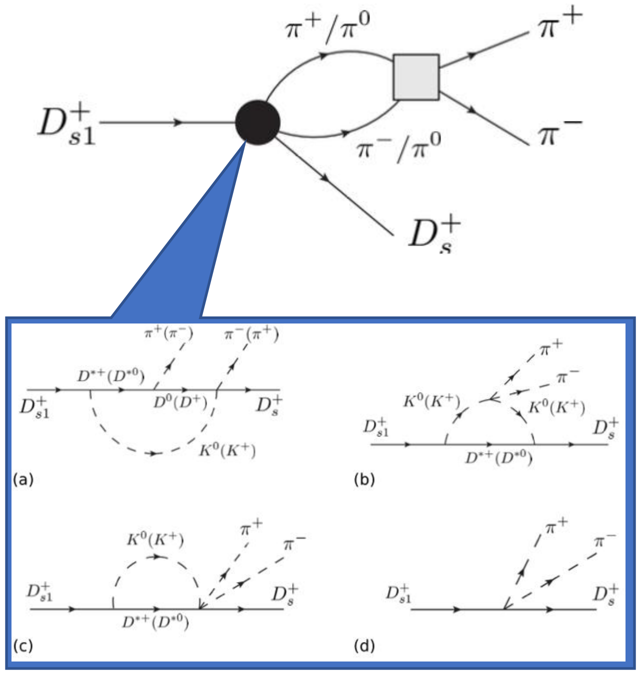
- $D_{s0}^*(2317), D_{s1}(2460)$: total width∼ 100 keV



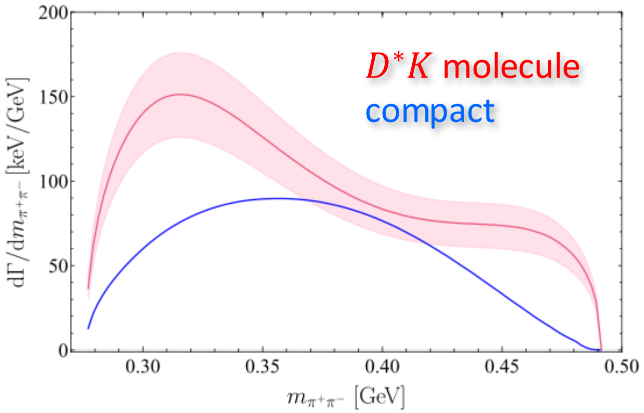


- $D_{s1}(2460) \to D_s\pi^+\pi^-$: double-bump

M.-N. Tang, Y.-H. Lin, FKG, U.-G. Meißner, CTP 75 (2023) 055203



Prediction to be tested:
Belle II & LHCb



➢ BESIII measured $\mathrm{Br}(D_{s0}^* \to D_s\pi^0) \approx 100\%$ BESIII, PRL 97 (2018) 051103

width still not measured! At PANDA? M.C. Mertens (2012)

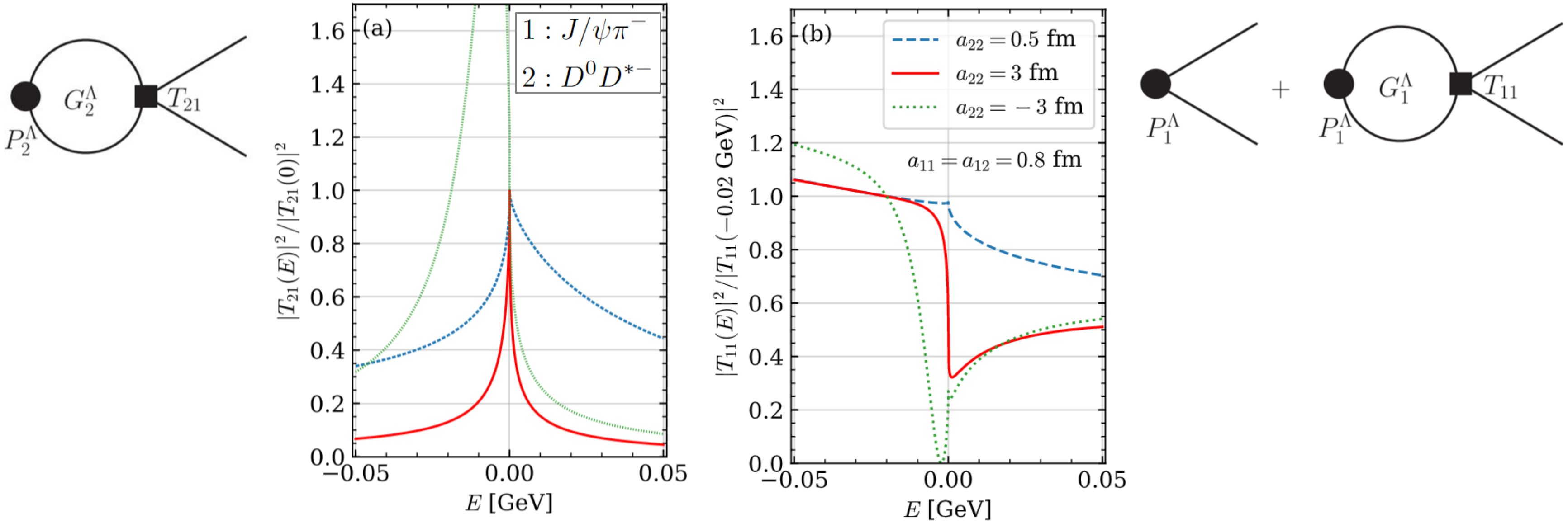
Universality of kaonic interaction with isospin-1/2 matter fields
⇒ a whole family of kaonic bound states!
✓ $\Lambda(1405)$, K-nucleus bound states, … Dalitz, Tuan, Oller, Meißner, Jido, Oset, Ramos, Hyodo, Weise, Mai, …

(Near-)threshold structures

X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001
Extension: classification of 2-channel near-threshold structures, Z.-H. Zhang, FKG, arXiv:2407.10620

- (Near-)threshold structures (S-wave)
  - Nonrelativistic EFT at LO: nontrivial (near-)threshold structures for attractive S-wave interaction
  - Either threshold cusp or below-threshold peak
  - Peak more pronounced for heavier hadrons and stronger interaction
    - ✓ That's why many (near-)threshold structures were observed in hidden-charm spectra
  - Structures are process (production-mechanism) dependent
    - ✓ Universality of a dip for large scattering length in T_{11}

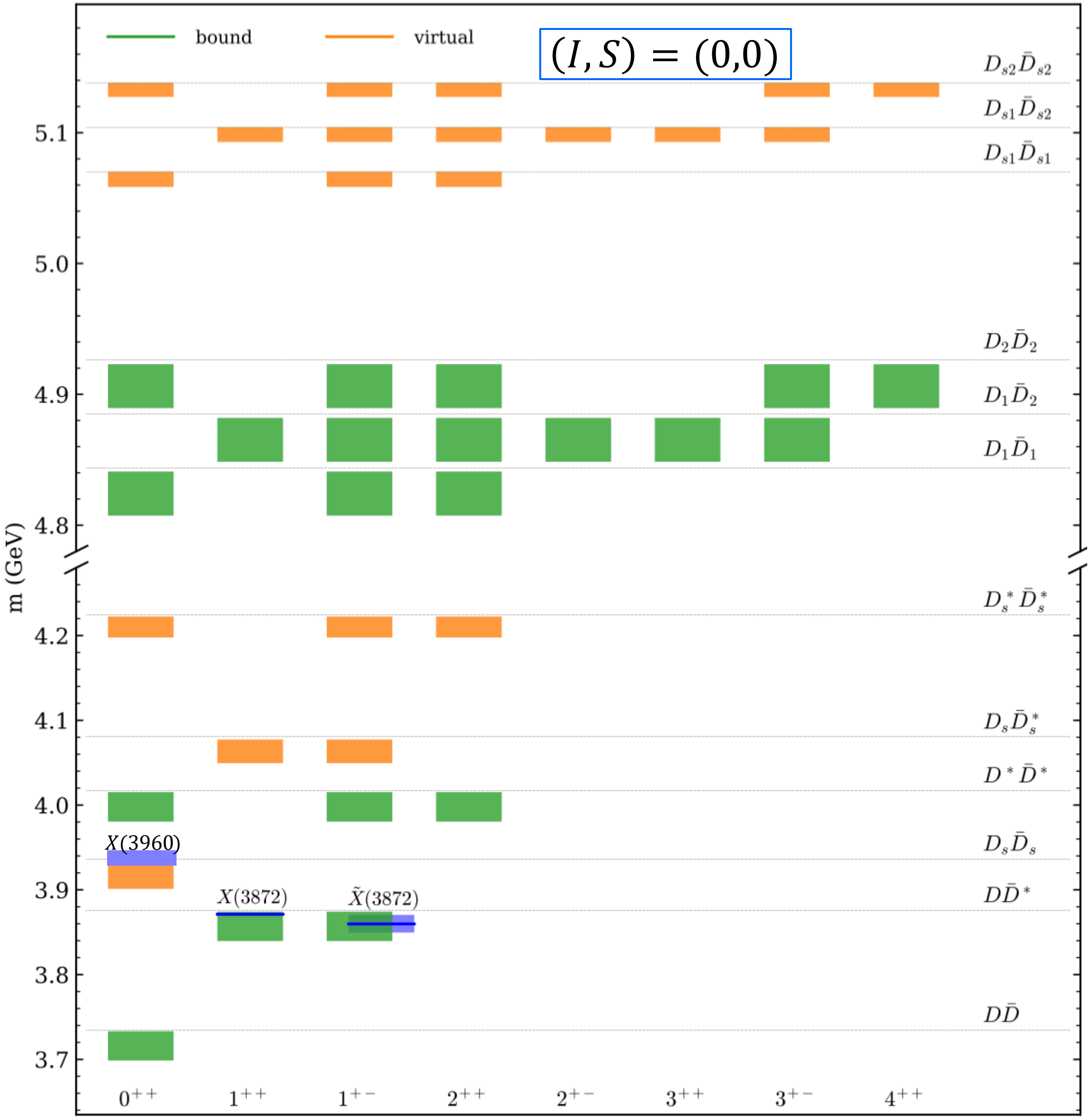
Correction due to 3-body threshold, talk by Alexey Nefediev



Distinct line shapes of amplitudes in the same coupled channels with the same poles

Hidden-charm mesons: $P = +$

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



✓ Approximations: light-vector exchanges, single channel, no mixing

✓ $X(3872)$ as a $\bar{D}D^*$ bound state. First predicted in Törnqvist (1993)

Some debates:

- ☐ Are radiative decays ($\to \psi\gamma$) sensitive to the structure?

  The answer is no! E. Swanson, PLB 598 (2004) 297; FKG et al., PLB 742 (2015) 394

- ☐ What can be learned from its production in heavy-ion collisions?

  S. Cho et al., PRL 106 (2011) 212001;
  H. Zhang et al., PRL 126 (2021) 012301;
  B. Chen et al., PRC 105 (2022) 054901;
  E. Braaten et al., arXiv:2408.03935; …

✓ $\bar{D}D$ bound state.

Conflicting lattice QCD results, what is the reason?

- ✓ Near-threshold bound state S.Prelovsek et al., JHEP 06 (2021) 035
- ✗ No near-threshold state D.Wilson et al., PRL 132 (2024) 241901

Closer look into $X(3872)$

Z.-H. Zhang, T. Ji, X.-K. Dong, FKG et al., JHEP 08 (2024) 130

- Chiral EFT for the $J^{PC} = 1^{++}$ $D\bar{D}^*$ interaction with three-body effects. Two low-energy constants at LO
- Two inputs from $X(3872)$ properties :
  - Mass

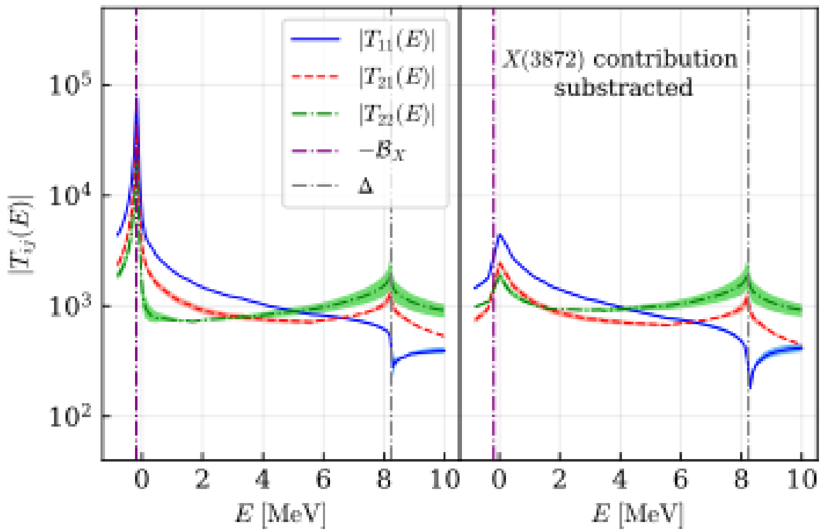
$$M_X = 3871.69^{+0.00+0.05}_{-0.04-0.13}\,\text{MeV}$$ LHCb, PRD 102 (2020) 092005

$$M_{D^0} + M_{D^{*0}} = 3871.69(7)\ \text{MeV}$$ PDG 2024

  - Isospin breaking in decays LHCb, PRD 108 (2023) L011103

$$R_X = \left|\frac{\mathcal{M}_{X(3872)\to J/\psi\rho^0}}{\mathcal{M}_{X(3872)\to J/\psi\omega}}\right| = 0.29 \pm 0.04$$

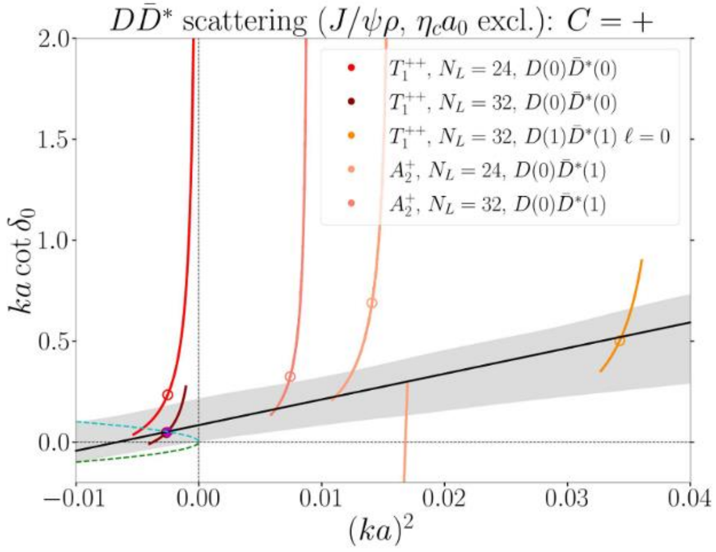
- Prediction: there must exist an isovector $J^{PC} = 1^{++}$ state ($W_{c1}^{0,\pm}$)



- Virtual state (like the $^1S_0$ NN)
- Threshold cusps
- $W_{c1}^{\pm}$: -8^{+8}_{-5} MeV from D^0D^{*-} threshold

✓ Support from lattice QCD

M. Sadl et al., arXiv:2406.09842 [hep-lat]



J^{PC}	interpolators	$1/a_0$ [fm^{-1}]	r_0 [fm]	χ^2/N_{dof}	Δm_V [MeV]
1^{+-}	all	$0.46^{+1.16}_{-0.45}$	$0.96^{+0.43}_{-0.73}$	0.13	$-3.0^{+3.0}_{-31.1}$
	$\eta_c\rho$ excl.	$0.54^{+1.07}_{-0.44}$	$2.23^{+0.95}_{-1.08}$	0.24	$-2.8^{+2.6}_{-17.1}$
1^{++}	all	$0.62^{+1.30}_{-0.51}$	$1.78^{+0.25}_{-2.44}$	0.18	$-3.8^{+3.6}_{\text{a}}$
	$J/\psi\rho$, $\eta_c a_0$ excl.	$0.96^{+1.42}_{-0.91}$	$2.19^{+0.36}_{-1.00}$	0.15	$-6.7^{+6.7}_{-19.5}$

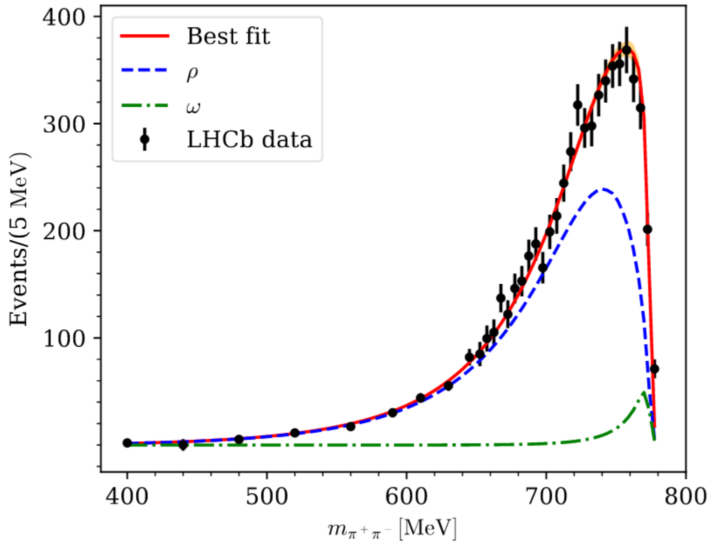
[a] Uncertainty is so large that it is unbounded from below.

Closer look into $X(3872)$

J. M. Dias, T. Ji, X.-K. Dong et al., arXiv:2409.13245

- Update with model-independent analysis of the isospin breaking in $X \to J/\psi\pi^+\pi^-$ decay
  - Omnes description of the $\pi\pi$ final state interaction
  - $\rho - \omega$ mixing from $\omega \to \pi^+\pi^-$ with vac. pol. correction

$$R_X = \left|\frac{\mathcal{M}_{X(3872)\to J/\psi\rho^0}}{\mathcal{M}_{X(3872)\to J/\psi\omega}}\right| = 0.19 \pm 0.02$$



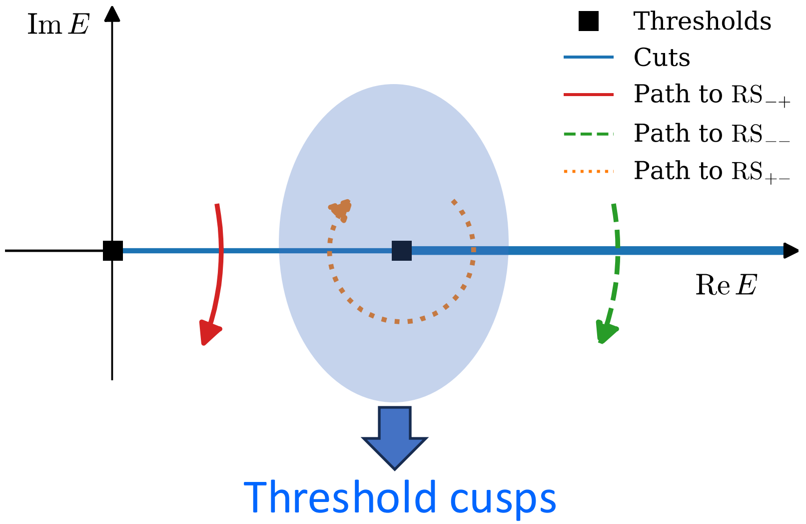
- Updated pole position for the $J^{PC} = 1^{++}$ state ($W_{c1}^{0,\pm}$)

W_{c1}^0 : $3884.2^{+1.4}_{-1.1} + i(2.3 \pm 0.8)\mathrm{MeV}$

$4.3^{+1.4}_{-1.1}$ above the D^+D^{*-} threshold

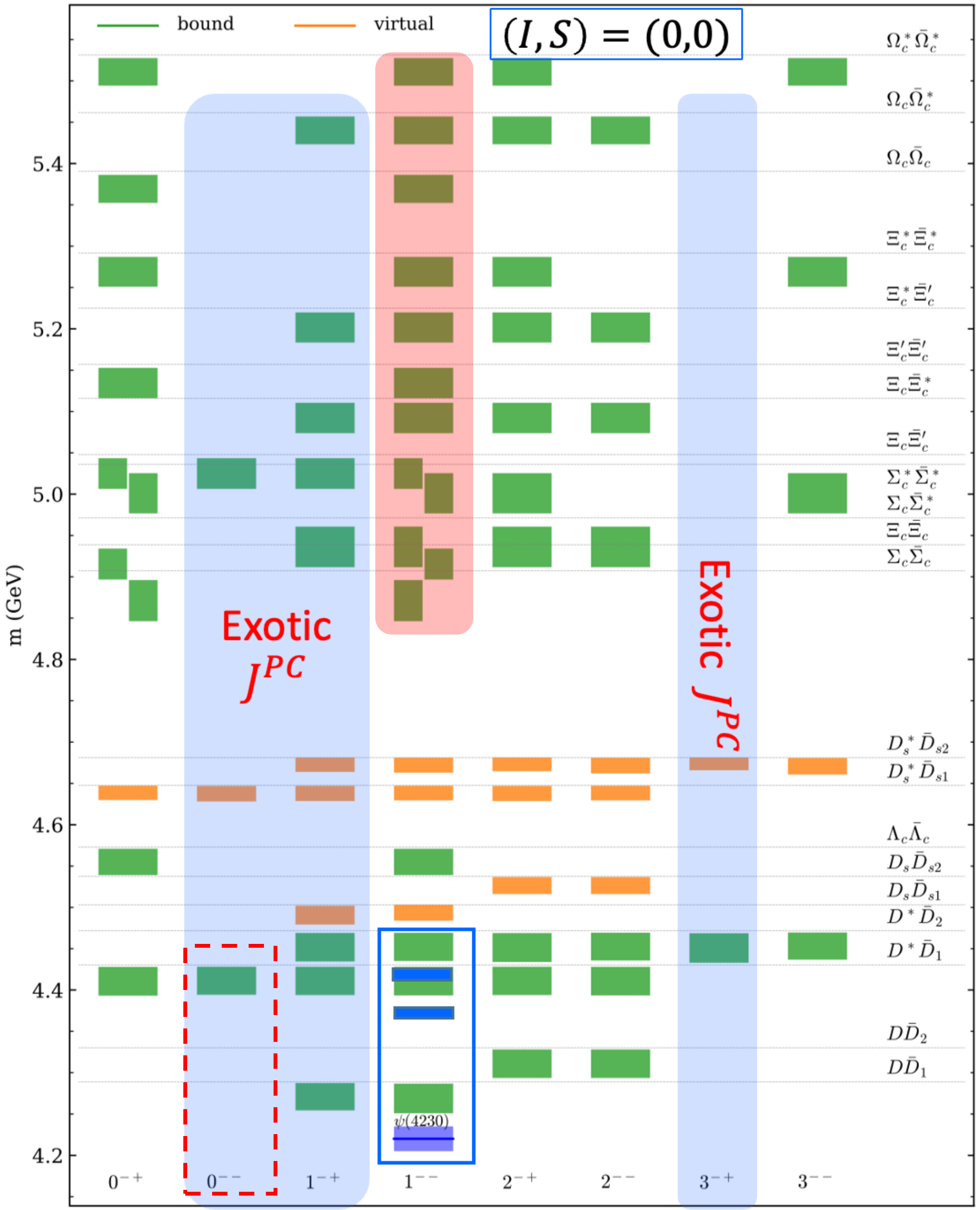
$W_{c1}^{\pm}$: $3844.6^{+13.0}_{-19.8} - i(0.06 \pm 0.00)\mathrm{MeV}$

31^{+20}_{-13} below the D^0D^{*-} threshold

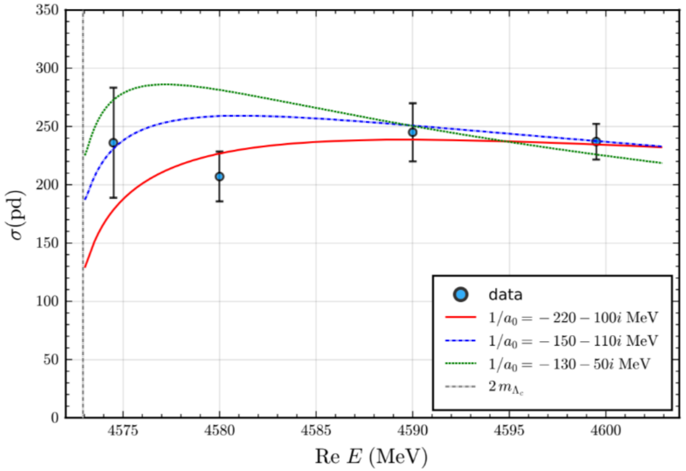


- Experimental confirmation (cusp in $J/\psi\pi^{\pm}\pi^0$)?

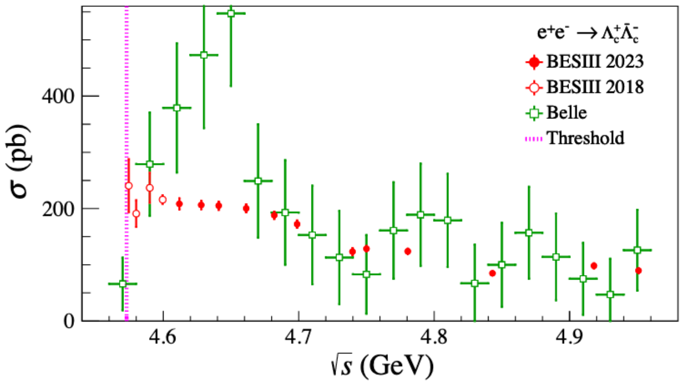
Hidden-charm mesons: $P = -$



- ✓ $Y(4260)/\psi(4230)$ as a $\bar{D}D_1$ bound state
- ✓ $\psi(4360), \psi(4415)$: $D^*\bar{D}_1, D^*\bar{D}_2$?
- ✓ Evidence for 1^{--} $\Lambda_c\bar{\Lambda}_c$ bound state in BESIII data
  - Sommerfeld factor + Near-threshold pole



Data taken from BESIII, PRL 120 (2018) 132001;
See also Q.-F. Cao et al., PRD 100 (2019) 054040



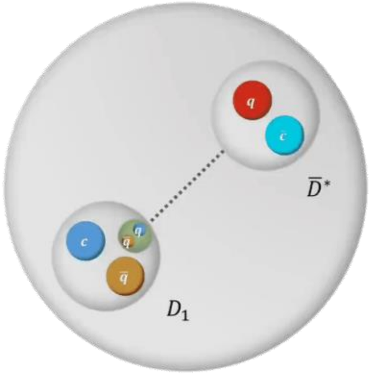
Updated measurement: BESIII, PRL 131 (2023) 191901

- ✓ Numerous states with exotic quantum numbers
- ✓ Many 1^{--} states in [4.8, 5.6] GeV: BEPC-II-Upgrade, Belle-II, STCF

Closer look into the 0^{--} state

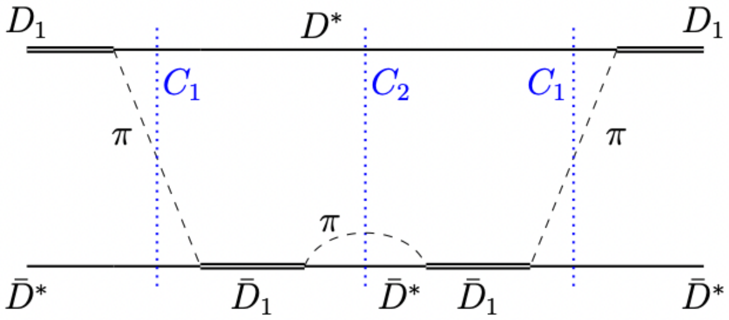
T. Ji, X.-K. Dong, FKG, B.-S. Zou, PRL 129 (2022) 102002

- Prediction of an exotic 0^{--} spin partner $\psi_0(4360)$ $[D^*\bar{D}_1]$ of $\psi(4230), \psi(4360), \psi(4415)$ as $D\bar{D}_1, D^*\bar{D}_1, D^*\bar{D}_2$ hadronic molecules



- Robust against the inclusion of coupled channels and three-body effects

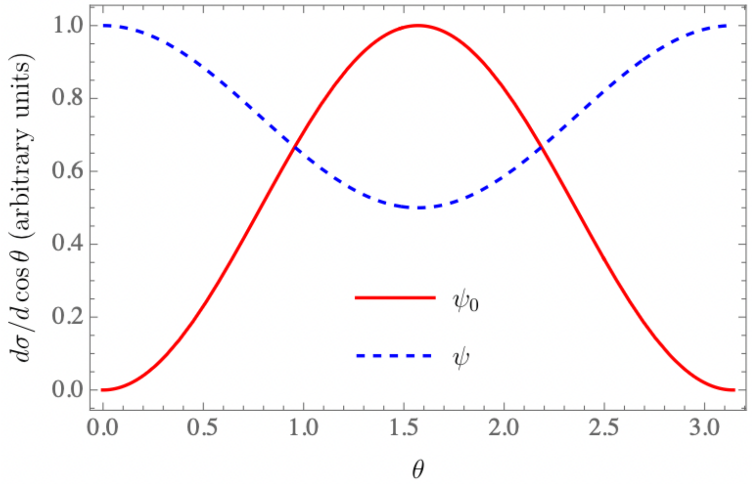
Molecule	Components	J^{PC}	Threshold	E_B
$\psi(4230)$	$\frac{1}{\sqrt{2}}(D\bar{D}_1 - \bar{D}D_1)$	1^{--}	4287	67 ± 15
$\psi(4360)$	$\frac{1}{\sqrt{2}}(D^*\bar{D}_1 - \bar{D}^*D_1)$	1^{--}	4429	62 ± 14
$\psi(4415)$	$\frac{1}{\sqrt{2}}(D^*\bar{D}_2 - \bar{D}^*D_2)$	1^{--}	4472	49 ± 4
ψ_0	$\frac{1}{\sqrt{2}}(D^*\bar{D}_1 + \bar{D}^*D_1)$	0^{--}	4429	**63 ± 18**



- May be searched for using $e^+e^- \to \psi_0\eta, \psi_0 \to J/\psi\eta, D\bar{D}^*, D^*\bar{D}^*\pi, \ldots$

$$M = (4366 \pm 18)\ \mathrm{MeV},$$

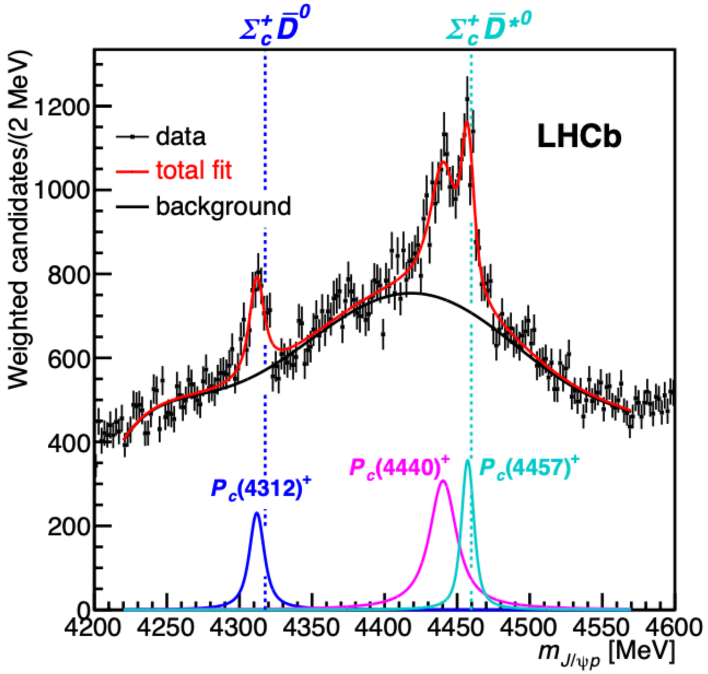
$$\Gamma < 10\ \mathrm{MeV}$$



Can be searched for at BEPC-II-Upgrade, Belle-II, STCF

Hidden-charm pentaquarks

- ✓ LHCb: 3 narrow P_c states below $\Sigma_c \bar{D}^{(*)}$ thresholds



LHCb, PRL 122 (2019) 222001

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

- ✓ $\bar{D}^{(*)}\Sigma_c$ hadronic molecules above 4 GeV were predicted well before

J.-J. Wu, R. Molina, E. Oset, B.-S. Zou, PRL 105 (2010) 232001;

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

Other predictions: W.L.Wang et al. (2011); Z.C. Yang et al. (2012); Xiao, Nieves, Oset (2013); Karliner, Rosner (2015); …

- ✓ Heavy quark spin symmetry: 7 $\bar{D}^{(*)}\Sigma_c^{(*)}$ hadronic molecules

Xiao, Nieves, Oset (2013); Liu et al. (2018, 2019); Sakai et al. (2019); . . .

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

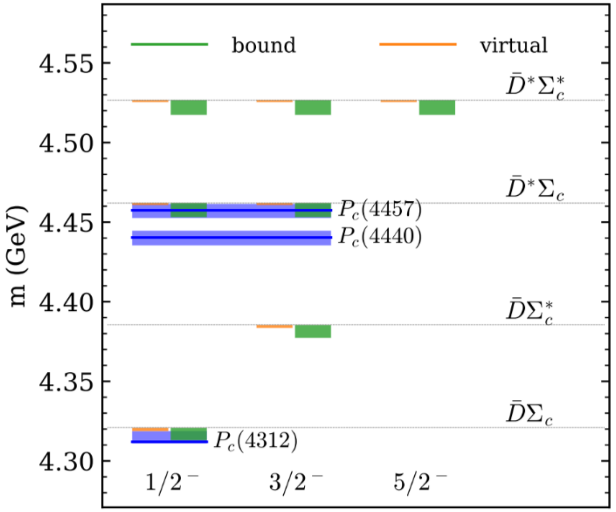
M.-Z. Liu et al., PRL 122 (2019) 242001

Hidden-charm pentaquarks

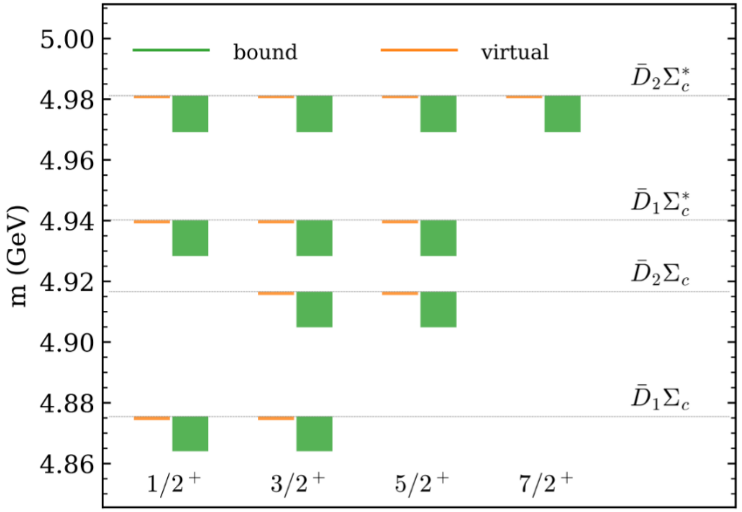
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys. 41 (2021) 65

M.-L. Du et al., PRL 124 (2020) 072001; JHEP 08 (2021) 157

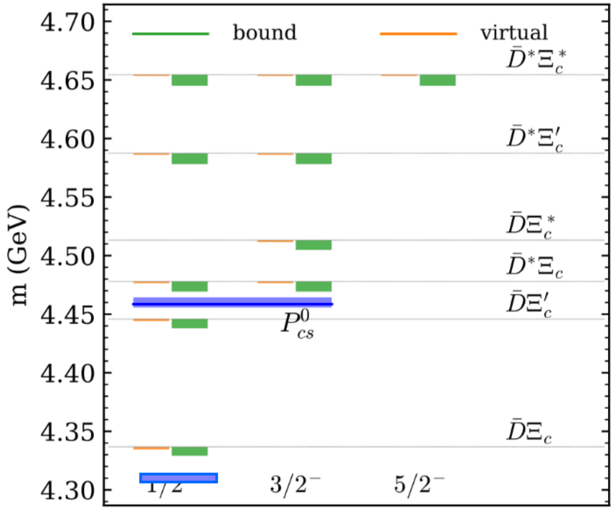
$(I,S) = (1/2,0)$



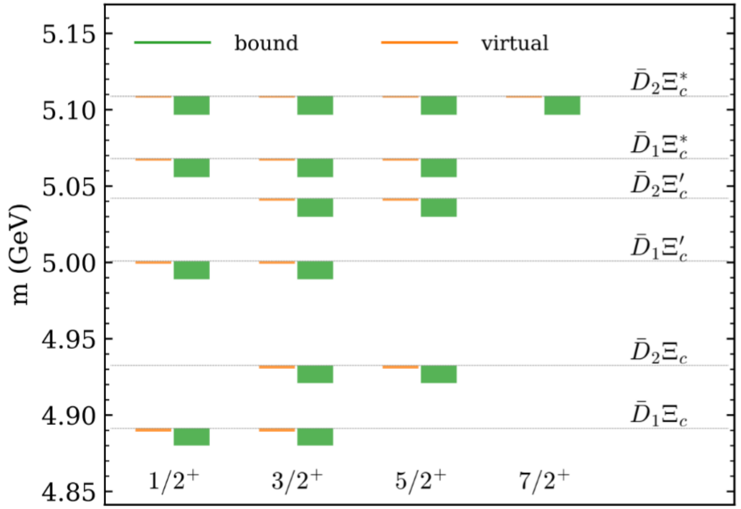
$(I,S) = (1/2,0)$



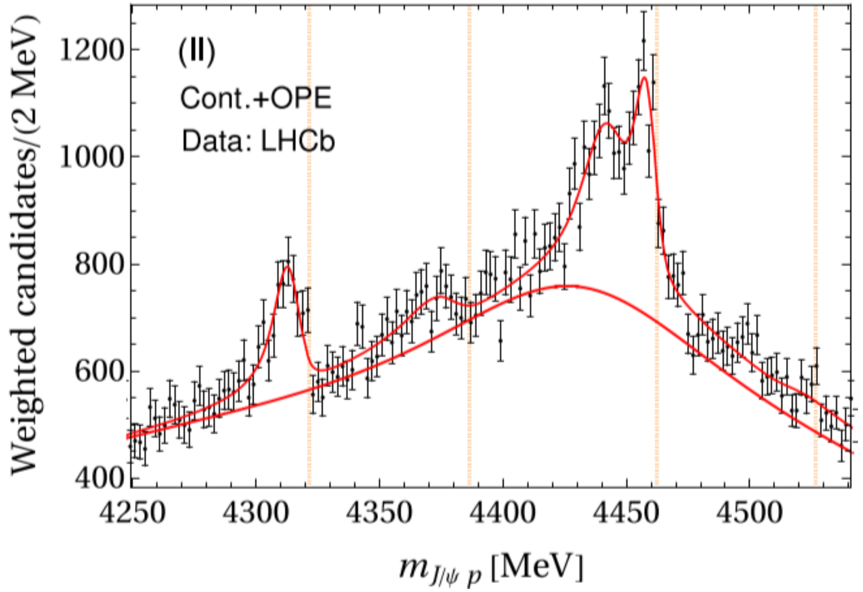
$(I,S) = (0,1)$



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



- ✓ P_c states as $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules
- ✓ The LHCb data can be well described with a chiral EFT



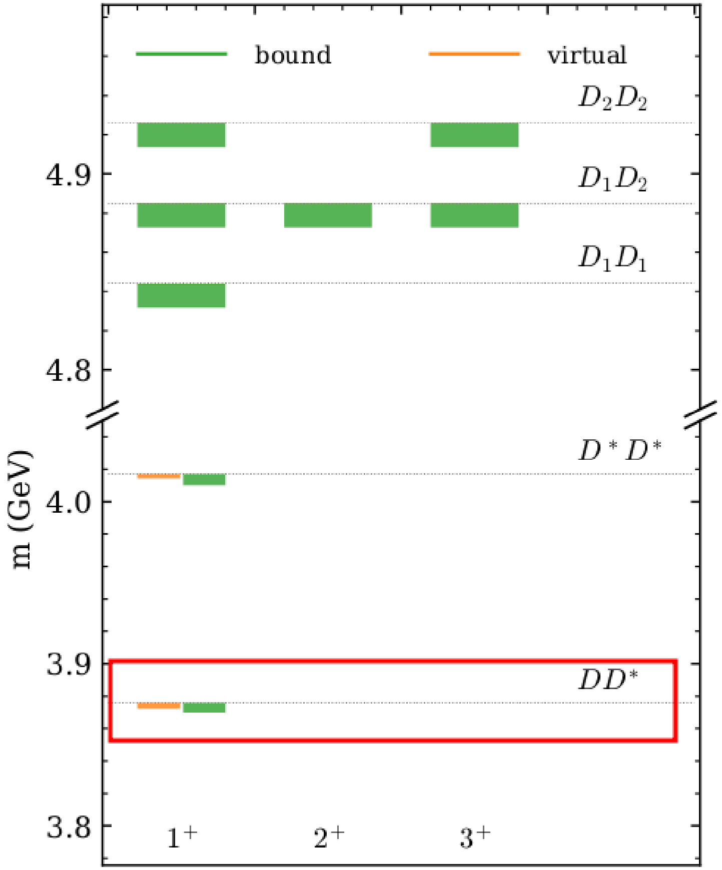
- ✓ $P_{cs}(4459)$: 2 $\bar{D}^*\Xi_c$ molecular states
- ✓ $P_{cs}(4338)$: $\bar{D}\Xi_c$ molecular state

STCF can contribute here: $e^+e^- \to J/\psi p\bar{p}, \Lambda_c\bar{D}^{(*)}p, J/\psi\Lambda\bar{\Lambda}, \Sigma_c^{(*)}\bar{D}^{(*)}p, \ldots$

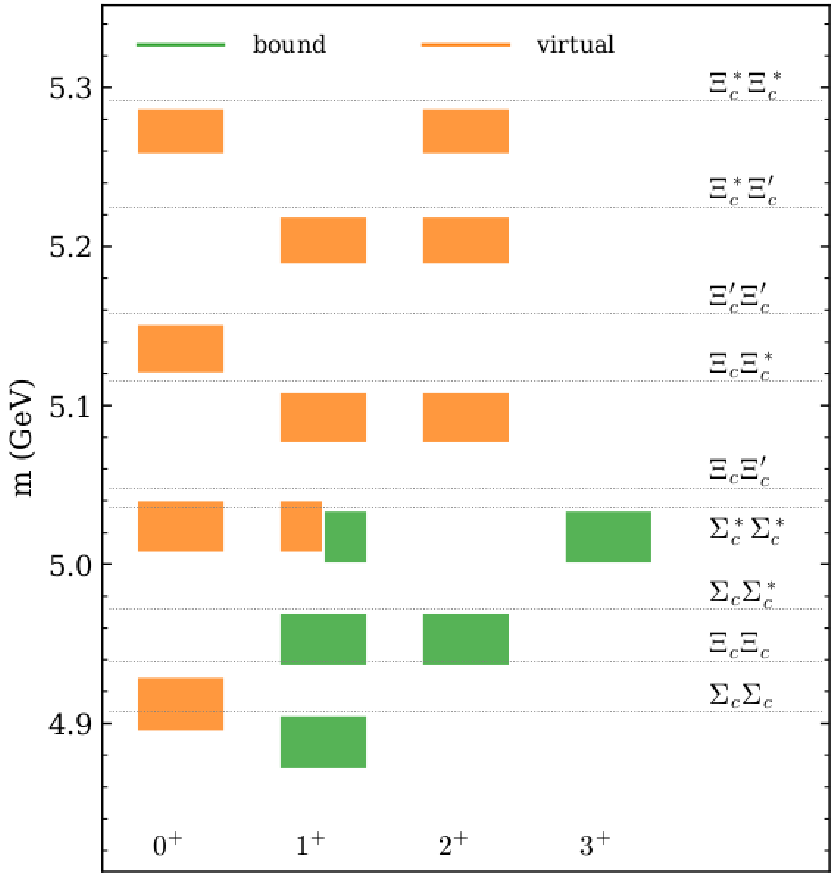
Double-charm tetraquarks and dibaryons

X.-K. Dong, FKG, B.-S. Zou, CTP 73 (2021) 125201

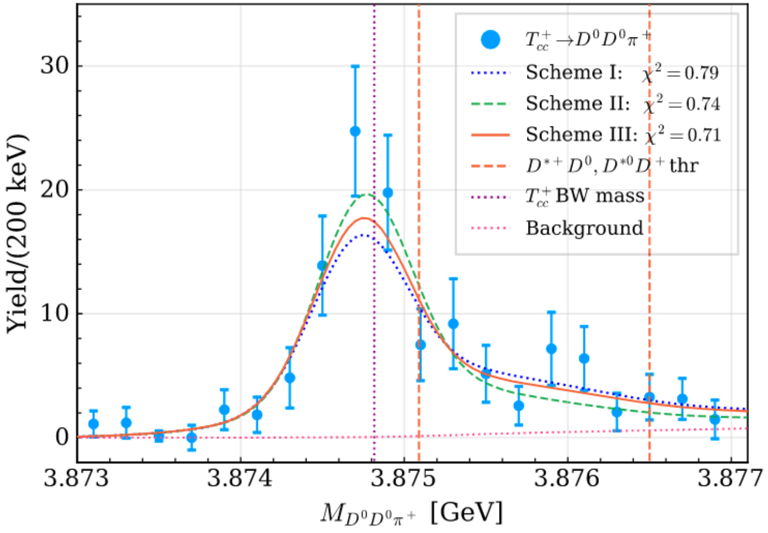
$(I, S, B) = (0,0,0)$



$(I, B) = (0,2)$



- ✓ $T_{cc}(3875)$ as D^*D molecule
- ✓ The LHCb data can be well described in a chiral EFT w/ 3-body effects



M.-L. Du et al., PRD 105 (2022) 014024;
For discussions on related left-hand cut effects,
M.-L. Du et al., PRL 131 (2023) 131903;
J.-Z. Wang et al., PRD 109 (2024) L071505;
L. Meng et al., PRD 109 (2024) L071506;
M.T. Hansen et al., JHEP 06 (2024) 051; …
Talks by A. Rusetsky, M.-L. Du, X. Zhang, M. Mai

- ✓ There is an isoscalar DD^* molecular state
- ✓ It has a spin partner 1^+ D^*D^* state
- ✓ Many (> 100) double-charm molecular states in other sectors
- ✓ 3- and 4-body effects for most of them remain to be explored

Reviews ($\gg$ 10) in the last few years

- H.-X. Chen et al., *The hidden-charm pentaquark and tetraquark states*, Phys. Rept. 639 (2016) 1
- A. Hosaka et al., *Exotic hadrons with heavy flavors: X, Y, Z, and related states*, PTEP 2016 (2016) 062C01
- J.-M. Richard, *Exotic hadrons: review and perspectives*, Few Body Syst. 57 (2016) 1185
- R. F. Lebed, R. E. Mitchell, E. Swanson, *Heavy-quark QCD exotic*a, PPNP 93 (2017)143
- A. Esposito, A. Pilloni, A. D. Polosa, *Multiquark resonances*, Phys. Rept. 668 (2017) 1
- FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, *Hadronic molecules*, RMP 90 (2018) 015004
- A. Ali, J. S. Lange, S. Stone, Exotics: *Heavy pentaquarks and tetraquarks*, PPNP 97 (2017) 123
- S. L. Olsen, T. Skwarnicki, *Nonstandard heavy mesons and baryons: Experimental evidence*, RMP 90 (2018) 015003
- Y.-R. Liu et al., *Pentaquark and tetraquark states*, PPNP107 (2019) 237
- N. Brambilla et al., *The XYZ states: experimental and theoretical status and perspectives*, Phys. Rept. 873 (2020) 154
- Y. Yamaguchi et al., *Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners*, JPG 47 (2020) 053001
- FKG, X.-H. Liu, S. Sakai, *Threshold cusps and triangle singularities in hadronic reactions*, PPNP 112 (2020) 103757
- G. Yang, J. Ping, J. Segovia, *Tetra- and penta-quark structures in the constituent quark model*, Symmetry 12 (2020) 1869
- C.-Z. Yuan, Charmonium and charmoniumlike states at the BESIII experiment, Natl. Sci. Rev. 8 (2021) nwab182
- H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, *An updated review of the new hadron states*, RPP 86 (2023) 026201
- M. Mai, U.-G. Meißner, C. Urbach, Towards a theory of resonances, Phys. Rept. 1001 (2023) 2248;
- L. Meng, B. Wang, G.-J. Wang, S.-L. Zhu, *Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules*, Phys. Rept. 1019 (2023) 2266;
- M.-Z. Liu et al., *Three ways to decipher the nature of exotic hadrons: multiplets, three-body hadronic molecules, and correlation functions*, arXiv: 2404.06399
- ……

- \+ a book:
  - A. Ali, L. Maiani, A. D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)

Open questions

- Open questions for almost every exotic hadron candidate …
- How can the many resonant structures beyond naïve quark model be classified?
  - Which ones are reliable, i.e., lay the foundation for deeper insights?
  - What can be learned about confinement mechanism?
- Lessons from Zweig (1980):

> Twenty-six states are listed. Seven are "exotic." It is now known that nineteen out of these twenty-six resonances do not exist!

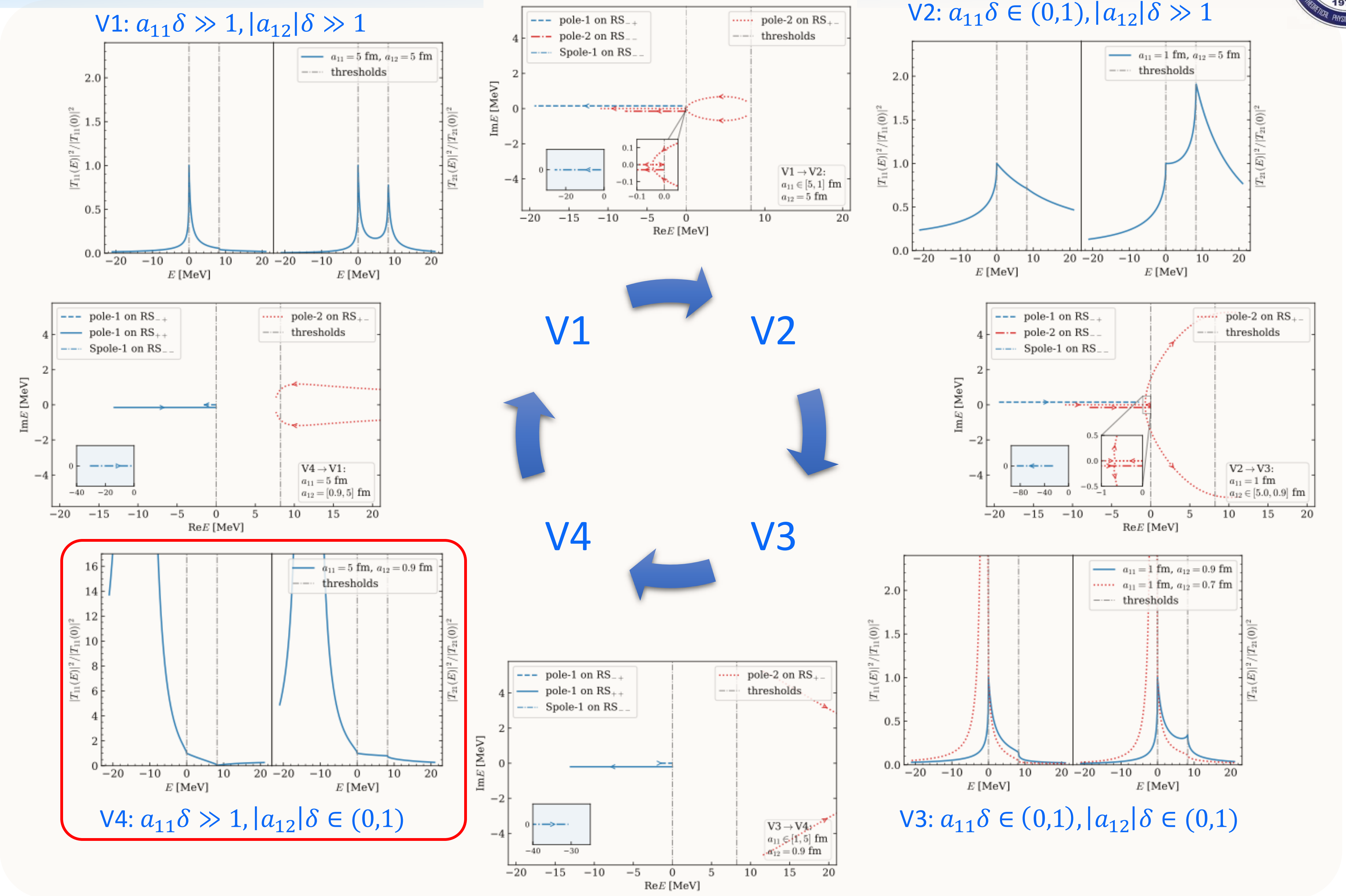
> For me, the origin of the quark model lay in the experiments that established the existence and properties of the ϕ meson:

Thank you for your attention!

Poles and line shapes

- The $X(3872)-W_{c1}$ system corresponds to case V4 in the classification of coupled-channel near-threshold structures in

Zhen-Hua Zhang, FKG, arXiv:2407.10620



Poles and line shapes

- Other cases with two poles

Zhen-Hua Zhang, FKG, arXiv:2407.10620