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Exotics from EFT prespective

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Introduction

This talk focuses only on EFT at hadronic level; for quark-level EFT treatments of exotic heavy quarkonia (pNRQCD, Born-Oppenheimer EFT for hybrid charmonia etc.), see Brambilla, Vairo, Tarrus Castella, Braaten, …

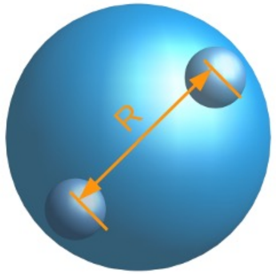
- EFT: separation of scales, symmetries (heavy quark, chiral)
  - Nonrelativistic EFT, chiral EFT
  - Analysis framework of both experimental and lattice results

Related talks by J. Bulava, A. Pilloni, R. Molina, X.-L. Ren, S. Nakamura, …

- Hadronic molecule: analogues of 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
  - EFT applicable

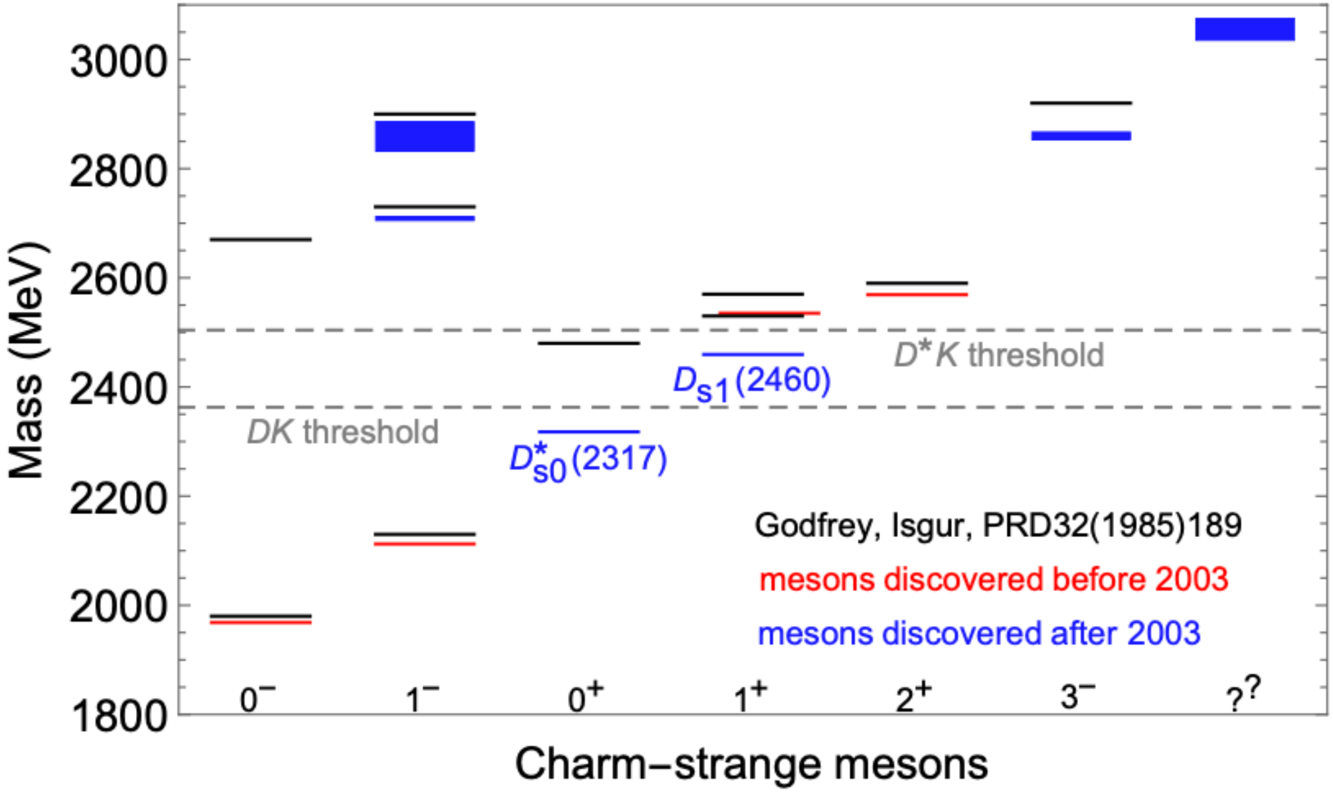
$$R \sim \frac{1}{\sqrt{2\mu E_B}} > r_{\rm hadron}$$



  - 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

Example 1: Charm-strange mesons

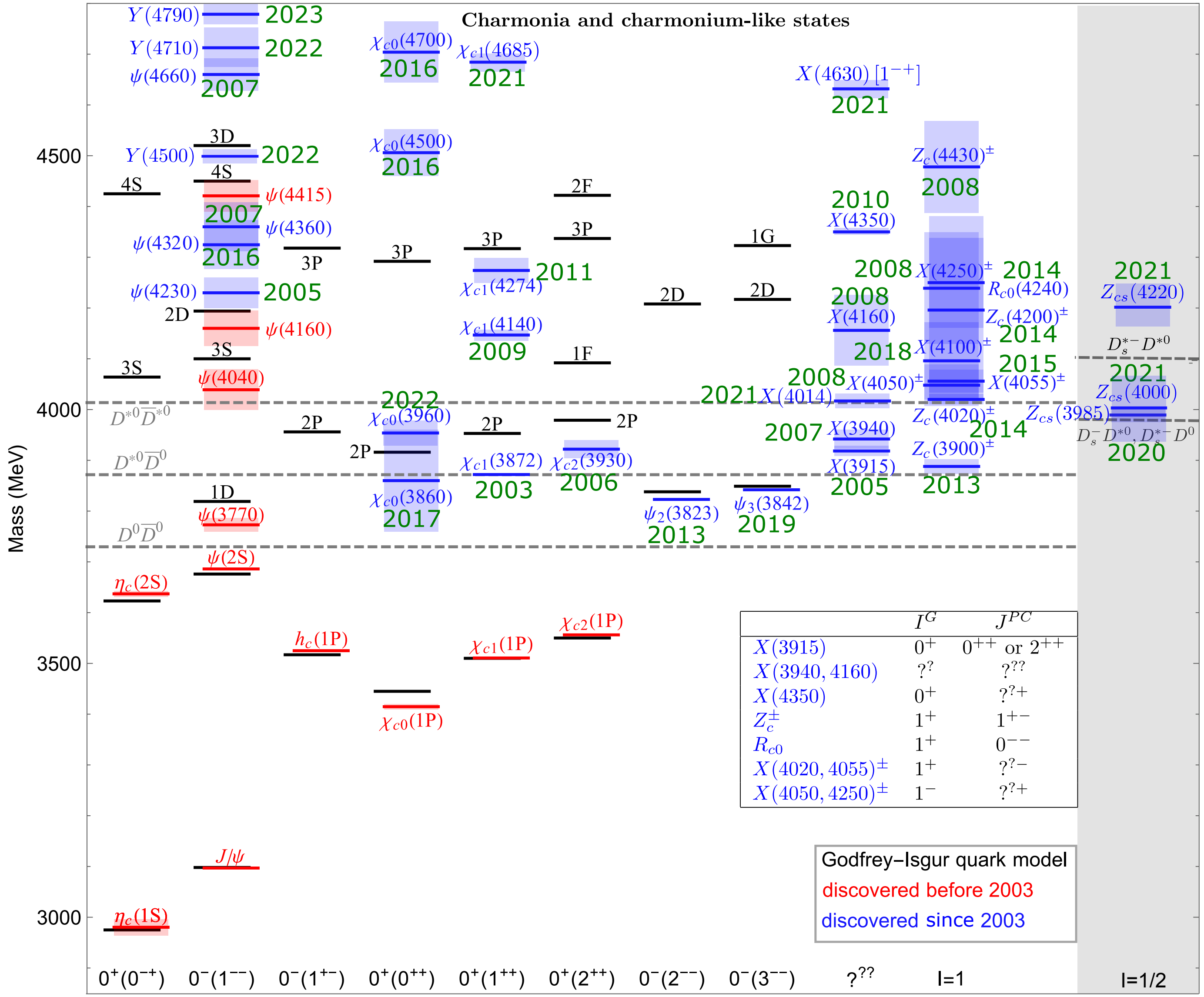


- $D^*_{s0}(2317)$: BaBar (2003)
  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$: CLEO (2003)
  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths
  $\Rightarrow I = 0$

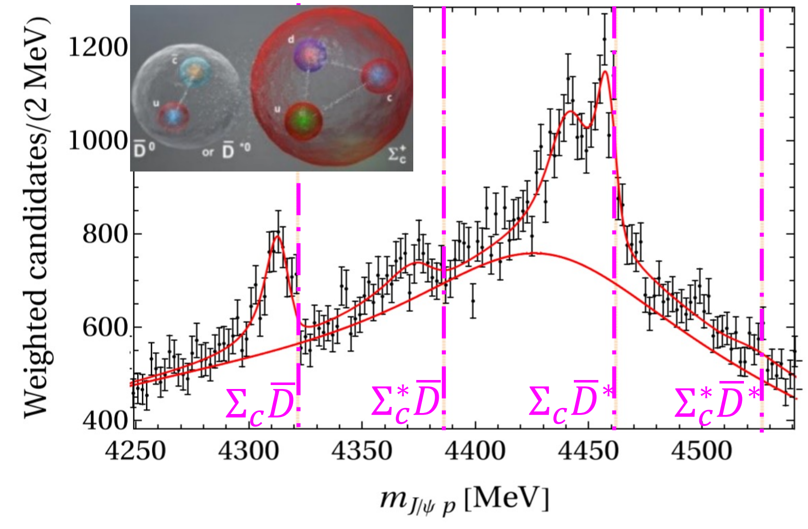
- Mass problem: Why are $D^*_{s0}(2317)$ and $D_{s1}(2460)$ so light?
- Naturalness problem: Why $\underbrace{M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)}}_{(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{(140.67\pm0.08)\text{ MeV}}$?

Example 2: Hidden-charm and double-charm exotics

- Charmonium-like states

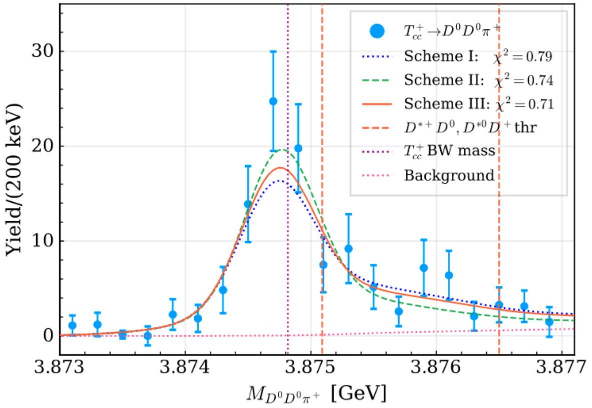


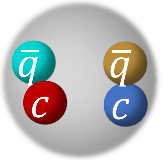
- Hidden-charm pentaquarks



Data: LHCb, PRL122 (2019) 222001;
Fit: M.-L. Du, et al., PRL124 (2020) 072001

- Double-charm tetraquarks





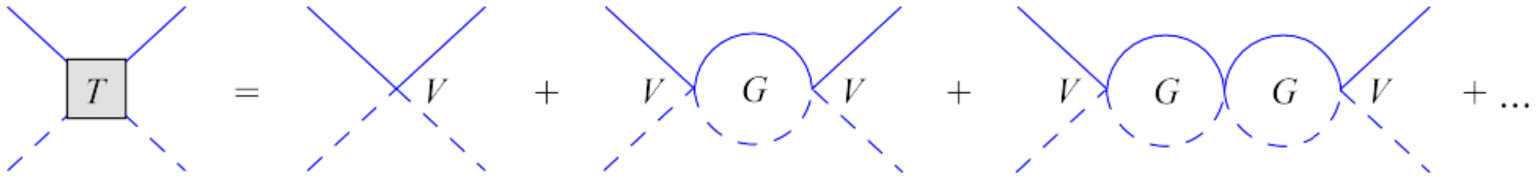
Data: LHCb, Nature Phys. 18 (2022) 751;
Fit: M.-L. Du et al., PRD105 (2022) 014024

Charm-strange mesons from chiral EFT and lattice QCD

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

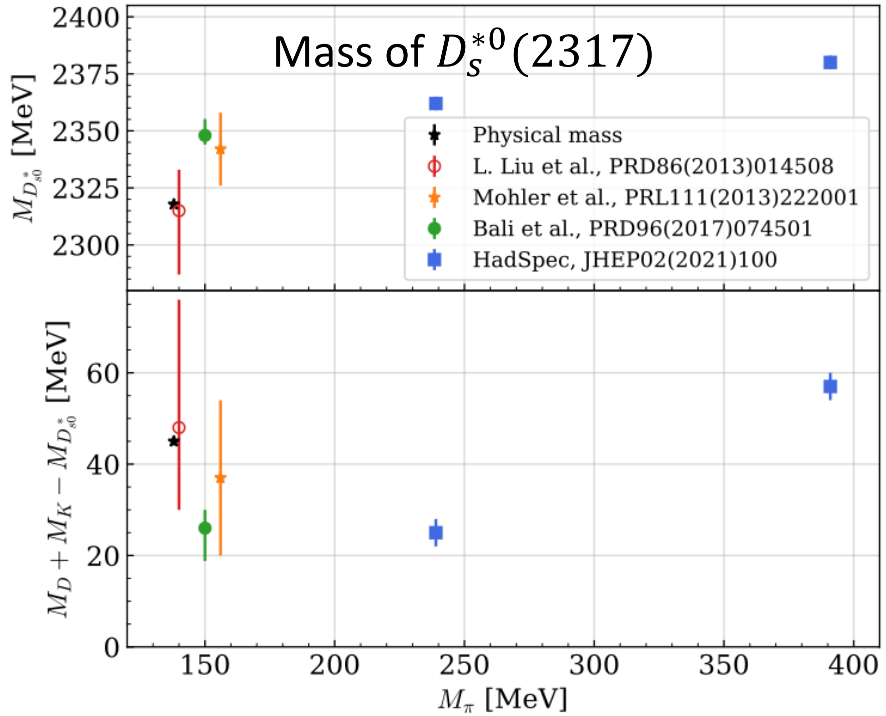
Barnes, Close, Lipkin(2003); van Beveren, Rupp(2003); Kolomeitsev, Lutz(2004); FKG et al.(2006); …

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

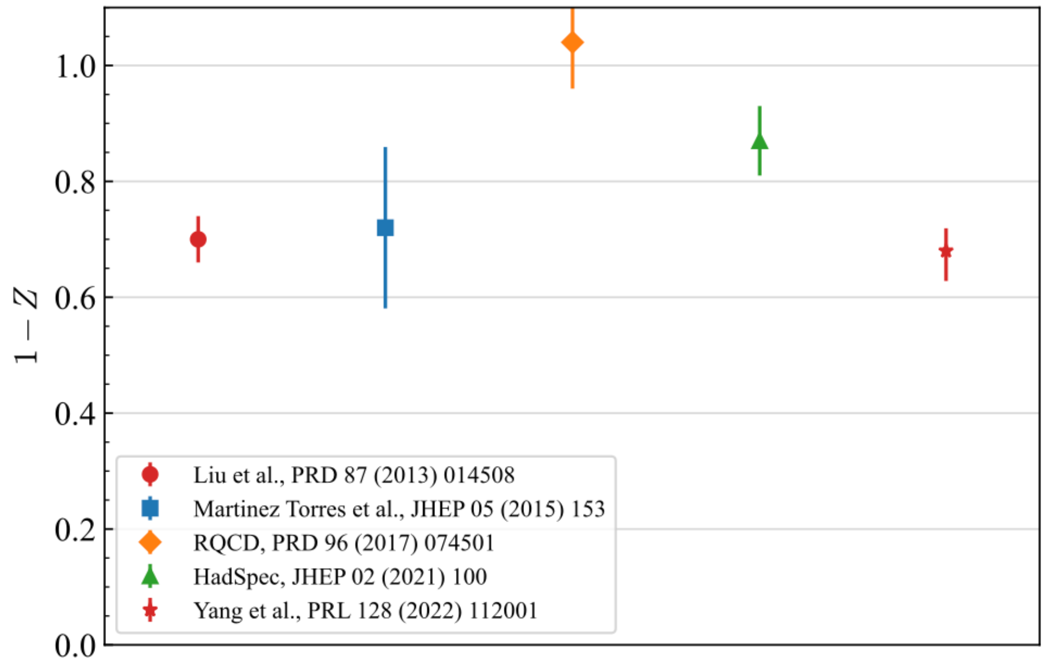


➢ Parameters fixed from fitting to lattice QCD results

L. Liu, Orginos, FKG, Hanhart, Meißner, PRD 86 (2013) 014508



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

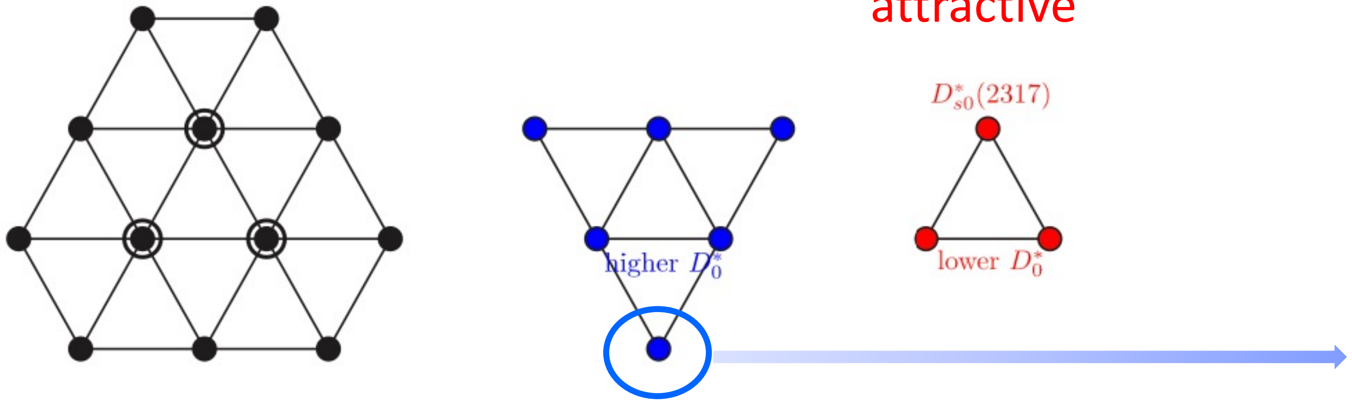


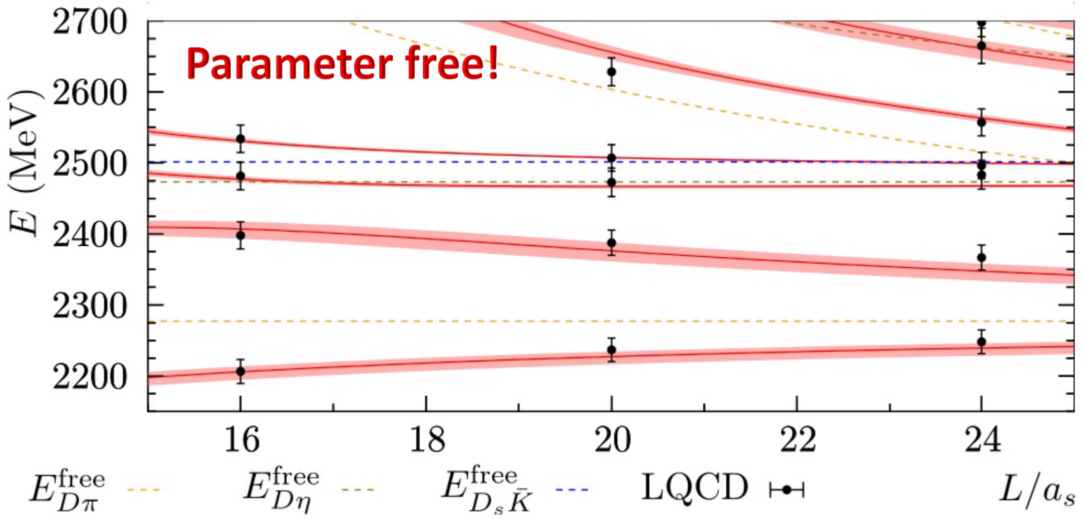
Charm-strange mesons from chiral EFT and lattice QCD

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

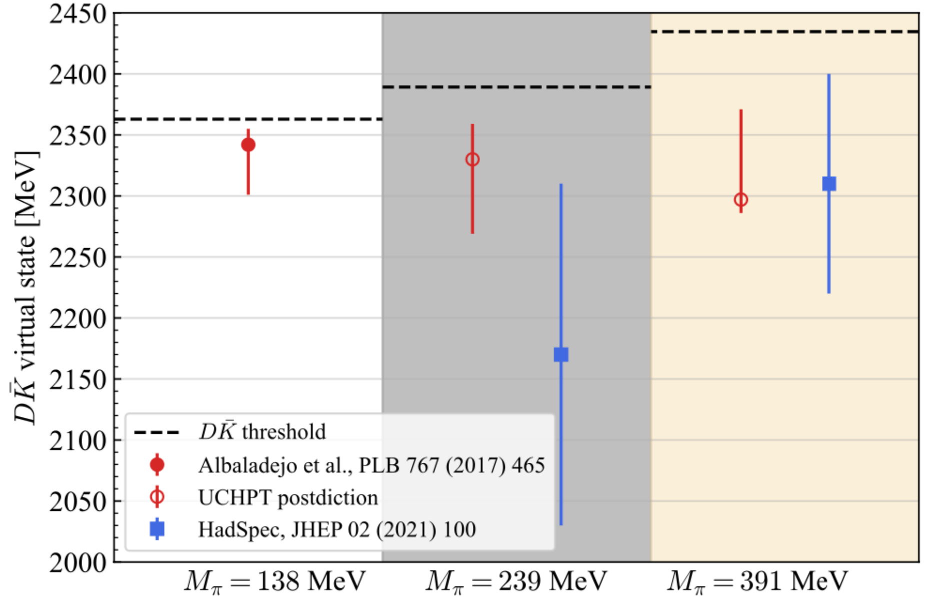
M.Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB 767 (2017) 465

repulsive | attractive | most attractive





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



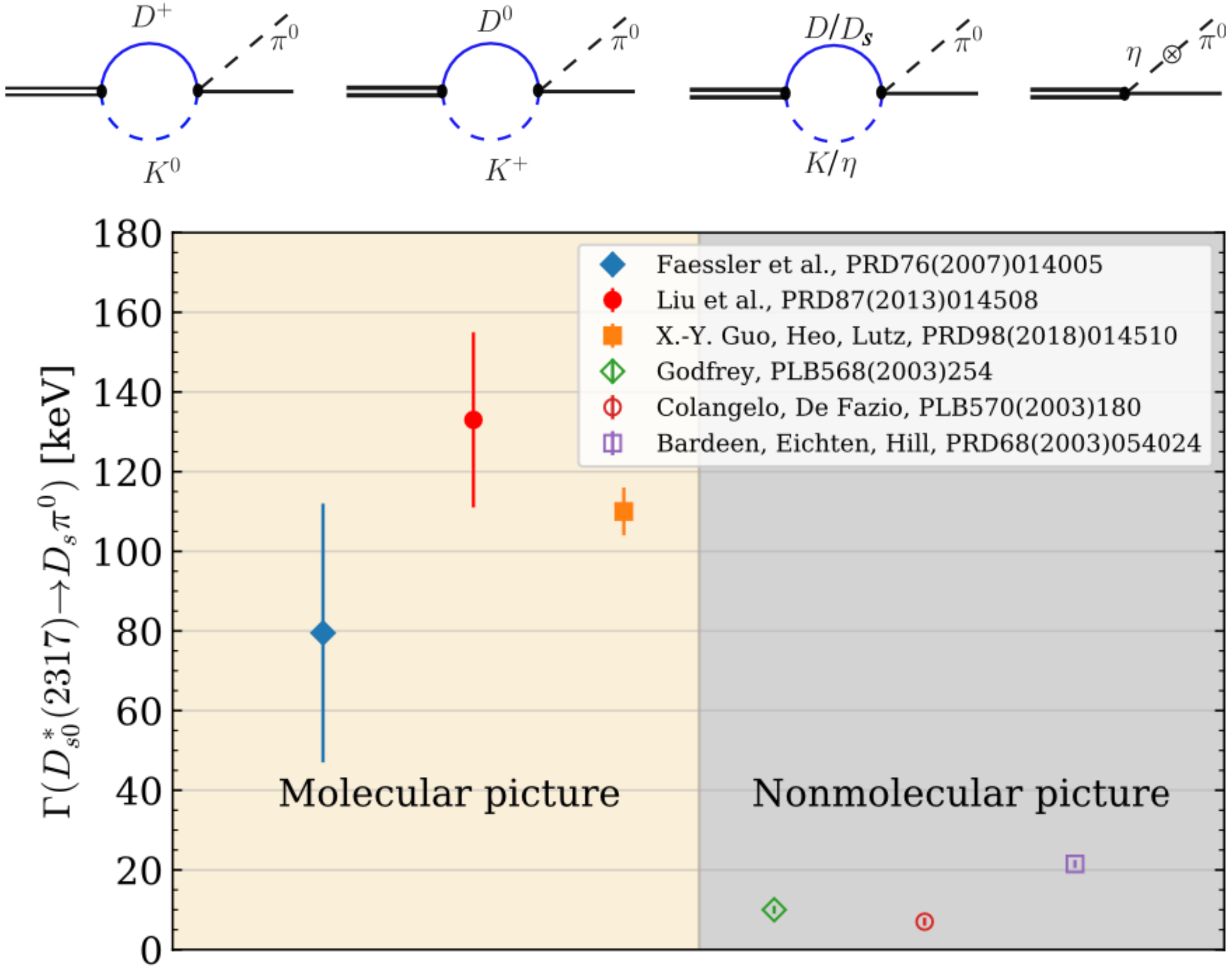
- Reasonable to expect $D^{(*)}\bar{K}^*$ to exist: $T_{cs}(2900)$

talk by R. Molina

- Solutions to the two problems:
  - ➢ D^*_{s0} and D_{s1} as 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$\sim$ 100 keV



Hadronic decays of $D_{s1}(2460)$

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

- Experimental measurements of $D_{s1}(2460)$

$$\frac{\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right)}{\Gamma\left(D_{s1}(2460)^+ \to D_s^{*+}\pi^0\right)} = \begin{cases} 0.14 \pm 0.04 \pm 0.02 \\ 0.09 \pm 0.02 \end{cases}$$

- $D_{s1}(2460) \to D_s\pi^+\pi^-$
  - ➢ CHPT results   S. Fajfer, A. Prapotnik Brdnik, PRD 92 (2015) 074047

$$\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right) = 0.25(4)(7)\left({}^{+2}_{-4}\right)\,\text{keV}$$

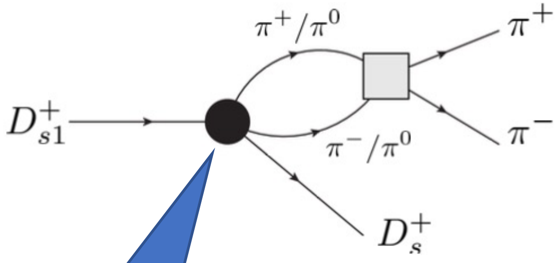
Both D_s and D_{s1} were treated statically, so P-wave happens between π^+ and π^-

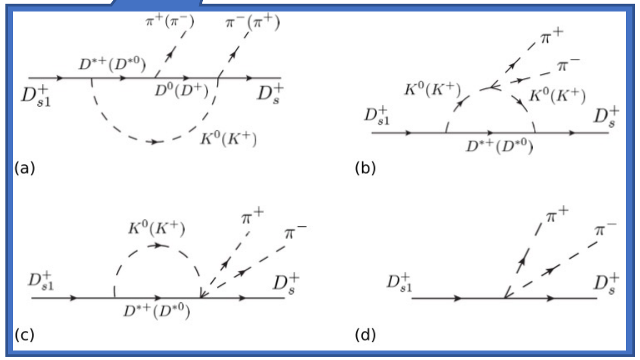
$\Rightarrow I(\pi^+\pi^-) = 1$, isospin breaking

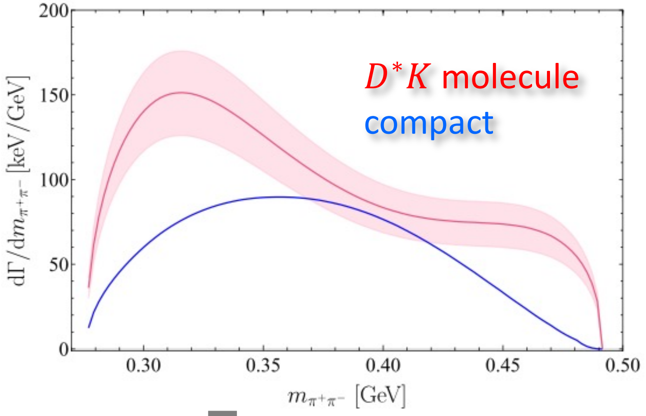
✓ But isospin is conserved (!!) for P-wave between D_s and isoscalar $\pi^+\pi^-$

✓ $\pi\pi$ FSI: region of $f_0(500)$

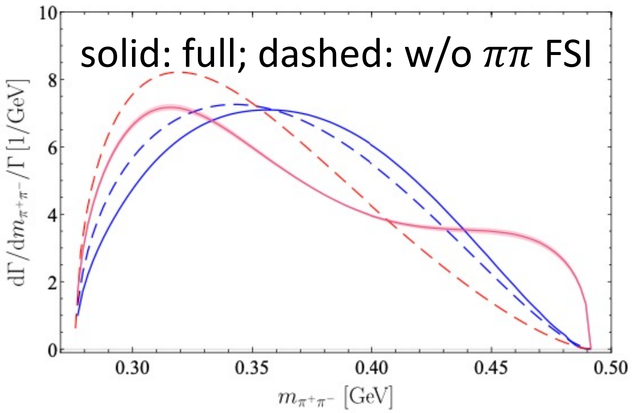
- Double-bump structure from
  - ➢ D^*K (triangle) loops
  - ➢ $\pi\pi$ FSI







normalizing

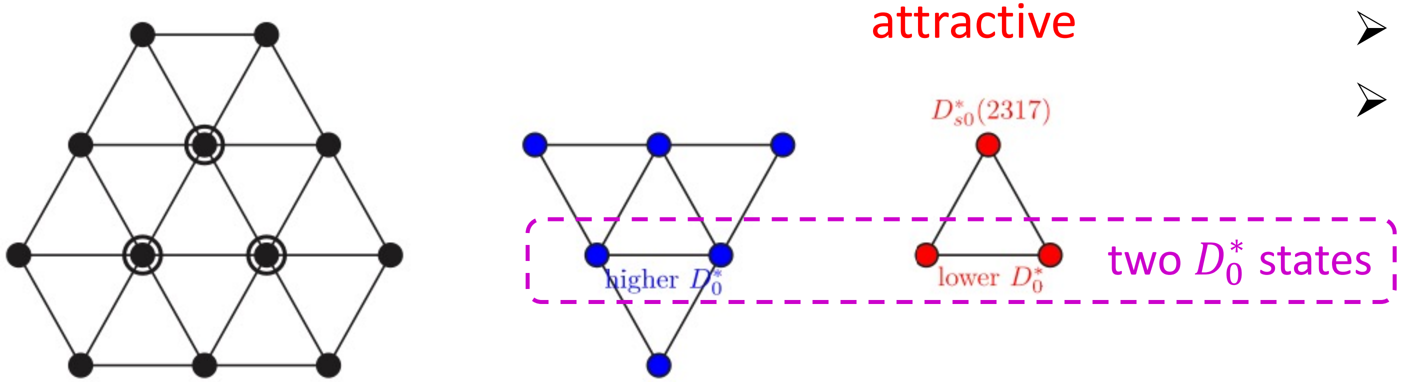


$$\left.\frac{\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right)}{\Gamma\left(D_{s1}(2460)^+ \to D_s^{*+}\pi^0\right)}\right|_{\text{mol.}} = 0.19^{+0.07}_{-0.05}$$

Charm-nonstrange mesons

- 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



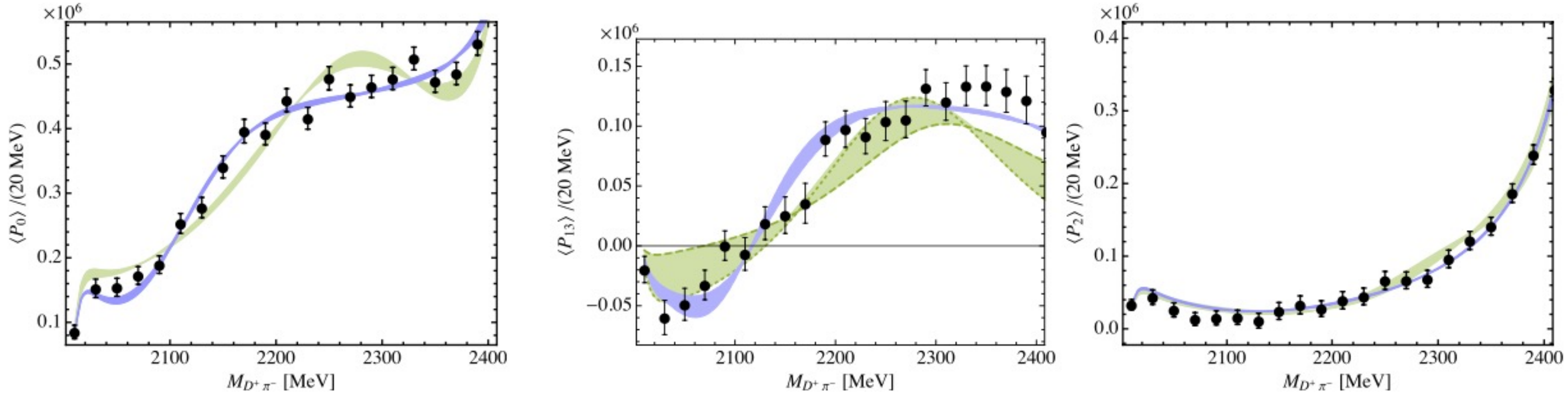
- Two D^*_0 states below 2.5 GeV instead of a single $D^*_0(2300)$

van Beveren, Rupp (2003); Kolomeitsev, Lutz (2004); FKG et al. (2006); Albaladejo et al. (2017); Lutz et al. (2022); …

  - coupled strongly to $D\pi, D_s\bar{K}$, respectively
  - similar to the two-pole structure of $\Lambda(1405)$

Talks by J. Bulava, B. Cid-Mora, X.-L. Ren

- Fits to LHCb data of $B^- \to D^+\pi^-\pi^-$ with the Khuri-Treiman equation: using S-wave $D\pi$ scattering phase from UCHPT (χ^2/d.o.f. = 1.2) and from BW (χ^2/d.o.f. = 2.0) M.-L. Du et al., PRL 126 (2021) 192001



Data: LHCb, PRD 94 (2016) 072001

Data on more B decays consistent with two D^*_0 poles analyzed in

M.-L. Du et al., PRD 98 (2018) 094018; M.-L. Du, FKG, U.-G. Meißner, PRD 99 (2019) 114002

Charm-nonstrange mesons

$D_0^*(2300)$ $I(J^P) = 1/2(0^+)$

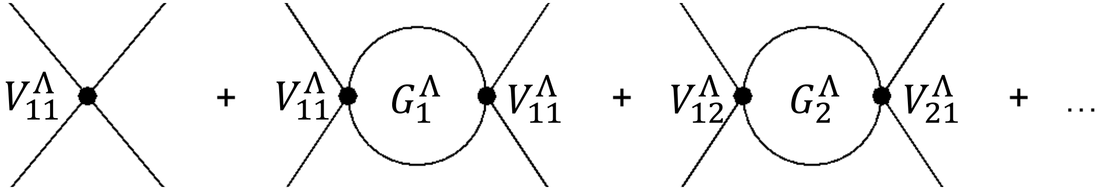
was $D_0^*(2400)$

There is a strong evidence that recent data on $B \to D\pi\pi$ (AAIJ 2015Y, AAIJ 2016AH) and $B \to D\pi K$ (AAIJ 2014BH, AAIJ 2015V, AAIJ 2015X) call for two poles in the scalar $I = 1/2\ \pi D$ amplitude in this mass range. The data are consistent with a lower pole at $(2105\ ^{+6}_{-8}) - i(102\ ^{+10}_{-11})$ MeV and a higher pole at $(2451\ ^{+35}_{-26}) - i(134\ ^{+7}_{-8})$ MeV (DU 2018A, DU 2019 , DU 2021). For details see review on "Heavy Non-$q\bar{q}$ Mesons."

Independent analyses of data from other groups are called for!!

(Near-)threshold structures

- (Near-)threshold structures (S-wave)
  - ✓ Two-channel NREFT at LO: nontrivial (near-)threshold structures for attractive S-wave interaction
  - ✓ Peak more pronounced for heavier hadrons and stronger interaction



X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001

Expanding around the higher threshold, E is small

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

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

- ➢ Similar to the NREFT in T. Cohen, B. Gelman, U. van Kolck, PLB 588 (2004) 57
- ➢ Difference: here lower channel can be relativistic

(Near-)threshold structures

- Structures are process dependent

X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001

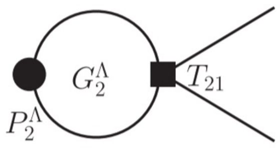
  - ✓ Universality of a dip in T_{11} for large scattering length in the higher channel

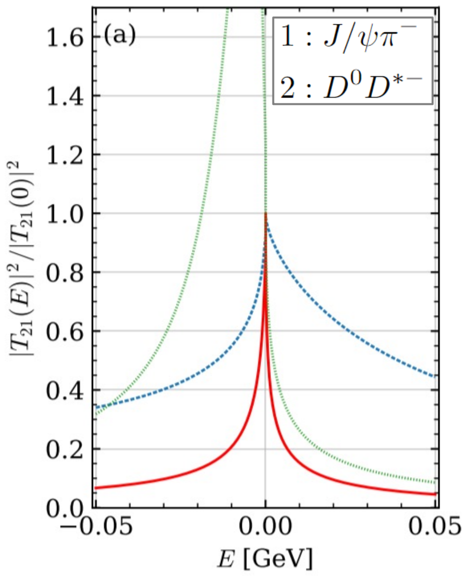
Pole only	One pole and one zero

Pole only

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

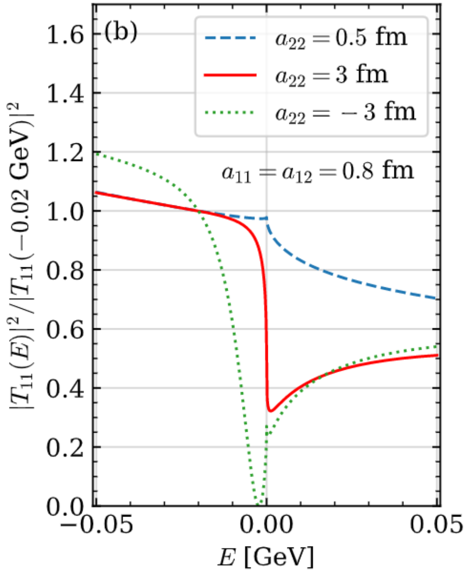
$$T_{22}(E) = -\frac{8\pi}{\Sigma_2} \left[\frac{1}{a_{22,\text{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E) \right]^{-1}$$

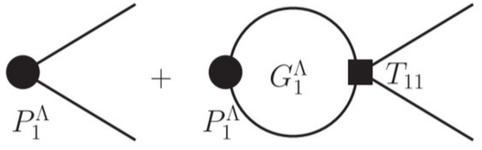




One pole and one zero

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





Poles in complex momentum plane:

$(-0.08 - i0.37)$GeV

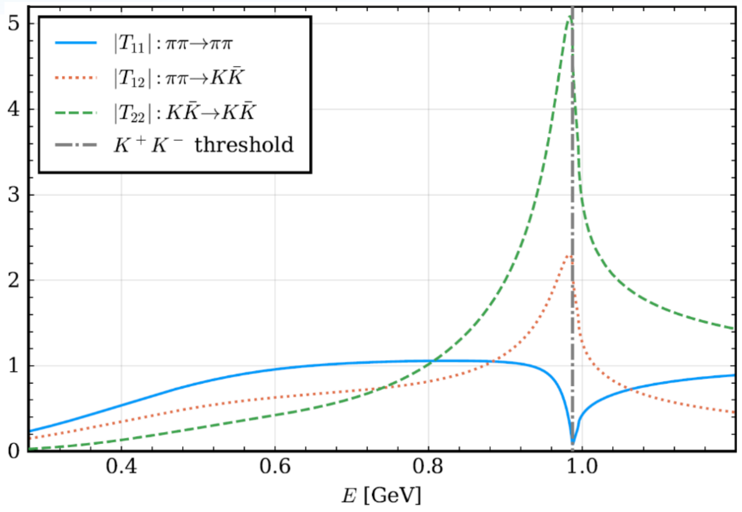
$(-0.08 - i0.04)$GeV

$(-0.08 - i0.09)$GeV

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

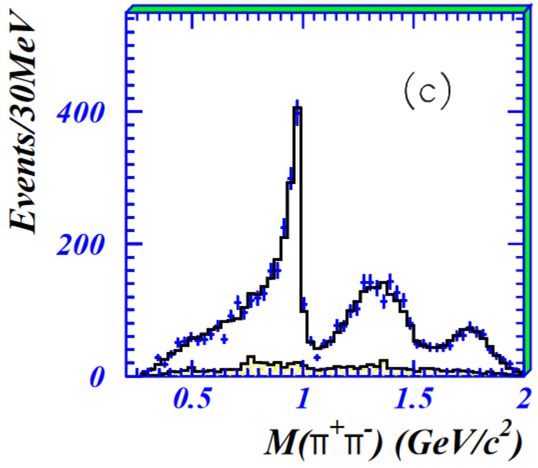
Example of dips

- In S-wave $\pi\pi$-$K\bar{K}$ system

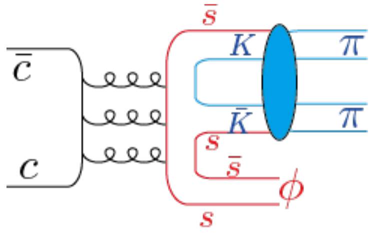


T-matrix elements from
L.-Y. Dai, M. R. Pennington, PRD 90 (2014) 036004

➢ $f_0(980)$ in $J/\psi \to \phi\pi^+\pi^-$



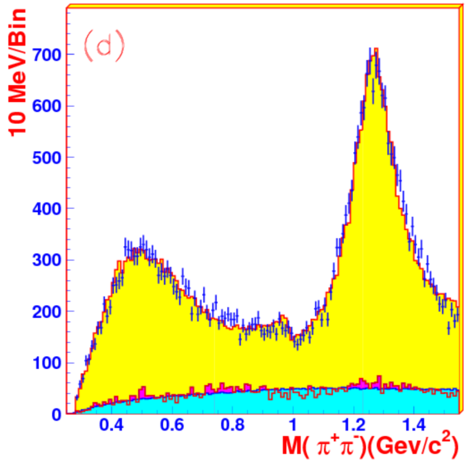
BES, PLB 607 (2005) 243



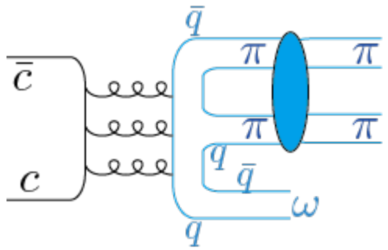
Driving channel: $K\bar{K}$

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

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



BES, PLB 598 (2004) 149

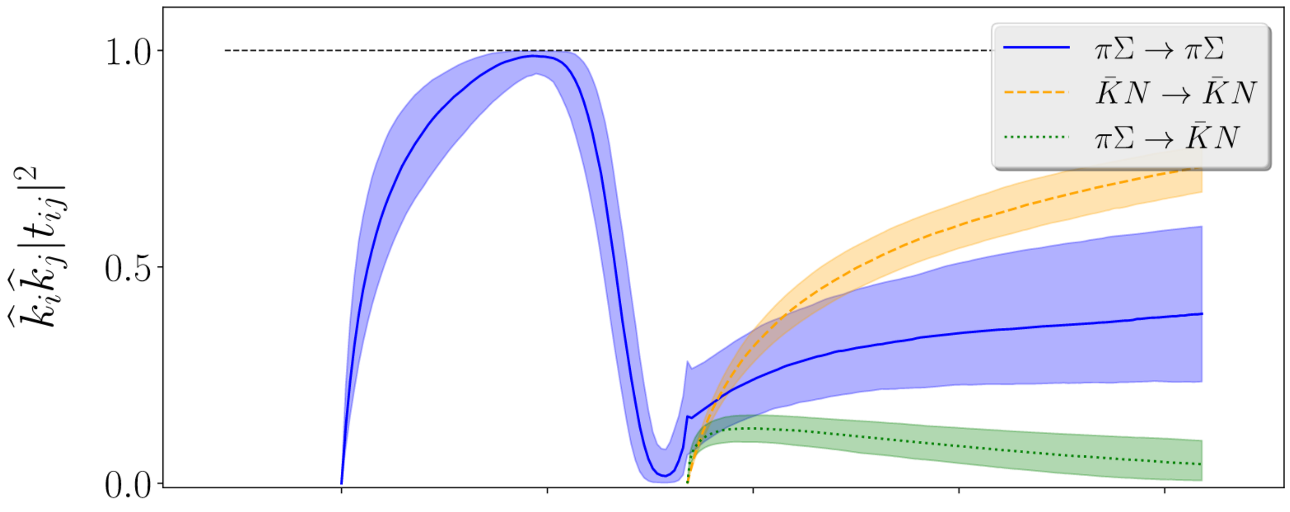


Driving channel: $\pi\pi$

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

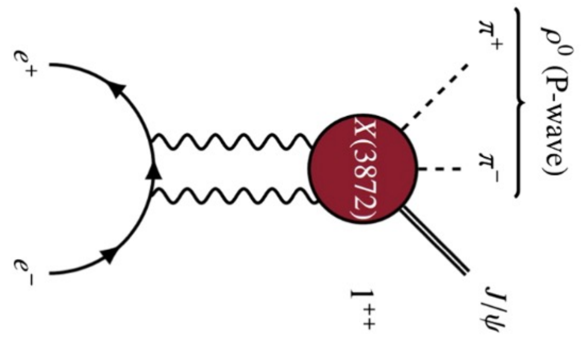
Example of dips

- S-wave $\pi\Sigma \to \pi\Sigma$ scattering

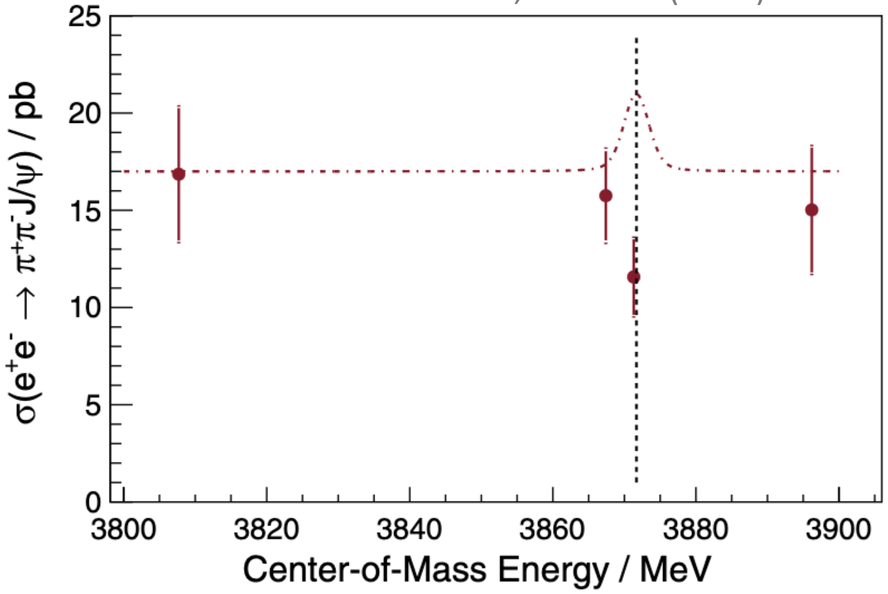


J. Bulava et al. [BaSc], arXiv:2307.10413; arXiv:2307.13471; talks by J. Bulava and B. Cid-Mora

- $X(3872)$ in $e^+e^- \to J/\psi\pi^+\pi^-$?



BESIII, PRD 107 (2023) 032007



Example of dips

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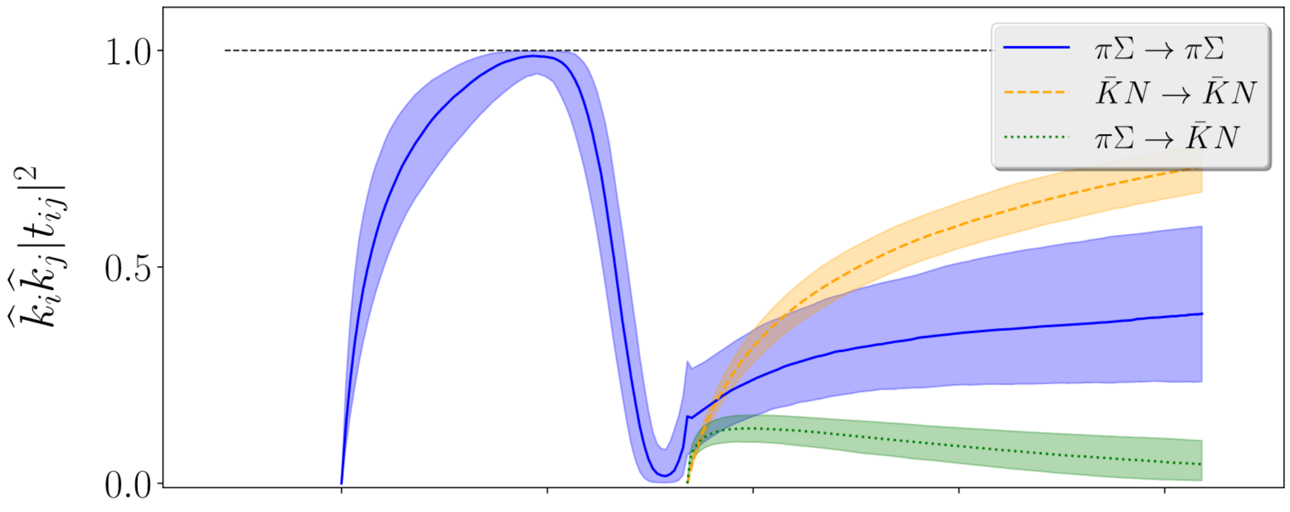

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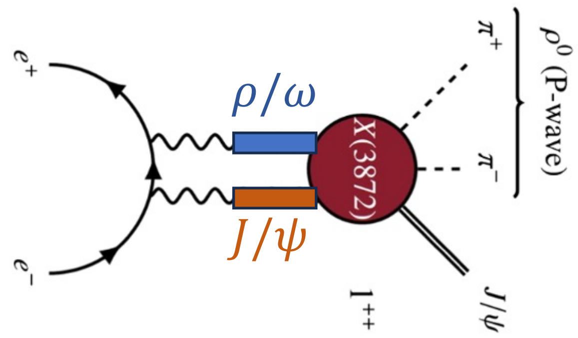
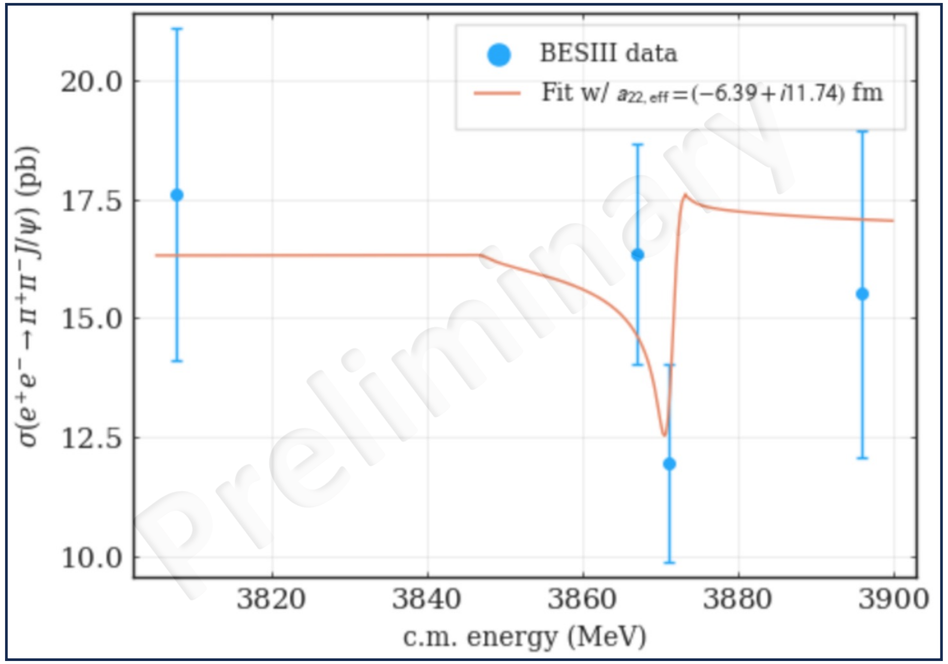
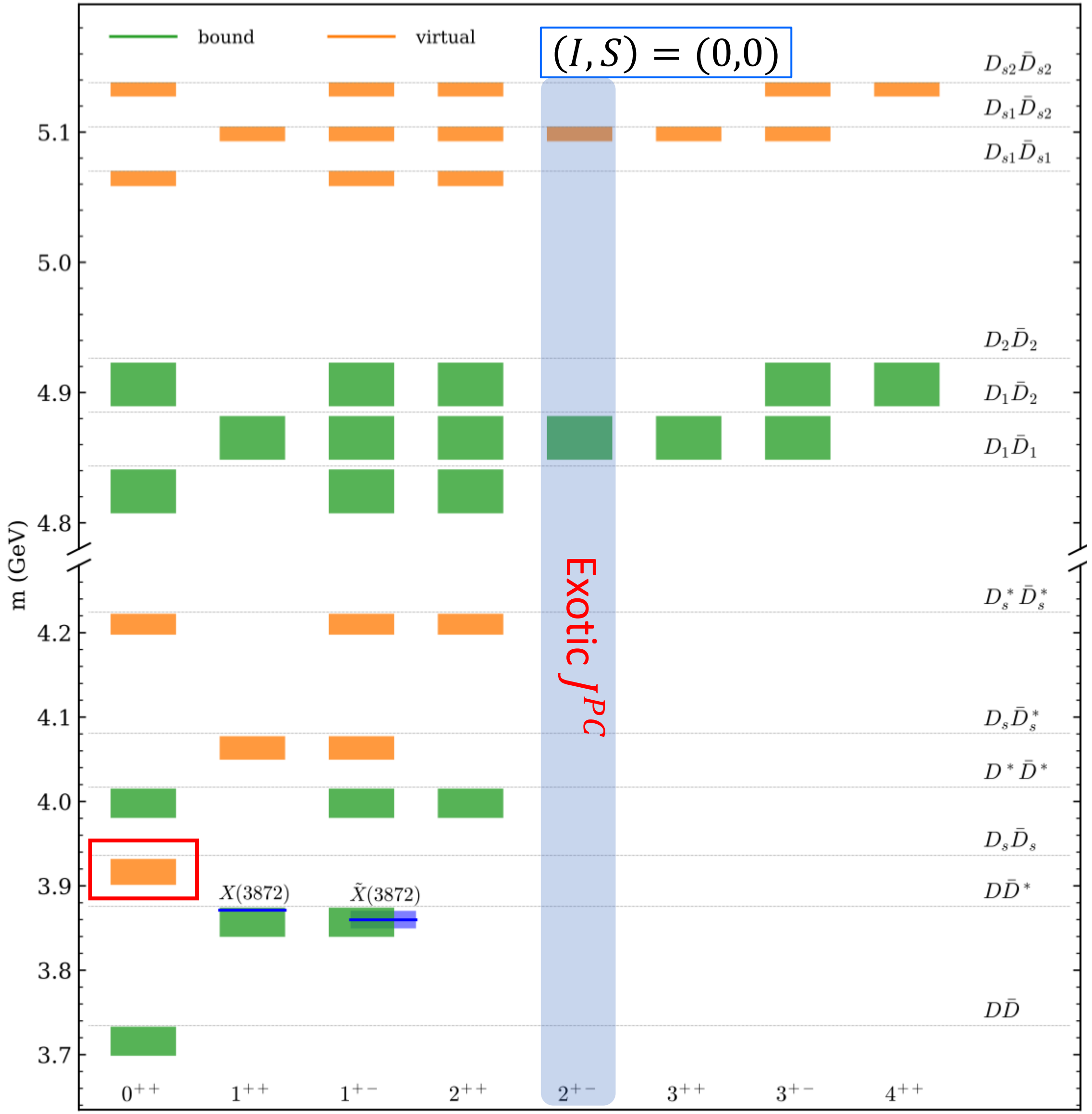




Attractive hadron pairs: Hidden-charm mesons w/ $P = +$

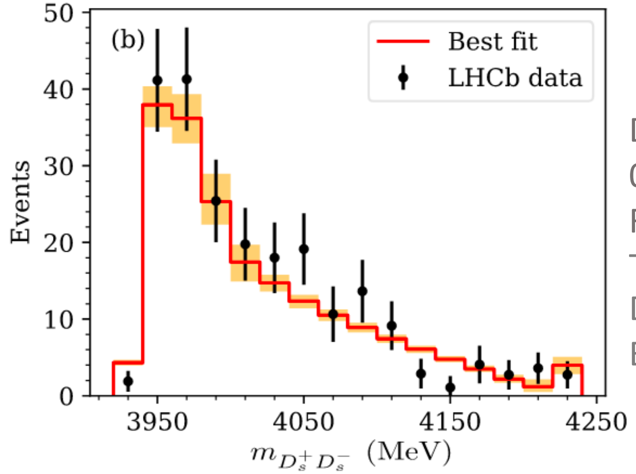


X.-K. Dong, FKG, B.-S. Zou, Prog. Phys. 41 (2021) 65

- ✓ Model here: light-vector exchanges, single channel, no mixing
- ✓ $X(3872)$ as a $\bar{D}D^*$ bound state
- ✓ $\tilde{X}(3872)$ COMPASS, PLB783(2018)334
- ✓ $\bar{D}D$ bound state predicted in models C.-Y.Wong (2004); Y.-J.Zhang et al. (2006); Gamermann et al. (2007); Nieves, Valderrama (2012); …

  by one lattice group Prelovsek et al., JHEP2106,035

  but not by HadSpec, arXiv:2309.14070; arXiv:2309.14071; talk by D. Wilson
- ✓ $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$



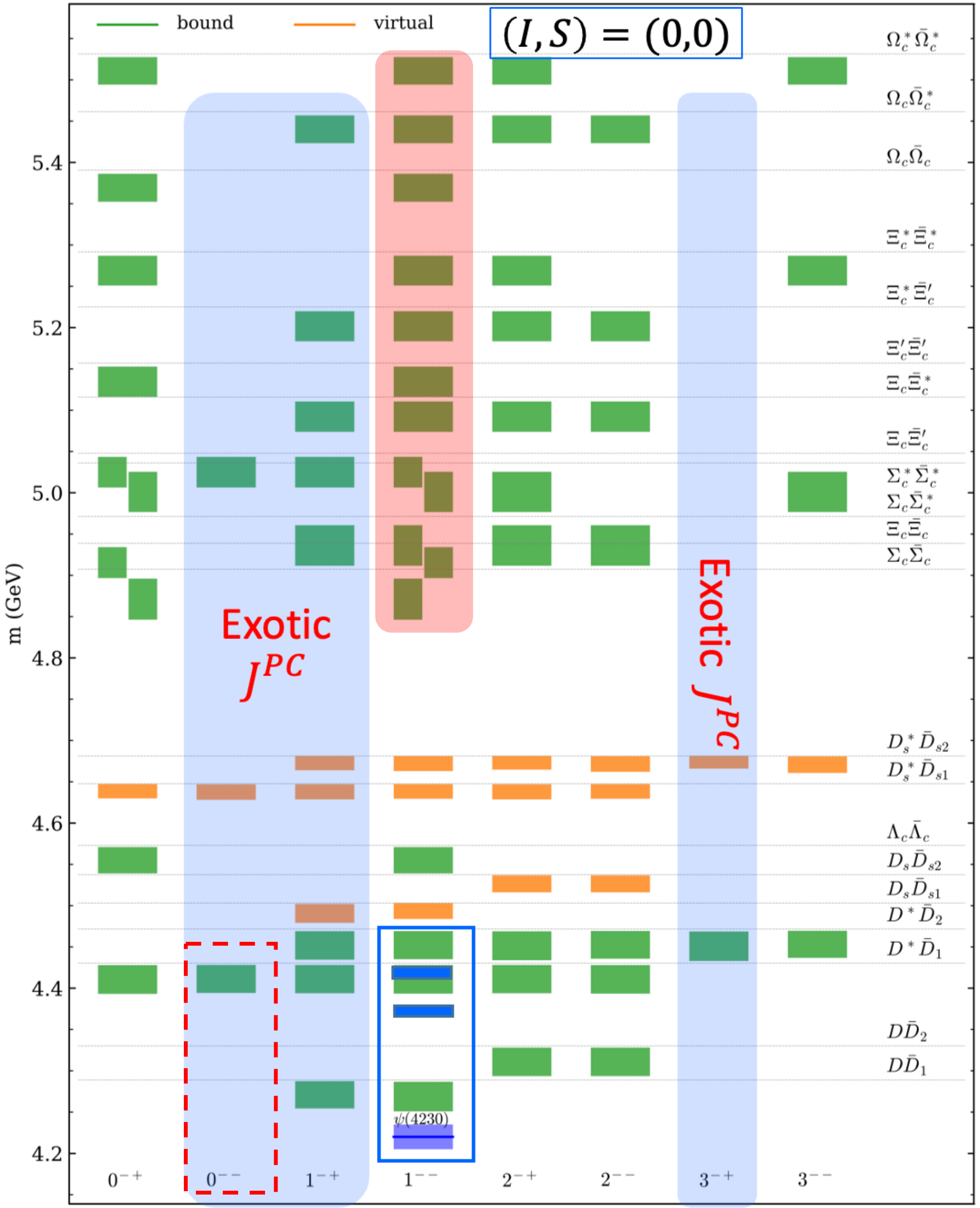
Data from LHCb, PRL 131 (2023) 071901

Fit in

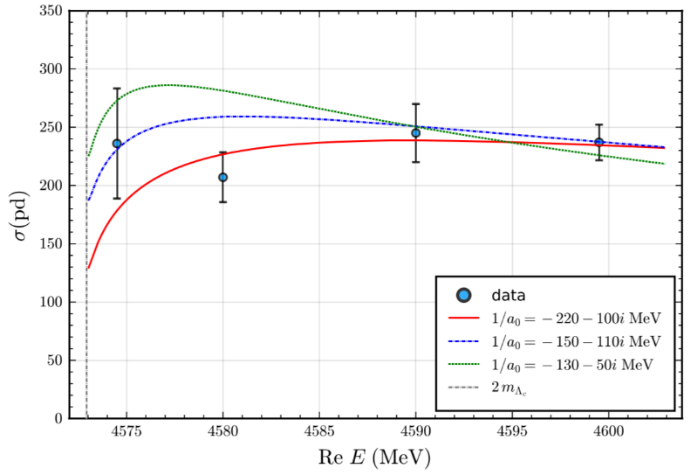
T. Ji, X.-K. Dong, M. Albaladejo, M.-L. Du, FKG, J. Nieves, B.-S. Zou, Sci. Bull. 68 (2023) 2056

pole at $3936.5^{+0.4}_{-0.9} + i\left(16.1^{+4.2}_{-2.2}\right)$ MeV

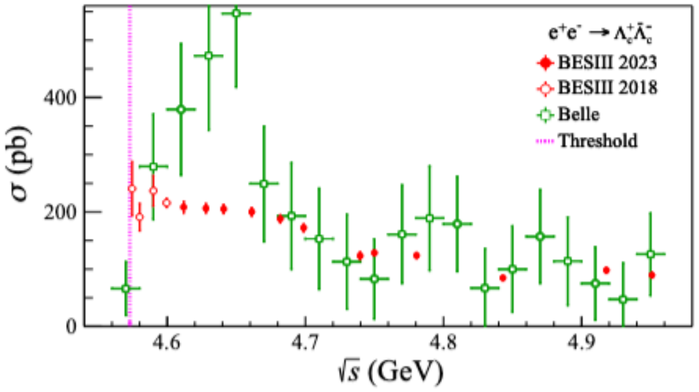
Hidden-charm mesons: $P = -$



- ✓ $Y(4260)/\psi(4230)$ 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



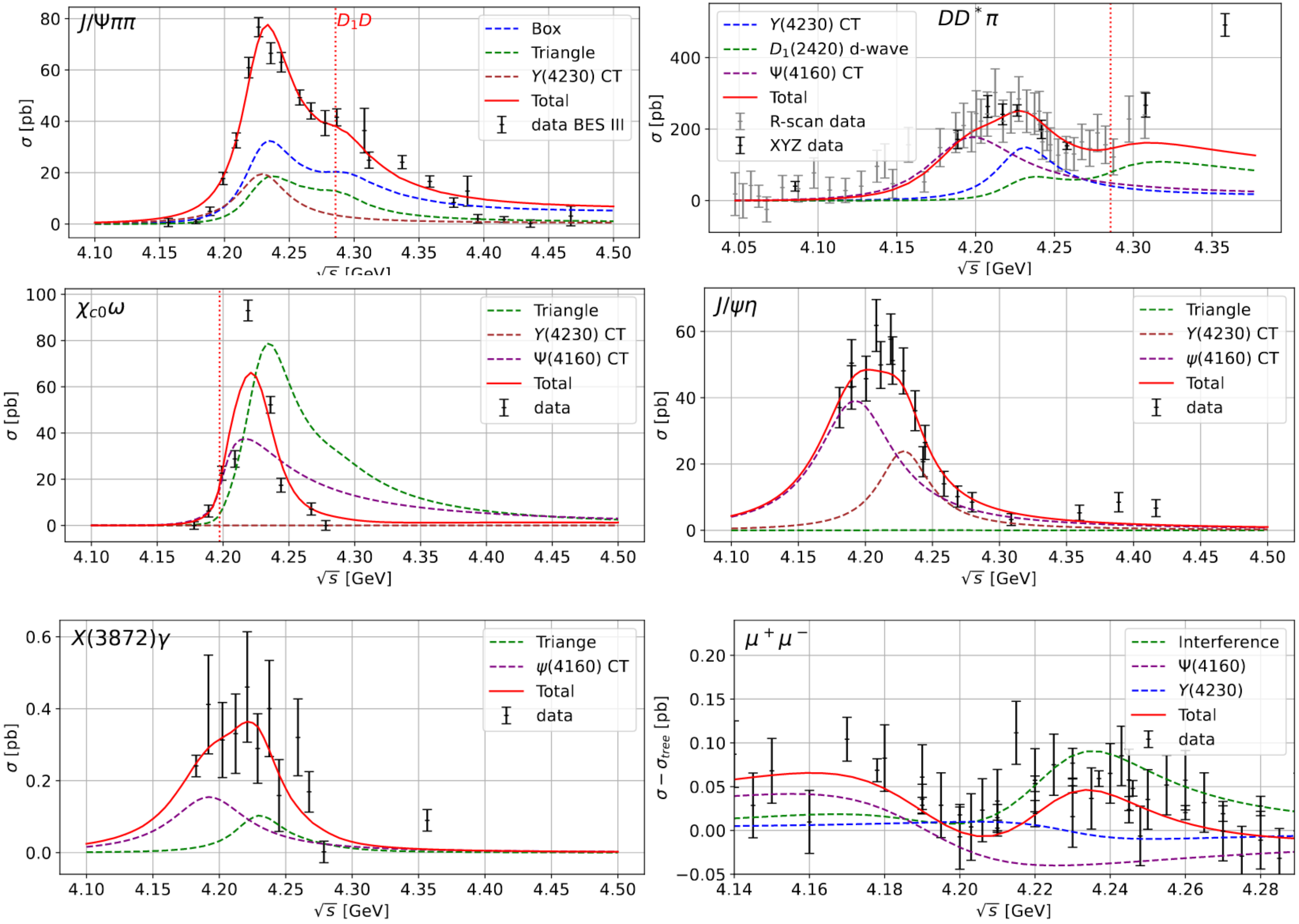
Data taken from BESIII, PRL 120 (2018) 132001; See also Q.-F. Cao et al., PRD 100 (2019) 054040



Updated BESIII results, arXiv:2307.07316

$\psi(4230)$ as a $D_1\bar{D}$ molecular state

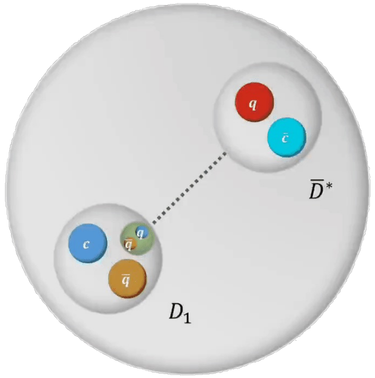
L. von Detten, C. Hanhart, V. Baru, arXiv:2309.11970



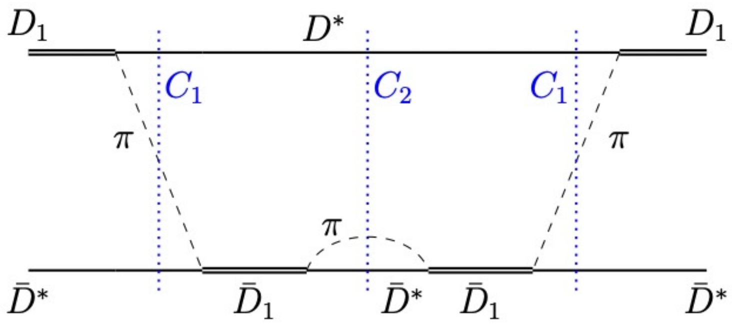
Closer look at the 0^{--} state

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

- EFT 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: consequence of heavy quark spin symmetry
- Robust against the inclusion of coupled channels and three-body effects



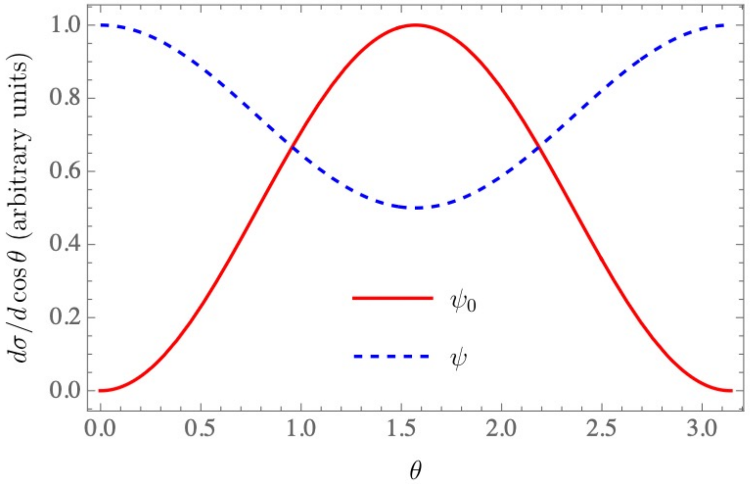
Molecule	Components	J^{PC}	Threshold	E_B
$\psi(4230)$	$\frac{1}{\sqrt{2}}(D\bar{D}_1 - \bar{D}D_1)$	1^{--}	4287	67 ± 15
$\psi(4360)$	$\frac{1}{\sqrt{2}}(D^*\bar{D}_1 - \bar{D}^*D_1)$	1^{--}	4429	62 ± 14
$\psi(4415)$	$\frac{1}{\sqrt{2}}(D^*\bar{D}_2 - \bar{D}^*D_2)$	1^{--}	4472	49 ± 4
ψ_0	$\frac{1}{\sqrt{2}}(D^*\bar{D}_1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



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

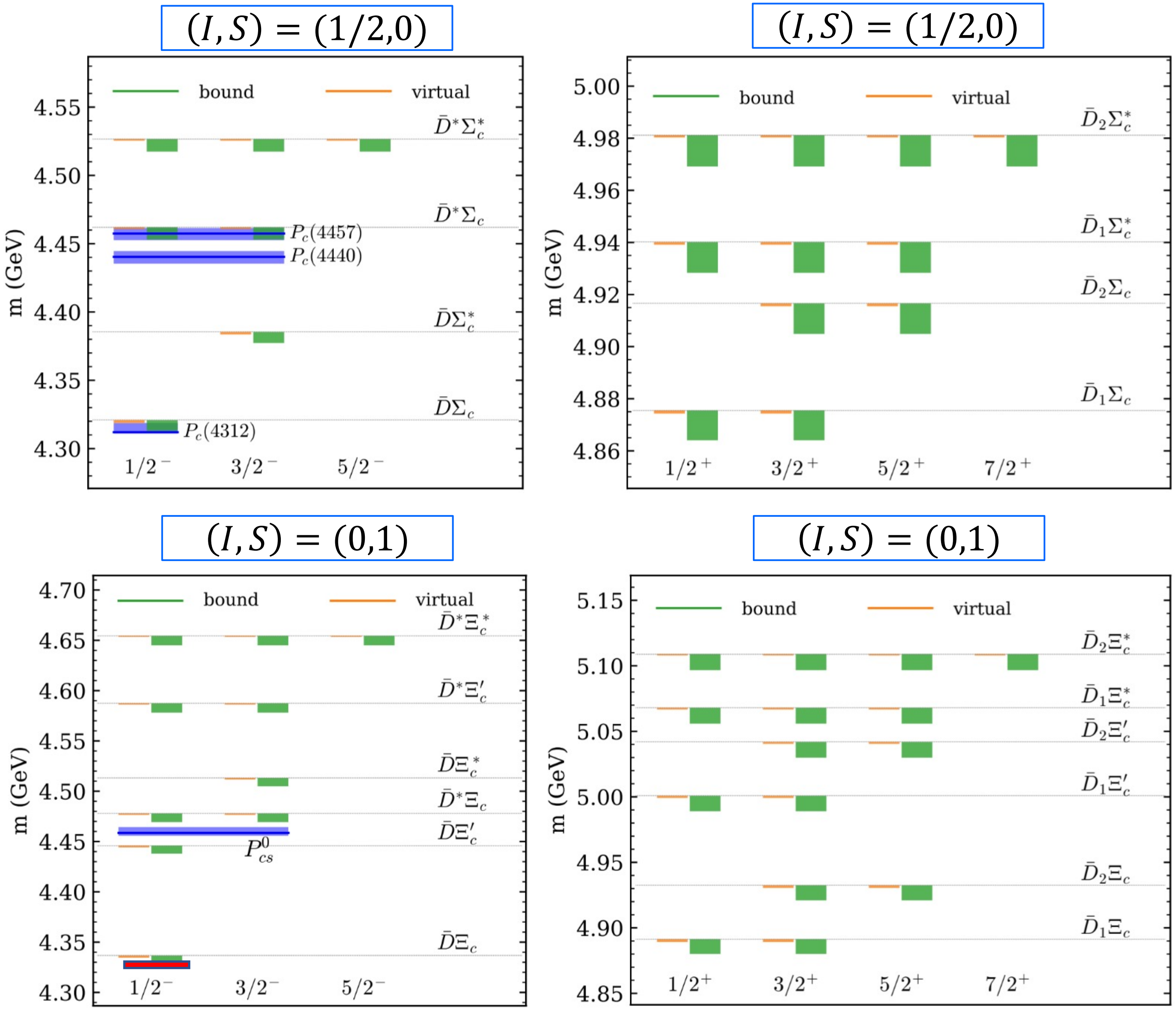
$M = (4366 \pm 18)$ MeV,

$\Gamma < 10$ MeV



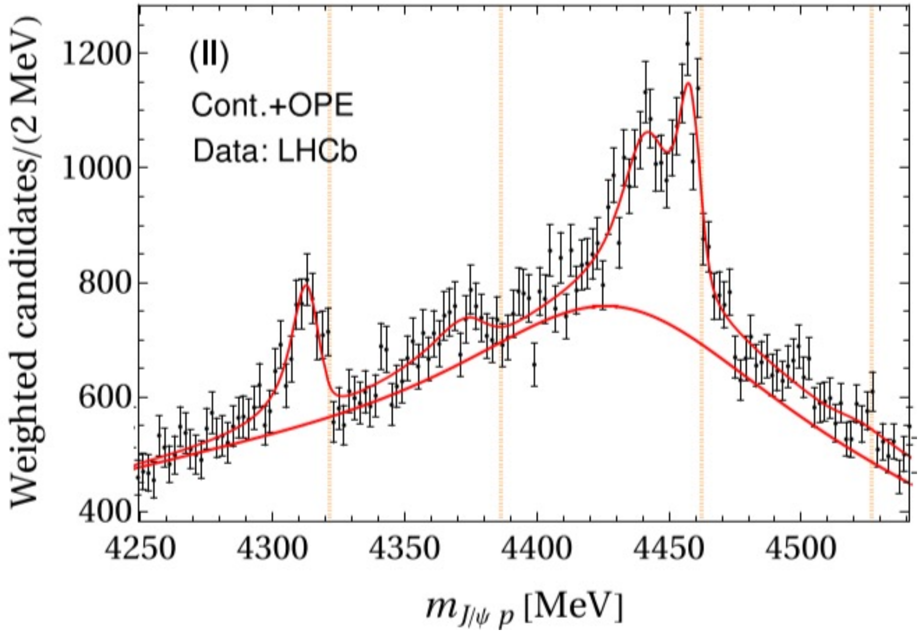
Hidden-charm pentaquarks

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



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

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

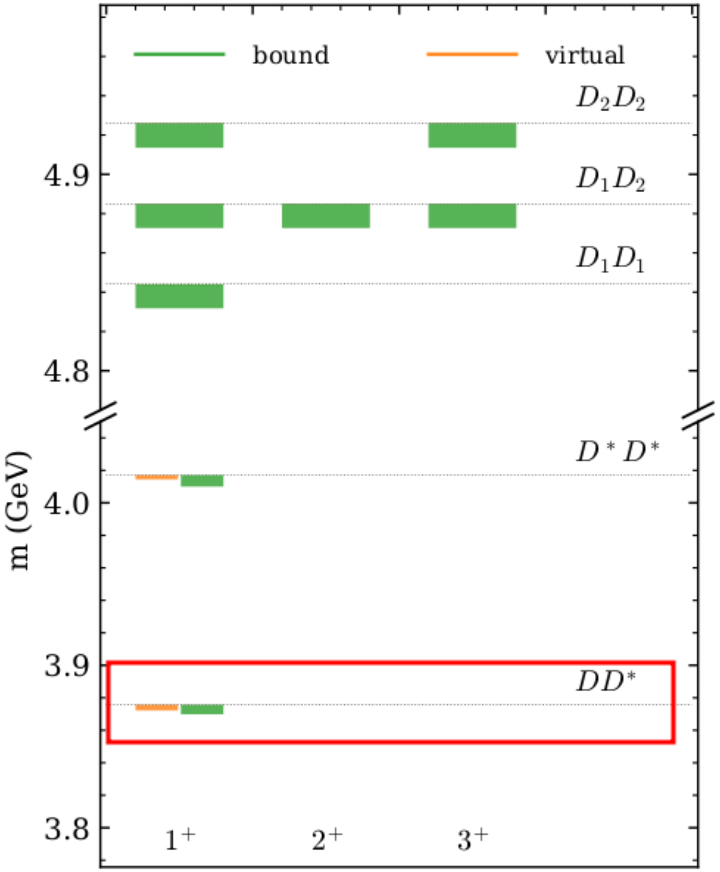


- ✓ $P_{cs}(4459)$: 2 $\bar{D}^*\Xi_c$ molecular states
- ✓ $P_{cs}(4338)$: $\bar{D}\Xi_c$ molecular state

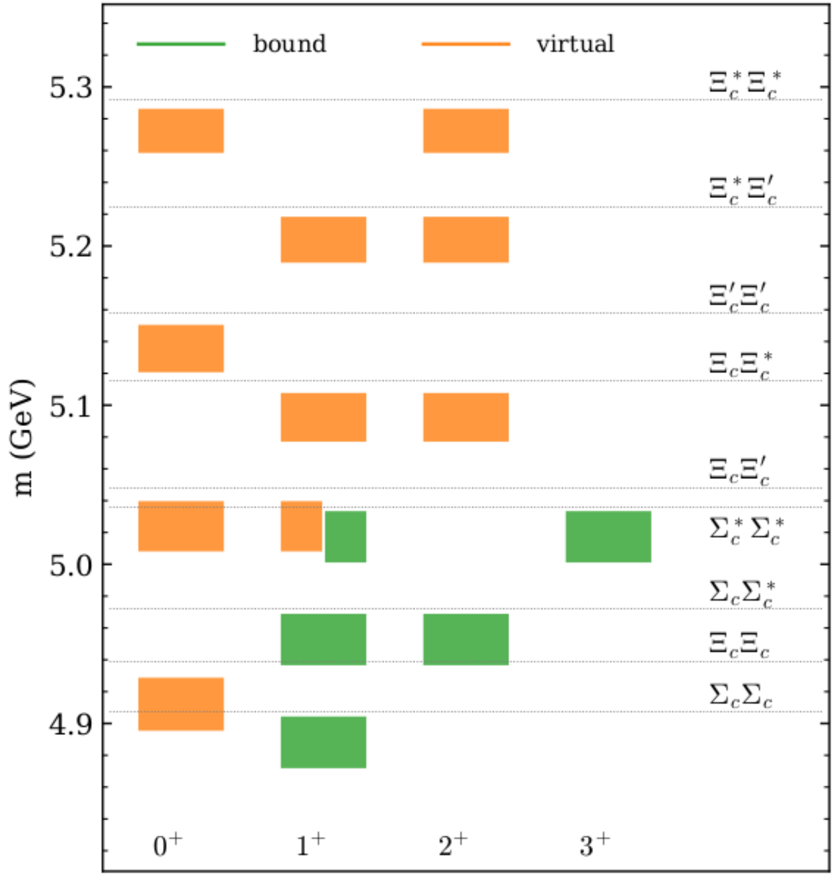
Double-charm tetraquarks and dibaryons

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

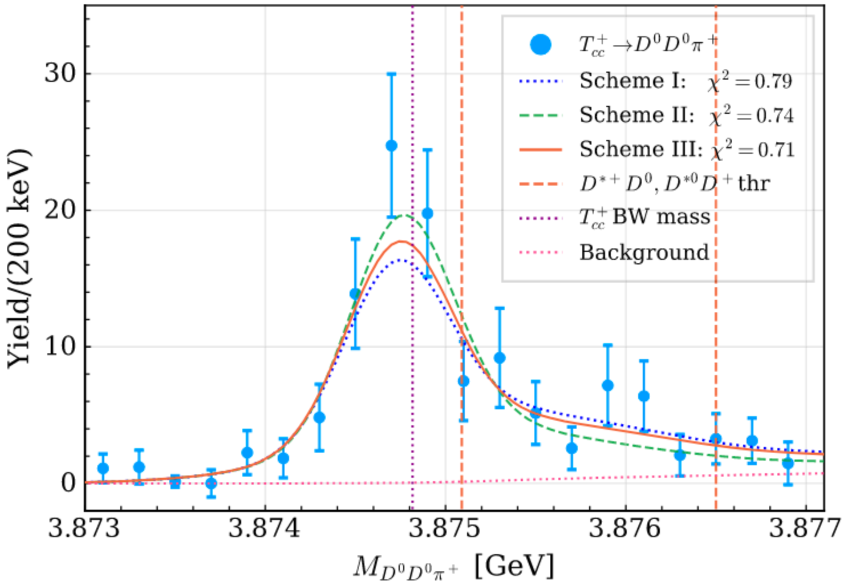
$(I, S, B) = (0,0,0)$



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



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

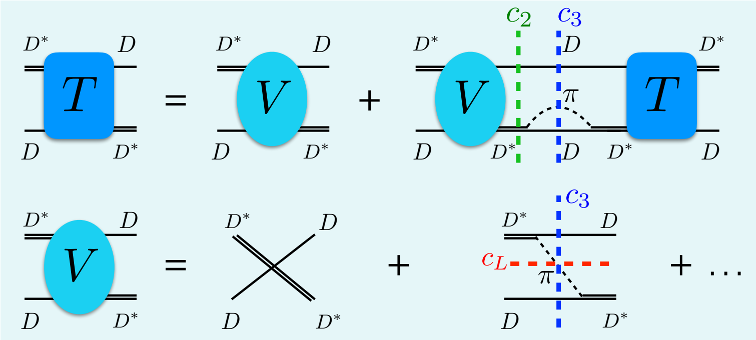


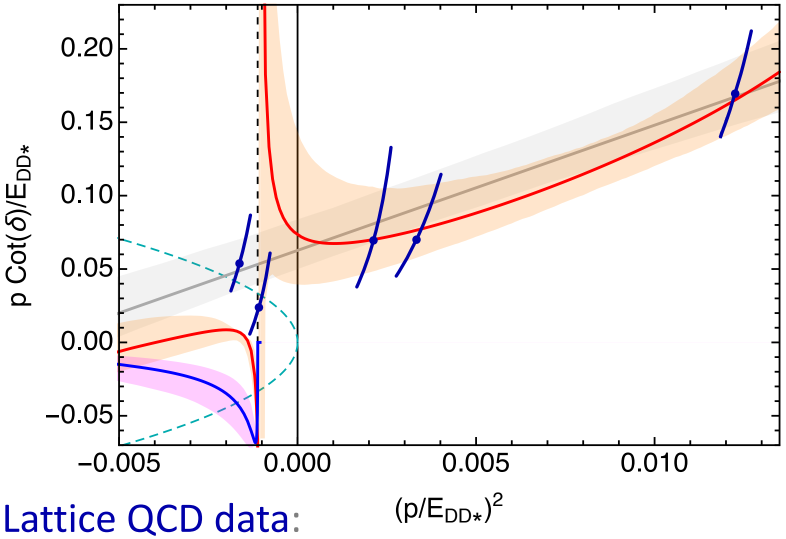
M.-L. Du et al., PRD 105 (2022) 014024

- ✓ There is an isoscalar DD^* molecular state
- ✓ It has a spin partner 1^+ D^*D^* state
- ✓ Many (> 100) other similar double-charm molecular states in other sectors

Three-body effects

- Lattice results on scattering often analyzed using ERE, convergence radius could be significantly reduced by three-body effects
  - left-hand cut A. Raposo, M. Hansen, PoS Lattice2022, 051; S. Dawid et al., PRD 108 (2023) 034016; M.-L. Du et al., PRL 131 (2023) 131903
  - zero of amplitude

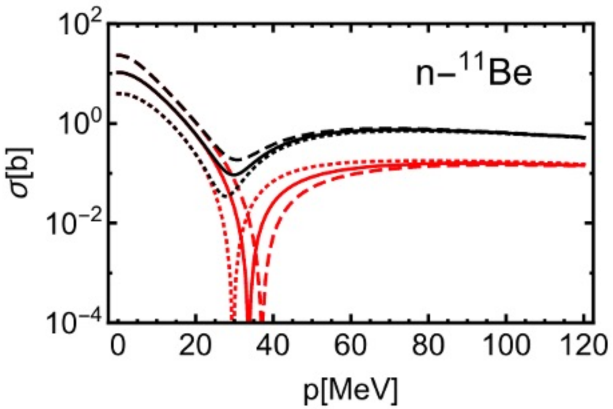




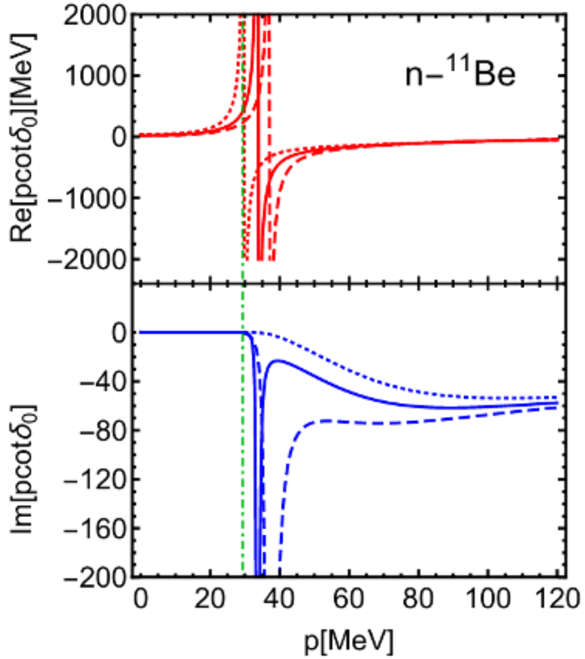
Lattice QCD data:
M. Padmanath, S. Prelovsek, PRL 129 (2022) 032002
Fit: M.-L. Du et al., PRL 131 (2023) 131903

- zero of amplitude for 3-body system known before for nd, n-one-neutron-halo (^{11}Be, ^{19}C, …) scattering

W.T.H. van Oers, J.D. Seagrave, PLB 24 (1967) 562; M. T. Yamashita, T. Frederico, L. Tomio, PLB 670 (2008) 49; X. Zhang et al., PRC 108 (2023) 044304…



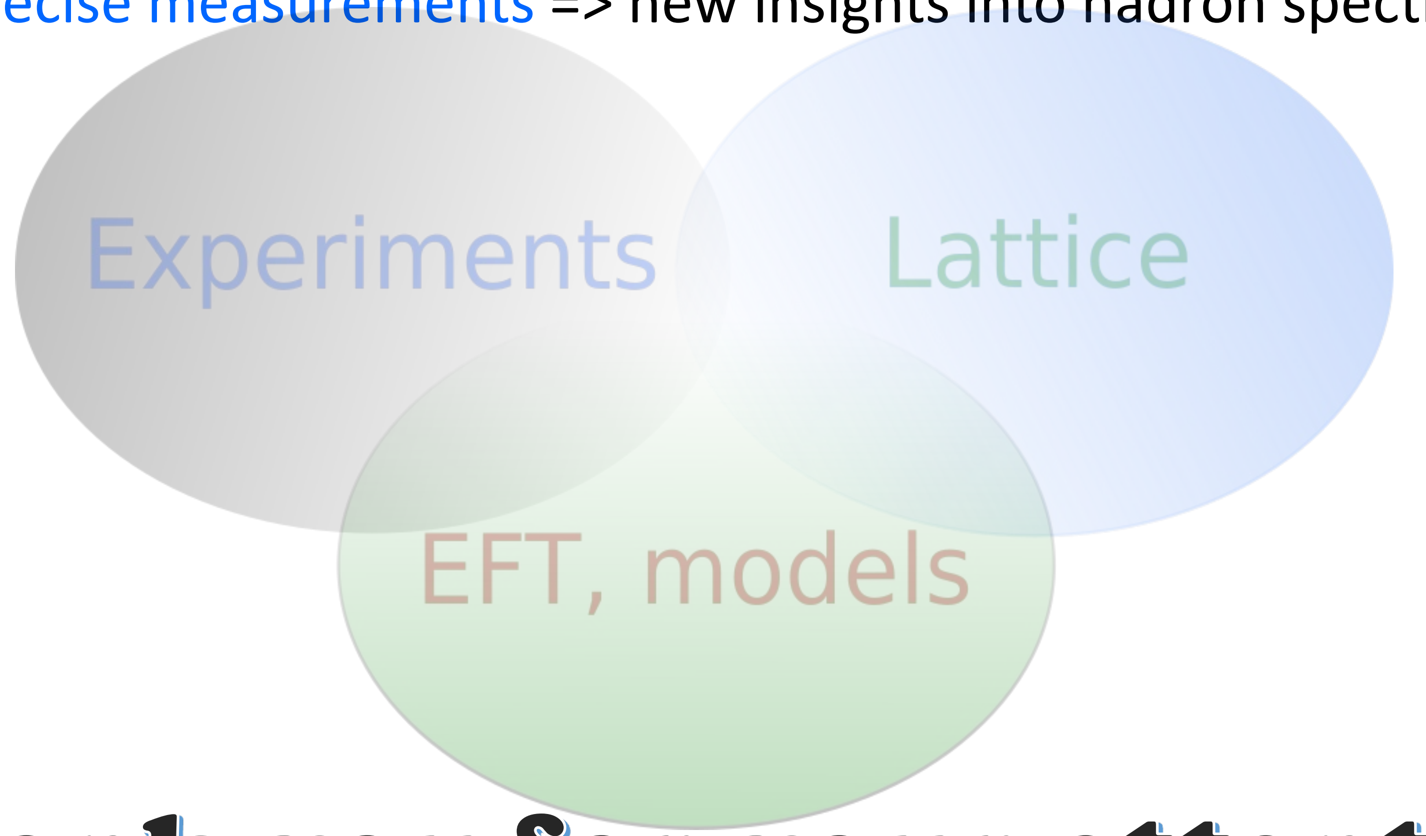
[red: S-wave, black: $l \leq 4$]



X. Zhang, H.-L. Fu, FKG, H.-W. Hammer, PRC 108 (2023) 044304

Conclusion

- Near-threshold structures can be analyzed with hadronic EFT
- EFT + lattice + precise measurements => new insights into hadron spectroscopy



Thank you for your attention!