Physics of multiquark states

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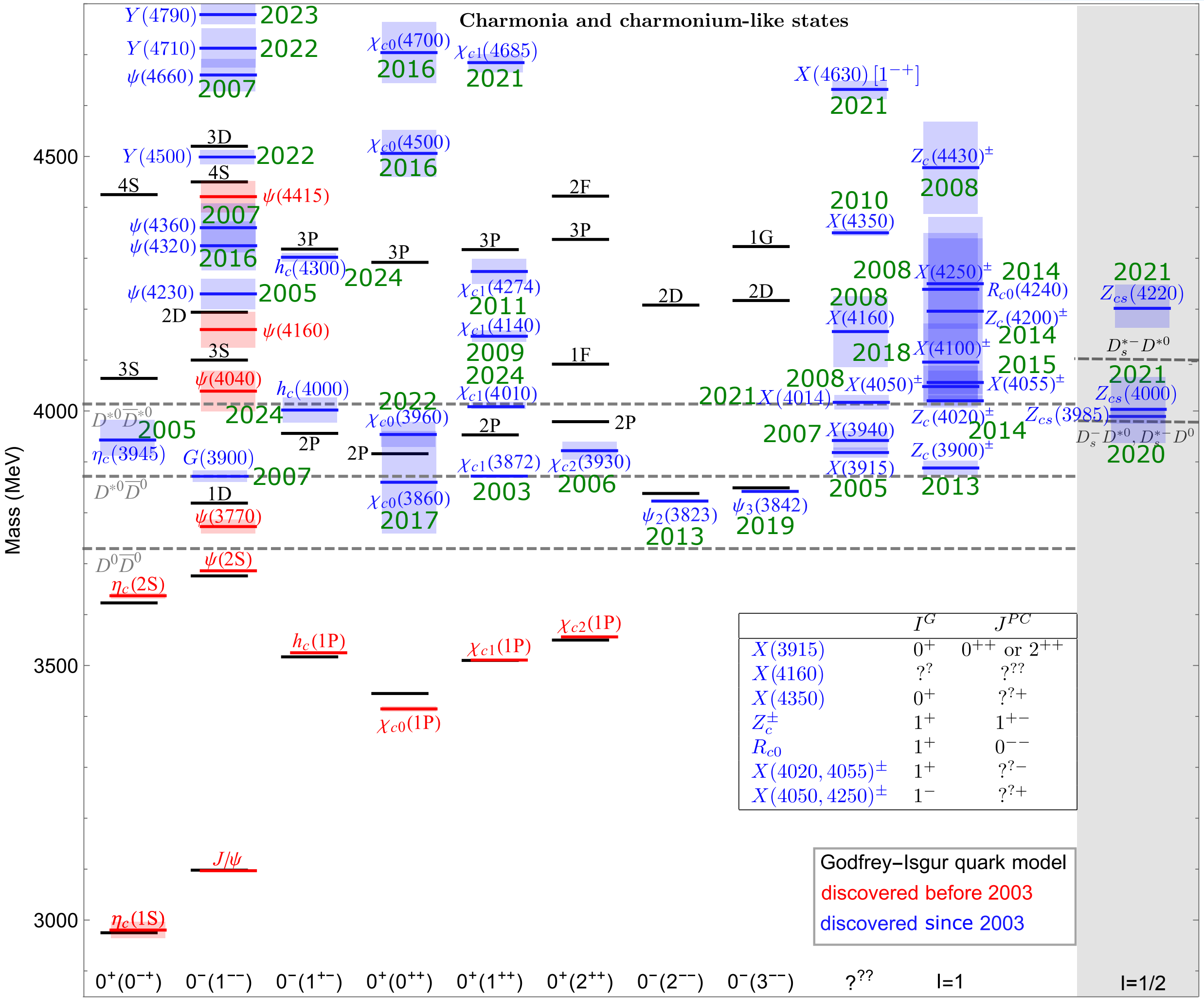
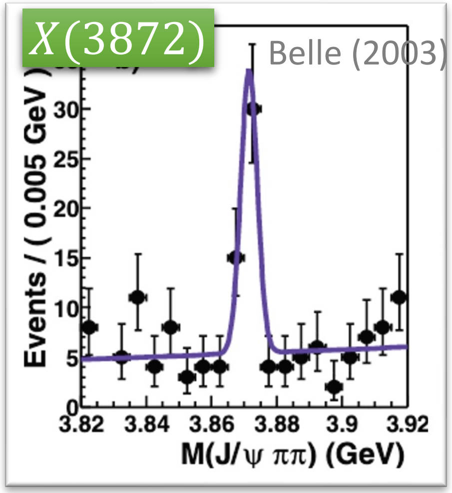
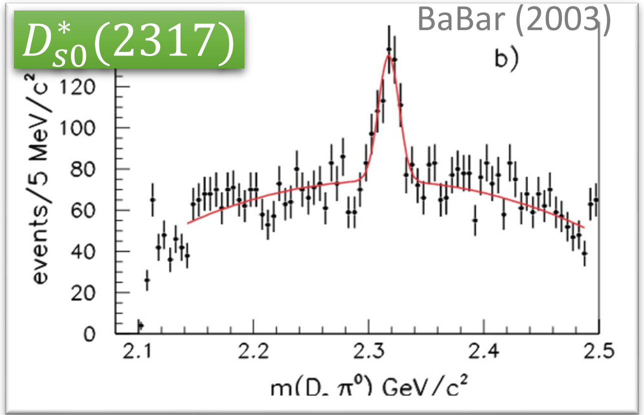
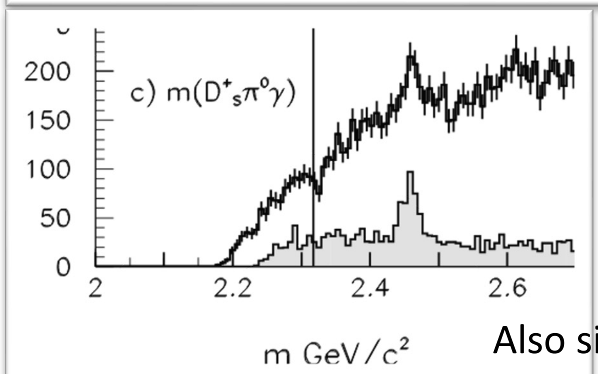


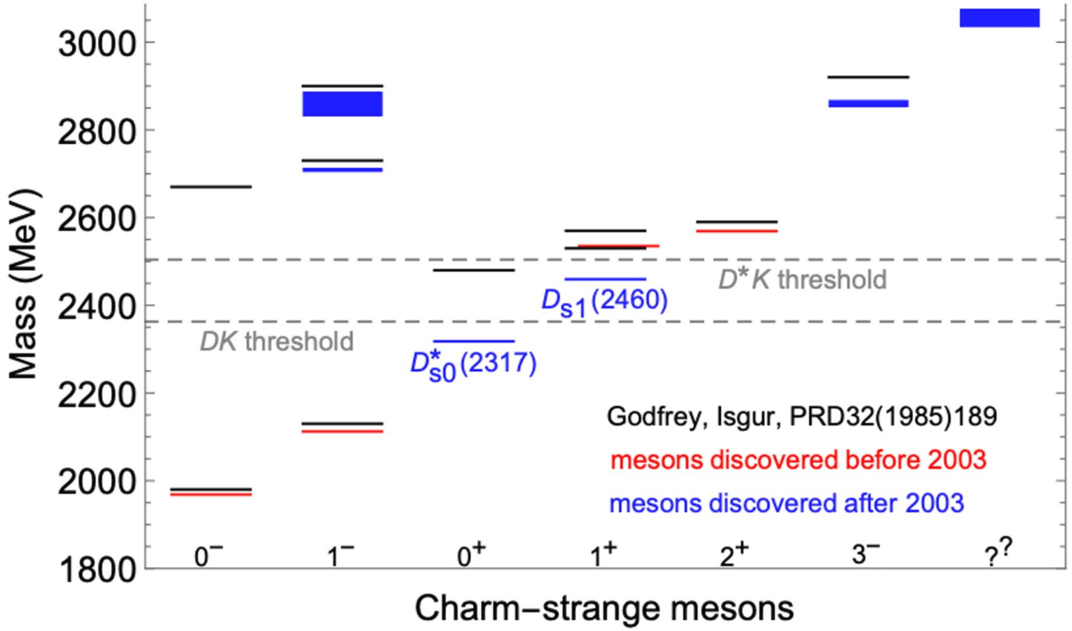
Renaissance of hadron spectroscopy in 2003







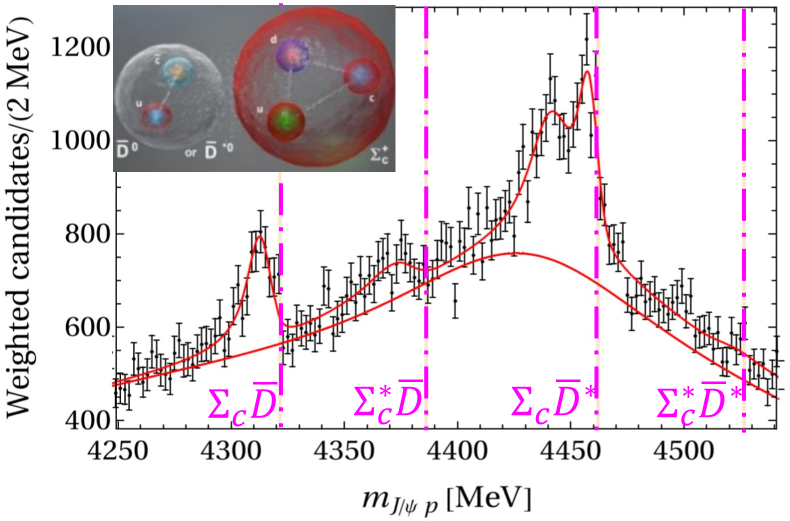
Also signal for $D_{s1}(2460)$ in BaBar (2003)



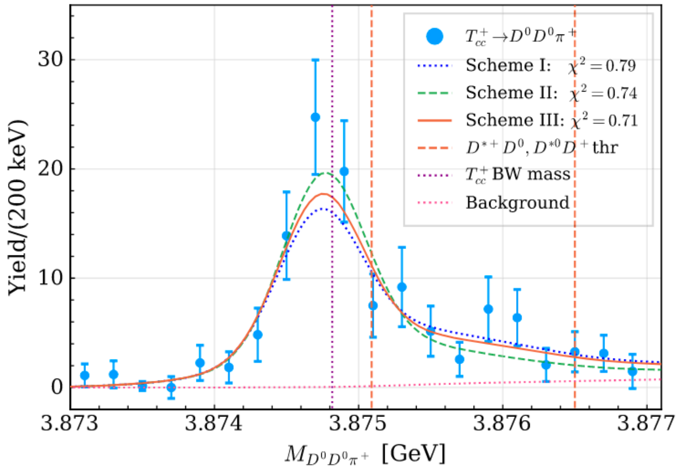
- $D_{s0}^*(2317)$ BaBar (2003)
  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$ CLEO (2003)
  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths
  $\Rightarrow I = 0$

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

Peaks and dips (some LHCb data)



Data: LHCb, PRL122 (2019) 222001;
Fit: M.-L. Du, et al., PRL 124 (2020) 072001



data from LHCb, Nat.Phys.18 (2022) 751;
fit from M.-L. Du et al., PRD 105 (2022) 014024

Neither all peaks correspond to resonances, nor all resonances appear as peaks

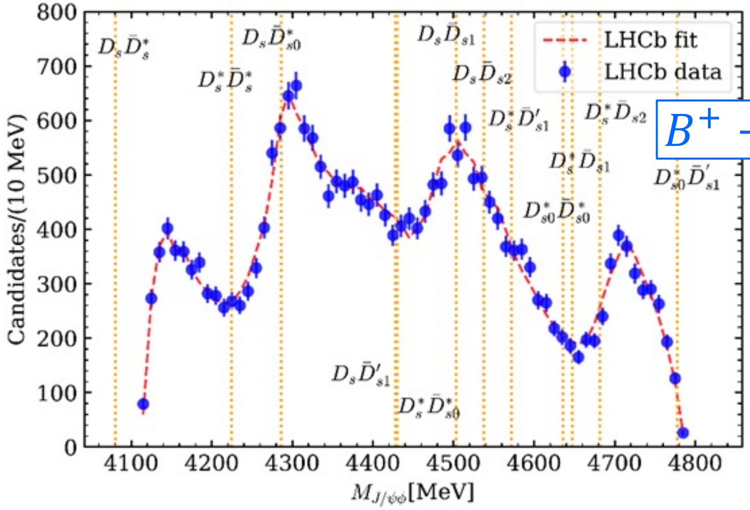
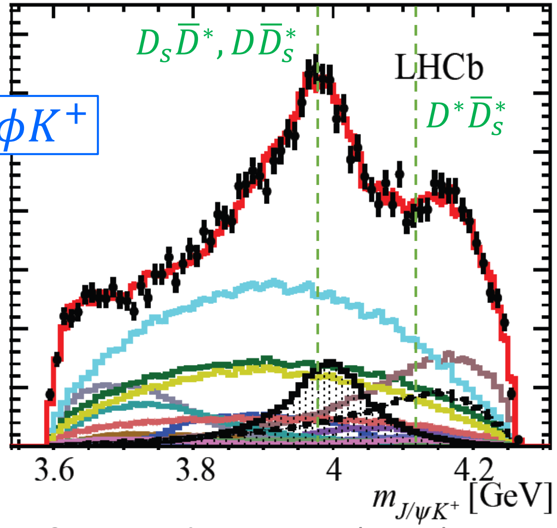
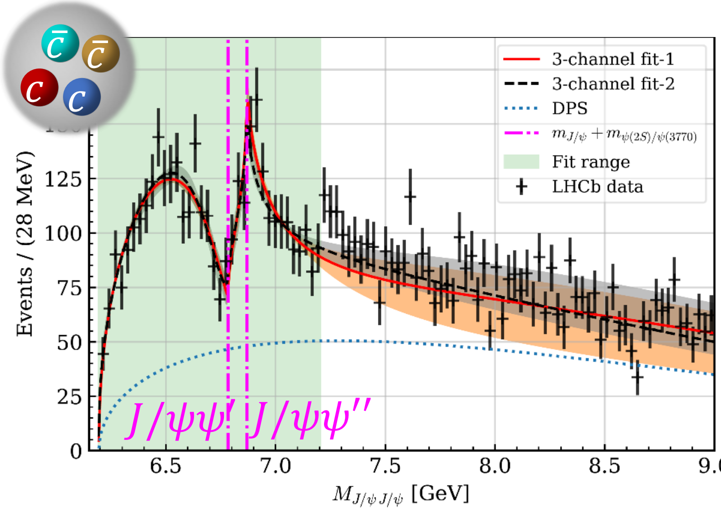


Fig. from X.-K. Dong, FKG, B.-S. Zou, arXiv:2101.01021;

$B^+ \to J/\psi\phi K^+$

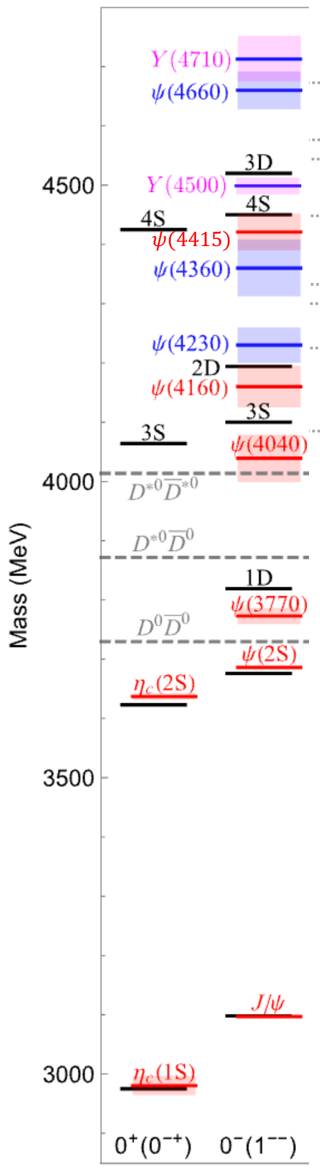


data from LHCb, PRL 127 (2021) 082001



data from LHCb, Sci.Bull.65 (2020) 1983;
fit from X.-K. Dong et al., PRL 126 (2021) 132001

Many hidden-charm thresholds above 4 GeV



$\psi' f_0(980)$

$D_{s1}\bar{D}_s^*, \Lambda_c^+\bar{\Lambda}_c^-$

$\chi_{c0,1,2}\phi$

$D_{s0}^*\bar{D}_s^*,\ D_{s1}\bar{D}_s$

$D_2(2460)\bar{D}^*$

$D_1(2420)\bar{D}^*$

$D_1(2420)\bar{D}$

$\chi_{c0,1,2}\omega$

$J/\psi f_0(980)$

2-body S-wave thresholds

Thresholds can play an essential role

- Complicates extraction of resonance properties! Measurements on various final states are important

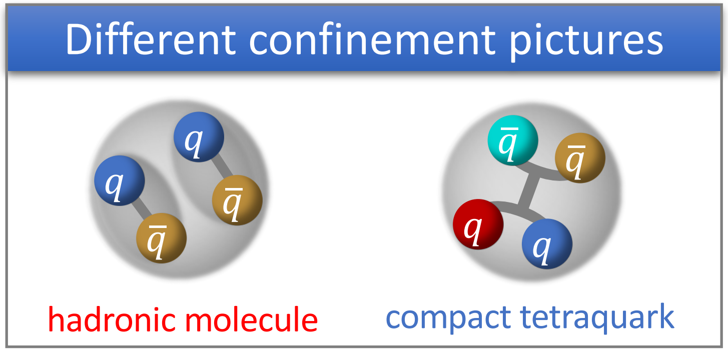
Reliable amplitude analysis lays the foundation to answer important questions

- How do quarks and gluons form hadrons?

See also talk by Q. Zhao

Multiquark states

- 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?



- Crucial quantity for near-threshold states: compositeness X, 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 …

Scattering phase shift

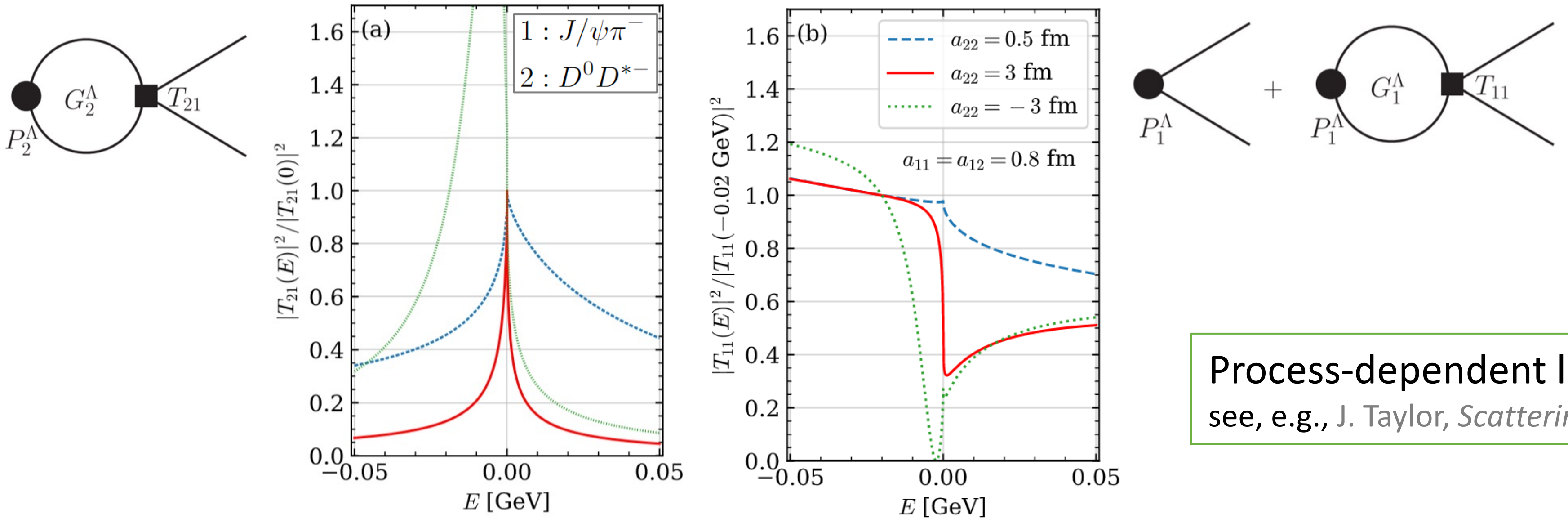
$$X \approx 1 - \exp\left(\frac{1}{\pi}\int_0^\infty dE\,\frac{\delta(E)}{E-E_B}\right) \in [0,1]$$

binding energy

How thresholds affect line shapes

X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001
Extension: classification of 2-channel near-threshold structures,
Z.-H. Zhang, FKG, PLB 863 (2025) 139387

- (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 (⇒ hadronic molecules)
    - ✓ That’s why many (near-)threshold structures were observed in hidden-charm spectra
  - ➢ Structures are process (production-mechanism) dependent
    - ✓ Universality of a dip of $|T_{11}|$ when the higher channel has a large scattering length

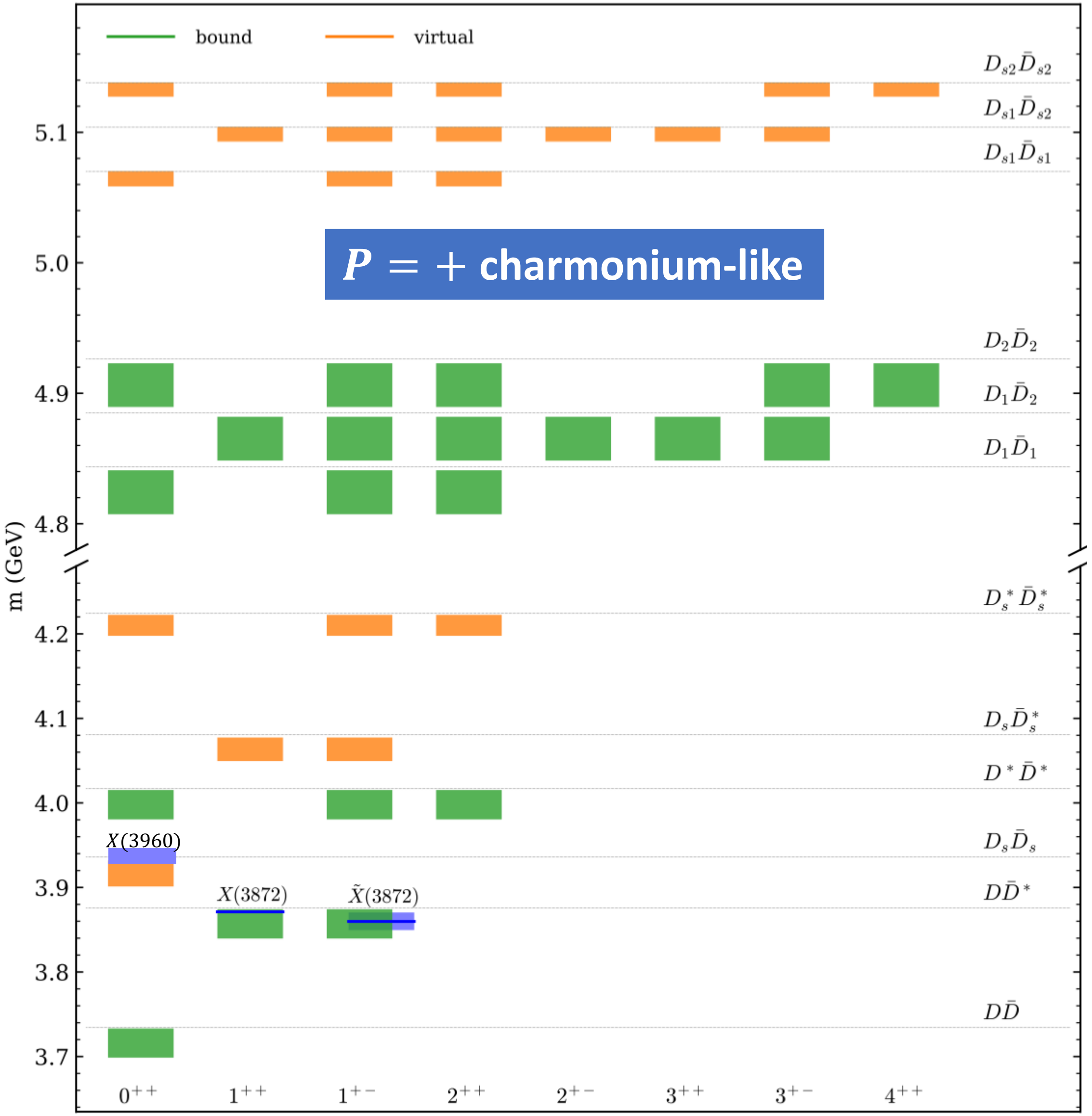


Process-dependent line shapes known since long;
see, e.g., J. Taylor, *Scattering Theory*

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

Survey of hadronic molecules

X.-K. Dong, FKG, B.-S. Zou, Progr. Phys. 41 (2021) 65 [arXiv:2101.01021]; Commun. Theor. Phys. 73 (2021) 125201



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

- ➢ >200 hidden-charm + >100 double-charm molecules

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

Some open questions (debates):

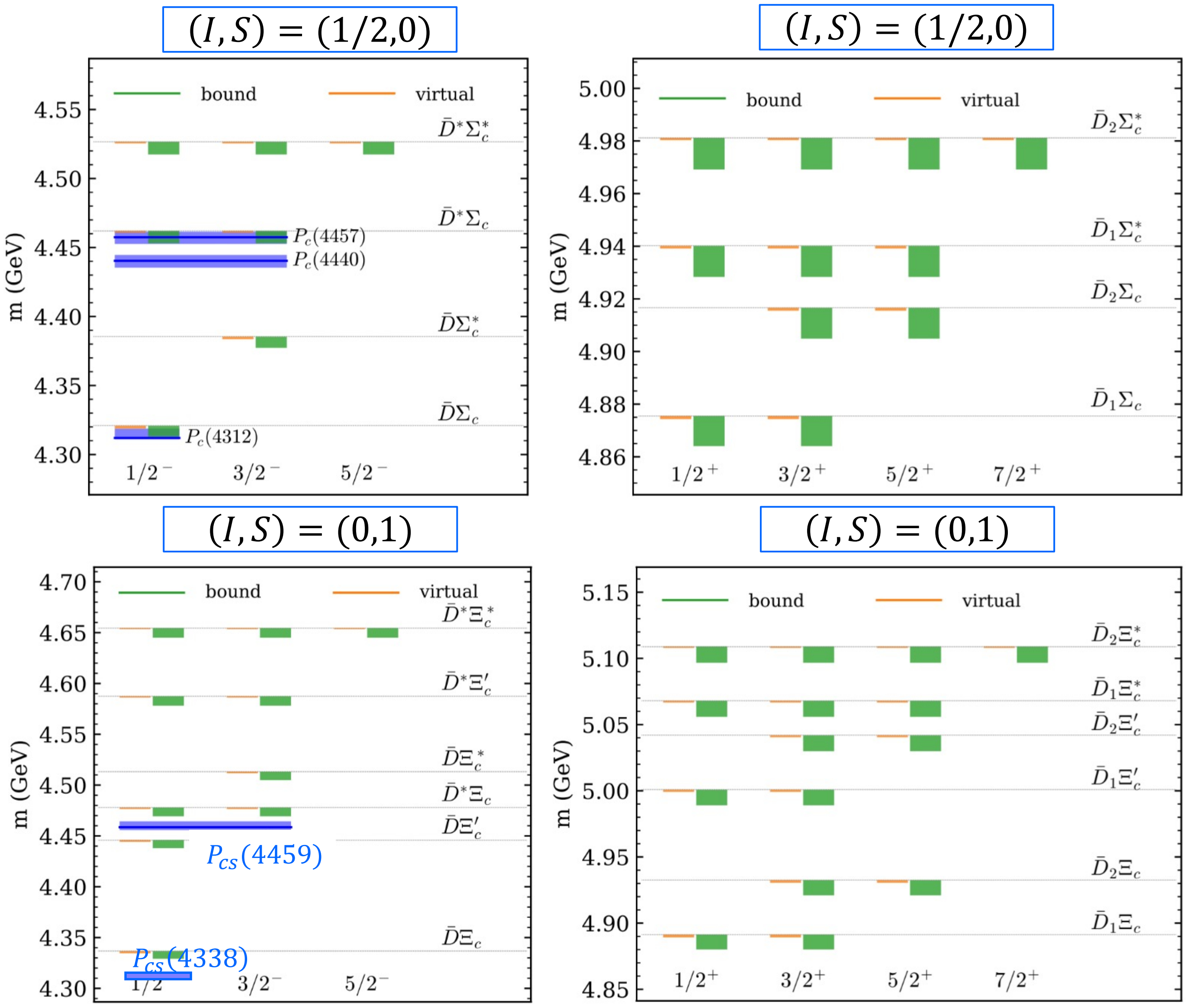
- ☐ Are radiative decays $(\to \psi\gamma)$ sensitive to the structure?
  E. Swanson, PLB 598 (2004) 297;
  FKG et al., PLB 742 (2015) 394
- ☐ What can be learned from its production in heavy-ion collisions?
  S. Cho et al., PRL 106 (2011) 212001;
  H. Zhang et al., PRL 126 (2021) 012301;
  B. Chen et al., PRC 105 (2022) 054901;
  E. Braaten et al., PRL 134 (2025) 252301; …

✓ $\bar{D}D$ bound state

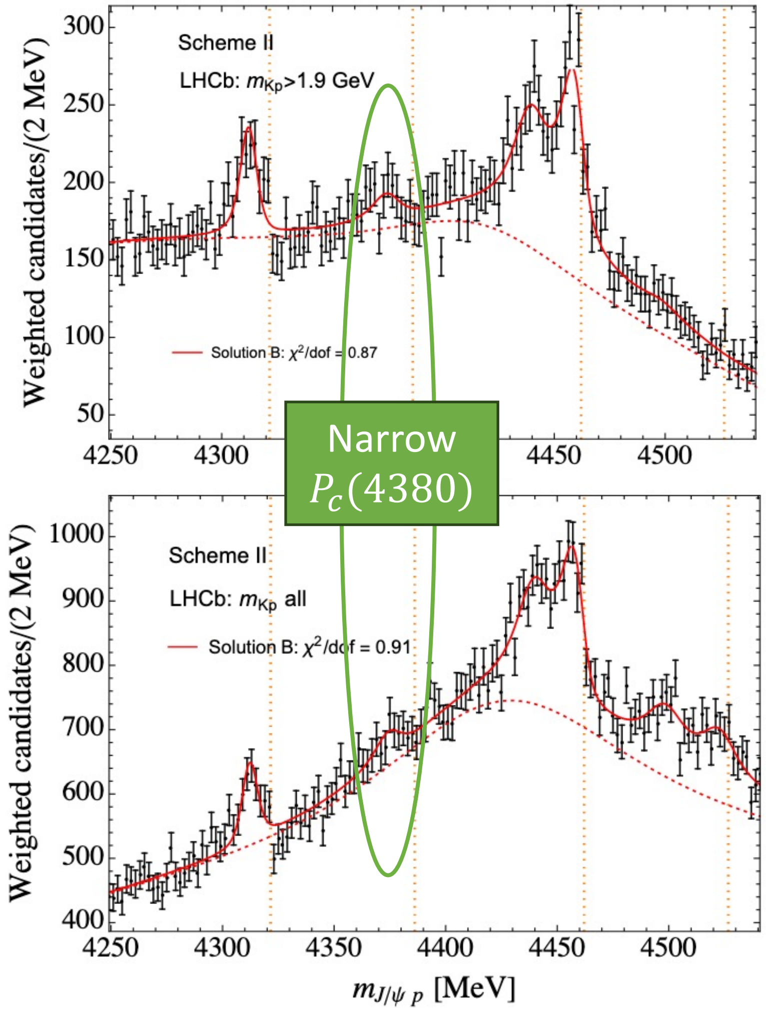
Conflicting lattice QCD results, what is the reason?

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

Survey of hadronic molecules: hidden-charm pentaquarks



- ✓ The LHCb data can be well described with a chiral EFT — M.-L. Du et al., JHEP 08 (2021) 157

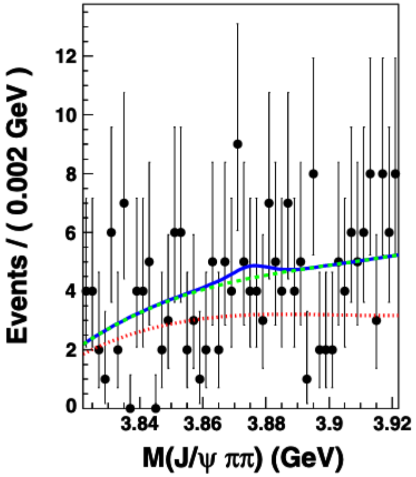


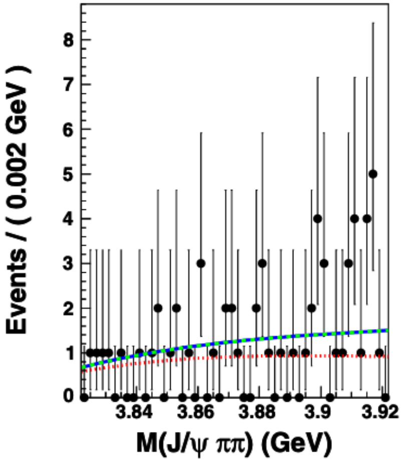
Closer look at $X(3872)$: Isospin-1 partner?

- Isospin-1 partner of X(3872) was predicted in the compact tetraquark model

L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRD 71 (2004) 014028

- No signal in the charged channel so far

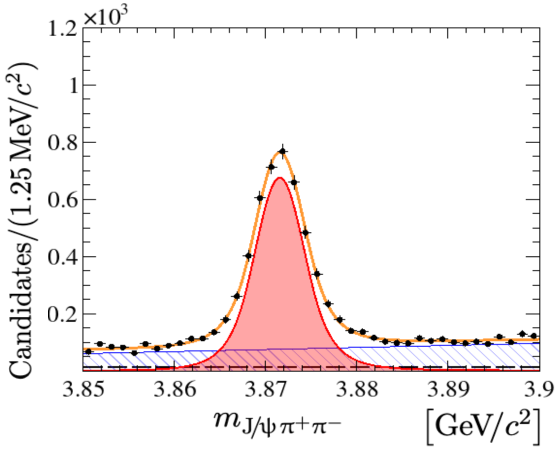




$\bar{B}^0 \to K^- \pi^+ \pi^0 J/\psi$ $\quad$ $B^+ \to K^0 \pi^+ \pi^0 J/\psi$

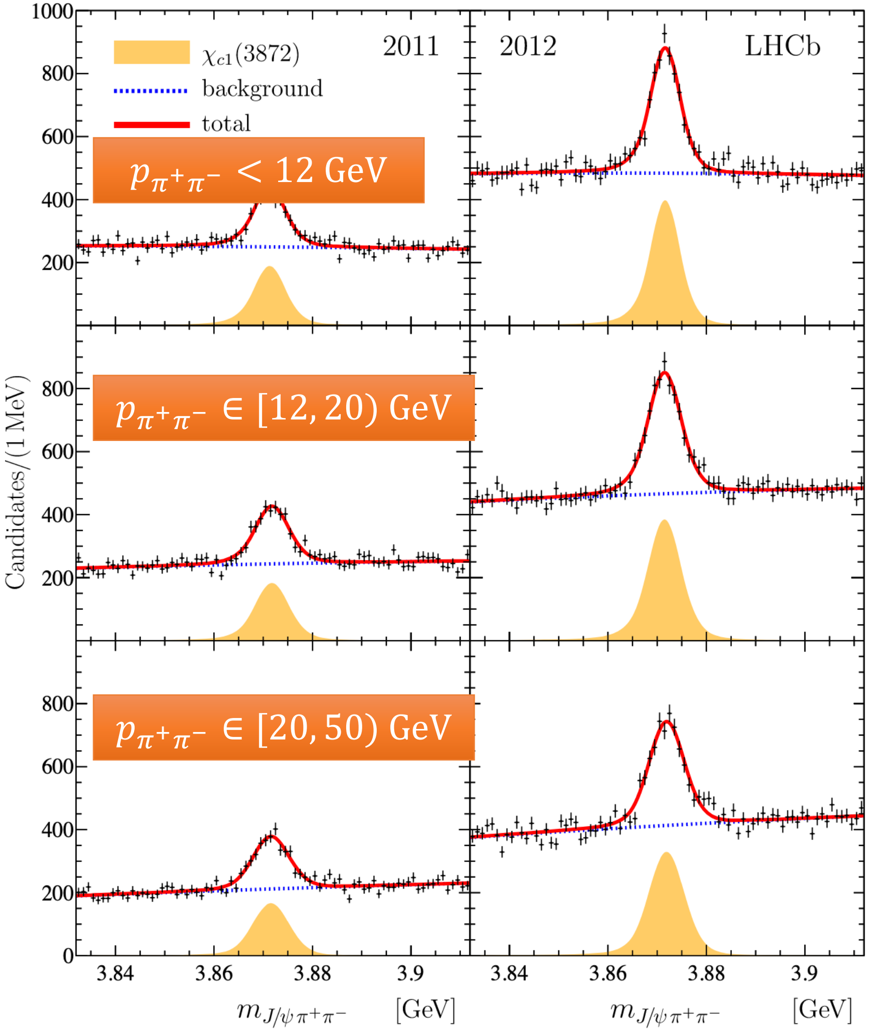
Belle, PRD 84 (2011) 052004

- No signal around the $D^+ D^{*-}$ threshold



$B^+ \to K^+ \pi^+ \pi^- J/\psi$

LHCb, JHEP 08 (2020) 123



$\pi^+ \pi^- J/\psi$ from b-hadrons

LHCb, PRD 102 (2020) 092005

Closer look into $X(3872)$

Z.-H. Zhang, T. Ji, X.-K. Dong, FKG et al., JHEP 08 (2025) 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

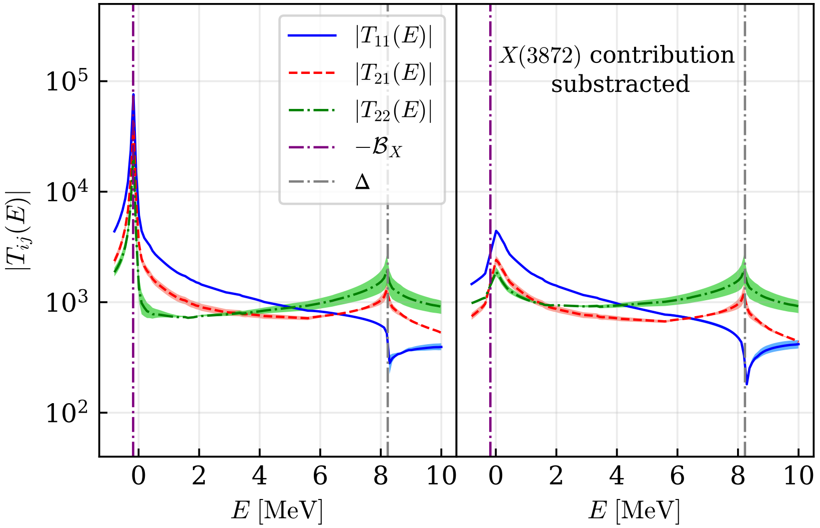
$$M_X = 3871.69^{+0.00+0.05}_{-0.04-0.13}\,\text{MeV}$$ LHCb, PRD 102 (2020) 092005

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

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

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

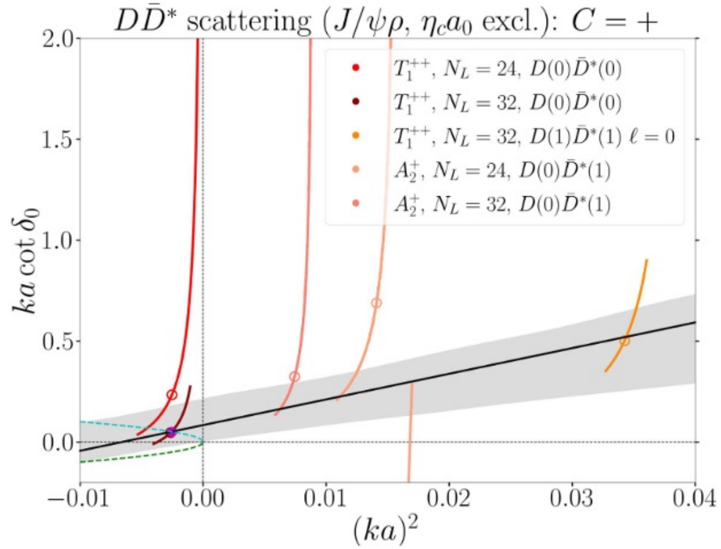
- Prediction: there must exist an isovector $J^{PC} = 1^{++}$ state ($W_{c1}^{0,\pm}$)



- 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., PRD 111 (2025) 054513



J^{PC}	interpolators	$1/a_0$ [fm^{-1}]	r_0 [fm]	$\chi^2/N_{\rm dof}$	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	$-3.8^{+3.6}_{\rm a}$
	$J/\psi\rho$, $\eta_c a_0$ 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.

✓ Also in one-boson exchange model

X.-X. Chen, Z.-M. Ding, J. He, PRD 111 (2025) 114008

Combined analysis of BESIII + LHCb data w/ chiral EFT

Teng Ji, X.-K. Dong, FKG, C. Hanhart, U.-G. Meißner, arXiv:2502.04458

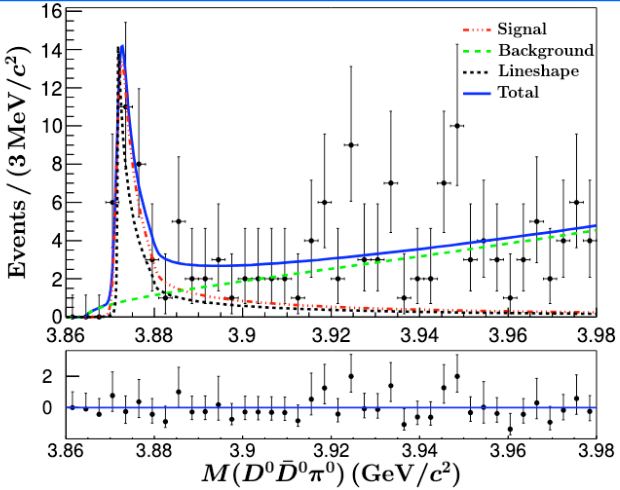
- $X(3872)$ line shapes ⇒ $X(3872)$ + possible $W_{c1}(3880)^0$
- $\pi^+\pi^-$ invariant mass distribution ⇒ isospin breaking, information on $I = 1$

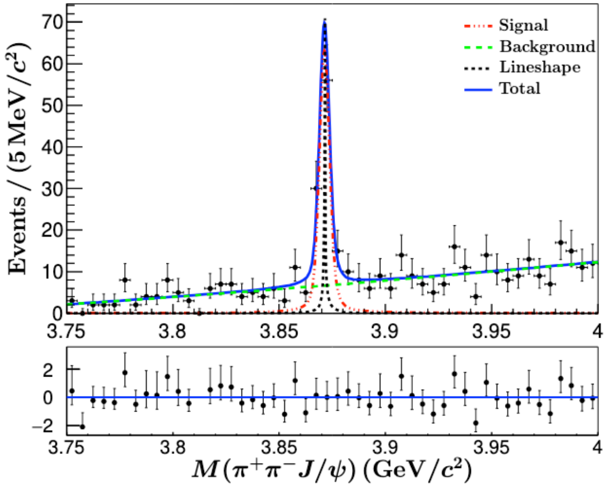
BESIII:

$e^+e^- \to \gamma[D^0\bar{D}^0\pi^0]$

$e^+e^- \to \gamma[J/\psi\pi^+\pi^-]$

BESIII, PRL 132 (2024) 151903

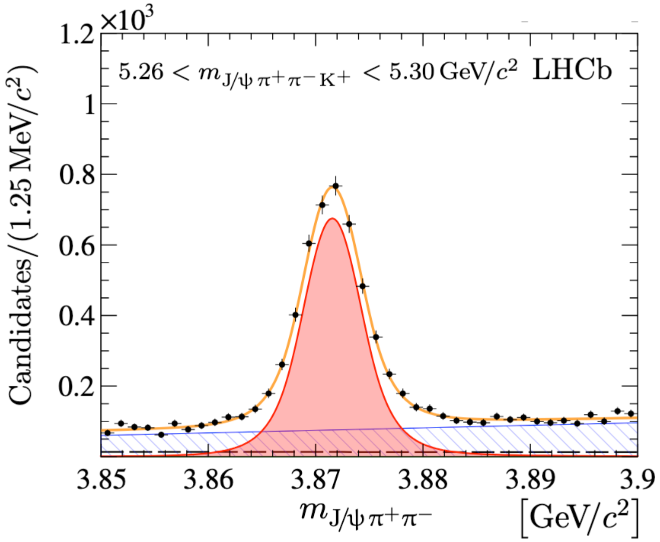


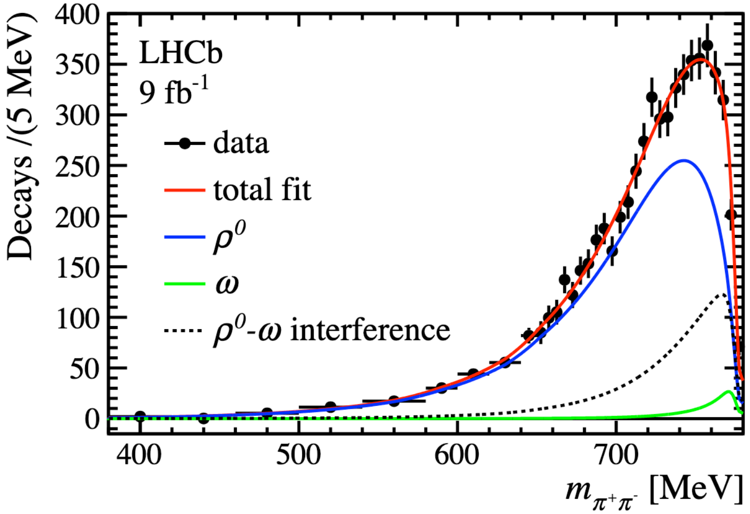


LHCb:

$B^+ \to K^+[J/\psi\pi^+\pi^-]$

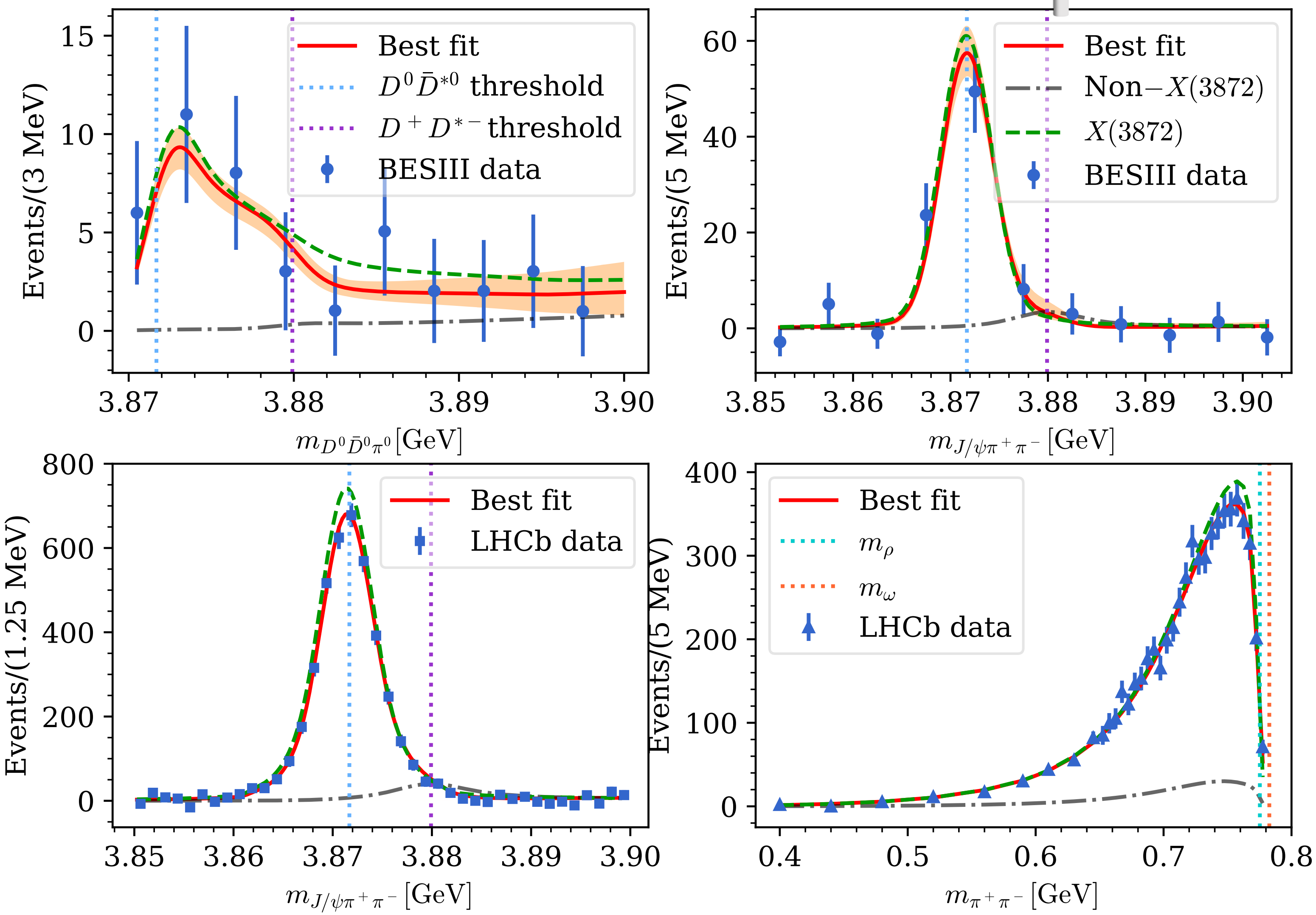
LHCb, JHEP 08 (2020) 123;
PRD 108 (2023) L011103





Combined analysis of BESIII + LHCb data w/ chiral EFT

Results updated

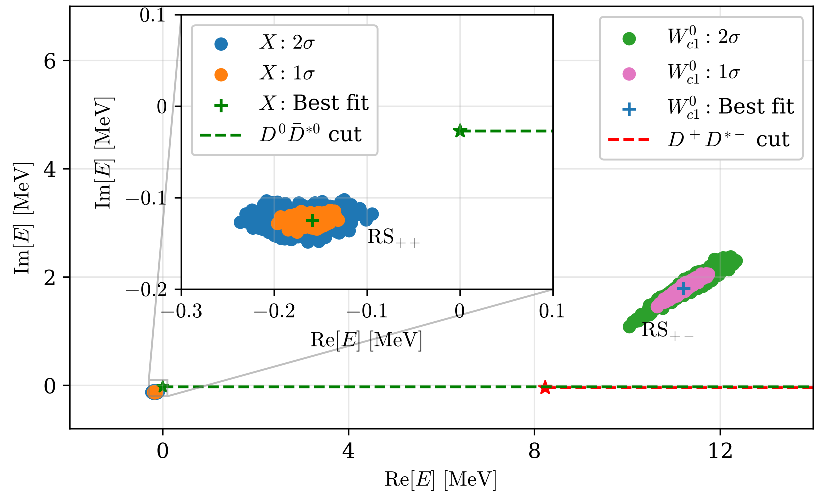


- Poles
  - $X(3872)$ as a bound state below $D^0\bar{D}^{*0}$ threshold (2.8σ)

$$E_X = \left(-160^{+43+38}_{-47-57} - 125^{+18+15}_{-25-28} i\right)\ \text{keV}$$

  - $W_{c1}(3880)^0$ pole on RS_{+-}, relative to the D^+D^{*-} threshold:

$$E_W = \left(3.1 \pm 0.7 + 1.3^{+1.9}_{-0.6} i\right)\ \text{MeV}$$



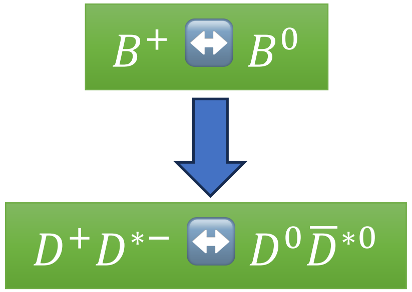
$\chi^2/\text{dof} = 57/(96-10) = 0.66$

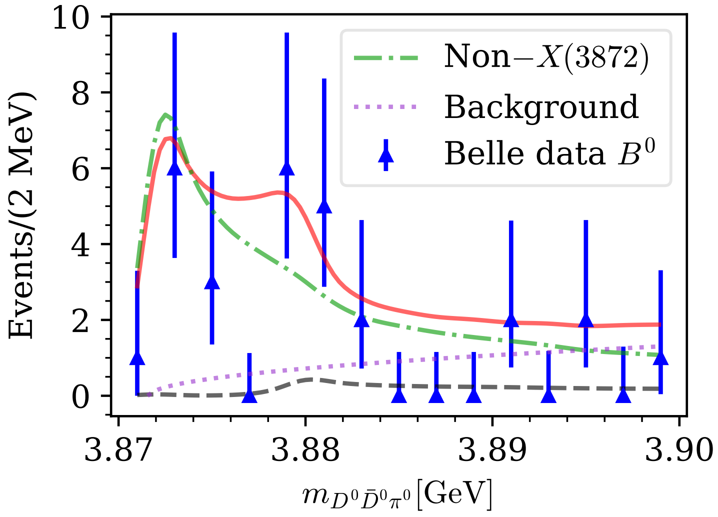
$$X = 1 - \exp\left(\frac{1}{\pi}\int_0^\infty dE \frac{\text{Re}\,\delta(E)}{E - \text{Re}\,E_X}\right) = 0.97(2)$$

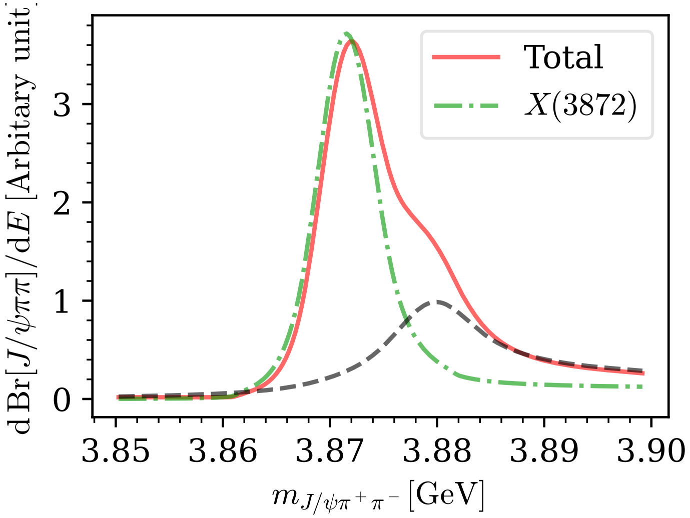
X is predominantly molecular!

Implications of the existence of $W_{c1}(3880)$

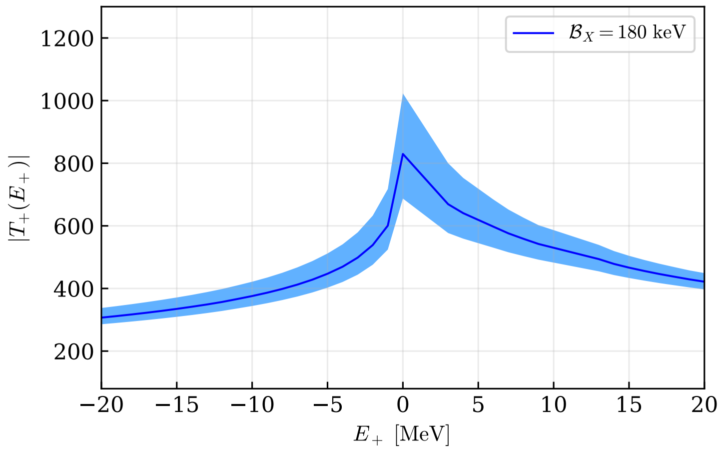
- $W_{c1}(3880)^0$ signal should be stronger in $B^0 \to K^0[D^0\bar{D}^0\pi^0, J/\psi\pi^+\pi^-]$ decays, to be checked @ LHCb, Belle II







- Cusp at $D^+\bar{D}^{*0}/D^{*+}\bar{D}^0$ threshold in $J/\psi\pi^\pm\pi^0$

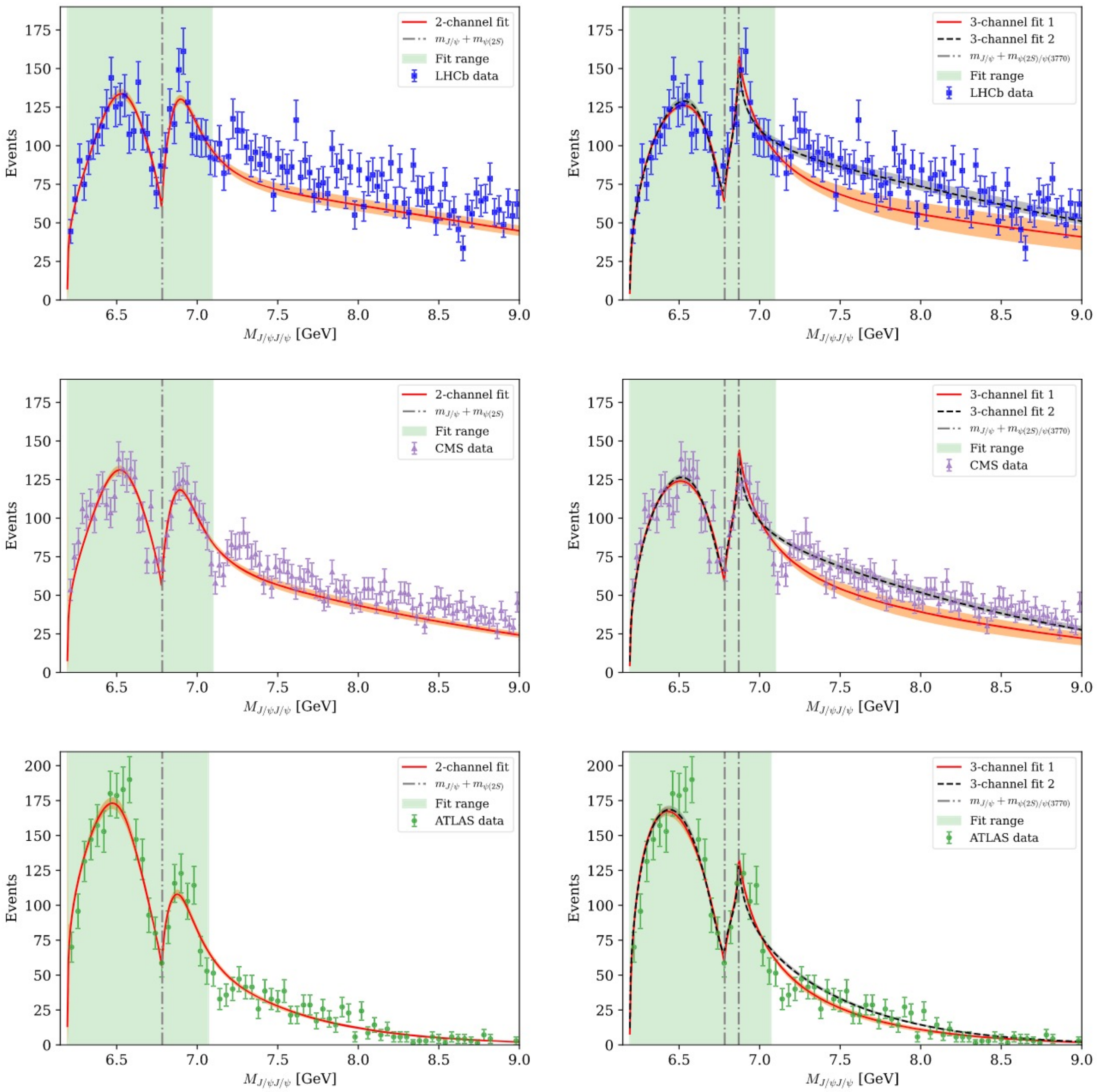


Z.-H. Zhang et al., JHEP 08 (2024) 130

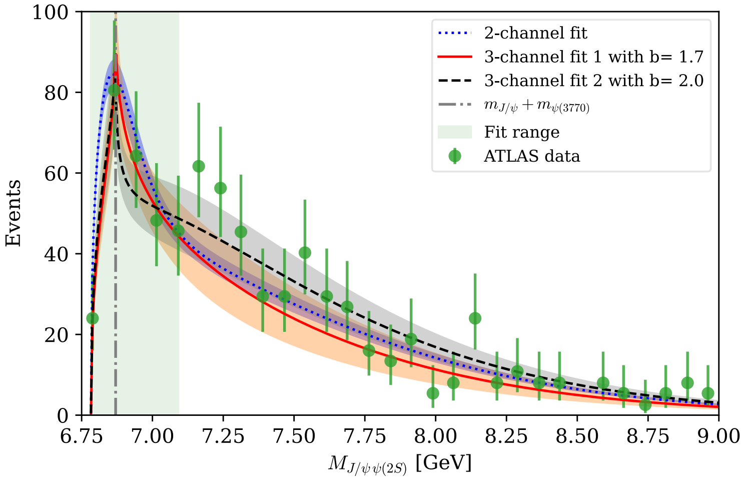
- Compact tetraquarks (Maiani et al. (2005)) cannot be virtual states as they do not feel the thresholds

Structures in double-J/ψ distributions

Y.-L. Song et al., PRD 111 (2025) 034038 [updating analysis from X.-K. Dong et al., PRL 126 (2021) 132001]



- Threshold effects could be important
- Two minimal coupled-channel models:
  - ☐ $J/\psi J/\psi$-$J/\psi\psi'$
  - ☐ $J/\psi J/\psi$-$J/\psi\psi'$-$J/\psi\psi''$



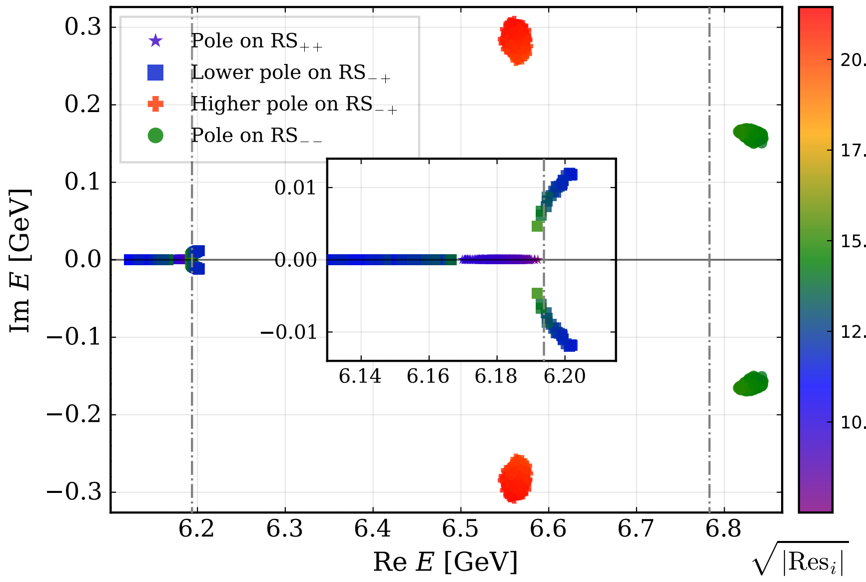
Data:
LHCb, Sci.Bull. 65 (2020) 1983;
CMS, PRL 132 (2024) 111901;
ATLAS, PRL 131 (2023) 151902

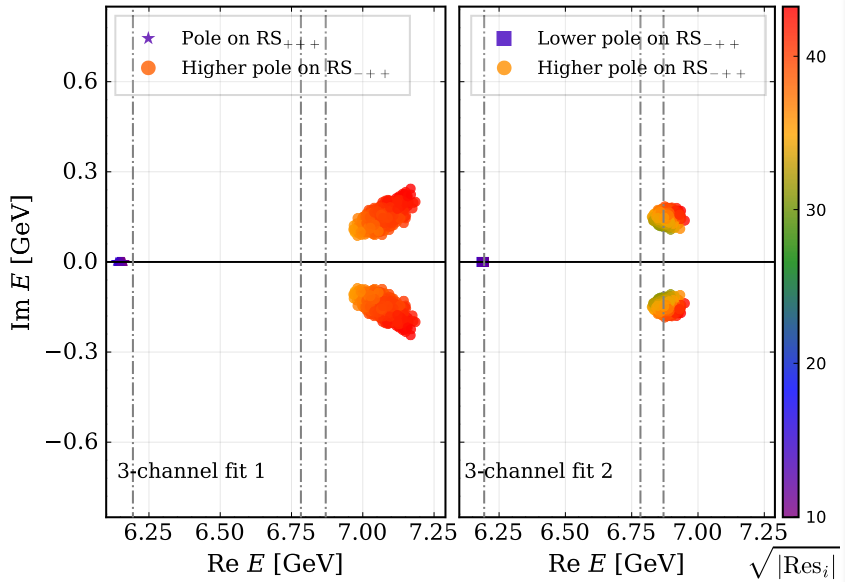
Structures in double-J/ψ distributions

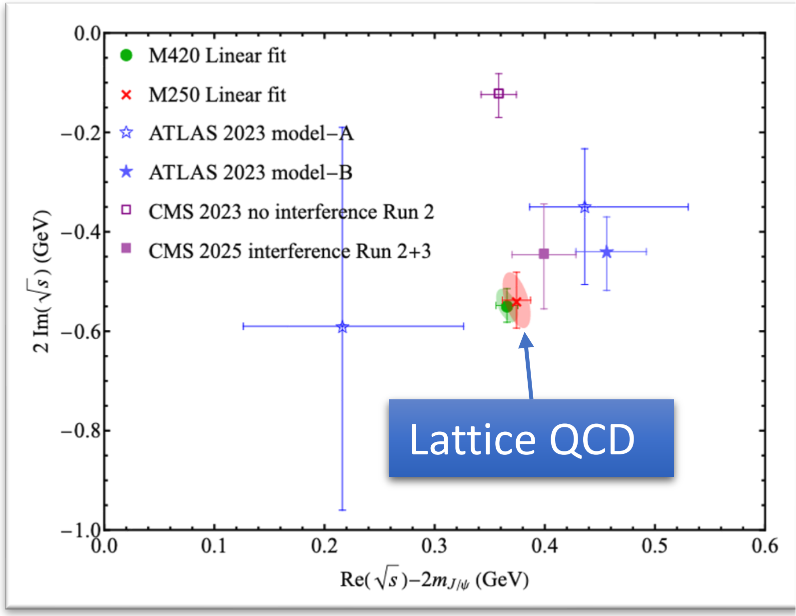
- Pole content (resonances) depend on the amplitude model

Should go beyond summing BWs in amplitude analysis!

- ☐ A pole near 6.2 GeV
- ☐ A pole near 6.9 GeV (location depends on model)
- ☐ The one near 6.6 GeV exists only in the 2-channel model







- Lattice QCD results with $M_\pi \approx 250, 420$ MeV

G. Li, C. Shi, Y. Chen, W. Sun, arXiv:2505.23220; arXiv: 2505.24213

- ☐ A 2^{++} resonance around 6.54 GeV
- ☐ A 0^{++} double-J/ψ virtual state 30-40 MeV below threshold

Summary

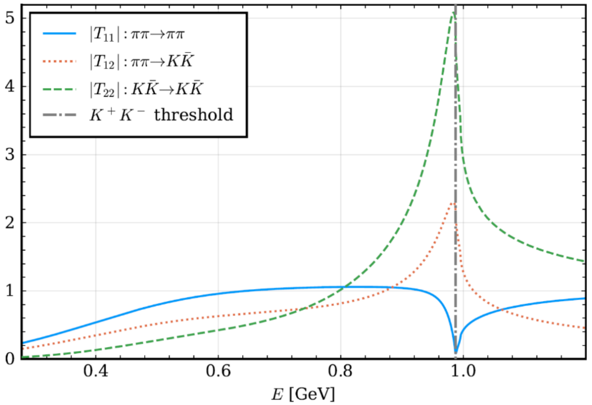
- Multiquark candidates offer the opportunity to gain deep insights into confinement
- General rules for (near-)threshold structures
  - S-wave attraction, more prominent for heavier particles and stronger attraction
  - Pole behavior: distinct line shapes depending on reaction mechanism
  - Universality for the presence of a dip in certain line shapes
- Large number of hadronic molecular candidates
- Amplitude analyses with coupled-channel formalisms
  - Chiral EFT: prediction of an isovector partner of $X(3872)$: $W_{c1}^{\pm,0}$ as virtual states
  - Model: double-J/ψ distributions, full-charm tetraquarks

Thank you for your attention!

Distinct line shapes of the same pole

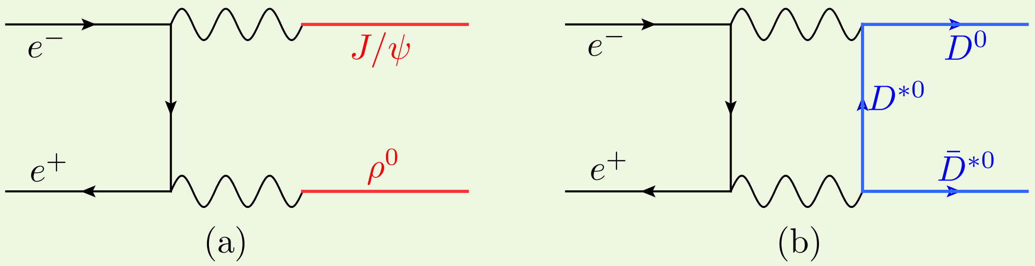
- Example-1: $f_0(980)$
  - T-matrix for $\pi\pi$ and $K\bar{K}$ coupled channels

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



- Example-2: direct production of $X(3872)$ in e^+e^-

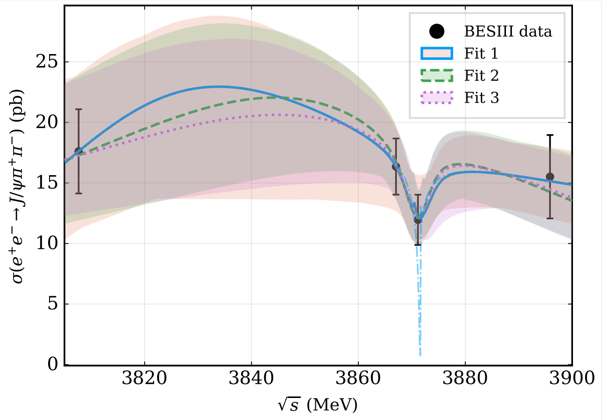
V. Baru, FKG, C. Hanhart, A. Nefediev, PRD 109 (2024) L111501



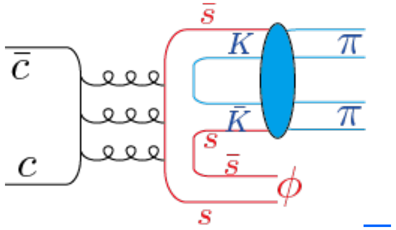
- Driving channel:

  J/ψ +light vector

- Prediction: dip around $D^*\bar{D}^*$ threshold

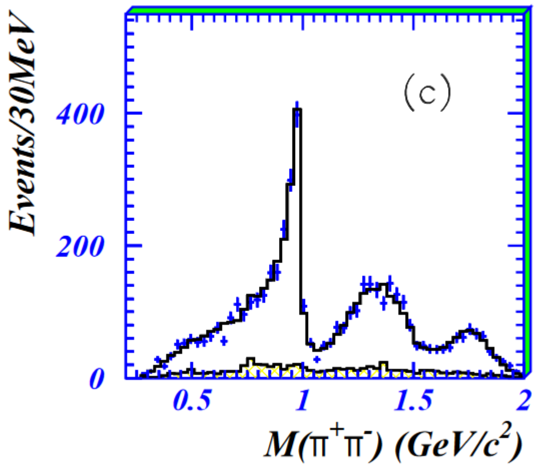


- $J/\psi \to \phi\pi^+\pi^-$



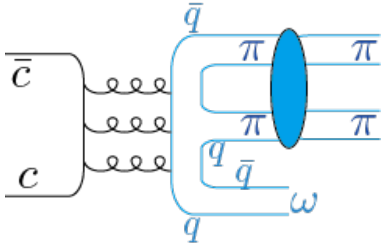
Driving channel: $K\bar{K}$

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



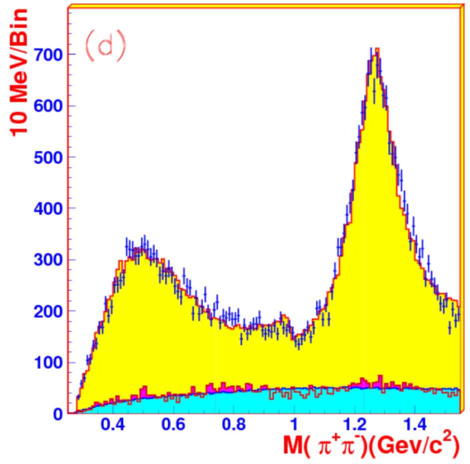
BES, PLB 607 (2005) 243

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



Driving channel: $\pi\pi$

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



BES, PLB 598 (2004) 149

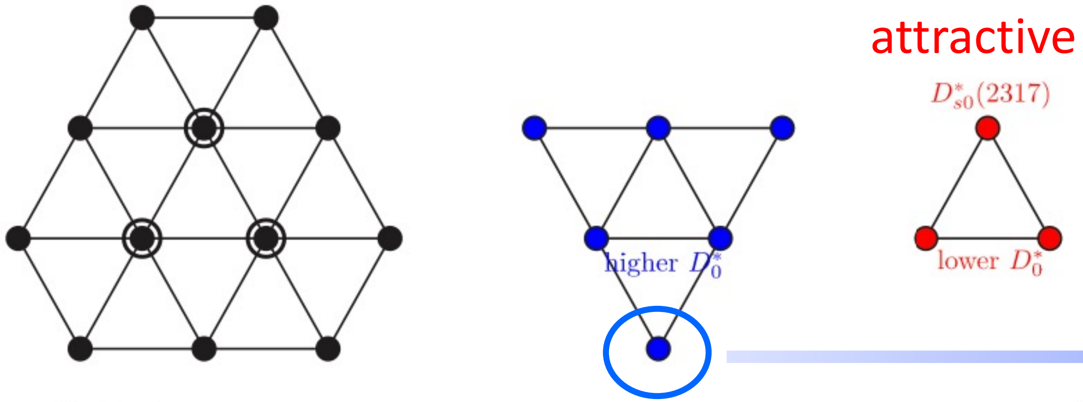
Charm-strange mesons from chiral EFT and lattice QCD

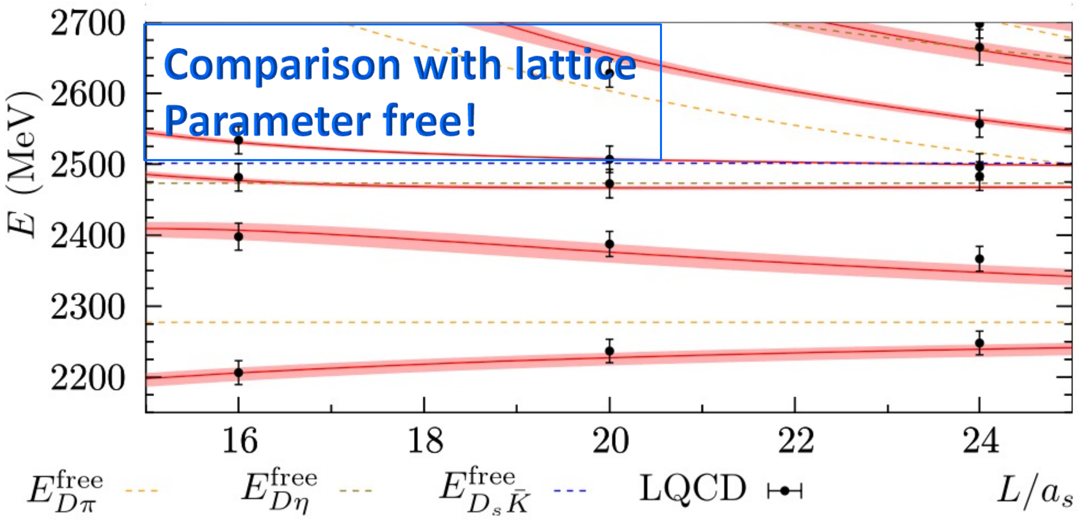
- SU(3) structures differ from quark model!

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

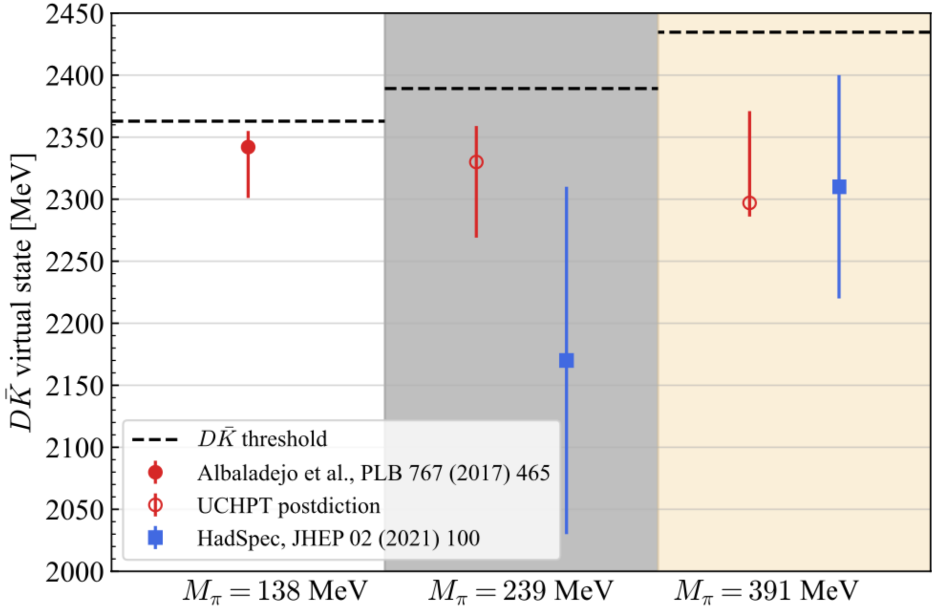
M.Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB 767 (2017) 465

repulsive | attractive | most attractive





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



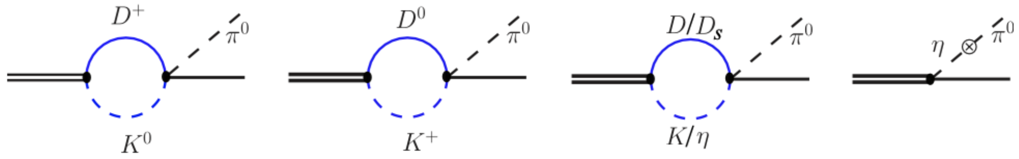
- More supports from lattice & exp. not shown

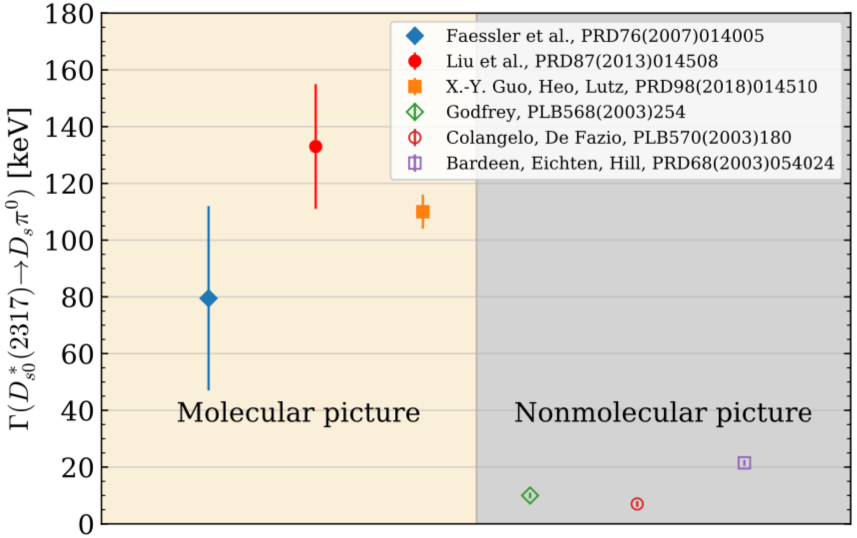
M.-L. Du, FKG, Hanhart, Kubis, Meißner, PRL 126 (2021) 192001; …

- 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

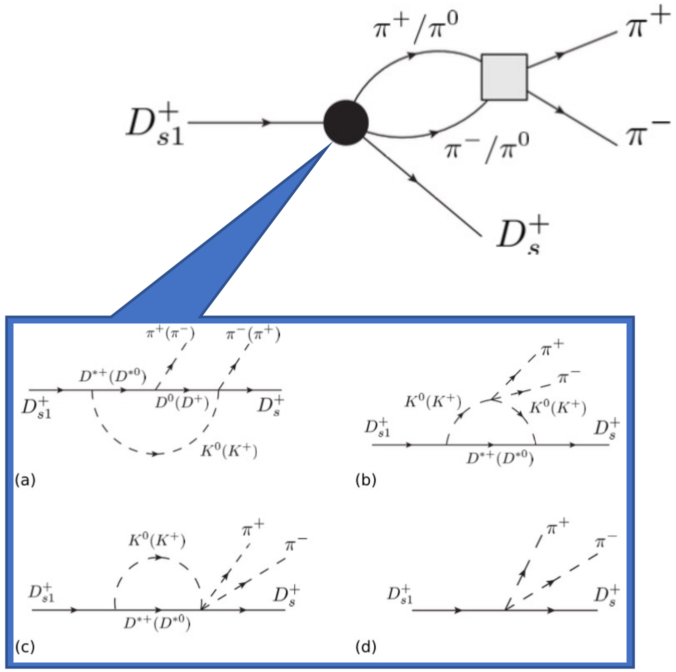


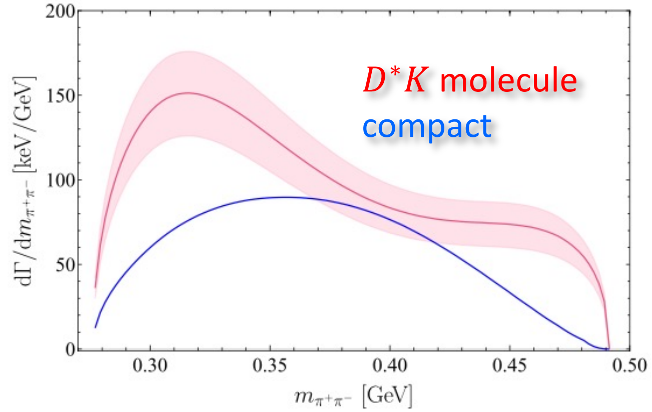


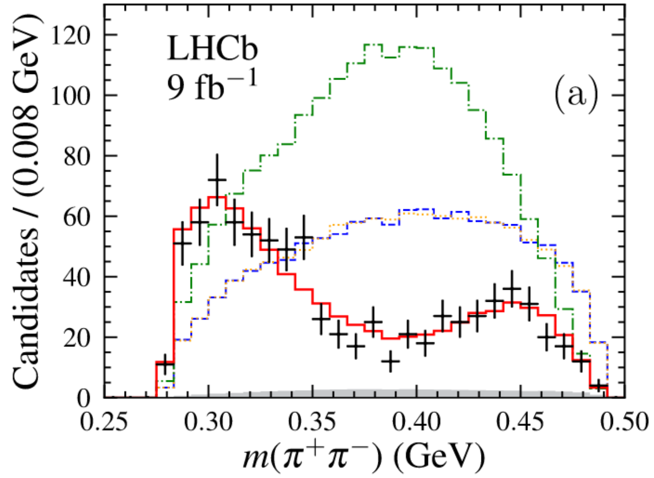
➢ BESIII measured $\text{Br}(D_{s0}^* \to D_s\pi^0) \approx 100\%$ BESIII, PRL 97 (2018) 051103
width still not measured!

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

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







double-bump seen by LHCb,
Sci.Bull. 70 (2025) 3219

Universality of kaonic interaction with isospin-1/2 matter fields
⇒ a whole family of kaonic bound states!
✓ $\Lambda(1405)$, K-nucleus bound states, …

Molecular line shapes at LO

- Scattering length approx.: $p\cot\delta = -\frac{1}{a} + \cdots$
- Poles: bound or virtual state ($\kappa = 1/|a|$)
  - ☐ Bound and virtual state can hardly be distinguished above threshold ($E > 0$)

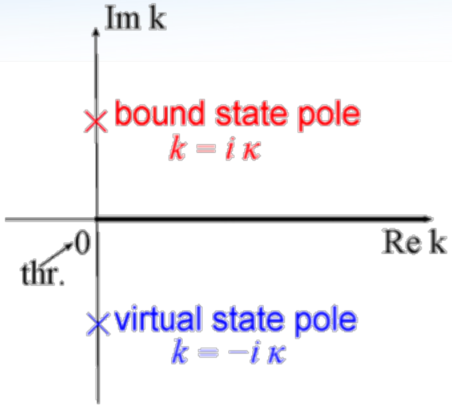
$$|T_{\rm NR}(E)|^2 \propto \left|\frac{1}{\pm\kappa + i\sqrt{2\mu E}}\right|^2 = \frac{1}{\kappa^2 + 2\mu E}$$

  - ☐ Different below threshold ($E < 0$)
    - ➢ bound state: peaked below threshold

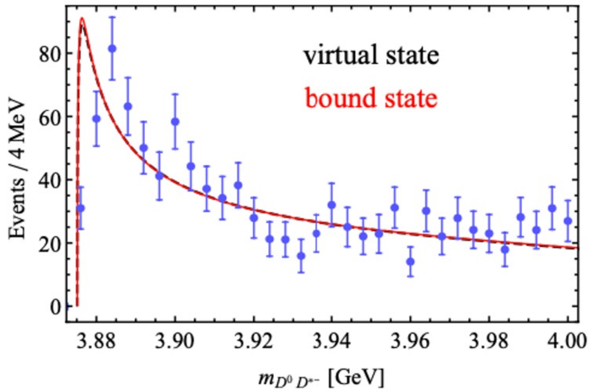
$$|T_{\rm NR}(E)|^2 \propto \frac{1}{(\kappa - \sqrt{-2\mu E})^2}$$

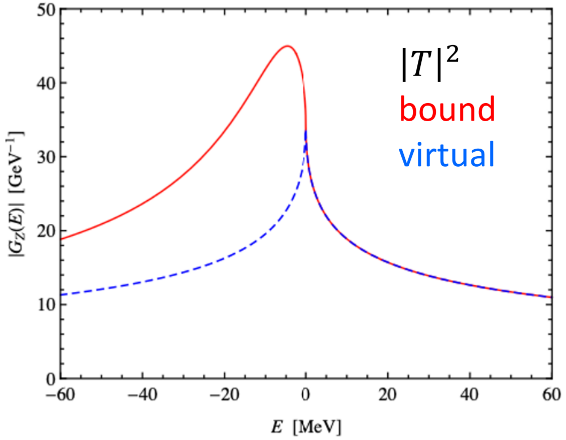
    - ➢ virtual state: sharp cusp at threshold

$$|T_{\rm NR}(E)|^2 \propto \frac{1}{(\kappa + \sqrt{-2\mu E})^2}$$

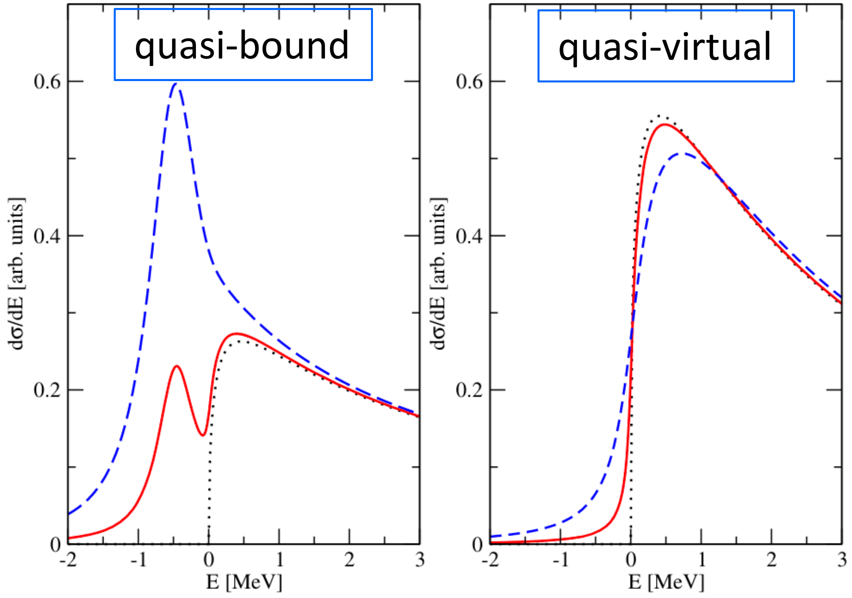


FKG, et al., RMP 90 (2018) 015004;
N. Brambilla et al., Phys.Rept. 873 (2020) 1





line shapes w/ phase space;
one unstable constituent:



$\Gamma = 0$	0.1 MeV	1 MeV
dotted	dashed	solid

Other properties of X(3872)

Teng Ji, X.-K. Dong, FKG, C. Hanhart, U.-G. Meißner, arXiv:2502.04458

- Width (twice of the imaginary part of the pole): 250^{+36+30}_{-50-56} keV
  - Branching fractions computed using the method in L.A. Heuser, G. Chanturia, FKG, C. Hanhart, M. Hoferichter, B. Kubis, EPJC 84 (2024) 599

Mode	$D^0\bar{D}^0\pi^0$	$D^0\bar{D}^0\gamma$	$J/\psi\pi^+\pi^-$	$J/\psi\pi^+\pi^-\pi^0$	others
BR(%)	41^{+3}_{-4}	22 ± 2	5^{+2}_{-1}	16^{+4}_{-3}	16 ± 2

- Isospin breaking ratio $R_X \equiv \left|\frac{g_{XJ/\psi\rho}}{g_{XJ/\psi\omega}}\right| = 0.26(2)$

Results updated