LHCb meets Theory: Probing the nature of the $X(3872)$ state using radiative decays

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17/1-007 (CERN)

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Predicting isovector charmonium-like states from X(3872) properties

Feng-Kun Guo

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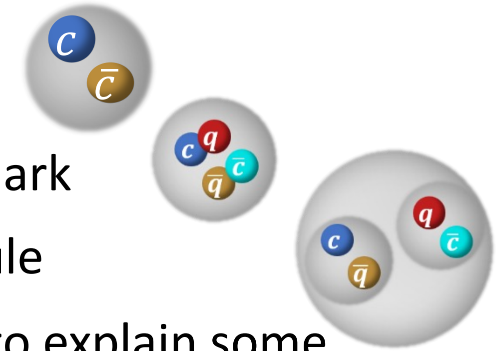
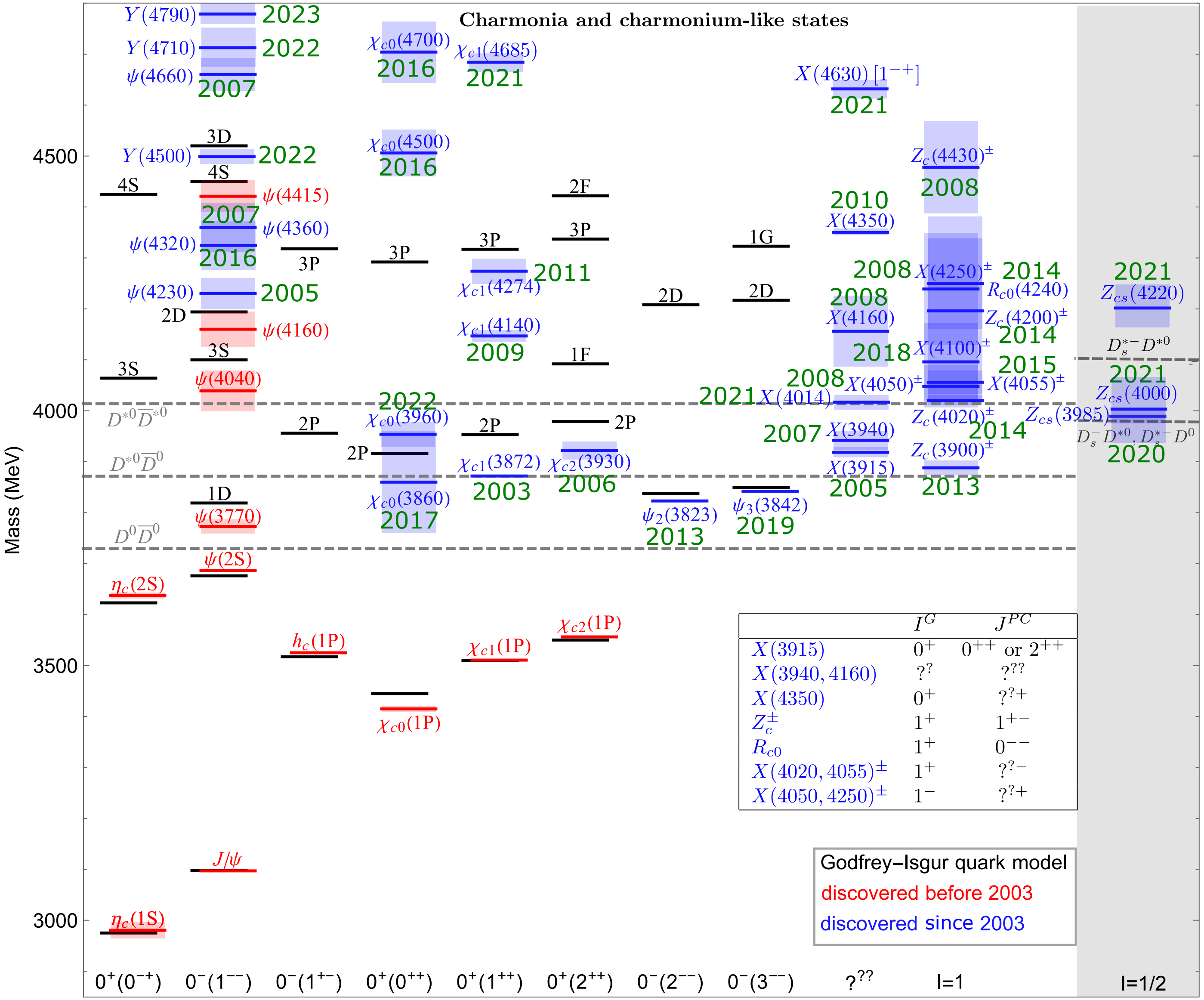
Zhen-Hua Zhang, Teng Ji, Xiang-Kun Dong, FKG, C. Hanhart, U.-G. Meißner, A. Rusetsky, arXiv:2404.11215

$X(3872)$: debates forever?

- X(3872): the first XYZ state   Belle (2003)
- Models
  - Charmonium
  - Compact tetraquark
  - Hadronic molecule



- Each model claims to explain some experimental measurements
- Warnings
  - All components can mix as a fact of nonperturbative QCD
  - Subleading component can be crucial in certain processes
- What are we (am I) talking about?
  - Dominant component for formation/static properties



For more discussions, see talk by Alexey

One excellent observable

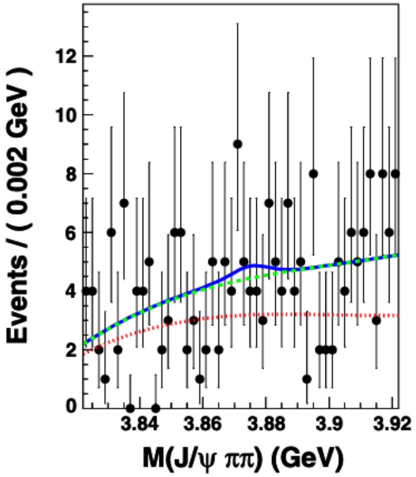
- Isospin-1 partners!
  - No, in charmonium model
  - Quark bound states, in compact tetraquark model L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRD 71 (2005) 014028
    - With isospin-independent quark interactions, isoscalar and isovector tetraquarks must coexist

$$I = 1 \text{ multiplet: } [cu][\bar{c}\bar{d}],\ \frac{1}{\sqrt{2}}([cu][\bar{c}\bar{u}] - [cu][\bar{c}\bar{d}]),\ [cd][\bar{c}\bar{u}]$$

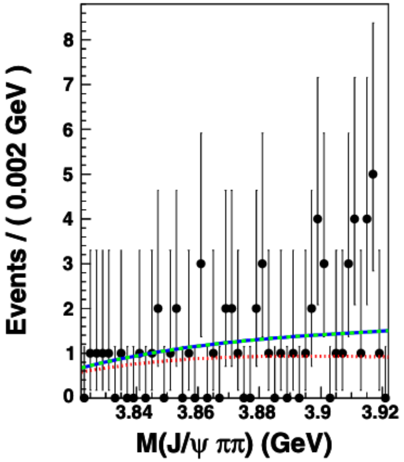
  - How about hadronic molecular model?
- $I = 1, J^{PC} = 1^{++}$ states will be called W_{c1}, following the notation by Voloshin M. Voloshin, PRD 84 (2011) 031502

So far negative signal

- No signal in the charged channel so far



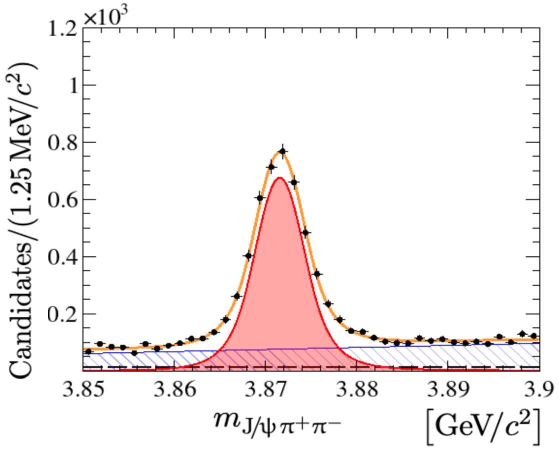
$\bar{B}^0 \to K^- \pi^+ \pi^0 J/\psi$



$B^+ \to K^0 \pi^+ \pi^0 J/\psi$

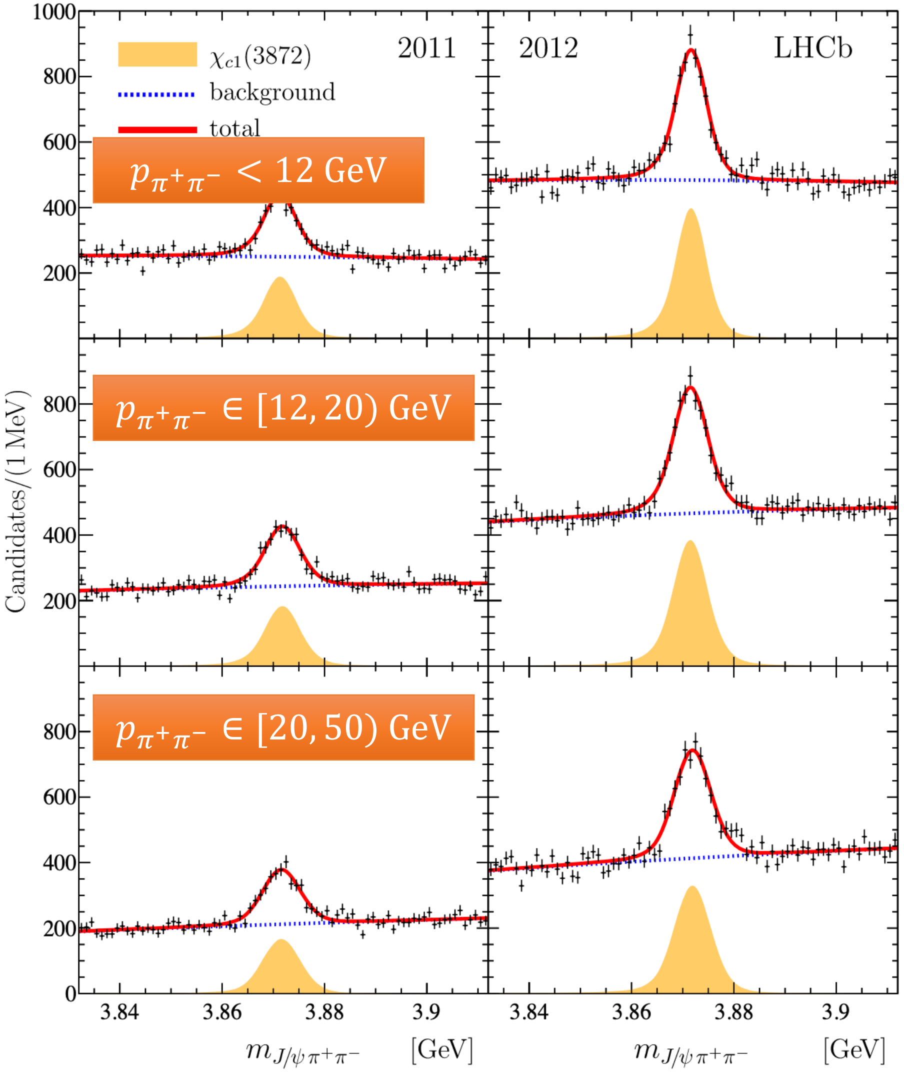
Belle, PRD 84 (2011) 052004

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



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

LHCb, JHEP 08 (2020) 123

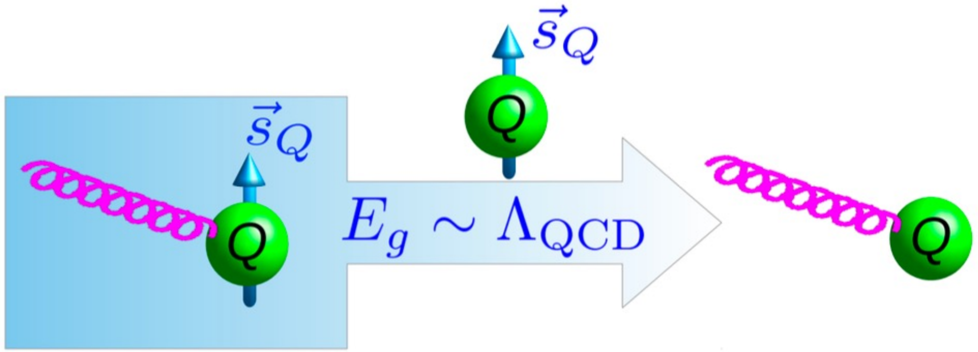


$\pi^+ \pi^- J/\psi$ from b-hadrons

LHCb, PRD 102 (2020) 092005

HQSS for hadronic molecules

- Heavy quark spin symmetry (HQSS)
  - In the heavy quark limit, heavy quark spin decouples
  - Good quantum number s_ℓ: light quark spin + orbital AM



- Consider S-wave interaction between a pair of $s_\ell^P = \frac{1}{2}^-$ (anti-)heavy mesons:

$$0^{++}: \quad D\bar{D}, \quad D^*\bar{D}^*$$

$$1^{+-}: \quad \frac{1}{\sqrt{2}}\left(D\bar{D}^* + D^*\bar{D}\right), \quad D^*\bar{D}^*$$

$$1^{++}: \quad \frac{1}{\sqrt{2}}\left(D\bar{D}^* - D^*\bar{D}\right); \qquad 2^{++}: \quad D^*\bar{D}^*$$

here, phase convention: $D \stackrel{C}{\to} +\bar{D},\ D^* \stackrel{C}{\to} -\bar{D}^*$

HQSS for hadronic molecules

- For the HQSS consequences, convenient to use the basis of states: $s_L^{PC} \otimes s_{c\bar{c}}^{PC}$
  - ☞ S-wave: $s_L^{PC}, s_{c\bar{c}}^{PC} = 0^{-+}$ or 1^{--}
  - ☞ multiplet with $s_L = 0$:

$$0_L^{-+} \otimes 0_{c\bar{c}}^{-+} = 0^{++}, \qquad 0_L^{-+} \otimes 1_{c\bar{c}}^{--} = 1^{+-}$$

Two parameters at LO for each isospin!

  - ☞ multiplet with $s_L = 1$:

$$1_L^{--} \otimes 0_{c\bar{c}}^{-+} = 1^{+-}, \qquad 1_L^{--} \otimes 1_{c\bar{c}}^{--} = 0^{++} \oplus \boxed{1^{++}} \oplus 2^{++}$$

- Multiplets in strict heavy quark limit:
  - ☞ $X(3872)$ has three partners with 0^{++}, 2^{++} and 1^{+-}

Hidalgo-Duque et al., PLB 727 (2013) 432; Baru et al., PLB 763 (2016) 20

  - ☞ Z_b, Z_b' as $B^{(*)}\bar{B}^*$ molecules would imply 6 $I = 1$ hadronic molecules:
    $Z_b[1^{+-}], Z_b'[1^{+-}]$ and $W_{b0}[0^{++}], W_{b0}'[0^{++}], W_{b1}[1^{++}]$ and $W_{b2}[2^{++}]$

Bondar et al., PRD 84 (2011) 054010; Voloshin, PRD 84 (2011) 031502; Mehen, Powell, PRD 84 (2011) 114013

$J^{PC} = 1^{++}$ sector

- For each isospin, only two low-energy constants (LECs) at LO for S-wave interactions of 6 meson pairs
- For the $J^{PC} = 1^{++}$ sector, also two LECs at LO:
  - $I = 0$: C_{0X}
  - $I = 1$: C_{1X}

- 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

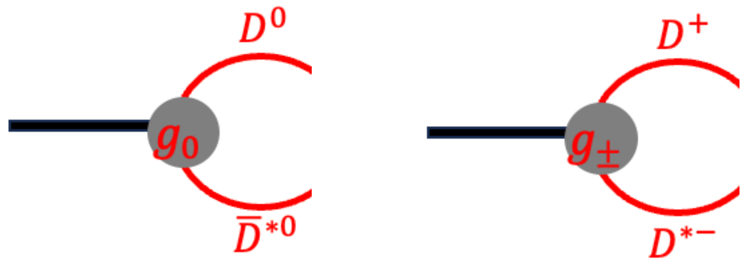
    $$R_X = \left|\frac{\mathcal{M}_{X(3872)\to J/\psi\rho^0}}{\mathcal{M}_{X(3872)\to J/\psi\omega}}\right| = 0.29 \pm 0.04$$

- Neutral systems X and W_{c1}^0: coupled channels
  - ✓ $(D\bar{D}^*)_0 \equiv (D^0\bar{D}^{*0} - \bar{D}^0 D^{*0})/\sqrt{2}$
  - ✓ $(D\bar{D}^*)_\pm \equiv (D^+D^{*-} - D^-D^{*+})/\sqrt{2}$
- Charged systems $W_{c1}^\pm$: single channel

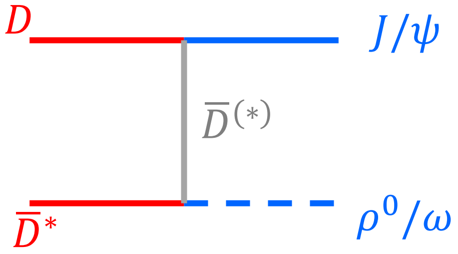
Decays of $X \to J/\psi V$

- In the hadronic molecular model, decays of $X \to J/\psi\rho^0$ and $X \to J/\psi\omega$ contain both long-distance and short-distance parts $\mathcal{B}_X \equiv M_{D^0} + M_{D^{*0}} - M_{X(3872)}$

Long-distance: momentum scale $\sqrt{2\mu\mathcal{B}_X}$

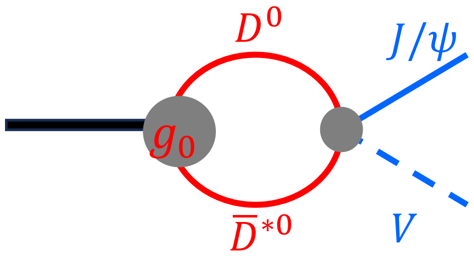


Short-distance: momentum scale $\sqrt{2\mu(2m_D - m_\psi)}$



- Factorization

E. Braaten, M. Kusunoki, PRD 72 (2005) 014012; N. Li, S.-L. Zhu, PRD 86 (2012) 074022

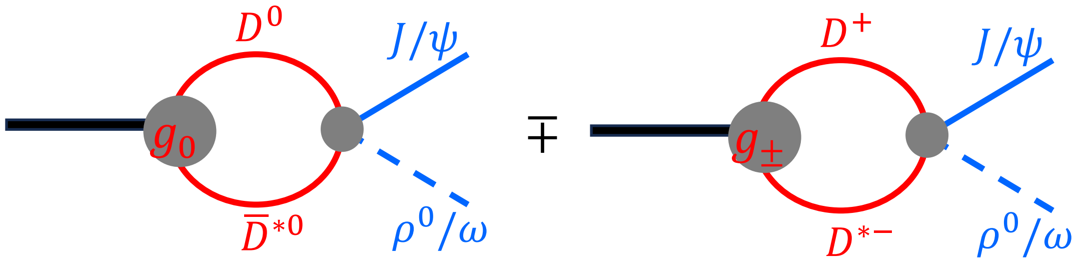


$$= g_0\, G_0\, g_{D\bar{D}^*\to J/\psi V} = g_0 \underbrace{\left(-\frac{\mu\Lambda}{\pi^2} + i\frac{\mu}{2\pi}p\right) g_{D\bar{D}^*\to J/\psi V}}_{\mathcal{M}^{\text{s.d.}}_{[D\bar{D}^*\to J/\psi V]}}$$

higher order

Lippmann-Schwinger equation (LSE)

- Relation between the isospin breaking ratio and the ratio of couplings of X to $(D\bar{D}^*)_0$ and $(D\bar{D}^*)_\pm$



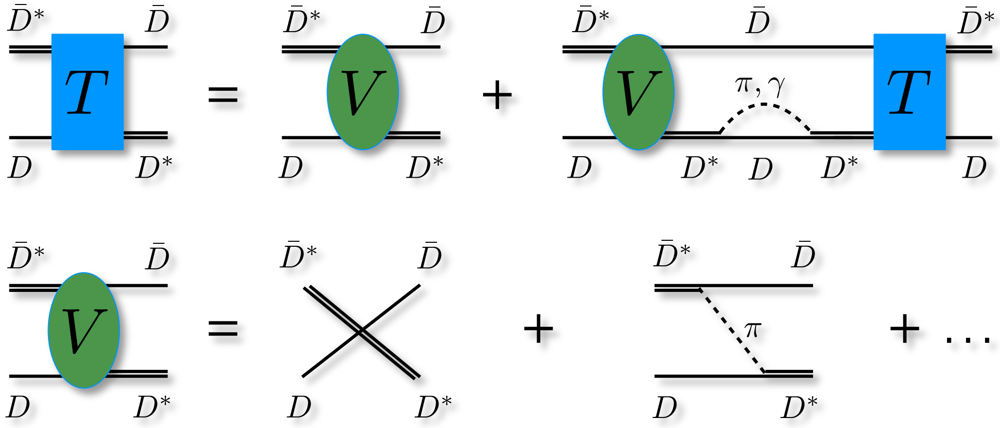
$$R_X = \left|\frac{\mathcal{M}_{X(3872)\to J/\psi\rho^0}}{\mathcal{M}_{X(3872)\to J/\psi\omega}}\right| = 0.29 \pm 0.04 = \left|\frac{g_0 - g_\pm}{g_0 + g_\pm}\right|$$

- Couplings g_0 and $g_\pm$: residues of the $(D\bar{D}^*)_0 - (D\bar{D}^*)_\pm$ coupled-channel T matrix elements at the $X(3872)$ pole
- T matrix is given by the LSE:

$$T(E;p',p) = V(E;p',p) + \int \frac{l^2 dl}{2\pi^2} V(E;p',l)G(E;l)T(E;l;p)$$

Potential: contact term (C_{0X}, C_{1X}) + one-pion exchange (OPE)

$$V_{\rm ct} = \frac{1}{2}\begin{pmatrix} C_{0X}+C_{1X} & C_{0X}-C_{1X} \\ C_{0X}-C_{1X} & C_{0X}+C_{1X} \end{pmatrix}$$



Determination of LECs

Z.-H. Zhang, T. Ji, X.-K. Dong, FKG, C. Hanhart, U.-G. Meißner, A. Rusetsky, arXiv:2404.11215

- $D^0\bar{D}^{*0}, D^+D^{*-}$ coupled channels: $I = 0, 1$
  - Interactions at leading order: two LECs ($I = 0, 1$) C_{0X}, C_{1X}
  - Two inputs from $X(3872)$ properties

> Mass ⇒ real part of the X pole
>
> $M_X = 3871.69^{+0.00+0.05}_{-0.04-0.13}\,\text{MeV}$ LHCb, PRD 102 (2020) 092005
>
> $M_{D^0} + M_{D^{*0}} = 3871.69(7)$ MeV PDG 2024
>
> Isospin breaking in decays LHCb, PRD 108 (2023) L011103
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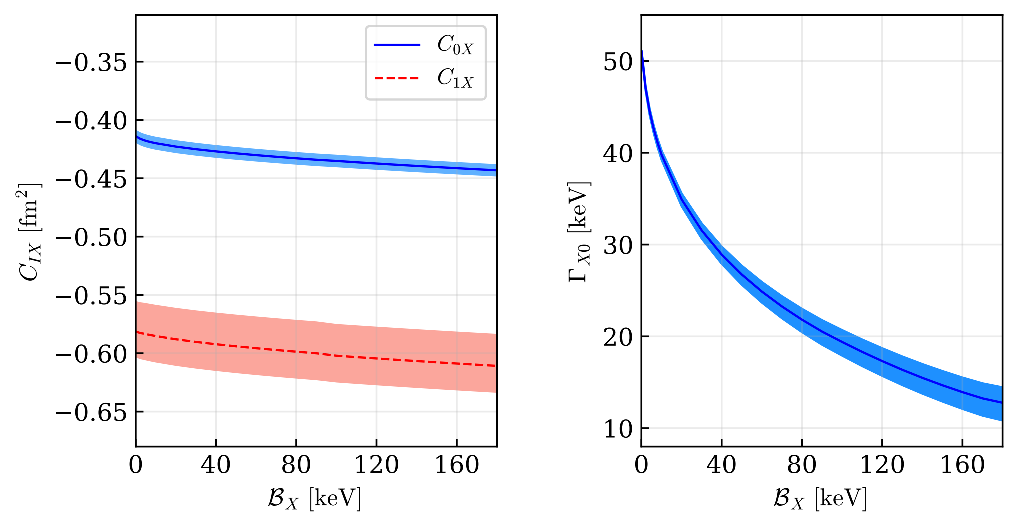
> $$R_X = \left|\frac{\mathcal{M}_{X(3872)\to J/\psi\rho^0}}{\mathcal{M}_{X(3872)\to J/\psi\omega}}\right| = 0.29 \pm 0.04 = \left|\frac{g_0 - g_\pm}{g_0 + g_\pm}\right|$$
>
> ⇒ ratio of residues
>
> $$R_{\pm/0} \equiv \frac{g_\pm}{g_0} = \lim_{E\to-\mathcal{B}_X-\frac{i\Gamma_{X0}}{2}} \frac{T_{21}(E)}{T_{11}(E)} = 0.55 \pm 0.05$$

- Search for poles, compute residues
- LECs ($\Lambda = 0.6$ GeV)



Open-charm partial width of $X(3872)$ from the $D\bar{D}\pi$ and $D\bar{D}\gamma$ modes from the D^* decays

Prediction of an isospin vector partner of $X(3872)$

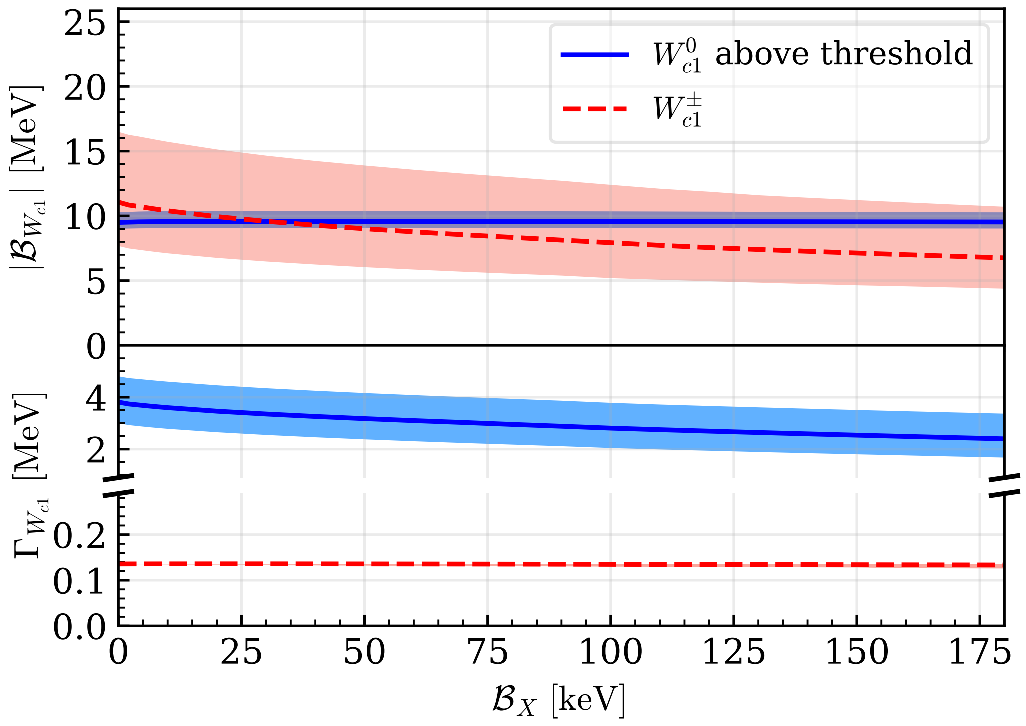
Z.-H. Zhang, T. Ji, X.-K. Dong, FKG, C. Hanhart, U.-G. Meißner, A. Rusetsky, arXiv:2404.11215

- There must be near-threshold isovector W_{c1} states
  - Virtual state pole in the stable D^* limit
    - W_{c1}^{+} in $D^+\bar{D}^{*0}$ single-channel scattering amplitude: pole on the 2nd Riemann sheet (RS), 8^{+8}_{-5} MeV below $D^0 D^{*-}$ threshold

$$W_{c1}^{\pm}: \quad 3866.9^{+4.6}_{-7.7} - i(0.07 \pm 0.01)\ \text{MeV}$$

    - W_{c1}^{0} in $(D\bar{D}^*)_0 - (D\bar{D}^*)_\pm$ scattering amplitudes: pole on the 4th RS (RS_{+-}), $1.3^{+0.8}_{-0.0}$ MeV above D^+D^{*-} threshold

$$W_{c1}^{0}: \quad 3881.2^{+0.8}_{-0.0} + i1.6^{+0.7}_{-0.9}\ \text{MeV}$$



Cutoff independence checked: pole positions relative to thresholds changed within 5% for $\Lambda \in [0.5, 1.0]$ GeV

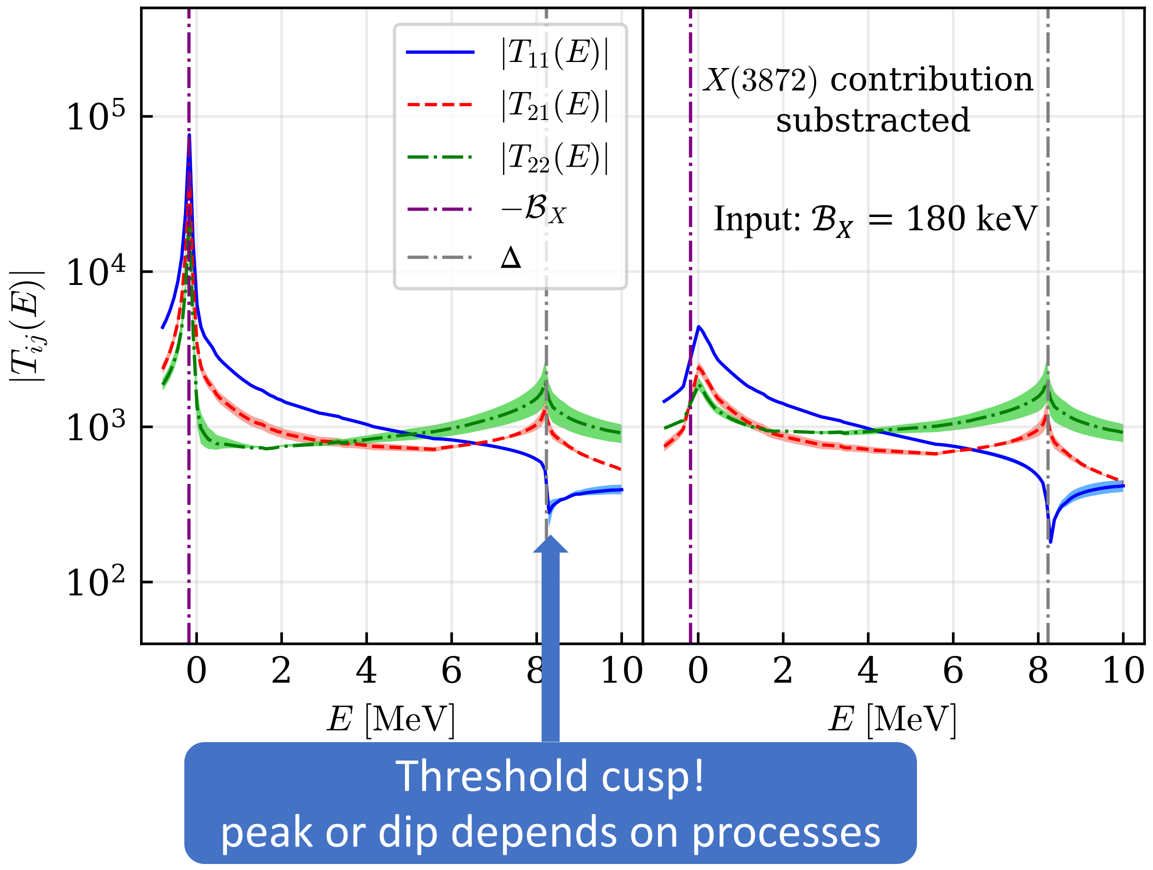
  - Must appear as threshold cusps!!!
  - Compact tetraquarks (Maiani et al. (2005)) cannot be virtual states as they do not feel the thresholds

Why have they not been observed?

Z.-H. Zhang, T. Ji, X.-K. Dong, FKG, C. Hanhart, U.-G. Meißner, A. Rusetsky, arXiv:2404.11215

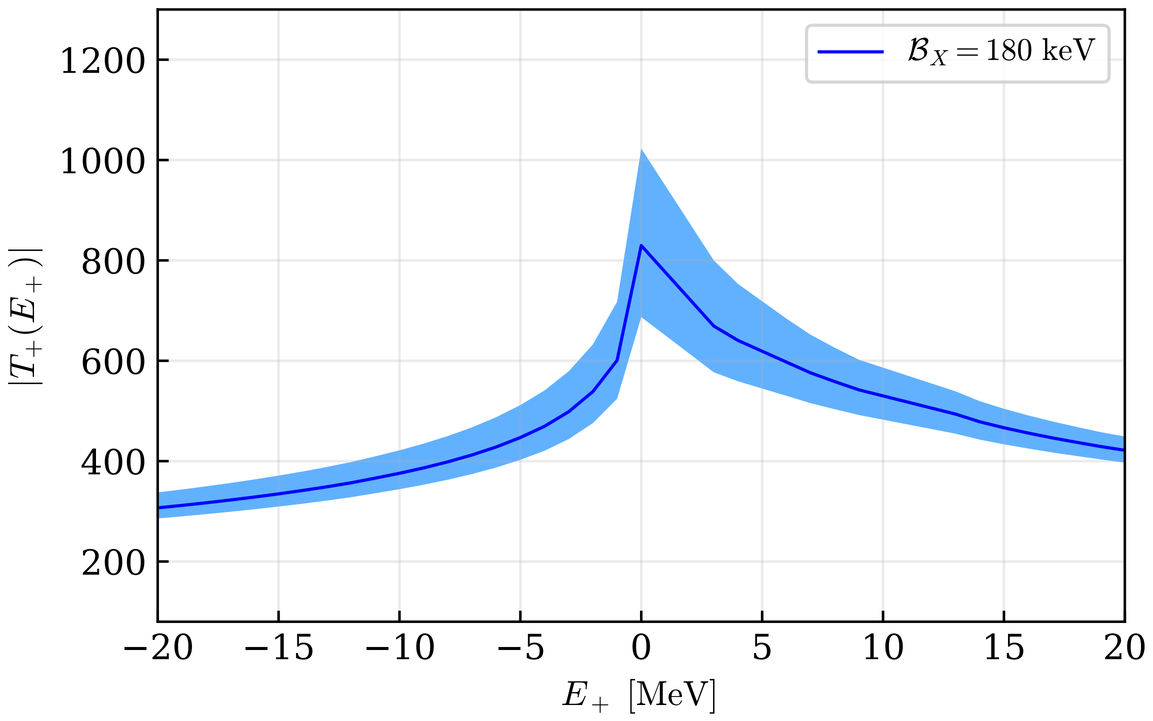
- The observed $X(3872)$ signals should contain the W_{c1}^0 contribution (but marginal) as well
- W_{c1}^0 lives in the same amplitudes as the $X(3872)$, effects shielded by X

➢ W_{c1}^0 in $D^0\bar{D}^{*0} - D^+D^{*-}$ scattering amplitudes



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

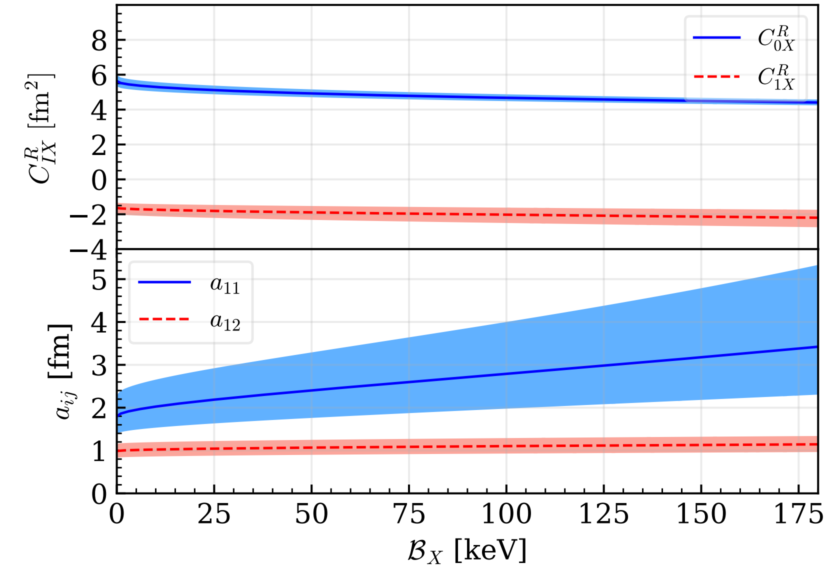
➢ W_{c1}^+ in $D^+\bar{D}^{*0}$ scattering amplitude: height much lower than the X peak

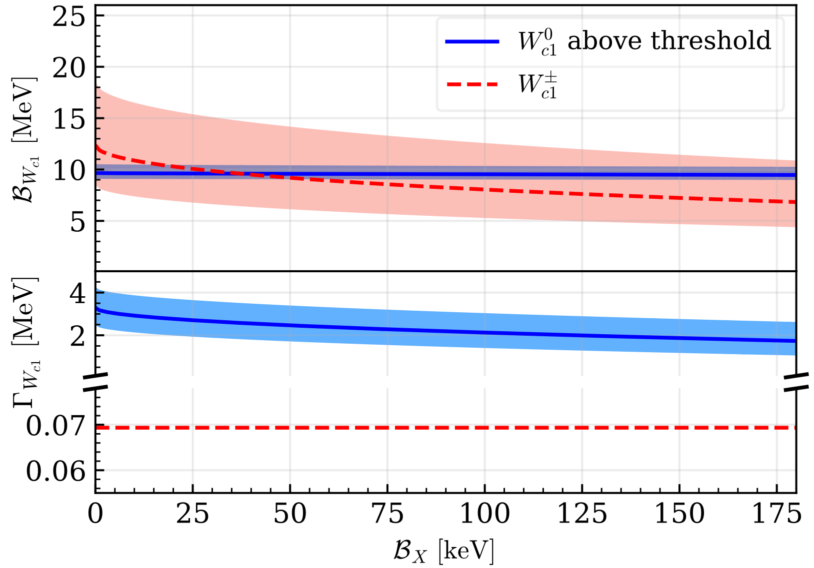


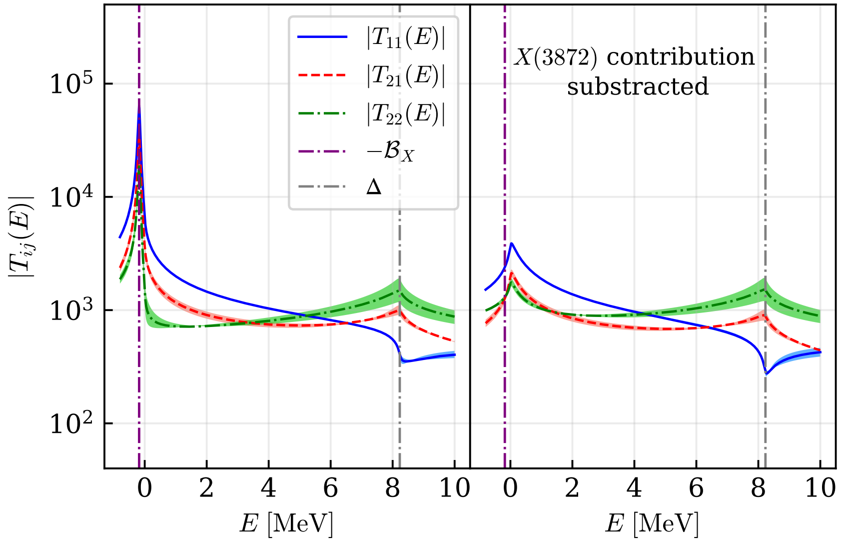
➢ should be searched for in high-statistic $J/\psi\pi^{\pm}\pi^0$ data

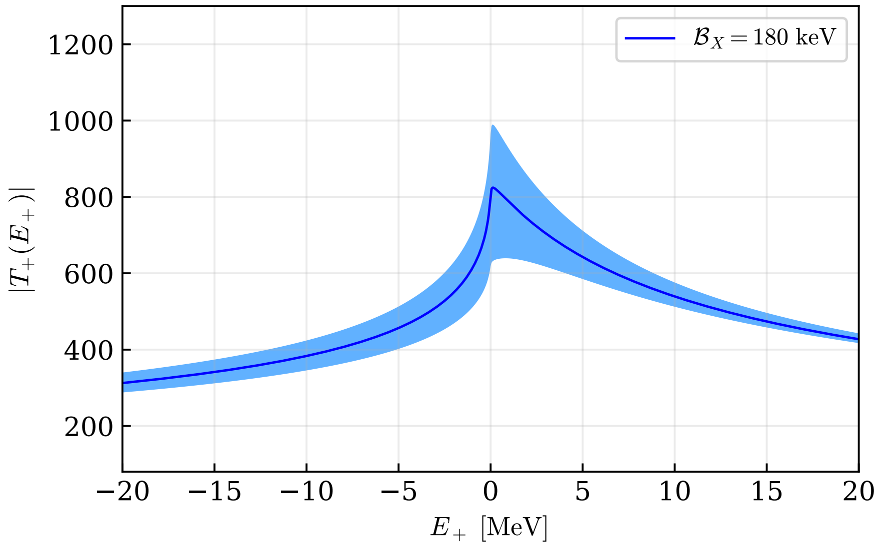
Results in the pionless theory

- All the qualitative features in the pion-full theory persist in the much simpler pionless theory





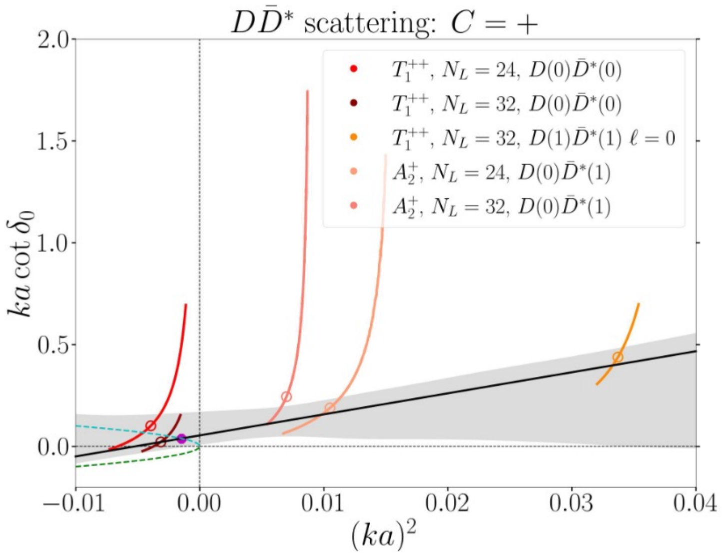


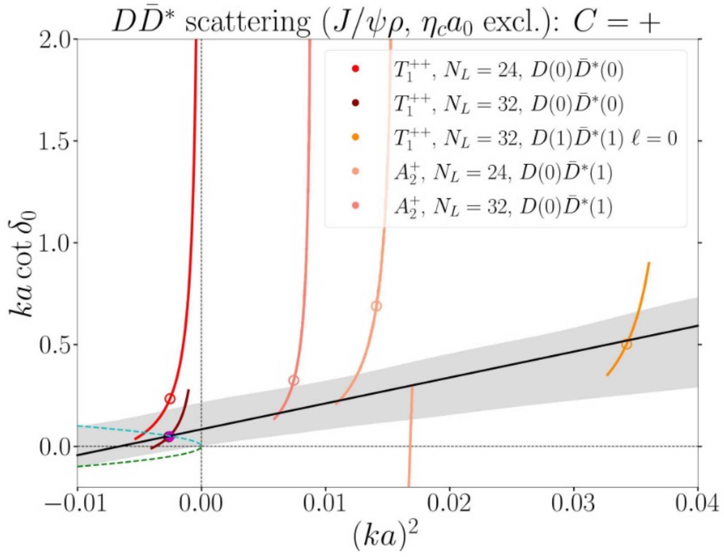


Confirmation from lattice QCD

- The virtual state W_{c1} was confirmed in a very recent lattice QCD calculation with $M_\pi = 280$ MeV

M. Sadl, S. Collins, Z.-H. Guo, M. Padmanath, S. Prelovsek, L.-W. Yan, arXiv:2406.09842 [hep-lat]





J^{PC}	interpolators	$1/a_0$ [fm^{-1}]	r_0 [fm]	$\chi^2/N_{\rm dof}$	$\Delta m_{\rm V}$ [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.

$$\Delta m_{\rm V} = E^{\rm p}_{\rm cm} - m_D - m_{D^*}.$$

versus our prediction: -8^{+5}_{-8} MeV

Summary

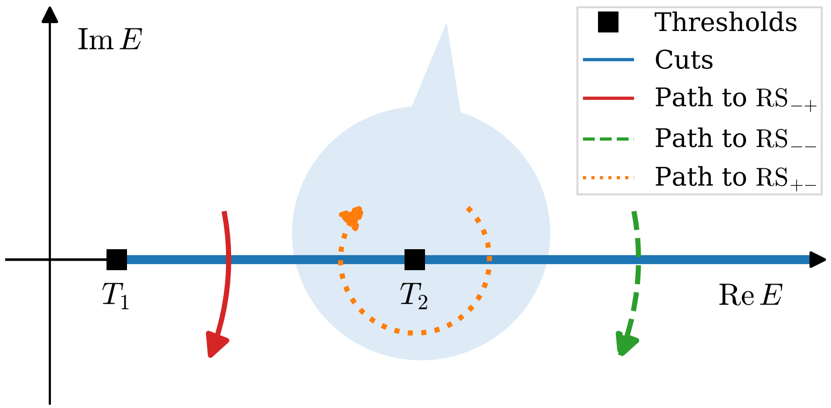
- Robust prediction of an isovector partner of $X(3872)$ in the hadronic molecular picture: $W_{c1}^{\pm,0}$
- Virtual state poles (poles on RSs not directly connected to physical region), thus threshold cusps
  - confirmed in lattice QCD calculation by the group of Prelovsek
- $|T|$ at the D^+D^{*-} and D^0D^{*-} thresholds much smaller than that at the $D^0\bar{D}^{*0}$ threshold (dominated by $X(3872)$), explaining why W_{c1} has not been seen
- HQSS partners in the heavy quark limit:
  - $I=1, J^{PC}=0^{++}(W_{c0}), 2^{++}(W_{c2}), 1^{+-}(Z_c)$

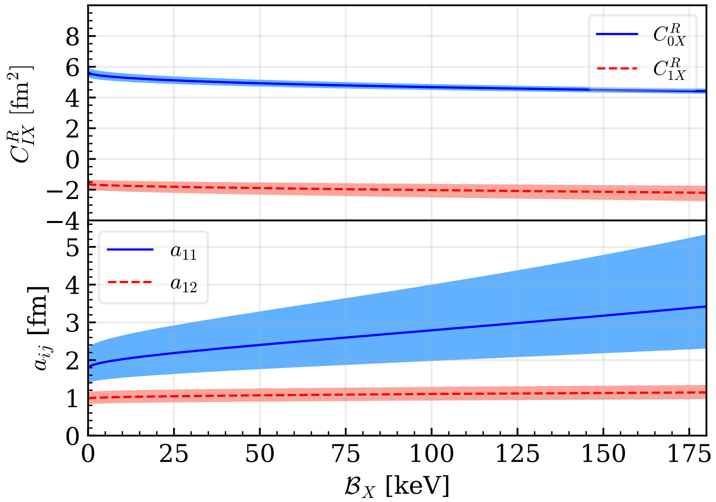
- Search for threshold cusps in high-statistic data
  - at D^0D^{*-} threshold in $J/\psi\pi^\pm\pi^0$: distinguishing hadronic molecular and compact tetraquark models for $X(3872)$
  - at D^+D^{*-} threshold in $J/\psi\pi^+\pi^-$: could be more difficult due to interference between peak and dip

Thank you for your attention!

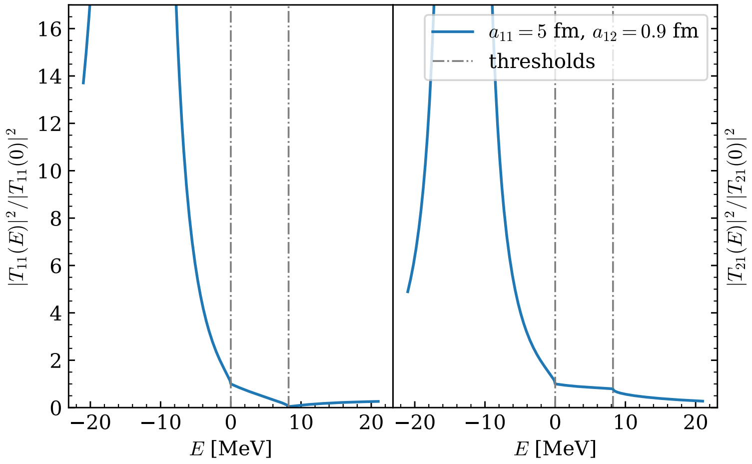
More about the W_{c1}^0 pole

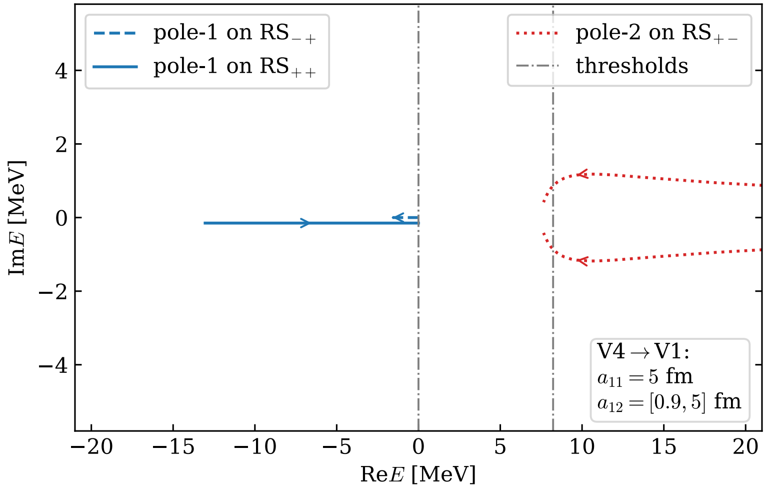
- The pole is on the 4th RS (RS_{+-}) in $(D\bar{D}^*)_0 - (D\bar{D}^*)_\pm$ coupled channels

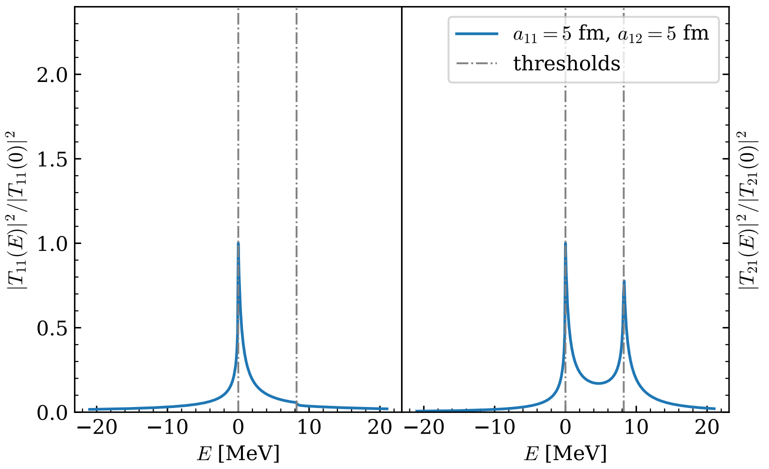




Channel coupling: effective attraction for the lower channel, but repulsion for the higher one







Pole evolution from V4: $a_{11}\delta \gg 1$ & $a_{12}\delta \in (0,1)$

to V1: $a_{11}\delta \gg 1$ & $a_{12}\delta \gg 1$

Z.-H. Zhang, FKG, arXiv:2407.0xxxx;
FKG, talk at STRONG2020 Hadron Spectroscopy (HaSP) General Workshop, 13-16 Sept. 2022