Exotic heavy meson spectroscopy and structure with EIC: Next-level physics and detector simulations

14-18 April 2025, CFNS, Stony Brook University

Exotic heavy quarkonium structure and production from a hadronic perspective

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Zhen-Hua Zhang et al., Predicting isovector charmonium-like states from X(3872) properties, arXiv:2404.11215;

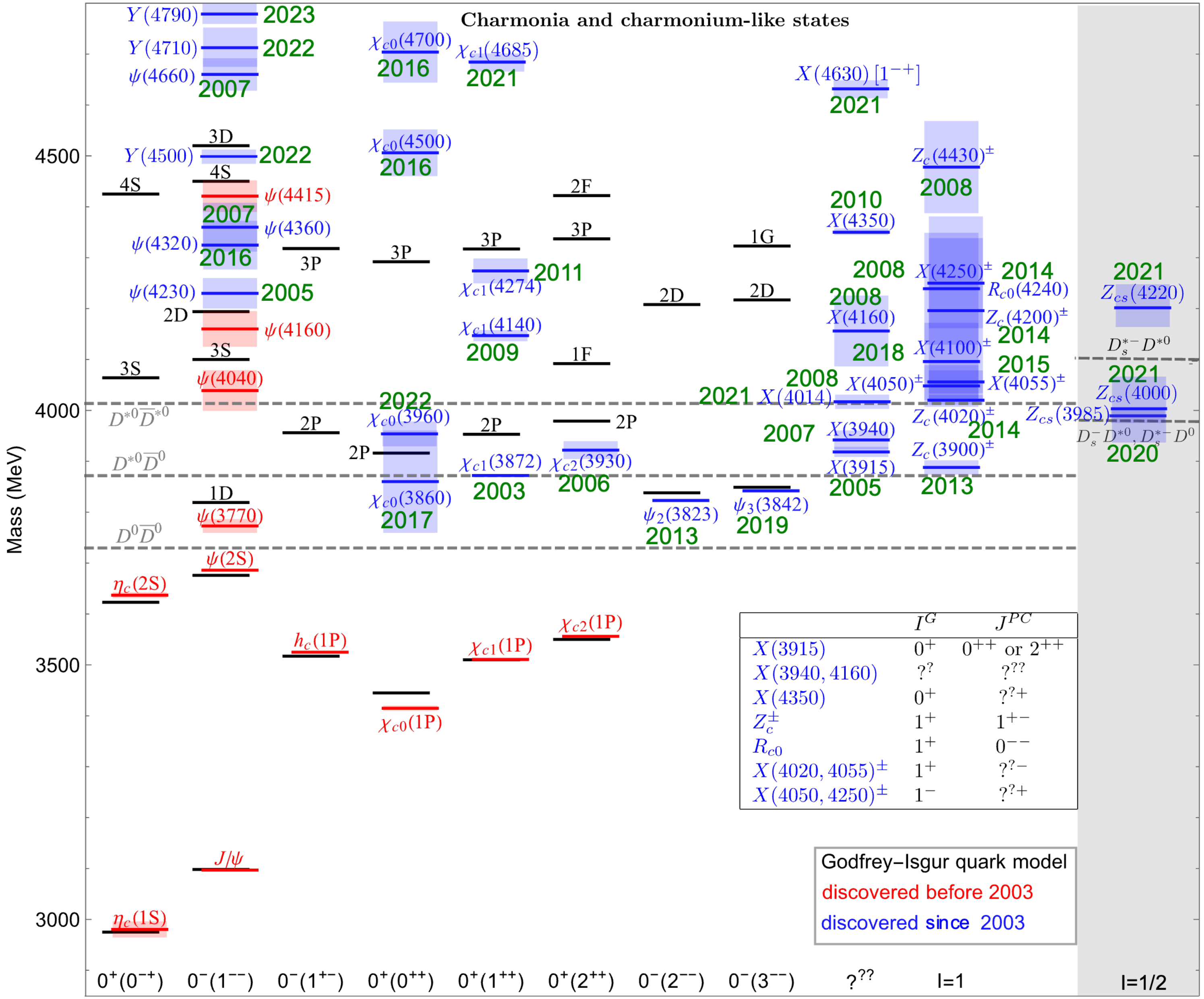
Teng Ji et al., Precise determination of the properties of X(3872) and of its isovector partner W_{c1}, arXiv:2502.04458;

Xiong-Hui Cao, M.-L. Du, FKG, Photoproduction of the X(3872) beyond vector meson dominance: the open-charm coupled-channel mechanism, arXiv:2401.16112;

Zhi Yang, FKG, Semi-inclusive lepto-production of hidden-charm exotic hadrons, arXiv:2107.12247;

Pan-Pan Shi, FKG, Z. Yang, Semi-inclusive electroproduction of hidden-charm and double-charm hadronic molecules, arXiv:2208.02639

Charmonia and charmonium-like (XYZ) states



X(3872) and possible isospin-1 partners

- X(3872) has been discovered by Belle for more than 20 years, debates are still ongoing!
- Excellent observable for distinguishing models: Isospin-1 partners!
  - No, in charmonium model

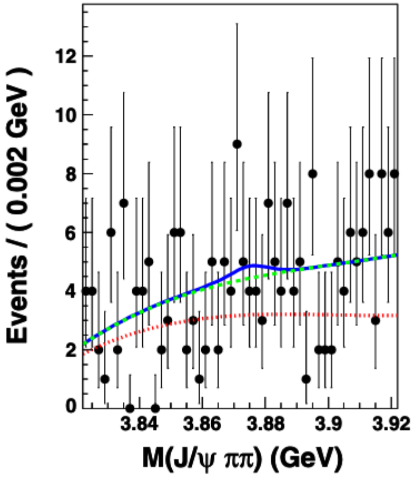
    L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRD 71 (2005) 014028
  - Quark bound states, in compact tetraquark model
    - With isospin-independent quark interactions, isoscalar and isovector tetraquarks must coexist

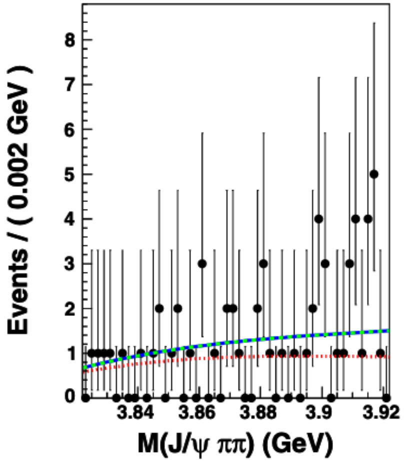
$$I = 1 \text{ multiplet: } [cu][\bar{c}\bar{d}],\ \frac{1}{\sqrt{2}}([cu][\bar{c}\bar{u}] - [cu][\bar{c}\bar{d}]),\ [cd][\bar{c}\bar{u}]$$

  - How about hadronic molecular picture?
    - Thought to be non-existing, but never model-independent investigated
    - Will be shown to exist as virtual states in this talk

So far negative signal

- No signal in the charged channel so far

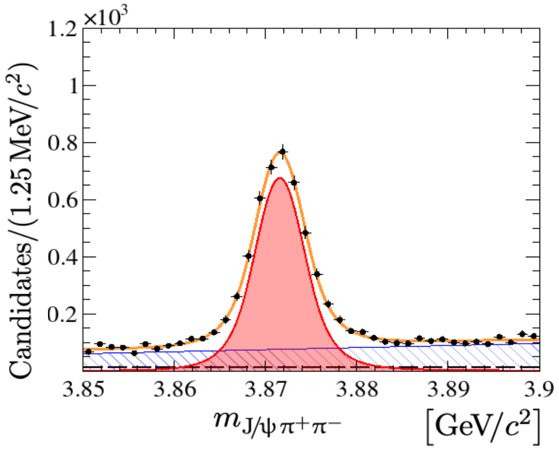




$\bar{B}^0 \to K^- \pi^+ \pi^0 J/\psi$ $B^+ \to K^0 \pi^+ \pi^0 J/\psi$

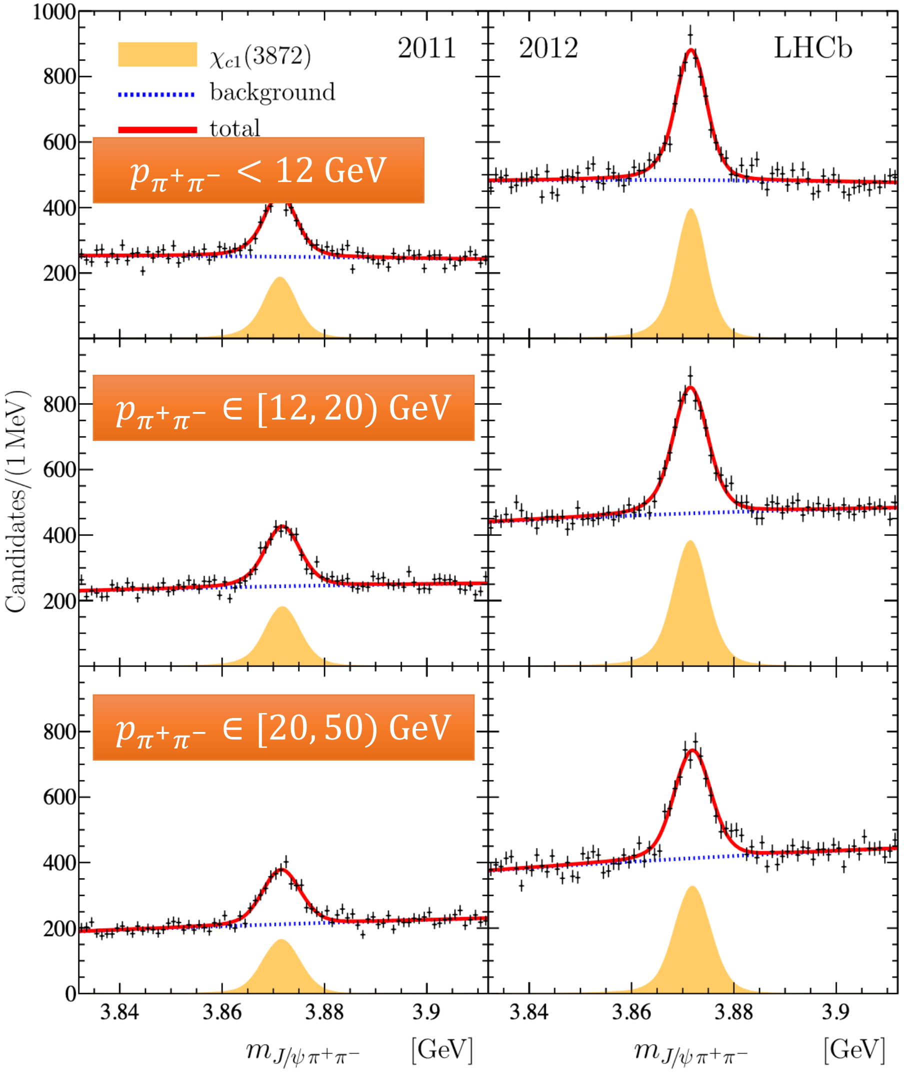
Belle, PRD 84 (2011) 052004

- 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

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

- Hadronic molecules: consider S-wave interactions between charm and anti-charm mesons
- For each isospin, only two low-energy constants (LECs) at LO in nonrelativistic expansion 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 :

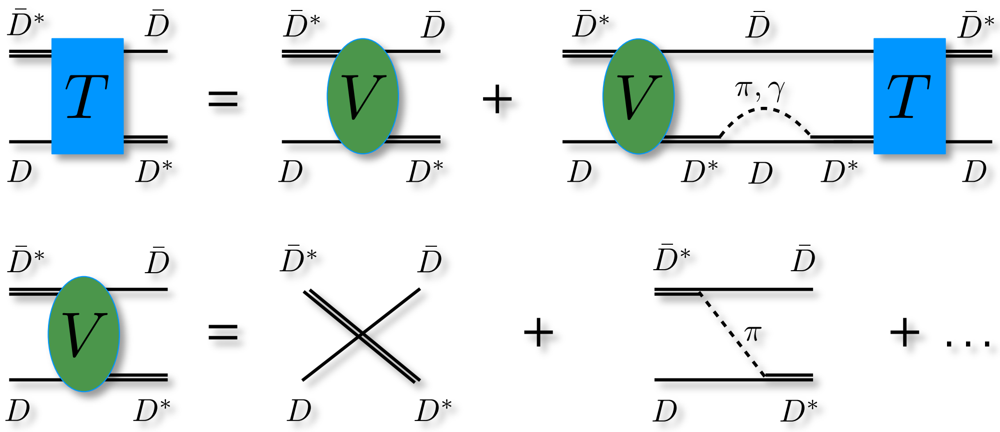
> Mass
>
> $M_X = 3871.69^{+0.00+0.05}_{-0.04-0.13}$MeV LHCb, PRD 102 (2020) 092005
>
> $M_{D^0} + M_{D^{*0}} = 3871.69(7)$ MeV PDG 2024
>
> Isospin breaking in decays LHCb, PRD 108 (2023) L011103
>
> $$R_X = \left|\frac{\mathcal{M}_{X(3872)\to J/\psi\rho^0}}{\mathcal{M}_{X(3872)\to J/\psi\omega}}\right| = 0.29 \pm 0.04$$

- 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

Extracted using BW for resonances;
updated using Omnes dispersion representation for $\pi\pi$ P-wave in
J. Dias et al., PRD 111 (2025) 014031

Lippmann-Schwinger equation (LSE)

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



- Coupled channels: $D^0\bar{D}^{*0}, D^+D^{*-}$ with $C = +$
- T matrix is given by the LSE:

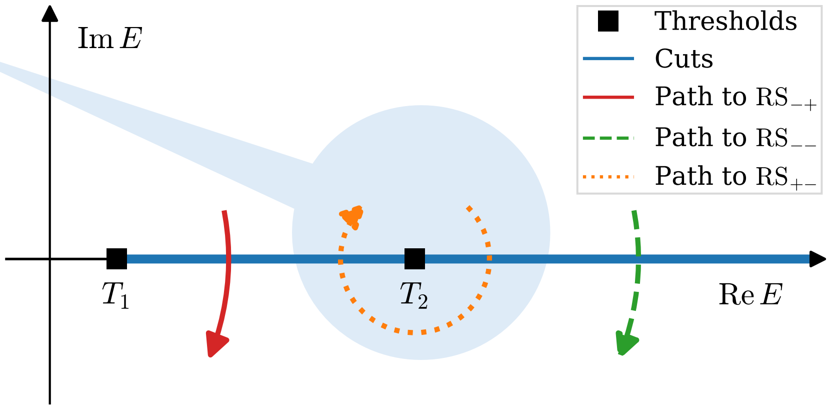
$$T(E;p',p) = V(E;p',p) + \int \frac{l^2 dl}{2\pi^2} V(E;p',l)G(E;l)T(E;l;p)$$

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

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

- ➢ 3-body effects: one-pion exchange, D^* selfenergy

- Two poles of the T-matrix for the $(D\bar{D}^*)_0 - (D\bar{D}^*)_\pm$ scattering amplitudes (4 Riemann sheets)
  - ➢ $X(3872)$ pole on the 1st RS (RS_{++})
  - ➢ $W_{c1}(3880)$ on the 4th RS (RS_{+-})
    - ✧ Threshold cusp!!!



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

- 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 2[nd] Riemann sheet (RS), 8^{+8}_{-5} MeV below D^0D^{*-} threshold

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

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

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

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

- Virtual state W_{c1} was confirmed in lattice QCD calculation with $M_\pi = 280$ MeV

M. Sadl et al., PRD 111 (2025) 054513

J^{PC}	Interpolators	$1/a_0[\mathrm{fm}^{-1}]$	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	$-3.8^{+3.6\mathrm{a}}$
	$J/\psi\rho, \eta_c a_0$ excl	$0.96^{+1.42}_{-0.91}$	$2.19^{+0.36}_{-1.00}$	0.15	$-6.7^{+6.7}_{-19.5}$

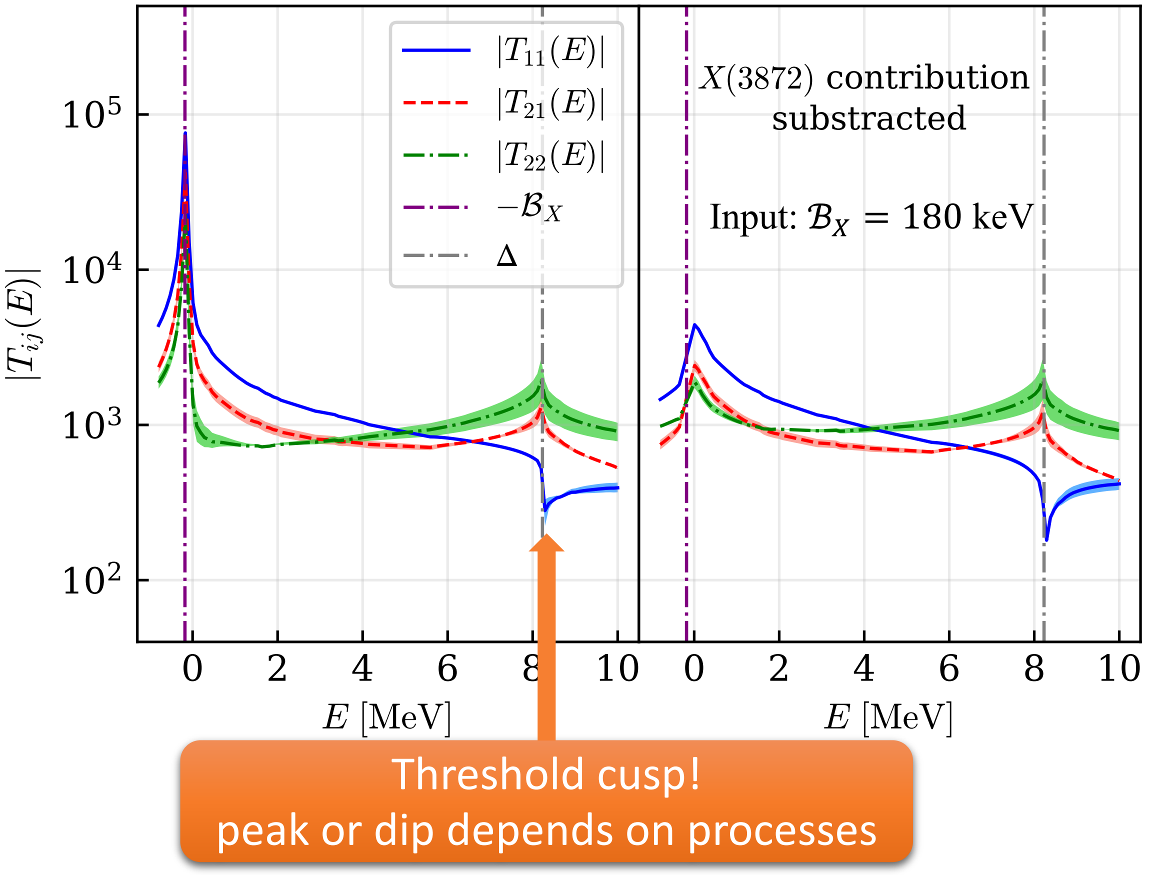
[a]Uncertainty is so large that it is unbounded from below.

sign convention different from ours

Cutoff insensitivity checked: poles relative to thresholds varied within 5% for $\Lambda \in [0.5, 1.0]$ GeV

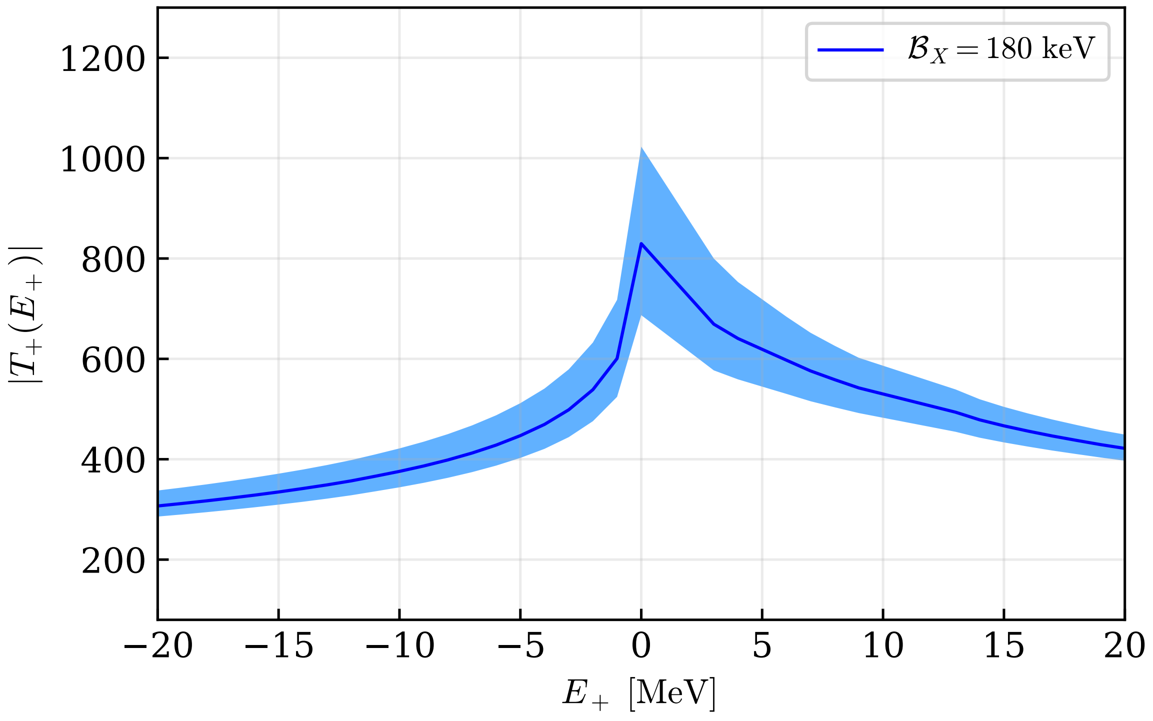
Why have they not been observed?

- 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

- The observed $X(3872)$ signals should contain the W_{c1}^0 contribution as well ⇒ combined analysis !!

Combined analysis of BESIII and LHCb data for $X(3872)$

Teng Ji et al., arXiv:2502.04458

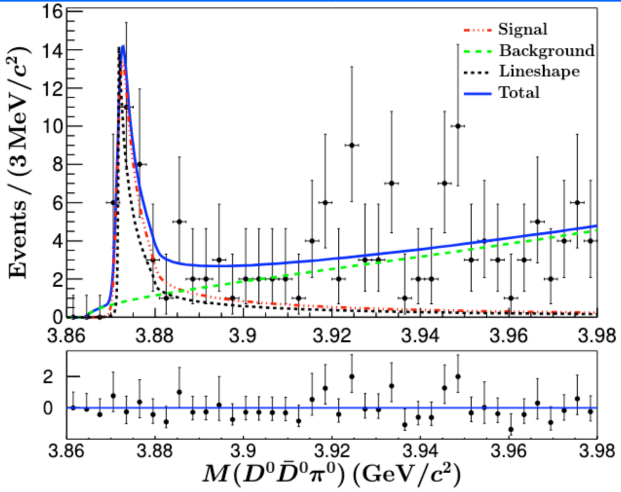
- $X(3872)$ line shapes ⇒ $X(3872)$ + possible $W_{c1}(3880)^0$
- $\pi^+\pi^-$ invariant mass distribution ⇒ isospin breaking, information on $I = 1$

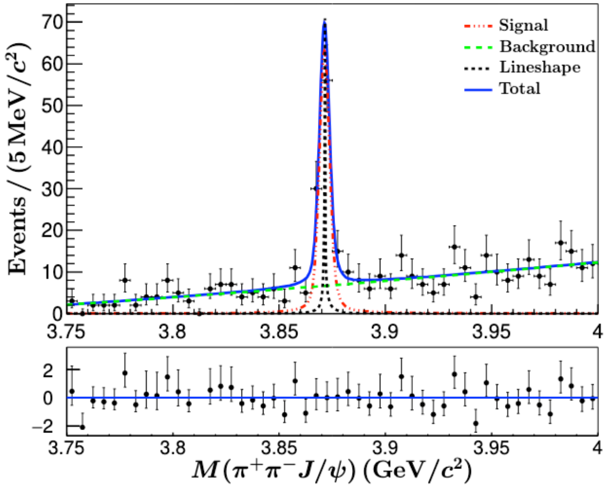
BESIII:

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

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

BESIII, PRL 132 (2024) 151903

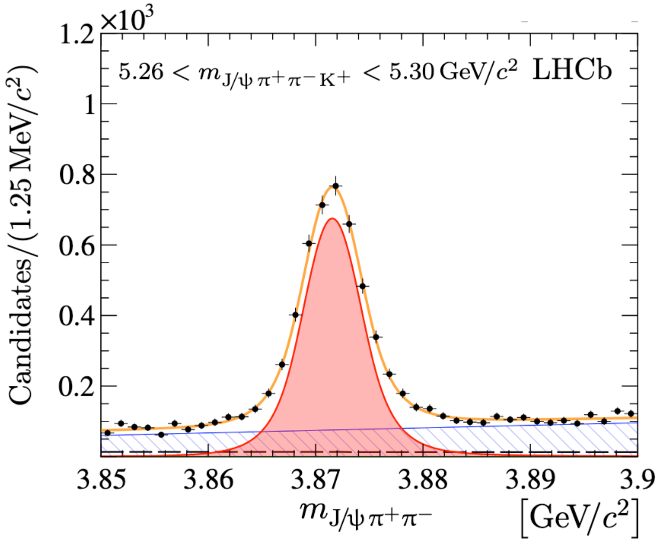


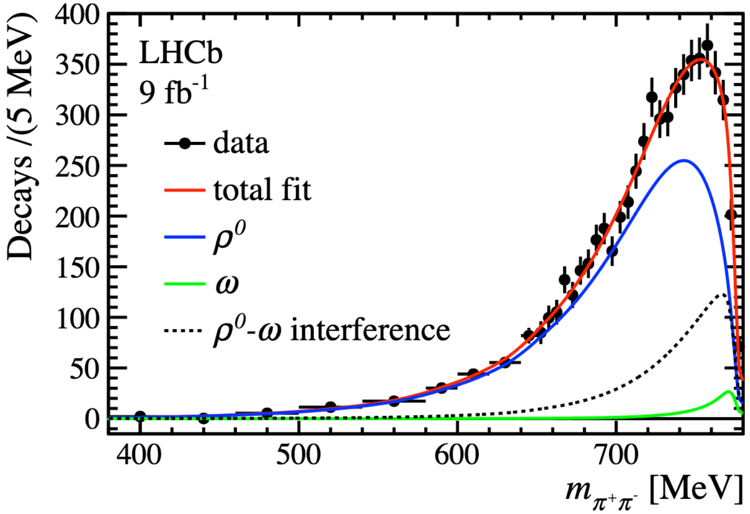


LHCb:

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

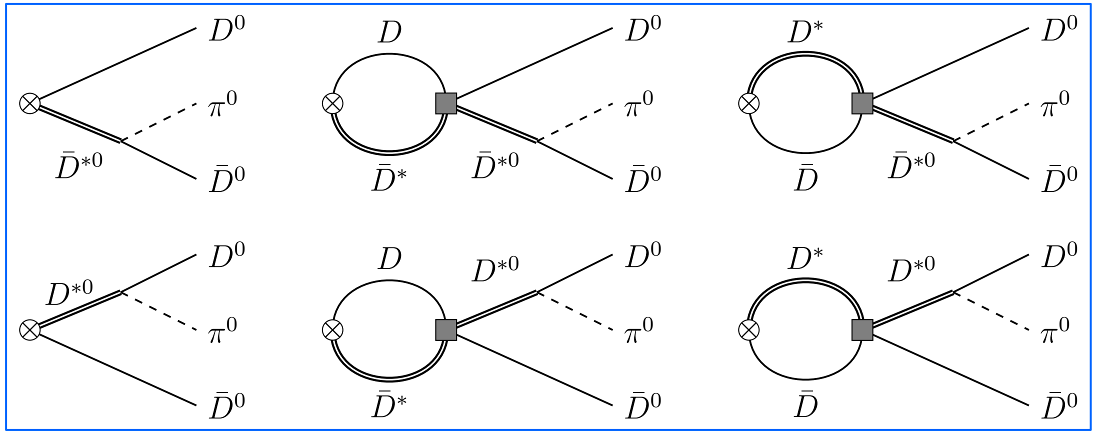
LHCb, JHEP 08 (2020) 123;
PRD 108 (2023) L011103

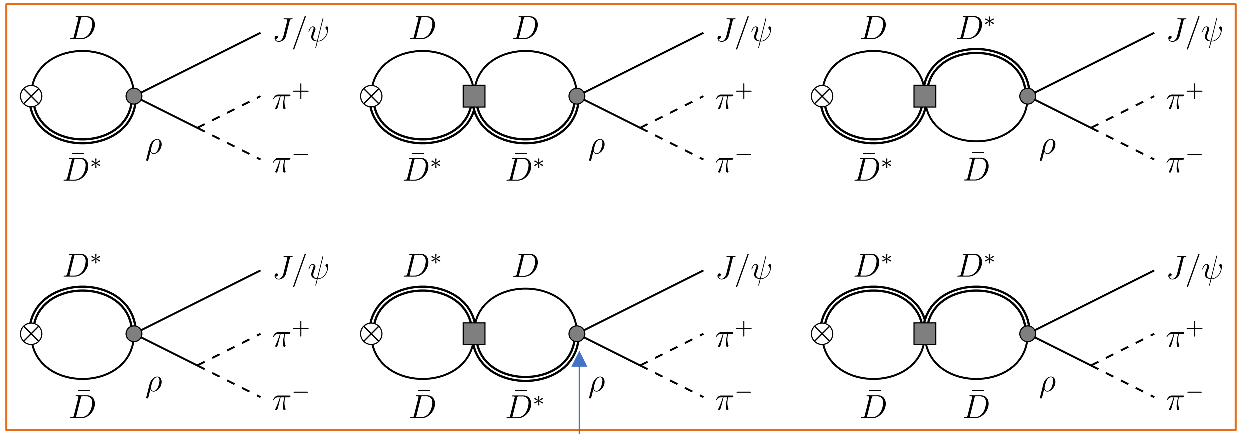




Combined analysis of BESIII and LHCb data for $X(3872)$

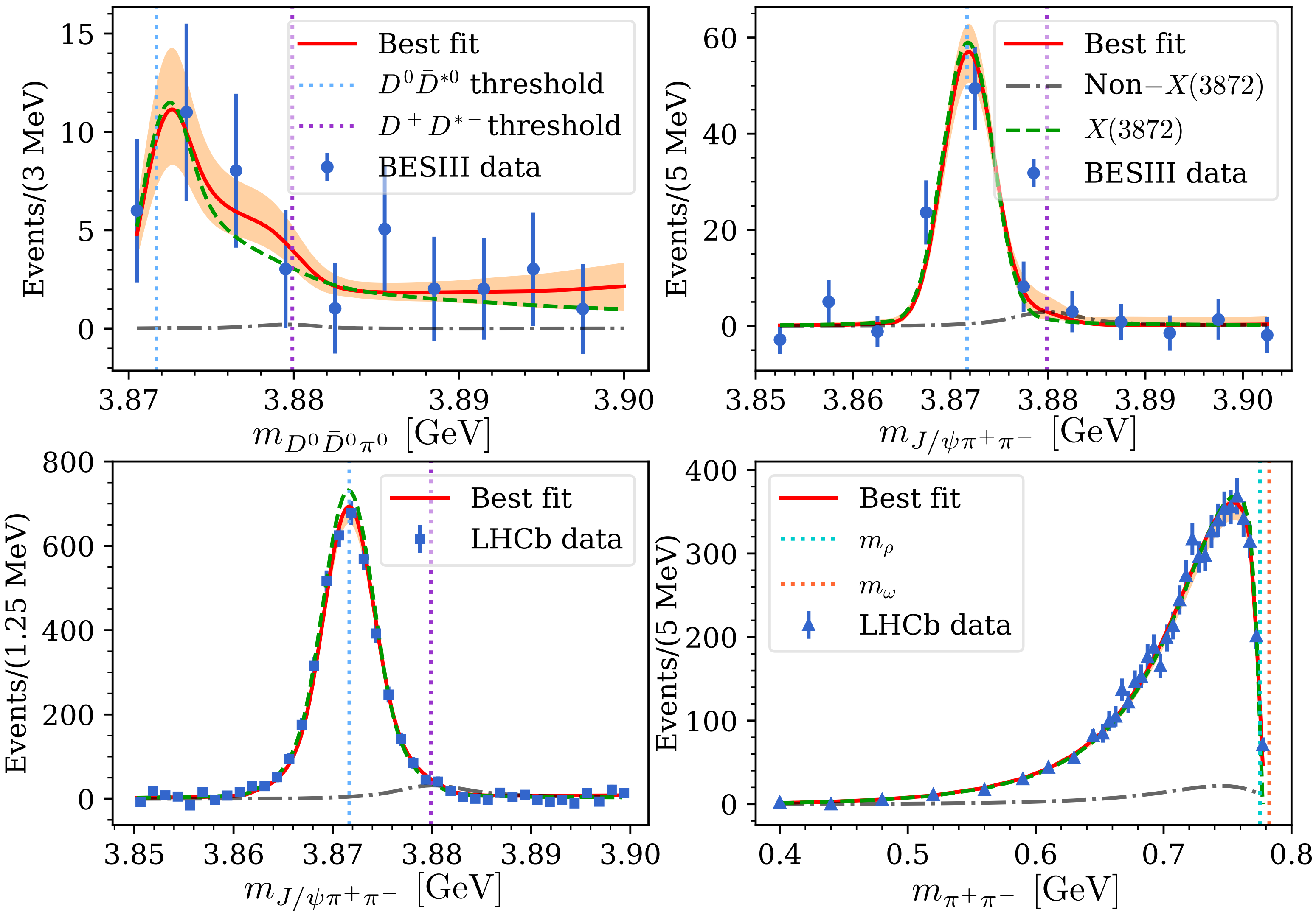
- Coupled channels
  - $(D\bar{D}^*)_0$, $(D\bar{D}^*)_\pm$: contact terms + OPE, $D\bar{D}\pi$ three-body effects considered
  - Inelastic channels:
    - $J/\psi\rho, J/\psi\omega$: ρ included using the Omnes dispersive approach, ρ-ω mixing considered
    - $J/\psi\gamma, \psi'\gamma, \chi_{cJ}(1P)\pi^0$: neglected in the baseline fit, included in uncertainty analysis





ρ-ω mixing included

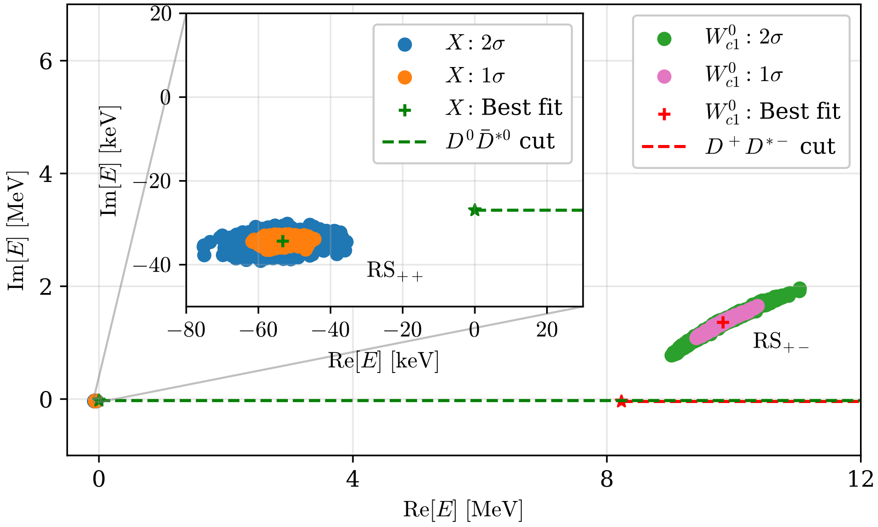
Combined analysis of BESIII and LHCb data for $X(3872)$



- Poles
  - ☐ $X(3872)$ as a bound state below $D^0\bar{D}^{*0}$ threshold (5σ)

    $E_X = \left(-53^{+10}_{-25} - i34^{+2}_{-12}\right)$ keV
  - ☐ $W_{c1}(3880)^0$ pole on RS_{+-}, relative to the D^+D^{*-} threshold:

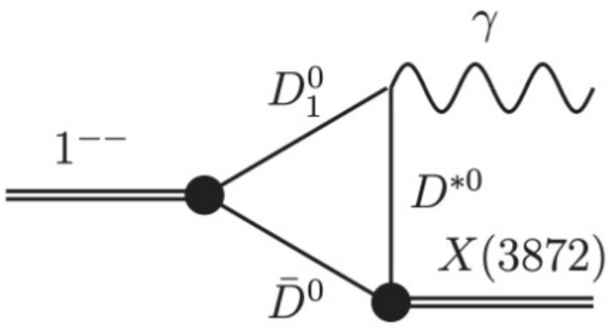
    $E_W = \left(1.6^{+0.7}_{-0.9} + i1.4^{+0.3}_{-0.6}\right)$ MeV



Best fit: $\chi^2/\mathrm{dof} = 67.5/(88-9) = 0.78$

Signal of $W_{c1}(3880)$?

- Signal of $W_{c1}(3880)^0$ almost invisible in the current data, reasons:
  - Virtual state, threshold cusp
  - $(D\bar{D}^*)_0$ easier produced than $(D\bar{D}^*)_\pm$ for both $e^+e^- \to \gamma D\bar{D}^*$ @ $\sqrt{s} \approx 4.23$ GeV and $B^+ \to K^+ D\bar{D}^*$



FKG et al., PLB 725 (2013) 127

$\Gamma(D_1^0 \to \gamma D^{*0}) \gg \Gamma(D_1^+ \to \gamma D^{*+})$

J.G. Korner et al., PRD 47 (1993) 3955;
Fayyazuddin et al., PRD 50 (1994) 2329

- For B^+ decays, fit parameters (ratio of production vertices): $P_\pm/P_0 = 0.45 \pm 0.05$

  Data: PDG 2024

$$\frac{\mathrm{Br}\left[B^+ \to K^+ (D^+ D^{*-} + D^- D^{*+})\right]}{\mathrm{Br}\left[B^+ \to K^+ \left(D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0}\right)\right]} = 0.14 \pm 0.02$$

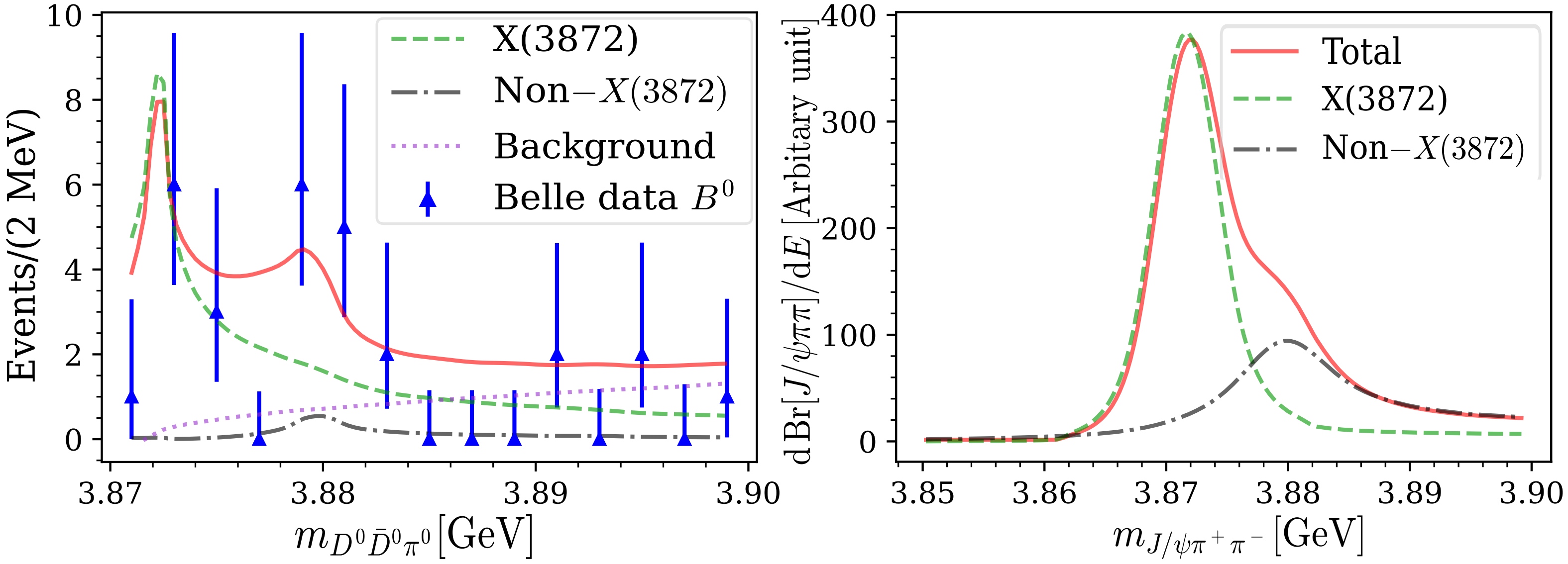
- Switching $u \leftrightarrow d$, situation should be different for B^0 decays

  Data: PDG 2024

$$\frac{\mathrm{Br}\left[B^0 \to K^0 (D^+ D^{*-} + D^- D^{*+})\right]}{\mathrm{Br}\left[B^0 \to K^0 \left(D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0}\right)\right]} = 5.8 \pm 2.7$$

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 $D^+\bar{D}^{*0}$ threshold in $J/\psi\pi^\pm\pi^0$
- Might the reason why different experiments reported seemingly contradicting results for $\mathrm{Br}(X \to \psi'\gamma)/\mathrm{Br}(X \to J/\psi\gamma)$

- Signal of $X(3872)$ and $W_{c1}(3880)$ in lepto-/photo-production?
  - Should depend on the dominant production mechanism!

X(3872) line shapes

- Line shapes of a near-threshold resonance depend on reaction mechanism! X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001
  - Peak for $|T_{21}|$ (1: lower inelastic channel; 2: elastic channel)

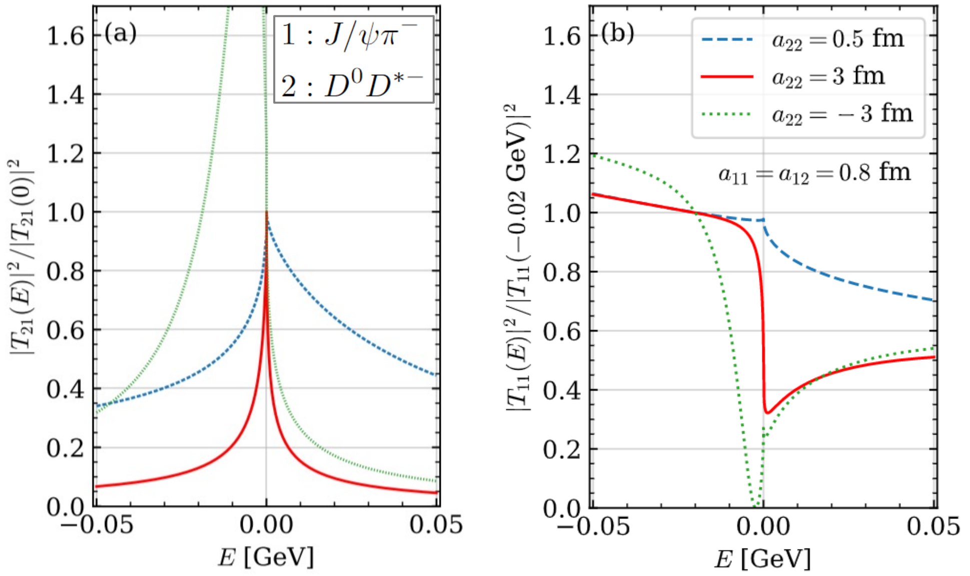
$$T_{21}(E) = \frac{-8\pi\Sigma_2}{a_{12}(1/a_{11} - ik_1)} \left[\frac{1}{a_{22,\rm eff}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}.$$

  - Dip for $|T_{11}|$ if scattering length for channel-2 is large

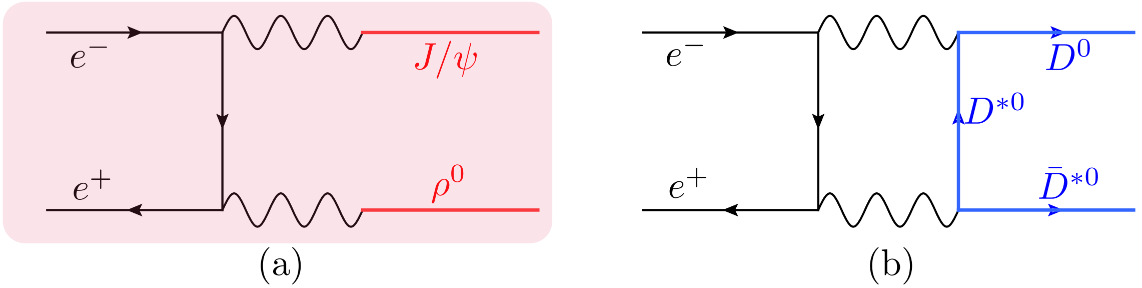
$$T_{11}(E) = \frac{-8\pi\Sigma_2\left(\frac{1}{a_{22}} - i\sqrt{2\mu_2 E}\right)}{\left(\frac{1}{a_{11}} - i\,k_1\right)\left[\frac{1}{a_{22,\rm eff}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]}$$

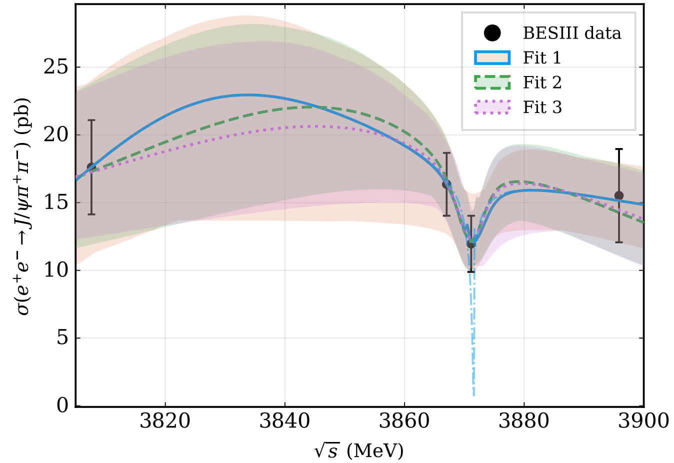
$$= -8\pi E_2^{\rm thr}\left(\frac{1}{a_{11}^{-1} - ik_1} + \frac{a_{12}^{-2}(a_{11}^{-1} - ik_1)^{-2}}{a_{22,\rm eff}^{-1} - ik_2}\right)$$

background pole term The interfering phase is fixed by unitarity!



- $X(3872)$ shows up as a dip in $e^+e^- \to X \to J/\psi\pi\pi$ direct production



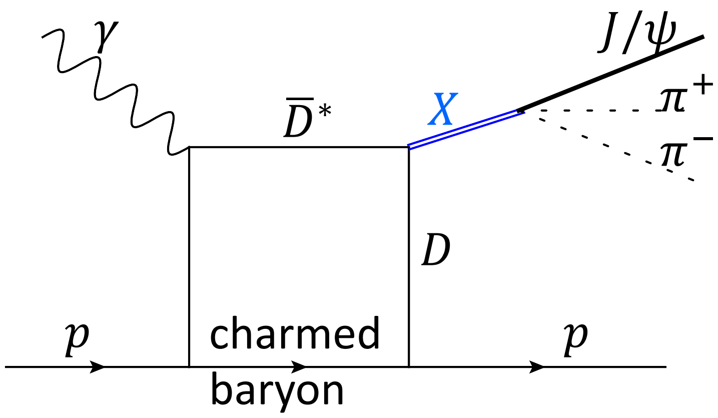


V. Baru, FKG, C. Hanhart, A. Nefediev, PRD 109 (2024) L111501

X(3872) line shapes in photoproduction

- Two mechanisms for $X(3872)$ lepto/photo-production $\gamma p \to J/\psi\pi^+\pi^- p$

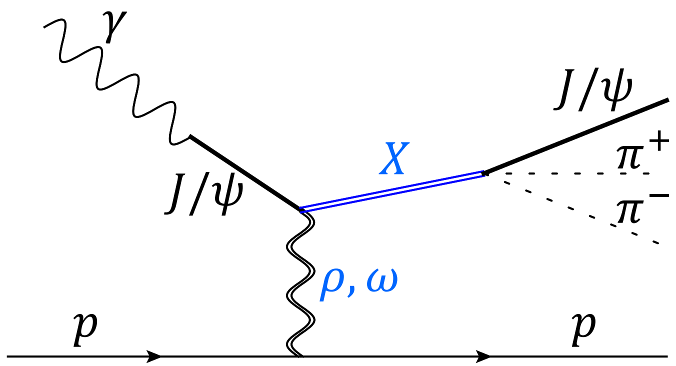
☐ Coupled-channel mechanism



$\mathcal{A}_{\text{prod}}^{\text{CC}} \propto T_{D\bar{D}^* \to J/\psi\rho}$ (i.e., T_{21})

- Peak in $J/\psi\pi^+\pi^-$ invariant mass distribution

☐ Vector-meson dominance mechanism



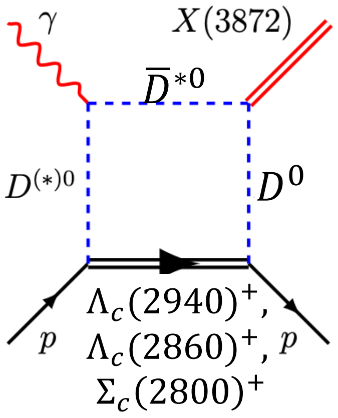
$\mathcal{A}_{\text{prod}}^{\text{VMD}} \propto T_{J/\psi\rho \to J/\psi\rho}$ (i.e., T_{11})

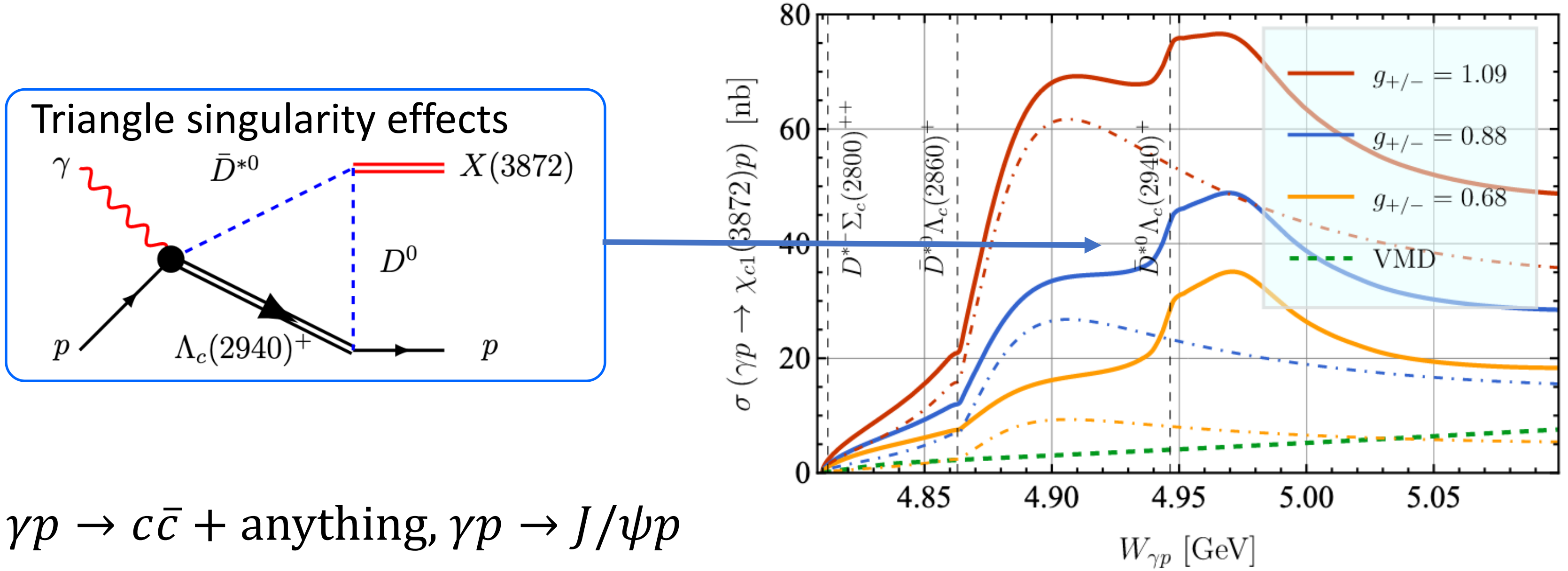
- Dip in $J/\psi\pi^+\pi^-$ invariant mass distribution

X(3872) in exclusive photoproduction

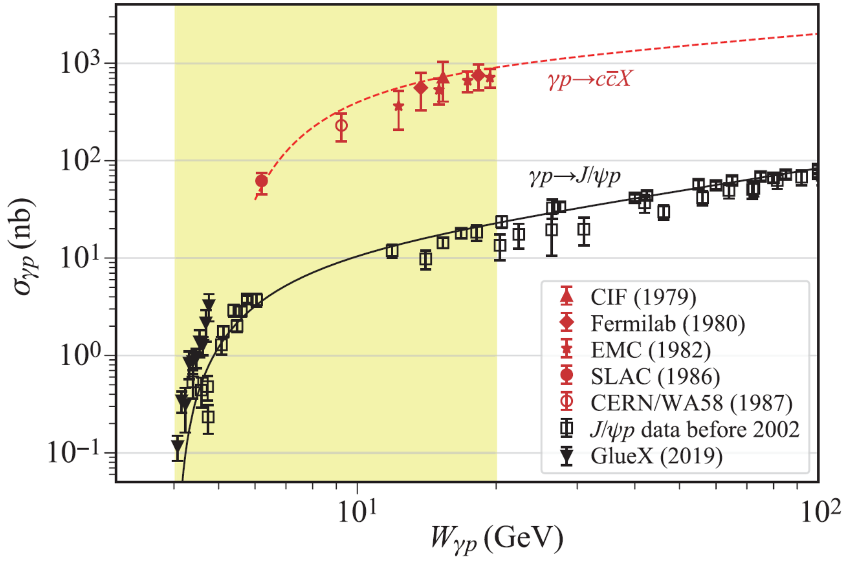
- Nontrivial energy dependence of the total cross section

X.-H. Cao, M.-L. Du, FKG, JPG 51 (2024) 105002





- Cross sections for inclusive $\gamma p \to c\bar{c} + \text{anything}$, $\gamma p \to J/\psi p$



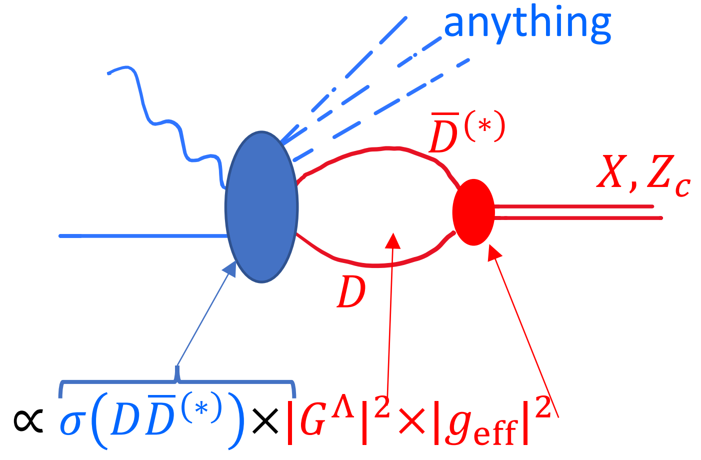
- Leptoproduction: cross sections are roughly two orders of magnitude (α) smaller
- Many more open-charm hadrons $\bar{D}$ and Λ_c than $J/\psi p$

Plot from D. P. Anderle et al., Front.Phys. 16 (2021) 64701

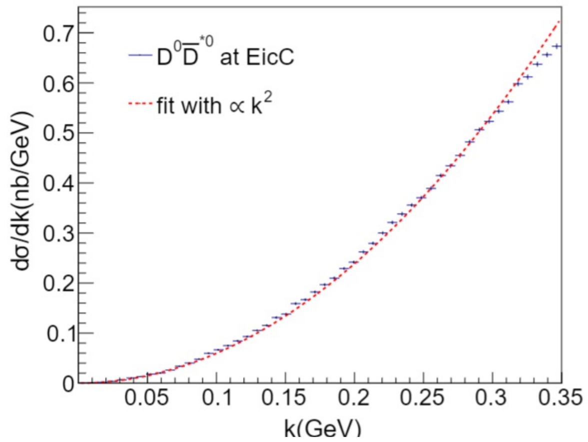
Cross section estimates for inclusive productions

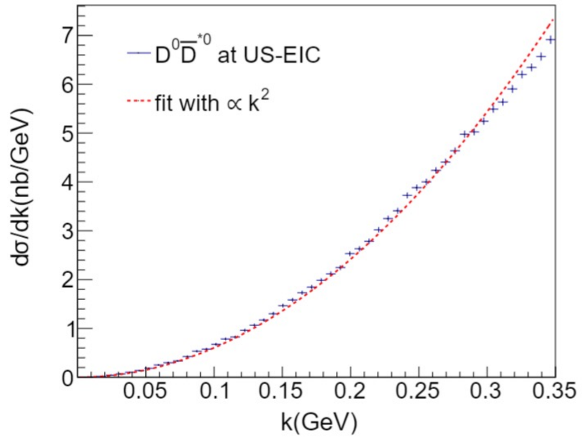
- Order-of-magnitude estimates of inclusive lepto-production of near-threshold hadronic molecules
- The cross section can be estimated as

Artoisenet, Braaten (2011); FKG, Meißner, W. Wang, Z. Yang (2014); …



☐ Charmed hadron pairs generated with Pythia6.4





- Consider machine configurations

Z. Yang, FKG, CPC 45 (2021) 123101

	EicC	EIC
e^- energy (GeV)	3.5	20
proton energy (GeV)	20	250
luminosity ($\mathrm{cm^{-2}\,s^{-1}}$)	2×10^{33}	10^{34}

Cross section estimates for inclusive productions

- Order-of-magnitude estimates of the semi-inclusive electro-production of hidden/double-charm hadronic molecules (in units of pb)

Z. Yang, FKG, CPC 45 (2021) 123101; P.-P. Shi, FKG, Z. Yang, PRD 106 (2022) 114026

	Constituents	$I, J^{P(C)}$	EicC	EIC
$X(3872)$	$D\bar{D}^*$	$0, 1^{++}$	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	$1, 1^{+-}$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	$1/2, 1^+$	19(69)	250(900)
$P_c(4312)$	$\Sigma_c\bar{D}$	$1/2, 1/2^-$	0.8(4.1)	15(73)
$P_{cs}(4338)$	$\Xi_c\bar{D}$	$0, 1/2^-$	0.1(1.6)	1.8 (30)
Predicted	$\Lambda_c\bar{\Lambda}_c$	$0, 0^{-+}$	0.3 (3.0)	10 (110)
T_{cc}^+	DD^*	$0, 1^+$	0.3×10^{-3} (1.2×10^{-3})	0.1 (0.5)

➢ Daily production rate: $\mathcal{O}(10^3)$ $X(3872)$ events @EIC reconstructed from $J/\psi[\to \ell^+\ell^-]\pi^+\pi^-$

Results for more systems can be found in the above refs.

Summary and outlook

- Pole position of the $X(3872)$ precisely determined to be -53^{+10}_{-24} keV below the $D^0\bar{D}^{*0}$ threshold
- Existence of an isovector $W_{c1}(3880)$
  - Signal of $W_{c1}(3880)^0$ predicted to be more visible in $B^0 \to K^0[D^0\bar{D}^0\pi^0, J/\psi\pi^+\pi^-]$
  - Signal of $W_{c1}(3880)^\pm$: threshold cusp at $D^+\bar{D}^{*0}$ threshold in $J/\psi\pi^\pm\pi^0$
- Photoproduction of $X(3872)$, $W_{c1}(3880)$. Line shapes depend on reaction mechanism
  - Coupled-channel mechanism ⇒ peak in $J/\psi\pi^+\pi^-$
  - VMD mechanism ⇒ dip in $J/\psi\pi^+\pi^-$
- Cross section estimates of semi-inclusive productions of X and Z states

Thank you for your attention!

Results in the pionless theory

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