XYZ states: selected topics

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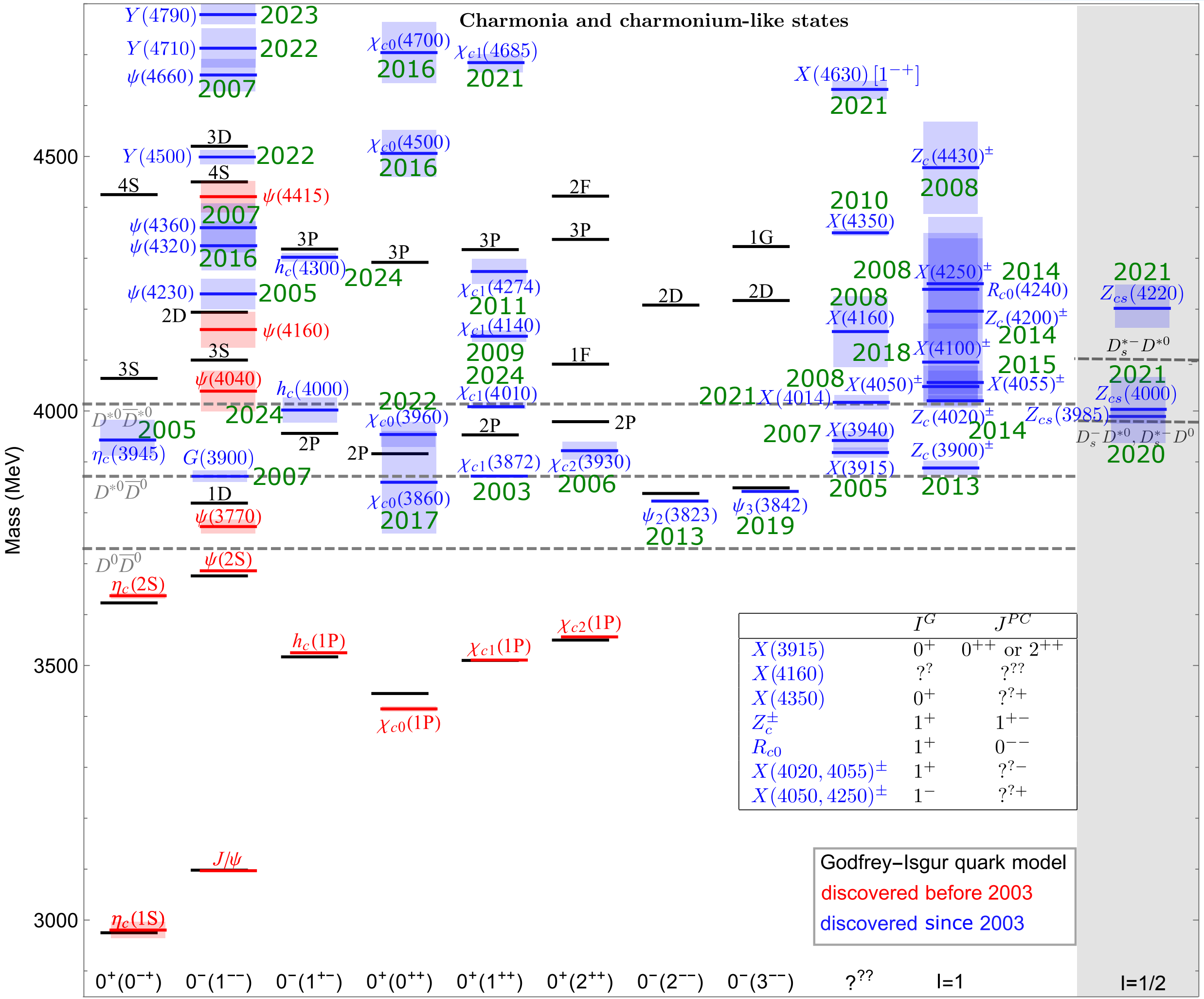
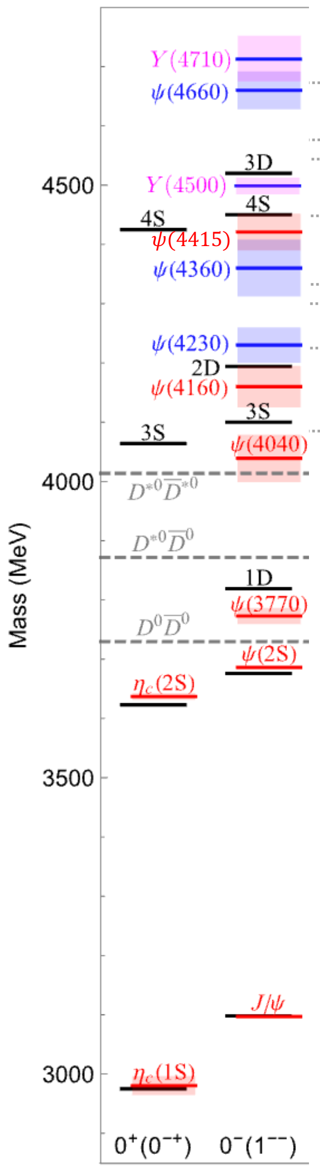


Many hidden-charm thresholds above 4 GeV



$\psi' f_0(980)$

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

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

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

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

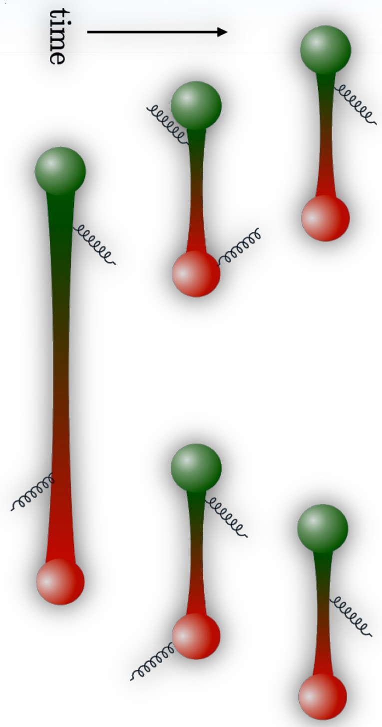
$D_1(2420)\bar{D}^*$

$D_1(2420)\bar{D}$

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

$J/\psi f_0(980)$

2-body S-wave thresholds



Thresholds can play an essential role

Essential nonperturbative feature !!!

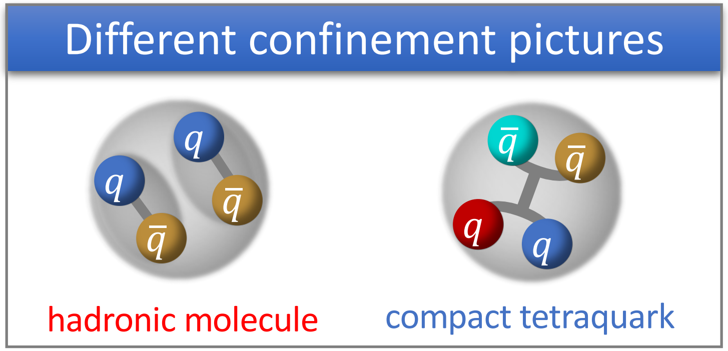
- Hadronic molecules
- Complicates extraction of resonance properties, measurements on various final states are important

Reliable amplitude analysis lays the foundation to answer important questions

- How do quarks and gluons form hadrons?

From spectroscopy to confinement

- 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)?



  - ☐ If compact multiquarks exist too, why are the extended molecules so easily produced?
    - ➢ Possible unambiguous non-mol. multiquark: $[QQ]\bar{q}\bar{q}$ at $m_Q \to \infty$, $\sim \bar{Q}\bar{q}\bar{q}$; but is bottom heavy enough?

      $1/r_{bb} \sim m_b 2\alpha_s/3 \sim 1$ GeV

- 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

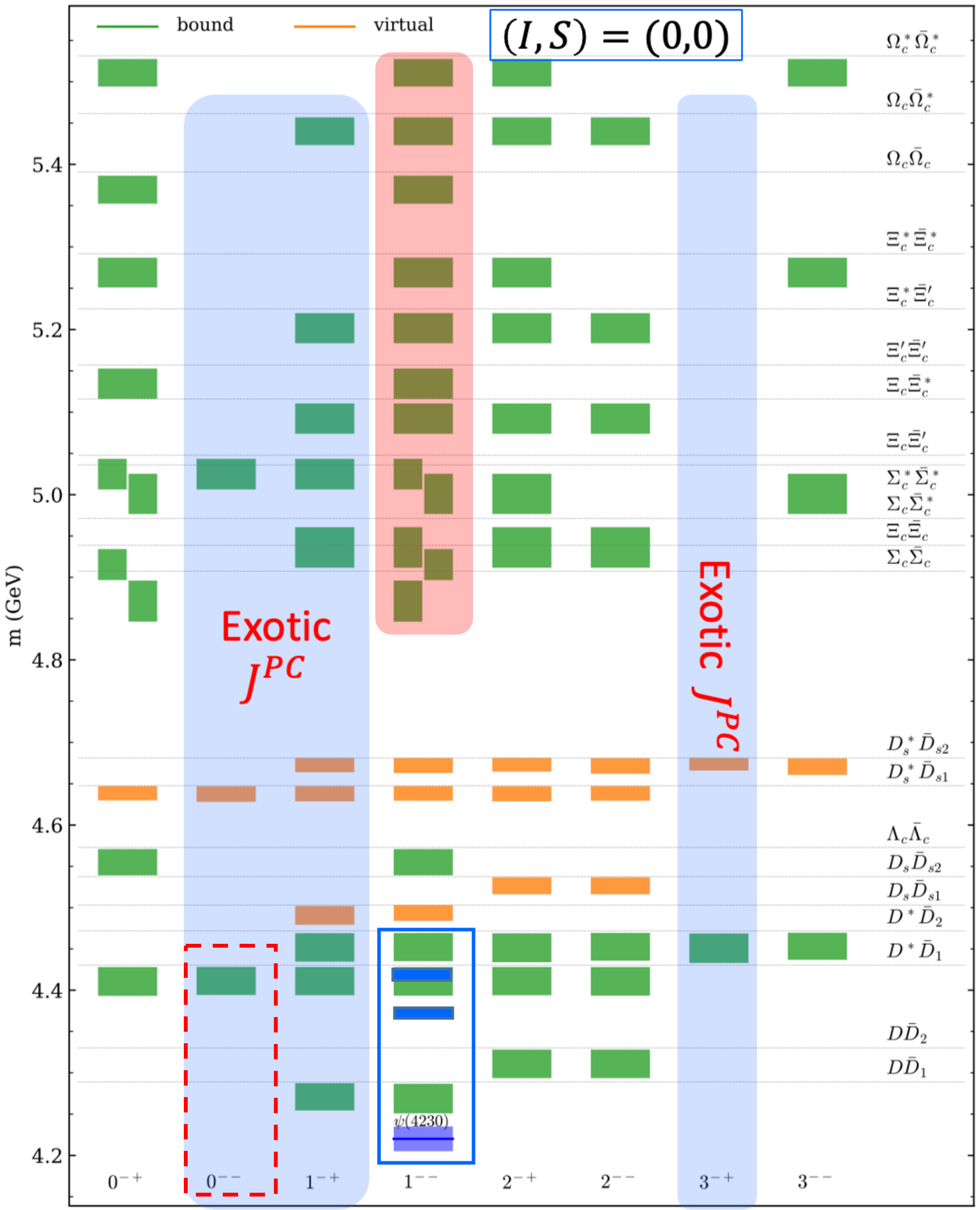
  S. Weinberg (1965); V. Baru et al. (2004); T. Hyodo et al. (2012); F. Aceti, E. Oset (2012); Z.-H. Guo, J. Oller (2016); I. Matuschek et al. (2021); J. Song et al. (2022); M. Albaladejo, J. Nieves (2022) ; Y. Li, FKG, J.-Y. Pang, J.-J. Wu, PRD 105 (2022) L071502 …

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

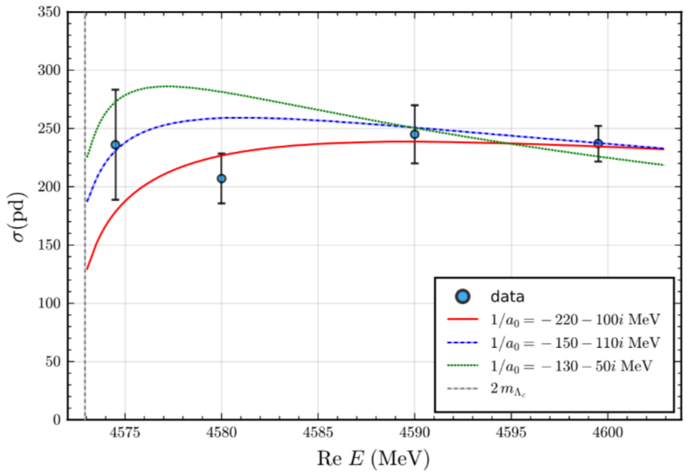
Scattering phase shift — binding energy

Hidden-charm molecules: $P = -$

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



- ✓ $Y(4260)/\psi(4230)$ 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



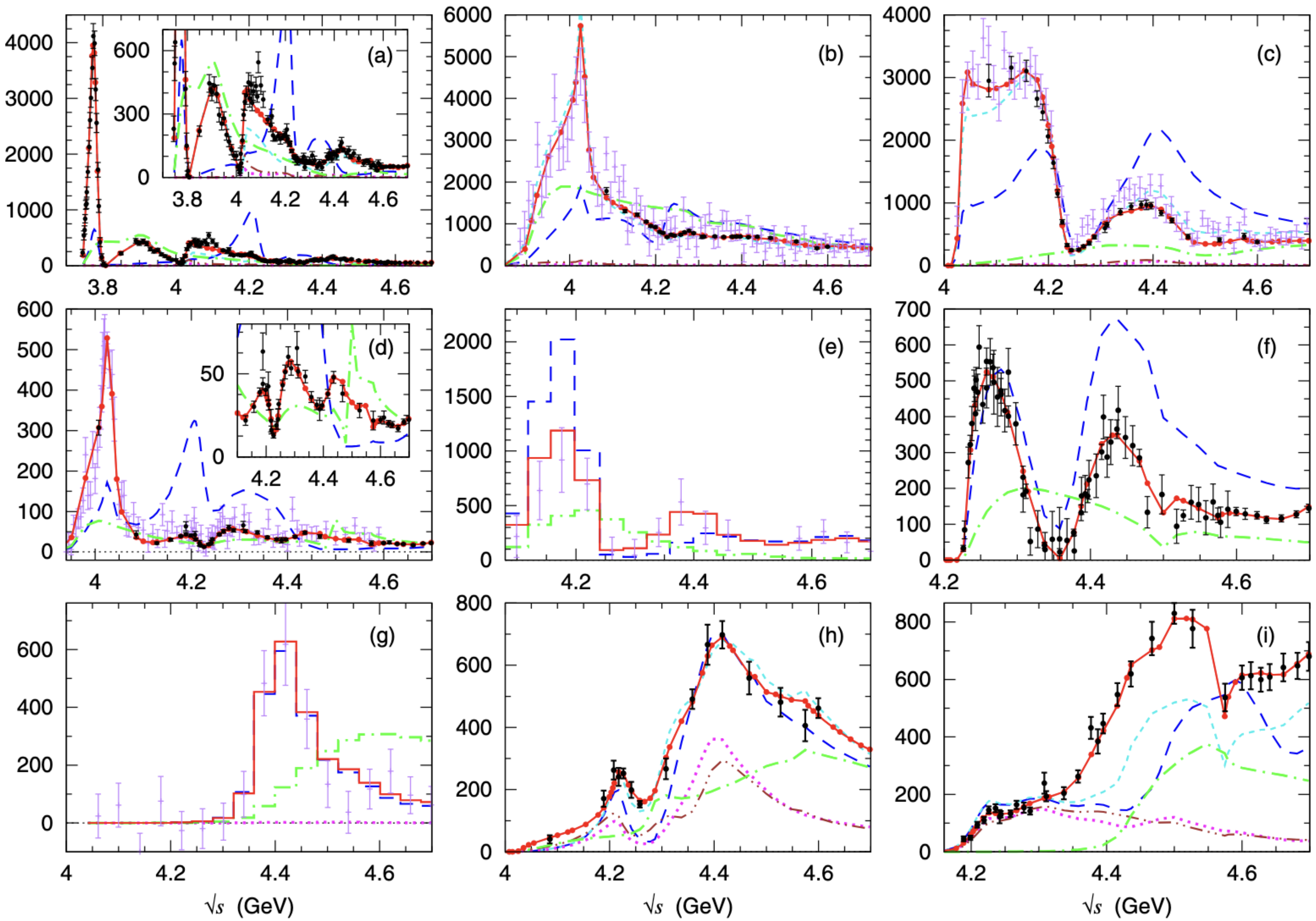
Data taken from BESIII, PRL 120 (2018) 132001;
See also Q.-F. Cao et al., PRD 100 (2019) 054040
Updated measurement: BESIII, PRL 131 (2023) 191901

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

Vector structures

S.X. Nakamura, X.-H. Li, H.-P. Peng, Z.-T. Sun, X.-R. Zhou, PRD 112 (2025) 054027

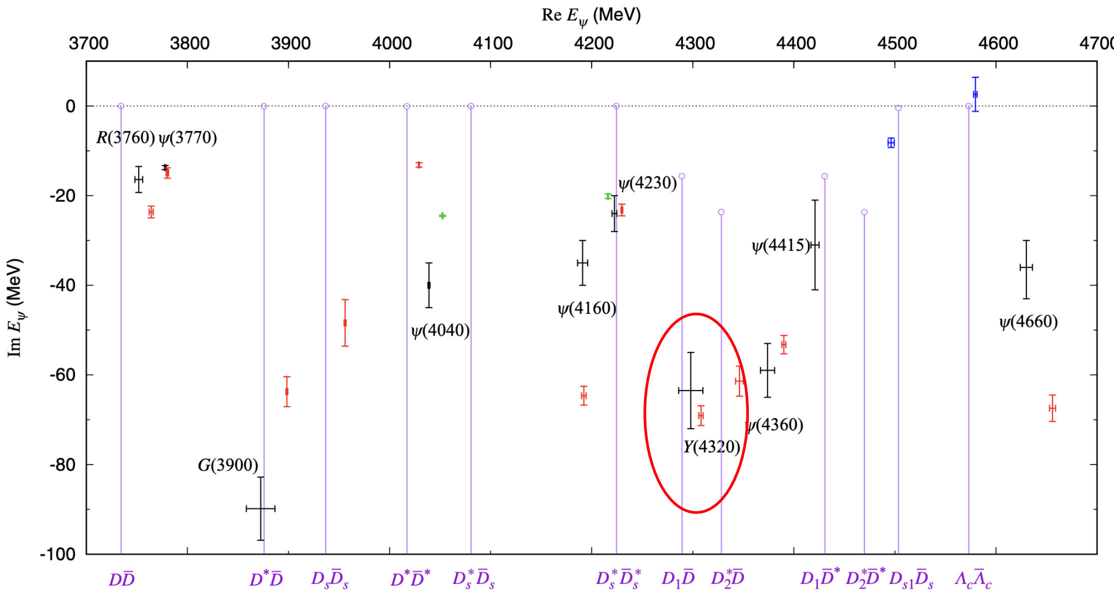
- Most sophisticated coupled-channel analysis of vector structures: 20 channels, more than 200 parameters



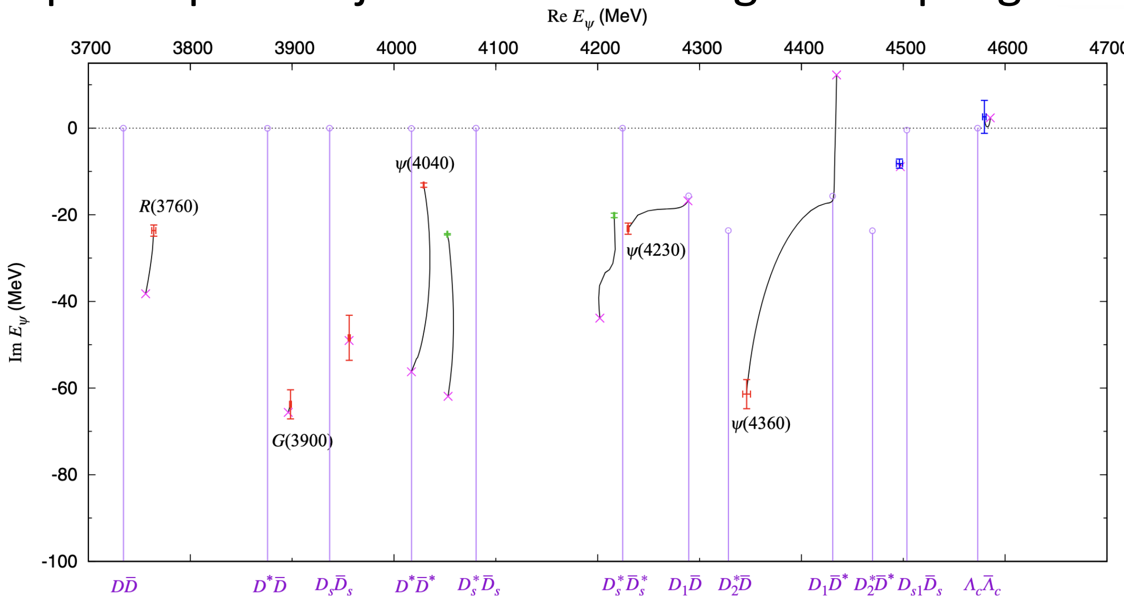
Vector structures

S.X. Nakamura, X.-H. Li, H.-P. Peng, Z.-T. Sun, X.-R. Zhou, PRD 112 (2025) 054027

- Vector poles:



- Molecular vec. poles: pole trajectories switching on couplings to charmonia



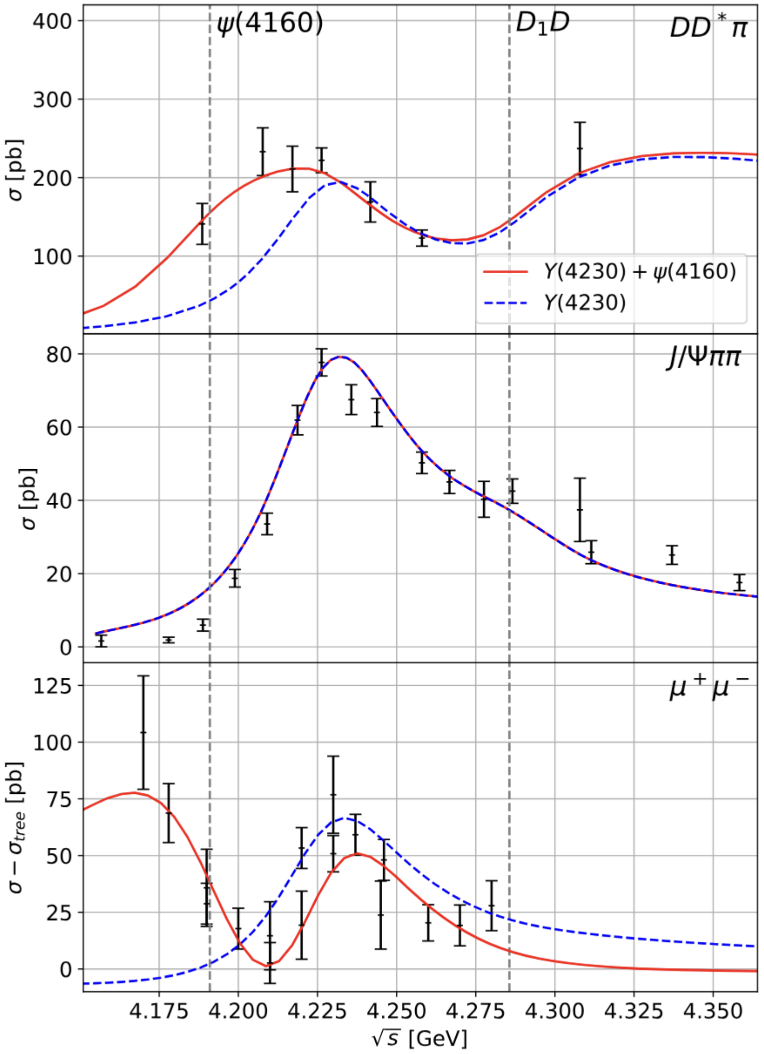
- ➢ G(3900) as a P-wave molecular resonance

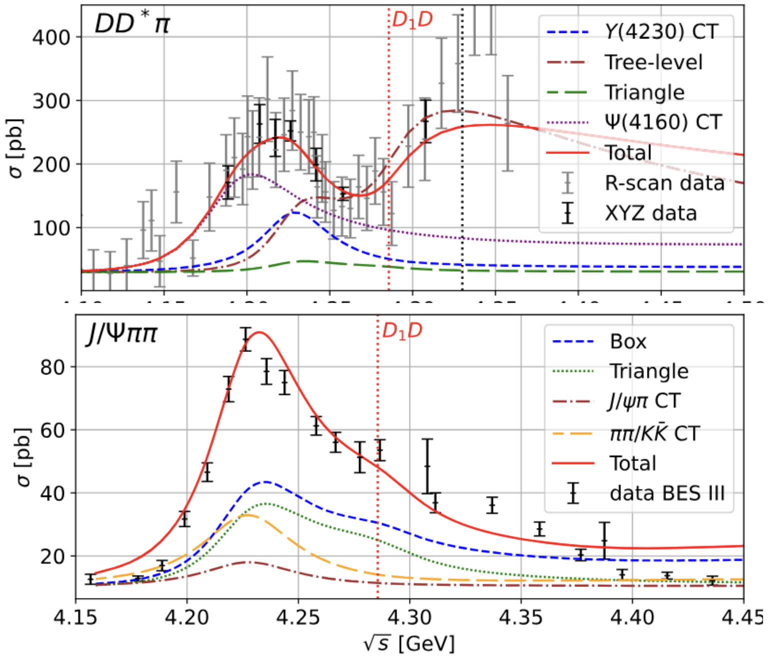
Z.-Y. Lin, J.-Z. Wang, J.-B. Cheng, L. Meng, S.-L. Zhu, PRL 133 (2025) 241903

Vector structures

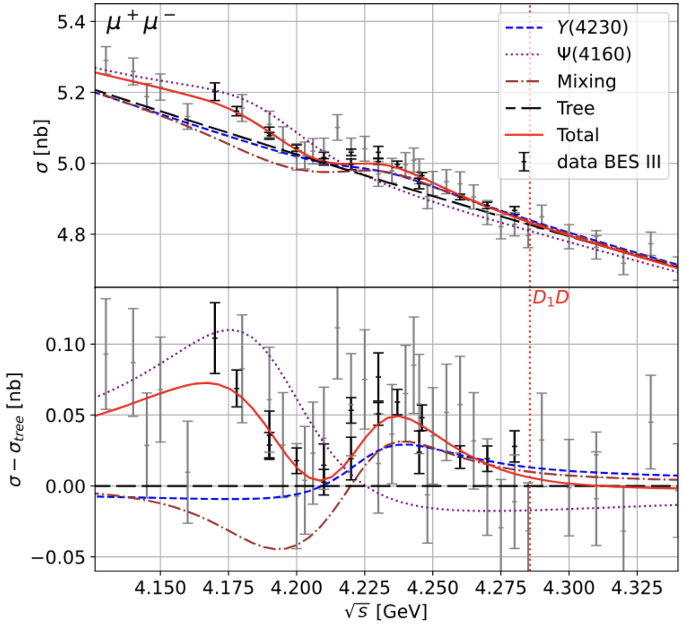
L. von Detten, V. Baru, C. Hanhart, Q. Wang, D. Winney, Q. Zhao, PRD 109 (2024) 116002

- Another analysis focusing on 4.2 – 4.35 GeV: no $\Upsilon(4320)$ needed





$D_{1,2}\bar{D}^*$ channels not yet considered



Vector structures

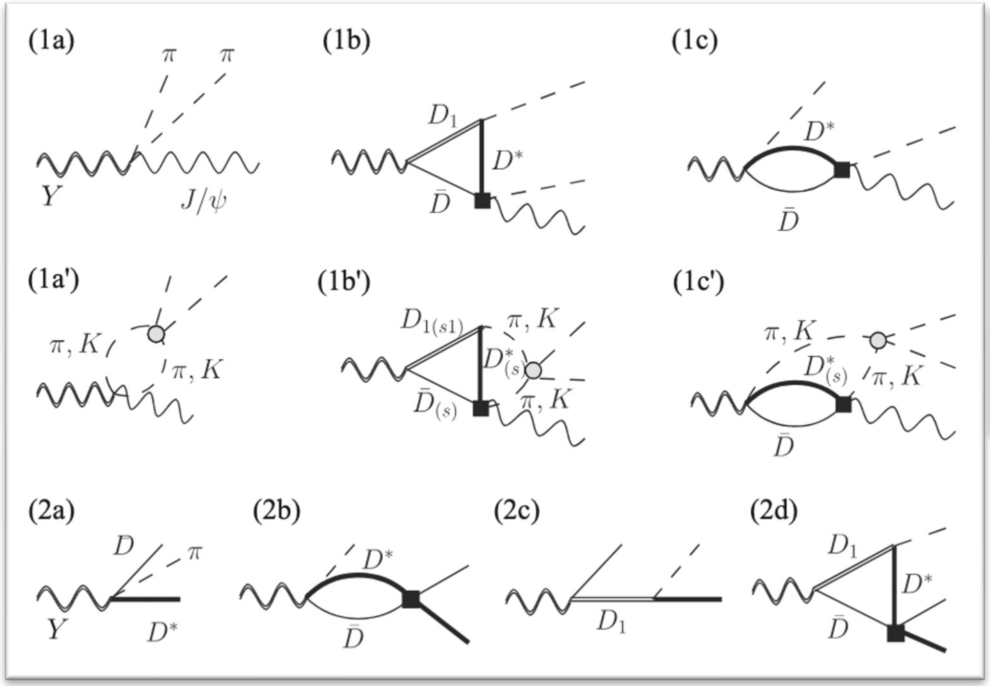
Topic	2741866 (Nakamura et al.; global DCC)	2755412 (von Detten et al.; focused molecular fit)
Energy range	Broad: $\sqrt{s} = 3.75$–4.7 GeV	Focused: $\sqrt{s} = 4.2$–4.35 GeV
Channels included	"Global" set of quasi-2-body channels in $J^{PC} = 1^{--}$, including $D^{(*)}\bar{D}^{(*)}$, $D_{1,2}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s^{(*)}$, $J/\psi\,\eta^{(\prime)}$, $\omega\chi_{c0}$, $\Lambda_c\bar{\Lambda}_c$, plus effective channels like $f_0 J/\psi$, $Z_c\pi$, …	Exactly **8** production channels in 4.2–4.35: $D^0 D^{*-}\pi$, $J/\psi\pi\pi$, $J/\psi KK$, $h_c\pi\pi$, $\mu^+\mu^-$, $\chi_{c0}\omega$, $J/\psi\eta$, $X(3872)\gamma$
Dynamical picture	Dynamical coupled-channel (DCC) model with **bare** ψ states + **short-range open-charm interactions** that can generate hadron-molecule poles; approximate 3-body unitarity	Start from the hypothesis $Y(4230) \sim D_1\bar{D}$ molecule; enforce unitarity constraints in the production/FSI machinery and include $\pi\pi/\bar{K}K$ FSI; needs interference with $\psi(4160)$
What is "one Y?"	In practice: multiple nearby poles can interfere differently in different channels → process-dependent "Y" line shapes	In 4.2–4.35 GeV: **one exotic pole** (plus $\psi(4160)$ as a known charmonium) can describe all channels consistently
Pole counting around 4.2–4.4	Reports **multiple** poles; they explicitly state "4 poles with $M \sim 4.23$ GeV, and 2 poles with $M \sim 4.38$ GeV" (Table III entries cluster as $M = 4192$, 4216, 4229, 4308 MeV and $M = 4346$, 4390 MeV)	Extracts a single $Y(4230)$ pole $\sqrt{s_{\text{pole}}} = (4227 \pm 4) - \frac{i}{2}(50^{+8}_{-2})$ MeV (in that window) and does not require an additional $Y(4320)$-like pole

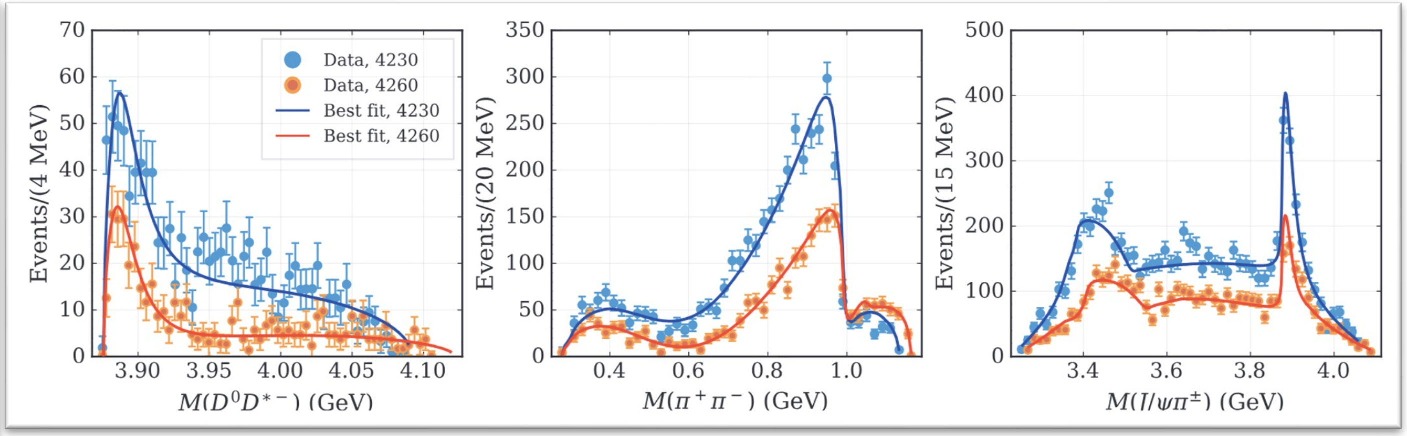
Practical takeaway for slides: **2741866** is a "global, many-channel DCC" view that naturally produces **multiple poles** and emphasizes process dependence; **2755412** is a "targeted multi-channel EFT/FSI" view arguing that in 4.2–4.35 GeV the data are already consistent with **one** exotic vector pole (plus $\psi(4160)$) once interference and FSI are treated carefully.

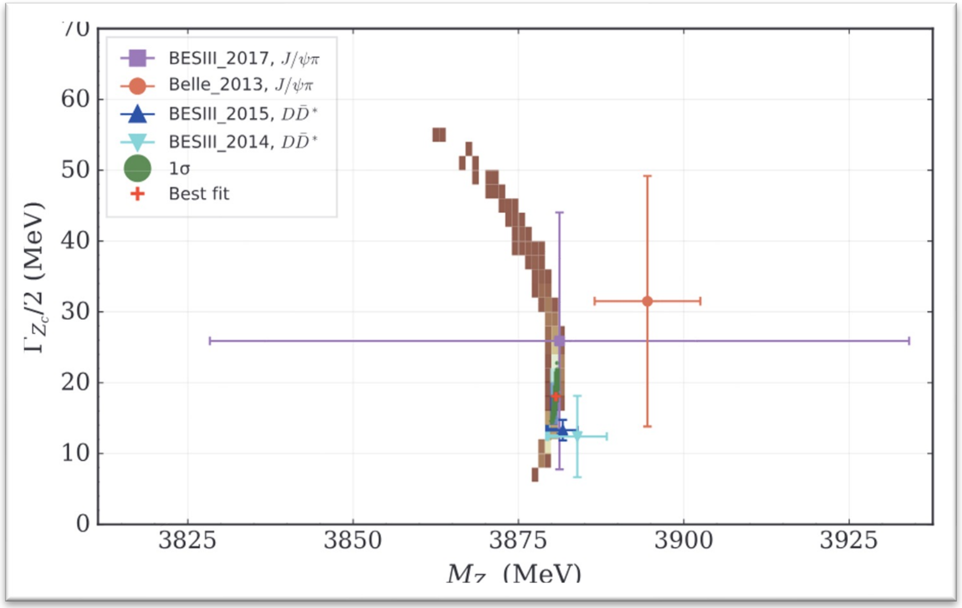
Most sophisticated analysis of $Z_c(3900)$

Y.-H. Chen, M-L. Du, FKG, SCPMA 67 (2024) 291011

- Take into account: $D\bar{D}^*$-$J/\psi\pi$ FSI ($Z_c(3900)$ lives here), triangle singularities, $\pi\pi - K\bar{K}$ FSI with left-hand cuts (from triangles & Z_c)





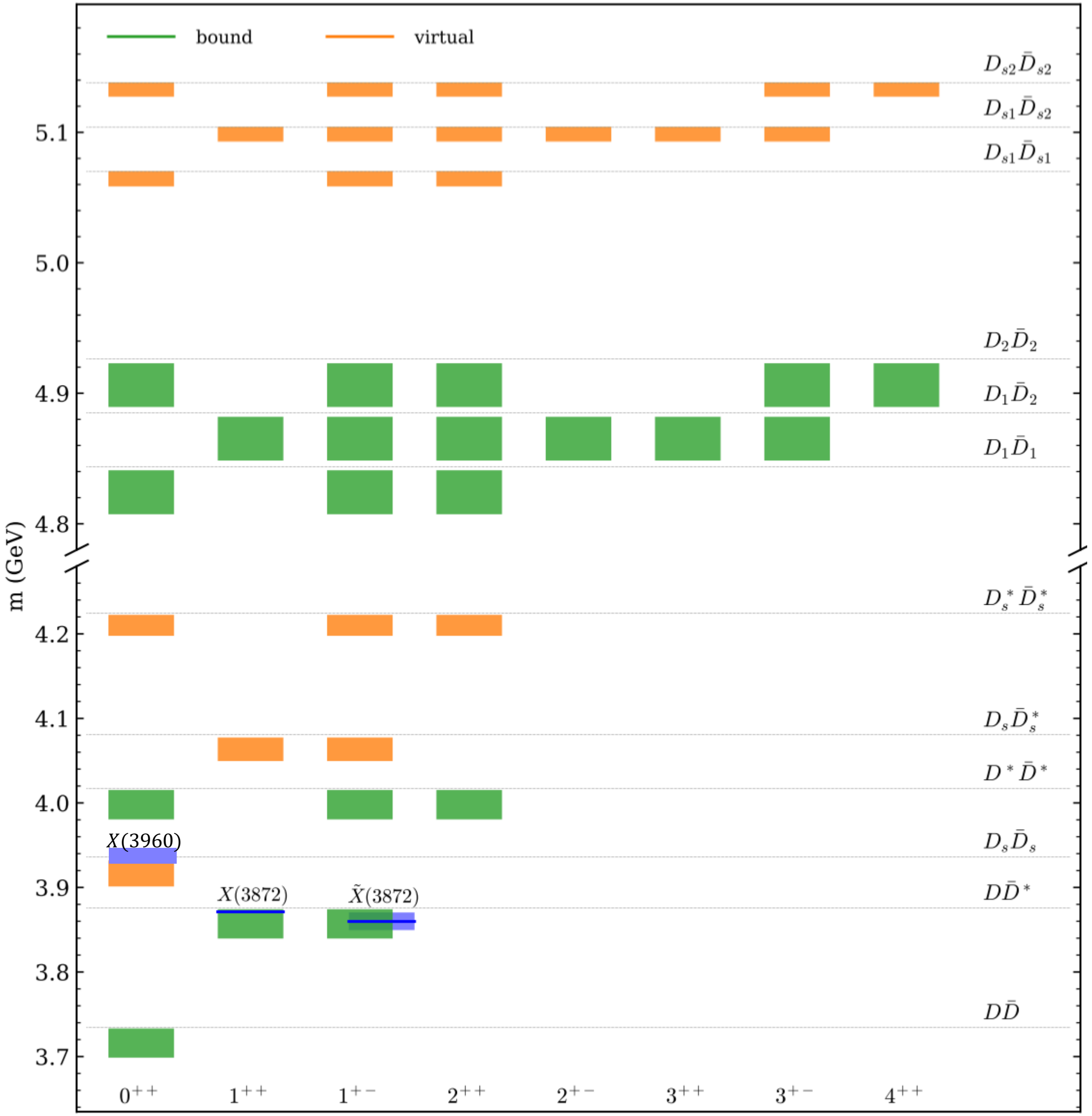


✓ $Z_c(3900)$ pole position

$$(3880.7 \pm 1.7 \pm 22.4) - \mathrm{i}(17.9 \pm 0.7 \pm 7.7)\ \mathrm{MeV}$$

Hidden-charm molecules: $P = +$

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



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

Some open questions (debates):

- ☐ Can radiative decays ($\to \psi\gamma$) be used to exclude mol.?

  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., PRL 134 (2025) 252301; …

✓ $\bar{D}D$ bound state

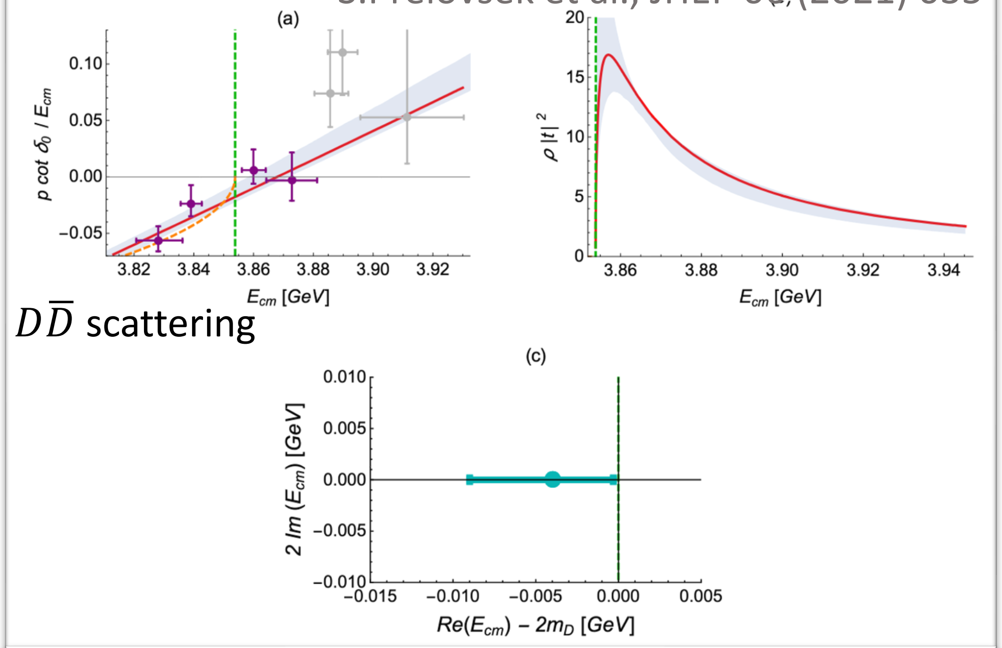
Conflicting lattice QCD results, what is the reason?

✓ Near-threshold bound state S.Prelovsek et al., JHEP 06 (2021) 035

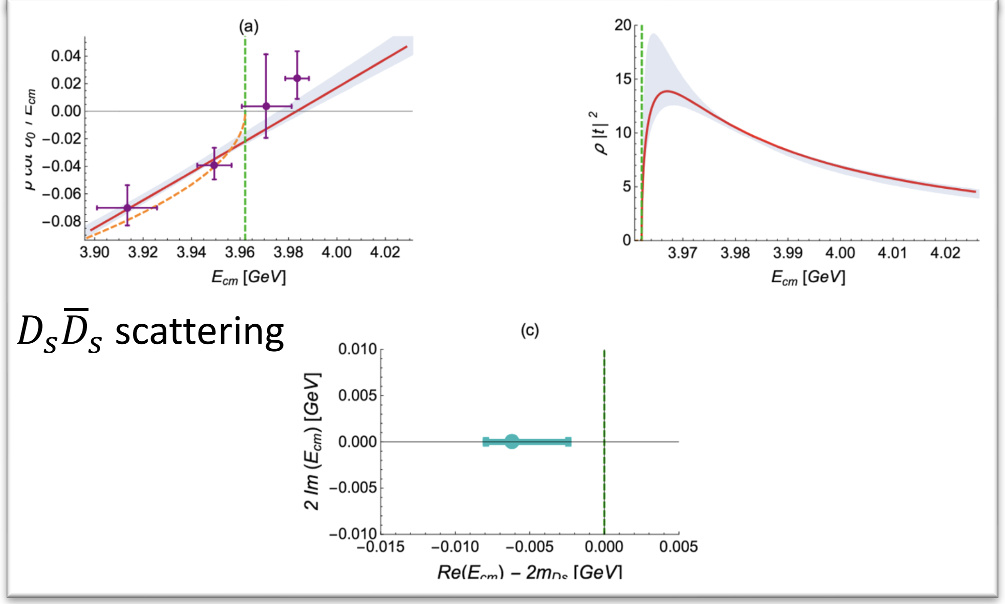
✗ No near-threshold state D.Wilson et al., PRL 132 (2024) 241901

Lattice results for $P = +$

S.Prelovsek et al., JHEP 06 (2021) 035



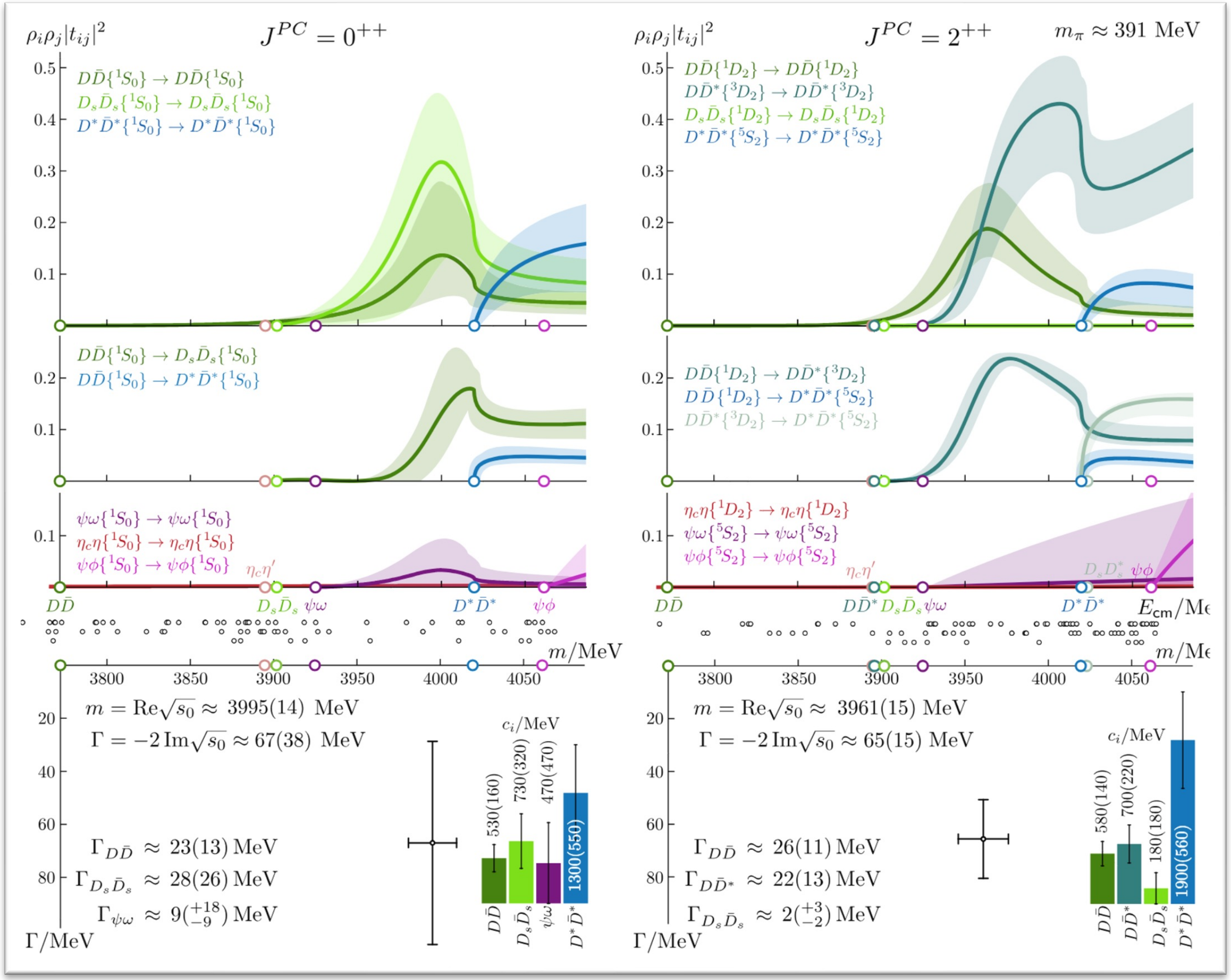
$D\bar{D}$ scattering



$D_s\bar{D}_s$ scattering

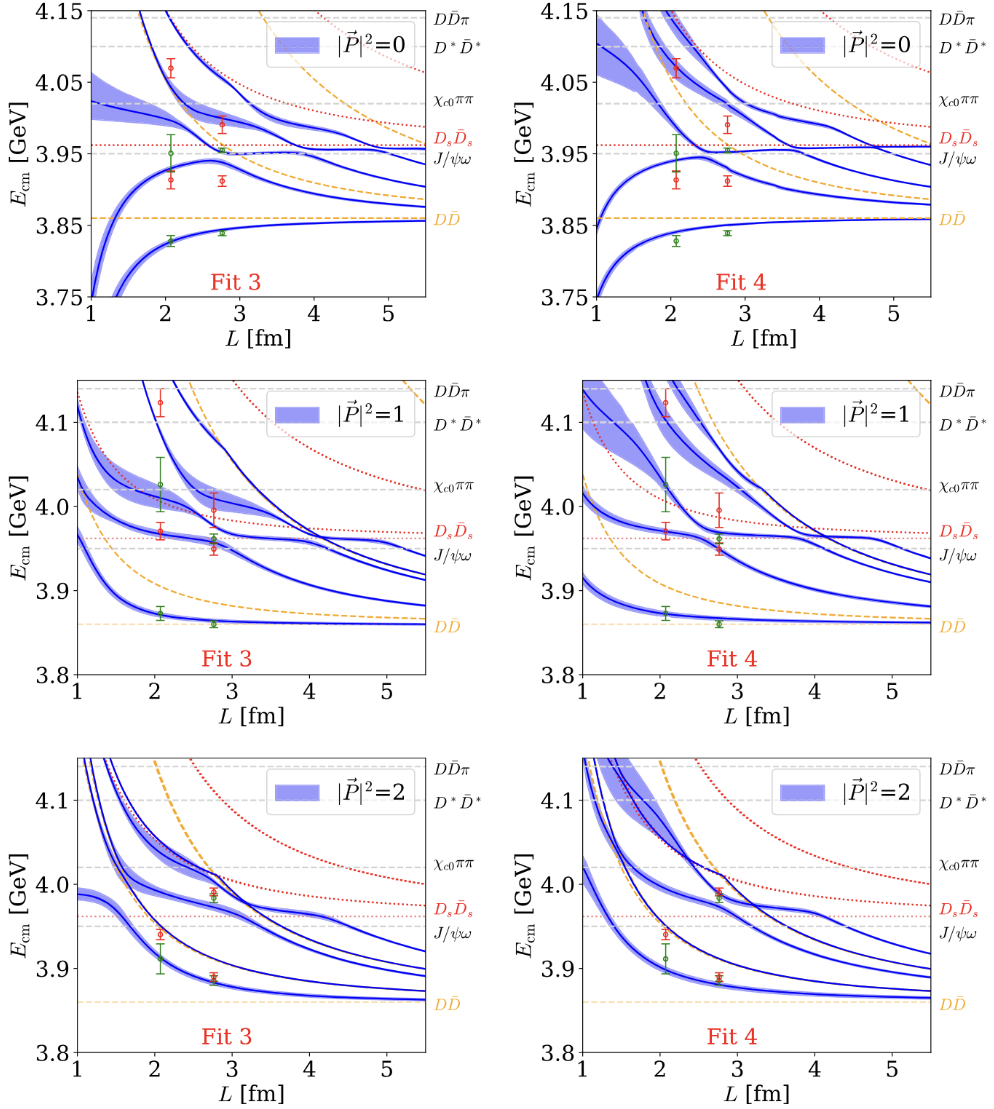
- HadSpec: one 0^{++}, one 2^{++}

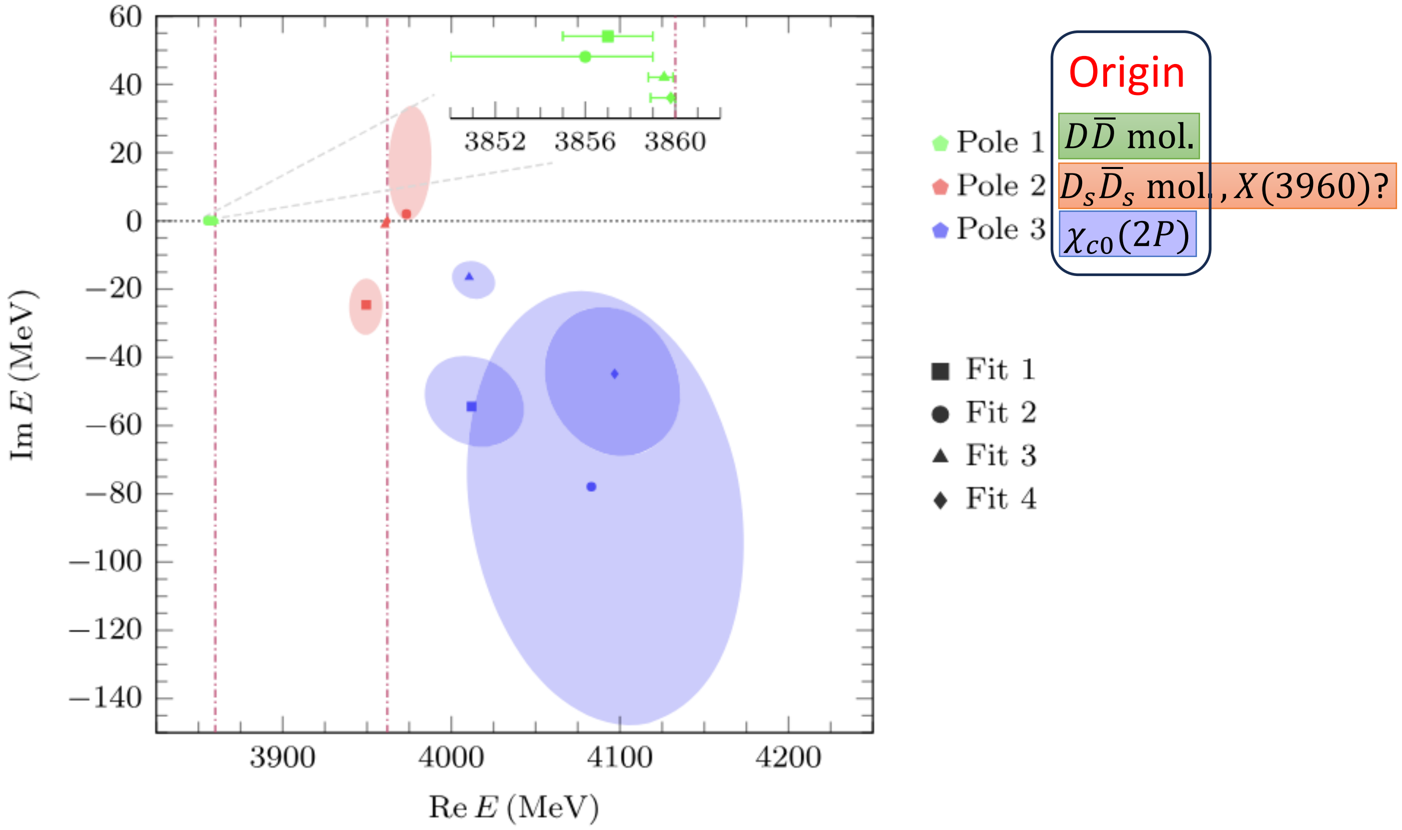
D.Wilson et al., PRL 132 (2024) 241901



Interplay of hadronic molecules and charmonia

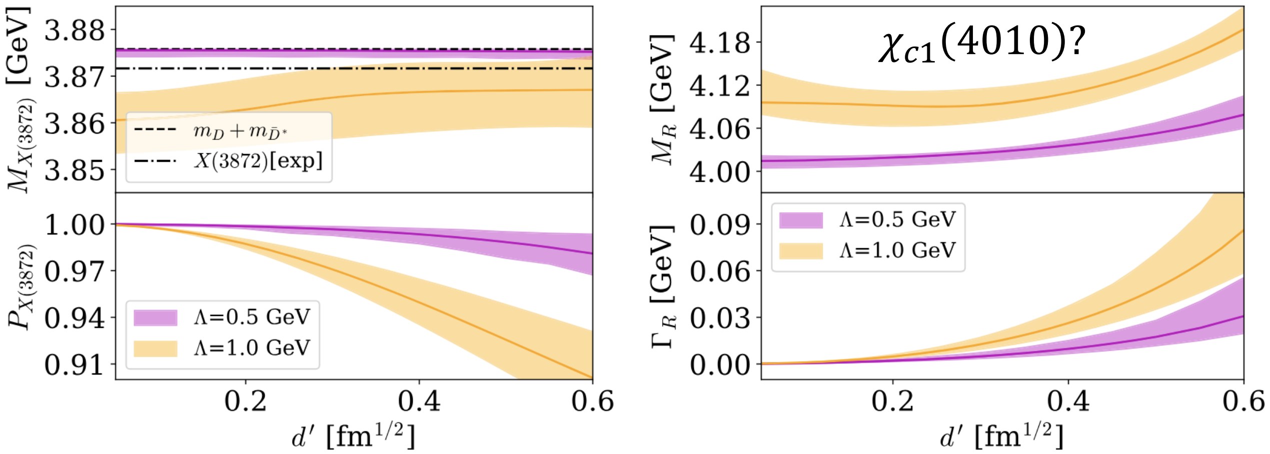
- Analysis of lattice energy levels P.-P. Shi, M. Albaladejo, M.-L. Du, FKG, J. Nieves, PRD 111 (2025) 074043; data from Prelovsek et al. (2021)
- 0^{++}: $D\bar{D} - D_s\bar{D}_s - \chi_{c0}(2P)$

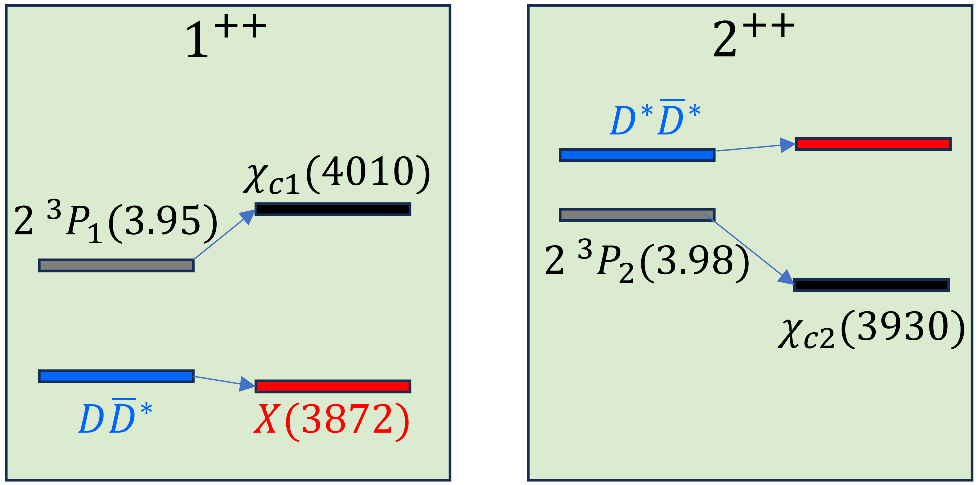




Interplay of hadronic molecules and charmonia

- Analysis of lattice energy levels P.-P. Shi, M. Albaladejo, M.-L. Du, FKG, J. Nieves, PRD 111 (2025) 074043; data from Prelovsek et al. (2021)
- 1^{++}, 2^{++} :
  - ☐ Essential feature of two-level mixing of Hermitian systems: levels pushed apart
    - ➢ Effective attraction to the lower, effective repulsion to the upper





$\chi_{c1}(4010)$: LHCb, PRL 133 (2024) 131902

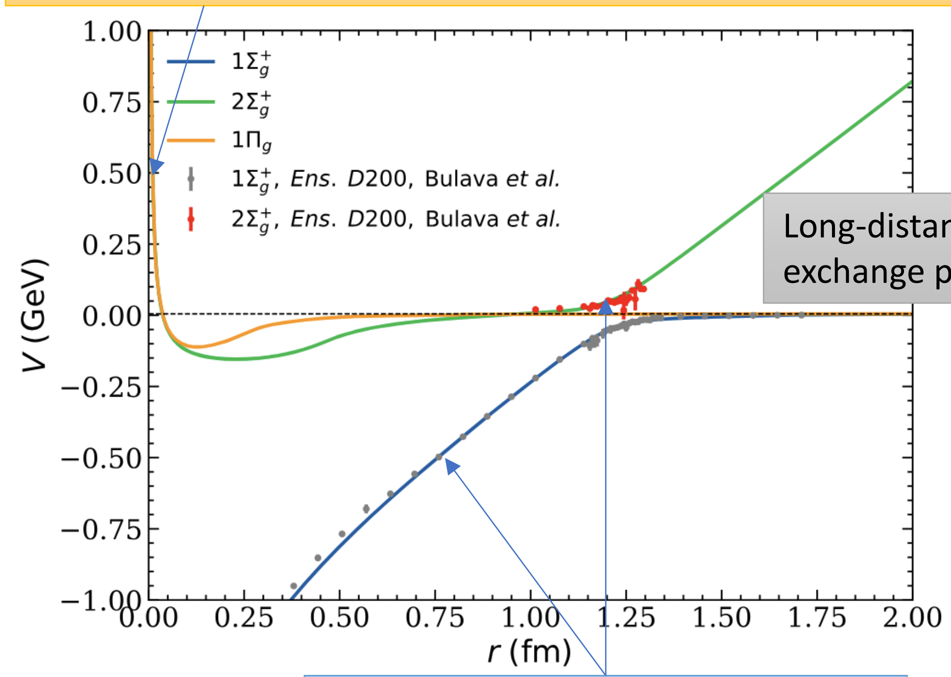
- Similar results (one more state in addition to $X(3872)$) for 1^{++} obtained, e.g.,
  - ☐ Lattice QCD: $\sim$ 4.0 GeV H.-Z. Li, C.-J. Shi, Y. Chen, M. Gong, J.-Z. Liang, Z.-F. Liu, arXiv:2402.14541
  - ☐ Boson-exchange model + bare charmonia: $\sim$ 3.96 GeV G.-J. Wang, Z. Yang, J.-J. Wu, M. Oka, S.-L. Zhu, Sci.Bull. 69 (2024) 2855

Some results from Born-Oppenheimer method

N. Brambilla, A. Mohapatra, T. Scirpa, A. Vairo, PRL 135 (2025) 131902

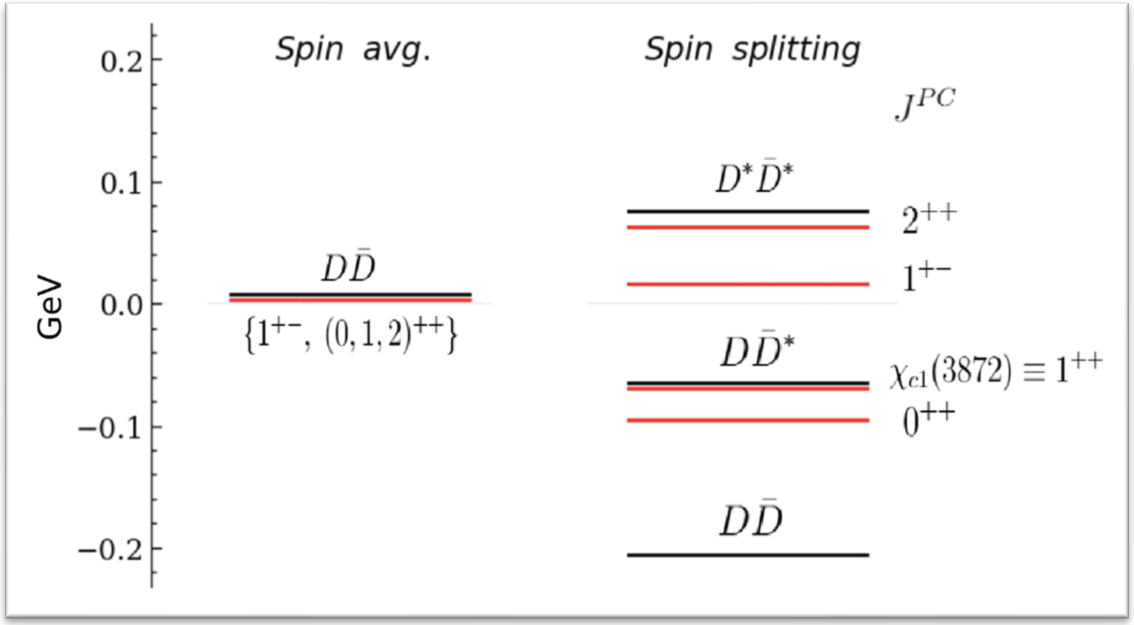
- Solve Schrödinger equation for $c\bar{c}$ in a BO potential (QCD static energy of light dof in the presence of static heavy sources separated by a distance)

Repulsive Coulomb (color octet), quenched lattice parametrization



Long-distance: two-pion exchange parametrization

Lattice (full QCD) parametrization,
Bulava et al., PLB 854 (2024) 138754



$X(3872)$: ~8% $c\bar{c}$, ~92% "tetraquark"

See also E. Braaten, R. Bruschini, PLB 863 (2025) 139386; D. Germani, B. Grinstein, A.D. Polosa, JHEP 04 (2025) 004

But what does this "tetraquark" mean?
Hadronic molecule is also dominated by color-octet $c\bar{c}$:

$$|(c\bar{q})_{\mathbf{1}}(\bar{c}q)_{\mathbf{1}}\rangle = \frac{1}{3}\,|(c\bar{c})_{\mathbf{1}}(q\bar{q})_{\mathbf{1}}\rangle + \frac{2\sqrt{2}}{3}\,|(c\bar{c})_{\mathbf{8}}(q\bar{q})_{\mathbf{8}}\rangle_{\mathbf{1}}$$

Closer look into $X(3872)$

Z.-H. Zhang, T. Ji, X.-K. Dong, FKG et al., JHEP 08 (2025) 130

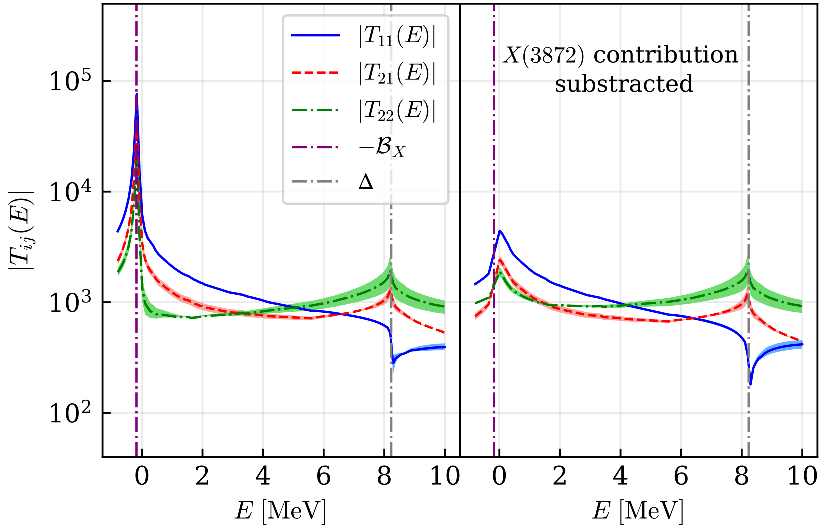
- Chiral EFT for the $J^{PC}=1^{++}$ $D\bar{D}^*$ interaction with three-body effects. Two low-energy constants at LO
- Two inputs from $X(3872)$ properties :
  - Mass

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

    $M_{D^0}+M_{D^{*0}} = 3871.69(7)$ MeV PDG 2024
  - Isospin breaking in decays LHCb, PRD 108 (2023) L011103

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

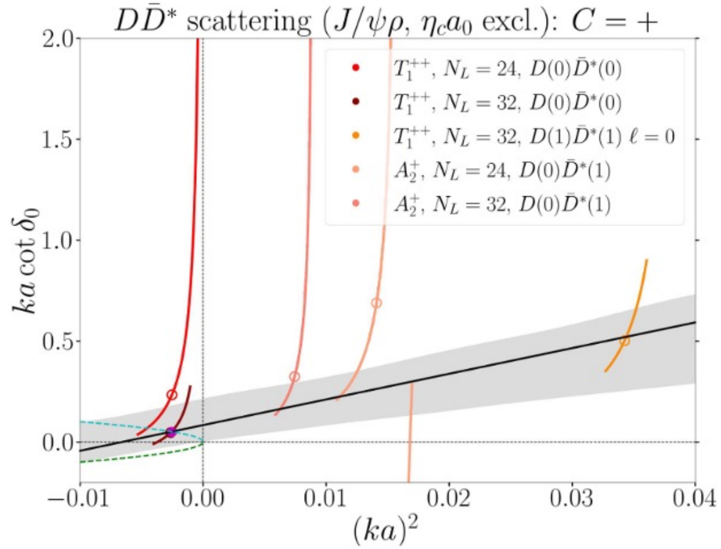
- Prediction: there must exist an isovector $J^{PC}=1^{++}$ state ($W_{c1}^{0,\pm}$)



- 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

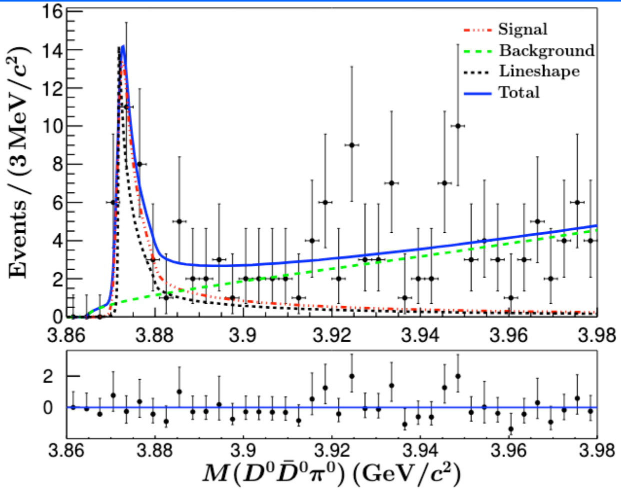
- $X(3872)$ line shapes ⇒ $X(3872)$ + possible $W_{c1}(3880)^0$
- $\pi^+\pi^-$ invariant mass distribution ⇒ isospin breaking, information on $I = 1$

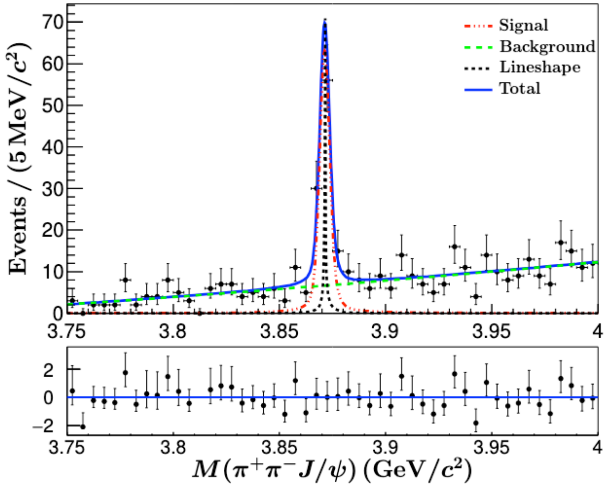
BESIII:

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

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

BESIII, PRL 132 (2024) 151903

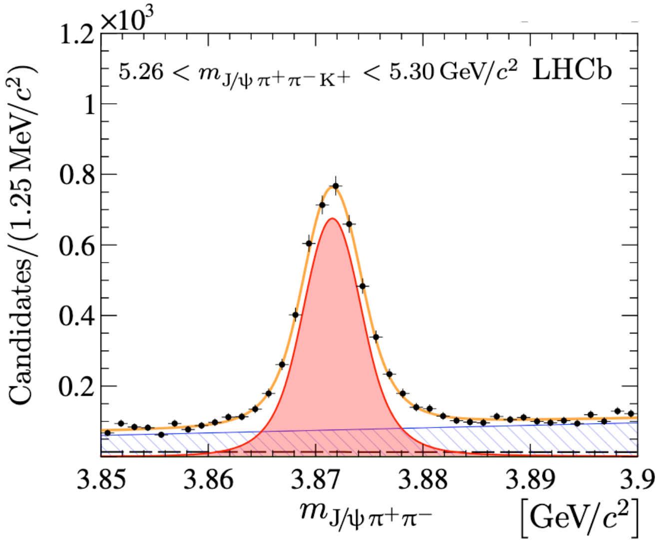


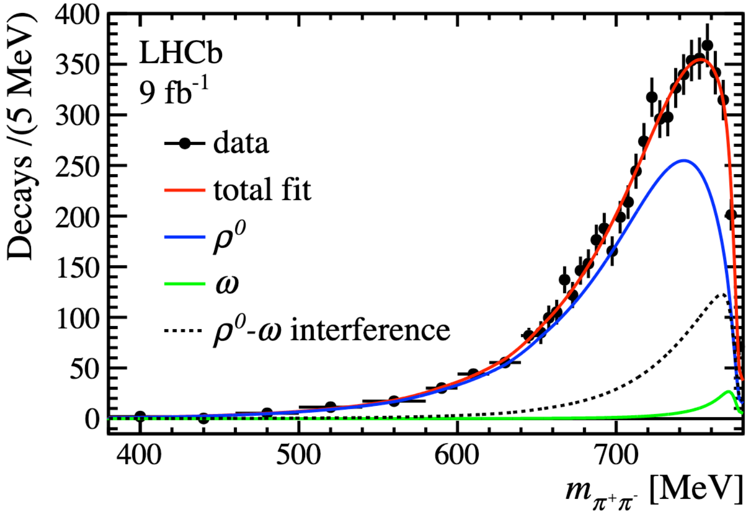


LHCb:

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

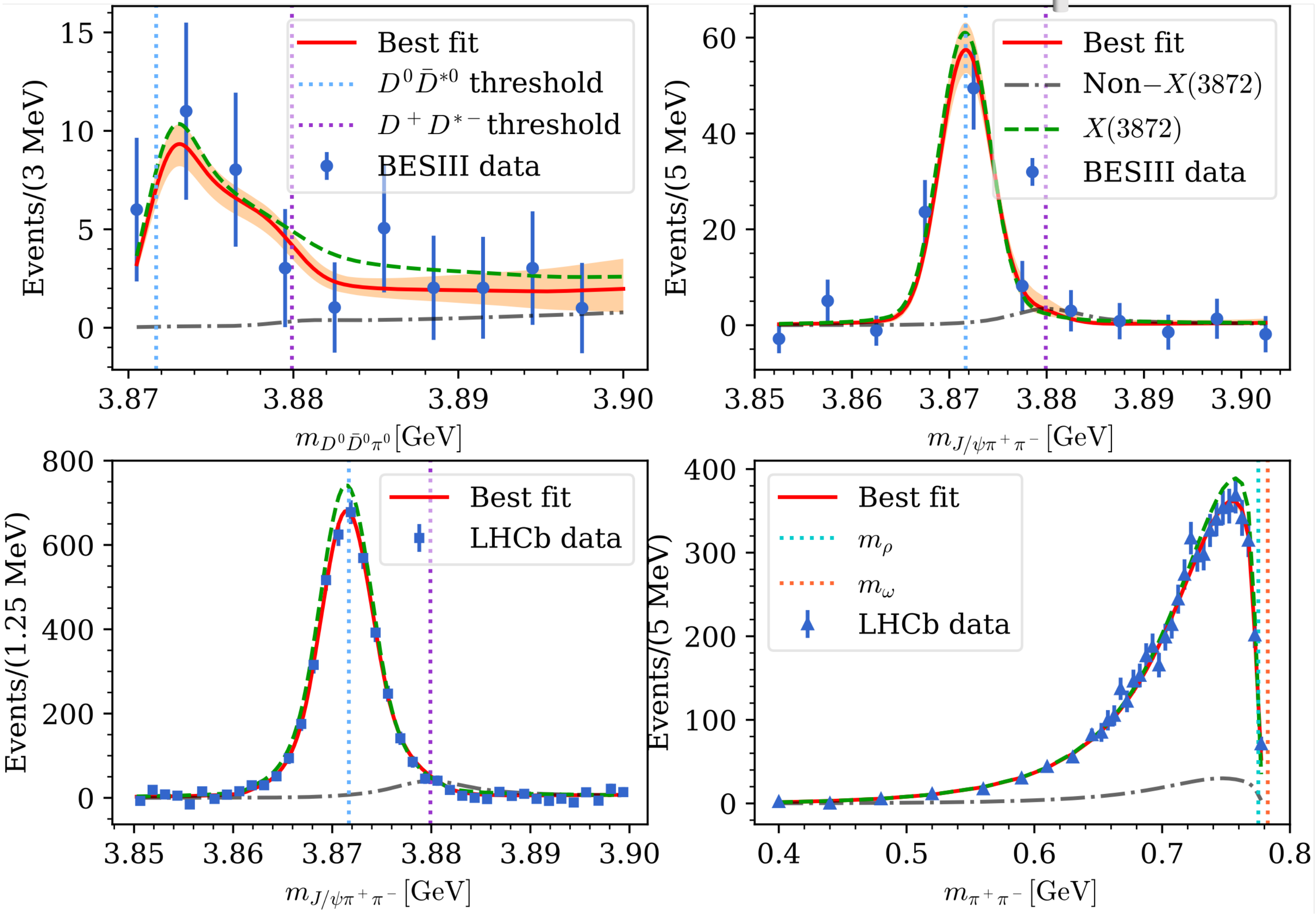
LHCb, JHEP 08 (2020) 123;
PRD 108 (2023) L011103





Combined analysis of BESIII + LHCb data w/ chiral EFT

Results updated

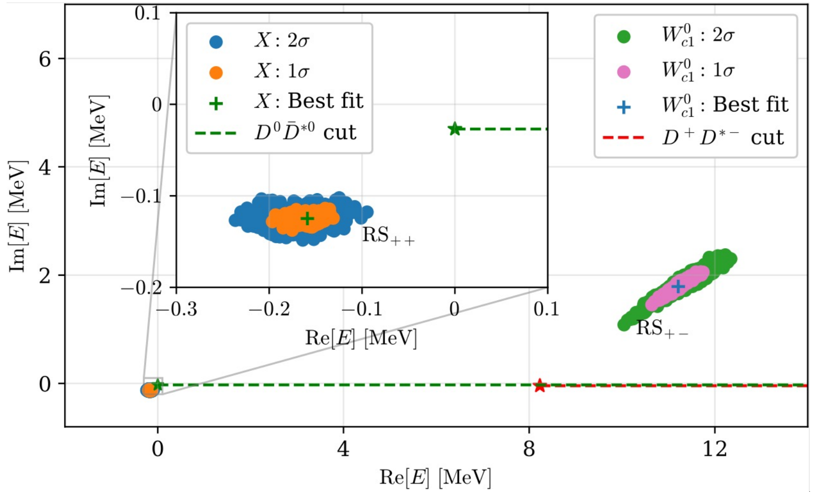


- Poles
  - $X(3872)$ as a bound state below $D^0\bar{D}^{*0}$ threshold (2.8σ)

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

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

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



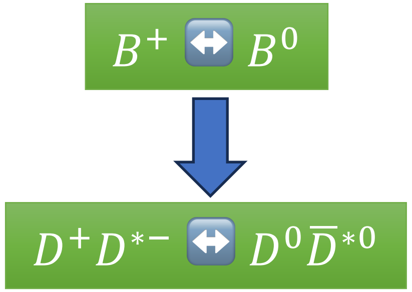
$\chi^2/\text{dof} = 57/(96-10) = 0.66$

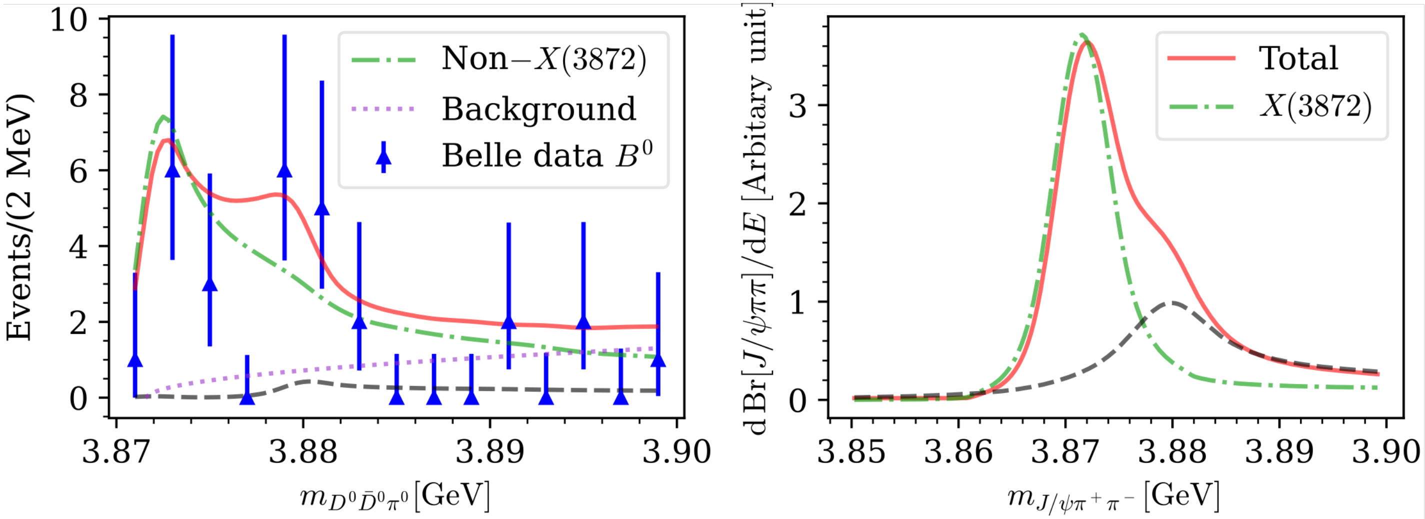
$$X = 1 - \exp\left(\frac{1}{\pi}\int_0^\infty dE\,\frac{\text{Re}\,\delta(E)}{E - \text{Re}\,E_X}\right) = 0.97(2)$$

X is predominantly molecular!

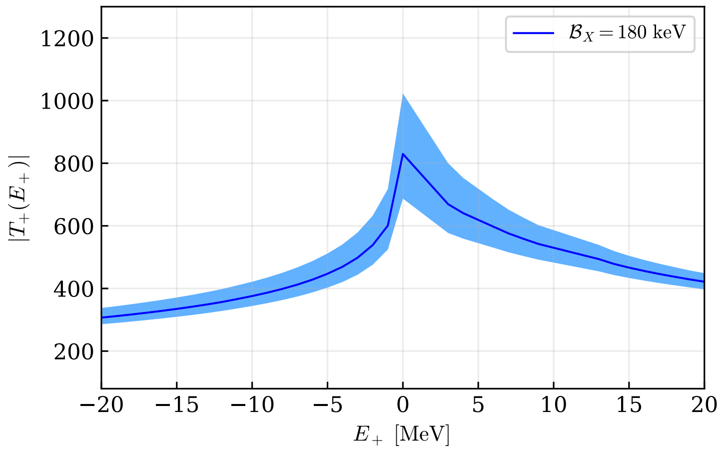
Implications of the existence of $W_{c1}(3880)$

- $W_{c1}(3880)^0$ 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

Some estimates for production

- Production of exotic 1^{-+} $\eta_{c1}^{(\prime)}$ from radiative decays of $\psi(4360{,}4415)$ X.-Y. Zhang, P.-P. Shi, FKG, PLB 867 (2025) 139603
- Direct production of X_2 P.-P. Shi, V. Baru, FKG, A. Nefediev, C. Hanhart, CPL 41 (2024) 031301

See the last couple of pages of the attached AI generated slides

Summary

- Existence of multiquark candidates and threshold effects is an essential feature of nonperturbative physics, offering unique opportunity to gain deep insights into confinement
- Lots of progress, but many unsolved problems

Thank you for your attention!

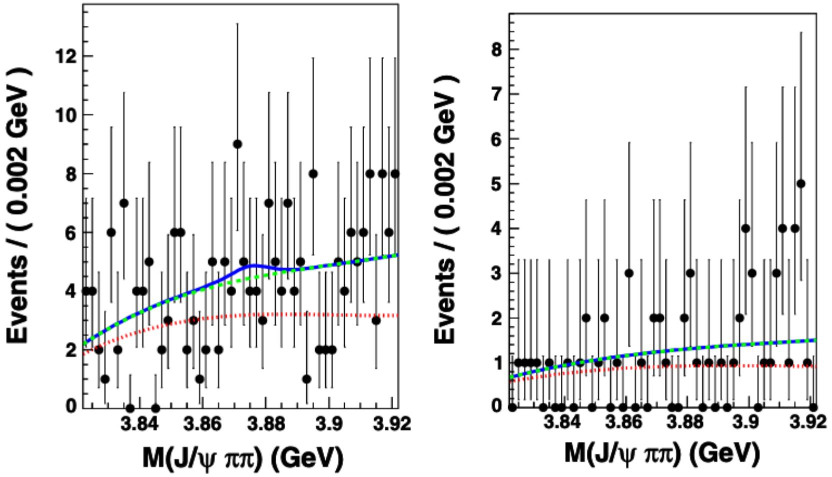

2026 马年大吉
马到成功

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

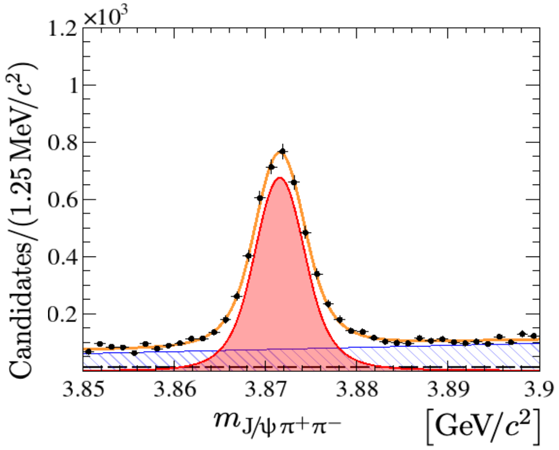
- No signal in the charged channel so far



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

Belle, PRD 84 (2011) 052004

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

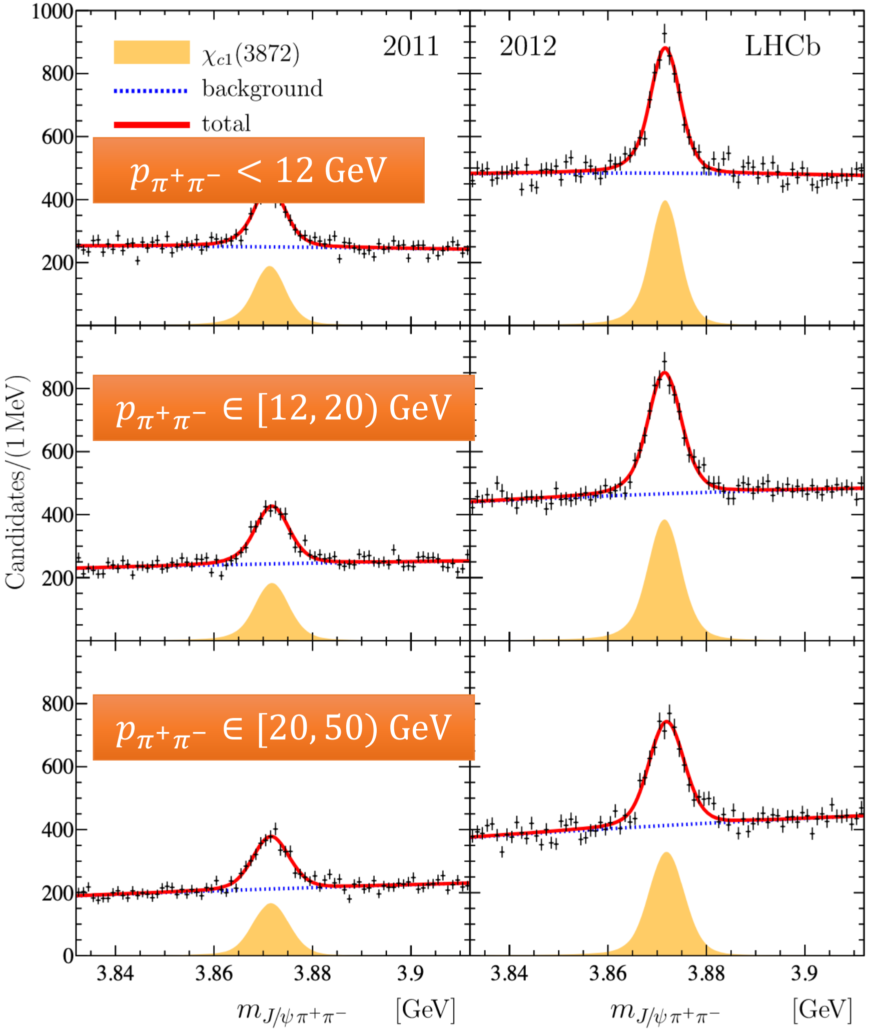


$B^+ \to K^+ \pi^+ \pi^- J/\psi$

LHCb, JHEP 08 (2020) 123

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

LHCb, PRD 102 (2020) 092005



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