

東南大學
SOUTHEAST UNIVERSITY

The 1st Annual Conference on EicC @Qingdao

Probing the Nature of $Z_c(3900)$ at EicC: Clues to DDD^* Bound State

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Southeast University

Apr. 20, 2026

Based on [Phys.Rev.D 111 \(2025\) 9, 094022](#)

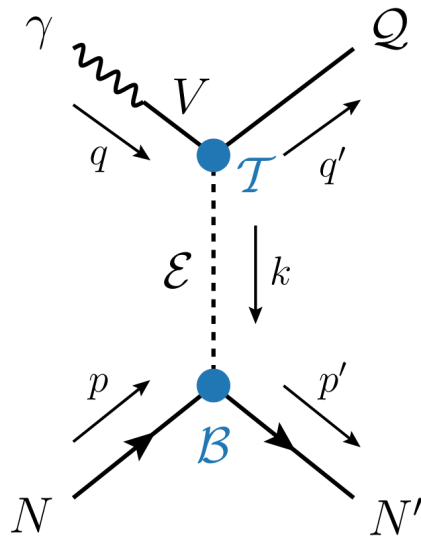
Collaborated with Hai-Xiang Zhu, Yao Ma, Ning Li, Wei Chen and Shi-Lin Zhu

EicC: A Promising Facility to Investigate $Z_c(3900)$

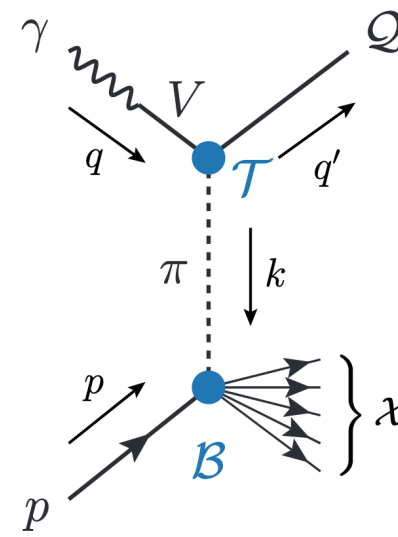


- **Photo- and electro-production facilities complement** the existing experiments producing exotic states

COMPASS, EIC-US and EicC



Exclusive photoproduction



Semi-inclusive photoproduction



- $Z_c(3900)$: $I^G(J^{PC}) = 1^+(1^+ -)$, minimal quark content: $q\bar{q}c\bar{c}$

- $e^+e^- \rightarrow Z_c(3900)\pi$

BESIII, PRL110 (2013) 252001;

Belle, PRL110 (2013) 252002;

CLEO-c, PLB727 (2013) 366-370;

- ▶ $\rightarrow (J/\psi\pi)\pi$

- ▶ $\rightarrow (D^*\bar{D})\pi$

...

- ▶ E_{cm} around 4.23 and 4.26 GeV

- No observations in b-hadron decay

- ▶ Evidence (4.6σ) in semi-inclusive weak decays of b-flavored hadrons

D0, PRD 98, 052010 (2018).

- Debates

- ▶ **Triangle singularity** amplifies the production \Rightarrow sensitive to E_{cm}

Q. Wang et al, PRL111 (2013) 13, 132003; X.H.Liu and G.Li PRD88 (2013) 014013

- ▶ Purely triangle singularity, or **do poles also contribute?**

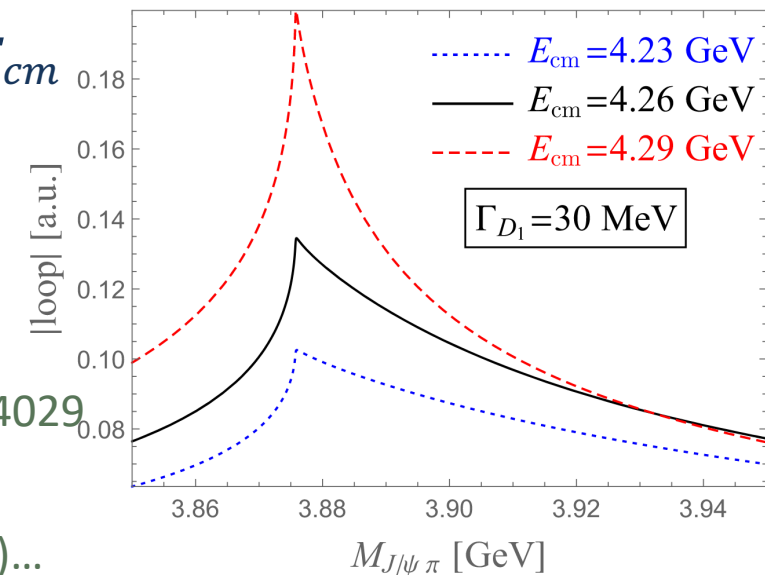
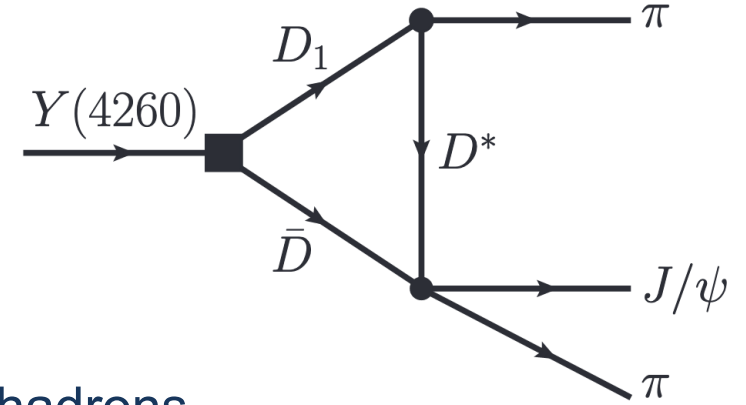
JPAC, PLB 772, 200 (2017); M. Albaladejo, F. K. Guo, et al, PLB755 (2016), 337...

- ▶ If pole exists, **bound state, resonance, or virtual state?**

S. X. Nakamura et al, PRD112 (2025), 054027, K.Yu et al, PRD110 (2024), 114029

- ▶ If pole exists, **hadronic molecule or compact tetraquark?**

L.-W. Yan et al, PRD109, 014026 (2024), S. X. Nakamura et al, PRD112 (2025)...



F.-K. Guo, X.-H. Liu, and S. Sakai, PPNP112, 103757 (2020).

Refit Ex. data using amplitudes with exact unitarity.

M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	[1] (BESIII)	$J/\psi \pi$
3895 ± 8	32 ± 18	[2] (Belle)	$J/\psi \pi$
3886 ± 5	19 ± 5	[3] (CLEO-c)	$J/\psi \pi$
3884 ± 5	12 ± 6	[4] (BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	[5] (BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda = 1.0$ GeV	$J/\psi \pi, \bar{D}^* D$
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda = 0.5$ GeV	$J/\psi \pi, \bar{D}^* D$
$3831 \pm 26^{+7}_{-28}$	virtual state	$\Lambda = 1.0$ GeV	$J/\psi \pi, \bar{D}^* D$
$3844 \pm 19^{+12}_{-21}$	virtual state	$\Lambda = 0.5$ GeV	$J/\psi \pi, \bar{D}^* D$

solution I: resonance

Solution II: virtual state

Below thresh. 30-40 MeV

M. Albaladejo, F. K. Guo, C. Hidalgo-Duque and J. Nieves, PLB755 (2016), 337-342

Three-coupled-channel analysis: $D\bar{D}^*$, $J/\psi \pi$, and $\rho\eta_c$

	Pole Position	Type	Scheme($\Lambda_{\pi J/\psi}$)
This work	3798.72 - 1.10i	Virtual	1(1.3GeV)
	3798.46 - 1.71i		1(1.5GeV)
	3798.12 - 2.26i		1(1.7GeV)
	3798.27 - 2.02i		2(1.5GeV)
	3797.80 - 2.64i		2(1.7GeV)

Virtual state Pole below threshold 80 MeV

K.Yu, G.J.Wang, J.J.Wu and Z.Yang, PRD110 (2024), 114029

Global coupled-channel analysis of $e^+e^- \rightarrow c\bar{c}$

TABLE VI. $IJ^{PC} = 11^{+-}$ $D^*\bar{D} - D^*\bar{D}^* - J/\psi\pi - \psi'\pi - h_c\pi - \eta_c\rho$ coupled-channel scattering amplitude poles (unit:MeV). $Z_c(3900)$ and $Z_c(4020)$ are $D^*\bar{D}$ and $D^*\bar{D}^*$ virtual (resonance) poles in this work (PDG [4]).

$E_{Z_c}^{\text{This work}}$	$M_{Z_c}^{\text{PDG}}$	$\Gamma_{Z_c}^{\text{PDG}}$	
$(3837.7 \pm 7.4) + (19.4 \pm 1.6)i$	3887.1 ± 2.6	28.4 ± 2.6	$Z_c(3900)$
$(3989.9 \pm 5.6) + (26.1 \pm 4.3)i$	4024.1 ± 1.9	13 ± 5	$Z_c(4020)$

Virtual state: below thresh. 30-40 MeV

S. X. Nakamura, X. H.Li, H.P.Peng, Z.T.Sun and X.R.Zhou, PRD112 (2025), 054027

$\pi^+\pi^-$ and $J/\psi\pi^\pm$ mass spectra @ $e^+e^- \rightarrow J/\psi\pi^+\pi^-$
 D^*D^{*-} mass spectrum @ $e^+e^- \rightarrow D^*D^{*-}\pi^+$

resonance:

$(3880.7 \pm 1.7 \pm 22.4) - i(17.9 \pm 0.7 \pm 7.7)$ MeV.

Y.H.Chen, M.L.Du and F.K.Guo, *Sci.China Phys.Mech.Astron.* 67 (2024) 9, 291011

- **Abundant production** of near-threshold hidden-charm molecular states
- Likely free from triangle singularity

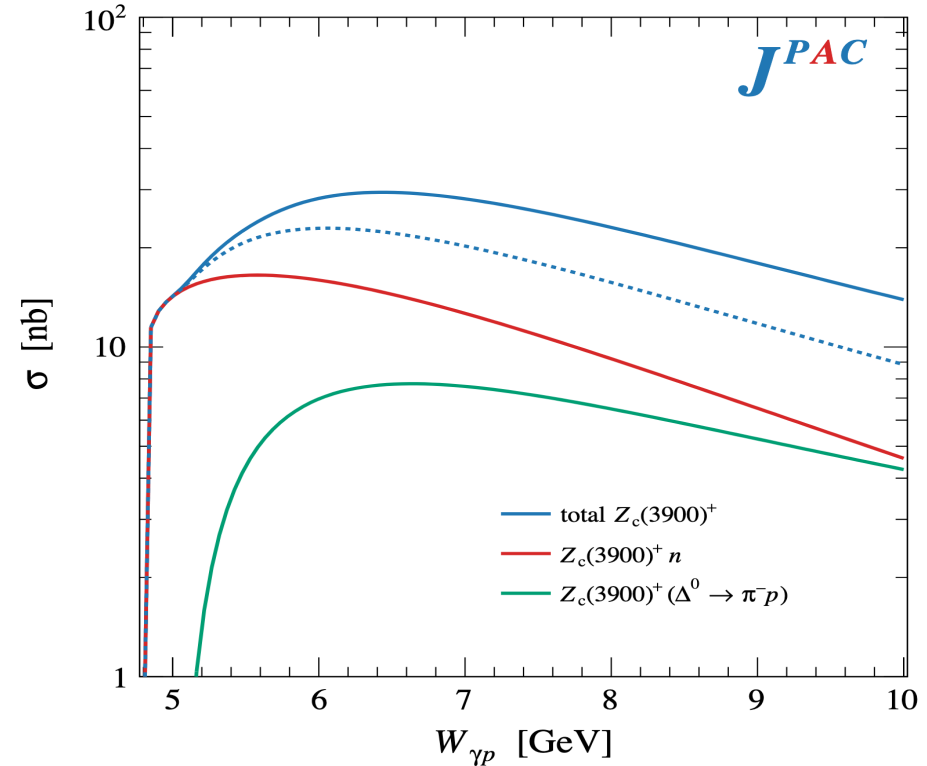
Integrated cross sections (in units of pb)

	Constituents	$J^{P(C)}$	COMPASS	EicC	US-EIC
$X(3872)$	$D\bar{D}^*$	1^{++}	19(78)	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	$0.3 \times 10^3 (1.2 \times 10^3)$	$0.4 \times 10^3 (1.3 \times 10^3)$	$3.8 \times 10^3 (14 \times 10^3)$
$Z_c(3900)^+$	$D^* \bar{D}^0$	1^+	$0.2 \times 10^3 (0.9 \times 10^3)$	$0.3 \times 10^3 (1.0 \times 10^3)$	$2.7 \times 10^3 (9.9 \times 10^3)$
$Z_c(4020)^0$	$D^* \bar{D}^*$	1^{+-}	$0.1 \times 10^3 (0.5 \times 10^3)$	$0.2 \times 10^3 (0.6 \times 10^3)$	$1.7 \times 10^3 (6.3 \times 10^3)$

Semi-inclusive production in **molecular** scheme

Z. Yang and F.-K. Guo, CPC45, 123101 (2021).

Q.-Y. Lin, X. Liu, and H.-S. Xu, Phys. Rev. D 88, 114009 (2013).
 Y.-P. Xie, X.-Y. Wang, and X. Chen, Eur. Phys. J. C 81, 710 (2021).
 X. Cao, Front. Phys. 18, 44600 (2023).
 ...

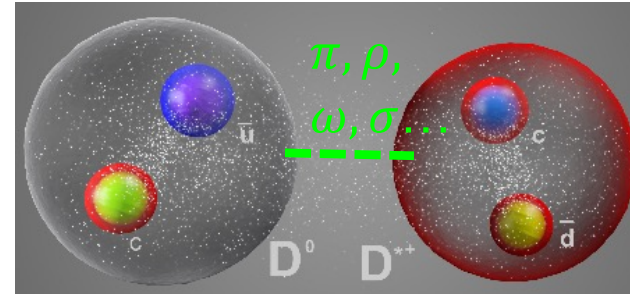
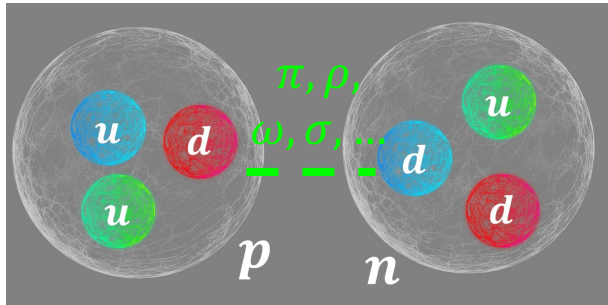


JPAC, PRD106, 094009 (2022).

$Z_c(3900)$ nature: clue to the DDD^* Bound State



- Hadronic molecule: deuteron as a typical example

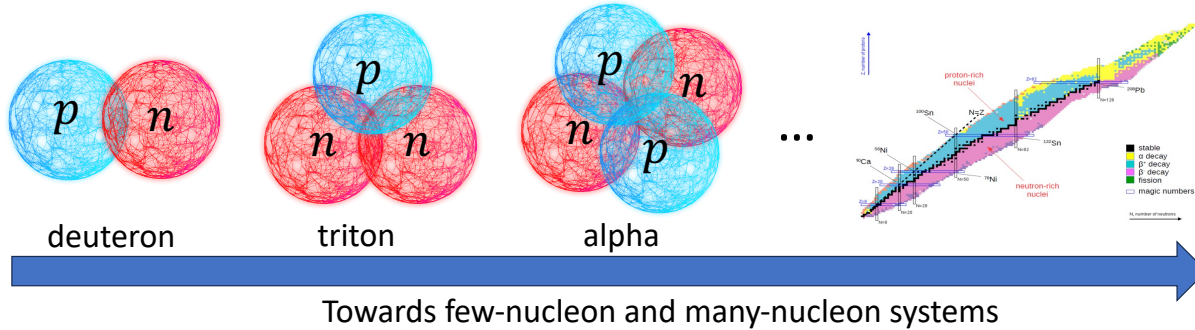


- Great interest in DD^* and $\bar{D}D^*/D\bar{D}^*$ molecular states

	Quark contents	$I^G(J^{PC})$	Threshold	ΔM [MeV]	Γ [MeV]	Ref
$X(3872)$	$q\bar{q}c\bar{c}/c\bar{c}$	$0^+(1^{++})$	$D^0\bar{D}^{0*}$	$0.0068^{+0.1655}_{-0.17000}$	$0.380^{+0.412}_{-0.322}$	BESIII:2023hml
$Z_c(3900)$	$q\bar{q}c\bar{c}$	$1^+(1^{+-})$	$D\bar{D}^*$	11.3 ± 2.6	28.4 ± 2.6	PDG
$T_{cc}(3875)$	$\bar{q}\bar{q}cc$?	$D^{*+}D^0$	$-0.360^{+0.040}_{-0.040}$	$0.048^{+0.002}_{-0.014}$	LHCb:2021auc

Towards three-body systems

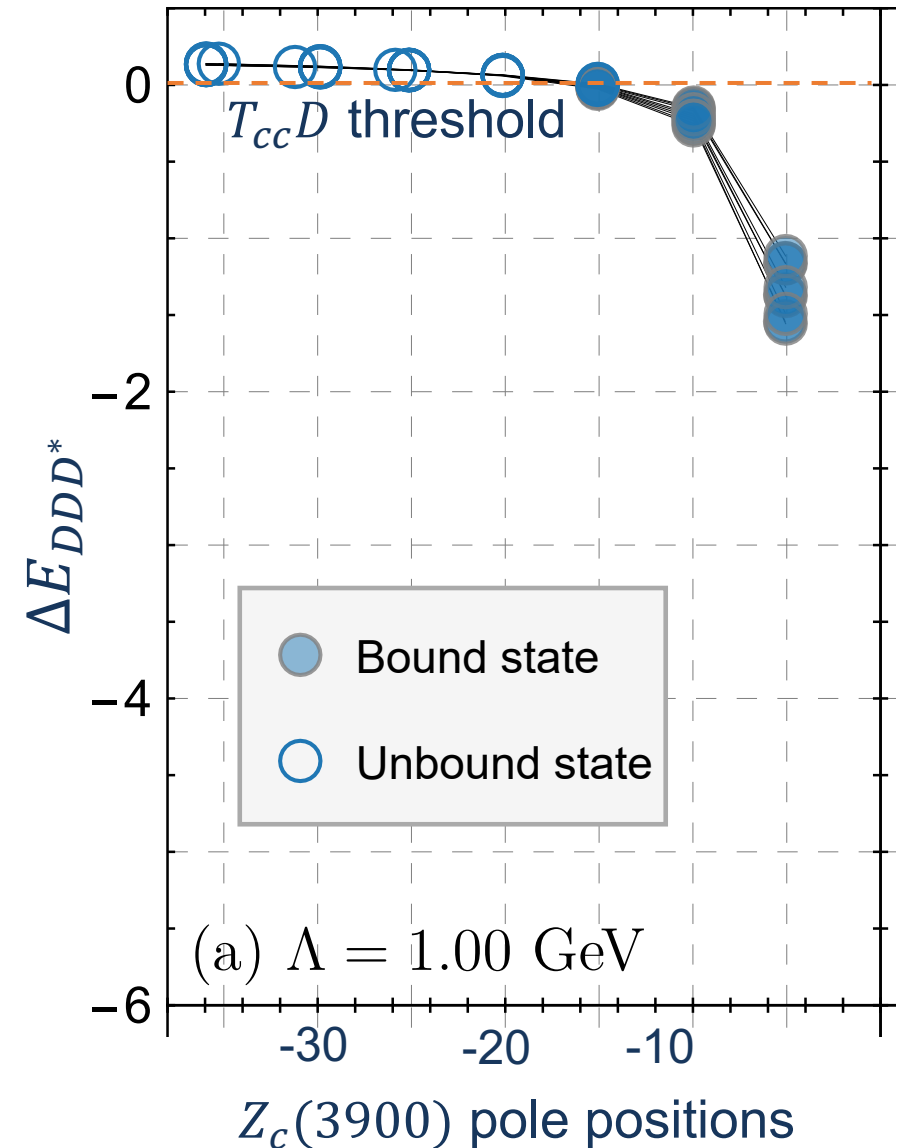
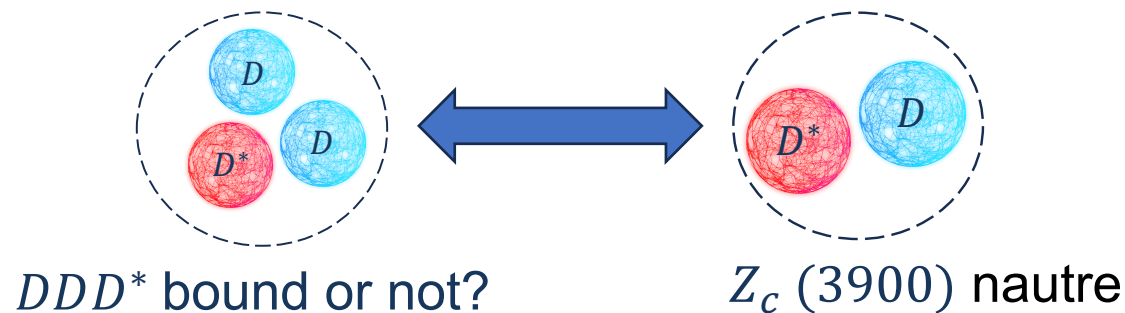
- Nucleon as the “building block”



- New frontier: D and D^* as “building block”

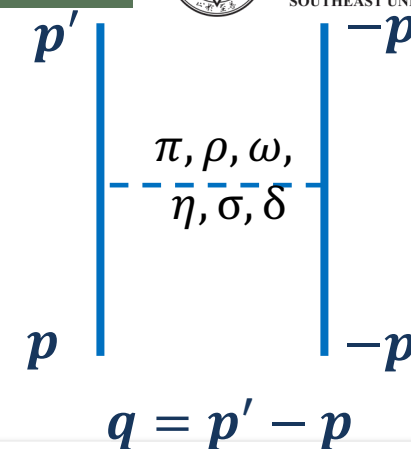
M.-Z. Liu, Y.-W. Pan, Z.-W. Liu, T.-W. Wu, J.-X. Lu, and L.-S. Geng, Phys. Rept. 1108, 2368 (2024).

- Unraveling the nature of $Z_c(3900) \Rightarrow$ existence of DDD^*



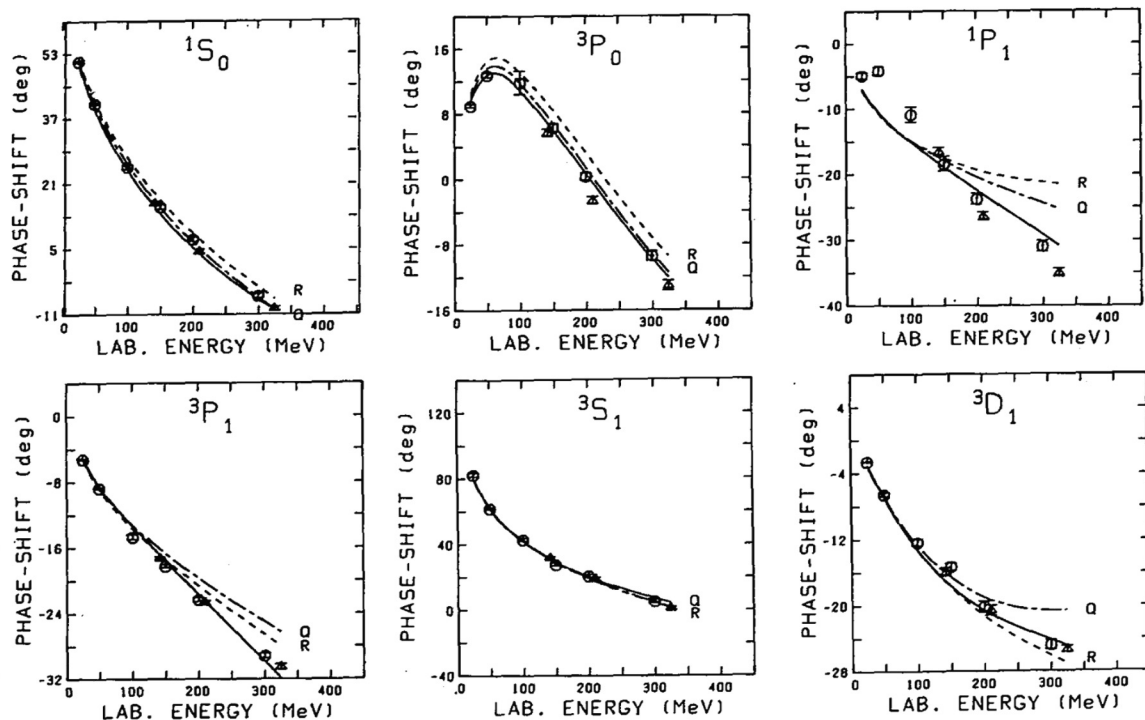
NN in meson-exchange models

- Interaction via one-boson exchange
- Great success in nuclear force
- G-parity rules (particle-particle \leftrightarrow particle-antiparticle)



R. Machleidt, K. Holinde, and C. Elster, Phys. Rept. **149**, 1 (1987).

Phase shift



Properties of deuteron

	Theory	Experiment
ϵ_d (MeV)	2.2246	2.224644 ± 0.000046
P_D (%)	4.38	—
Q_d (fm ²)	0.274^a	0.2860 ± 0.0015
μ_d (μ_N)	0.8548^a	0.857406 ± 0.000001
A_S (fm ^{-1/2})	0.8862	0.8846 ± 0.0016
D/S	0.0262	0.0271 ± 0.0008
r_d (fm)	1.9684	1.9660 ± 0.0068
a_s (fm)	-23.744	-23.748 ± 0.010
r_s (fm)	2.704	2.75 ± 0.05
a_t (fm)	5.424	5.424 ± 0.004
r_t (fm)	1.760	1.759 ± 0.005

Hadronic molecules in OBE

Predictions in OBE model

N. A. Tornqvist, *PRL67 (1991) 556-559*

J.-J. Wu, R. Molina, E. Oset, and B. S. Zou, *PRL105, 232001 (2010)*,
Z.-C. Yang, Z.-F. Sun, J. He, X. Liu, and S.-L. Zhu, *CPC36, 6(2012)*

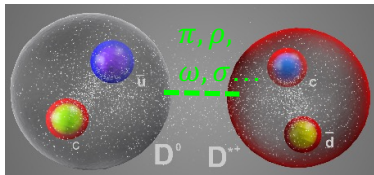
N. Li, Z.-F. Sun, X. Liu, and S.-L. Zhu, *PRD88, 114008 (2013)*.

$X(3872)$
The 1st charmonium-like state

$Z_c(3900)$
The 1st manifestly exotic charmonium-like state

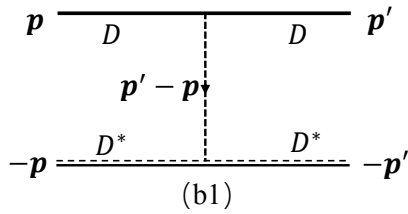
$P_{c\bar{c}}$
The 1st pentaquark states

$T_{cc}(3875)$
The 1st open double charm tetraquark state

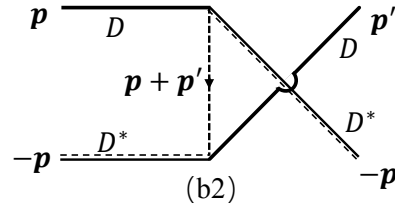


Hadronic molecules in OBE

D. Gamermann, E. Oset, D. Strottman, and M. J. Vicente Va cas, *PRD76, 074016 (2007)*
 Y.-R. Liu, X. Liu, W.-Z. Deng, and S.-L. Zhu, *EPJC56, 63 (2008)*
 X. Liu, Y.-R. Liu, W.-Z. Deng, and S.-L. Zhu, *PRD77, 094015 (2008)*,
 C. E. Thomas and F. E. Close, *PRD78, 034007 (2008)*
 G.-J. Ding, J.-F. Liu, and M.-L. Yan, *PRD79, 054005 (2009)*
 X. Liu, Z.-G. Luo, Y.-R. Liu, and S.-L. Zhu, *EPJC61, 411 (2009)*
 X. Liu, Z.-G. Luo, Y.-R. Liu, and S.-L. Zhu, *EPJC 61, 411 (2009)*
 I. W. Lee, A. Faessler, T. Gutsche, and V. E. Lyubovitskij, *PRD80, 094005 (2009)*
 Z.-F. Sun, J. He, X. Liu, Z.-G. Luo, and S.-L. Zhu, *PRD84, 054002 (2011)*
 N. Li and S.-L. Zhu, *PRD86, 074022 (2012)*
 R. Chen, A. Hosaka, and X. Liu, *PRD96, 116012 (2017)*
 R. Chen, Z.-F. Sun, X. Liu, and S.-L. Zhu, *Phys. Rev. D 100, 011502 (2019)*
 J. He, *EPJC 79, 393 (2019)*
 M. Pavon Valderrama, *PRD 100, 094028 (2019)*
 R. Chen and Q. Huang, *PRD103,034008 (2021)*
 R.Chen,Q.Huang,X.Liu,andS.-L.Zhu, *PRD104,114042(2021)*
 X.-K. Dong, F.-K. Guo, and B.-S. Zou, *Commun.Theor.Phys.73, 125201(2021)*,
 X.-K.Dong,F.-K.Guo, andB.-S.Zou, *Progr. Phys. 41, 65 (2021)*
 M.-Z. Liu, T.-W. Wu, M. Sanchez, M. P. Valderrama, L.-S. Geng, and J.-J. Xie, *PRD,103, 054004 (2021)*,
 R. Chen, X. Liu, X. Q. Li and S.L.Zhu, *PRL115, 132002, (2015)*
 R. Chen, J.He and X. Liu, *CPC41, 103105 (2017)*
 R. Chen, A. Hosaka and X. Liu, *PRD96, 114030 (2017)*
 F. L. Wang, R. Chen, Z. W. Liu and X. Liu, *PRC101, 025201, (2020)*



(b1)
 g_s for σ ,
 β for ρ, ω



(b2)
 g_a for π, η ;
 λ for ρ, ω

- 4 Coupling constants in SU(3) flavor and heavy quark symmetry
- g_a : extracted from $D^* \rightarrow D\pi$
- Three remains unknown: λ, β, g_s
 - ▶ Badly determined, *not in unified framework*
 - ▶ The g_s^2 in different papers are different by **20 times!!!**

Model-I { [53] N. Li and S.L.Zhu, PRD86, 074022 (2012)

[54] N. Li, Z.-F. Sun, X.Liu and S.-L. Zhu, PRD88, 114008 (2013)

Model-II { [65] T.-W. Wu, Y.-W.Pan, M.-Z.Liu,S.-Q.Luo, L.-S. Geng, X.Liu, PRD105,L031505(2022)

[84] M.-Z.Liu, T.-W. Wu, M.P. Valderrama, J.-J.Xie and L.-S.Geng, PRD99, 094028 (2019)

V	C_{coupling}			
		Model-I[53, 54]	Model-II[65, 84]	
V_ρ^D	$\frac{\beta^2 g_v^2}{2}$	13.62	$2g_\rho^2$	13.52
V_ω^D	$\frac{\beta^2 g_v^2}{2}$	13.62	$2g_\omega^2$	13.52
V_σ^D	g_s^2	0.58	g_σ^2	11.56
V_π^C	$\frac{g_a^2}{f_\pi^2}$	19.15	$\frac{g^2}{f_\pi^2}$	20.66
V_η^C	$\frac{g_a^2}{f_\pi^2}$	19.15	0	0
V_ρ^C	$2\lambda^2 g_v^2$	21.10	$\frac{f_\rho^2}{2M^2}$	19.64
V_ω^C	$2\lambda^2 g_v^2$	21.10	$\frac{f_\omega^2}{2M^2}$	19.64

	Model-I	Model-II
$DDD^*, S = 1, I = 1/2$	unbound	binding energy ~ 1 MeV
$Z_c(3900)$	~ -40 MeV (virtual)	~ -5 MeV (virtual)

- Singular terms in potential : $\delta^3(r)$ and $1/r^3$

$$\frac{\mathbf{q}_i \mathbf{q}_j}{u^2 + \mathbf{q}^2} \rightarrow -\frac{e^{-ur}}{4\pi r} \left(\frac{u^2}{3} + \frac{u}{r} + \frac{1}{r^2} \right) T_{ij} + \frac{1}{3} \left(\delta^3(\mathbf{r}) - \frac{u^2 e^{-ur}}{4\pi r} \right) \delta_{ij},$$

- ▶ Short-range: structure of the hadron become important
- Regulator and cutoff

$$V(\mathbf{p}', \mathbf{p}) \rightarrow V(\mathbf{p}', \mathbf{p}) \frac{\Lambda^2}{\Lambda^2 + p^2} \frac{\Lambda^2}{\Lambda^2 + p'^2}$$
$$V(\mathbf{p}', \mathbf{p}) \rightarrow V(\mathbf{p}', \mathbf{p}) \left(\frac{\Lambda^2 - u^2}{\Lambda^2 + q^2} \right)^2 \quad \text{or other options...}$$

- NN systems
 - ▶ Coupling constants and cutoff are determined by NN scattering data
 - ▶ Almost independent of regulator form
- DD^* and $\bar{D}D^*$: **lack** data to fix all parameters in the past

This work: refit the 3 unknown coupling constants using data



- Use the model-I as the baseline

$$\lambda \rightarrow \lambda R_\lambda, \quad \beta \rightarrow \beta R_\beta, \quad g_s \rightarrow g_s R_s$$

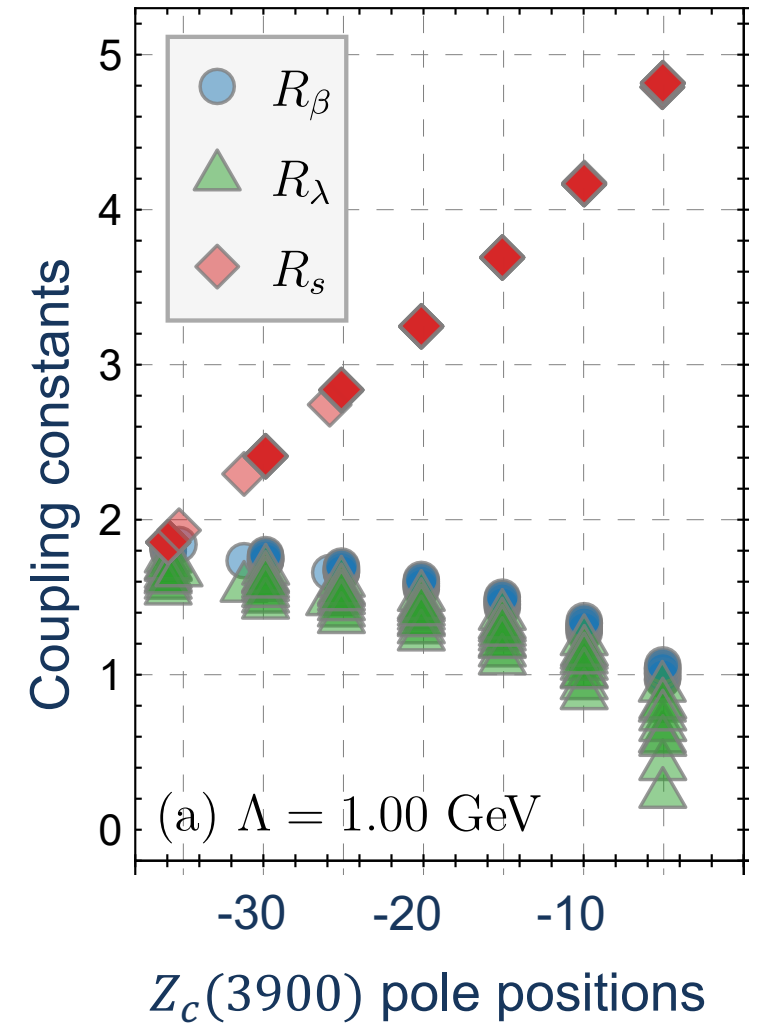
- Chosse 63 sets of pole positions

$$\begin{aligned} X(3872) &: (-1) \times (0.2, 0.4, 0.6)^B \text{ MeV}, \\ T_{cc}(3875) &: (-1) \times (0.2, 0.4, 0.6)^B \text{ MeV}, \\ Z_c(3900) &: (-1) \times (5, 10, 15, 20, 25, 30, 35)^V \text{ MeV}, \end{aligned} \quad (13)$$

Large uncertainty of $Z_c(3900)$

- R_s : dramatic variation

► Related to $Z_c(3900)$ poles



- $Z_c(3900)$: the ω and ρ exchange nearly cancel out

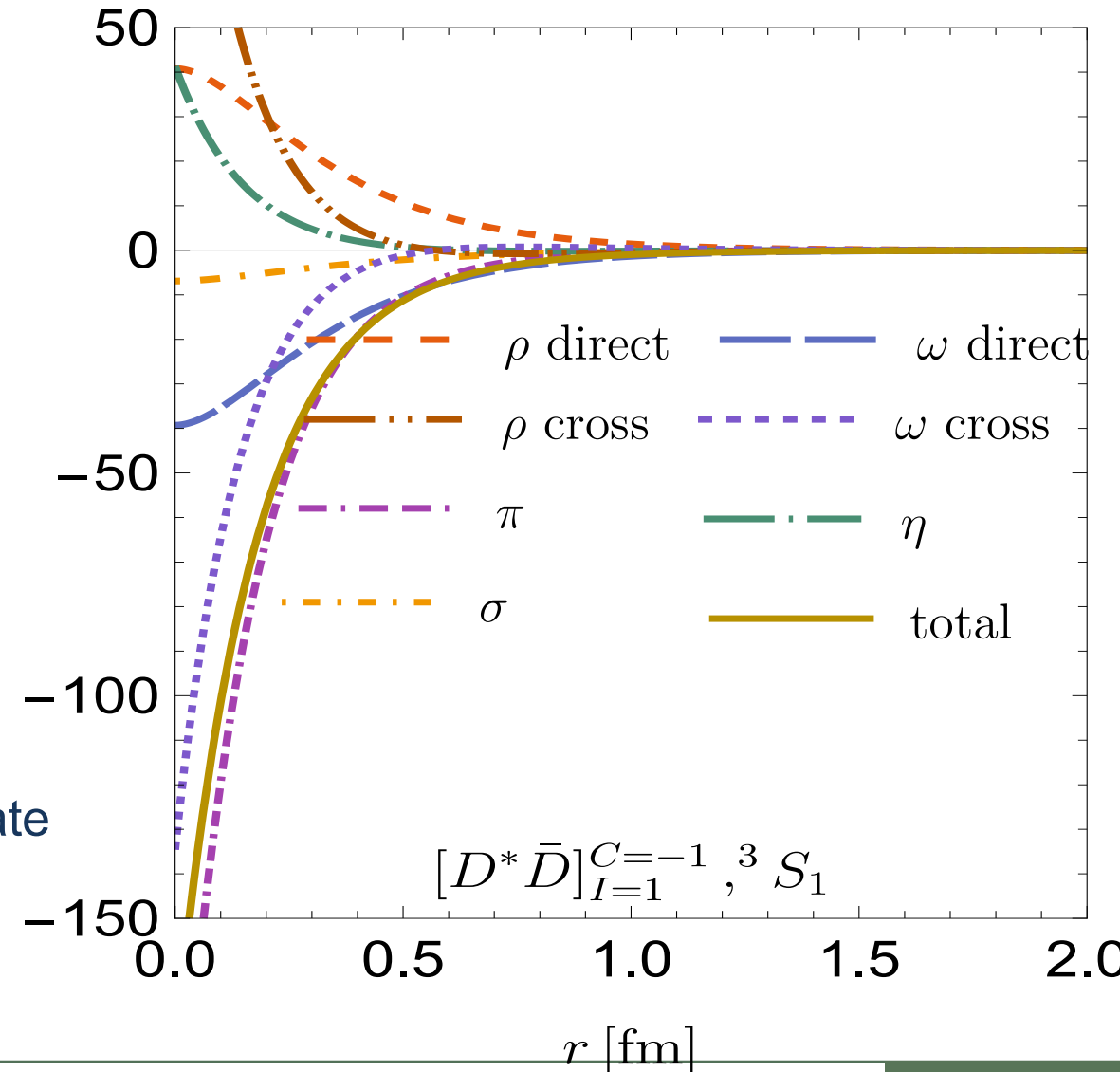
- ▶ Exact cancellation if $m_\omega = m_\rho$
- ▶ The couplings of π and η are fixed
- ▶ Highly sensitive to the σ -exchange

- σ -exchange:

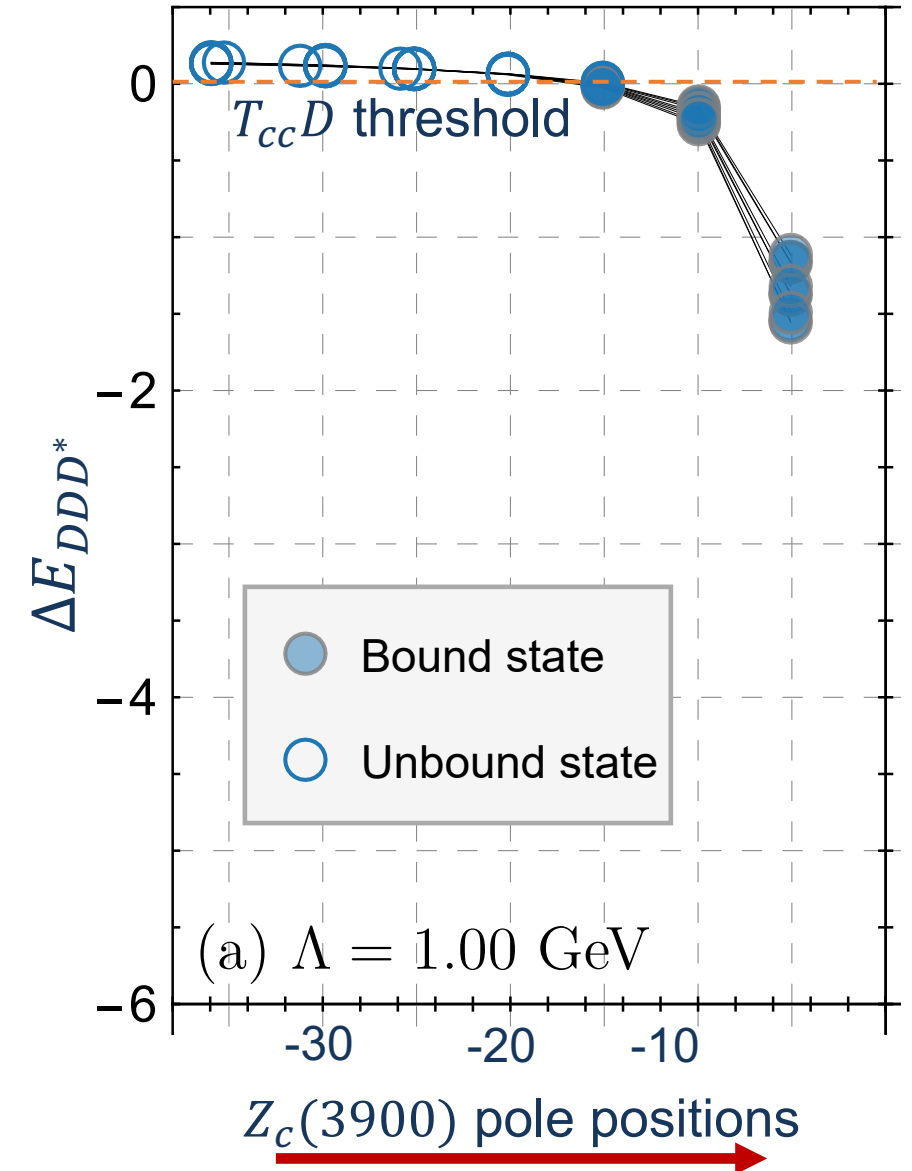
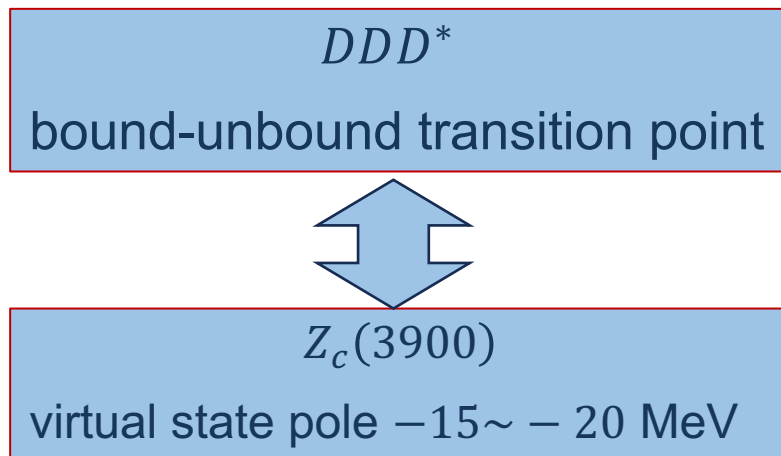
- ▶ blind to the spin and isospin
- ▶ Attractive for all pairs
- ▶ 3-body: 3 pairs

More easily show the effect

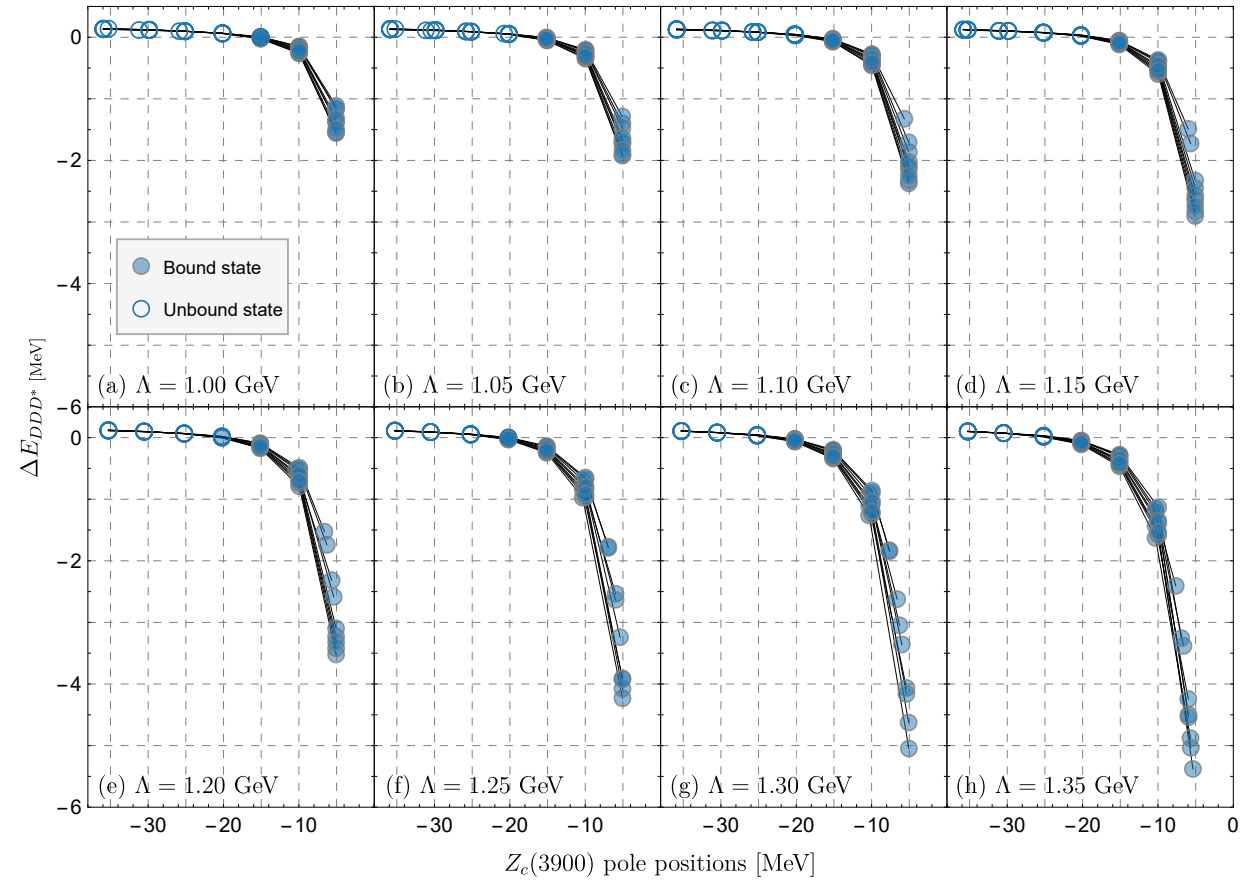
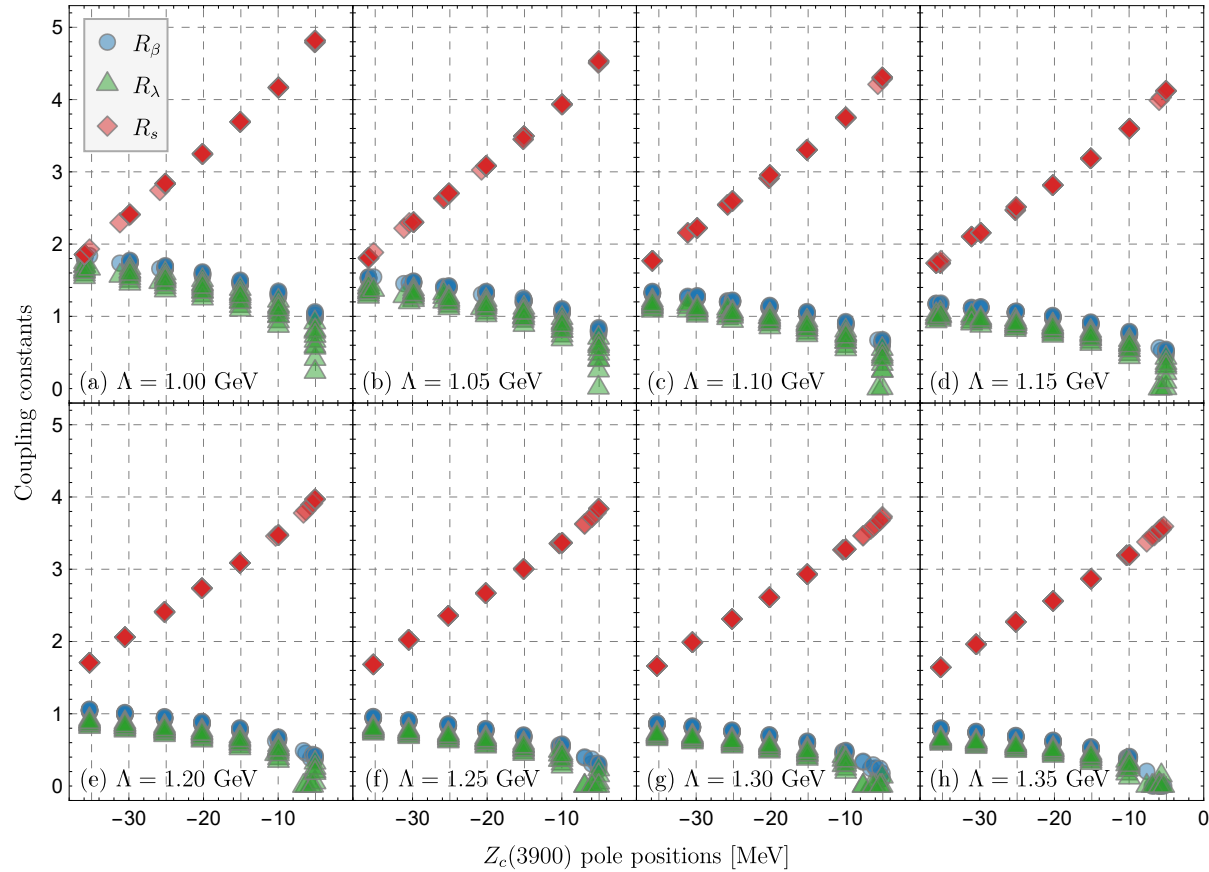
- $Z_c(3900)$ pole position $\xleftrightarrow{\sigma\text{-exchange}}$ DDD* bound state



- Remain uncertain:
 - ▶ DDD^* bind or not
 - ▶ $Z_c(3900)$ pole position
- They are closely related
 - ▶ $Z_c(3900)$ pole position
 - ▶ Progress in either direction shed light on the other



Systematics of cutoff



8 different cutoffs



- **EicC complement** the existing experiments producing exotic states
- The debates of $Z_c(3900)$: triangle singularity and pole
- EicC: promising facility to investigate $Z_c(3900)$
 - ▶ Large number of events is anticipated
 - ▶ Likely free of triangle singularity
- Probing the Nature of $Z_c(3900)$ at EicC: Clues to DDD^* Bound State
 - ▶ Based on meson-exchange model: successes in NN
 - ▶ DDD^* bind or not and $Z_c(3900)$ pole position remain uncertain
 - ▶ **DDD^* bound state and $Z_c(3900)$ pole position are closely related**
 - ▶ Data sets **systematically** taking into account the uncertainty from the cutoff

Thanks for your attention!





backup



"Superstars"

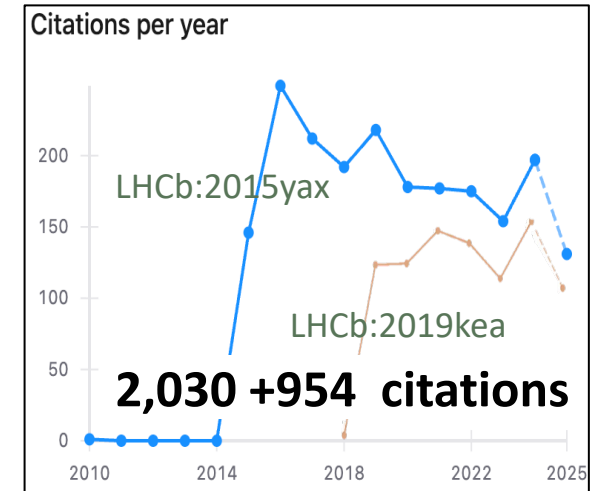
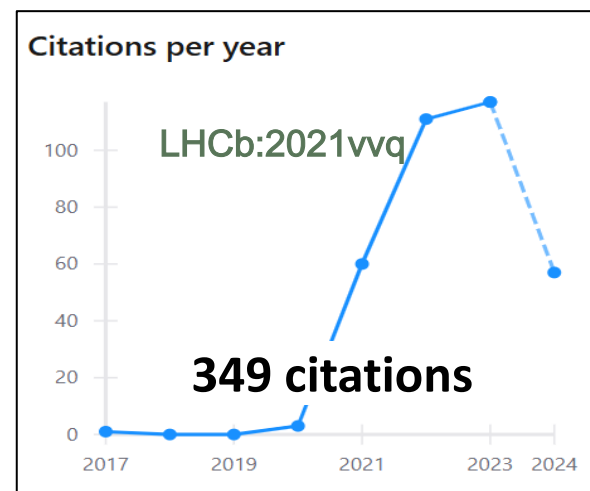
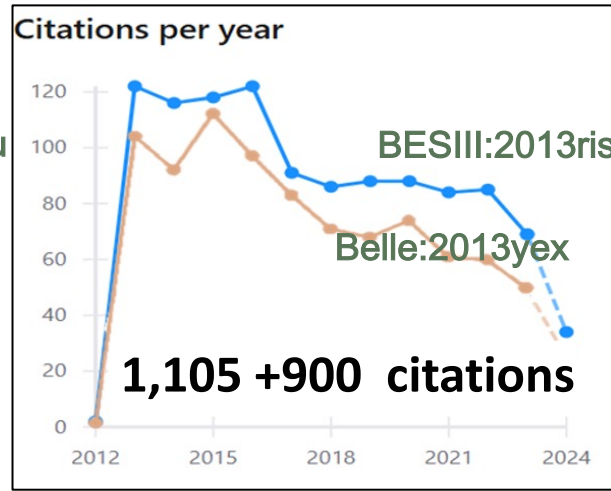
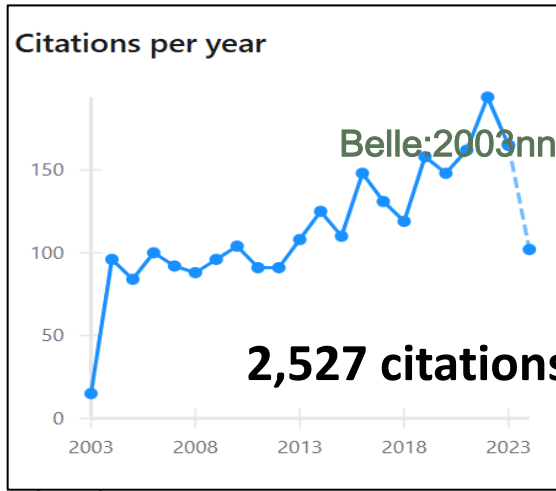
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The 1st charmonium-like state					
$Z_c(3900)$	$q\bar{q}c\bar{c}$	$1^+(1^{+-})$	$D\bar{D}^*$	11.3 ± 2.6	28.4 ± 2.6
The 1st manifestly exotic charmonium-like state					
$T_{cc}(3985)$	$\bar{q}\bar{q}cc$?	$D^{*+}D^0$	$-0.360^{+0.040}_{-0.040}$	$0.048^{+0.002}_{-0.014}$
The 1st open double charm tetraquark state					
$P_{c\bar{c}}$ states	$qqqc\bar{c}$?	$\Sigma_c\bar{D}^{(*)}$	$-5 \sim -20$	~ -10
The 1st pentaquark states					

BESIII:2023hmt

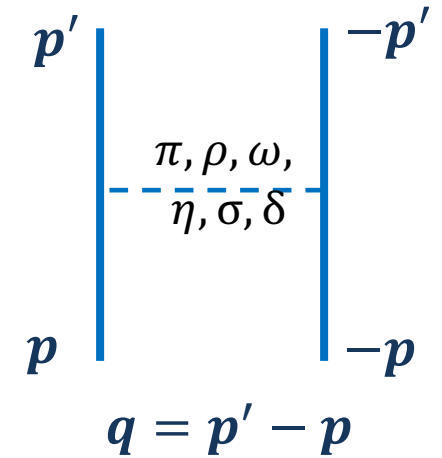
PDG

LHCb:2021auc

LHCb:2015yax



- Exchanged mesons
 - ▶ Hidden local gauge symmetry: vector-meson exchange
 - ▶ $\pi, \rho, \omega, \sigma, \dots$: e.g. Bonn potential
- Determine coupling constants: Exp., Lattice, Models
- Regulator and cutoff



- ▶ Singular terms: $\delta^3(r)$ and $1/r^3$
 - ▶ Short-range: structure of the hadron become important
- Coupled channel or not?
 - ▶ Hard to incorporate properly, relativistic effect
 - ▶ Not important? $M_D^* - M_D \sim 130$ MeV, $M_{\Sigma_c} - M_{\Sigma_c^*} \sim 70$ MeV, Neglected in our works

$$V(\mathbf{p}', \mathbf{p}) \rightarrow V(\mathbf{p}', \mathbf{p}) \frac{\Lambda^2}{\Lambda^2 + p^2} \frac{\Lambda^2}{\Lambda^2 + p'^2}$$

$$V(\mathbf{p}', \mathbf{p}) \rightarrow V(\mathbf{p}', \mathbf{p}) \left(\frac{\Lambda^2 - u^2}{\Lambda^2 + q^2} \right)^2$$

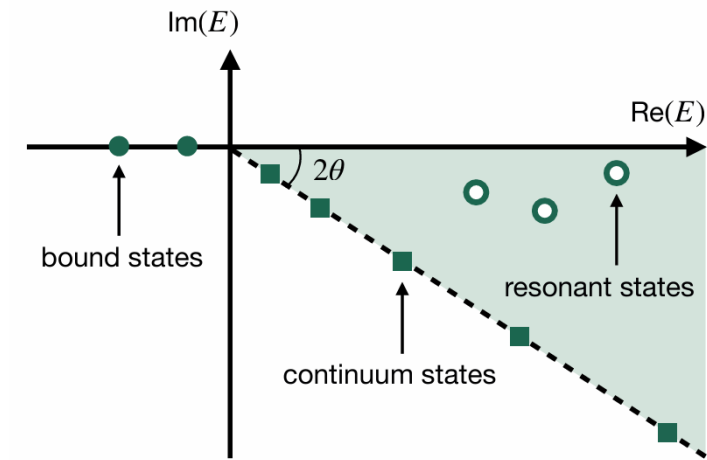
Other options...



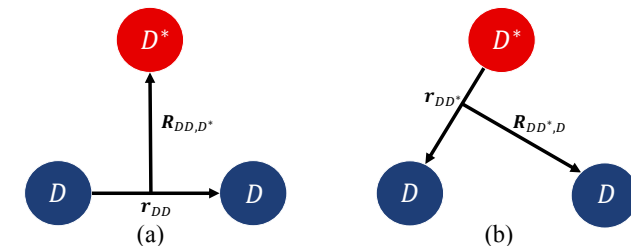
- Momentum space:
 - ▶ Discretize the momenta
 - ▶ Deformed contour: resonance, virtual state

$$\frac{p^2}{2\mu}\psi(p) + \int_C \frac{dq}{(2\pi)^3} q^2 V_{l=0}(p, q)\psi(q) = E\psi(p),$$

- Coordinate space
 - ▶ Basis expansion method, Finite element method
 - ▶ Resonant: complex scaling method...
- 3-body/4-body systems
 - ▶ Faddeev equation
 - ▶ **Gaussian expansion method+ Complex scaling**



$$\phi_{nlm}(\mathbf{r}) = \sqrt{\frac{2^{l+5/2}}{\Gamma(l + \frac{3}{2}) r_n^3}} \left(\frac{r}{r_n}\right)^l e^{-\frac{r^2}{r_n^2}} Y_{lm}(\hat{r}),$$



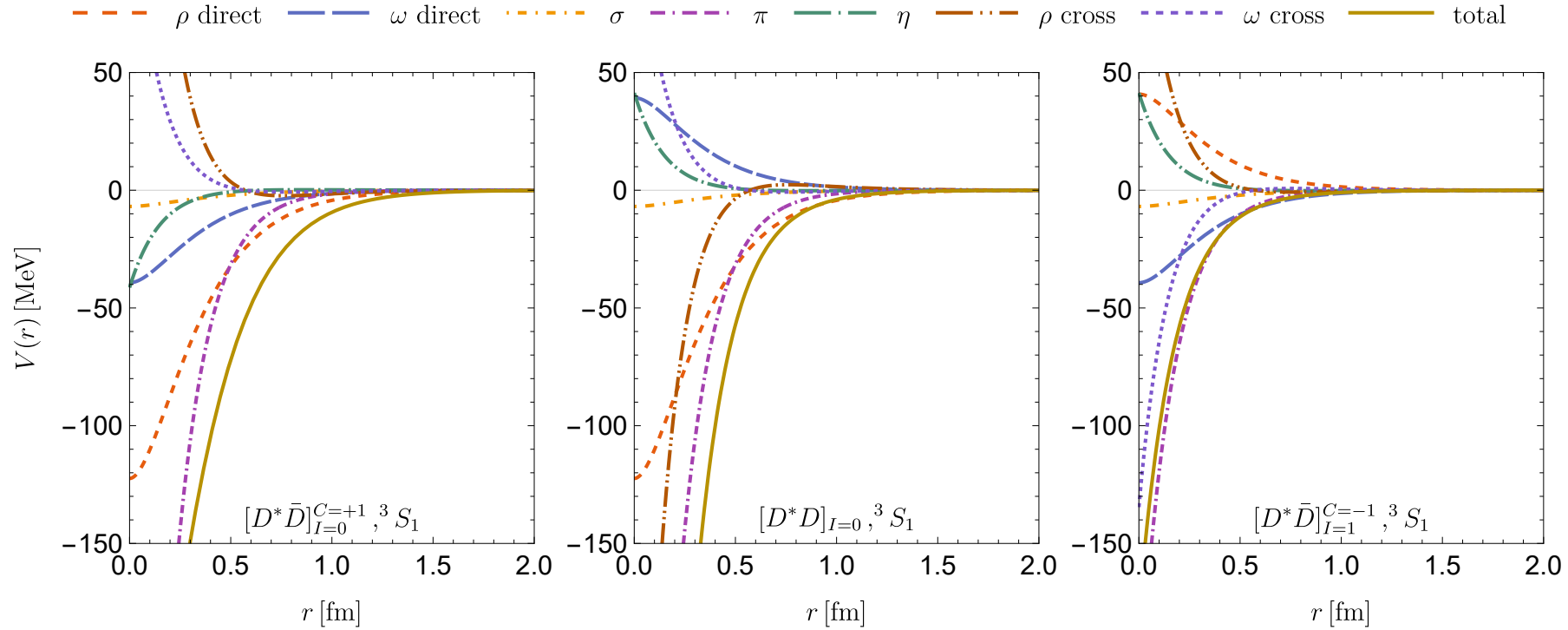
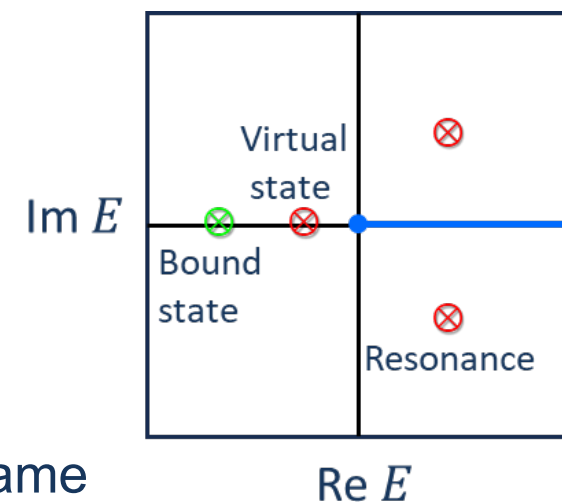


FIG. 2. The coordinate space potentials in the isospin limit for the systems corresponding to the $X(3872)$, $T_{cc}(3875)$, and $Z_c(3900)$ states. The parameter Λ is set to 1.20 GeV, with R_β , R_λ , and R_s fixed at 1.

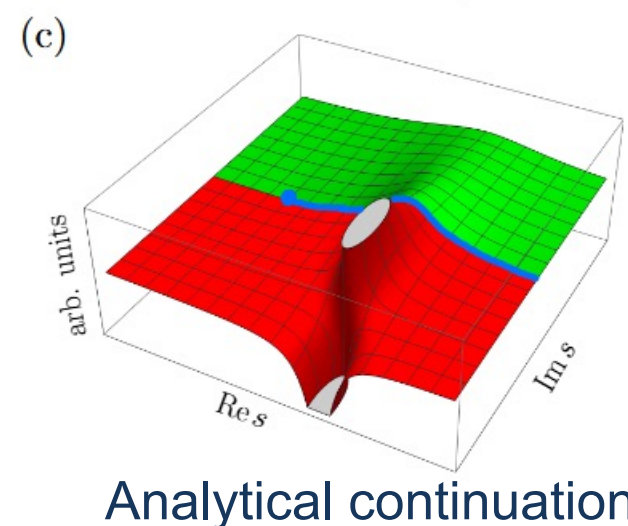
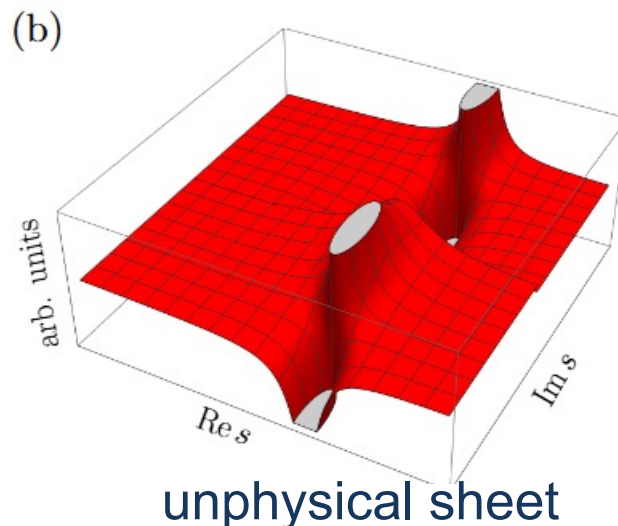
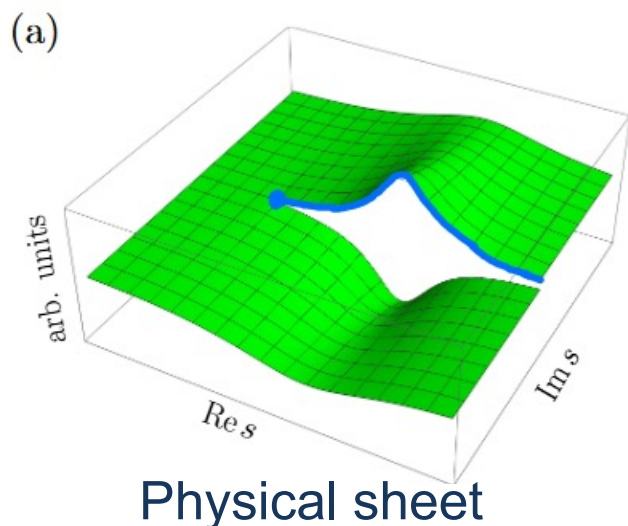


Bound state, Virtual state and Resonance

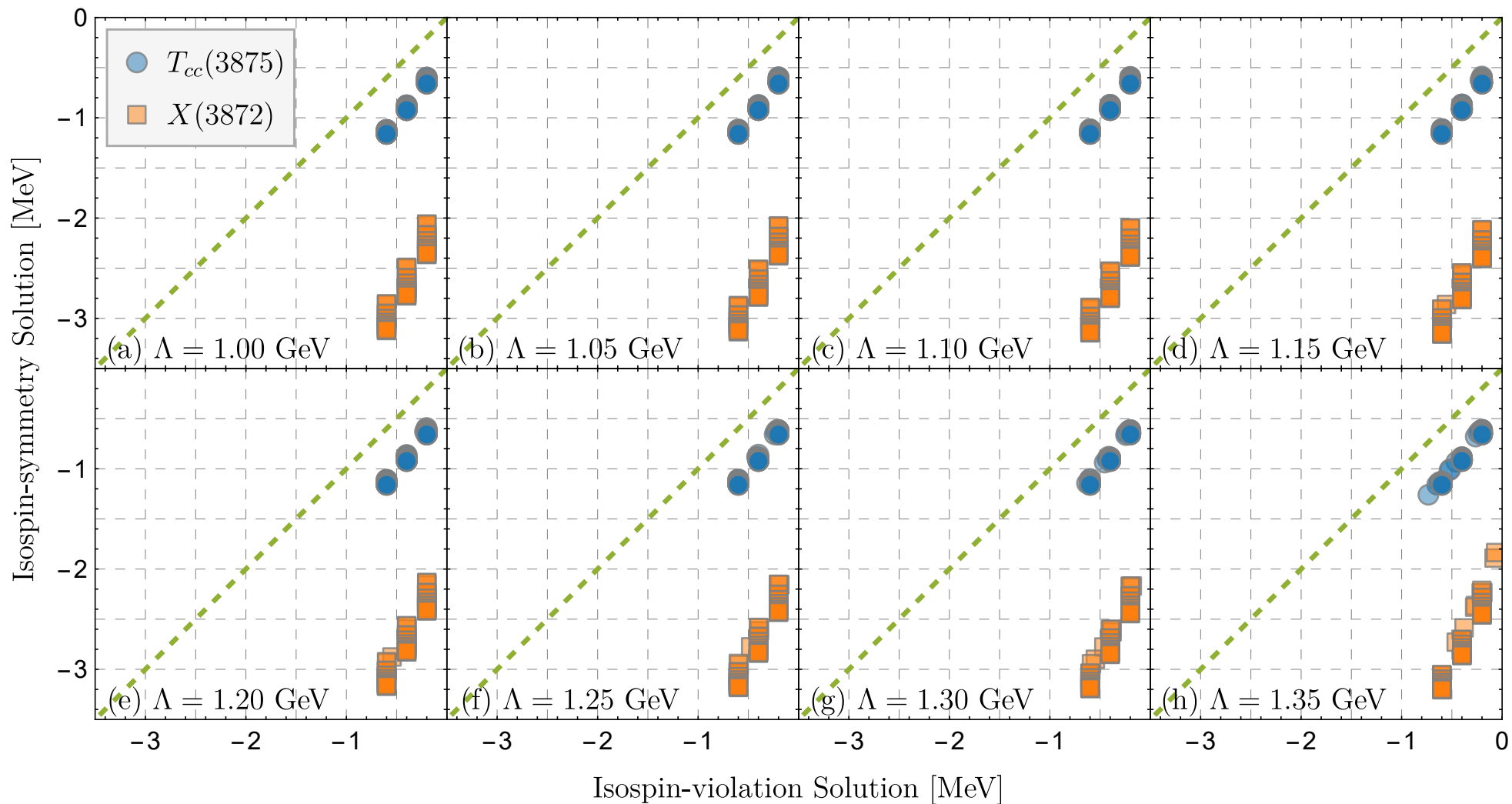
- Single channel scattering as an example
- T-matrix: Unitary cut \Rightarrow multivalued function \Rightarrow Riemann sheets
- “States” \Leftrightarrow T-matrix poles
 - ▶ Bound state: real axis of physical sheet
 - ▶ Virtual state: real axis of unphysical sheet
 - ▶ Resonance: lower unphysical sheet
- Line shapes vary with processes, however, pole positions keeps the same
- Observables: bound state, $|T|^2$ with $E > 0$ in physical sheet
- Exact pole positions: **general** amplitudes satisfying **physical constraints**

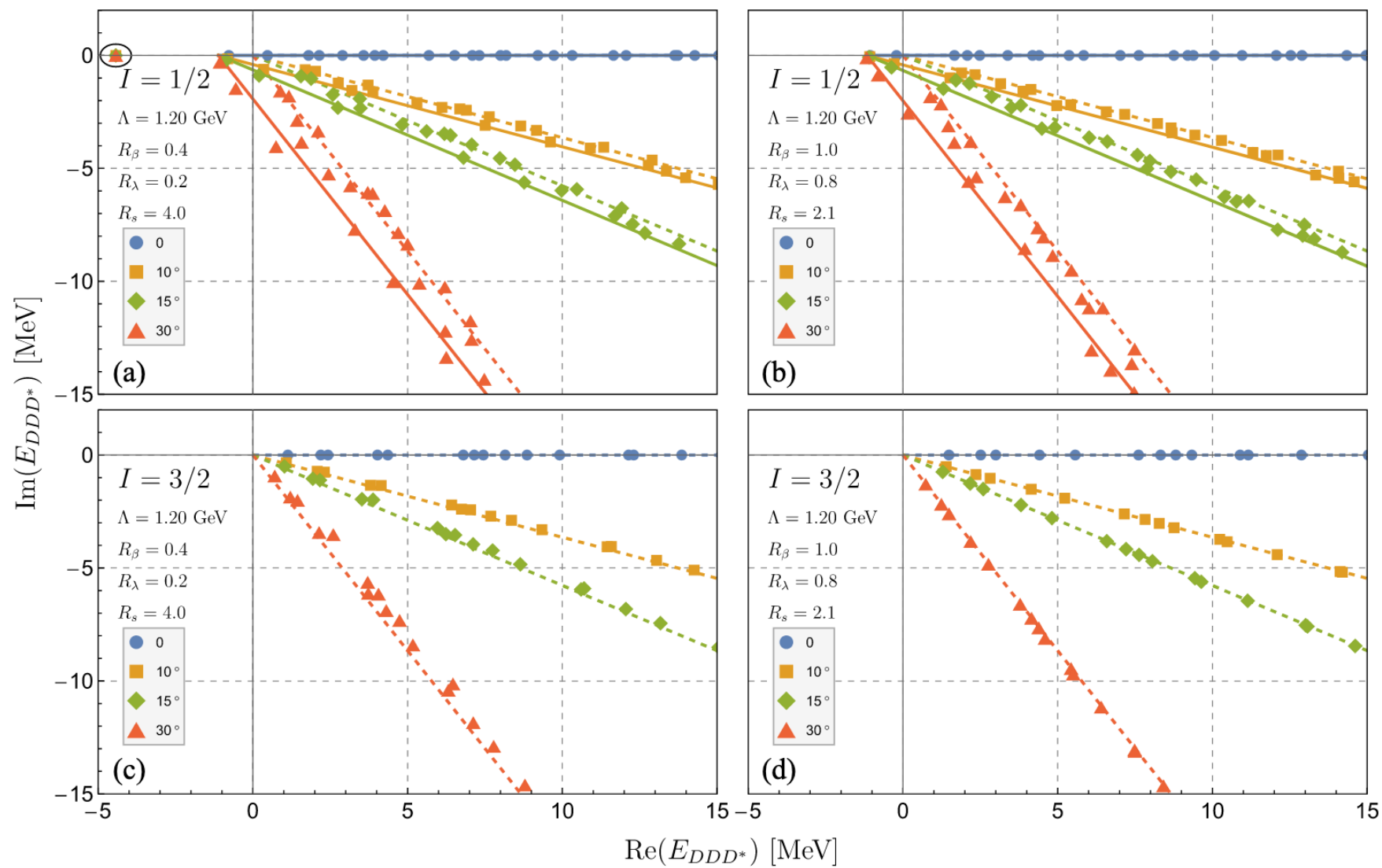


Mizera:2023tfe; PDG

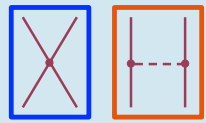
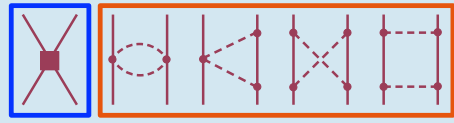


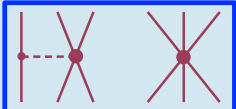

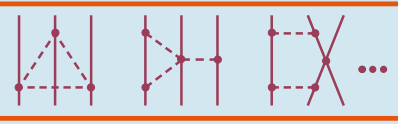
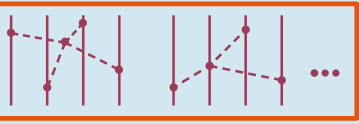
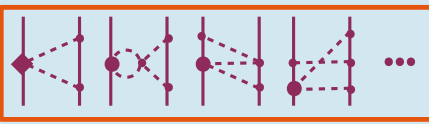

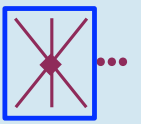


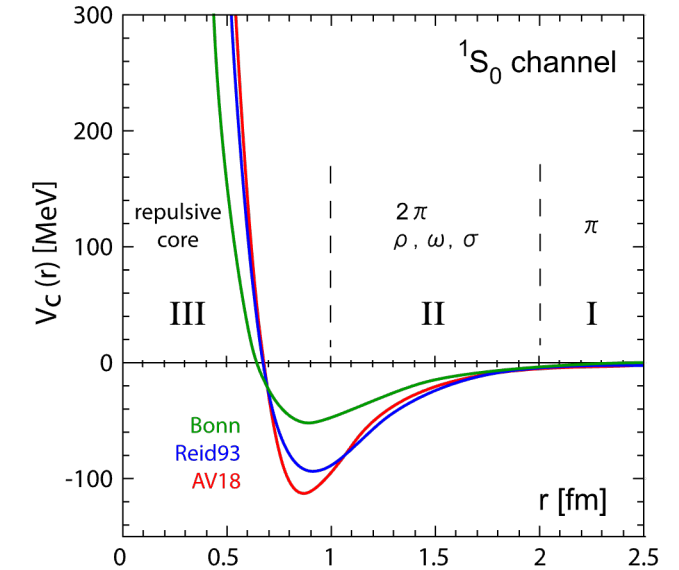
Isospin violation effect





Nuclear force in ChEFT

	Two-nucleon force	Three-nucleon force	Four-nucleon force
LO:		—	—
NLO:		—	—
N ² LO:			
N ³ LO:			
N ⁴ LO:			



Chiral dynamics: Long-range interactions are predicted in terms of on-shell amplitudes



Short-range few-N interactions are tuned to experimental data

Chiral nuclear force

Phenomenological nuclear force

