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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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Apr. 20, 2026

Based on Phys.Rev.D 111 (2025) 9, 094022

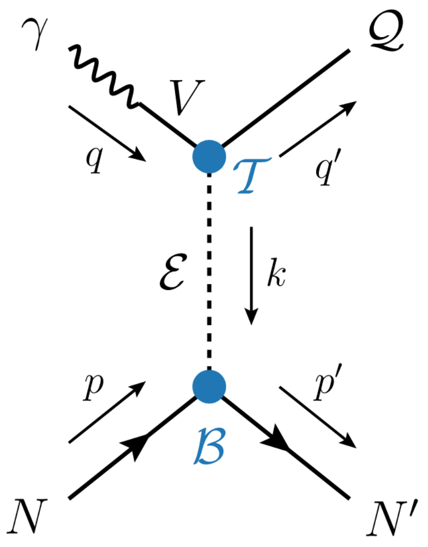
Collaborated with Hai-Xiang Zhu, Yao Ma, Ning Li, Wei Chen and Shi-Lin Zhu

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

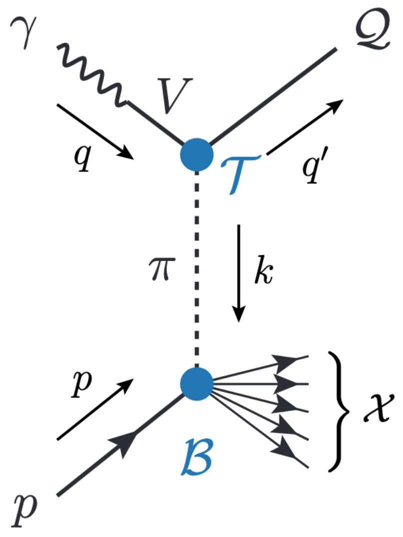
Complement current experiments

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

COMPASS， EIC-US and EicC



Exclusive photoproduction

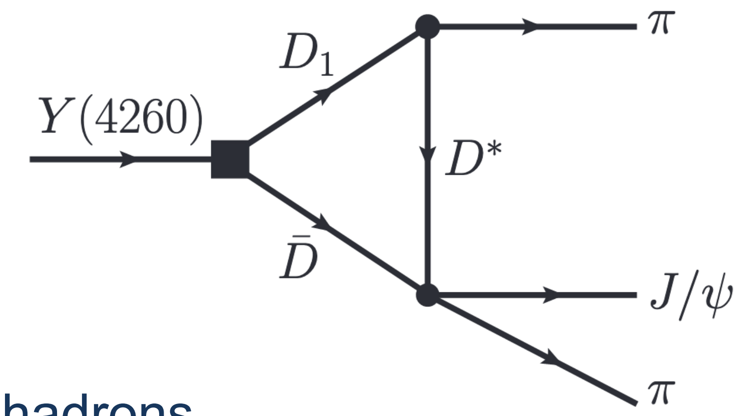


Semi-inclusive photoproduction

Debates on the $Z_c(3900)$

- $Z_c(3900)$: $I^G(J^{PC}) = 1^+(1^{+-})$, minimal quark content: $q\bar{q}c\bar{c}$
- $e^+e^- \to Z_c(3900)\pi$
  - $\to (J/\psi\pi)\pi$
  - $\to (D^*\bar{D})\pi$
  - E_{cm} around 4.23 and 4.26 GeV

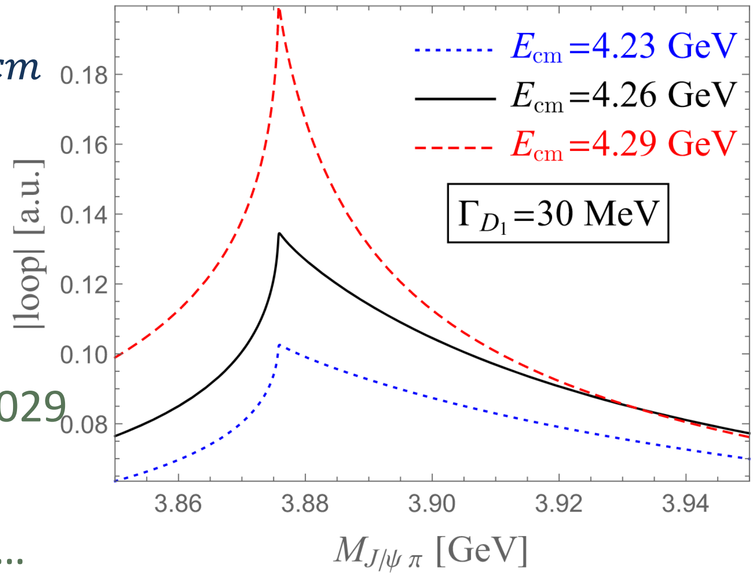
BESIII, PRL110 (2013) 252001;
Belle, PRL110 (2013) 252002;
CLEO-c ,PLB727 (2013) 366-370;
…



- 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 ⇒ sensitive to E_{cm}
    *Q. Wang et al, PRL*111 (2013) 13, 132003; X.H.Liu and G.Li *PRD*88 (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).

$Z_c(3900)$ poles

Refit Ex. data using amplitudes with exact unitarity.

solution I: resonance

Solution II: virtual state

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	$J/\psi\,\pi, \bar{D}^*D$

Below thresh. 30-40 MeV

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

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

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]).

$E_{Z_c}^{\text{This work}}$	$M_{Z_c}^{\text{PDG}}$	$\Gamma_{Z_c}^{\text{PDG}}$	
$(3837.7\pm7.4)+(19.4\pm1.6)i$	3887.1 ± 2.6	28.4 ± 2.6	$Z_c(3900)$
$(3989.9\pm5.6)+(26.1\pm4.3)i$	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

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 threshod 80 MeV

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

$\pi^+\pi^-$ and $J/\psi\pi^\pm$ mass spectra @ $e^+e^- \to J/\psi\pi^+\pi^-$

D^*D^{*-} mass spectrum @ $e^+e^- \to D^*D^{*-}\pi^+$

resonance:

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

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

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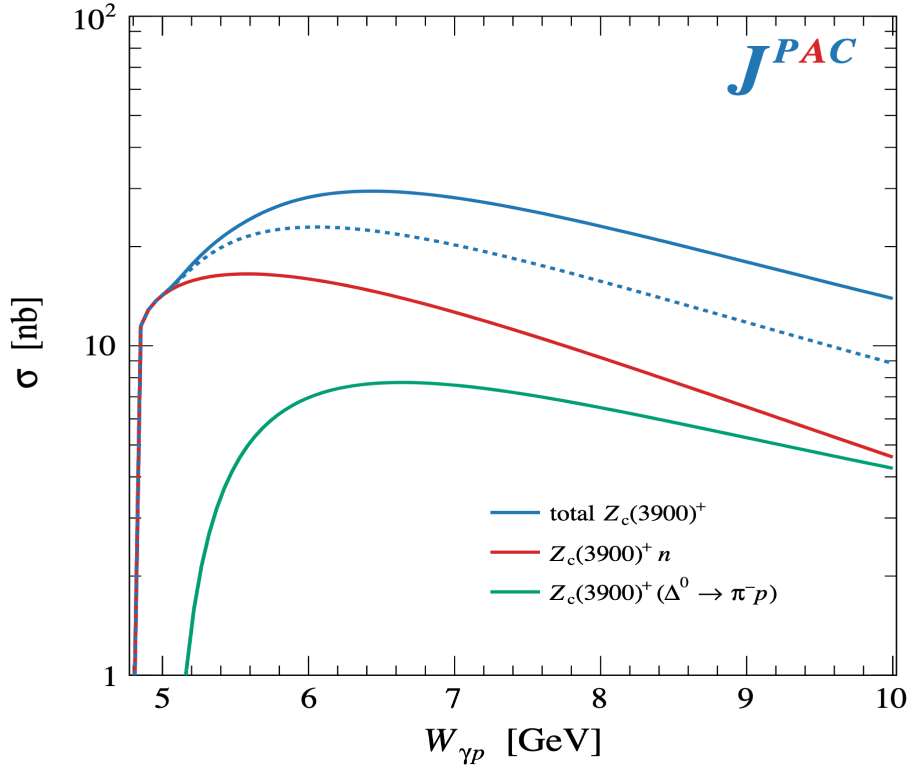
- **Abundant production** of near-threshold hidden-charm molecular states
- Likely free from triangle singularity

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^{+-}	$0.3\times10^3(1.2\times10^3)$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	1^+	$0.2\times10^3(0.9\times10^3)$	$0.3\times10^3(1.0\times10^3)$	$2.7\times10^3(9.9\times10^3)$
$Z_c(4020)^0$	$D^*\bar{D}^*$	1^{+-}	$0.1\times10^3(0.5\times10^3)$	$0.2\times10^3(0.6\times10^3)$	$1.7\times10^3(6.3\times10^3)$

Semi-inclusive production in **molecular** scheme

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



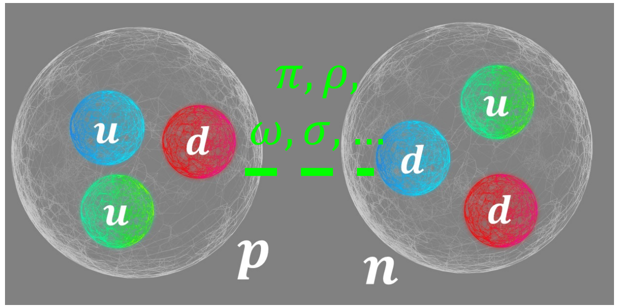
JPAC, PRD106, 094009 (2022).

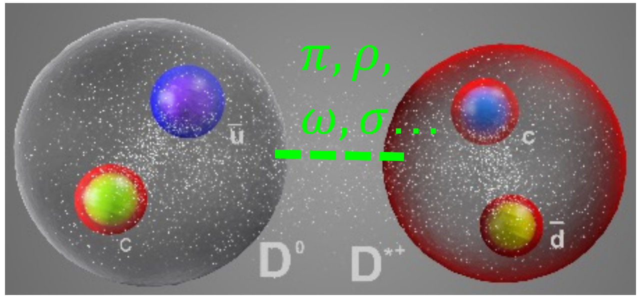
Q.-Y. Lin, X. Liu, and H.-S. Xu, Phys. Rev. D 88, 114009 (2013).
Y.-P. Xie, X.-Y. Wang, and X. Chen, Eur. Phys. J. C 81, 710 (2021).
X. Cao, Front. Phys. 18, 44600 (2023).
…

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

Molecular states

- Hadonic molecule: deuteron as a typical example



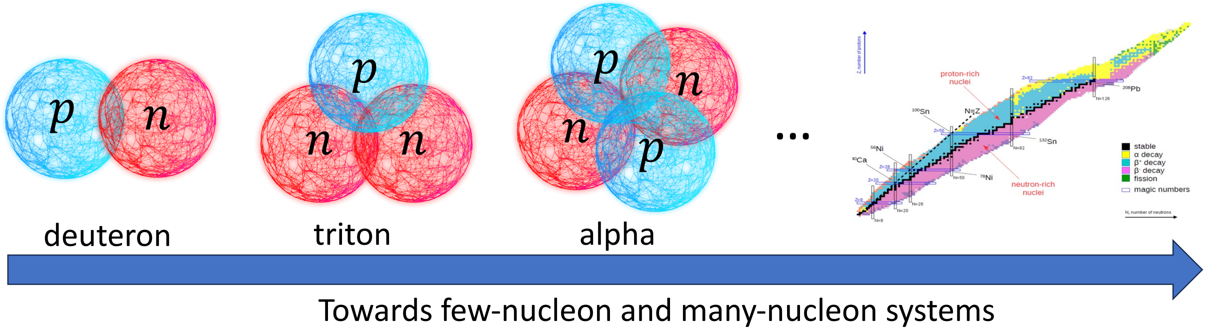


- Great interest in DD^* and $\bar{D}D^*/D\bar{D}^*$ molecular states

	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

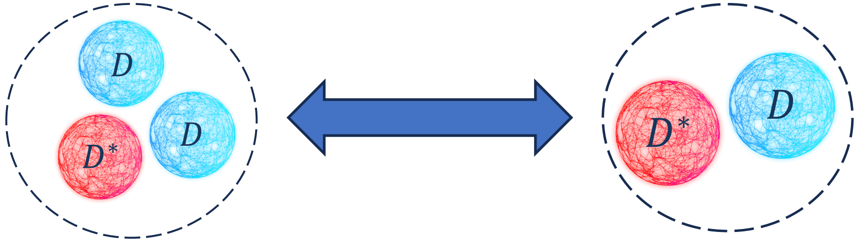
Towards three-body systems

- Nucleon as the "building block"



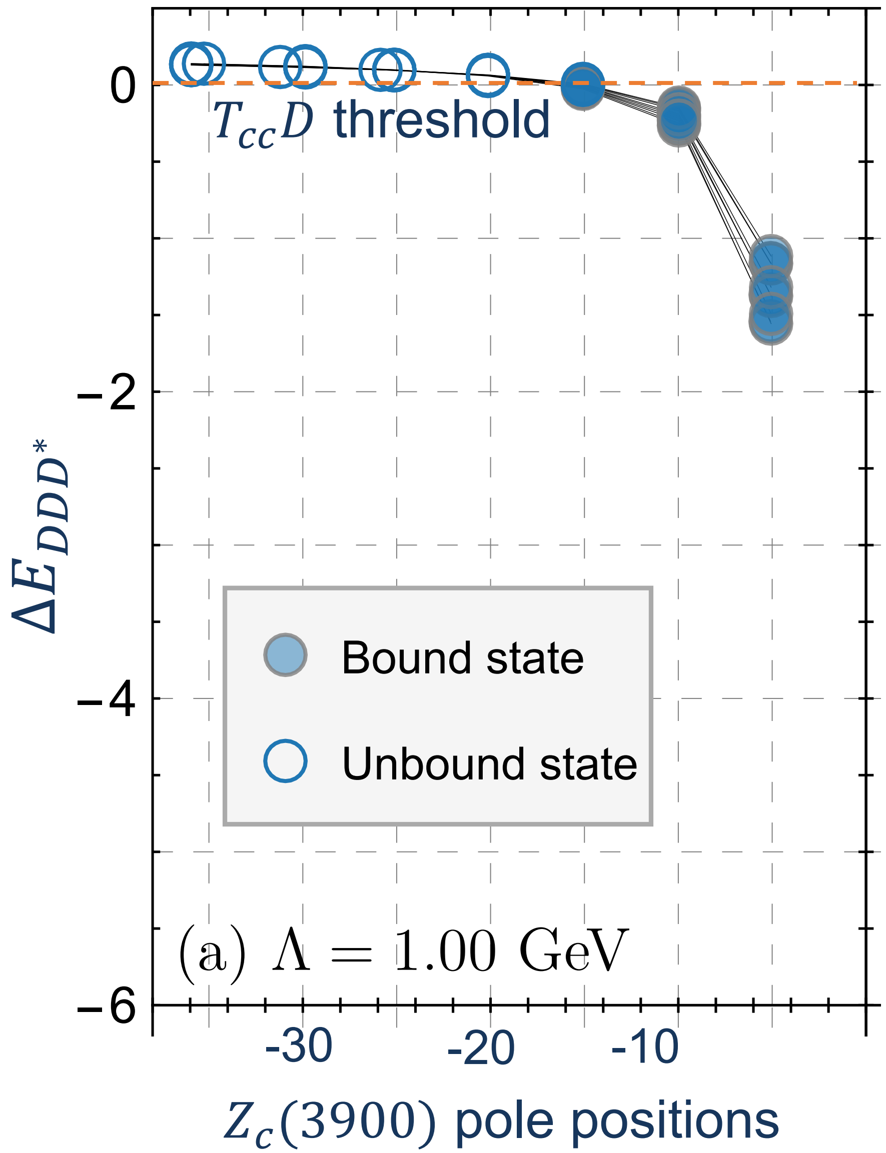
- New frontier: D and D^* as "building block"
  M.-Z. Liu, Y.-W. Pan, Z.-W. Liu, T.-W. Wu, J.-X. Lu, and L.-S. Geng, Phys. Rept. 1108, 2368 (2024).

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



DDD^* bound or not?

$Z_c\,(3900)$ nautre



NN in meson-exchange models

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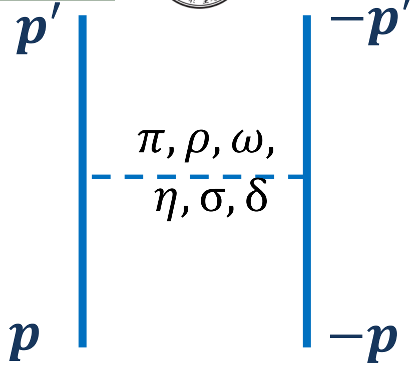
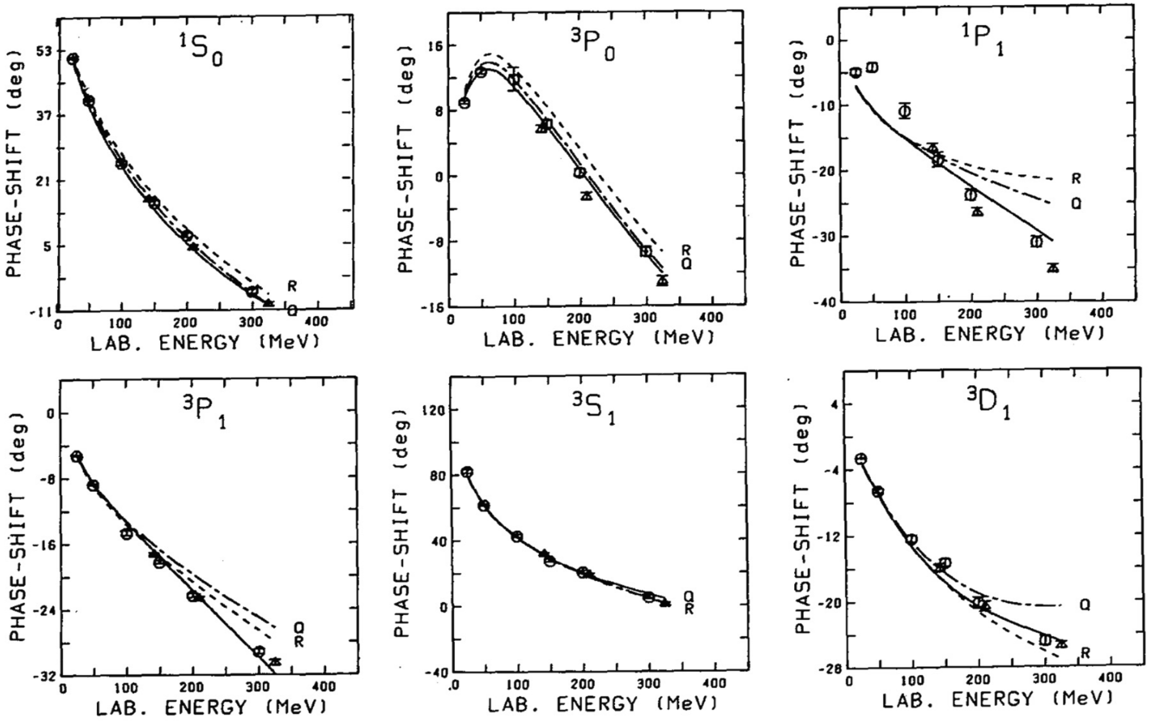
- Interaction via one-boson exchange
- Great succuss in nuclear force
- G-parity rules (particle-particle $\Leftrightarrow$ particle-antiparticle)



$q = p' - p$

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

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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).

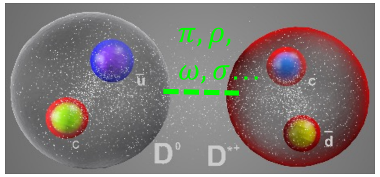
$X(3872)$ The 1st charmonium-like state

$Z_c(3900)$ 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

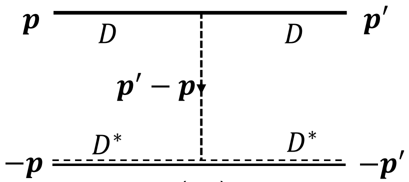
2003 2013 2015 2019 2021



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)
….

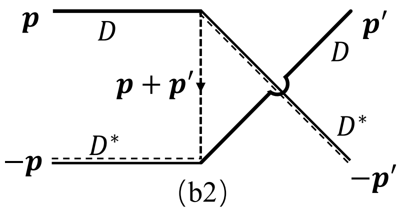
Uncertainties in OBE: coupling constants



(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 $D^* \to D\pi$
- 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
$\boxed{V_\sigma^D}$	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)

Uncertainties in OBE: cutoff and regulator

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

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

  - ▶ Short-range: structure of the hadron become important

- Regulator and cutoff

$$V(\boldsymbol{p}',\boldsymbol{p}) \to V(\boldsymbol{p}',\boldsymbol{p})\frac{\Lambda^2}{\Lambda^2+p^2}\frac{\Lambda^2}{\Lambda^2+p'^2}$$

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

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 unknow coupling constants using data

Refit the coupling

- Use the model-I as the baseline

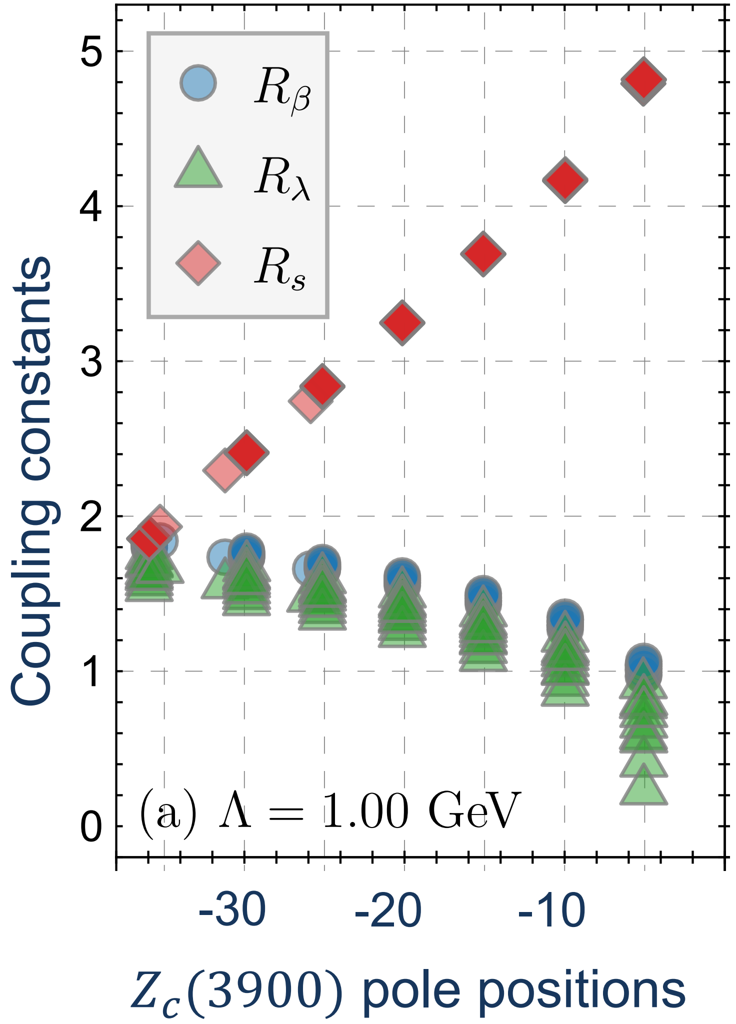
$$\lambda \to \lambda R_\lambda, \quad \beta \to \beta R_\beta, \quad g_s \to g_s R_s$$

- Chosse 63 sets of pole positions

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

Large uncertainty of $Z_c(3900)$

- R_s: dramatic variation
  - ▶ Related to $Z_c(3900)$ poles

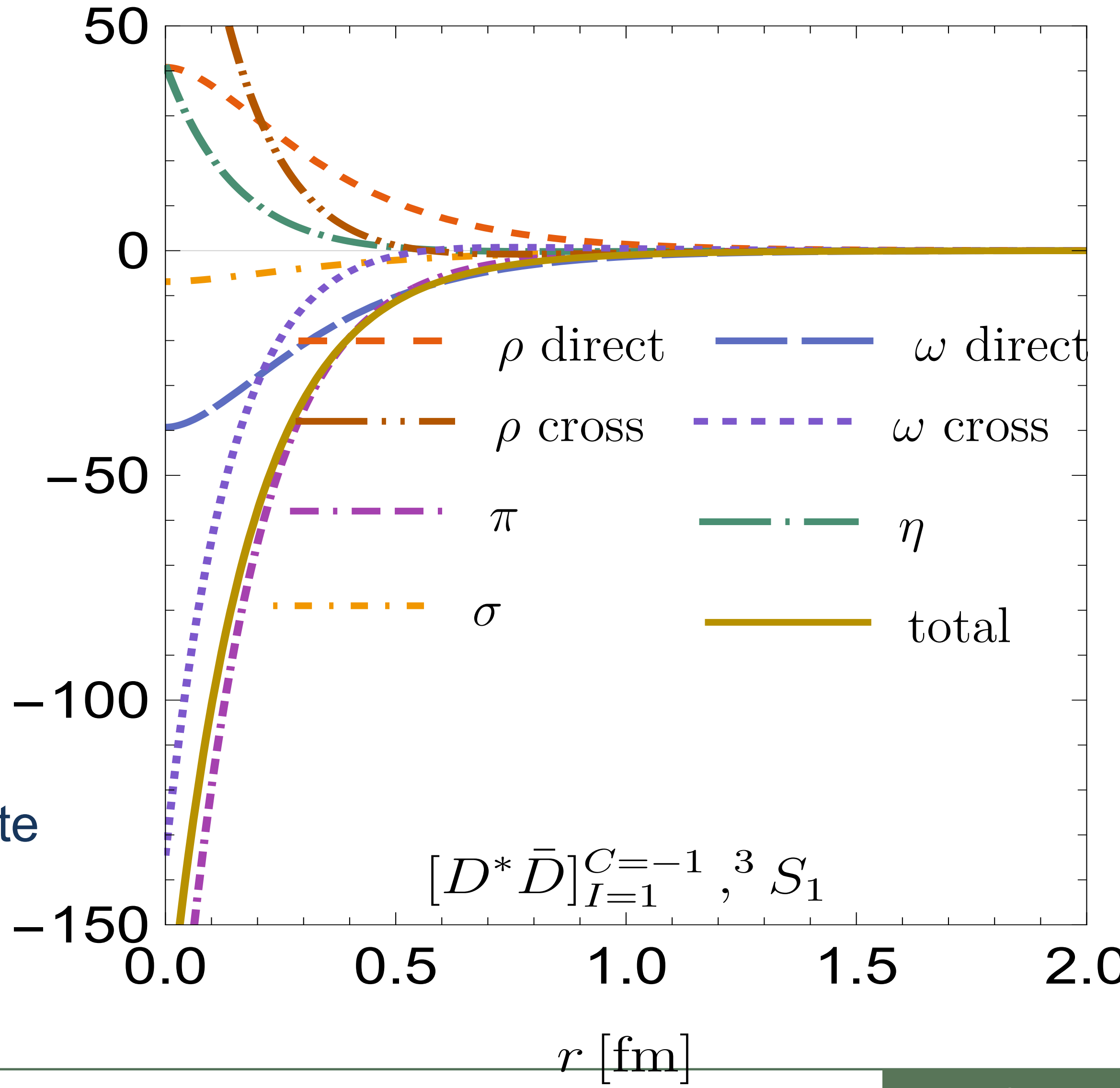


DDD^* state and $Z_c(3900)$

- $Z_c(3900)$: the ω and ρ exchange nearly cancel out
  - ▶ Exact cancellation if 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 $\overset{\sigma-\text{exchange}}{\Longleftrightarrow}$ DDD^* bound state



DDD^* state and $Z_c(3900)$

- 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

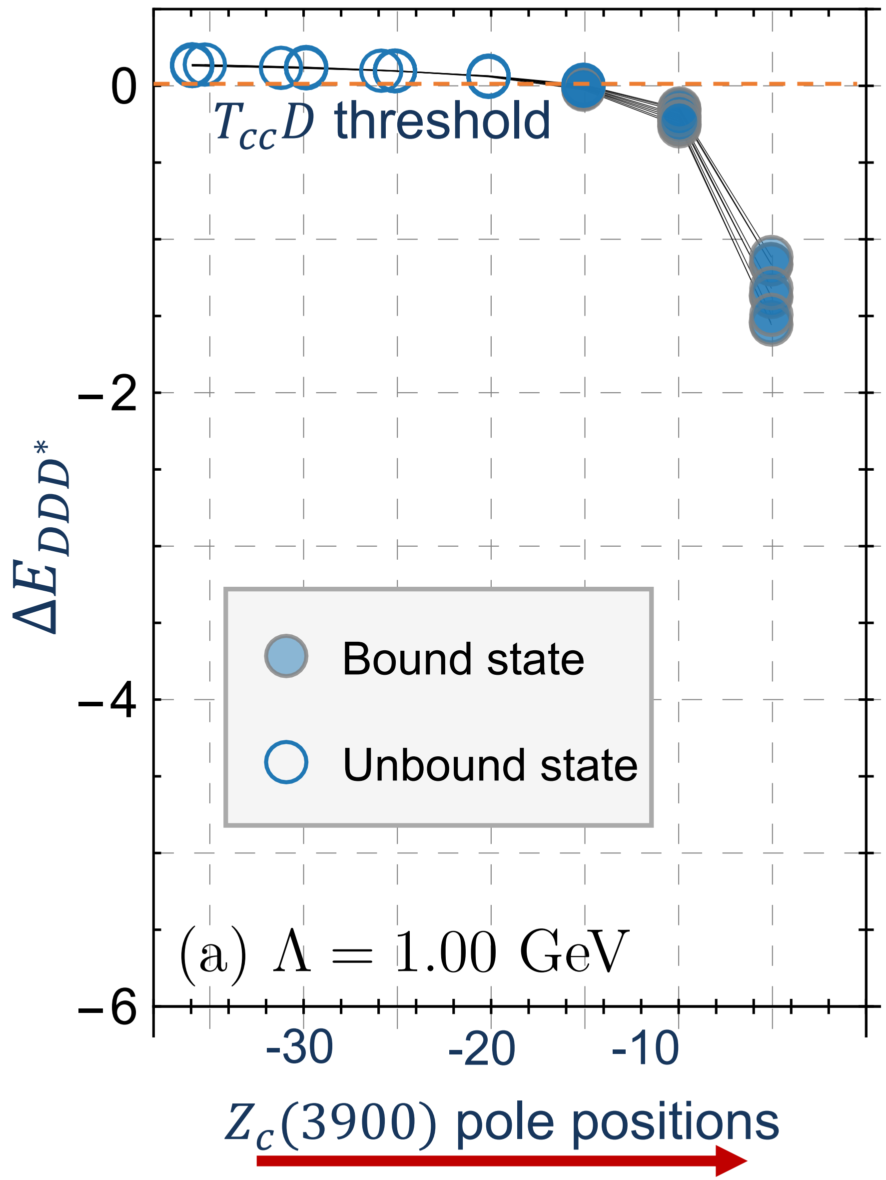
DDD^*

bound-unbound transition point

⇕

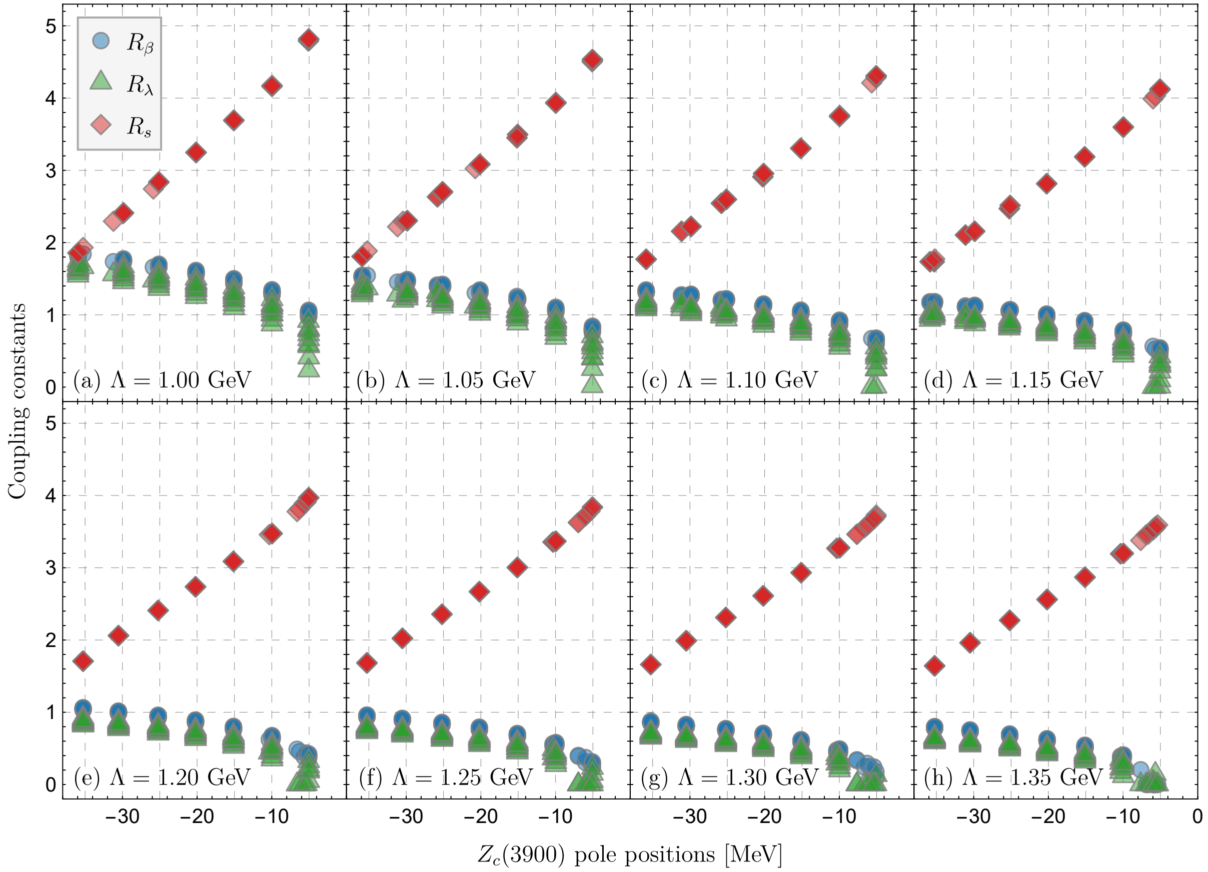
$Z_c(3900)$

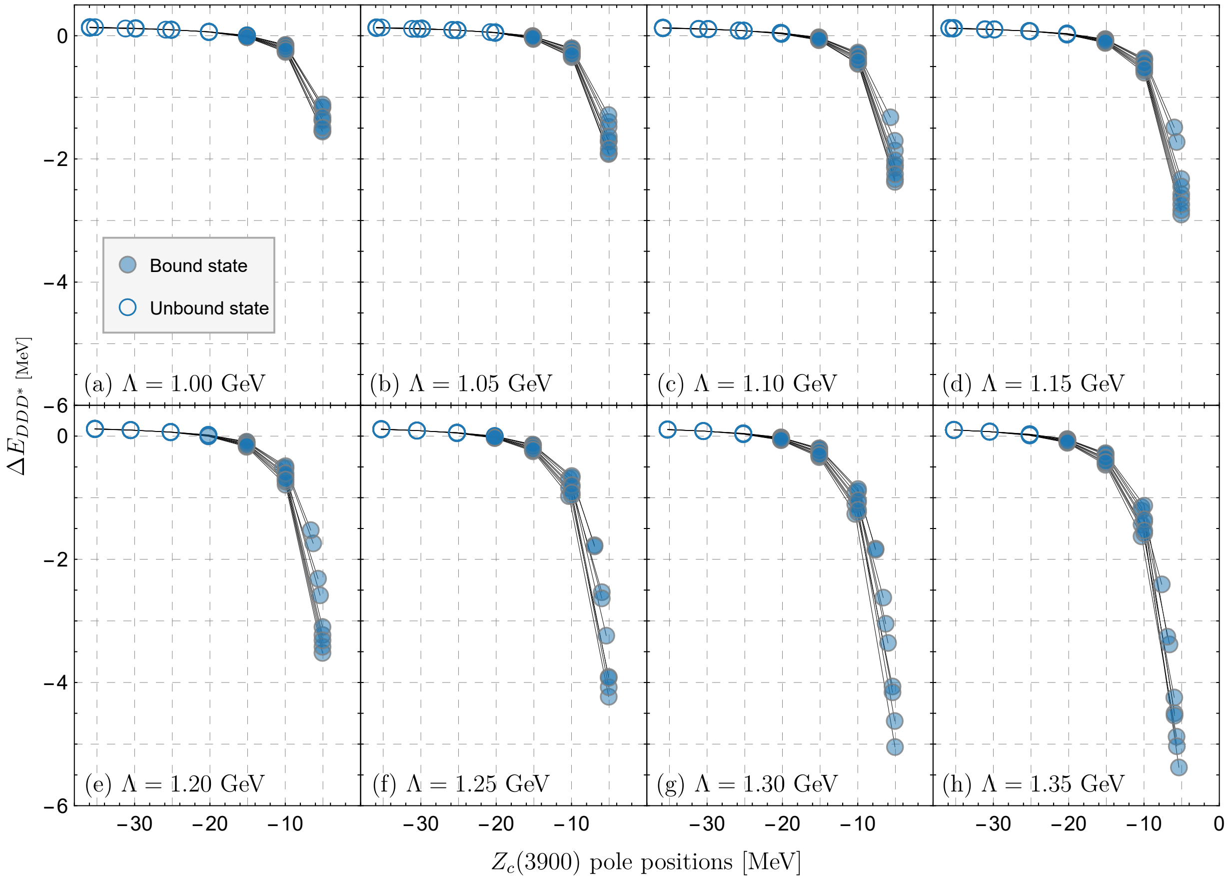
virtual state pole $-15\sim-20$ MeV



Stronger σ coupling, toward bound DDD^*

Systematics of cutoff





8 different cutoffs

Summary

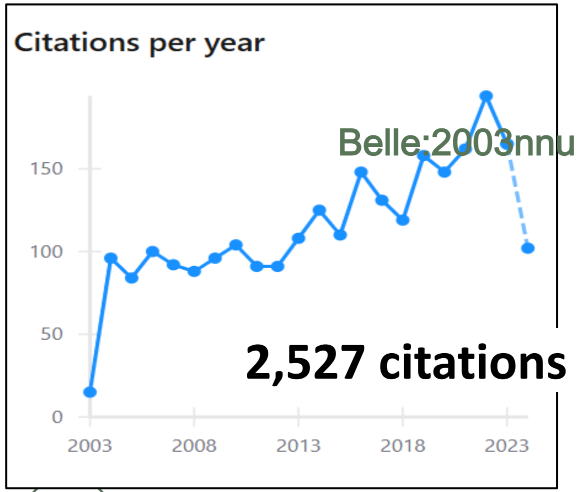
- **EicC complement** the existing experiments producing exotic states
- The debates of $Z_c(3900)$: triangle singularity and pole
- EicC: promising facility to investigate $Z_c(3900)$
  - ▶ Large number of events is anticipated
  - ▶ Likely free of triangle singularity
- Probing the Nature of $Z_c(3900)$ 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

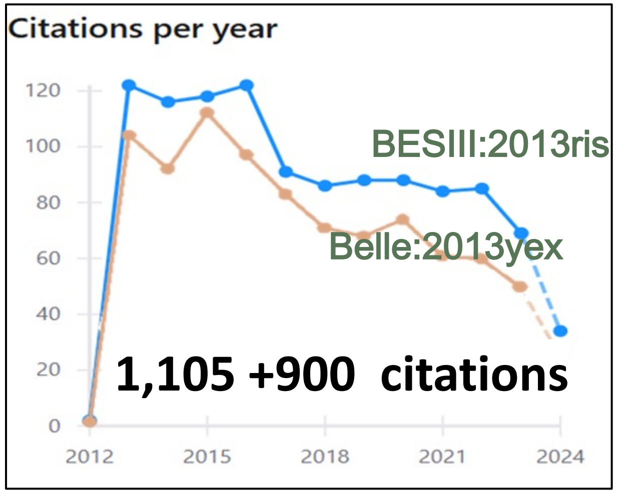
Thanks for your attention!

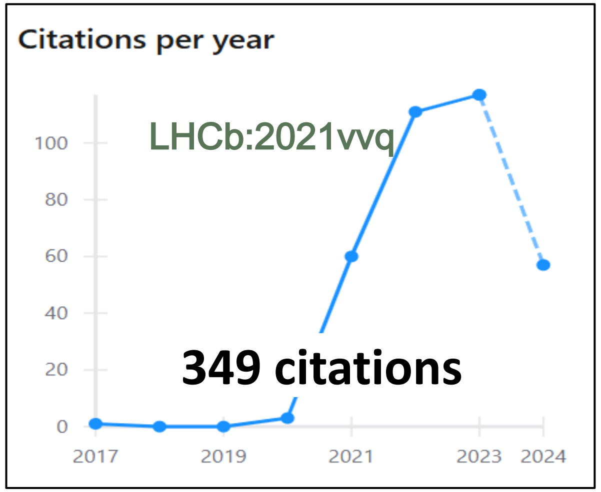
backup

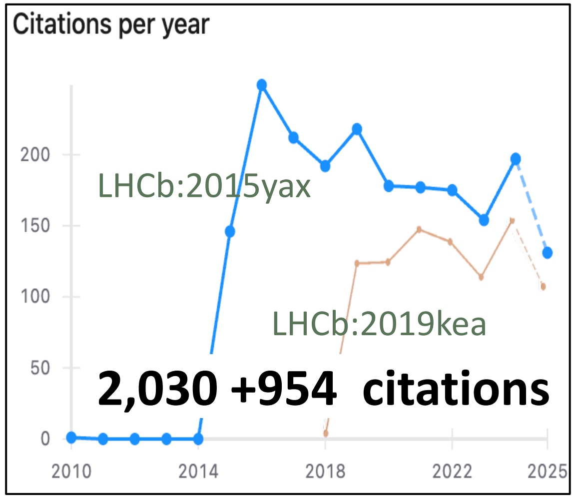
"Superstars"

	Quark contents	$I^G(J^{PC})$	Threshold	ΔM [MeV]	Γ [MeV]
$X(3872)$	$q\bar{q}c\bar{c}/c\bar{c}$	$0^+(1^{++})$	$D^0\bar{D}^{0*}$	$0.0068^{+0.1655}_{-0.17000}$	$0.380^{+0.412}_{-0.322}$
	The 1st charmonium-like state				BESIII:2023hmi
$Z_c(3900)$	$q\bar{q}c\bar{c}$	$1^+(1^{+-})$	$D\bar{D}^*$	11.3 ± 2.6	PDG 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				LHCb:2021auc
$P_{c\bar{c}}$ states	$qqqc\bar{c}$	?	$\Sigma_c\bar{D}^{(*)}$	$-5\sim-20$	$\sim-$ **10**
	The 1st pentaquark states				LHCb:2015yax



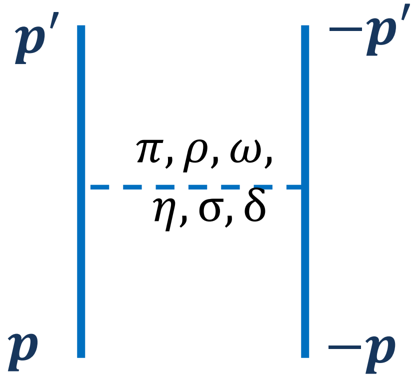






Components of OBE model

- Exchanged mesons
  - ▶ Hidden local gauge symmetry: vector-meson exchange
  - ▶ π, ρ, ω, σ,…: 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 incopoerate properly, relativistic effect
  - ▶ Not important? $\mathrm{M}_D^* - M_D \sim 130\ \mathrm{MeV}, M_{\Sigma_c} - M_{\Sigma_c^*} \sim 70\ \mathrm{MeV}$, Neglected in our works



$$\boldsymbol{q} = \boldsymbol{p}' - \boldsymbol{p}$$

$$V(\boldsymbol{p}',\boldsymbol{p}) \to V(\boldsymbol{p}',\boldsymbol{p}) \frac{\Lambda^2}{\Lambda^2 + p^2} \frac{\Lambda^2}{\Lambda^2 + p'^2}$$

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

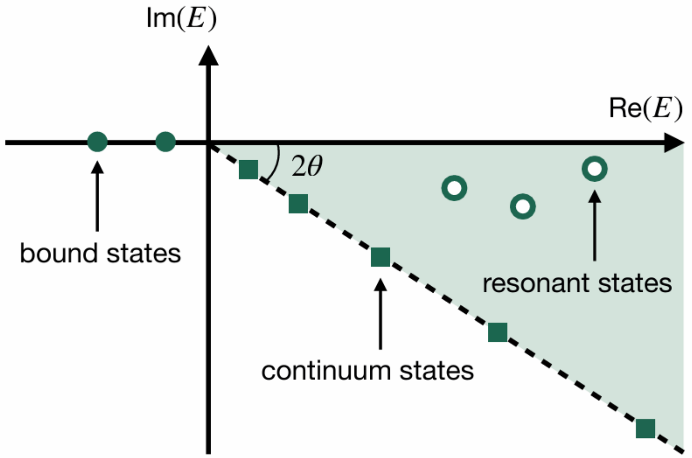
Other options…

Schrodinger/Lippman-Schwinger equation

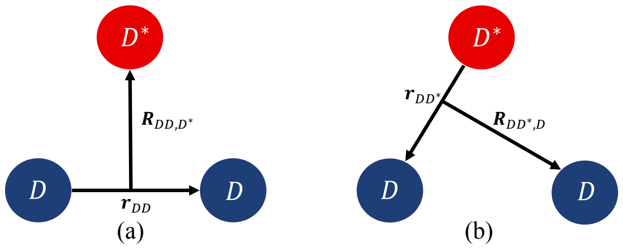
- Momentum space:
  - ▶ **Discrize the momenta**
  - ▶ **Deformed contour**: resonance, virtual state

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

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



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



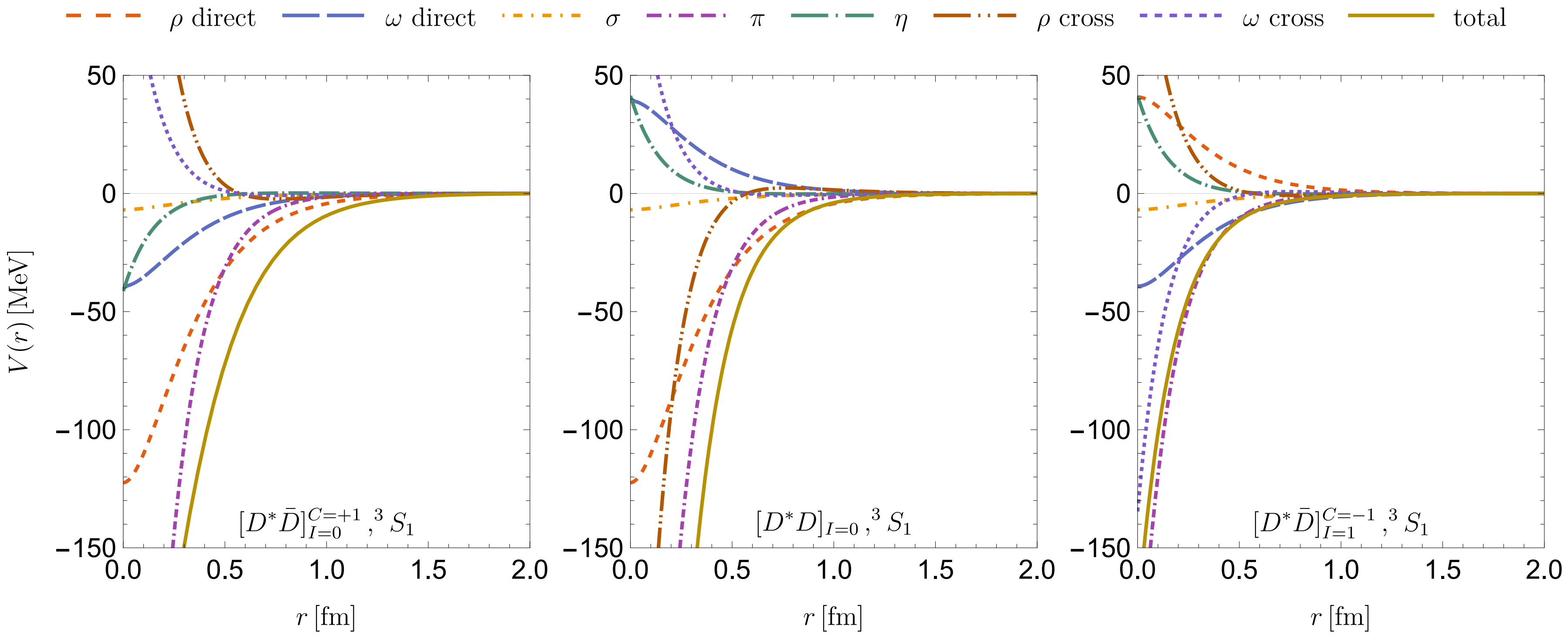
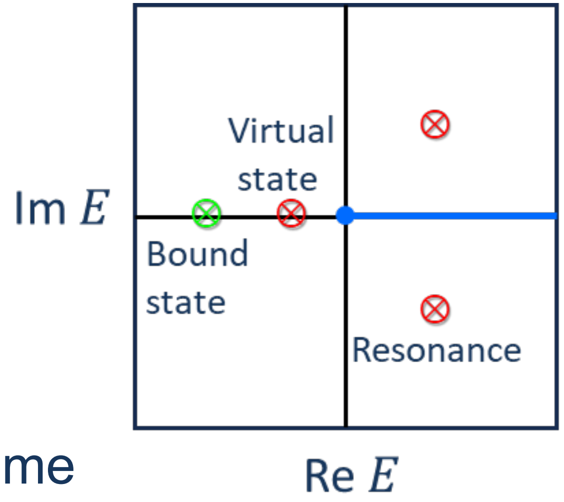


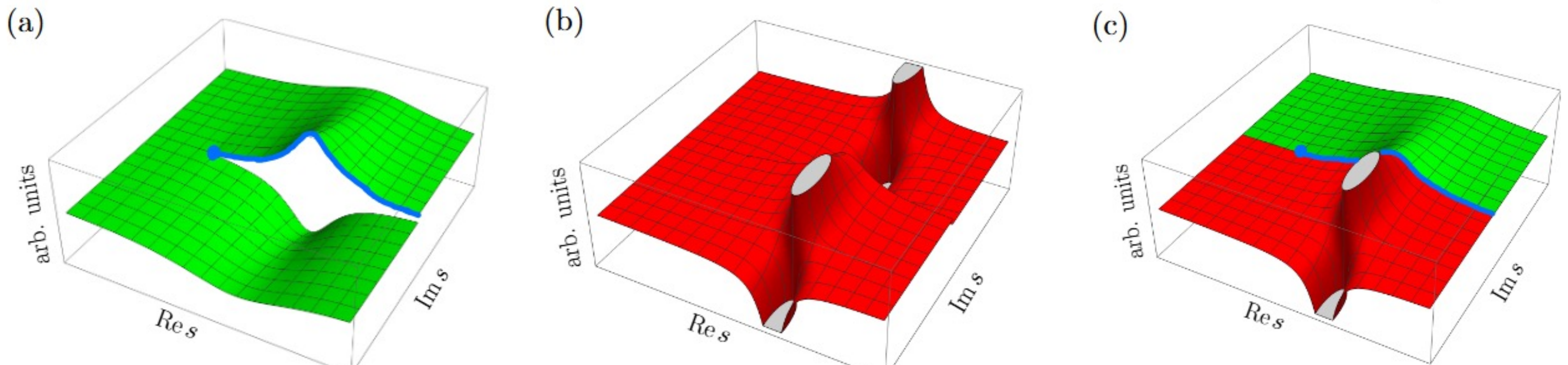
FIG. 2. The coordinate space potentials in the isospin limit for the systems corresponding to the $X(3872)$, $T_{cc}(3875)$, and $Z_c(3900)$ states. The parameter Λ is set to 1.20 GeV, with R_β, R_λ, and R_s fixed at 1.

Bound state, Virtual state and Resonance

- Single channel scattering as an example
- T-matrix: Unitary cut ⇒ multivalued function ⇒ Riemann sheets
- "States" ⇔ 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

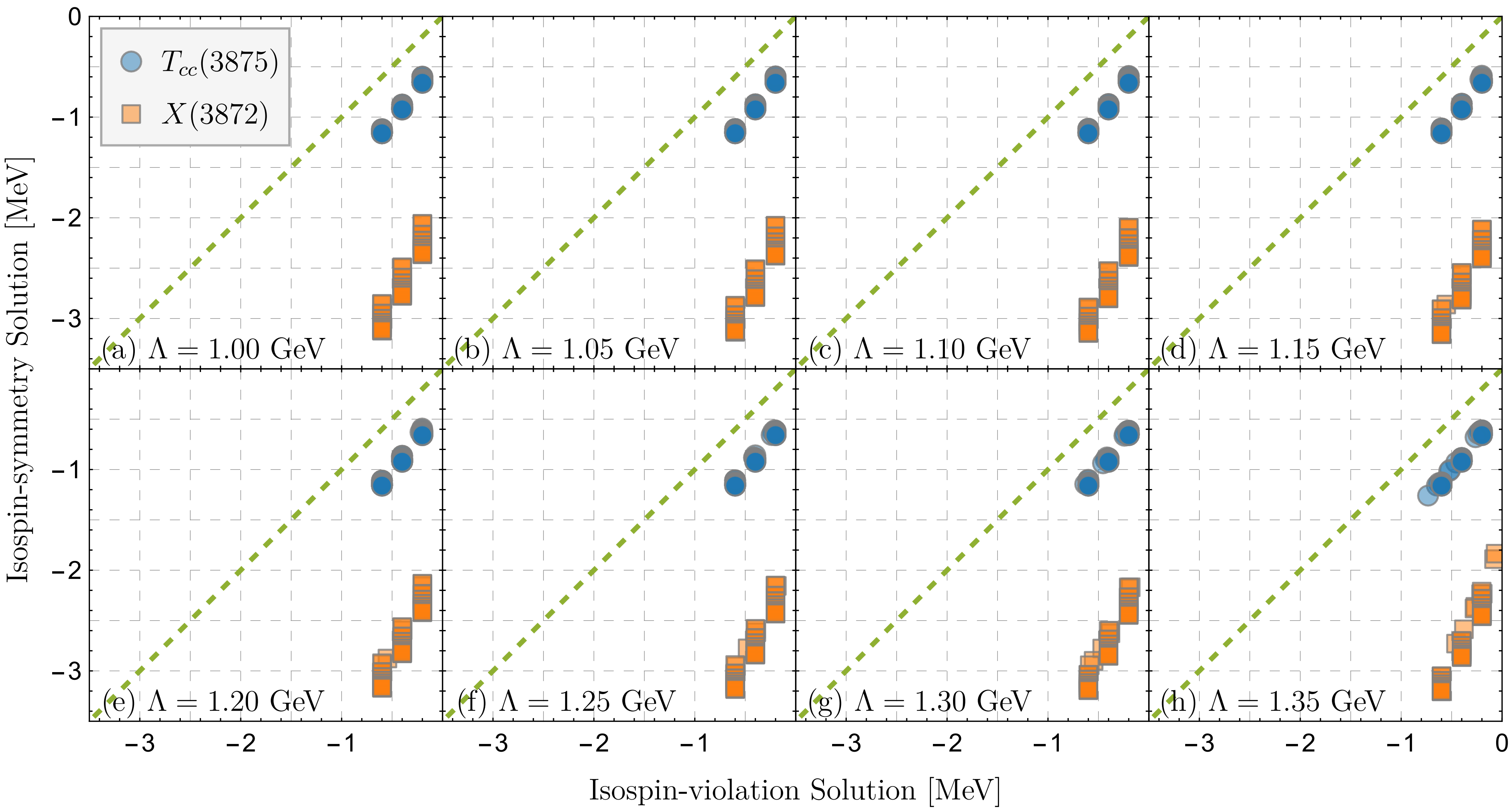


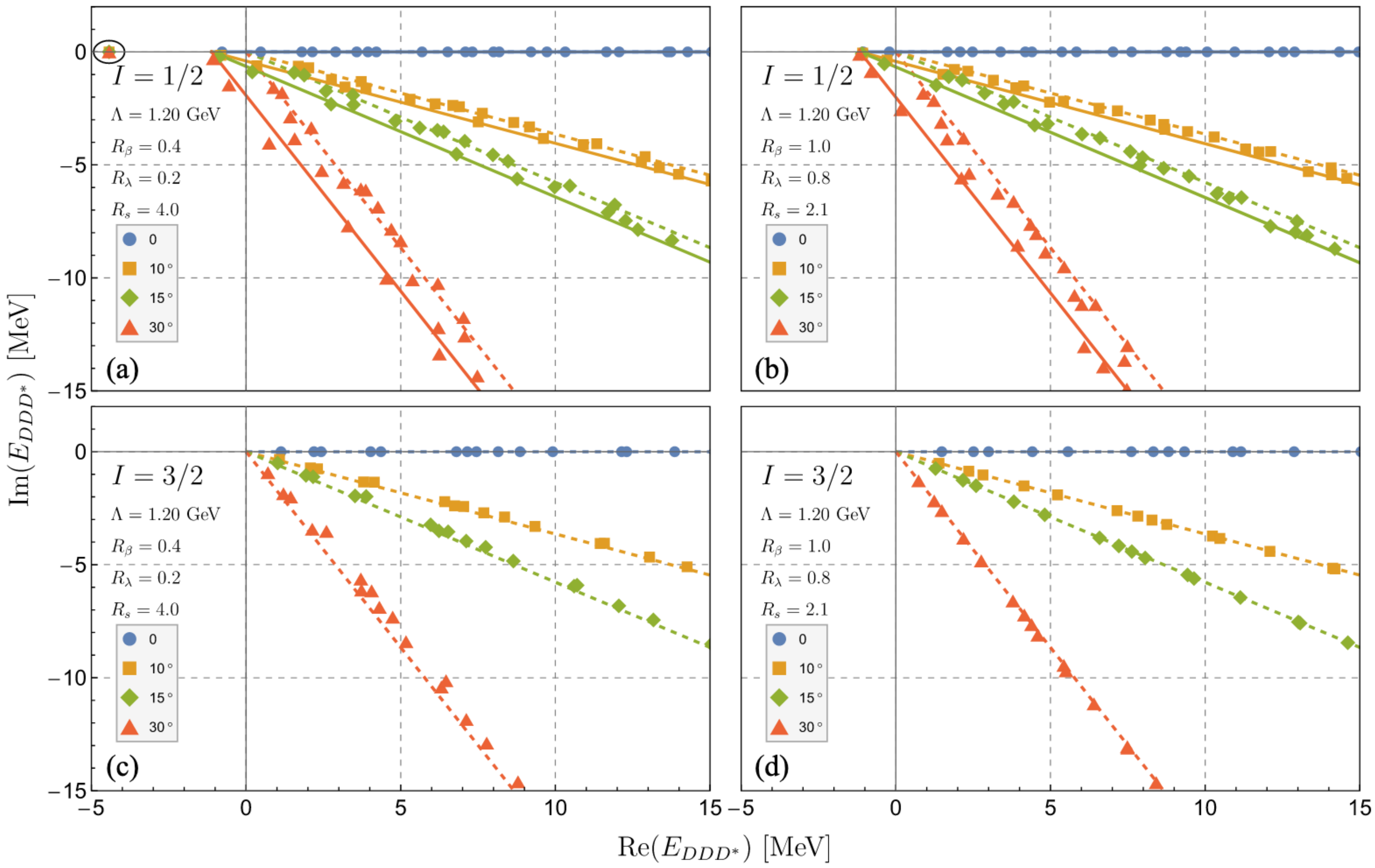
Mizera:2023tfe; PDG



Physical sheet　　unphysical sheet　　Analytical continuation

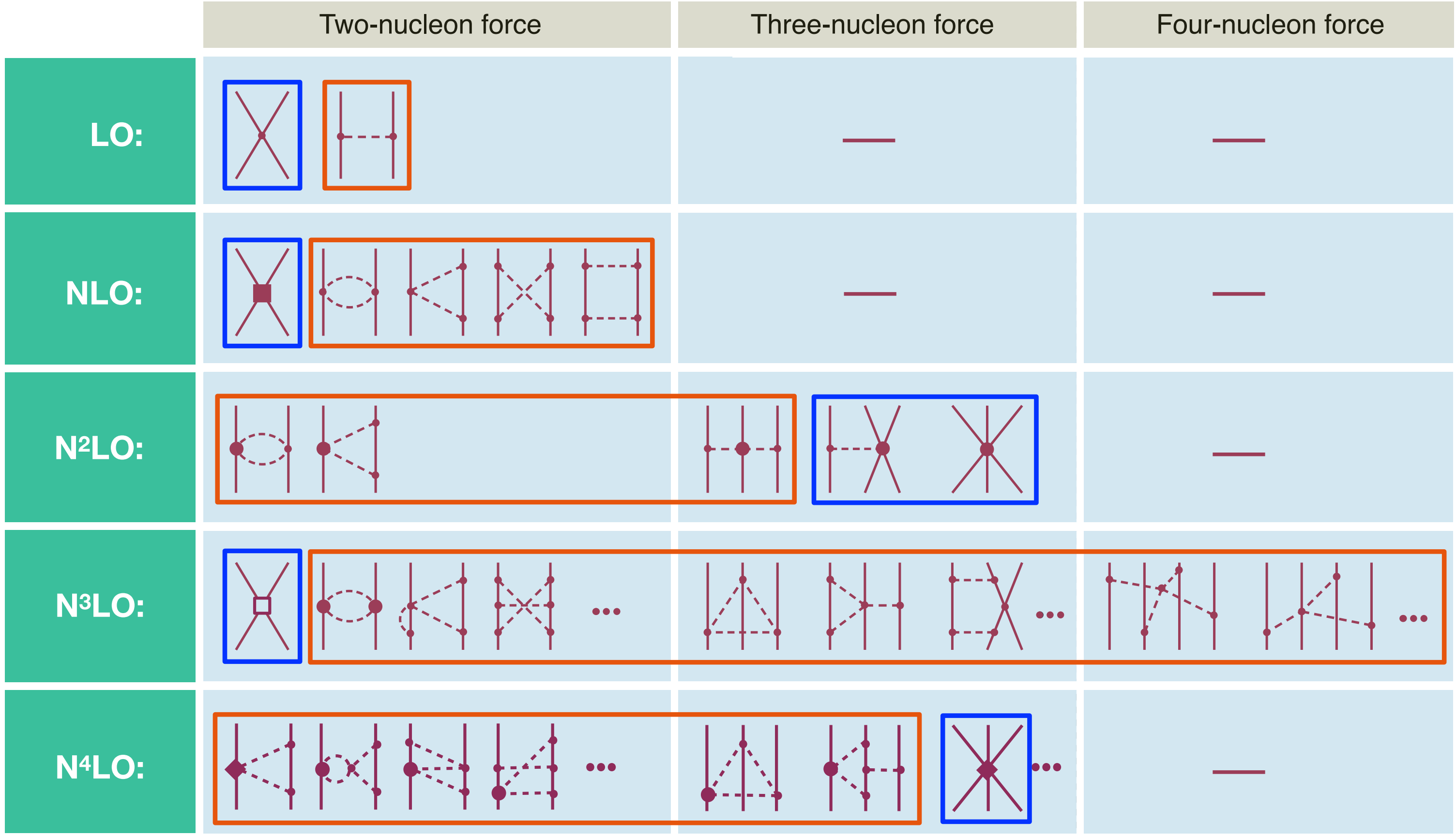
Isospin violation effect

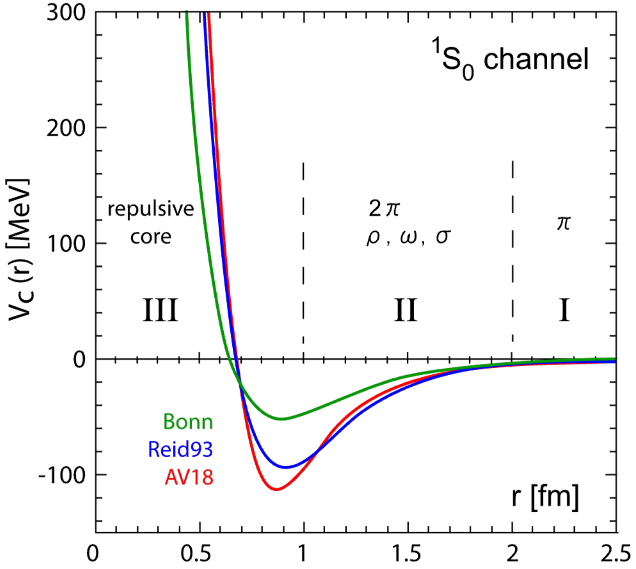


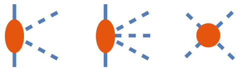


$I = 1/2$
$\Lambda = 1.20$ GeV
$R_\beta = 0.4$
$R_\lambda = 0.2$
$R_s = 4.0$
0
10°
15°
30°
(a)
$I = 1/2$
$\Lambda = 1.20$ GeV
$R_\beta = 1.0$
$R_\lambda = 0.8$
$R_s = 2.1$
(b)
$I = 3/2$
$\Lambda = 1.20$ GeV
$R_\beta = 0.4$
$R_\lambda = 0.2$
$R_s = 4.0$
(c)
$I = 3/2$
$\Lambda = 1.20$ GeV
$R_\beta = 1.0$
$R_\lambda = 0.8$
$R_s = 2.1$
(d)
$\mathrm{Im}(E_{DDD^*})$ [MeV]
$\mathrm{Re}(E_{DDD^*})$ [MeV]

Nuclear force in ChEFT





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

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

Chiral nucear force

Phenomenologial nucear force