Hadron interactions from lattice QCD

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HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)

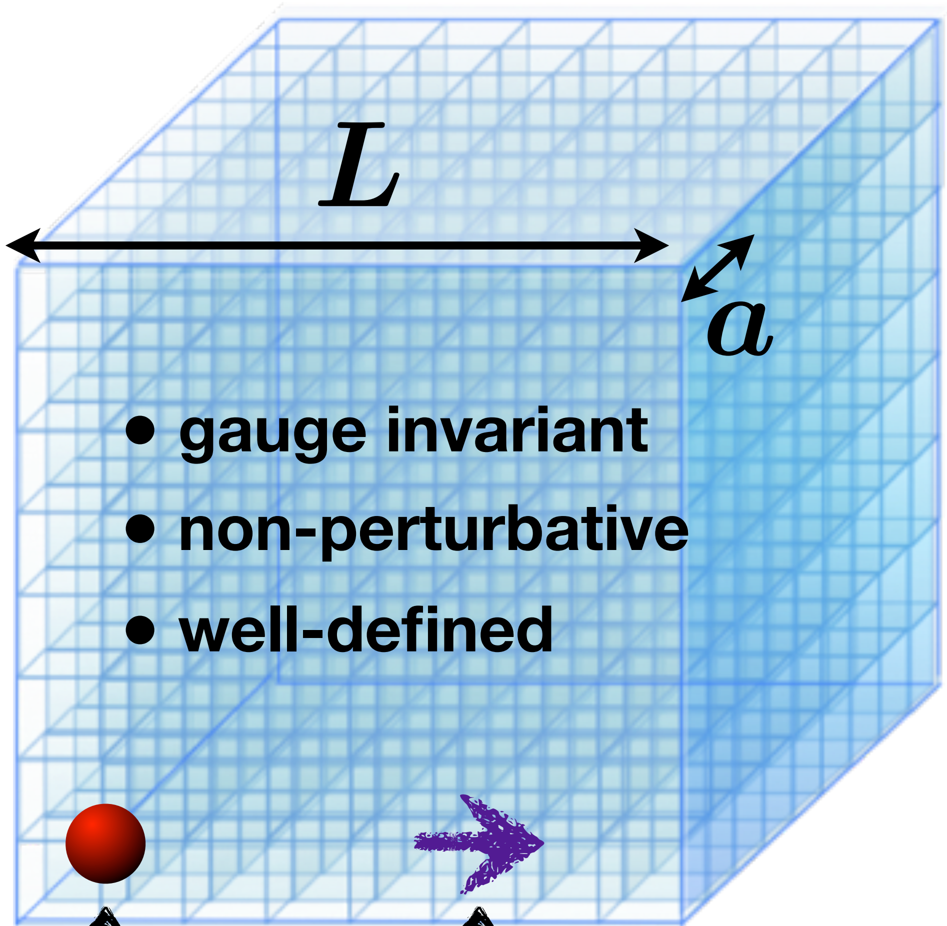
S. Aoki, T. Aoyama, Y. Akahoshi, K. Sasaki, T. Miyamoto (YITP, Kyoto Univ.)
T. Doi, T. M. Doi, S. Gongyo, T. Hatsuda, T. Iritani, T. Sugiura (RIKEN)
Y. Ikeda, N. Ishii, K. Murano, H. Nemura (RCNP, Osaka Univ.)
T. Inoue (Nihon Univ.)

Few-body systems in Hadron, Nuclear, Atomic and Molecular Physics
Aug. 9, RIKEN, Wako, Saitama

Lattice QCD =1st-principles calculation of QCD

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m \bar{q} q$$

★ strong coupling $\alpha_s = g^2/4\pi \sim 1$, non-Abelian --> non-trivial vacuum...



quarks q
on the sites

gluons $U_\mu = exp(iaA_\mu)$
on the links

- path integral formulation

$$Z = \int [dU][d\bar{q}dq] \; \exp\Big(-\int d\tau d^3x \mathcal{L}_E\Big)$$

typically $(30\text{-}100)^4 \sim 10^{6\text{-}8}$ sites employed

Monte Carlo Simulations

input parameters

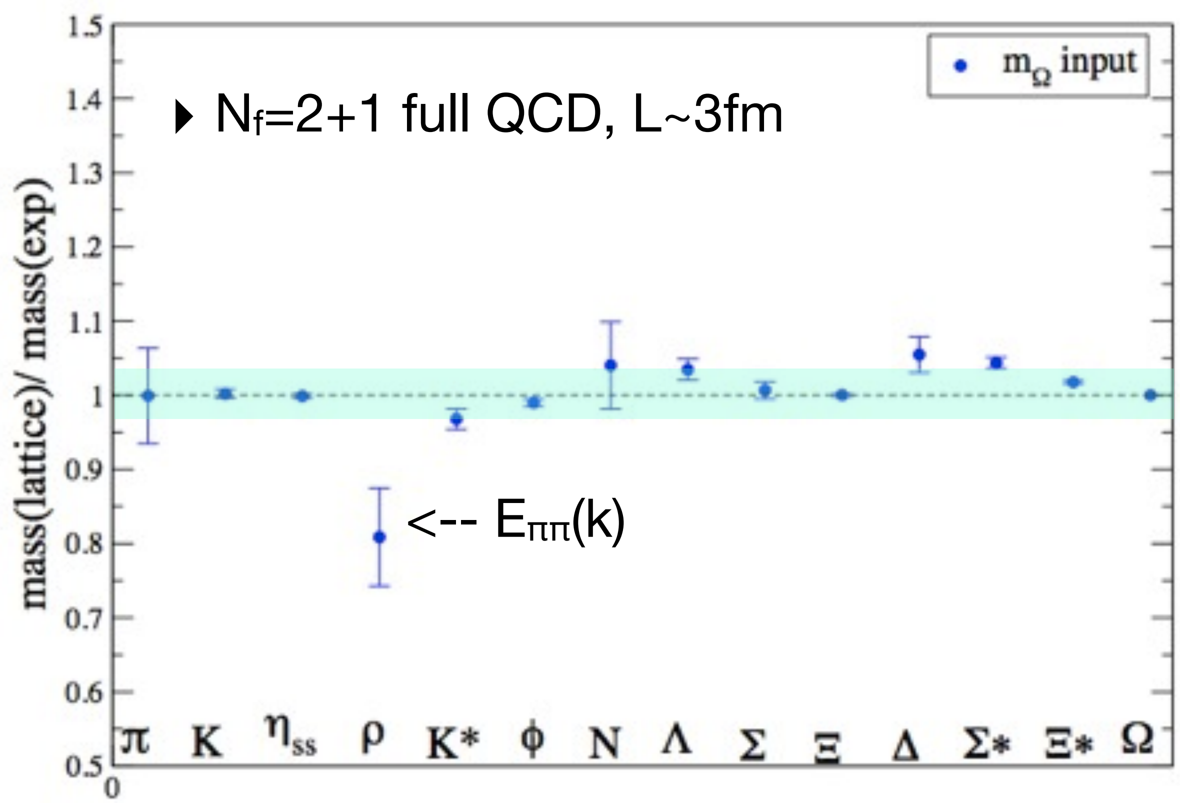
- quark mass m_q
- gauge coupling g

observables <O(r,t)>

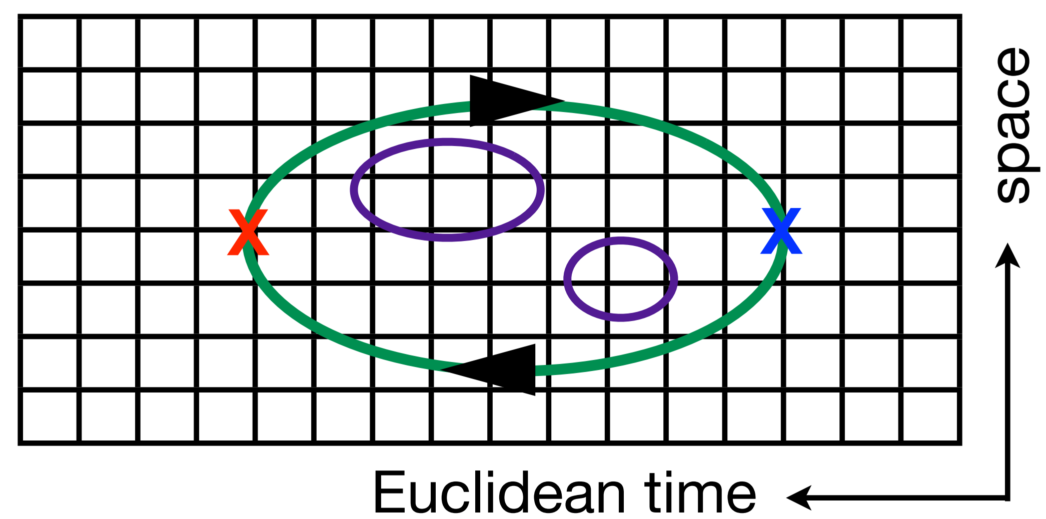
- ensemble average of O

Single hadron spectroscopy from LQCD

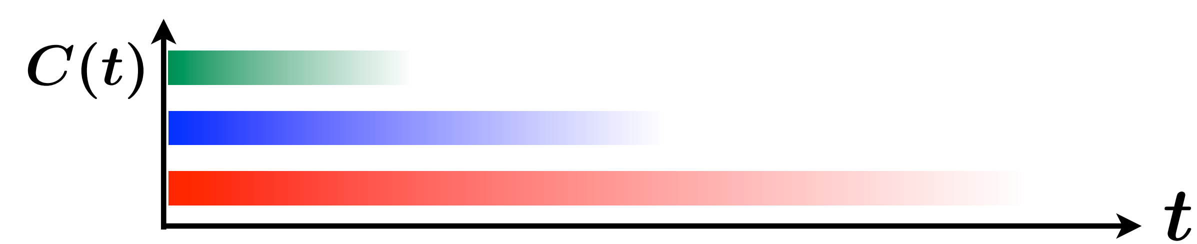
★ Low-lying hadrons on physical point (physical m_q)

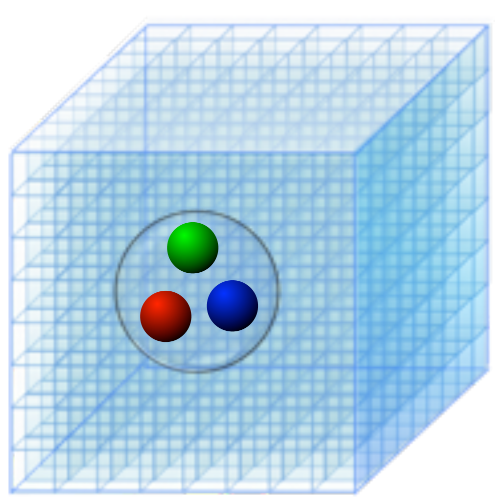


Aoki et al. (PACS-CS), PRD81 (2010).



$$C(t) = \sum_{\vec{x}} \langle 0 | \phi(\vec{x}, t) \phi(\vec{0}, 0)^\dagger | 0 \rangle$$
$$= A_1 e^{-M_1 t} + A_2 e^{-M_2 t} + A_3 e^{-M_3 t} + \cdots$$





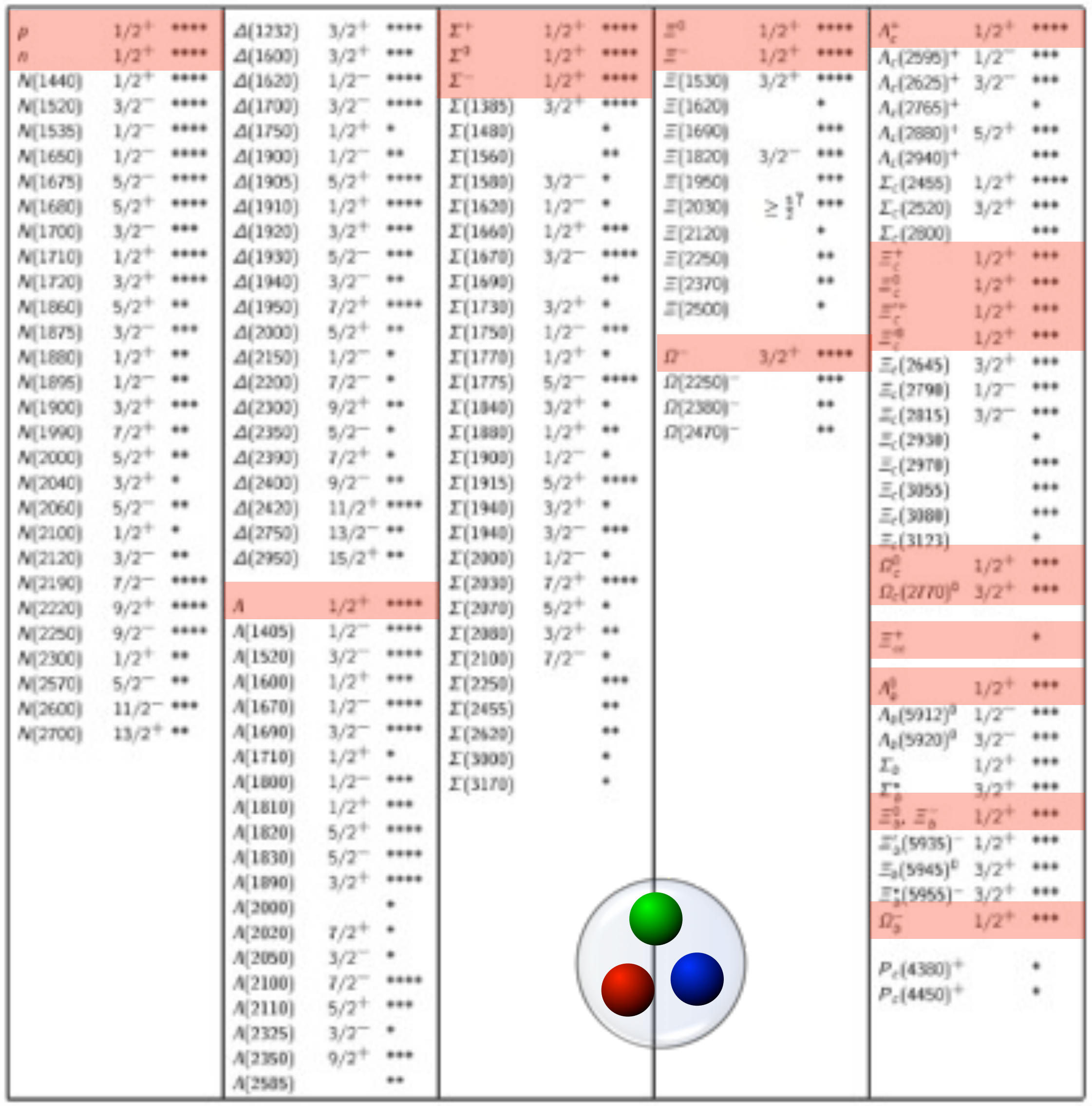
✓ a few % accuracy achieved for single hadrons

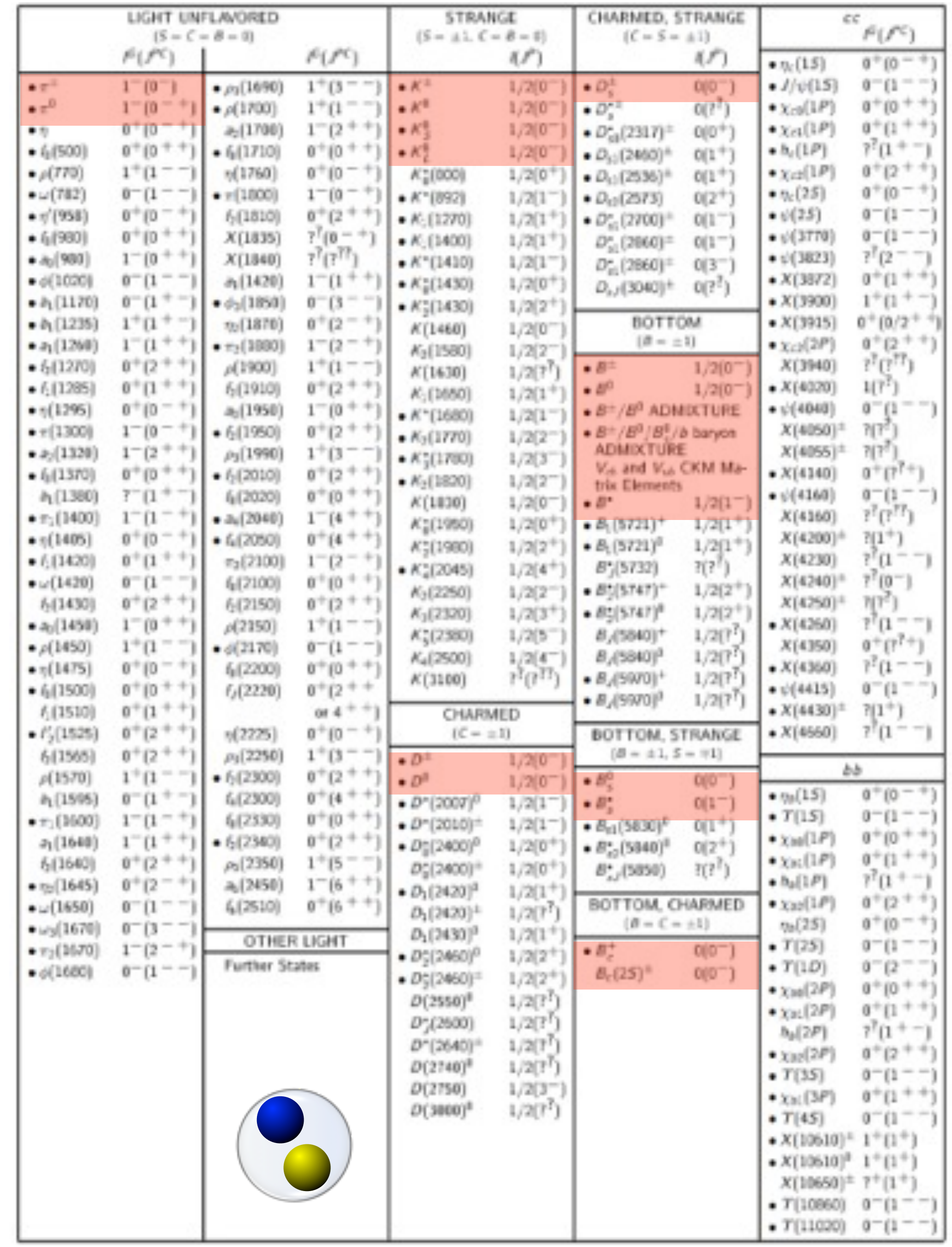
➡ **Next challenge in spectroscopy : hadron resonances**

Hadron resonances

- **Particle data group**

  http://www-pdg.lbl.gov/



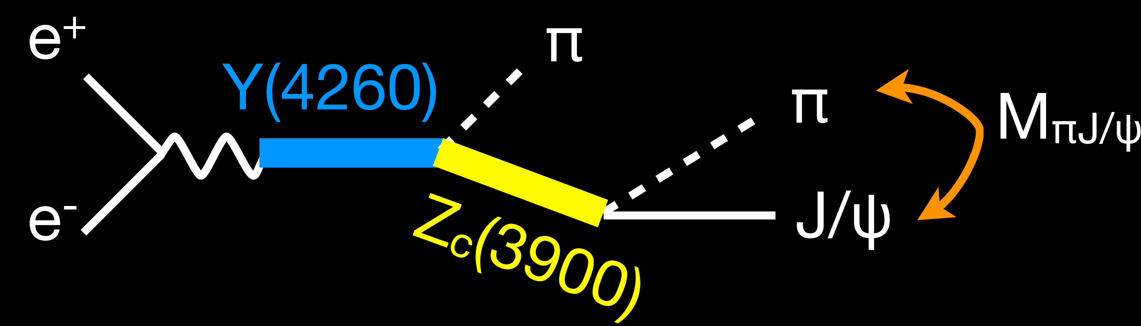


- Most hadrons are consistent with qqq / qq^{bar} quantum number (non-trivial)
- Only 10% is stable, others are unstable (resonances) and some can be fake..
- Understanding hadron resonances from QCD is important issue in hadron physics

Tetraquark candidate $Z_c(3900)$

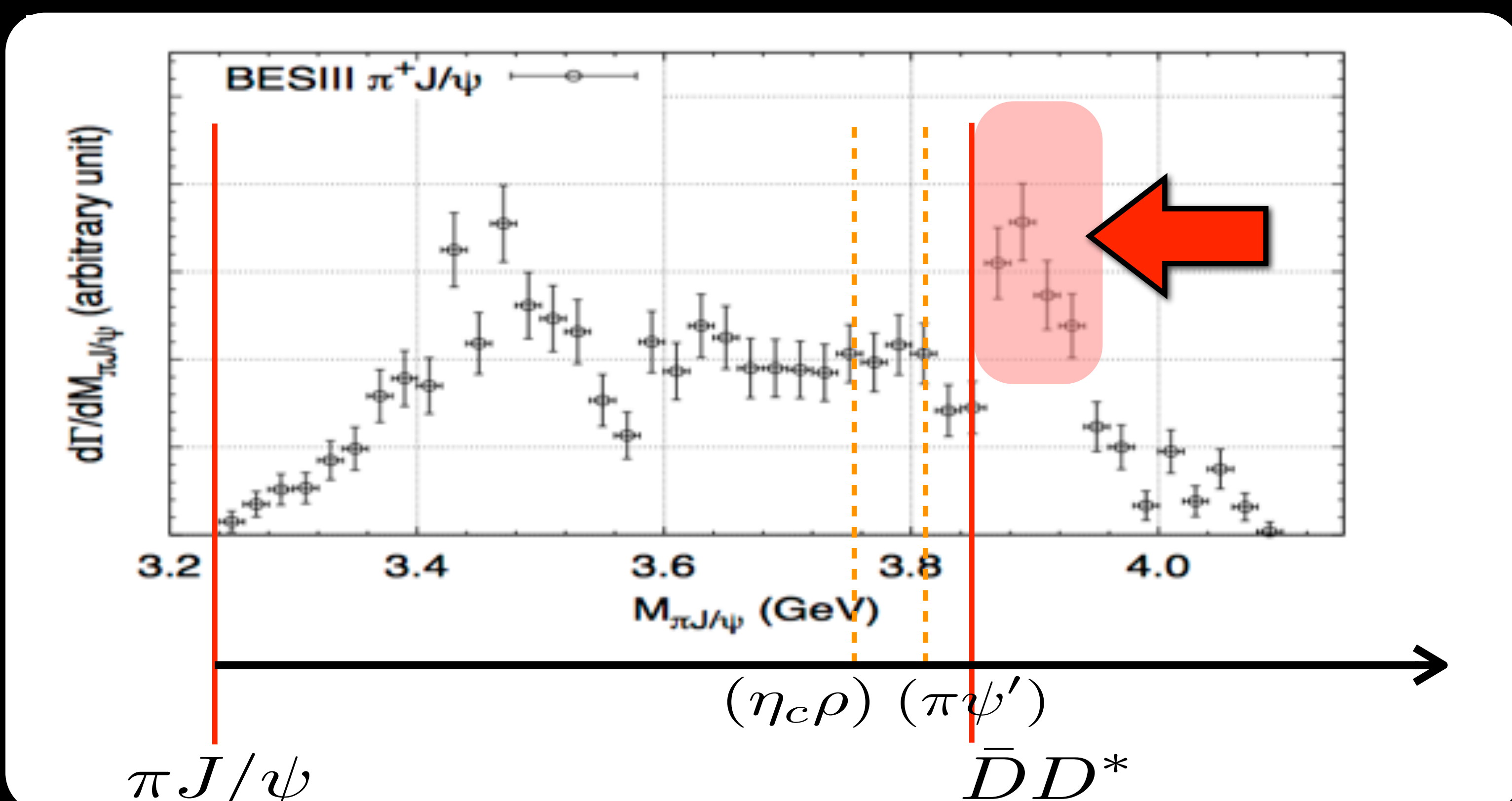
- **Expt. observations**

  Y(4260) 3-body decay



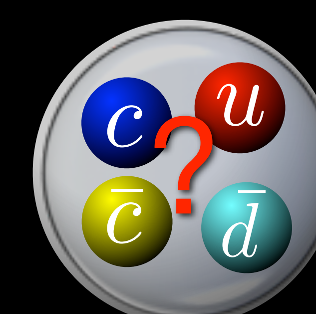
- $e^+ + e^-$ --> Y(4260) --> π + $\underline{Z_c(3900)}$

  ➡ $\pi^{+/-}$ + J/ψ



BESIII Coll., PRL110 (2013).

see also Belle Coll., PRL110 (2013).



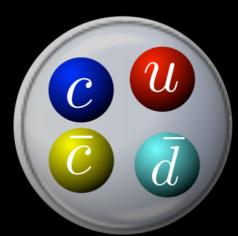
- peak in $\pi^{+/-}$J/ψ invariant mass (minimal quark content cc^{bar} ud^{bar} <--> tetraquark?)
- M ~ 3900, Γ ~ 60 MeV (Breit-Wigner, Flatte) --> just above $D^{bar}D^*$ threshold
- $J^{PC}=1^{+-}$ is most probable <--> couple to s-wave meson-meson states

Tetraquark candidate $Z_c(3900)$

★ **structure of $Z_c(3900)$ studied by models**

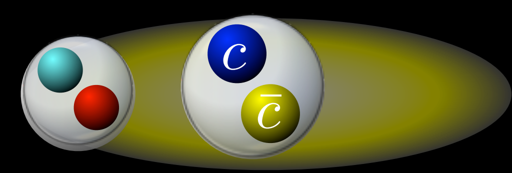
genuine resonance

tetraquark



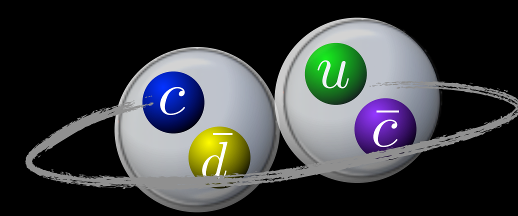
Maiani et al.('13)

J/ψ + π atom



Voloshin('08)

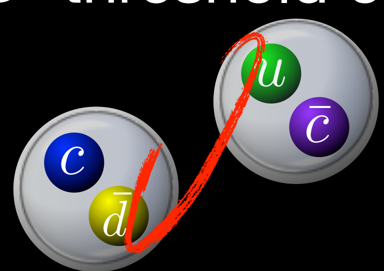
D^{bar}D* molecule



Nieves et al.('11) + many others

kinematical origin

D^{bar}D* threshold effect

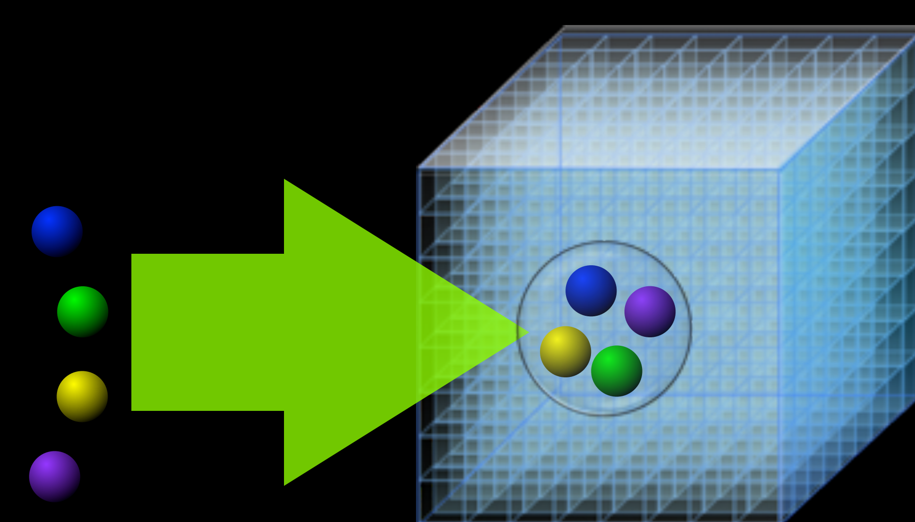


Chen et al.('14), Swanson('15)

conclusion not achieved

➡ **poor information on interactions**

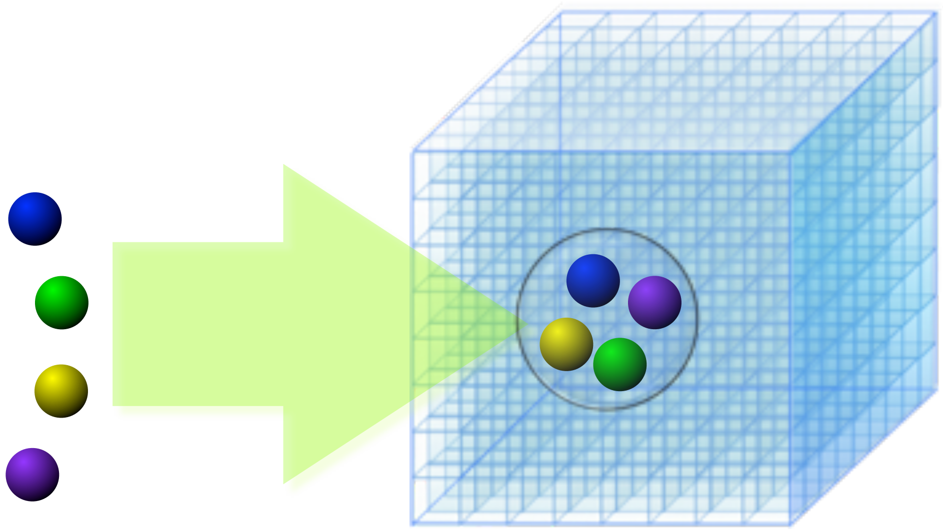
★ LQCD simulations for $Z_c(3900)$



$Z_c(3900)$ on the lattice

✦ Conventional approach: temporal correlation

➡ identify all relevant $W_n(L)$ ($n=0,1,2,3,\ldots$)

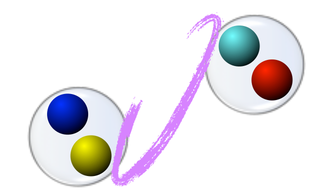


$$\langle 0|\Phi(x)\Phi^\dagger(0)|0\rangle = A_1 e^{-W_1\tau} + A_2 e^{-W_2\tau} + \cdots$$

(W_1, W_2, ... are eigen-energies)

e.g., 4-quark operator

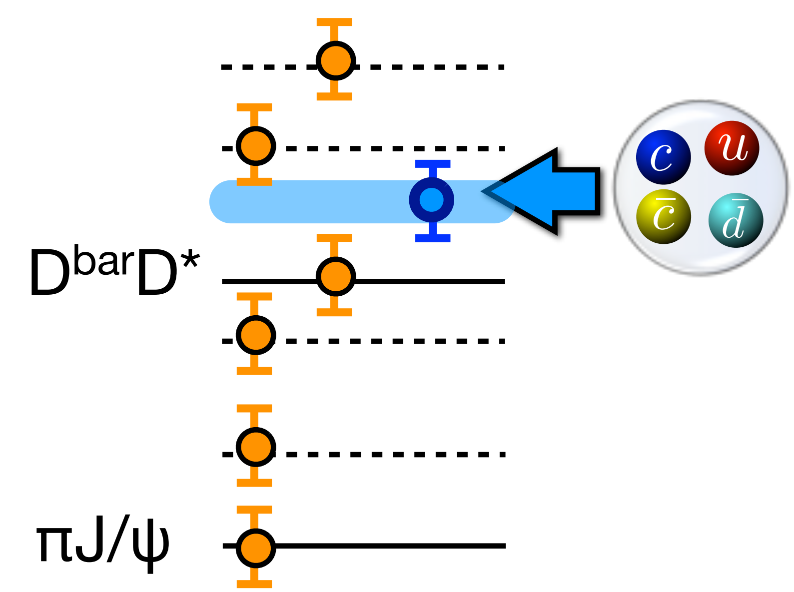
$$\Phi(x) = \bar{q}(x)\bar{q}(x)q(x)q(x)$$



✔ No positive evidence for $Z_c(3900)$ in $J^{PC}=1^{+-}$

(observed spectrum consistent with scat. states)

S. Prelovsek et al., PLB 727 (2013), PRD91 (2015).
S.-H. Lee et al., PoS Lattice2014 (2014).



variational method

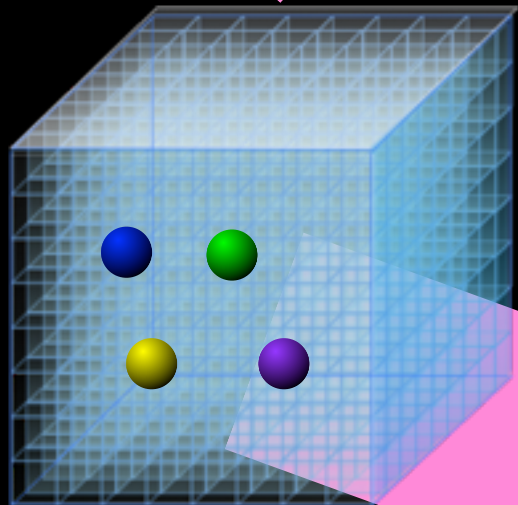
★ Why is the peak observed in expt.?

- (broad) resonance? threshold effect?

★ How can we find resonance in LQCD data?

Strategy for studies of resonances from LQCD

lattice QCD



Conventional approach

$$\langle 0|\Phi(x)\Phi^\dagger(0)|0\rangle = A_1 e^{-W_1\tau} + A_2 e^{-W_2\tau} + \cdots$$

(W_1, W_2, ... are eigen-energies)

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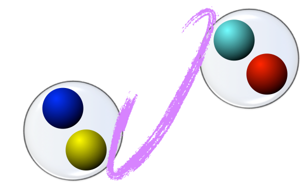
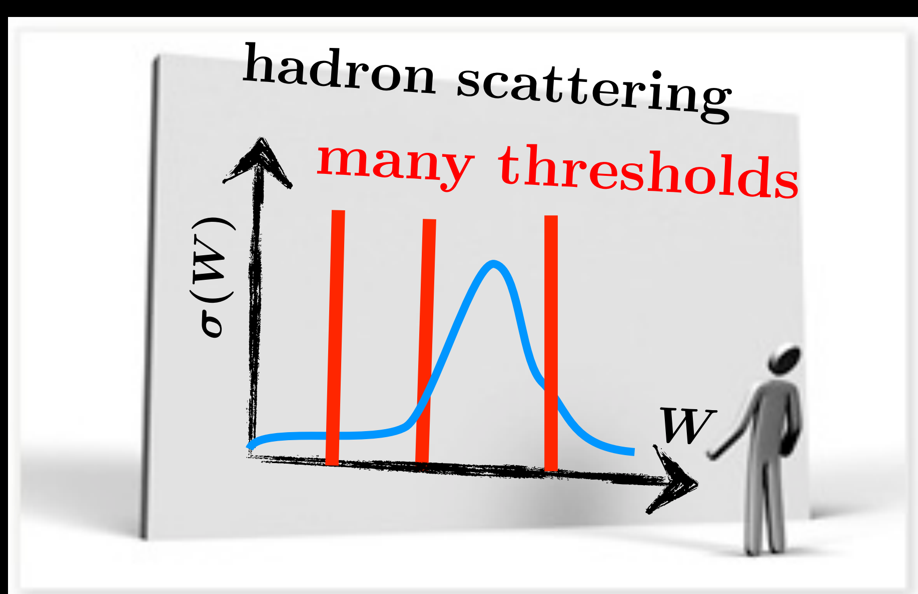
$$\Phi(x) = \bar{q}(x)\bar{q}(x)q(x)q(x)$$





hadron resonances

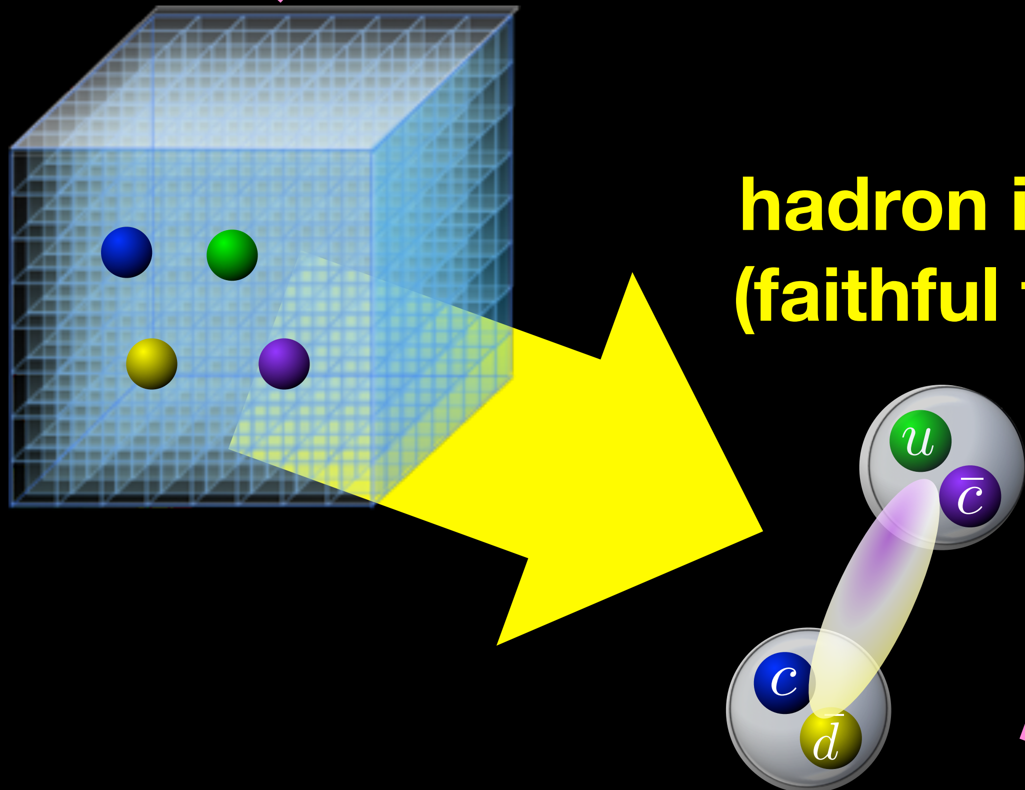
★ **Resonance energy does NOT correspond to eigen-energy**

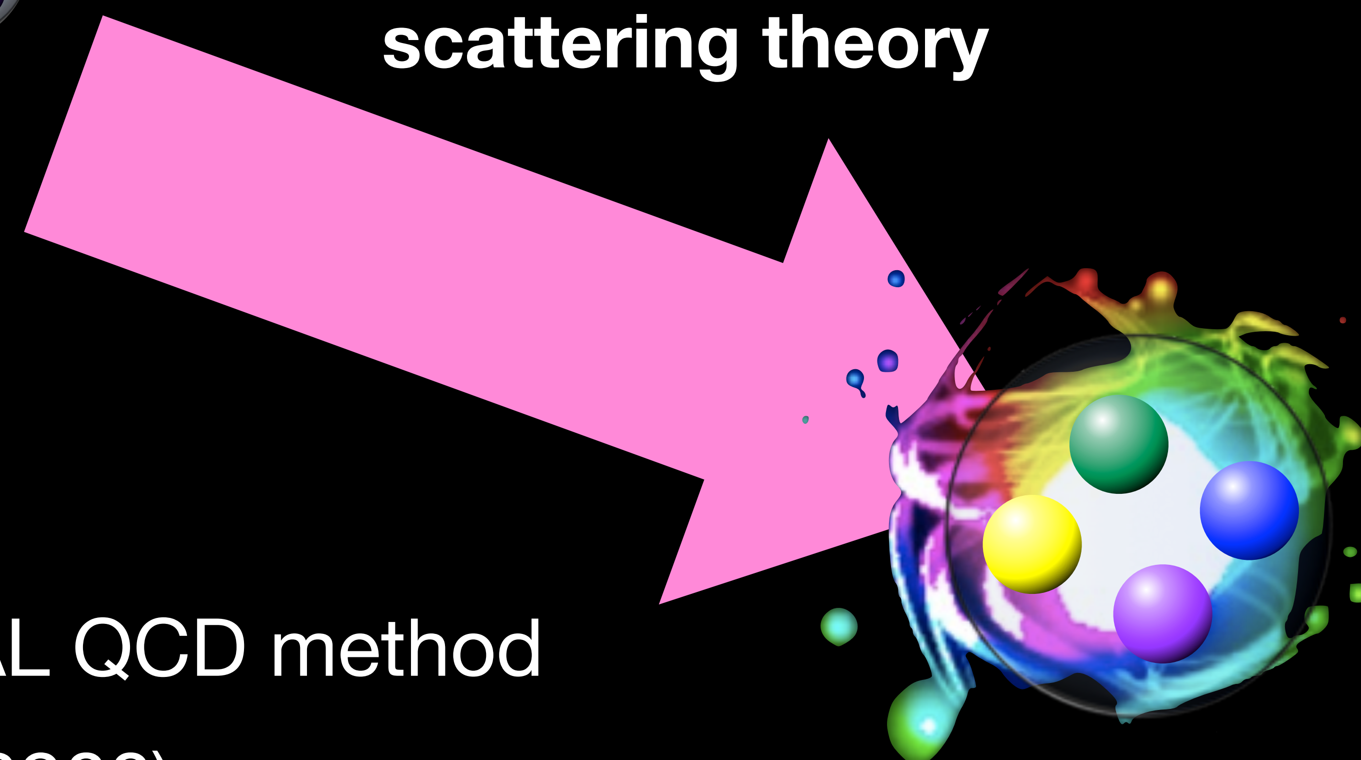
★ **Resonances are embedded into coupled-channel scattering states**

➡ **Resonance energy is determined from pole of coupled-channel S-matrix**

Strategy for studies of resonances from LQCD

(Resonance search through scattering observable)

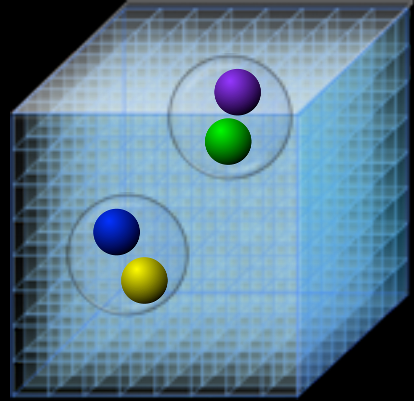




contents

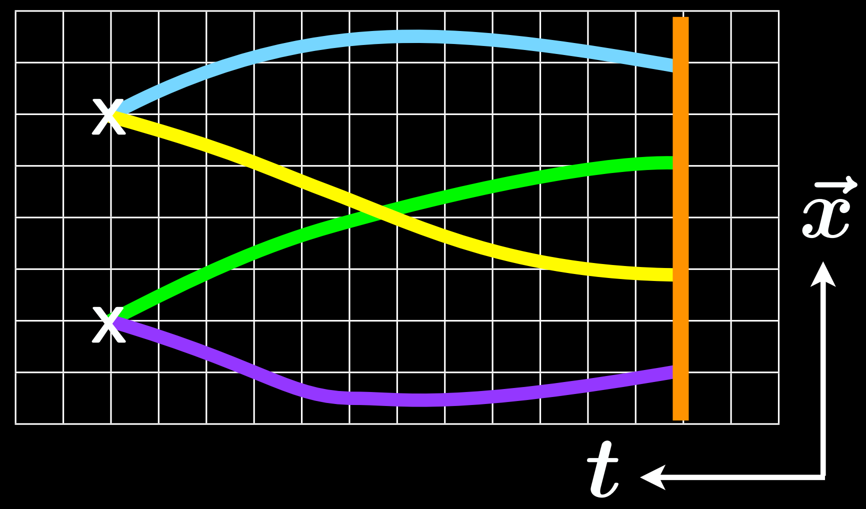
- hadron interactions & HAL QCD method
- tetraquark candidate $Z_c(3900)$
- dibaryon systems
- summary

Hadronic interactions from LQCD



hadronic correlation function

$$C_{(2)}(\vec{r},t) \equiv \langle 0|\phi_1(\vec{r},t)\phi_2(\vec{0},t)\mathcal{J}^\dagger(t=0)|0\rangle$$
$$= \sum_n A_n \psi_n(\vec{r}) e^{-W_n t}$$



- Energy eigenvalue $W_n(L)$
- NBS (Nambu-Bethe-Salpeter) wave function $\psi_n(r)$ (--> $\sin(k_n r + \delta(k_n)) / k_n r$)

C.D. Lee et al., NPB619 (2001).

HAL QCD Method (derive potential as representation of S-matrix)

- **$\psi_n(r)$ --> 2PI kernel ($\psi = \varphi + G_0 U \psi$)**

$$\left(\nabla^2 + k_n^2\right)\psi_n(\vec{r}) = 2\mu \int d\vec{r}' U(\vec{r},\vec{r}')\psi_n(\vec{r}')$$
$$U(\vec{r},\vec{r}') \equiv \sum_{n<n_{\rm th}} \left(E_n - H_0\right)\psi_n(\vec{r})\bar{\psi}_n(\vec{r}')$$

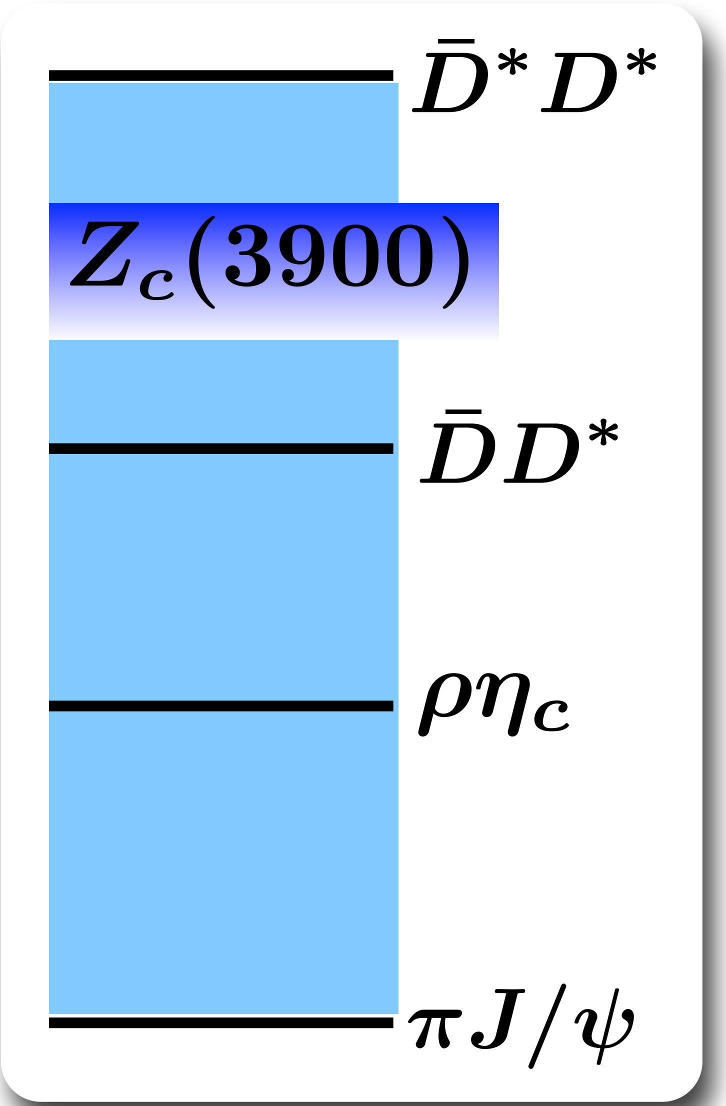
--> phase shift, resonance pole, ...

Ishii, Aoki, Hatsuda, PRL 99, 022001 (2007).

Ishii et al. [HAL QCD], PLB 712, 437 (2012).

Results on $Z_c(3900)$ in $I^G(J^{PC})=1^+(1^{+-})$

Y. Ikeda et al., [HAL QCD], PRL117, 242001 (2016).



light meson mass (MeV)

m_π= 411(1), 572(1), 701(1)

m_ρ= 896(8), 1000(5), 1097(4)

charm meson mass (MeV)

$m_{\eta c}$= 2988(1), 3005(1), 3024(1)

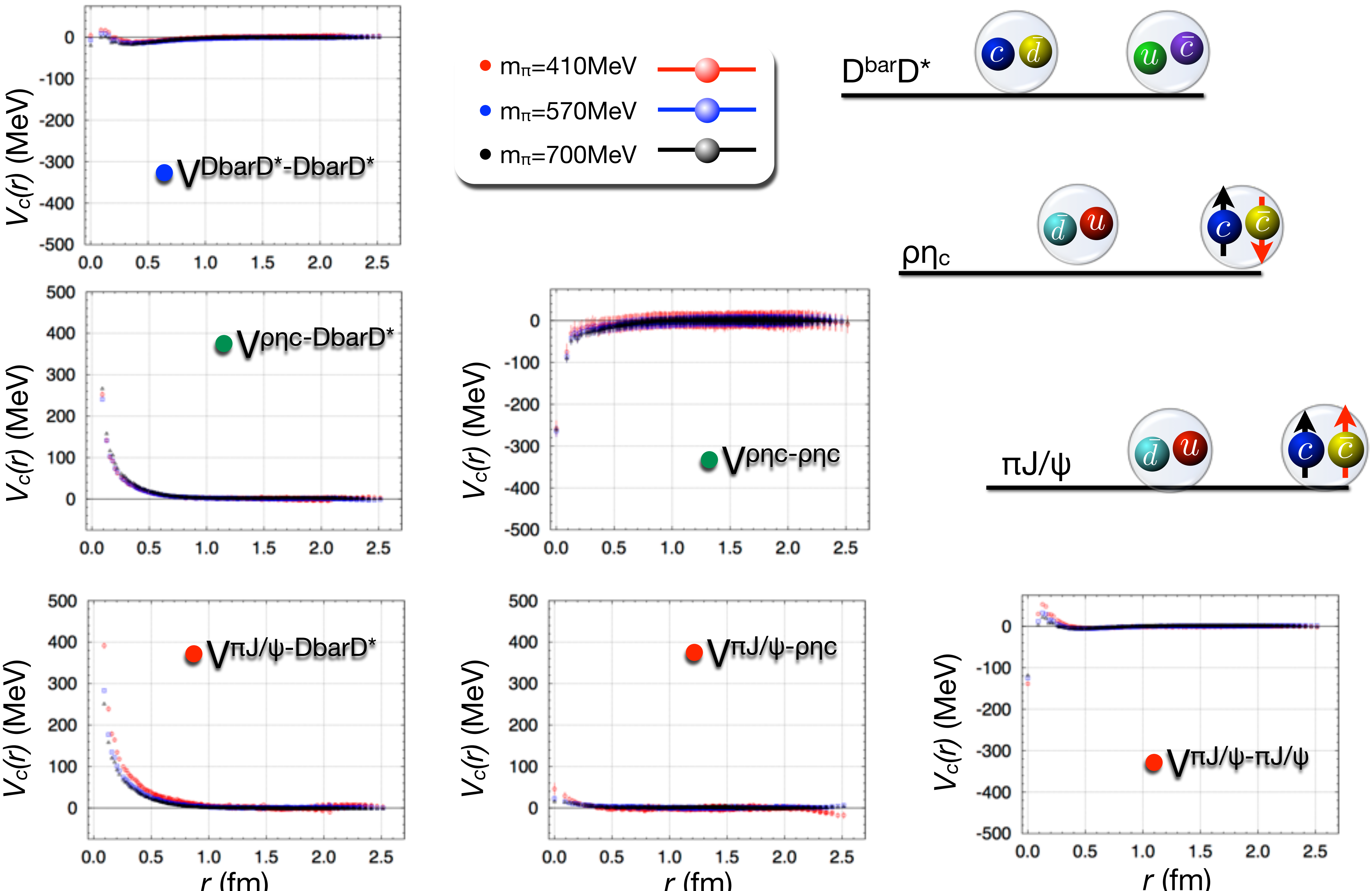
$m_{J/\psi}$= 3097(1), 3118(1), 3143(1)

m_D= 1903(1), 1947(1), 2000(1)

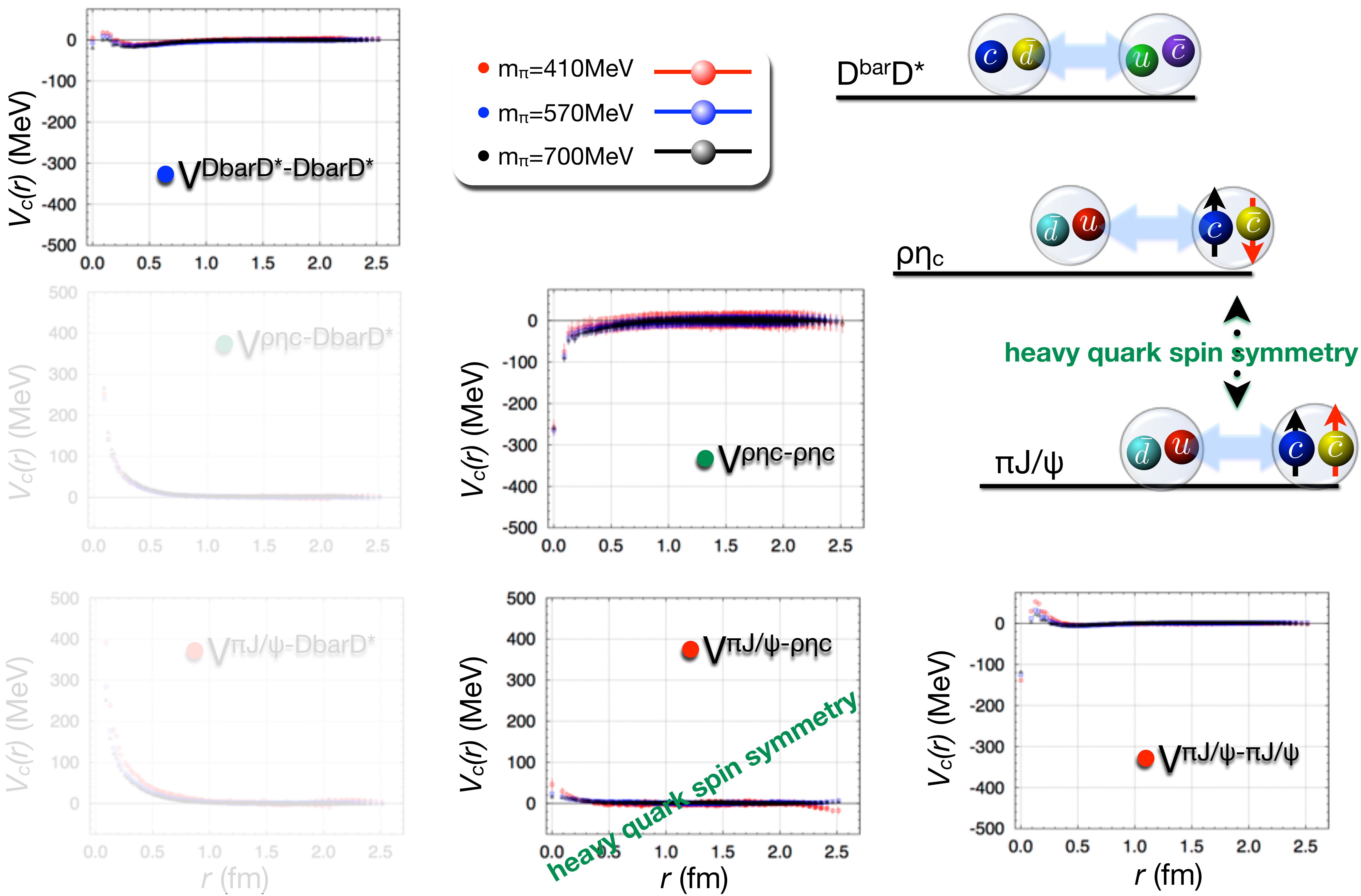
m_{D^*}= 2056(3), 2101(2), 2159(2)

- s-wave coupled-channel ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$) potential
- 2-body observable
- comparison w/ expt. data

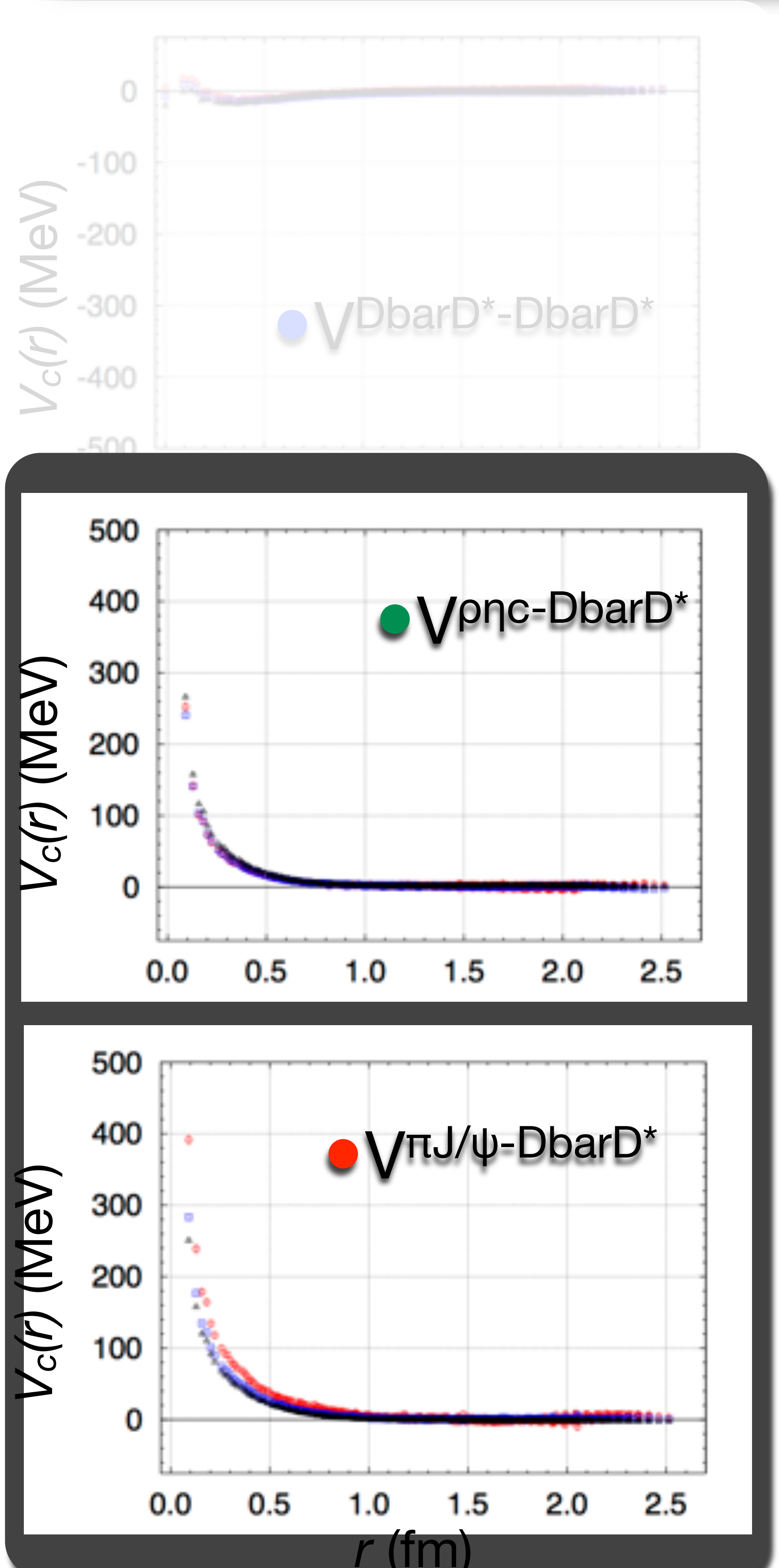
3x3 potential matrix (πJ/ψ - ρηc - DbarD*)

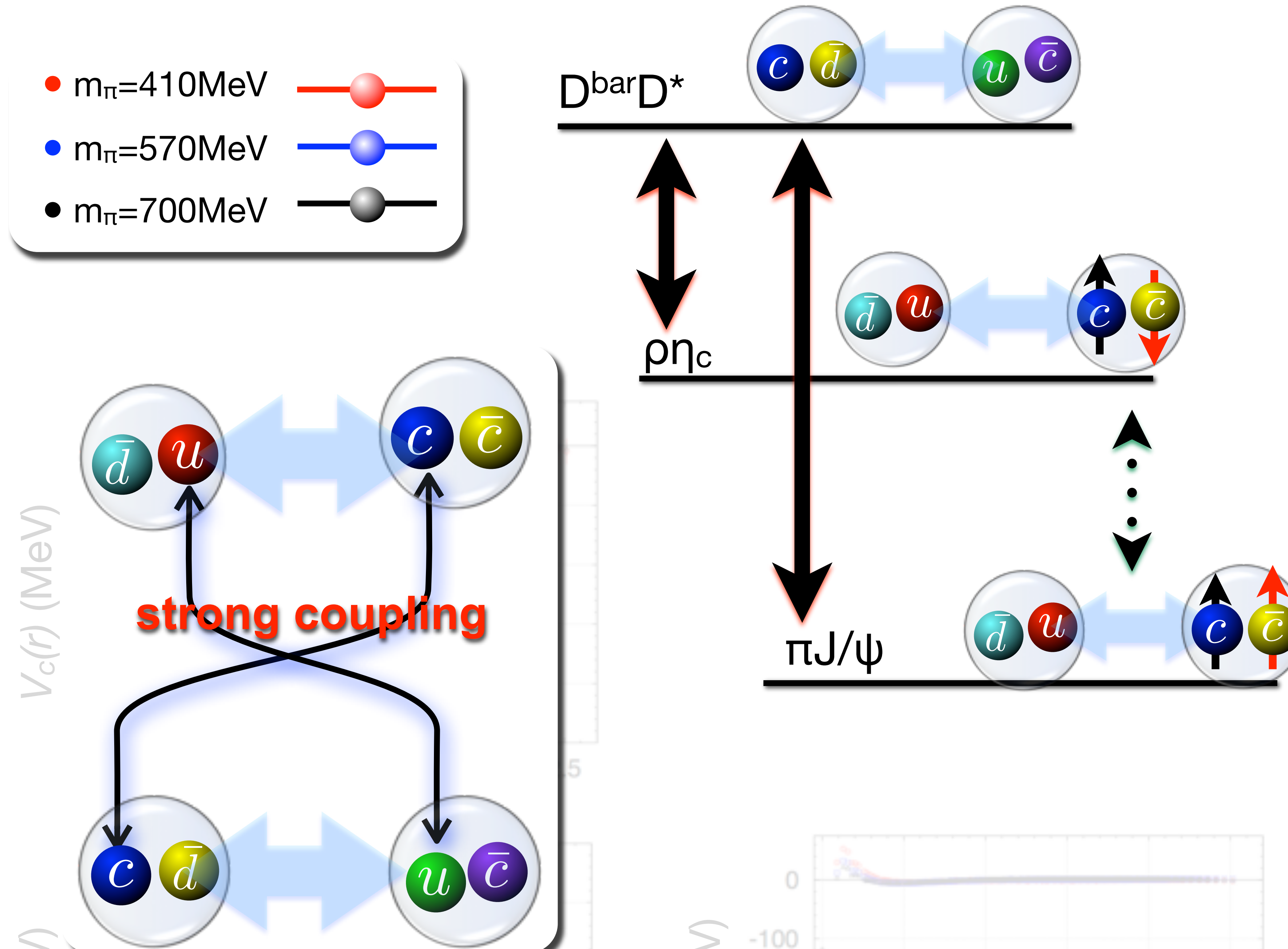


3x3 potential matrix (πJ/ψ - ρηc - DbarD*)



3x3 potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)



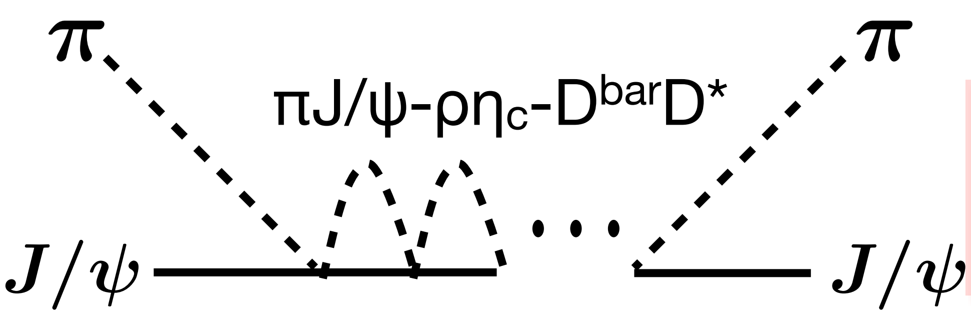


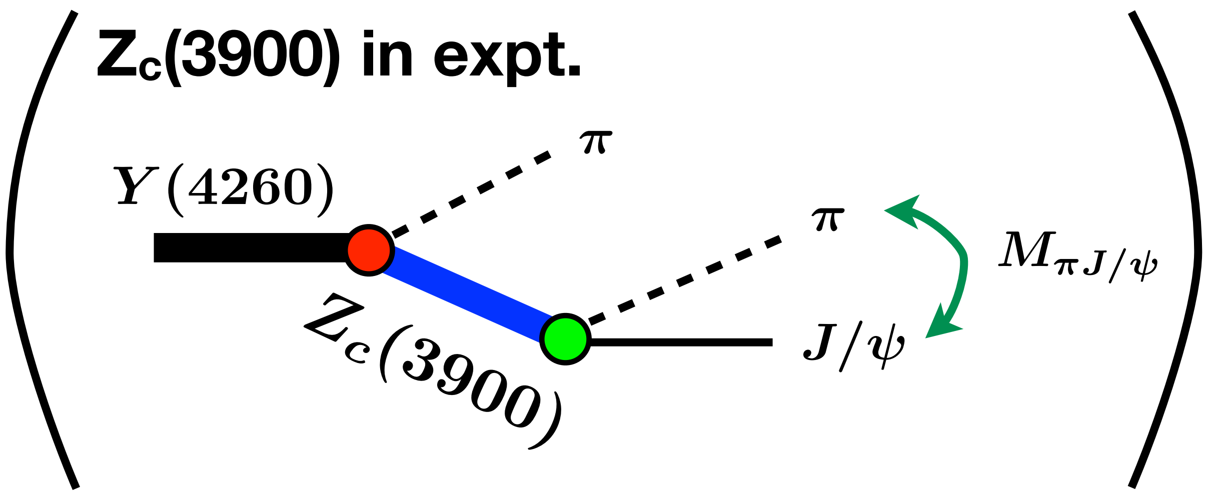
- strong $V^{\pi J/\psi,DbarD^*}$ & $V^{\rho\eta c,DbarD^*}$

➡ charm quark exchange process

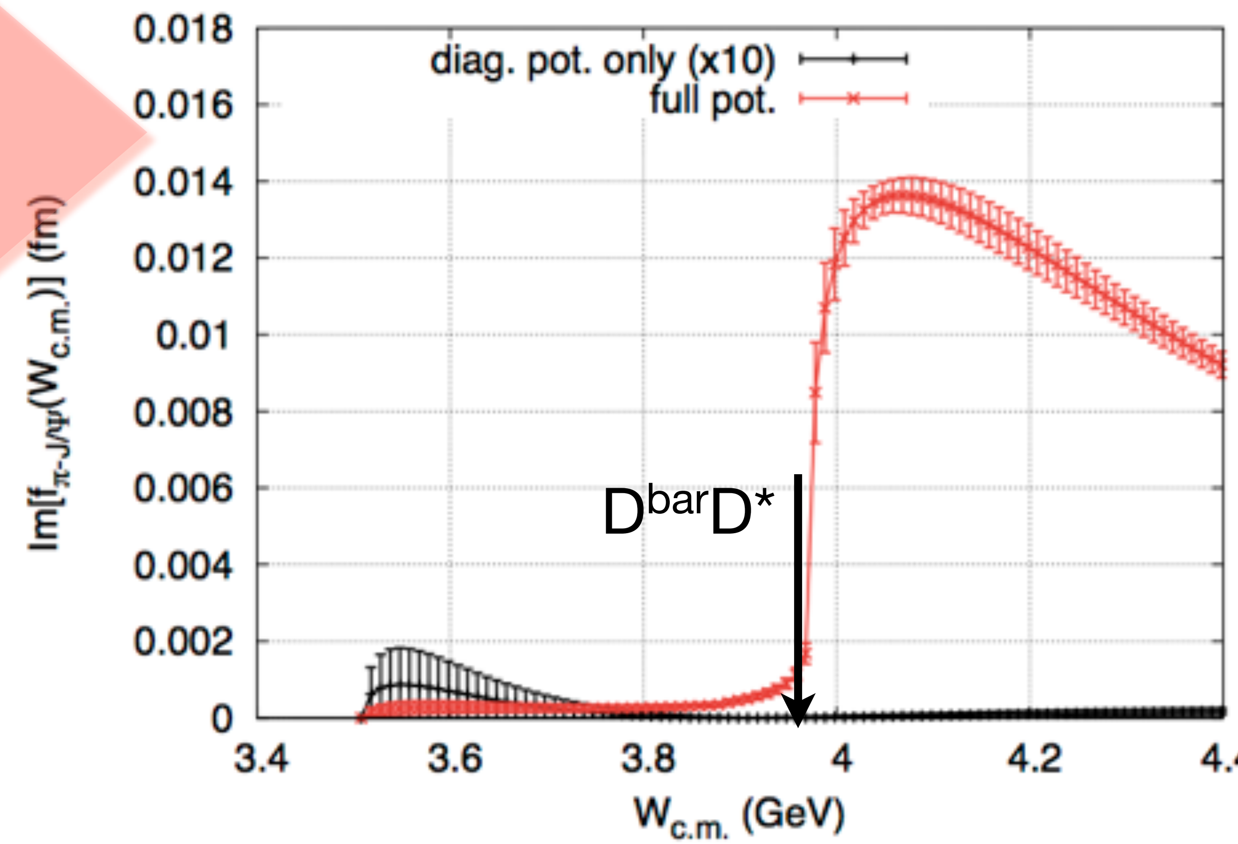
Mass spectra of $\pi J/\psi$ (2-body scattering)

★ 2-body scattering (the most ideal to understand Z_c(3900))





● $\pi J/\psi$ invariant mass (m_π=410MeV)



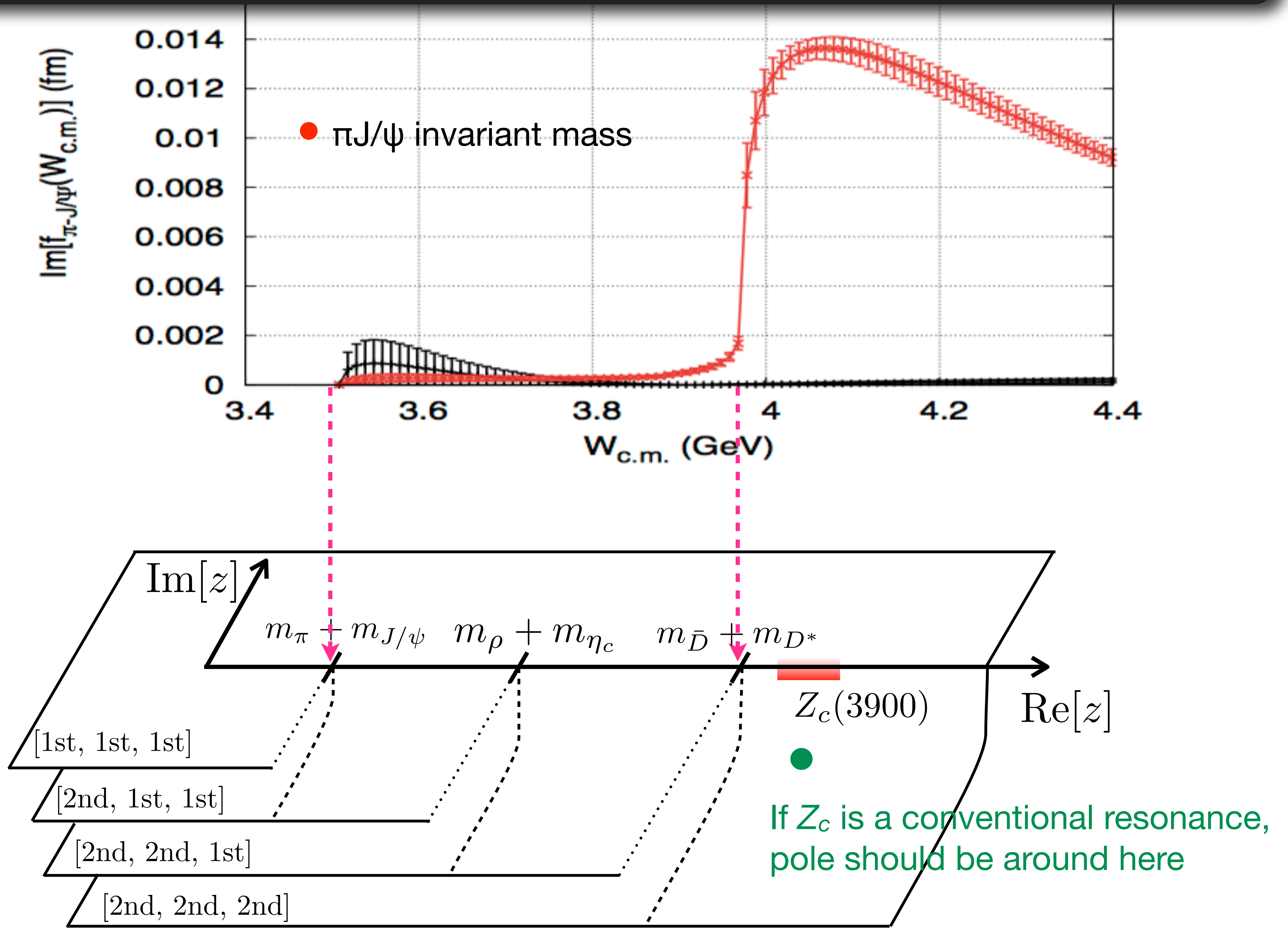
✓ Enhancement just above $D^{bar}D^*$ threshold

➡ **effect of strong $V^{\pi J/\psi,\ DbarD^*}$** (black --> $V^{\pi J/\psi,\ DbarD^*}$=0)

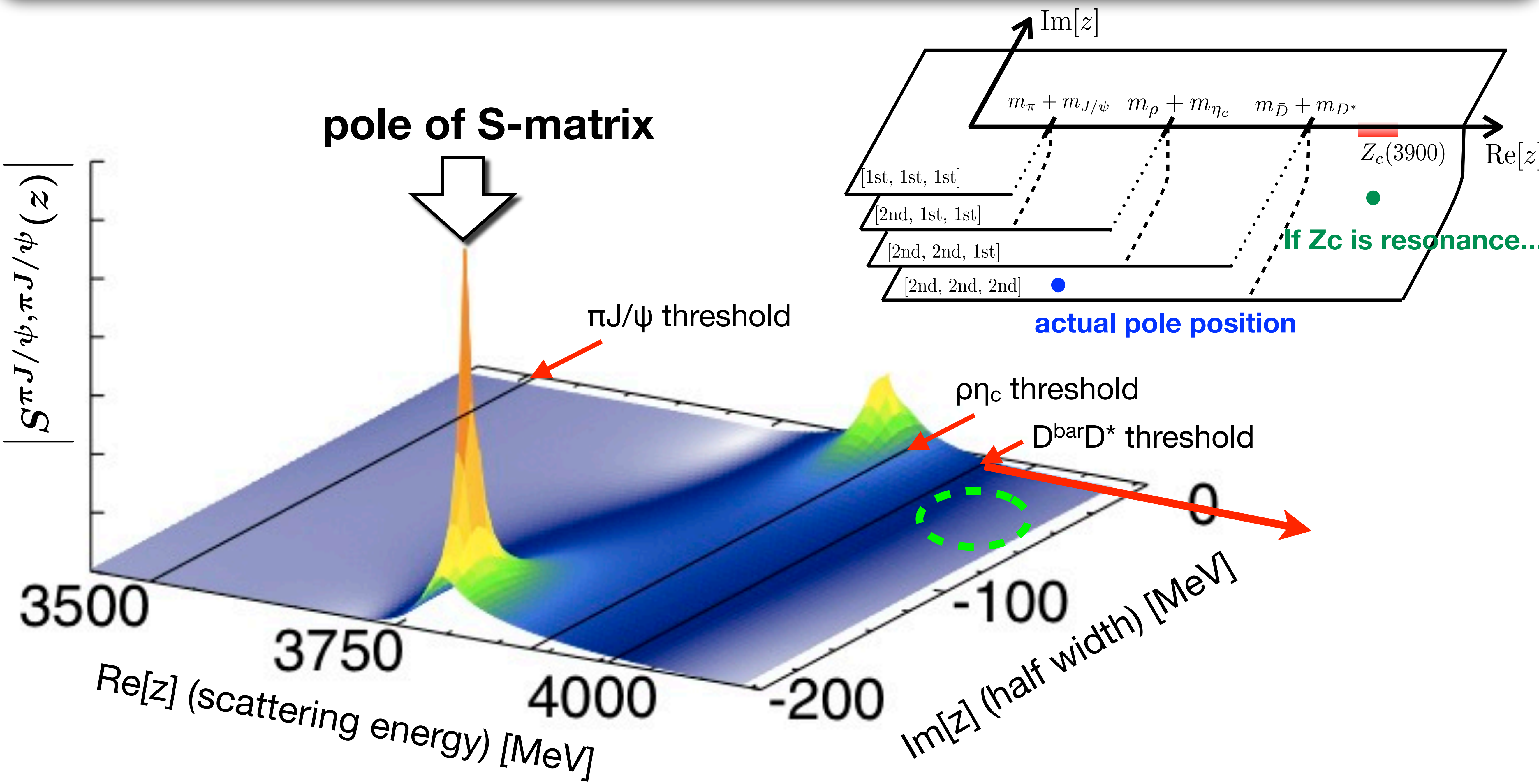
● line shape not Breit-Wigner

✓ Is Z_c(3900) a conventional resonance? --> pole of S-matrix

Pole of S-matrix on complex energy plane



Pole of S-matrix ($\pi J/\psi$:2nd, $\rho\eta_c$:2nd, $D^{bar}D^*$:2nd)

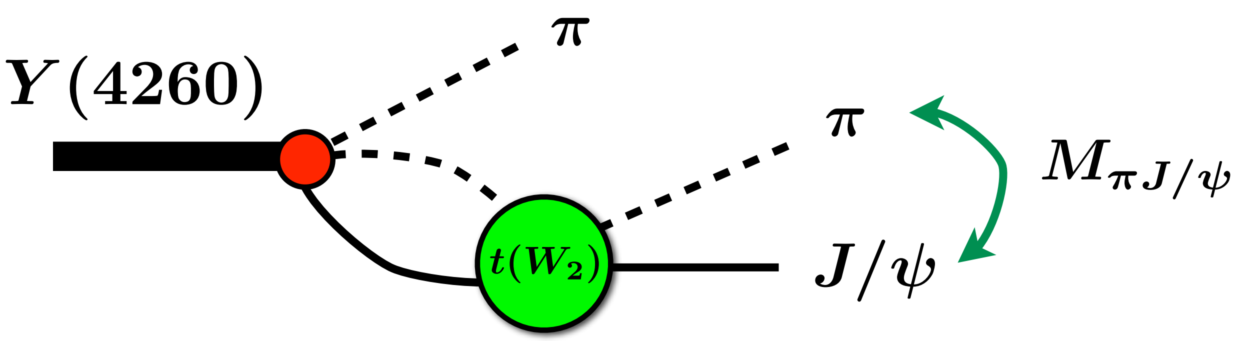


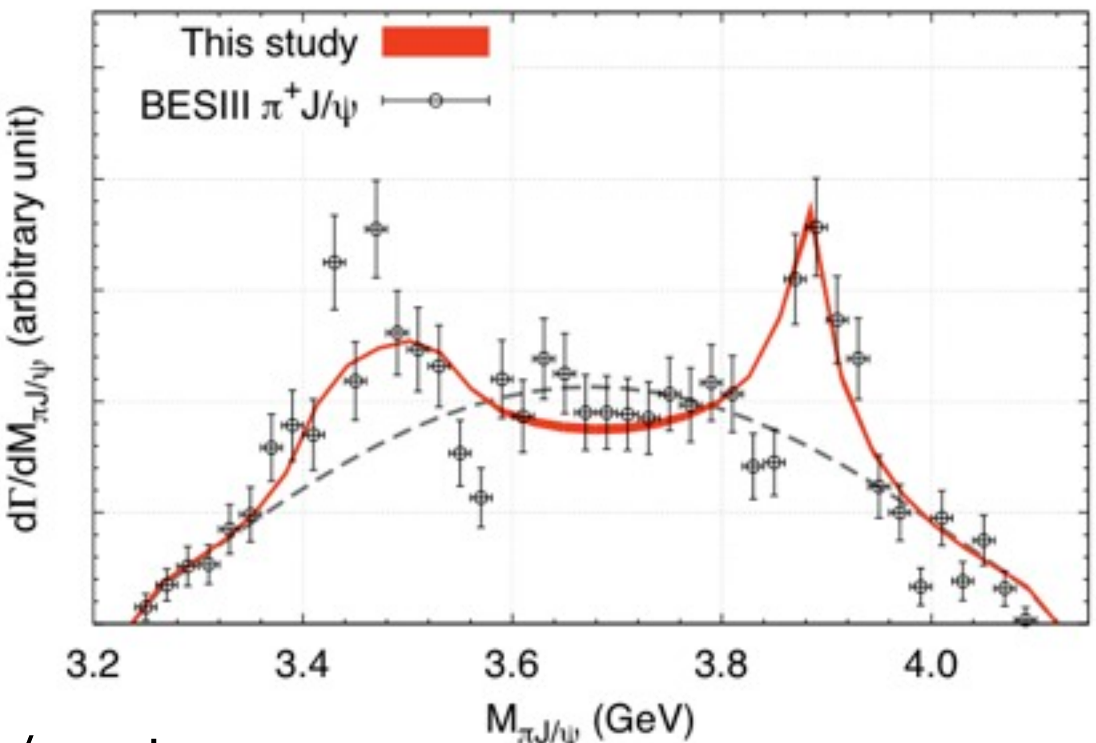
- Pole corresponding to “virtual state”
- **Pole contribution to scat. observable is small** (far from scat. axis)
- **Z_c(3900) is not a resonance but “threshold cusp” induced by strong $V^{\pi J/\psi, DbarD^*}$**

Invariant mass of 3-body decay

Ikeda [HAL QCD], J. Phys. G45, 024002 (2018).

Z_c(3900) in expt.





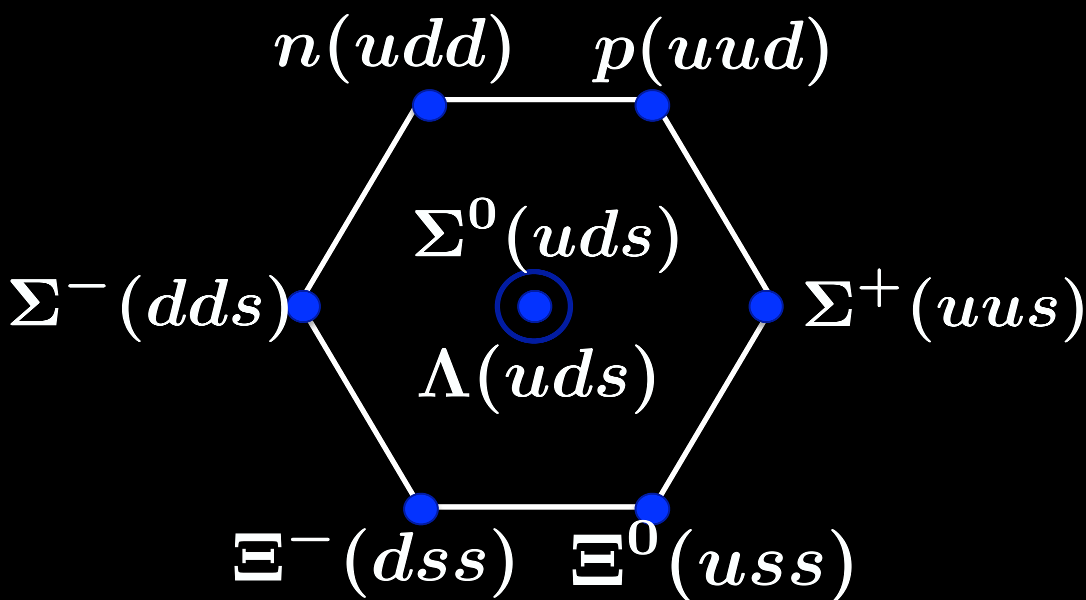
➡ physical hadron masses employed to compare w/ expt.

➡ t-matrix for subsystem obtained from $V^{LQCD}(r)$

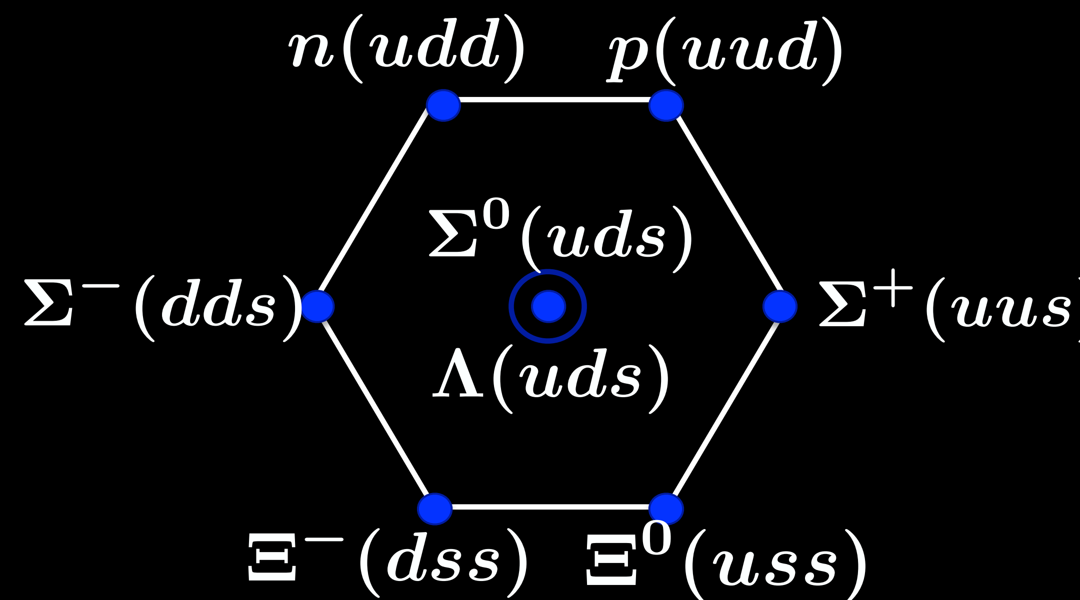
- **Expt. data well reproduced with cusp scenario**

conclusion: Z_c(3900) is threshold cusp caused by strong $V^{\pi J/\psi,\ \bar{D}D^*}$

Octet BB forces & H-dibaryon



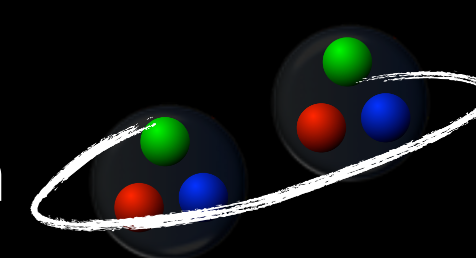
X



$$= (\mathbf{27} \oplus \mathbf{8} \oplus \mathbf{1})_{\text{sym.}} \oplus (\mathbf{10}^* \oplus \mathbf{10} \oplus \mathbf{8})_{\text{anti-sym.}}$$

NN ($^1S_0$)

NN ($^1S_0$) : deuteron



H-dibaryon (ΛΛ-ΞN-ΣΣ)? **Jaffe (1977)**

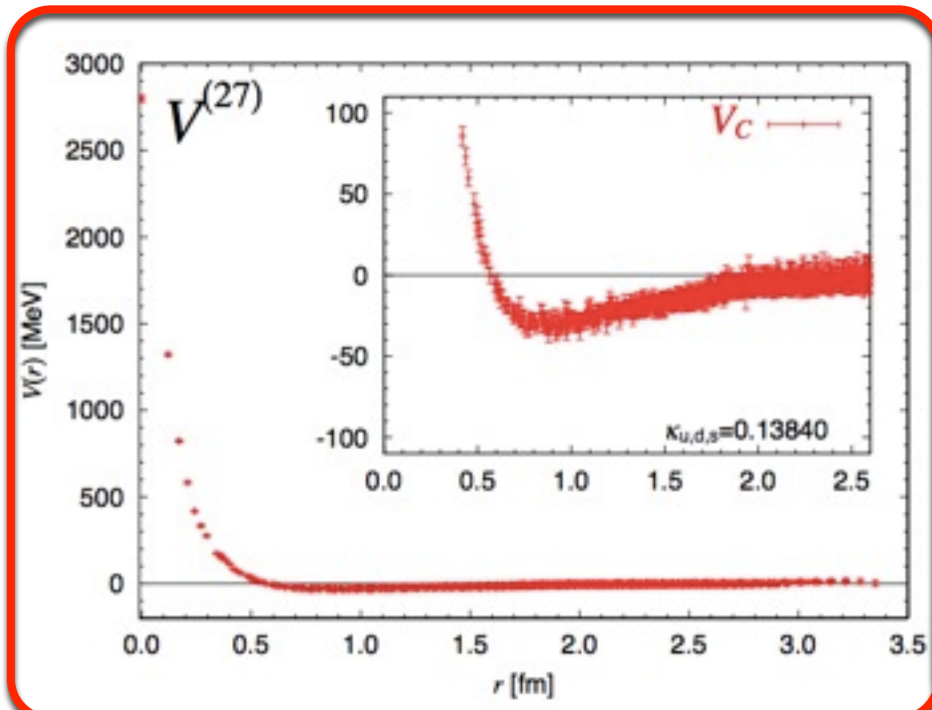
Generalized BB forces in flavor SU(3) limit

❖ Full QCD in $SU(3)_F$ limit : m_π~0.47GeV, L=3.9 fm

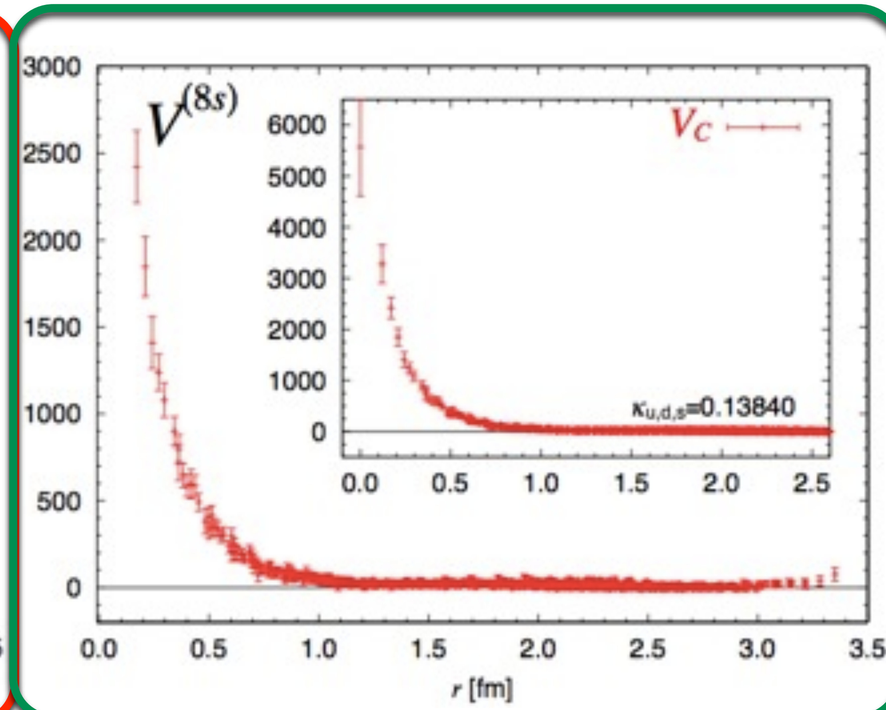
Inoue et al. (HAL QCD), PRL106 (2011), NPA881 (2012).

★ **potentials in flavor symmetric channels, 27 + 8_s + 1**

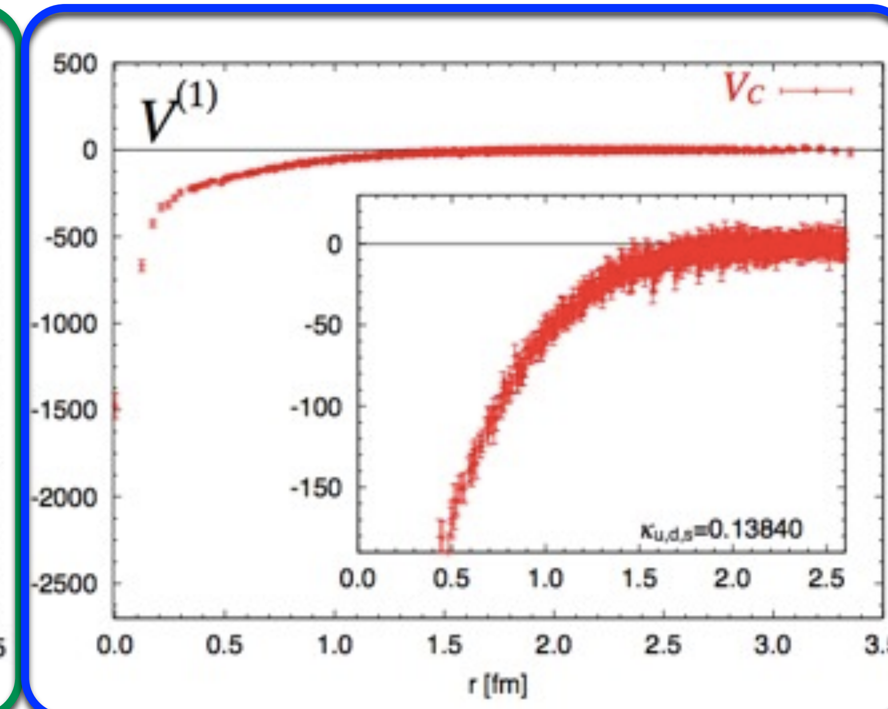
NN $^1S_0$ channels
(partially Pauli blocked)



8_s channel
(Pauli forbidden)



H-dibaryon channel
(Pauli allowed)



H-dibaryon?

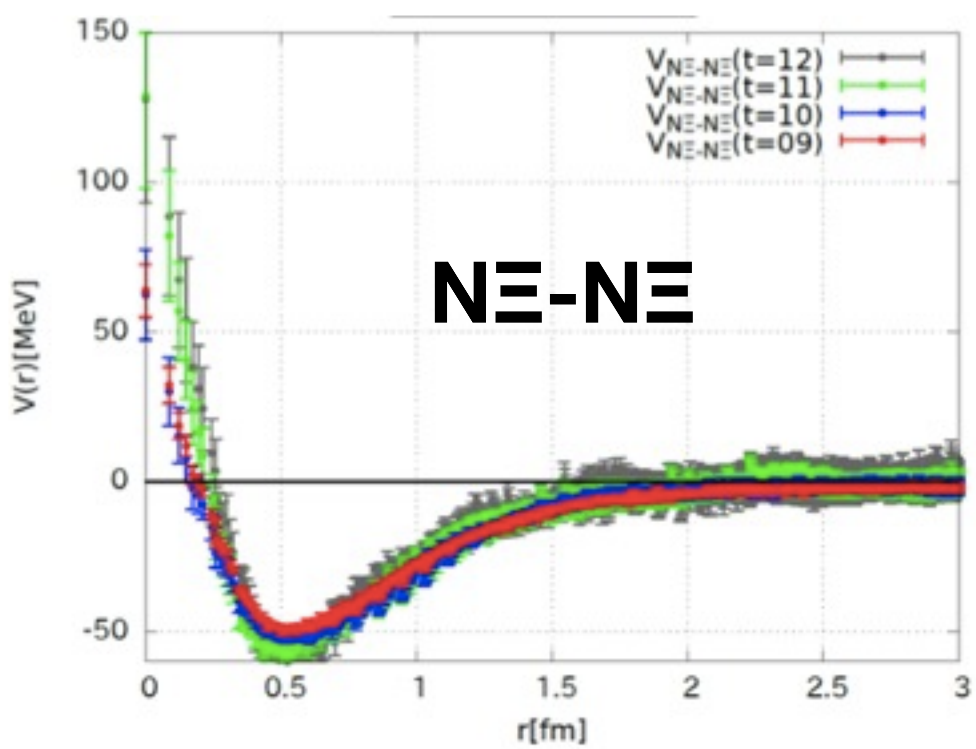
✦ **origin of repulsive core <--> Pauli principle**

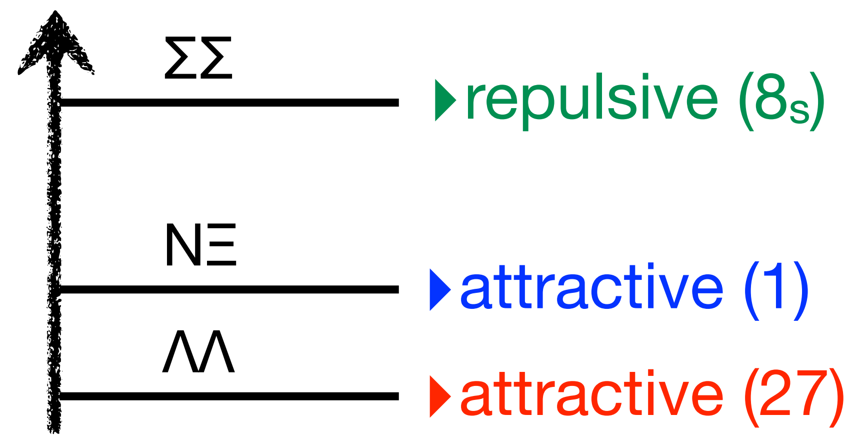
(+ gluon exchange)

see, Oka & Yazaki, NPA464 (1987)

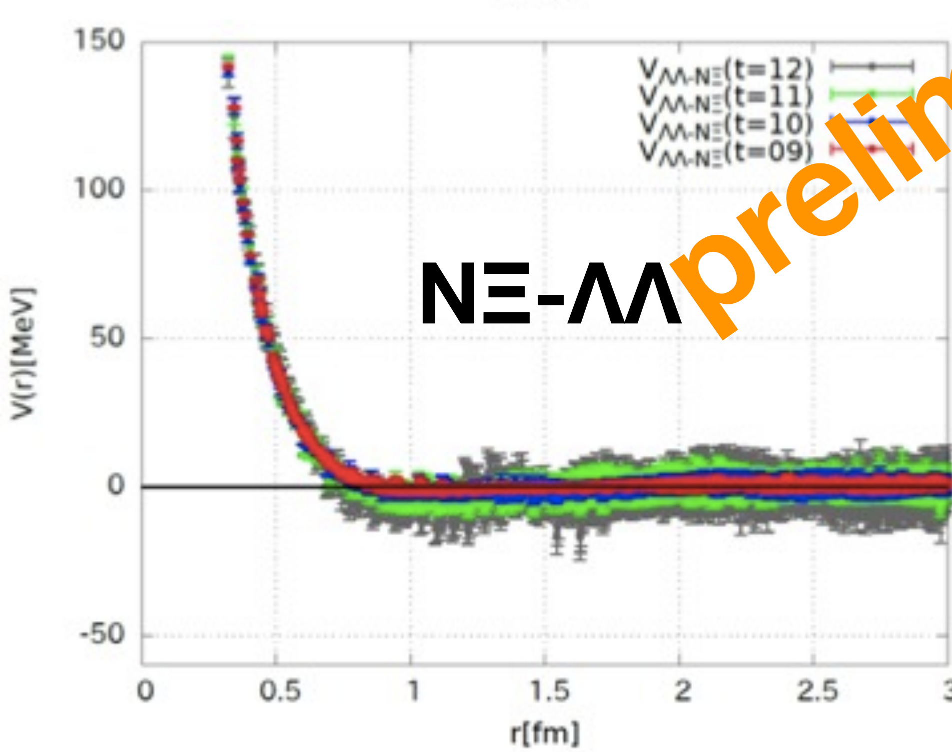
Fate of H-dibaryon @ almost physical point

- N_f=2+1 full QCD, m_π~0.146GeV (almost physical), L~8.1fm (large volume)

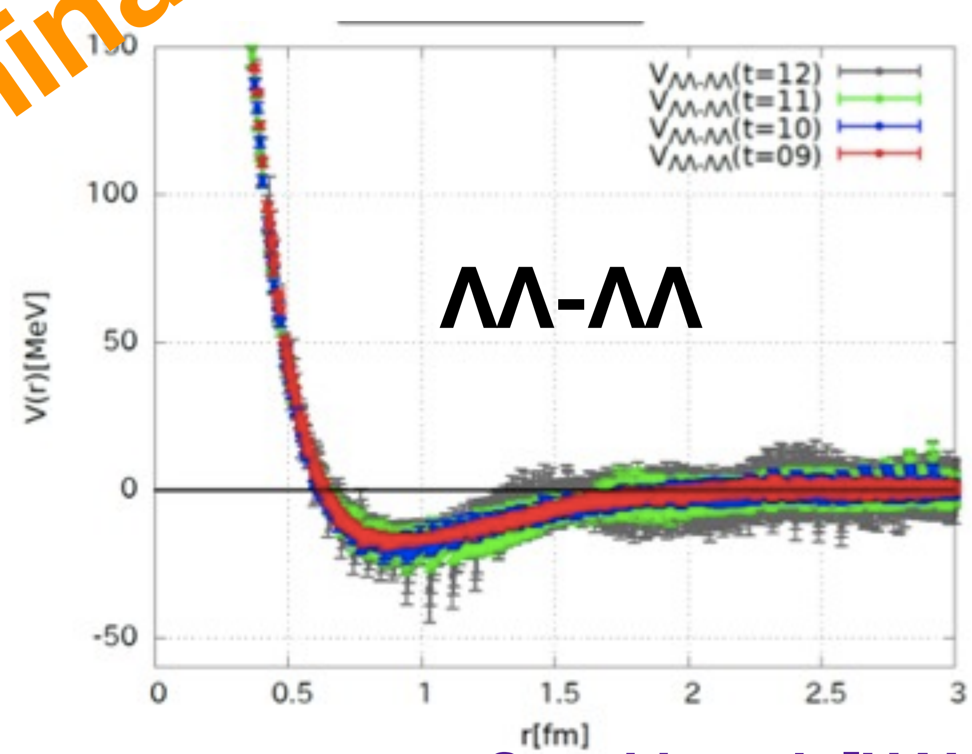




$$\begin{pmatrix} |\Sigma\Sigma\rangle \\ |N\Xi\rangle \\ |\Lambda\Lambda\rangle \end{pmatrix} = \frac{1}{\sqrt{40}} \begin{pmatrix} -1 & -\sqrt{24} & \sqrt{15} \\ \sqrt{12} & \sqrt{8} & \sqrt{20} \\ \sqrt{27} & -\sqrt{8} & -\sqrt{5} \end{pmatrix} \begin{pmatrix} |27\rangle \\ |8_s\rangle \\ |1\rangle \end{pmatrix}$$



preliminary



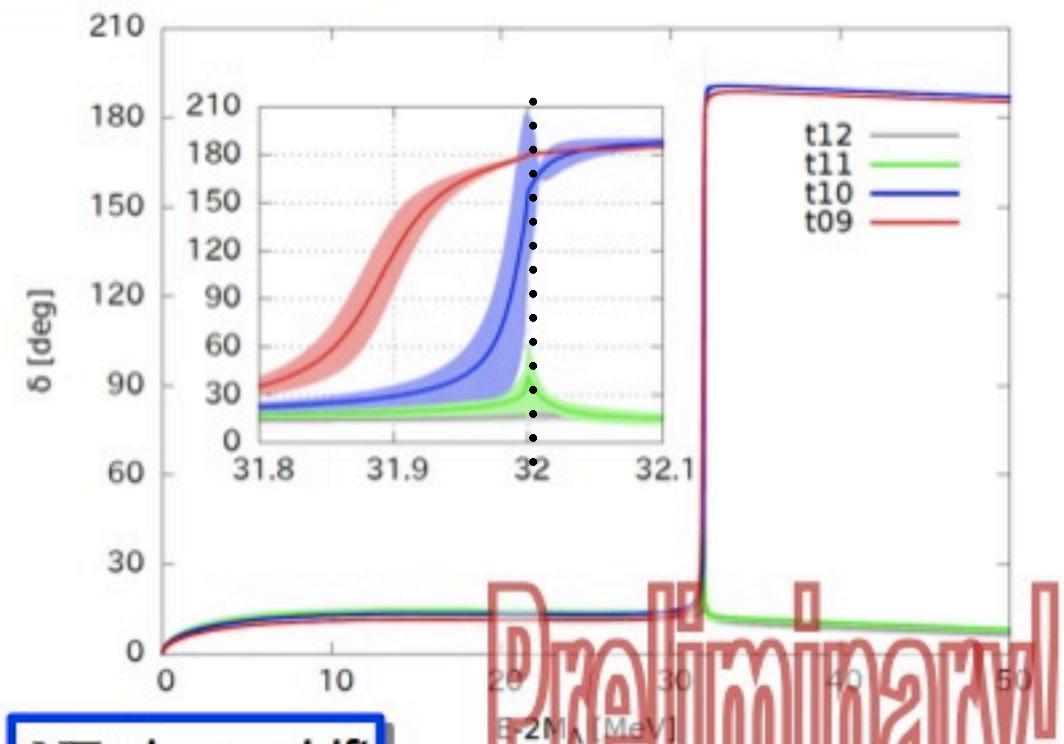
Sasaki et al. [HAL QCD], in preparation.

Fate of H-dibaryon @ almost physical point

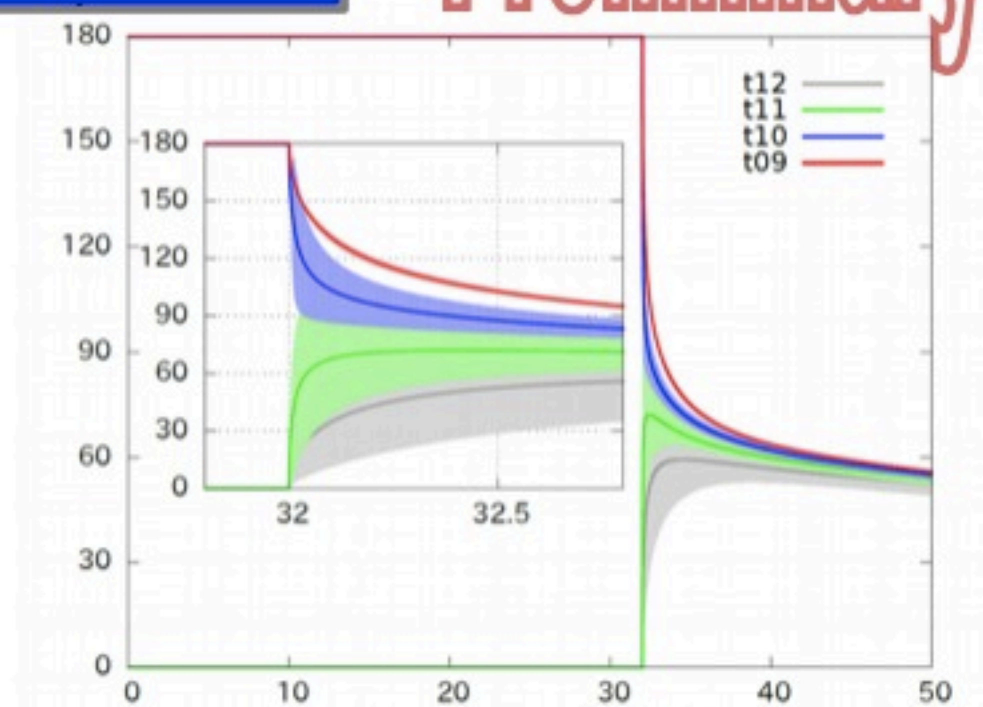
★ ΛΛ and ΞN phase shifts

$$S(k) = \begin{pmatrix} \eta e^{2i\delta_1} & i\sqrt{1-\eta^2} e^{i(\delta_1+\delta_2)} \\ i\sqrt{1-\eta^2} e^{i(\delta_1+\delta_2)} & \eta e^{2i\delta_2} \end{pmatrix}$$

ΛΛ phase shift



NΞ phase shift

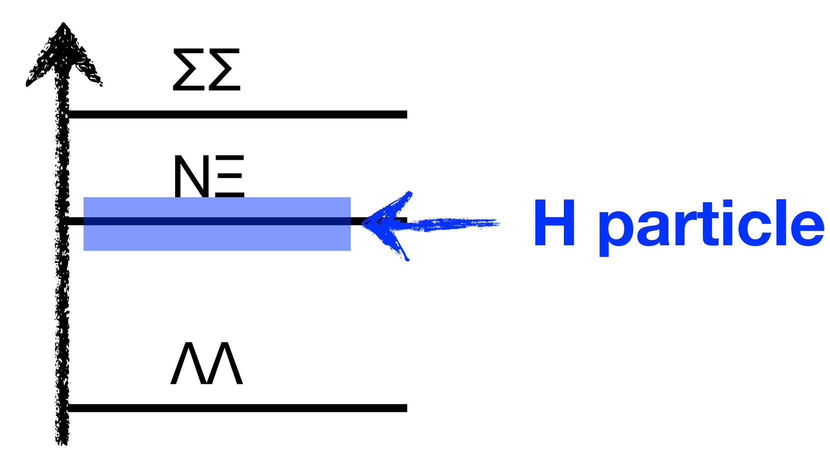


Original prediction of H-dibaryon

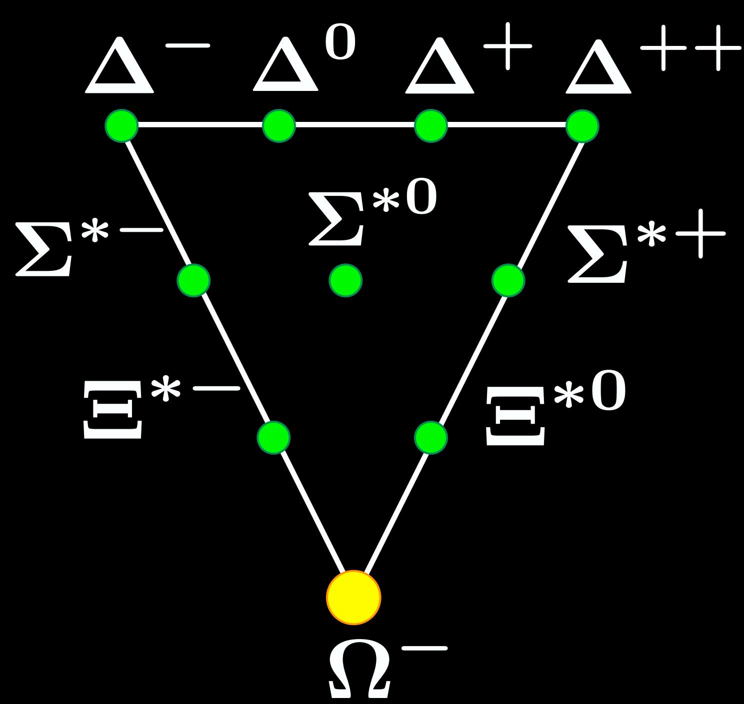
Jaffe (1977) based on quark model,
<u>“Perhaps a Stable Dihyperon”</u>

Answer from QCD for H-dibaryon

<u>“Perhaps near threshold Dihyperon”</u>



Extension to decuplet baryon Ω

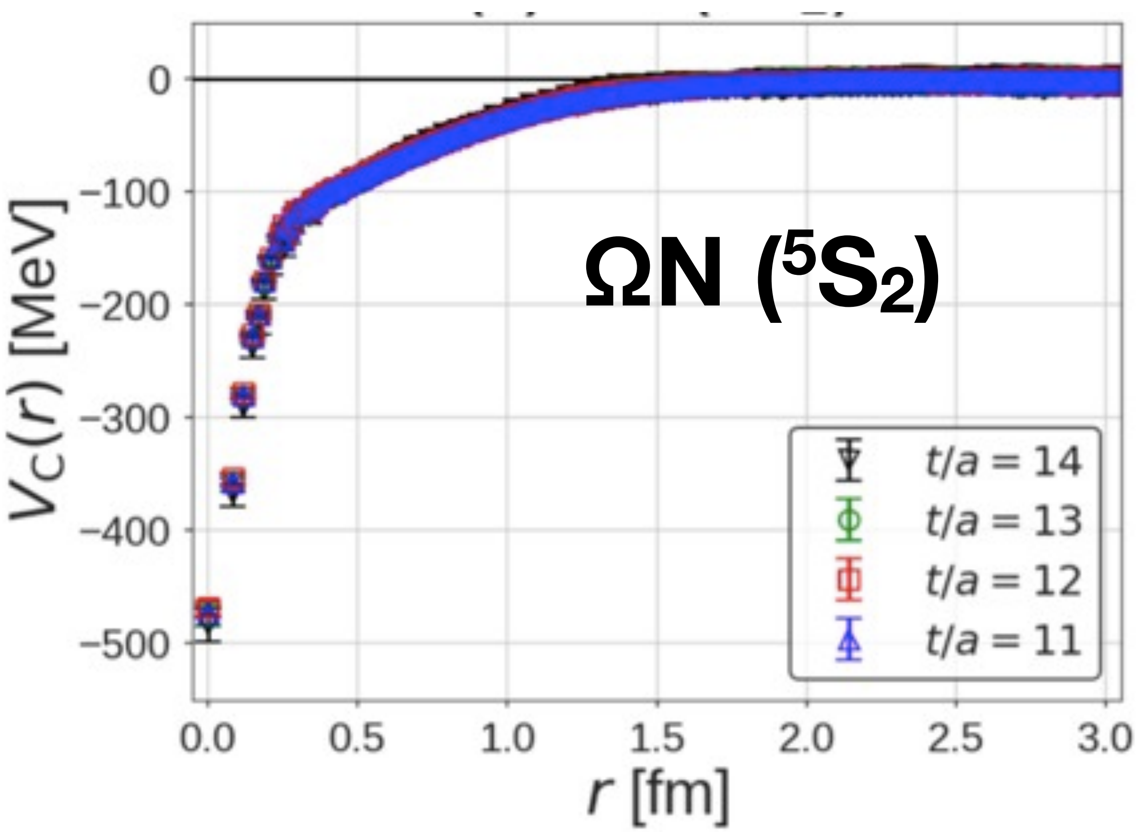


- *ΩN ($^5S_2$) : 8 x 10 = 35 + 8 + 10 + 27*
- *ΩΩ ($^1S_0$) : 10 x 10 = 28 + 27 + 35 + 10**

Both are Pauli allowed states

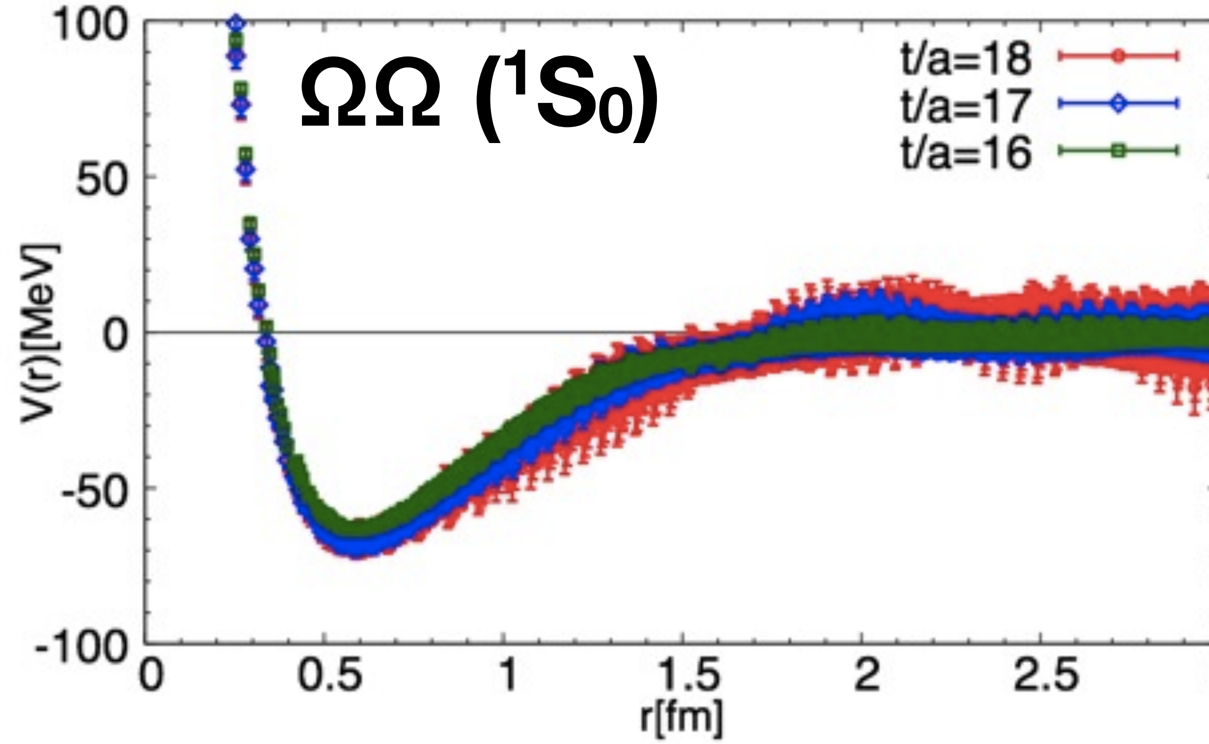
Ω-dibaryon systems @ almost physical point

Iritani et al. [HAL QCD], PLB792 (2019).



- entirely attractive

Gongyo, Sasaki et al. [HAL QCD], PRL120 (2018).



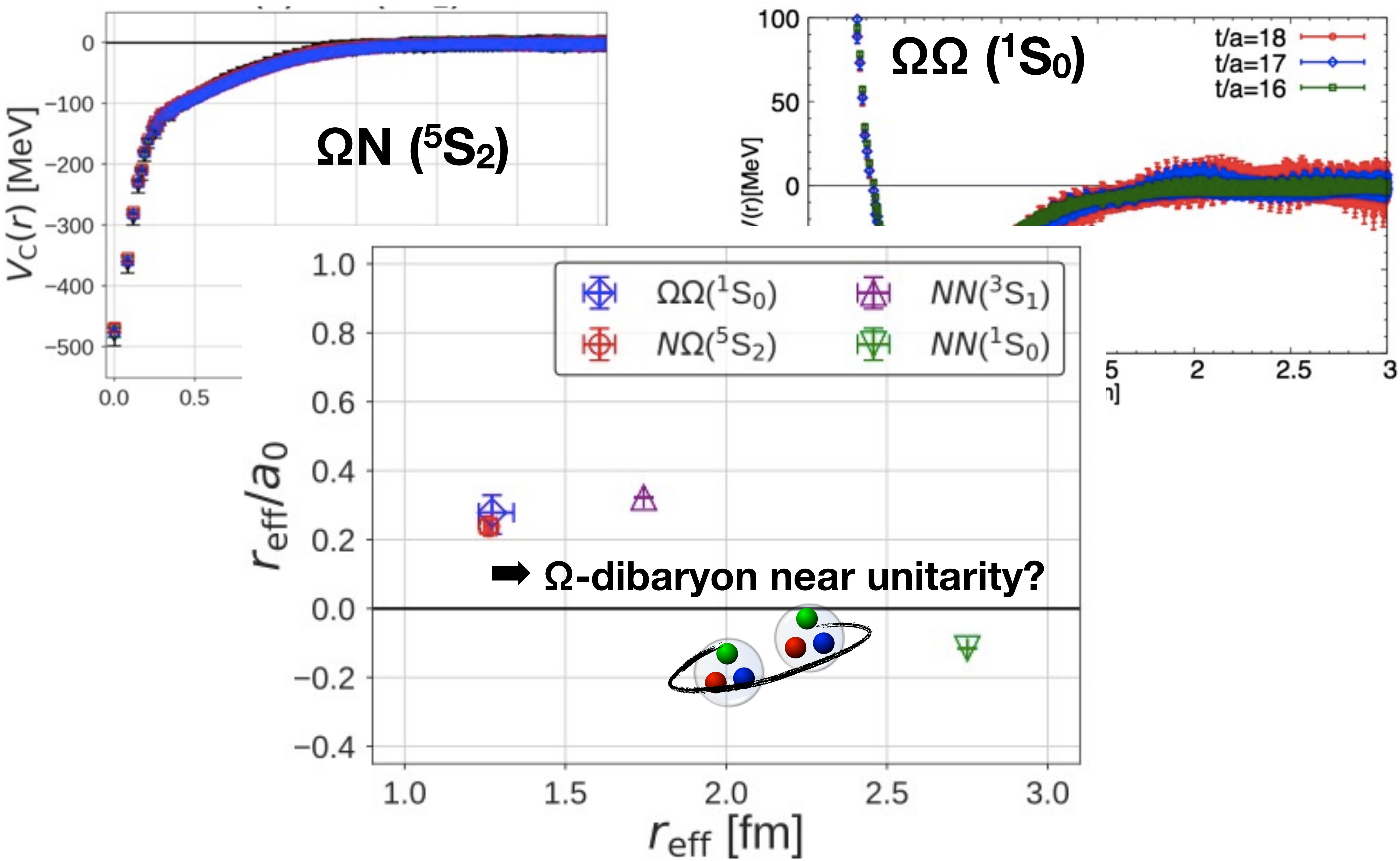
- repulsive core + attractive pocket
  - ▸ repulsive force by gluon exchange

Oka, Yazaki (1980)

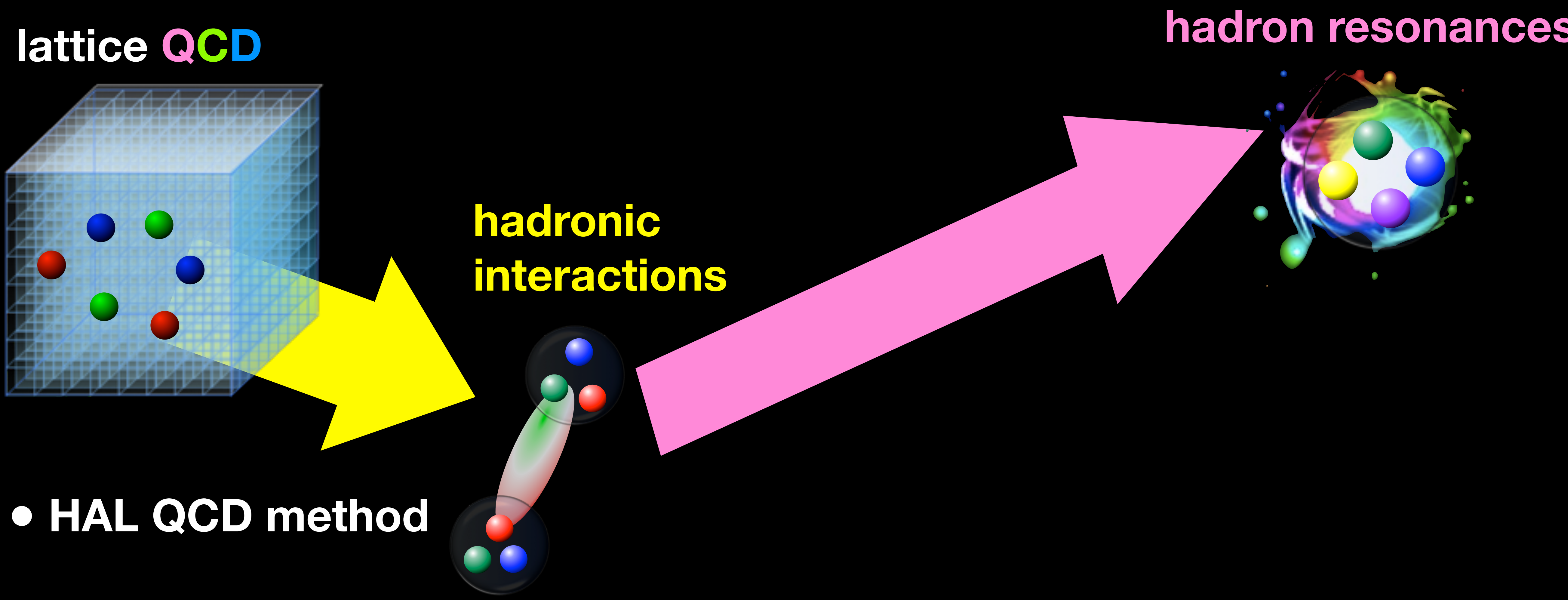
Ω-dibaryon systems @ almost physical point

Iritani et al. [HAL QCD], PLB792 (2019).

Gongyo, Sasaki et al. [HAL QCD], PRL120 (2018).



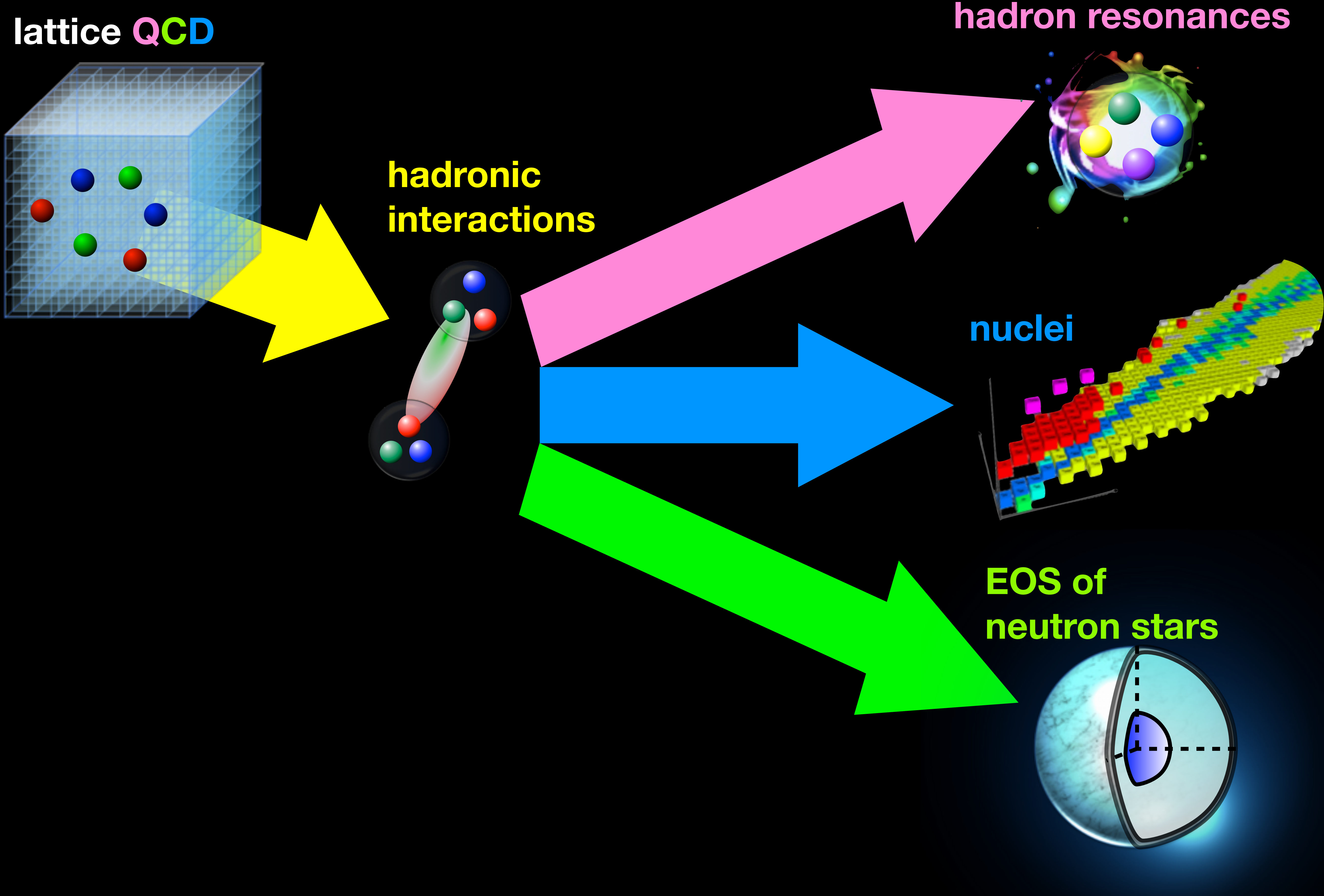
Summary



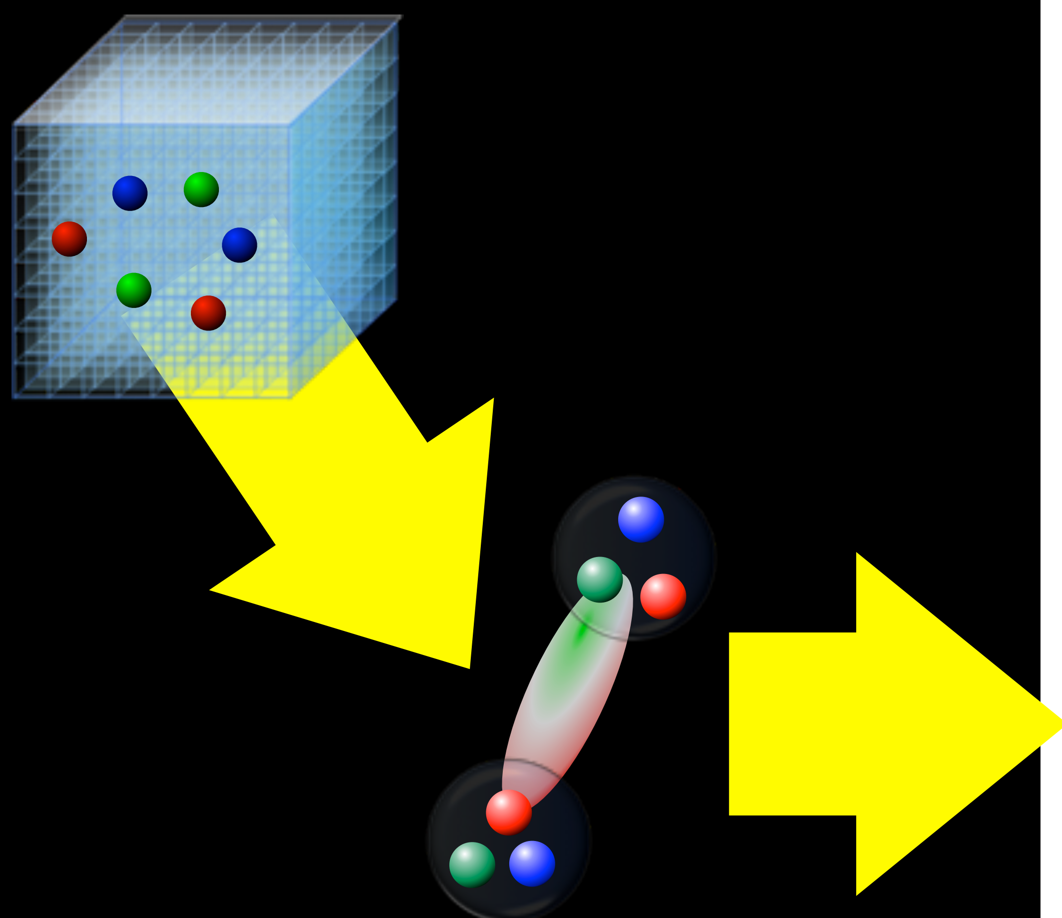
- HAL QCD method

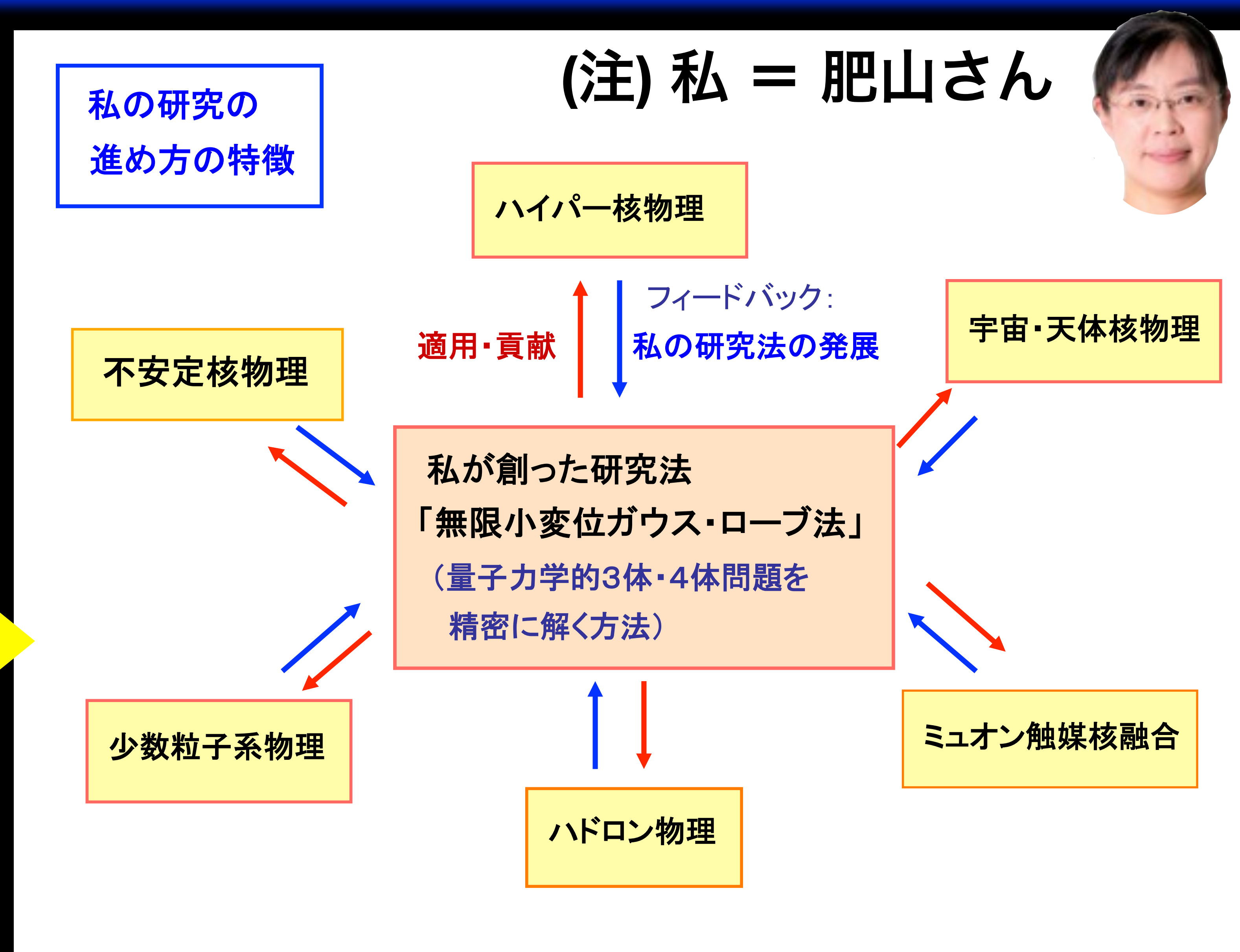
- $Z_c(3900)$ is threshold cusp induced by strong $V^{DbarD^*,\ \pi J/\psi}$
- H particle is very close to NΞ threshold
- Ω-dibaryons are similar to deuteron

Future: from quarks to hadrons, nuclei & neutron stars



Collaboration w/ Prof. Emiko Hiyama





肥山さん、文部科学大臣表彰「科学技術賞」の受賞

おめでとうございます!!