Charm hadron interactions from lattice QCD

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HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)

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International Workshop on Strangeness Nuclear Physics (SNP2017)

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Why charm quark?

★ **<u>Good testing ground to understand nature of non-Ablian interactions</u>**

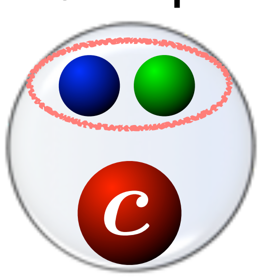
- Exotic hadrons have not been established yet, but many candidates are experimentally reported in heavy (charm & bottom) quark sectors

- tetraquarks
  (X, Y, Z_c, Z_b, ...)

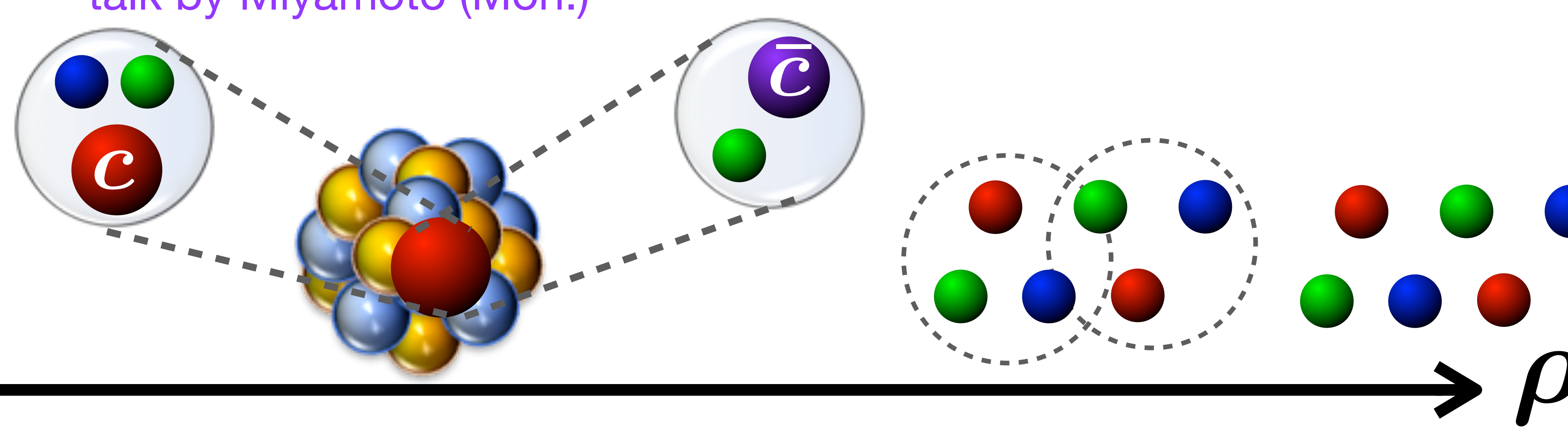
- pentaquarks
  (P_c, ...)

- Charm baryons & nuclei may tell nature of non-Abelian interactions (color, spin, isospin)

- $\Lambda_c^{(*)}$, $\Sigma_c^{(*)}$ spectra (color)



- Λc-nuclei (spin)
  talk by Miyamoto (Mon.)
- D^{bar}-nuclei (isospin)



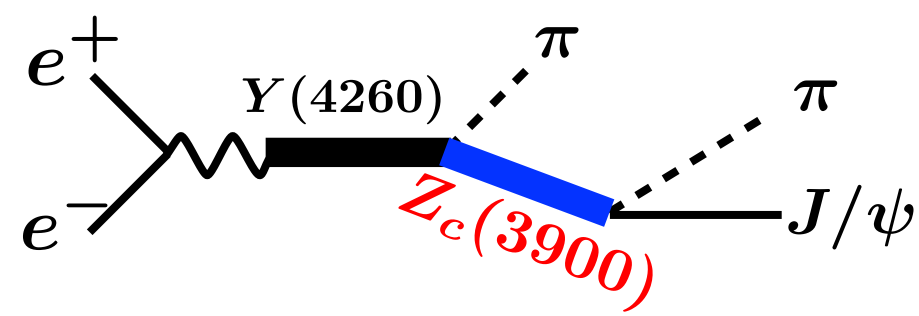
- heavy quark as color source
  (diquark DoF?)
  talk by Noumi (Mon.)
- heavy hadrons as impurity
  (emergence of Kondo effect?) talk by Yasui (Mon.)
- property of quark matter?

Topics covered in this talk

✤ Tetraquark candidate $Z_c(3900)$

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

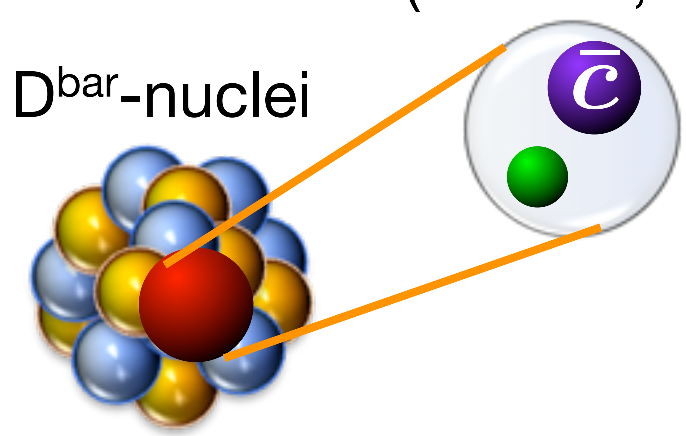
- ✓ How to analyze exotic hadrons on the lattice
- ✓ Coupled-channel HAL QCD method
- ✓ Nature of $Z_c(3900)$
- ✓ Comparison with experiments



✤ D^{bar}-nucleon interaction & D^{bar}-nuclei

- ✓ D^{bar}-nucleon interaction from LQCD
- ✓ Possible structure of D^{bar}-nuclei

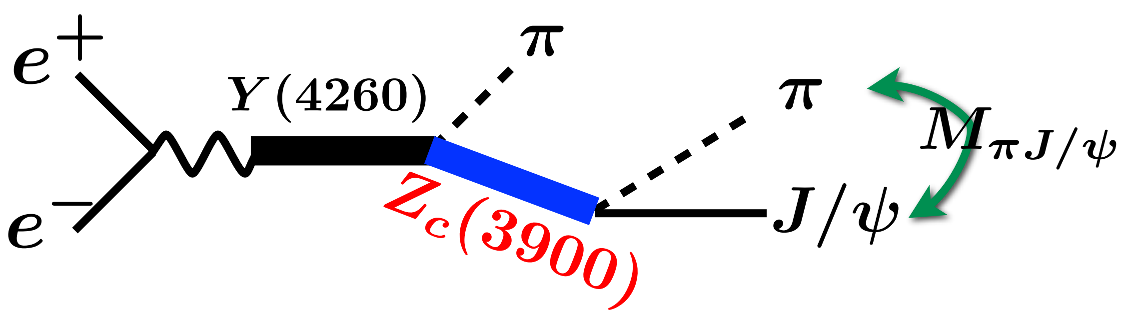
$D^{bar} = (D^0 = uc^{bar}, D^- = dc^{bar})$



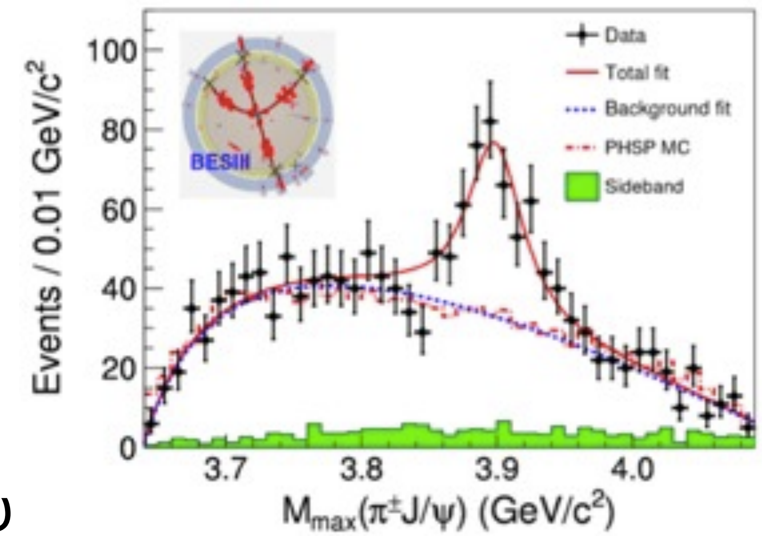
✤ Summary

What is $Z_c(3900)$?

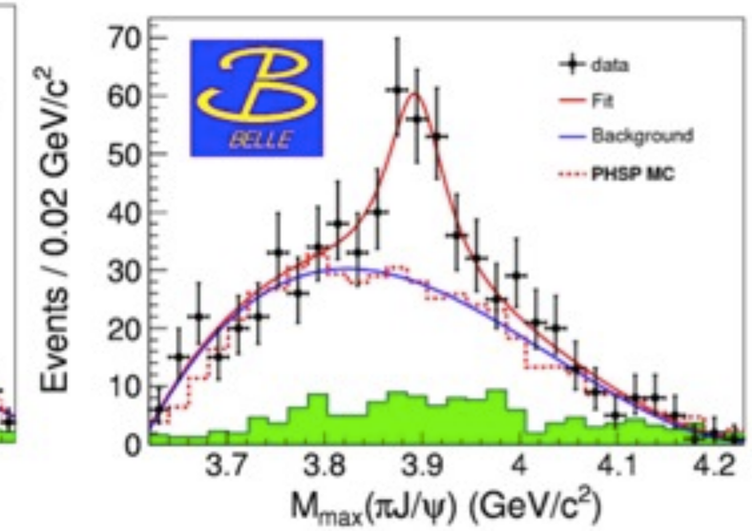
- **Tetraquark $Z_c(3900)$?**



BESIII Coll., PRL110 (2013).



Belle Coll., PRL110 (2013).



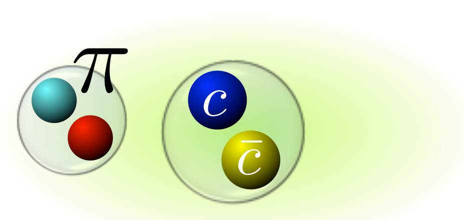
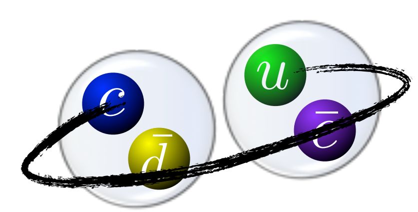
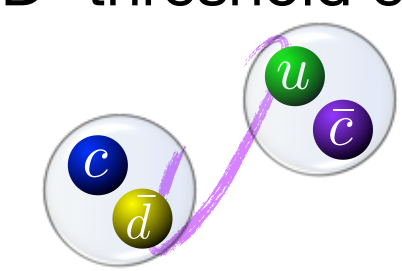
$e^+ + e^-$ --> Y(4260) --> π + $Z_c(3900)$

➡ $\pi^{+/-}$ + J/ψ

- peak in **$\pi^{+/-}J/\psi$ invariant mass** (minimal quark content cc^{bar} ud^{bar} <--> tetraquark candidate)
- M ~ 3900, Γ ~ 60 MeV (Breit-Wigner) --> just above $D^{bar}D^*$ threshold

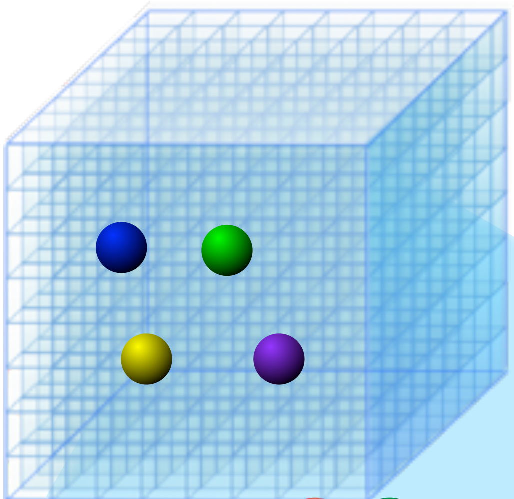
($J^P=1^+$ <--> couple to **s-wave** meson-meson continuum)

★ structure of $Z_c(3900)$ from models

tetraquark	J/ψ + π atom	$D^{bar}D^*$ molecule	$D^{bar}D^*$ threshold effect
			
Maiani et al.('13)	Voloshin('08)	Nieves et al.('11) + many others	Chen et al.('14), Swanson('15)

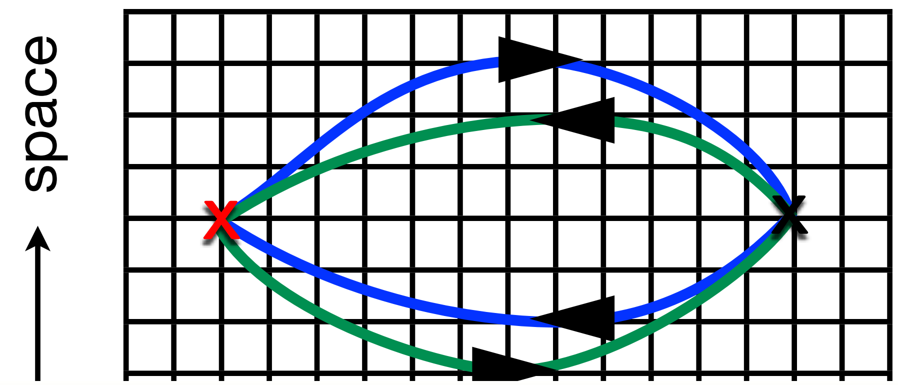
genuine state expected **kinematical origin**

Exotic hadrons on the lattice



lattice QCD

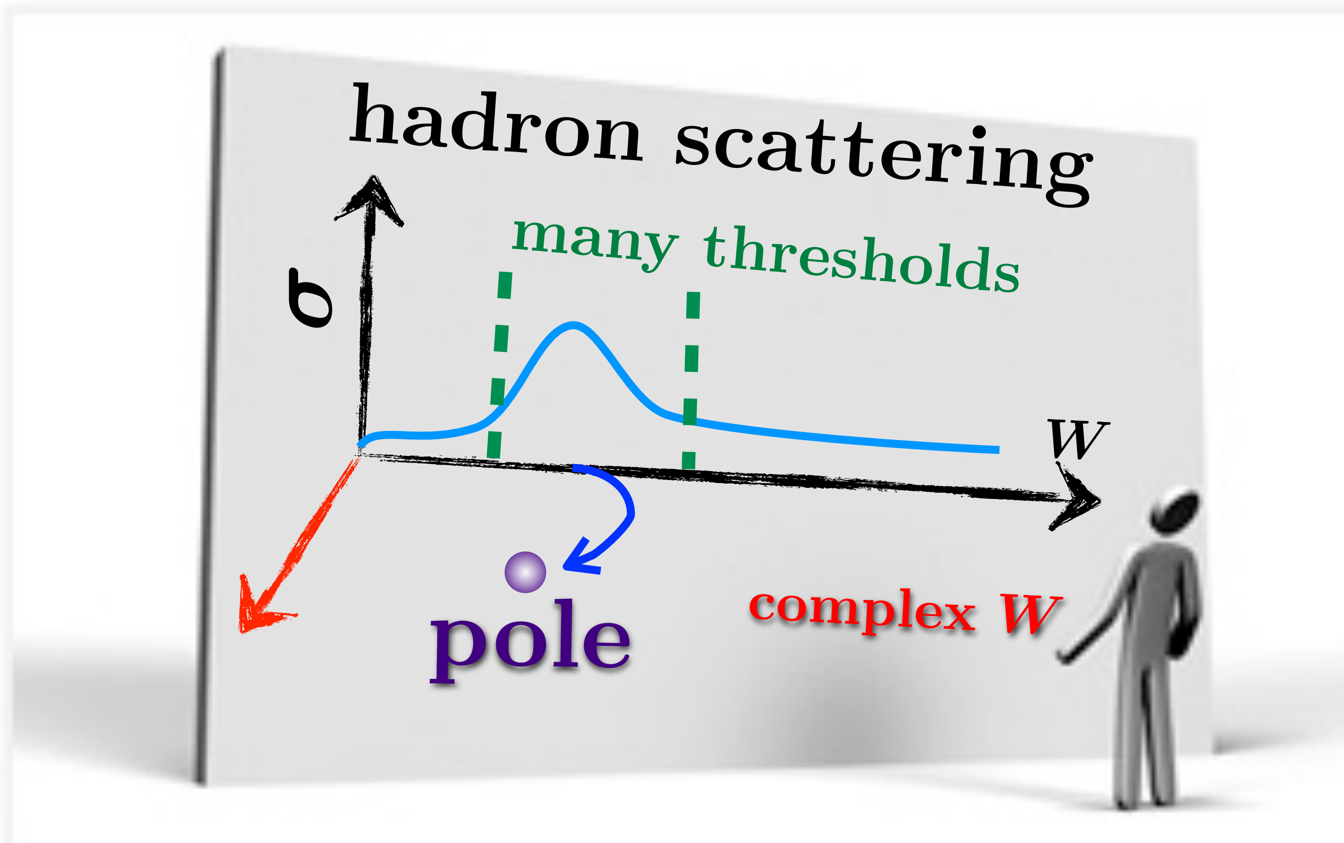
Lattice QCD spectroscopy by conventional approach



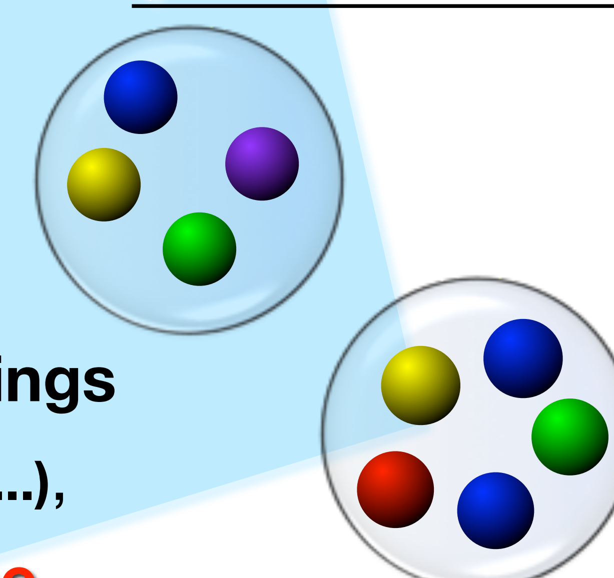
temporal corr. = $\langle 4q(\tau)\, 4q(0) \rangle$

$$= A_1 e^{-W_1 \tau} + A_2 e^{-W_2 \tau} + \cdots$$

(W_1, W_2,... ; QCD eigen-energies)



Exotic hadrons



★ Exotic hadrons are **resonance in coupled-channel scatterings**

★ Resonance energies are **NOT QCD eigen-energies (W_1, W_2, ...),**

but **determined by pole of S-matrix on complex energy plane**

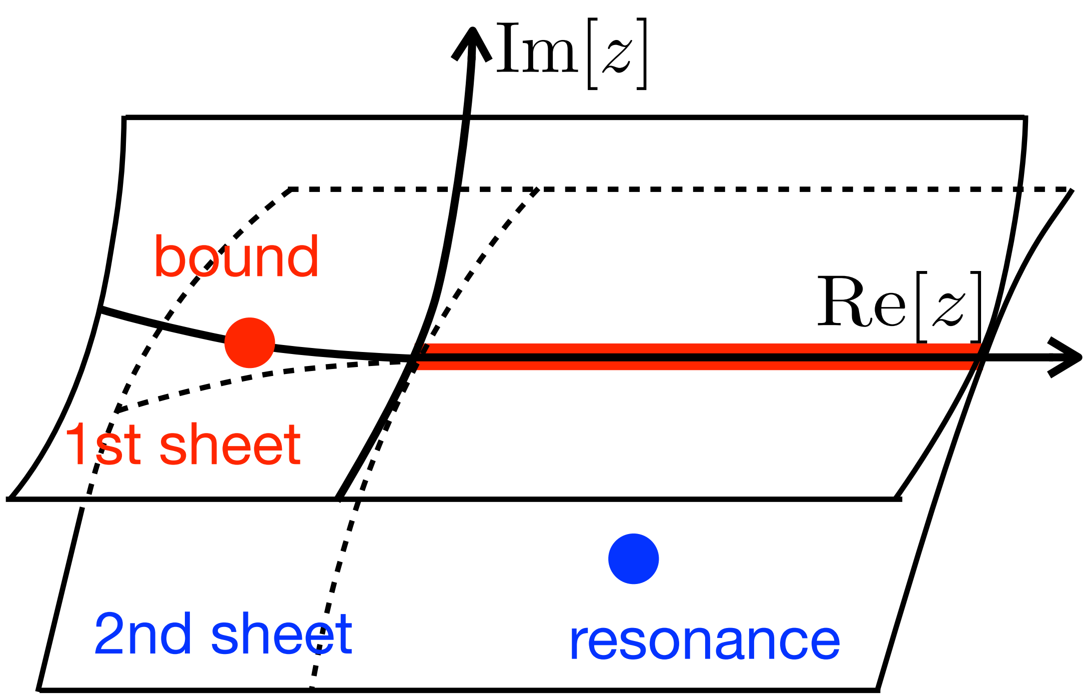
How to search for resonances?

If S-matrix based on QCD (in local energy regime) obtained...

$S(W)$ ← **partial wave analysis of expt. data**

- cross sections ($d\sigma/d\Omega$)
- spin polarization observables
- etc.

Analyticity of S-matrix is **uniquely** determined **(S-matrix theory)**



bound state (1st sheet)

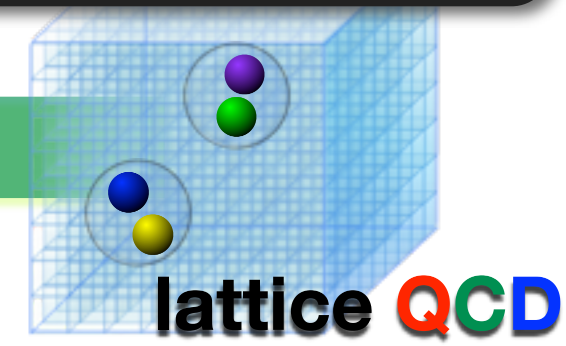
- pole position --> binding energy
- residue --> coupling to scattering state

resonance (2nd sheet)

- analytic continuation onto 2nd sheet
- pole position --> resonance energy
- residue --> coupling to scat. state, partial decay

How to search for resonances on the lattice

S-matrix based on QCD (in local energy regime)

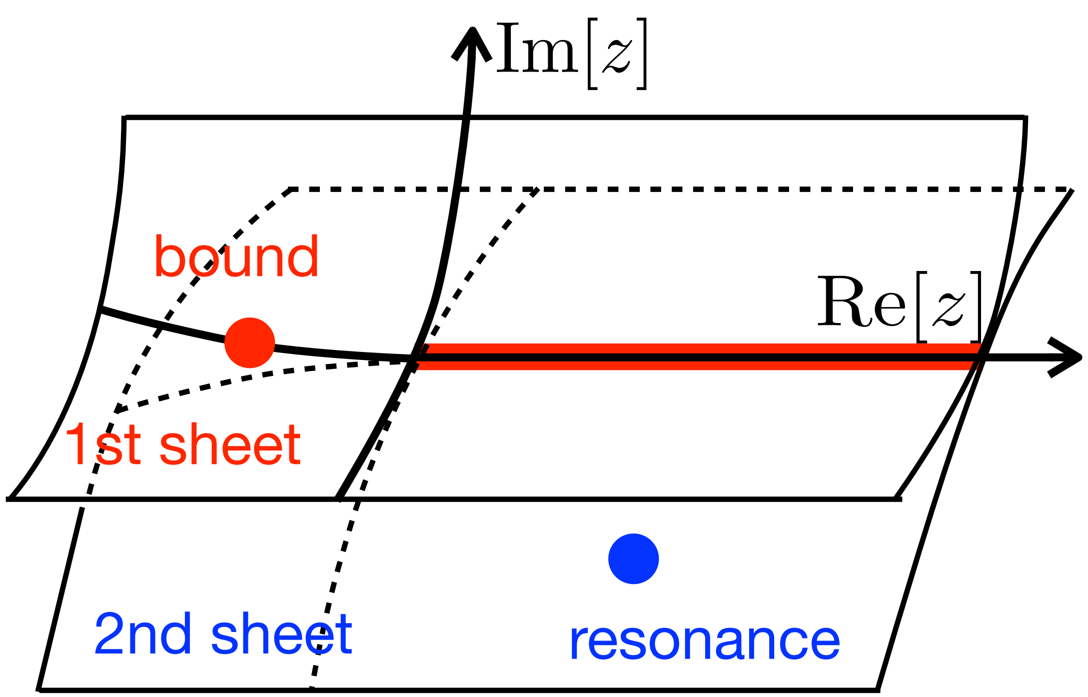


$S(W)$

two identical methods

- **Lüscher**: temporal correlation --> eigen-energy W_n --> S(W)
  (difficulty in coupled-channel scattering & large volume simulation)
- **HAL QCD**: space-time correlation --> “potentials” --> S(W)

Analyticity of S-matrix is **uniquely** determined **(S-matrix theory)**



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- analytic continuation onto 2nd sheet
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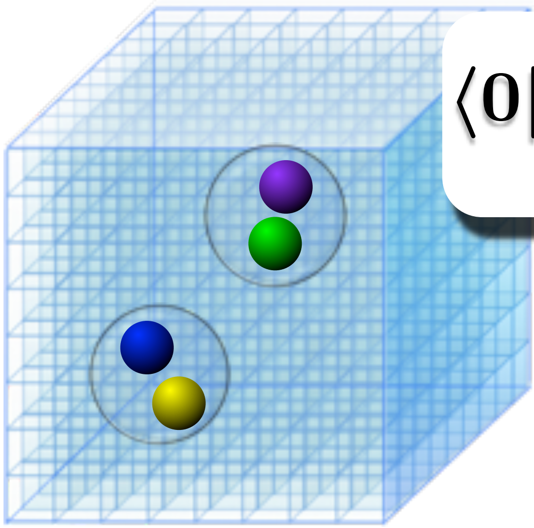
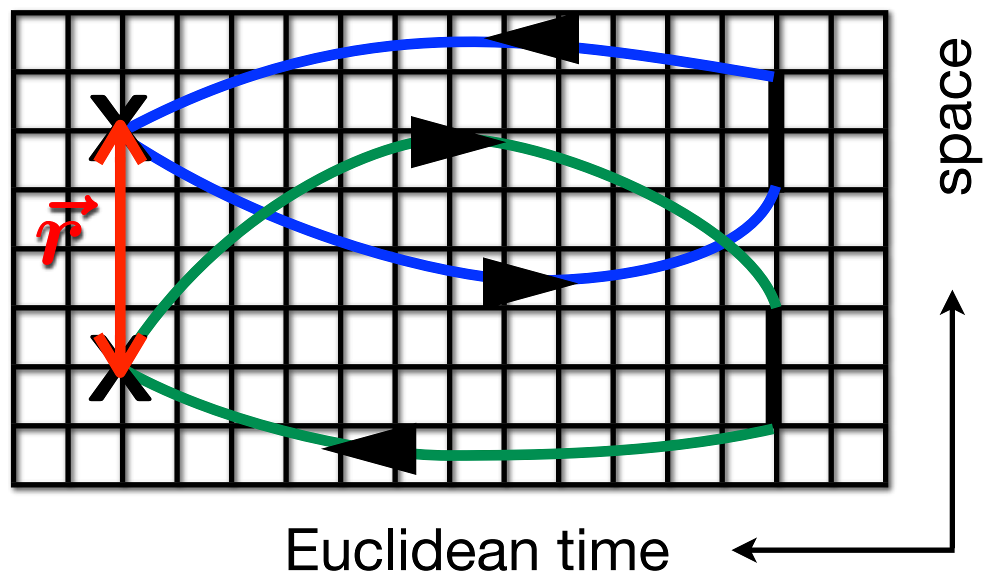
HAL QCD method "potentials as representation of S-matrix"

✦ **measure not only temporal but also spatial correlation**

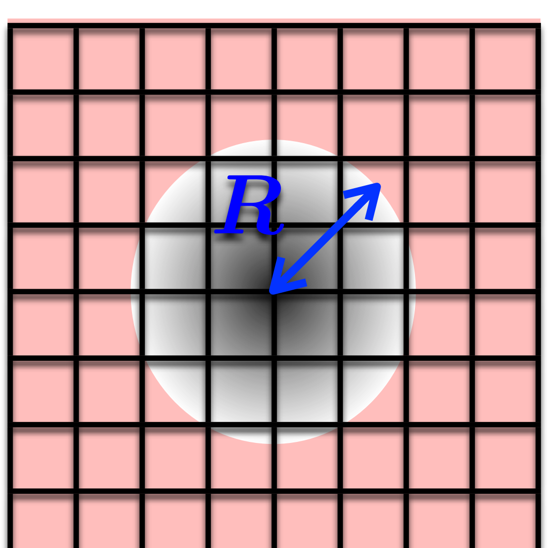


$$\langle 0|\phi_1(\vec{x}+\vec{r},\tau)\phi_2(\vec{x},\tau)\Phi^\dagger(0)|0\rangle = \sqrt{Z_1 Z_2}\sum_n A_n \psi_n(\vec{r}) e^{-W_n \tau}$$



Ishii, Aoki, Hatsuda, PRL99, 02201 (2007).
Aoki, Hatsuda, Ishii, PTP123, 89 (2010).
Ishii et al. (HAL QCD), PLB712, 437(2012).

★ **Nambu-Bethe-Salpeter (NBS) wave function: $\psi_n(r)$**



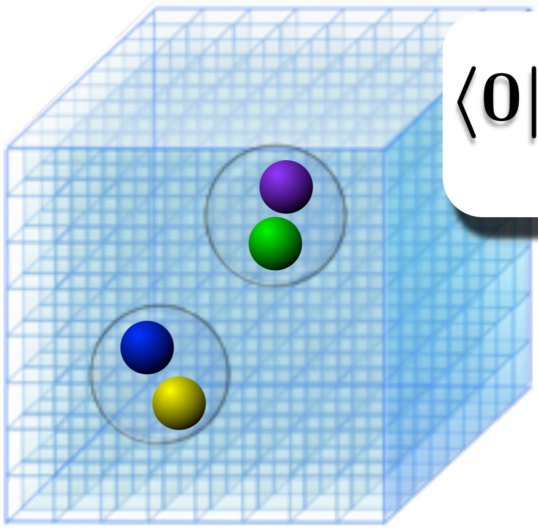
- NBS wave functions (r>|R|) satisfy **Helmholtz equation**

$$\left(\nabla^2 + \vec{k}_n^2\right)\psi_n(\vec{r}) = 0 \quad (|\vec{r}| > R)$$

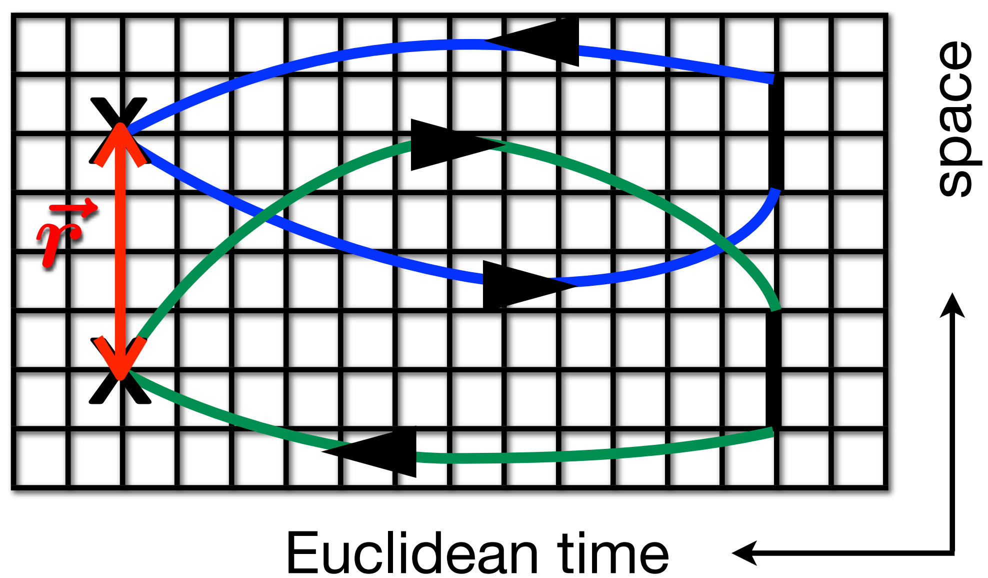
➡ **faithful to S-matrix** ($S(W)=e^{2i\delta(W)}$)

HAL QCD method “potentials as representation of S-matrix”

✦ **measure not only temporal but also spatial correlation**

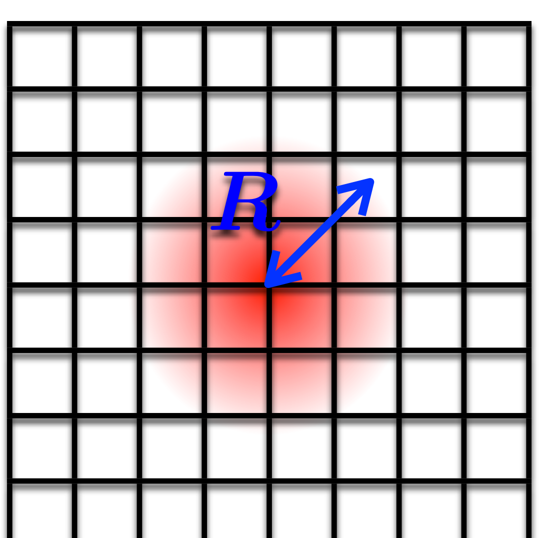


$$\langle 0|\phi_1(\vec{x}+\vec{r},\tau)\phi_2(\vec{x},\tau)\Phi^\dagger(0)|0\rangle = \sqrt{Z_1 Z_2}\sum_n A_n \psi_n(\vec{r}) e^{-W_n \tau}$$



Ishii, Aoki, Hatsuda, PRL99, 02201 (2007).
Aoki, Hatsuda, Ishii, PTP123, 89 (2010).
Ishii et al. (HAL QCD), PLB712, 437(2012).

★ **NBS wave function** (r<|R|) **--> “potential U(r,r’)”**



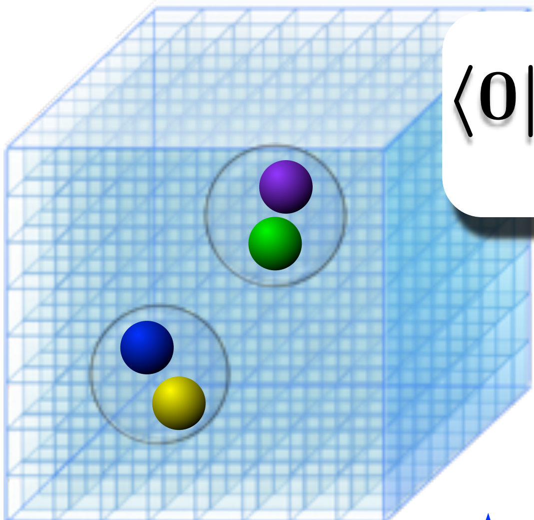
$$\left(\nabla^2 + \vec{k}_n^2\right)\psi_n(\vec{r}) = 2\mu \int d\vec{r}' U(\vec{r},\vec{r}')\psi_n(\vec{r}')$$

- U(r,r’) is faithful to **S-matrix**
- U(r,r’) is **energy independent** (until new threshold opens)
- U(r,r’) contains all 2PI contributions

(Non-relativistic approximation is NOT necessary)

Coupled-channel HAL QCD method

✦ **measure not only temporal but also spatial correlation**



$$\langle 0|\phi_1^a(\vec{x}+\vec{r},\tau)\phi_2^a(\vec{x},\tau)\Phi^\dagger(0)|0\rangle = \sqrt{Z_1^a Z_2^a}\sum_n A_n \psi_n^a(\vec{r}) e^{-W_n\tau}$$

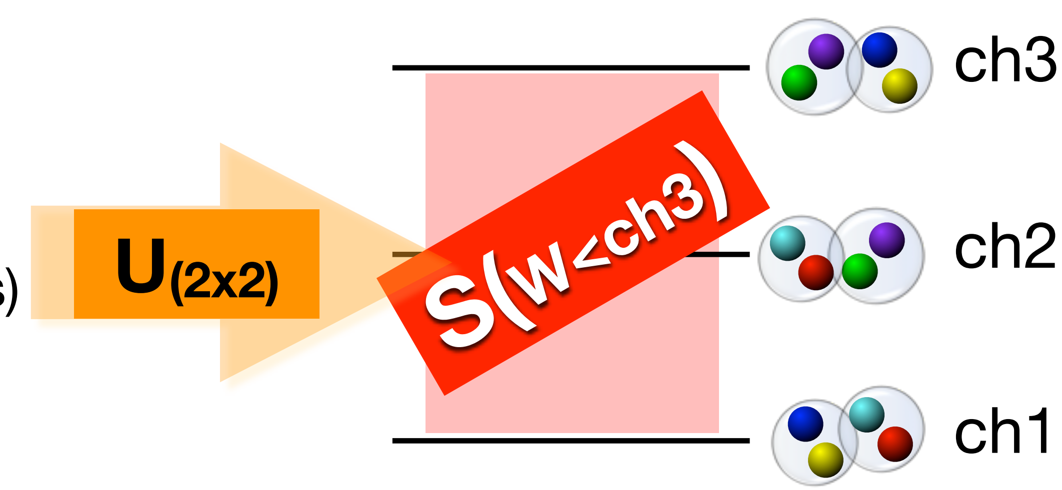
Ishii, Aoki, Hatsuda, PRL99, 02201 (2007).
Aoki, Hatsuda, Ishii, PTP123, 89 (2010).
Ishii et al. (HAL QCD), PLB712, 437(2012).

★ **spatial correlation --> identify channel wave function**

$$\left(\nabla^2 + (\vec{k}_n^a)^2\right)\psi_n^a(\vec{r}) = 2\mu^a \sum_b \int d\vec{r}' U^{ab}(\vec{r},\vec{r}')\psi_n^b(\vec{r}')$$

★ **coupled-channel potential U^{ab}(r,r'):**

- U^{ab}(r,r') is faithful to **coupled-channel S-matrix**
- U^{ab}(r,r') is **energy independent** (until new threshold opens)
- Non-relativistic approximation is not necessary
- U^{ab}(r,r') contains all 2PI contributions

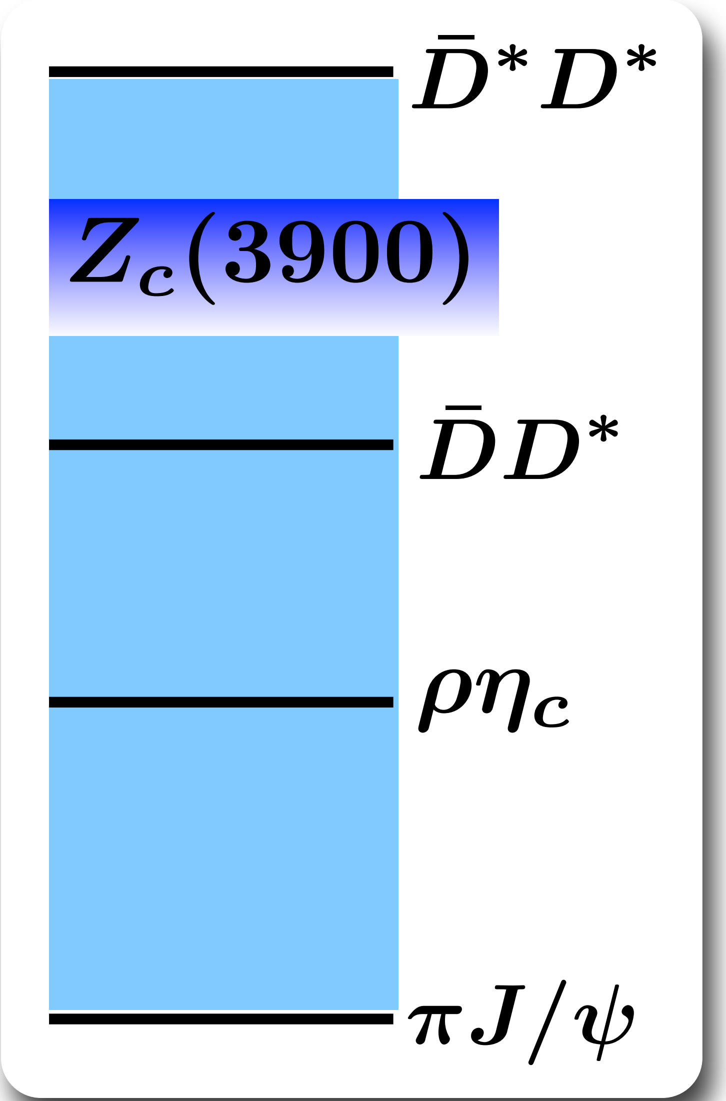


➡ **potential derived from time-dependent HAL QCD method** talk by Sasaki (Sun.)

Full details, Aoki et al. (HAL QCD), PTEP 2012, 01A105 (2012); Proc. Jpn. Acad., Ser. B, 87 (2011).

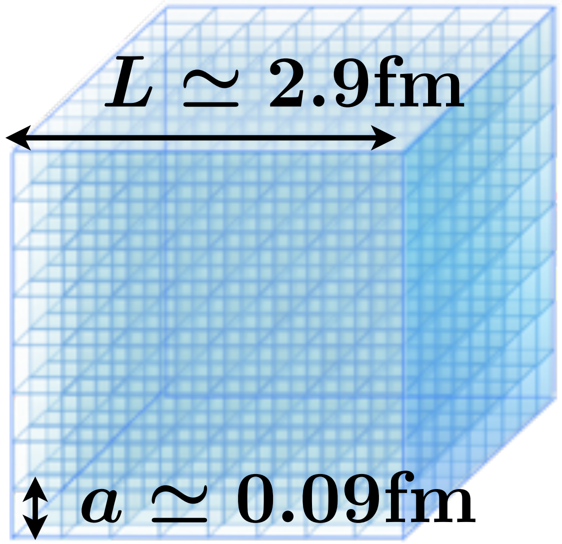
$Z_c(3900)$ in $I^G(J^{PC})=1^+(1^{+-})$
-- $\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$ coupled-channel --

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



❖ N_f=2+1 full QCD

- Iwasaki gauge
- clover Wilson quark
- 32^3 x 64 lattice



❖ Relativistic Heavy Quark (charm)

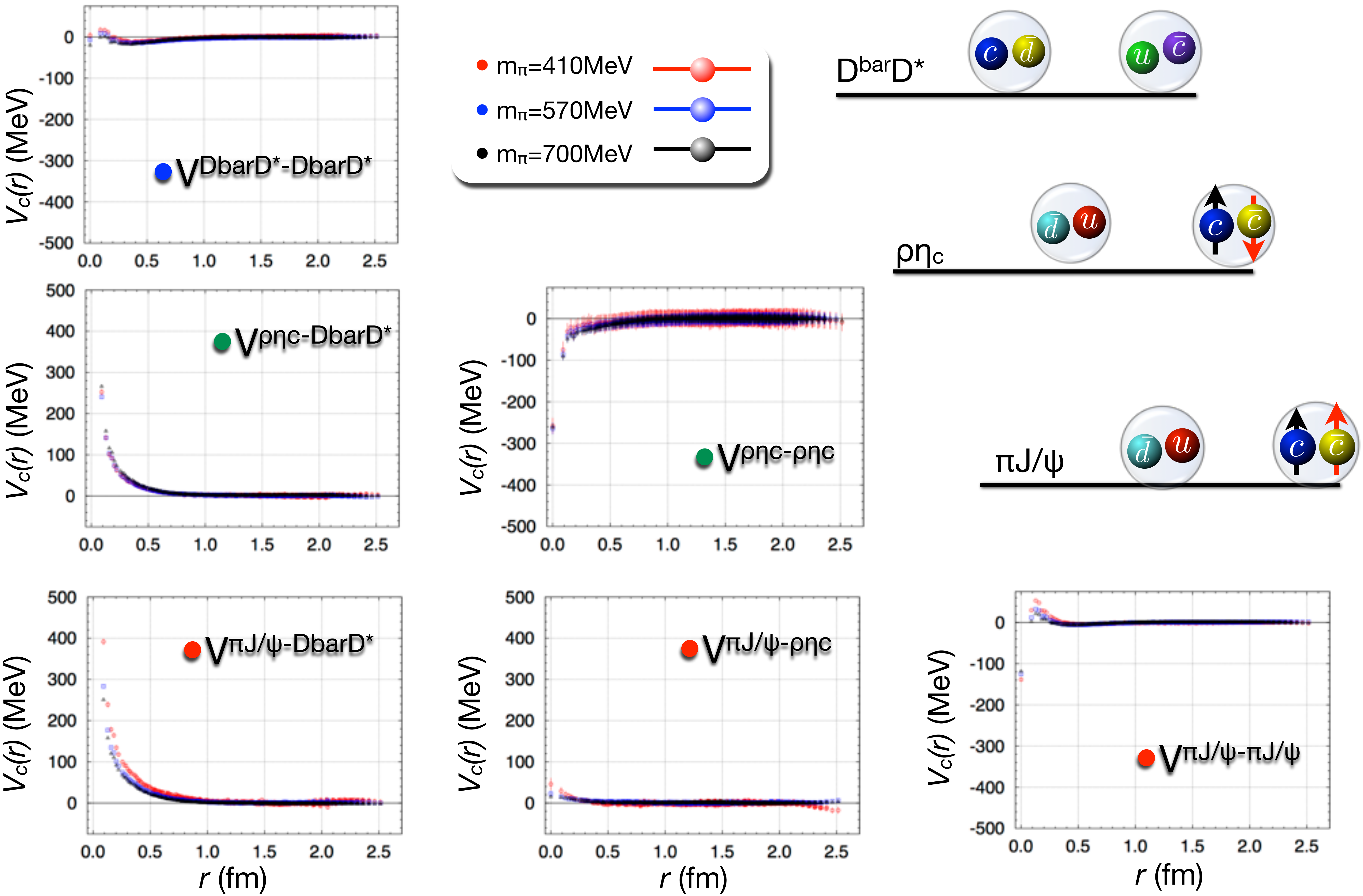
- remove leading cutoff errors $O((m_c a)^n)$, $O(\Lambda_{QCD} a)$, ...

➡ We are left with $O((a\Lambda_{QCD})^2)$ syst. error (~ a few %)

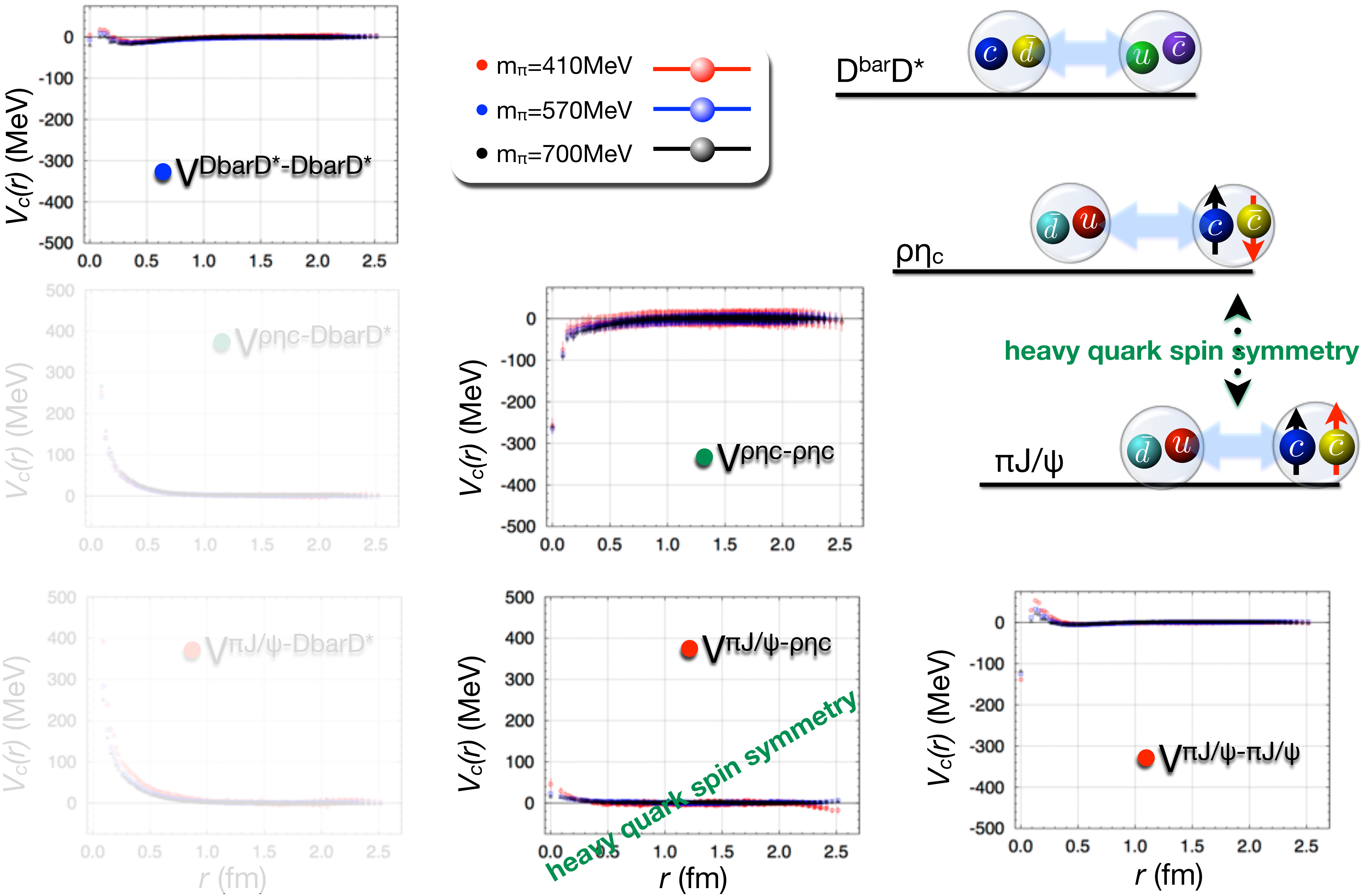
light meson mass (MeV)
m_π= 411(1), 572(1), 701(1)
m_ρ= 896(8), 1000(5), 1097(4)

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)

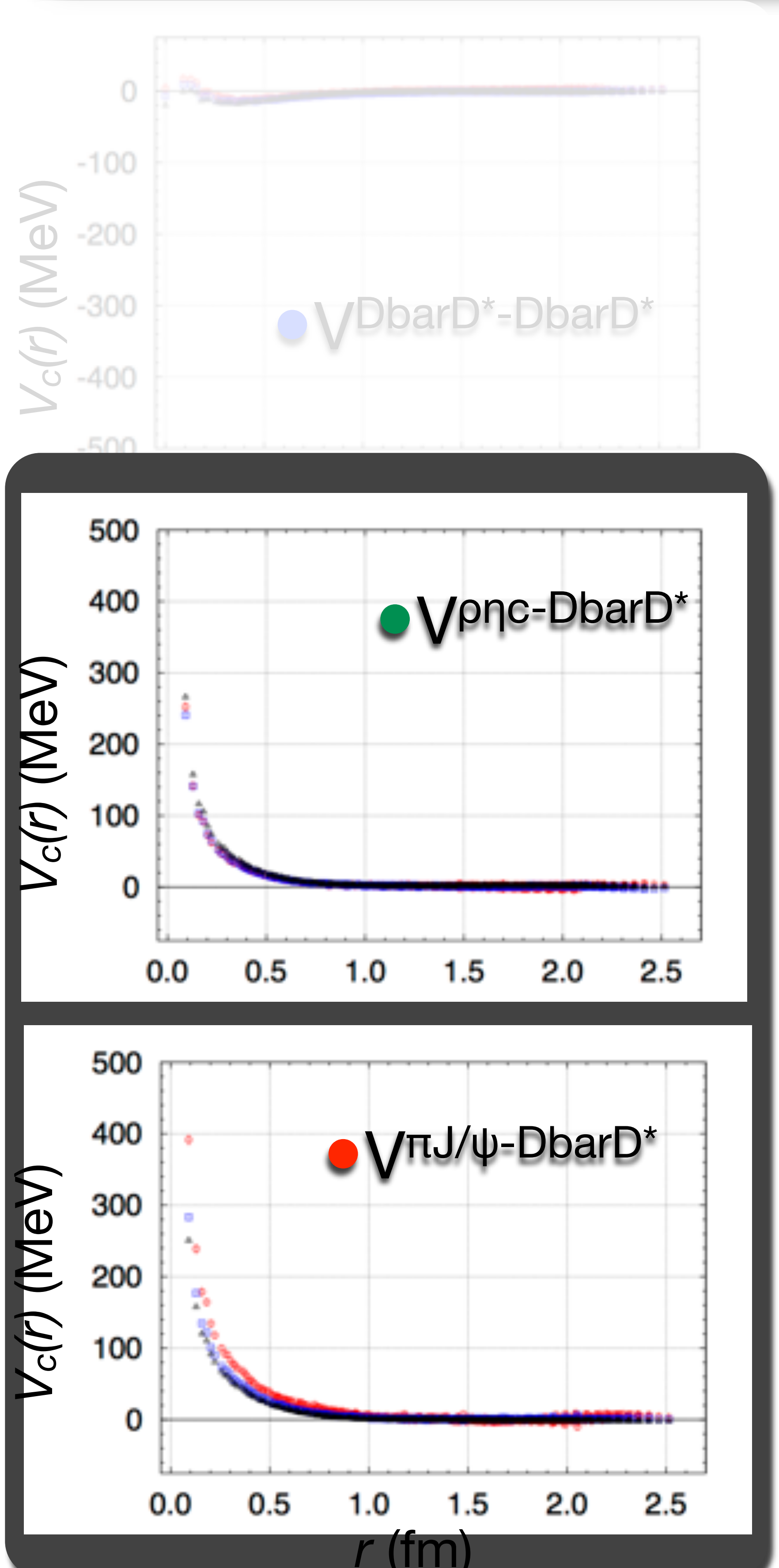
3x3 potential matrix (πJ/ψ - ρηc - DbarD*)



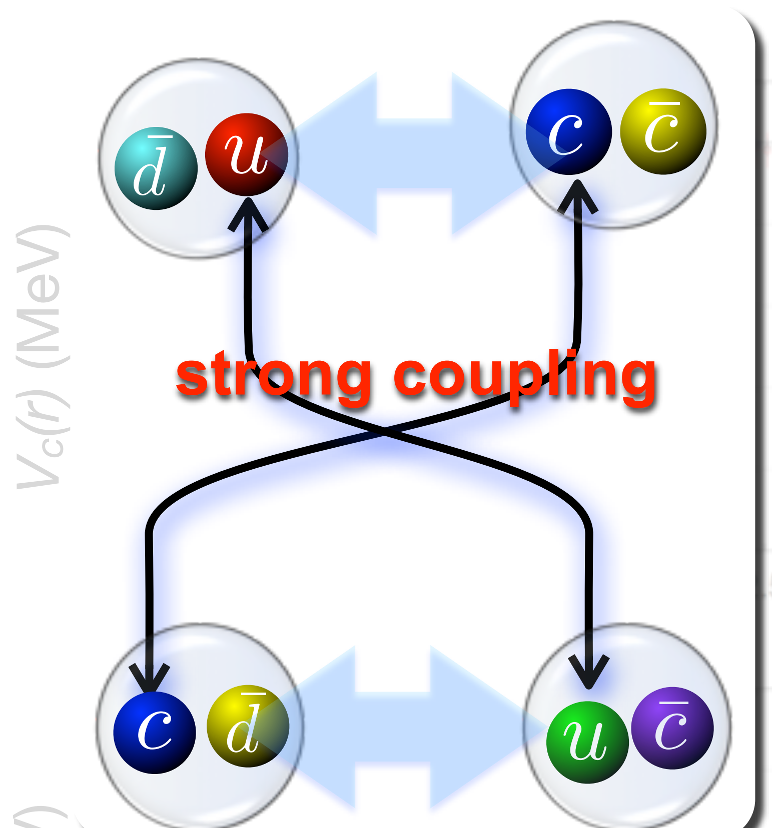
3x3 potential matrix (πJ/ψ - $\rho\eta_c$ - $D^{bar}D^*$)

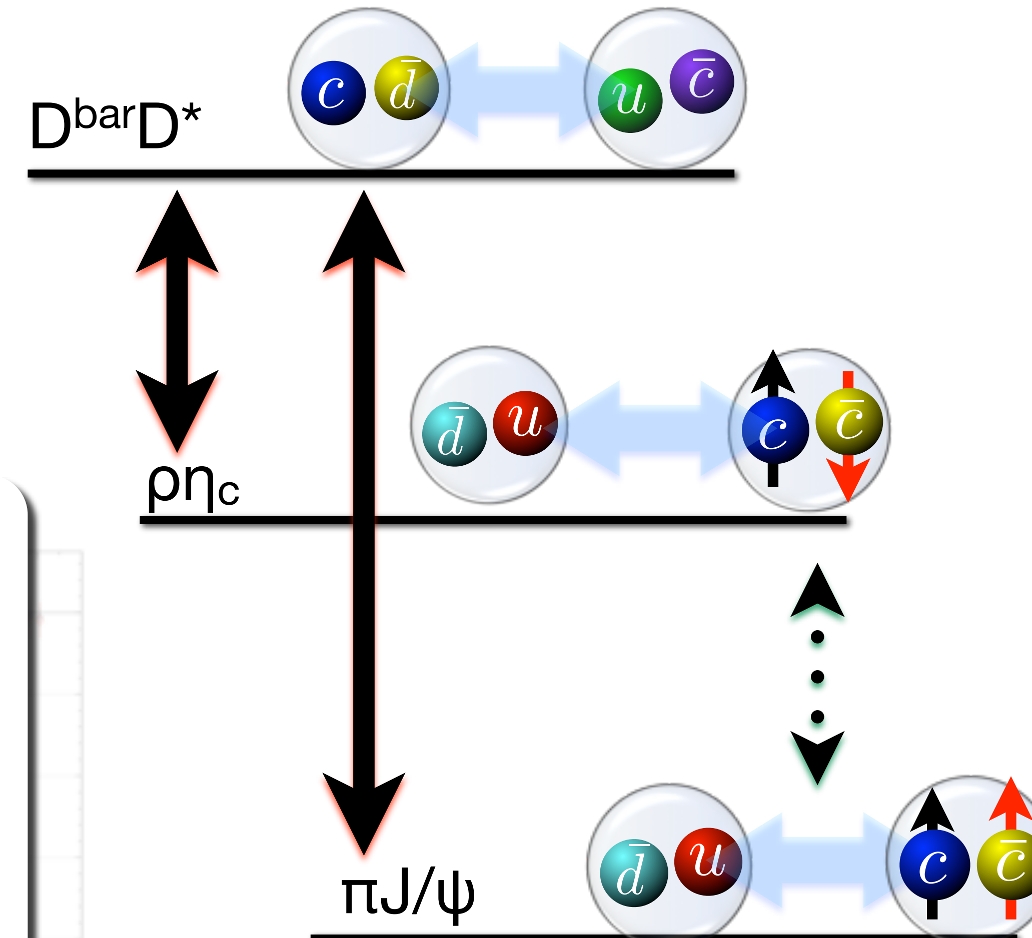


3x3 potential matrix (πJ/ψ - $\rho\eta_c$ - $D^{bar}D^*$)



- m_π=410MeV
- m_π=570MeV
- m_π=700MeV





- strong $V^{\pi J/\psi, D^{bar}D^*}$ & $V^{\rho\eta_c, D^{bar}D^*}$

➡ charm quark exchange process

Structure of $Z_c(3900)$ studied by the most ideal scattering process

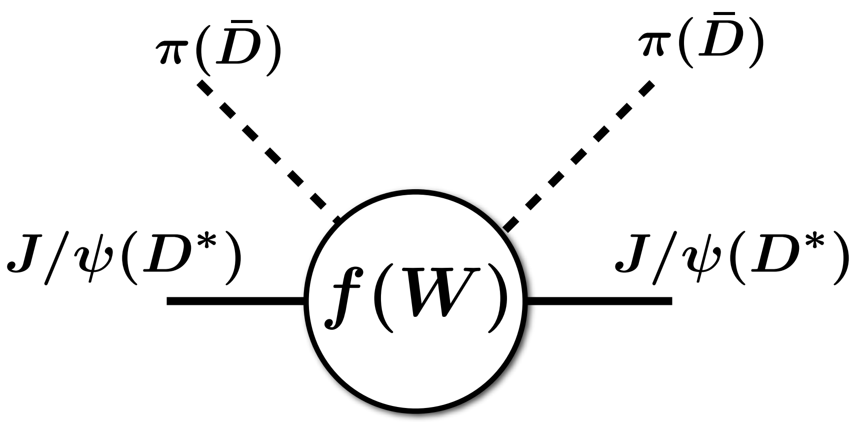
- **S-wave $\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$ coupled-channel scattering**

➡ **$Z_c(3900)$ is observed in $\pi J/\psi$ & $D^{bar}D^*$ -> 2-body scattering is the most ideal reaction**

1. invariant mass distribution of 2-body scattering

\# of scat. particles proportional to imaginary part of amplitude

$$N_{\mathrm{sc}} \propto (\mathrm{flax}) \cdot \sigma(W) \propto \mathrm{Im} f(W)$$



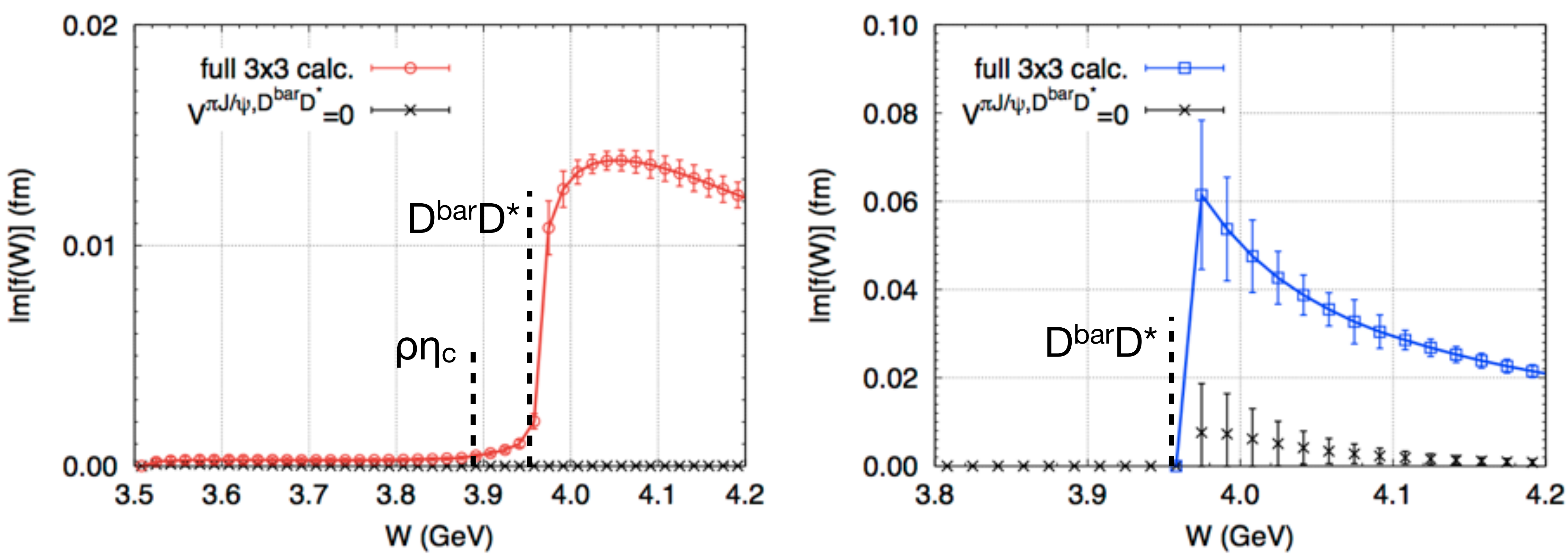
2. pole position of S-matrix

- analytic continuation of c.c. S-matrix onto complex energy plane
- understand nature of $Z_c(3900)$

- Results w/ m_π=410MeV are shown. (**weak quark mass dependence observed**)

Invariant mass of $\pi J/\psi$ & $D^{bar}D^*$ (2-body scat.)

- $\pi J/\psi$ invariant mass
- $D^{bar}D^*$ invariant mass



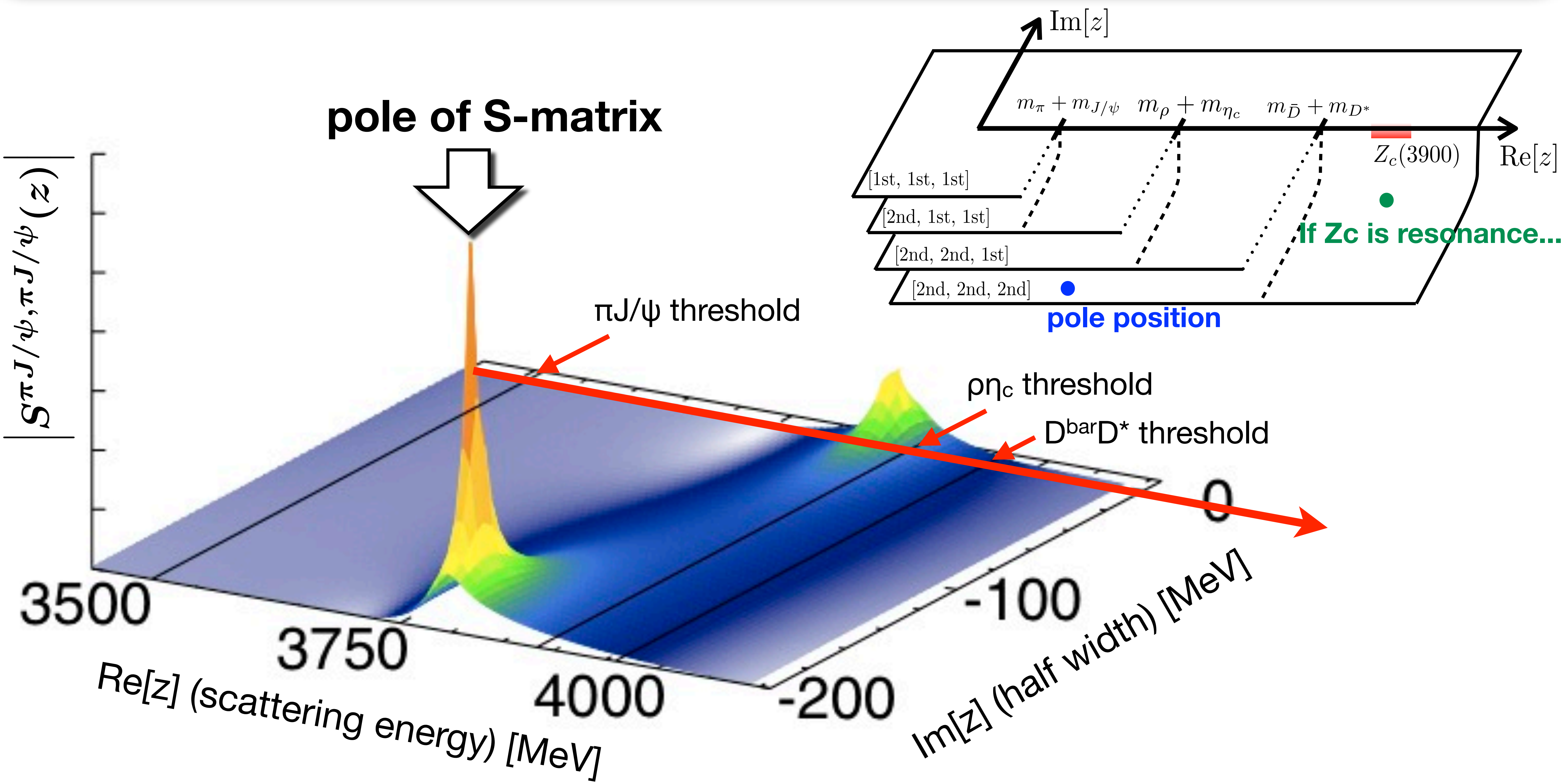
✓ **Enhancement near $D^{bar}D^*$ threshold** in both amplitudes

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

- peak in $\pi J/\psi$ inv. mass (not Breit-Wigner line shape)

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

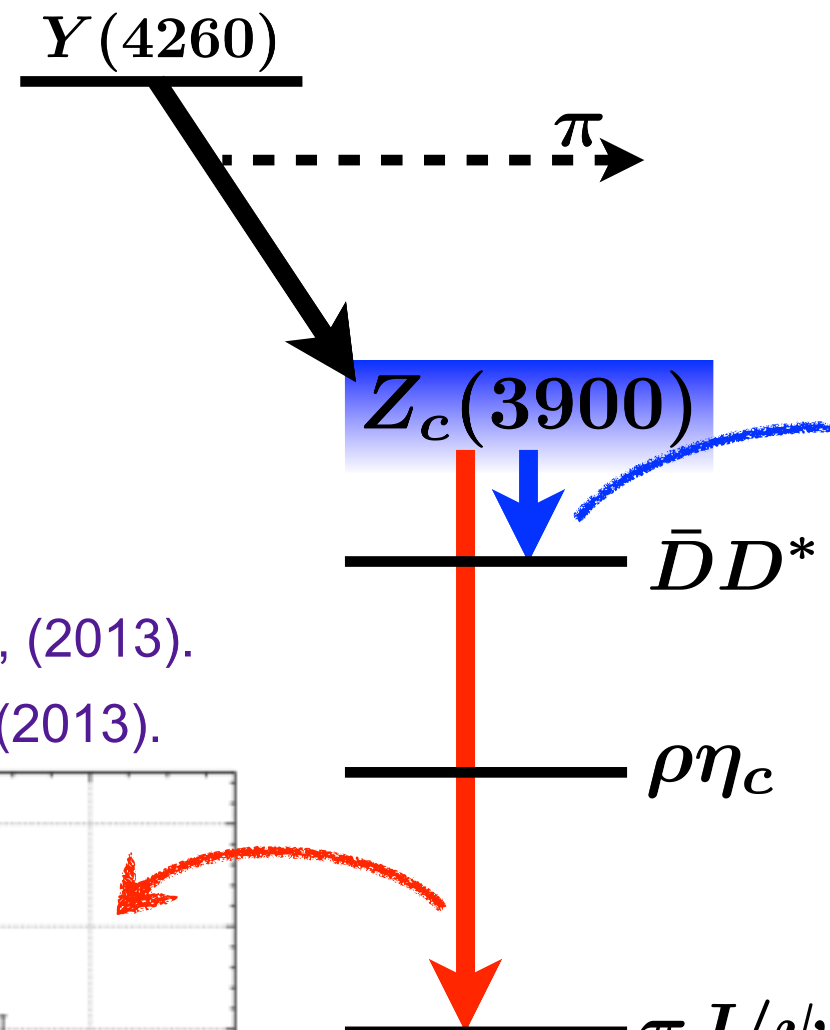
Pole of S-matrix ($\pi J/\psi$:2nd, $\rho\eta_c$:2nd, $D^{bar}D^*$:2nd)



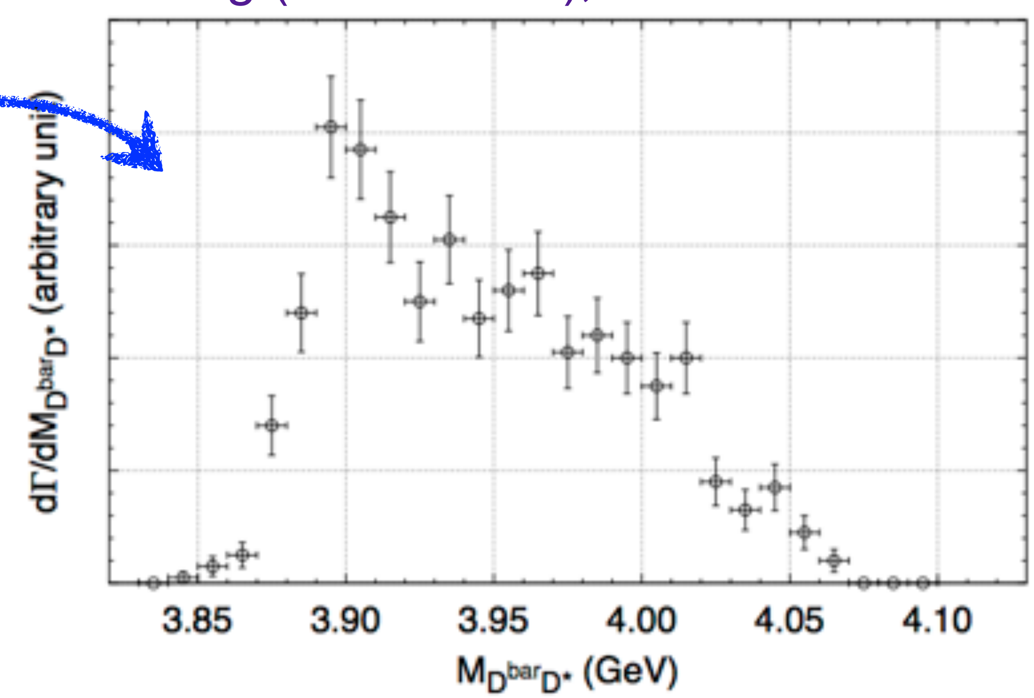
- Pole corresponding to "**virtual state**"
- Pole contribution to scat. observables is small (far from scat. axis)
- **Z_c(3900) is not a resonance but "threshold cusp" induced by strong $V^{\pi J/\psi, DbarD^*}$**

Comparison with expt. data:

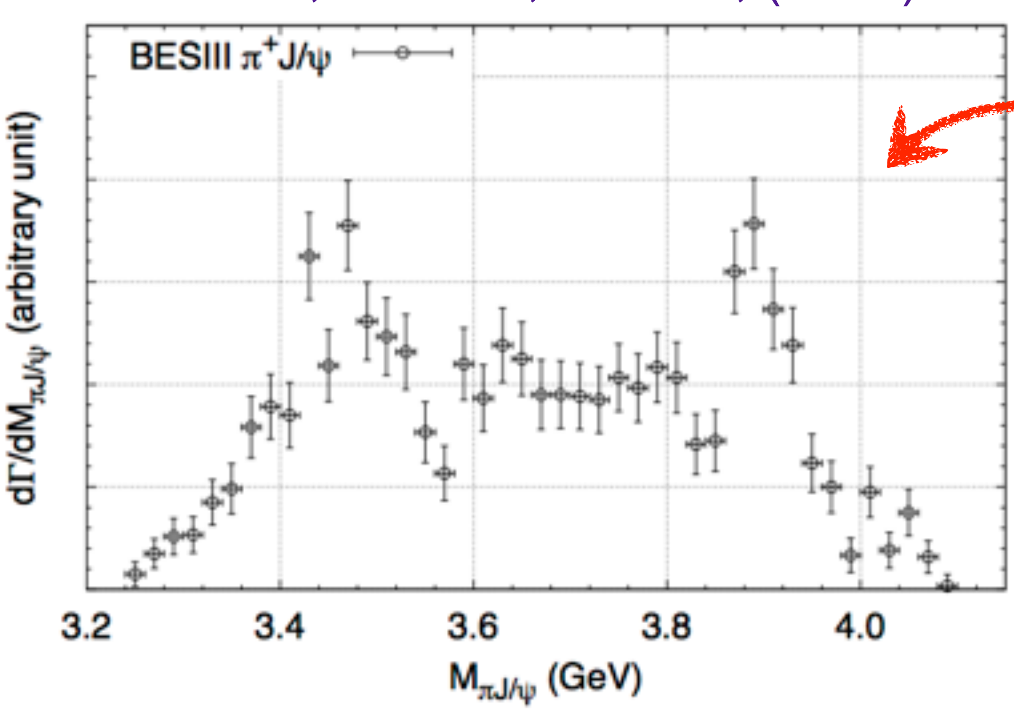
-- spectrum of Y(4260) 3-body decay --

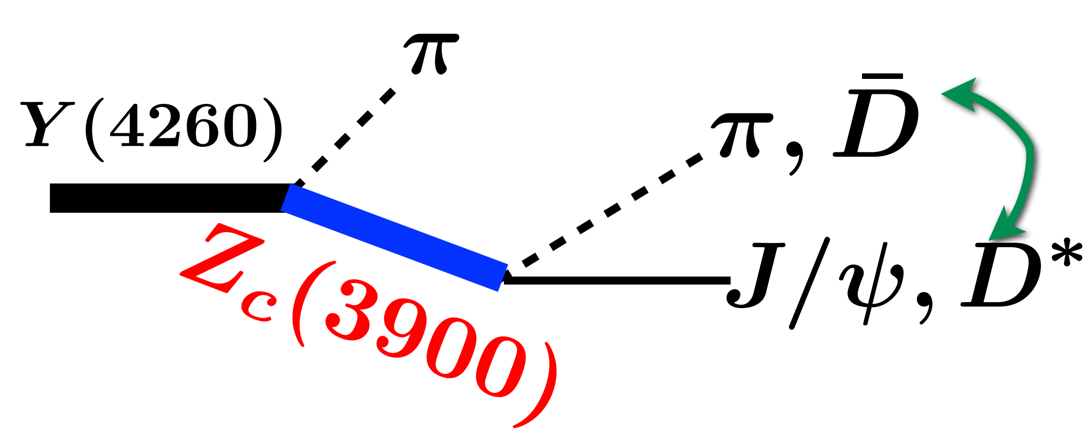


BESIII Coll., PRL112, 022001, (2014).
Wang (BESIII Coll.), MENU2016 talk



BESIII Coll., PRL110, 252001, (2013).
Belle Coll., PRL110, 252002, (2013).



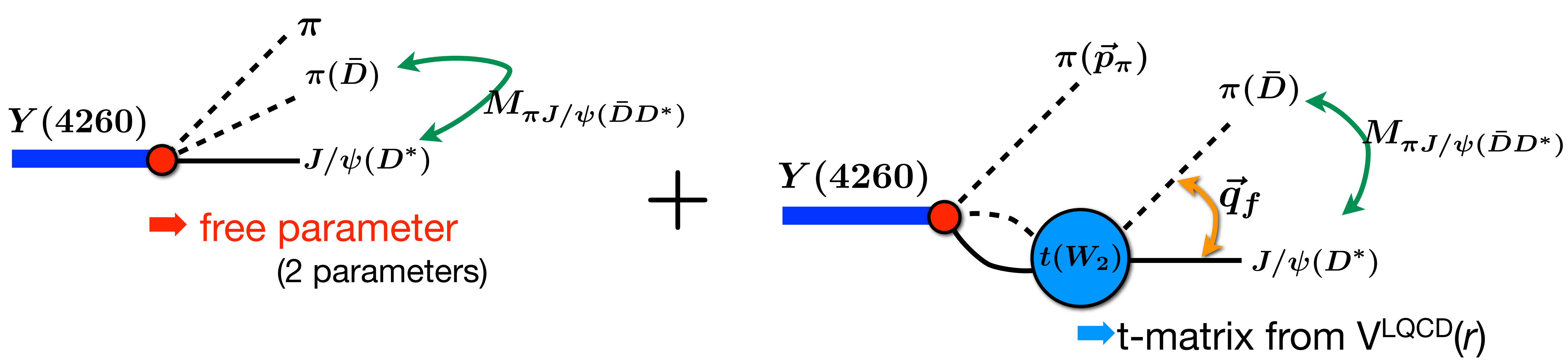


Y(4260) --> ππJ/ψ & πD^{bar}D*

$$d\Gamma_{Y\to\pi+f} = (2\pi)^4\delta(W_3 - E_\pi(\vec{p}_\pi) - E_f(\vec{q}_f))d^3p_\pi d^3q_f|T_{Y\to\pi+f}(\vec{p}_\pi,\vec{q}_f;W_3)|^2$$

✓ 3-body T-matrix: $T_{Y\text{->}\pi+f}(W_3\text{=}4260\text{MeV})$

$$T_{Y\to\pi+f}(\vec{p}_\pi,\vec{q}_f;W_3) = \sum_{n=\pi J/\psi,\bar{D}D^*} C^{Y\to\pi+n}\left[\delta_{nf} + \int d^3q' \frac{t_{nf}(\vec{q}',\vec{q}_f,\vec{p}_\pi;W_3)}{W_3 - E_\pi(\vec{p}_\pi) - E_n(\vec{q}',\vec{p}_\pi) + i\epsilon}\right]$$



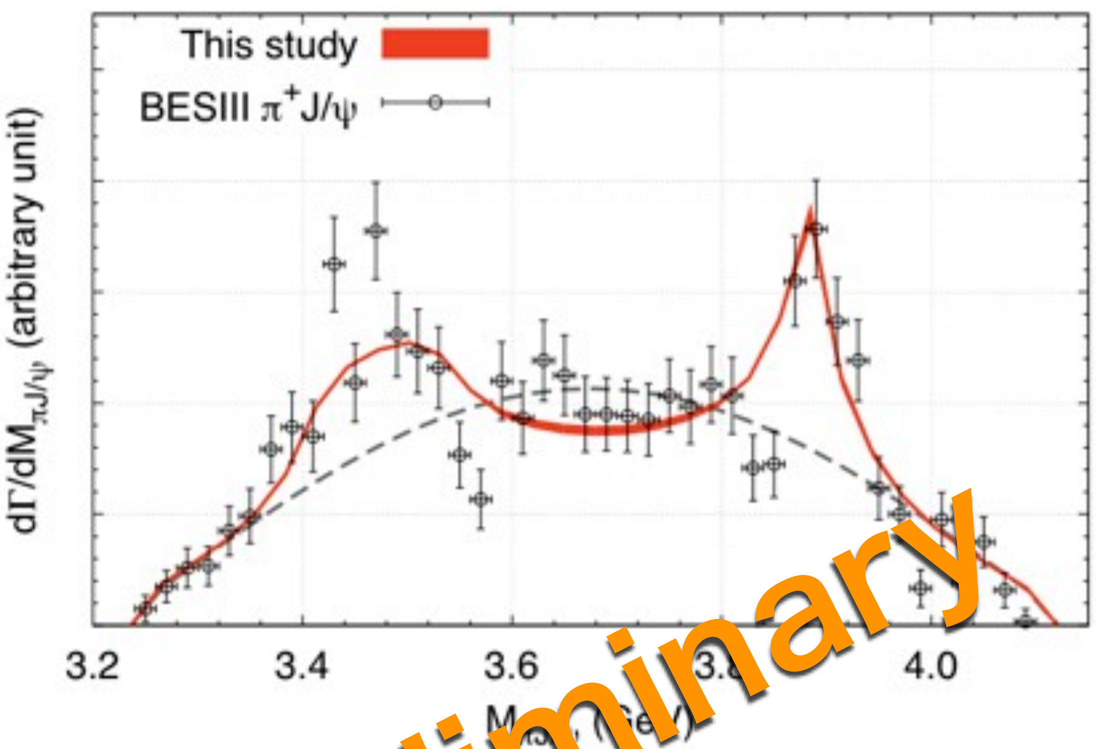
employ physical hadron masses to compare w/ expt. data

✓ LQCD V(r) is taken into account

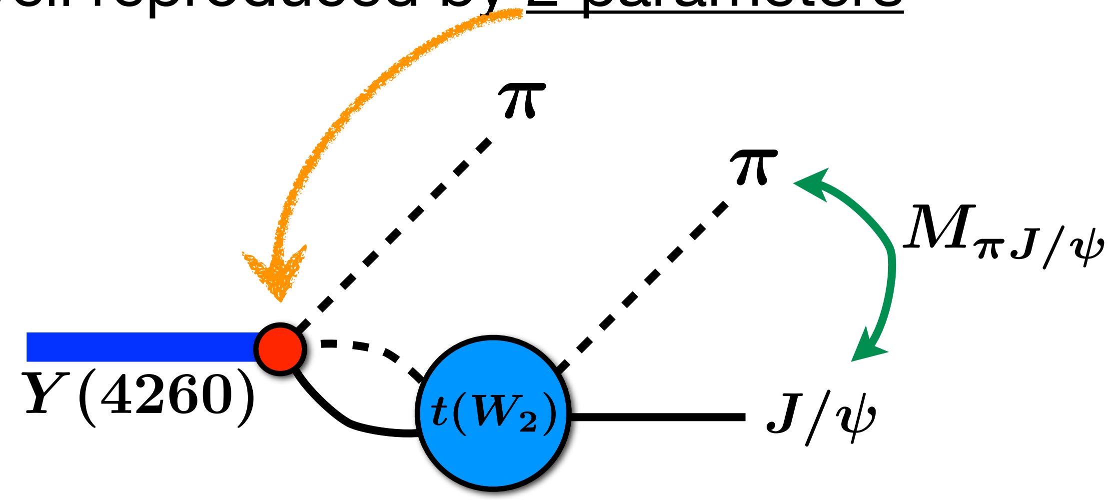
✓ fix free parameters by fitting Y(4260)-->ππJ/ψ expt. data

Invariant mass of 3-body decay (relativistic dispersion)

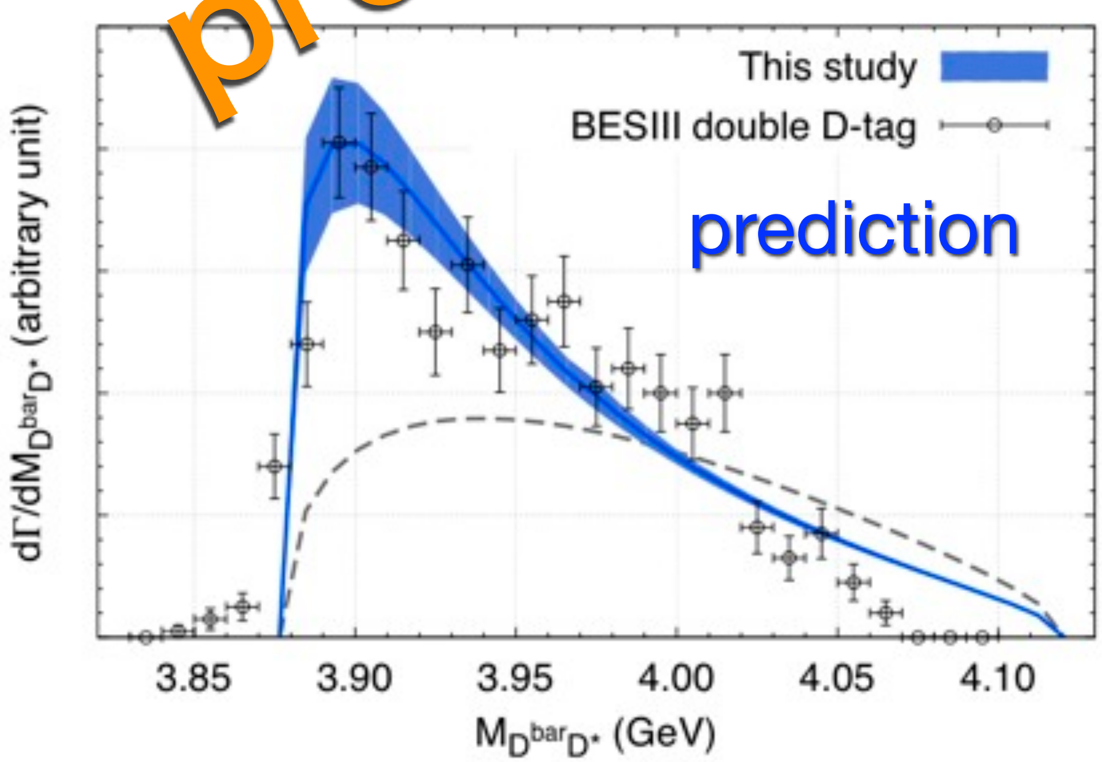
Y. Ikeda et al., [HAL QCD], PRL117 & in preparation



- Expt. data well reproduced by 2 parameters



- When $V^{\pi J/\psi,\ DbarD^*}=0$ (dashed curve), expt. data are not reproduced.



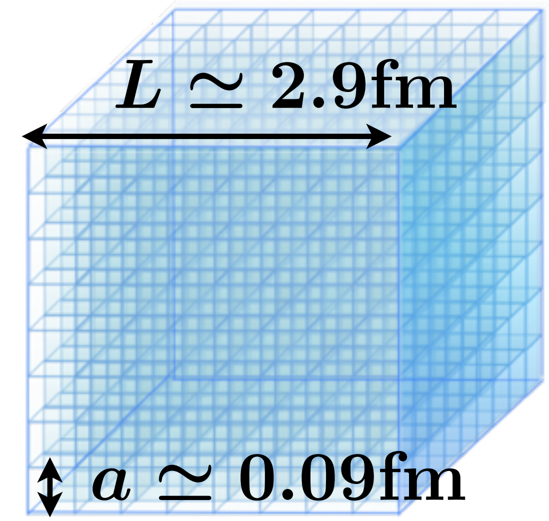
- **predicted curve well agrees with expt. data**

- When $V^{\pi J/\psi,\ DbarD^*}=0$ (dashed curve), peak disappears

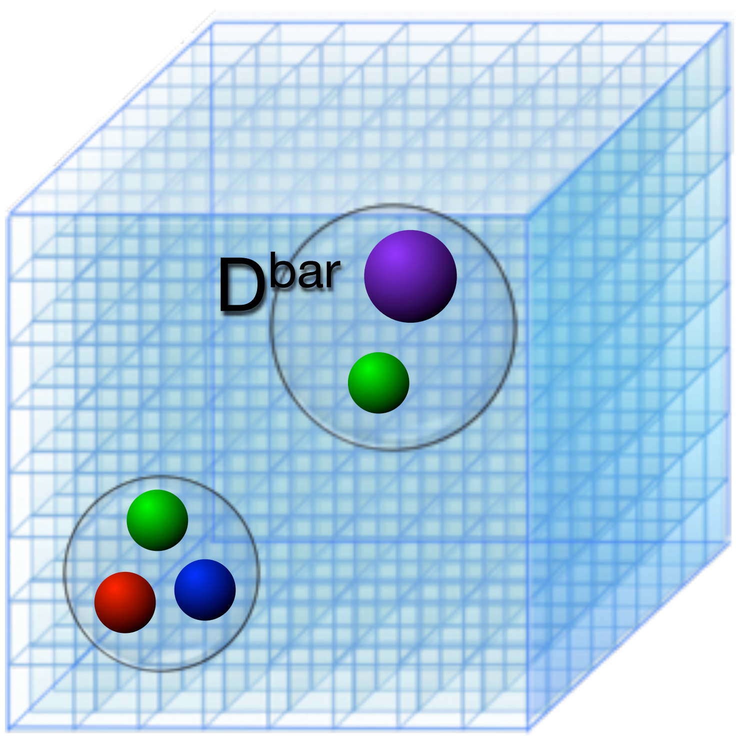
conclusion: $Z_c(3900)$ is threshold cusp caused by strong $V^{\pi J/\psi,\ DbarD^*}$

S-wave D^{bar}-nucleon interaction and D^{bar}-nuclei

- N_f=2+1 full QCD configs. (PACS-CS collaboration)
- RHQ action for charm quark



m_π= 411, 572, 701
m_N= 1215, 1411, 1583
m_D= 1903, 1947, 2000
$m_{\Lambda c}$= 2434, 2584, 2710

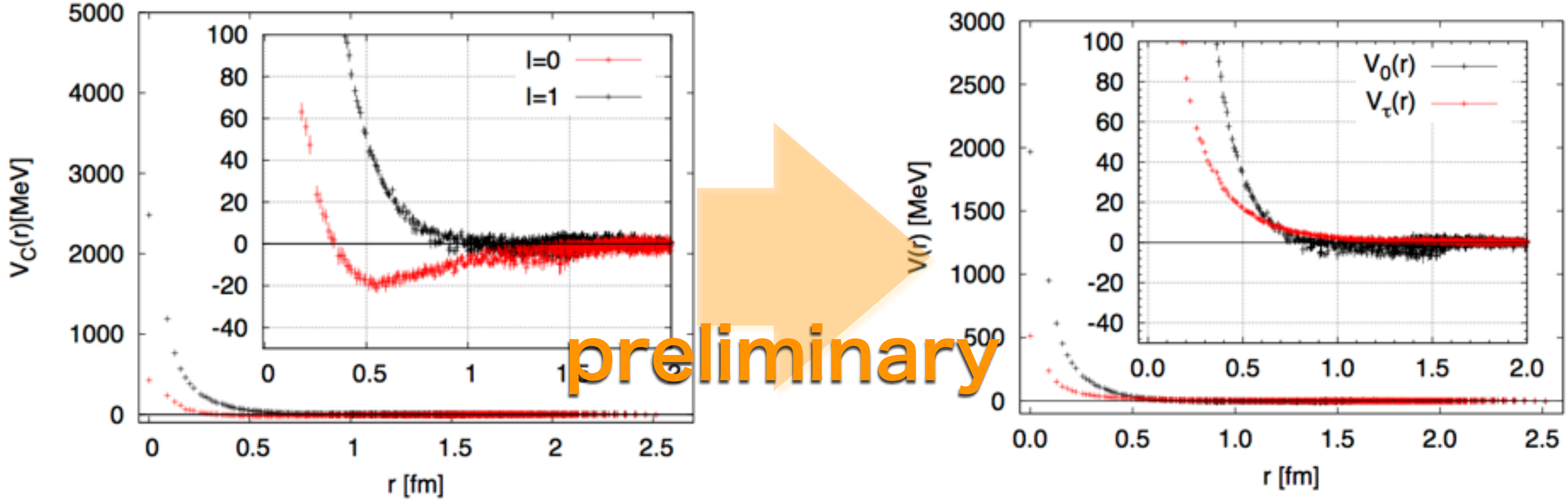


- $D^{bar}N$ interaction in I=0 & 1 by HAL QCD method
- Naive expectation to D^{bar}-nuclei by simple folding potential model

S-wave $D^{bar}N$ interaction in I=0 & 1 @m_π=410MeV

I=0 & I=1 potentials

$$V_{\bar{D}N}(\vec{r}) = V_0(\vec{r}) + V_\tau(\vec{r})(\vec{\tau}_{\bar{D}} \cdot \vec{\tau}_N)$$



$$a_{\bar{D}N} = \begin{cases} 0.79(42) & (I=0) \\ -0.20(1) & (I=1) \end{cases}$$

- $V_0(r)$ is repulsive, $V_\tau(r)$ is positive

Y. Ikeda [HAL QCD], in preparation

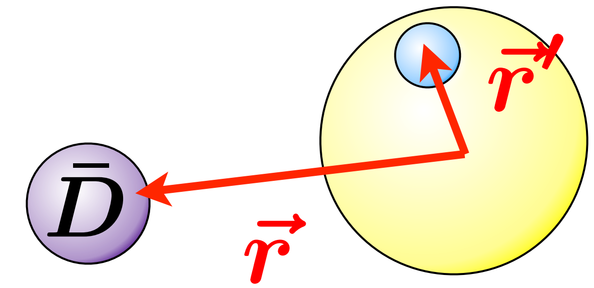
$D^{bar}N$ interaction

(1) attractive in I=0 & repulsive in I=1

(2) $V_0(r)$ is repulsive, $V_\tau(r)$ is positive

D^{bar}-nuclei (naive expectation from $D^{bar}A$ folding potential model)

✓ What is possible structure of D^{bar}-nuclei?



$$V_{\bar{D}N}(\vec{r}) = V_0(\vec{r}) + V_\tau(\vec{r})(\vec{\tau}_{\bar{D}} \cdot \vec{\tau}_N)$$

$$V_{\bar{D}A}(\vec{r}) = \sum_{i=1}^{A} \int d^3r' \rho_{N_i}(\vec{r}') \left[V_0(\vec{r} - \vec{r}') + V_\tau(\vec{r} - \vec{r}')(\vec{\tau}_{\bar{D}} \cdot \vec{\tau}_{N_i})\right]$$

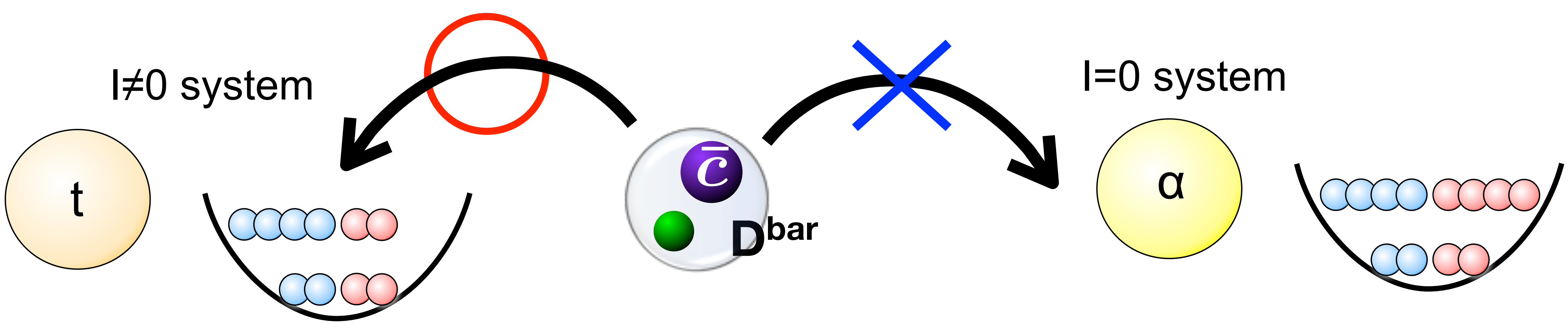
contact interaction : $V_{\bar{D}N}(\vec{r}) \to \{g_0 + g_\tau(\vec{\tau}_{\bar{D}} \cdot \vec{\tau}_N)\}\,\delta(\vec{r})$

g_0 : repulsive, g_τ : positive

Energy shift

$$\Delta E = \int d^3r V_{\bar{D}A}(\vec{r}) = A\left[g_0 + g_\tau(\vec{\tau}_{\bar{D}} \cdot \vec{\tau}_A)\right], \quad \vec{\tau}_A = \sum_{i=1}^{A} \vec{\tau}_{N_i}$$

✓ Isospin correlation plays crucial role to make D^{bar} bound into nuclei



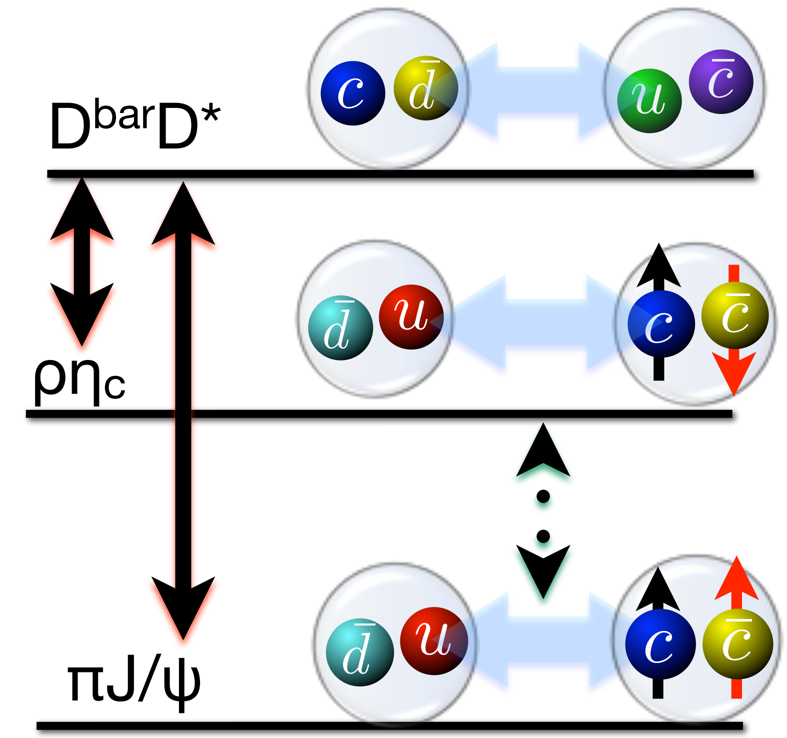
Summary

✦ Coupled-channel HAL QCD method

- derive potential faithful to S-matrix from BS wave function
- a solution to coupled-channel problems from LQCD

Tetra-quark candidate $Z_c(3900)$

- $Z_c(3900)$ is threshold cusp induced by strong $V^{\bar{D}D^*,\, \pi J/\psi}$
  - pole position very far from scat. axis
  - expt. data of Y(4260) decay well reproduced
  - no peak structure when $V^{\bar{D}D^*,\, \pi J/\psi}=0$



D^{bar}-nuclei

- D^{bar} may be bound into neutron or proton rich nuclei
  - repulsive isospin-independent & positive sign of isospin-dependent interactions
  - D^{bar} is good probe to explore isospin correlation inside nuclei

Future: physical point calculations

Thank you for your attention!!