Z_c(3900) from Lattice QCD Simulation

Yoichi IKEDA (RCNP, Osaka Univ.)

HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)

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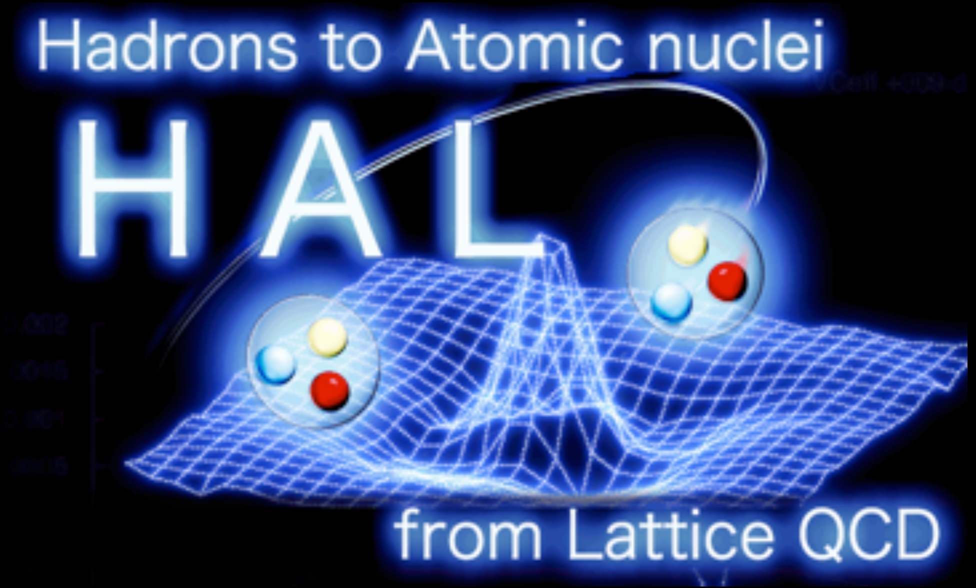

The 14th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon
@Kyoto, Japan (Jul. 25 -- 30, 2016.)

Charm Hadron Interactions from Lattice QCD Simulation

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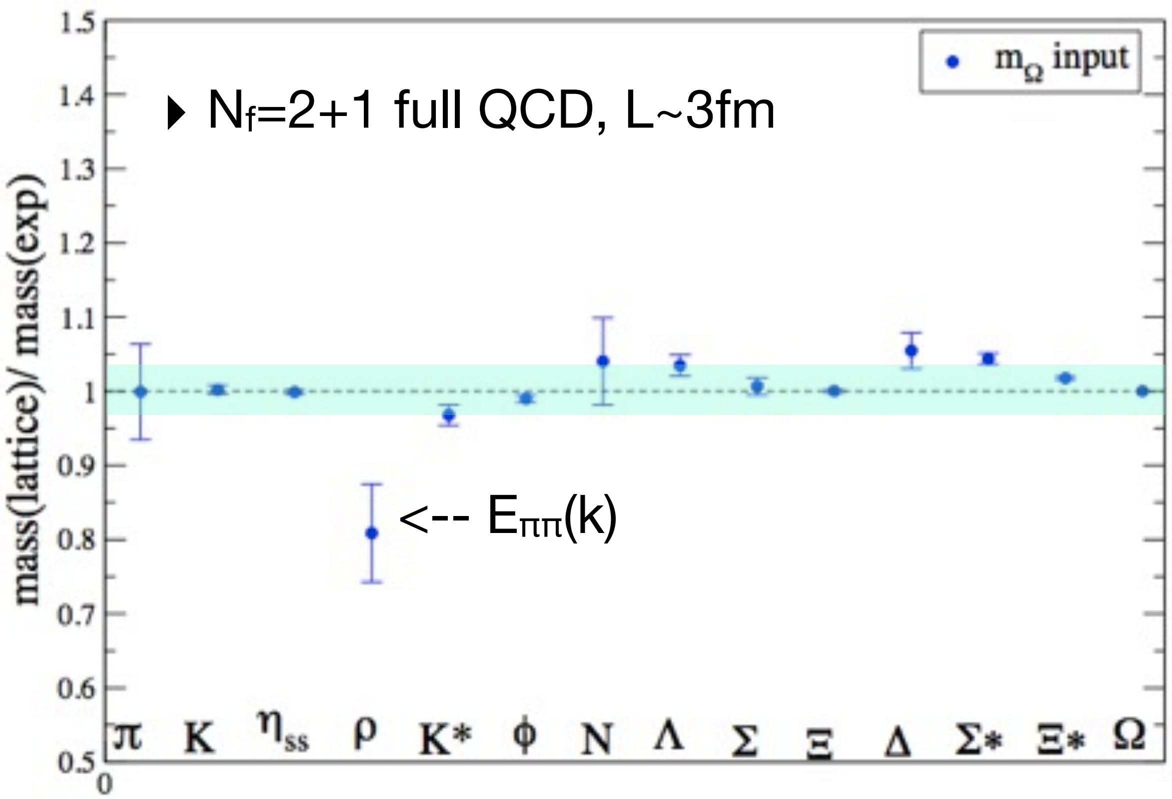
Contents

- ✓ Lattice QCD at physical point -- single hadron spectroscopy --
- ✓ Problems in multi-hadron scatterings in LQCD simulation
  - large volume problem (lattice has to accommodate hadron interactions)
  - coupled-channel problem (many resonances are embedded into c.c. continuum)
- ✓ HAL QCD approach to extract hadron interactions
- ✓ Results on charm hadron interactions
  - $Z_c(3900)$ in s-wave meson-meson scattering
  - D^{bar} & Λ_c interactions
- ✓ Summary

Single hadron spectroscopy from LQCD

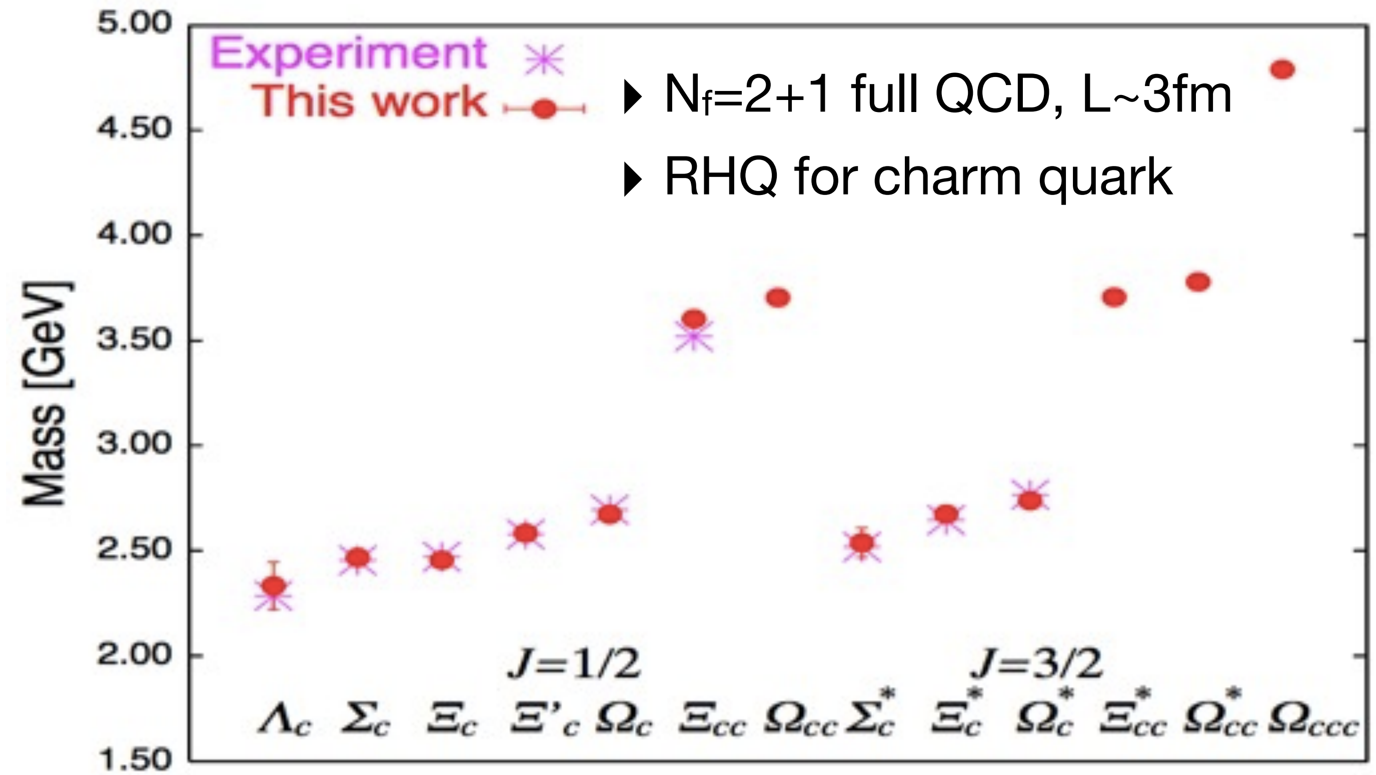
★ **Low-lying hadrons on physical point (physical m_q)**

light-quark sector

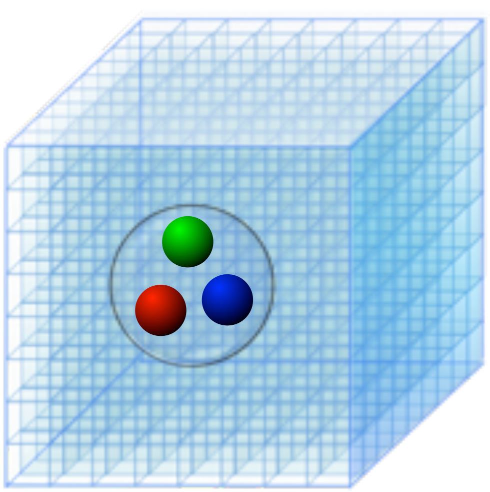


Aoki et al. (PACS-CS), PRD81 (2010).

charm baryons



Namekawa et al. (PACS-CS), PRD84 (2011); PRD87 (2013).



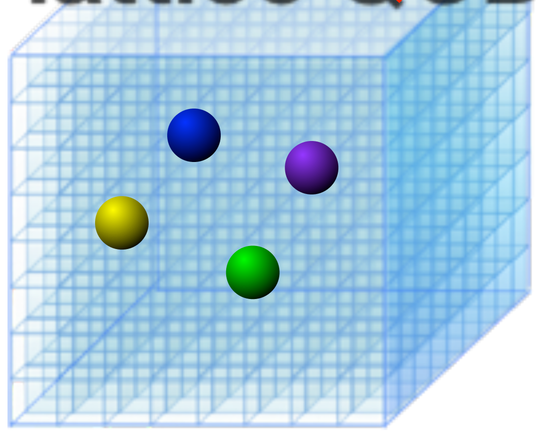
a few % accuracy already achieved for single hadrons

LQCD now can predict undiscovered charm hadrons (Ξ_{cc}, Ξ^*_{cc}, Ω_{ccc},...)

➡ **Next challenge : multi-hadron systems**

Problems in multi-hadron scatterings (1)

lattice QCD

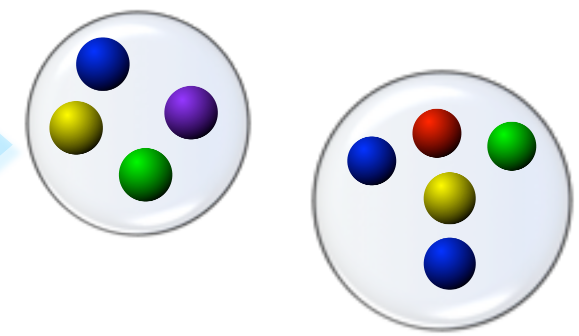


Scattering on the lattice

(1) large V

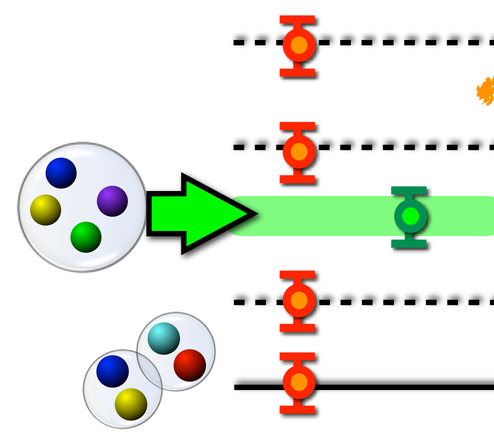
(2) coupled-channel

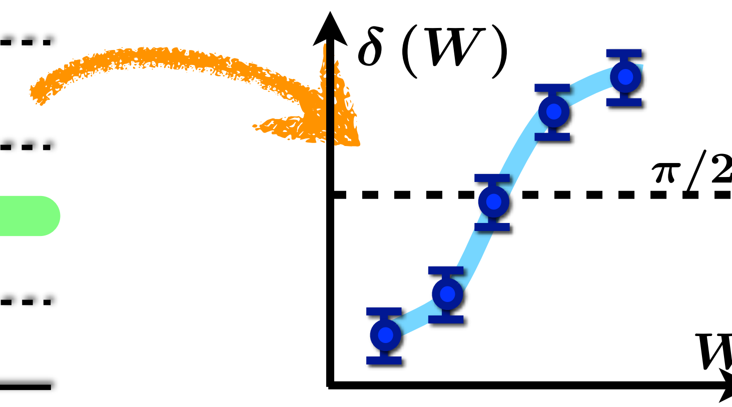
✓ X, Y, Z, P_c,...



★ single channel scattering

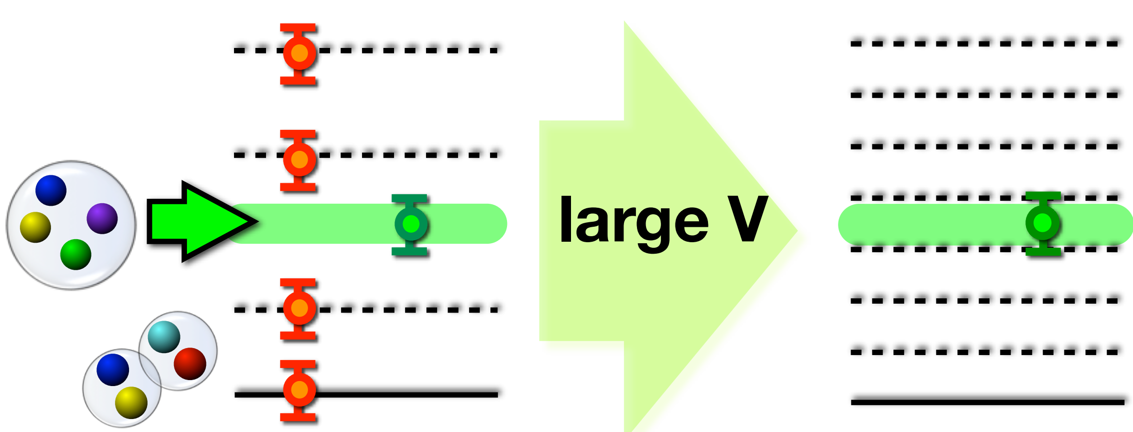
$$\langle 0|\Phi(\tau)\Phi^\dagger(0)|0\rangle = \sum_n A_n e^{-W_n \tau}$$

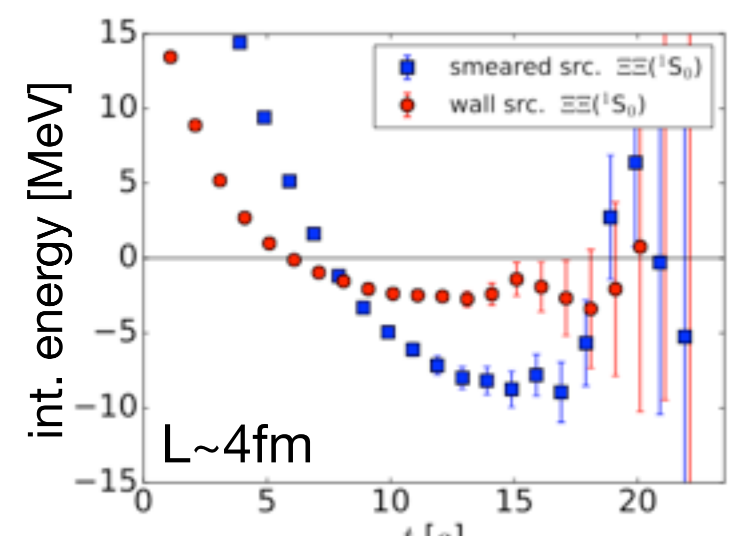




❖ Lüscher's formula Lüscher, NPB354 (1991).

- finite V spectrum --> phase shift $\delta(W_n)$



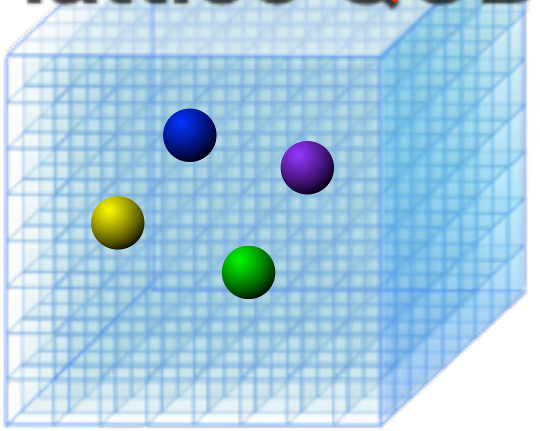


- fake plateau easily appears...

Iritani [HAL QCD], arXiv:1607.06371(2016).

Problems in multi-hadron scatterings (1)

lattice QCD

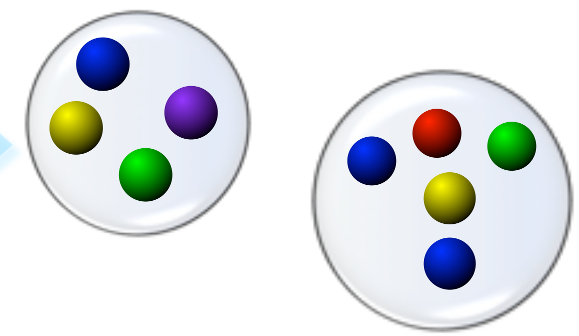


Scattering on the lattice

(1) large V

(2) coupled-channel

✓ X, Y, Z, P_c,...



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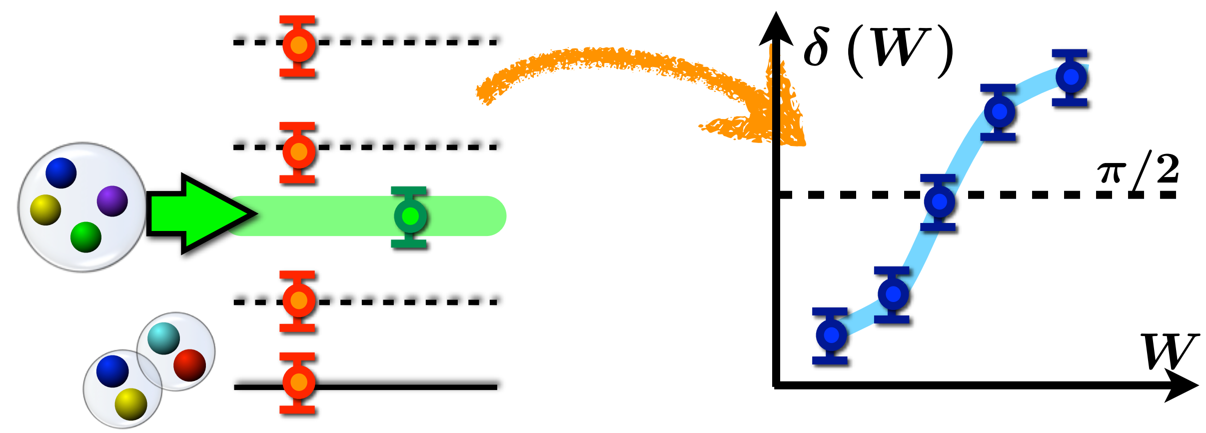
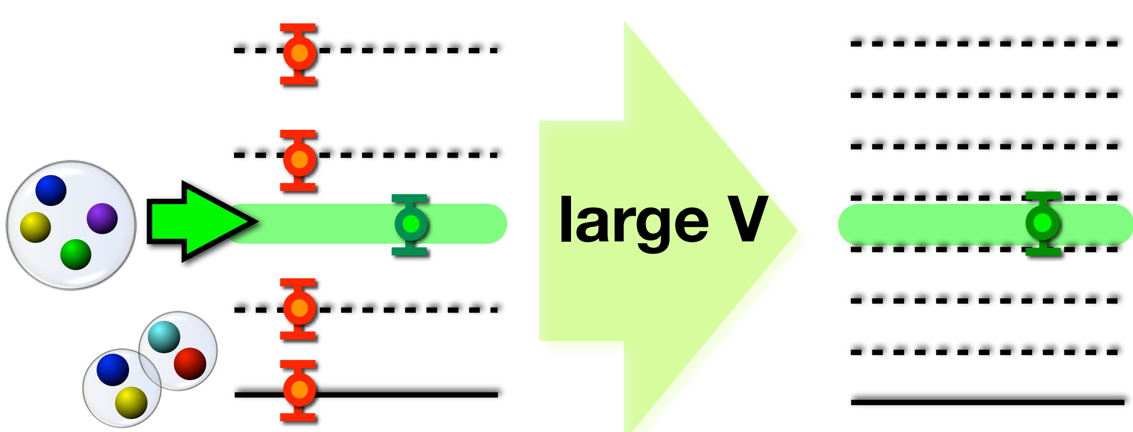
$$\langle 0|\Phi(\tau)\Phi^\dagger(0)|0\rangle = \sum_n A_n e^{-W_n \tau}$$



❖ Lüscher's formula Lüscher, NPB354 (1991).

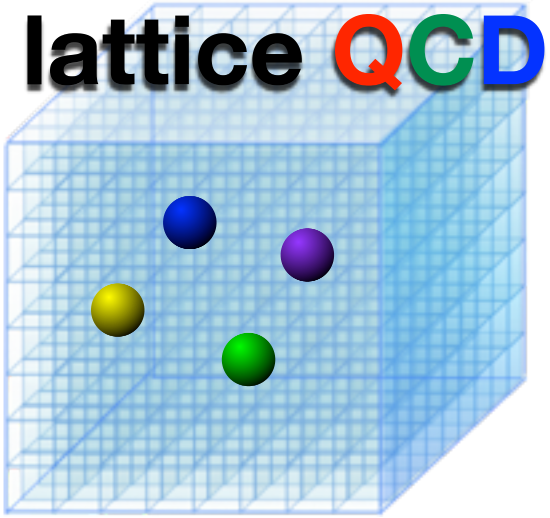
- finite V spectrum --> phase shift $\delta(W_n)$



★ difficult to identify W_n due to contamination

➡ energy-independent quantity from LQCD to obtain S-matrix is a key

Problems in multi-hadron scatterings (2)

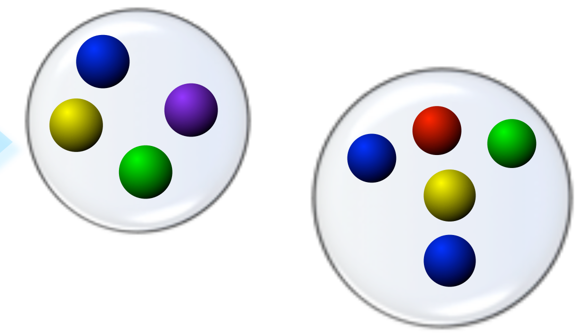


Scattering on the lattice

(1) large V

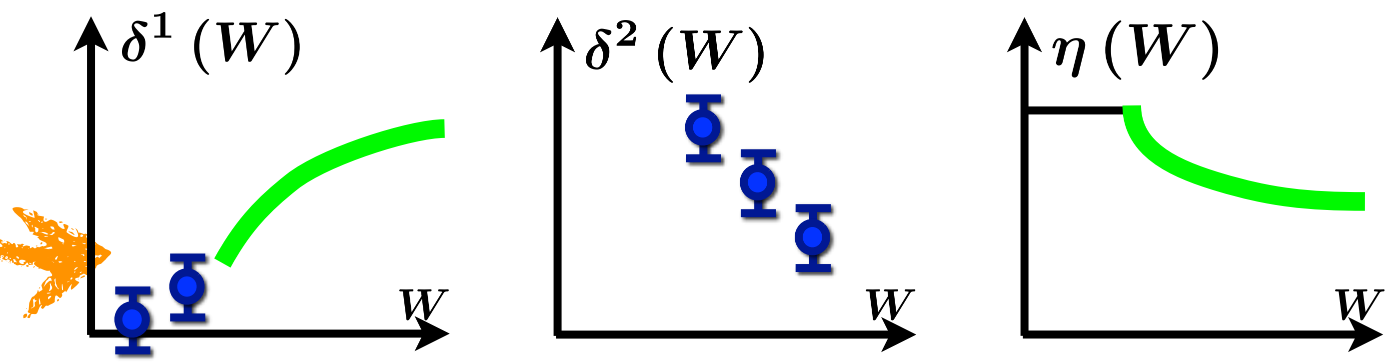
(2) coupled-channel

✓ X, Y, Z, P_c,...



★ coupled-channel scattering

$$\langle 0|\Phi(\tau)\Phi^\dagger(0)|0\rangle = \sum_n A_n e^{-W_n \tau}$$



➡ coupled-channel Lüscher's formula

e.g., 2-channel : $\delta^1(W)$, $\delta^2(W)$, $\eta(W)$ --> find $W(L_1)=W(L_2)=W(L_3)$

➡ assumptions about interaction or K-matrices necessary...

★ indicate more information mandatory to solve coupled-channel scatterings

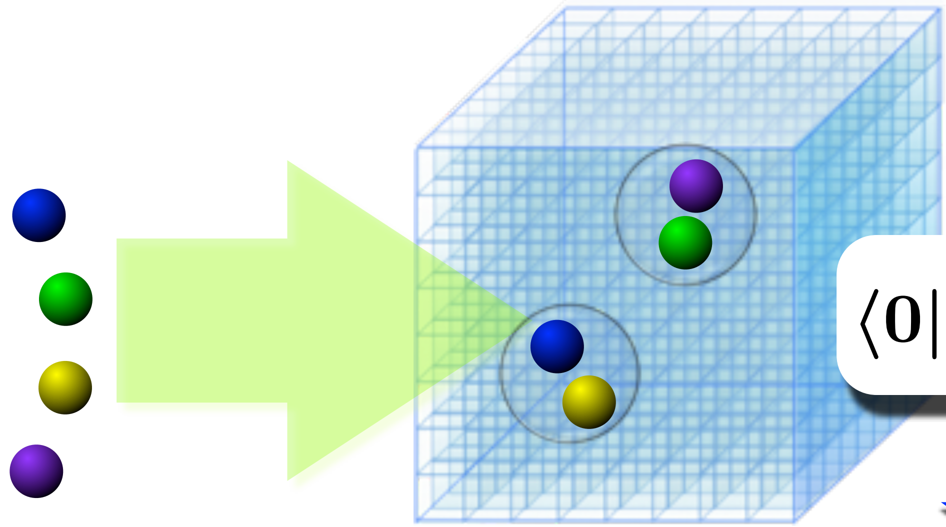
➡ What can we measure in addition to temporal correlations?

HAL QCD “potential” approach

✦ HAL QCD approach: derive energy-independent interaction kernel

➡ measure spatial correlation as well as temporal correlation

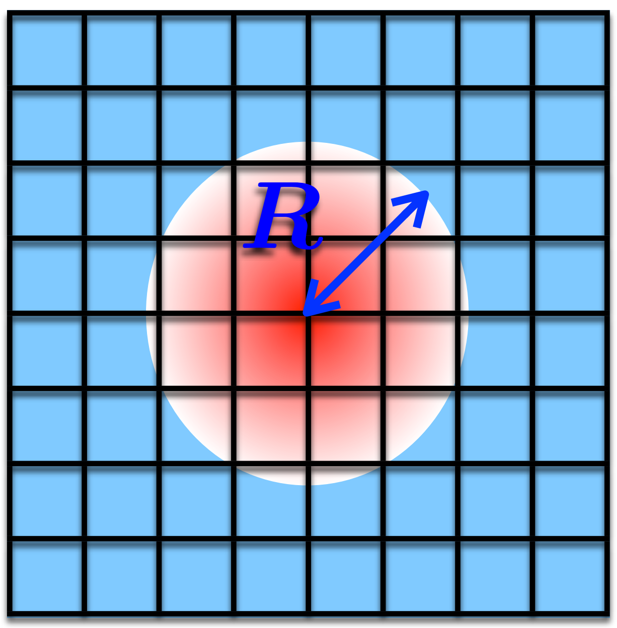
Ishii, Aoki, Hatsuda, PRL99, 02201 (2007).
Aoki, Hatsuda, Ishii, PTP123, 89 (2010).
Ishii et al,(HAL QCD), PLB712, 437(2012).



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

★ Nambu-Bethe-Salpeter wave functions: $\psi_n(r)$

➡ Equal-time choice of NBS amplitudes



✓ NBS wave functions satisfy Helmholtz equation outside interactions (phase shift --> S-matrix)

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

➡ Nonrelativistic approx. is NOT required

HAL QCD "potential" approach

✦ HAL QCD approach: derive energy-independent interaction kernel

➡ measure spatial correlation as well as temporal correlation

Ishii, Aoki, Hatsuda, PRL99, 02201 (2007).
Aoki, Hatsuda, Ishii, PTP123, 89 (2010).
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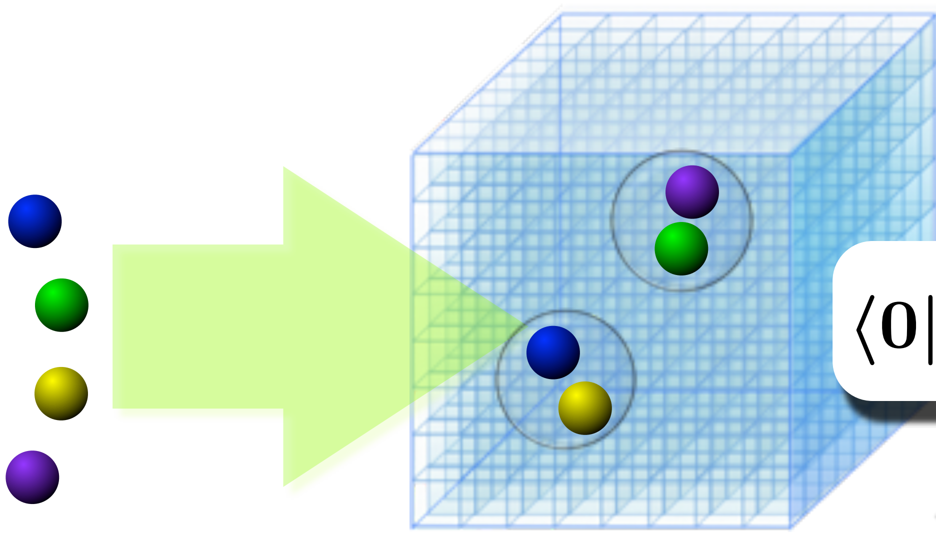
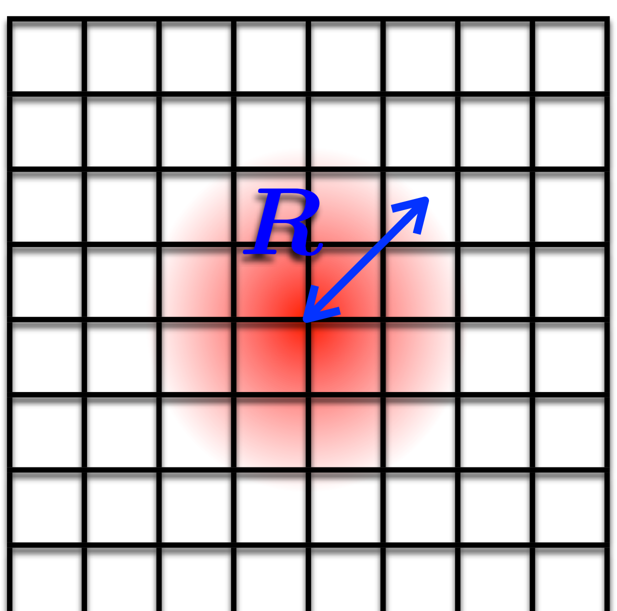


$$\langle 0|\phi_1(\vec{x}+\vec{r},\tau)\phi_2(\vec{x},\tau)|W_n\rangle = \sqrt{Z_1 Z_2}\,\psi_n(\vec{r})\,e^{-W_n\tau}$$

★ Nambu-Bethe-Salpeter wave functions: $\psi_n(r)$

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

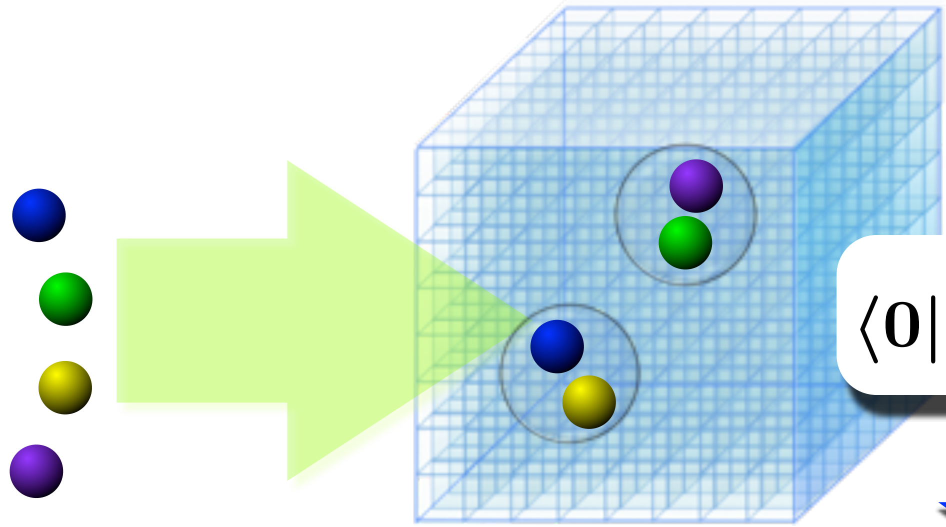


- U(r,r') is energy-independent (until new threshold opens)
- U(r,r') contains all 2PI contributions
- U(r,r') is NOT an observables (faithful to S-matrix)

Coupled-channel HAL QCD approach

✦ HAL QCD approach: derive energy-independent interaction kernel

➡ measure spatial correlation as well as temporal correlation



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

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

★ NBS wave functions for each channel: $\psi^a_n(r)$

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

✓ derivative expansion:

$$U(\vec{r},\vec{r}') = \{V_{\rm LO}(\vec{r}) + \mathcal{O}(\nabla)\}\,\delta(\vec{r}-\vec{r}')$$

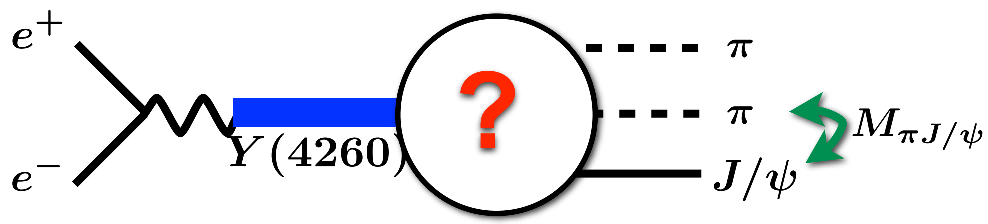
This work: extract effective LO potential

$$\left(\nabla^2 + (\vec{k}_n^a)^2\right)\psi_n^a(\vec{r}) = 2\mu^a \sum_b V_{\rm LO}^{ab}(\vec{r})\psi_n^b(\vec{r})$$

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

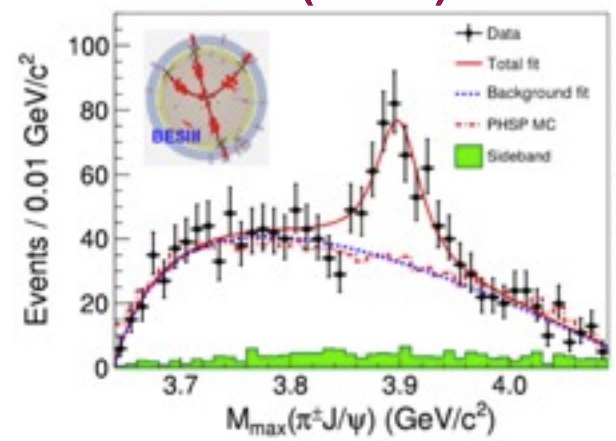
Targets: charm tetraquark & charm nuclei

✓ Tetraquark candidate $Z_c(3900)$

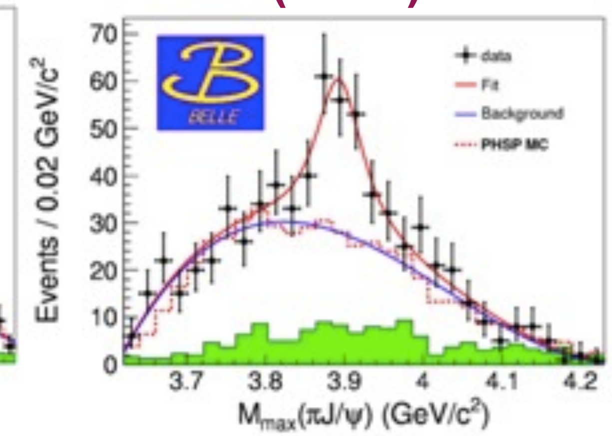


- $Z_c(3900)$ found in $\pi^{+/-}J/\psi$ ($c c^{bar} u d^{bar}$)

BESIII (2013)

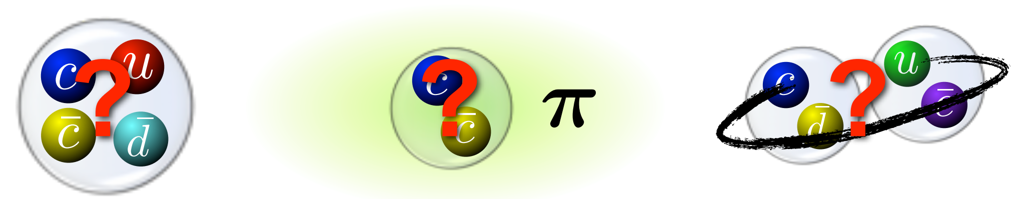


Belle (2013)



structure of $Z_c(3900)$

- tetraquark?, hadro-charmonium?, $D^{bar}D^*$ molecule?
- threshold kinematical effect?

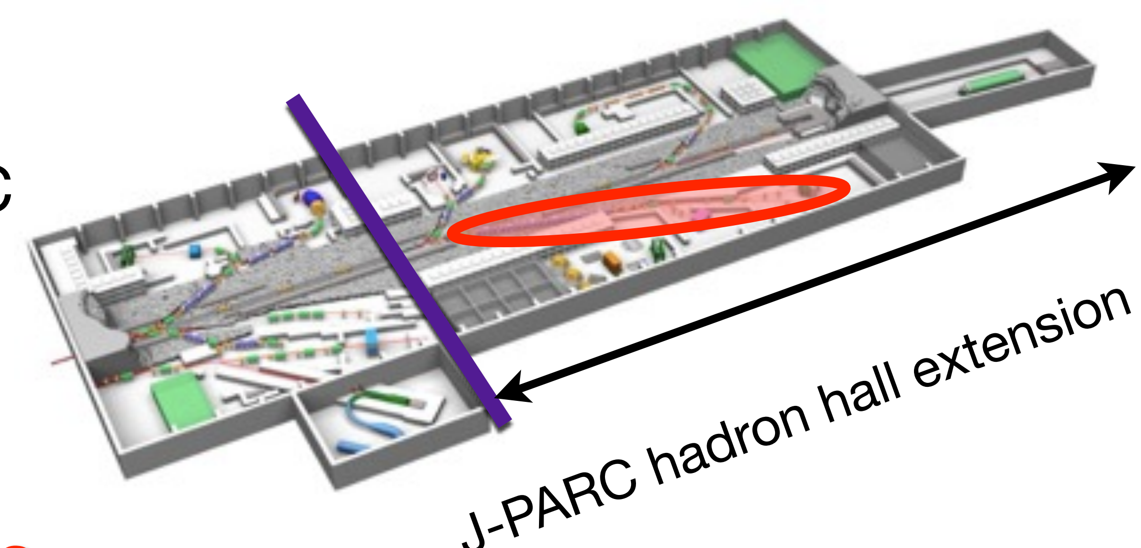


$Z_c(3900)$ in s-wave $\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$ coupled-channel system

✓ D^{bar} & Λ_c nuclei

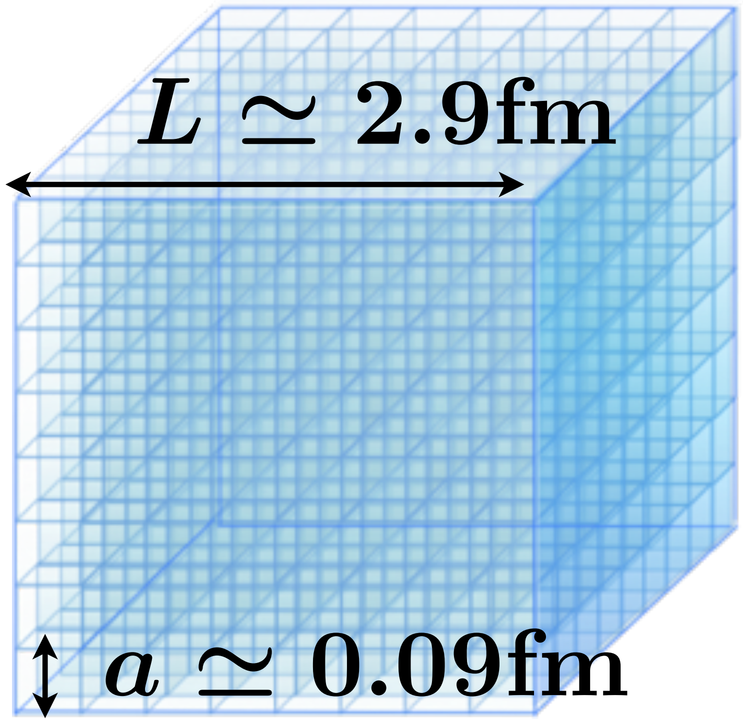
- Charm nuclei will be produced @K10, J-PARC
  - What are possible structures?

    see e.g., Yasui, Sudoh, Yamaguchi, Hyodo, Hosaka, arXiv:1606.08685 (2016).



s-wave $D^{bar}N$ & $\Lambda_c N$ interactions

Lattice QCD setup



★ **N_f=2+1 full QCD**

PACS-CS Coll., S. Aoki et al., PRD79, 034503, (2009).

- Iwasaki gauge & O(a)-improved Wilson quark actions
- a=0.0907(13) fm --> L~2.9 fm (32^3 x 64)

★ **Relativistic Heavy Quark action for charm**

S. Aoki et al., PTP109, 383 (2003).
Y. Namekawa et al., PRD84, 074505 (2011).

- 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 %)

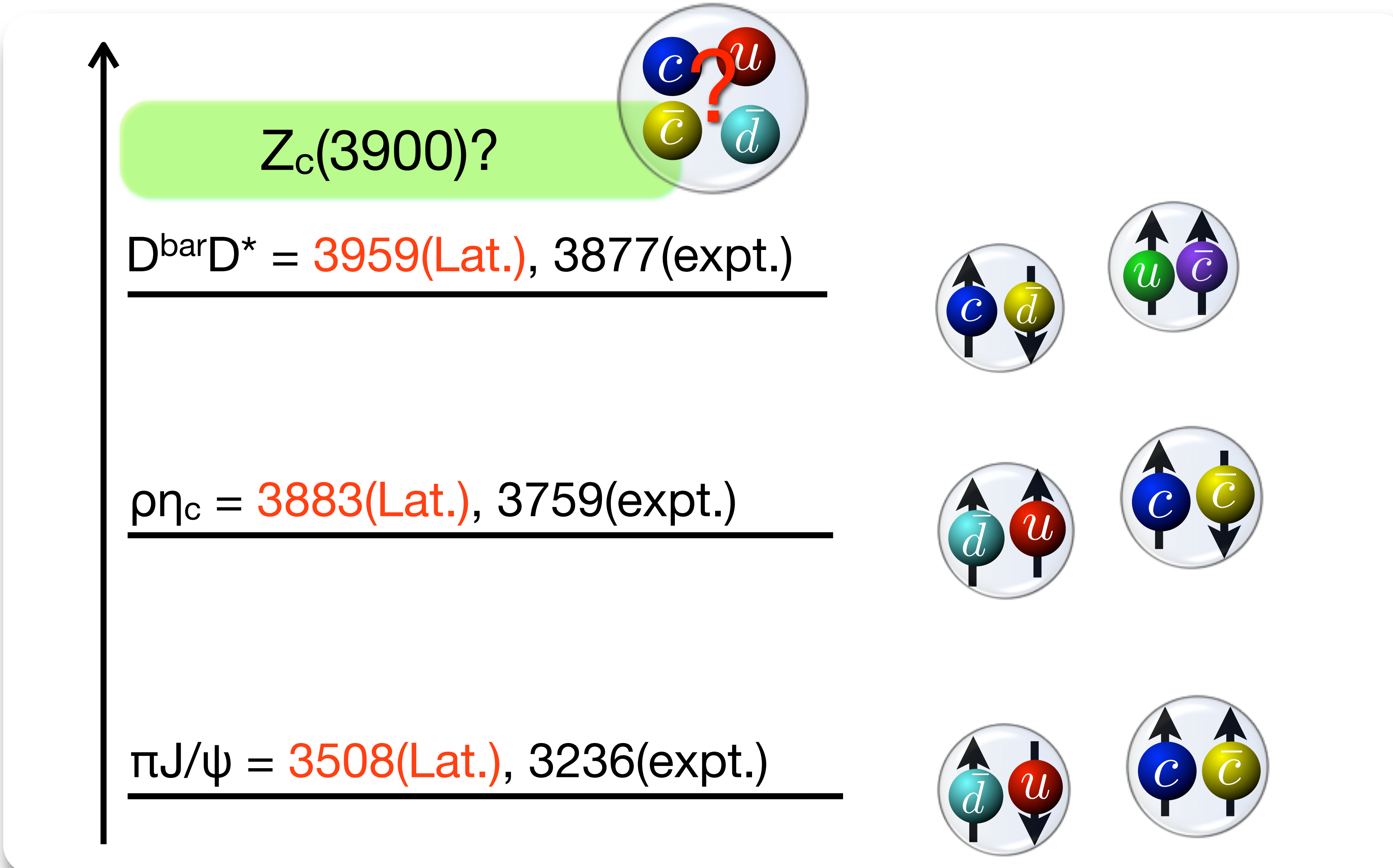
- three sets of full QCD gauge configs. used (m_π~410-700MeV)

light hadron mass (MeV)			
m_π=	411	572	701
m_K=	635	714	787
m_ρ=	896	1000	1097
m_N=	1215	1411	1583

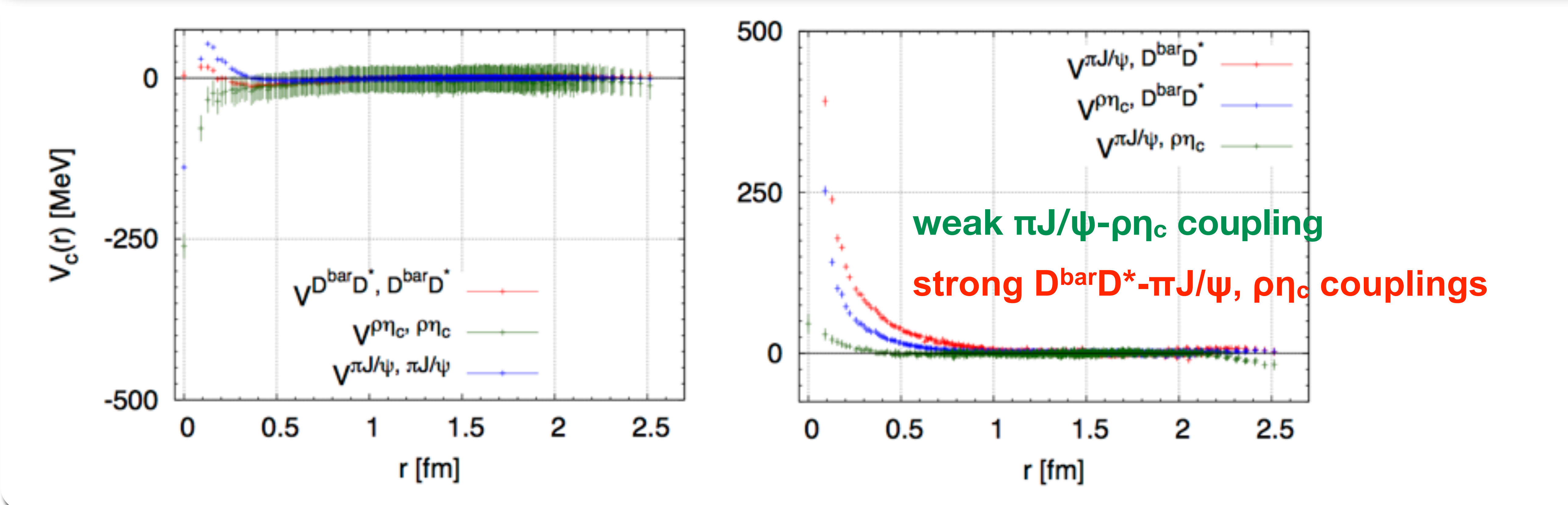
Charmed meson mass (MeV)			
$m_{\eta c}$=	2988	3005	3024
$m_{J/\psi}$=	3097	3118	3143
m_D=	1903	1947	2000
m_{D^*}=	2056	2101	2159
$m_{\Lambda c}$=	2434	2584	2710

Structure of $Z_c(3900)$

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



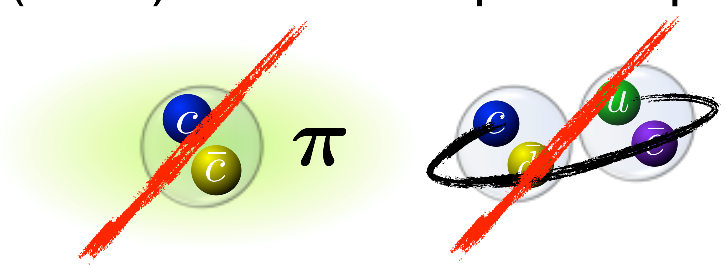
S-wave πJ/ψ - ρη$_c$ - D^{bar}D* potential @m$_\pi$=410MeV



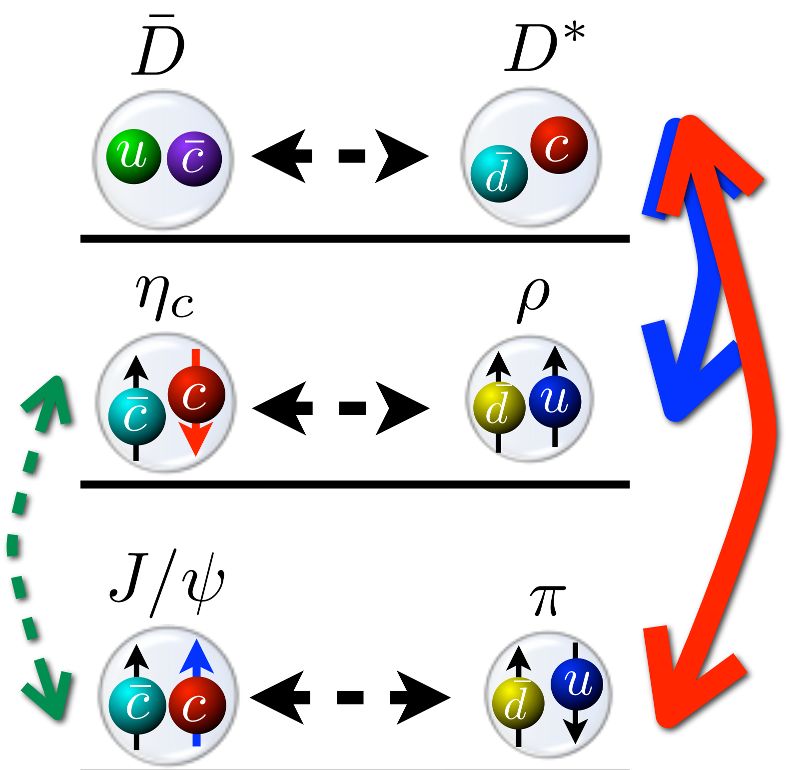
Y. Ikeda (HAL QCD), arXiv.1602.03465(hep-lat).

★ **weak diagonal potentials:**

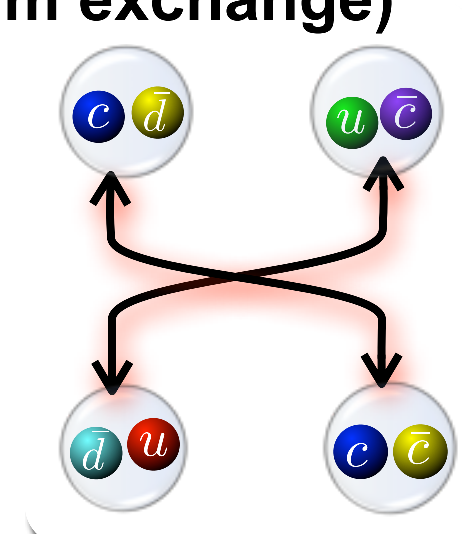
Z$_c$(3900) is NOT simple πJ/ψ & D^{bar}D*



✦ **heavy quark spin symmetry**



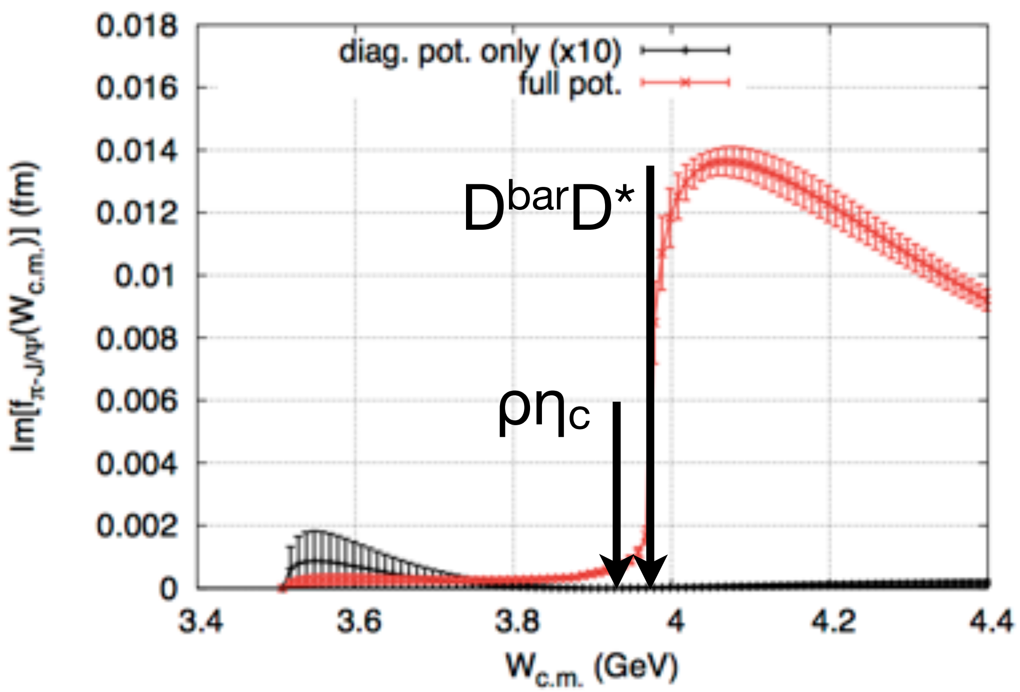
✦ **strong couplings (charm exchange)**



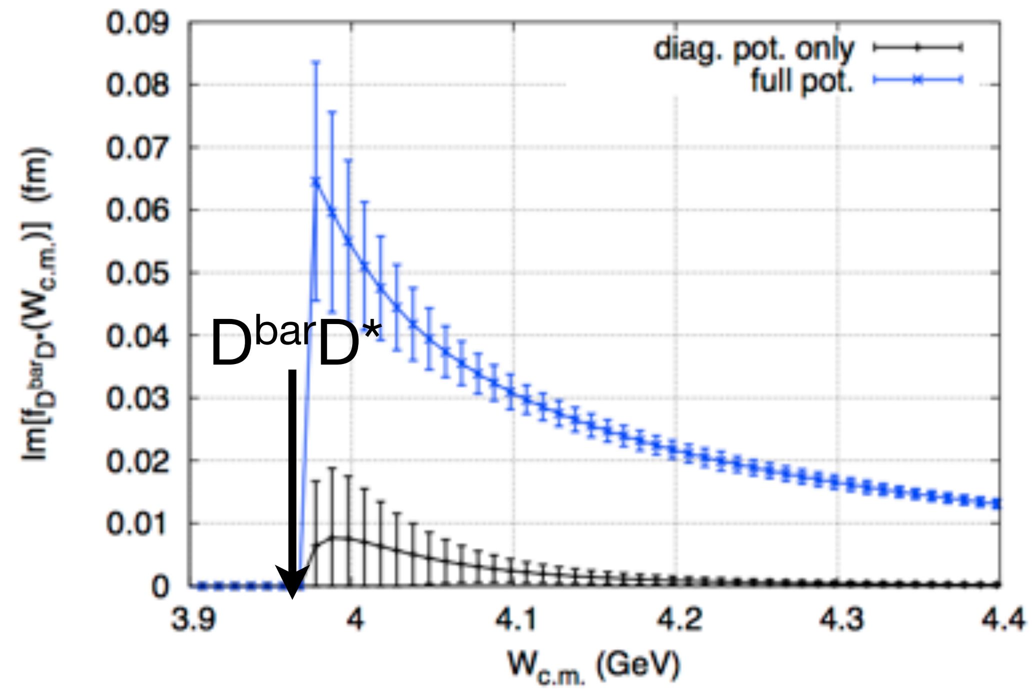
Invariant mass spectra of πJ/ψ & $D^{bar}D^*$

★ **2-body scattering (ideal setting to understand Z_c(3900) structure)**

- πJ/ψ invariant mass



- $D^{bar}D^*$ invariant mass



$$\frac{\Gamma(Zc(3900)\to \bar{D}D^*)}{\Gamma(Zc(3900)\to \pi J/\psi)} = 6.2(1.1)(2.7)$$

BESIII Coll., PRL112 (2014).

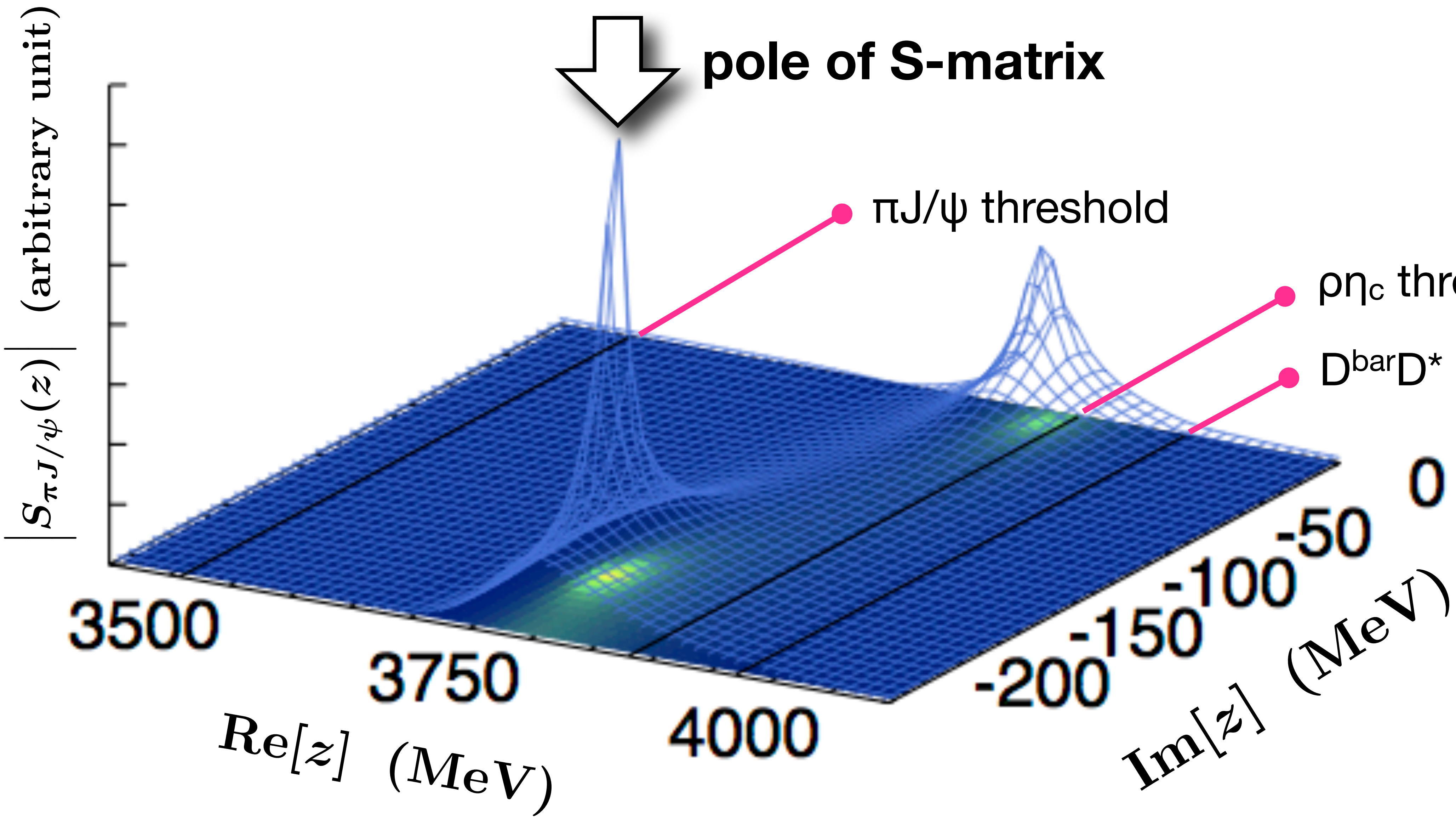
✓ Enhancement near $D^{bar}D^*$ threshold due to strong $V^{\pi J/\psi,\, DbarD^*}$

- Peak in πJ/ψ (not Breit-Wigner line shape)
- Threshold enhancement in $D^{bar}D^*$

✓ Is Z_c(3900) a conventional resonance? --> pole positions

Complex pole position ($\pi J/\psi$:2nd, $\rho\eta_c$:2nd, $D^{bar}D^*$:2nd)

✤ analytic continuation of S-matrix onto complex energy plane



- "Virtual" pole on [2nd, 2nd, 2nd] sheet is found (far from $D^{bar}D^*$ threshold)
- $Z_c(3900)$ is not a conventional resonance
- How large does the pole contribute to the amplitude?

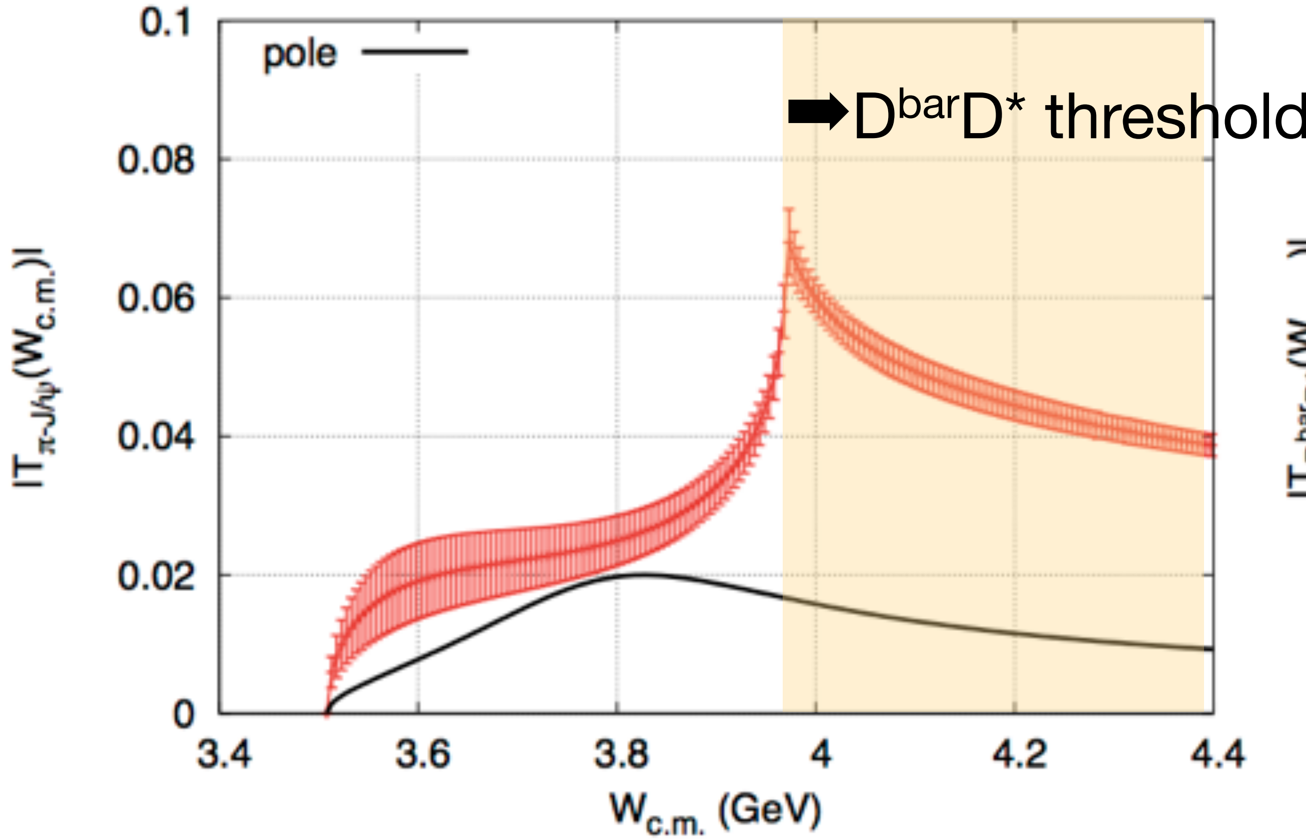
Y. Ikeda [HAL QCD], arXiv.1602.03465 [hep-lat] (2016).

T-matrix of πJ/ψ & $D^{bar}D^*$

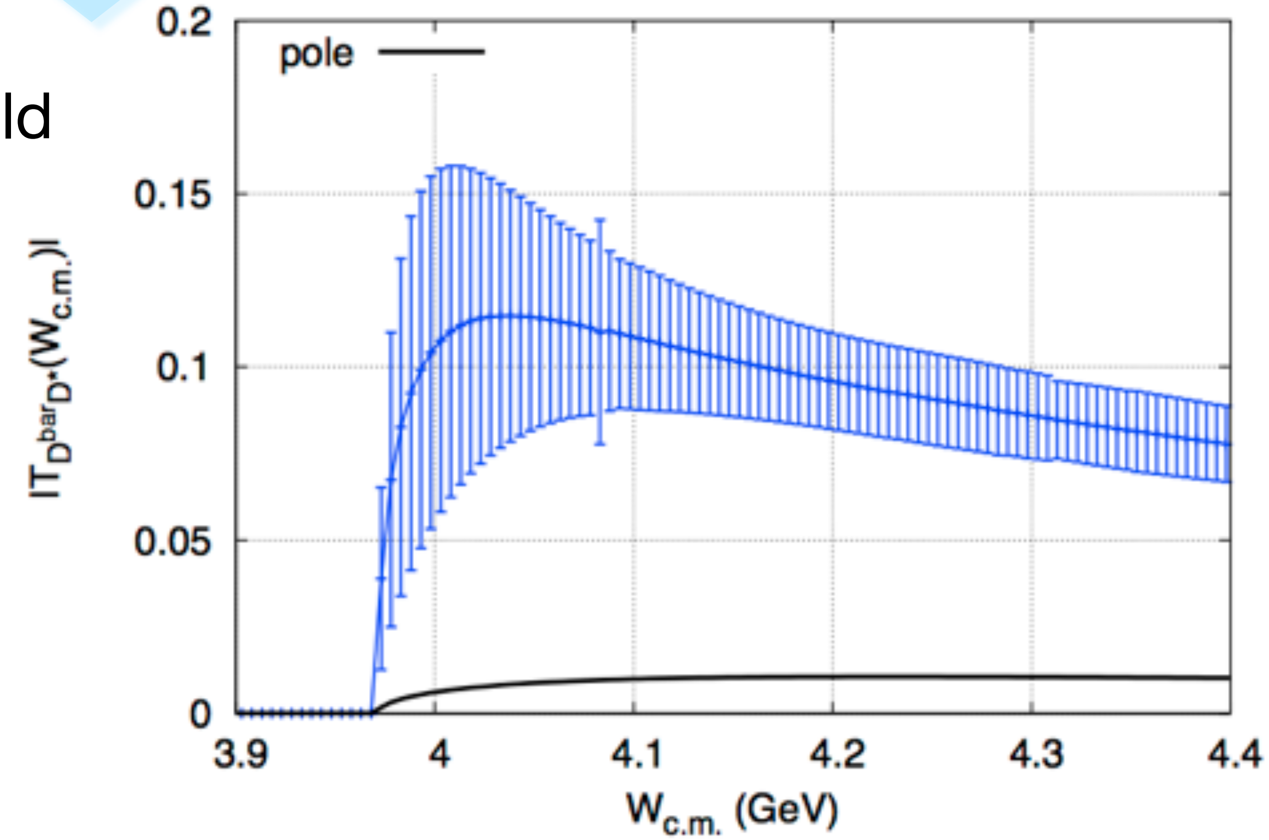
- calculate residues of T-matrices in πJ/ψ & $D^{bar}D^*$ channels

$$S(k) = 1 + 2iT(k)$$

- πJ/ψ-πJ/ψ T-matrix



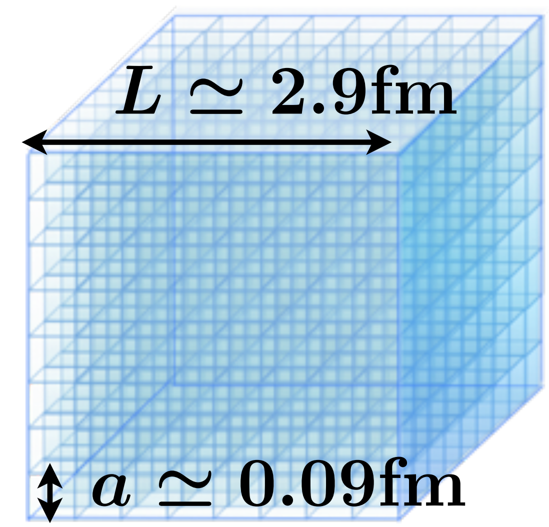
- $D^{bar}D^*$-$D^{bar}D^*$ T-matrix



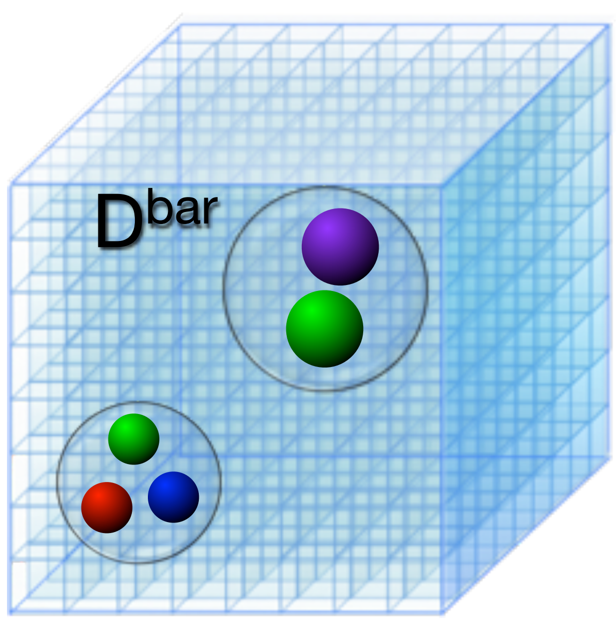
- contribution from virtual pole to T-matrix is small
- Z_c(3900) is cusp at $D^{bar}D^*$ threshold induced by off-diagonal $V^{\pi\psi,\, DbarD^*}$

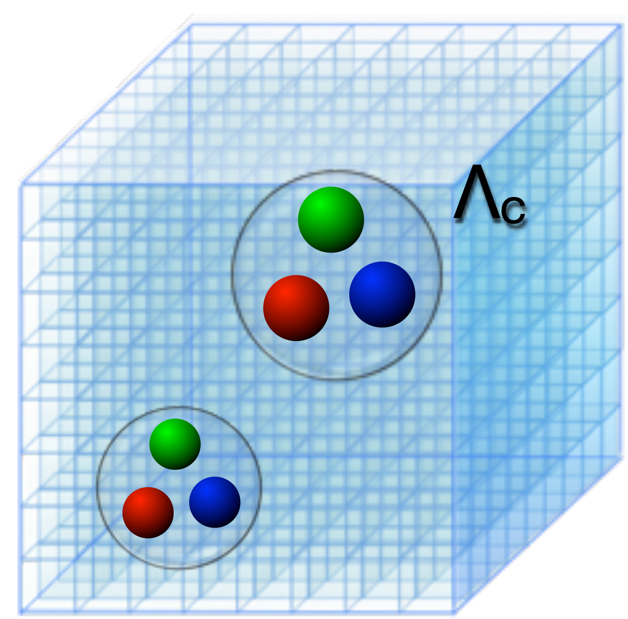
S-wave $D^{bar}N$ & $\Lambda_c N$ interactions
-- implications to D^{bar} & Λ_c nuclei --

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

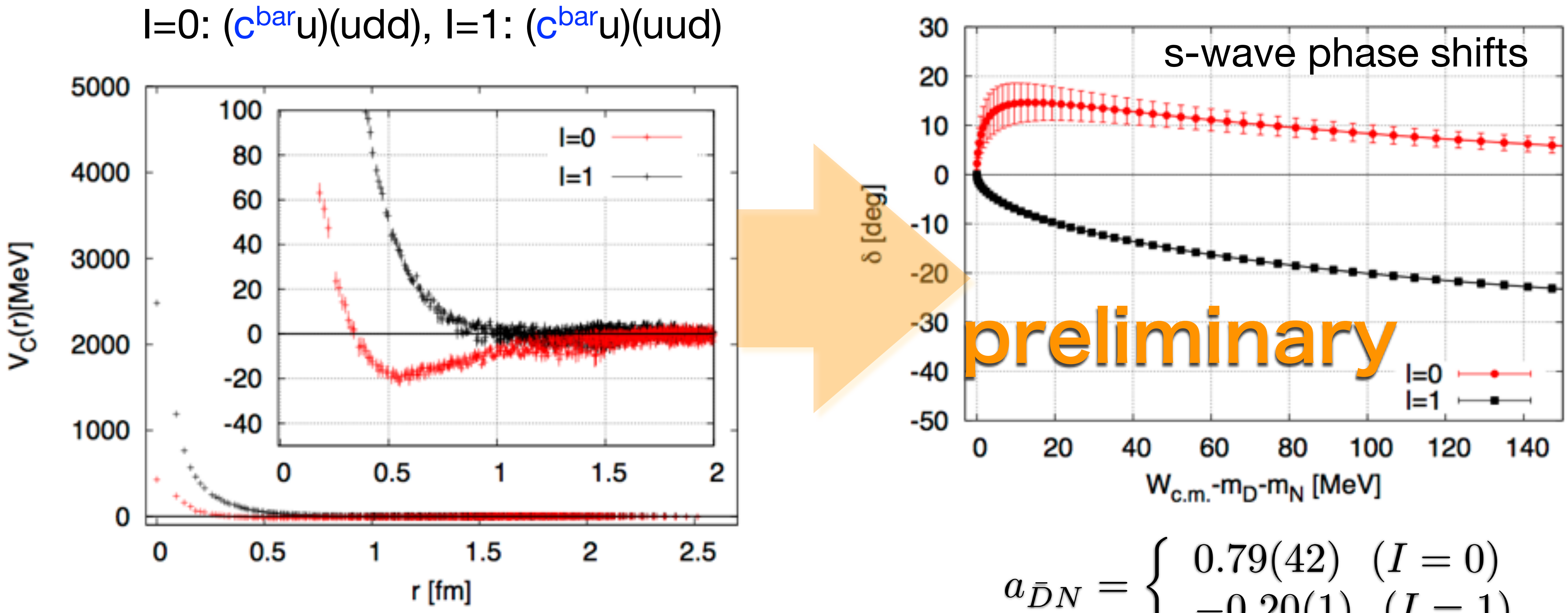


m_π= 411, 572, 701
m_N= 1215, 1411, 1583
m_D= 1903, 1947, 2000
$m_{\Lambda c}$= 2434, 2584, 2710





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



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

Y. Ikeda [HAL QCD], in preparation

$D^{bar}N$ potentials

(I=0) short-range repulsion + mid-range attractions, net attraction

(I=1) short-range repulsion, weak repulsion

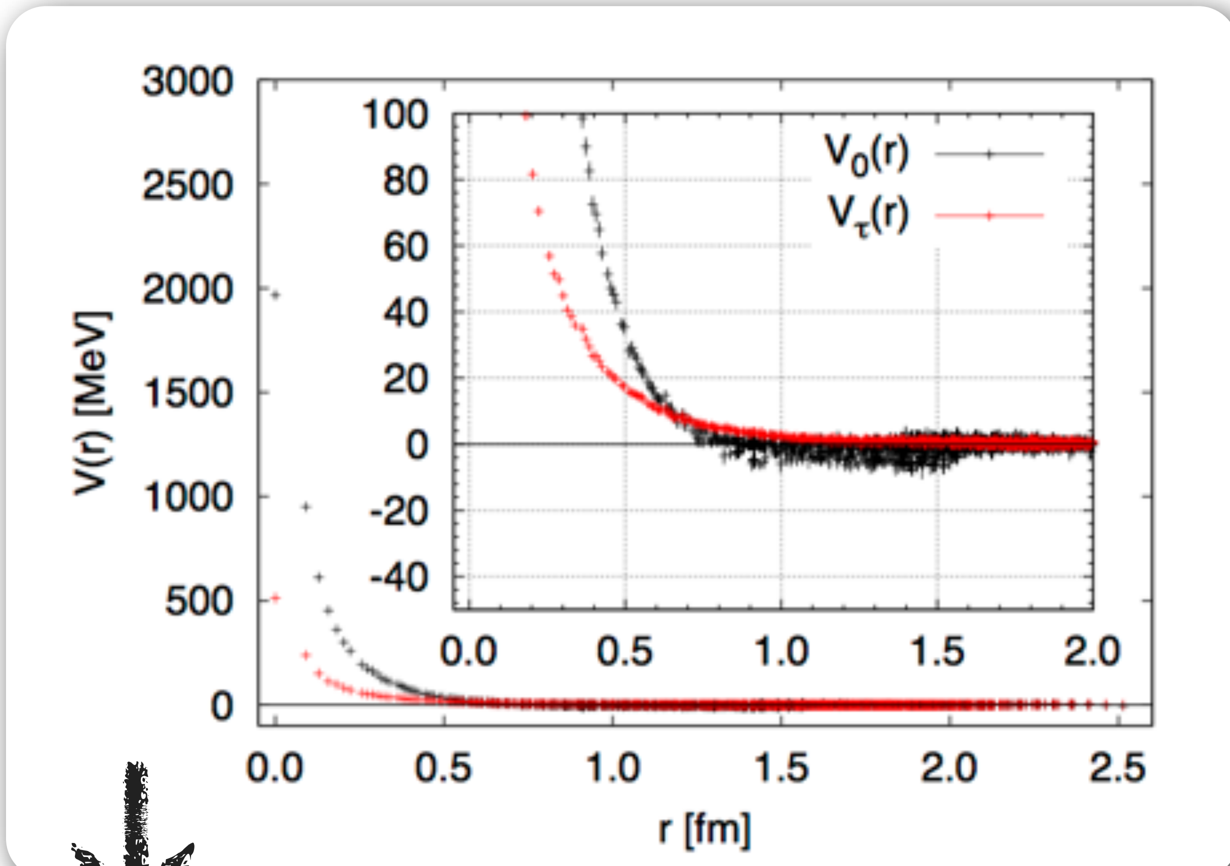
Pauli-blocking at work in meson-baryon system

Machida, Namiki, PTP33 (1965).

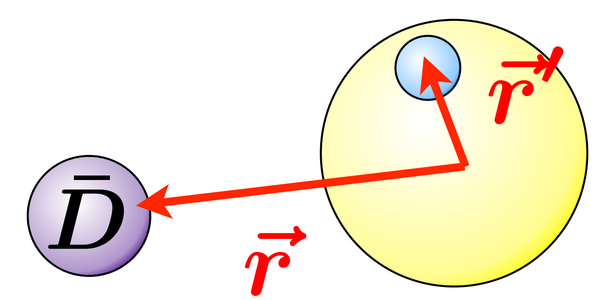
Isospin dependence of potentials

✓ decomposition of potentials -- input for nuclear calculations --

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



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



Dbar-nucleus folding potential

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

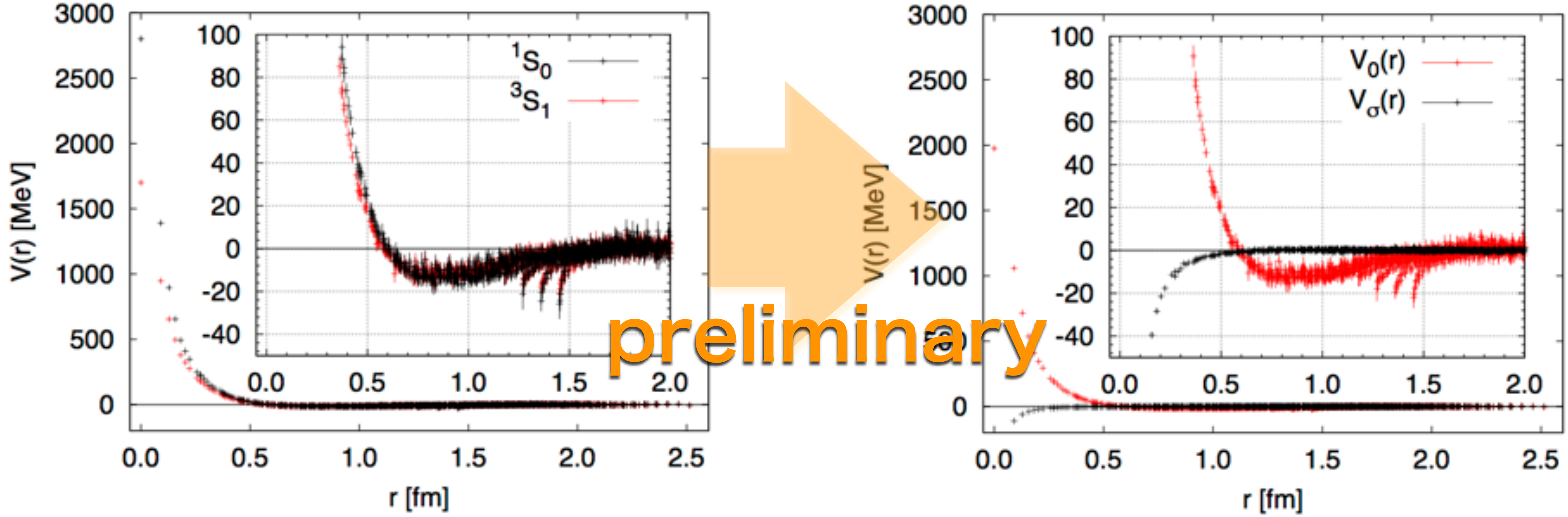
➡ **Dbar can be bound in neutron/proton rich nuclei**

AMD calc.: M. Isaka, YI, E. Hiyama, in progress

S-wave $\Lambda_c N$ potentials @m_π=410MeV

$^1S_0$ & $^3S_1$ channels

$$V_{\Lambda_c N}(\vec{r}) = V_0(\vec{r}) + V_\sigma(\vec{r})(\vec{\sigma}_{\Lambda_c} \cdot \vec{\sigma}_N)$$



$$a_{\Lambda_c N} = \begin{cases} 0.29(16) & (^1S_0) \\ 0.28(13) & (^3S_1) \end{cases}$$

- V_0(r) is attractive, V_σ(r) is very small

<u>Λ_cN potentials in $^1S_0$ & $^3S_1$ channels</u>

(1) weak net attractions in both $^1S_0$ and $^3S_1$ channels

(2) weak spin dependence --> HQ spin symmetry at work

(3) Λ_c can be bound in heavy nuclei

<u>T. Miyamoto [HAL QCD], arXiv:1602.07797. + in preparation</u>

Summary

✦ **HAL QCD approach** for coupled-channel hadron interactions

- energy-independent “potentials” from equal-time NBS wave functions
- a solution of multi-hadron problems (large V, coupled-channel)

✤ Charmed tetraquark candidate $Z_c(3900)$ in $J^P=1^+$ channel

- $Z_c(3900)$ is threshold cusp induced by strong $V^{\bar{D}D^* - \pi J/\psi}$

✤ D^{bar} nuclei

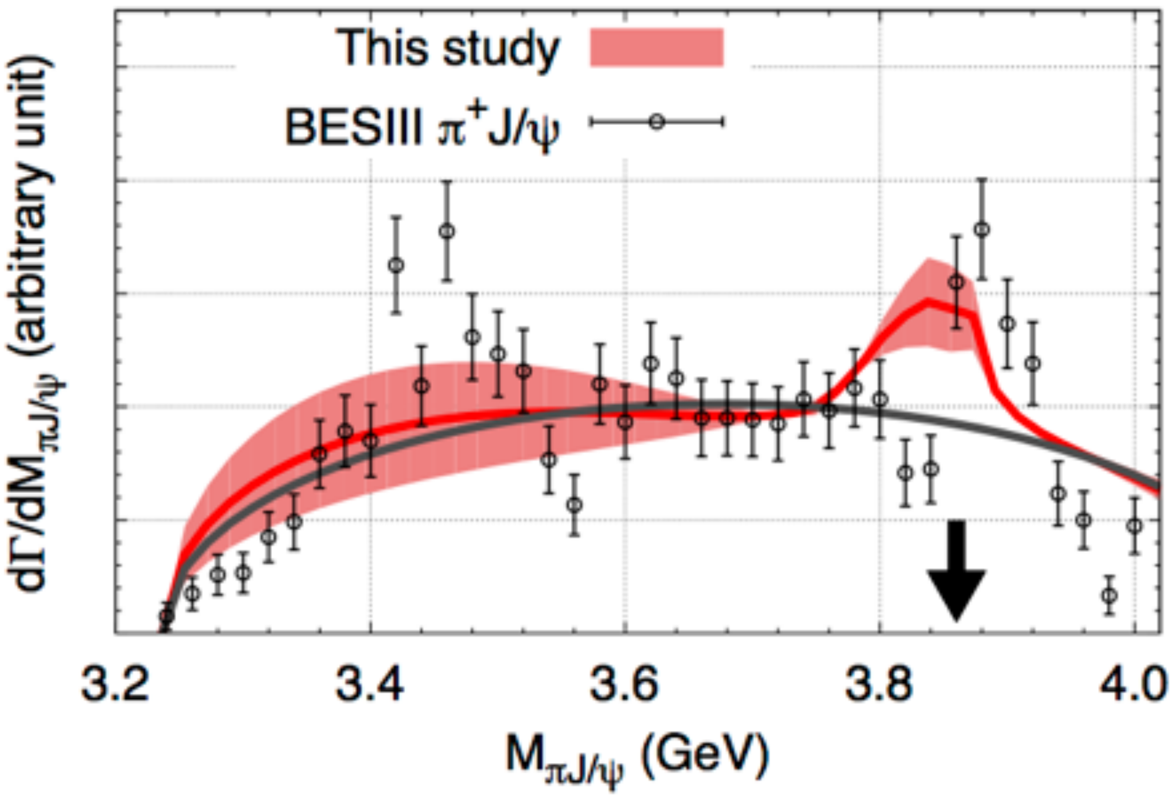
- Isospin dependent interaction plays important role (neutron/proton rich favored)

✤ Λ_c nuclei

- Spin independent interaction is weak net attraction (heavy nuclei favored)

✦ Prospects : physical point simulation is next step

Mass spectra (πJ/ψ & $D^{bar}D^*$)



parameters: $C_{\pi D^{bar}D^*}/C_{\pi\pi J/\psi} = Re^{i\theta}$

--> R=0.95(18), θ=-58(44) deg. (+overall factor)

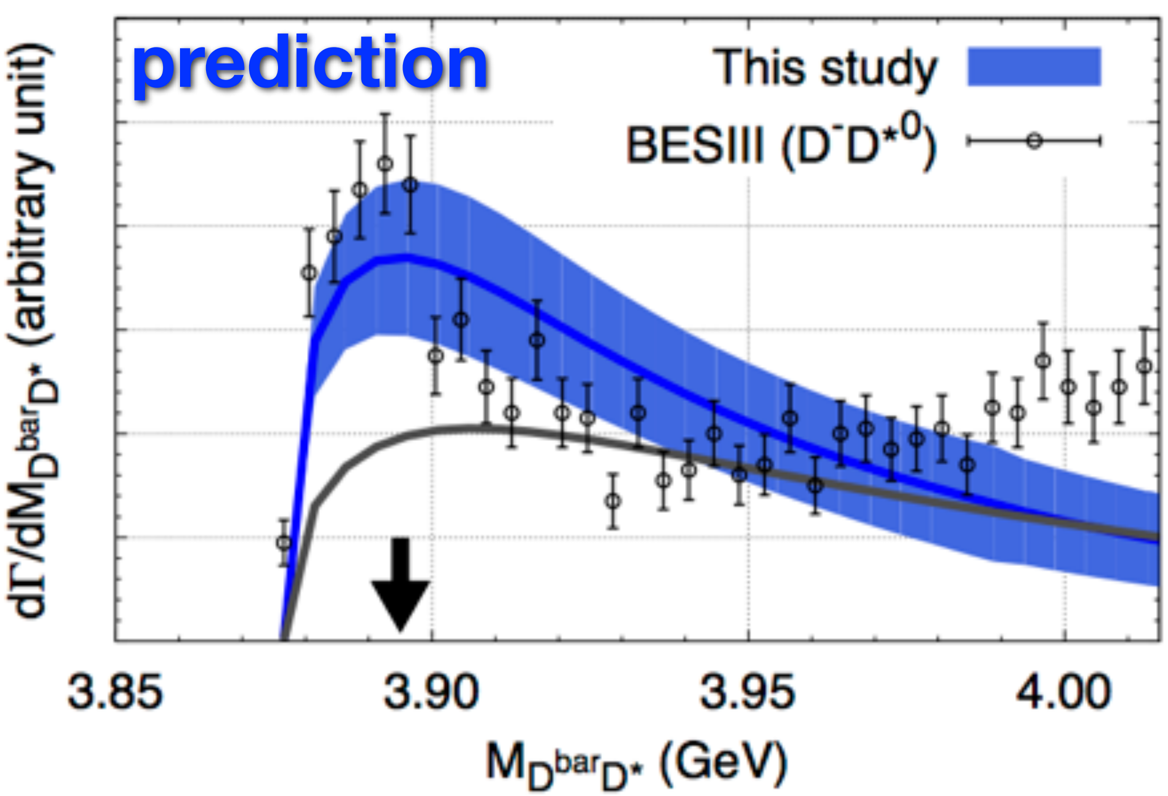
★ Z_c(3900) production rate in expt.

$$21.5 \pm 3.3\% \text{ (BESIII)}$$

$$29.0 \pm 8.9\% \text{ (Belle)}$$

★ Calculation w/ LQCD potential

$$32 \pm 1\%$$



★ Good agreement around 3.9 GeV

- Deviation from expt. data at high energies
  - explicit $D^{bar*}D^*$ channel coupling?
  - higher partial wave?