$Z_c(3900)$ from lattice QCD

based on Y. Ikeda et al., (HAL QCD), arXiv.1602.03465(hep-lat).

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HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)

S. Aoki, D. Kawai, T. Miyamoto, K. Sasaki (YITP, Kyoto Univ.)

T. Doi, T. Hatsuda, T. Iritani (RIKEN)

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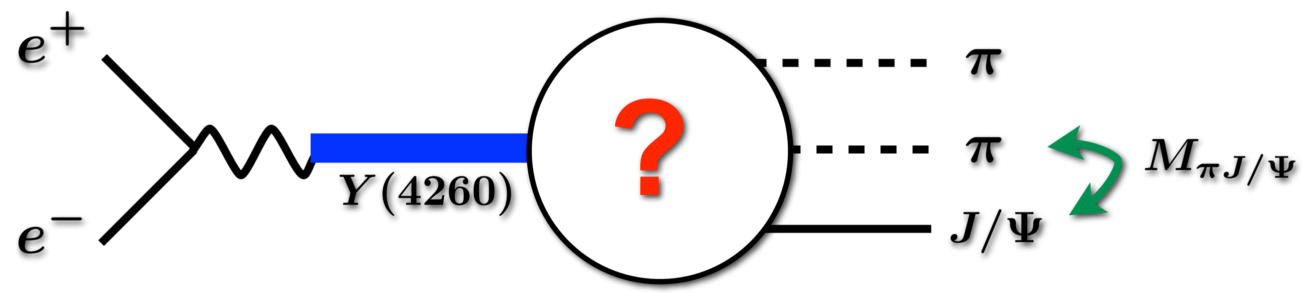
H. Nemura (Univ. Tsukuba)

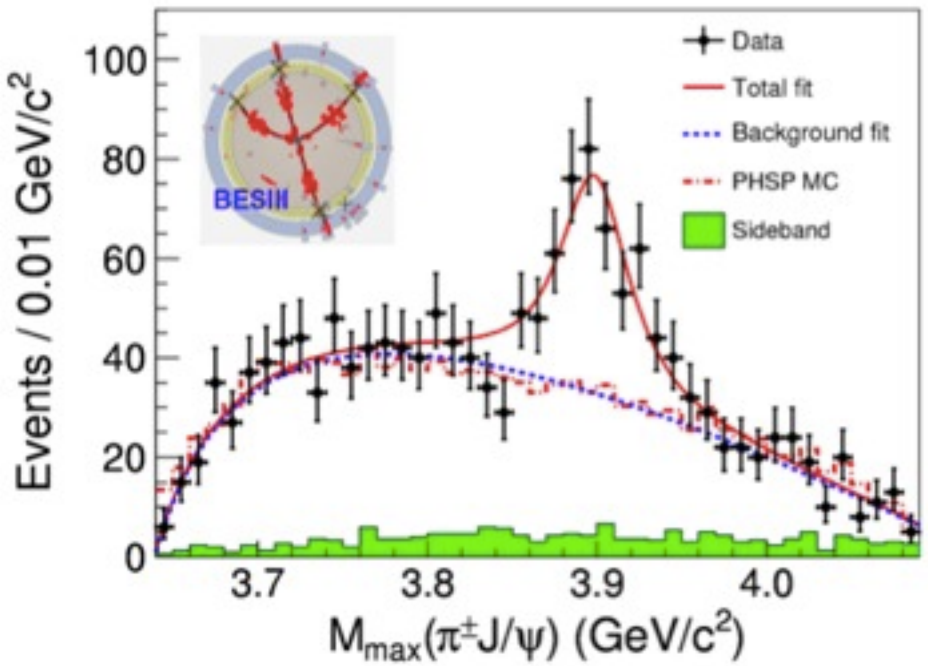
Intensive workshop in Realistic Hadron Interactions in QCD (RHIQCD2016)

@YITP, Kyoto (Nov. 28, 2016.)

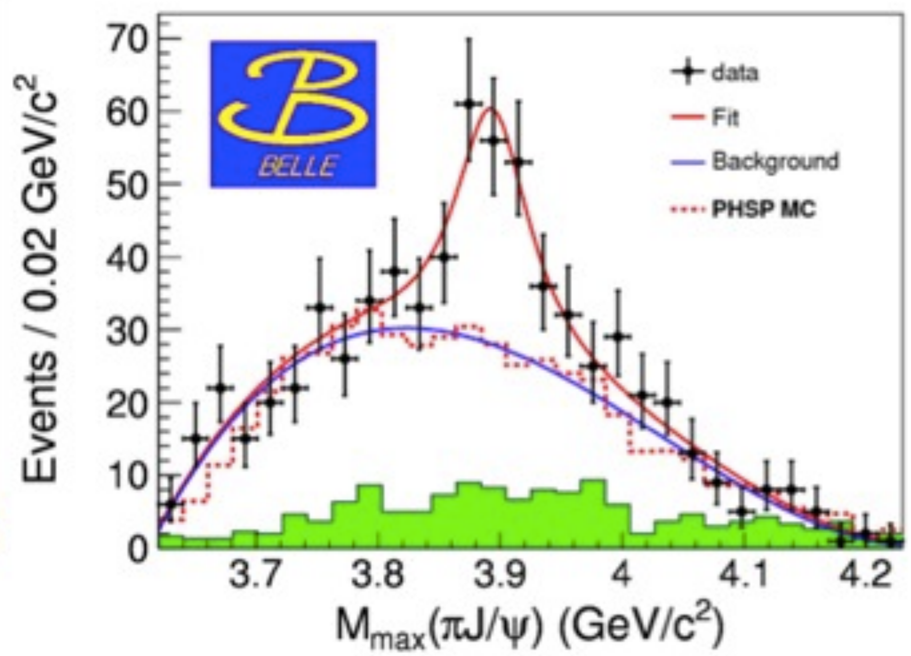
What is $Z_c(3900)$?



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



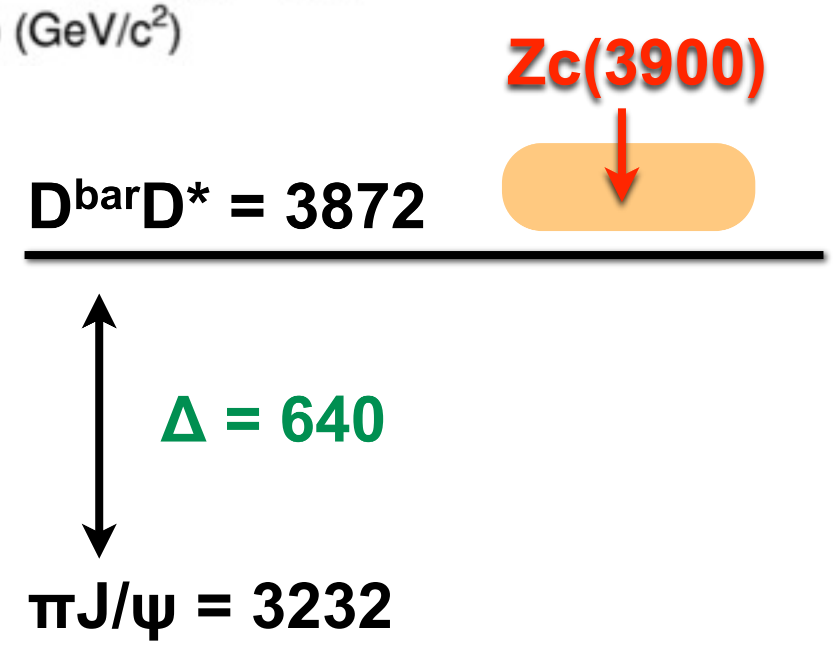
Belle Coll., PRL110, 252002, (2013).



- observed in $\pi^{\pm}J/\psi$ invariant mass spectra
- require 4 quarks ($cc^{bar}ud^{bar}$)
- $J^P = 1^+$ most probable --> couple to s-wave $D^{bar}D^*$?

  BESIII Coll., PRL112 (2014).
- peak confirmed by CLEO-c

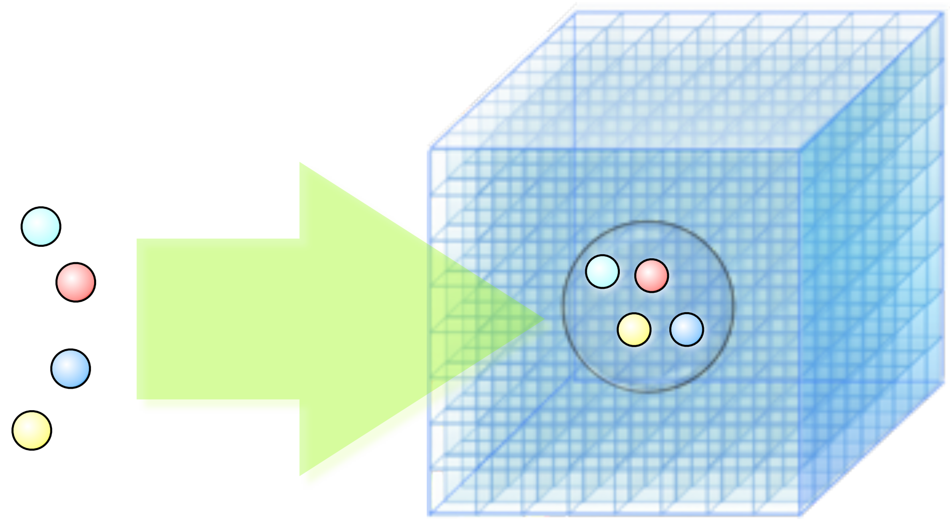
  Xiao et al., PLB727 (2013).



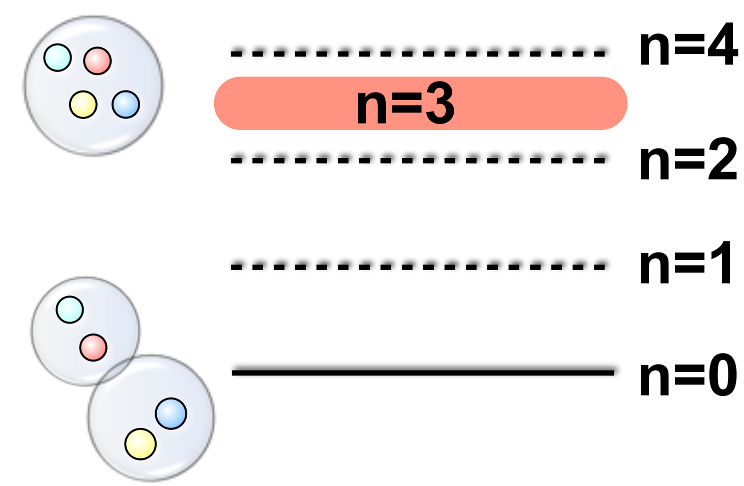
How to study $Z_c(3900)$ on the lattice?

✦ Conventional approach: LQCD spectrum

➡ identify all relevant $W_n(L)$ (n=0,1,2, ...) from temporal correlations



$$\langle 0|\Phi[c\bar{c}u\bar{d}](\tau)|W_n\rangle = e^{-W_n\tau}$$



✓ No positive evidence for Zc(3900) in $J^P=1^+$

S. Prelovsek et al., PLB 727, 172 (2013).
S.-H. Lee et al., PoS Lattice2014 (2014).
S. Prelovsek et al., PRD91, 014504 (2015).

★ Why is the peak observed in expt.?

- Broad resonance? Threshold effect?
- Key is S-matrix elements w/ coupled-channel

➡ Lüscher's finite size formula in coupled-channel system

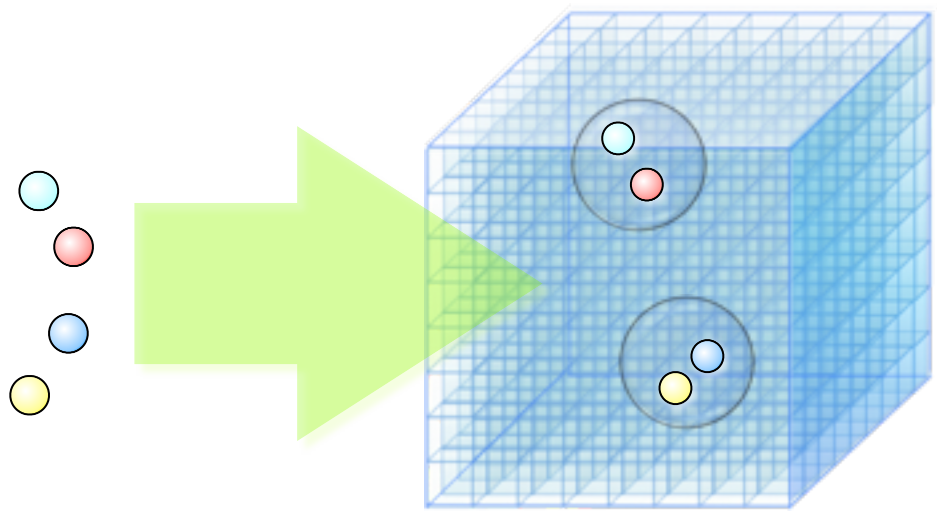
in practice, assumption about interaction kernels or K-matrices necessary

How to study $Z_c(3900)$ on the lattice?

✦ HAL QCD approach: energy-independent interaction kernel

➡ measure not only temporal but also spatial correlation

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



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

★ *NBS 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 and contains all 2PI contributions*

➡ **Extension to coupled-channel system is straightforward**

- measure wave functions in each channel (asymptotic states --> S-matrix)
- extract potential matrix faithful to S-matrix
- calculate observables (mass spectrum, pole position, ...)

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

Resonances from lattice QCD

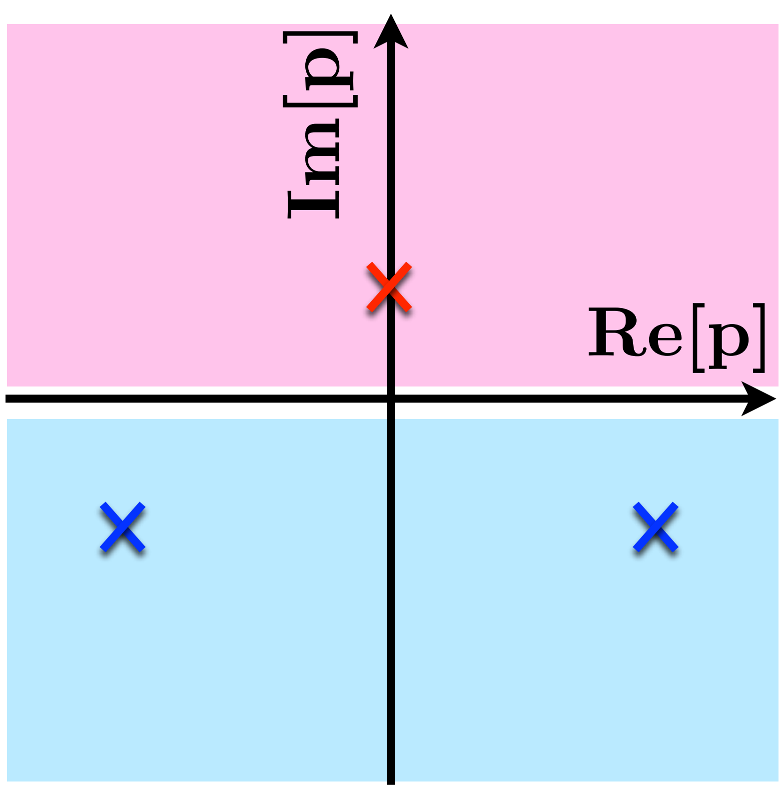
T-matrix in formal scattering theory (N/D method)

$$T^{-1}(\sqrt{s}) = V^{-1} + \frac{1}{2\pi}\int_{s_+}^{\infty} ds' \frac{\rho(s')}{s'-s}$$

Interaction part is not determined within scattering theory

➡ **interactions faithful to S-matrix in QCD**

Analyticity of T-matrix is uniquely determined



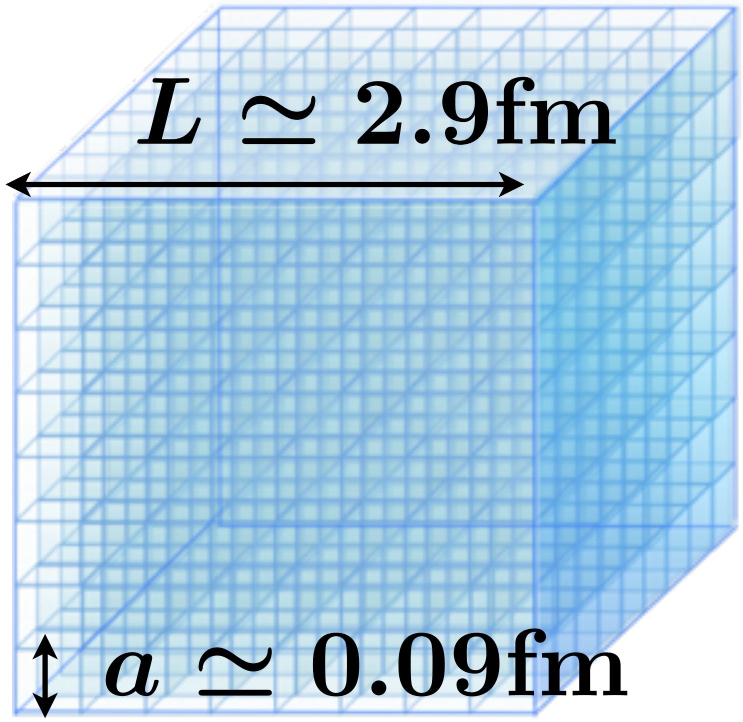
Bound states (physical sheet, 1st)

- binding energy --> T-matrix pole position
- coupling --> residue of pole

Resonance/virtual states (unphysical sheet, 2nd)

- Analytic continuation of T-matrix
- resonance energy --> T-matrix pole position
- coupling --> (complex) residue of pole?

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 $O((m_c a)^n)$, $O(\Lambda_{QCD} a)$, ...

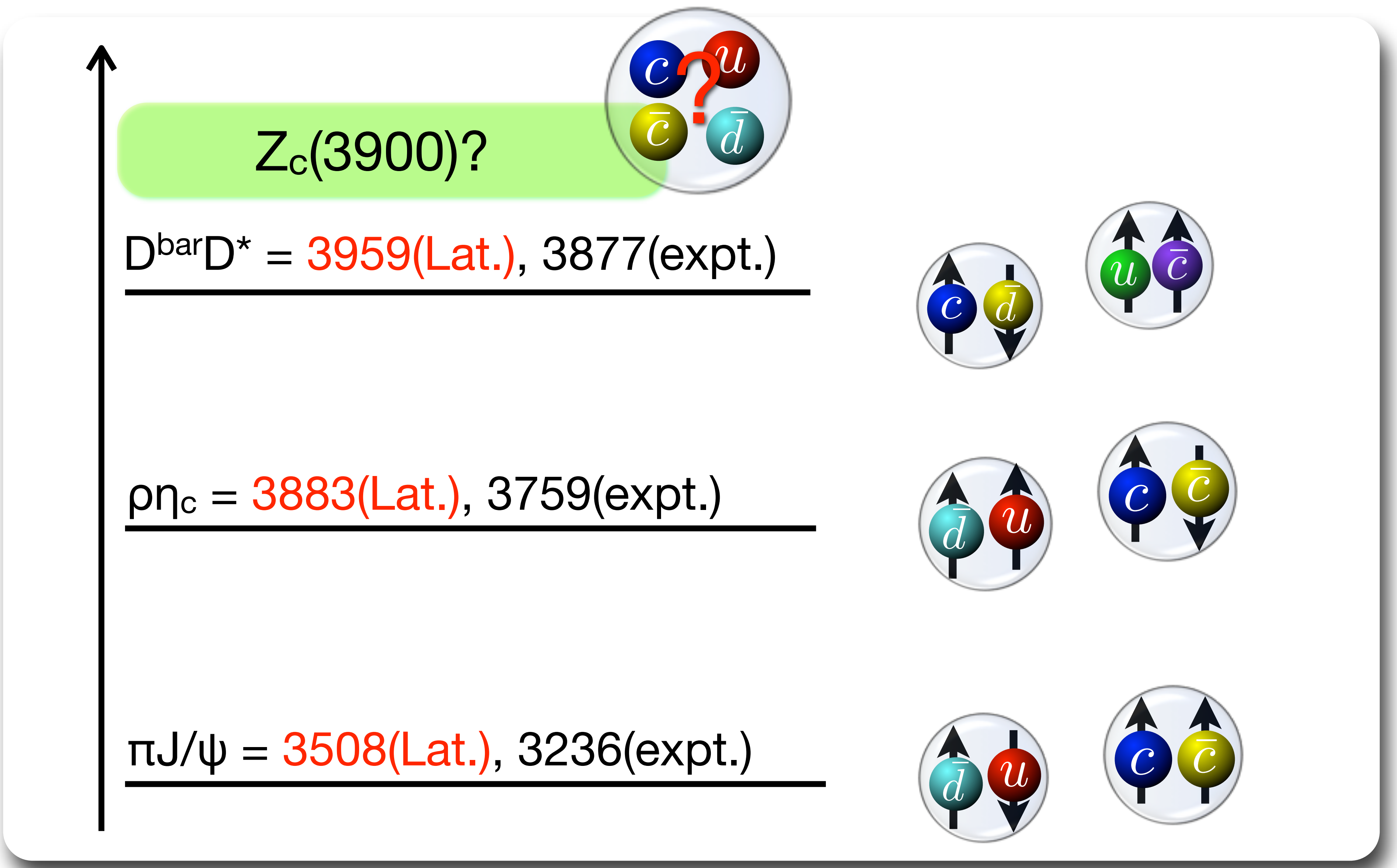
➡ We are left with $O((a\Lambda_{QCD})^2)$ syst. error (~ a few %)

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

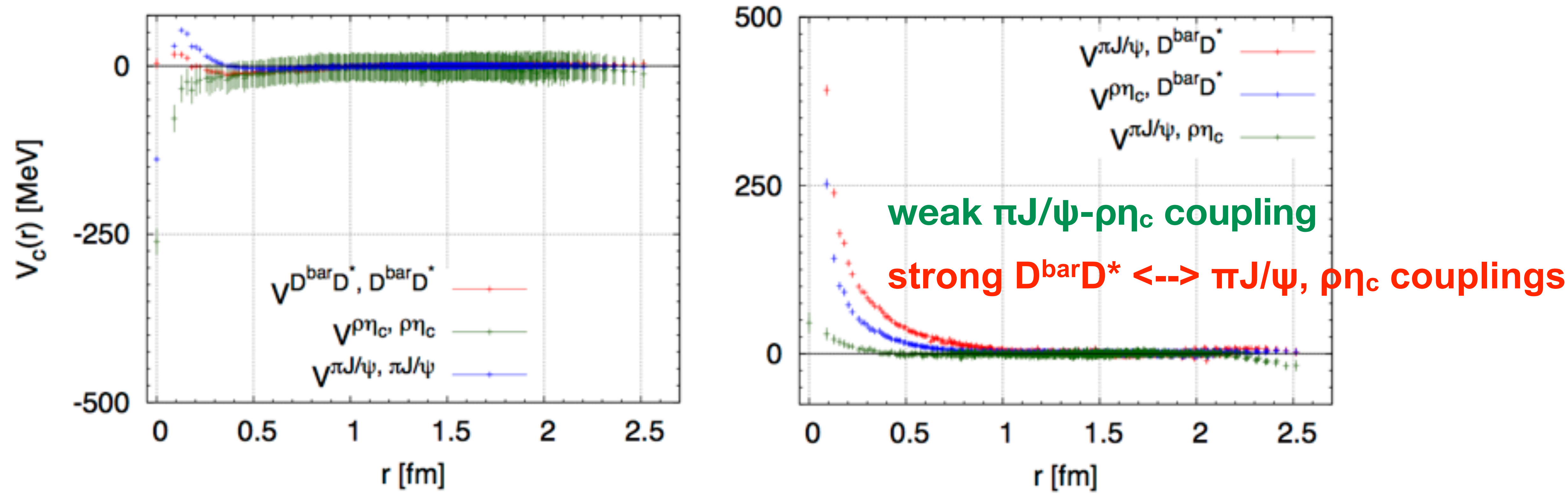
light hadron mass (MeV)	Charm meson mass (MeV)
m_π= 411, 572, 701	$m_{\eta c}$= 2988, 3005, 3024
m_K= 635, 714, 787	$m_{J/\psi}$= 3097, 3118, 3143
m_ρ= 896, 1000, 1097	m_D= 1903, 1947, 2000
m_N= 1215, 1411, 1583	m_{D^*}= 2056, 2101, 2159

Structure of $Z_c(3900)$

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



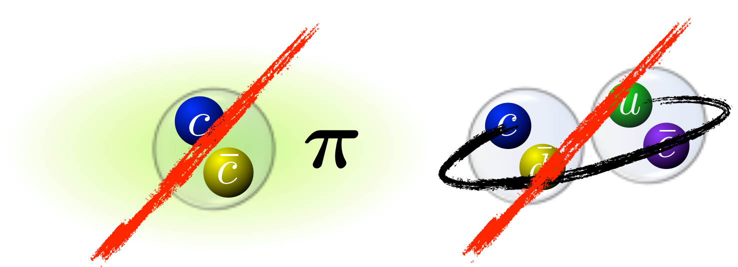
S-wave $\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$ potential @m_π=410MeV



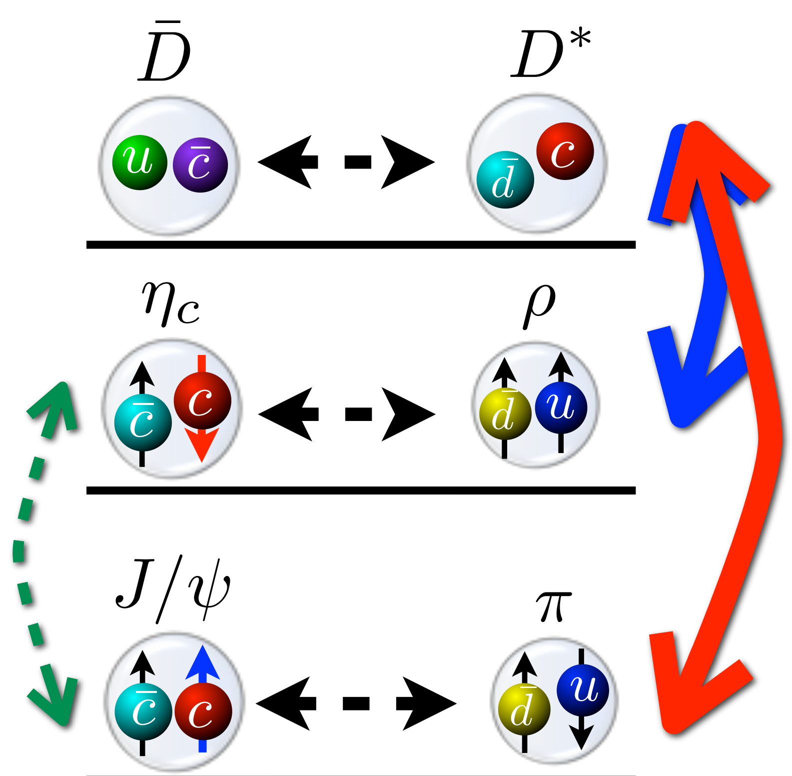
Y. Ikeda et al., (HAL QCD), arXiv.1602.03465(hep-lat).

★ **weak diagonal potentials:**

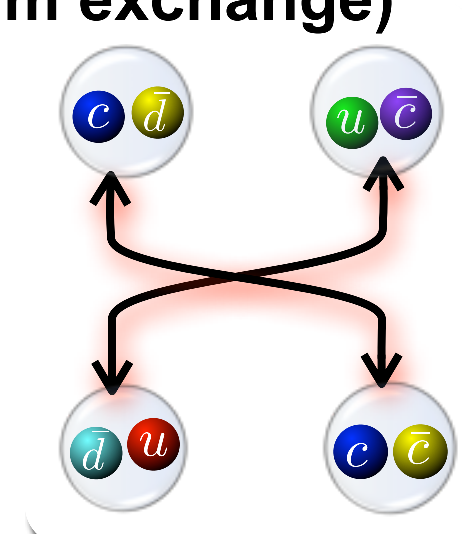
Z_c(3900) is NOT simple $\pi J/\psi$ & $D^{bar}D^*$



✦ **heavy quark spin symmetry**



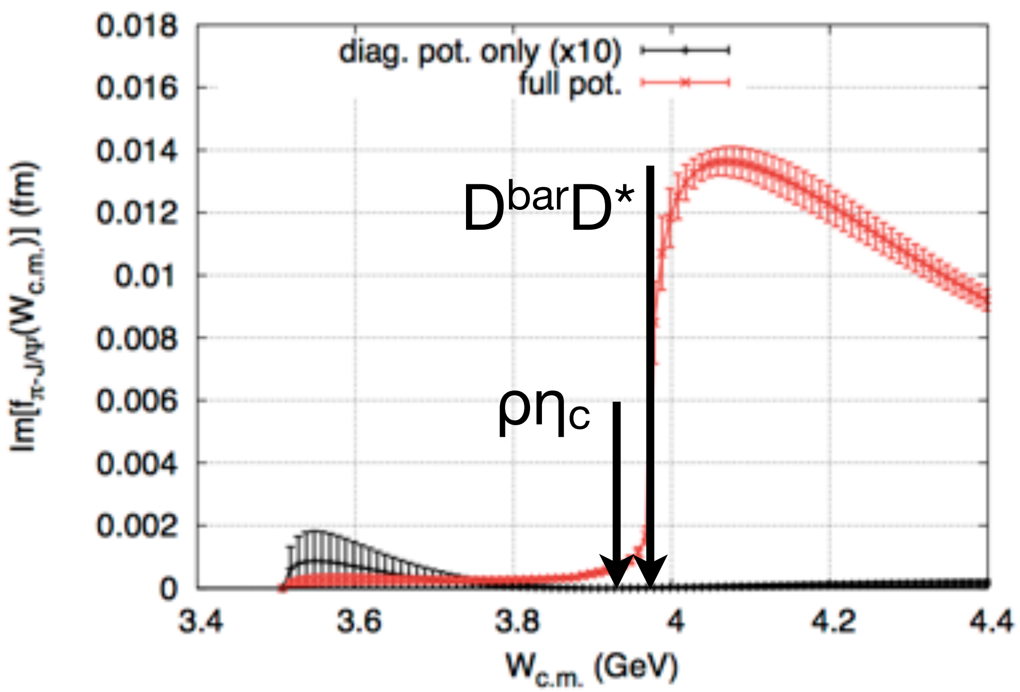
✦ **strong couplings**
(charm exchange)



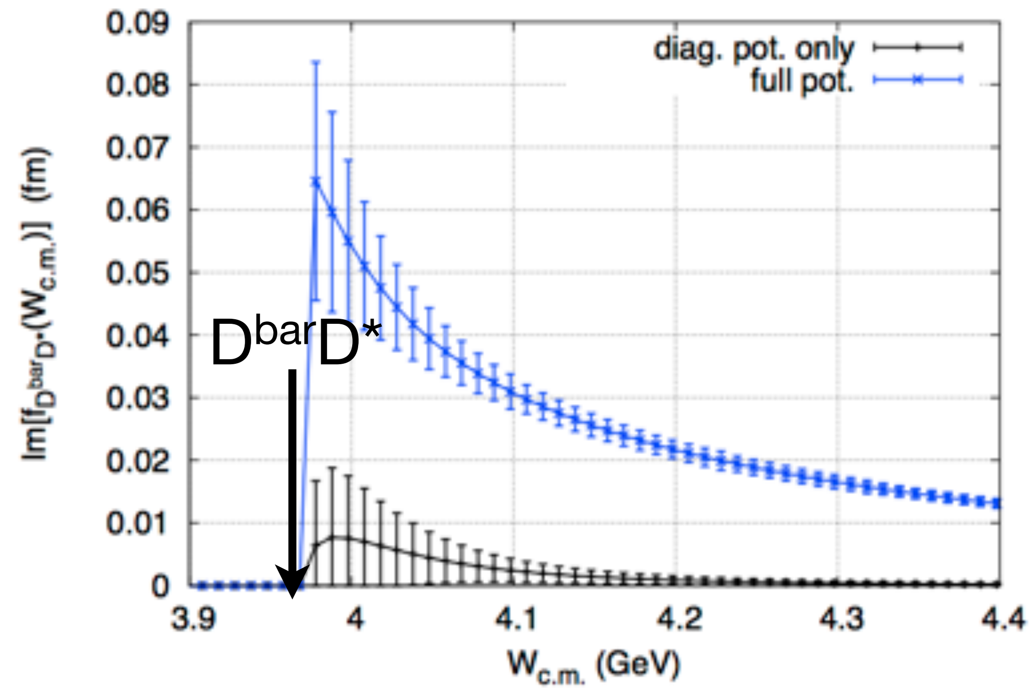
Invariant mass spectra of πJ/ψ & $D^{bar}D^*$

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

- πJ/ψ invariant mass



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



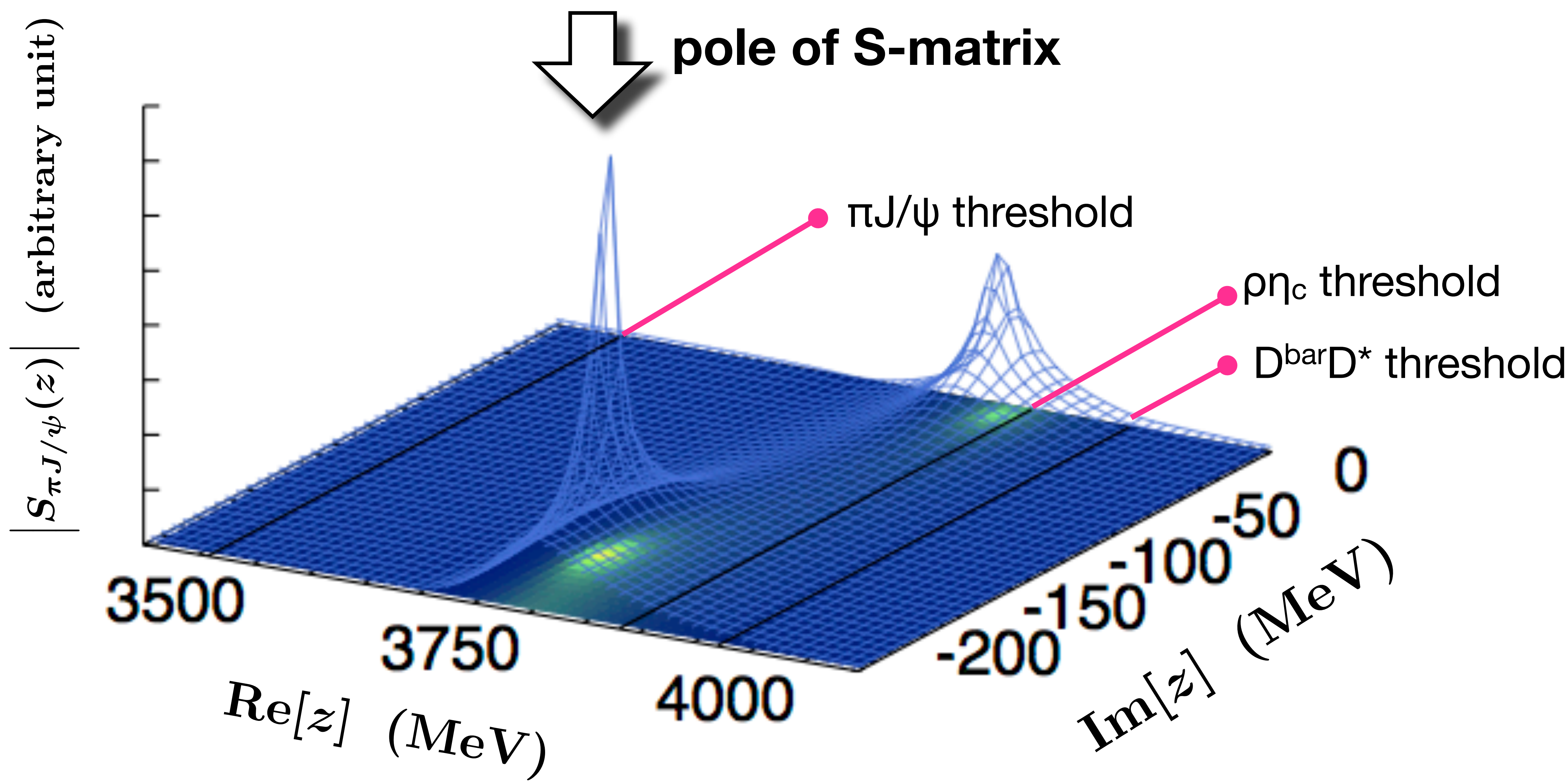
Y. Ikeda et al., [HAL QCD], arXiv.1602.03465 [hep-lat] (2016).

✓ 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 position

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



- "Virtual" pole on [2nd, 2nd, 2nd] sheet is found (far below $D^{bar}D^*$ threshold)
- No pole on other relevant sheets to $Z_c(3900)$
- $Z_c(3900)$ is not a conventional resonance
- $Z_c(3900)$ is cusp induced by off-diagonal $V^{\pi\psi,\ DbarD^*}$

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

Summary

✦ $Z_c(3900)$ in $I^G(J^P)=1^+(1^+)$ channel on the lattice@m_π>400MeV

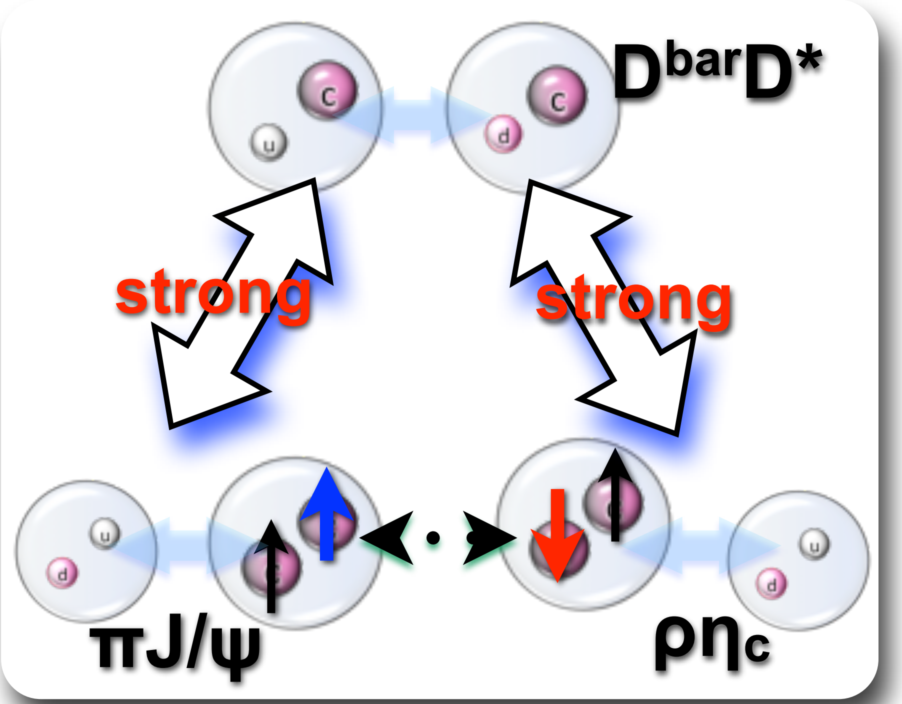
★ Large channel coupling between πJ/ψ and $D^{bar}D^*$ is a key

★ Enhancement at $D^{bar}D^*$ threshold in mass spectra

★ Heavy quark spin symmetry is observed in c.c. potentials

- $Z_c(3900)$ is neither simple $D^{bar}D^*$ molecule nor hadro-charmonium
- Virtual pole on complex energy plane is found (very far from $D^{bar}D^*$ threshold)

➡ **$Z_c(3900)$ is threshold effect induced by $D^{bar}D^*$-πJ/ψ coupling**



✤ Physical point simulation is the next step

✤ Future plans

- other systems : X(3872)
- extension to bottom systems