Charmed Tetra-quark states in Lattice QCD
— Interactions from HAL QCD method —

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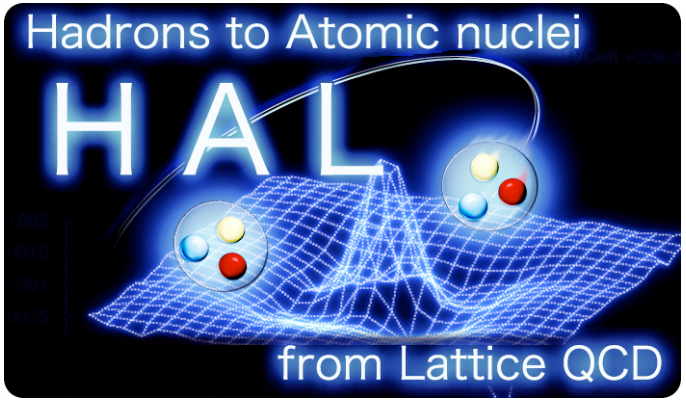
for HAL QCD Collaboration



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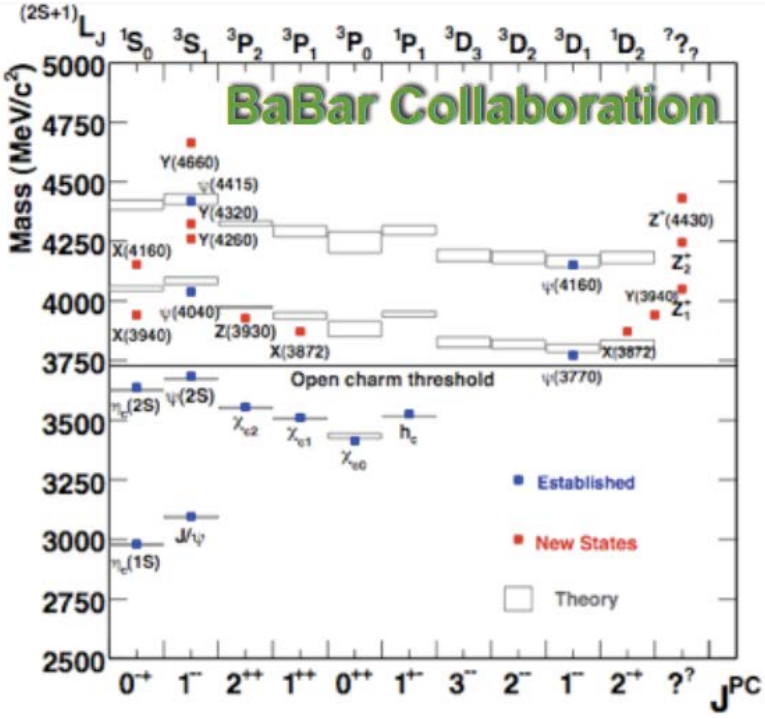
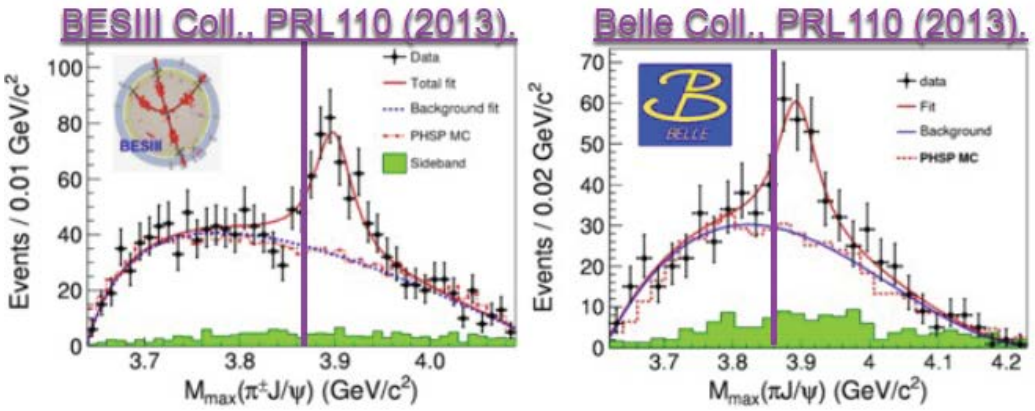
New hadronic DoF in charmed system ?

- Discoveries of XYZ mesons
  - What is the relevant effective DoF ?
    - Hadronic molecules ?
    - Diquarks ?
    - Gluonic excitations ?
    - (or threshold effects ?)
  - What kind of physics is hidden behind ?
    - The role of heavy quark sym ?



- Lattice QCD study of exotic states

  [Our approach]
  - Determine interactions and extract the physics
    ➔ exotic states



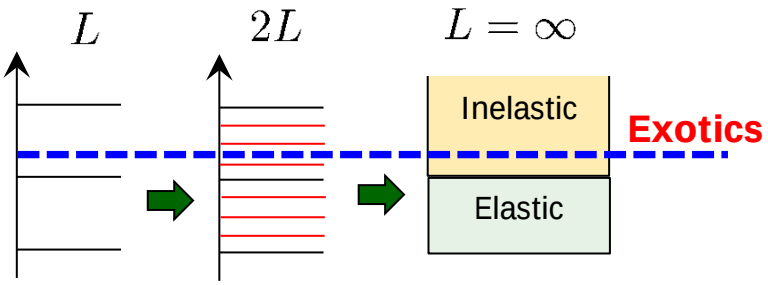
Zc(3900)

Interactions on the Lattice

- Traditional approach: Luscher's method
  - Phase shift & B.E. from temporal correlation in finite V
  - Spectrum of all states (incl. "continuum" states) have to be identified
  - Coupled channel: challenging

M.Luscher,
CMP104(1986)177
CMP105(1986)153
NPB354(1991)531

Talks by Prelovsek, Liu, etc.



- HAL QCD method
  - Potential from spacial (& temporal) correlation
  - Phase shift & B.E by solving Schrodinger eq in infinite V
  - All states (incl. "continuum" states) are automatically classified w.r.t. asymptotic states and their interactions
  - Coupled channel: straightforward

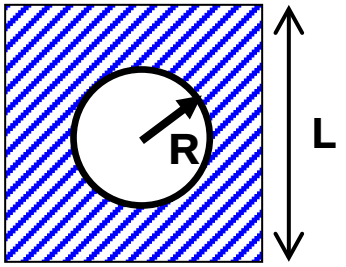
Ishii-Aoki-Hatsuda, PRL99(2007)022001, PTP123(2010)89
HAL QCD Coll., PTEP2012(2012)01A105

HAL QCD method

- Potential is constructed so as to reproduce the scattering phase shifts (or, S-matrix)
- Nambu-Bethe-Salpeter (NBS) wave function

$$\psi(\vec{r}) = \langle 0|H_1(\vec{x}+\vec{r})H_2(\vec{x})|H_1H_2, W_k\rangle_{\text{in}}$$

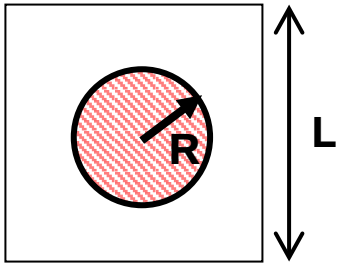
$$\psi_l(r) \simeq e^{i\delta(k)}\frac{\sin(kr - l\pi/2 + \delta(k))}{kr} \qquad (r > R)$$



M.Luscher (1991), C.-J.Lin eta l. (2001), CP-PACS Coll. (2005), Ishizuka (2009)

– Define (energy-independent) potential from wave func.

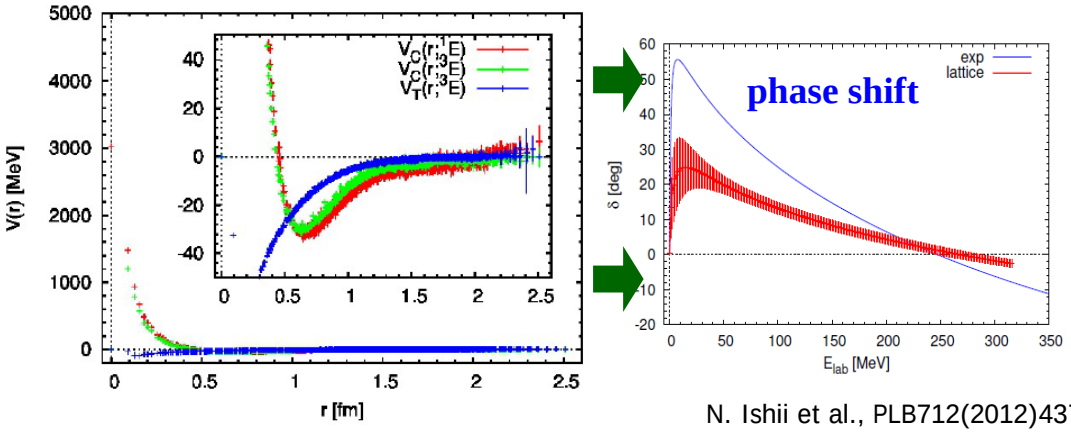
$$(\nabla^2 + k^2)\psi(\boldsymbol{r}) = m\int d\boldsymbol{r'}U(\boldsymbol{r},\boldsymbol{r'})\psi(\boldsymbol{r'}), \qquad r < R$$



- U is not observable but faithful to phase shift
- All information of elastic scatt. states encoded in U
- Extension to coupled channel system straightforward

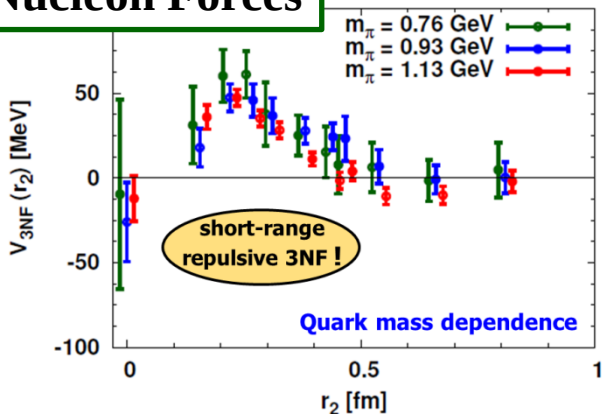
Successful applications to various interactions

NN forces (central & tensor)



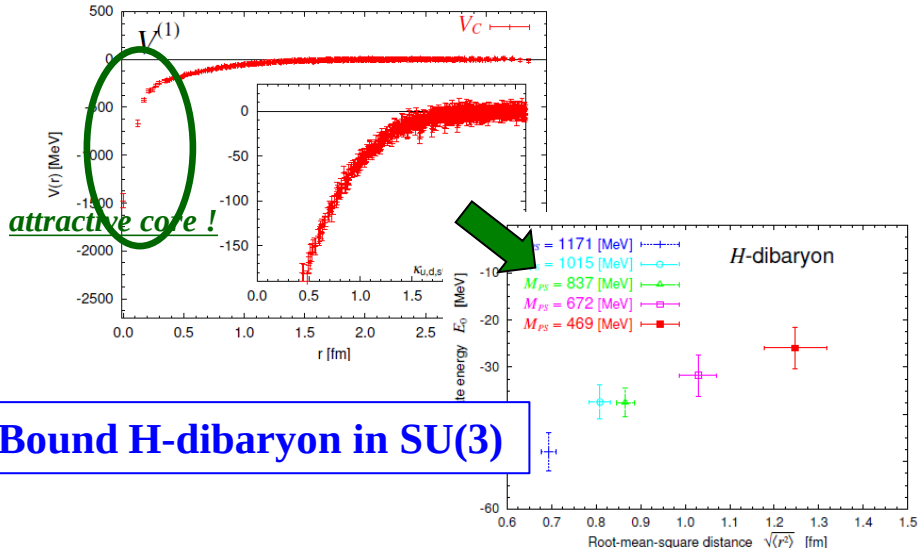
N. Ishii et al., PLB712(2012)437

Three-Nucleon Forces



T.D. et al., PTP127(2012)723

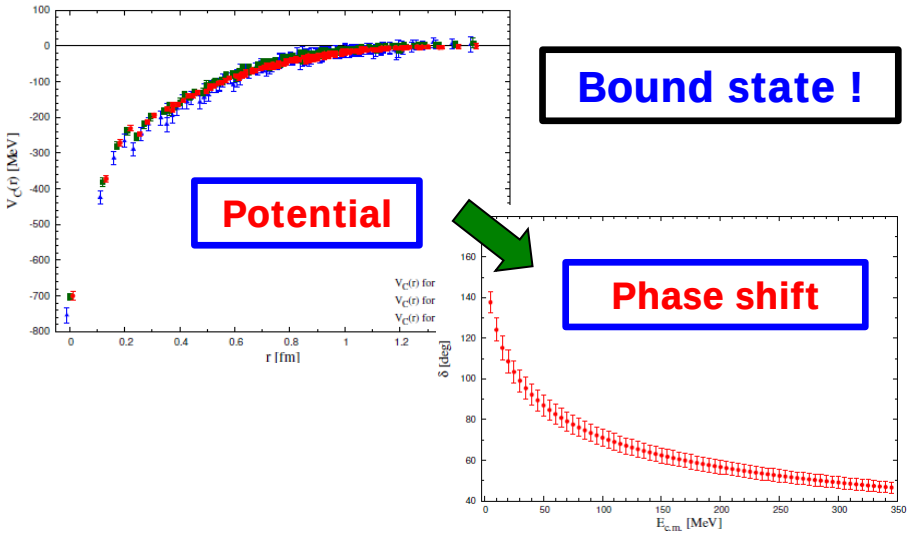
H-dibaryon



Bound H-dibaryon in SU(3)

T. Inoue et al., PRL106(2011)162002

NΩ forces



Bound state !

F. Etminan et al., NPA928(2014)89

Search of charmed exotics on Lattice

- Tcc ($ccu^{bar}d^{bar}$), Tcs($csu^{bar}d^{bar}$)
  - Manifestly exotic
  - Could be good probe of (ud)-diquark DoF (spin frozen by heavy quark sym)

- Zc states
  - Many experiments
  - Exotic w/ OZI rule

Color-magnetic int. in diquark

$$\langle v_{ij} \rangle = -\langle (\vec{\lambda}(i) \cdot \vec{\lambda}(j))(\vec{\sigma}(i) \cdot \vec{\sigma}(j)) \rangle$$

$\langle v_{ij} \rangle$	C=1	C=8	$C=3^{bar}$	C=6
S=0	-16	2	-8	4
S=1	16/3	-2/3	8/3	-4/3

➔ **Good(I=0)/bad(I=1) diquark**

Lattice QCD setup

- Nf=2+1 dynamical clover fermion + RG improved gauge action
  - Relativistic Heavy Quark (RHQ) action for charm
  - a^{-1}=2.176GeV, a=0.0907fm
  - 32^3 X 64 lattice, **L=2.9fm**
  - ~400configs
  - (disconnected diagram neglected)

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

Y. Namekawa et al., PRD84(2011)074505

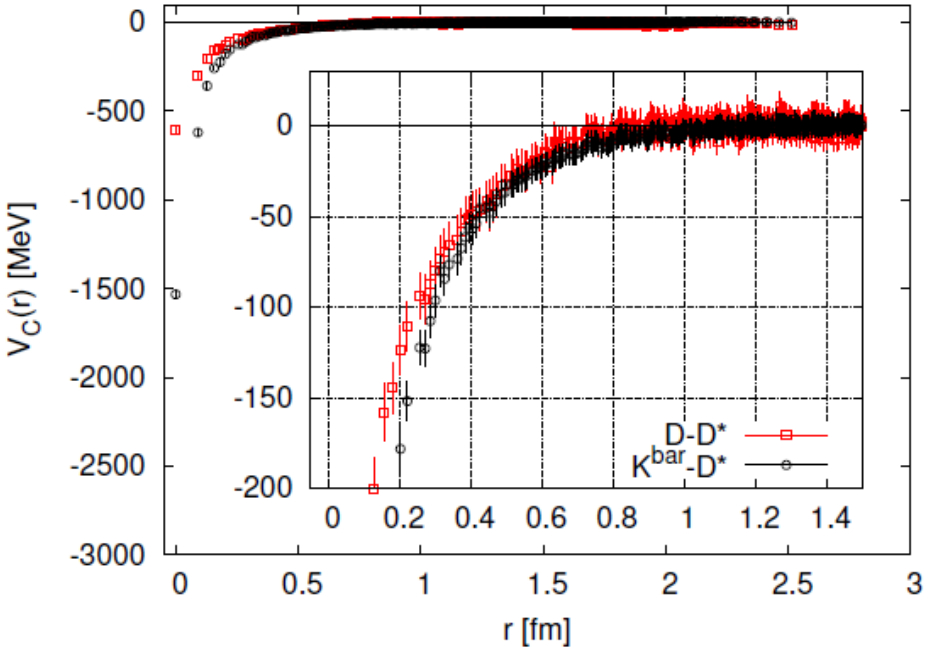
- Masses: [on the lattice] [PDG]
  - $m(\pi)$ = 0.41, 0.57, 0.70 GeV 0.14
  - m(K) = 0.64, 0.71, 0.79 GeV 0.50
  - m(D) = 1.90, 1.95, 2.00 GeV 1.87
  - M(D*) = 2.05, 2.10, 2.16 GeV 2.01
  - $M(\eta c)$ = 2.99, 3.01, 3.02 GeV 2.98
  - $M(J/\psi)$ = 3.10, 3.12, 3,02 GeV 3.10

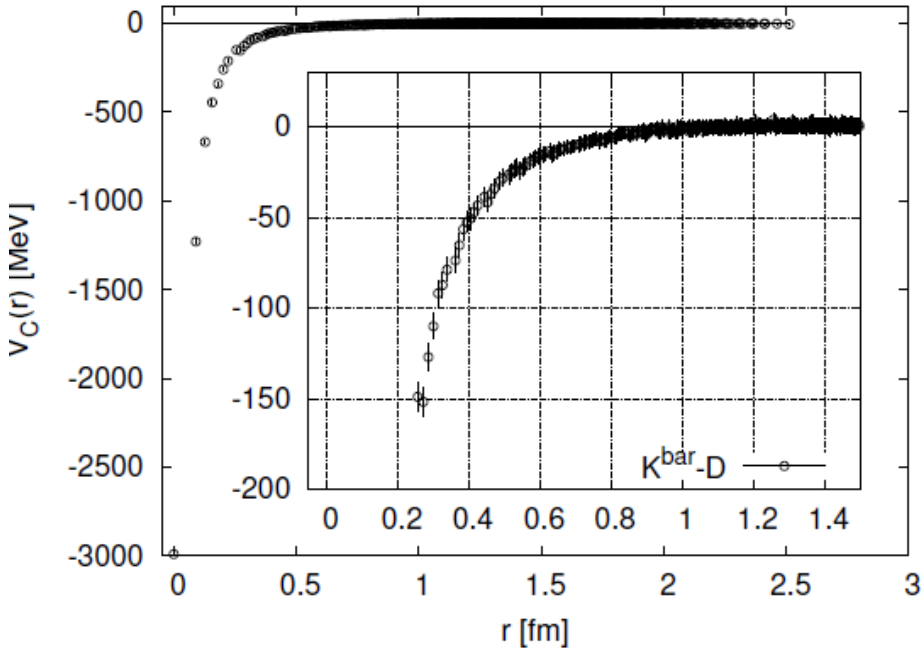
Tcc, Tcs states w/ "good" diquark

Tcc ($J^P=1^+, I=0$) $\Leftrightarrow$ D-D*

Tcs ($J^P=1^+, I=0$) $\Leftrightarrow$ K^{bar}-D*

Tcs ($J^P=0^+, I=0$) $\Leftrightarrow$ K^{bar}-D





mπ=410MeV

Attraction !

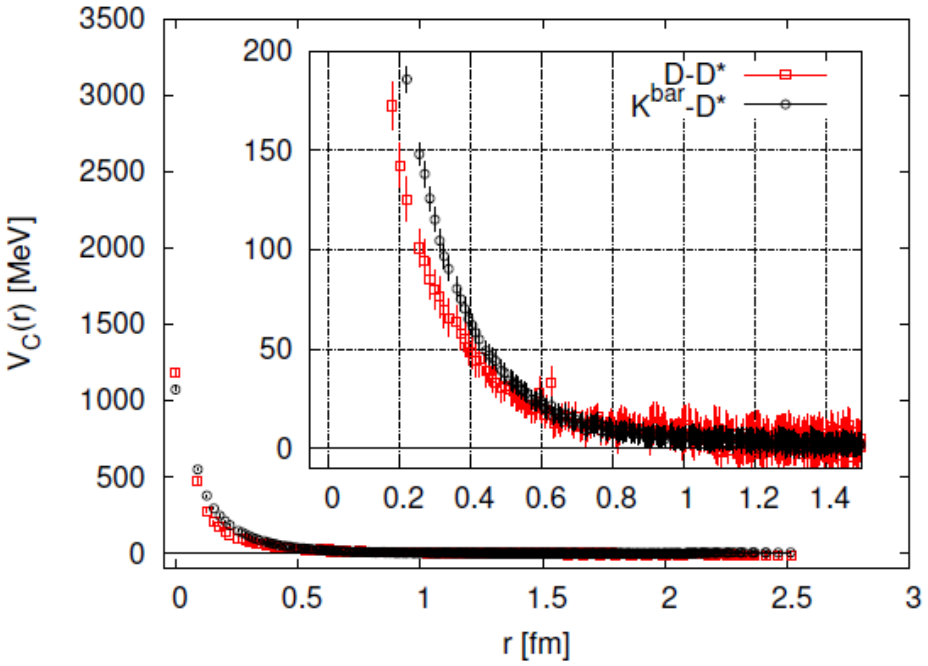
Tcc, Tcs states w/ "bad" diquark

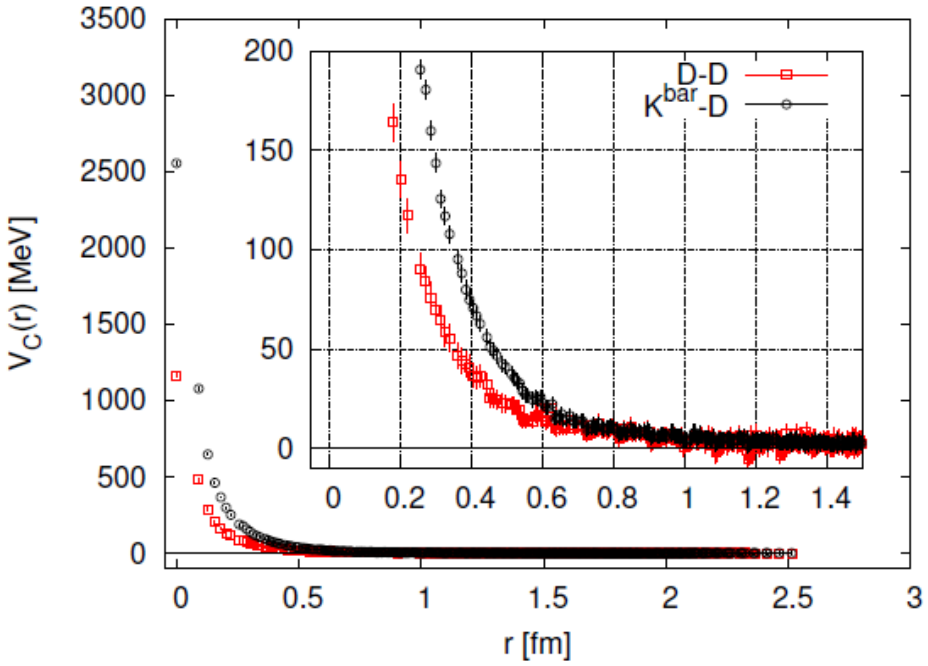
Tcc ($J^P=1^+, I=1$) $\Leftrightarrow$ D-D*

Tcs ($J^P=1^+, I=1$) $\Leftrightarrow$ K^{bar}-D*

Tcc ($J^P=0^+, I=1$) $\Leftrightarrow$ D-D

Tcs ($J^P=0^+, I=1$) $\Leftrightarrow$ K^{bar}-D





mπ=410MeV

Repulsion !

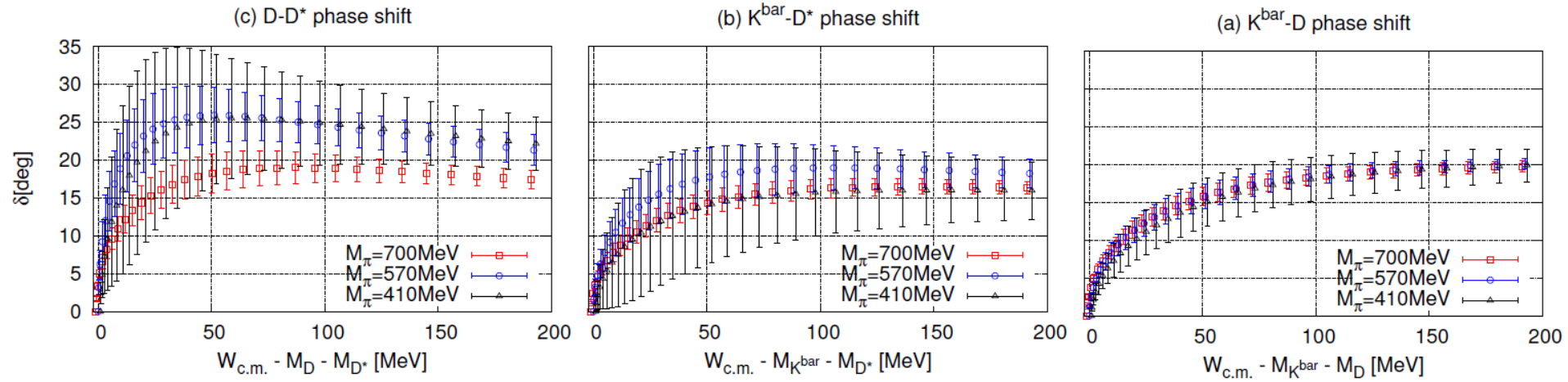
Tcc, Tcs states w/ good diquark

Phase Shift

Tcc ($J^P=1^+, I=0$) $\Leftrightarrow$ D-D*

Tcs ($J^P=1^+, I=0$) $\Leftrightarrow$ K^{bar}-D*

Tcs ($J^P=0^+, I=0$) $\Leftrightarrow$ K^{bar}-D



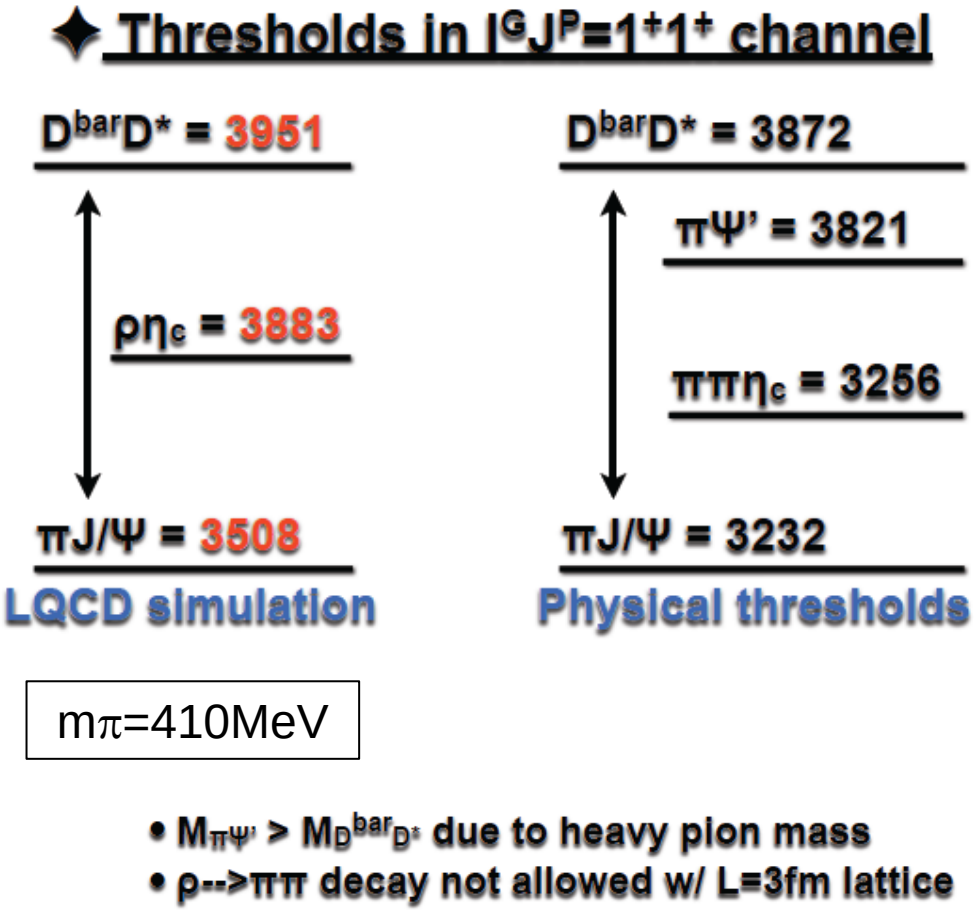
- Strong Attraction, but no bound state for $m\pi > 400$MeV
- More attractive for lighter quark mass
- T_{bb} has a bound state if we combine m_b & potential in Tcc

Y. Ikeda et al. (HAL QCD), PLB729(2014)85

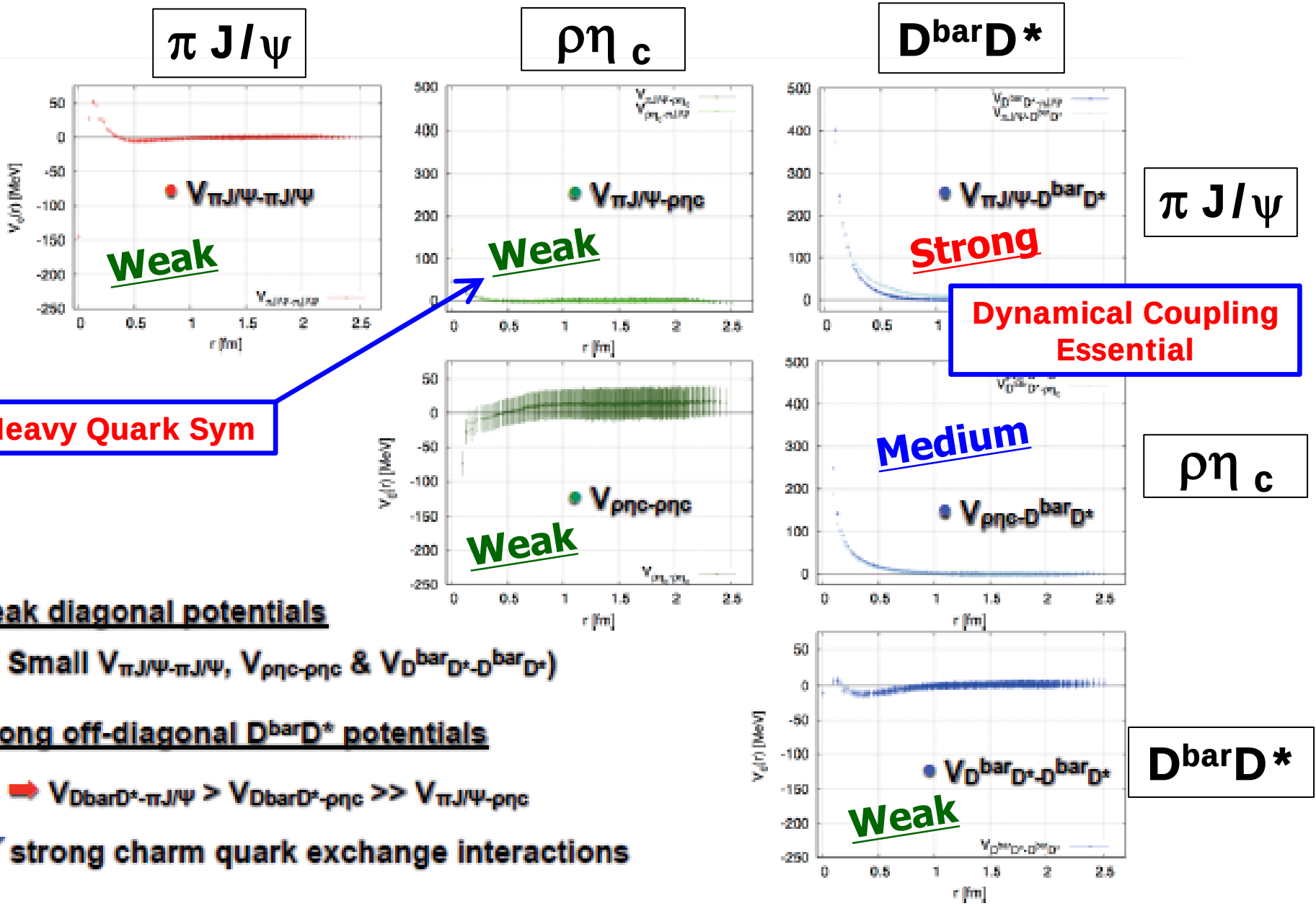
Zc(3900) search on the Lattice

Can "isolated" $D^{bar}\,D^*$ molecular state exist in QCD ?

Or, does dynamical coupling play an important role ?



3x3 coupled channel potential



- **Weak diagonal potentials**

  (Small $V_{\pi J/\Psi-\pi J/\Psi}$, $V_{\rho\eta c-\rho\eta c}$ & $V_{D^{bar}D^*-D^{bar}D^*}$)

- **Strong off-diagonal $D^{bar}D^*$ potentials**

  ➡ $V_{DbarD^*-\pi J/\Psi} > V_{DbarD^*-\rho\eta c} >> V_{\pi J/\Psi-\rho\eta c}$

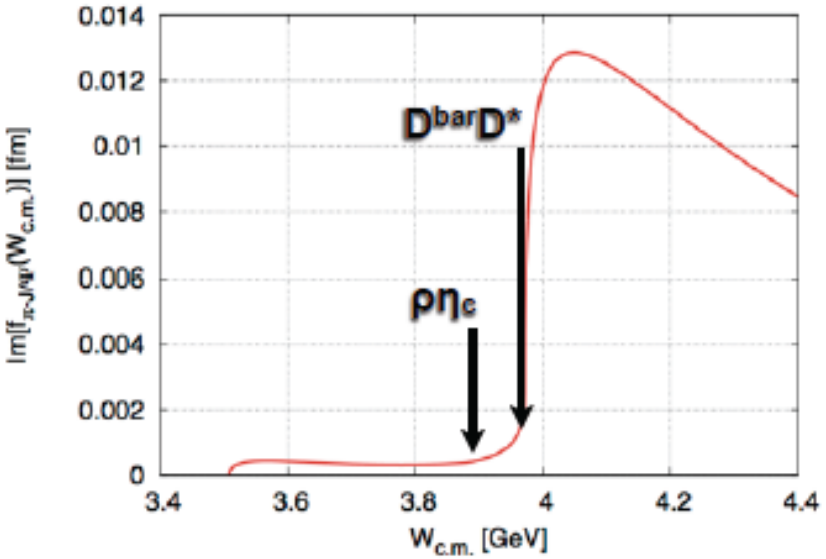
  ✓ strong charm quark exchange interactions

2-body invariant mass

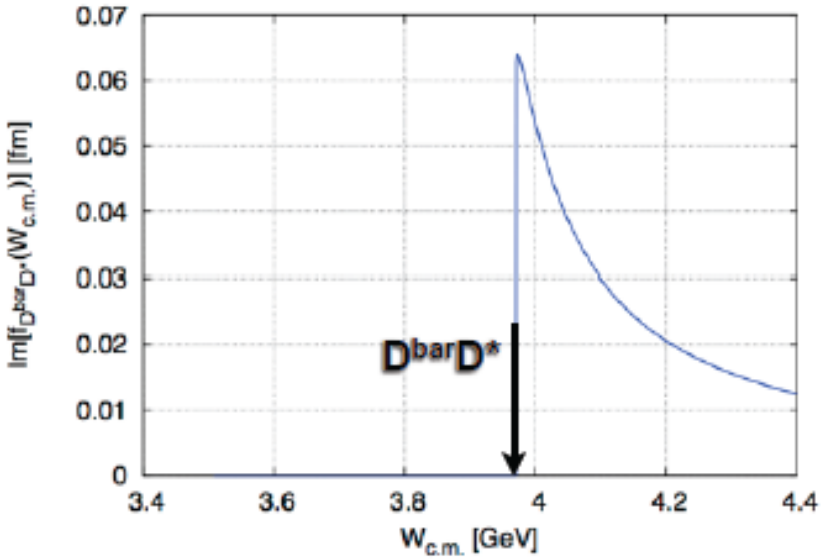
- **2-body invariant mass :** $\rho_i(W_{\mathrm{c.m.}}) \equiv |S_{ii}(W_{\mathrm{c.m.}}) - 1|^2/k_i \propto \mathrm{Im} f_{ii}(W_{\mathrm{c.m.}})$

$(i = \pi J/\Psi,\ \bar{D}D^*)$

- **πJ/Ψ invariant mass (m_π=410MeV)**



- **$D^{bar}D^*$ invariant mass (m_π=410MeV)**

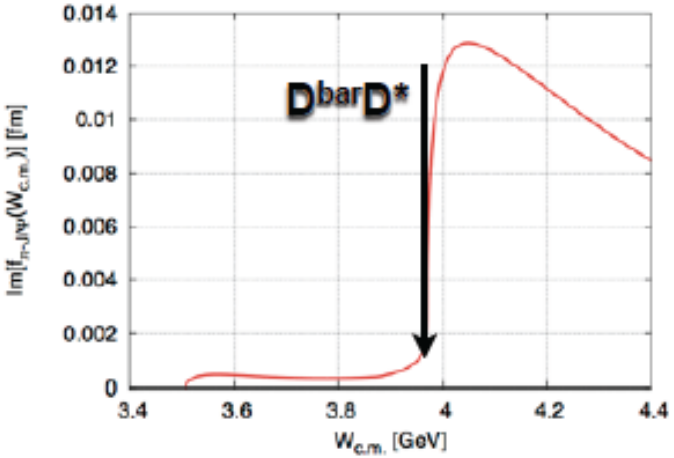


✓ **enhancement near $D^{bar}D^*$ threshold due to large πJ/Ψ-$D^{bar}D^*$ coupling**

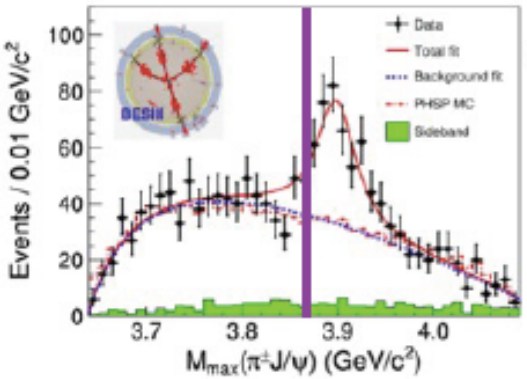
- **broad tail in πJ/Ψ invariant mass**
- **sharp enhancement in $D^{bar}D^*$ invariant mass**

LQCD results & EXP. results

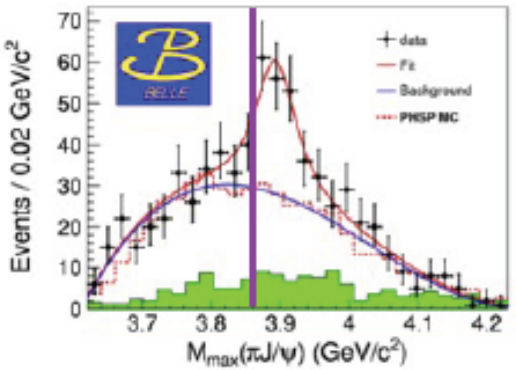
- πJ/Ψ invariant mass (m_π=410MeV)



- e^+e^- --> π(πJ/Ψ) @ 4.26GeV

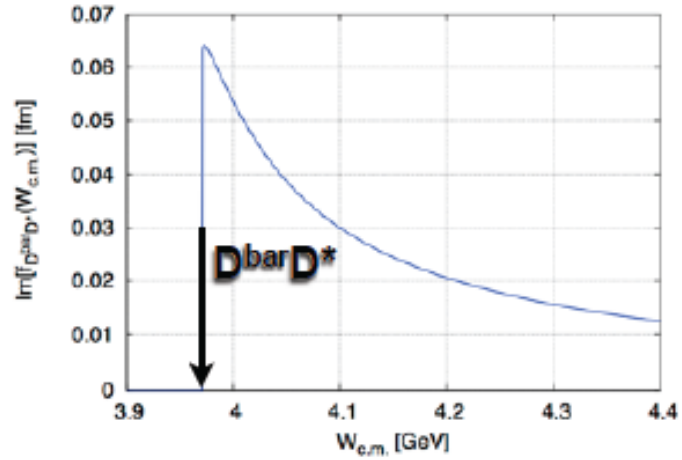


BESIII Coll., PRL110 (2013).

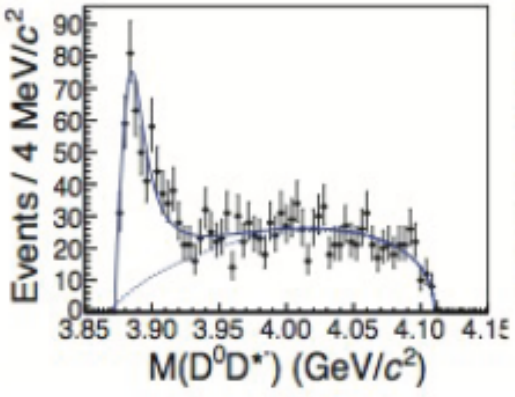


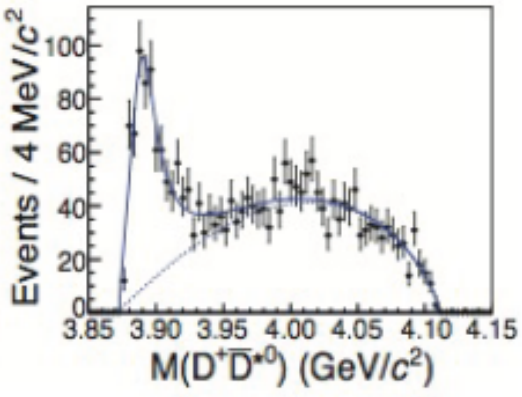
Belle Coll., PRL110 (2013).

- $D^{bar}D^*$ invariant mass (m_π=410MeV)



- e^+e^- --> $\pi^{+/-}$ $(D^{bar}D^*)^{-/+}$





BESIII Coll., PRL112 (2014).

Y. Ikeda et al. (HAL QCD Coll.)

c.f. S. Prelovsek et al., arXiv:1405.7623
No Zc found < 4.2GeV in 13 lowest states on lattice

Summary

- Charmed tetraquark states from HAL QCD method
  - Coupled channel potential is a powerful tool to probe (exotic) states in the continuum
- Tcc-tetraquark
  - Tcc ($J^P=1^+$,I=0) strong attraction; qualitatively consistent w/ diquark-picture
  - Tbb ($J^P=1^+$,I=0) : good candidate for a bound state
- Zc(3900)
  - Strong coupling exists between D^{bar} D* and π J/ψ, While heavy quark sym suppresses $\rho\eta_c$ - π J/ψ
  - Possibility of complex pole ? Search in progress
- **Outlook**
  - Challenge toward Physical point