On the structure of Zc(3900) from lattice QCD

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HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)

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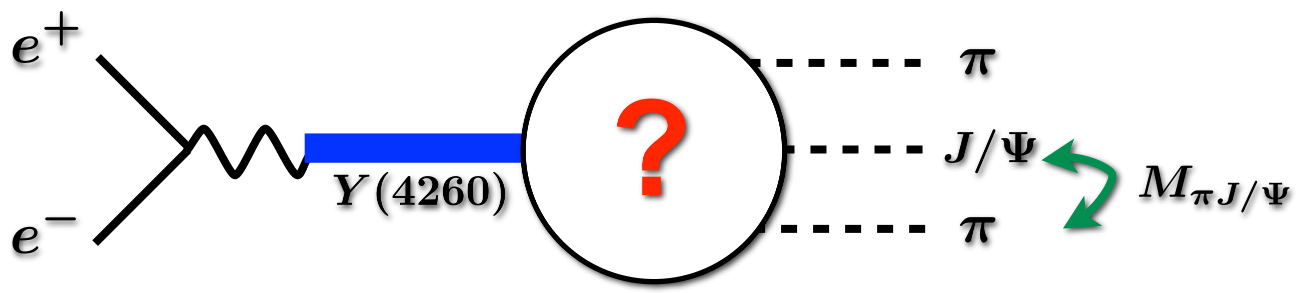
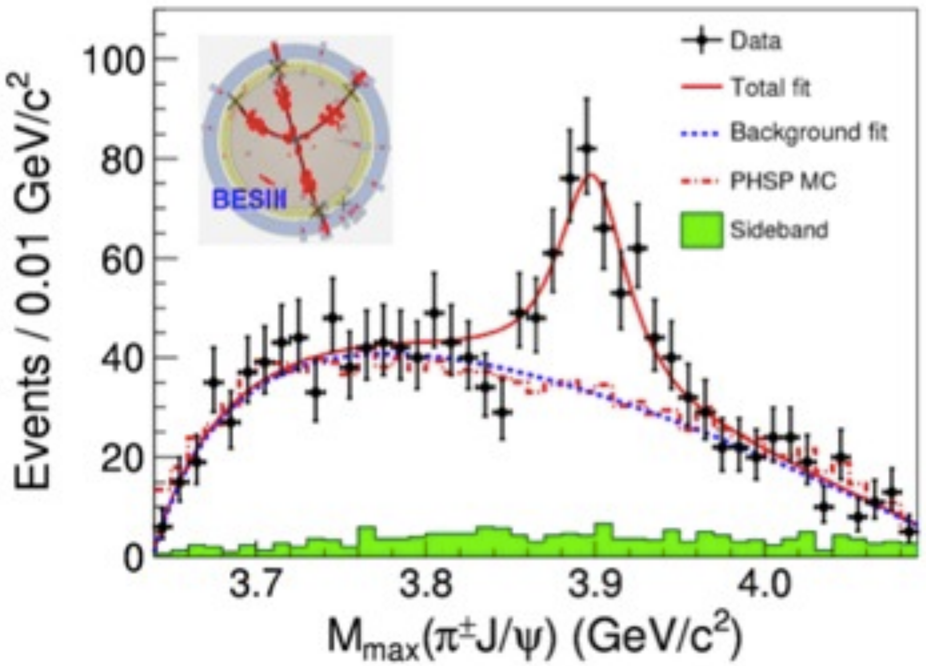
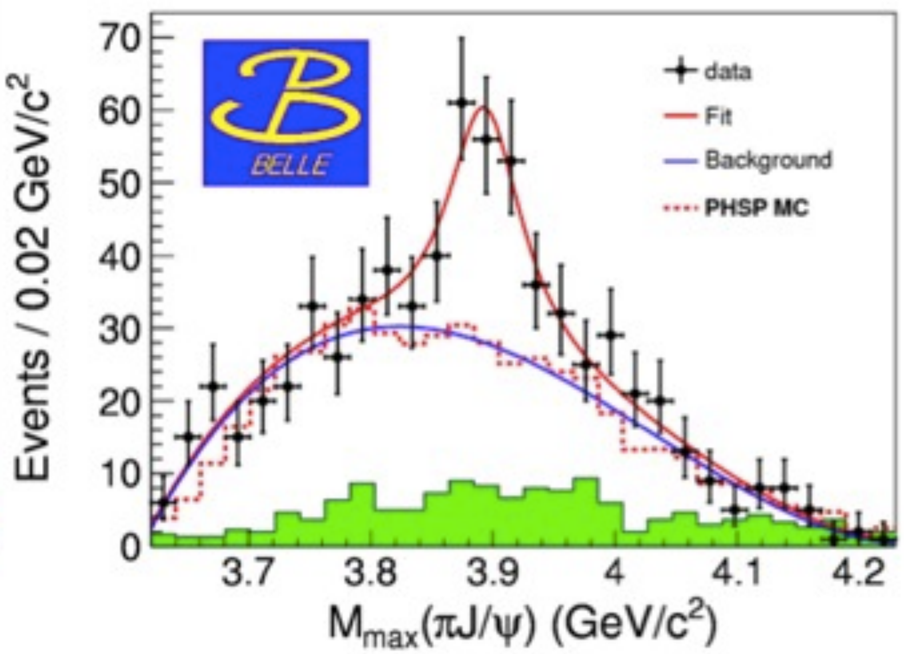
What is Zc(3900) ?

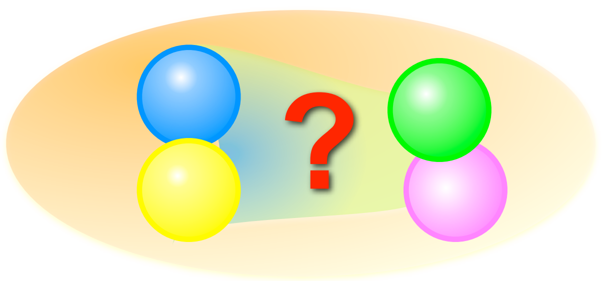


BESIII Coll., PRL110, 252001, (2013).



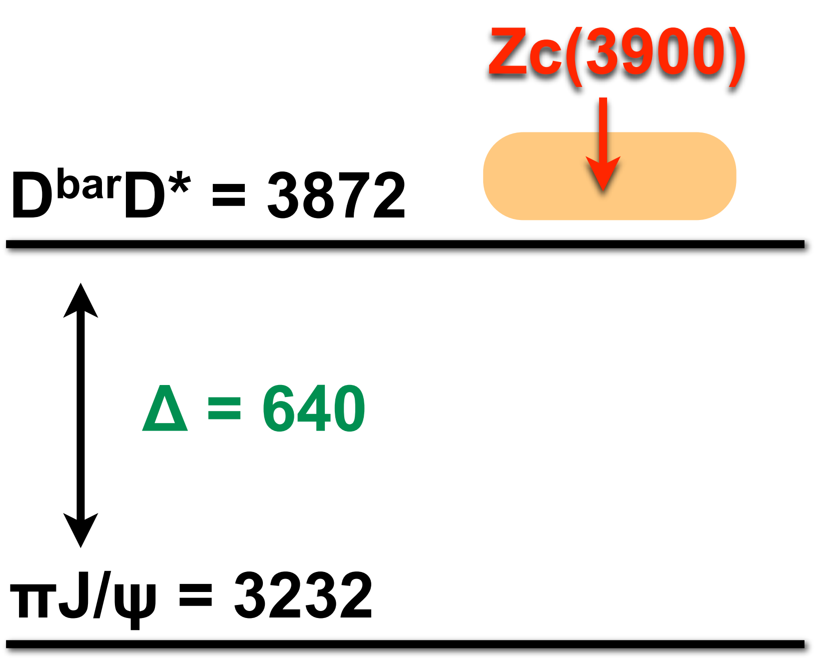
Belle Coll., PRL110, 252002, (2013).



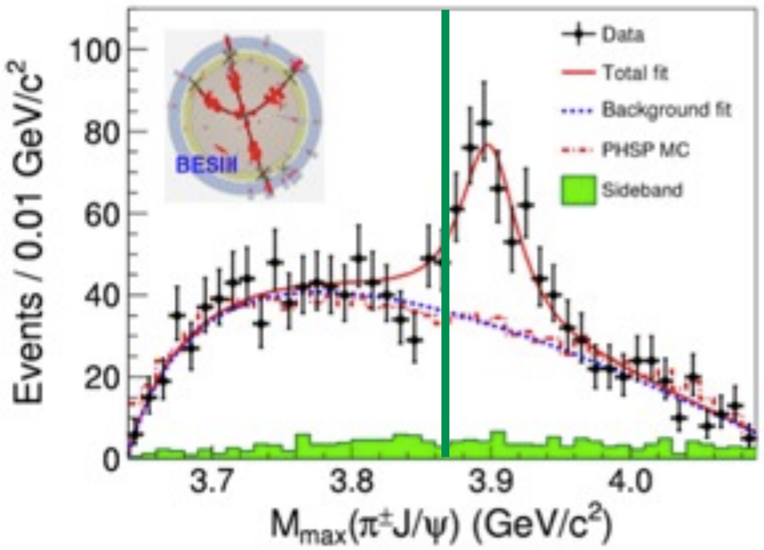


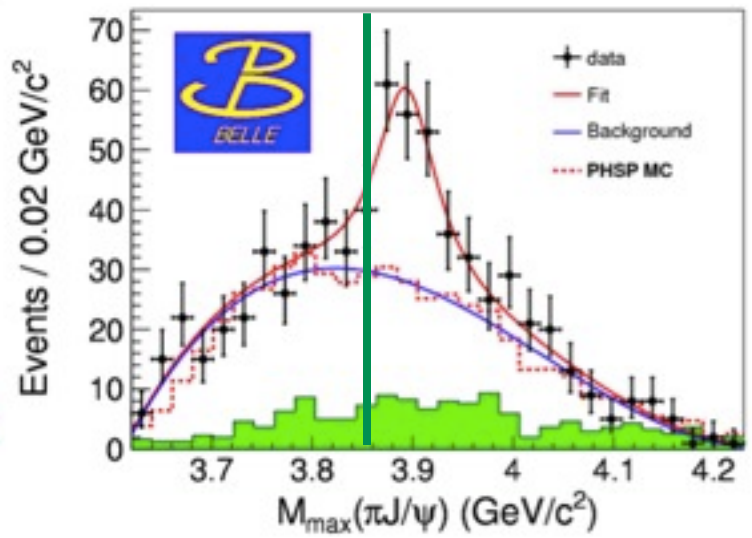
- Zc(3900) is observed in $\pi^{\pm}J/\psi$ invariant mass
- Charged tetraquarks? (4 quarks necessary)
- Isospin: $I^G=1^+$
- M ~ 3900, Γ ~ 60 MeV from BW line shape
- Peak confirmed by CLEO Coll.

Xiao et al., PLB727 (2013).



Status of Zc(3900)





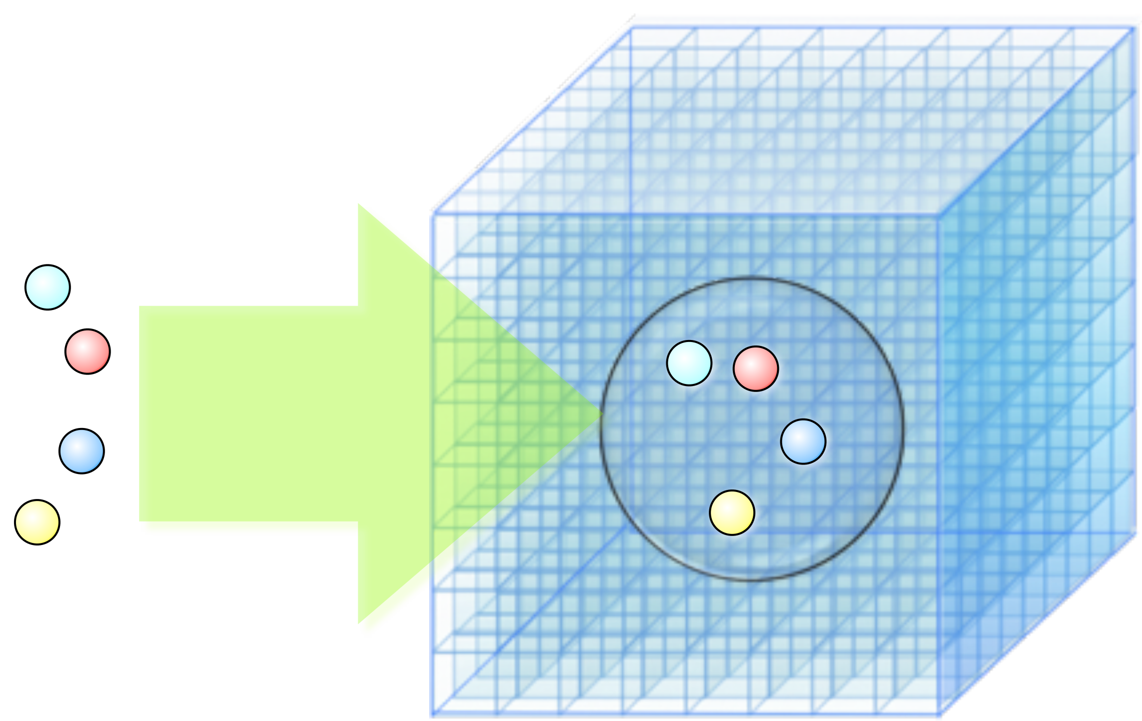
- observed in $\pi^{\pm}J/\psi$ & $D^{bar}D^*$ invariant mass spectra
- $J^P = 1^+$ seems most probable

BESIII Coll., PRL112 (2014).

★ structure of Zc(3900) from models ➡ poor information on interactions

- Tetraquark? Maiani et al. (2013).
- $D^{bar}D^*$ molecule? Nieves et al. (2011) + many others
- cc^{bar} + π cloud? Voloshin (2008).
- pole + $D^{bar}D^*$ cloud? Guo et al. (2015)
- cusp? Chen et al. (2013), Swanson (2015).

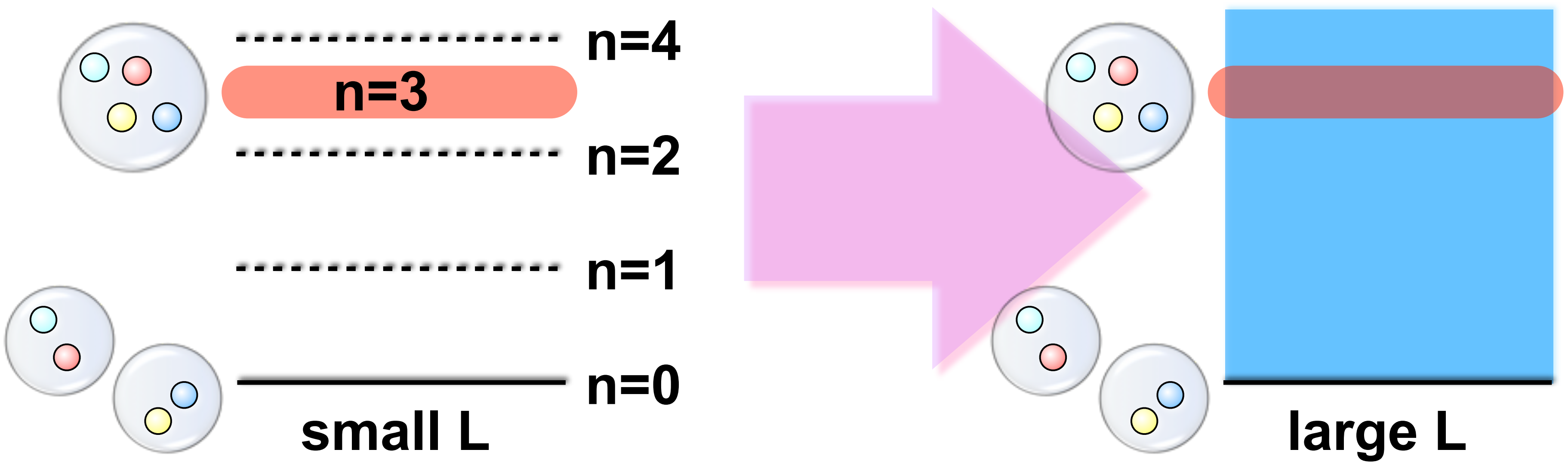
★ LQCD simulations for Zc(3900)

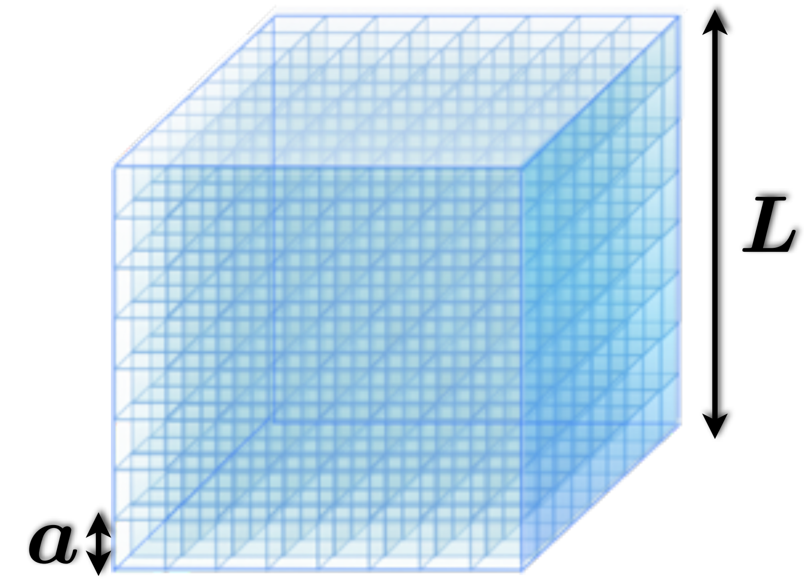


How to find Zc(3900) on the lattice?

✦ Conventional approach: LQCD spectrum

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





$$k_n = \frac{2\pi a}{L} n$$

➡ LQCD spectrum consistent with MM scattering up to n=13 (L=2fm)

S. Prelovsek et al., PRD91, 014504 (2015).

★ Zc(3900) can be resonance & coupled-channel system

- difficulties in finding broad resonances w/ large L

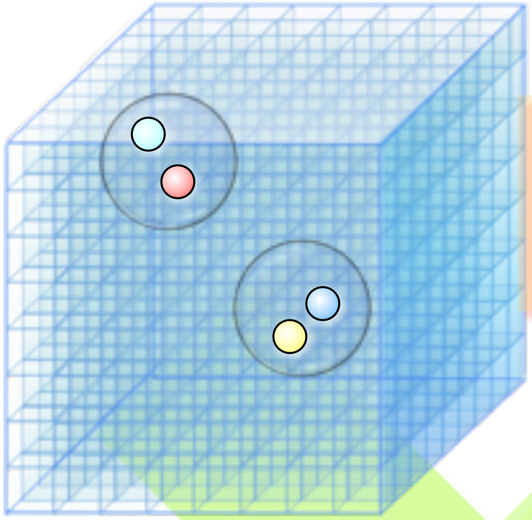
  ➡ scatterings on the lattice w/ channel coupling to extract S-matrix

Lüscher's finite size formula

➡ identify $W_{n=0,1,2,...}(L)$ & find degenerate $W_n(L)$ w/ different L

➡ in practice, it is difficult to find degenerate $W_n(L)$ (QCD eigenenergy)

HAL QCD approach



- ***Lüscher's finite size formula***

energy $W_n(L)$ --> phase shift, inelasticity

Lüscher, NPB354, 531 (1991).

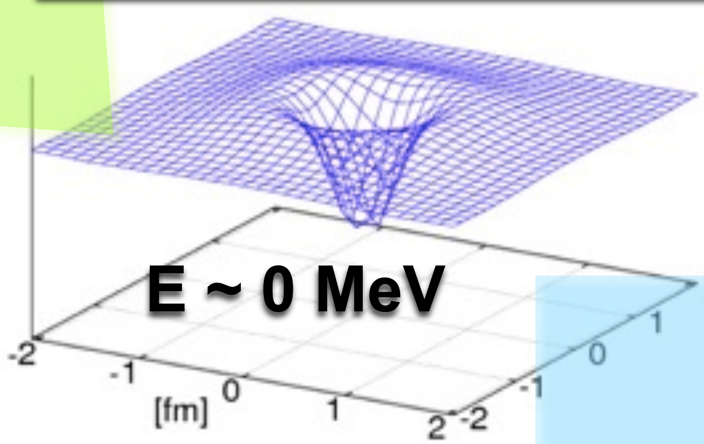
- ***S-matrix***

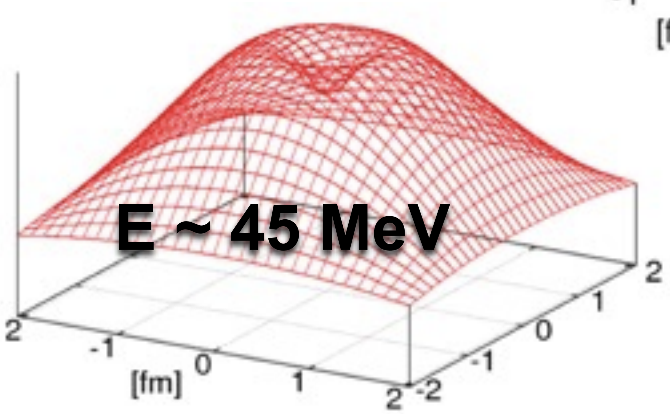
$$S(k) : \eta, \ \delta(k)$$

- **Guaranteed to be the same**

Kurth et al., JHEP 1312 (2013) 015.

- ***NBS wave function***

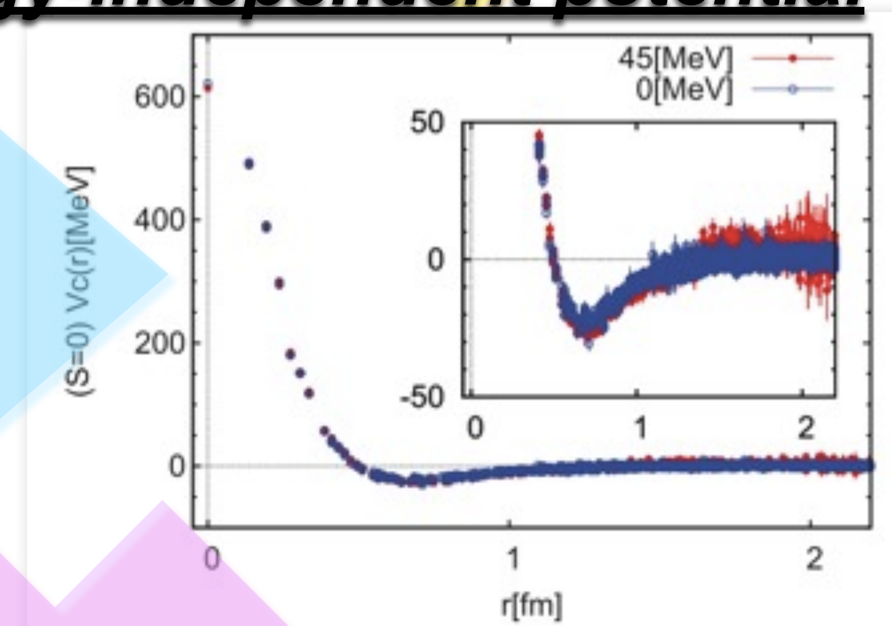




Ishii, Aoki, Hatsuda, PRL99, 02201 (2007).

Aoki, Hatsuda, Ishii, PPTP123, 89 (2010).

- ***Energy-independent potential***



✔ **Advantages of HAL QCD method:**

coupled-channel problem, resonance (pole position)

Contents

- Introduction
- Brief introduction to HAL QCD method to define “potential”

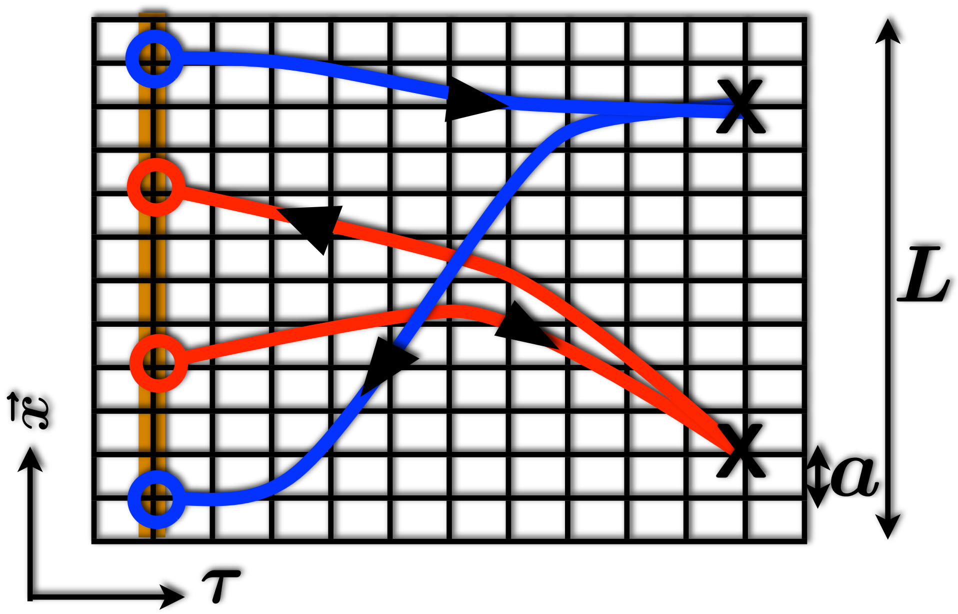
  ➡ talk by K. Sasaki (Wed.)

- Coupled-channel potential matrix for Zc(3900) in $I(J^P)=1(1^+)$
- Application of LQCD potential -- production reactions of Zc(3900) --
- Summary

“Potentials” in LQCD

Hadron 4pt function & Nambu-Bethe-Salpeter (NBS) wave function

$$R^{ab}(\vec{r},\tau) \equiv \sum_{\vec{x}} \langle 0|\phi_1^a(\vec{x}+\vec{r},\tau)\phi_2^a(\vec{x},\tau)\mathcal{J}^{b\dagger}(\tau=0)|0\rangle \frac{e^{(m_1^a+m_2^a)\tau}}{\sqrt{Z_1^a}\sqrt{Z_2^a}}$$
$$= \sum_n A_n^b \exp\left[-\Delta W_n \tau\right] \psi_n^a(\vec{r})$$



- Helmholtz eq. of NBS wave func.

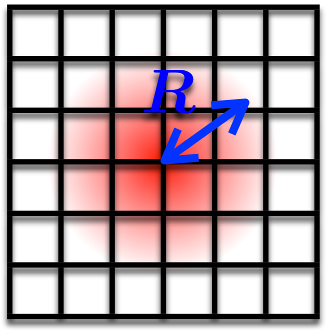
$$(\nabla^2 + (\vec{k}_n^a)^2)\psi_n^a(\vec{r}) = 0 \quad (|\vec{r}| > R)$$

$$\psi^{(l)}_{W(\vec{k})}(r) \sim \frac{e^{i\delta_l(k)}}{kr}\sin(kr+\delta_l(k)-l\pi/2)$$

- NBS wave func. in QFT ~ wave func. in Q.M.

- Coupled-channel potential matrix (faithful to S-matrix)

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



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

- Coupled-channel potentials are energy-independent (non-local in general)

HAL QCD method

✓ Define energy-independent coupled-channel potentials :

Aoki, Hatsuda, Ishii, PTP123, 89 (2010).

$$\psi_n^a(\vec{r}) = \langle 0|\phi_1^a(\vec{r}+\vec{x})\phi_2^a(\vec{x})|W_n; I, J^P\rangle$$

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

✤ Since energy-independent potential can produce all scattering states, we do NOT have to identify energy eigenstate $|W_n, I, J^P\rangle$

✓ Extract energy-independent potential from time-dependent Schrödinger-type eq.

Ishii et al,(HAL QCD), PLB712, 437(2012).

$$\left[-\partial_\tau + \nabla^2/2\mu^a + \partial_\tau^2/8\mu^a + \mathcal{O}(\delta^2)\right]R^{ab}(\vec{r},\tau) = \sum_c\int d\vec{r}'\Delta^{ac}U^{ac}(\vec{r},\vec{r}')R^{cb}(\vec{r}',\tau)$$

$$\delta = \frac{m_1^a - m_2^a}{m_1^a + m_2^a} \qquad \Delta^{ac} = \frac{e^{(m_1^a+m_2^a)\tau}}{e^{(m_1^c+m_2^c)\tau}}$$

✓ Velocity expansion:

$$U(\vec{r},\vec{r}') = V(\vec{r},\nabla)\delta(\vec{r}-\vec{r}')$$

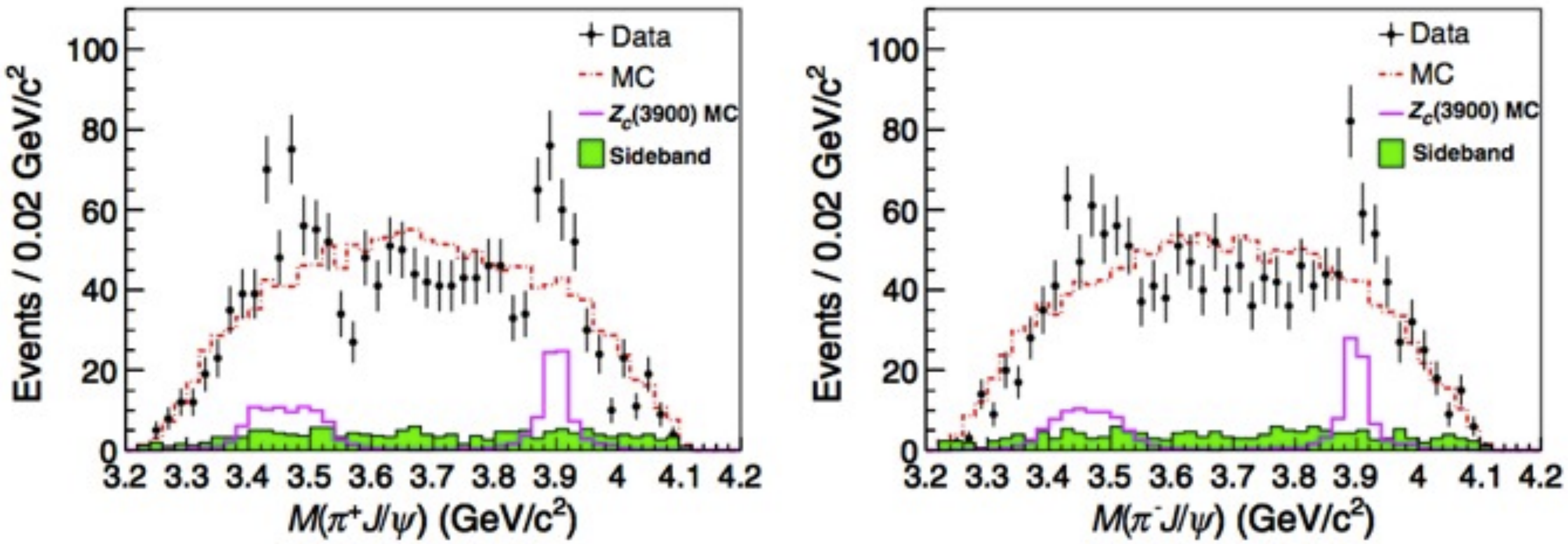
(LO) (NLO)

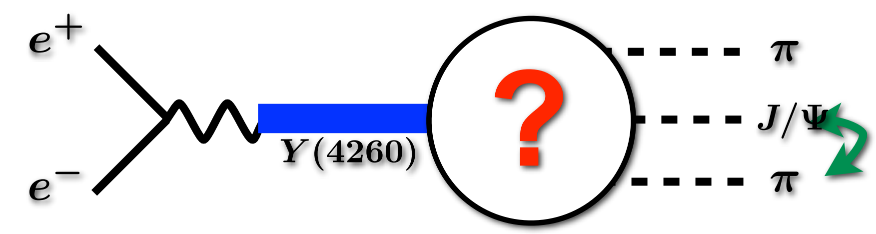
$$\Rightarrow V(\vec{r},\nabla) = V_C(\vec{r}) + \vec{L}\cdot\vec{S}V_{LS}(\vec{r}) + \mathcal{O}(\nabla^2)$$

✓ Calculate observable: phase shift, binding energy, pole position, ...

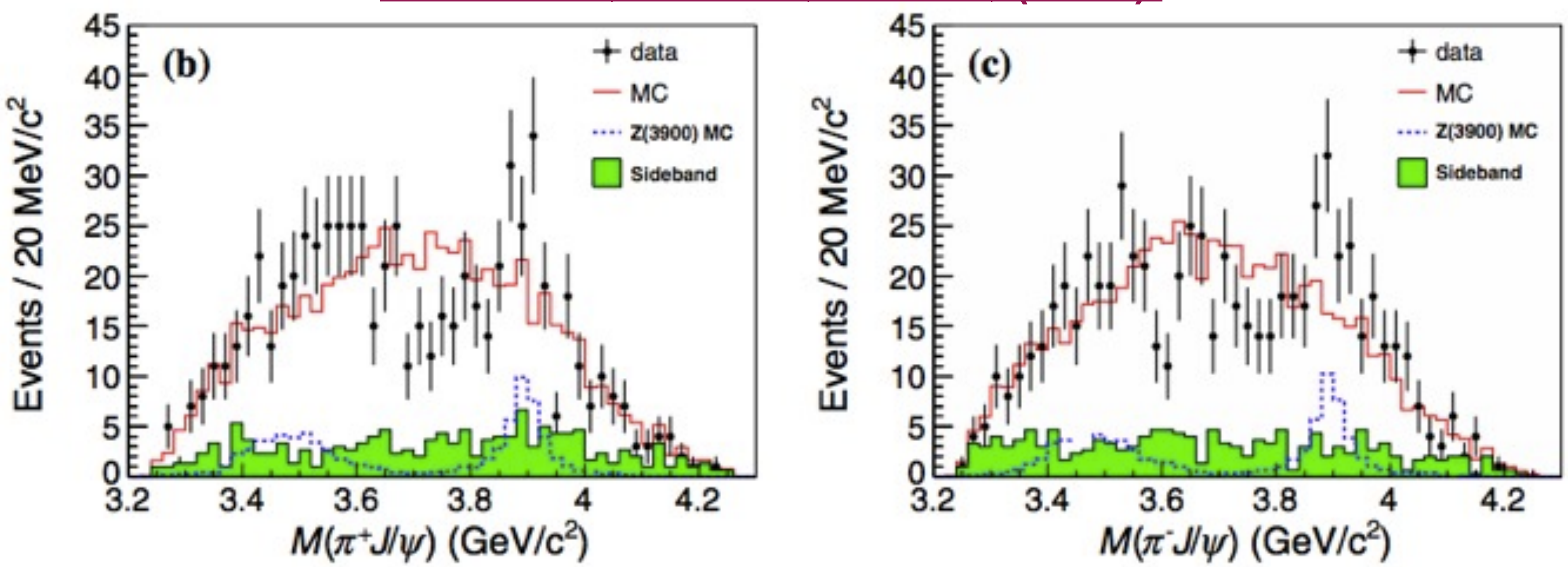
Lattice QCD simulations for Zc(3900) in $I^G(J^P)=1^+(1^+)$

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





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



Lattice QCD setup

N_f=2+1 full QCD configurations generated by PACS-CS Coll.

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)

Light meson mass [conf.1, conf.2, conf.3] (MeV)
M_π=701(1), 572(1), 411(1) [PDG:135 (π^0)]
M_ρ=1097(4), 1000(5), 896(8) [PDG:770 (ρ^0)]

Tsukuba-type Relativistic Heavy Quark (RHQ) action for charm quark

S. Aoki et al., PTP109, 383 (2003).

➡ remove leading cutoff errors O(m_c a), O(Λ_{QCD} a), ...

- We are left with O($(a\Lambda_{QCD})^2$) error (~ a few %)
- We employ RHQ parameters tuned by Namekawa et al.

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

Charmed meson mass [conf.1, conf.2, conf.3] (MeV)
$M_{\eta c}$=3024(1), 3005(1), 2988(1) [PDG:2981]
$M_{J/\psi}$=3143(1), 3118(1), 3097(1) [PDG:3097]
M_D=2000(1), 1947(1), 1903(1) [PDG:1865 (D^0)]
M_{D^*}=2159(2), 2101(2), 2056(3) [PDG:2007 (D^{*0})]

Lattice QCD setup : thresholds

✦ Thresholds in $I^G J^P = 1^+ 1^+$ channel

Physical thresholds

- $D^{bar}D^*$ = 3872
- $\pi\psi'$ = 3821
- $\pi\pi\eta_c$ = 3256
- $\pi J/\psi$ = 3232

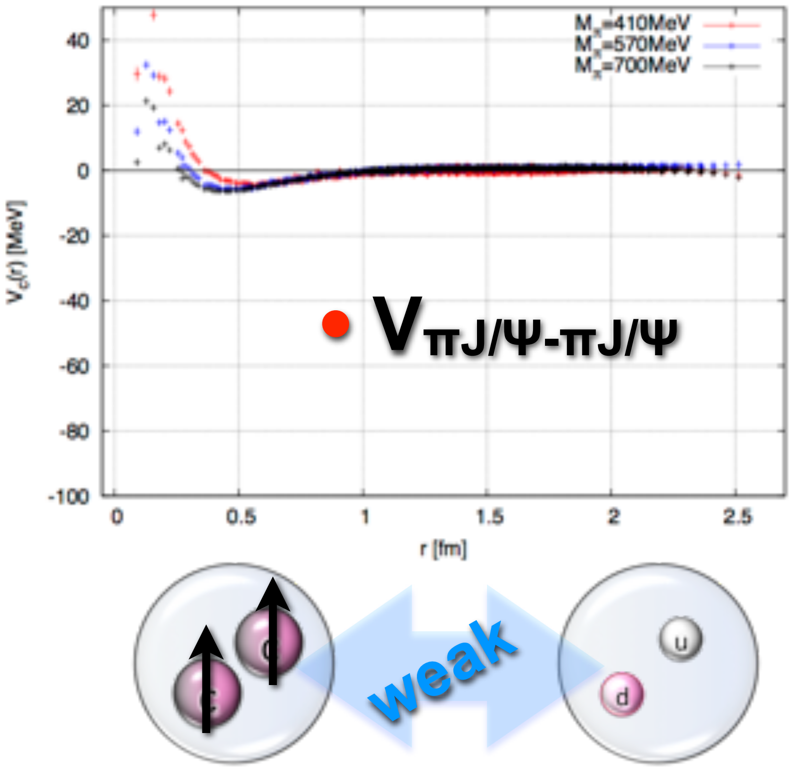
LQCD simulation

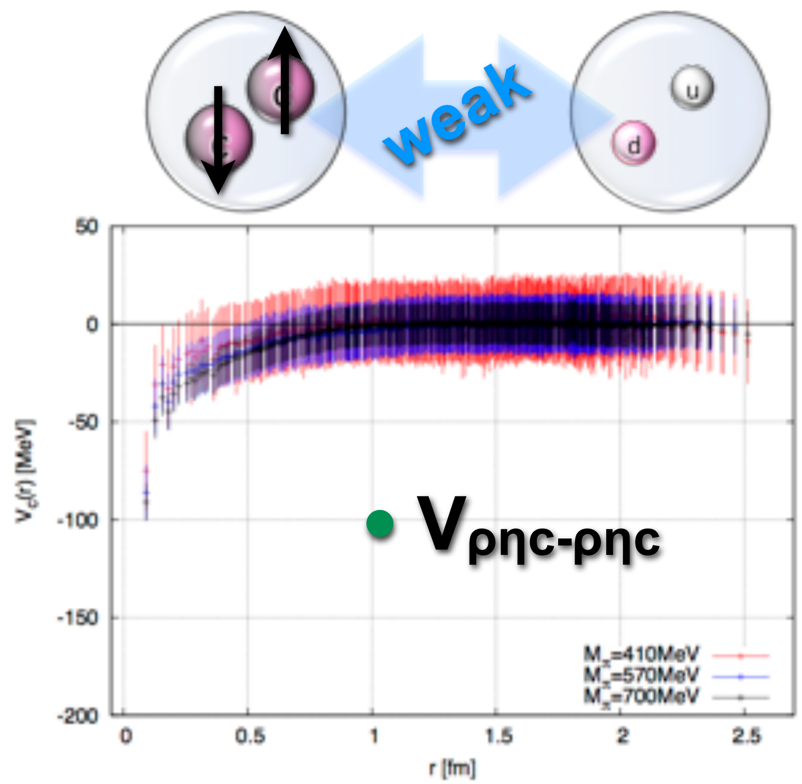
- $D^{bar}D^*$ = 4159, 4048, 3959
- $\rho\eta_c$ = 4121, 4005, 3884
- $\pi J/\psi$ = 3844, 3688, 3508

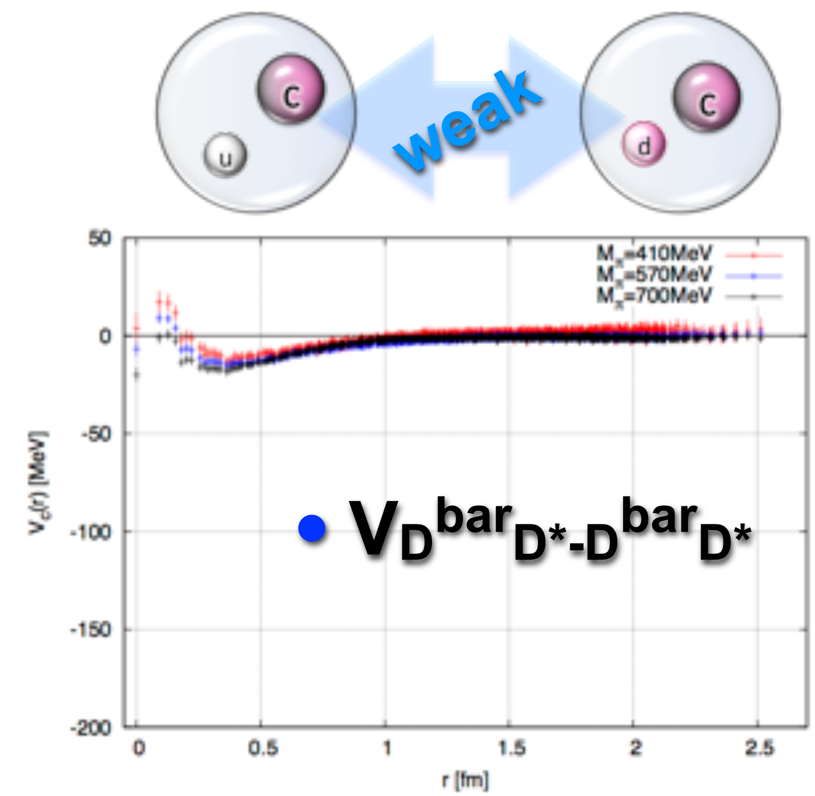
- $M_{\pi\psi'} > M_{D^{bar}D^*}$ due to heavy pion mass
- ρ-->ππ decay not allowed w/ L~3fm

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

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



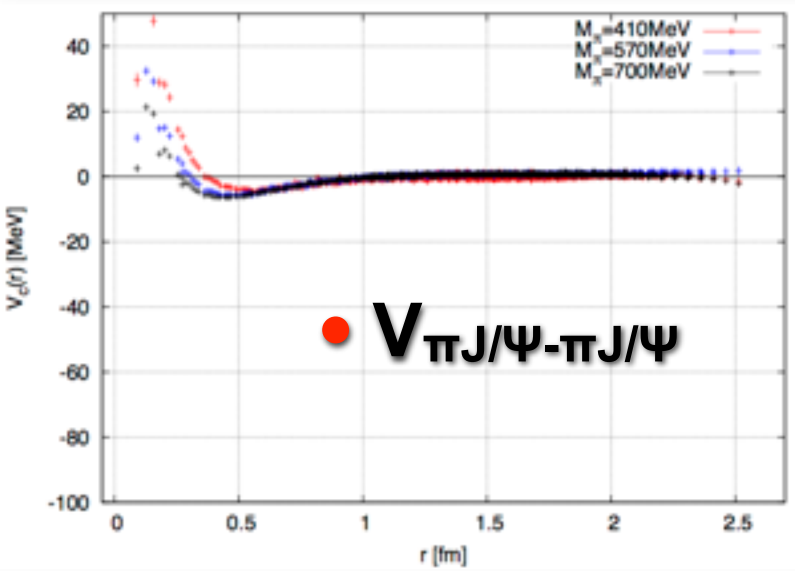


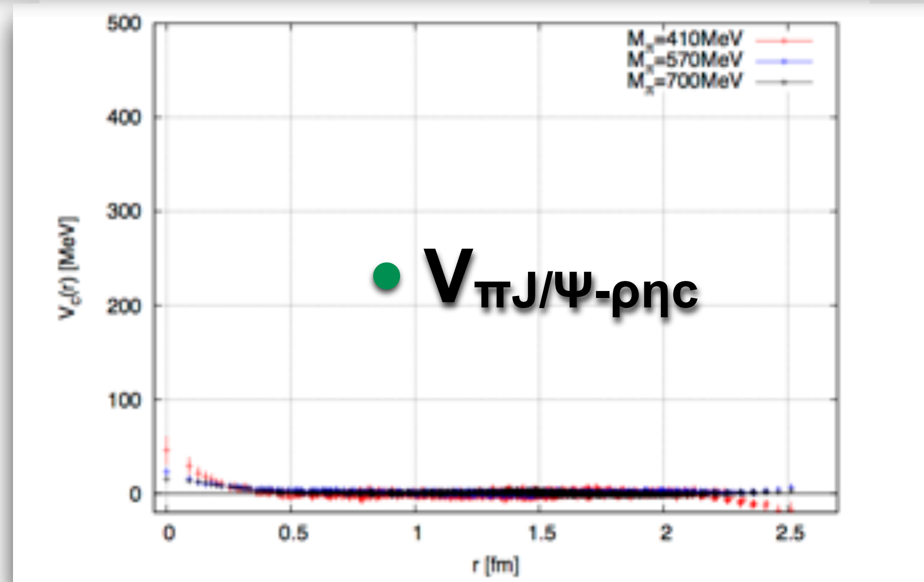


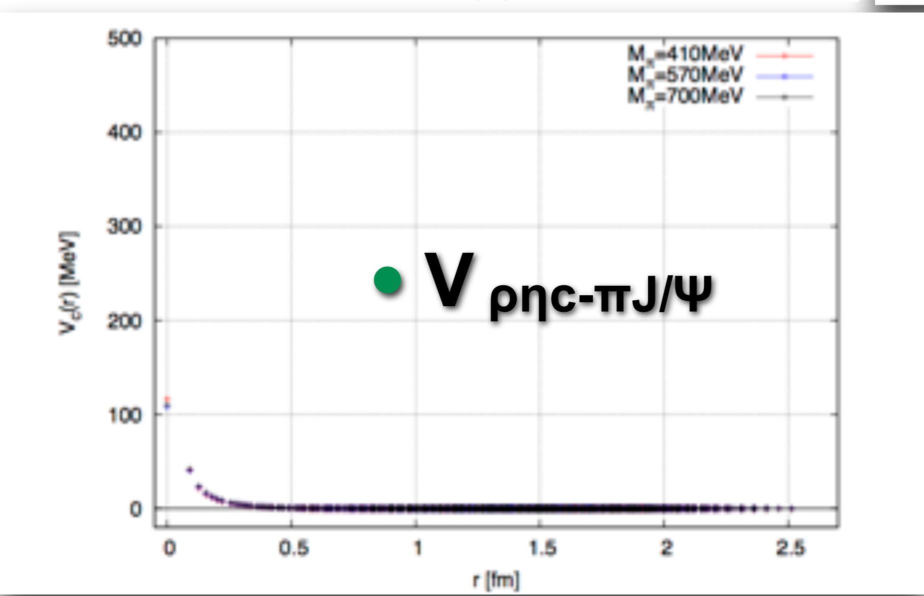
- **All diagonal potentials are weak**

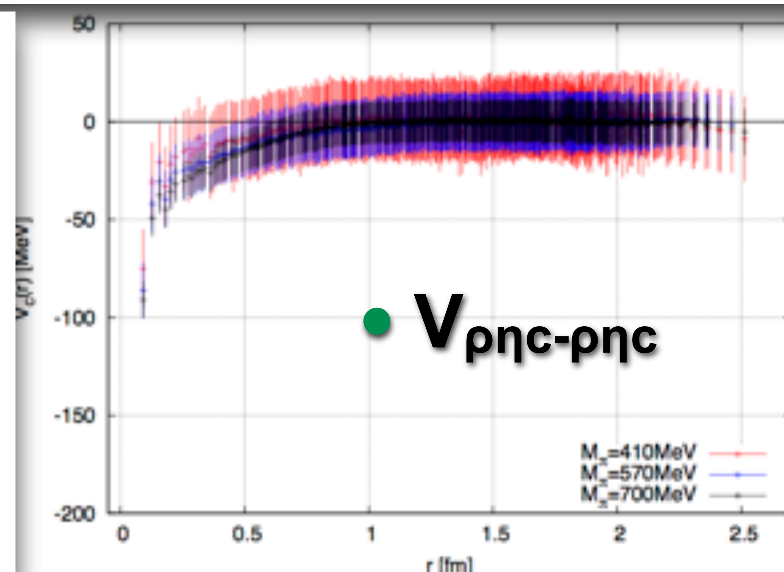
  ➡ **no bound $D^{bar}D^*$**

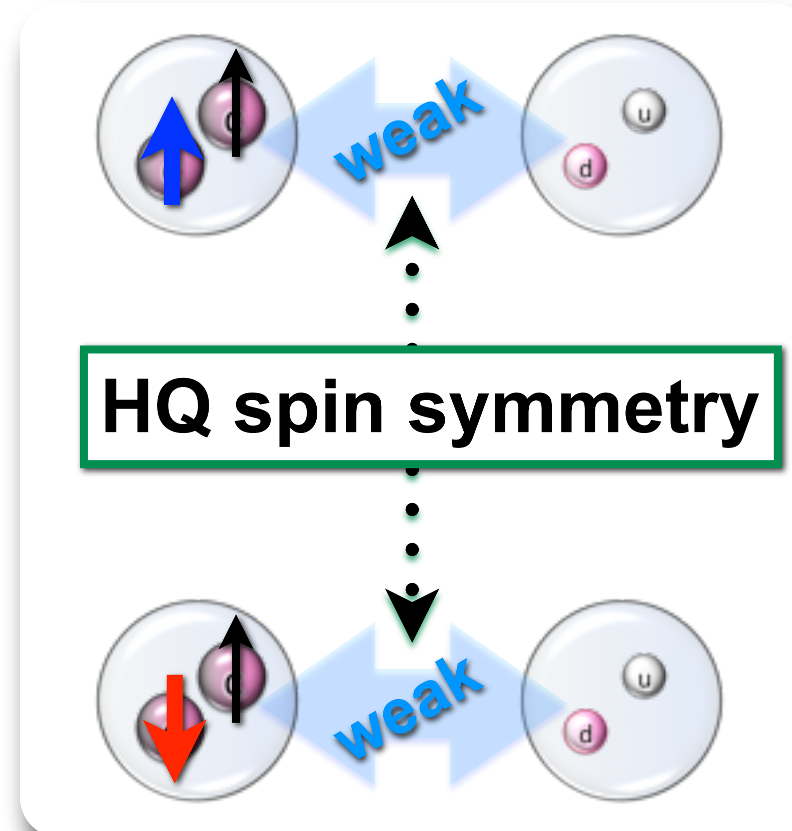
Potential matrix (πJ/ψ - ρη$_c$ - D^{bar}D*)







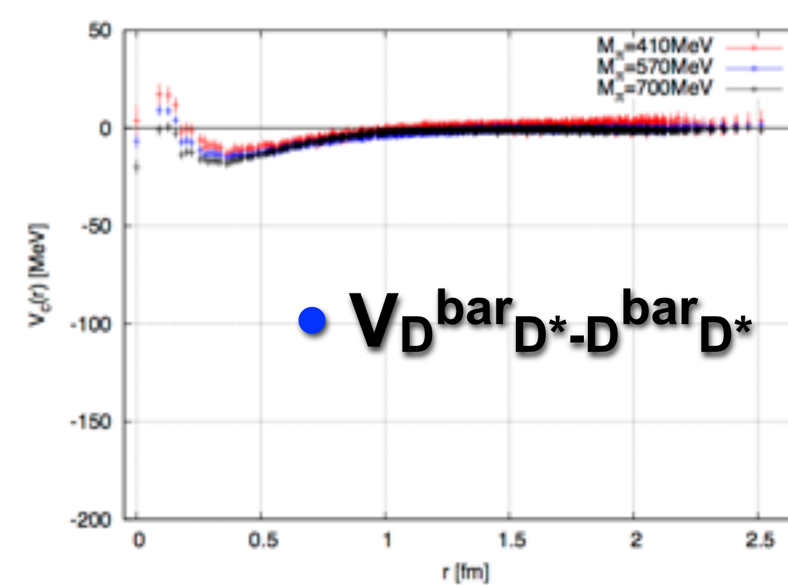




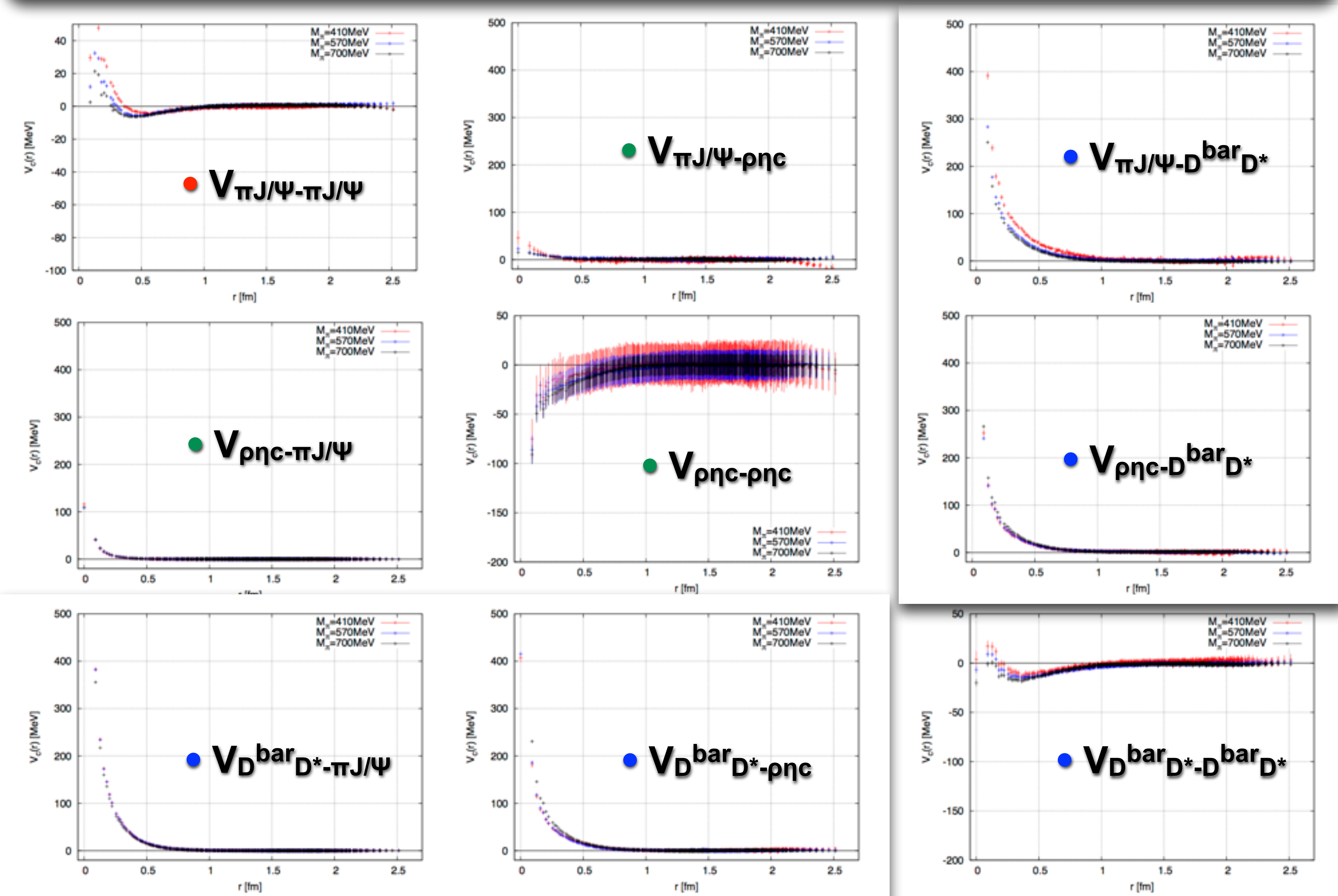
- **Weak charm spin-flip potential**

➡ **heavy quark spin symmetry**

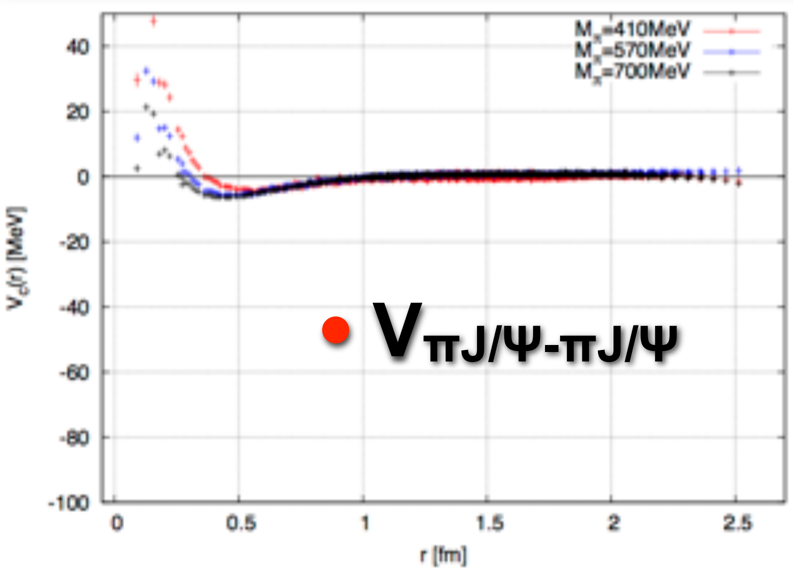
(charm quark spin-flip amplitude is suppressed)

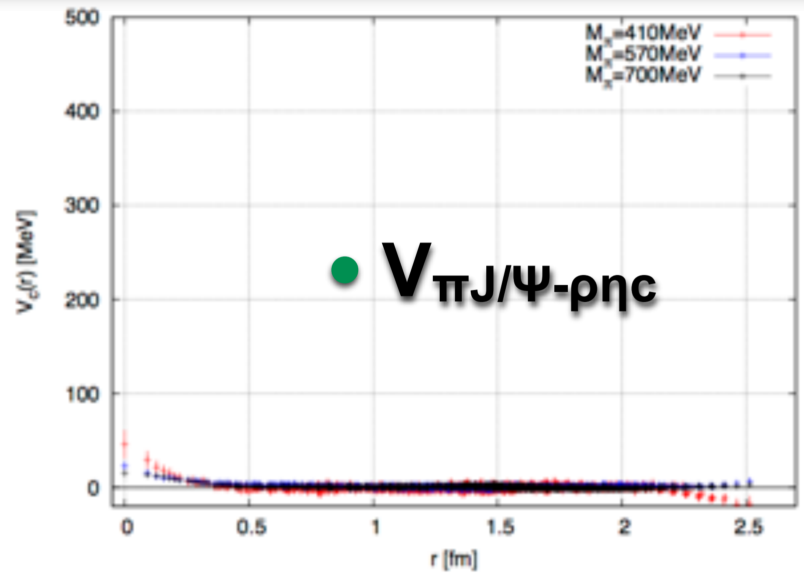


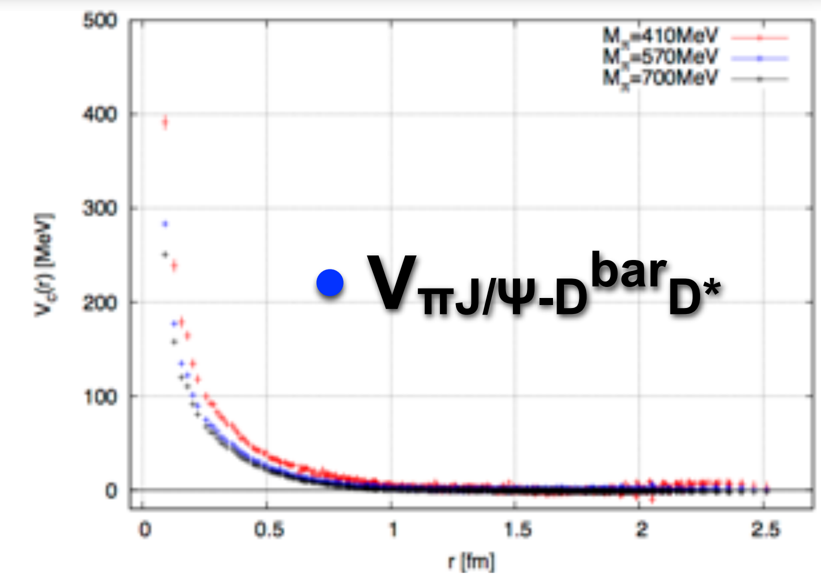
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)

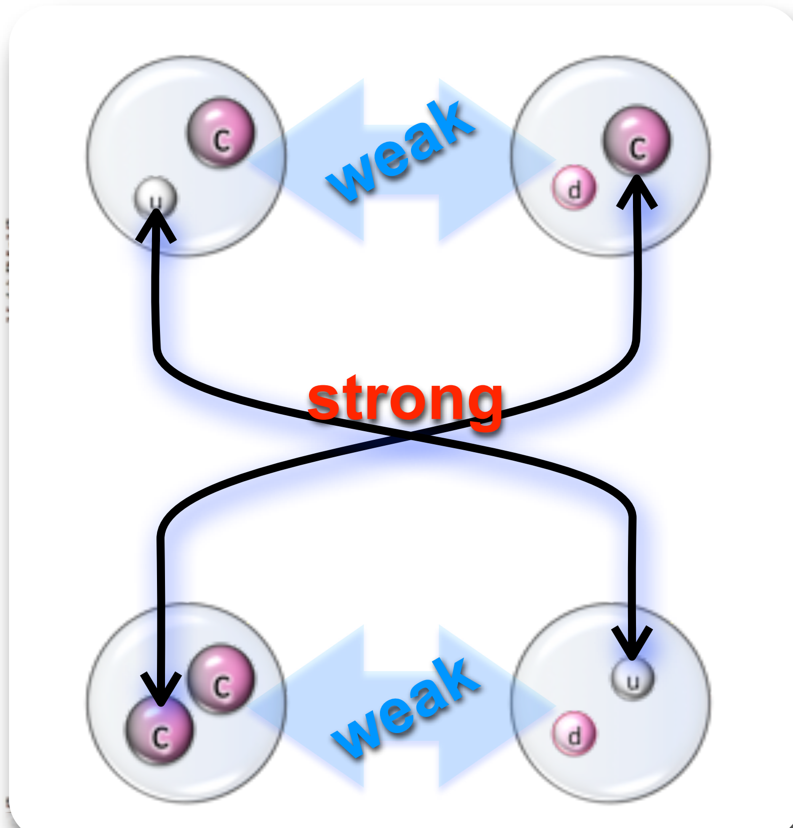


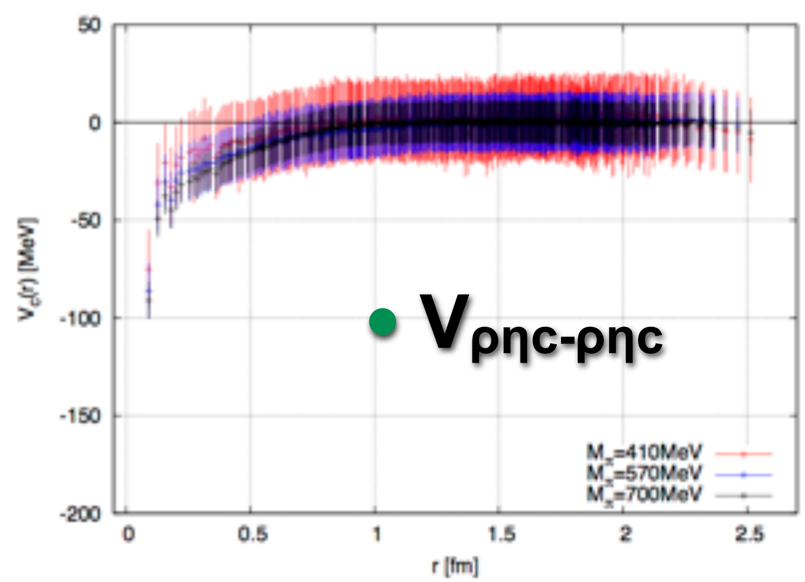
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)

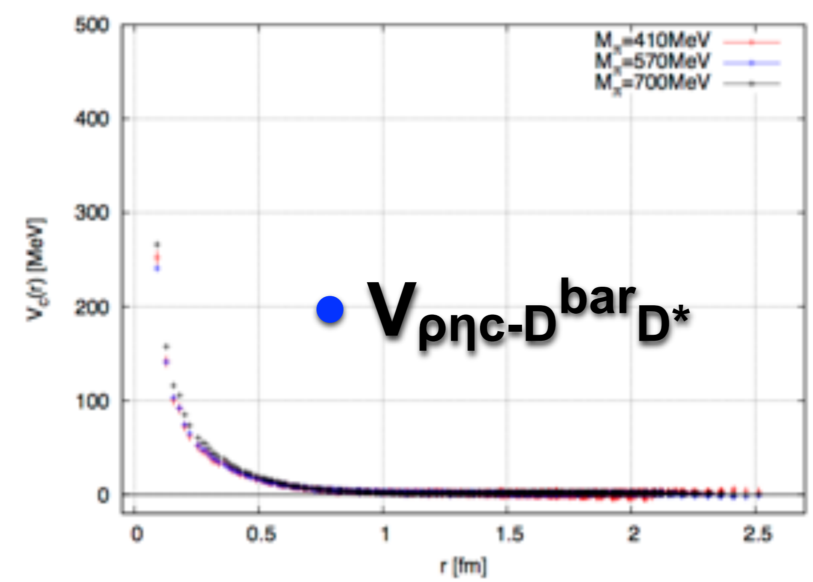


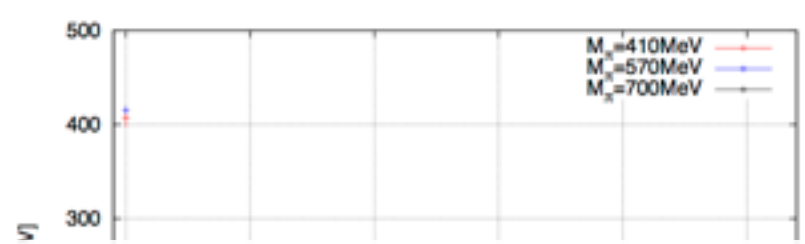


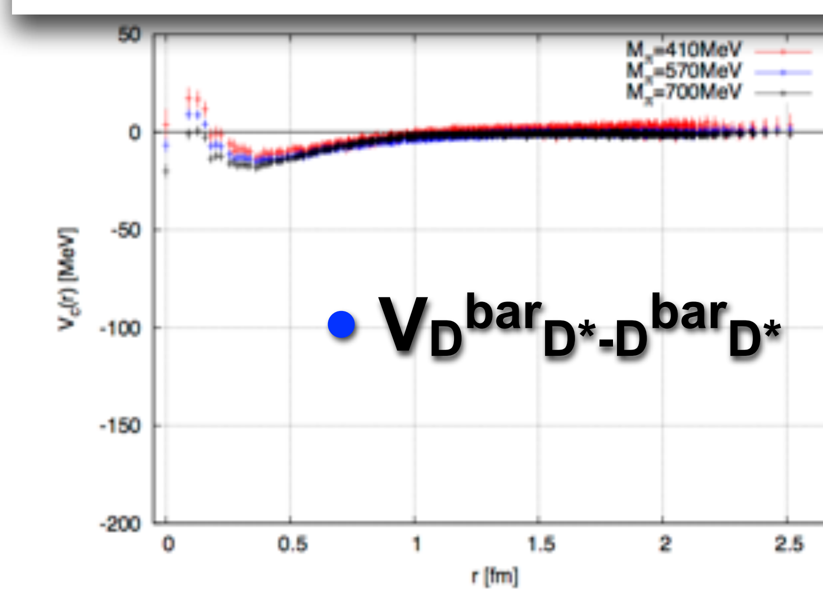






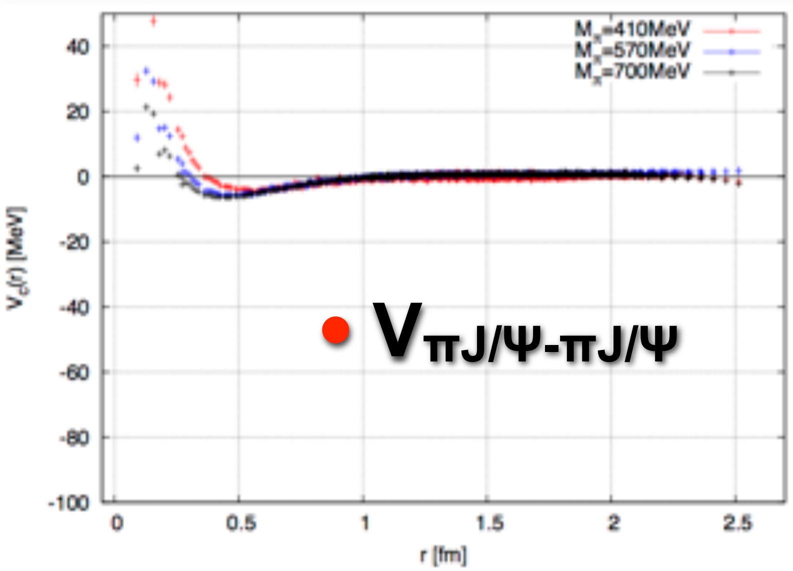


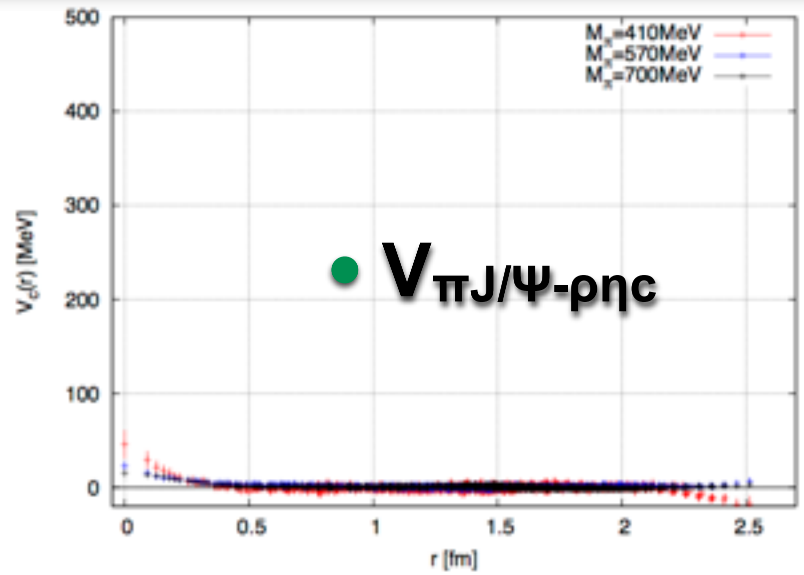


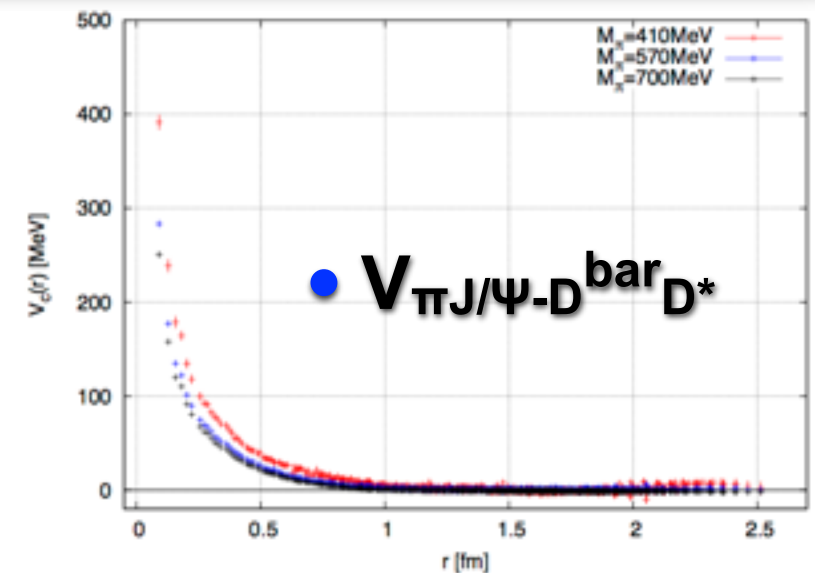


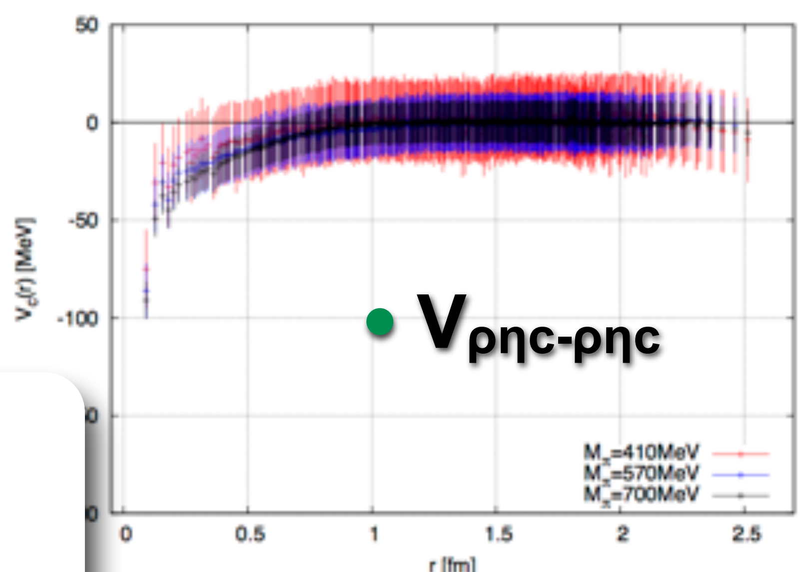
- **Strong off-diagonal $D^{bar}D^*$ potentials**
  - ✓ **strong charm-quark-exchange interactions**

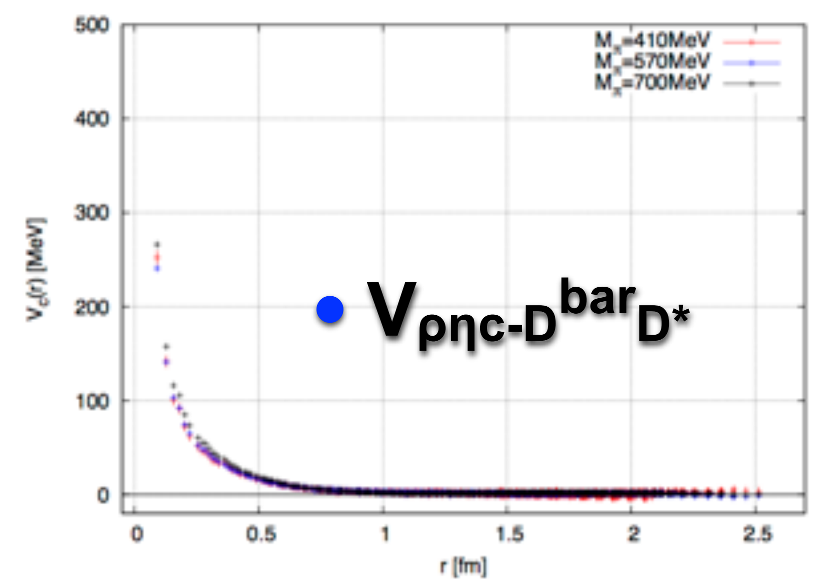
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $\bar{D}D^*$)

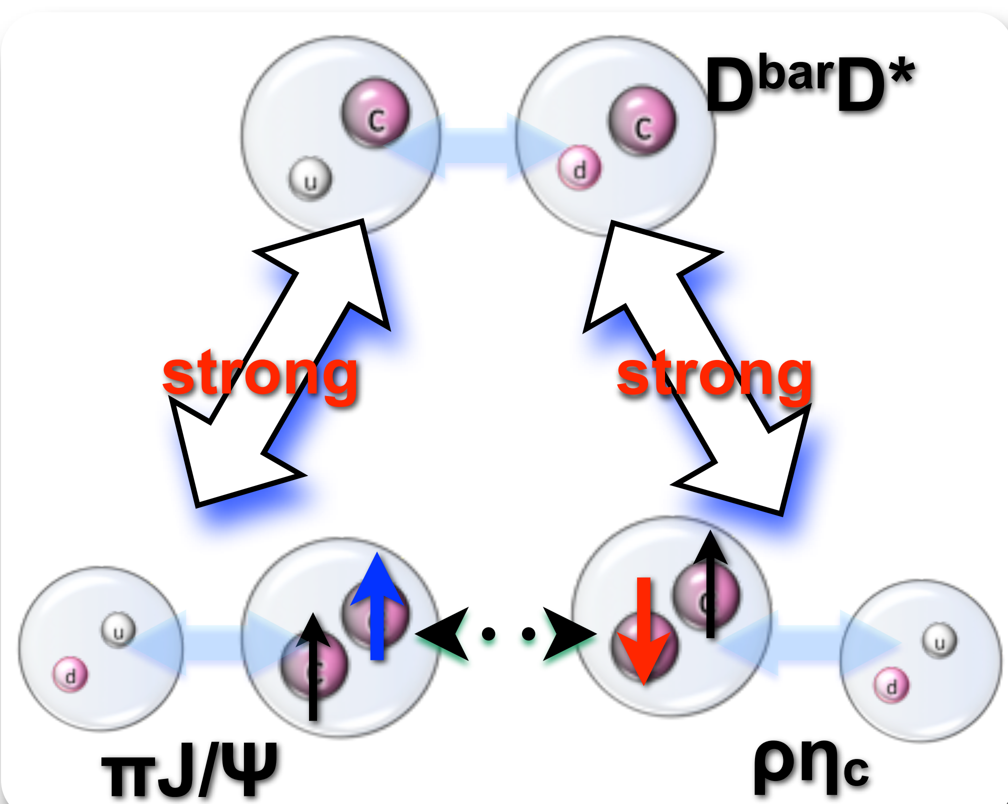


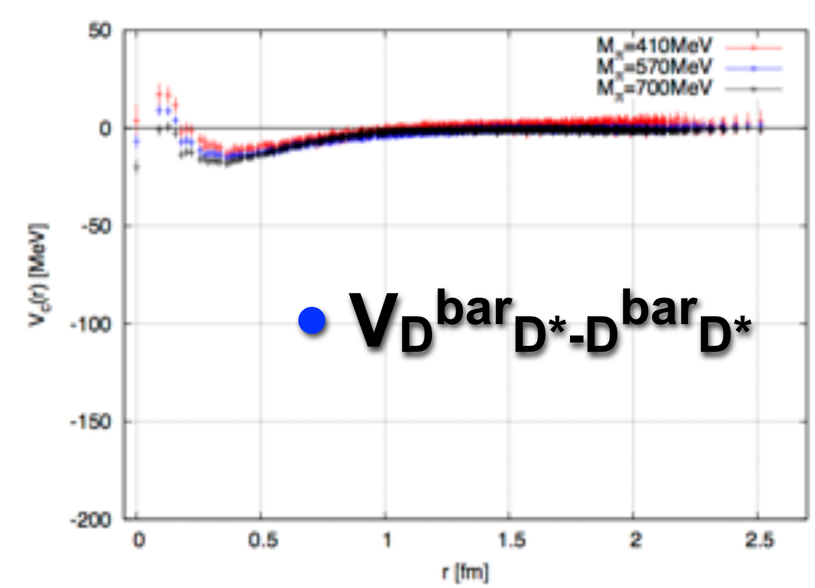






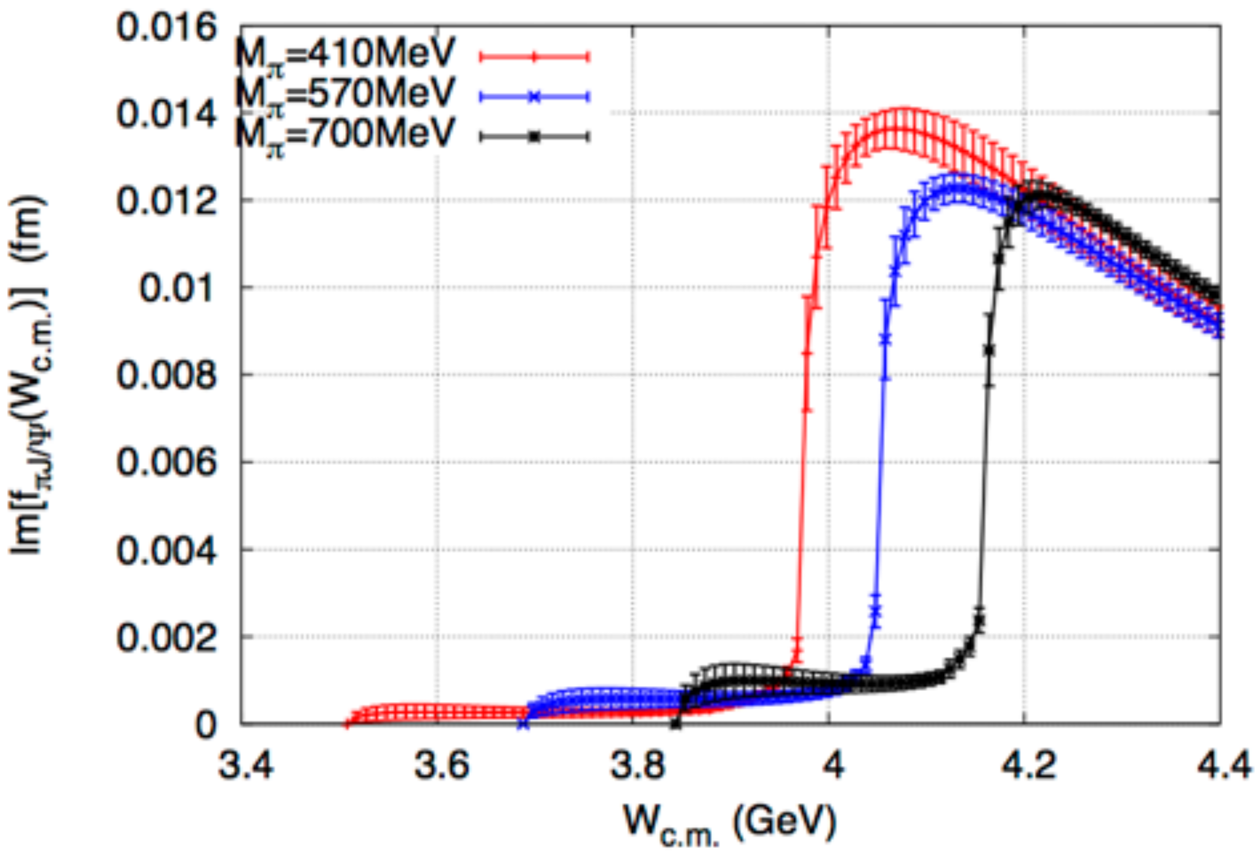




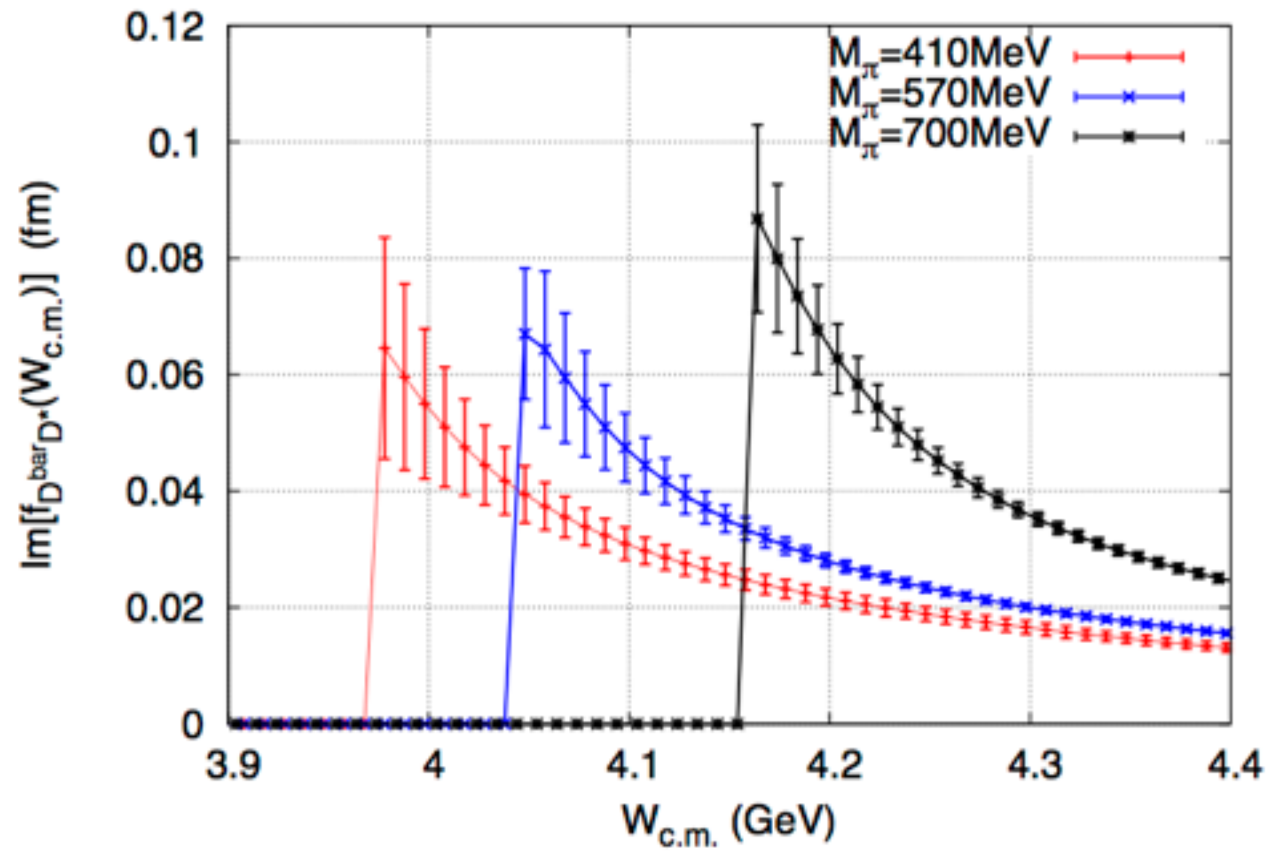


2-body scattering & inv. mass spectra

- $\pi J/\psi$ invariant mass



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



✓ enhancement near $D^{bar}D^*$ threshold due to large $\pi J/\Psi$-$D^{bar}D^*$ coupling

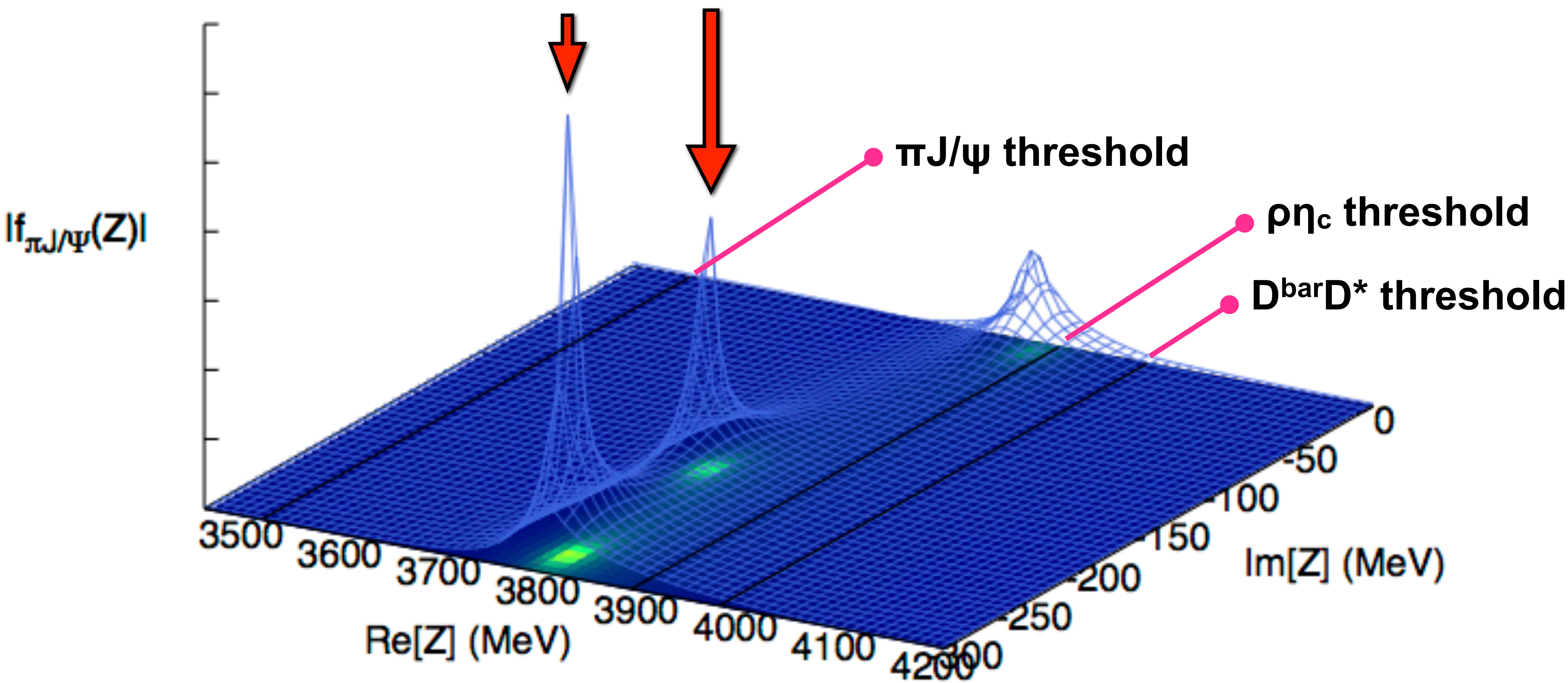
- peak in $\pi J/\psi$ invariant mass
- enhancement (cusp?) in $D^{bar}D^*$ invariant mass

(No m_q dependence on qualitative behaviors of line shapes)

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

✤ **input : LQCD potential matrix @ m_π=410MeV**

Poles of S-matrix

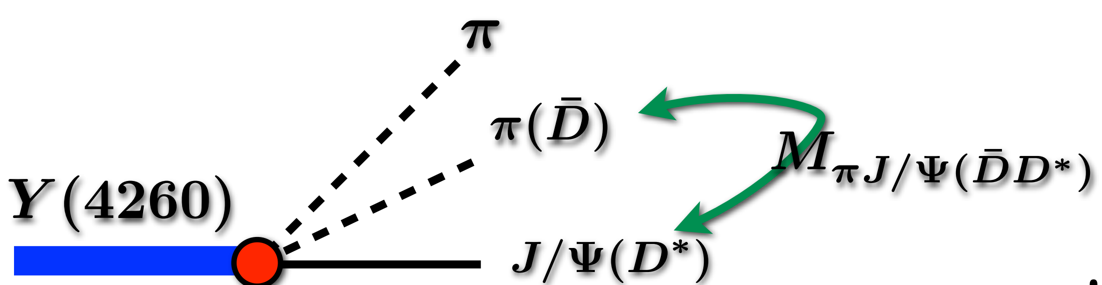


✓ "**Virtual (shadow)**" poles on the most adjacent complex energy plane for Z_c(3900) energy region are found

✓ These poles contribute to threshold enhancement of amplitude

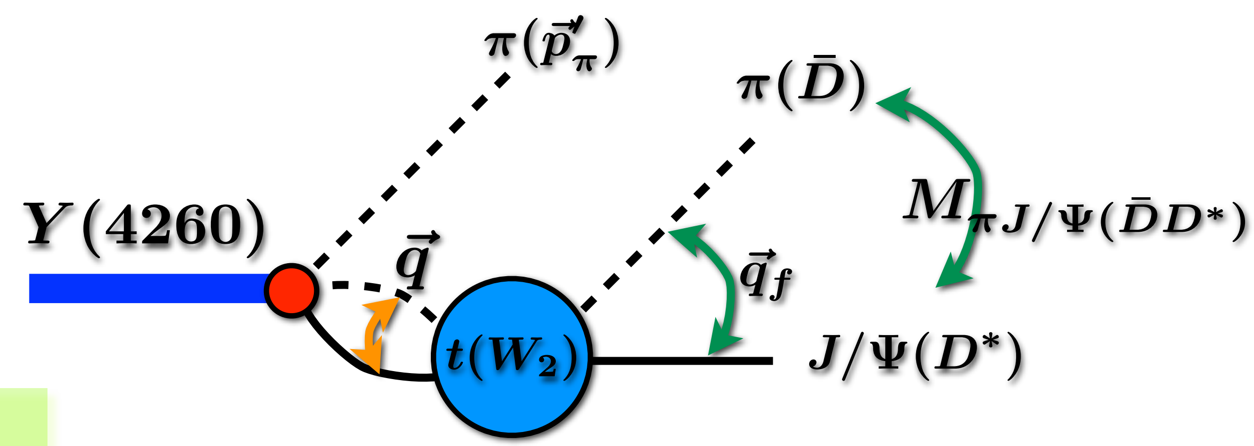
Three-body decay of Y(4260)

$$d\Gamma \propto (2\pi)^4 \delta^4(P - p'_\pi - p_{\pi(\bar{D})} - p_{J/\Psi(D^*)}) d^3p'_\pi d^3p_{\pi(\bar{D})} d^3p_{J/\Psi(D^*)} \sum_f |T_{if}|^2$$



➡ constant Y(4260) decay vertex is assumed

+



➡ LQCD input (NO free parameter)

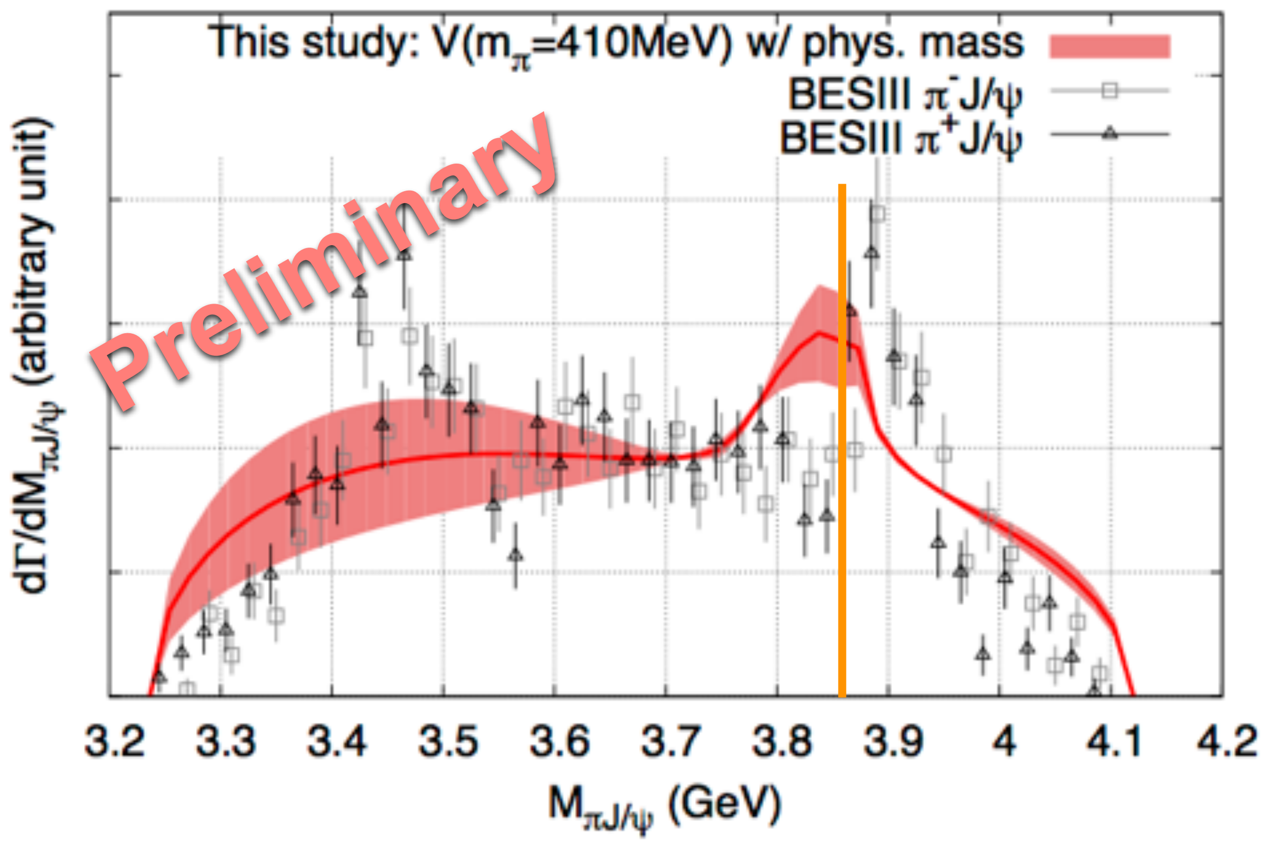
$$T_{if}(\vec{p}'_\pi, \vec{q}_f; W_3) = \sum_{n=\pi J/\Psi, \bar{D}D^*} C_n \left[\delta_{nf} + \int d^3q \frac{1}{W_3 - E_\pi(\vec{p}'_\pi) - E_n(\vec{q}, \vec{p}'_\pi) + i\epsilon} t(\vec{q}, \vec{q}_f) \right]$$

physical hadron masses employed & S-wave calculation

✓comparison with expt. data

✓property of Y(4260) decay

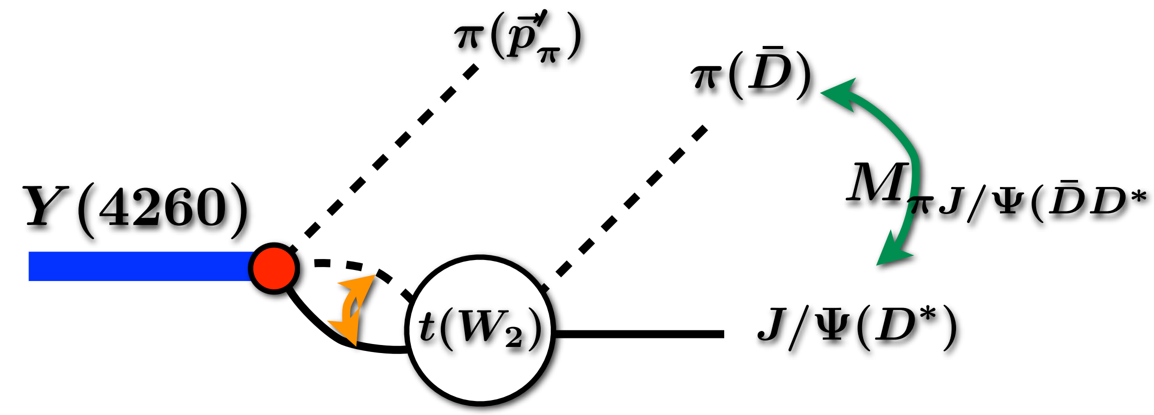
Invariant mass spectra (πJ/ψ & $D^{bar}D^*$)

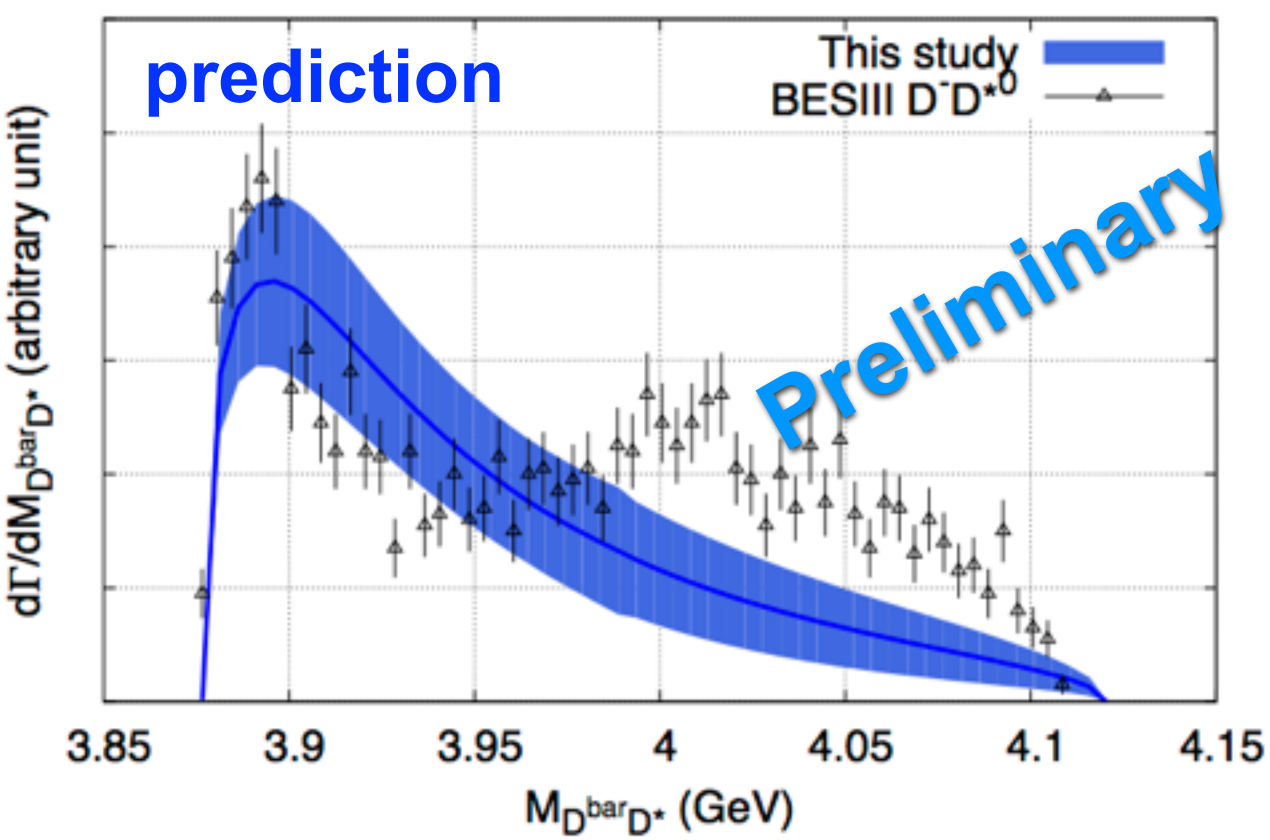


parameters: $C_{D^{bar}D^*}/C_{\pi J/\psi} = Re^{i\theta}$

--> R=0.95(18), θ=-58(44) deg.

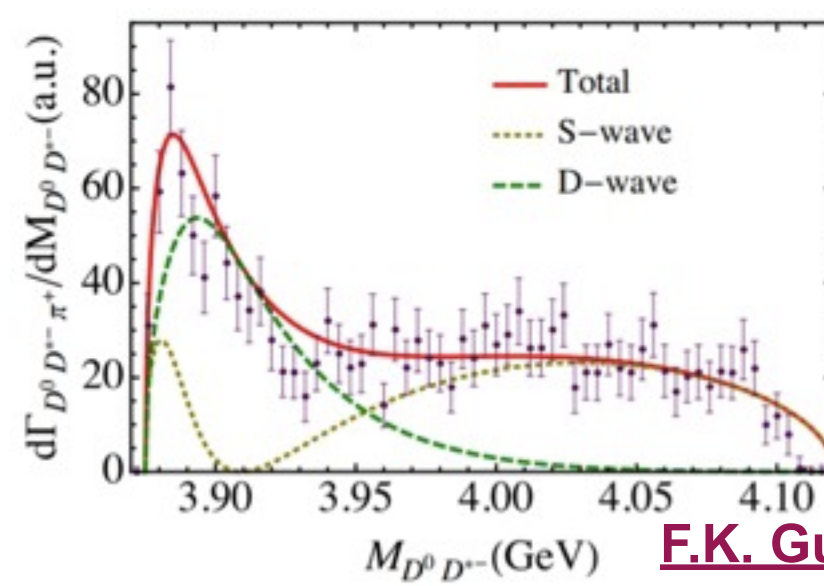
- Not only $D^{bar}D^*$ but also πJ/ψ loop is important for Y(4260) decay





- Qualitatively good line shape
- Deviation from EXPT. data at high energies

--> higher partial wave??



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Summary

✤ Applications of coupled-channel HAL QCD method

• Zc(3900) in $I^G(J^P)=1^+(1^+)$ channel on the lattice@m_π=410-700MeV

➡ Large channel coupling between $\pi J/\Psi$ and $D^{bar}D^*$ is a key

➡ Heavy quark spin symmetry is seen in c.c. potentials

➡ Similar line shape of inv. mass to EXPT. is observed

- Zc(3900) is neither simple $D^{bar}D^*$ molecule nor J/Ψ + π-cloud
- shadow poles on complex energy plane are found (w/ relatively large width)

✤ Physical point simulation is the next step

✤ Future targets

- other systems : Zc(4025), X(3872)
- extension to bottom systems