Zc(3900) from coupled-channel HAL QCD approach on the lattice

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HAL QCD (Hadrons to Atomic nuclei from Lattice QCD)

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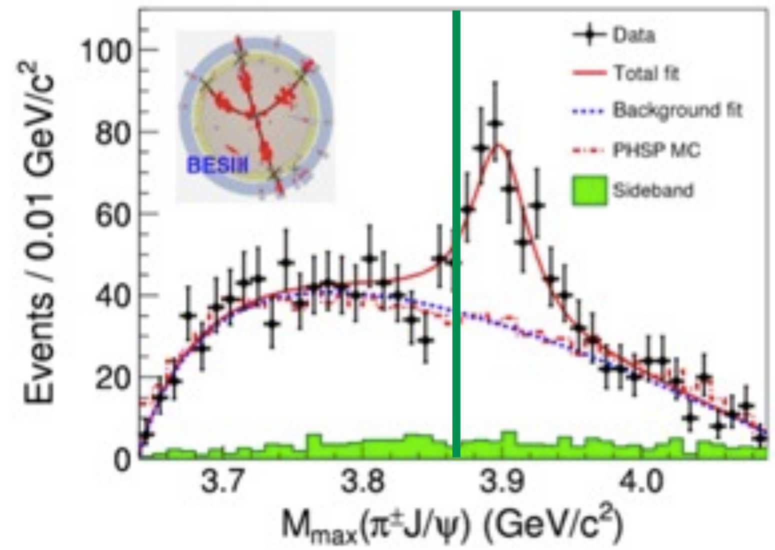
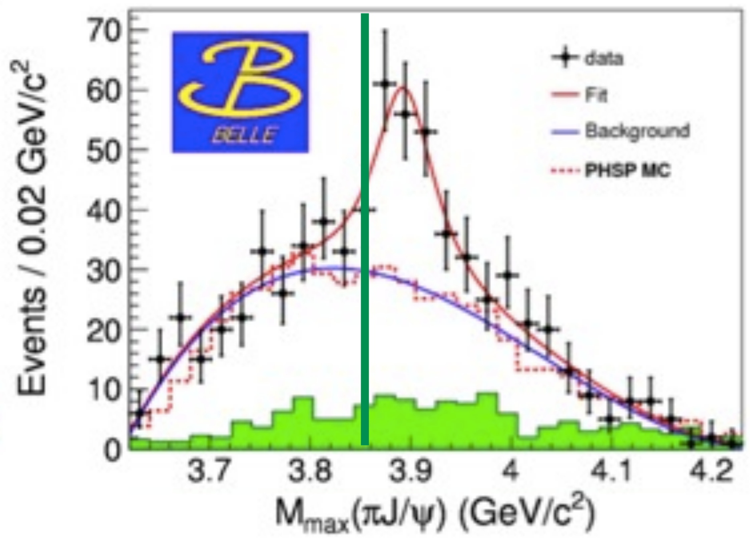
The 33rd International Symposium on Lattice Field Theory(Lattice2015)
@Kobe International Conference Center, Jul. 14--18, 2015.

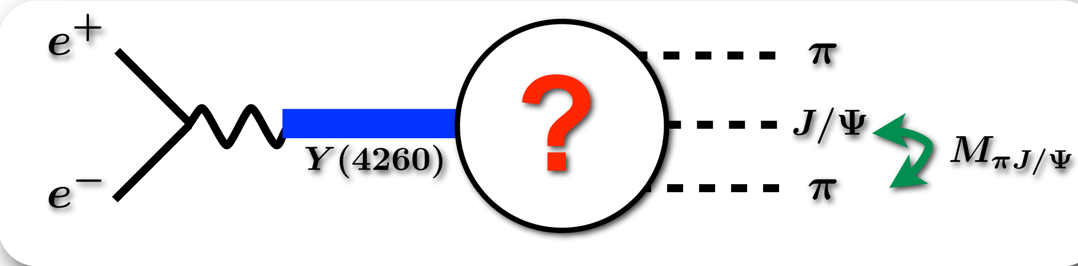
What is Zc(3900)?

BESIII Coll., PRL110 (2013).



Belle Coll., PRL110 (2013).





- observed in $\pi^{\pm}J/\psi$ invariant mass spectra
- require 4 quarks ($c\bar{c}u\bar{d}$)
- $J^P = 1^+$ seems most probable

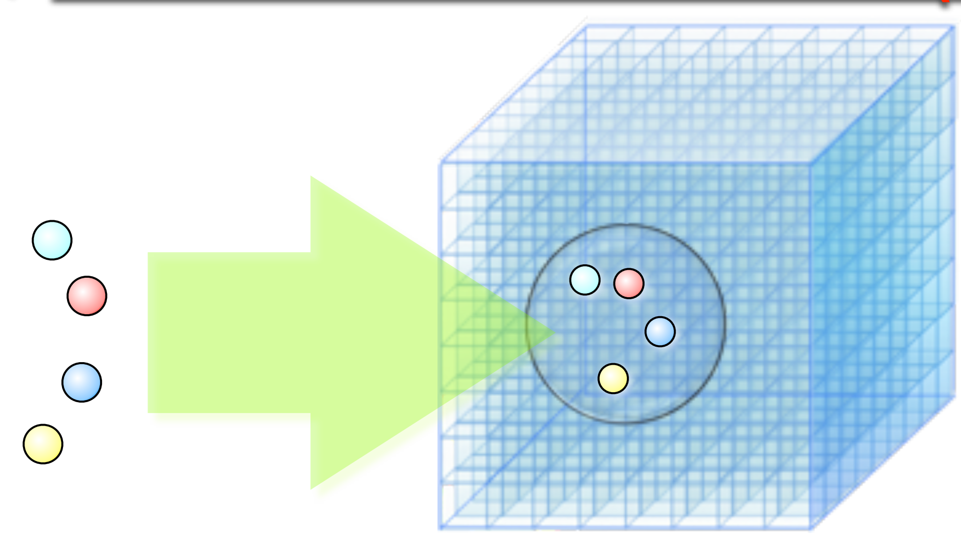
BESIII Coll., PRL112 (2014).

★ structure of Zc(3900) from models

- Tetraquark? Maiani et al. (2013).
- $\bar{D}D^*$ molecule? Nieves et al. (2011) + many others
- Charmo-hadronium? Voloshin (2008).
- cusp? Chen et al. (2013), Swanson (2015).

➡ poor information on interactions

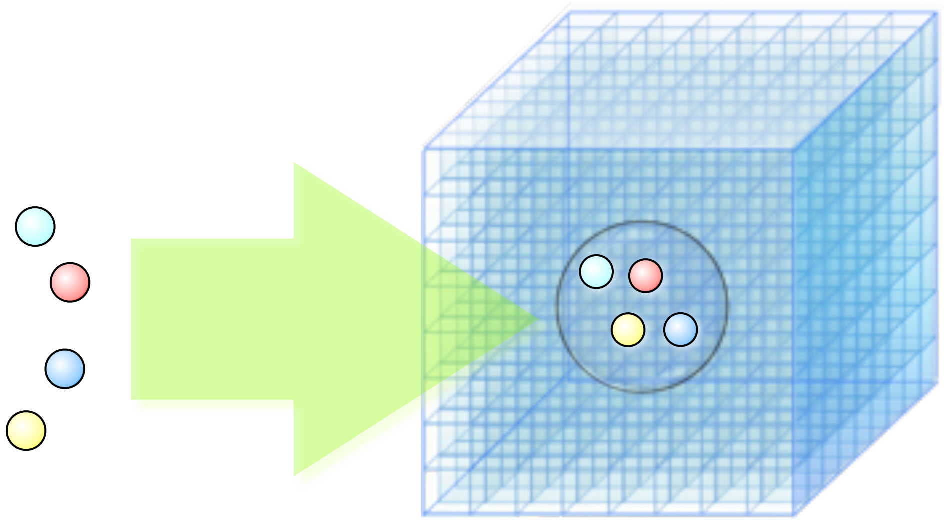
★ LQCD simulations for Zc(3900)



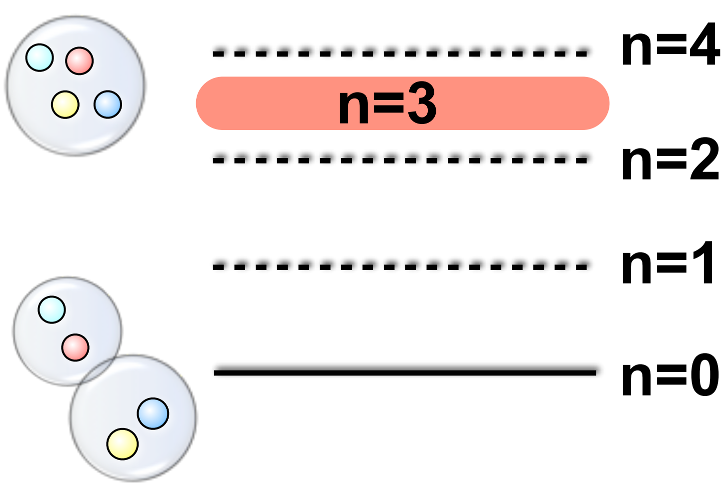
How to study Zc(3900) on the lattice?

✦ Conventional approach: LQCD spectrum

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



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



✓ **No positive evidence for Zc(3900)**

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? Kinematical effect?
- Key is S-matrix elements w/ coupled-channel

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

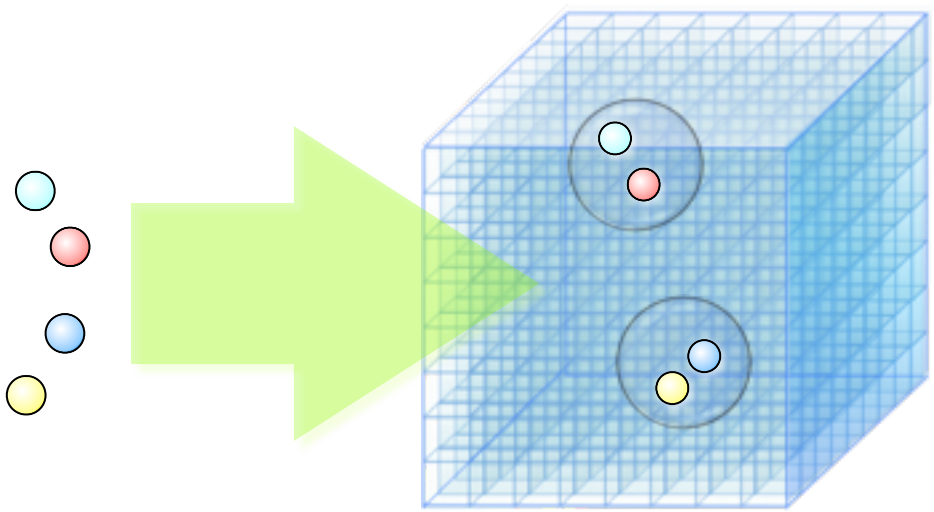
in practice, assumption about interaction kernels or K-matrices necessary

How to study Zc(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).



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

★ *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') contains all 2PI contributions*

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

- measure wave functions in each channel
- 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).

Contents

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

- 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

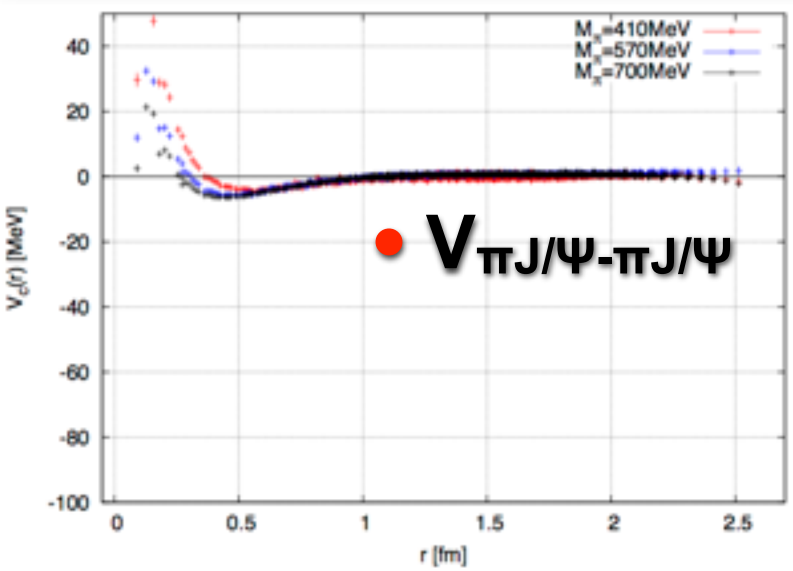
$\rho\eta_c$ = 4121, 4005, 3884

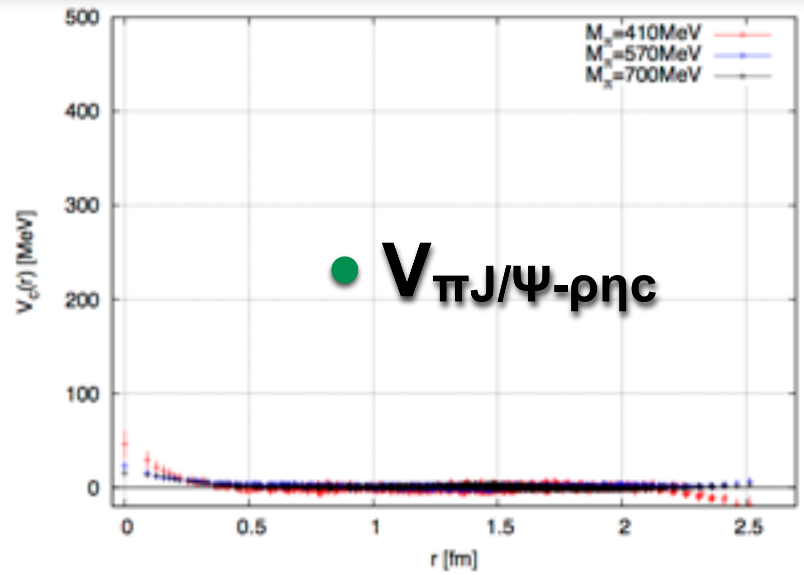
$\pi J/\psi$ = 3844, 3688, 3508

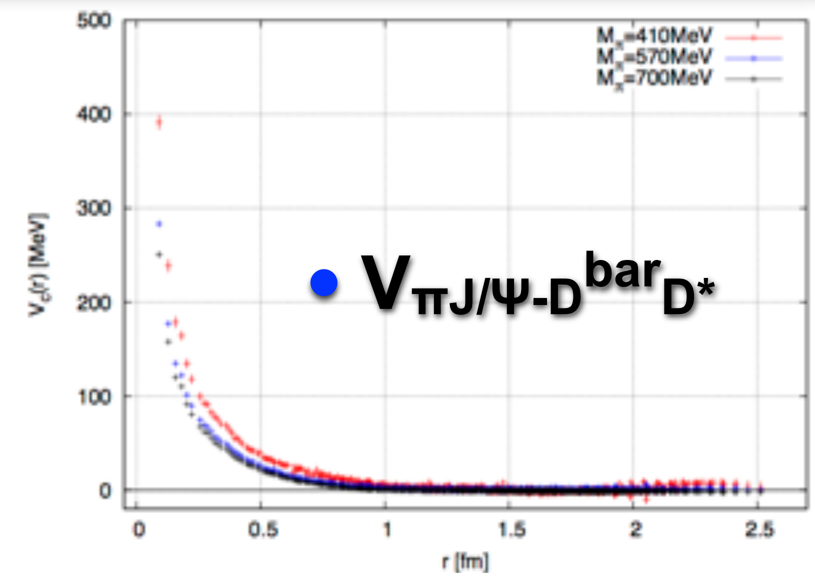
- $M_{\pi\psi'} > M_{D^{bar}D^*}$ due to heavy pion mass
- $\rho \to \pi\pi$ decay not allowed w/ L~3fm

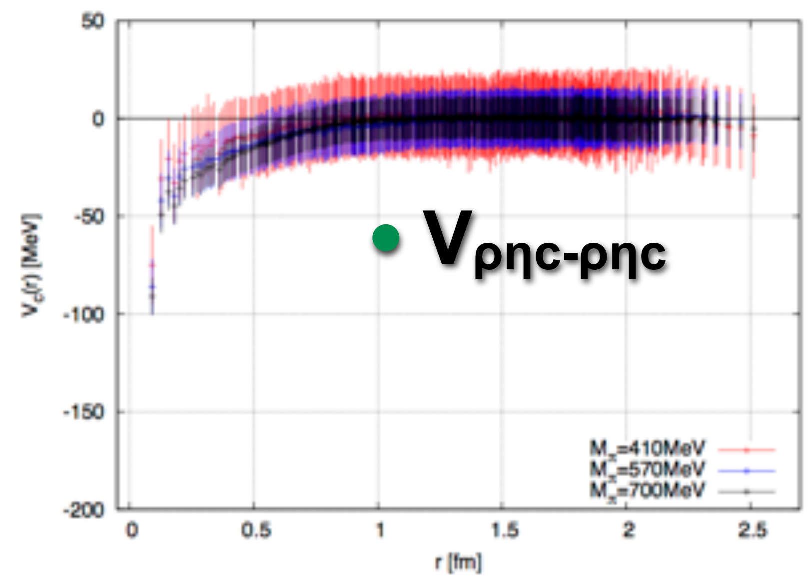
S-wave $\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$ coupled-channel analysis

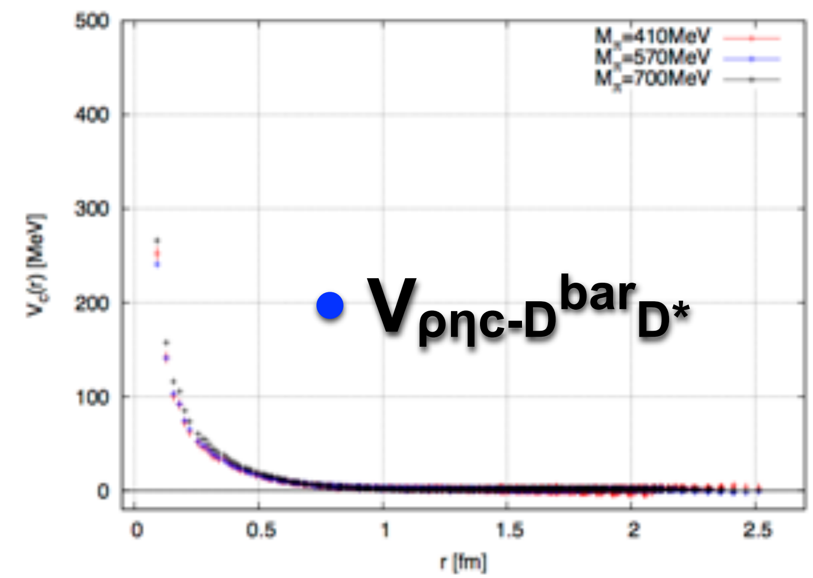
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)

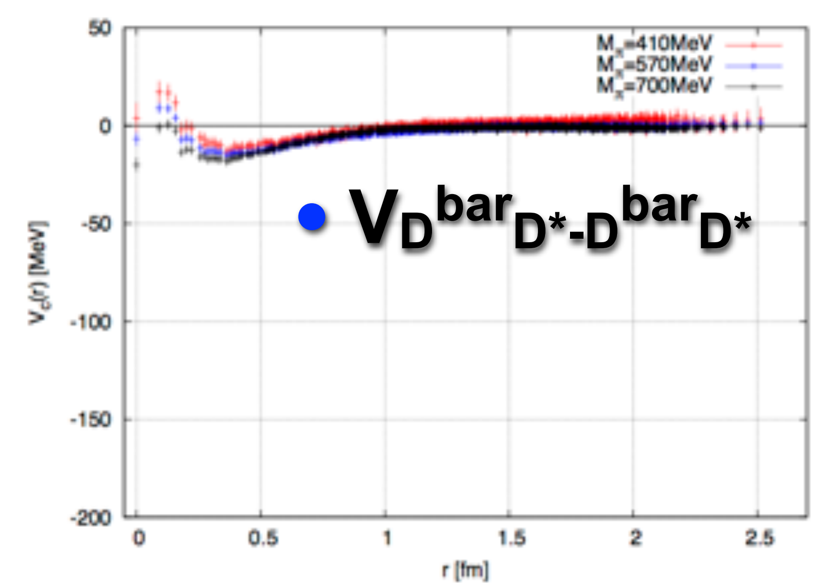




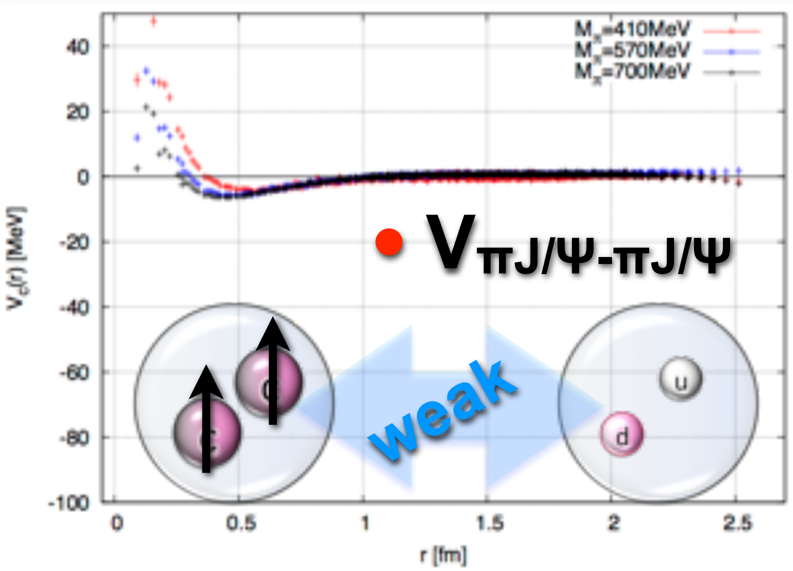


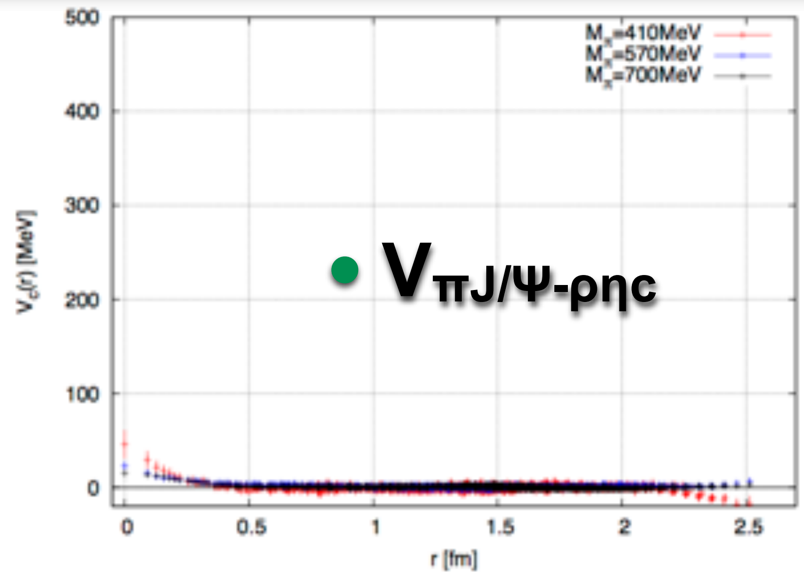


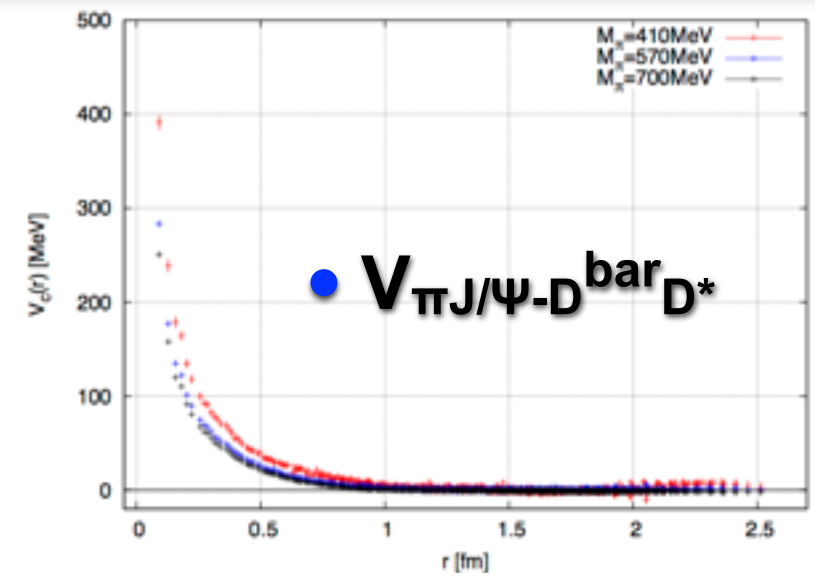


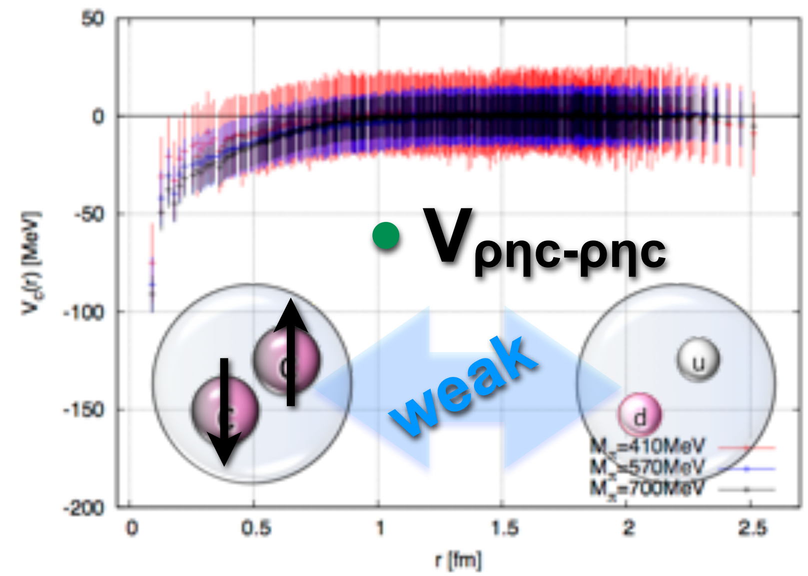


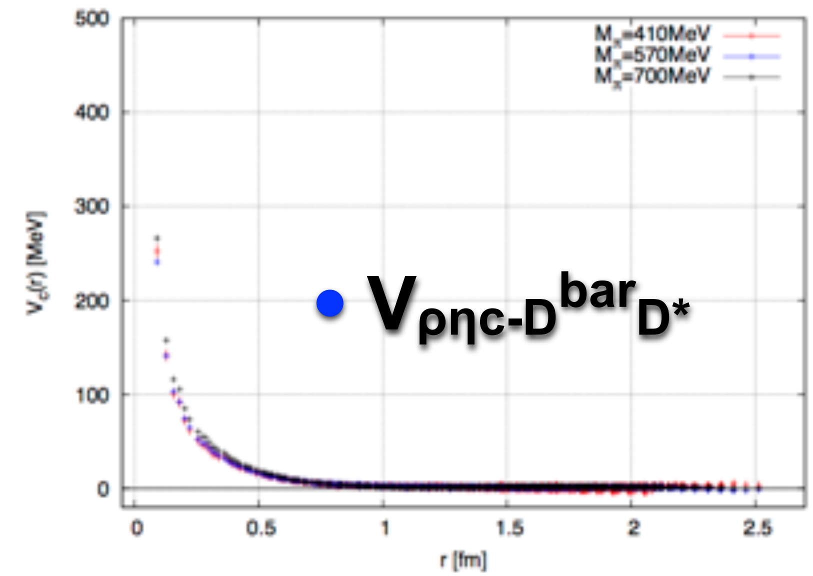
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)

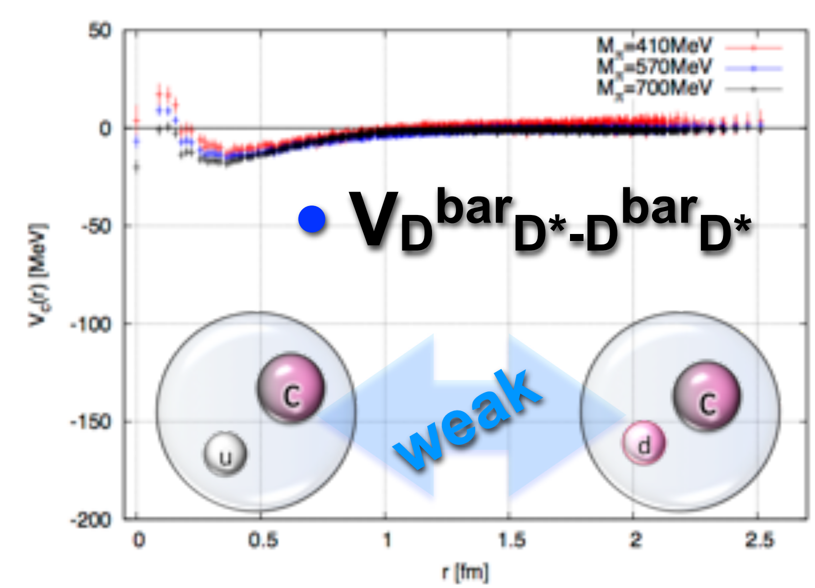








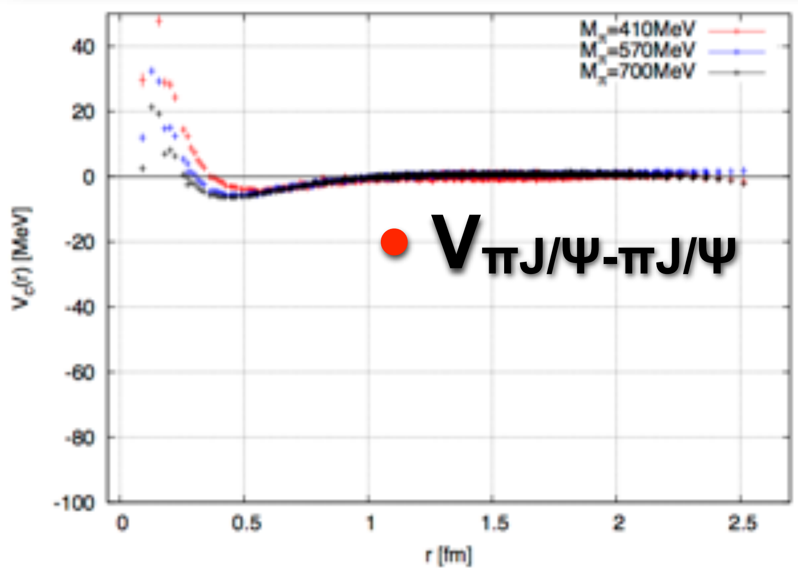


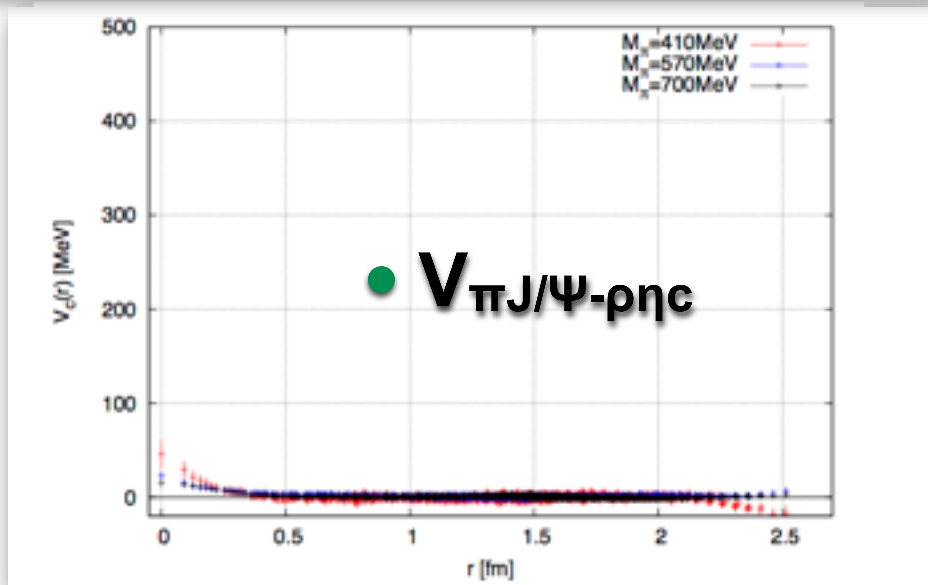


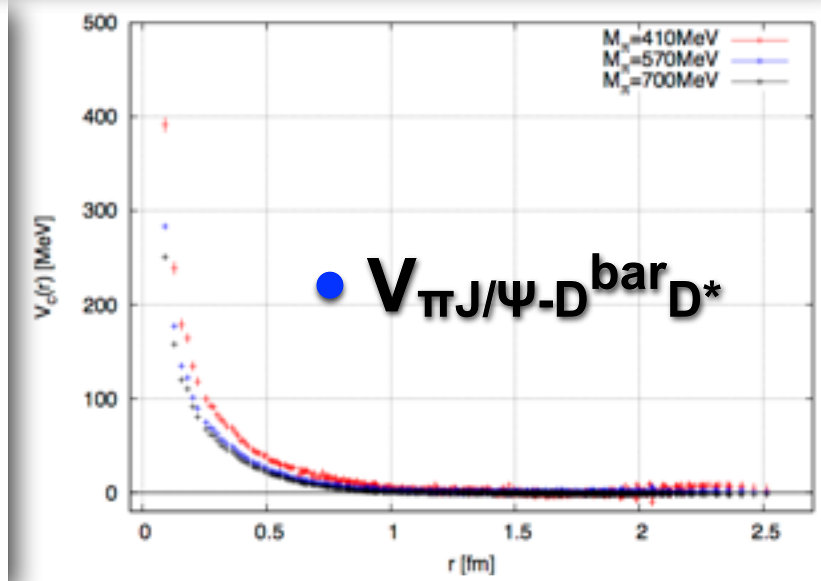
- **All diagonal potentials are weak**

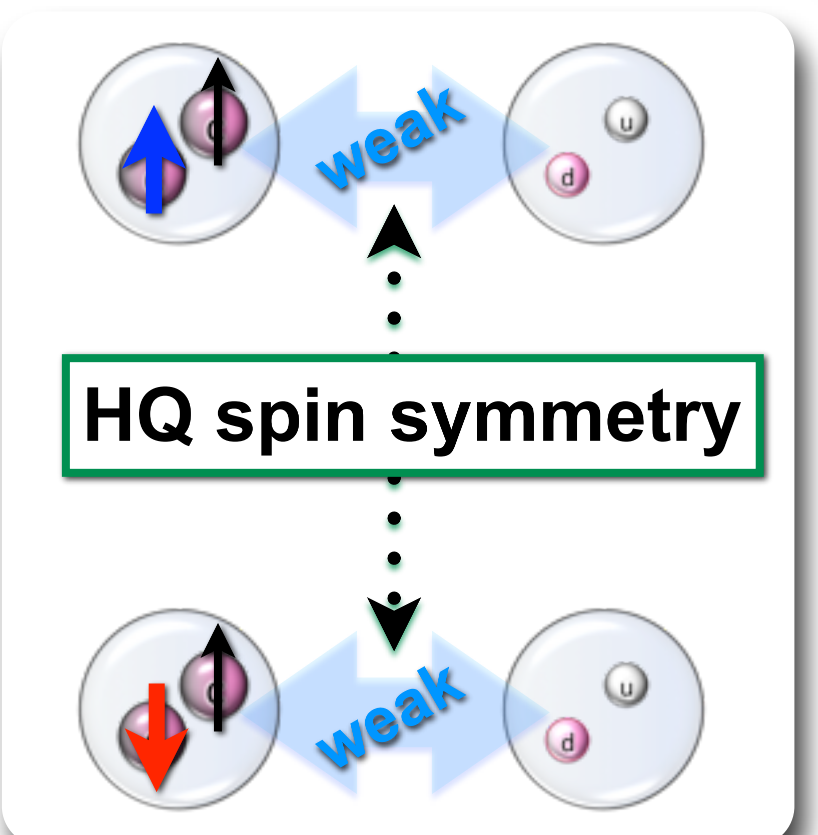
  ➡ **no bound $D^{bar}D^*$**

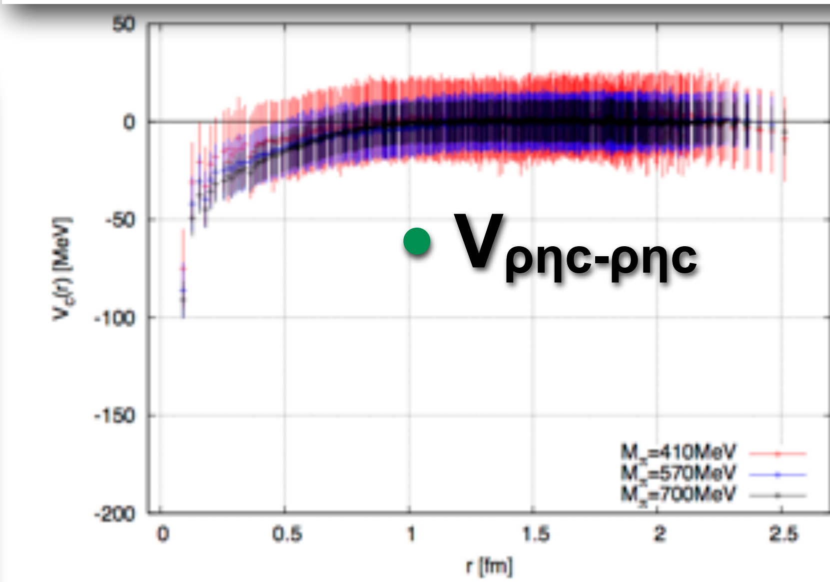
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)

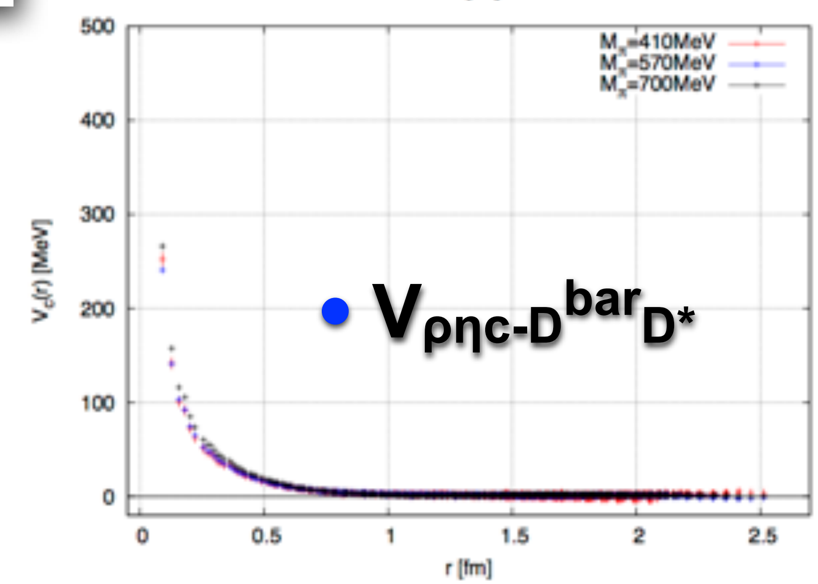


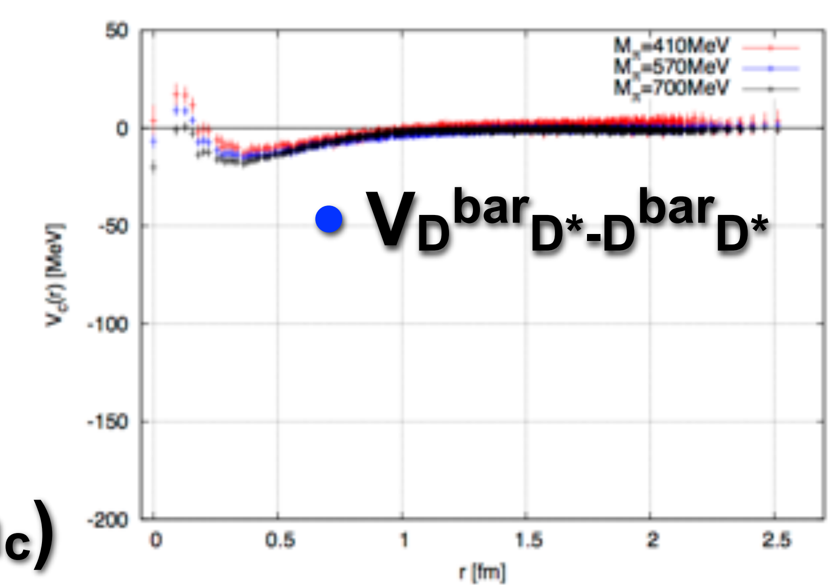








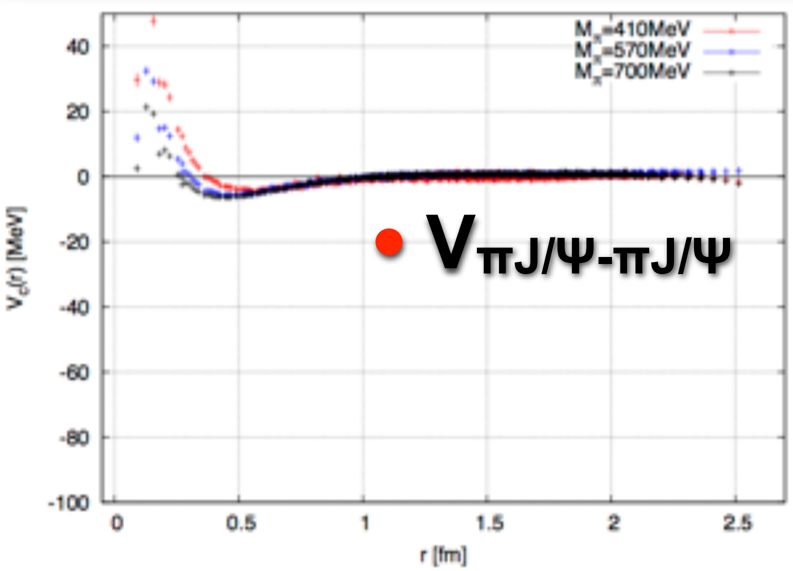


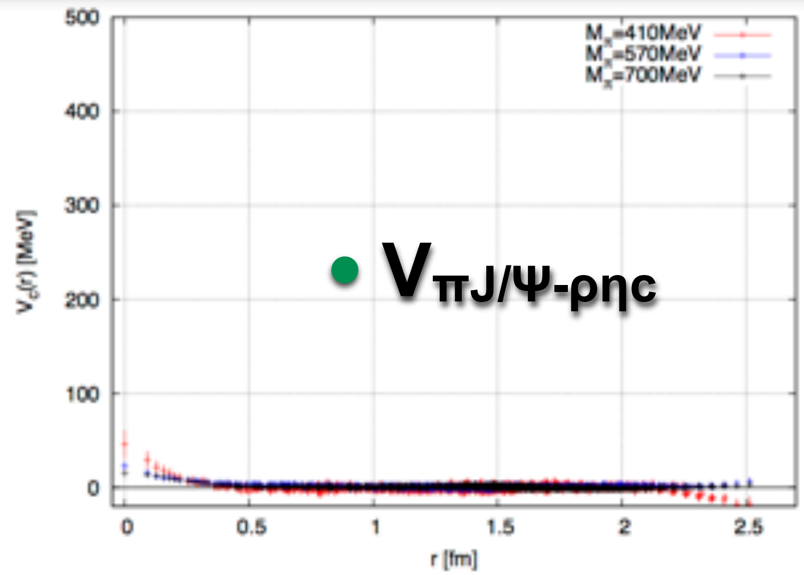


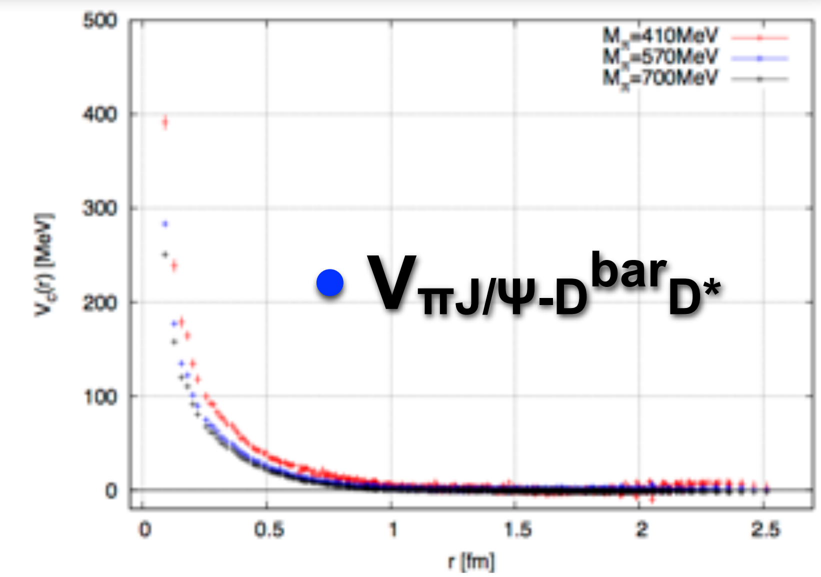
- **Weak** $\pi J/\psi$-$\rho\eta_c$ potential

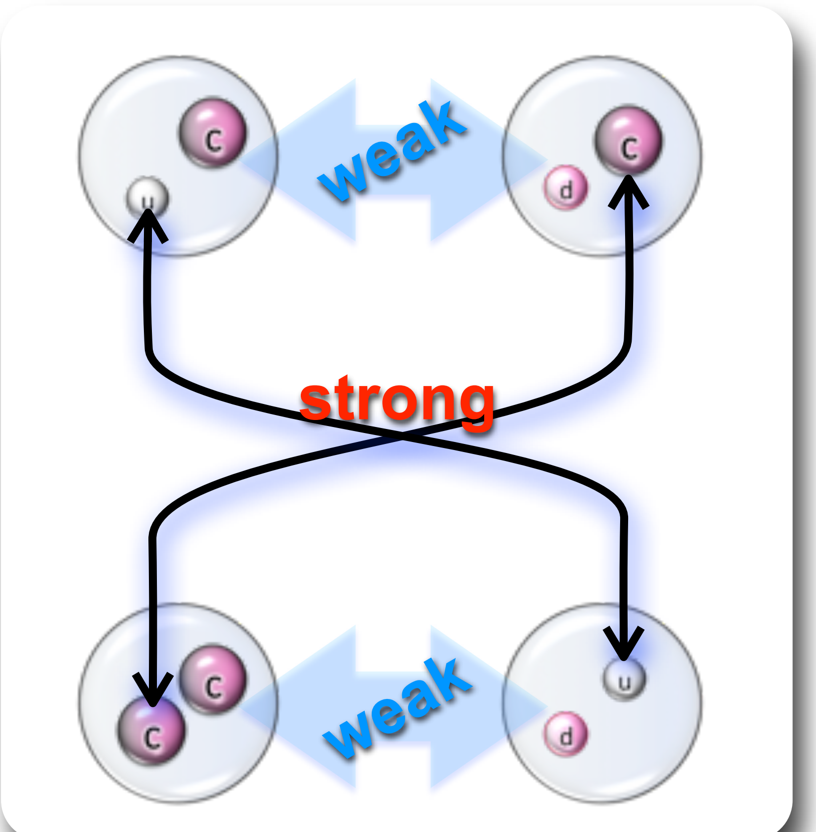
➡charm quark spin-flip is suppressed by $O(1/m_c)$

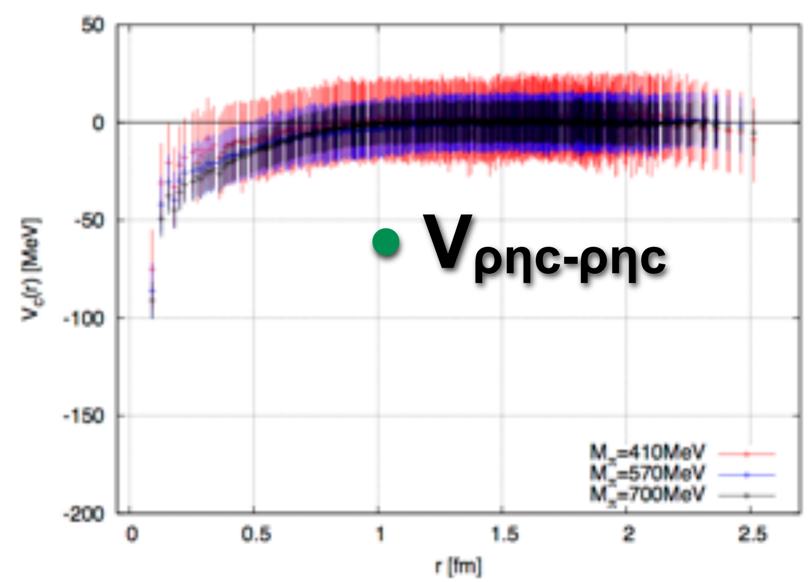
Potential matrix ($\pi J/\psi$ - $\rho\eta_c$ - $D^{bar}D^*$)

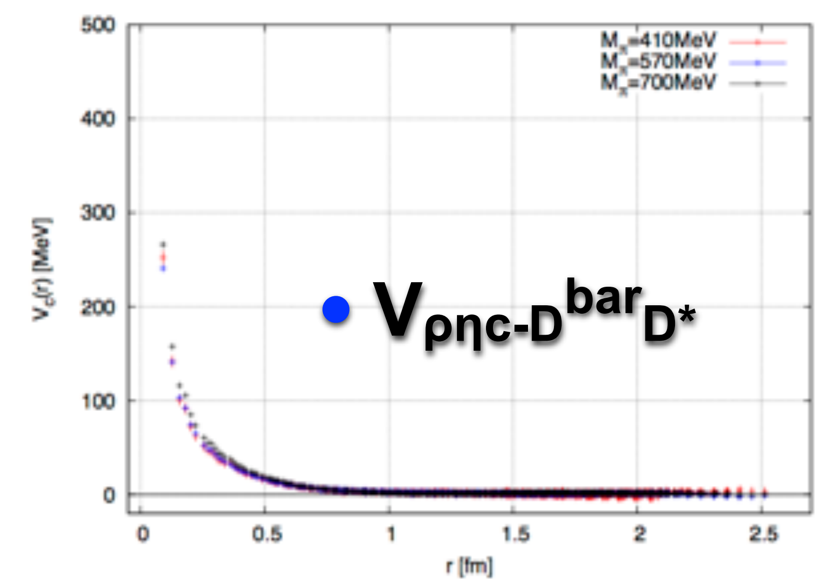


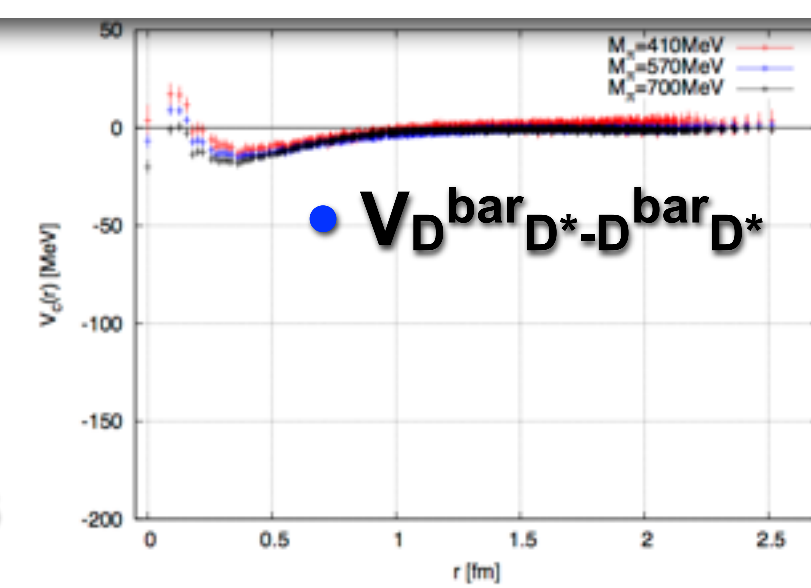










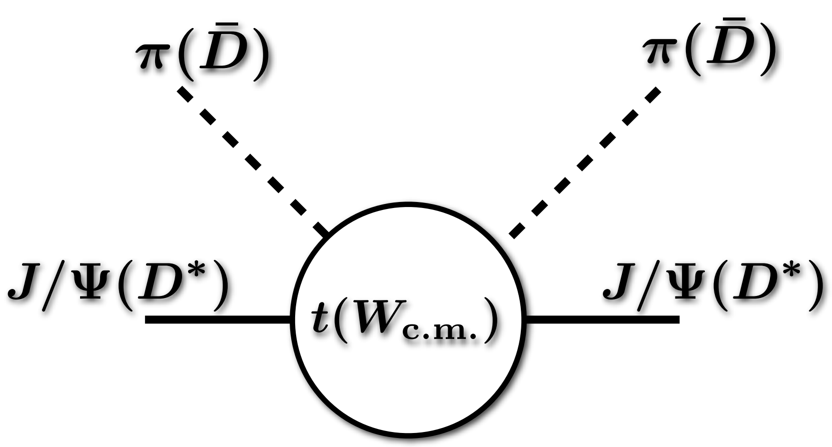


- **Strong off-diagonal $D^{bar}D^*$ potentials**
  - ✓ strong charm-quark-exchange interactions

Two-body observables : structure of Zc(3900) in $I^G(J^P)=1^+(1^+)$

- Invariant mass distributions of πJ/ψ & $D^{bar}D^*$ s-wave scattering

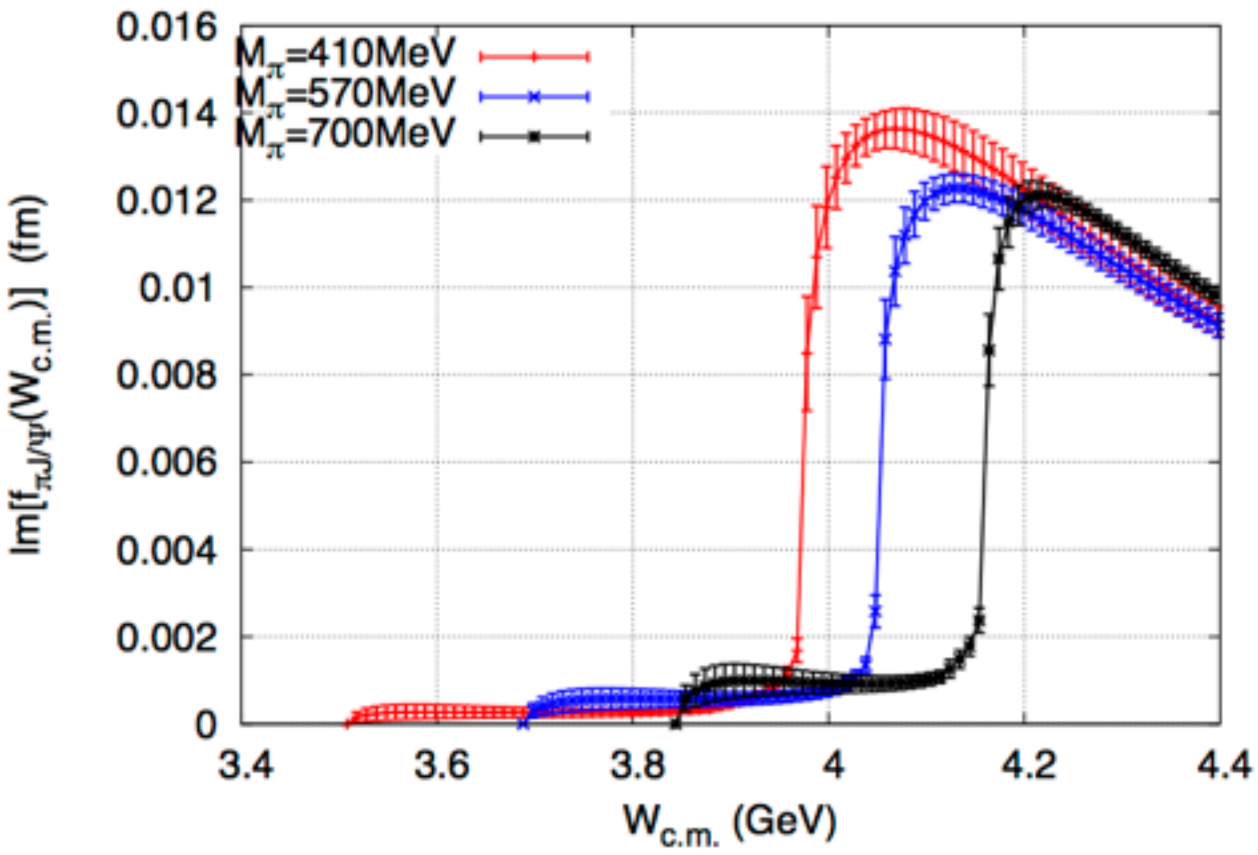
➡ ideal experimental setting for production reactions of Zc(3900)

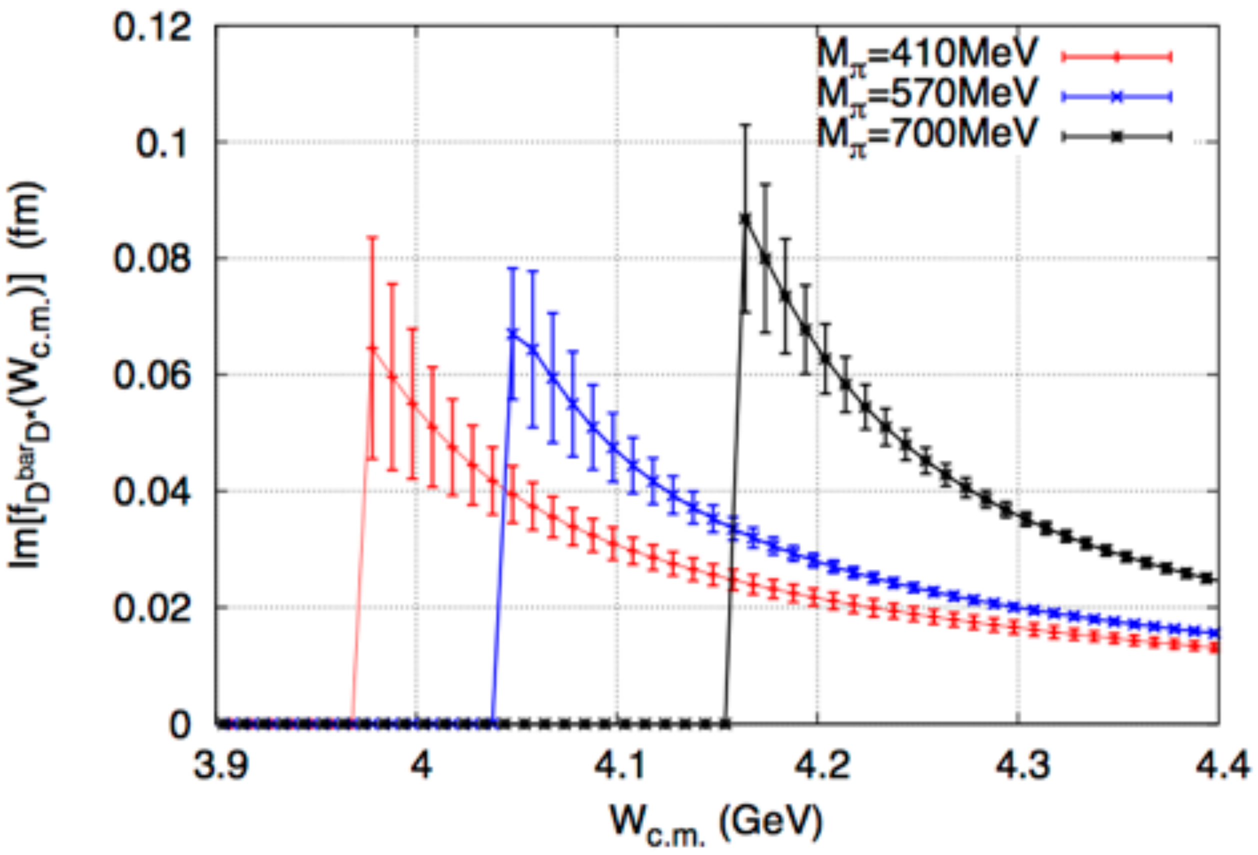


- Pole positions of Zc(3900) to determine structure of Zc(3900)

2-body scattering & inv. mass spectra

- πJ/ψ invariant mass
- $D^{bar}D^*$ invariant mass





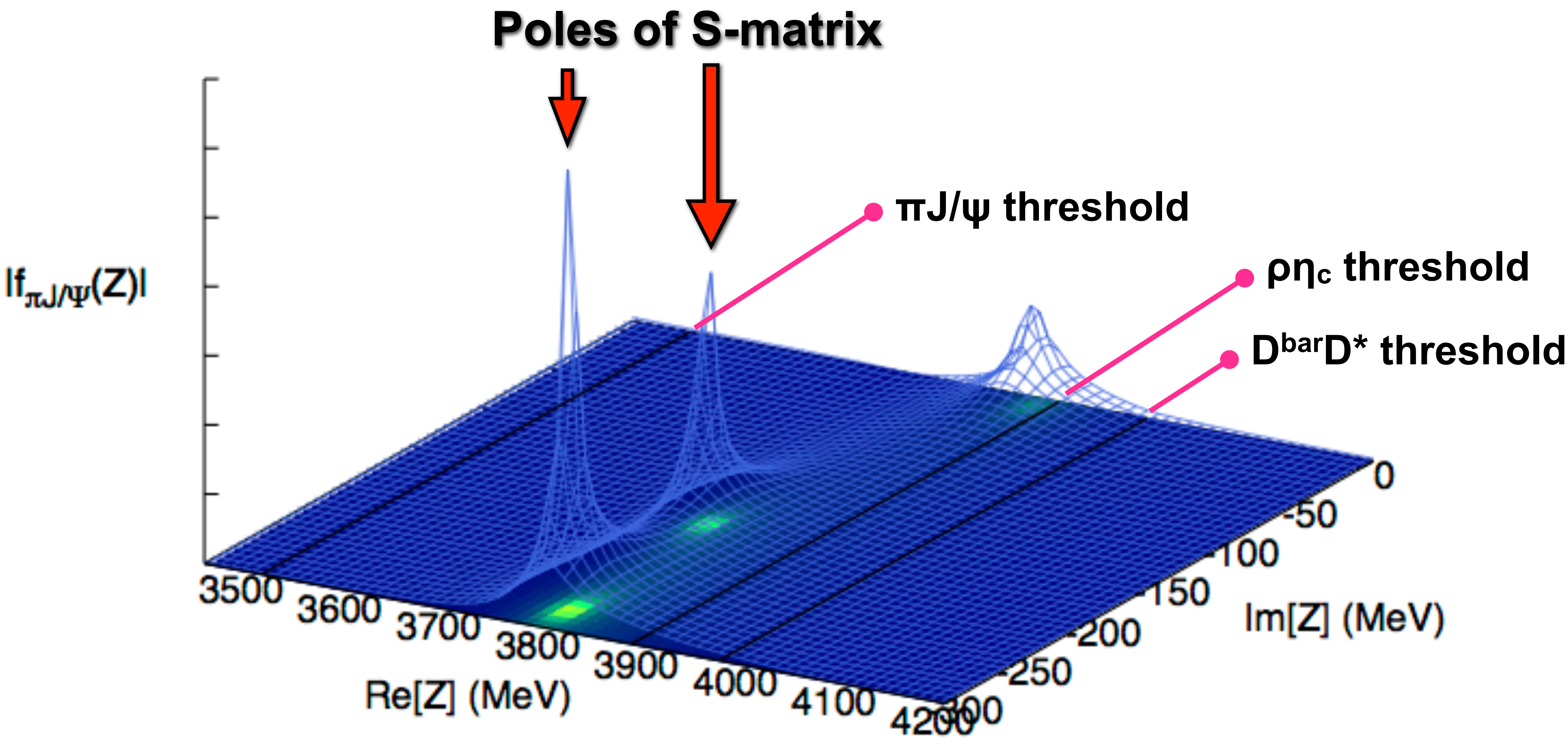
✓ enhancement near $D^{bar}D^*$ threshold due to large πJ/Ψ-$D^{bar}D^*$ coupling

- peak in πJ/ψ 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**

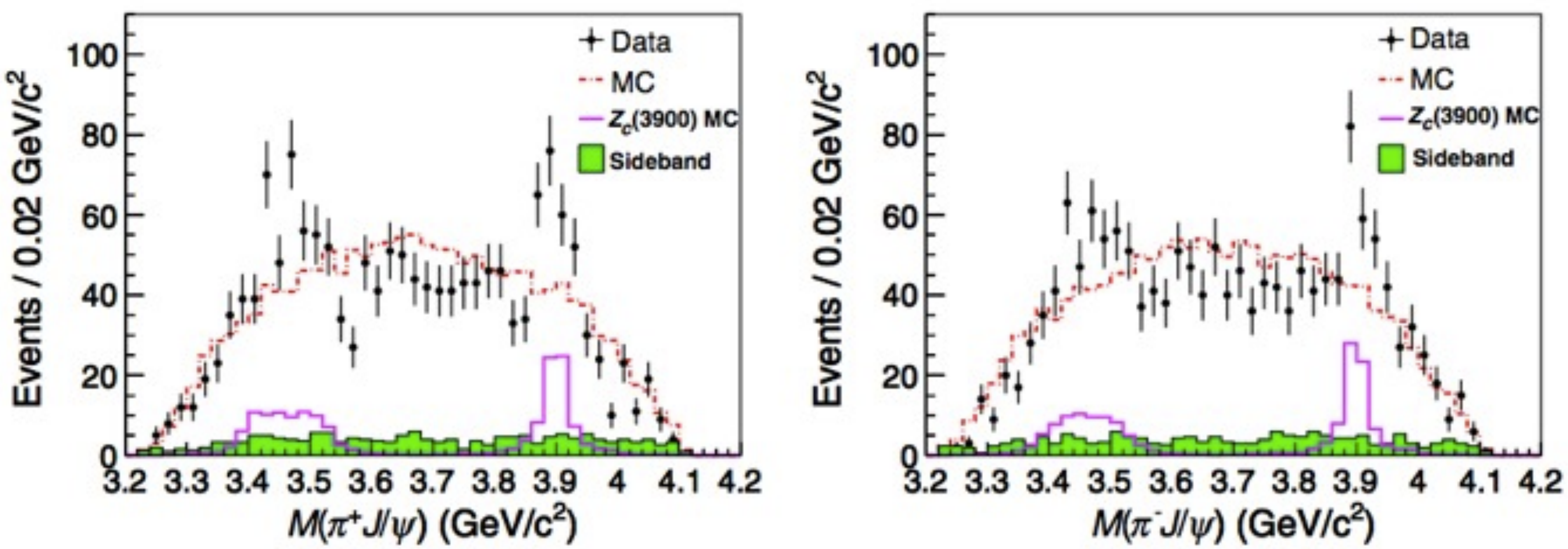


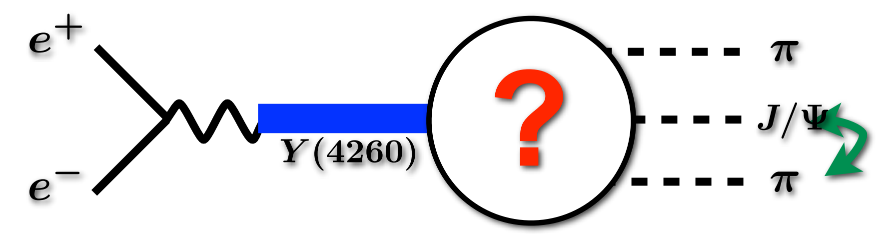
✓ "**Virtual (shadow)**" poles on the most adjacent complex energy plane for Z_c(3900) energy region are found

✓ These poles contribute to threshold enhancement of amplitude

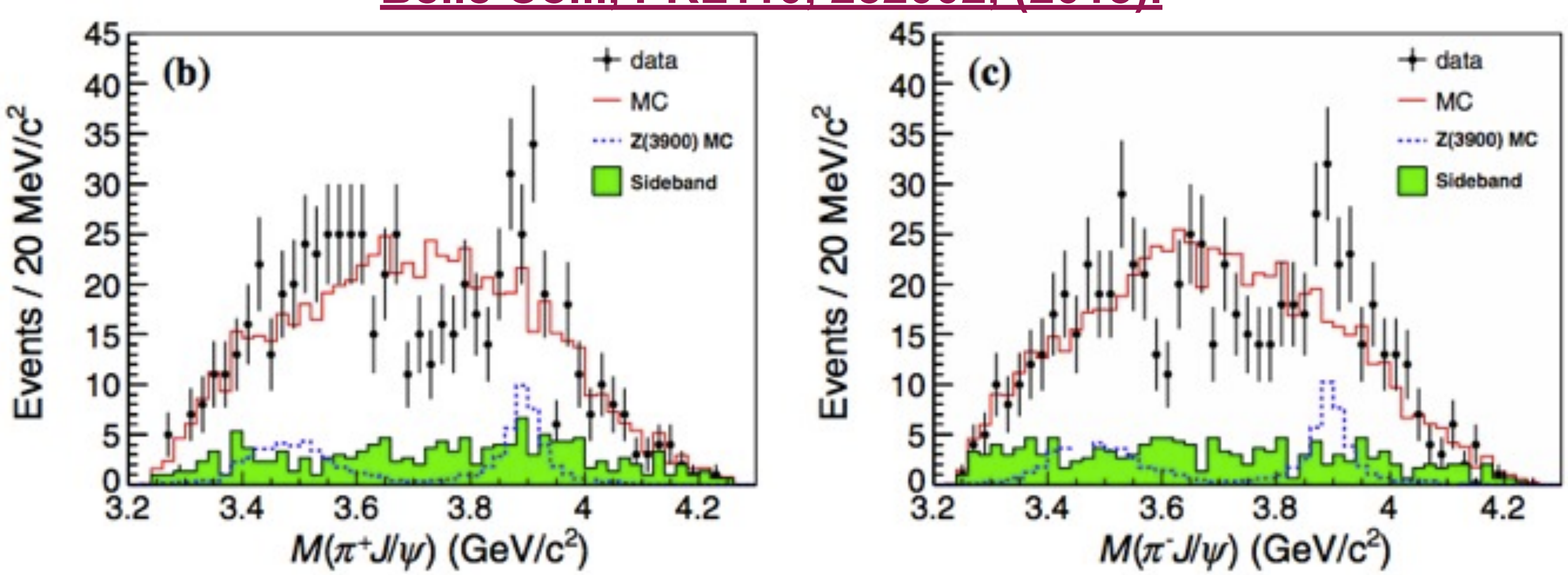
Y(4260) three-body decay : comparison with expt. data

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



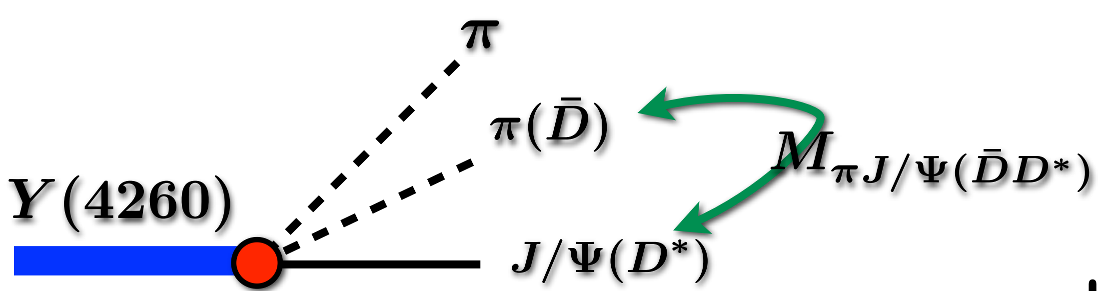


Belle Coll., PRL110, 252002, (2013).



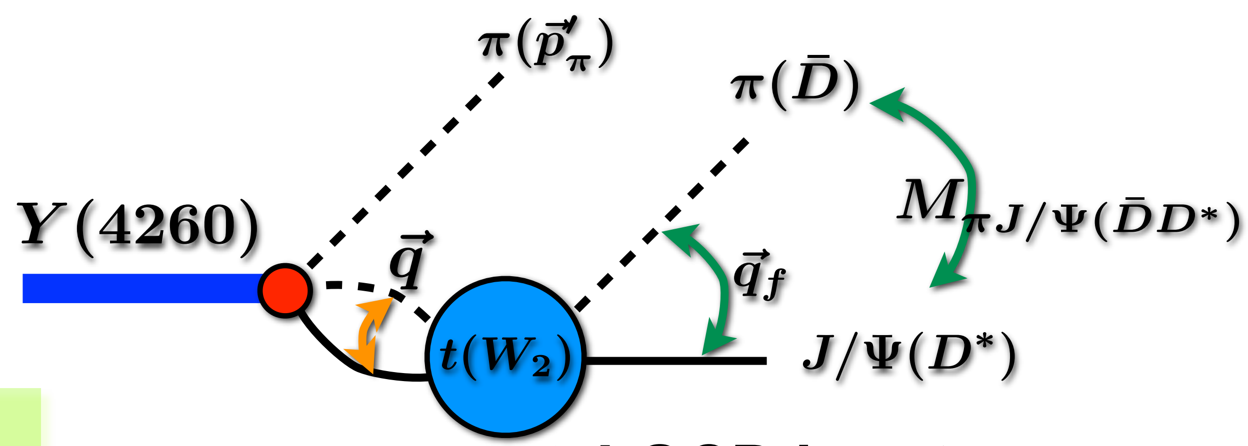
Three-body decay of Y(4260)

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



➡ constant Y(4260) decay vertex is assumed

+



➡ LQCD input
(NO free parameter)

✔ **Leading order of Faddeev equations**

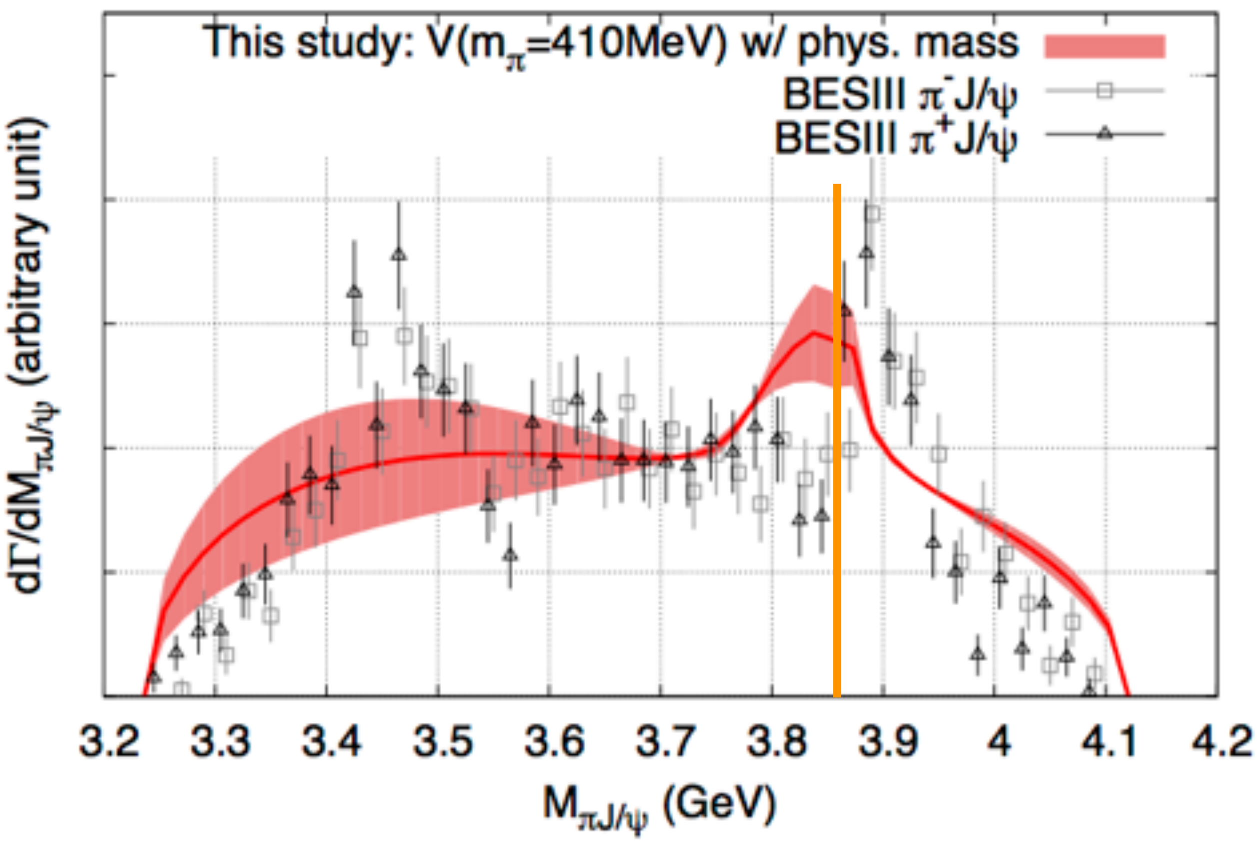
$$T_{if}(\vec{p}'_\pi, \vec{q}_f; W_3) = \sum_{n=\pi J/\Psi, \bar{D}D^*} C_n \left[\delta_{nf} + \int d^3q \frac{1}{W_3 - E_\pi(\vec{p}'_\pi) - E_n(\vec{q}, \vec{p}'_\pi) + i\epsilon} t(\vec{q}, \vec{q}_f) \right]$$

physical hadron masses employed & S-wave calculation

✔**comparison with expt. data**

✔**property of Y(4260) decay**

Invariant mass spectra ($\pi J/\psi$ & $D^{bar}D^*$)



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

--> R=0.95(18), θ=-58(44) deg.

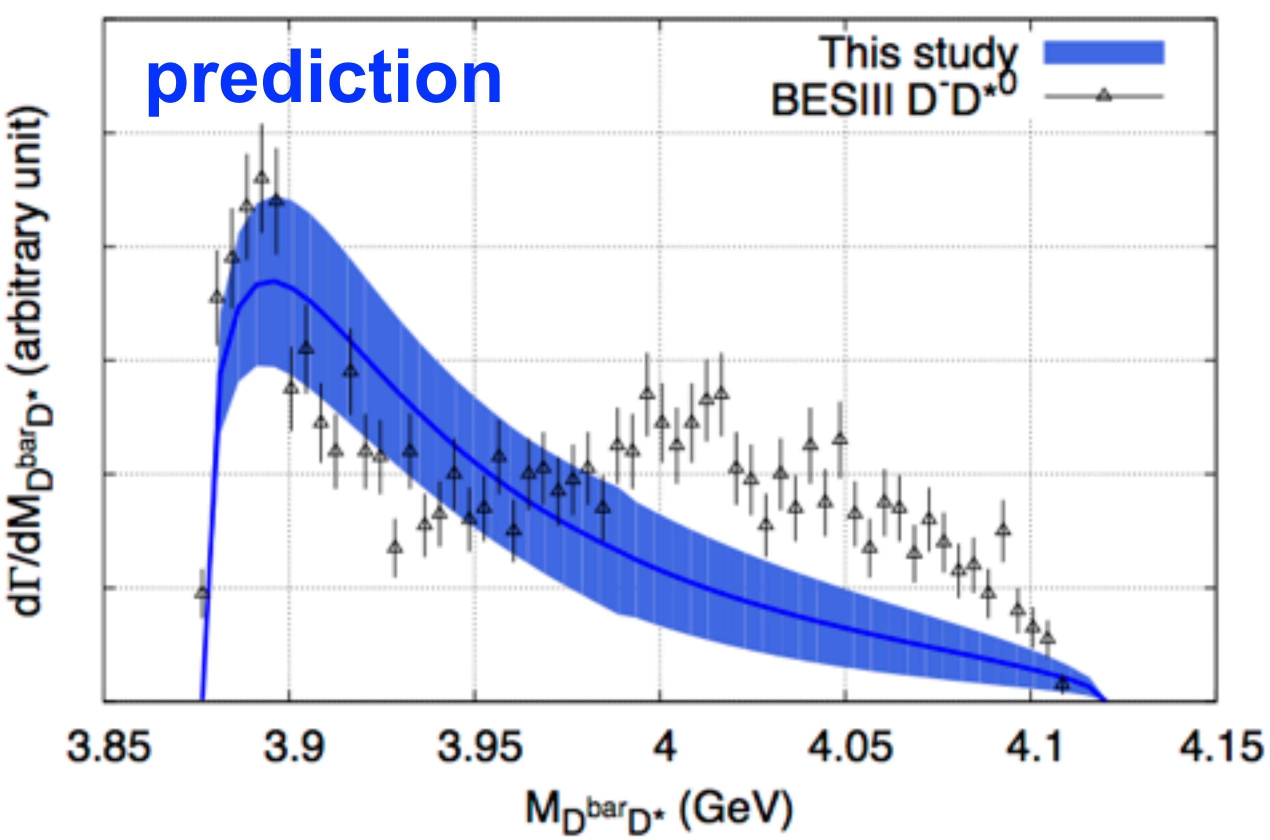
★ Zc(3900) production ratio

- **LQCD prediction**

$$27 \pm 7\%$$

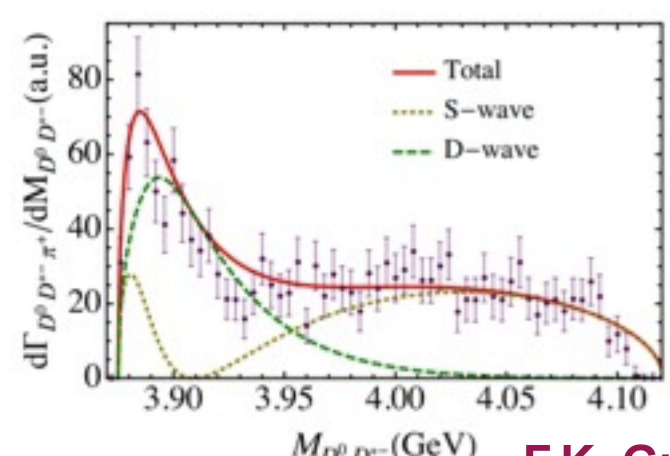
- **Expt.**

$$21.5 \pm 3.3\% \text{ (BESIII)}$$
$$29.0 \pm 8.9\% \text{ (Belle)}$$



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

--> higher partial wave??



F.K. Guo@HHIQCD2015

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 plans

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