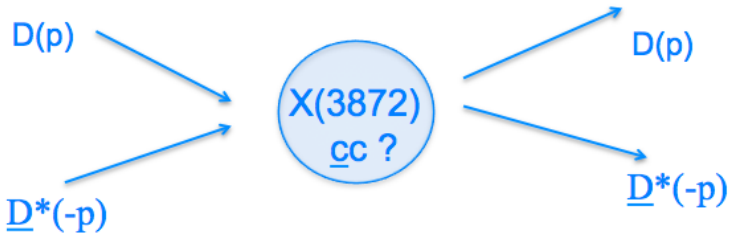
Charmonium-like states from scattering on the lattice



Lattice 2013

29th July – 3rd August, Mainz

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In collaboration with:

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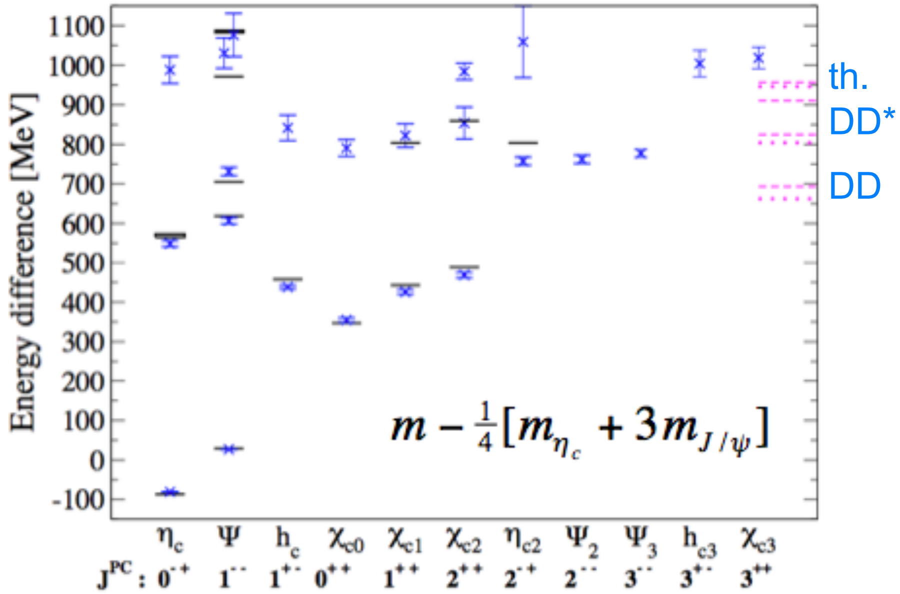
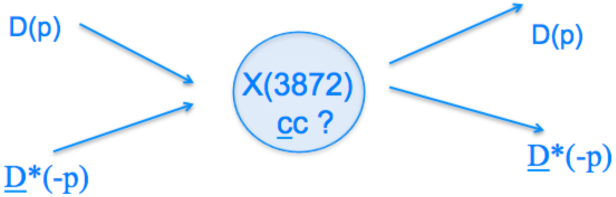
Motivation

typical results obtained using only $\bar{C}C$ interpolators

[Mohler, S. P., Woloshyn, arXiv:1208.4059, PRD 2013]



- Why simulate $\bar{c}c$ via



- Status of previous simulations

(a) only $\bar{c}c$ well below th. treated OK

(b) interesting $\bar{c}c$ states lie near threshold :

treatment ignored existence of threshold

(c) treatment of $\bar{c}c$ resonances ignored the strong decay

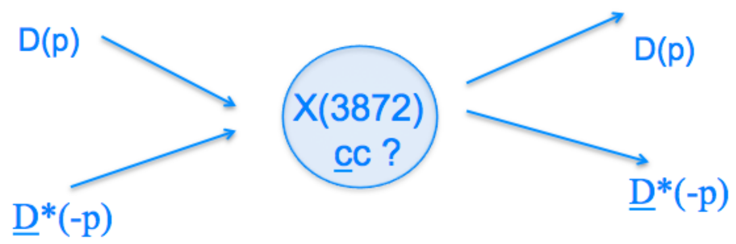
exception: [Bali, Ehmann, Collins 2011]

I will present results for three channels:

- X(3872)

  exp: $J^{PC}=1^{++}$, I=0 & 1

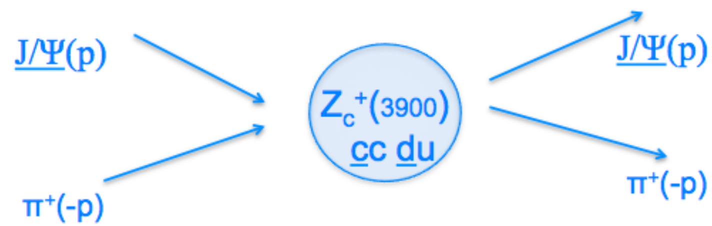
  near D^0D^{0*} threshold: (b)



- $Z_c^+(3900)$ ➔ J/Ψ π^+

  exp: $J^{PC}=?^{?+}$, I=1

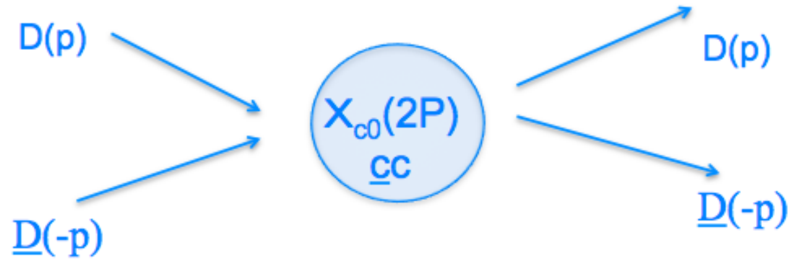
  near DD* threshold: (b,c)



- $X_{c0}(2P)$: exp ?

  $J^{PC}=0^{++}$, I=0

  resonance above DD threshold (c)



Lattice simulation

- 280 gauge config with dynamical u,d quarks [generated by A. Hasenfratz]

$$N_f = 2 \quad a = 0.1239 \pm 0.0013\ fm \quad a^{-1} = 1.58 \pm 0.02\ GeV$$

$$N_L^3 \times N_T = 16^3 \times 32 \qquad L \approx 2\ fm \qquad T = 4\ fm \qquad m_\pi \approx 266\ MeV$$

reasons for small L : 1) D(p)D(-p) , p=n 2π/L to dense for larger L

2) allows full distillation method [Peardon et al, 2009]

- dynamical u, d , valence u,d,s : Improved Wilson Clover

valence c: Fermilab method [El-Khadra et al. 1997]

a set using r0;

m_s set using φ

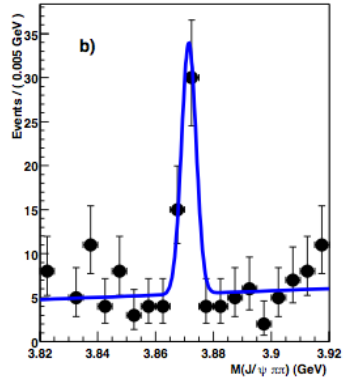
m_c set using $\frac{1}{4}[M_2(\eta_c) + 3M_2(J/\psi)]_{lat} = \frac{1}{4}[M(\eta_c) + 3M(J/\psi)]_{\exp}$

- heavy quark treatment tested on conventional charmonium and charmed resonances mesons with satisfactory results: [D. Mohler, S.P., R. Woloshyn, PRD 2013]

Charmonium-like

X(3872)

X(3872): experimental facts

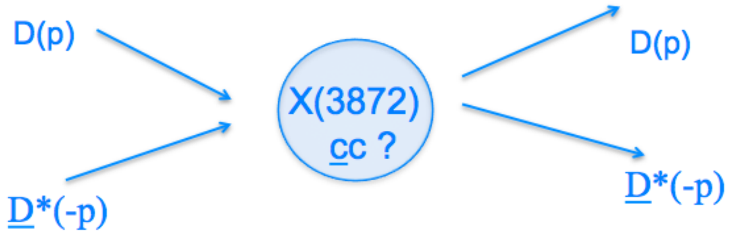


- first observed in 2003 [Belle PRL 2003, cited >800 times]
- **$J^{PC}=1^{++}$** [LHCb, 2013]
- sits within 1 MeV of D^0D^{0*} threshold
- selected decays

X(3872) → J/Ψ ω (I=0)

X(3872) → J/Ψ ρ (I=1)

Interpolators : $J^{PC}=1^{++}$ (T_1^{++}) , P=0, I=0, 1



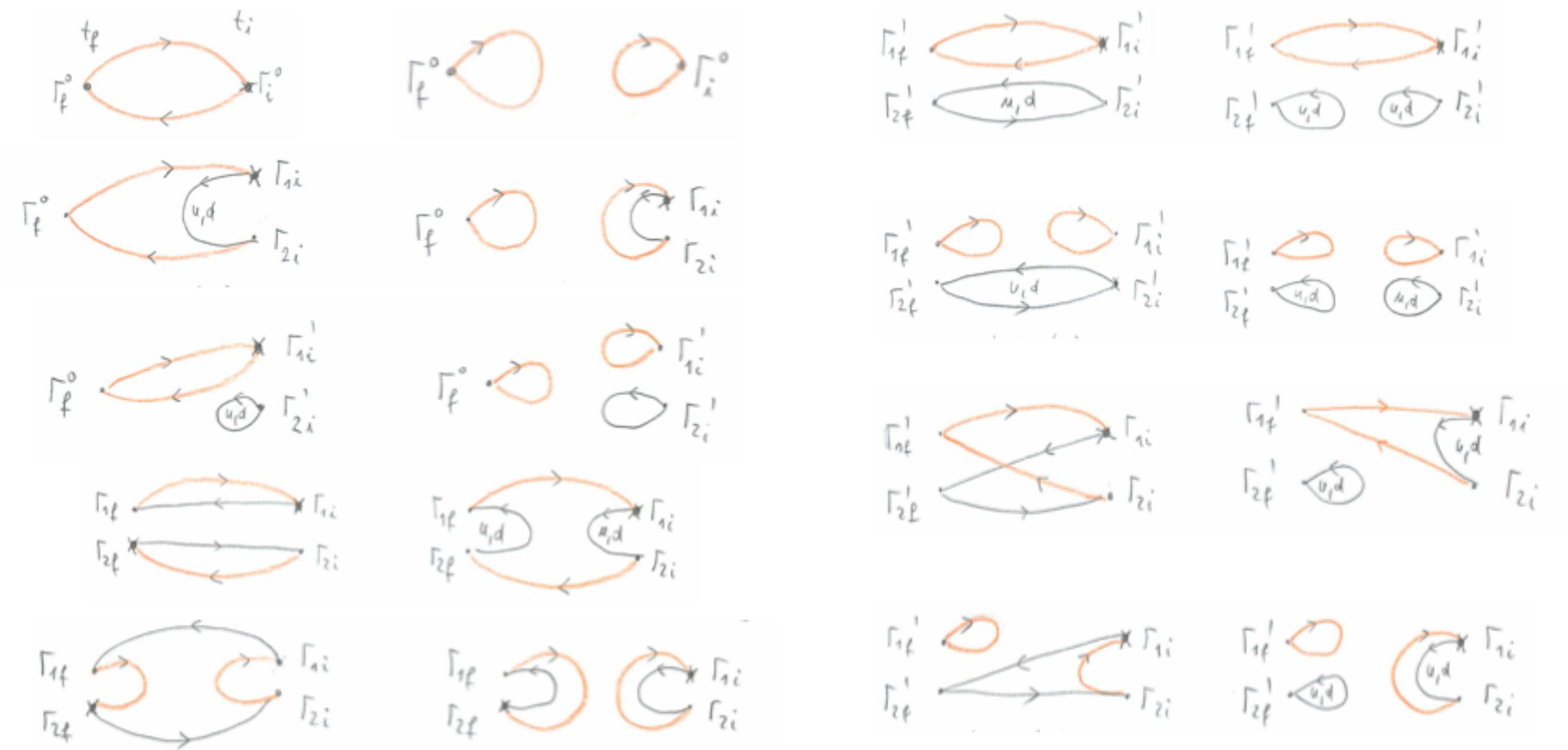
$$O^{\bar{c}c}_{1-8} = \bar{c}\ \hat{M}_i\ c(0) \qquad\qquad (\text{only } I=0)$$

$$O_1^{DD^*} = [\bar{c}\gamma_5 u(0)\ \bar{u}\gamma_i c(0) - \bar{c}\gamma_i u(0)\ \bar{u}\gamma_5 c(0)] + f_I\{u\to d\}$$
$$O_2^{DD^*} = [\bar{c}\gamma_5\gamma_t u(0)\ \bar{u}\gamma_i\gamma_t c(0) - \bar{c}\gamma_i\gamma_t u(0)\ \bar{u}\gamma_5\gamma_t c(0)] + f_I\ \{u\to d\}$$
$$O_3^{DD^*} = \sum_{e_k=\pm e_{x,y,z}} [\bar{c}\gamma_5 u(e_k)\ \bar{u}\gamma_i c(-e_k) - \bar{c}\gamma_i u(e_k)\ \bar{u}\gamma_5 c(-e_k)] + f_I\ \{u\to d\}$$

$$O_1^{J/\psi V} = \epsilon_{ijk}\ \bar{c}\gamma_j c(0)\ [\bar{u}\gamma_k u(0) + f_I\ \bar{d}\gamma_k d(0)]$$
$$O_2^{J/\psi V} = \epsilon_{ijk}\ \bar{c}\gamma_j\gamma_t c(0)\ [\bar{u}\gamma_k\gamma_t u(0) + f_I\ \bar{d}\gamma_k\gamma_t d(0)]$$

$$I=0: \quad f_I = 1, \quad V=\omega$$
$$I=1: \quad f_I = -1, \quad V=\rho$$

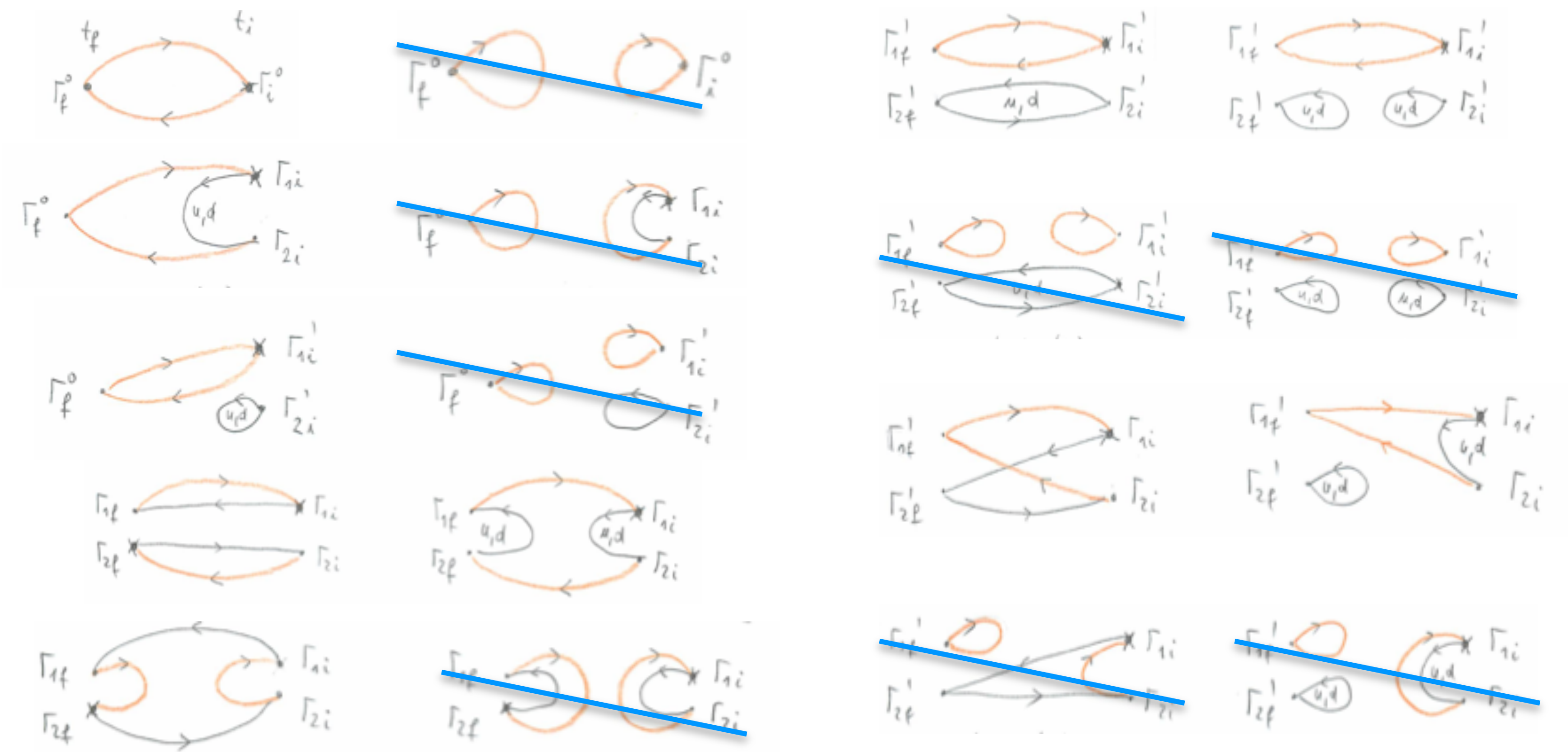
Wick contractions $C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\, \mathcal{O}_j^+(0) | 0 \rangle$



- we calculate all contractions

- certain contractions where c does not propagate from t_i to t_f are nosiy

Following results based on Wick contractions



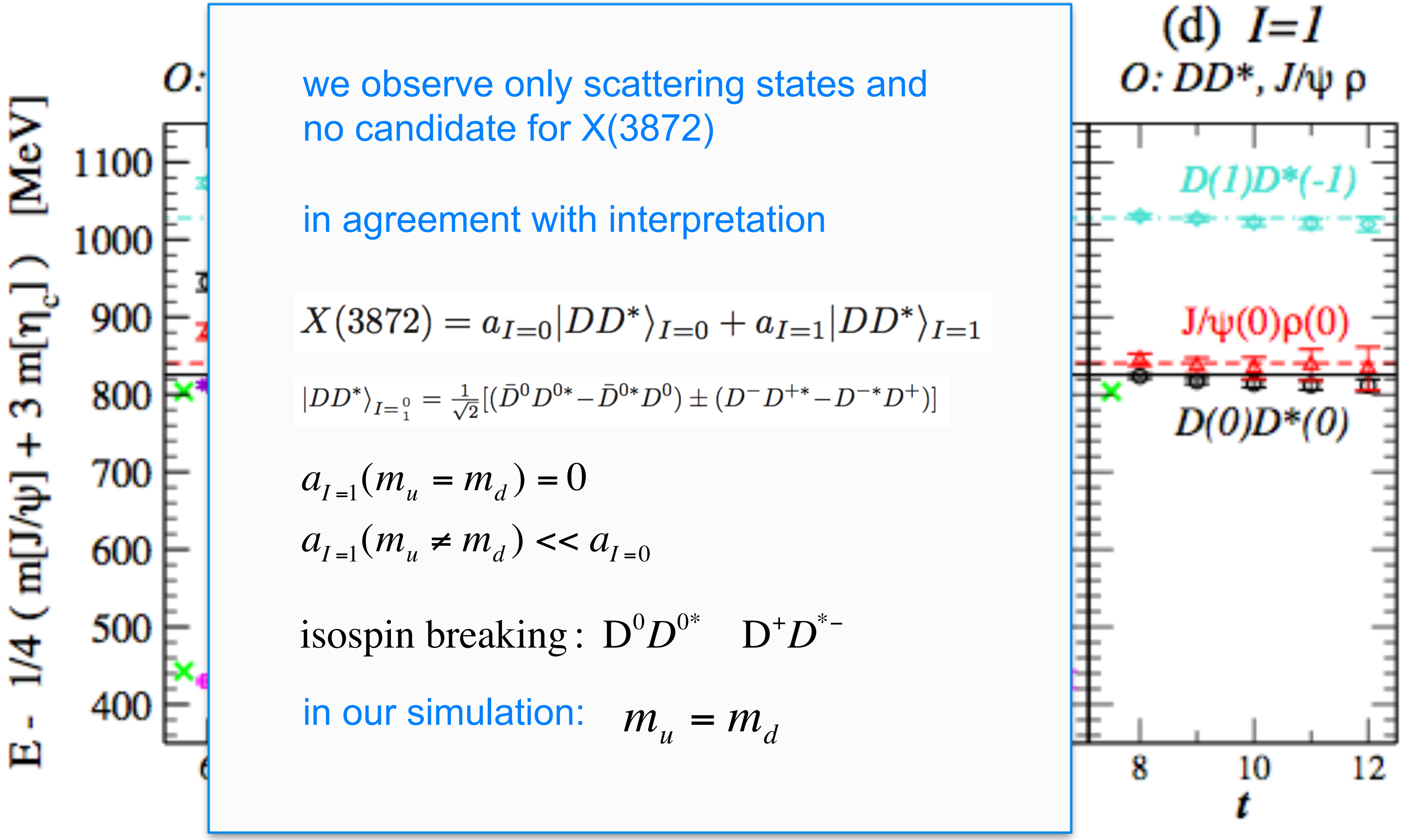
- results that follow are based only on Wick contractions where c propagates from t_i to t_f
- the remaining ones suppressed by OZI rule [see also Levkova, DeTar 2011]
- their effect will be addressed on follow-up analysis

$$\text{variational method: } C(t)\,\vec{\psi}^{(n)}(t) = \lambda^{(n)}(t)\,C(t_0)\,\vec{\psi}^{(n)}(t) \quad \to \quad E_n\,, \quad \langle O_i | n \rangle$$

[S.P. , L. Leskovec, arXiv: 1307.5172]

Spectrum for $J^{PC}=1^{++}$, I=1

$$E - \tfrac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$$



we observe only scattering states and no candidate for X(3872)

in agreement with interpretation

$$X(3872) = a_{I=0}|DD^*\rangle_{I=0} + a_{I=1}|DD^*\rangle_{I=1}$$

$$|DD^*\rangle_{I=\substack{0\\1}} = \tfrac{1}{\sqrt{2}}[(\bar{D}^0 D^{0*} - \bar{D}^{0*} D^0) \pm (D^- D^{+*} - D^{-*} D^+)]$$

$$a_{I=1}(m_u = m_d) = 0$$

$$a_{I=1}(m_u \neq m_d) << a_{I=0}$$

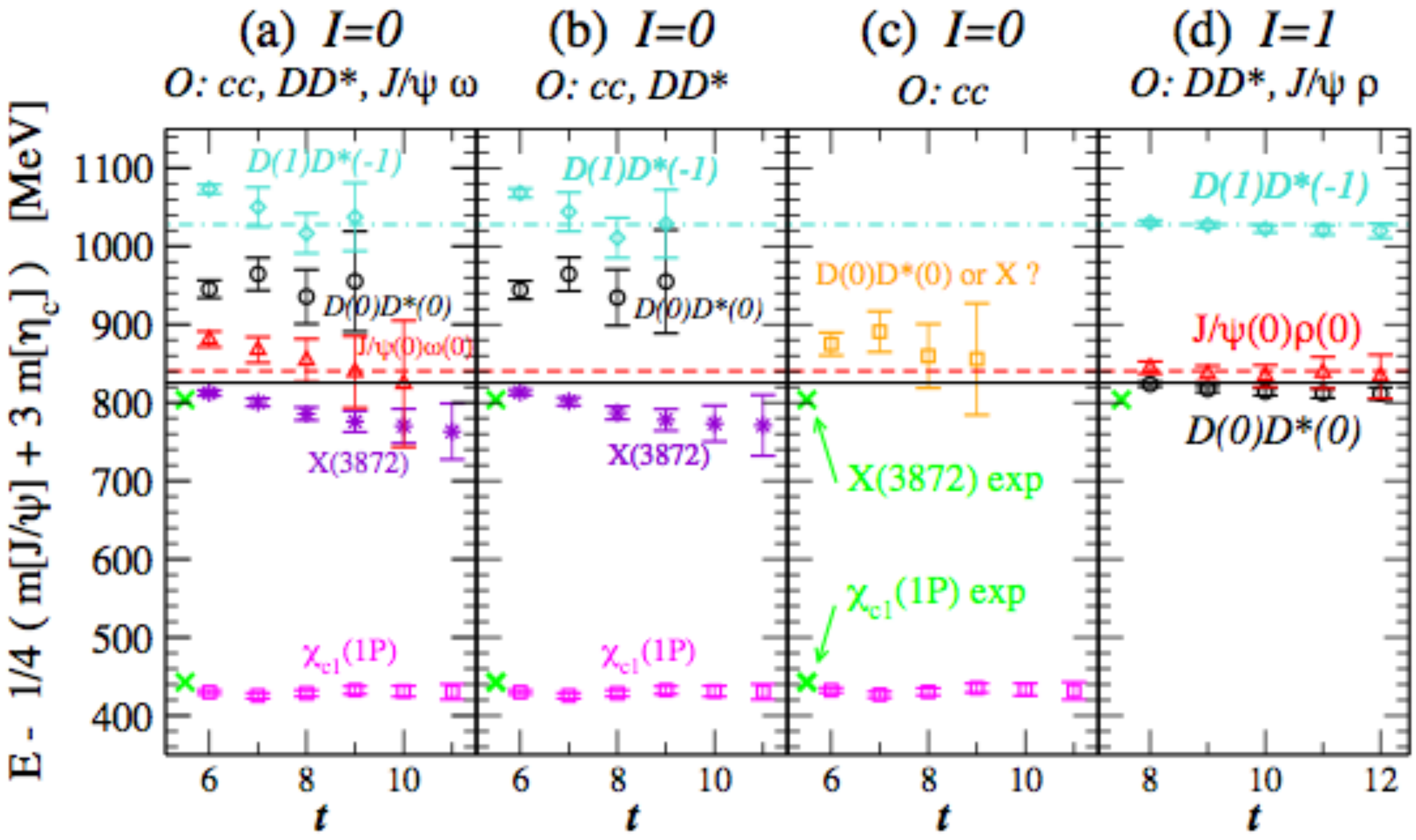
isospin breaking : $D^0 D^{0*}$ $D^+ D^{*-}$

in our simulation: $m_u = m_d$

Spectrum for $J^{PC}=1^{++}$, I=1& 0

[S.P. , L. Leskovec, arXiv: 1307.5172]

$$E - \tfrac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$$



Spectrum for $J^{PC}=1^{++}$, I=1& 0

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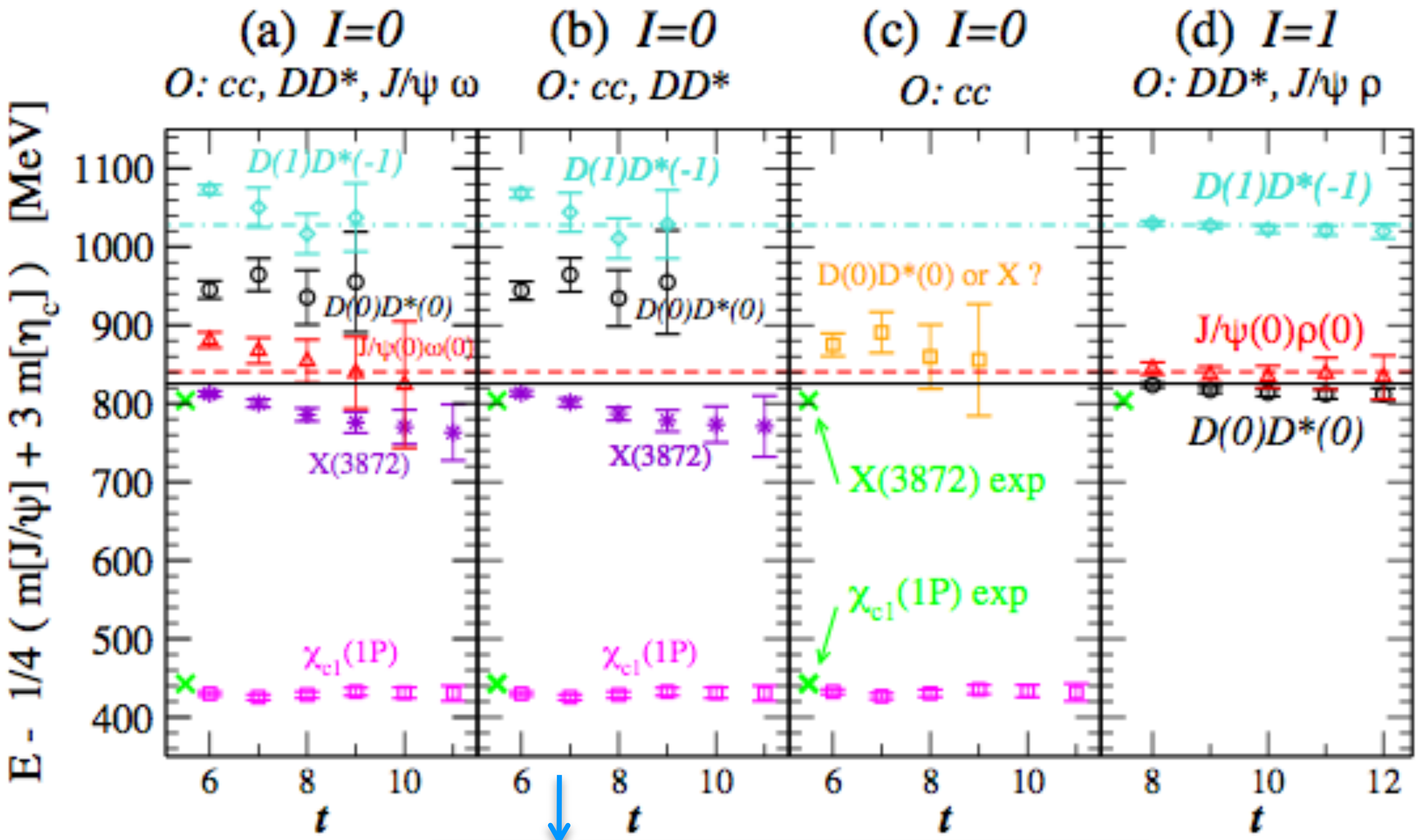
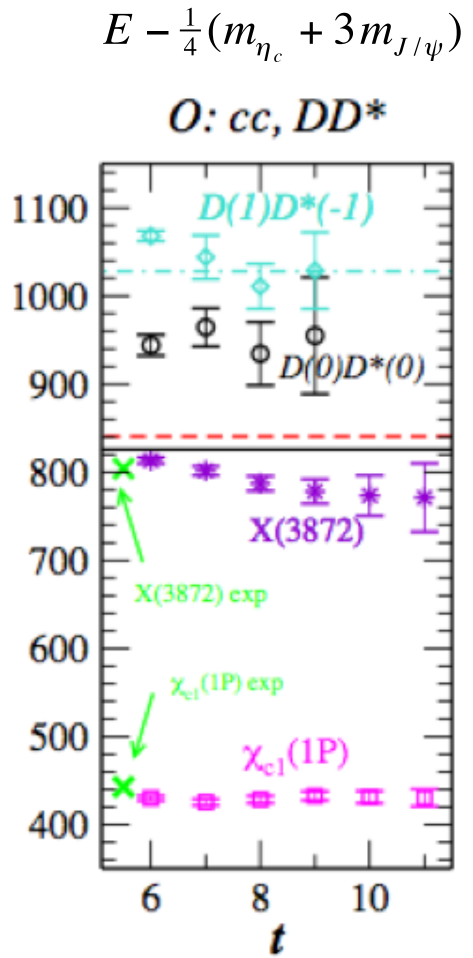
$$E - \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$$



- no visible effect from J/Ψ ω in basis (b)
- exp: Γ [X(3872) → J/Ψ ω] < 1.2 MeV
- DD̲* elastic scattering assumed for basis (b)

DD* scattering phase shift in s-wave (I=0)



Similar phenomenon observed for:

• pn bound st.: NPLQCD:1301.5790, PACS-CS PRD84 (2011) 054506]

• DK bound st.: [talk my D. Mohler]

• δ from levels 2,3 using Luscher's f.: $p \cdot \cot\delta(p) = \frac{2\, Z_{00}(1;q^2)}{\sqrt{\pi} L}$

• effective range approx. $p\cot\delta(p) = \frac{1}{a_0} + \frac{1}{2} r_0 p^2$

$a_0 = -1.7 \pm 0.4$ fm

$r_0 = 0.5 \pm 0.1$ fm

• large negative a_0 agrees with one shallow BS according to Levinson's t. [Sasaki & Yamazaki 2006]

• L→∞ bound st. X

$S \propto [\cot\delta - i]^{-1} = \infty, \quad \cot\delta(p_{BS}) = i$

$p^2_{BS} = -0.020(13)\ \mathrm{GeV}^2$

$m_X^{lat, L\to\infty} = E_D(p_{BS}) + E_{D^*}(p_{BS})$

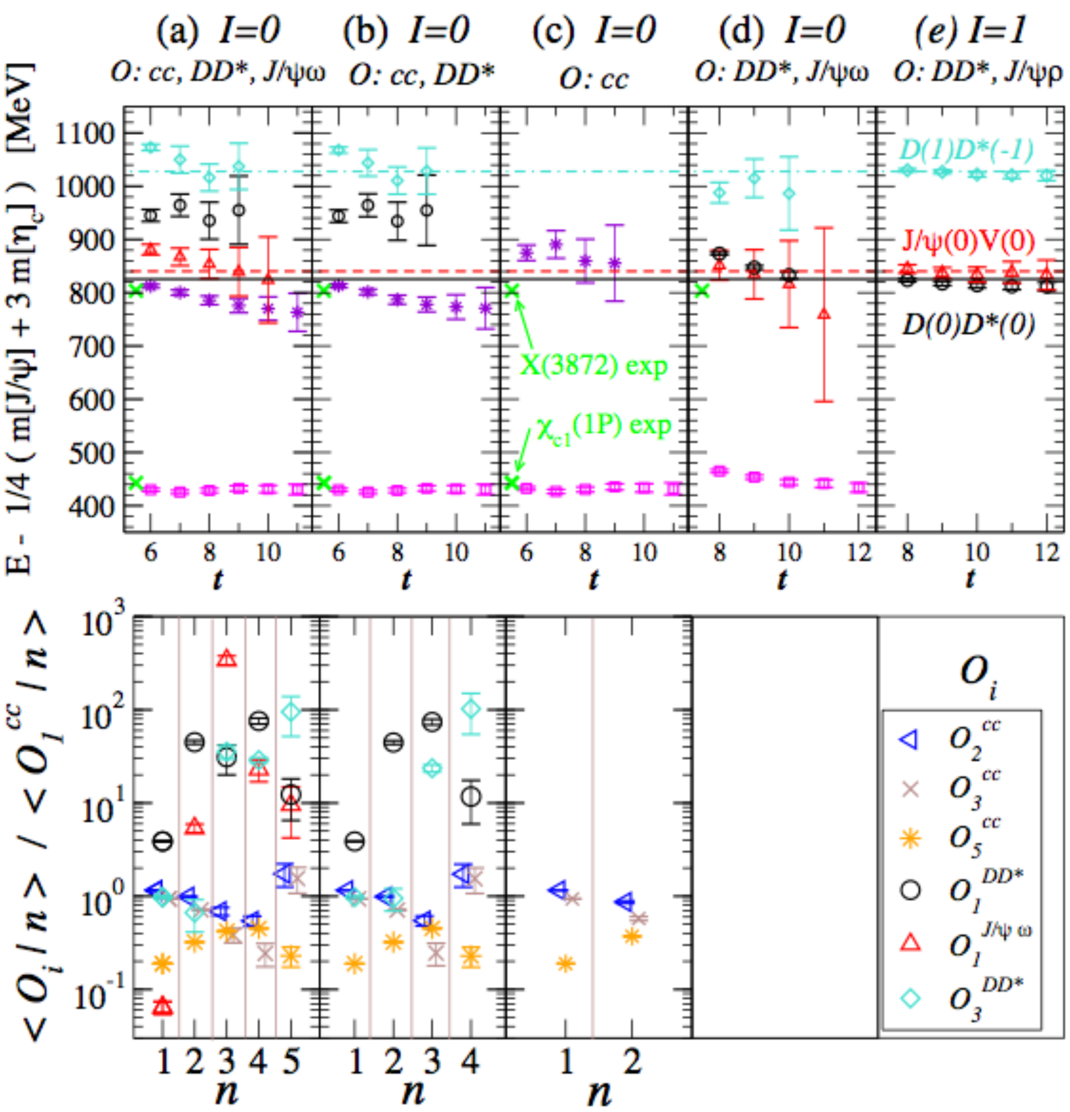
$X(3872)$	$m_X - \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$	$m_X - (m_{D^0} + m_{D^{0*}})$
$\mathrm{lat}^{L\to\infty}$	815 ± 7 MeV	-11 ± 7 MeV
exp	804 ± 1 MeV	-0.14 ± 0.22 MeV

[S.P. , L. Leskovec, arXiv: 1307.5172]

Composition of established X(3872)

overlaps

$\langle O_i | n \rangle$



$Z_c^+(3900)$ channel

$Z_c^+(3900)$: experimental facts

- discovered by Bes III

  [march 2013, arXiv:1303.5949]

- confirmed by Belle, CleoC

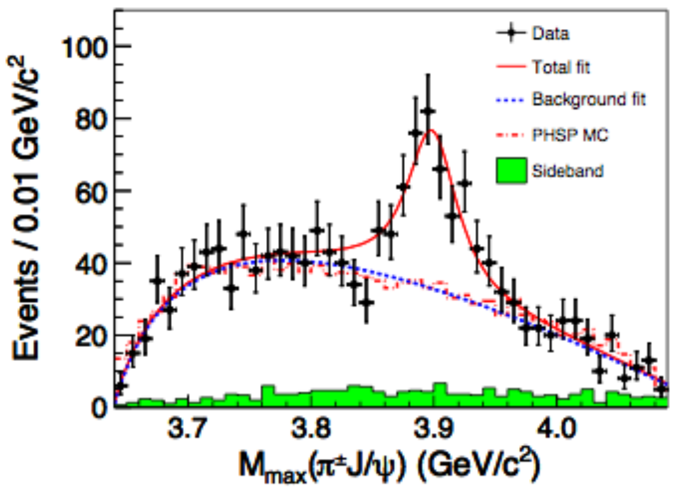
  [april 2013]

- $Z_c^+(3900) \rightarrow J/\Psi\ \pi^+$

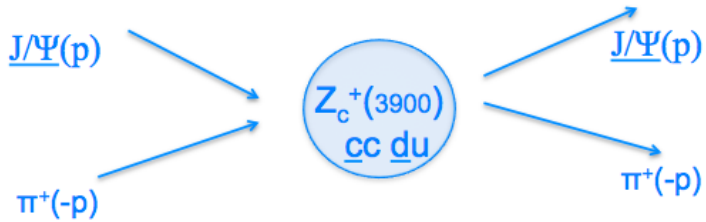
  $\underline{c}c\ \ \underline{d}u$

  can not be quark-antiquark !!

- exp: I=1, C = − , J^P = ??



Lattice search for $Z_c^+(3900)$ in $J^{PC}=1^{+-}$, I=1 channel



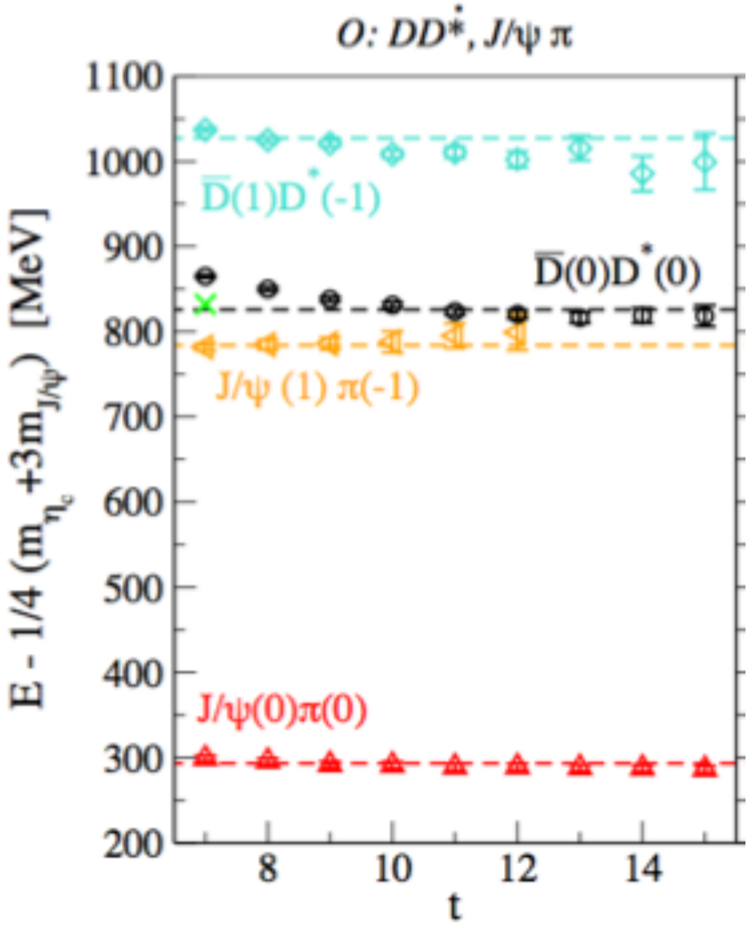
- $J^P=1^+$ is phenomenologicaly favored choice; J/Ψ π^+ are in s-wave

- Interpolators: $J^{PC}=1^{+-}$ (T_1^{+-}) , P=0, I=1

$$O_1^{J/\psi\ \pi} = \bar{c}\gamma_i c(0)\ [\bar{u}\gamma_5 u(0) - \ \{u \to d\}]$$
$$O_2^{J/\psi\ \pi} = \bar{c}\gamma_i\gamma_t c(0)\ [\bar{u}\gamma_5\gamma_t u(0) - \ \{u \to d\}]$$
$$O_3^{J/\psi\ \pi} = \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_i c(e_k)\ [\bar{u}\gamma_5 u(-e_k) - \ \{u \to d\}]$$

$$O_1^{DD^*} = [\bar{c}\gamma_5 u(0)\ \bar{u}\gamma_i c(0) + \bar{c}\gamma_i u(0)\ \bar{u}\gamma_5 c(0)] - \ \{u \to d\}$$
$$O_2^{DD^*} = [\bar{c}\gamma_5\gamma_t u(0)\ \bar{u}\gamma_i\gamma_t c(0) + \bar{c}\gamma_i u\gamma_t(0)\ \bar{u}\gamma_5\gamma_t c(0)] - \ \{u \to d\}$$
$$O_3^{DD^*} = \sum_{e_k=\pm e_{x,y,z}} [\bar{c}\gamma_5 u(e_k)\ \bar{u}\gamma_i c(-e_k) + \bar{c}\gamma_i u(e_k)\ \bar{u}\gamma_5 c(-e_k)] - \ \{u \to d\}$$

Lattice search for $Z_c^+(3900)$ in $J^{PC}=1^{+-}$, I=1 channel



- only scattering states found
- small energy shifts → small interaction
- **we find no candidate for $Z_c^+(3900)$ in 1^{+-} channel**
- Possible reasons:

✧ perhaps $J^{PC} \neq 1^{+-}$ (exp unknown)

✧ perhaps our interpolators (all of scat. type) are not diverse enough : calls for further simulations

✧ does the state really exist ?

Charmonium
0^{++} resonance(s)
above $D\underline{D}$ threshold

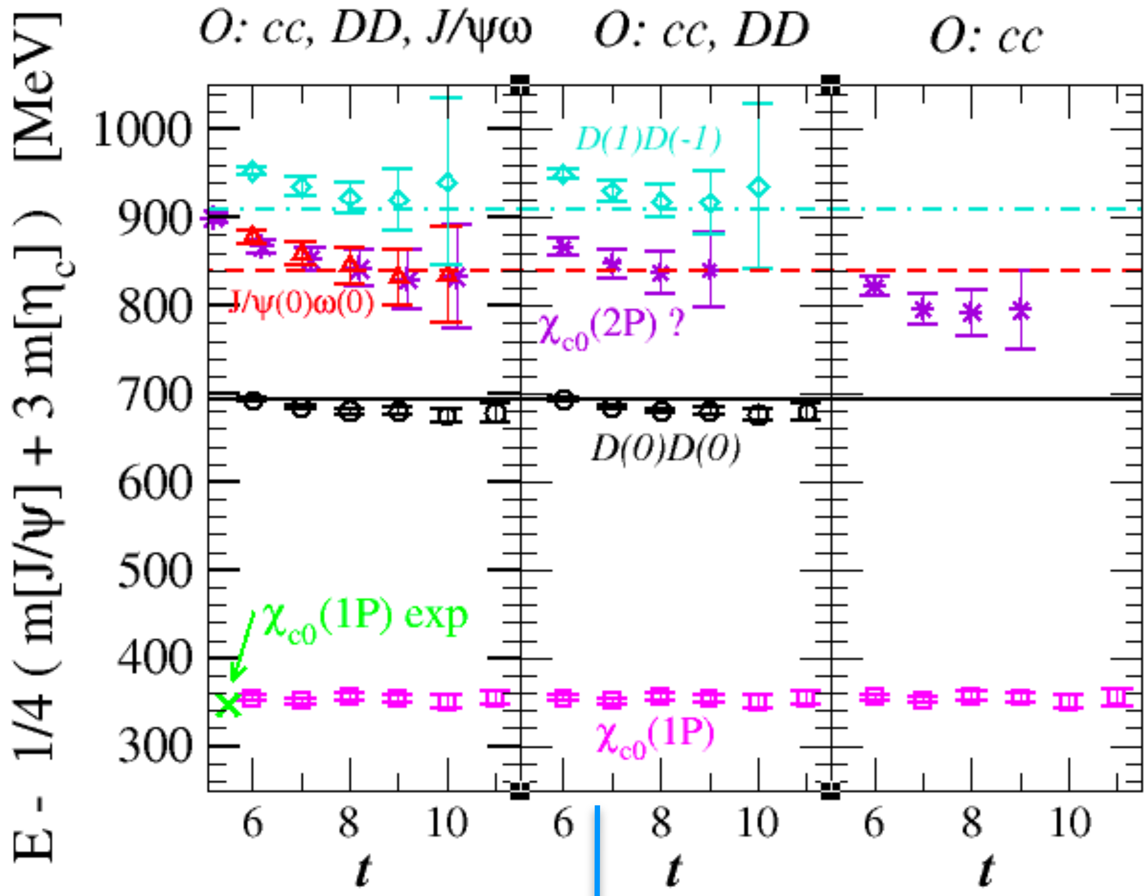
Interpolators : $J^{PC}=0^{++}$ (A_1^{++}) , P=0, I=0

$$O^{\bar{c}c}_{1-9} = \bar{c}\ \hat{M}_i\ c(0)$$

$$O^{DD}_1 = \bar{c}\gamma_5 u(0)\ \bar{u}\gamma_5 c(0) + \ \{u \to d\}$$
$$O^{DD}_2 = \bar{c}\gamma_5\gamma_t u(0)\ \bar{u}\gamma_5\gamma_t c(0) + \ \{u \to d\}$$
$$O^{DD}_3 = \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_5 u(e_k)\ \bar{u}\gamma_5 c(-e_k) + \ \{u \to d\}$$

$$O^{J/\psi\ \omega}_1 = \sum_j \bar{c}\gamma_j c(0)\ [\bar{u}\gamma_j u(0) + \ \{u \to d\}]$$
$$O^{J/\psi\ \omega}_2 = \sum_j \bar{c}\gamma_j\gamma_t c(0)\ [\bar{u}\gamma_j\gamma_t u(0) + \ \{u \to d\}]$$

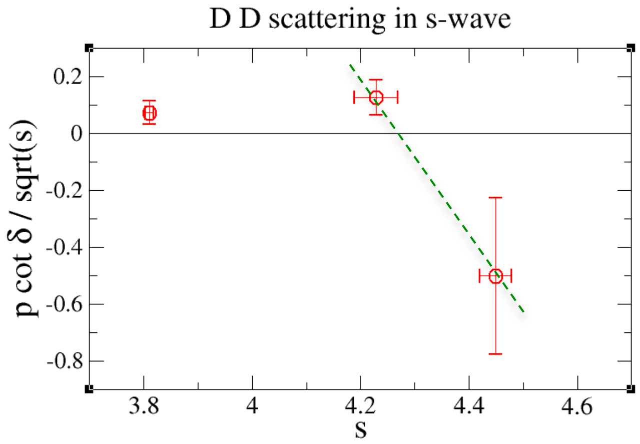
Spectrum for $J^{PC}=0^{++}$, I=0



- no visible effect from J/Ψ ω in the middle plot
- elastic DD scattering assumed for the middle plot

$D\underline{D}$ scattering in s-wave: PRELIMINARY

- δ from levels 2,3,4 in middle plot
- obviously not just one BW resonance
- there appears to be a narrow resonance between higher two points and we fit it with BW



$$\frac{p\cot\delta}{\sqrt{s}} = \frac{1}{g^2}(m^2 - s) \qquad \Gamma = g^2\frac{p}{s}$$

$$\text{lat}: \ \text{m} - \tfrac{1}{4}[m_{\eta_c} + 3m_{J/\psi}] = 864 \pm 25 \text{ MeV} \qquad \text{predict}: m = 3932 \pm 25 \text{ MeV}$$

$$\text{lat}: \ g = 0.94 \pm 0.23 \text{ GeV} \qquad \text{predict}: \ \Gamma[R \to D\bar{D}] = 36 \pm 17 \text{ MeV}$$

- using result on the left we predict where it would be expected in experiment
- experimental candidate for Xc0(2P) not commonly accepted
  - ✧ recently PDG assigned X(3915) as Xc0(2P)
  - ✧ serious objections to this: for example [Guo & Meissner, PRD86 (2012) 091501]
- the interaction does not seem to be negligible away from this narrow resonance:
  - ✧ there seems to be sizable interaction near threshold
  - ✧ in agreement with suggestion in [Guo & Meissner, PRD86 (2012) 091501]

Conclusions & outlook

- Status of previous simulations:

✧ states well-below open-charm threshold well understood

✧ states near thresholds and above them not treated rigorously

✧ I presented an exploratory study in this direction for three channels:

- $J^{PC}=1^{++}$ & X(3872)

✧ I=1: we do not find candidate for X(3872): maybe due to $m_u=m_d$

✧ I=0: we find candidate for X(3872) to be 11 ± 7 MeV below th.

Simulation on larger L will be needed for more reliable quantitative results

- $J^{PC}=1^{+-}$, I=1 & $Z_c^+(3900)$

✧ only scattering states found

✧ we do not find candidate for $Z_c^+(3900)$ in $J^{PC}=1^{+-}$ channel

✧ future simulations using additional types of interpolators needed

- $J^{PC}=0^{++}$, I=0

✧ indication for a narrow resonance and additional non-negligible int. near th.