Charmonium-hadron scatterings and exotics
from
lattice QCD

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Contents

- Introduction
- Charmonium(J/ψ)-Φ scattering and Y(4140) search
- Bottomonium-hadron scatterings
- Summary

Introduction

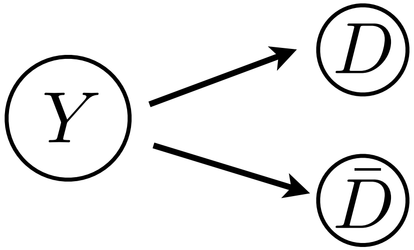
- Recently many charmonium($c\bar{c}$) like particles XYZ are observed in several big facilities in the world.

- Among them, some Y resonances have interesting features.

1) Although these resonances are heavy, these are very stable.

Widths are quite “narrow” as compared to typical hadron resonances.

2) Open charm channel decays seem to be suppressed.



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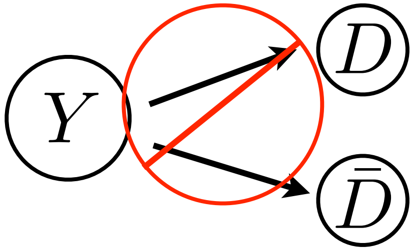
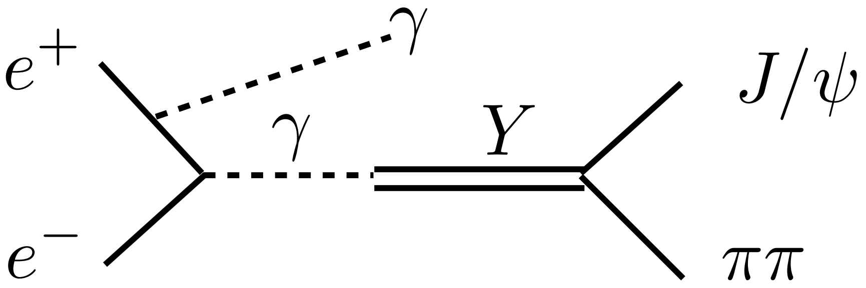
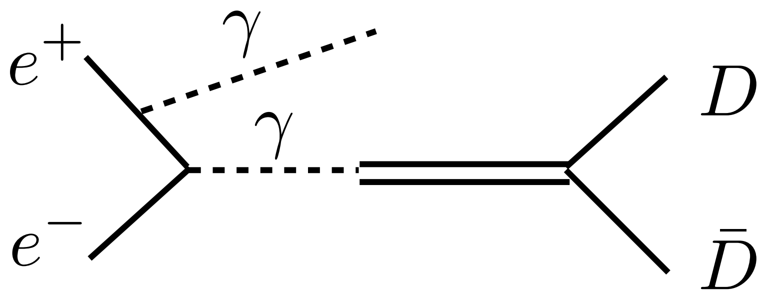


Example 1) Initial State Radiation(ISR)-produced 1^-- Y families (including Y(4260)):



→ Many Y states



→ No such Y states

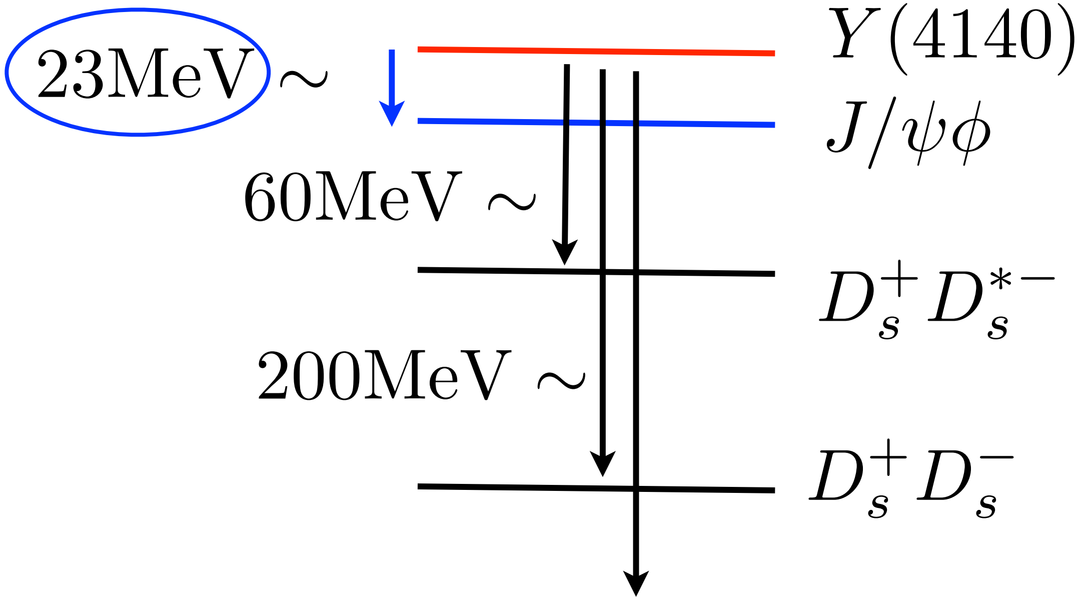
in Belle experiments

Example 2) Y(4140).

T.Aaltonen et al, PRL 102, 242002 (2009)

$$B \to \underbrace{J/\psi\phi}_{Y(4140)} K \qquad M_Y = 4143.0 \pm 2.9 \pm 1.2\mathrm{MeV}$$

$$\Gamma_Y = 11.6^{+8.3}_{-5.0} \pm 3.7\mathrm{MeV}$$ quite narrow width



It seems that some Y states do not couple to open charm channels.

⟶ Is there a specific selection rule?

These features should be related <u>to the structure of Y states</u>, and <u>charmonium(J/ψ)-hadron interactions</u>.

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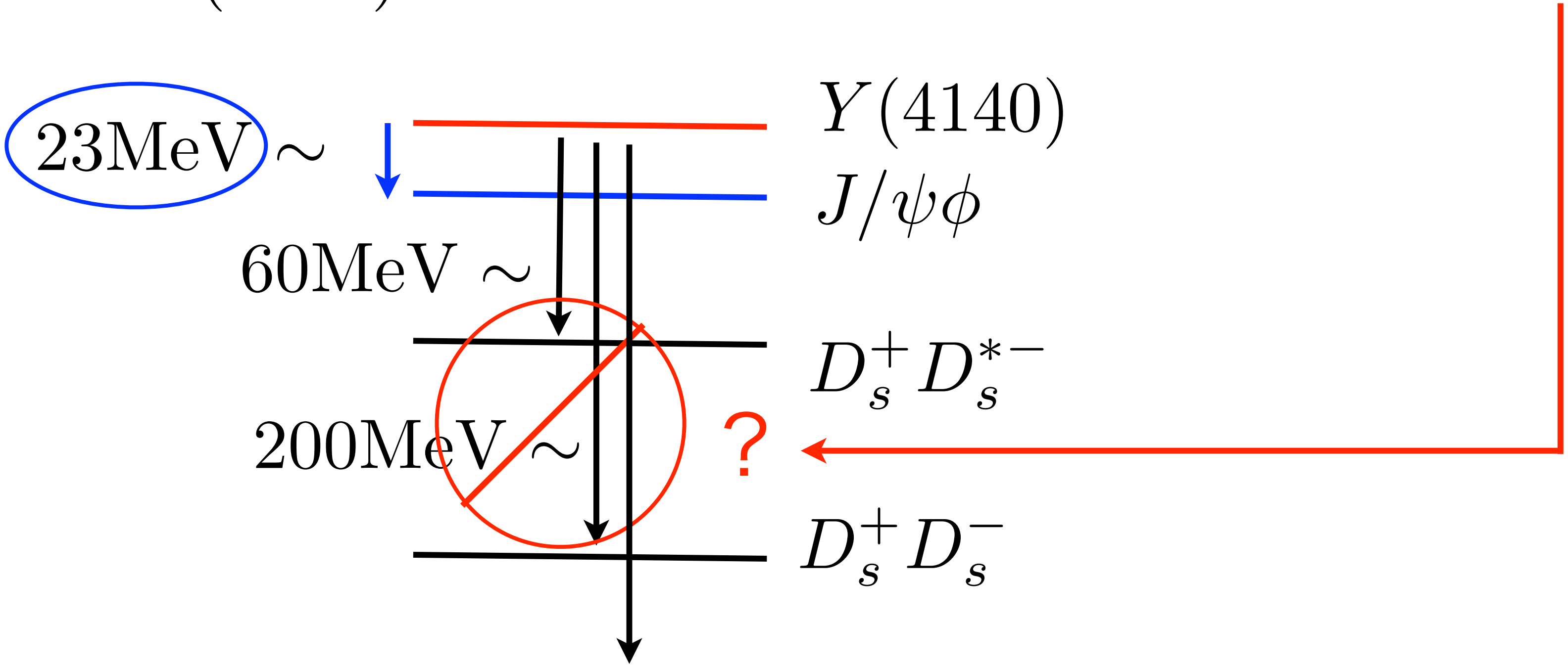

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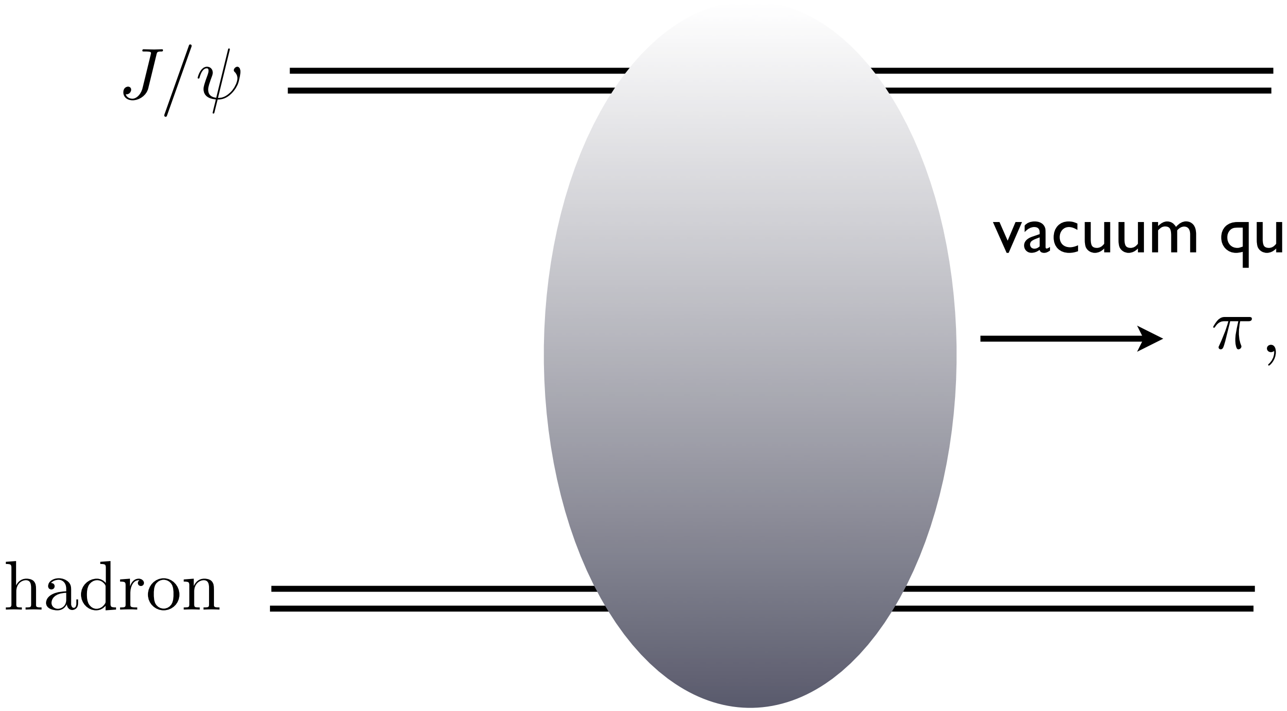
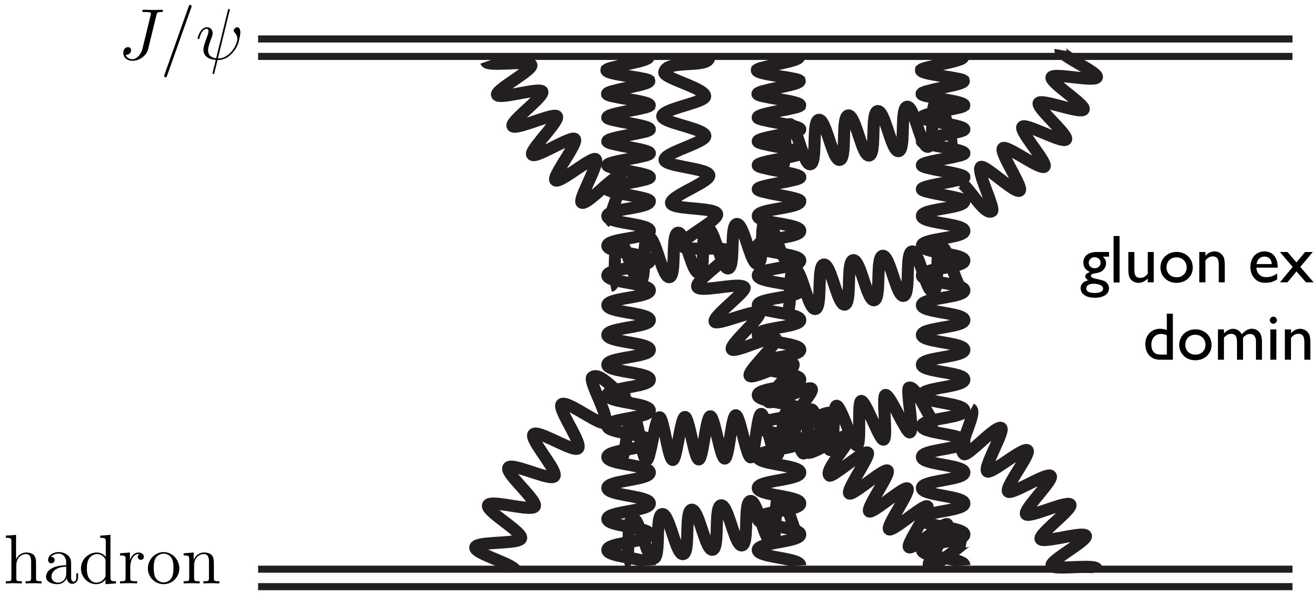
Charmonium-hadron interactions



vacuum quantum number

$\longrightarrow$ $\pi\,,\,\rho$ exchanges are forbidden!

Charmonium-hadron interactions

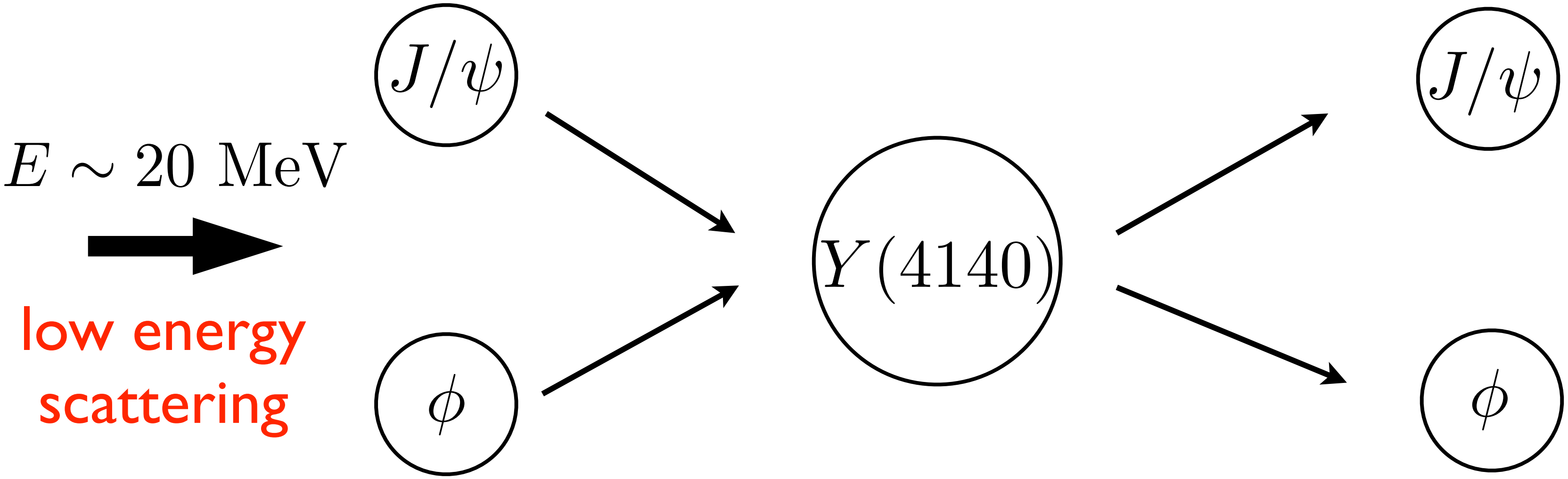


gluon exchange dominance

So if there exist a (Y) resonance in charmonium-hadron system, gluons would play very interesting role!

Non-perturbative method such as lattice QCD is really needed to study this system.

J/ψ-Φ scattering and Y(4140)



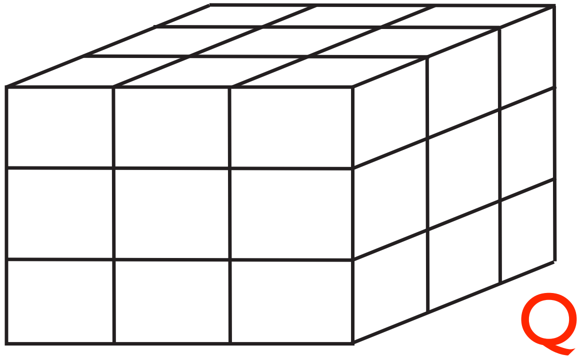
$E \sim 20$ MeV

low energy scattering

with

$J^P = (0^\pm, 1^\pm, 2^\pm)$ channels

on



QCD

Today, we focus on s-wave: $J^P = (0^+, 1^+, 2^+)$

In order to search a "narrow" resonance in "low energy" regions near thresholds, we introduce the twisted boundary condition.

Periodic Boundary Condition

$$\phi(\vec{x}+L\vec{\epsilon}_i)=\phi(\vec{x}) \quad , \qquad i=x,y,z$$

$$\longrightarrow \vec{k}=\frac{2\pi}{L}\vec{n}$$

$$E_1=k_1^2/2\mu\sim 100\ \mathrm{MeV}$$ ⟶ Bad resolution

Twisted Boundary Condition (TBC)

P.F. Bedaque, PLB593 (2004) 84

$$\phi(\vec{x}+L\vec{\epsilon}_i)=\underline{e^{i\theta_i}}\phi(\vec{x})$$

$$\longrightarrow \vec{k}=\frac{2\pi}{L}(\vec{n}+\underline{\vec{d}}) \quad , \qquad \vec{d}=(\frac{\theta_x}{2\pi},\frac{\theta_y}{2\pi},\frac{\theta_z}{2\pi})$$

We can investigate low energy scatterings and search a narrow resonance with a good energy resolution.

Finite size method

M. Luscher, NPB354 (1991) 531-578

Finite size formula

$$\tan\,\delta_0(k) = \frac{\pi^{3/2}q}{\mathcal{Z}_{00}(1,q^2)} \qquad \text{where} \quad q = \frac{Lk}{2\pi}$$

Generalized zeta-function

$$\mathcal{Z}_{00}(s,q^2) = \frac{1}{\sqrt{4\pi}}\sum_{\vec{n}\in Z^3}(\vec{n}^2 - q^2)^{-s}$$

- Finite size formula is the relation which connects energy eigenvalue in a finite volume with scattering phase shift in an infinite volume.

- This method successfully describe ρ meson from π-π scattering.

S.Aoki et al (CP-PACS) PRD 76, 094506 (07)

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▶ Finite size formula is the relation which connects energy eigenvalue in a finite volume with scattering phase shift in an infinite volume.

▶ Here we would like to search Y(4140) from J/ψ-Φ scattering in terms of the finite size method.

Combine finite size method with TBC

Finite size formula with TBC

$$\tan\,\delta_0(k) = \frac{\pi^{3/2} q}{\mathcal{Z}^{\theta}_{00}(1, q^2)}$$

$$\mathcal{Z}^{\theta}_{00}(1, q^2) = \frac{1}{\sqrt{4\pi}} \sum_{\vec{r}\in\Gamma_\theta} (\vec{r}^{\,2} - q^2)^{-1}$$

$$\Gamma_\theta = \{\vec{r} \mid \vec{r} = \frac{2\pi}{L}(\vec{n} + \frac{\vec{\theta}}{2\pi}), \quad \vec{n} \in Z^3\}$$

- The derivation and calculation techniques with arbitrary angles will be shown in the paper which is currently in preparation.
- By using this formula, we can investigate "low energy" hadron scatterings near thresholds and search "narrow" resonances with a desired resolution.

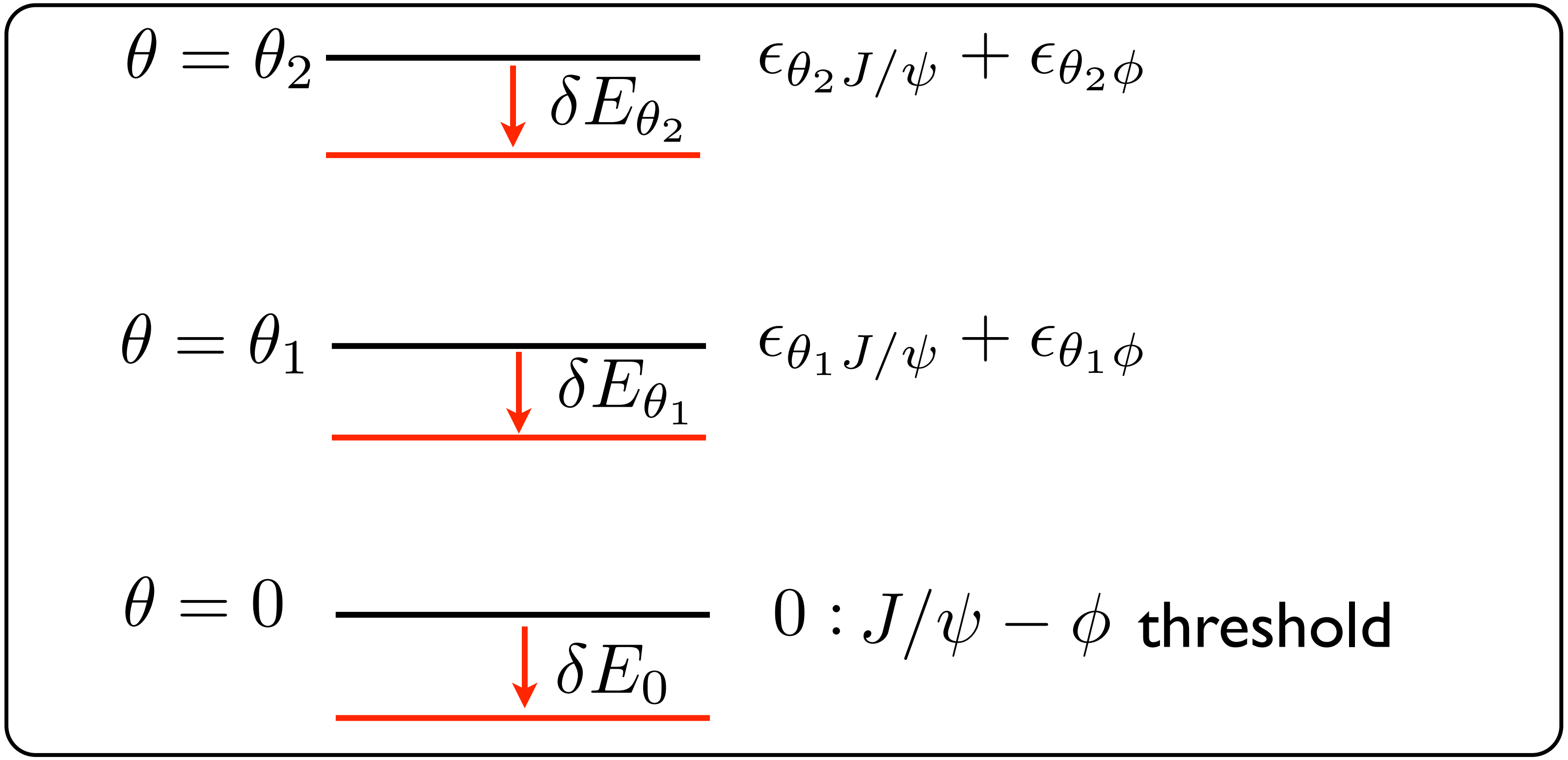
$$\boxed{k = \sqrt{2\mu \underline{\Delta E}}}$$

$$E_{\theta V} = \sqrt{\left(\frac{\theta}{L}\right)^2 + M_V^2}$$

$$\begin{aligned} \underline{\Delta E} &= E_{J/\psi-\phi} - (M_{J/\psi} + M_\phi) \\ &= \underline{[E_{J/\psi-\phi} - (E_{\theta J/\psi} + E_{\theta\phi})]} + \underline{[E_{\theta J/\psi} - M_{J/\psi}] + [E_{\theta\phi} - M_\phi]} \end{aligned}$$

$$\Delta E = \underline{\delta E_\theta} + \underline{\epsilon_{\theta J/\psi} + \epsilon_{\theta\phi}}$$

Interaction strength Energy of free 2 particles



$\theta = \theta_2$ δE_{θ_2} $\epsilon_{\theta_2 J/\psi} + \epsilon_{\theta_2 \phi}$

$\theta = \theta_1$ δE_{θ_1} $\epsilon_{\theta_1 J/\psi} + \epsilon_{\theta_1 \phi}$

$\theta = 0$ δE_0 $0 : J/\psi - \phi$ threshold

Measurement of δE

Two-point function

$$G^{\phi}(t, t_{src}) = \langle \hat{O}_{\phi}(t)\hat{O}^{\dagger}_{\phi}(t_{src})\rangle$$

$$G^{J/\psi}(t, t_{src}) = \langle \hat{O}_{J/\psi}(t)\hat{O}^{\dagger}_{J/\psi}(t_{src})\rangle$$

with

$$\hat{O}^{\phi}(t) = \bar{s}(t)\gamma_i\bar{s}(t)$$

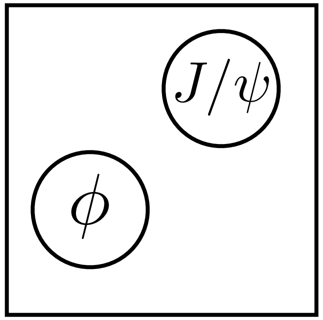
$$\hat{O}^{J/\psi}(t) = \bar{c}(t)\gamma_i\bar{c}(t)$$

Four-point function

$$G^{J/\psi-\phi}(t, t_{src}) = \langle \hat{O}_{\phi}(t)\hat{O}_{J/\psi}(t)[\hat{O}_{\phi}(t_{src})\hat{O}_{J/\psi}(t_{src})]^{\dagger}\rangle$$

$$\frac{G^{J/\psi-\phi}(t, t_{src})}{G^{J/\psi}(t, t_{src})G^{\phi}(t, t_{src})} \sim e^{-\underline{\delta E}t}$$

$\underline{\delta E}$ =



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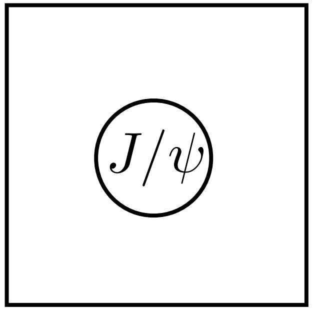

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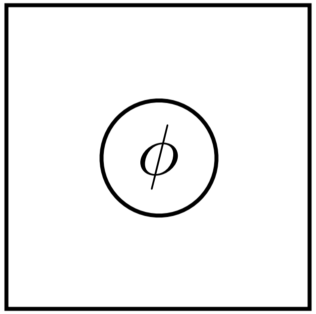


)

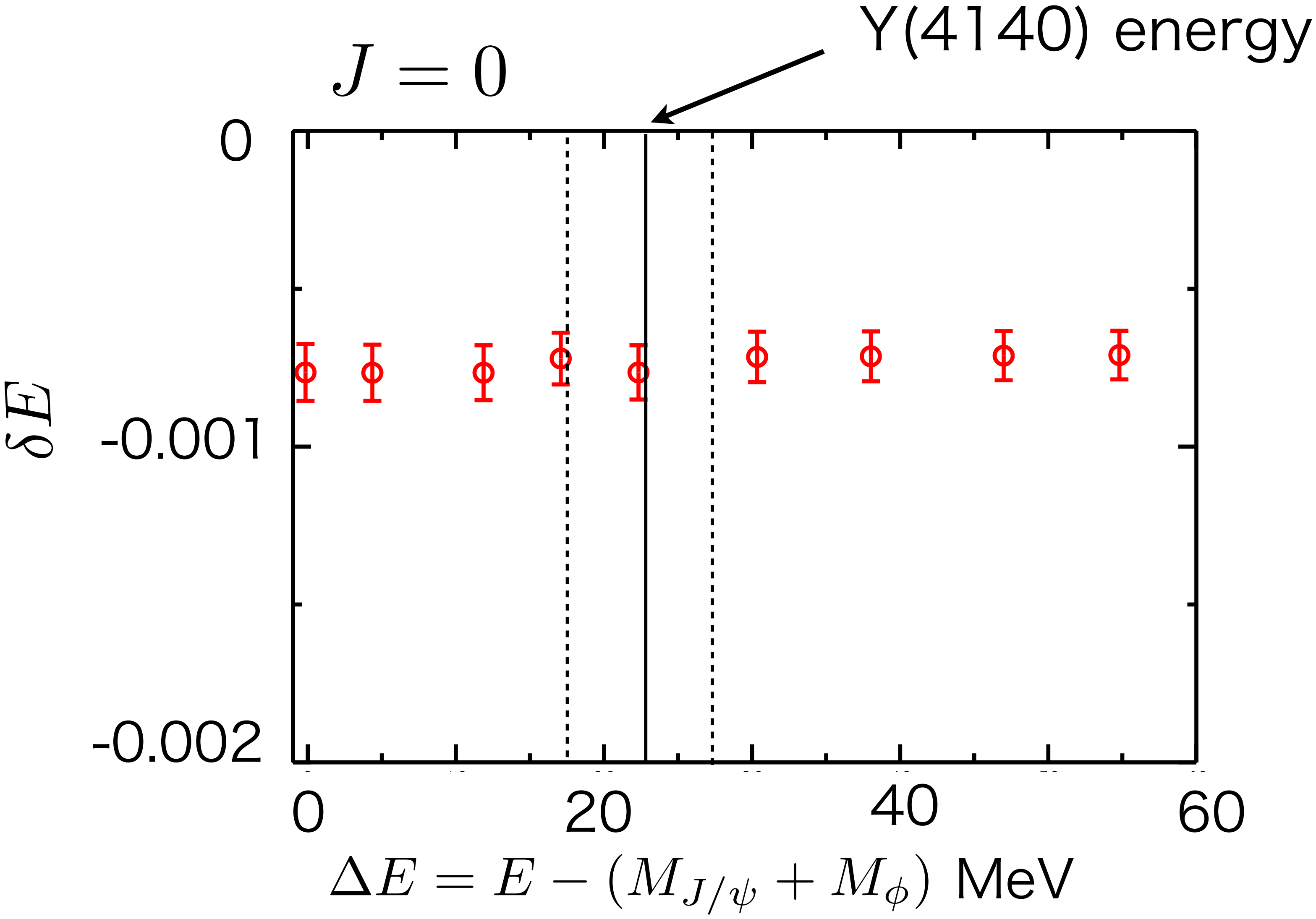
Lattice set up

- PACS-CS 2+1 flavor dynamical gauge configurations at $m_\pi = 156 \text{ MeV}$ S.Aoki et al, PRD79, 034503, 2009
  - 32^3 x 64 lattice
  - a = 0.0907(13) fm
  - La ~ 2.9 fm
  - 198 configs
  - $\kappa_s = 0.13640$
  - Wall source
- Relativistic Heavy Quark (RHQ) action for charm

  Y. Namekawa et al, PRD84:074505, 2011
  - Tsukuba type RHQ action (5 parameters)

$\kappa_{\rm charm}$	ν	r_s	c_B	c_E
0.1082	1.2153	1.2131	2.0268	1.7911

Result of δE



- J/ψ-Φ interaction is attractive.
- The strength of the interaction is E-independent.

Threshold parameters: Scattering lengths

$$a^{J=0}_{J/\psi-\phi} = -0.151(20)\ \mathrm{fm}$$

$$a^{J=1}_{J/\psi-\phi} = -0.130(18)\ \mathrm{fm}$$

$$a^{J=2}_{J/\psi-\phi} = -0.109(18)\ \mathrm{fm}$$

Our definition

$$-\frac{\tan\delta_0}{k}\Big|_{k\to 0} = a_{J/\psi-\phi}$$

$a_{J/\psi-\phi} < 0$: attractive

Quenched results

$$a^{J=0}_{J/\psi-\phi} = -0.178(21)\ \mathrm{fm}$$

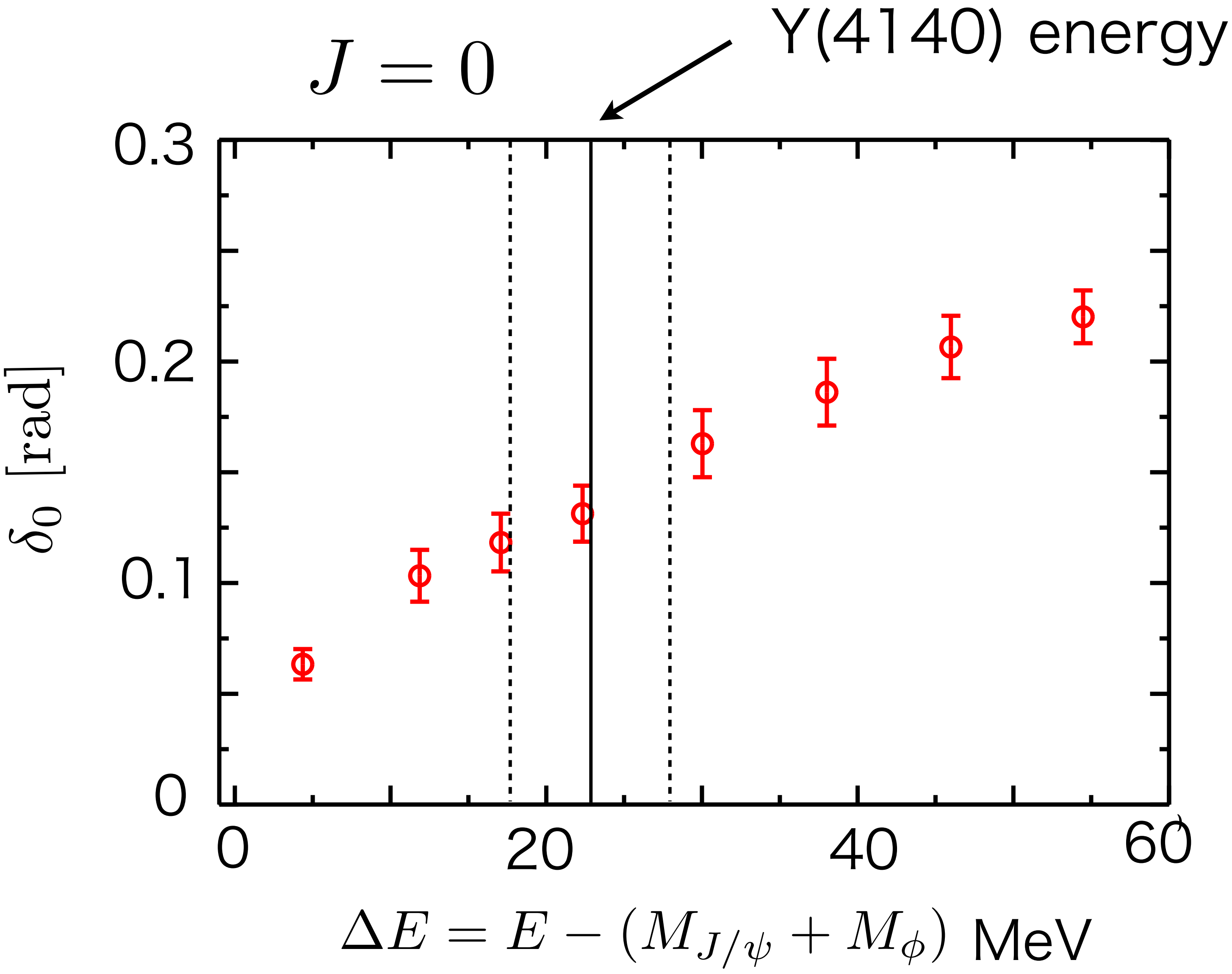
$$a^{J=1}_{J/\psi-\phi} = -0.152(23)\ \mathrm{fm}$$

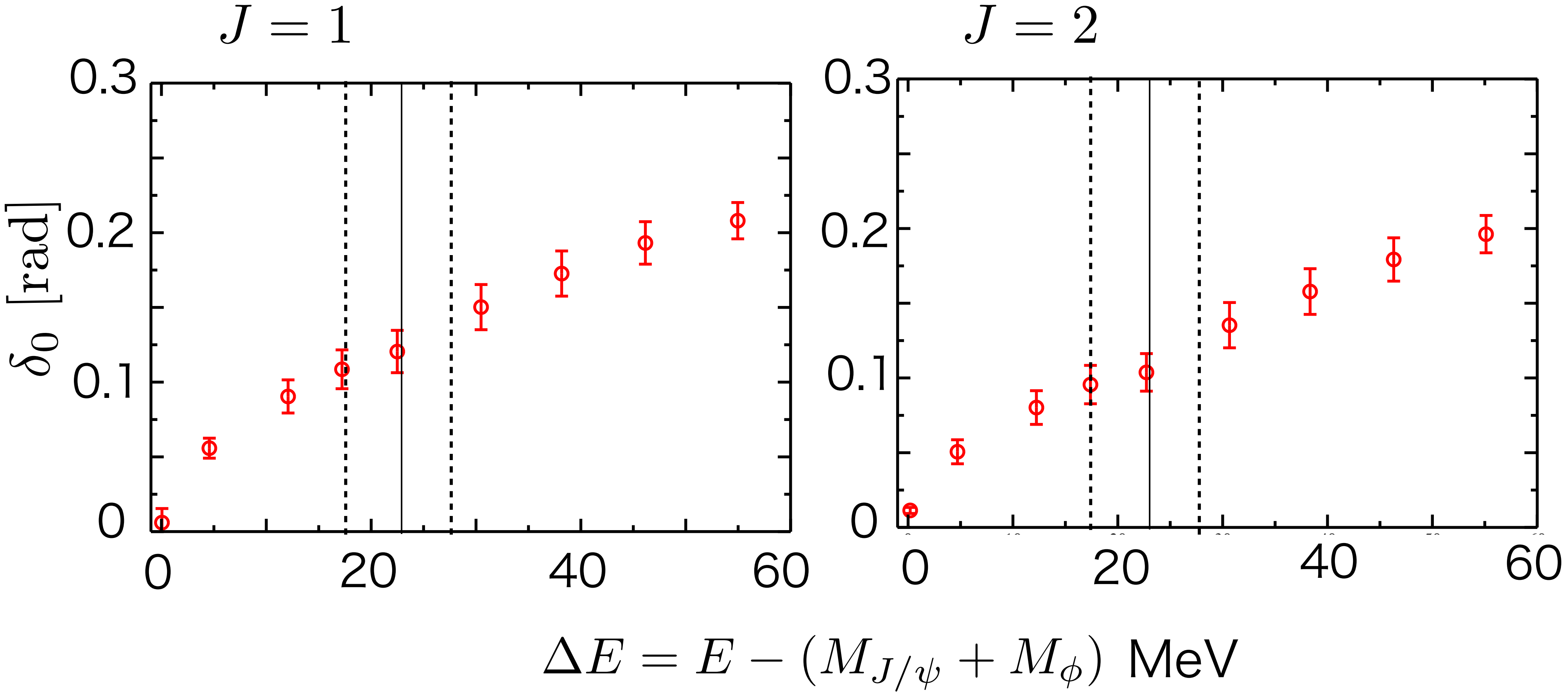
$$a^{J=2}_{J/\psi-\phi} = -0.123(16)\ \mathrm{fm}$$

Quenched results and full QCD results are quite close within 1σ.

⟶ This would reflects that J/Ψ-Φ system
is indeed governed by gluon-dynamics.

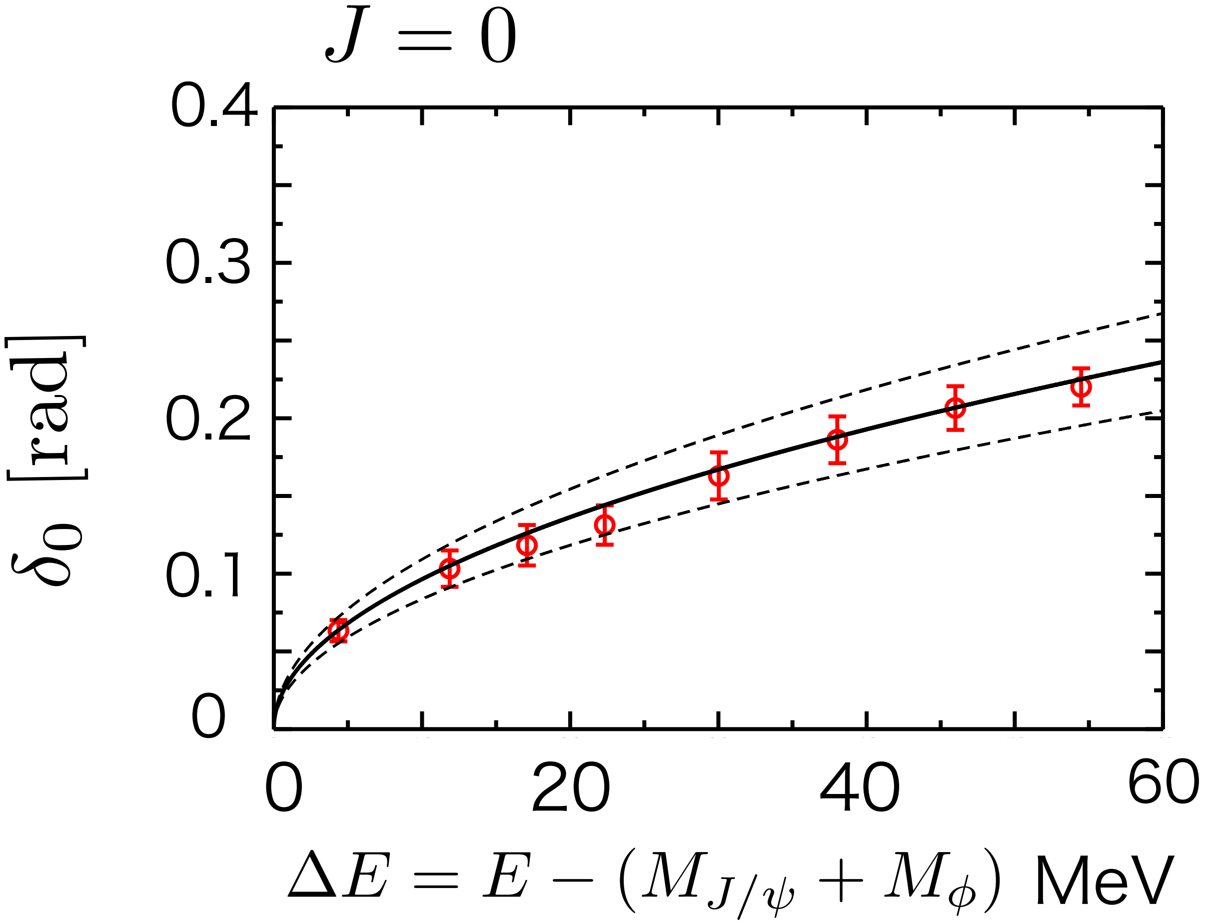
Low energy behaviors of scattering phase shift





No structure in low energy J/ψ-Φ system near the thresholds.

These seem typical s-wave behaviors: $\delta_l \sim (\Delta E)^{l+\frac{1}{2}}$

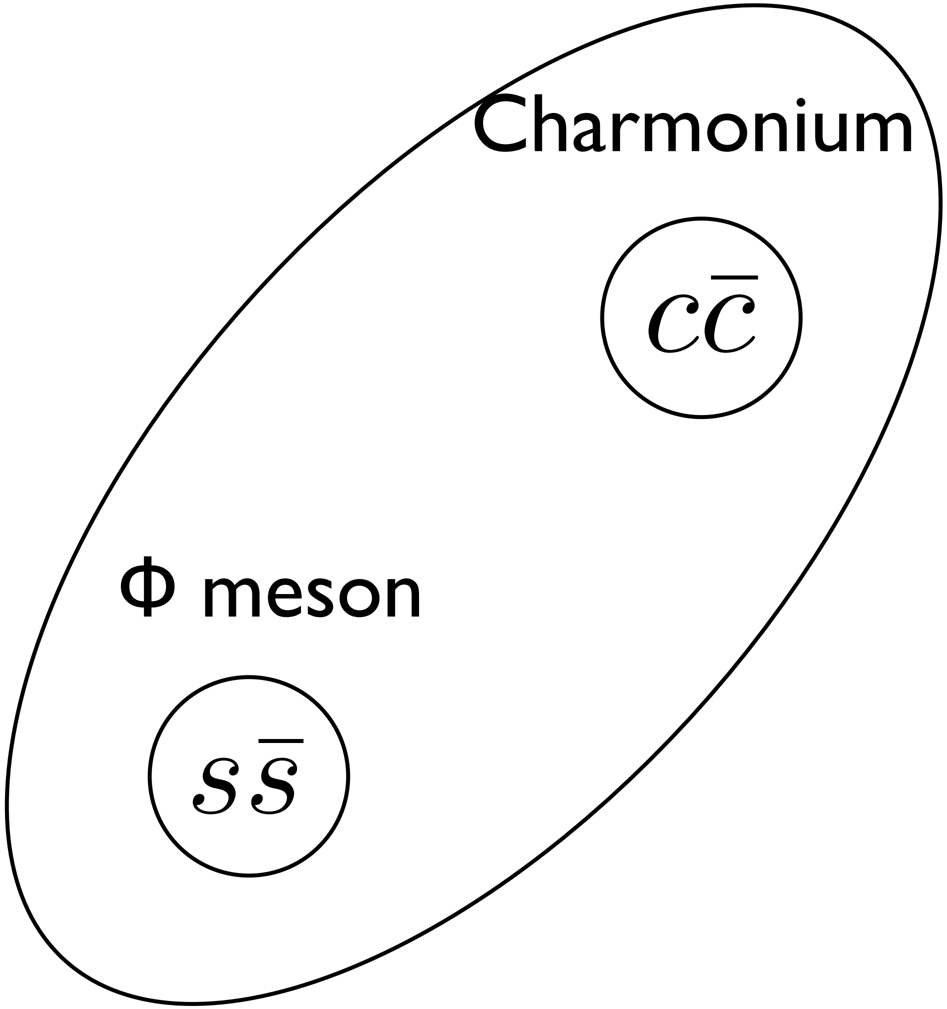


The data show a leading order behavior of s-wave phase shift:

$$\delta_0(k) = -a_0 k = -a_0\sqrt{2\mu\Delta E}$$

with the scattering length determined at the threshold

$$a^{J=0}_{J/\psi-\phi} = -0.151(20)\ \mathrm{fm}$$

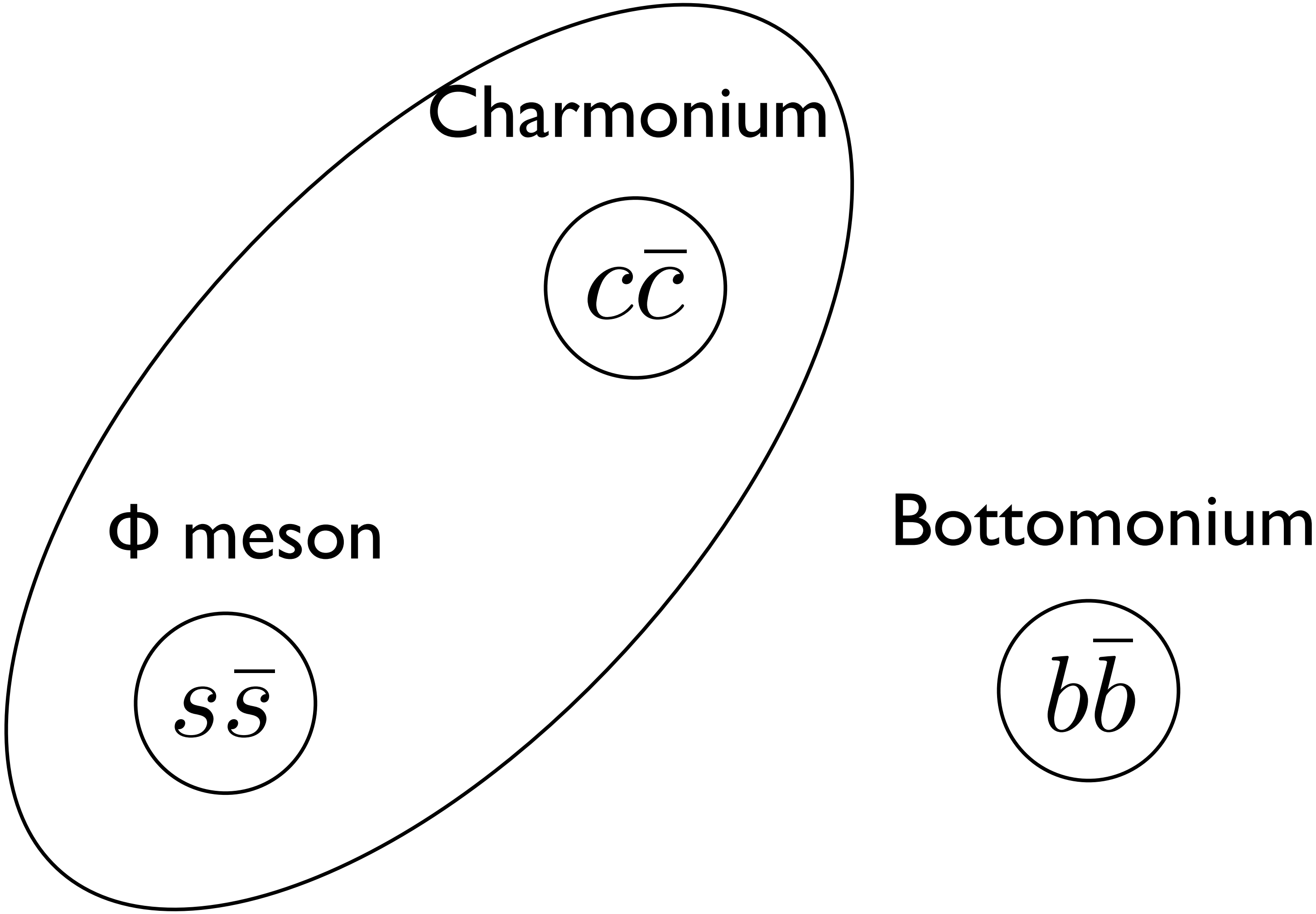


Charmonium

$c\bar{c}$

Φ meson

$s\bar{s}$



Charmonium

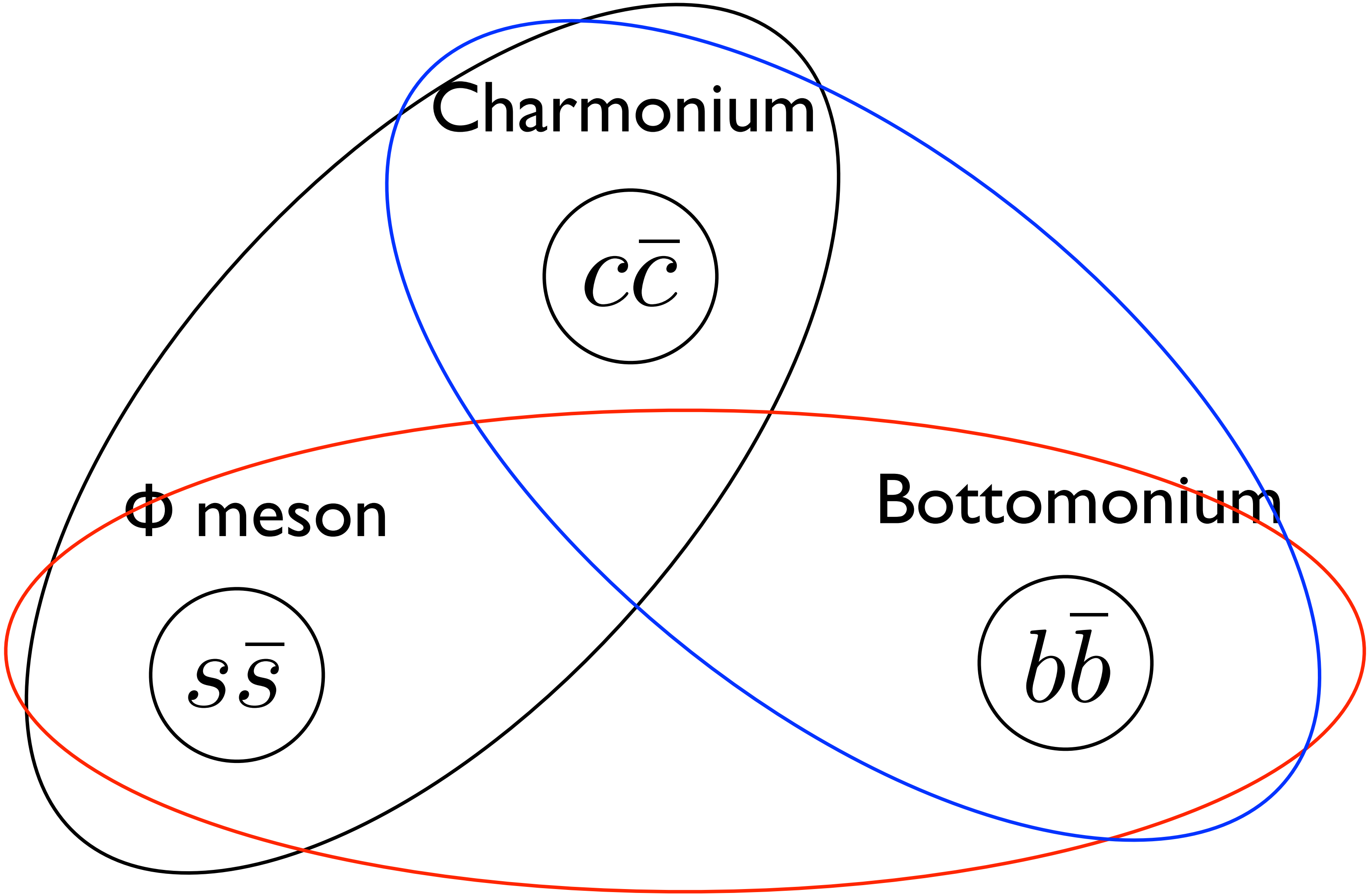
$c\bar{c}$

Φ meson

$s\bar{s}$

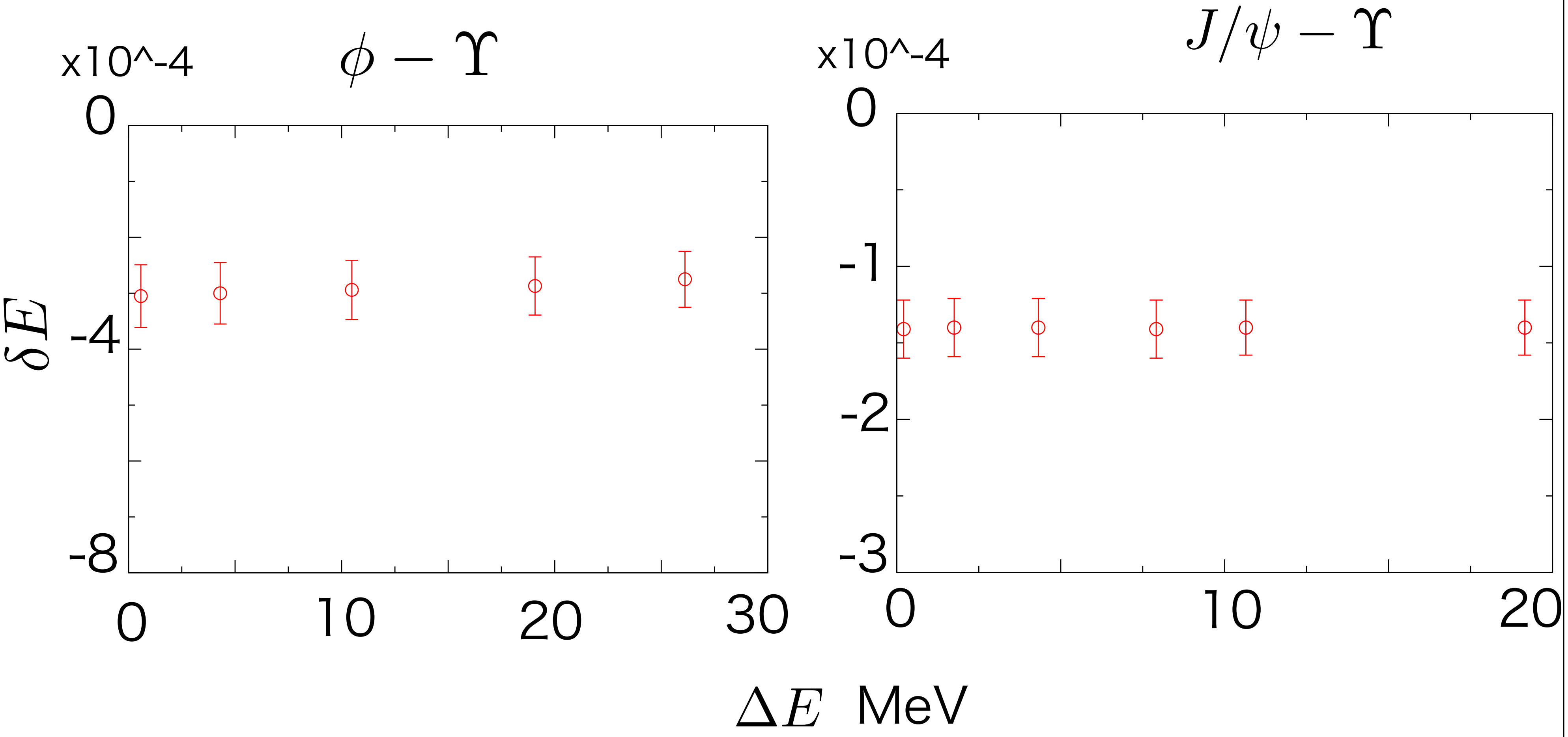
Bottomonium

$b\bar{b}$


Charmonium
$c\bar{c}$
Φ meson
$s\bar{s}$
Bottomonium
$b\bar{b}$

Result of δE

$$J=0$$



Φ-ϒ scattering length

$$a_{\phi-\Upsilon}^{J=0} = -0.068(13)\ \mathrm{fm}$$

$$a_{\phi-\Upsilon}^{J=1} = -0.063(13)\ \mathrm{fm}$$

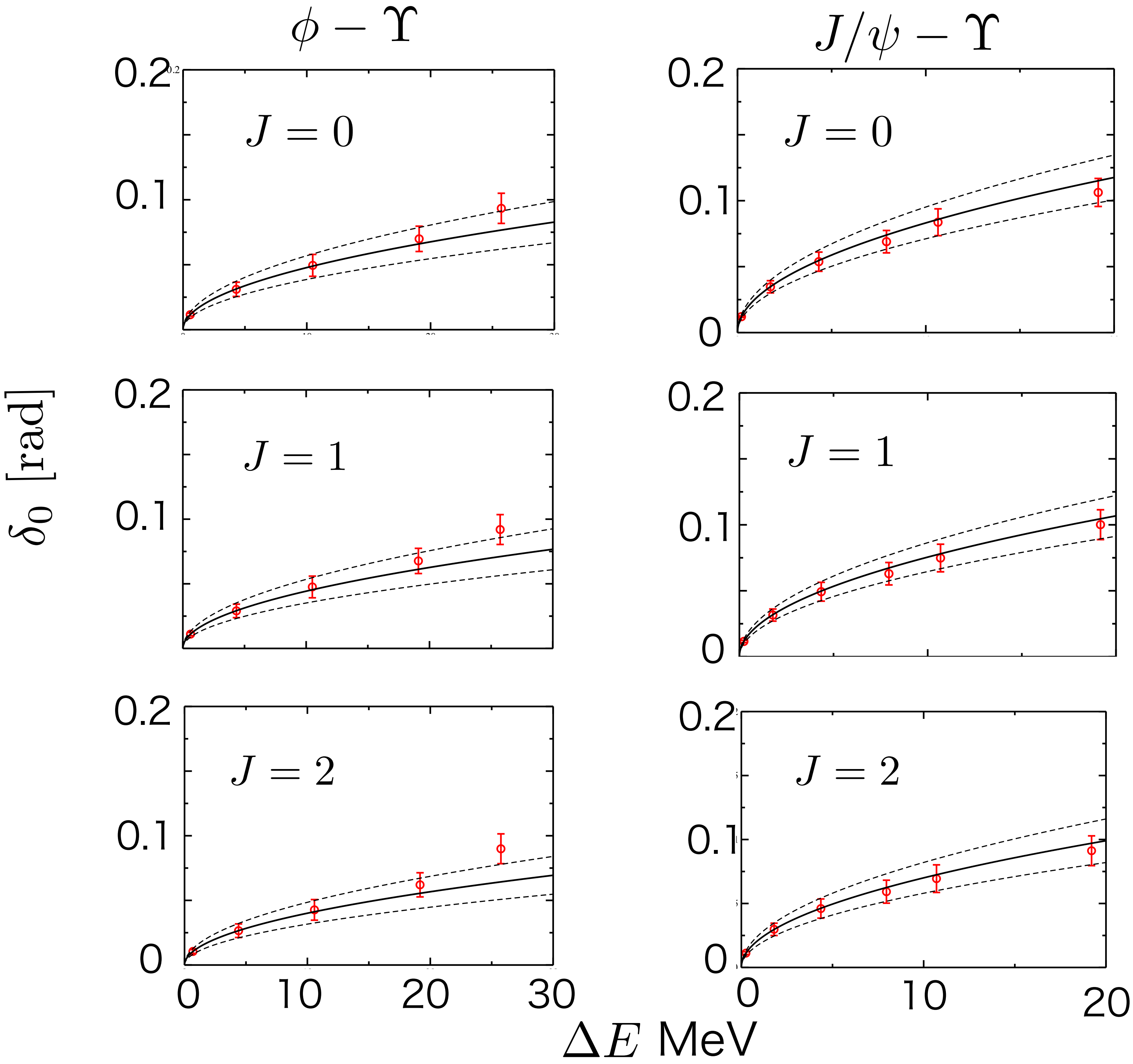
$$a_{\phi-\Upsilon}^{J=2} = -0.057(12)\ \mathrm{fm}$$

J/ψ-ϒ scattering length

$$a_{J/\psi-\Upsilon}^{J=0} = -0.076(11)\ \mathrm{fm}$$

$$a_{J/\psi-\Upsilon}^{J=1} = -0.069(10)\ \mathrm{fm}$$

$$a_{J/\psi-\Upsilon}^{J=2} = -0.064(11)\ \mathrm{fm}$$


$\phi - \Upsilon$
$J/\psi - \Upsilon$
$J = 0$
$J = 1$
$J = 2$
δ_0 [rad]
0.2
0.1
0
0
10
20
30
ΔE MeV

Summary

- We investigate the low energy s-wave J/ψ-Φ scattering with PACS-CS 2+1 dynamical gauge configurations (m_π=156 MeV).
- Their interactions are attractive, but no E-dependence.
- In terms of the finite size method with TBC, we calculate scattering phase shifts near the threshold. The data show typical s-wave behaviors but there is no resonance in low energy s-wave J/ψ-Φ systems.
- We calculate scattering lengths, and compare with quenched results.

  $\longrightarrow$ gluon-dynamics seem important in this system.
- We also investigate Bottomonium scatterings.

Prospects

- As a next step we will perform P-wave calculations (J^P = (0^- , 1^-, 2^-)) and search Y(4140) resonance.

If Y(4140) resonance exist on the lattice...

- Determine parity and spin of the resonance.
- Construct J/ψ-Φ potential, and investigate the structure of Y(4140) resonance in terms of its BS wave function.