J/ψ-Φ interaction and Y(4140) on the lattice QCD

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in collaboration with

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Introduction

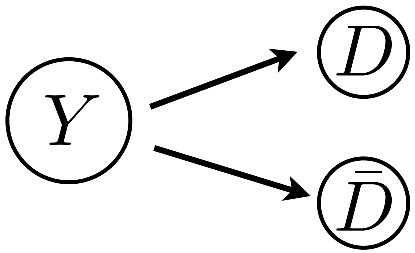
- Recently many charmonium($c\bar{c}$) like particles XYZ are observed in several big facilities in the world.

- 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.



Introduction

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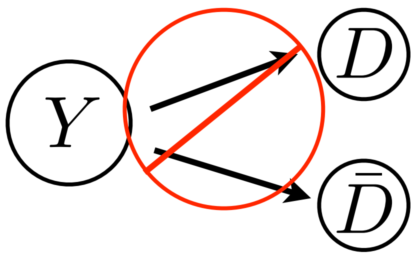
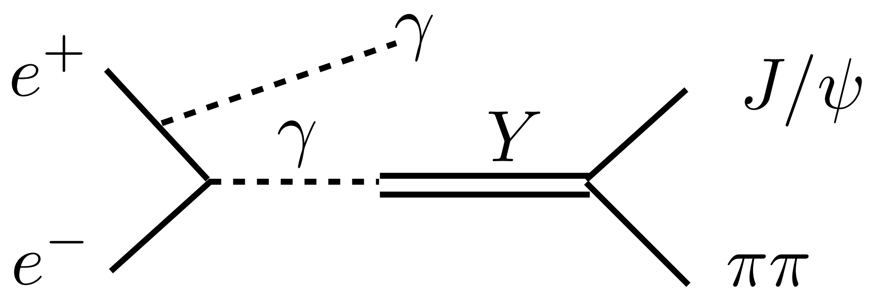
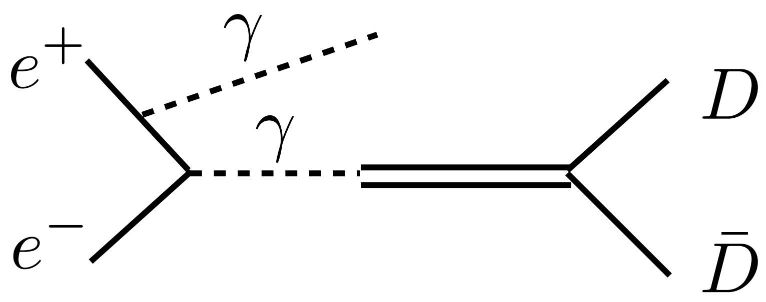


Example 1) Initial State Radiation(ISR)-produced 1^-- Y families (including Y(4260)):



many Y states



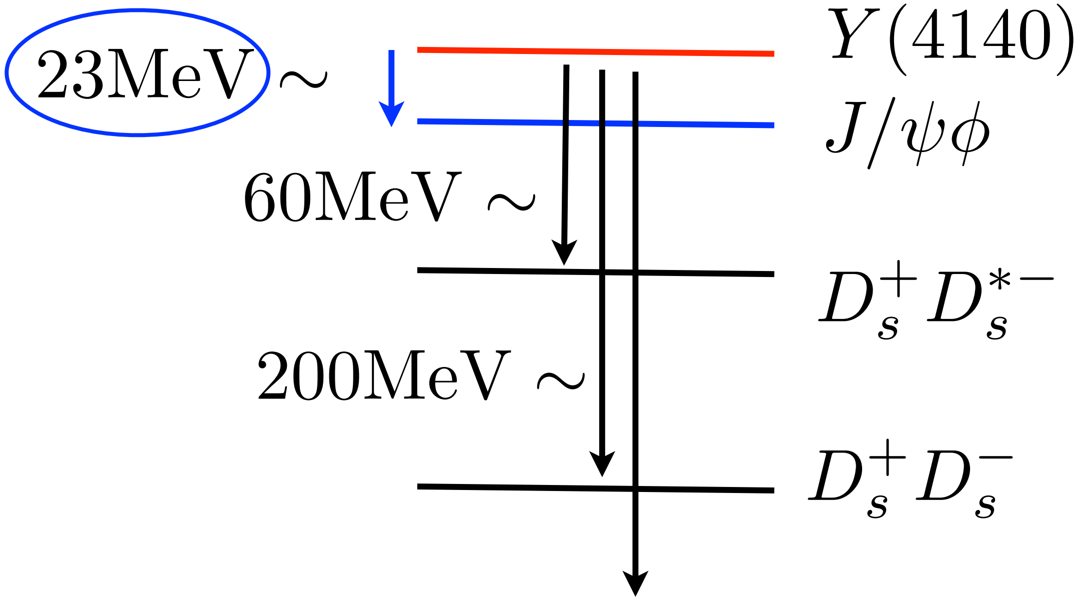
No such Y states

Example 2) Y(4140).

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

$$B \to \underline{J/\psi\phi} K \qquad M_Y = 4143.0 \pm 2.9 \pm 1.2\mathrm{MeV}$$

$$Y(4140) \qquad \Gamma_Y = 11.6^{+8.3}_{-5.0} \pm 3.7\mathrm{MeV}$$ quite narrow width



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

$\longrightarrow$ Is there a specific selection rule?

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

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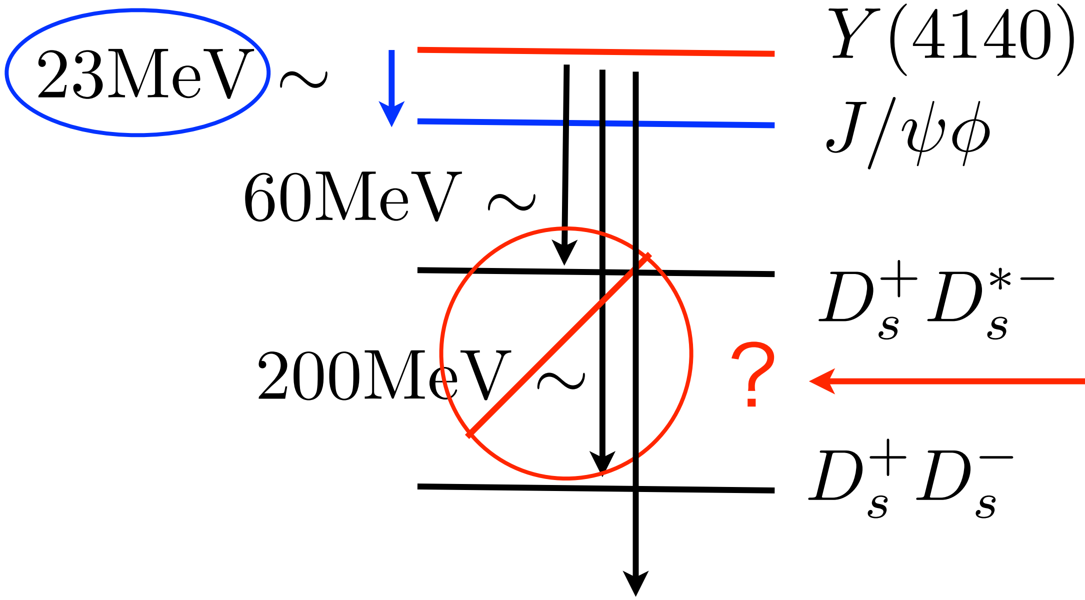

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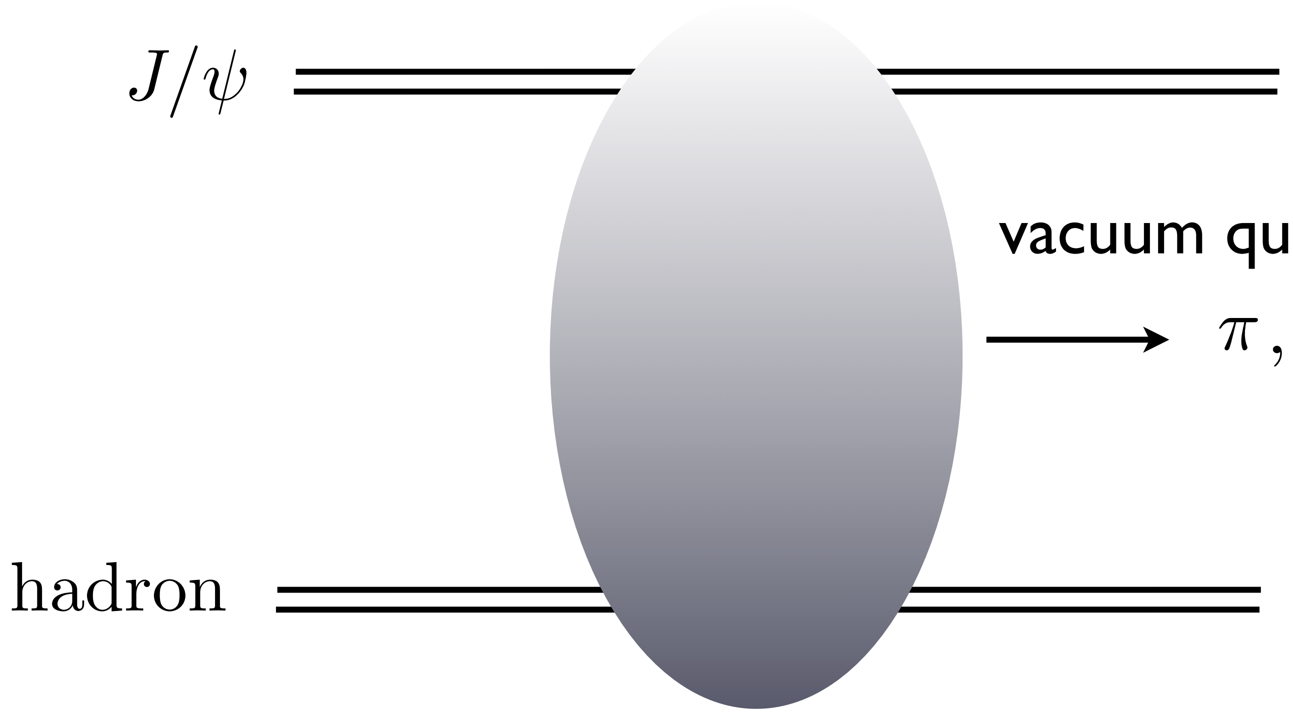
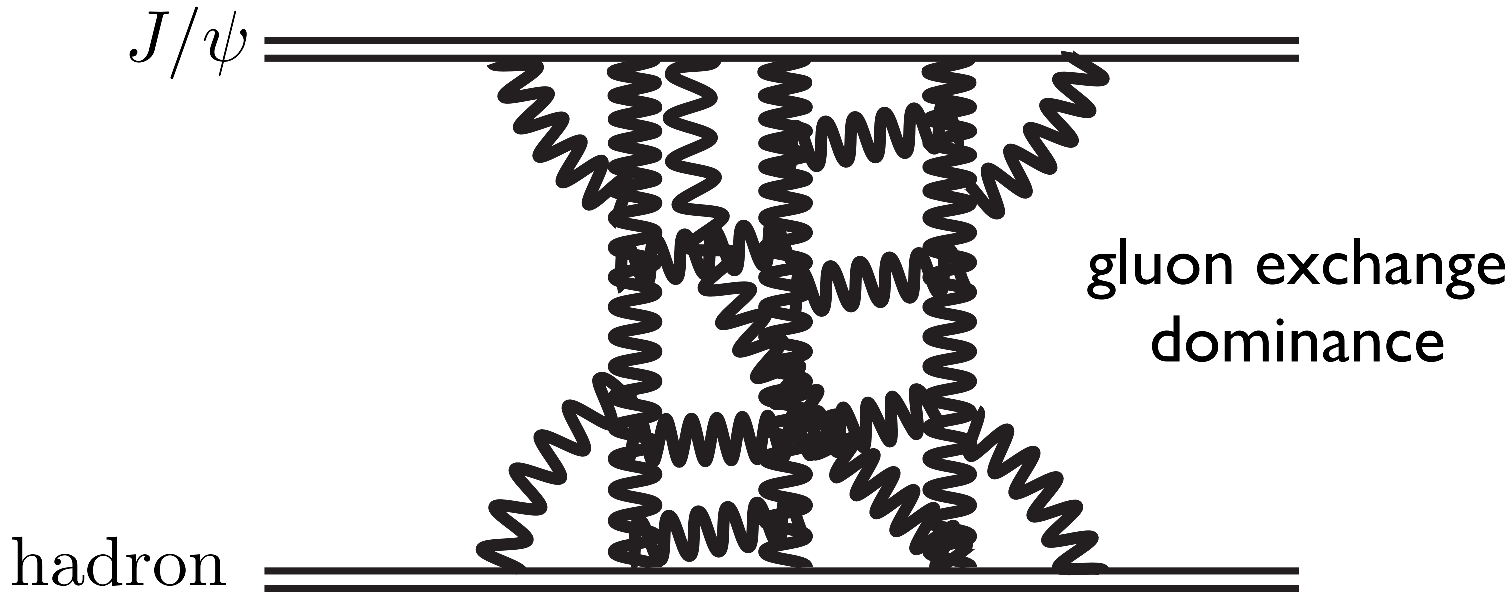
Charmonium-hadron interactions



vacuum quantum number

$\longrightarrow$ π , ρ exchanges are forbidden!

Charmonium-hadron interactions



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.

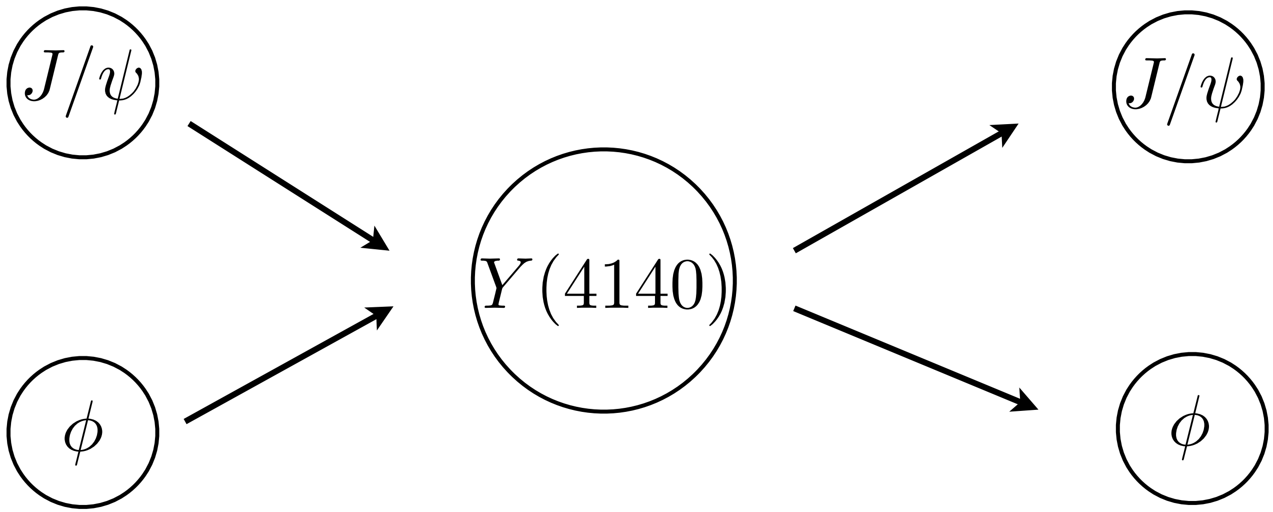
J/ψ-Φ scattering and Y(4140)

$E \sim 20\ \mathrm{MeV}$

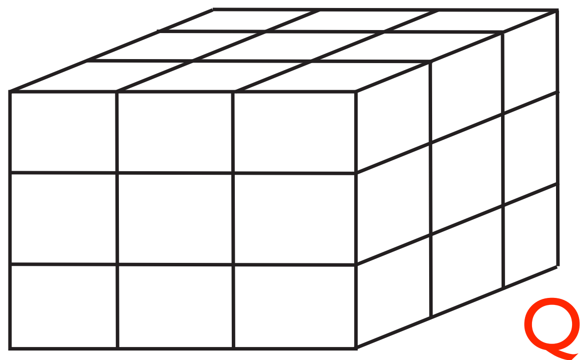
low energy scattering

with

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



on



QCD

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

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.

- We would like to successfully describe Y(4140) from J/ψ-Φ scattering in terms of the finite size method.

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

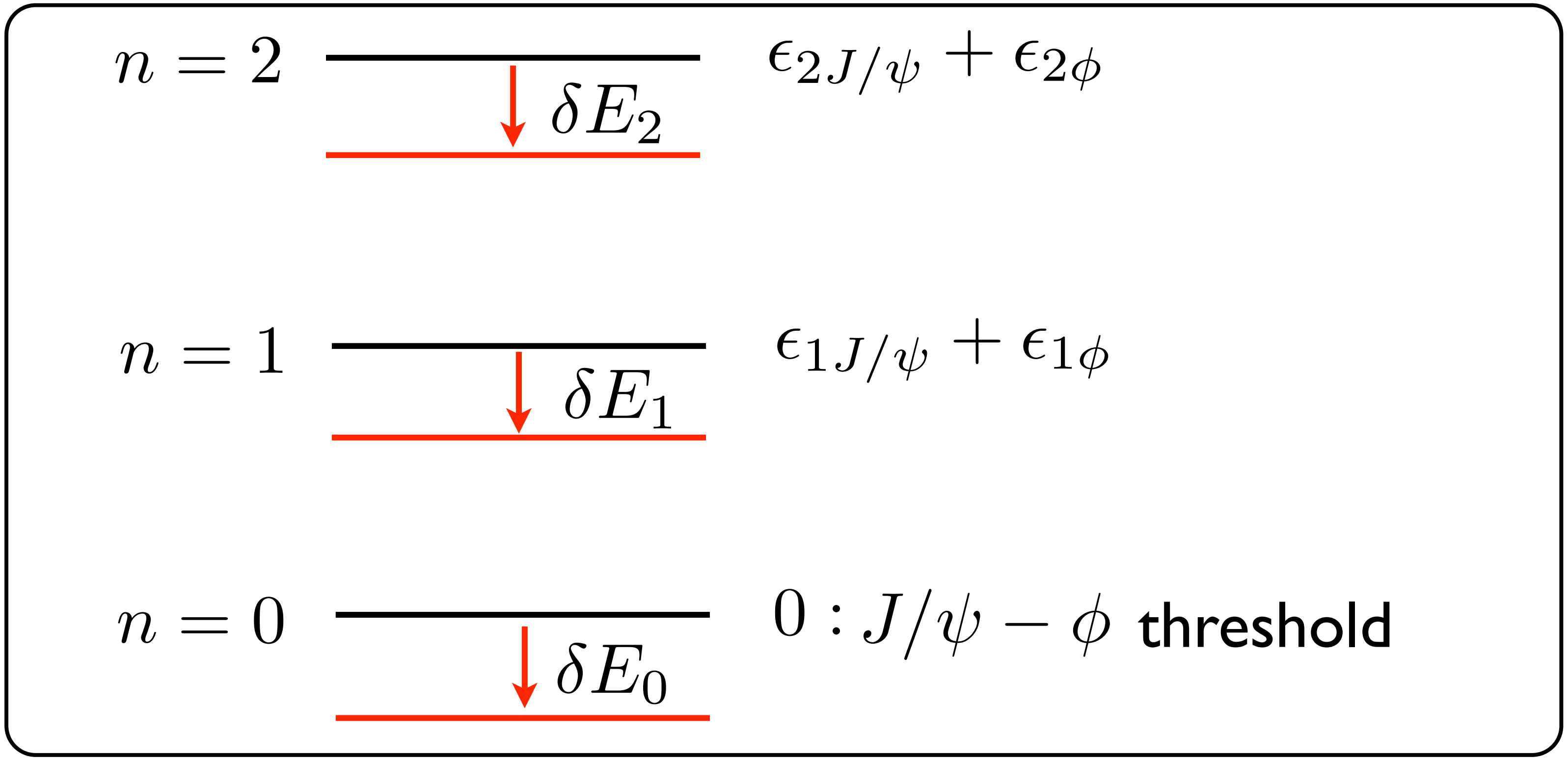
$$E_{nV} = \sqrt{\left(\frac{2\pi}{L}n\right)^2 + M_V^2}$$

$$\underline{\Delta E} = E_{J/\psi-\phi} - (M_{J/\psi} + M_\phi)$$

$$= \underline{[E_{J/\psi-\phi} - (E_{nJ/\psi} + E_{n\phi})]} + \underline{[E_{nJ/\psi} - M_{J/\psi}] + [E_{n\phi} - M_\phi]}$$

$$\Delta E = \underline{\delta E_n} + \underline{\epsilon_{nJ/\psi} + \epsilon_{n\phi}}$$

Interaction strength Energy of free 2 particles



Measurement of δE_n

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

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

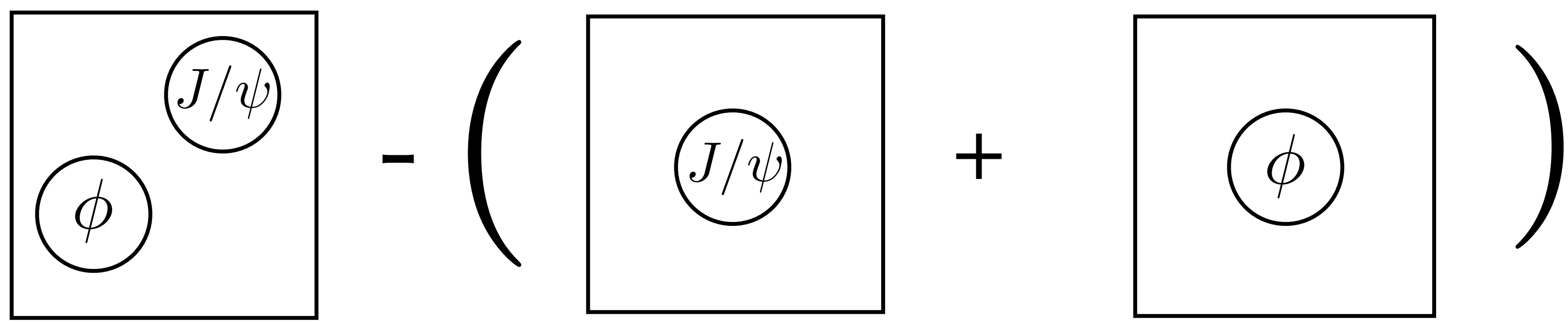
$$\hat{O}^{J/\psi}(t) = \bar{c}(t)\gamma_i\bar{c}(t)$$

Four-point function

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

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

$\underline{\delta E_n}$ =



Twisted Boundary Condition

P.F. Bedaque, PLB593 (2004) 84

Periodic Boundary Condition

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

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

$$E_1 = k_1^2/2\mu = 115 \text{ MeV}$$ $\longrightarrow$ Bad resolution

Twisted Boundary Condition

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

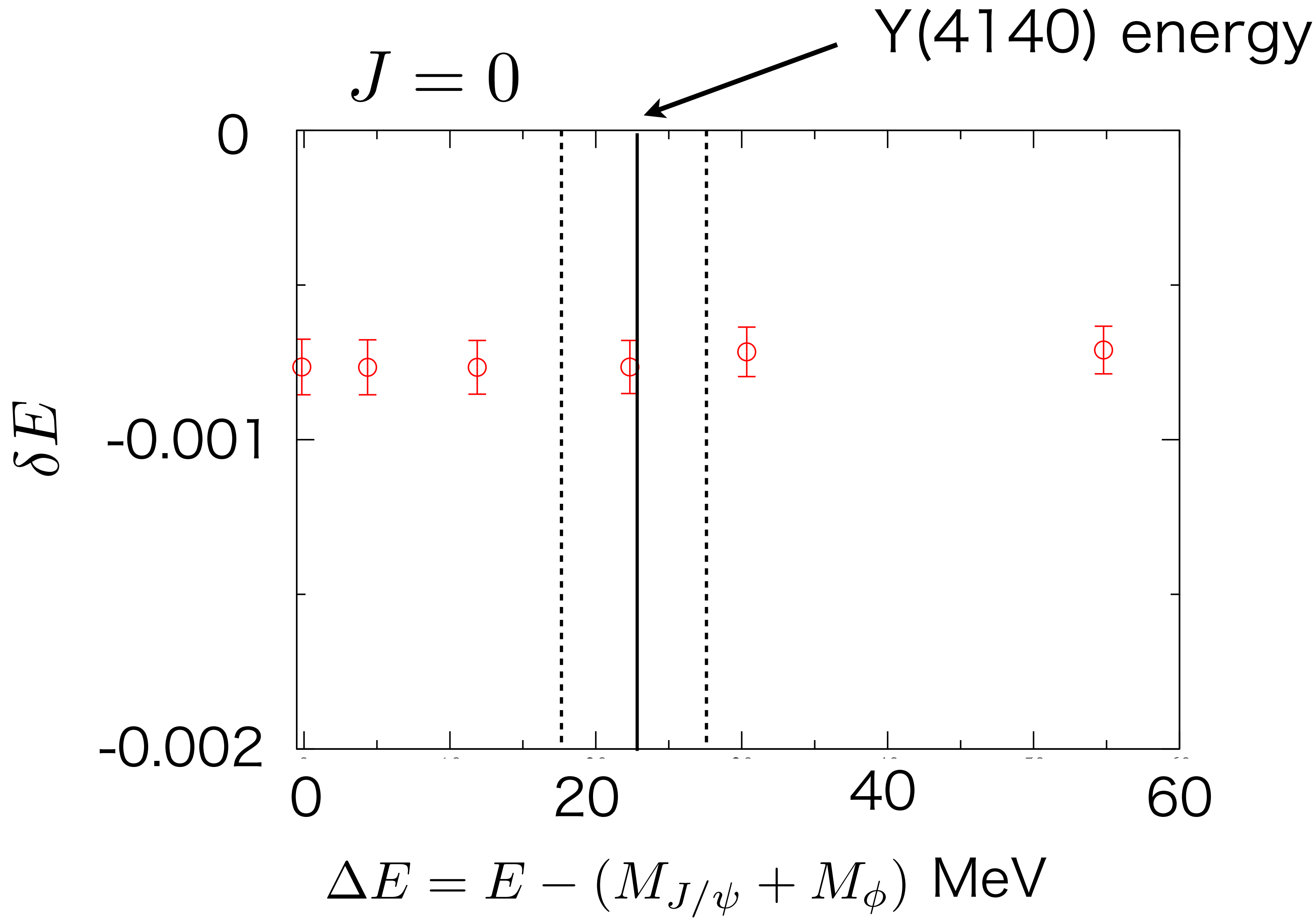
$$\longrightarrow \vec{k} = \frac{2\pi}{L}(\vec{n} + \underline{\vec{d}}) \quad , \qquad \vec{d} = (\frac{\theta_x}{2\pi}, \frac{\theta_y}{2\pi}, \frac{\theta_z}{2\pi})$$

Lattice set up

- PACS-CS 2+1 flavor dynamical gauge configurations at $m_\pi = 156\ \mathrm{MeV}$ 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)

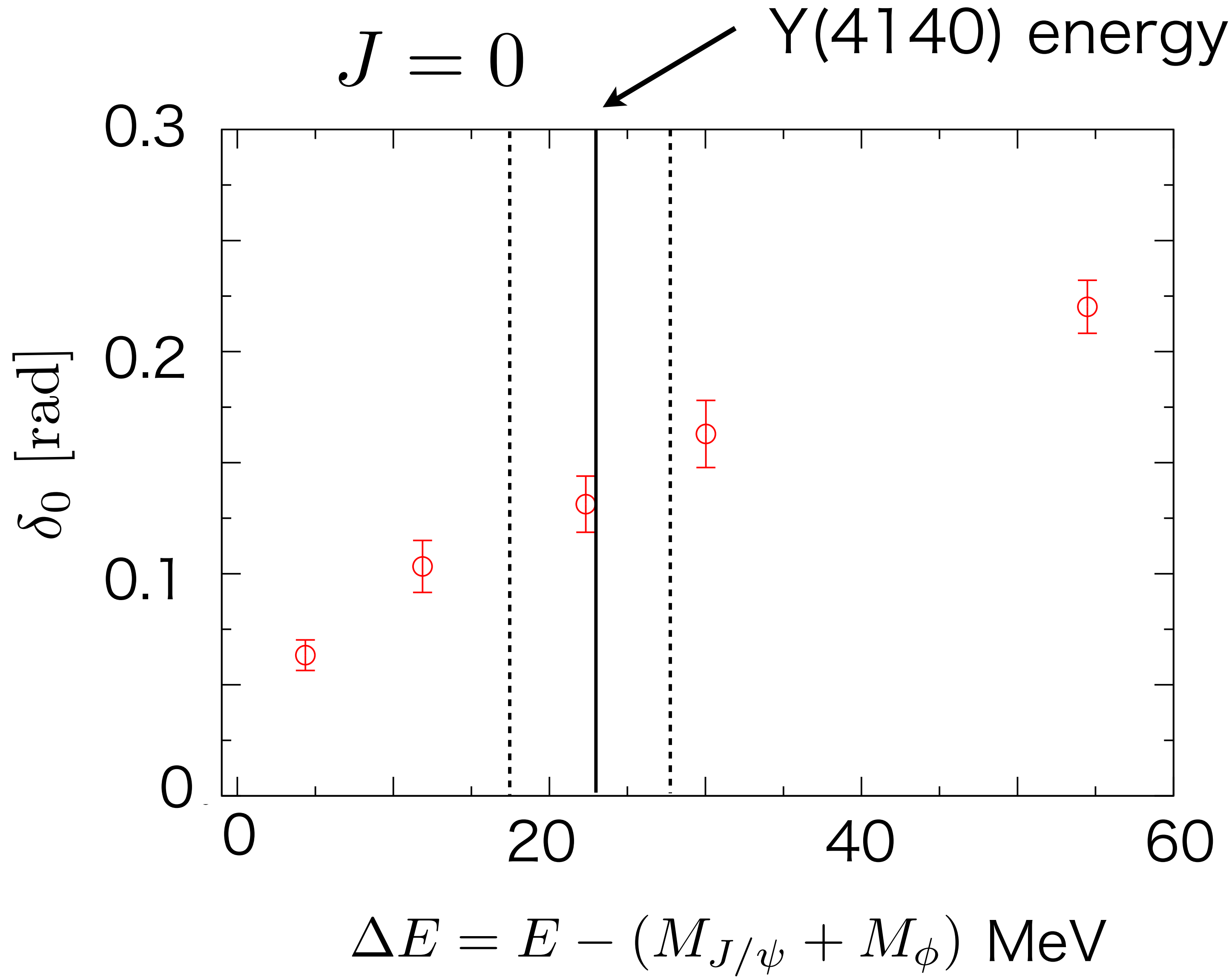
κ_{charm}	ν	r_s	c_B	c_E
0.1082	1.2153	1.2131	2.0268	1.7911

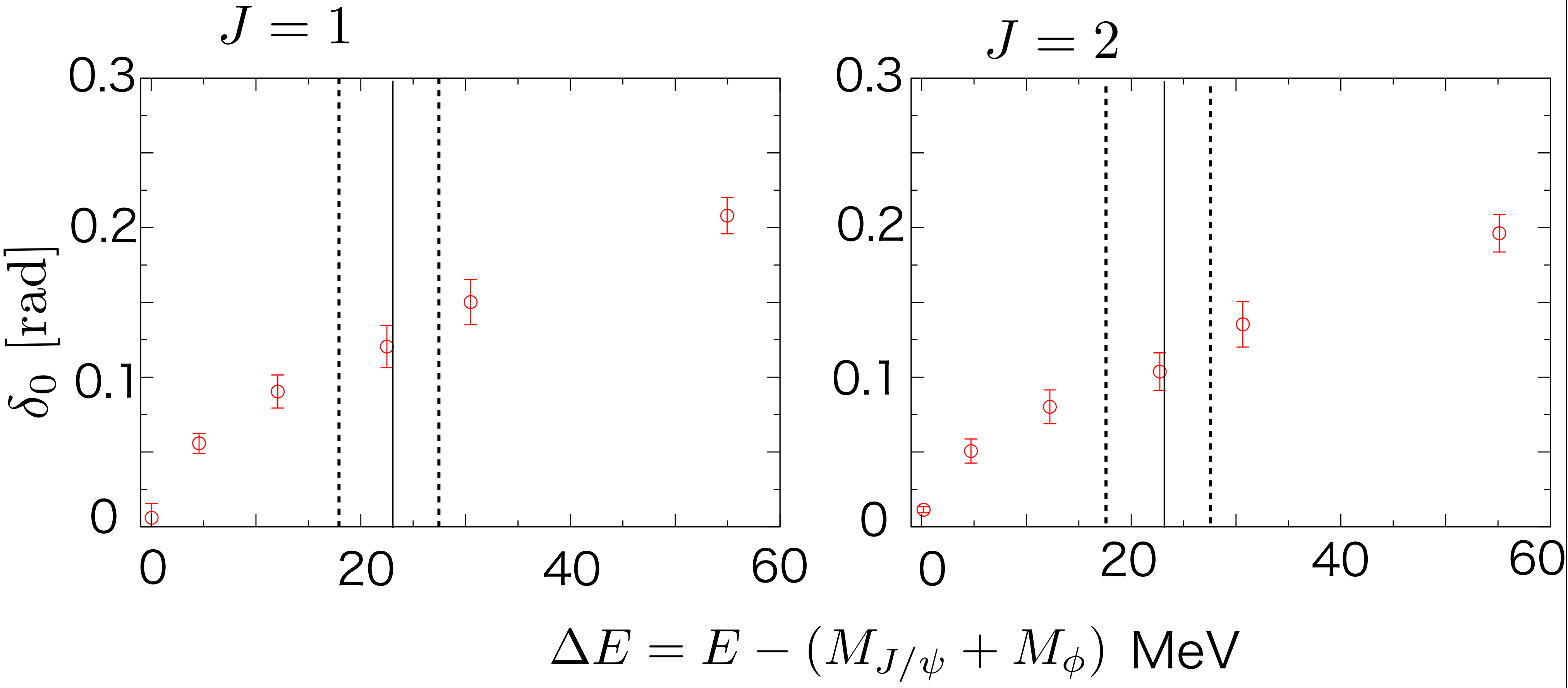
Result of δE



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

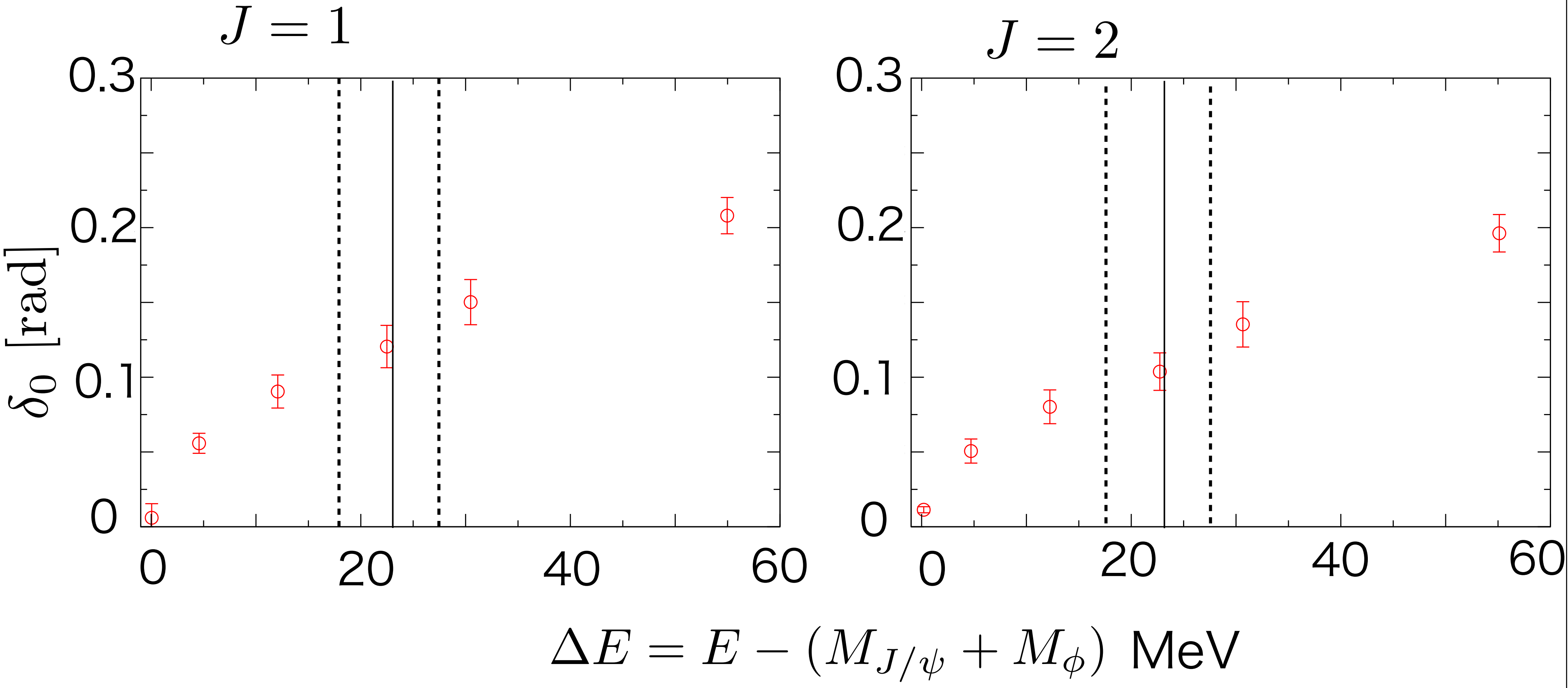
Scattering phase shift





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

No structure in s-wave J/ψ-Φ system.



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

No structure in s-wave J/Ψ-Φ system.

→ We will study P-wave J/Ψ-Φ scattering as a next step. [Our homework]

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

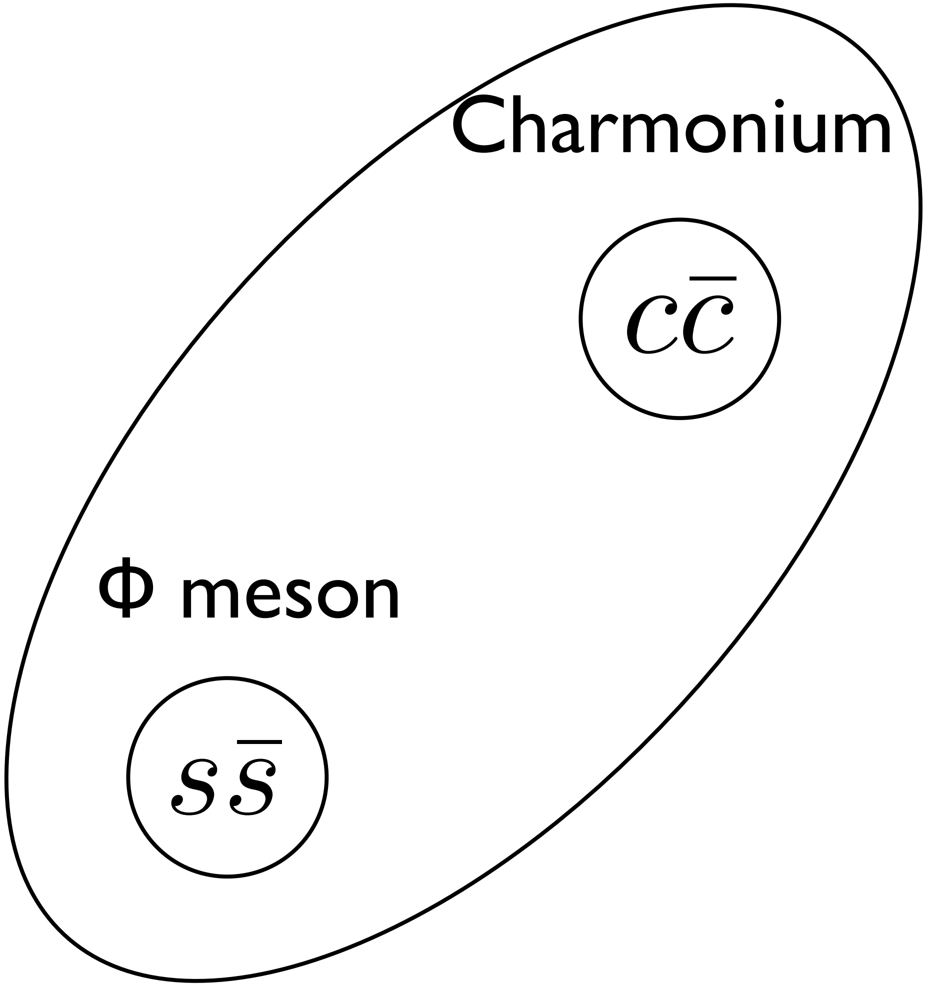
$$a^{J=0}_{J/\psi-\phi} = -0.178(21)\ \mathrm{fm}$$

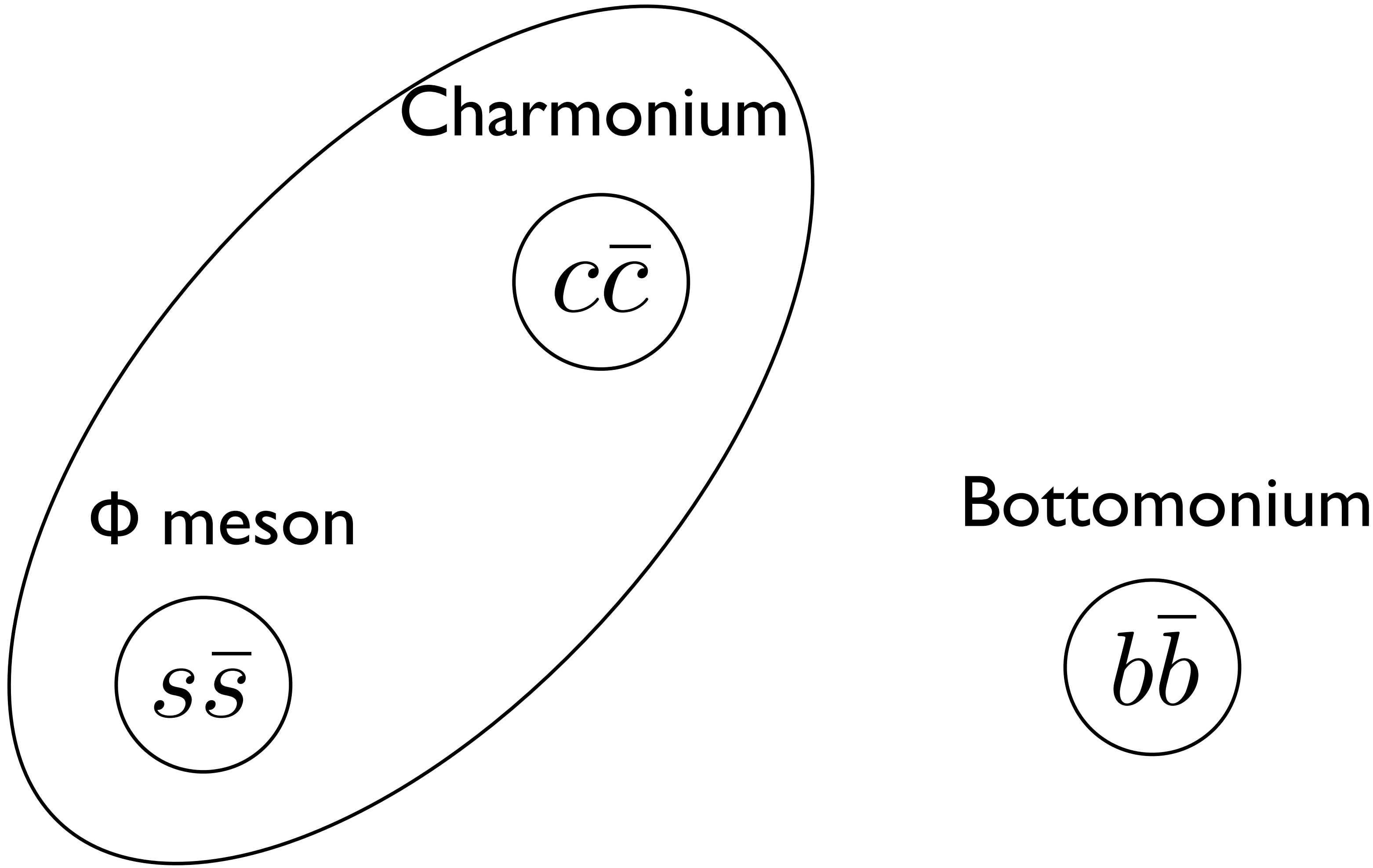
$$a^{J=1}_{J/\psi-\phi} = -0.152(23)\ \mathrm{fm}$$

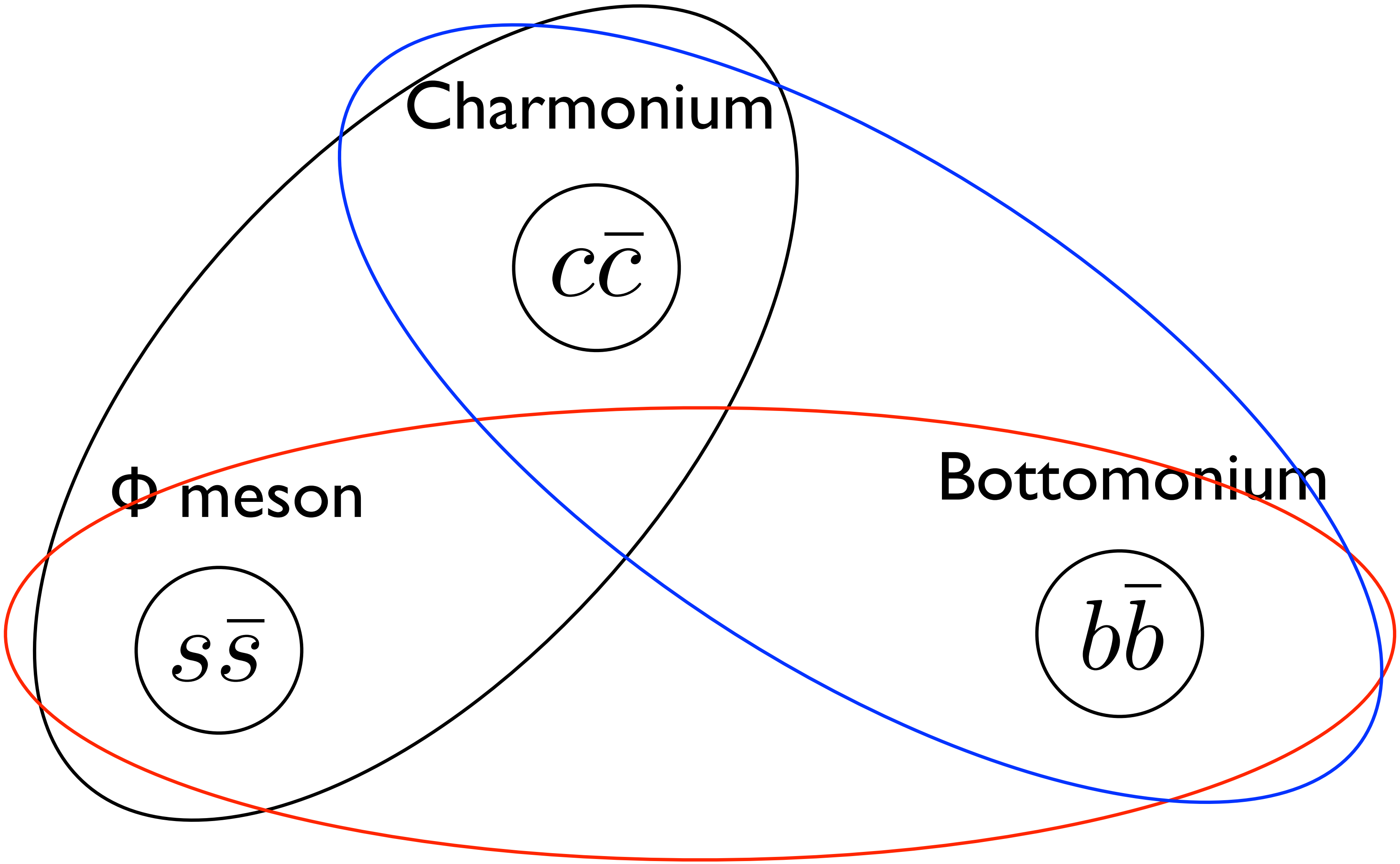
$$a^{J=2}_{J/\psi-\phi} = -0.123(16)\ \mathrm{fm}$$

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

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


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


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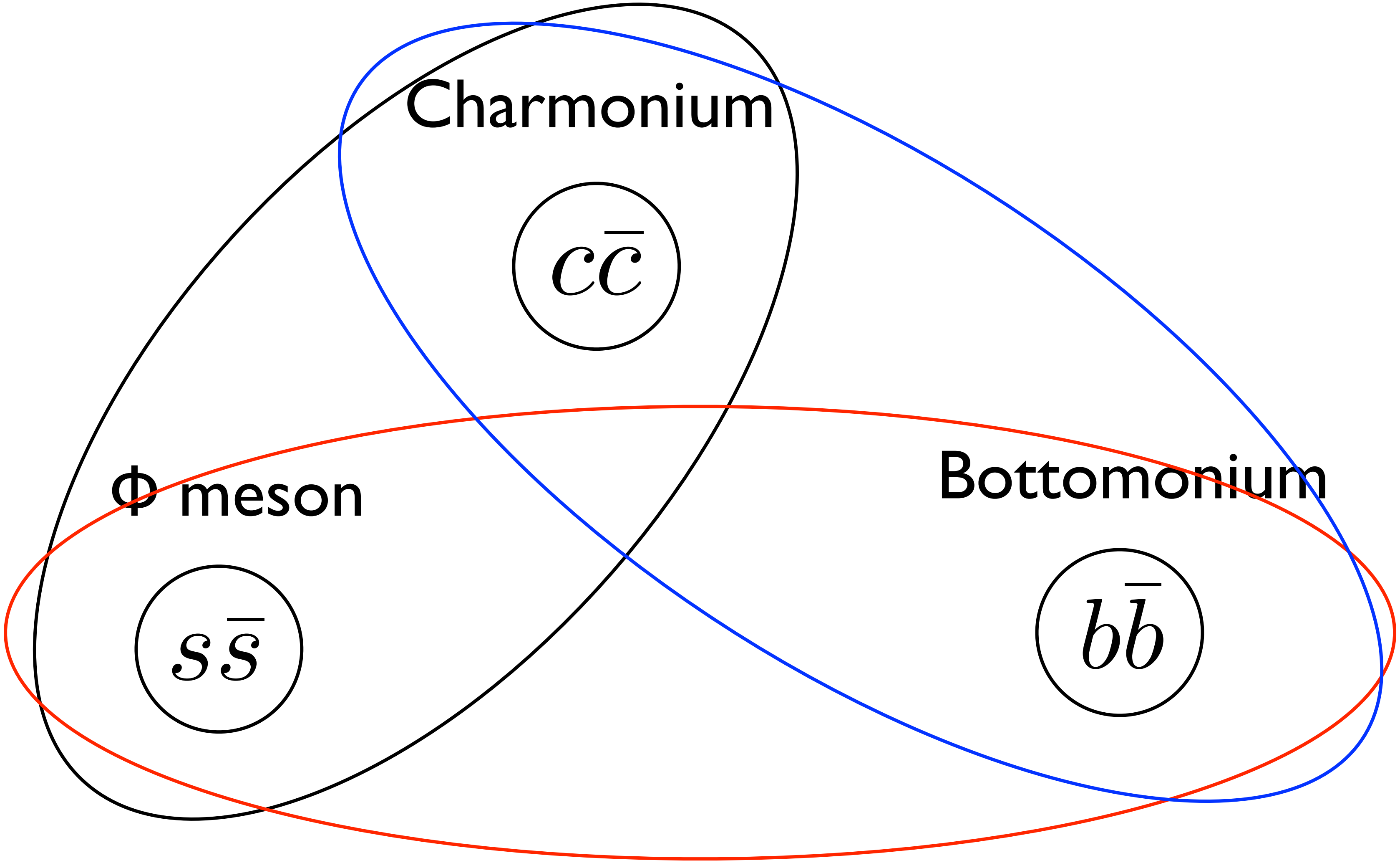
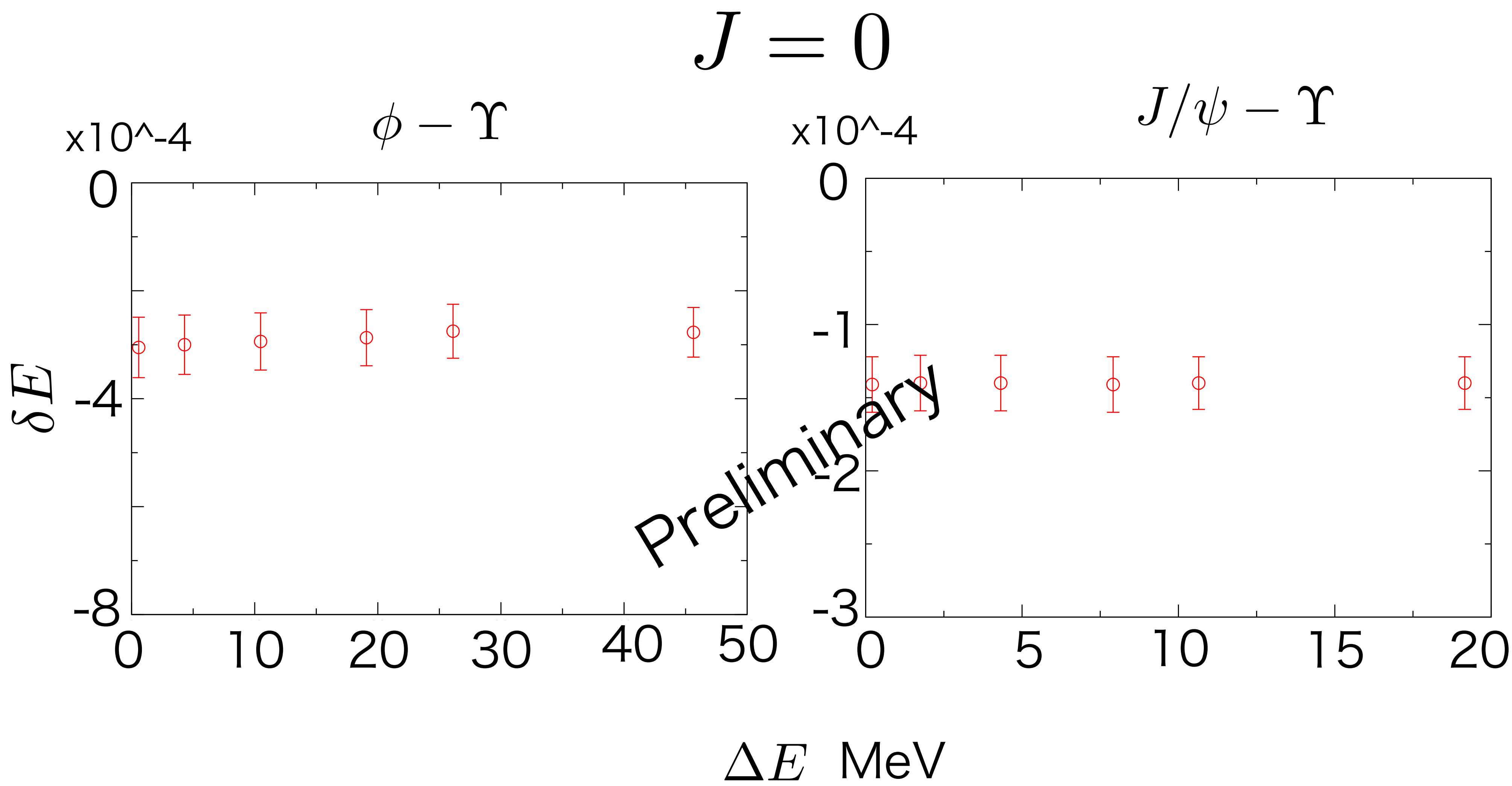
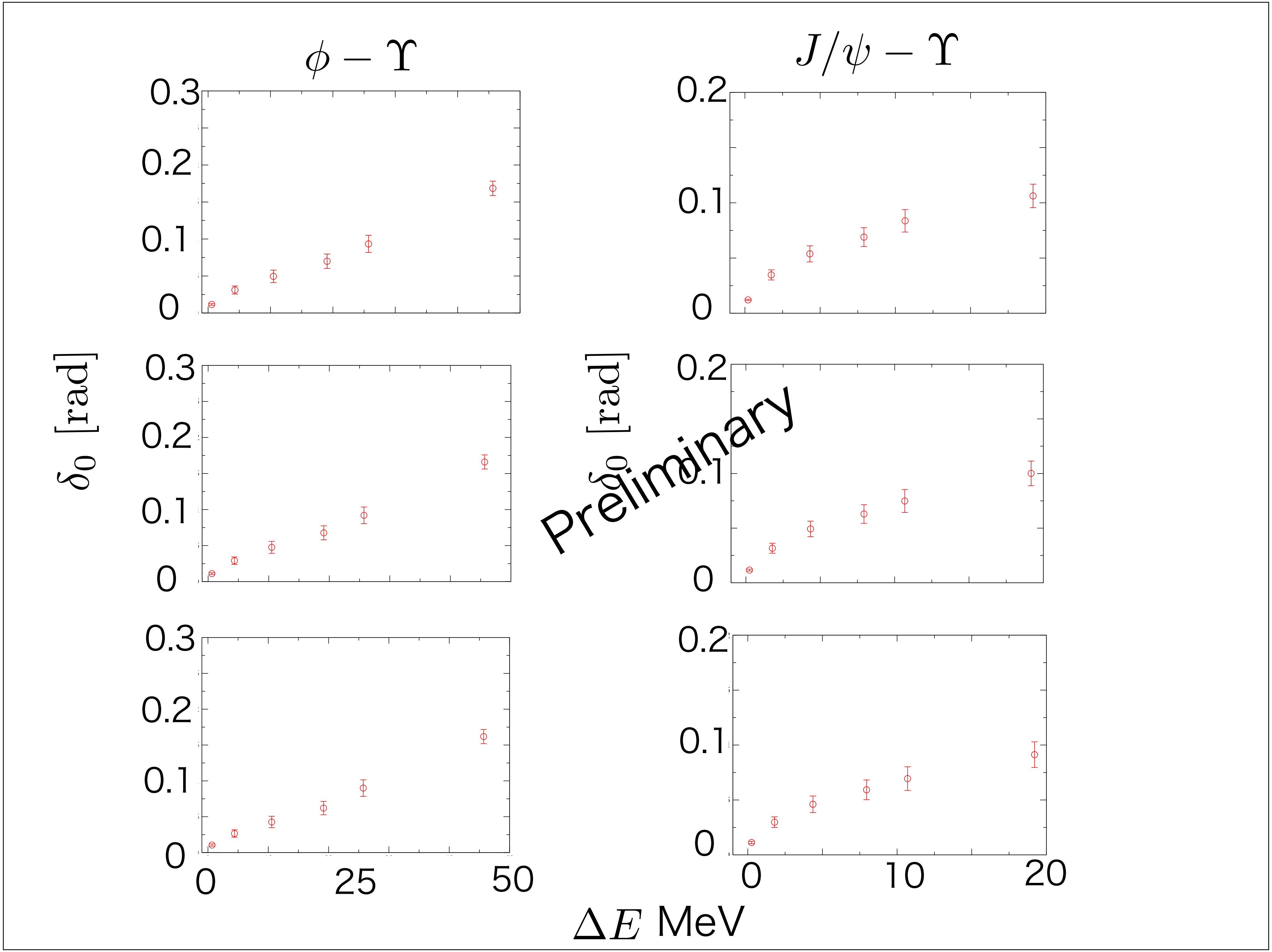


Results are preliminary.

Result of δE





$\phi - \Upsilon$
$J/\psi - \Upsilon$
δ_0 [rad]
δ_0 [rad]
0.3
0.2
0.1
0
0.2
0.1
0
0
25
50
0
10
20
Preliminary
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, we calculate scattering phase shifts, but there is no resonance in s-wave systems.
- We also calculate scattering lengths, and compare with quenched results.
  $\longrightarrow$ gluon-dynamics seem important in this system.
- Bottomonium scatterings are now ongoing.

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 term of its BS wave function.