Lattice study of J/ψ-Φ scattering at low energies to search for narrow resonance

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Introduction

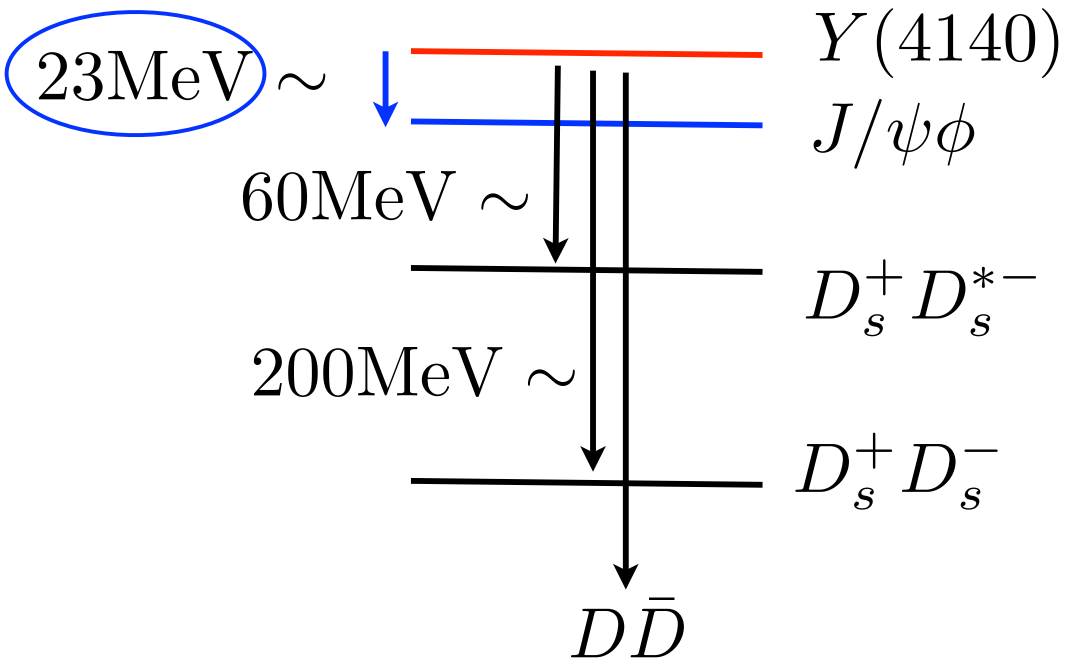
- Recently many charmonium($c\bar{c}$) and bottomonium($b\bar{b}$) like particles XYZ and $Y_b Z_b$ are observed in several high energy experiments in the world.
- Among them, some resonances such as X(3872), Z(4430), and Z_b have very narrow widths and are observed near the hadron-hadron thresholds.
- These experimental observations draw attention to the properties and the structures of such resonances.
- It is important to understand these interesting resonances from Lattice QCD.

In 2009, a new hadron resonance Y(4140) are reported from B-meson decay by CDF collaboration.

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

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

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



- ▶ Y(4140) is very close to J/ψ-Φ threshold.
- ▶ Y(4140) has a narrow width.
- ▶ It seems that Y(4140) does not couple to open charm channels.

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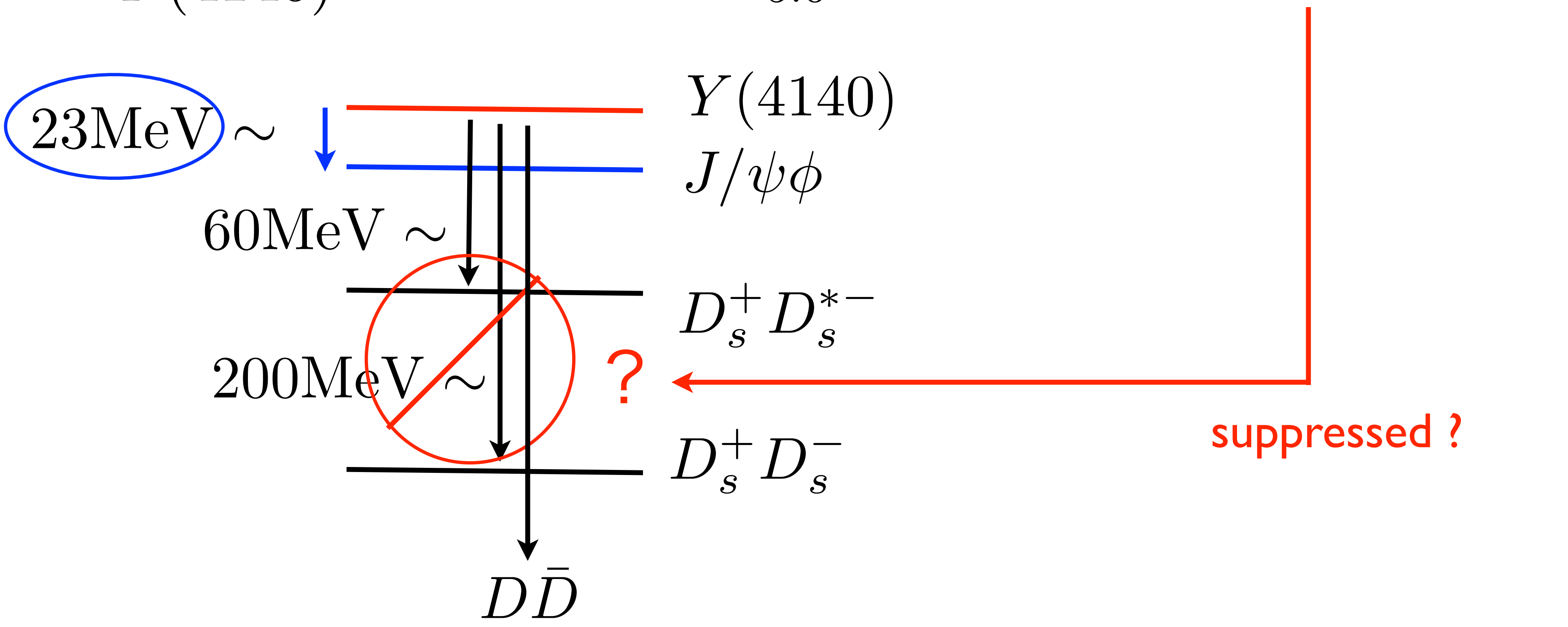


- ▶Y(4140) is very close to J/ψ-Φ threshold.
- ▶Y(4140) has a narrow width.
- ▶It seems that Y(4140) does not couple to open charm channels.

In last year, CDF again reported the same peak with higher statistics.

T. Aaltonen et al, arXiv:1101.6058

On the other hand, two photon scattering experiment by Belle and B-meson decay in LHCb experiment did not observe Y(4140) yet.

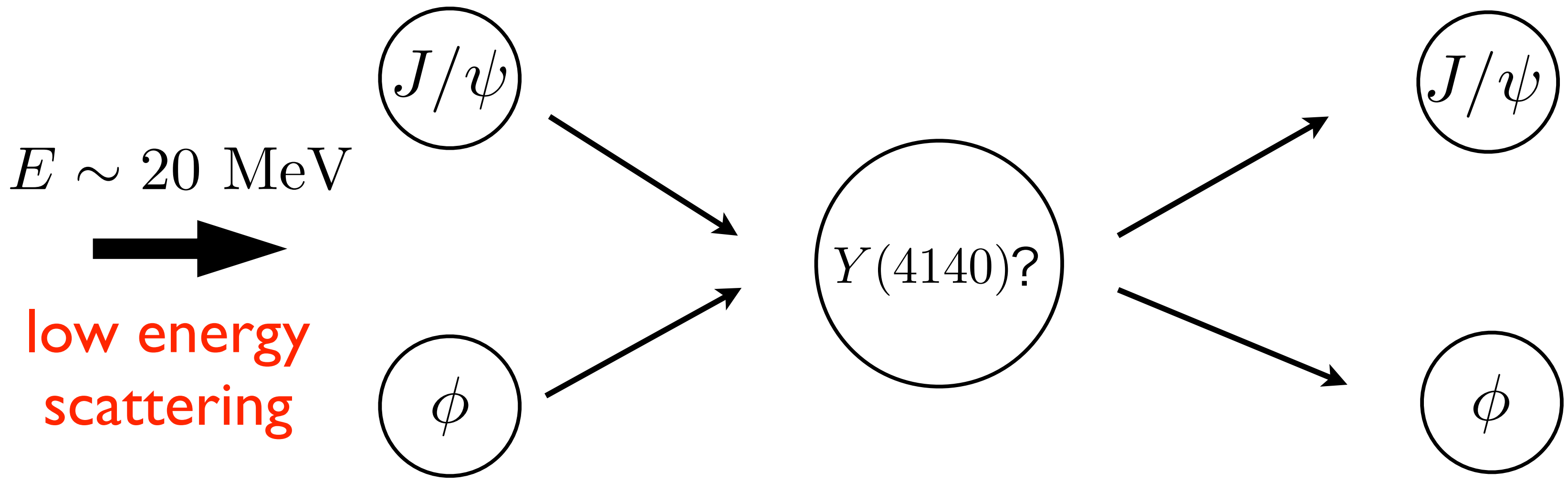
C. P. Shen et al PRL104, 112004 (2010)
R. Aaij et al, PRD85, 091103 (2012)

If Y(4140) exits, it has interesting features, but its existence is still controversial experimentally.

The purpose of this study is to develop an approach to investigate low energy hadron-hadron scatterings and to search for a narrow resonance.

Then, we apply our approach to J/psi-phi system and to gain a new insight into Y(4140) from Lattice QCD.

Low energy J/ψ-Φ scattering and narrow resonance Y(4140) in C.M. system (zero total momentum)



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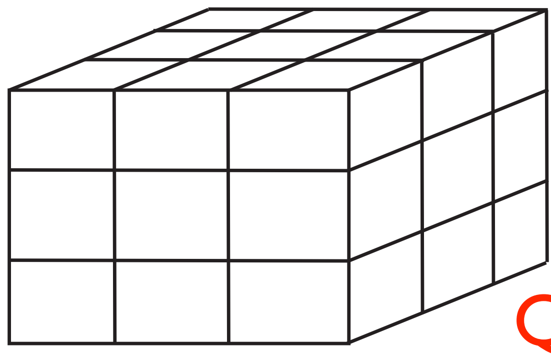


QCD

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

Periodic Boundary Condition

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

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

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

Twisted Boundary Condition (TBC)

P.F. Bedaque, PLB593 (2004) 84

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

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

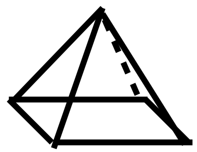
We can investigate low energy scatterings and search for a narrow resonance with a good energy resolution.

Symmetries with TBC in C.M. System

In the case of $\vec{\theta} = 0 \longrightarrow$ Cubic symmetry: O_h

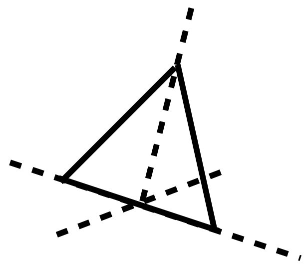
i) $\vec{\theta} = (0, 0, \theta)$

$\longrightarrow$ Tetragonal: C_{4v}



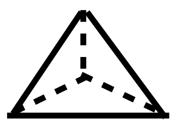
ii) $\vec{\theta} = (\theta, \theta, 0)$

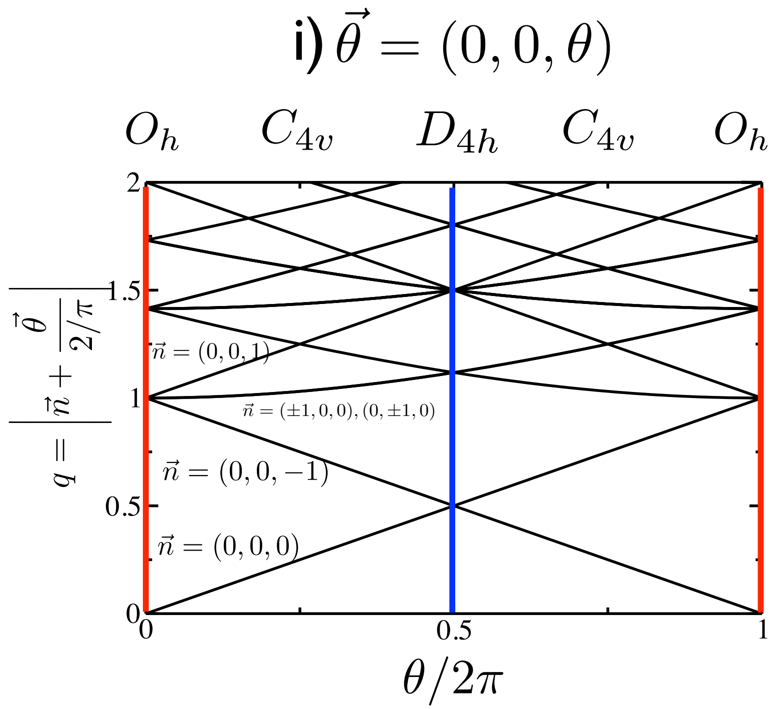
$\longrightarrow$ Rhombic: C_{2v}



iii) $\vec{\theta} = (\theta, \theta, \theta)$

$\longrightarrow$ Trigonal: C_{3v}





- C_{nv} DO NOT have parity symmetry.
- Actually, these symmetries are same to two particle system of different mass and non-zero total momentum.

Z. Fu, PRD85, 014506 (2012)

L. Leskovec and S. Prelovsek, PRD85, 114507(2012)

M. Doring, et al, arXiv:1205. 4838 [hep-lat]

With good parity symmetry, we can apply

►Luscher and Rummukainen-Gottlieb finite size formula

M. Luscher, NPB354, 531, (1991)

K. Rummukainen and S. Gottlieb, NPB450, 397, (1995)

$$\cot\delta_0 = \frac{1}{\pi^{3/2} q} Z_{00}^{(\vec{d})}(1; q^2) \qquad q = \frac{Lk}{2\pi}$$

with the zeta-funciton

$$Z_{lm}^{\vec{d}}(1; q^2) = \sum_{\vec{r} \in \Gamma_{\vec{d}}} \frac{\mathcal{Y}_{lm}(\vec{r})}{\vec{r}^2 - q^2}, \qquad \mathcal{Y}_{lm}(\vec{r}) = |\vec{r}|^l Y_{lm}(\Omega_r)$$

$$\Gamma_{\vec{d}} = \{\vec{r} | \vec{r} = \vec{n} + \frac{\vec{d}}{2}, \ \vec{n}, \vec{d} \in Z^3\}$$

The finite size formula connects the energy eigenvalue in a finite volume system with the scattering phase shift in infinite volume system.

In the case of a finite twisted angle

▶ Finite size formula with twisted BC with (0,0, θ)

For A1 sector

$$\cot\delta_0 = m_{00} + \frac{|m_{10}|^2}{\cot\delta_1 - m_{11}}$$

mixing term from p-wave

$$Z^{\vec{\theta}}_{lm}(1;q^2) = \sum_{\vec{r}\in\Gamma_{\vec{\theta}}} \frac{\mathcal{Y}_{lm}(\vec{r})}{\vec{r}^2 - q^2}$$

$$\Gamma_{\vec{\theta}} = \{\vec{r}|\vec{r} = \vec{n} + \frac{\vec{\theta}}{2\pi}, \vec{n} \in Z^3\}$$

where

$$m_{00} = \frac{1}{\pi^{3/2}q} Z^{\vec{\theta}}_{00}(1;q^2)$$

$$m_{11} = \frac{1}{\pi^{3/2}q} Z^{\vec{\theta}}_{00}(1;q^2) + \frac{2}{\sqrt{5}\pi^{3/2}q^3} Z^{\vec{\theta}}_{20}(1;q^2)$$

$$m_{10} = \frac{i}{\pi^{3/2}q^2} Z^{\vec{\theta}}_{10}(1;q^2)$$

Here, we neglect higher wave contributions above l=2 owing to low energy scatterings near the threshold.

Our strategy

i) Firstly we calculate δ_0 at $\vec{\theta}$= (0,0,0), (0,0,π),(π,π,0), (π,π,π) data with parity symmetry from Luscher and Rummukainen-Gottlieb formula:

$$\underline{\cot\delta_0} = \frac{1}{\pi^{3/2}q} Z_{00}^{\vec{\theta}}(1;q^2)$$

ii) From this δ_0, we calculate δ_1 with (θ, θ, θ) data from the formula:

$$\underline{\cot\delta_1} = \tilde{m}_{11} + \frac{|\tilde{m}_{10}|^2}{\underline{\cot\delta_0} - \tilde{m}_{00}}$$

$$\tilde{m}_{00} = \frac{1}{\pi^{3/2}q} Z_{00}^{\vec{\theta}}(1;q^2)$$

$$\tilde{m}_{11} = \frac{1}{\pi^{3/2}q} Z_{00}^{\vec{\theta}}(1;q^2) + \frac{2\sqrt{6}}{\pi^{3/2}\sqrt{5}q^3} \mathrm{Im}(Z_{22}^{\vec{\theta}}(1;q^2))$$

$$\tilde{m}_{10} = \frac{\sqrt{3}i}{\pi^{3/2}q^2} Z_{10}^{\vec{\theta}}(1;q^2)$$

iii) Using the δ_1, we also calculate low energy δ_0 with $(0, 0, \theta)$ data from the formula:

$$\cot\delta_0 = m_{00} + \frac{|m_{10}|^2}{\underline{\cot\delta_1} - m_{11}}$$

where

$$m_{00} = \frac{1}{\pi^{3/2} q} Z^{\vec{\theta}}_{00}(1; q^2)$$

$$m_{11} = \frac{1}{\pi^{3/2} q} Z^{\vec{\theta}}_{00}(1; q^2) + \frac{2}{\sqrt{5}\pi^{3/2} q^3} Z^{\vec{\theta}}_{20}(1; q^2)$$

$$m_{10} = \frac{i}{\pi^{3/2} q^2} Z^{\vec{\theta}}_{10}(1; q^2)$$

We obtain information of low energy s-wave and p-wave scattering phase shifts.

Lattice set up

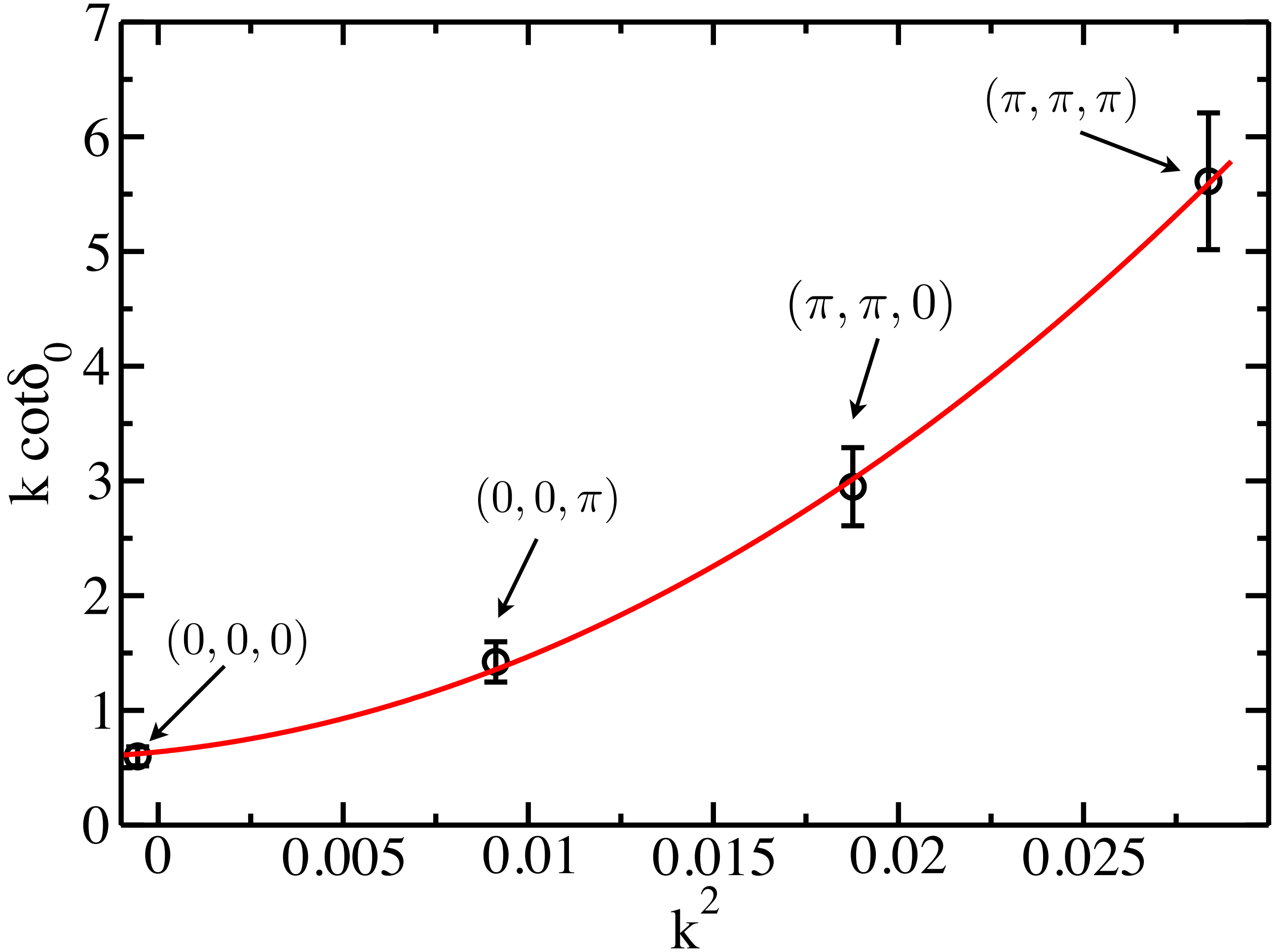
- PACS-CS 2+1 flavor dynamical gauge configurations at $m_\pi = 156\ \mathrm{MeV}$ S. Aoki et al, PRD79, 034503, 2009
  - Iwasaki gauge action + Clover fermion action
  - 32^3 x 64 lattice
  - a = 0.0907(13) fm
  - La ~ 2.9 fm
  - 198 configs
  - Wall source
- Relativistic Heavy Quark (RHQ) action for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

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

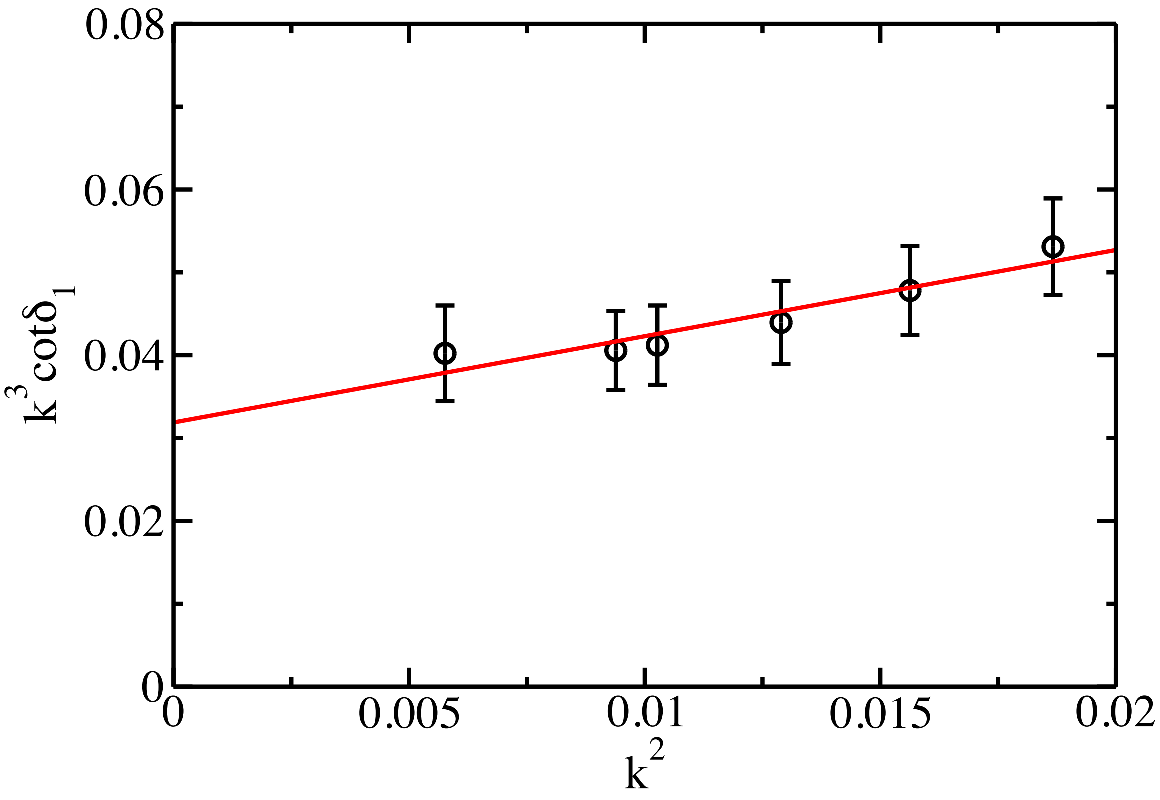
κ_{charm}	ν	r_s	c_B	c_E
0.1082	1.2153	1.2131	2.0268	1.7911

Result

i) kcotδ0 from $(0,0,0)$, $(0,0,\pi)$, $(\pi,\pi,0)$, (π,π,π) data



ii) k^3cotδ1 from (θ,θ,θ) data

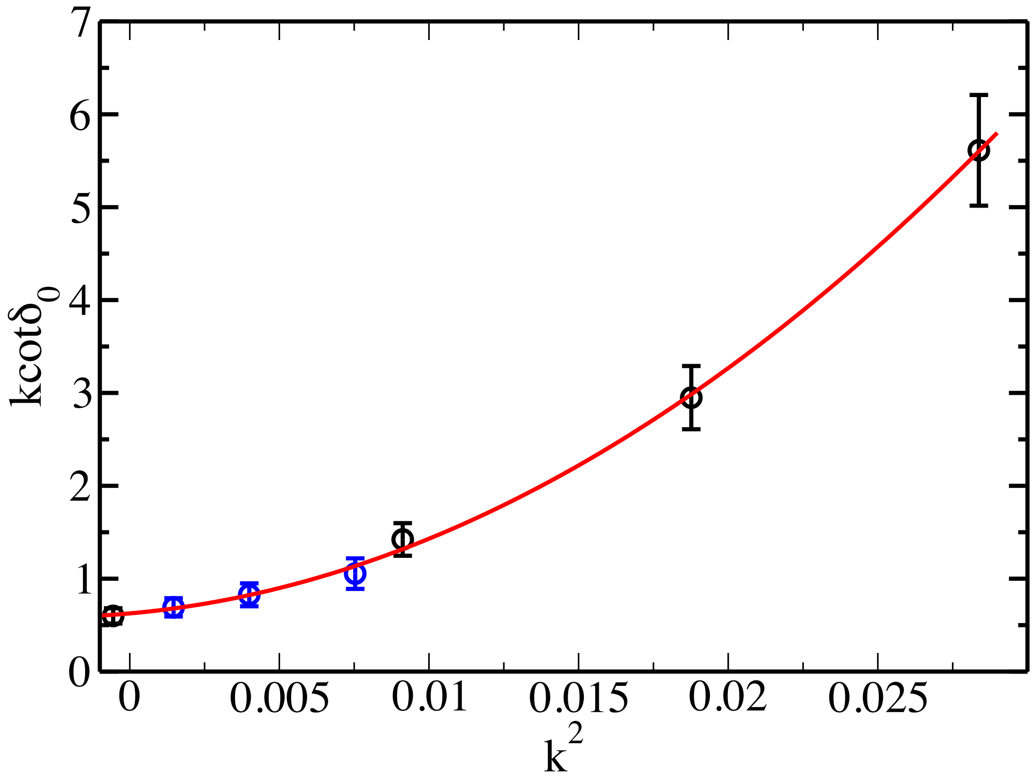


At k=0, we can obtain threshold parameter of p-wave

$$\frac{\tan\delta_1}{k^3}|_{k=0} = a_1$$

$$a_1 = 0.0234 \pm 0.0039 \ [\mathrm{fm}^3]$$

iii) Using previous δ1, we evaluate low energy δ0 from $(0, 0, \theta)$ data



Effective range expansion

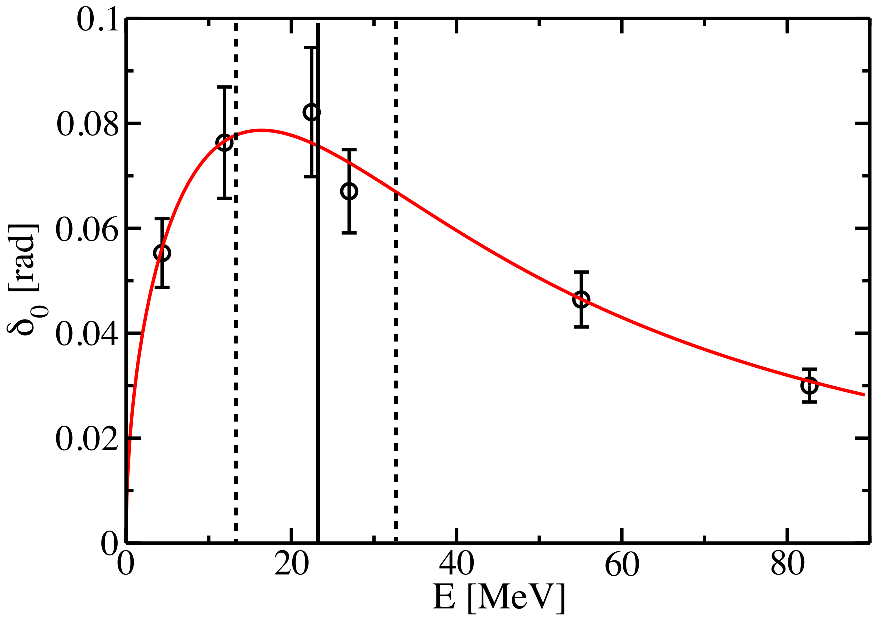
$$k\cot\delta_0 = \frac{1}{a_0} + \frac{1}{2} r_0 k^2 + p r_0^3 k^4$$

From jack knife fit

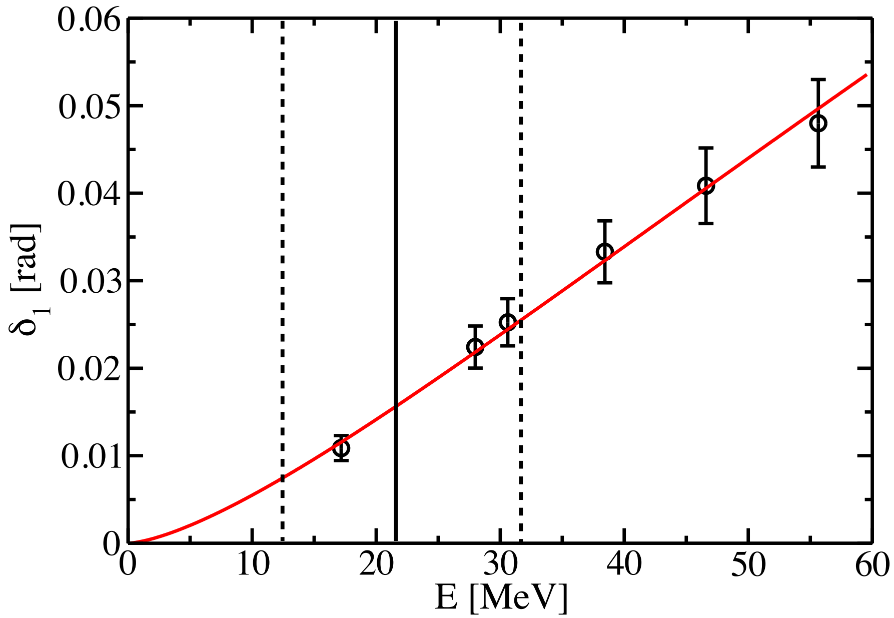
$$a_0 = 0.145 \pm 0.021 \ [\mathrm{fm}]$$
$$r_0 = 5.21 \pm 1.46 \ [\mathrm{fm}]$$
$$p r_0^3 = 3.85 \pm 0.47 \ [\mathrm{fm}^3]$$

Phase shifts near the threshold

s-wave



p-wave



Both figures show typical behaviors of low energy s- and p-wave phase shifts.

No structure in resonance point reported from CDF collaboration.

⟶ Our results prefer Belle and LHCb experiments.

Summary

- We develop an approach to investigate low energy hadron-hadron scatterings from lattice QCD by using finite size formula with twisted boundary condition.
- We apply our approach to low energy J/psi-phi scattering.
- Our result shows typical behaviors of low energy s-wave and p-wave phase shifts, but there is no structure at resonance point reported from CDF collaboration.

  ⟶ This result is consistent with Belle and LHCb experiments.
- We also obtain low energy scattering parameters such as scattering length, effective range and effective volume from effective range expansion.
- Our approach can be applied to other systems in order to study low energy hadron-hadron scatterings and search for narrow resonances.