Short range $\pi J/\psi - D\bar{D}^*$ potential

Yasuhiro Yamaguchi [1]

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International workshop on

Hadron structure and interaction in dense matter

KEK Tokai campus, 11-12 Nov. 2018

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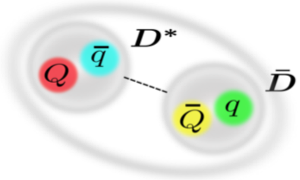
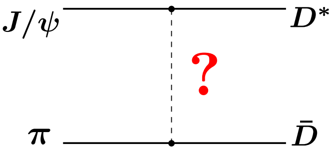
Kenji Fukukawa (Suma Gakuen), Atsushi Hosaka (RCNP, Osaka Univ.),
in preparation

Outline

- Introduction
  - Exotic hadrons
  - $Z_c(3900)$
- Interaction model
  - Meson exchange model
  - Quark exchange model
- Summary

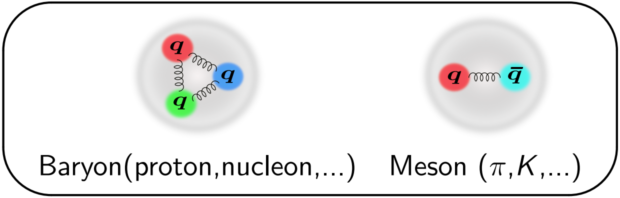


Exotic hadron



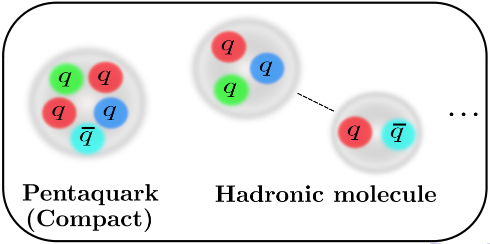
Hadron interaction

- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)

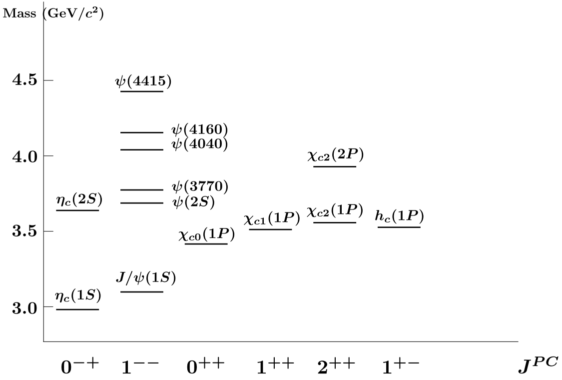


*q: "Constituent quark"

- Exotic Hadrons ($\neq qqq$, $q\bar{q}$): **Multiquark? Multihadron?**

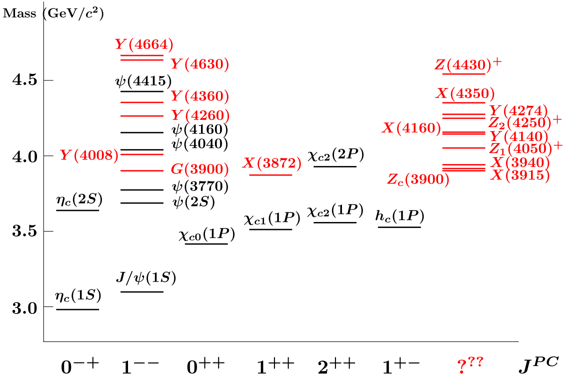


- e.g. $c\bar{c}$ mesons (Charmonium)



N. Brambilla,*et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

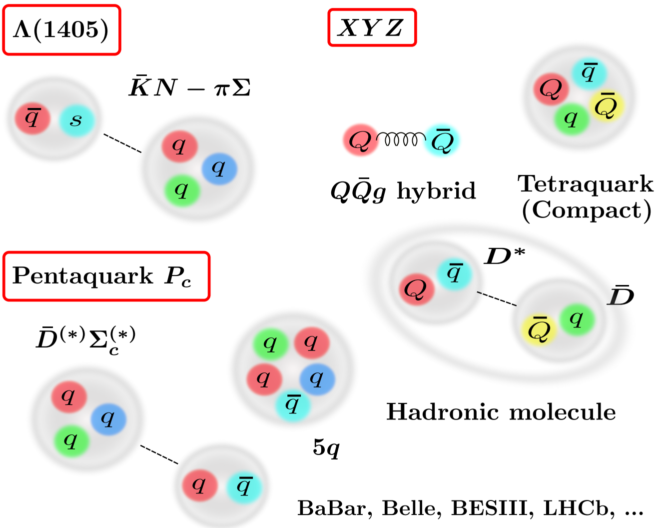
▷ e.g. $c\bar{c}$ mesons (Charmonium) and **Unexpected *X*, *Y*, *Z***



N. Brambilla,*et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) $\Rightarrow$ **Q. Structure? Physics?**

Many exotic candidate!! Many models!!

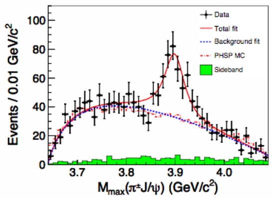


T. Hyodo, D. Jido, PPNP**67**(2012)55, N. Brambilla *et al.*,Eur.Phys.J.C(2011)71,1534

H.X.Chen, et al., Phys.Rept.**639**(2016)1,...

- Charged Charmonium??
- $Y(4260) \to Z_c(3900)\pi \to J/\psi\pi\pi$

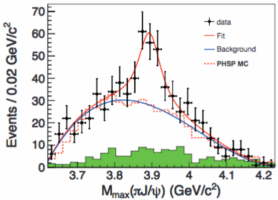
BESIII,PRL**110**(2013)252001



$M = 3899.0 \pm 3.6_{sta} \pm 4.9_{sys}$ MeV

$\Gamma = 46 \pm 10_{sta} \pm 20_{sys}$ MeV

Belle,PRL**110**(2013)252002



$M = 3894.5 \pm 6.6_{sta} \pm 4.5_{sys}$ MeV

$\Gamma = 63 \pm 24_{sta} \pm 26_{sys}$ MeV

CLEO-c,PLB**727**(2013)366(2013), DØ,PRD**98**(2018)052010

Charged Charmonium: $Z_c(3900)$

Introduction

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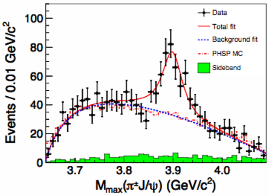

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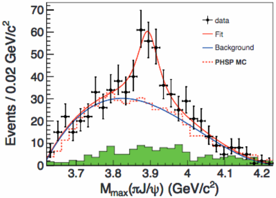

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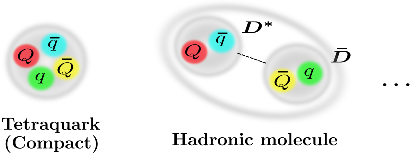
CLEO-c,PLB**727**(2013)366(2013), DØ,PRD**98**(2018)052010

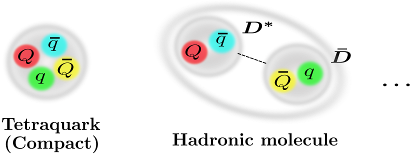
▷ Ordinal Charmonium $c\bar{c}$: no electric charge.
$\Rightarrow Z_c^+(3900)$: **Genuine Exotic State!?** $c\bar{c}u\bar{d}$



Multiquark states?

A. Hosaka *et al.* PTEP **2016** (2016) no.6, 062C01, D.-Y. Chen *et al.* PRD**88**(2013)036008,...

- Molecules? — $Z_c(3900)$ close to the $D\bar{D}^*$ threshold (~ 3875)



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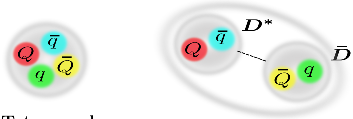
$\Rightarrow$ Exotic state may be **a loosely bound state (resonance)** of the meson-meson.

$\rightarrow$ Analogous to atomic nuclei (Deuteron: B ~2.2 MeV)

What is the structure of $Z_c(3900)$?

Introduction

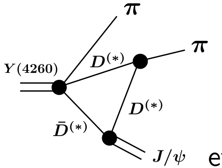


Tetraquark (Compact)

Hadronic molecule

. . .

Multiquark states?



etc.

No bound state?

A. Hosaka *et al.* PTEP **2016** (2016) no.6, 062C01, D.-Y. Chen *et al.* PRD**88**(2013)036008,...

- Molecules? — $Z_c(3900)$ close to the $D\bar{D}^*$ threshold (~ 3875)

$\Rightarrow$ Exotic state may be **a loosely bound state (resonance)** of the meson-meson.

$\rightarrow$ Analogous to atomic nuclei (Deuteron: $B \sim$2.2 MeV)

$\Leftrightarrow$ Kinematical effect? **No bound state explanation**

D.-Y. Chen,X.Liu,T.Matsuki,PRD**88**(2013)036008,J.He,D.-Y.Chen,EPJC**78**(2018)94,...

- Lattice QCD simulation by HALQCD at $m_\pi = 410 - 700$ MeV

$\Rightarrow$ Coupled-channel $\pi J/\psi - \rho\eta_c - D\bar{D}^*$

PRL **117**, 242001 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

Fate of the Tetraquark Candidate $Z_c(3900)$ from Lattice QCD

Yoichi Ikeda,[1,2] Sinya Aoki,[3,4] Takumi Doi,[2] Shinya Gongyo,[3] Tetsuo Hatsuda,[2,5] Takashi Inoue,[6] Takumi Iritani,[7] Noriyoshi Ishii,[1] Keiko Murano,[1] and Kenji Sasaki[3,4]

(HAL QCD Collaboration)

$Z_c(3900)$: Lattice QCD (Numerical Experiments)

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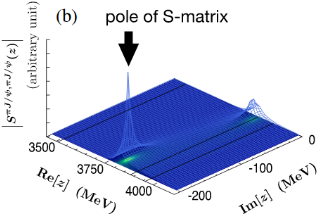

$\Rightarrow$ **Virtual state** is obtained.

- $Z_c(3900)$ is Threshold cusp

Ikeda, *et al.*,PRL**117**(2016)242001

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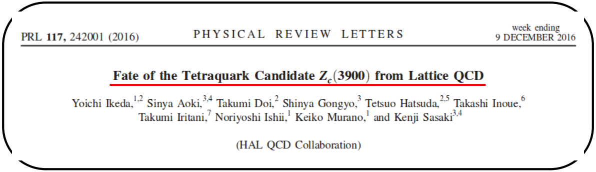

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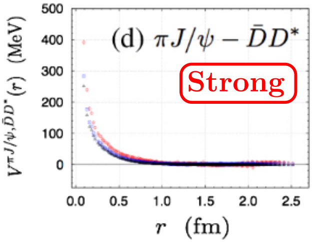


$\Rightarrow$ **Virtual state** is obtained.

- $Z_c(3900)$ is Threshold cusp induced by $\boldsymbol{\pi J/\psi - \bar{D}D^*}$ **potential**

Charm flavor exchange?

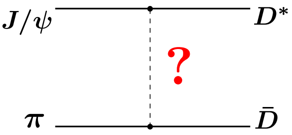
Ikeda, *et al.*,PRL**117**(2016)242001

Bound state? Threshold cusp? $\rightarrow$ Hadron int.

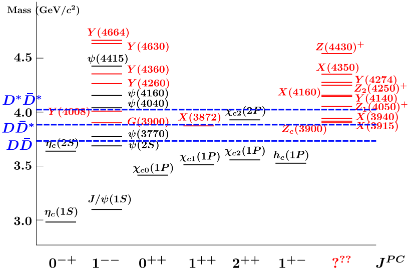
Exotic structure:
Bound state? Cusp?

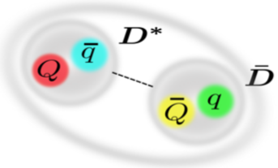
Exotic structure:
Bound state? Cusp?

$\Leftrightarrow$



- **Hadron-hadron interaction** is important to understand the nature of exotic states! not only Z_c but also others.





Model of Hadron-hadron interaction
Introduction

- **Long-range force:** one π exchange potential (OPEP)
  Lightest meson π, Importance in the nuclear force,
  Heavy Quark Spin Symmetry ($0^- - 1^-$ mixing)

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▷ How can we understand **strong $\pi J/\psi - D\bar{D}^*$ potential?**

Model of Hadron-hadron interaction
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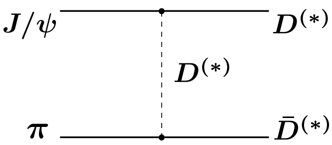
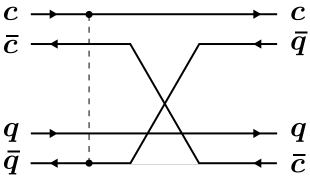
(a) $D^{(*)}$ meson exchange?



$\rightarrow$ next sec.

(b) Quark exchange?



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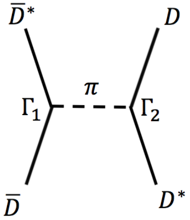
Comparison between **D exchange** and **Quark exchange**

- One boson exchange potential (OBEP)



$D\bar{D}^*$ potential

$DD^*\pi$ vertex induces OPEP ($DD\pi$ vertex violates the parity conservation)

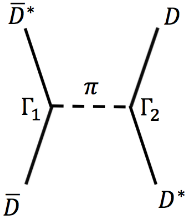
$\boxed{\text{OPEP}}$

$$V^\pi = -\frac{1}{2}\left(\frac{g_\pi}{f_\pi}\right)^2 \left[\vec{S}_1 \cdot \vec{S}_2 C(r) + S_{12}(\hat{r})T(r)\right] \vec{\tau}_1 \cdot \vec{\tau}_2$$

Comments

- HQS induces **$D(0^-) - D^*(1^-)$ coupling** $\rightarrow$ OPEP works!

- One boson exchange potential (OBEP) **with Tensor force!**



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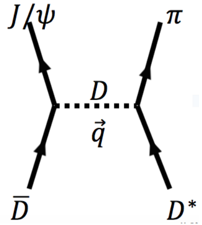
Comments

- HQS induces ***$D(0^-) - D^*(1^-)$ coupling*** $\rightarrow$ OPEP works!
- Tensor force $T(r) \Rightarrow$ **the driving force** in atomic nuclei
  $S_{12}(\hat{r}) = 3(\vec{S}_1 \cdot \hat{r})(\vec{S}_2 \cdot \hat{r}) - \vec{S}_1 \cdot \vec{S}_2 \rightarrow S$-$D$ mixing

- $D^{(*)}$ meson exchange potential in $\pi J/\psi - D^{(*)}\bar{D}^{(*)}$



$\pi J/\psi - D\bar{D}^*$ potential

$\boxed{D \text{ exchange}}$

$$V^D = \frac{2}{3}\frac{g_\psi g_\pi}{f_\pi\sqrt{E_\pi}}\left[\vec{S}_1\cdot\vec{S}_2 C(r) + S_{12}(\hat{r})T(r)\right]$$

$\boxed{D^* \text{ exchange}}$

$$V^{D^*} = \frac{2}{3}\frac{g_\psi g_\pi}{f_\pi\sqrt{E_\pi}}\left[2\vec{S}_1\cdot\vec{S}_2 C(r) - S_{12}(\hat{r})T(r)\right]$$

$g_\psi = 8.0$ (Assuming VMD), $\Lambda_\psi = 2.2$ GeV

A. Deandrea, G. Nardulli and A. D. Polosa, PRD**68**(2003)034002

Comments

- Spin-spin ($\vec{S}_1\cdot\vec{S}_2$) and Tensor (S_{12}) terms
- Energy-dependence ($1/\sqrt{E_\pi}$)

Numerical results: Phase shift
Meson exchange model

- We found...

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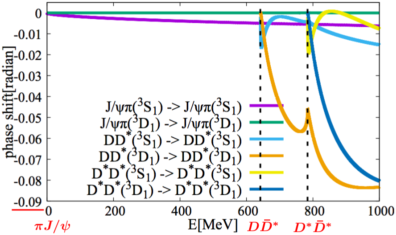
Meson exchange model

- We found... **No Bound state, No Resonance**
  Very Small phase shift $|\delta| < 0.09$ [rad]



- $D^{(*)}\bar{D}^{(*)}$ channel: **Small** contribution from OPEP

- $\pi J/\psi$ channel: $D^{(*)}$ exchange is **Negligible**

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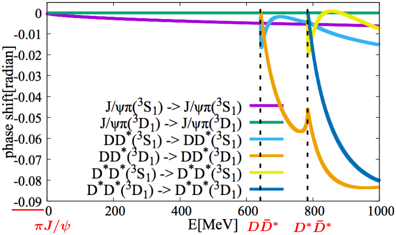
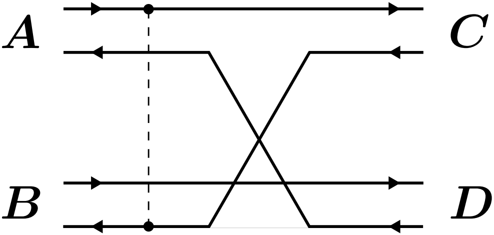


- $D^{(*)}\bar{D}^{(*)}$ channel: **Small** contribution from OPEP
  Why?: Isospin factor $\vec{\tau}_1 \cdot \vec{\tau}_2$, $\mathbf{-3\ (I=0)}$, but $\mathbf{Z_c{:}{+}1\ (I=1)}$
- $\pi J/\psi$ channel: $D^{(*)}$ exchange is **Negligible**
  Why?: Volume Integral $V_C^D(\vec{q}^{\,2}=0) = 3.14\ \mathrm{GeV}^{-2}$
  $\leftrightarrow V_{NN}^{\sigma} \sim \mathbf{3.00 \times 10^2\ GeV^{-2}}$

- **Born-order quark-exchange diagram**

  T. Barnes and E. S. Swanson, PRD**46**(1992)131. Swanson, Ann. Phys. **220**(1992)73.

- $AB \to CD$ scattering $\quad \mathcal{M}_{fi} \propto \langle C, D|H_I|A, B\rangle$



- Ingredients: Meson Wavefunctions(A, B, C, D)
  Quark interaction (Quark Model)

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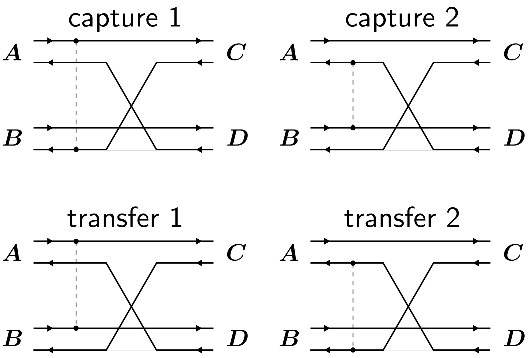

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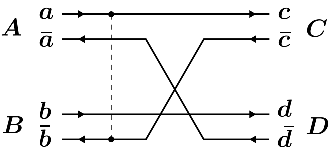
capture 1



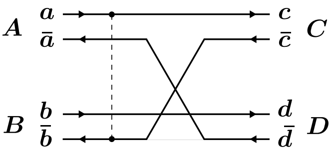
- Meson momenta: A, B, C, D
- Quark momenta: $a, \bar{a}, b, \bar{b}, c, \bar{c}, d, \bar{d}$
- Conservation: $A + B = C + D$, $\bar{a} = \bar{d}$, $b = d$

- Amplitude

$$\rightarrow \int\int d^3a d^3c \phi^*_C(2\vec{c} - \vec{C})\phi^*_D(2\vec{a} - 2\vec{A} - \vec{C})V(\vec{a} - \vec{c})\phi_A(2\vec{a} - \vec{A})\phi_B(2\vec{a} - \vec{A} - 2\vec{C})$$

Scattering Amplitude
Quark exchange interaction

capture 1



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- Conservation: $A + B = C + D$, $\bar{a} = \bar{d}$, $b = d$

- Amplitude

$$\to \int\int d^3a d^3c \phi_C^*(2\vec{c} - \vec{C})\phi_D^*(2\vec{a} - 2\vec{A} - \vec{C})V(\vec{a} - \vec{c})\phi_A(2\vec{a} - \vec{A})\phi_B(2\vec{a} - \vec{A} - 2\vec{C})$$

- Quark Potentials (momentum space)

Coulomb: $V^{Coul}(q) = -\frac{\alpha_s}{2\pi^2}\frac{1}{\vec{q}^{\,2}}$, **Hyperfine:** $V^{Hyp}(q) = -\frac{8\pi\alpha_h}{3m_i m_j}e^{-\vec{q}^{\,2}/4\sigma^2}$

Linear: $V^{Lin}(r) = br \times \boldsymbol{e^{-\varepsilon r}} \to V^{Lin}(q) = b\left[\frac{-8\pi}{(\vec{q}^{\,2} + \varepsilon^2)^2} + \frac{32\pi\varepsilon^2}{(\vec{q}^{\,2} + \varepsilon^2)^3}\right]$

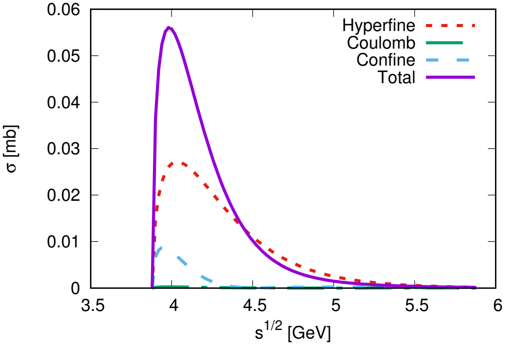
- $\pi J/\psi - D\bar{D}^*$: Amplitude

$\Rightarrow$ Cross section $\propto |(\text{Coulomb}) + (\text{Confine}) + (\text{Hyperfine})|^2$

Cross Section (Born term): $\pi J/\psi - D\bar{D}^*$
Numerical Result

- $\pi J/\psi - D\bar{D}^*$: Amplitude

$\Rightarrow$ Cross section $\propto |(\text{Coulomb}) + (\text{Confine}) + (\text{Hyperfine})|^2$



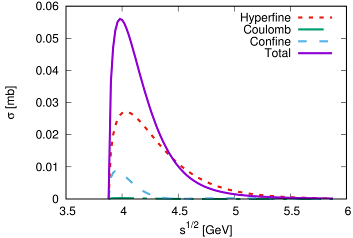
- Dominant role of the Hyperfine (Spin-spin) term

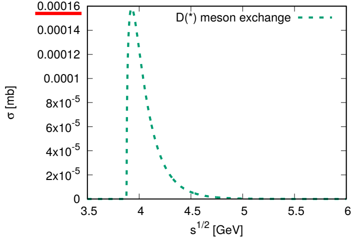
  $\Leftrightarrow$ Minor role of the Coulomb term.

- $\pi J/\psi - D\bar{D}^*$: Amplitude

$\Rightarrow$ Cross section $\propto |(\text{Coulomb}) + (\text{Confine}) + (\text{Hyperfine})|^2$

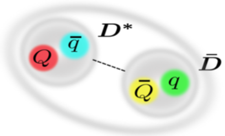
Quark exchange **$D^{(*)}$ exchange**

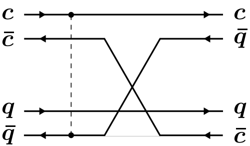




- Dominant role of the Hyperfine (Spin-spin) term
  $\Leftrightarrow$ Minor role of the Coulomb term.
- Large difference between Quark exchange and $D^{(*)}$ exchange

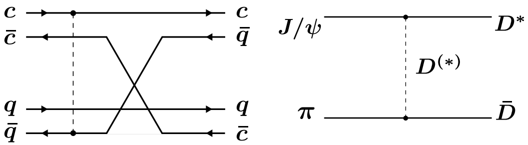
Summary





- Many exotic states near the threshold.
  $\rightarrow$ Understanding **the hadron-hadron interaction** is needed.
- Charged charmonium $Z_c(3900)$ has been discussed as the Hadronic molecules or the threshold cusp.
- OPEP contribution is not strong. $D^{(*)}$ meson exchange is **negligible**.
- Quark exchange interaction is introduced as Short range $\pi J/\psi - D^{(*)}\bar{D}^{(*)}$ potential.
  We find **Large difference** between results from Quark exchange and $D^{(*)}$ meson exchange.

Future Work



- Beyond Born-order $\rightarrow T = V + VGT$
  $\Rightarrow$ To compare the Exp. and Lattice result
- Introducing $\rho\eta_c$, $\psi'\pi$,...
- Bottom Sector: $Z_b(10610)$ and $Z_b(10650) \Rightarrow \pi\Upsilon - B\bar{B}^*$

Thank you for your kind attention.