X(3872) as a hybrid state of charmonium and the hadronic molecule

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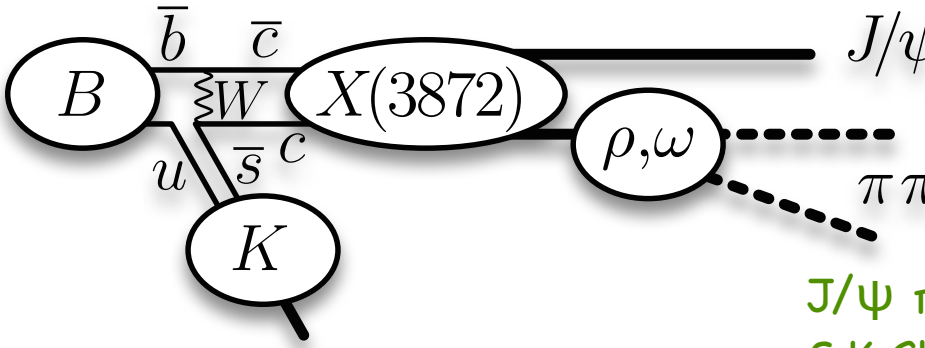
Structure and productions of charmed baryons II @ JPARC 8 Aug 2014

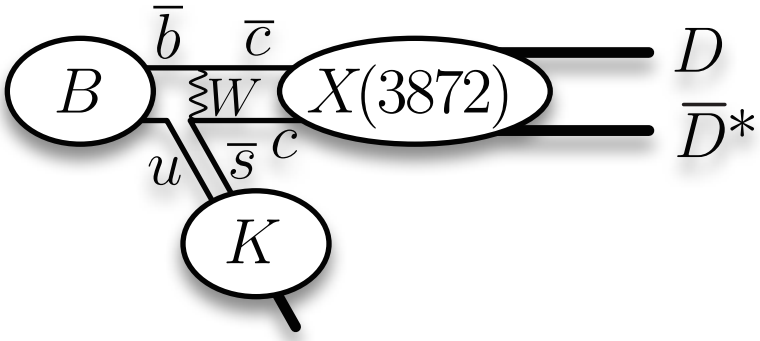
$B^+ \to K^+ + J/\psi + \pi\pi(\pi)$

- $B^+ \to X(3872) + K^+$



$\to J/\psi + \rho$ or $\omega \to \pi^n$

J/ψ π^2 Exp:
S.K.Choi et al. [Belle] PRL91, 262001 (2003)
B.Aubert et al. [BaBar] PRD71, 071103 (2005)



$\to D + D^*$

$D^0\bar{D}^{*0}$ exp
T.Aushev et al. [Belle] PRD81, 031103 (2010)
B.Aubert et al. [BaBar] PRD77, 011102 (2008)

Formation process of X(3872)

- X(3872) from
  - B^+ decay
  - B^0 decay
  - $p\bar{p}$ collision
    - $Br(p\bar{p} \to X)/Br(p\bar{p} \to \psi(2S)) > 0.046$
  - pp collision
    - $J^{PC}=1^{++}$
  - π^+Li ...?

$\bar{p}p$ exp
D.Acosta et al. [CDF] PRL93, 072001 (2004)
V.M.Abazov et al. [D0] PRL93, 162002 (2004)
C.Bignamini et al. PRL103, 162001 (2009)

pp exp
R.Aaij et al. [LHCb] EPJC72, 1972 (2012)

πA exp
L.Antoniazzi et al. [E705] PRD50, 4258 (1994)

Decay process of X(3872)

- X(3872) decays into
  - $J/\psi\ \pi\pi$ [Belle][BaBar][CDF][D0][CMS]
  - $J/\psi\ \pi^3$ [BaBar]([Belle] not published)
  - $D^0\bar{D}^{*0}$ [Belle][BaBar]
  - $J/\psi\gamma$ [Belle][BaBar][LHCb]
  - $\psi(2S)\gamma$ [BaBar][LHCb]([Belle] not seen)

in each Decay process

- X(3872) decays into
  - J/ψ ππ
    - mass 3871.68±0.17 MeV [PDG]
    - width < 1.2 MeV [PDG]
  - J/ψ ω π^3/π^2
    K.Abe et al. [Belle] arXiv:hep-ex/0505037
    P.del Amo Sanchez et al. [BaBar] PRD82, 011101 (2010)
    - $Br(X \to J/\psi\pi^3)/Br(X \to J/\psi\pi^2)$
      $= 1.0\pm0.4\pm0.3,\ 0.8\pm0.3$
      Belle BABAR

in each Decay process

- X(3872) decays into
  - $D^0\bar{D}^{*0}$ $D\bar{D}$
    T.Aushev et al. [Belle] PRD81, 031103 (2010)
    B.Aubert et al. [BaBar] PRD77, 011102 (2008)
    - mass $3872.9\ ^{+0.6+0.4}_{-0.4-0.5}$ MeV Belle
      $3875.1\ ^{+0.7}_{-0.5}\pm0.5$ MeV BABAR
    - width $3.9\ ^{+2.8+0.2}_{-1.4-1.1}$ MeV Belle
      $3.0\ ^{+1.9}_{-1.4}\pm0.9$ MeV BABAR
    - $Br(X\to D^0\bar{D}^{*0})/Br(X\to J/\psi\pi^2)$

      = 8.92 ± 2.42, 19.9 ± 8.05 (calc from papers)
      Belle BABAR

in each Decay process

- X(3872) decays into
  - J/ψγ [Belle][BaBar][LHCb]
  - ψ(2S)γ [BaBar][LHCb]([Belle] not seen)
    - Br(X→ψ(2S)γ)/Br(X→J/ψγ)

      = 3.21±1.4, <2.1, 2.46±0.64±0.29

      BABAR Belle LHCb

γ

B.Aubert et al. [BaBar] PRL102, 132001 (2009)

V.Bhardwaj et al. [Belle] PRL107, 091803 (2011)

R.Aaij et al. [LHCb] arXiv:1404.0275 [hep-ex]

X(3872) facts

- $J^{PC}=1^{++}$
- Mass 3871.68±0.17 MeV from $J/\psi\pi\pi$
- X(3872) ($uc\bar{u}\bar{c}$, $dc\bar{d}\bar{c}$) thresholds
  - $D^{\pm}D^{*\mp}$ 3879.91±0.20 MeV
  - $J/\psi\omega$ 3879.57±0.12 MeV
  - $J/\psi\rho$ 3872.18±0.25 MeV
  - $D^{0}\bar{D}^{*0}$ 3871.85±0.20 MeV
- Mass 3872.9~3875.1 MeV from $D^{0}\bar{D}^{*0}$

X(3872) facts

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  - $J/\psi\rho$ 3872.18±0.25 MeV
  - $D^0\bar{D}^{*0}$ 3871.85±0.20 MeV

X is almost 'on' the threshold!

- Mass 3872.9~3875.1 MeV from $D^0\bar{D}^{*0}$

Mass from $J/\psi\pi\pi$ < Mass from $D^0\bar{D}^{*0}$

X(3872) facts

- Width $\Gamma < 1.2$ MeV from $J/\psi\pi\pi$

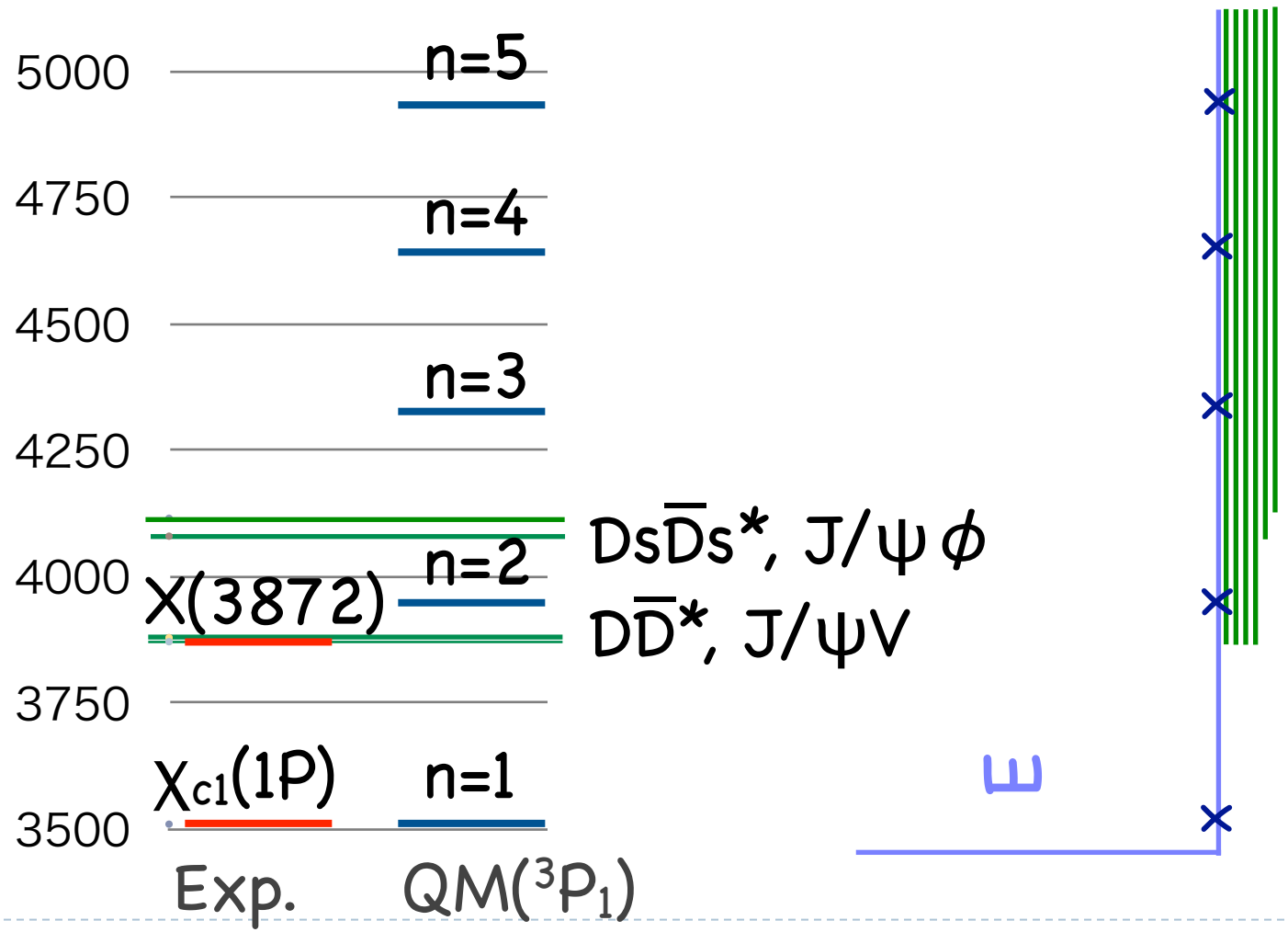
  X has a very small width!

- Width 3.0~3.9 MeV from $D^0\bar{D}^{*0}$

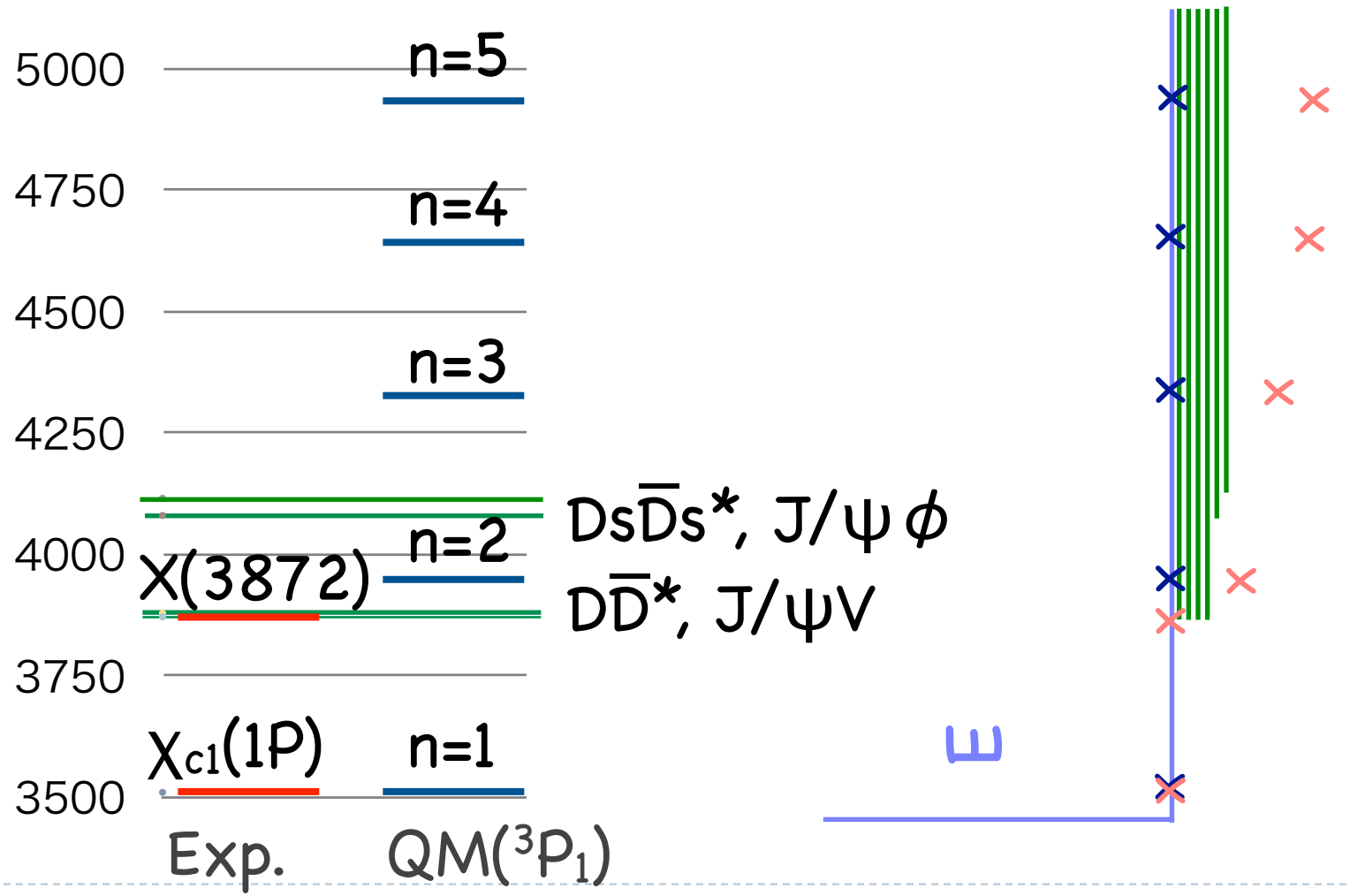
  Width from $J/\psi\pi\pi$ < Width from $D^0\bar{D}^{*0}$

- 1^{++} Spectrum
  - $\chi_{c1}(1P)$
    - m=3510.66±0.07 MeV, Γ= 0.86±0.05 MeV
  - Absence of $\chi_{c1}(2P)$
    - Quark model prediction m=3950 MeV

1^{++} Spectrum


5000
4750
4500
4250
4000
3750
3500
n=5
n=4
n=3
n=2
n=1
X(3872)
$\chi_{c1}(1P)$
$D_s\bar{D}_s^*$, $J/\psi\,\phi$
$D\bar{D}^*$, $J/\psi V$
Exp.
QM($^3P_1$)

1^{++} Spectrum


5000
4750
4500
4250
4000
3750
3500
n=5
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n=2
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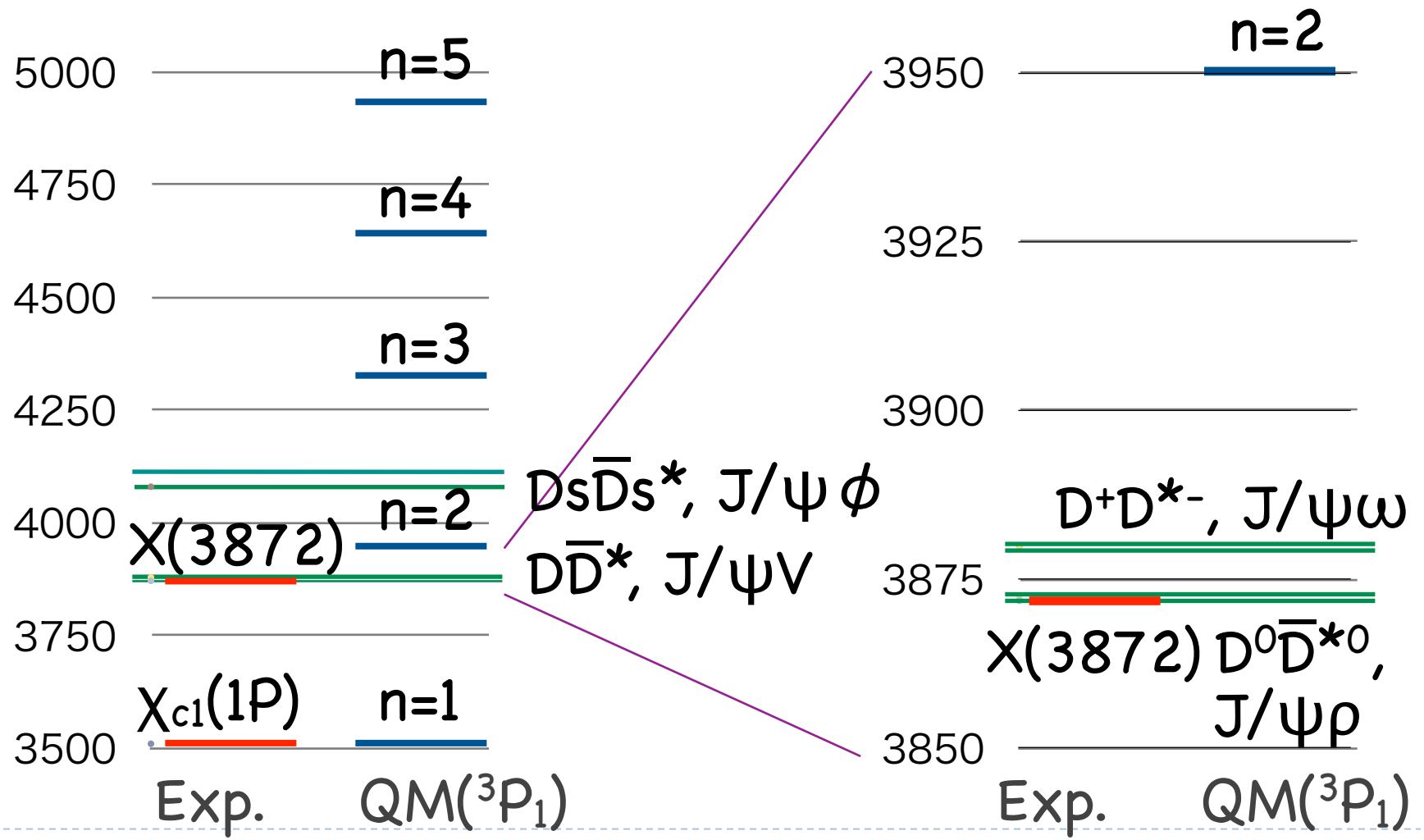
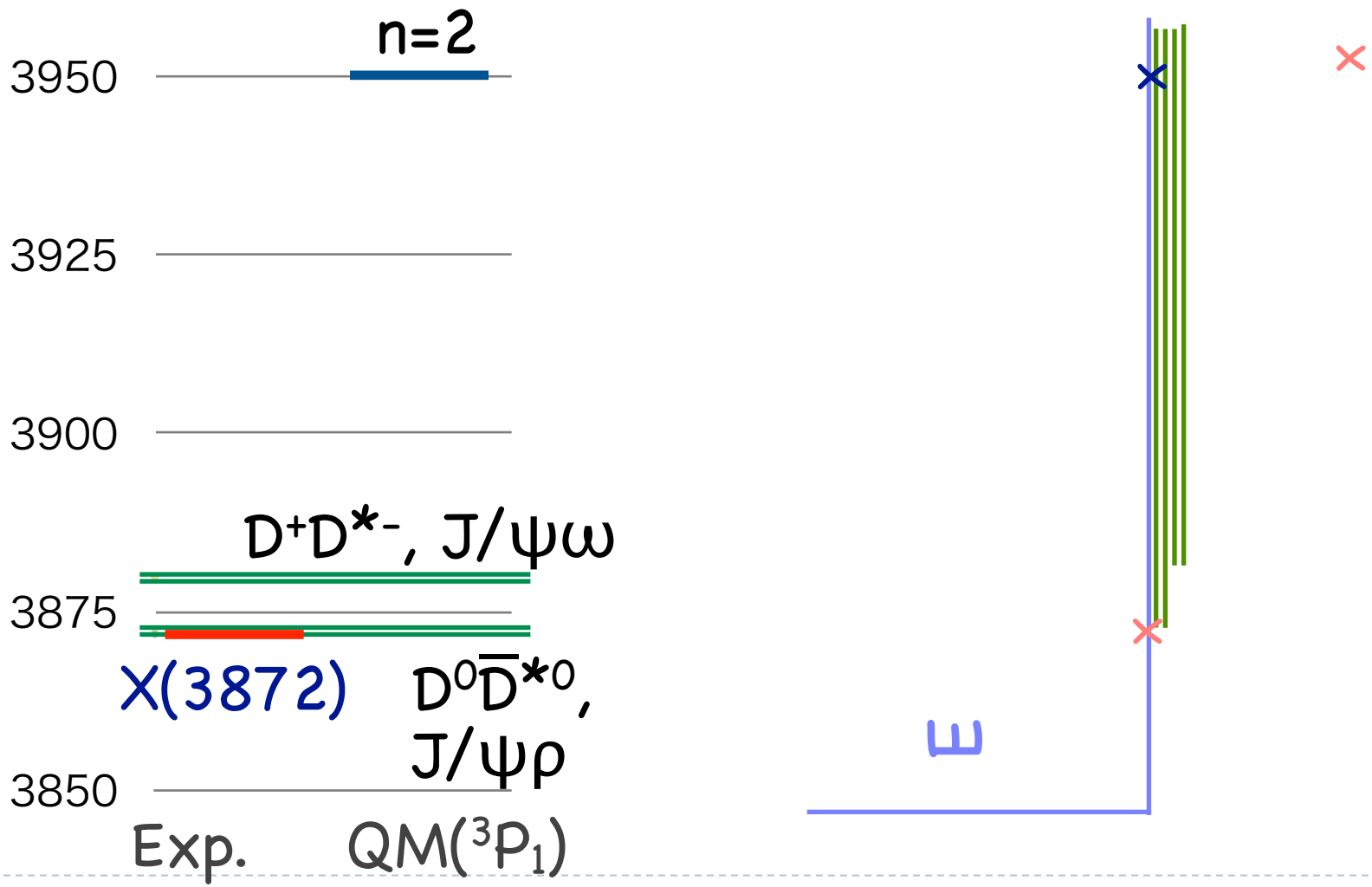
X(3872)
$\chi_{c1}(1P)$
$D_s\bar{D}_s^*$, $J/\psi\,\phi$
$D\bar{D}^*$, $J/\psi V$
Exp.
QM($^3P_1$)

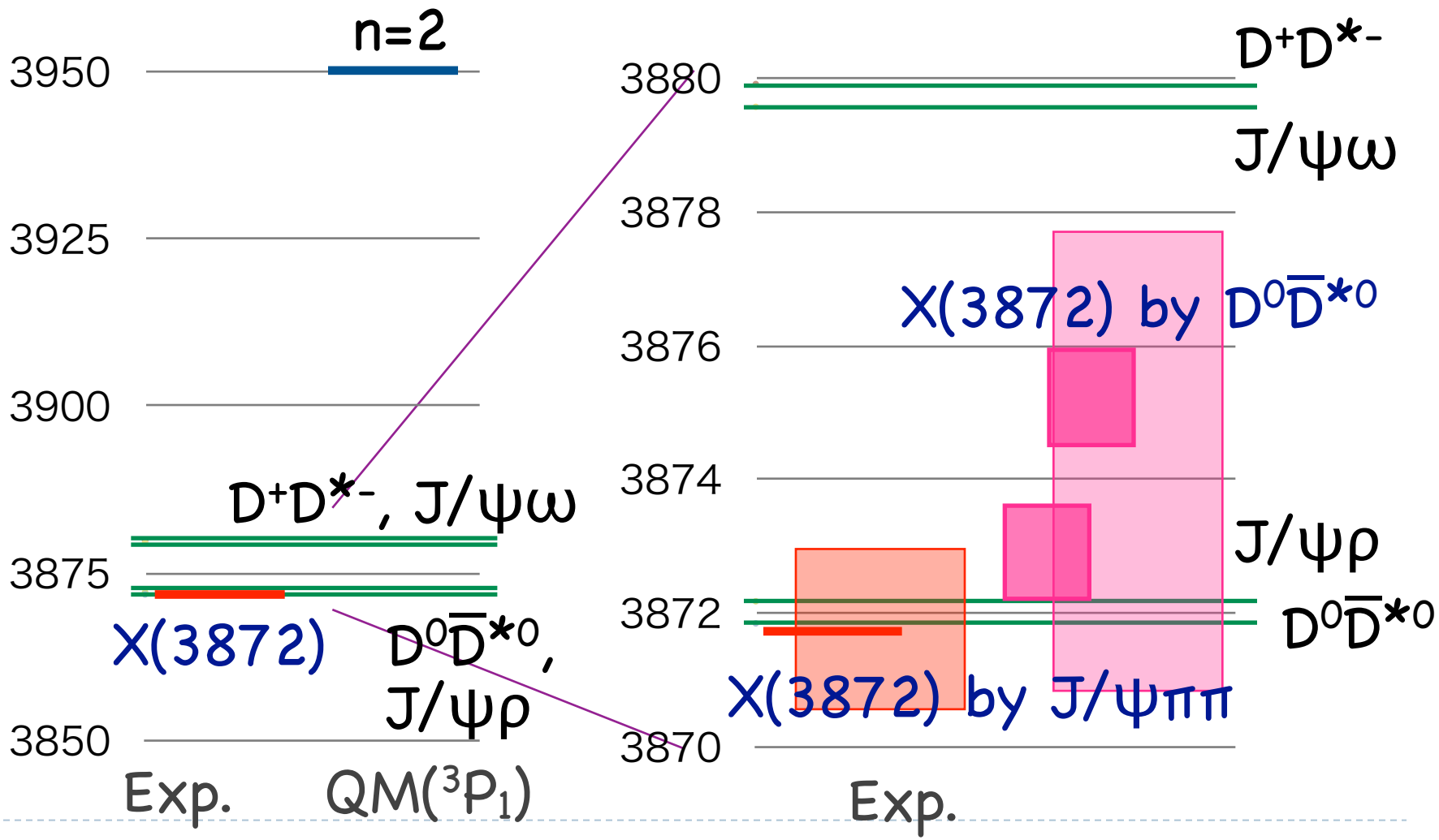
1^{++} Spectrum


5000
4750
4500
4250
4000
3750
3500
n=5
n=4
n=3
n=2
n=1
X(3872)
Xc1(1P)
Exp.
QM(3P1)
DsD̄s*, J/ψφ
DD̄*, J/ψV
3950
3925
3900
3875
3850
n=2
D+D*-, J/ψω
X(3872)
D0D̄*0, J/ψρ
Exp.
QM(3P1)

1^{++} Spectrum


n=2
3950
3925
3900
D^+D^{*-}, $J/\psi\omega$
3875
X(3872)
$D^0\bar{D}^{*0}$,
$J/\psi\rho$
3850
Exp.
QM($^3P_1$)
ω

1^{++} Spectrum


n=2
3950
3925
3900
3875
3850
D+D*-, J/ψω
X(3872)
D0D̄*0,
J/ψρ
Exp.
QM(3P1)
3880
3878
3876
3874
3872
3870
D+D*-
J/ψω
X(3872) by D0D̄*0
J/ψρ
D0D̄*0
X(3872) by J/ψππ
Exp.

Theory

- LQCD

LQCD
S.Prelovsek and L.Leskovec, PRL111, 192001 (2013)

  - X(3872) is seen below $D\bar{D}^*$, BE=11±7 MeV
  - $m_u=m_d$
    - how to deal a resonance, $m_u \neq m_d$, ρ width
- Phenomenological
  - $c\bar{c}$
  - $q\bar{q}c\bar{c}$ tetraquark
  - $D\bar{D}^*$ molecule
  - $D\bar{D}^*$ + $c\bar{c}$ coupled

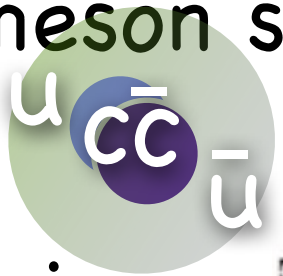
  → should couple to the $D\bar{D}^*$ (their thresholds nearby)

  → production rate requires a smaller object

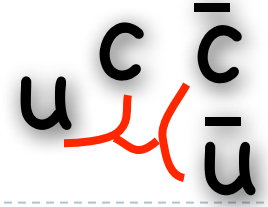
A LOT of Phenomenological model! Reviews are, e.g.,
E.S.Swanson, Phys.Rept.429, 243 (2006).
N.Brambilla, et al. Eur.Phys.J.C71, 1534 (2011).

Tetraquark for X(3872)

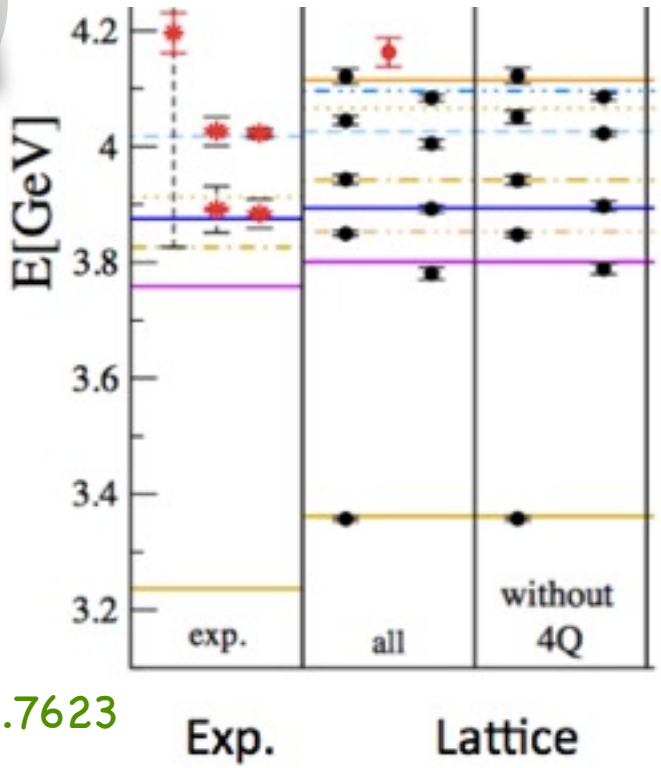
- $(qc)_{color\bar{3}}$-$(\bar{q}\bar{c})_{color3}$: diquark-diquark
  L.Maiani et al PRD71, 014028 (2005).
- It couples to two-meson states (weak coupling).



- LQCD, sometimes, it is necessary to put a tetraquark interpolator to get some levels, it seems...



Zc3900
S.Prelovsek et al, arXiv:1405.7623



What we'd like to discuss today

- There is a mechanism to have such a narrow peak of $J/\psi\pi^n$ that appears on the threshold.
  - That X(3872) is THERE may not be accidental.
  - The peak by $D\bar{D}^*$ is little heavier than the peak by $J/\psi\pi\pi$.
  - J/ψ-$\pi\pi$ width is very small while $D\bar{D}^*$ width is larger.

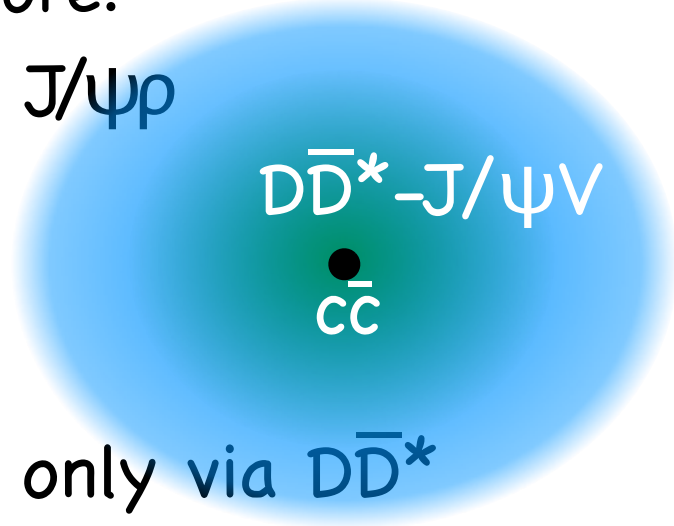
What we'd like to discuss today

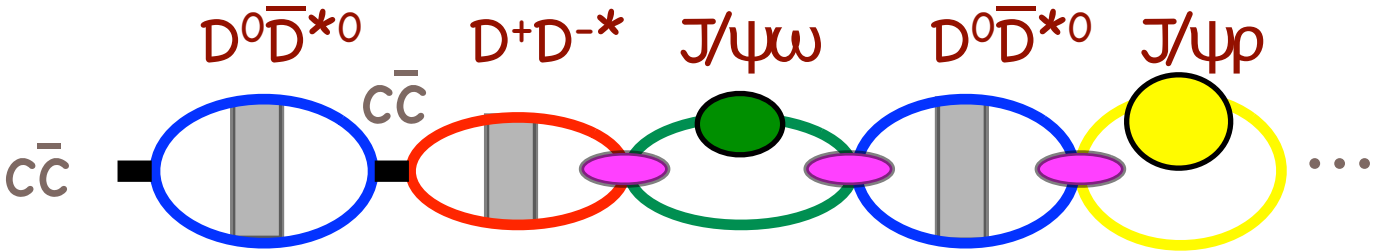
- Large isospin symmetry breaking appears.
  - A small breaking from $mD^0 \neq mD^+$ is enhanced by the large width of ρ meson.
- Size of isospin symmetry breaking and ratio of some transfer strength

  will give us info on
  - the size of $c\bar{c}$-$D\bar{D}^*$ coupling,
  - the interaction between D and $\bar{D}^*$.
    - → info for other charm or heavy Q systems

Our picture of X(3872)

- Two-meson molecule with a $c\bar{c}$ core:
  - $c\bar{c}$ – $D^0\bar{D}^{*0}$ – D^+D^{-*} – $J/\psi\omega$ – $J/\psi\rho$
  - ω and ρ have width.
  - $J/\psi\omega$ and $J/\psi\rho$ couple to $c\bar{c}$ only via $D\bar{D}^*$ channels (OZI).





M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 0903D01
S.Takeuchi, K.Shimizu, and M.Takizawa, arXiv:1408.0973 [hep-ph]

Model Hamiltonian

- $H = H_0 + V$

$$H_0 = \begin{pmatrix} H_0^{(P)} & 0 \\ 0 & E_0^{(Q)} \end{pmatrix} \qquad H_0^{(P)} = \sum_i \left(M_i + m_i + \frac{k_i^2}{2\mu_i} \right)$$

$$V = \begin{pmatrix} V_{PP} & V_{PQ} \\ V_{QP} & 0 \end{pmatrix}$$

P : $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ - $J/\psi\rho$, Q : $c\bar{c}$

V_{PP} : potential between the two mesons

V_{PQ} : coupling between the two-meson and $c\bar{c}$ channels

$E_0^{(Q)}$: QM predicted $\chi_{c1}(2P)$ mass = 3950 MeV

Potentials

- Isospin invariant

in this calculation, we take Λ = 500MeV

  - separable Lorentzian for D and $\bar{D}^*$ interaction $\frac{-\lambda}{\Lambda^2}\left(\frac{\Lambda^2}{q^2+\Lambda^2}\right)\left(\frac{\Lambda^2}{p^2+\Lambda^2}\right)$
  - Lorentzian for $D\bar{D}^*$-$c\bar{c}$ coupling $\frac{g}{\sqrt{\Lambda}}\left(\frac{\Lambda^2}{q^2+\Lambda^2}\right)$

	$D^0\bar{D}^{0*}$	D^+D^{-*}	$J/\psi\rho$	$J/\psi\omega$	$c\bar{c}$
$D^0\bar{D}^{0*}$	v	0	u	u	g
D^+D^{-*}		v	- u	u	g
$J/\psi\rho$			0	0	0
$J/\psi\omega$				0	0

$V(D\text{-}\bar{D}^*)$ is the same for I=0 and 1

$V(J/\psi V\text{-}c\bar{c})$ = 0 ← OZI

$V(J/\psi\text{-}V)$ = 0 ← no int btw light quarks

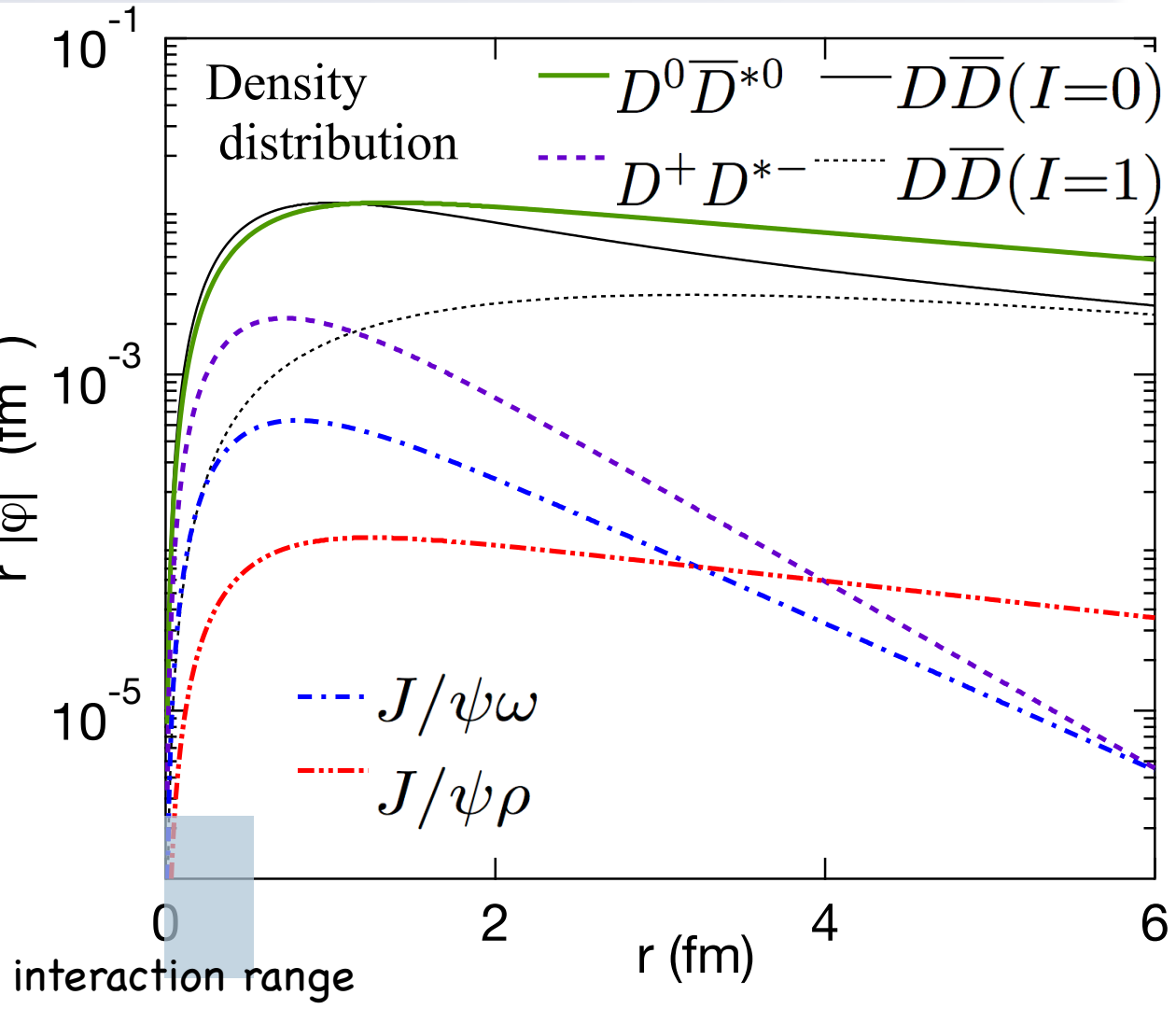
Potentials

	D^0D^{0*}	D^+D^{-*}	$J/\psi\,\rho$	$J/\psi\,\omega$	$c\bar{c}$
D^0D^{0*}	v	0	u	u	g
D^+D^{-*}		v	- u	u	g
$J/\psi\,\rho$			0	0	0
$J/\psi\,\omega$				0	0

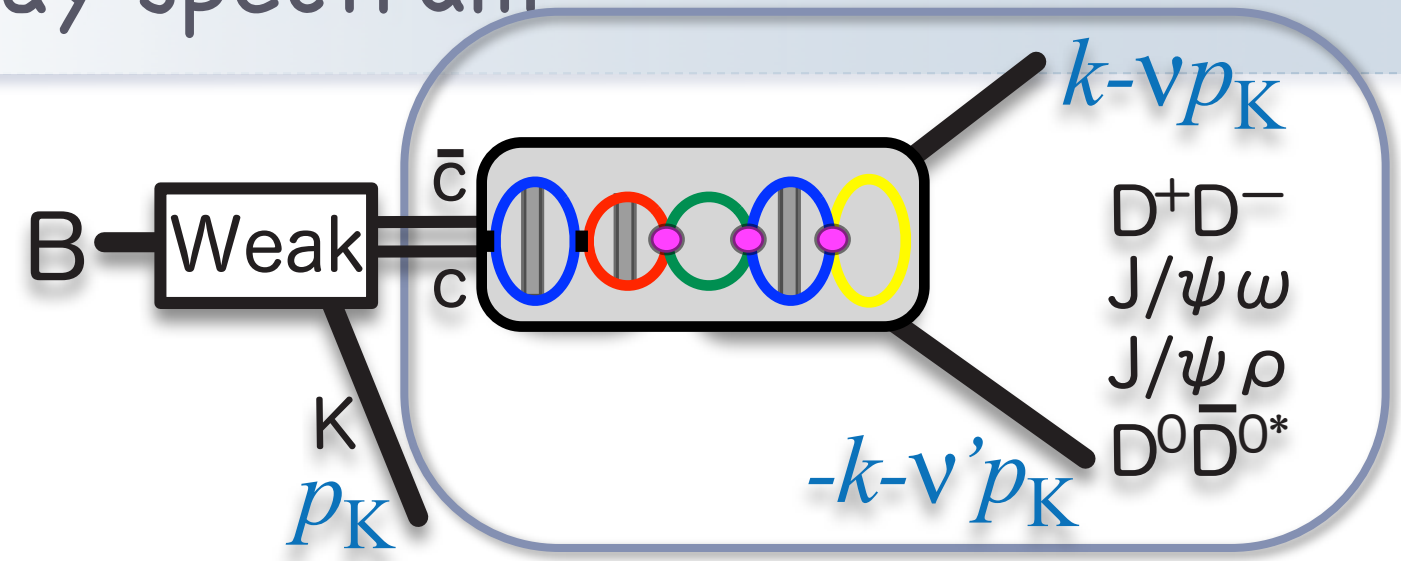
- Interaction strengths are determined by
  - $D\text{-}\bar{D}^*$ coupling **v** : we assume it is the same as the strength between B-B*, and B-B* interaction is taken so that it has a zero-energy resonance, like $Z_b(10610)$ or $Z_b(10650)$.
  - $D\bar{D}^*\text{-}J/\psi\omega$ coupling **u** : we assume the quark model with Godfrey-Isgur $q\bar{q}$ interaction to obtain this transfer strength.
    - RGM for QM → $V_{pp} = N^{-1/2}\,H\,N^{-1/2} - H_0$
  - $D\bar{D}^*\text{-}c\bar{c}$ coupling **g** : we use this strength as a free parameter to give the X(3872) peak energy.

X(3872) : a bound state

- Probability
  - 0.045 $c\bar{c}$
  - 0.892 $D^0\bar{D}^{*0}$
  - 0.043 D^+D^{-*}
  - 0.012 $J/\psi\omega$
  - 0.007 $J/\psi\rho$
- Density distri. of two mesons
  - $r^2|\varphi_{MM}(r)|^2$



Decay spectrum



- Decay rate ∝ $c\bar{c}$ self energy

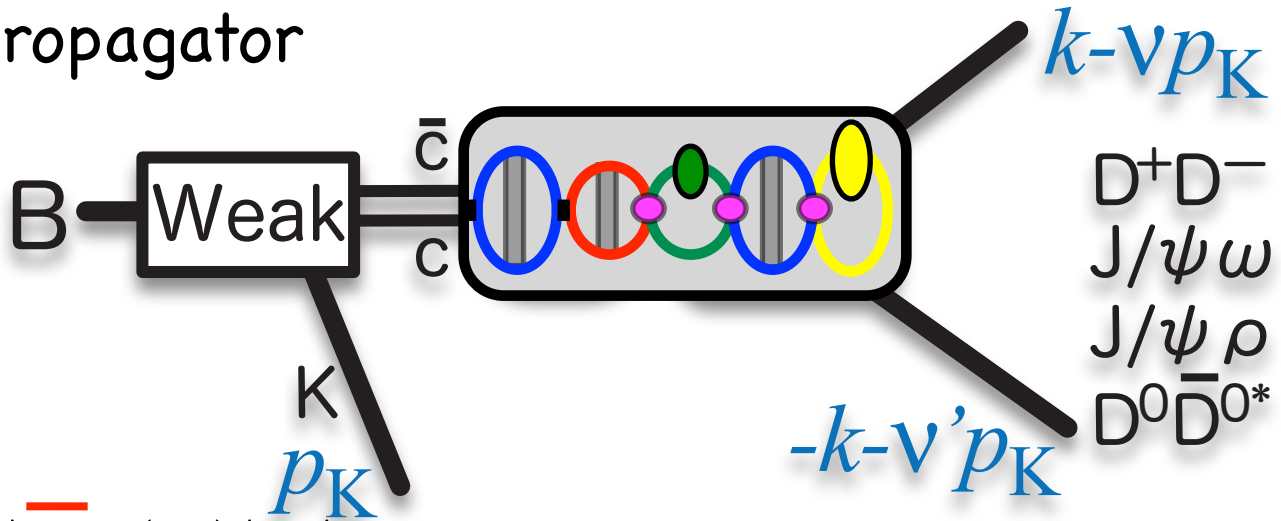
$$\frac{dW}{dE} = -\frac{1}{\pi} Im \langle c\bar{c}|G_Q(E)|c\bar{c}\rangle \qquad \int_{E_{threshold}}^{\infty} \frac{dW}{dE}\, dE = 1$$

$$\frac{dW(c\bar{c} \to f)}{dE} = \pi \mu_f k_f \left| \langle f; k_f | (1 + V_{PP} G^{(P)}) V_{PQ} G_Q | c\bar{c} \rangle \right|^2$$

S.Takeuchi, K.Shimizu, and M.Takizawa, arXiv:1408.0973 [hep-ph]

Introducing $\omega \to \pi^3$ and $\rho \to \pi^2$ decay

- Width in the propagator



$$\frac{dW}{dE} = -\frac{1}{\pi} Im \langle c\bar{c}|\overline{G}_Q(E)|c\bar{c}\rangle$$

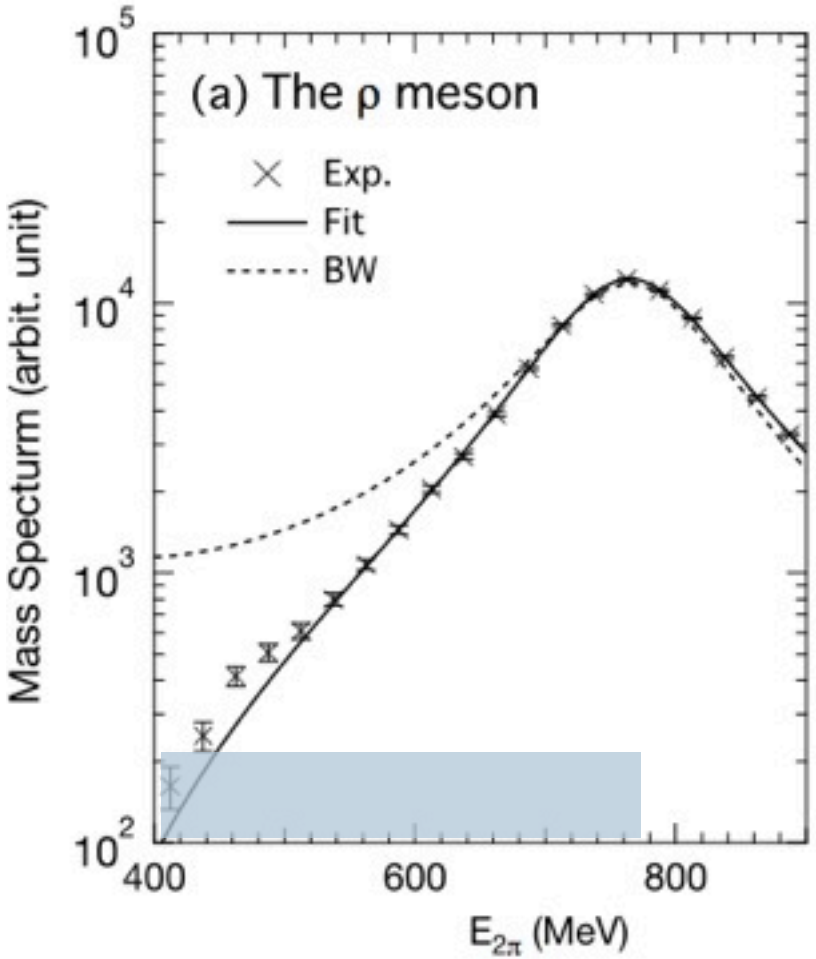
$$\overline{G} = \frac{1}{E - H + i\Gamma(E)/2}$$

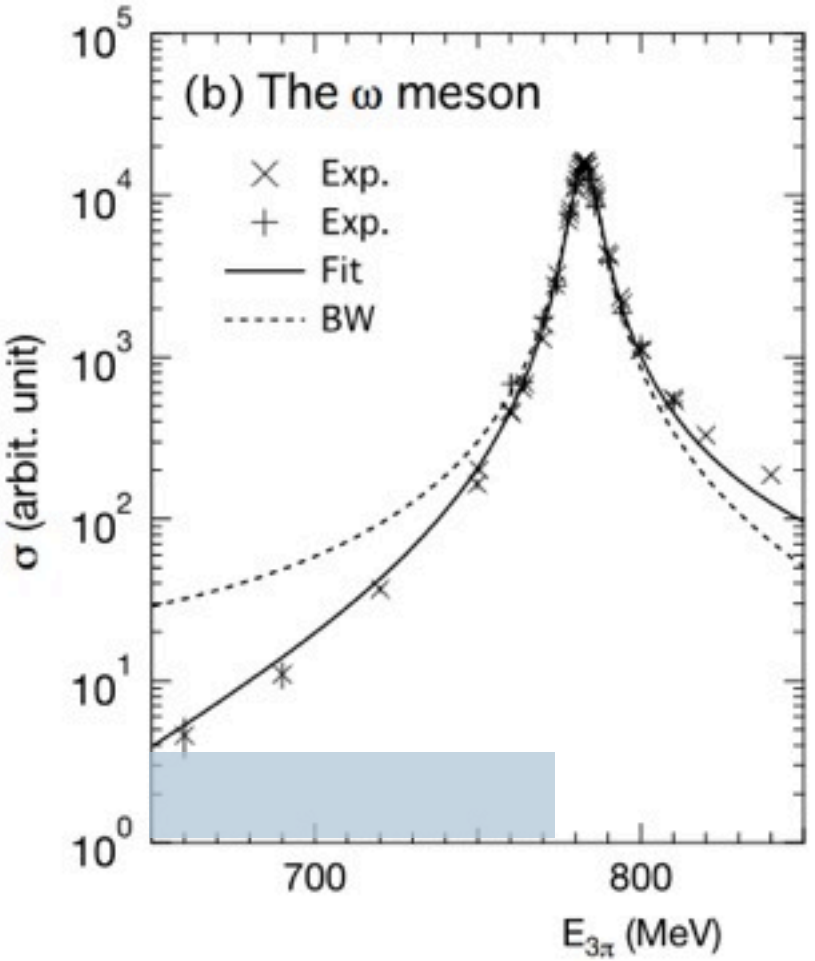
← observed $\rho \to \pi\,\pi$ or $\omega \to \pi\,\pi\,\pi$ width

$$\propto \int \frac{k^2 dk\ \mu_f \Gamma_V(s(k))}{(k_f^2 - k^2)^2 + (\mu_f \Gamma_V(s(k)))^2} \left| \langle f; k|(1 + V_{PP}\overline{G}^{(P)})V_{PQ}\overline{G}_Q|c\bar{c}\rangle \right|^2$$

Vector meson widths

- Energy dependent width for ρ and ω

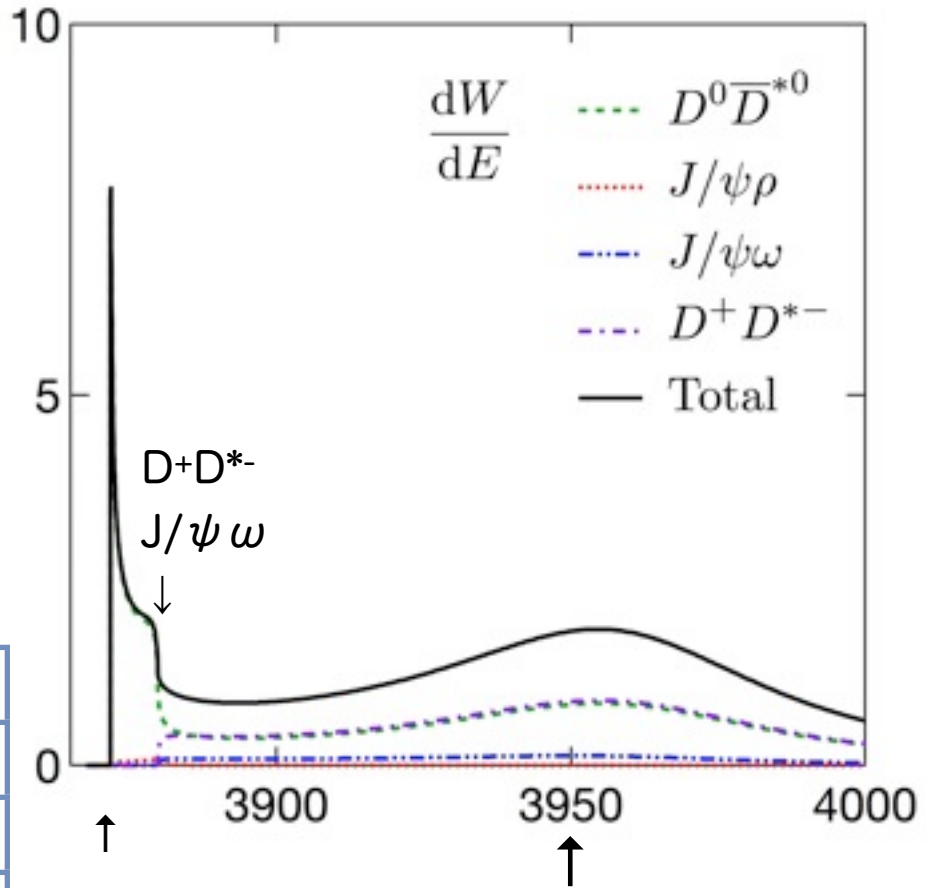




$c\bar{c}$ → two mesons : for bound X(3872)

- no width for ρω.
  - $D^0\bar{D}^{0*}$ peak appears
  - Almost no J/ψρ strength.
  - X(3872) is a bound state, $c\bar{c}$->X prob. is 0.045

v,u,g^2	$D^0\bar{D}^{0*}$	D^+D^{-*}	J/ψρ	J/ψω	$c\bar{c}$
$D^0\bar{D}^{0*}$	-0.19	0	0.19	0.19	0.66
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0



2014年 8月 8日 金曜日

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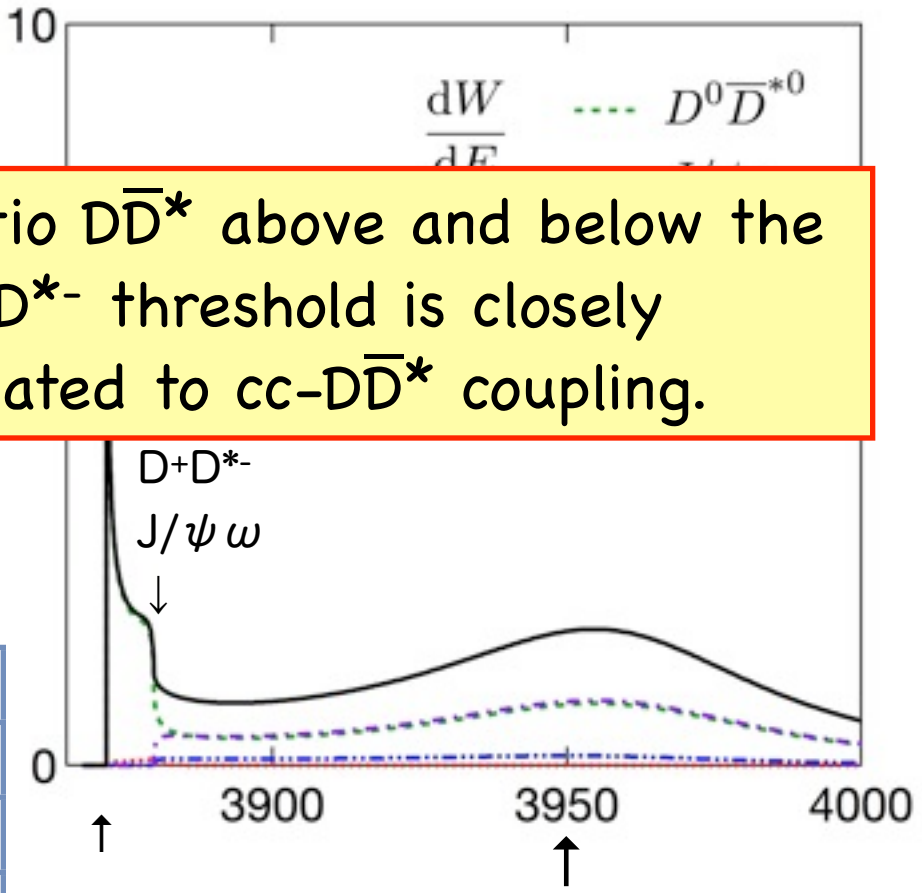
ratio $D\bar{D}^*$ above and below the D^+D^{*-} threshold is closely related to cc-$D\bar{D}^*$ coupling.



v,u,g^2	$D^0\bar{D}^{0*}$	D^+D^{-*}	J/ψρ	J/ψω	$c\bar{c}$
$D^0\bar{D}^{0*}$	-0.19	0	0.19	0.19	0.66
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0

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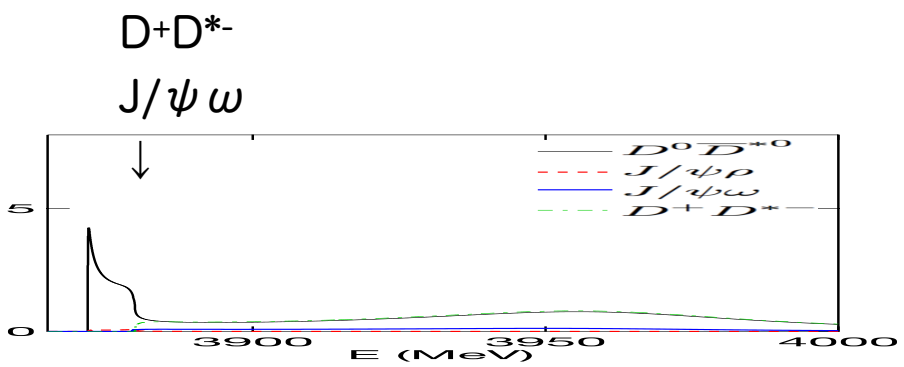
v,u,g^2	$D^0\bar{D}^{0*}$	D^+D^{-*}	J/ψρ	J/ψω	$c\bar{c}$
$D^0\bar{D}^{0*}$	-0.19	0	0.19	0.19	0.66
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0

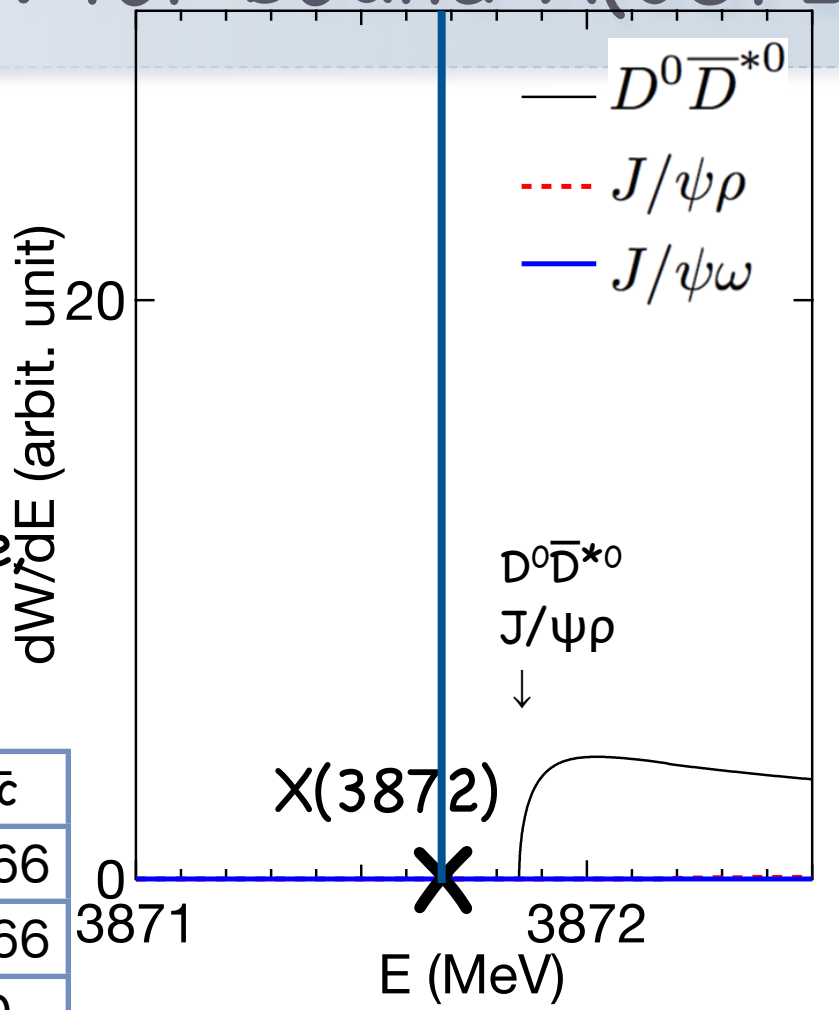


$D^0\bar{D}^{*0}$
J/ψρ

$c\bar{c}$(2P)
Sharp peak No more

$c\bar{c}$ → two mesons : for bound X(3872)

- no width for ρω.
  - $D^0\bar{D}^{0*}$ peak appears
  - Almost no J/ψρ strength.
  - X(3872) is a bound state $c\bar{c}$->X prob. is 0.045

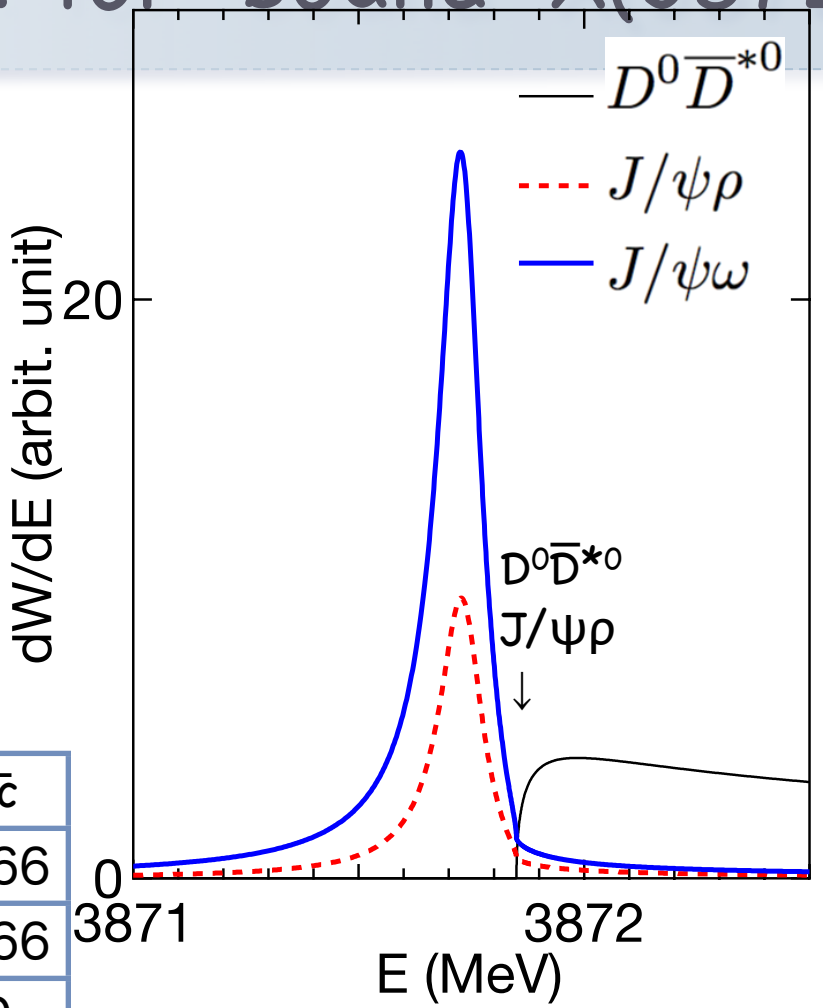


v,u,g^2	$D^0\bar{D}^{0*}$	D^+D^{-*}	J/ψρ	J/ψω	$c\bar{c}$
$D^0\bar{D}^{0*}$	-0.19	0	0.19	0.19	0.66
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0

$c\bar{c}$ → two mesons : for `bound' X(3872)

- with width for ρω.
  - $D^0\bar{D}^{0*}$ peak similar
  - J/ψω and J/ψρ peaks appear at the threshold.
  - J/ψω and J/ψρ are comparable.

v,u,g^2	$D^0\bar{D}^{0*}$	D^+D^{-*}	J/ψρ	J/ψω	$c\bar{c}$
$D^0\bar{D}^{0*}$	-0.19	0	0.19	0.19	0.66
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0



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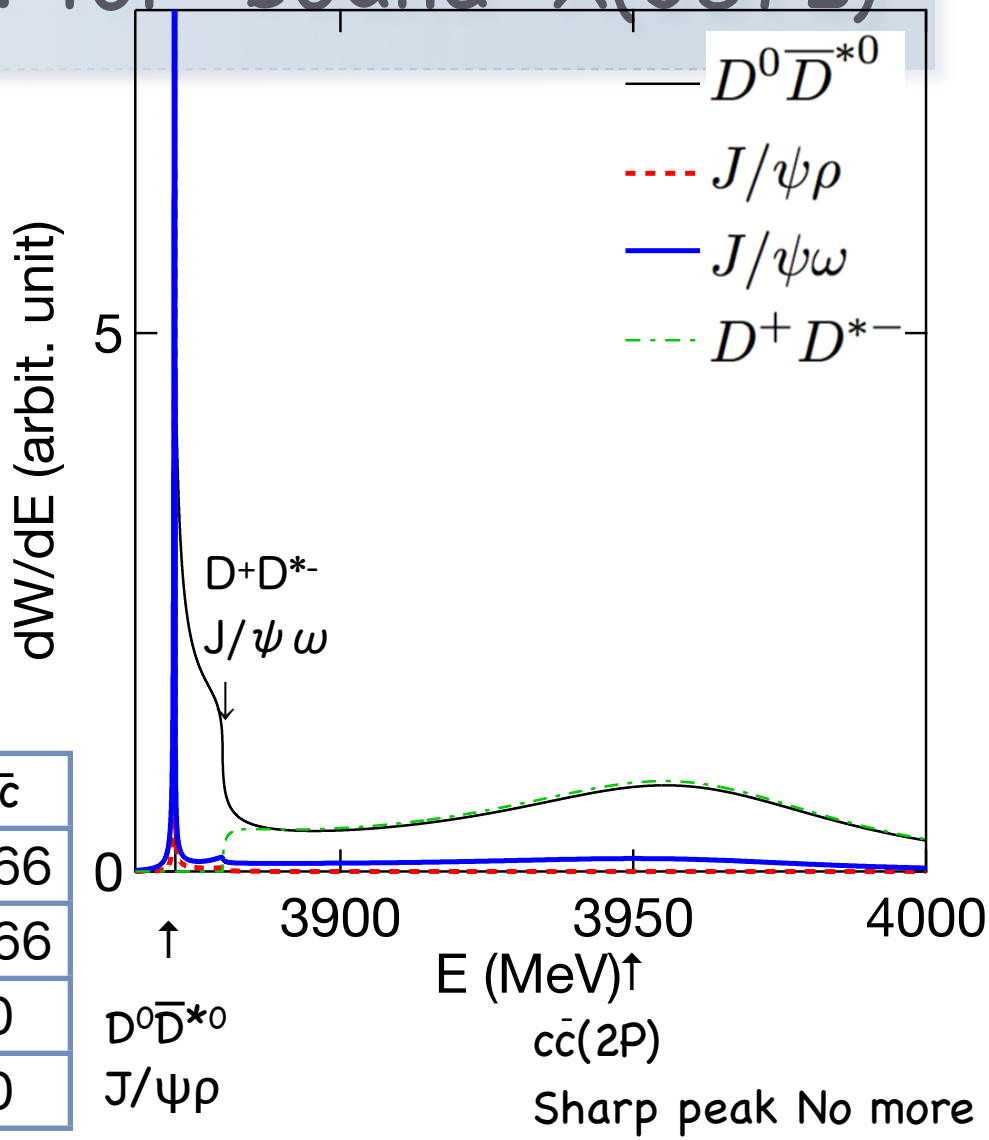
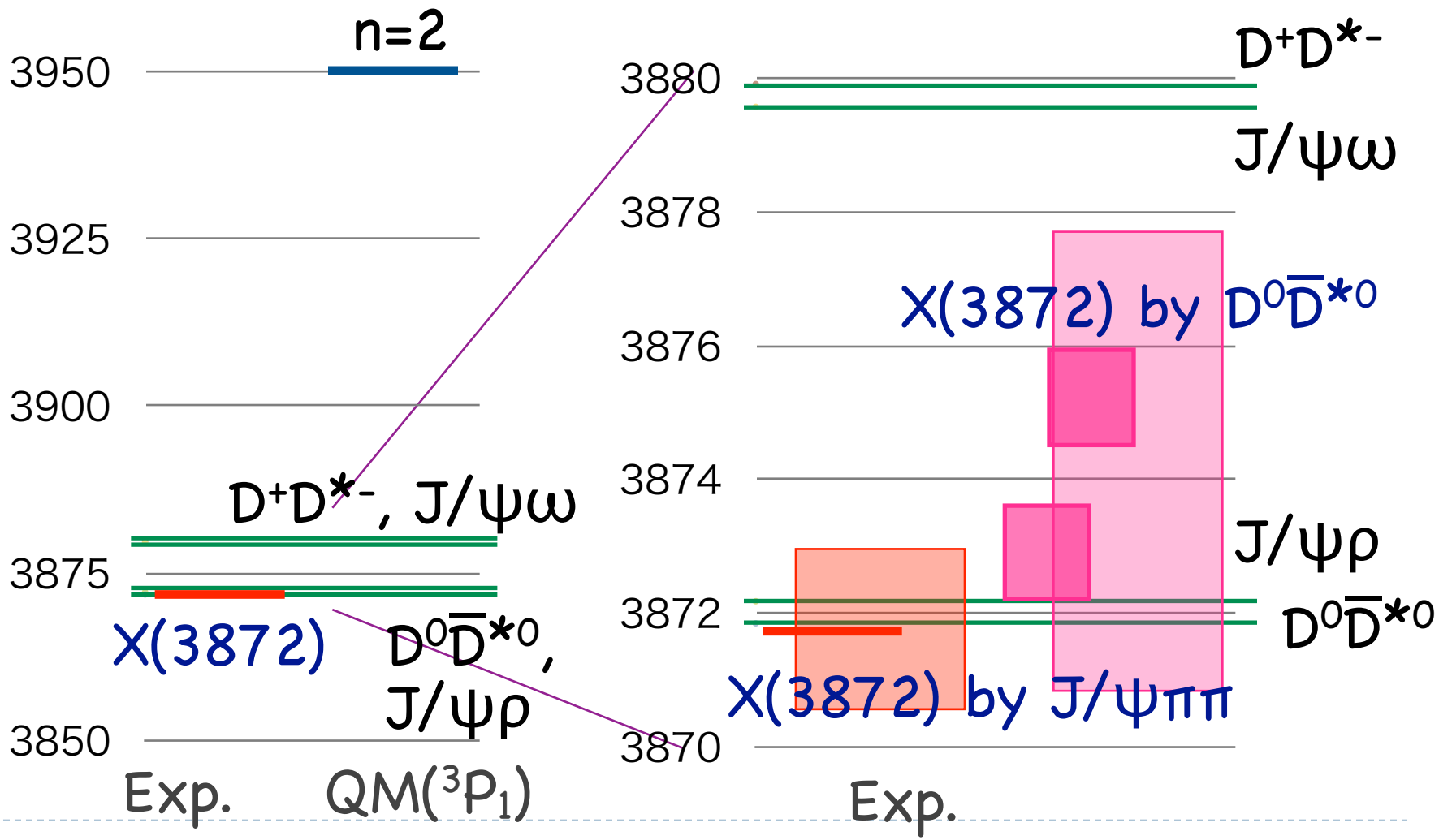
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0



2014年 8月 8日 金曜日

1^{++} Spectrum


n=2
3950
3925
3900
3875
3850
D+D*-, J/ψω
X(3872)
D0D̄*0,
J/ψρ
Exp.
QM(3P1)
3880
3878
3876
3874
3872
3870
D+D*-
J/ψω
X(3872) by D0D̄*0
J/ψρ
D0D̄*0
X(3872) by J/ψππ
Exp.

$c\bar{c}$ → two mesons : for `bound' X(3872)

- what makes the peak?

$$\frac{dW(c\bar{c}\to f)}{dE} = \frac{2}{\pi}\mu_f \int \frac{k^2 dk\ \mu_f\Gamma_f}{\left(k_f^2-k^2\right)^2+\left(\mu_f\Gamma_f\right)^2}\left|\langle f;k|(1+V_P\tilde{G}^{(P)*})V_{PQ}\tilde{G}_Q|c\bar{c}\rangle\right|^2$$

$$= \Delta_f(E)\, D_{PQ}(E)\, |\langle c\bar{c}|\tilde{G}_Q(E)|c\bar{c}\rangle|^2$$

$$\Delta_f(E) = \frac{2}{\pi}\int \frac{k^2 dk\ \mu_f\Gamma_f}{\left(k_f^2-k^2\right)^2+\left(\mu_f\Gamma_f\right)^2}\,\frac{f_\Lambda(k)^2}{f_\Lambda(k_f)^2}$$

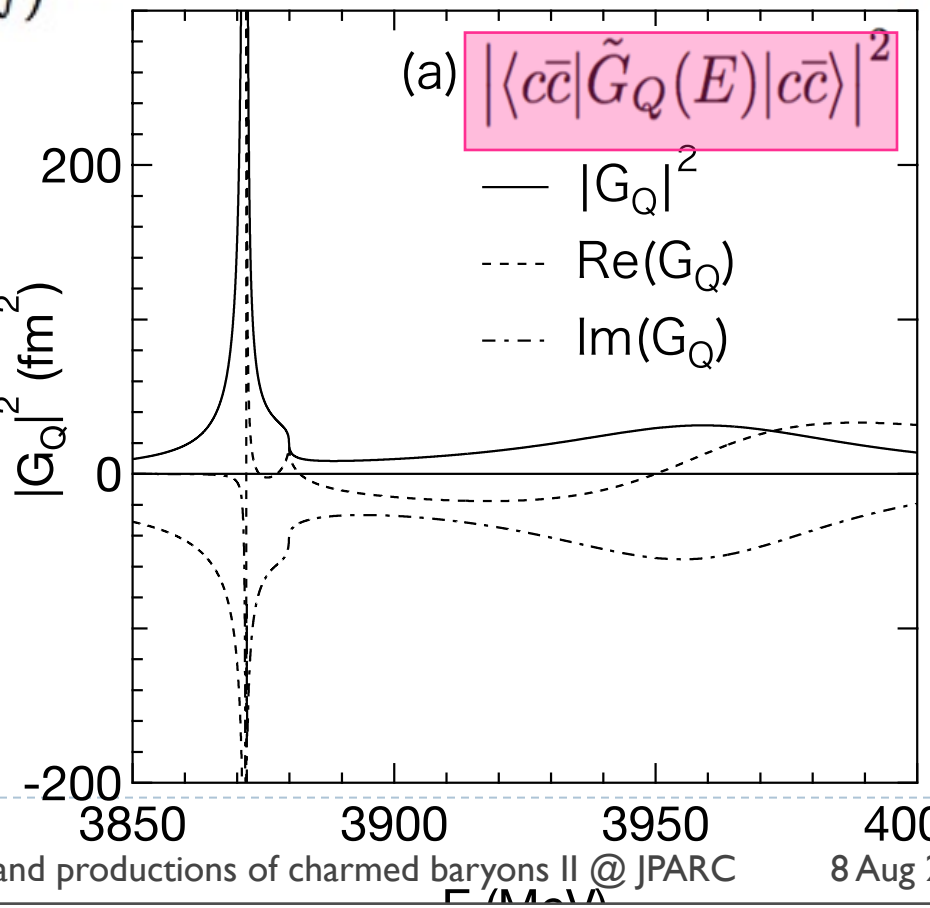
$$D_{PQ}(E) = \mu_f \left|\langle f;k_f|(1+V_P\tilde{G}^{(P)*})V_{PQ}|c\bar{c}\rangle\right|^2 = \mu_f|\langle\langle f;k_f|V_{PQ}|c\bar{c}\rangle|^2$$

$c\bar{c}$ → two mesons : for `bound' X(3872)

- what makes the peak?

$$\frac{2}{\pi}\mu_f \int \frac{k^2 \mathrm{d}k\ \mu_f \Gamma_f}{\left(k_f^2 - k^2\right)^2 + \left(\mu_f \Gamma_f\right)^2} \left| \langle f; k | (1 + V_P \tilde{G}^{(P)*}) V_{PQ} \tilde{G}_Q | c\bar{c} \rangle \right|^2$$

- G_Q makes the peak.
  - Im G_Q is the total transfer strength…
  - (The peak comes from V_{PQ} in G_Q.)

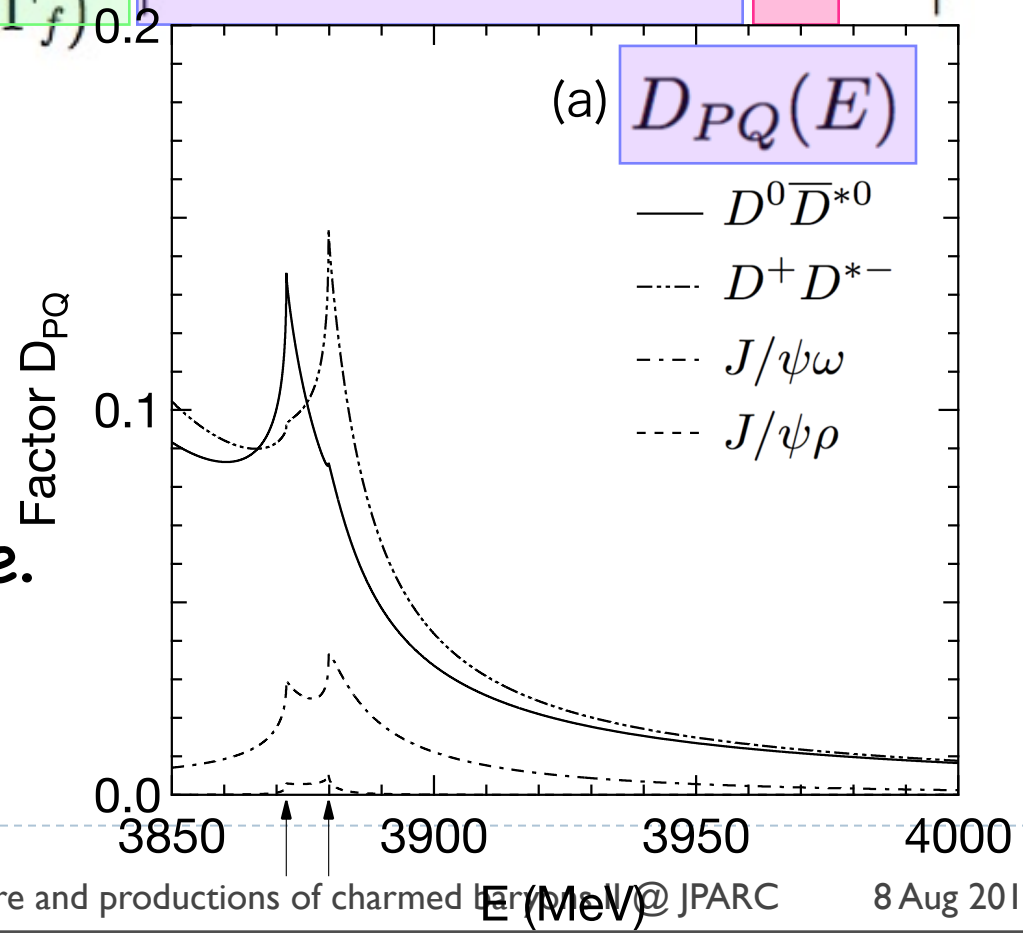


$c\bar{c}$ → two mesons : for `bound' X(3872)

- what makes the peak?

$$\frac{2}{\pi}\mu_f \int \frac{k^2 \mathrm{d}k\ \mu_f \Gamma_f}{\left(k_f^2 - k^2\right)^2 + \left(\mu_f \Gamma_f\right)^2} \left| \langle f; k | (1 + V_P \tilde{G}^{(P)*}) V_{PQ} \tilde{G}_Q | c\bar{c} \rangle \right|^2$$

- D_{PQ}
  - $D\bar{D}^*$ has a cusp at the threshold.
  - $J/\psi\omega$ is sizable.
  - reduces $J/\psi\rho$

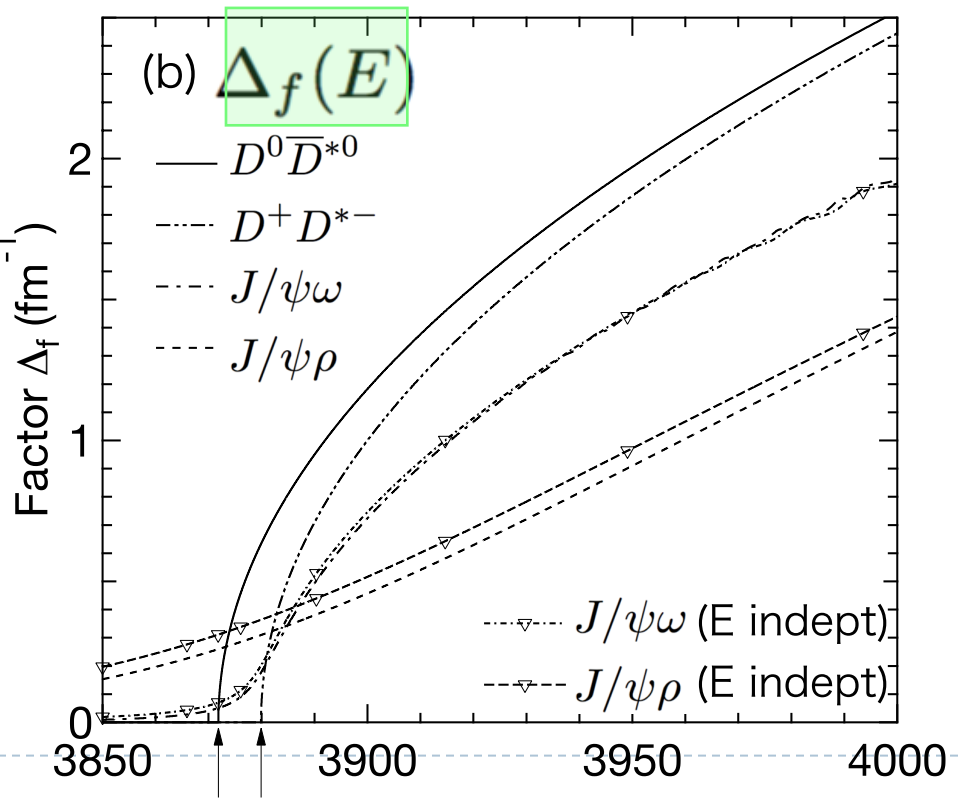


$c\bar{c}$ → two mesons : for `bound' X(3872)

- what makes the peak?

$$\frac{2}{\pi}\mu_f \int \frac{k^2 \mathrm{d}k\ \mu_f \Gamma_f}{\left(k_f^2 - k^2\right)^2 + \left(\mu_f \Gamma_f\right)^2} \left| \langle f; k | (1 + V_P \tilde{G}^{(P)*}) V_{PQ} \tilde{G}_Q | c\bar{c} \rangle \right|^2$$

- Δ_ρ
  - $\Delta_{D\bar{D}^*} = \mu k_{D\bar{D}^*}$.
  - $\Delta_{J/\psi\omega}$ and $\Delta_{J/\psi\rho}$ survive below the $D\bar{D}^*$ threshold.
  - $\Delta_{J/\psi\rho} > \Delta_{J/\psi\omega}$ (~5 times larger)



$c\bar{c}$ → two mesons : for `bound' X(3872)

- what makes the peak?

$$\frac{2}{\pi}\mu_f \int \frac{k^2 \mathrm{d}k\ \mu_f \Gamma_f}{\left(k_f^2 - k^2\right)^2 + \left(\mu_f \Gamma_f\right)^2} \left| \langle f; k | (1 + V_P \tilde{G}^{(P)*}) V_{PQ} \tilde{G}_Q | c\bar{c} \rangle \right|^2$$

- Δ_P.
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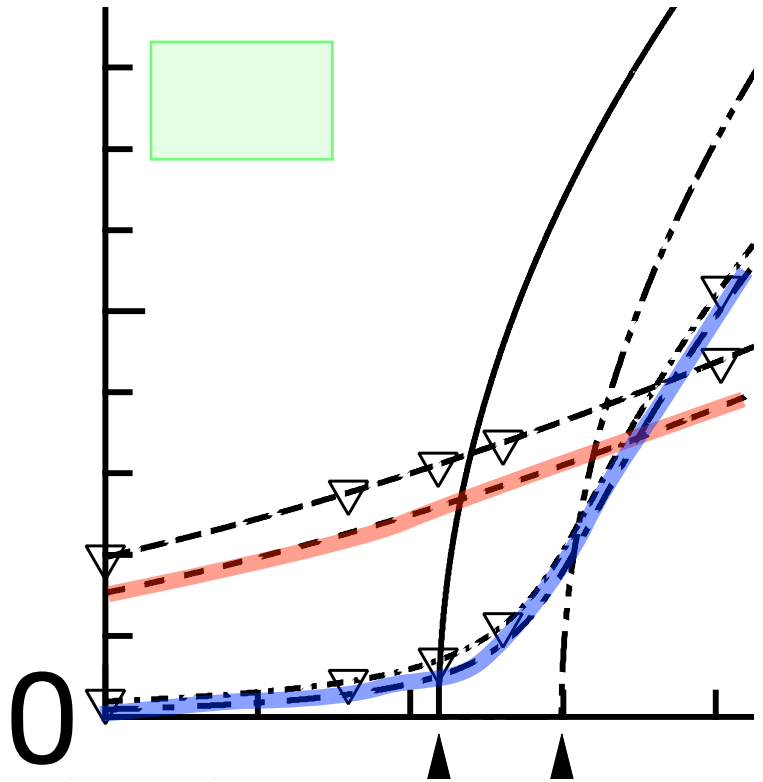

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$$\frac{2}{\pi}\mu_f \int \frac{k^2 \mathrm{d}k\ \mu_f \Gamma_f}{\left(k_f^2 - k^2\right)^2 + \left(\mu_f \Gamma_f\right)^2} \left| \langle f; k | (1 + V_P \tilde{G}^{(P)*}) V_{PQ} \tilde{G}_Q | c\bar{c} \rangle \right|^2$$

- Δ_P.
  - $\Delta_{D\bar{D}^*} = \mu k_{D\bar{D}^*}$.
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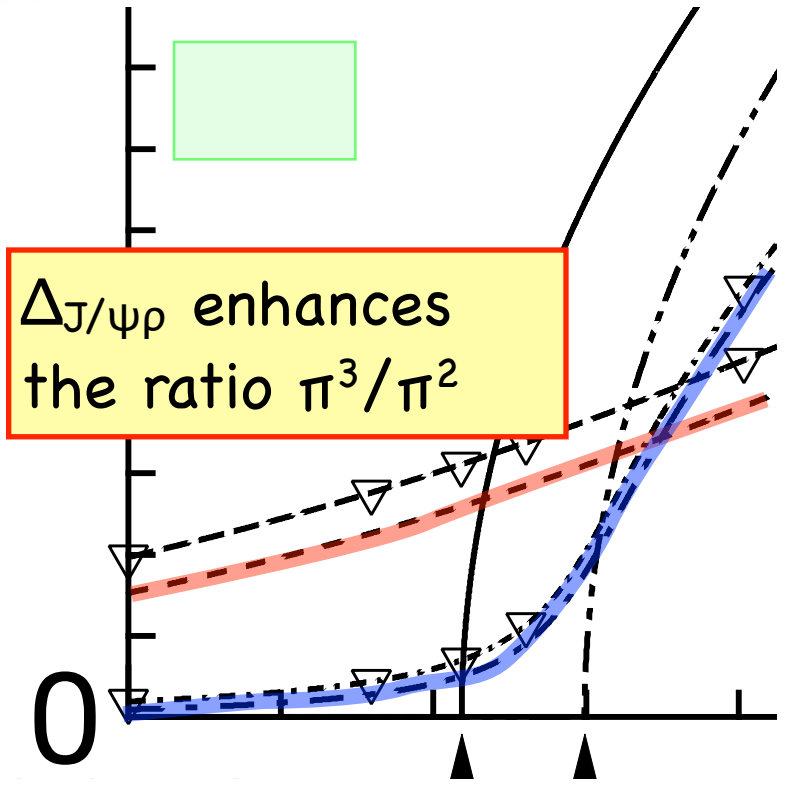
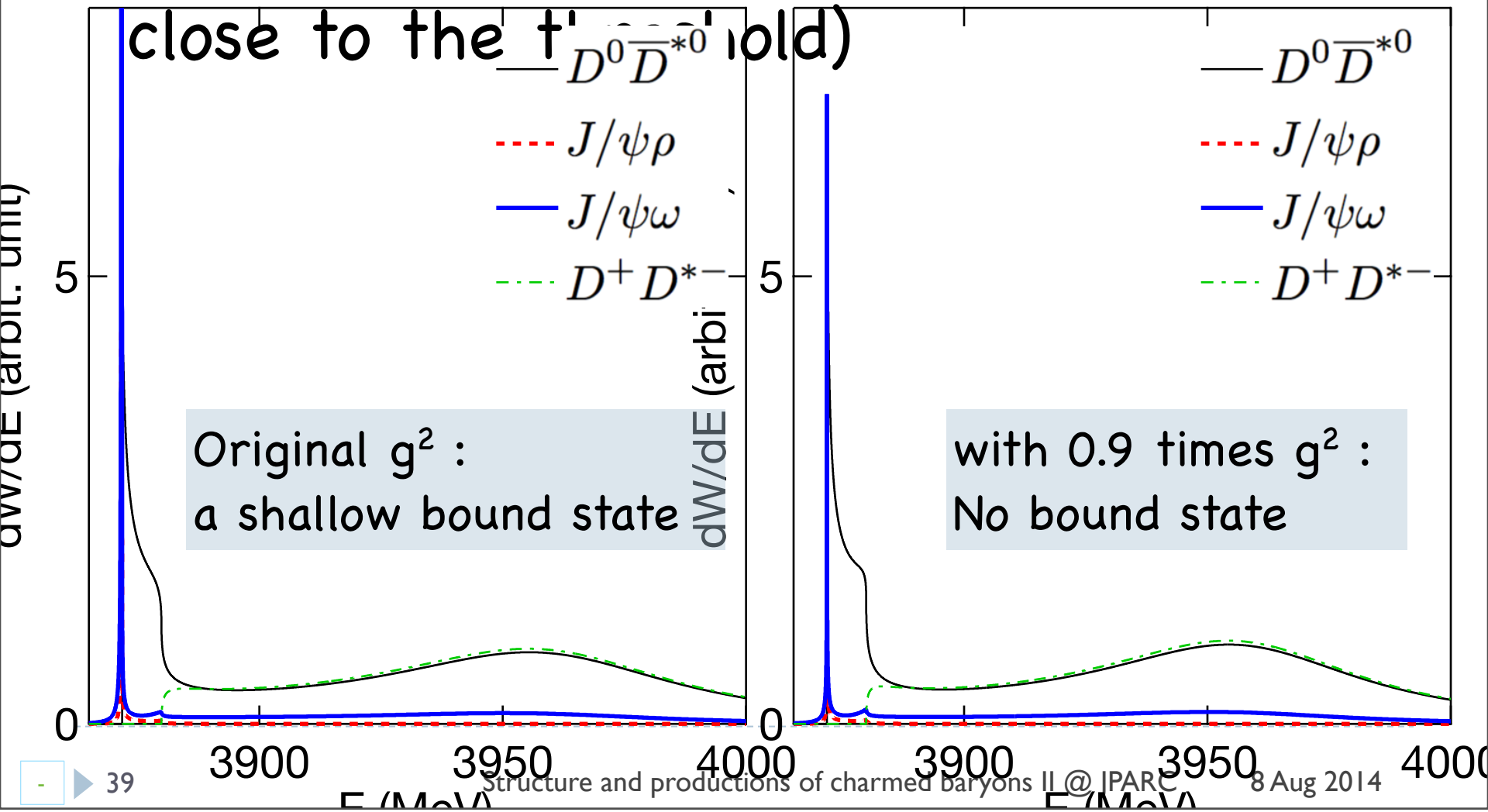


X(3872) needs to be a bound state?

- No... it can be a virtual state (if it is close to the threshold)



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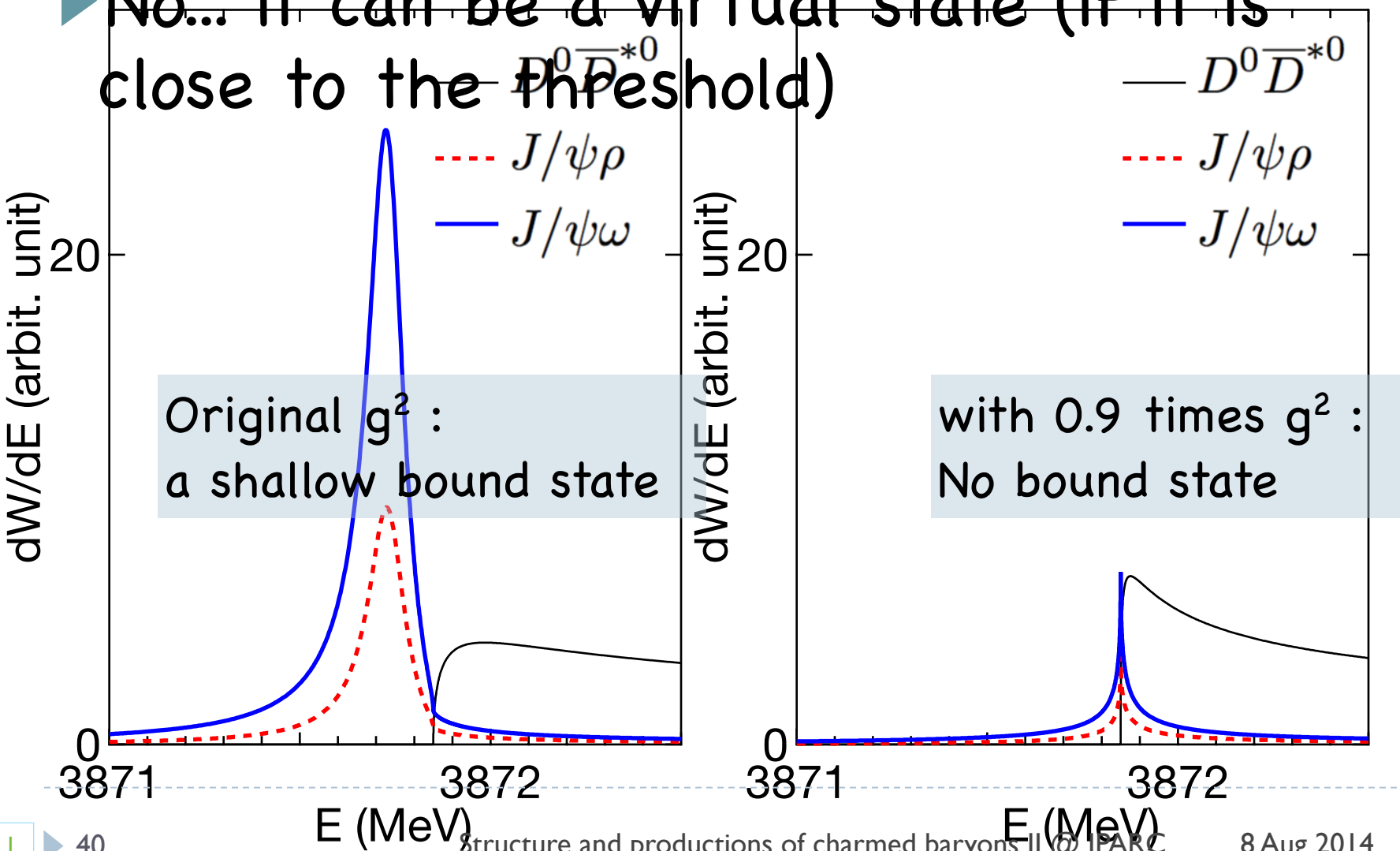

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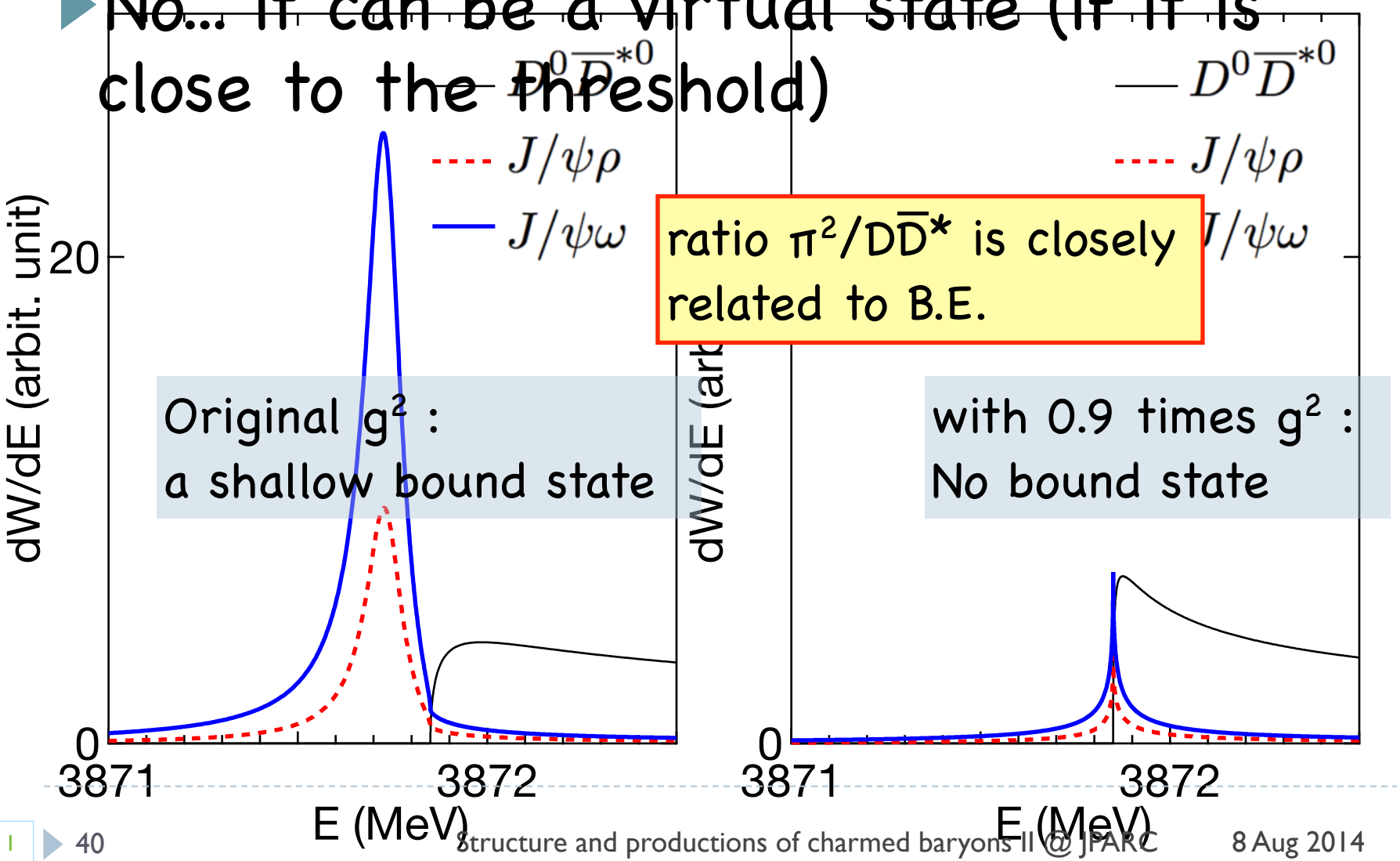
- No... it can be a virtual state (if it is close to the threshold)



Various ratios of transfer strength

- π^3 to π^2 (isospin symmetry breaking)

$$R_\Gamma = \frac{I_{J/\psi\omega}(m_X - \epsilon_X, m_X + \epsilon_X)}{I_{J/\psi\rho}(m_X - \epsilon_X, m_X + \epsilon_X)} \frac{\tilde{\Gamma}_{\omega\to 3\pi}}{\tilde{\Gamma}_{\rho\to 2\pi}}$$

- $D\bar{D}^*$ I=1 to $D\bar{D}^*$ I=0 (strength below and above D^+D^{*-} threshold)

$$D_{I=1/0} = \frac{I_{D^0\overline{D}^{*0}}(m_{D^0} + m_{\overline{D}^{*0}}, \infty) - I_{D^+D^{*-}}(m_{D^+} + m_{D^{*-}}, \infty)}{I_{D^0\overline{D}^{*0}}(m_{D^0} + m_{\overline{D}^{*0}}, \infty) + I_{D^+D^{*-}}(m_{D^+} + m_{D^{*-}}, \infty)}$$

- $D^0\bar{D}^{*0}$ to π^2 (binding energy)

$$r_{D^0\overline{D}^{*0}} = \frac{I_{D^0\overline{D}^{*0}}(m_{\mathrm{X(3872)}} - \epsilon, m_{\mathrm{X(3872)}} + \epsilon)}{I_{J/\psi\rho}(m_{\mathrm{X(3872)}} - \epsilon, m_{\mathrm{X(3872)}} + \epsilon)}$$

$$I_f(E_1, E_2) = \int_{E_1}^{E_2} \mathrm{d}E \, \frac{\mathrm{d}W(c\bar{c} \to f)}{\mathrm{d}E}$$

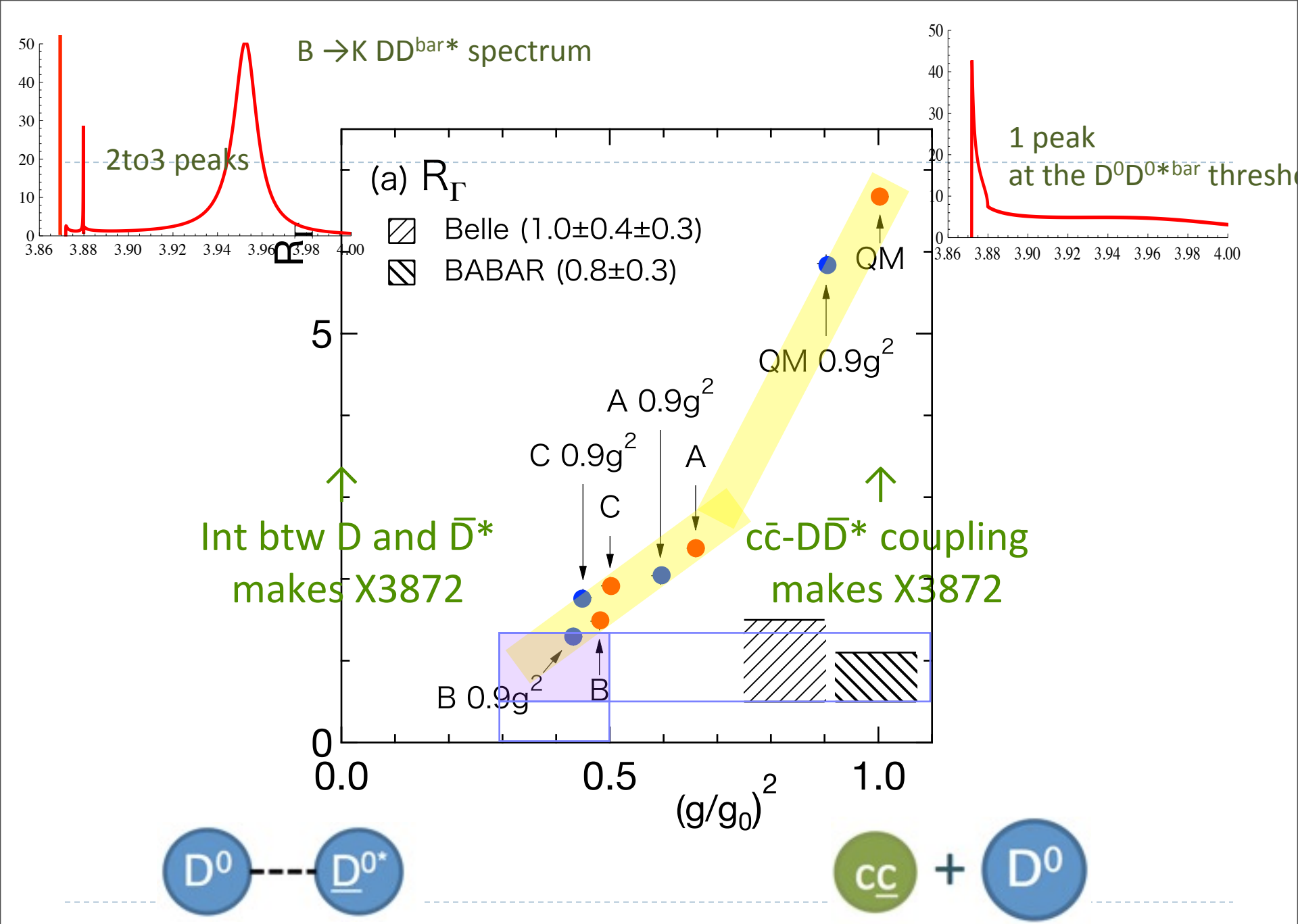
$(X \to J/\psi\pi^3)$ / $(X \to J/\psi\pi^2)$ ratio

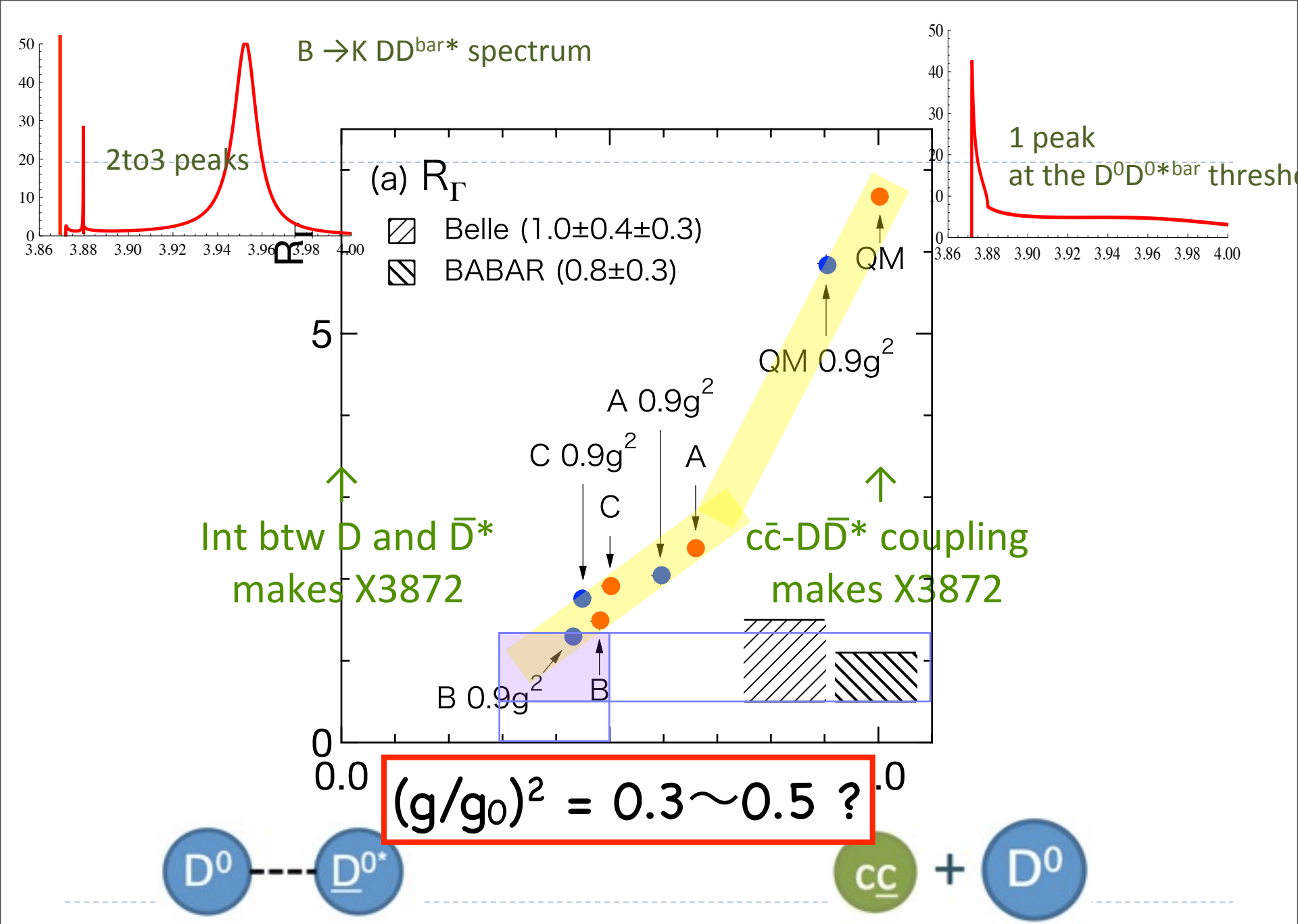
- Integrating for (M_X-1.2MeV, M_X +1.2MeV), we get
  - $(X \to J/\psi\omega)\ \Gamma_{\omega\to 3\pi}/\ (X \to J/\psi\rho)$ = 2.38

$$\frac{Br(X \to \pi^+\pi^-\pi^0 J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3 \quad \text{(Belle)}$$

$$= 0.8 \pm 0.3 \quad (BABAR).$$

- Ambiguities:
  - origin of the attraction to form X(3872), $c\bar{c}$-$D\bar{D}$ or D-$\bar{D}$ int?
    - Because origin of isospin breaking is in the $D\bar{D}^*$, the breaking is large if X is mostly $D\bar{D}^*$.


B →K DD^bar* spectrum
2to3 peaks
1 peak
at the D⁰D⁰*bar thresh
(a) R_Γ
Belle (1.0±0.4±0.3)
BABAR (0.8±0.3)
QM
QM 0.9g²
A 0.9g²
C 0.9g²
A
C
B 0.9g²
B
Int btw D and D̄* makes X3872
cc̄-DD̄* coupling makes X3872
(g/g₀)²
D⁰
D⁰*
cc̄
D⁰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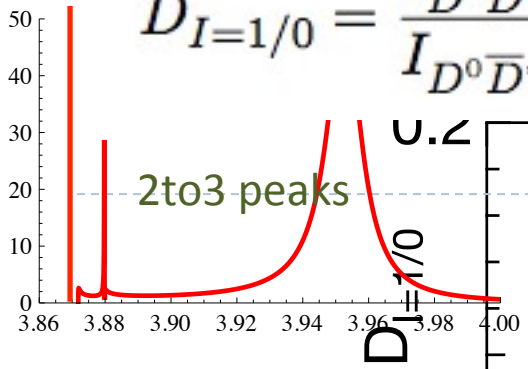
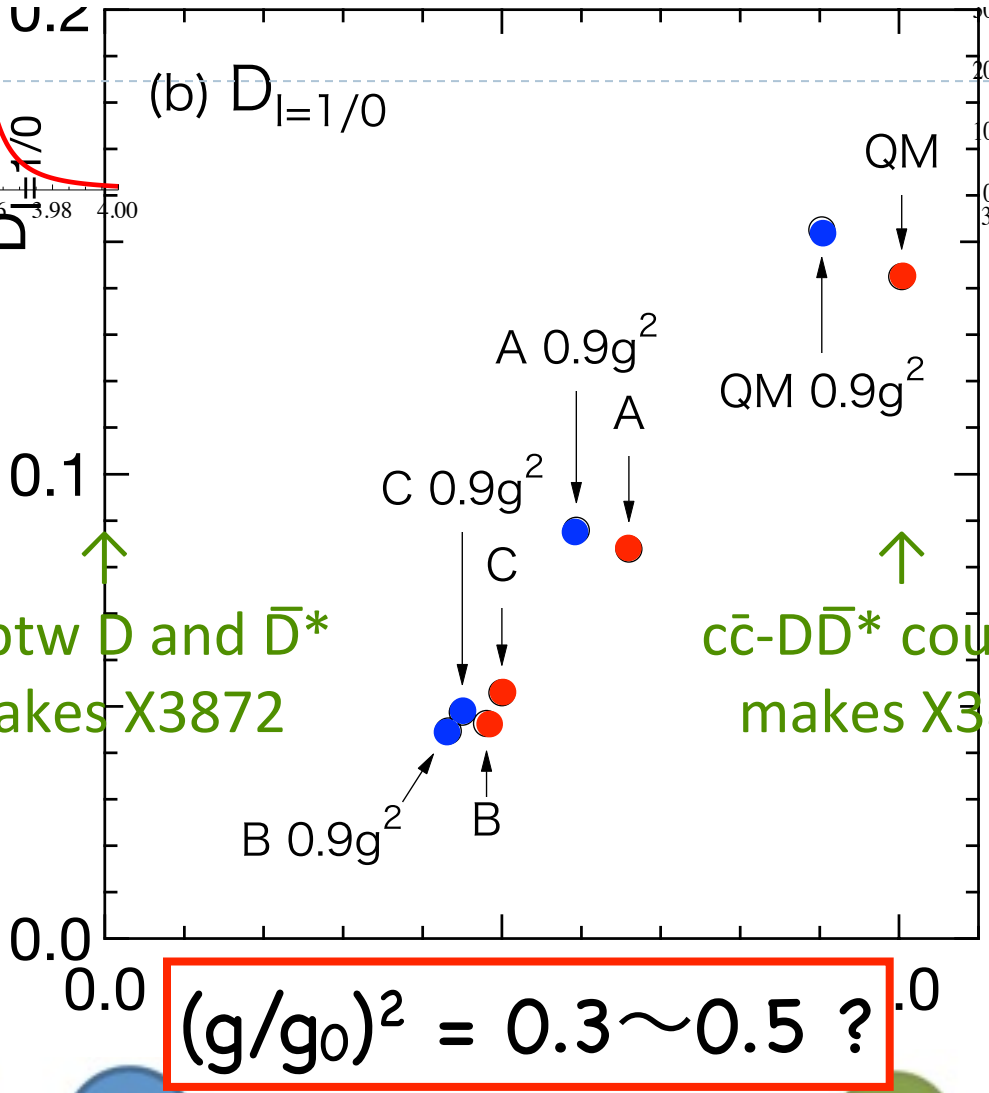
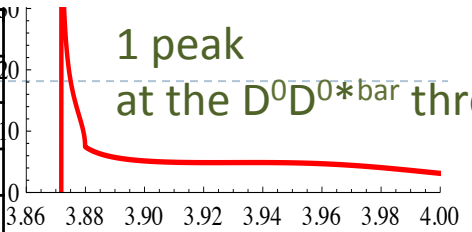
C 0.9g²
A
C
B 0.9g²
B
Int btw D and D̄* makes X3872
cc̄-DD̄* coupling makes X3872
(g/g0)² = 0.3~0.5 ?
D⁰
D⁰*
cc̄
D⁰

$$D_{I=1/0} = \frac{I_{D^0\overline{D}^{*0}}(m_{D^0}+m_{\overline{D}^{*0}},\infty) - I_{D^+D^{*-}}(m_{D^+}+m_{D^{*-}},\infty)}{I_{D^0\overline{D}^{*0}}(m_{D^0}+m_{\overline{D}^{*0}},\infty) + I_{D^+D^{*-}}(m_{D^+}+m_{D^{*-}},\infty)}$$



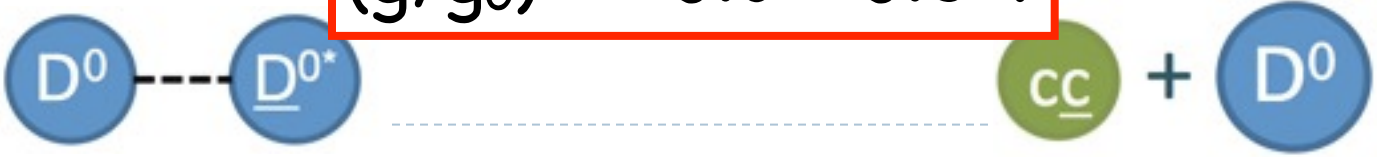




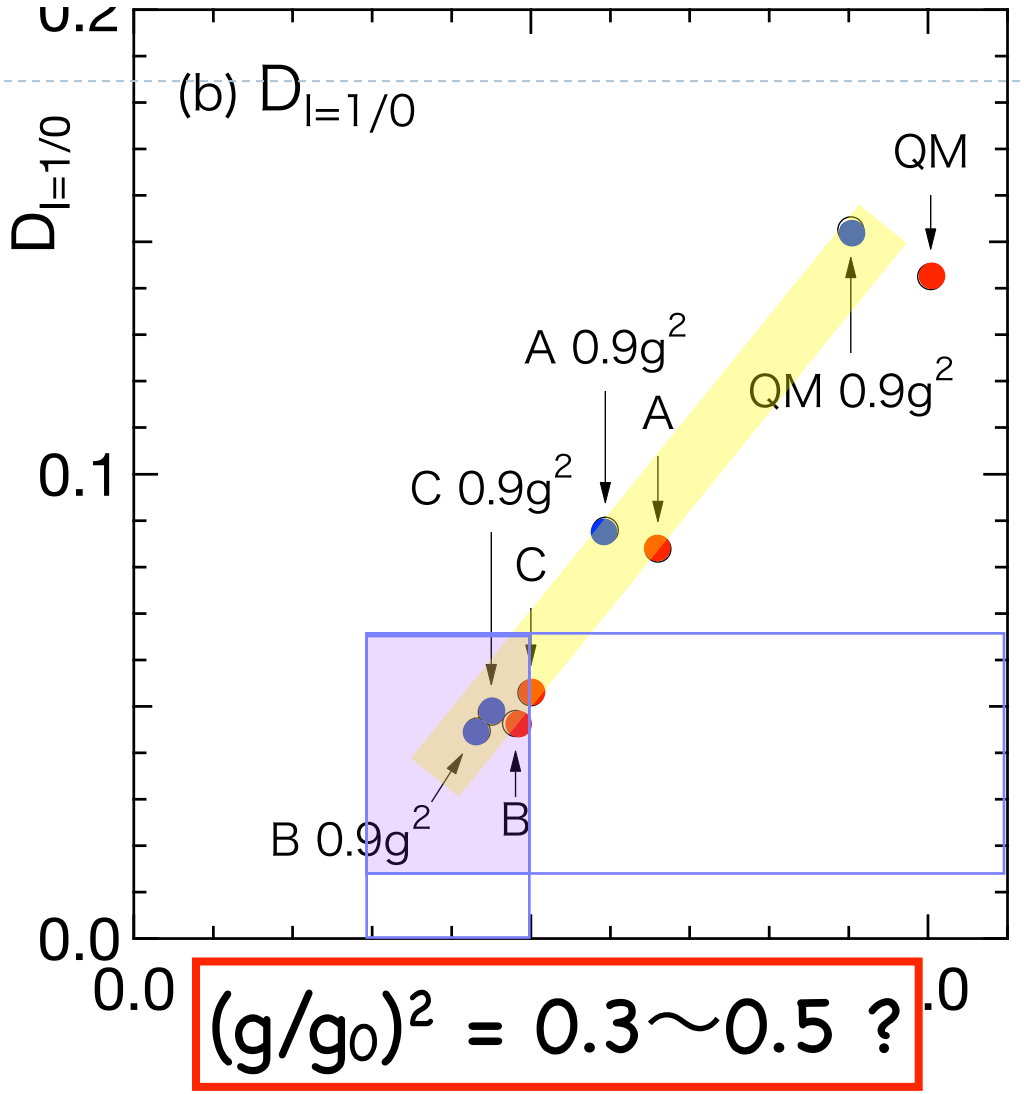
Int btw D and $\bar{D}^*$ makes X3872

$c\bar{c}$-$D\bar{D}^*$ coupling makes X3872

$(g/g_0)^2$ = 0.3～0.5 ?



$$D_{I=1/0} = \frac{I_{D^0\overline{D}^{*0}}(m_{D^0}+m_{\overline{D}^{*0}},\infty) - I_{D^+D^{*-}}(m_{D^+}+m_{D^{*-}},\infty)}{I_{D^0\overline{D}^{*0}}(m_{D^0}+m_{\overline{D}^{*0}},\infty) + I_{D^+D^{*-}}(m_{D^+}+m_{D^{*-}},\infty)}$$



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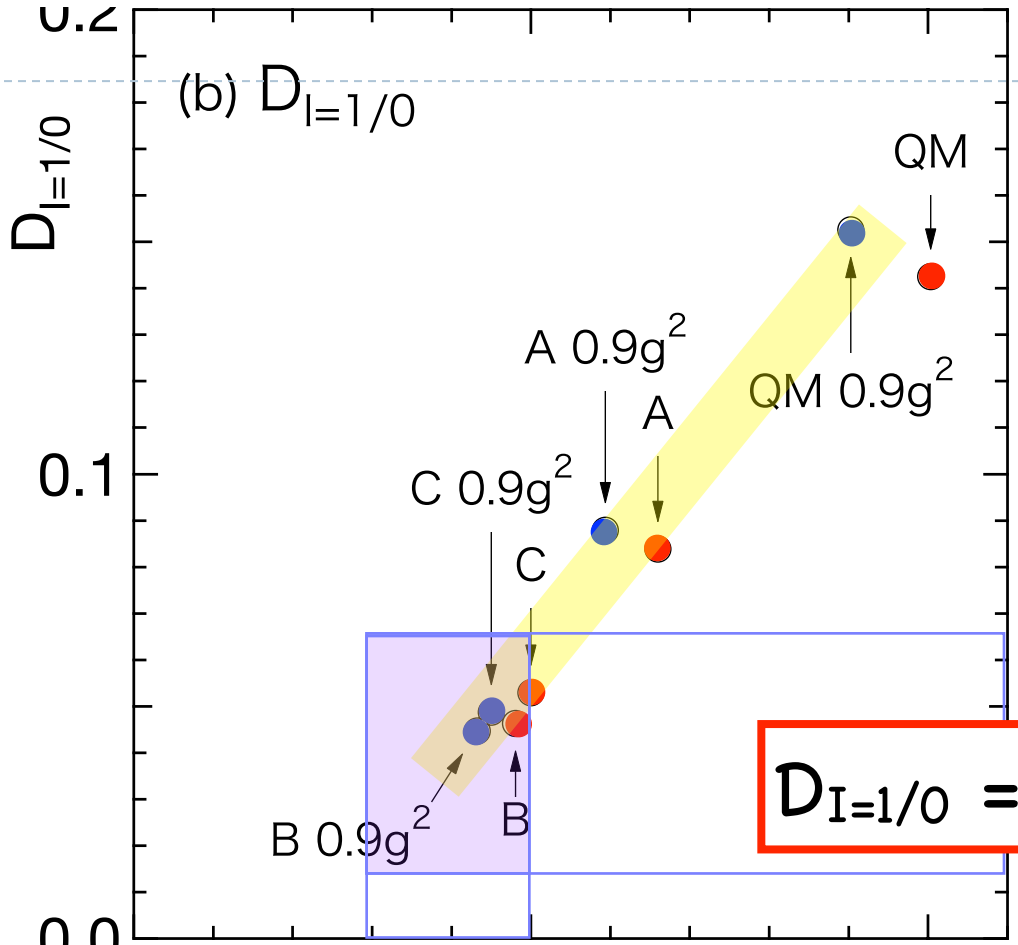

$D_{I=1/0}$ = 0.01～0.07 ?

$(g/g_0)^2$ = 0.3～0.5 ?

X(3872) is a bound or virtual state?

$$r_{D^0\overline{D}^{*0}} = \frac{I_{D^0\overline{D}^{*0}}(m_{\mathrm{X}(3872)} - \epsilon, m_{\mathrm{X}(3872)} + \epsilon)}{I_{J/\psi\rho}(m_{\mathrm{X}(3872)} - \epsilon, m_{\mathrm{X}(3872)} + \epsilon)}$$

Model	$(g/g_0)^2$	$r_{D^0\overline{D}^{*0}}(4\mathrm{MeV})$	$r_{D^0\overline{D}^{*0}}(8\mathrm{MeV})$
A	0.66	5.56	8.40
A$(0.9g^2)$	0.59	20.11	25.96
A_0	0.66	4.82	7.26
$\mathrm{A}_0(0.9g^2)$	0.59	16.88	21.84
B	0.48	4.34	6.73
B$(0.9g^2)$	0.43	10.23	13.89
C	0.50	4.77	6.69
C$(0.9g^2)$	0.45	8.11	10.42
QM	1.00	10.96	15.26
QM$(0.9g^2)$	0.90	41.49	51.17
Belle		8.92 ± 2.42	
BABAR		19.9 ± 8.05	

X(3872) is a bound or virtual state?

$$r_{D^0\overline{D}^{*0}} = \frac{I_{D^0\overline{D}^{*0}}(m_{X(3872)} - \epsilon, m_{X(3872)} + \epsilon)}{I_{J/\psi\rho}(m_{X(3872)} - \epsilon, m_{X(3872)} + \epsilon)}$$

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		16.88	21.84
		4.34	6.73
		10.23	13.89
		4.77	6.69
		8.11	10.42
		10.96	15.26
QM($0.9g^2$)	0.90	41.49	51.17
Belle		8.92 ± 2.42	
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$r_{D0\overline{D}^{*0}}$ <8
for a bound state
$r_{D0\overline{D}^{*0}}$ >8
for a virtual state ?

Radiative decay

- P : $D^0\bar{D}^{*0}$, D^+D^{-*}
- Q : $c\bar{c}(1P)$, $c\bar{c}(2P)$
- E1

$$\Gamma(X(3872)\to J/\psi(\psi')+\gamma)=\left(\frac{2}{3}\right)^4\alpha\left|\langle\psi_f|r|\psi_i\rangle\right|^2 E_\gamma^3\frac{E_f^{c\bar{c}}}{M_i^{c\bar{c}}}$$

$$\left|\langle J/\psi|r|\chi_{c1}(1P)\rangle\right|^2=4.13\times10^{-6}$$

$$\left|\langle J/\psi|r|\chi_{c1}(2P)\rangle\right|^2=1.49\times10^{-7}$$

$$\left|\langle\psi'|r|\chi_{c1}(1P)\rangle\right|^2=7.85\times10^{-6}$$

$$\left|\langle\psi'|r|\chi_{c1}(2P)\rangle\right|^2=1.08\times10^{-5}$$

T.Barnes, S.Godfrey, E.S.Swanson, PRD72, 054026 (2005)

E1 radiative decay from a bound X(3872)

small. but it changes the ratio.

$$|X(3872)\rangle = \boxed{0.071\,|c\bar{c}(1P)\rangle} - 0.326\,|c\bar{c}(2P)\rangle$$

Phase is not known!!

$$+0.907\,|D^0\overline{D^{*0}}\rangle + 0.255\,|D^+D^{*-}\rangle$$

$$\Gamma(X(3872)\to J/\psi+\gamma) = 29.2\ keV$$

$$\Gamma(X(3872)\to \psi'+\gamma) = 13.4\ keV$$

$$R_\gamma = \frac{\Gamma(X(3872)\to \psi'+\gamma)}{\Gamma(X(3872)\to J/\psi+\gamma)} = 0.458$$

cf. No $c\bar{c}$(1P)

$$R = \frac{\Gamma(X(3872)\to \psi'+\gamma)}{\Gamma(X(3872)\to J/\psi+\gamma)} = 1.50$$

M.Takizawa et al., FewBodySyst55, 779 (2014)

Summary

- $c\bar{c} \rightarrow J/\psi\omega$, $J/\psi\rho$ spectrum is calculated by
  - $c\bar{c}$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ - $J/\psi\rho$
- X(3872) is a two-meson molecule with a $c\bar{c}$ core.
- There is a mechanism to have such narrow peaks of $J/\psi\rho,\omega$ that appears on the threshold.
  - This occurs as far as large strength of DD exists just above threshold. Not so accidental.

Summary

- A large Isospin breaking can be realized.
  - a small breaking is enhanced by the large width of ρ meson, sensitive to $(g/g_0)^2$
- three other ratio, which show
  - $D_{I=0/1}$, probe of $(g/g_0)^2$
  - $r_{D0\bar{D}^*0}$, probe of the binding energy of X.
  - R_γ, probe of $c\bar{c}(1P)/c\bar{c}(2P)$

Summary

- This $c\bar{c}$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ - $J/\psi\rho$ picture can give many of the X(3872) properties.
  - X(3872) mass & width (diff in π^2 and $D\bar{D}^*$ spectra)
  - No $c\bar{c}(2P)$ peak
  - Size of Isospin symmetry breaking
  - connect various ratio to feature of the charm systems

Thank you !