Charmed hadron molecules
--what we have learnt from the study of the X(3872) properties--

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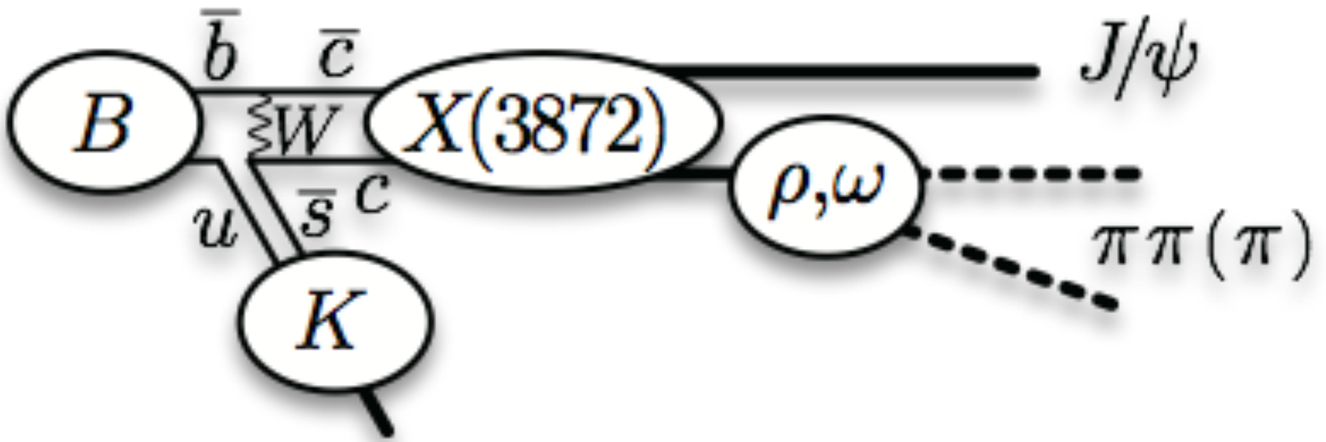
Outline

- X(3872): experimental results
- Charmonium-molecule hybrid model of X(3872)
- Summary of X(3872)
- Consideration about other hadronic molecules: $Z_b^+(10610)$, $Z_b^+(10650)$, $Z_c^+(3900)$
- At J-PARC

X(3872)

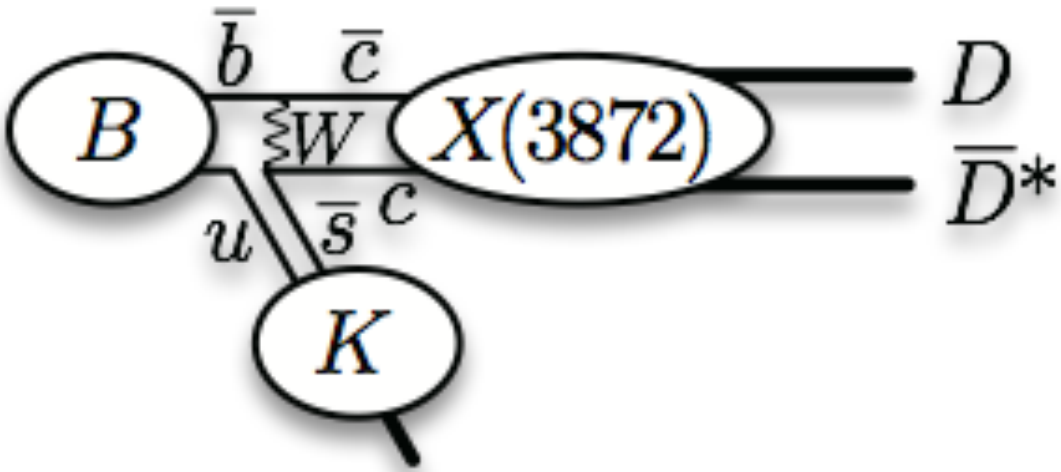
- First observed by B decay



X(3872) should be Charmonium-like state.

$J/\psi\ \pi^n$ Exp:
S.K.Choi et al. [Belle] PRL91, 262001 (2003)
B.Aubert et al. [BaBar] PRD71, 071103 (2005)

X(3872)



X(3872) decays to DD^{*bar}

$$Br(X \rightarrow D^0\bar{D}^{*0})/Br(X \rightarrow J/\psi\pi^2)$$

$$= 8.92 \pm 2.42,\ 19.9 \pm 8.05$$ (calc from papers)

Belle BABAR

$D^0\bar{D}^{*0}$ 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
  - pp^{bar} collision
    - $Br(pp^{bar} \rightarrow X)/Br(pp^{bar} \rightarrow \psi(2S)) > 0.046$
  - pp collision
    - $J^{PC}=1^{++}$

p̄p 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)

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)

X(3872) facts

4 two-meson thresholds are nearby.

- $J^{PC}=1^{++}$
- X(3872) ($uc\bar{u}\bar{c}$, $dc\bar{d}\bar{c}$) thresholds
  - $D^{\pm}D^{*\mp}$ 3879.87±0.12 MeV
  - $J/\psi\omega$ 3879.57±0.12 MeV
  - $J/\psi\rho$ 3872.18±0.25 MeV
  - $D^0\bar{D}^{*0}$ 3871.80±0.12 MeV (Lowest threshold)

Mass and Decay to $J/\psi\ \pi^n$

Binding energy is 0.11 MeV.

- X(3872) decays into
  - ▷ $J/\psi\ \pi\pi$ isovector
    - mass 3871.69±0.17 MeV
      width < 1.2 MeV

very narrow width

  - ▷ $J/\psi\ \pi^3$ isoscalar
    - $Br(X \to J/\psi\pi^3)/Br(X \to J/\psi\pi^2) =$
      1.0±0.4±0.3, 0.8±0.3
      Belle BABAR

A large isospin symmetry breaking

Decay to $D^0\bar{D}^{*0}$

- X(3872) decays into $D^0\bar{D}^{*0}$
  - ▷mass $3872.9\ ^{+0.6+0.4}_{-0.4-0.5}$ MeV Belle
    $3875.1\ ^{+0.7}_{-0.5}\pm0.5$ MeV BABAR

mass from $D^0\bar{D}^{*0}$ > mass from $J/\psi\pi\pi$

  - ▷width $3.9\ ^{+2.8+0.2}_{-1.4-1.1}$ MeV Belle
    $3.0\ ^{+1.9}_{-1.4}\pm0.9$ MeV BABAR

width from $D^0\bar{D}^{*0}$ > width from $J/\psi\pi\pi$

X(3872)

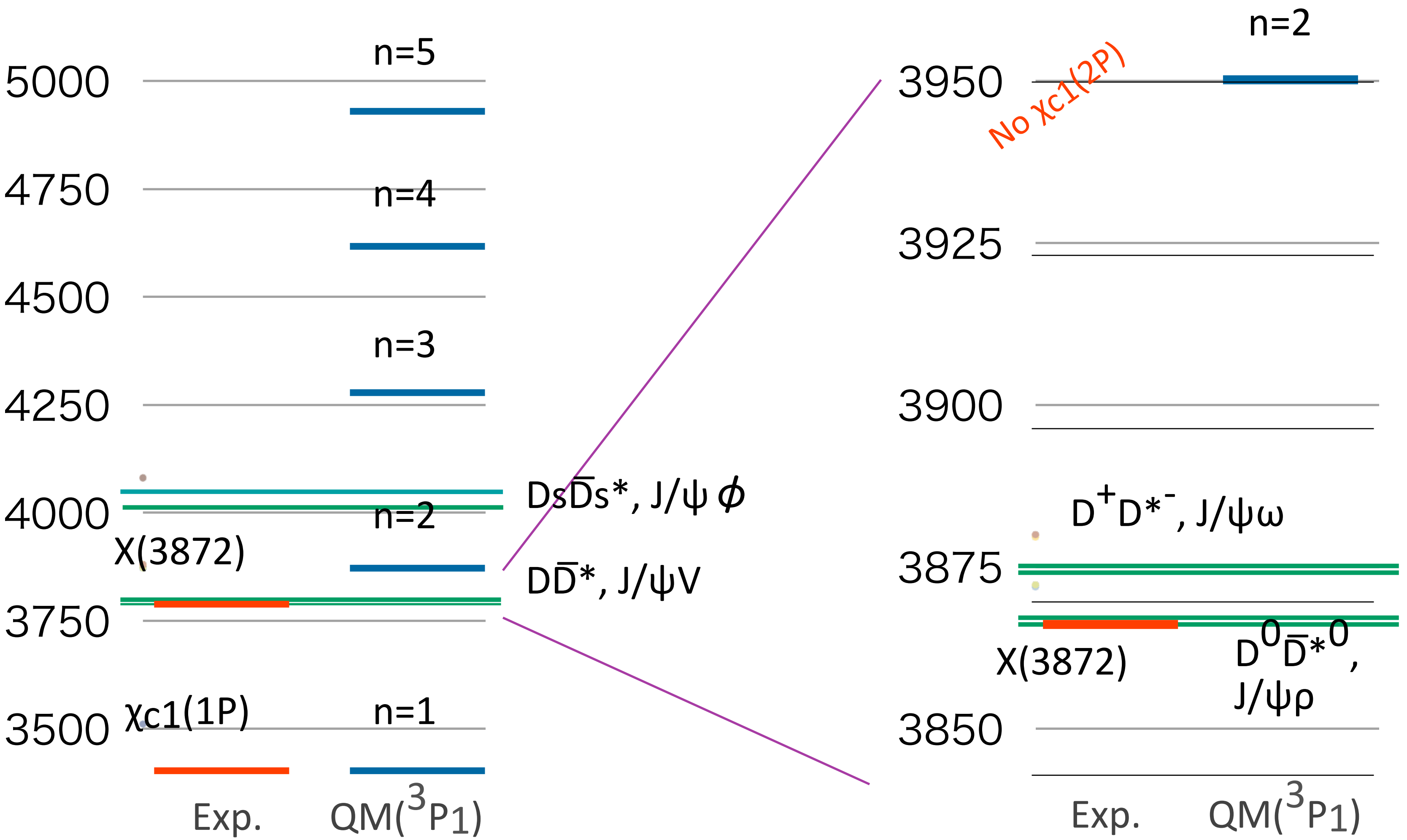
- Charmonium: 1^{++} corresponds $^3P_1$ state

$\chi_{c1}(1P)$ Mass: 3510.66 ± 0.07 MeV

$\chi_{c1}(2P)$ Mass: Quark model prediction
NR: 3925 MeV
GI: 3953 MeV

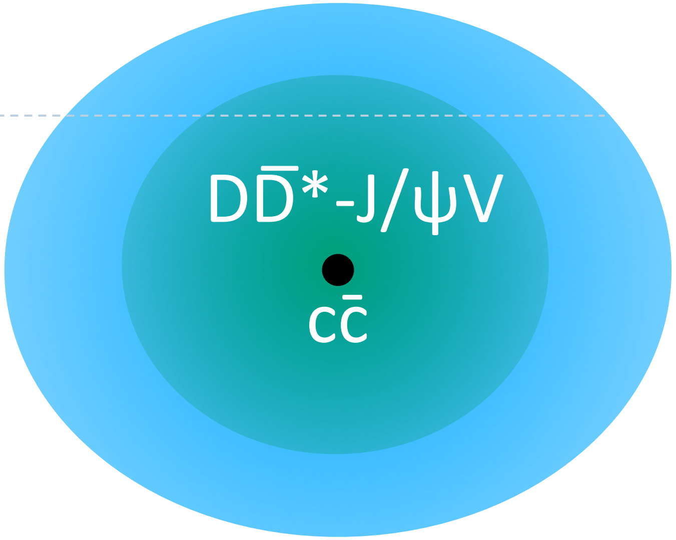
Not observed

1^{++} Spectrum

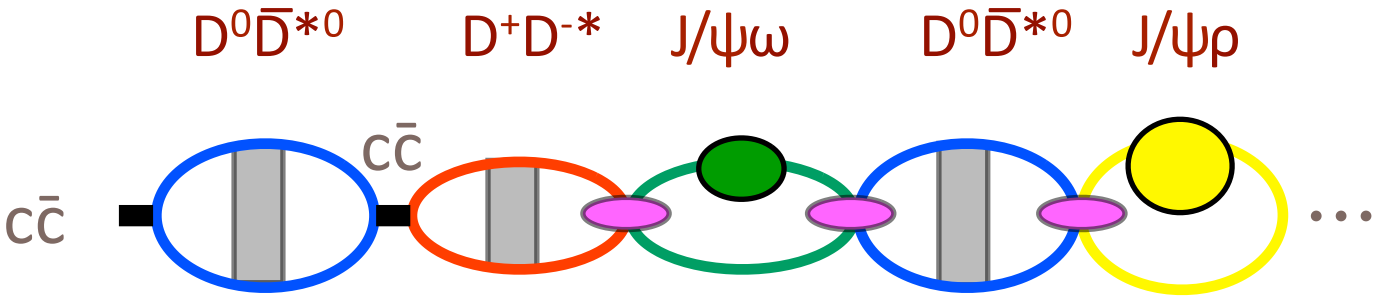


5000
4750
4500
4250
4000
3750
3500
n=5
n=4
n=3
n=2
n=1
X(3872)
χc1(1P)
DsD̄s*, J/ψ ϕ
DD̄*, J/ψV
Exp.
QM(3P1)
3950
3925
3900
3875
3850
n=2
No χc1(2P)
D+D*-, J/ψω
X(3872)
D0D̄*0,
J/ψρ
Exp.
QM(3P1)

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/ψ ω and J/ψ ρ couple to $c\bar{c}$ only via $D\bar{D}^*$ channels (OZI).



M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 093D01
S.Takeuchi, K.Shimizu, and M.Takizawa, Prog. Theor. Exp. Phys. 2014, 123D01

Model Hamiltonian

- $H = H_0 + V$

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

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

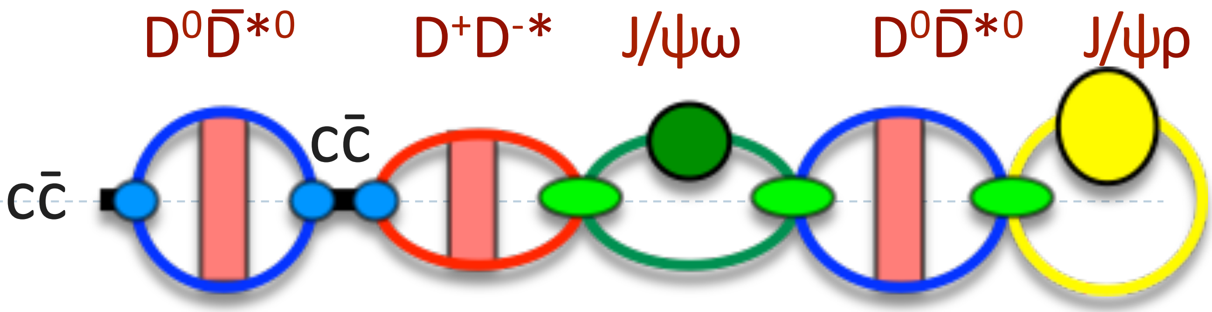
P : $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\,\omega$ – $J/\psi\,\rho$, Q : $c\bar{c}$

V_{PP} : potential between the two mesons

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

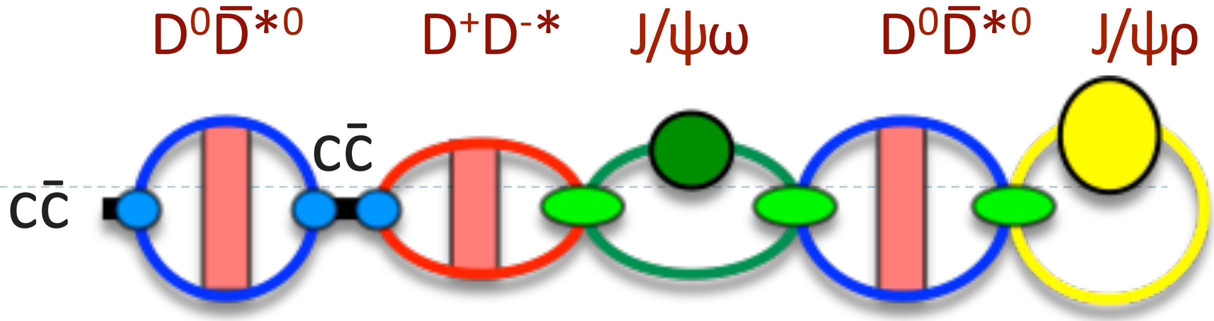
$E_0^{(Q)}$: QM predicted $\chi_{c1}(2P)$ mass = 3950 MeV

Potentials



- Interaction strengths are determined by
  - ▷$D\bar{D}^*$- $J/\psi\omega$ coupling u : ← the quark model
    - $q\bar{q}$ interaction to obtain this transfer strength. (Godfrey-Isgur)
    - RGM for QM → $V_{PP} = N^{-1/2}\, H\, N^{-1/2} - H_0$

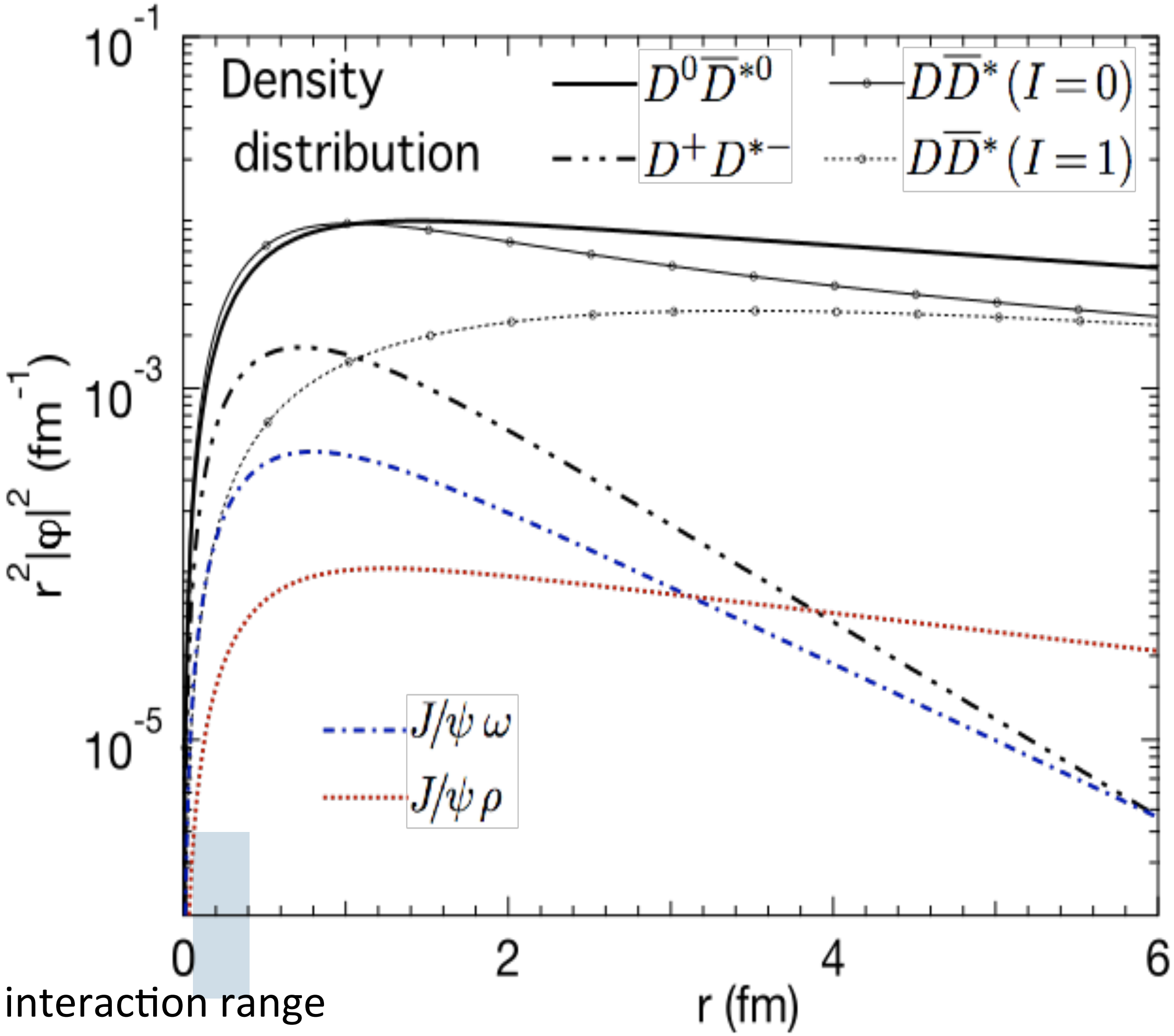
Potentials



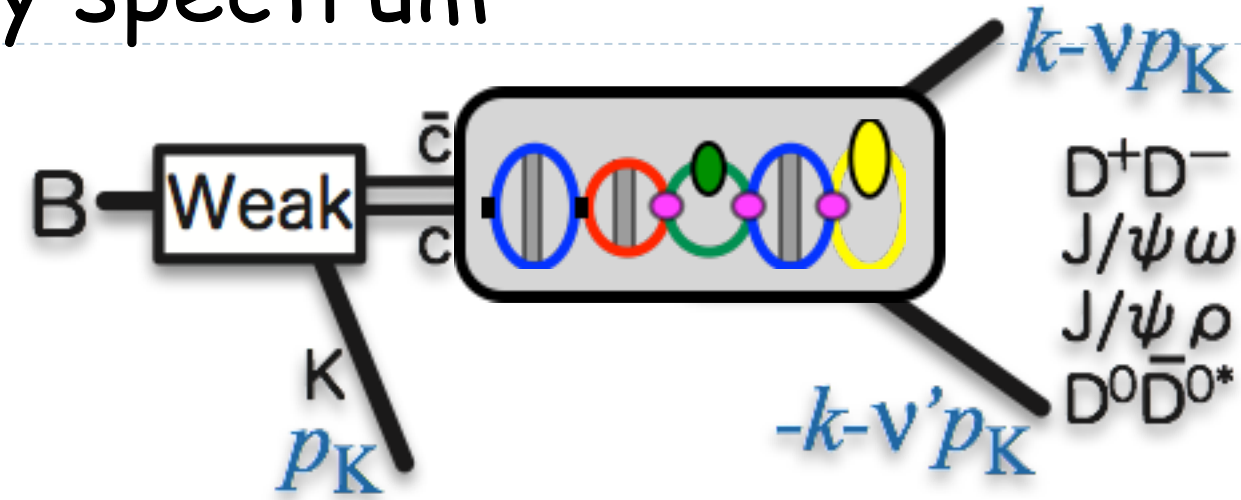
- Interaction strengths are determined by
  - ▷D-$\bar{D}$* interaction v :
    - Param set A: maximum attraction which does not make a bound state in B$\bar{B}$* systems.
    - Param set QM: use a quark model value
  - ▷D$\bar{D}$*- c$\bar{c}$ coupling g :
    - a free parameter to give the X(3872) peak energy.

X(3872) : a bound state

- Density distri. of two mesons
  - ▷ $r^2|\phi_{MM}(r)|^2$
- Probability
  - ▷ 0.036 $c\bar{c}$
  - ▷ 0.913 $D^0\bar{D}^{*0}$
  - ▷ 0.034 D^+D^{-*}
  - ▷ 0.010 $J/\psi\omega$
  - ▷ 0.006 $J/\psi\rho$



B Decay spectrum



- Decay rate ∝ cc̄ self energy

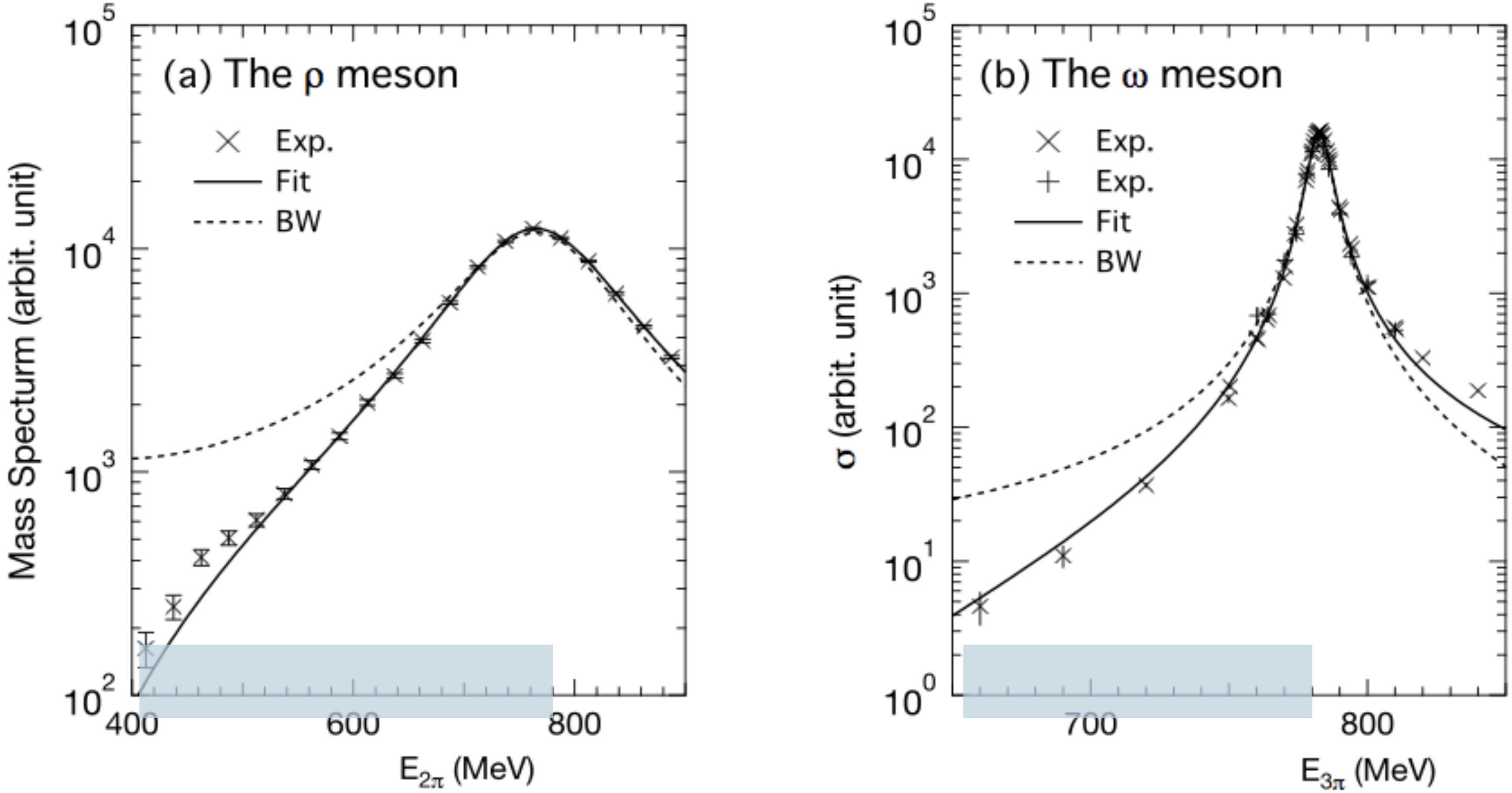
$$\frac{\mathrm{d}W}{\mathrm{d}E} = -\frac{1}{\pi} Im \langle c\bar{c}|G_Q(E)|c\bar{c}\rangle \qquad \int_{E_{threshold}}^{\infty} \frac{\mathrm{d}W}{\mathrm{d}E}\,\mathrm{d}E = 1$$

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

$$\tilde{G} = \frac{1}{E - H + i\Gamma(E)/2}$$ ← observed $\rho\to\pi\pi$ or $\omega\to\pi\pi\pi$ width

Vector meson widths

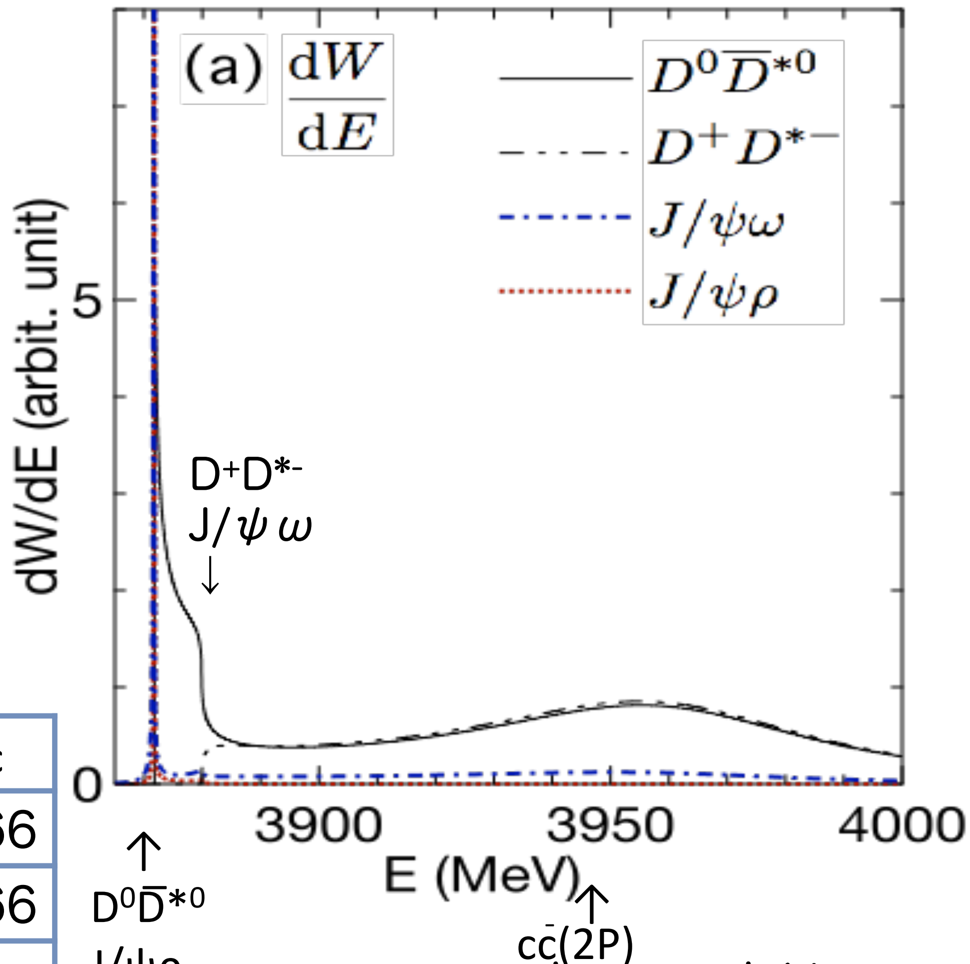
- Energy dependent width for ρ and ω



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

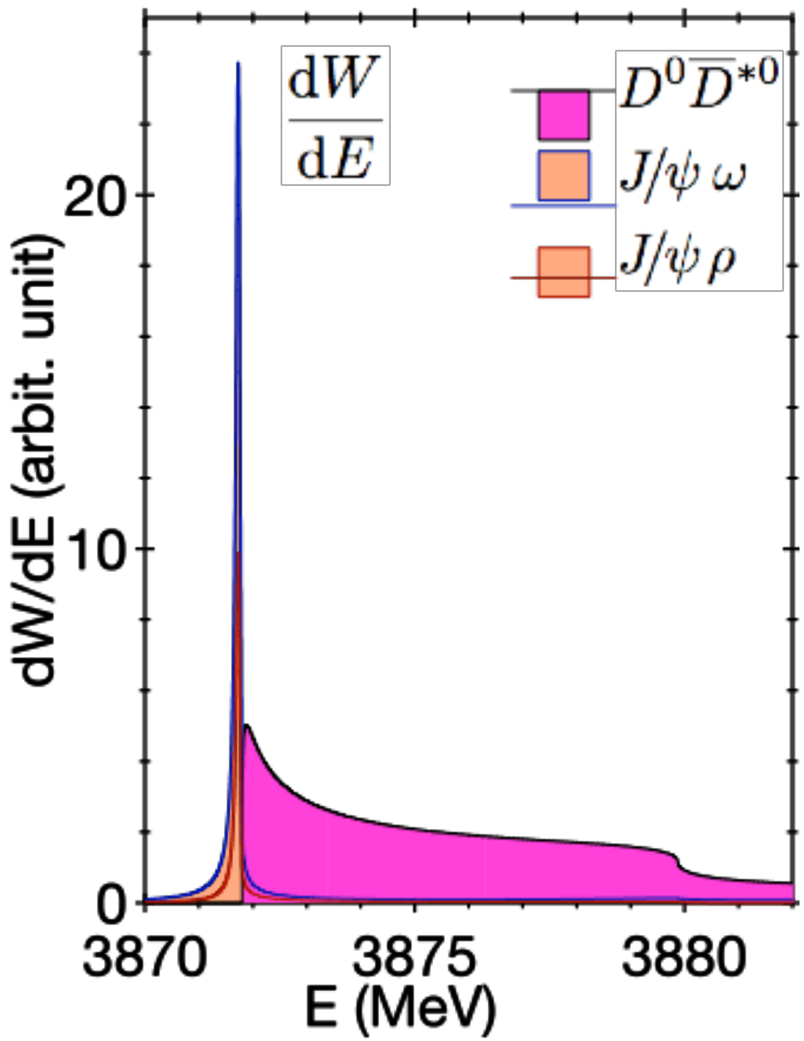
- $D^0\bar{D}^{0*}$ peak appears at the threshold.
- J/ψω and J/ψρ peaks appear at the threshold.
- J/ψω and J/ψρ are comparable.

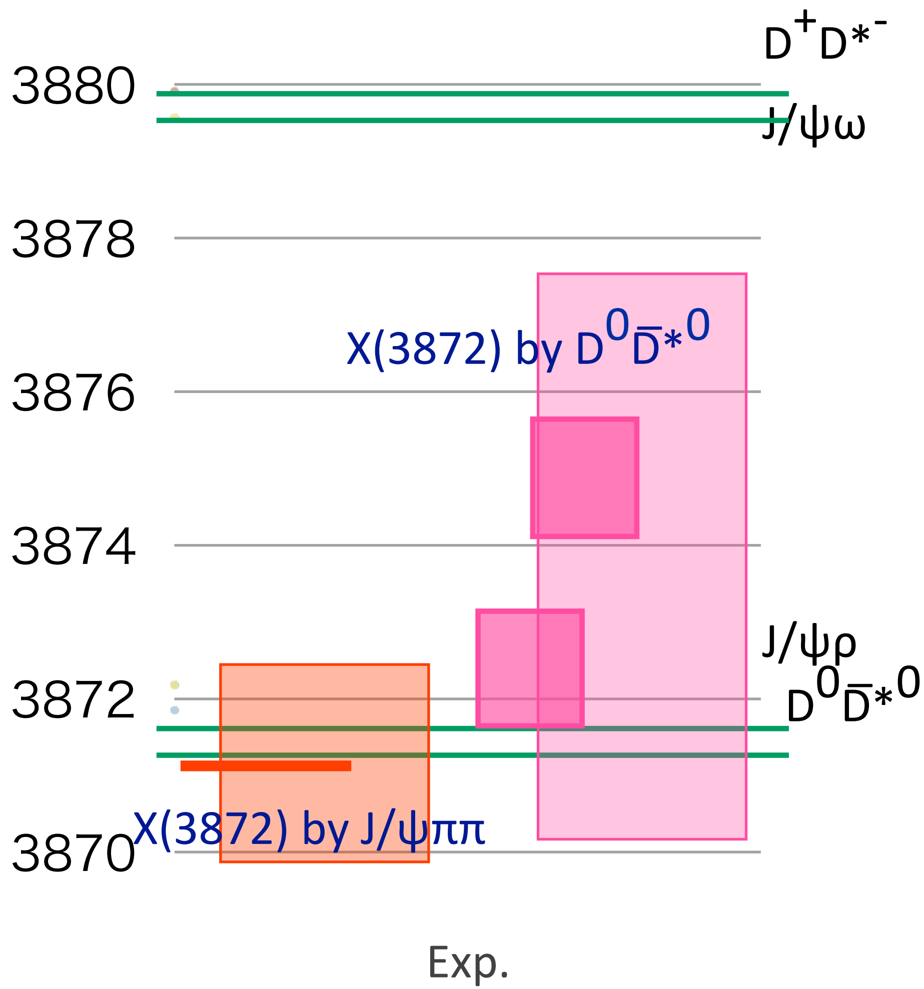
v,u,g²	$D^0\bar{D}^{0*}$	D^+D^{-*}	J/ψρ	J/ψω	$c\bar{c}$
$D^0\bar{D}^{0*}$	-0.19	0	0.19	0.19	0.66
D^+D^{-*}		-0.19	-0.19	0.19	0.66
J/ψρ			0	0	0
J/ψω				0	0



Sharp peak No more

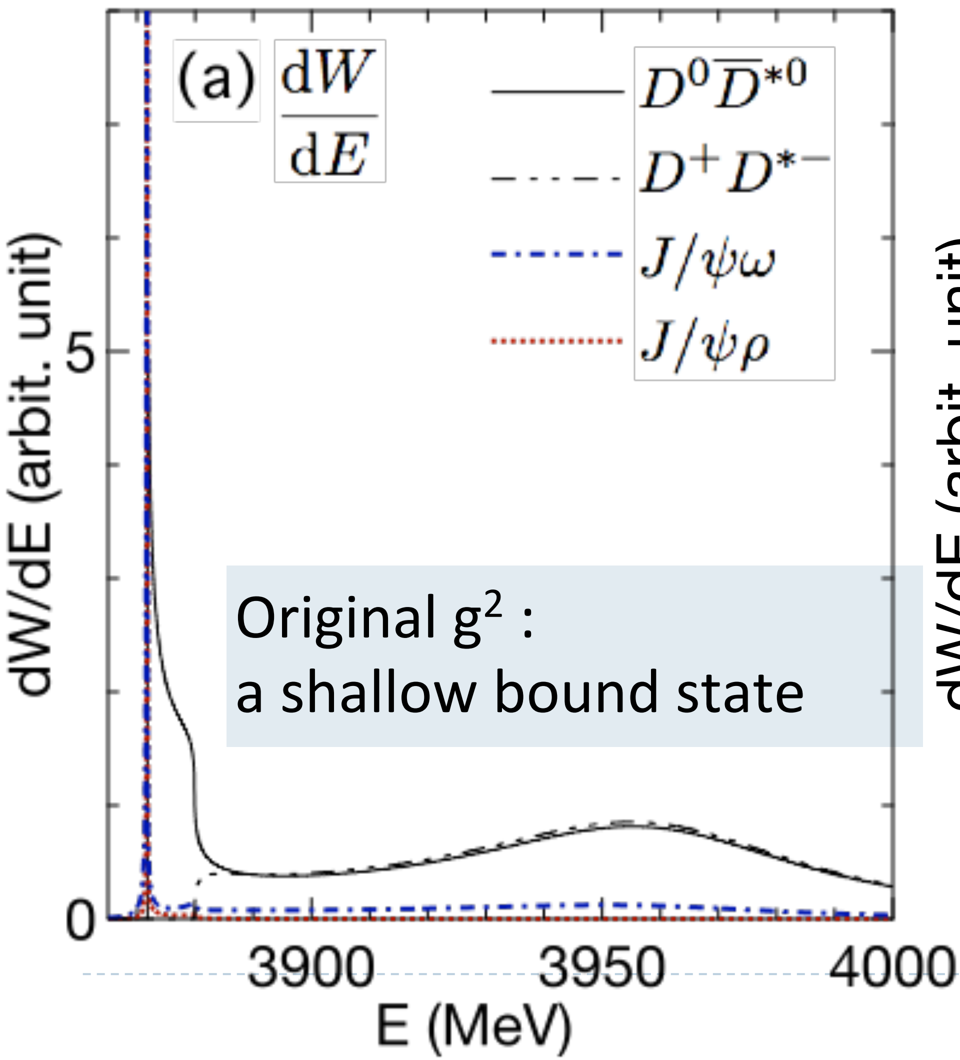
1^{++} Spectrum

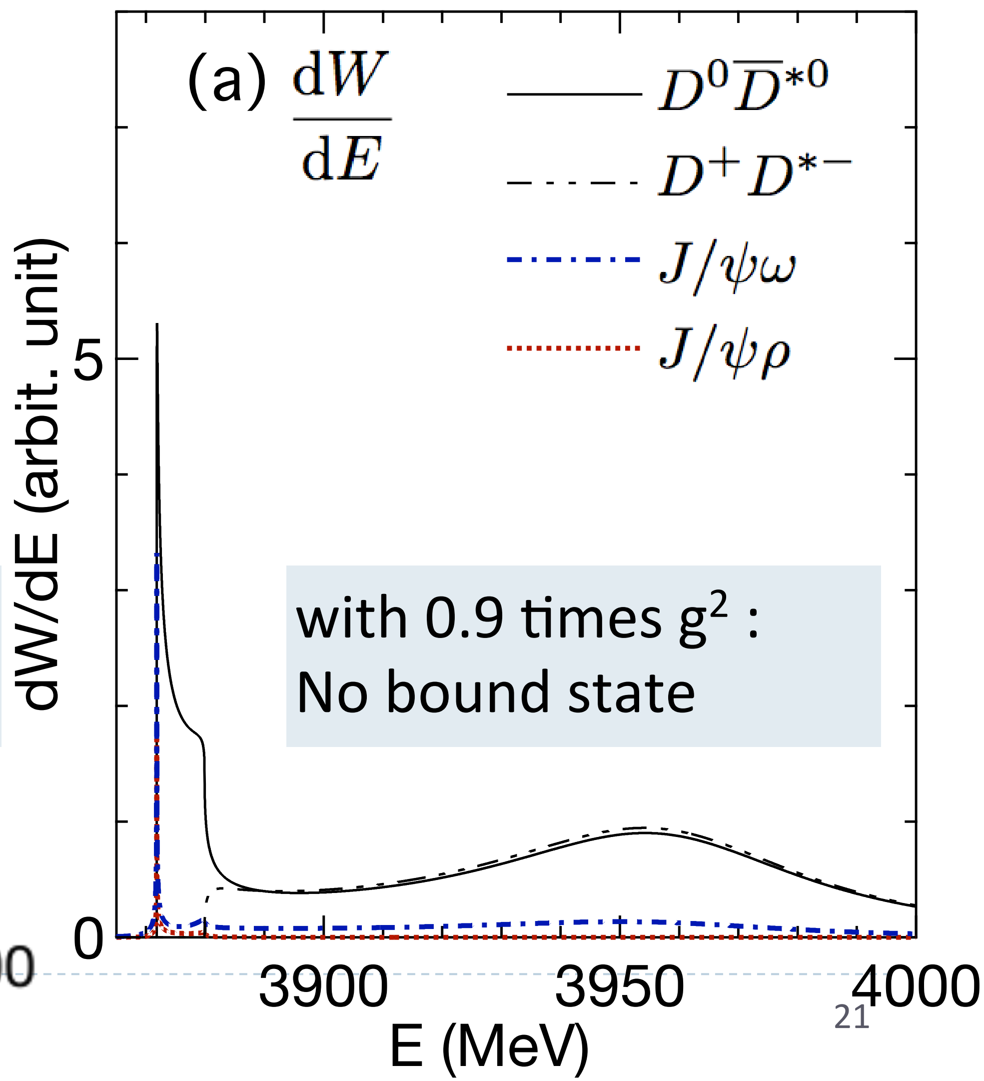

dW/dE (arbit. unit)
20
10
0
3870
3875
3880
E (MeV)
dW/dE
D0D̄*0
J/ψ ω
J/ψ ρ


D+D*-
3880
J/ψω
3878
X(3872) by D0D̄*0
3876
3874
J/ψρ
D0D̄*0
3872
3870
X(3872) by J/ψππ
Exp.

X(3872) needs to be a bound state?

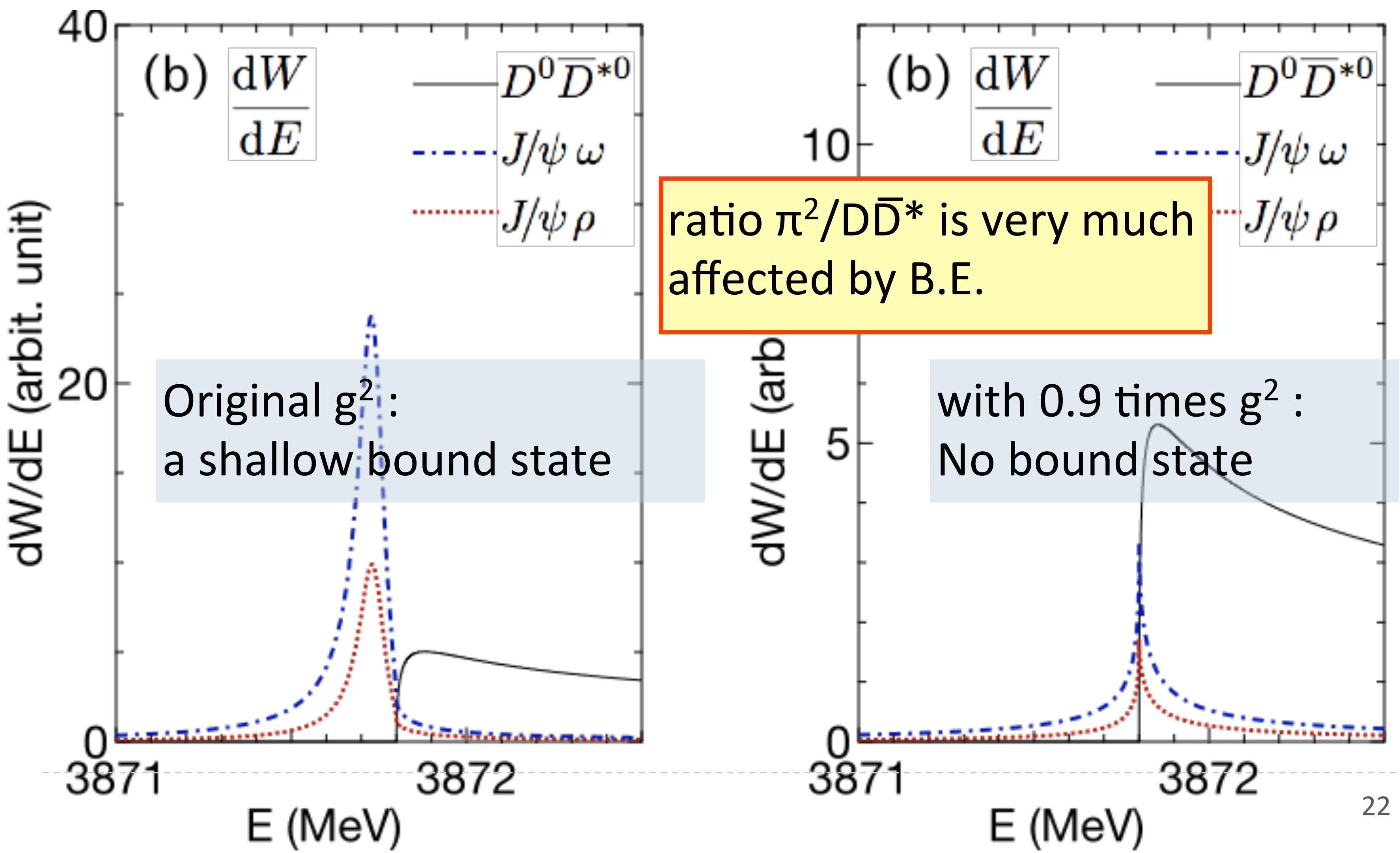
- No… it can be a virtual state





X(3872) needs to be a bound state?

- A virtual state can make $J/\psi\ \pi^n$ peak.



Summary of X(3872)

- In order to reproduce the properties of the X(3872), introduction of the all thresholds near the peak position is important.
- $c\bar{c}$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ – $J/\psi\rho$ full coupled channel calculation is necessary.
- $c\bar{c}$ component may explain the production rate of X(3872) in the pp^{bar} collisions.
- $c\bar{c}$ component gives rise to the additional attractive interaction effectively.

Summary of X(3872)

- Large rho-meson width enhances the isospin symmetry breaking.

- Calculation of the experimentally observed spectrum is important.

  There is a mechanism to have narrow peaks of $J/\psi\rho,\omega$ and broader peaks of $D\bar{D}^*$.

Summary of X(3872)

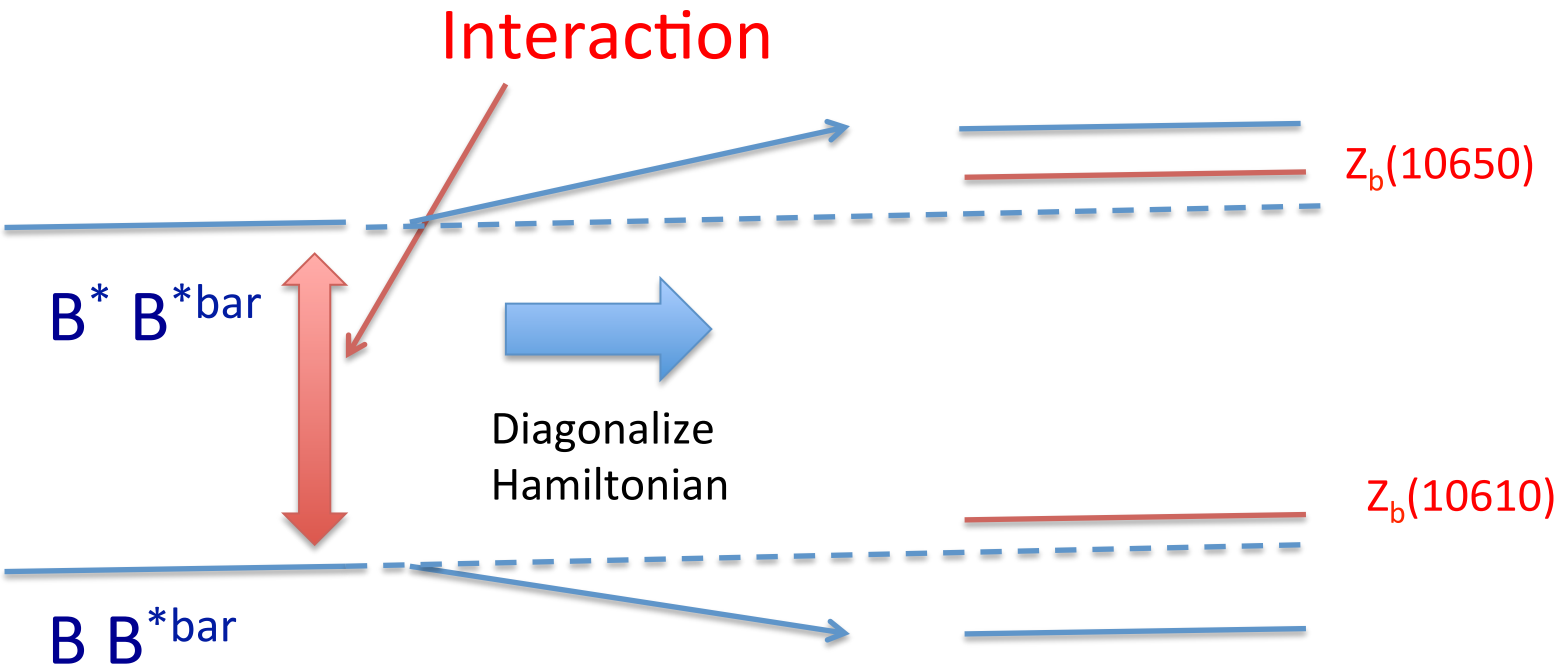
- A large Isospin breaking can be realized.
  ▷sensitive to $(g/g_0)^2$

- $$\frac{\Gamma(D^0\bar{D}^{0*})}{\Gamma(J/\psi\,\rho)}$$ probe of the binding energy of X(3872)

- $D\bar{D}^*$int, g, → other heavy quark systems
  $D\bar{D}^*$int ∼ $B\bar{B}^*$int (heavy quark symmetry)
  -> roughly consistent with $Z_b^+(10610)$, $Z_b^+(10650)$

Consideration about other hadronic molecules

- $Z_b^+(10610)$ and $Z_b^+(10650)$



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Consideration about other hadronic molecules

- $Z_c^+(3900)$

- Simultaneous explanation of $Z_b^\pm$ and $Z_c^\pm$ is rather difficult since heavy quark symmetry requires almost same interactions between DD^{*bar} and BB^{*bar}, but the kinetic energy of the BB^{*bar} system is much smaller than that of DD^{*bar} system.

At J-PARC

- So far, hadronic moleculer states have not been observed at the fixed target experiments.
- Target mass dependence of the production rate and the width of the hadronic molecule state may differ from that of the usual hadrons.

Further theoretical studies are necessary.

Backup

Radiative decays of X(3872)

Radiative decays of X(3872)

$$R_\gamma = \frac{B(X(3872 \to \psi(2S)\gamma)}{B(X(3872 \to J/\psi\,\gamma)}$$

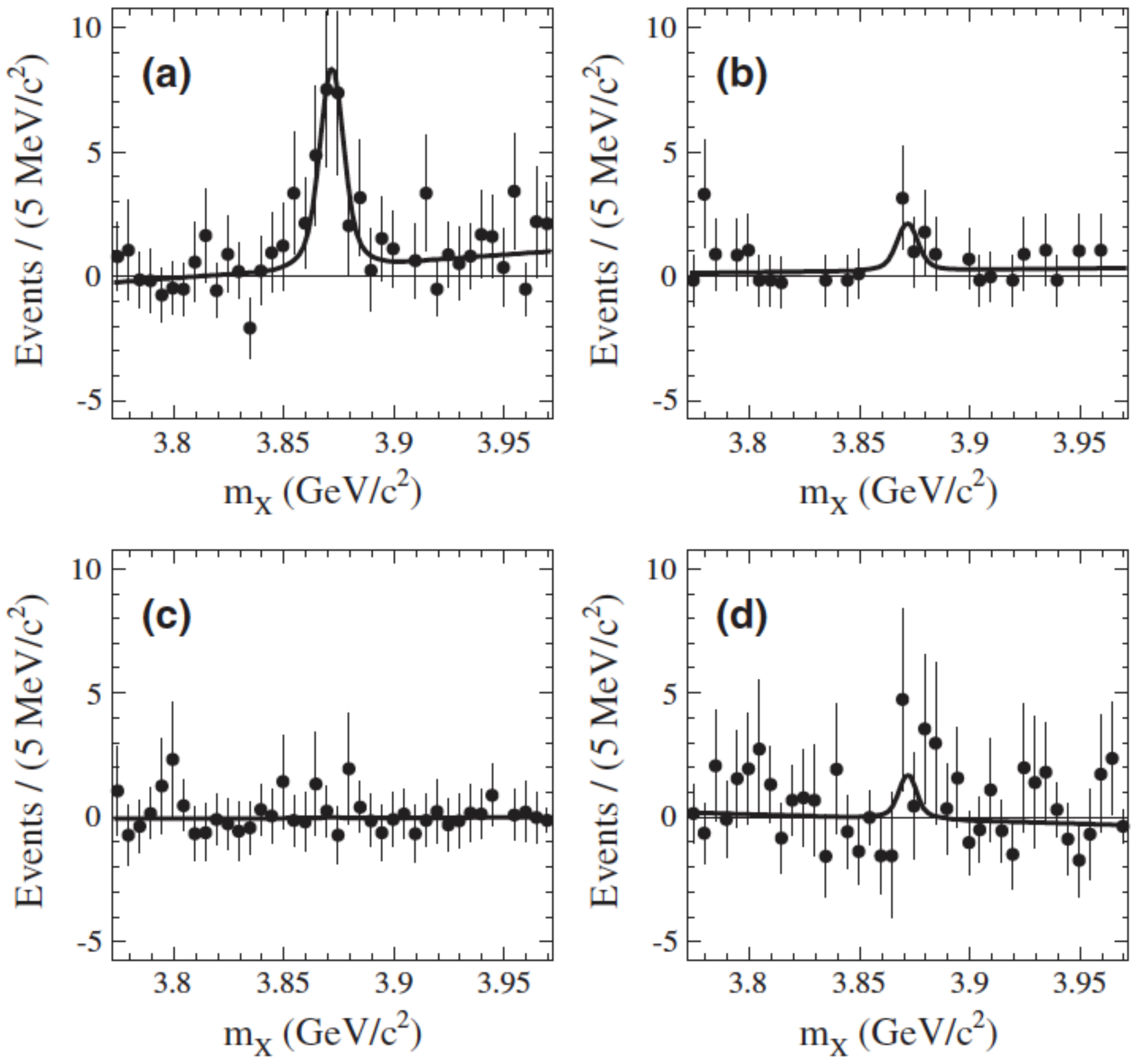
BaBar: 3.4 ± 1.4 (3.5σ) PRL102, 132001(2009)

Belle: < 2.1 (90%CL) PRL107, 091803(2011)

LHCb: 2.46 ± 0.64(stat) ± 0.29(sys) (4.4σ)
NP B886, 665 (2014)

BaBar's results ($J/\psi\gamma$)

$B^{\pm} \to X K^{\pm}$

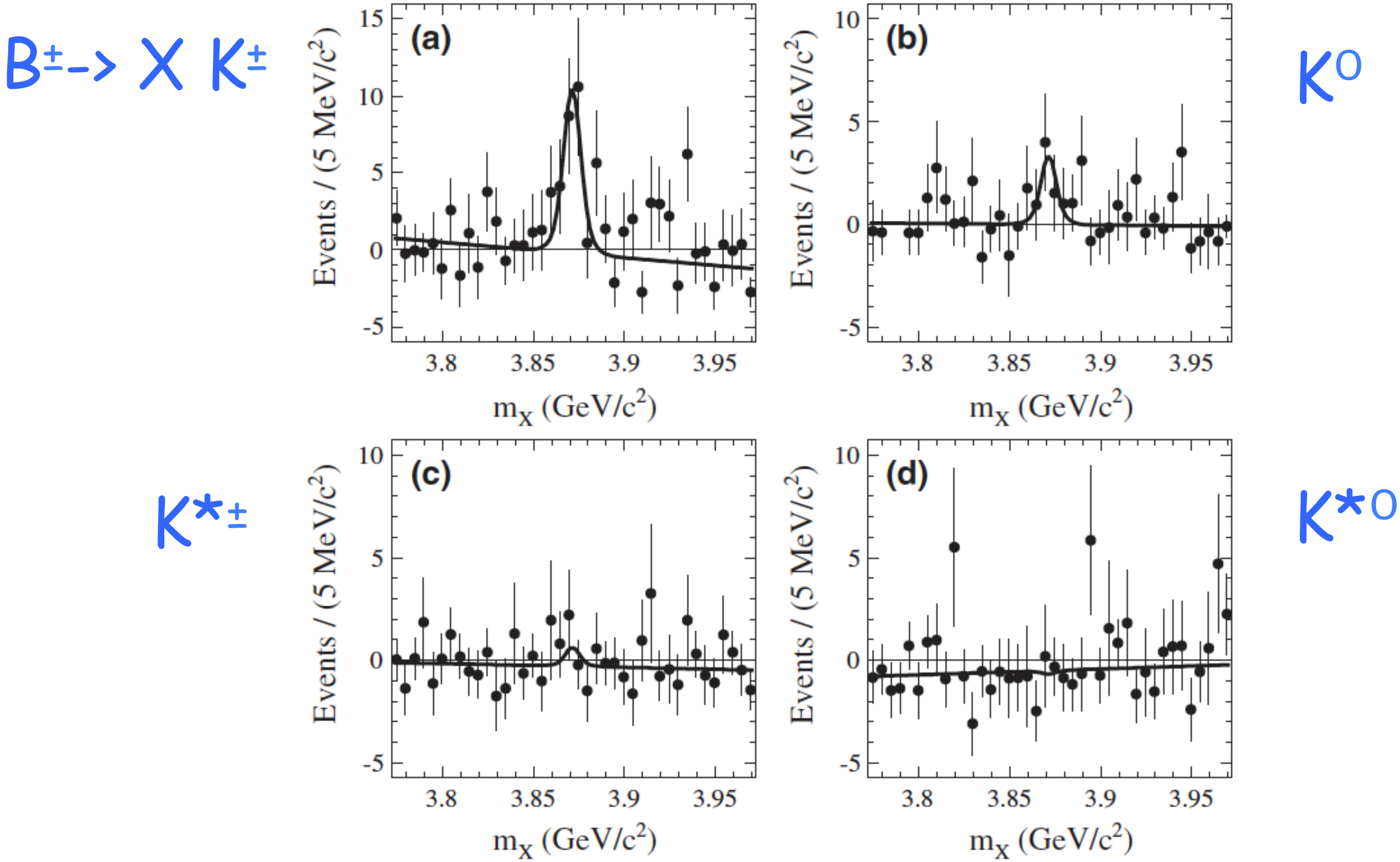


K_s^0

$K^{*\pm}$

K^{*0}

BaBar's results ($\psi'\gamma$)



Belle's results (J/ψγ)

$B^{\pm} \to X K^{\pm}$ $B^0 \to X K_s^0$

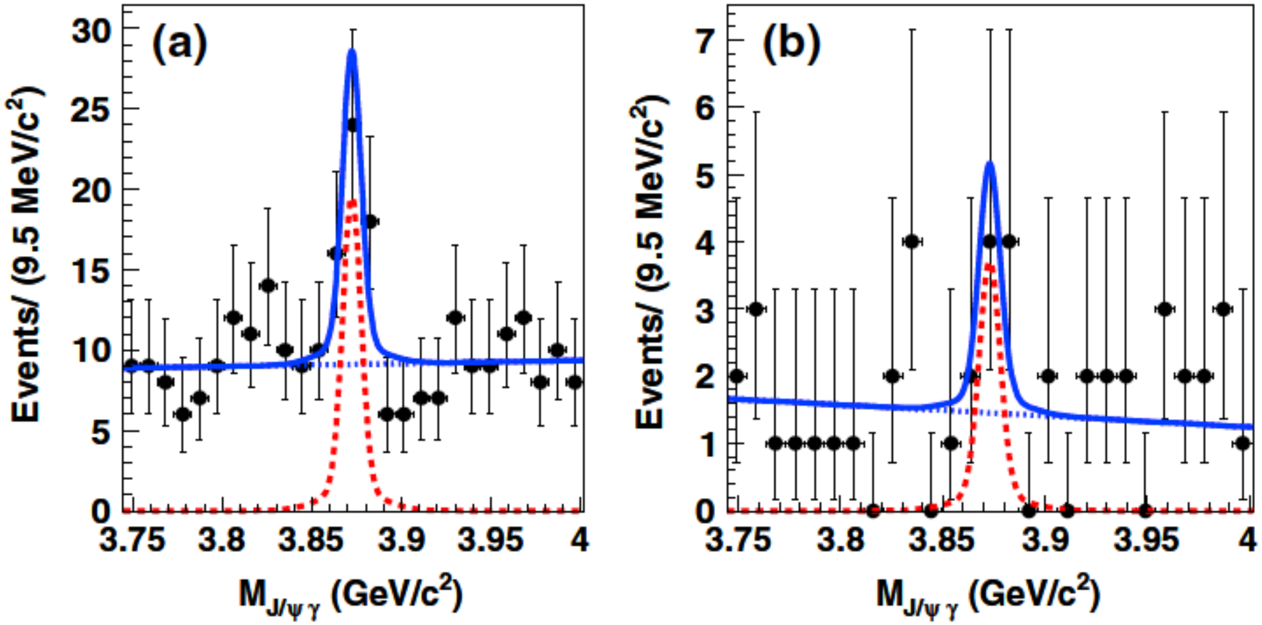


FIG. 2 (color online). $M_{J/\psi\gamma}$ distributions for (a) $B^+ \to X(3872)(\to J/\psi\gamma)K^+$ and (b) $B^0 \to X(3872)(\to J/\psi\gamma)K_S^0$ decays. The curves show the signal (red dashed) and the background component (blue dotted) as well as the overall fit (blue solid).

Belle's results (ψ'γ)

$B^{\pm}$ -> X $K^{\pm}$ B^0 -> X K_s^0

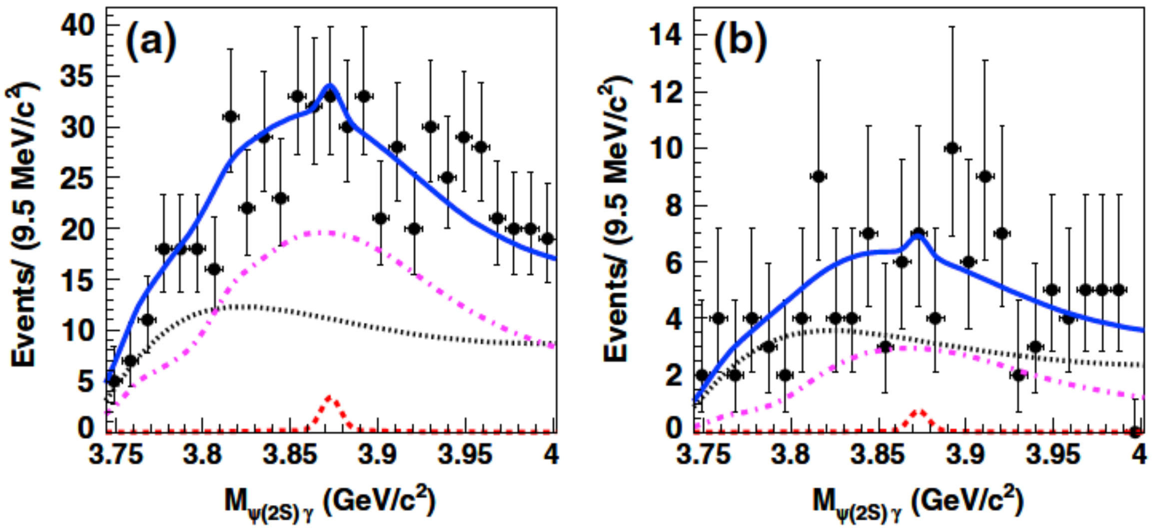
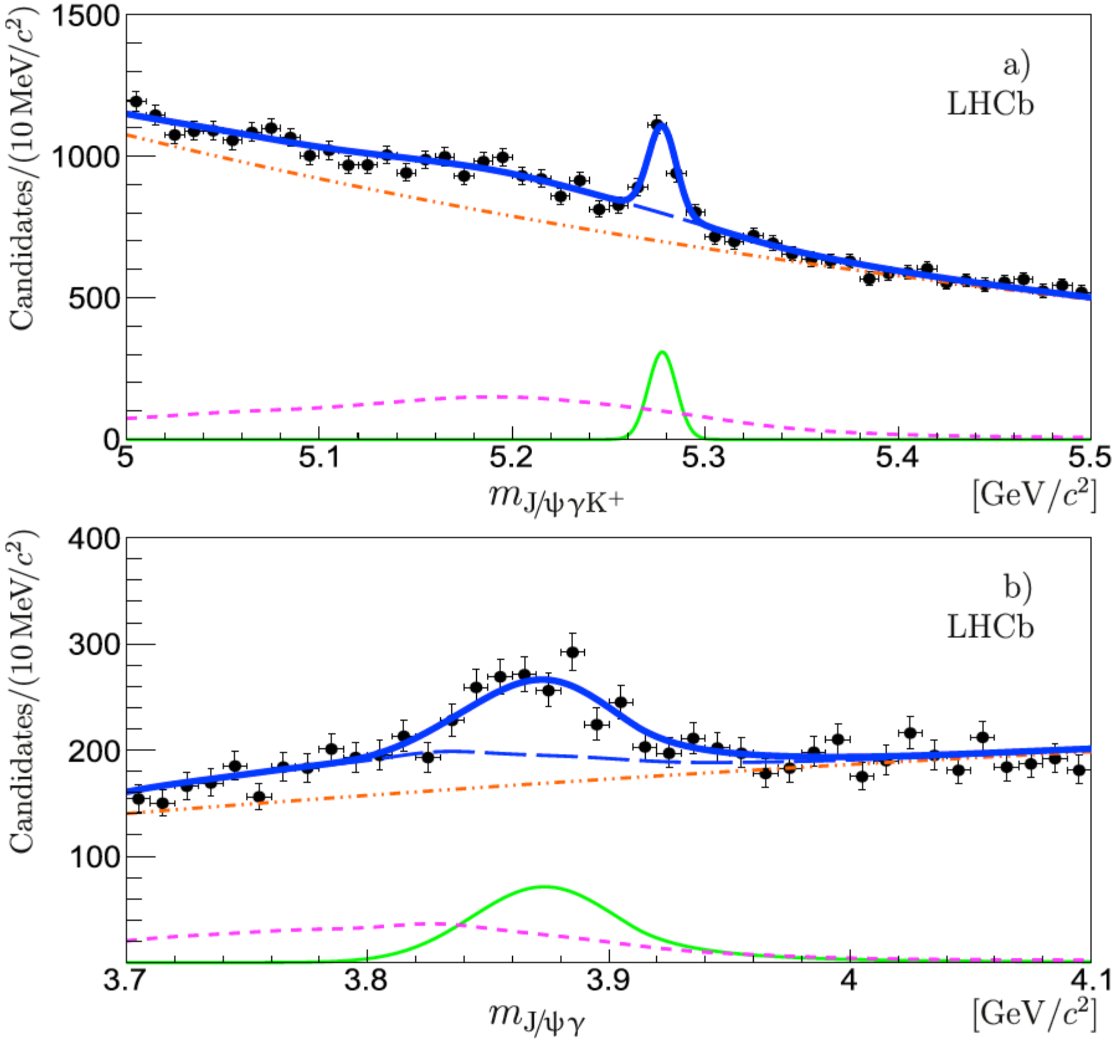


FIG. 3 (color online). $M_{\psi'\gamma}$ distributions for (a) $B^+ \to X(3872)(\to \psi'\gamma)K^+$ and (b) $B^0 \to X(3872)(\to \psi'\gamma)K^0$. The curves show the signal [red dashed for $X(3872)$] and the background component [pink dot-dashed for background from $B \to \psi' K^*$ and $B \to \psi' K$ component, and black dotted for combinatorial background modeled by the threshold function] as well as the overall fit (blue solid).

LHCb's results ($J/\psi\gamma$)

Invariant mass of $J/\psi\,\gamma\,K^{+}$

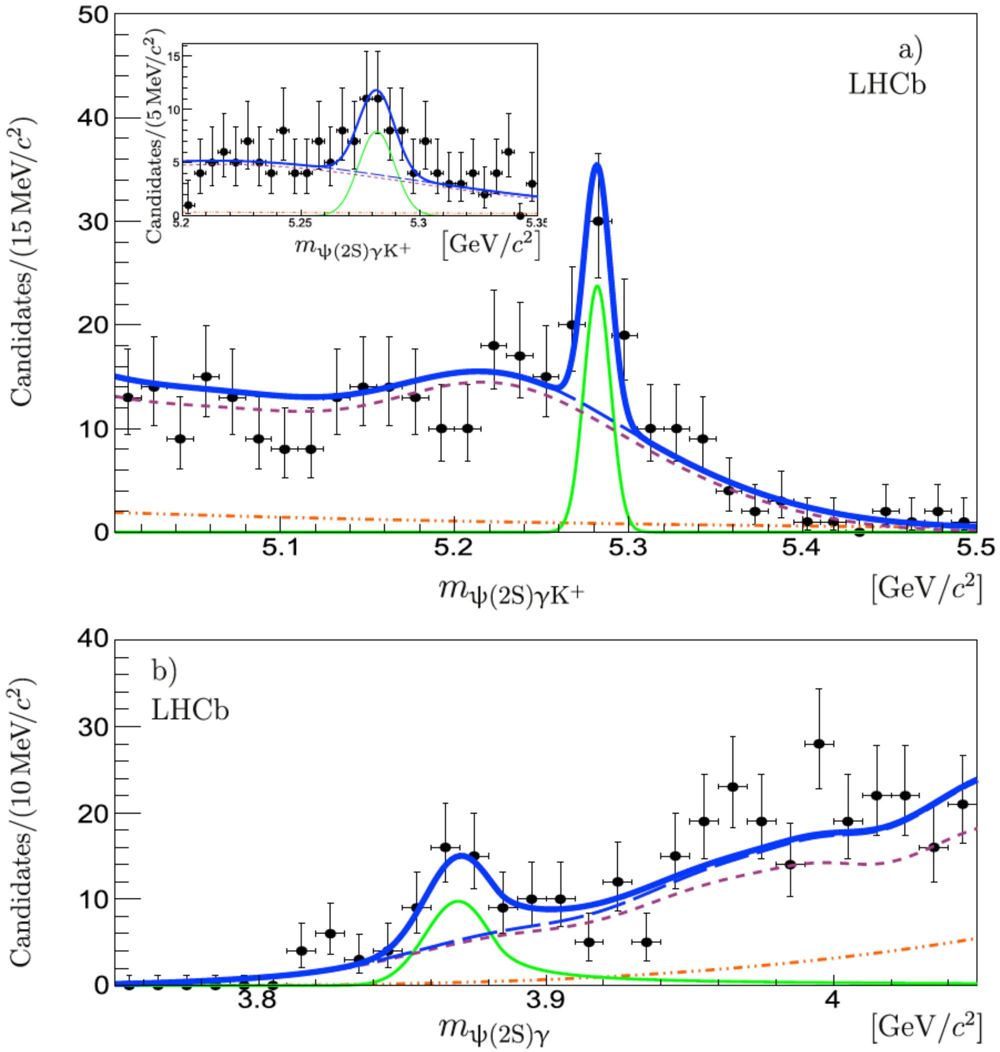
Invariant mass of $J/\psi\,\gamma$



LHCb's results (ψ'γ)

Invariant mass of $\psi(2S)\,\gamma\,K^{+}$

Invariant mass of $\psi(2S)\,\gamma$



Wavefunction of X(3872)

- Probability of the each component of X(3872)

  Our numerical results:

Model	$c\bar{c}$ (CCbar)	$D^0 \bar{D}^{*0}$	D^+D^{*-}	$J/\psi\rho$	$J/\psi\omega$
Case A	0.036	0.913	0.034	0.006	0.010
Case QM	0.061	0.864	0.019	0.007	0.019

ρ and ω widths are not introduced for the radiative decay calculations.

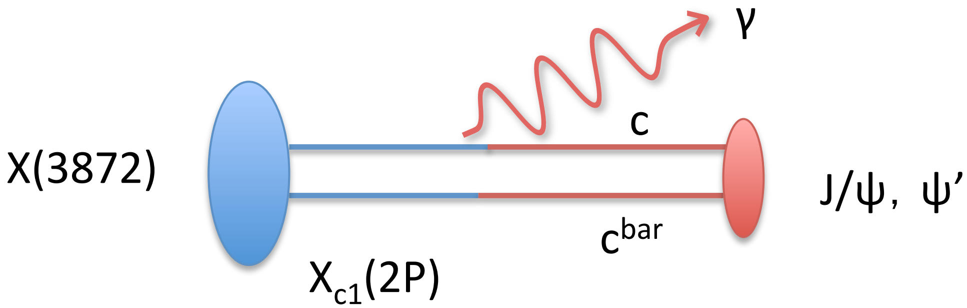
Wavefunctions of Charmonia

- Charmonia: $\chi_{c1}(2P)$, $\psi(2S)$, J/ψ
- As for the wavefunction of charmonium we used the potential model of S. Godfrey and N. Isgur, PRD 32, 189 (1985) (without the LS and tensor terms for simplicity)

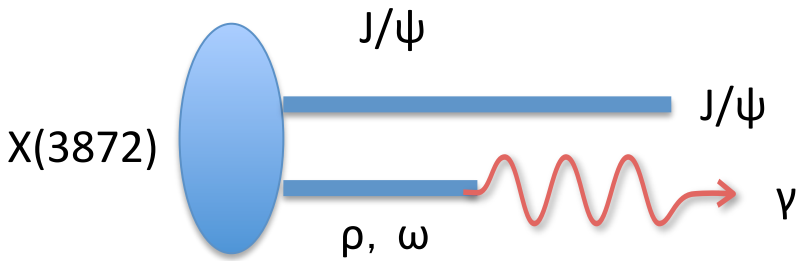
- $\chi_{c1}(2P)$ in the X(3872) is offshell, but we used the onshell wavefunction.

Radiative decays of X(3872)

- E1 transiton of cc^{bar} core to J/psi(psi') γ

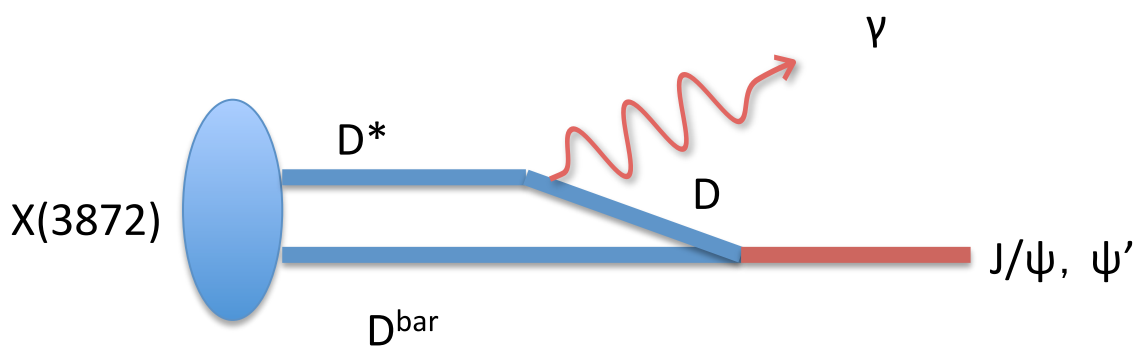


- Vector meson dominance



Radiative decays of X(3872)

- D meson loop (not considered here)



- Partial decay width $D^{*+} \rightarrow D^{+} \gamma$ = 1.3 keV
- Overlap of DD^{bar} – J/ψ is small

E1 transitions of cc^{bar} core

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

$$\langle J/\psi | r | \chi_{c1}(2P) \rangle = 0.0396\ fm$$

$$\langle \psi' | r | \chi_{c1}(2P) \rangle = 0.5225\ fm$$

$$\langle J/\psi | r | \chi_{c1}(2P) \rangle = 0$$

for harmonic oscillator wavefunction

Radiative decay widths (cc^{bar} core contribution)

Numerical result: *Case A*

$$\Gamma(X(3872) \to J/\psi + \gamma) = 0.7\ \mathrm{keV}$$

$$\Gamma(X(3872) \to \psi' + \gamma) = 2.6\ \mathrm{keV}$$

$$R = \frac{\Gamma(X(3872) \to \psi' + \gamma)}{\Gamma(X(3872) \to J/\psi + \gamma)} = 3.6$$

Radiative decay widths (cc^{bar} core contribution)

Numerical result: Case QM

$$\Gamma(X(3872) \to J/\psi + \gamma) = 1.0 \text{ keV}$$

$$\Gamma(X(3872) \to \psi' + \gamma) = 3.5 \text{ keV}$$

$$R = \frac{\Gamma(X(3872) \to \psi' + \gamma)}{\Gamma(X(3872) \to J/\psi + \gamma)} = 3.5$$

VMD contribution

$$\Gamma_{VMD} = \frac{4}{27}\alpha \frac{q\,E_{J/\psi}}{m_X} \left|\psi_\omega(r=0)\right|^2 \left(Z_{\omega J/\psi}\phi_{\omega J/\psi}(q) + 3Z_{\rho J/\psi}\phi_{\rho J/\psi}(q)\right)^2$$

q: photon momentum

$Z_\alpha{}^2$: probability of finding α component in X(3872)

Numerical result:

Case A

$$\Gamma_{VMD}(X(3872) \to J/\psi + \gamma) = 2.6\ \mathrm{keV}$$

Case QM

$$\Gamma_{VMD}(X(3872) \to J/\psi + \gamma) = 6.2\ \mathrm{keV}$$

Discussions

- Since we cannot determine the relative sign of the cc[bar] core contribution and VMD contribution, rough estimation is:

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

$$= \left(\sqrt{\Gamma_{VMD}} - \sqrt{\Gamma_{c\bar{c}}}\right)^2 \sim \left(\sqrt{\Gamma_{VMD}} + \sqrt{\Gamma_{c\bar{c}}}\right)^2$$

$$= 0.6\ \text{keV} \sim 6.0\ \text{keV} \quad (\text{Case A})$$

$$= 1.6\ \text{keV} \sim 12.2\ \text{keV} \quad (\text{Case QM})$$

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

$$= 0.43 \sim 4.3 \ (\text{Case A})$$

$$= 0.29 \sim 1.18 \, (\text{Case QM})$$

3.4 ± 1.4 [BaBar]   < 2.1 (90%CL) [Belle]

2.46 ± 0.64(stat) ± 0.29(sys) [LHCb]

Ψ(4040,4415) -> X(3872) + γ

- BESIII observed the radiative decay
  Y(4260) -> X(3872) + γ
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$$\frac{B\left[Y(4260) \rightarrow X(3872)\,\gamma\right]}{B\left[Y(4260) \rightarrow J/\psi\,\pi^+\pi^-\right]} = 0.1$$

- Y(4260) may be not a simple charmonium and the structure of Y(4260) is unclear.

Ψ(4040,4415) -> X(3872) + γ

- We consider well established ψ(3S, 4040) and ψ(4S, 4415) instead of Y(4260) .
- We consider E1 transiton of $c\bar{c}$ $^3S_1(n=3,4)$ -> $c\bar{c}$ core of X(3872) + γ .

Decay width	Ψ(4040) -> X(3872) γ	Ψ(4415)-> X(3872) γ
Case A	2.4 keV	0.16 keV
Case QM	4.0 keV	0.27 keV

Summary

- Estimation of $\Gamma(X(3872) \to J/\psi + \gamma)$ is rather difficult.

- $\Gamma(X(3872) \to \psi' + \gamma)$ is proportional to size of cc^{bar} core component in X(3872).

- The measurement of absolute value of $\Gamma(X(3872) \to \psi' + \gamma)$ is very important to determine the nature of X(3872).

Summary

- We have a chance to observe $\psi(4040) \to X(3872)\,\gamma$ decay.

- $\Gamma(Y(4260) \to X + \gamma) < \Gamma(\psi(4040) \to X + \gamma)$ since Y(4260) may have the non-$c\bar{c}$ component.