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Sachiko Takeuchi (Japan Colledge of Social Work)
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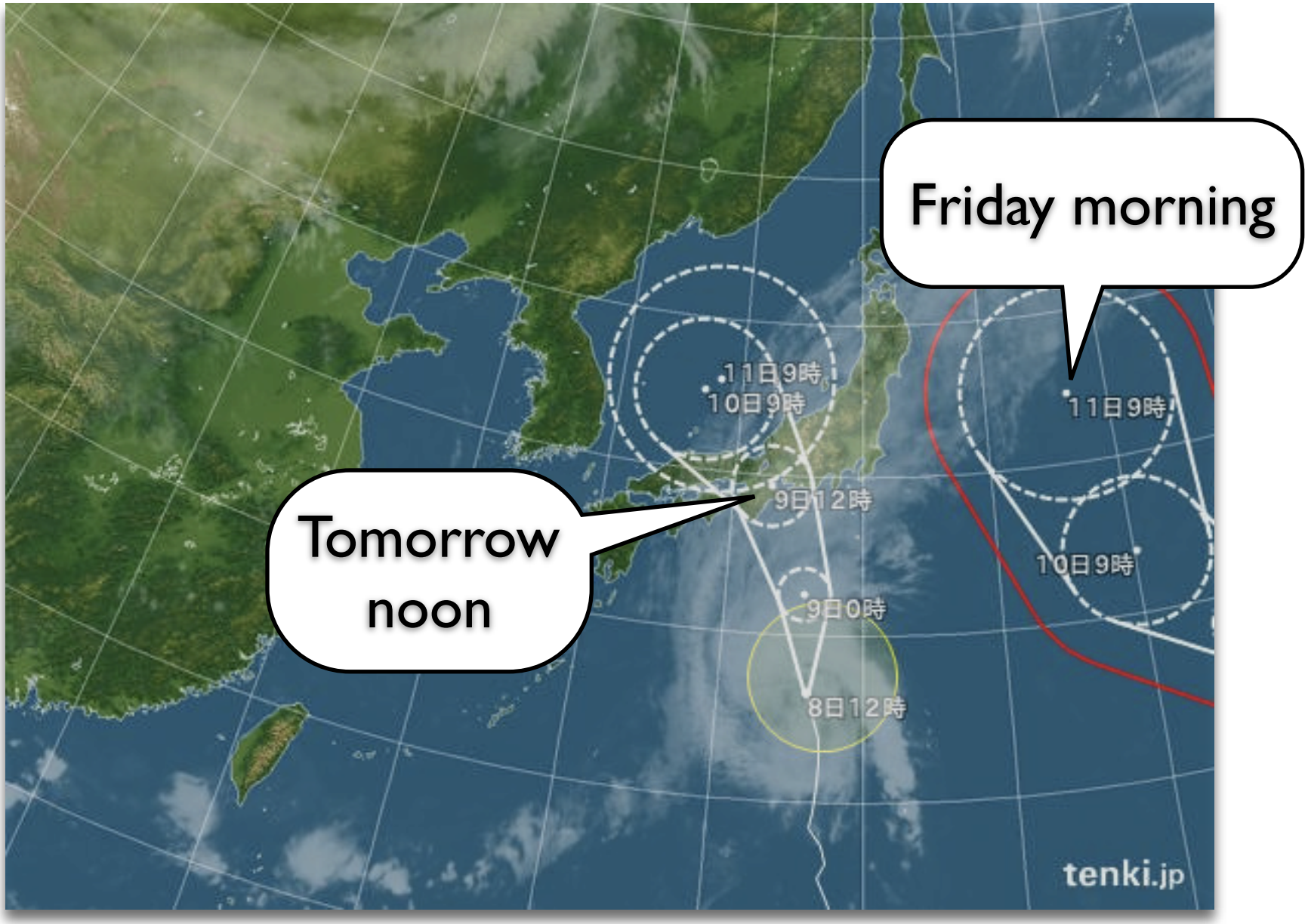
M. Takizawa and S. T., PTEP 2013, 0903D01 (2013)
S.T., K. Shimizu, M. Takizawa, [arXiv 1408.0973 hep-ph]

HYP2015 @ Sendai 8 Sep 2015


Friday morning
Tomorrow noon
11日9時
10日9時
9日12時
9日0時
8日12時
11日9時
10日9時
tenki.jp

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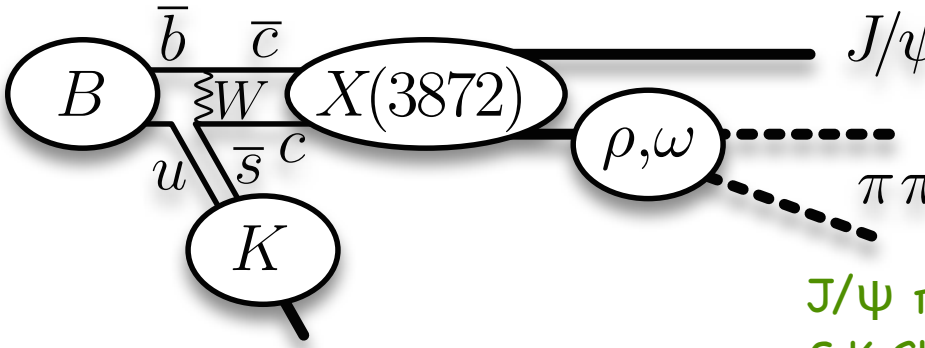
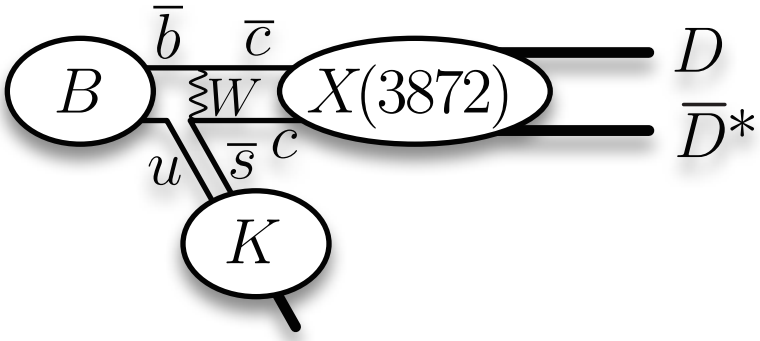
$B^+ \to K^+ + J/\psi + \pi\pi(\pi)$

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



$\to J/\psi + \rho$ 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)



$\to D + \bar{D}^*$

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

X(3872) JPC=1++

- Mass 3871.69±0.17 MeV from J/ψππ
- X(3872) ($uc\bar{u}\bar{c}$, $dc\bar{d}\bar{c}$) thresholds
  - $D^{\pm}D^{*\mp}$ 3879.91±0.20 MeV
  - J/ψω 3879.57±0.12 M
  - J/ψρ 3872.18±0.25 M
  - $D^{0}\bar{D}^{*0}$ 3871.80±0.20 MeV

X is almost 'on' the threshold!

- X(3872) is very large. Interaction range is very small. Structure of X(3872) is not clearly seen.

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)

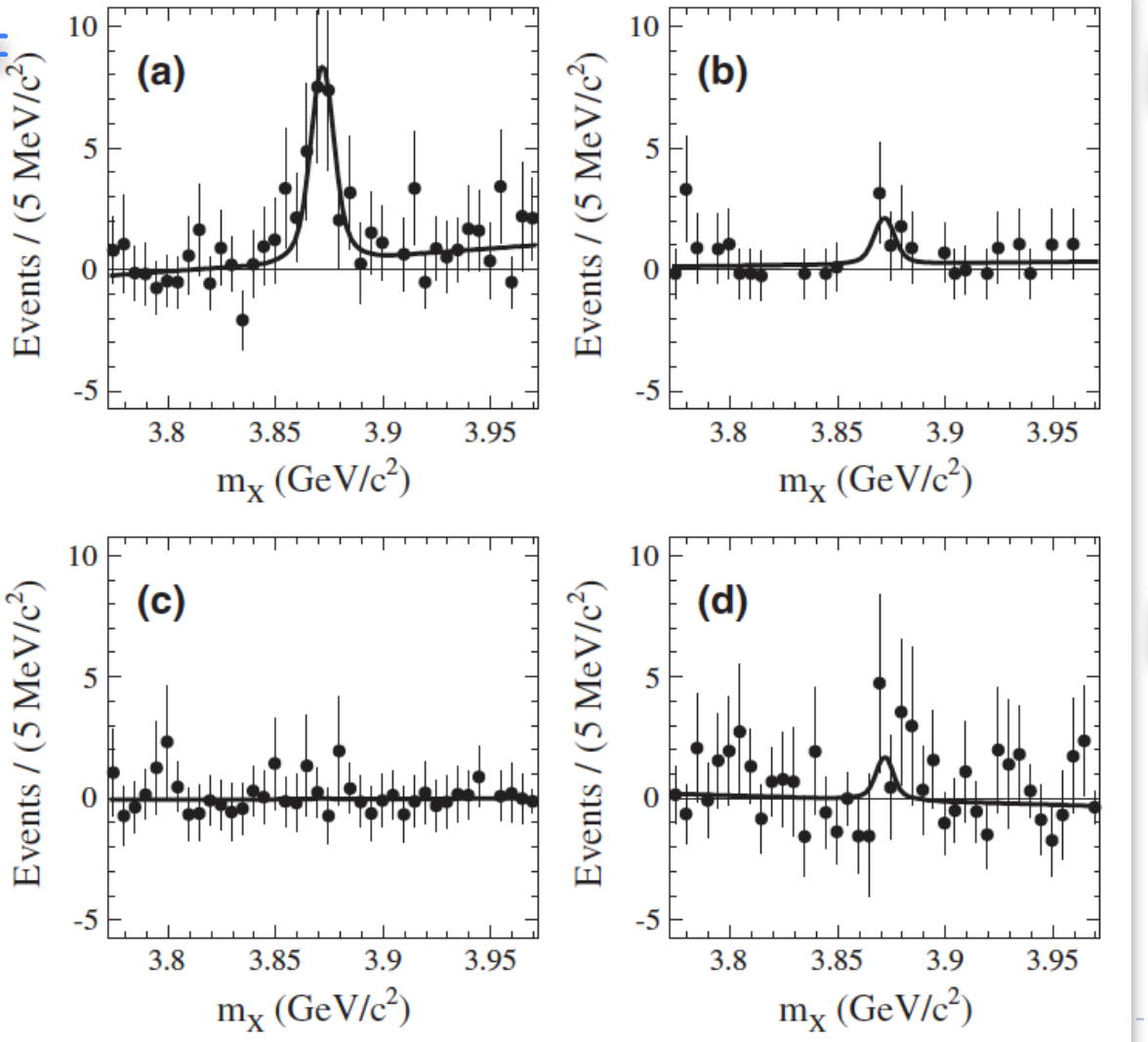
Radiative Decay Experiments

- 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)
      - = 3.4±1.4, BABAR
      - < 2.1, Belle
      - = 2.46±0.64±0.29 LHCb

B.Aubert et al. [BaBar] PRL102, 132001 (2009)
V.Bhardwaj et al. [Belle] PRL107, 091803 (2011)
R.Aaij et al. [LHCb] NPB886, 665 (2014)

BaBar's results: X(3872)→ J/ψγ

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



K_s^0

$K^{*\pm}$

K^{*0}

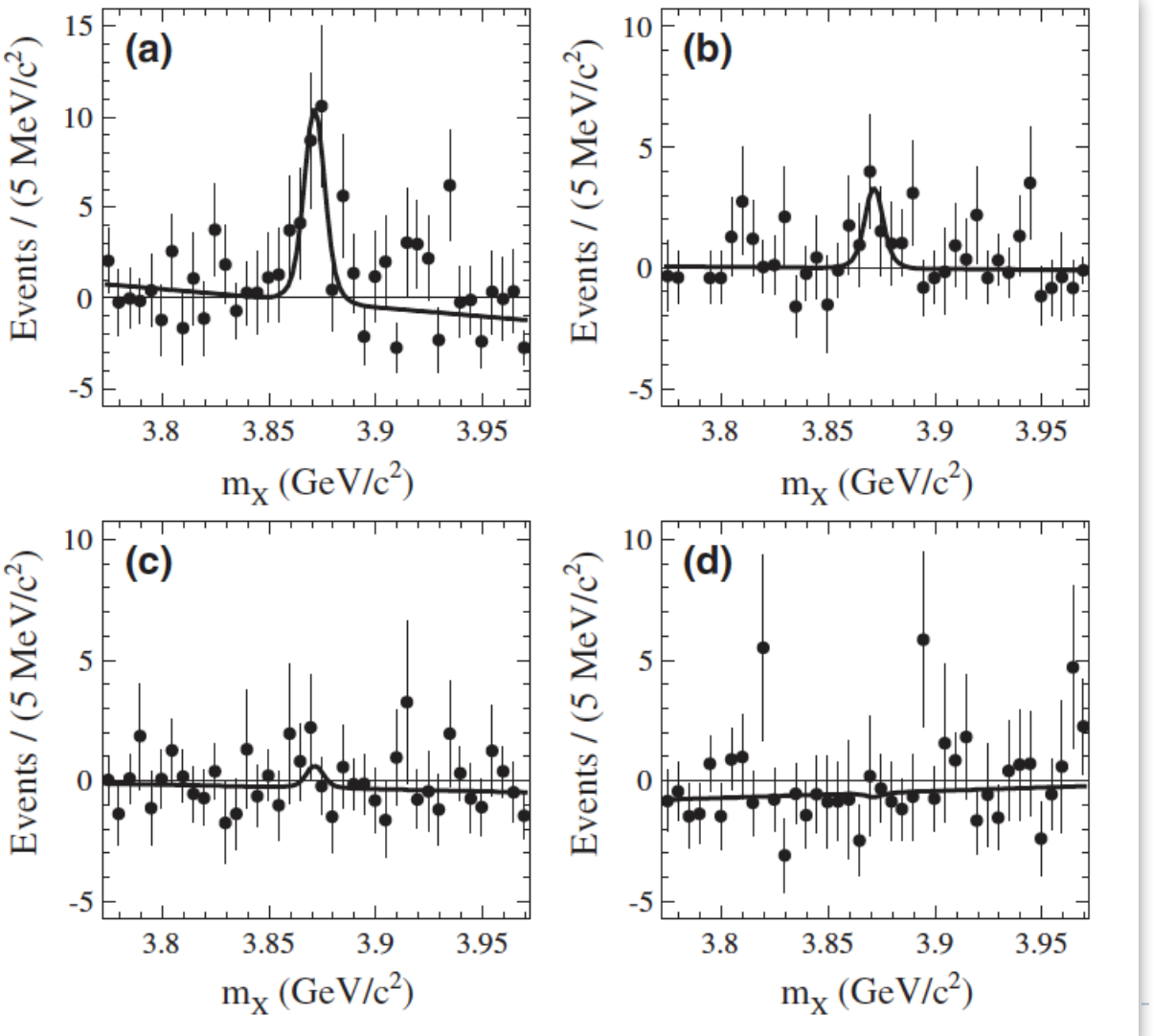
BaBar's results: X(3872)→ ψ(2S)γ

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

K^0

$K^{*\pm}$

K^{*0}



Belle's results: X(3872)→ J/ψγ

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

B^{0} -> X K_s^{0}

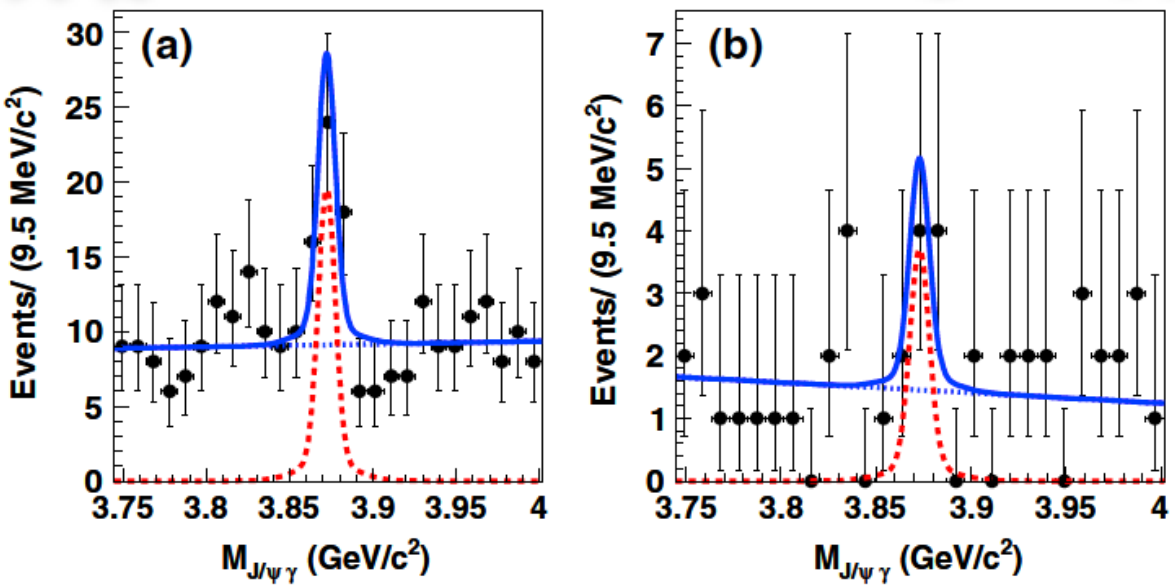


FIG. 2 (color online). $M_{J/\psi\gamma}$ distributions for (a) $B^+ \to X(3872)(\to J/\psi\gamma)K^+$ and (b) $B^0 \to X(3872)(\to J/\psi\gamma)K_S^0$ decays. The curves show the signal (red dashed) and the background component (blue dotted) as well as the overall fit (blue solid).

Belle's results: X(3872)→ ψ(2S)γ

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

B^{0} -> X K_s^{0}

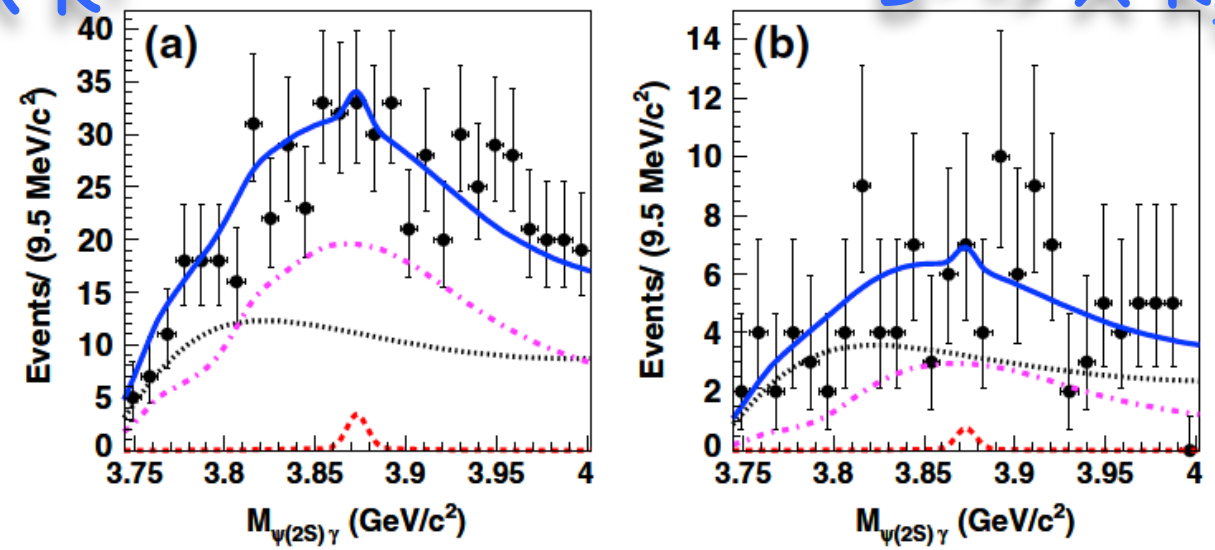
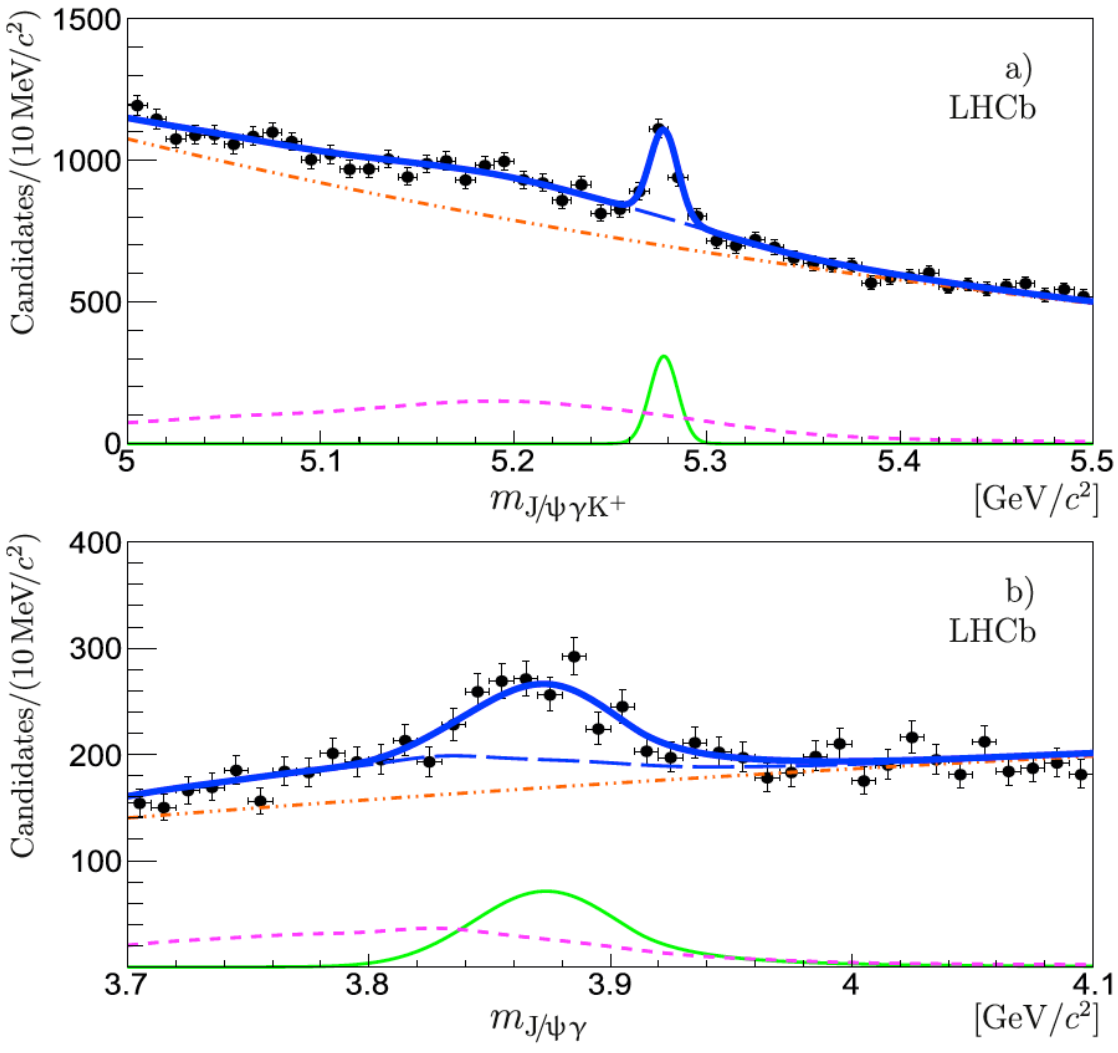


FIG. 3 (color online). $M_{\psi'\gamma}$ distributions for (a) $B^+ \to X(3872)(\to \psi'\gamma)K^+$ and (b) $B^0 \to X(3872)(\to \psi'\gamma)K^0$. The curves show the signal [red dashed for $X(3872)$] and the background component [pink dot-dashed for background from $B \to \psi' K^*$ and $B \to \psi'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

LHCb's results: X(3872)→ J/ψγ

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

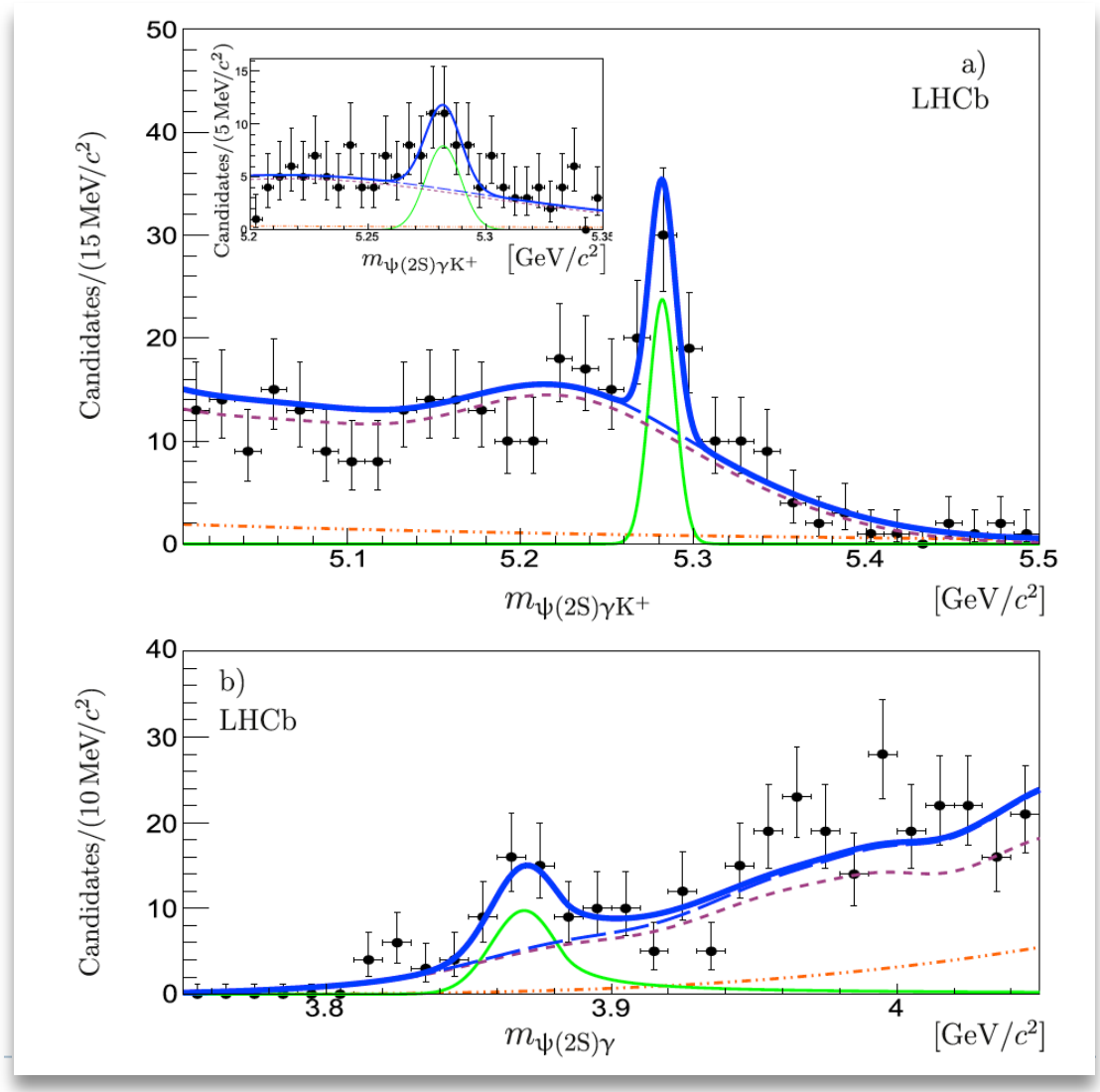
Invariant mass of $J/\psi\,\gamma$



LHCb's results: X(3872)→ ψ(2S)γ

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

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



Radiative Decay Experiments

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  - $J/\psi\gamma$ [Belle][BaBar][LHCb]
  - $\psi(2S)\gamma$ [BaBar][LHCb]([Belle] not seen)
    - $Br(X\to\psi(2S)\gamma)/Br(X\to J/\psi\gamma)$
      - $= 3.4\pm1.4,$ BABAR
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B.Aubert et al. [BaBar] PRL102, 132001 (2009)
V.Bhardwaj et al. [Belle] PRL107, 091803 (2011)
R.Aaij et al. [LHCb] NPB886, 665 (2014)

Theory for the X(3872) picture

- LQCD

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

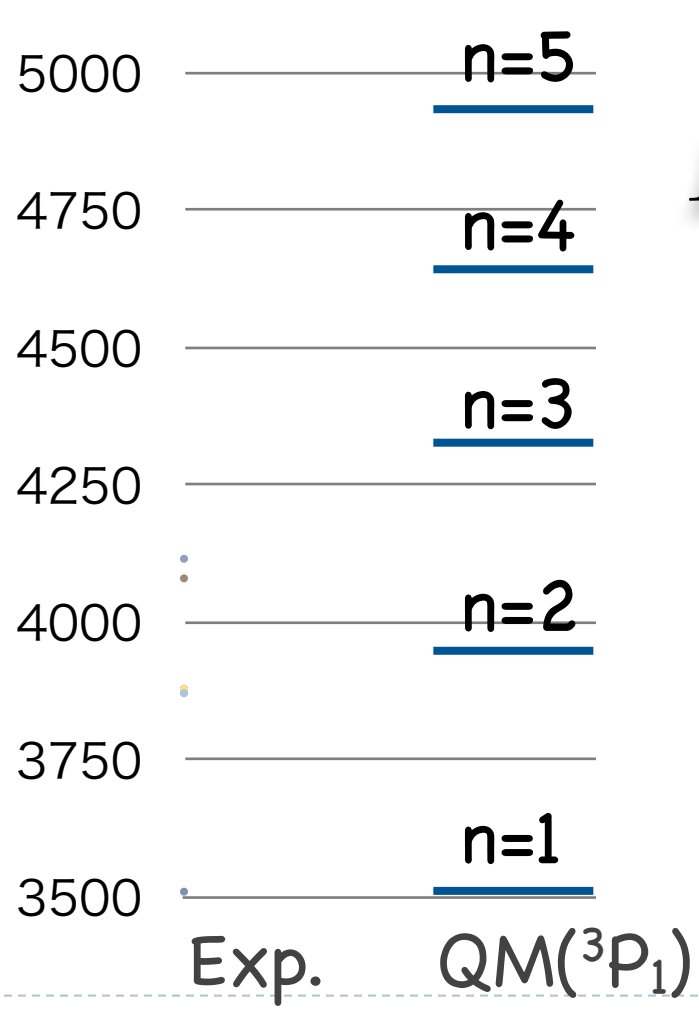
  - X(3872) is seen below $D\bar{D}^*$, BE=11±7 MeV
  - $m_u=m_d$
    - how to deal a resonance, $m_u \neq m_d$, ρ width
- Phenomenological
  - $c\bar{c}$
  - $q\bar{q}c\bar{c}$ tetraquark
  - $D\bar{D}^*$ molecule
  - $D\bar{D}^*$ + $c\bar{c}$ coupled

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

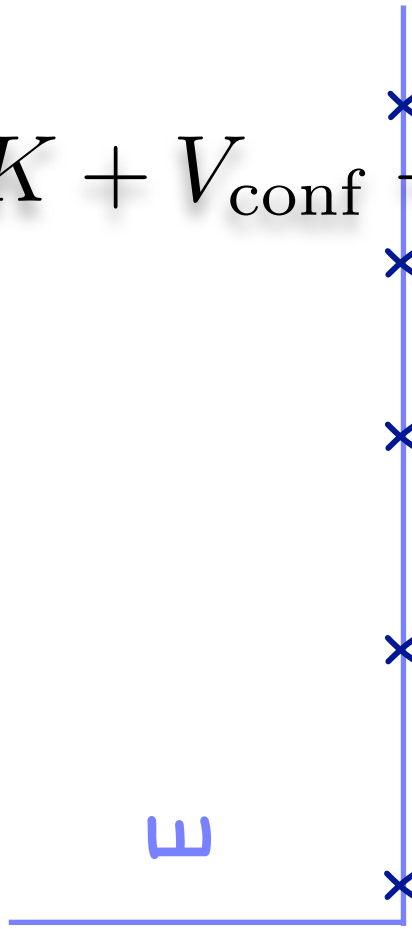
  → production rate requires a smaller object

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).

1^{++} Spectrum - quarkonium



$$H = K + V_{\rm conf} + V_{\rm oge}$$

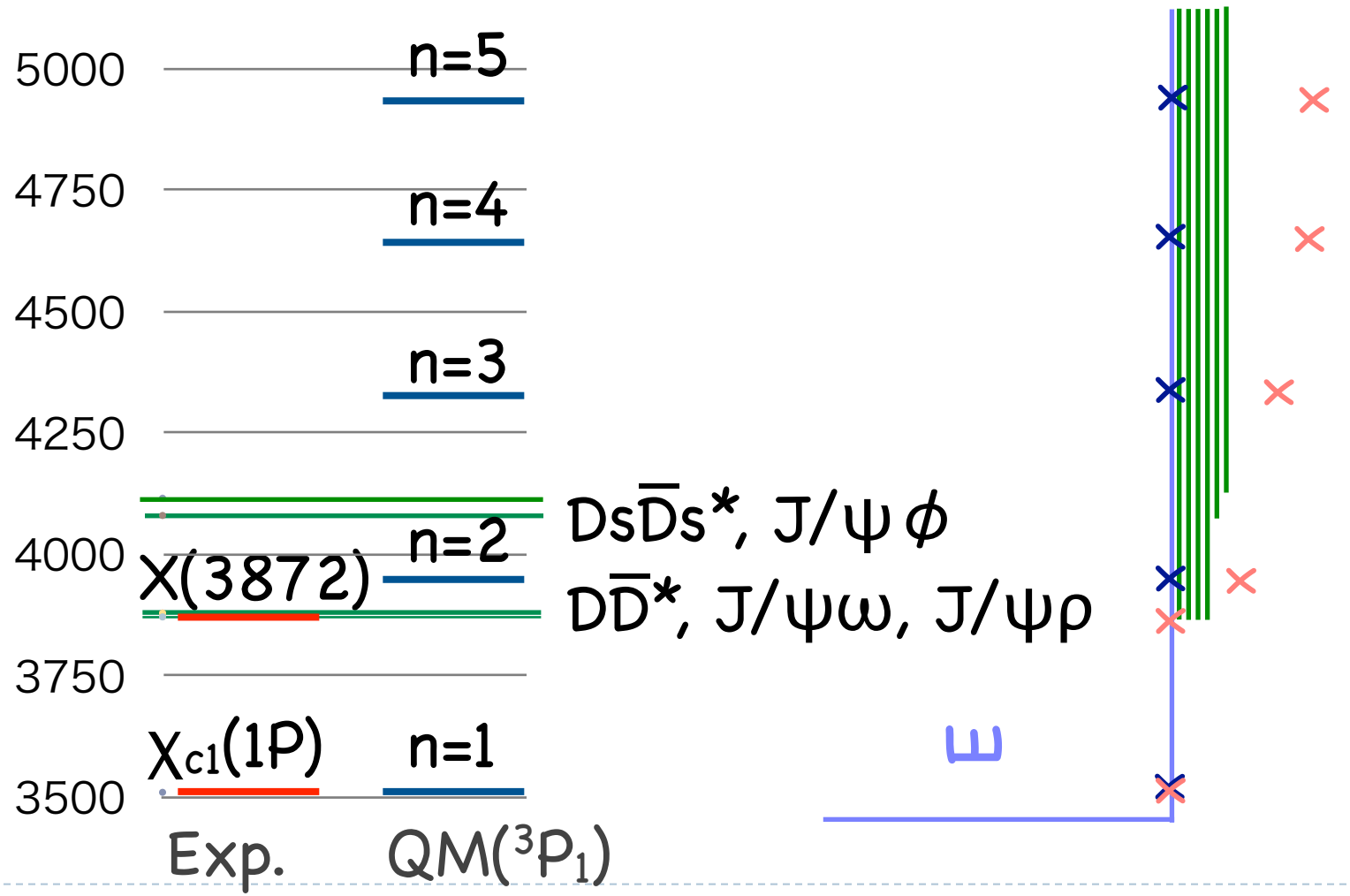


Thresholds to consider

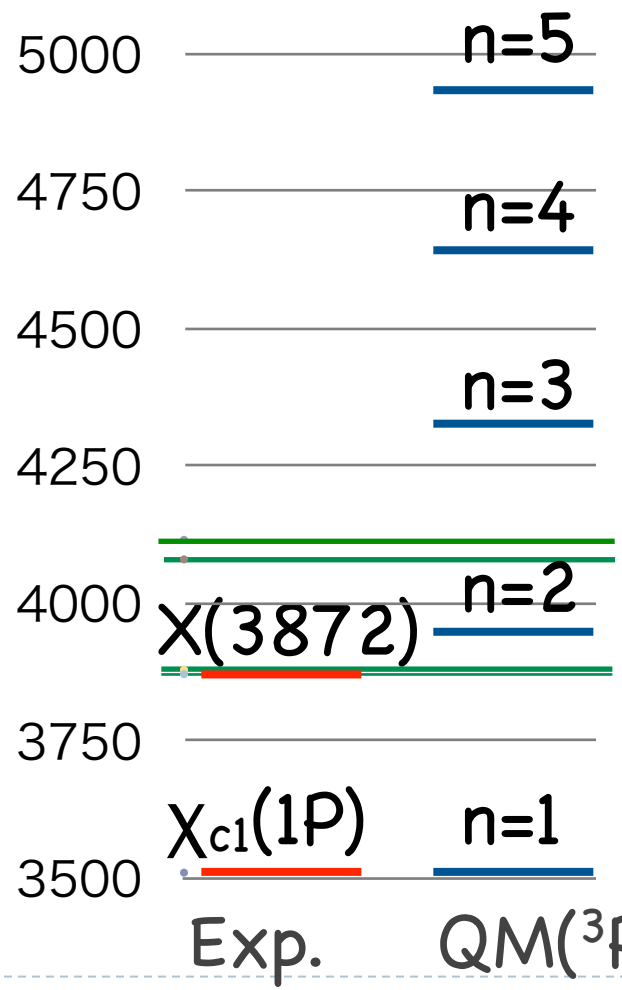
- X(3872) ($ucu^{bar}c^{bar}$, $dcd^{bar}c^{bar}$) thresholds
  - $J/\psi\omega$ 3879.79 MeV
  - $D^{\pm}D^{*\mp}$ 3879.57 MeV
  - $J/\psi\rho$ 3872.41 MeV
  - $D^{0}D^{*0bar}$ 3871.73 MeV

Isospin sym breaking

1^{++} Spectrum

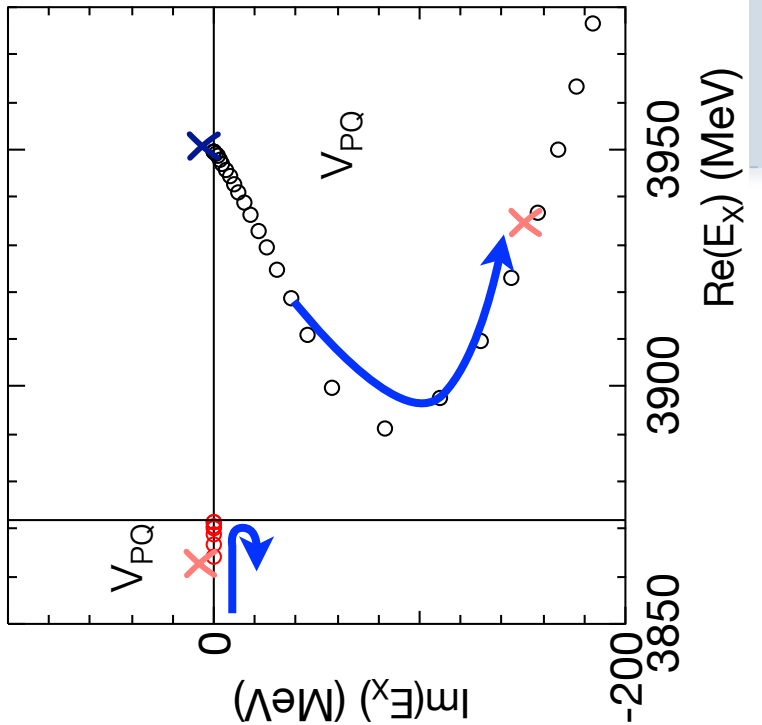

5000
4750
4500
4250
4000
3750
3500
n=5
n=4
n=3
n=2
n=1
X(3872)
$\chi_{c1}(1P)$
$D_s\bar{D}_s^*$, $J/\psi\phi$
$D\bar{D}^*$, $J/\psi\omega$, $J/\psi\rho$
Exp.
QM($^3P_1$)

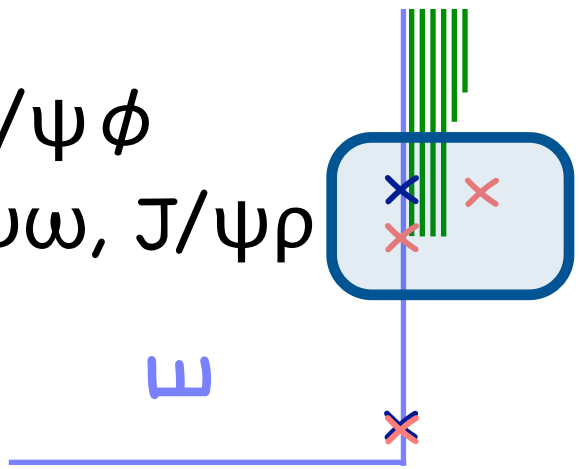
1^{++} Spectrum



$D_s\bar{D}_s^*$, $J/\psi\phi$

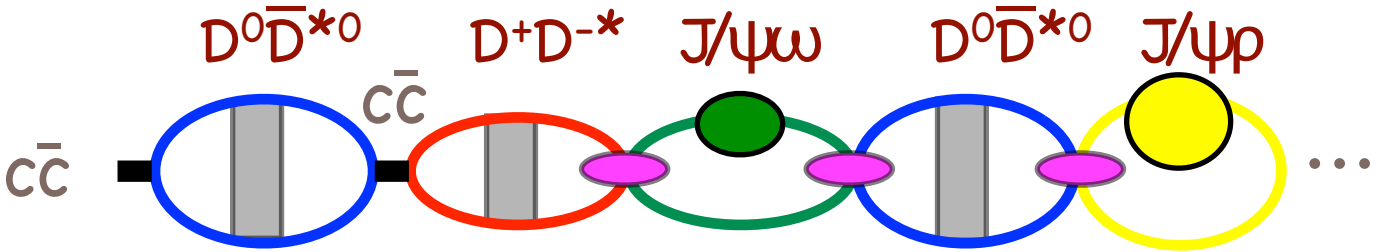
$D\bar{D}^*$, $J/\psi\omega$, $J/\psi\rho$





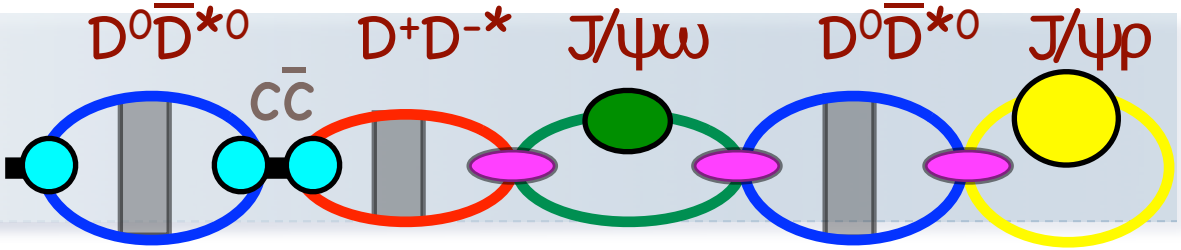
Our picture of X(3872)

- Two-meson molecule with a $c\bar{c}$ core:
  - $c\bar{c}(1P)$ - $c\bar{c}(2P)$ - $D^0\bar{D}^{*0}$ - 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]

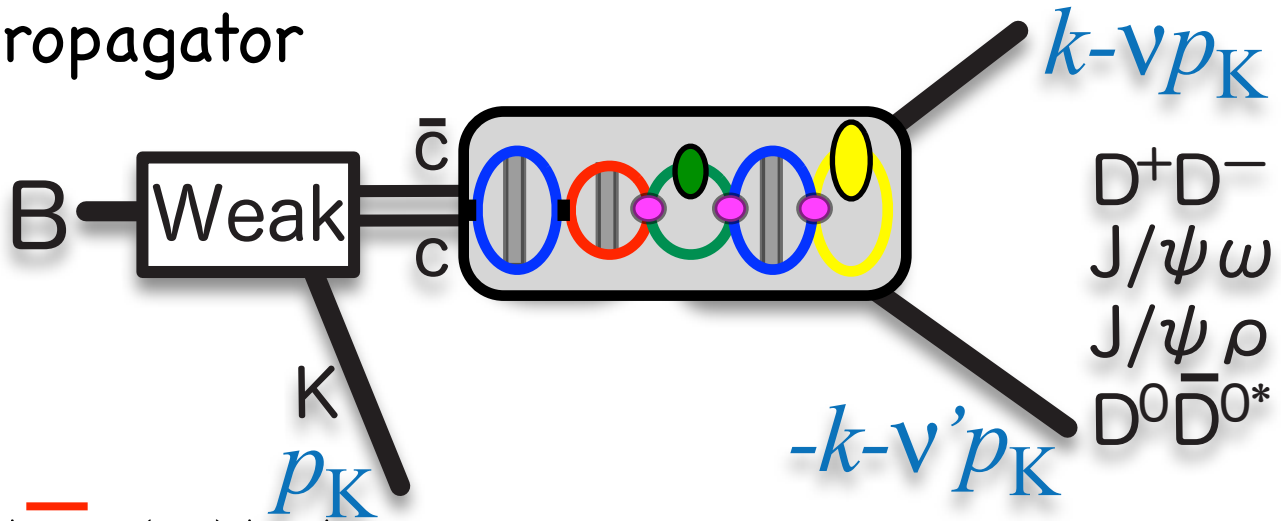
Potentials



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

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

- Width in the propagator



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

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

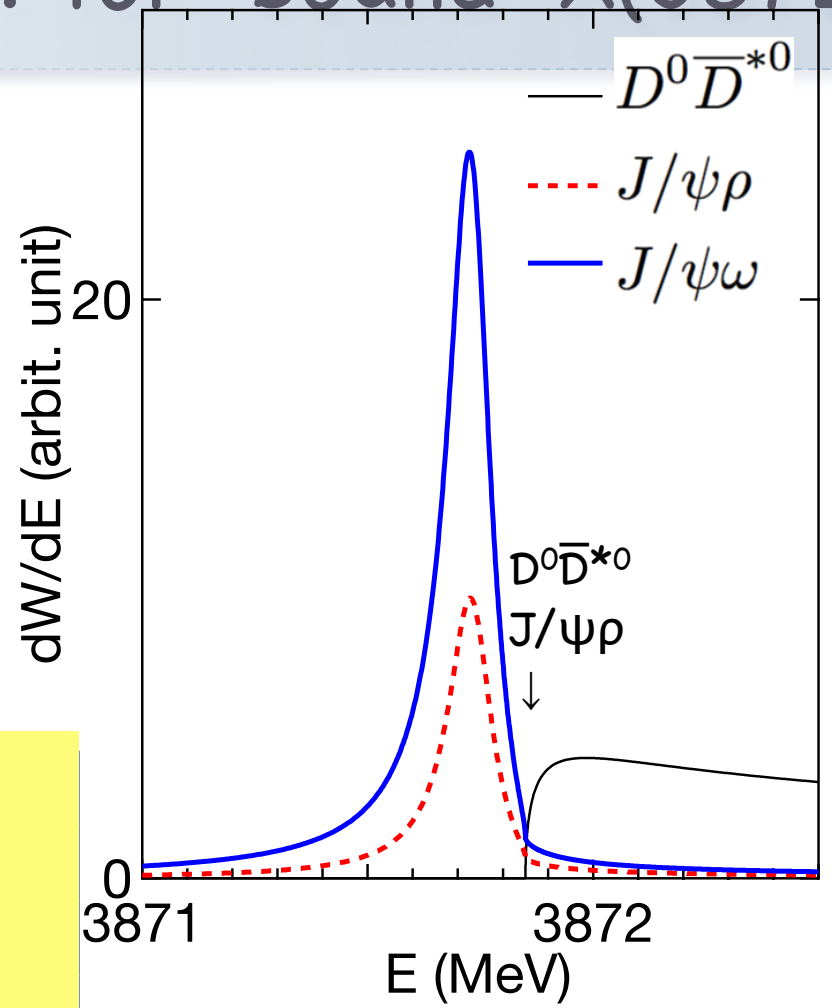
← observed $\rho \to \pi\,\pi$ or $\omega \to \pi\,\pi\,\pi$ width

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

$c\bar{c}$ → 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.

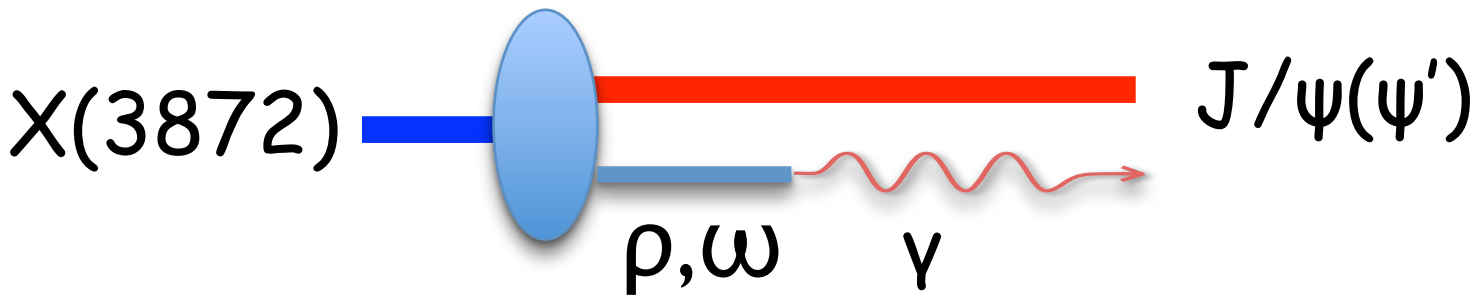
Thin peak, isospin mixing can be explained by this picture.



- Any other way to see the X(3872) structure??
  - radiative decay !

Radiative decay of X(3872)

- Vector meson dominance



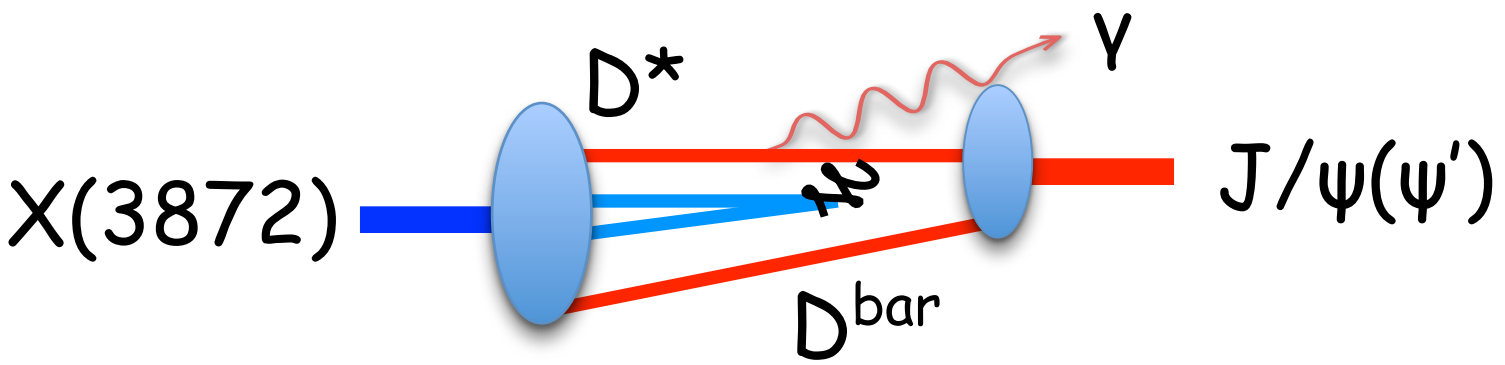
e.g. E.S. Swanson, PLB598, 197 (2004)

Y. Dong etal, J Phys.G: Nucl.Part.Phys.38 (2011) 015001

seems small if the $\rho,\omega \to e^+e^-,\mu^+\mu^-$ experimental widths are used

Radiative decay of X(3872)

- DD meson (or J/ψ_8 ρ_8) loop at the short range



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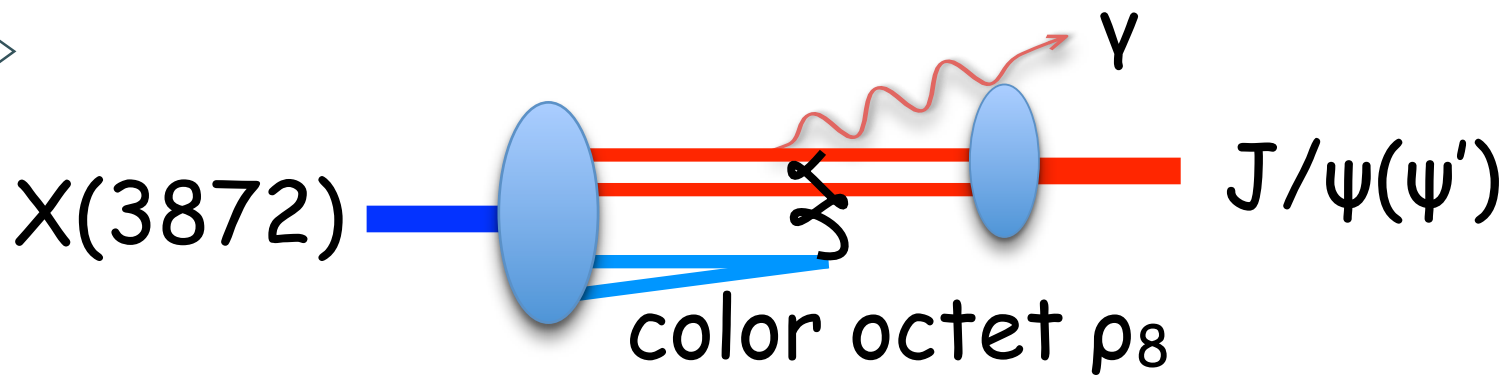
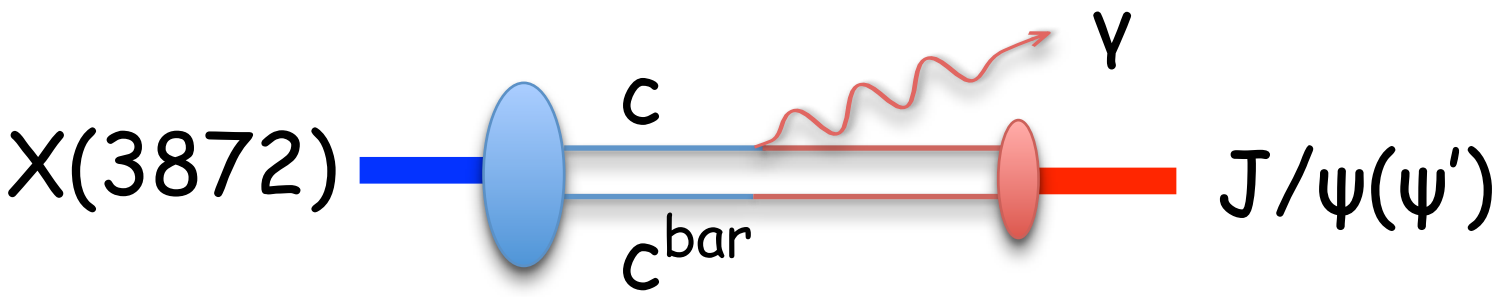
  - 

have to evaluate also in our picture
but not yet done

Radiative decay of X(3872)

- E1 transiton of cc^{bar} core to $J/\psi(\psi')\,\gamma$



e.g. E.S. Swanson, PLB598, 197 (2004)

Y. Dong etal, J Phys.G: Nucl.Part.Phys.38 (2011) 015001

Seems dominant.

We consider this diagram here.

Radiative decay width: bound X(3872)

- E1 transiton of $c\bar{c}$ core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

$Z^2_{c\bar{c}}$: $c\bar{c}$ probability in $X(3872)$.

$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

  - harmonic oscillator

<χ|r|ψ>	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	0	√5/2 b
$\chi_{c1}(1P)$	√3/2 b	-b

Radiative decay width: bound X(3872)

- E1 transiton of $c\bar{c}^{bar}$ core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

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$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

- Solved the K+Color-Coulomb+Conf

r	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	0.04	0.52
$\chi_{c1}(1P)$	0.33	-0.41

Γ(keV)	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	21	
$\chi_{c1}(1P)$	207	

(exp)
285keV

Radiative decay width: bound X(3872)

- E1 transiton of $c\bar{c}^{bar}$ core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

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$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

- Solved the K+Color-Coulomb+Co from M_X

r	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	0.04	0.52
$\chi_{c1}(1P)$	0.33	-0.41

Γ(keV)	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	16	57
$\chi_{c1}(1P)$	1111	36

Radiative decay width: bound X(3872)

- E1 transiton of $c\bar{c}^{bar}$ core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

$Z^2_{c\bar{c}}$: $c\bar{c}$ probability in $X(3872)$.

$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

  - To see the $\chi_{c1}(2P)$ pole, look into ψ(2S)γ

r	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	0.04	0.52
$\chi_{c1}(1P)$	0.33	-0.41

  - To explain the final J/ψ γ, $\chi_{c1}(1P)$ should be included.

Radiative decay width: bound X(3872)

- 3 parameter sets to reproduce bound X(3872) with BE=0.11 MeV.

model	$Z^2_{cc(1P)}$	$Z^2_{cc(2P)}$	
a) A00	—	0.036	$g_{DD-1P} = 0$
b) A01	0.001	0.036	$g_{DD-1P} = g_{DD-2P}/10$
c) A10	0.011	0.060	$g_{DD-1P} = - g_{DD-2P}$

Radiative decay width: bound X(3872)

- E1 transiton of $c\bar{c}^{bar}$ core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

$Z^2_{c\bar{c}}$: $c\bar{c}$ probability in $X(3872)$.

$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

model	J/ψγ	ψ(2S)γ	
a) A00	0.6	2.1	$g_{DD\text{-}1P} = 0$
b) A01	1.1	2.0	$g_{DD\text{-}1P} = g_{DD\text{-}2P}/10$
c) A10	6.1	6.2	$g_{DD\text{-}1P} = -g_{DD\text{-}2P}$

Radiative decay width: bound X(3872)

- E1 transiton of $c\bar{c}^{bar}$ core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

$Z^2_{c\bar{c}}$: $c\bar{c}$ probability in $X(3872)$.

$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

model	J/ψγ	ψ(2S)γ	ratio ψ'/J/ψ
a) A00	0.6	2.1	3.6
b) A01	1.1	2.0	1.8
c) A10	6.1	6.2	1.0

sensitive to the $\chi_{c1}(1P)$ mixing

Radiative decay : γ spectrum

- X(3872), created from cc^bar(2P), decays into ψγ :

$$\frac{\mathrm{d}W(c\bar{c}\to\psi\gamma)}{\mathrm{d}E} = -\frac{1}{\pi}\mathrm{Im}\; G_Q{}^{\gamma}$$

$$= \delta(E-(\Omega_\psi+\omega_\gamma))\sum_\epsilon \left|\langle\psi\gamma_{k\epsilon}|(V_{\gamma Q} + V_{\gamma P}G^{(P)}V_{PQ})G_Q|c\bar{c}\rangle\right|^2$$

$$= \sum_\epsilon \left|\sum_\beta \langle\psi\gamma_{k\epsilon}|V_{\gamma Q}|c\bar{c}_\beta\rangle\langle c\bar{c}_\beta|G_Q|c\bar{c}\rangle\right|^2_{E=\Omega_\psi+\omega_\gamma}$$

$$\Gamma\Big(\chi_{c1}(mP)\to\psi(nS)+\gamma\Big)$$

phase is not phenomenologically determined.

Radiative decay : γ spectrum

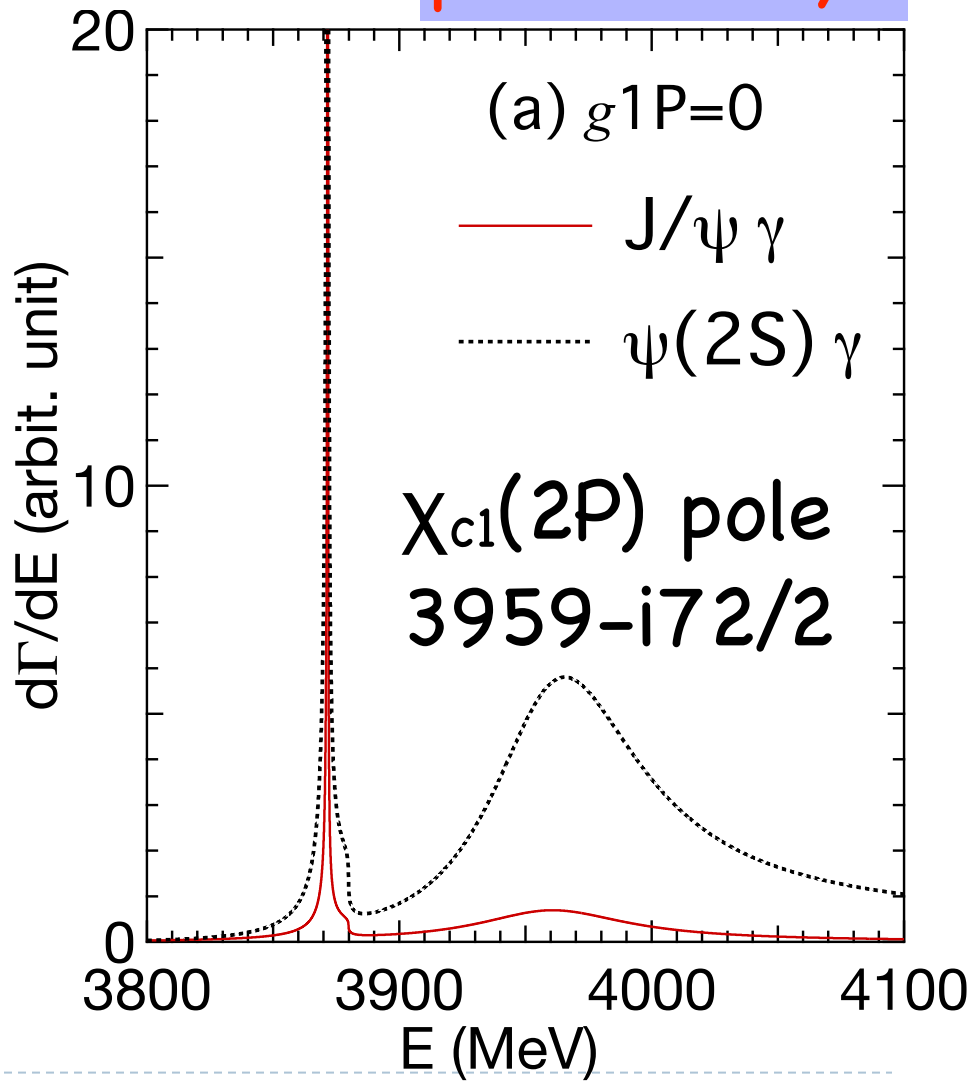
preliminary

- dΓ(X→ψγ)/dE
  - model only with cc^{bar}(2P)
  - Ratio of the strength at peak

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

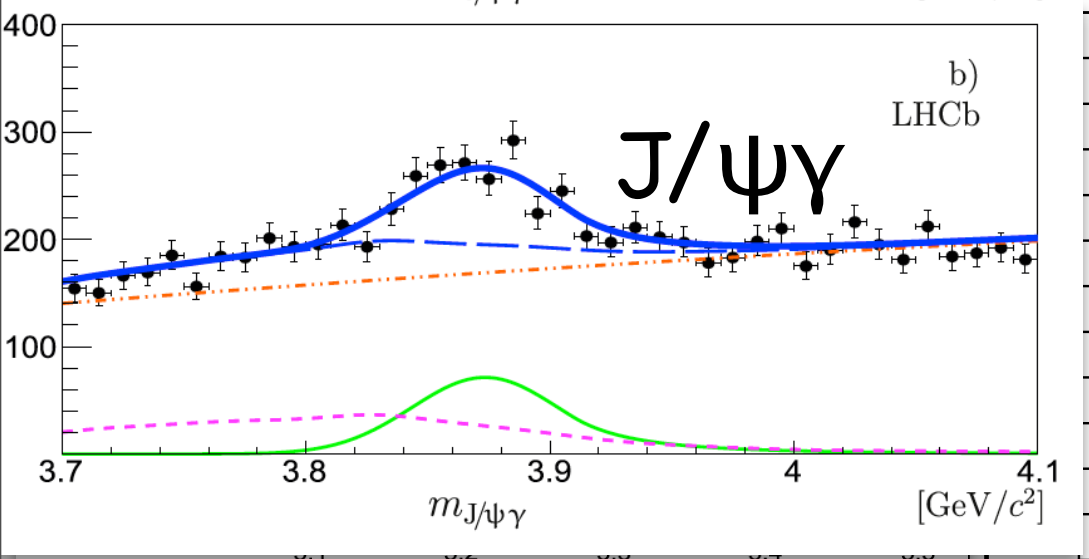
= 3.43

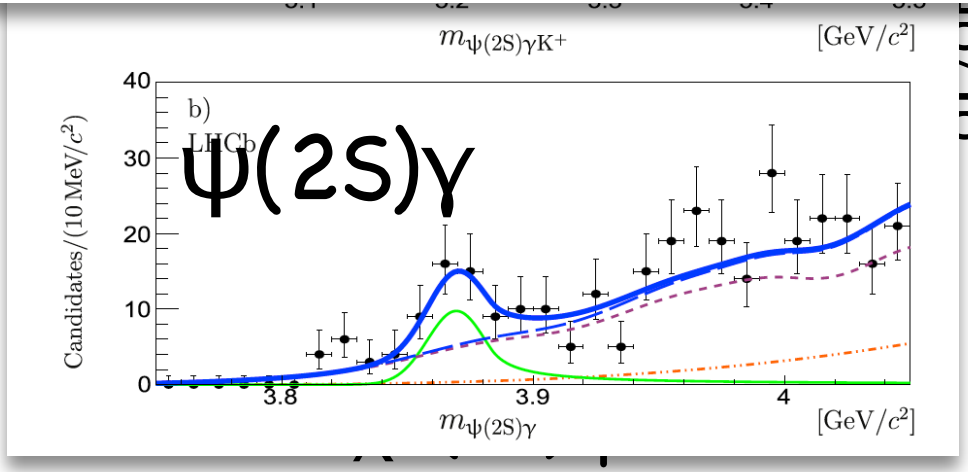
  - ψ(2S)γ spectrum shows the χ_{c1}(2P) pole.

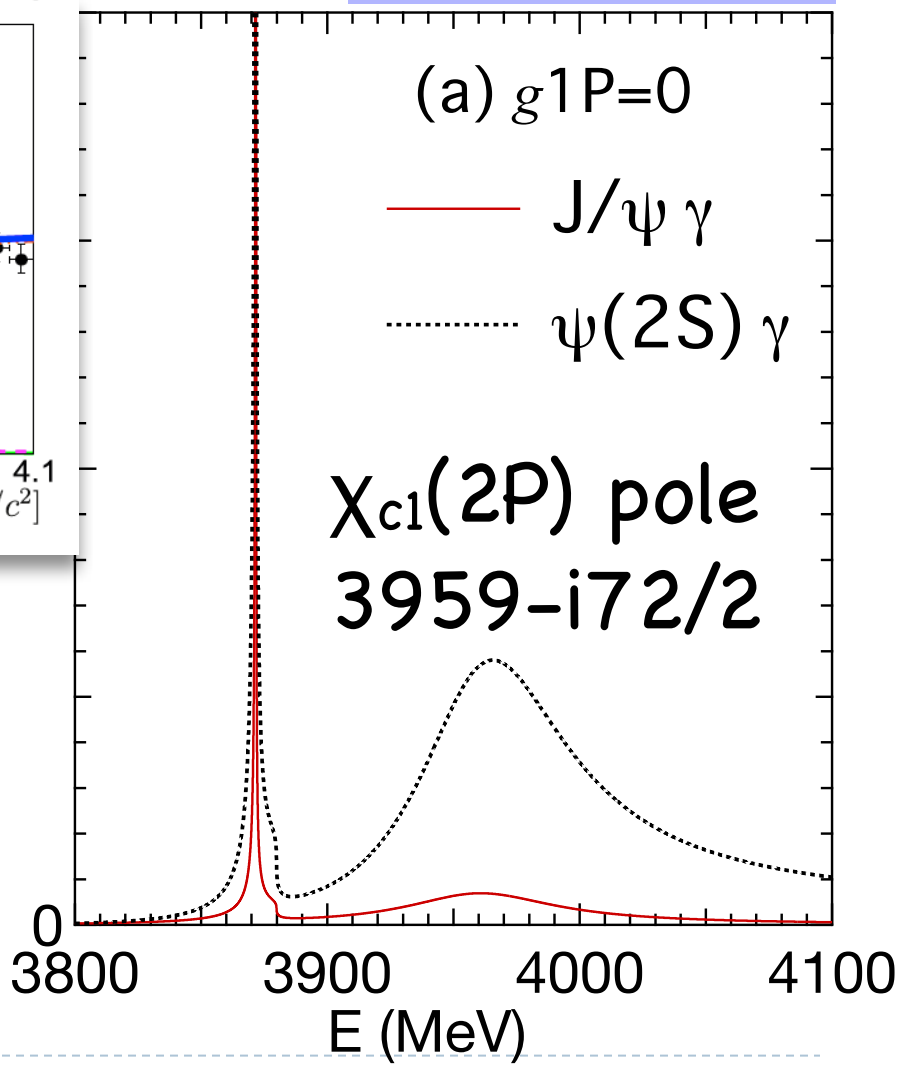


Radiative decay : γ spectrum

preliminary

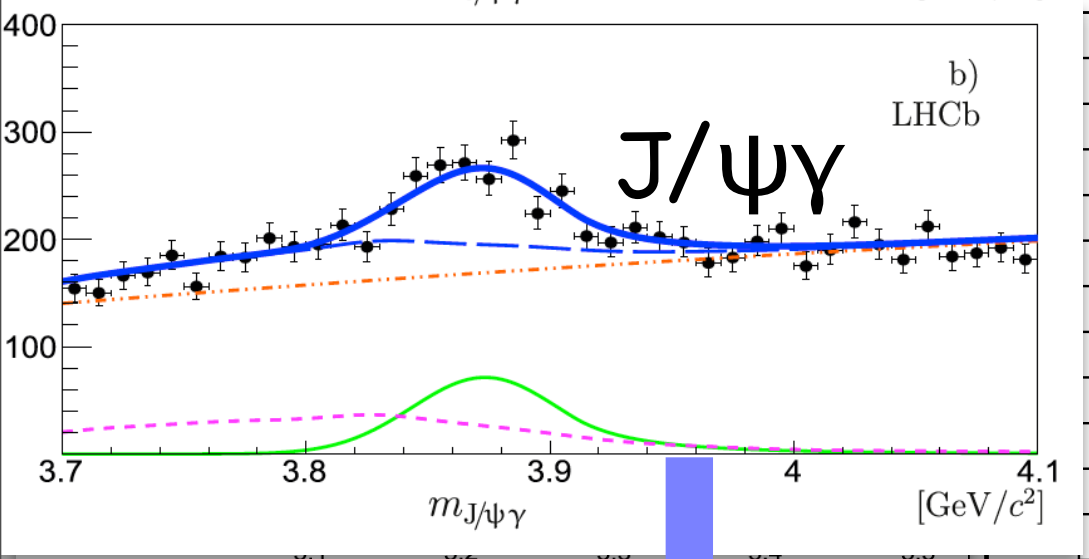


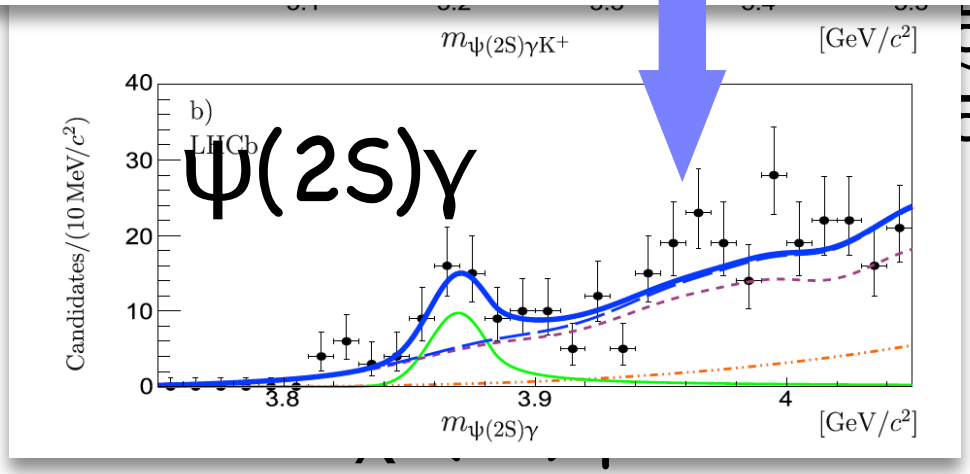


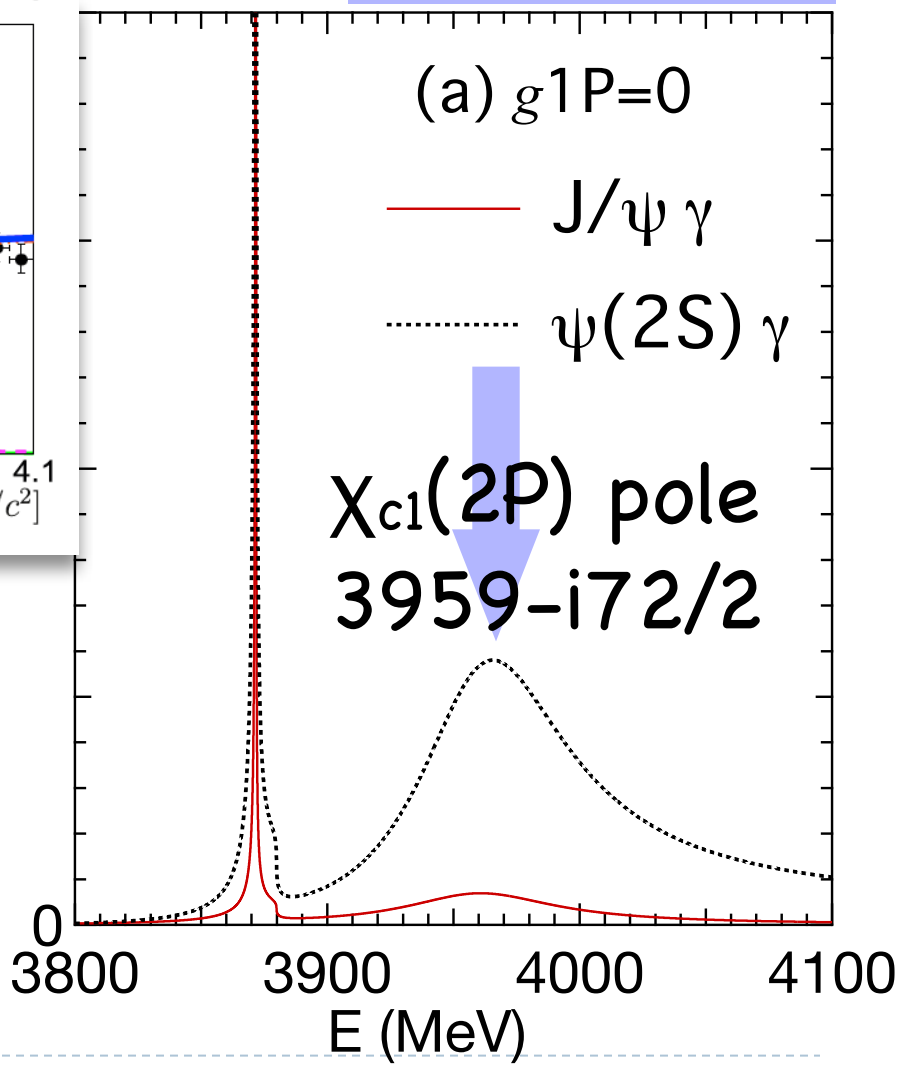


Radiative decay : γ spectrum

preliminary







Radiative decay : γ spectrum

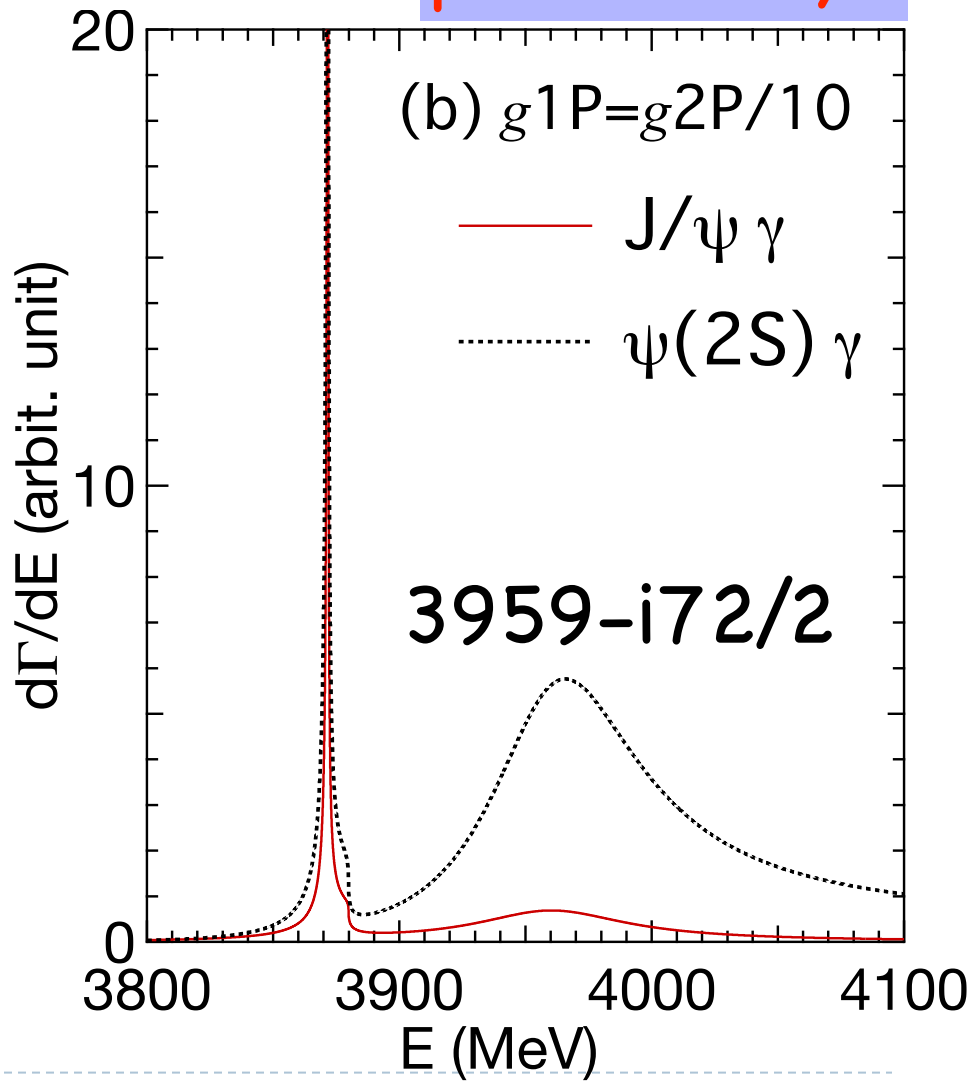
preliminary

- dΓ(X→ψγ)/dE
  - model
    $g_{DD\text{-}1P} = g_{DD\text{-}2P}/10$
  - Ratio of the strength at peak

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

= 1.85

  - ψ(2S)γ spectrum shows the $\chi_{c1}(2P)$ pole.



Radiative decay : γ spectrum

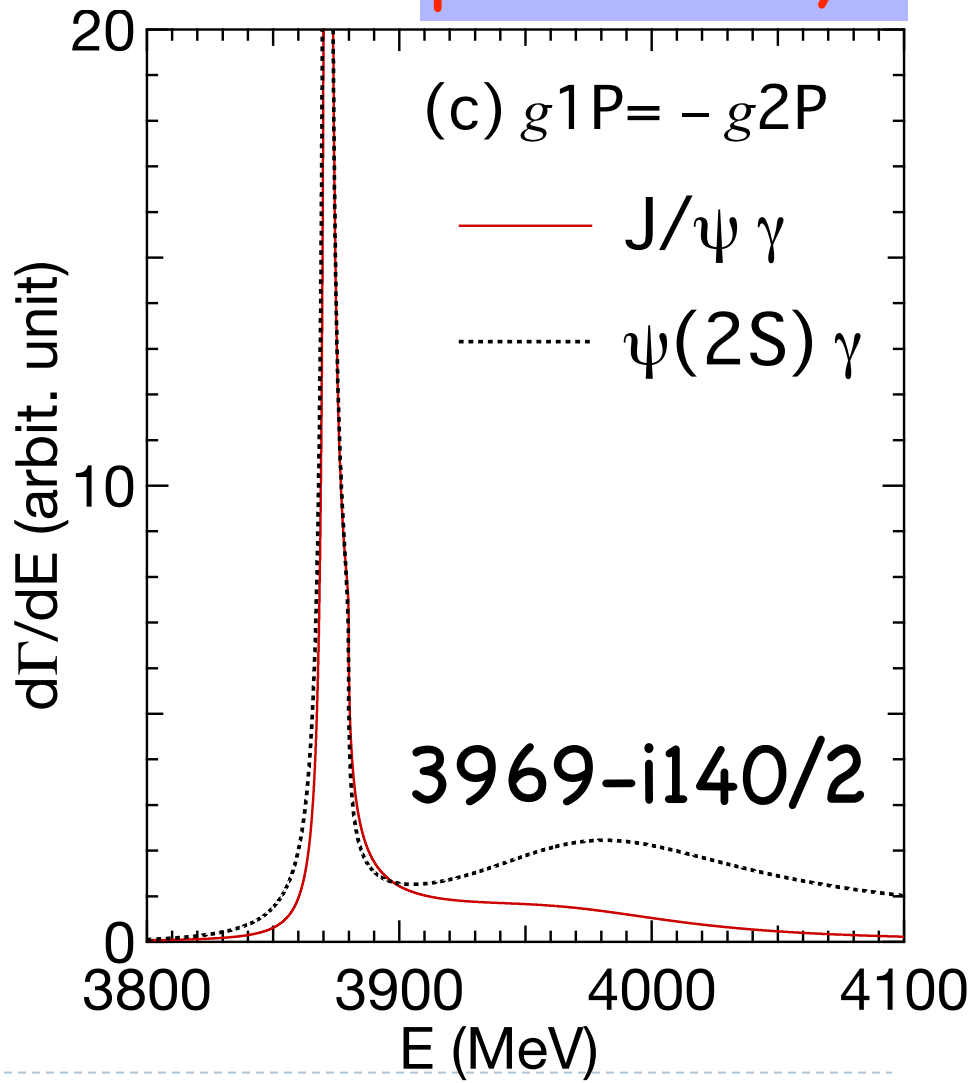
preliminary

- dΓ(X→ψγ)/dE
  - model
    $g_{DD\text{-}1P} = -g_{DD\text{-}2P}$
  - Ratio of the strength at peak

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

= 1.07

  - the $\chi_{c1}(2P)$ pole goes far from the axis.



Summary

- Radiative decay of X(3872) is calculated by using the model which includes
  - $\chi_{c1}(1P)$ - $c\bar{c}(2P)$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ - $J/\psi\rho$
- X(3872) feature can be explained by a two-meson molecule with the $c\bar{c}$ components.
- The structure of X(3872), such as $\chi_{c1}(2P)$ pole may be seen in the radiative decay spectrum.
- The ratio of the decay $R_\gamma = \dfrac{B(X(3872) \to \psi(2S)\,\gamma)}{B(X(3872 \to J/\psi\,\gamma)}$ is sensitive to the $\chi_{c1}(1P)$ component.