The Theory of X, Y, and Z States

XIV International Conference on Hadron Spectroscopy

R.P. Springer, Munich, June 2011

Observed spectrum of states (above DD)

Examples from theory landscape

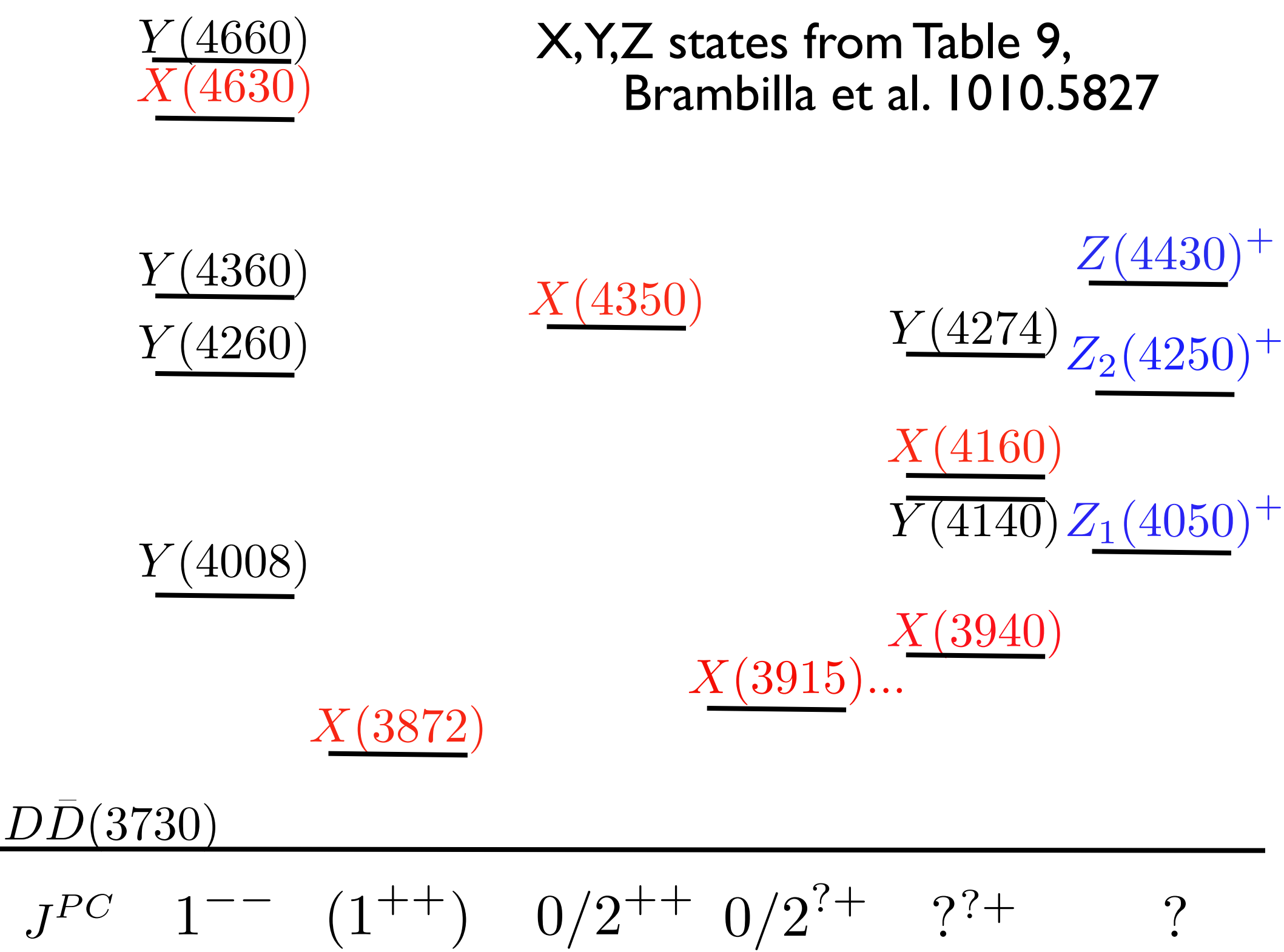
Effective field theory for the X(3872)

Selected X(3872) predictions

Reviews: Brambilla et al.1010.5827;Voloshin 0711.4556;

(hadron11: 9 talks on 3872; 6 on other X,Y,Z)

X,Y,Z states from Table 9,
Brambilla et al. 1010.5827



Techniques/Descriptions/Strategies

QCD Sum Rules

Non-relativistic QCD

Heavy Quark Effective Theory

Heavy Hadron Chiral Perturbation Theory

X-EFT Lattice Potential Models

Mixtures

Molecule

Baryonium

Tetraquark

Hybrids

Coupled channels

Hadrocharmonium

Hadron 2011 X,Y,Z Theory talks/posters
(to see or to have seen)

F. De Fazio (Plenary II) EFT radiative decays
X(3872)

C.Zanetti (Heavy Hadrons I) QCD Sum Rules
X(3872)

H. Noya (Quarkonia I) Diquark Cluster model (4-q- states)
X(3940),X(4260),X(4350),X(4430),X(4660)

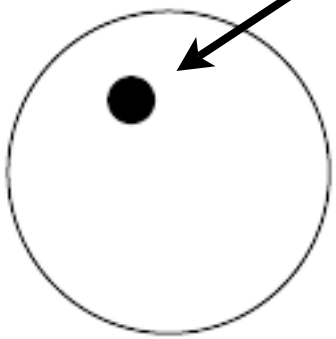
R. Molina (Poster) dynamically generated
Y(3940),Z(3930),X(4160)

D. Rodriquez Entem (Quarkonia 4) Molecules
X(3872),X(3915),X/Y(3940),Y(4008)

M. Karliner (Heavy Hadrons 5) Tetraquarks
X(3872), etc.

Hadrocharmonium

$J/\psi, \psi(2S), ...$even Υ? affinity for light hadronic matter



small $Q\overline{Q}$

light (excited) hadronic matter

Y's are 1^{--}

	widths (MeV)
$Z_1(4050)^+ \to \pi^+\chi_{c1}(1P)$	82^{+51}_{-55}
$Z_2(4250)^+ \to \pi^+\chi_{c1}(1P)$	177^{+321}_{-72}
$Y(4260) \to \pi\pi J/\psi$	108 ± 14
$Y(4360) \to \pi^+\pi^-\psi(2S)$	96 ± 42
$Z(4430)^+ \to \pi^+\psi(2S)$	107^{+113}_{-71}
$Y(4660) \to \pi^+\pi^-\psi(2S)$	48 ± 15

look for J/ψ with baryons; b analogs

Y(4260): BaBar/Belle/Cleo; no D's

- Charmonium Hybrid -- gluonic excitations

  Lattice; heavy quark symmetry; NRQCD

  Potential yields tower of excitations[1]

- Bound state or molecule (next slide)

- Tetraquark[2,3] $[cs][\overline{cs}]$

- Hadrocharmonium (previous slide)

- QCDSR[3] $[c\overline{q}]_1[\overline{c}q]_1;\ (S+V),(P+A)$

[1] Horn/Mandula; Hasenfratz/Horgan/Kuti/Richard; Juge/Kuti/Morningstar; Bali/Pineda; Zhu; Kou/Pene; Close/Page

[2] Maiani/Riquer/Piccinini/Polosa

[3] Nielsen/Navarra/Lee

Molecules: do the constituents retain their identify as hadrons?

(details in the X(3872) section)

$X(3872)$	$\overline{D}^0 D^{*0}$	
$X(3915)$	$\overline{D}^{*0} D^{*0} + D^{*+} D^{*-}$	BGL
$Y(4140)$	$D_s^{*+} D_s^{*-}$	BGL
$Y(4260)$	$D_0 \overline{D}^*, \psi(2S) f_0(980)$	AN, TKGO
$Z(4430)^+$	$D^{*+} \overline{D}_1^0$	LMNN/BGL
$X(4630)$	$\psi(2S) f_0(980)$	GHHM
$Y(4660)$	$\psi(2S) f_0(980)$	GHM

BGL=Branz,Gutsche,Lyubovitskij LMNN=Lee,Miharo,Navarro,Nielsen

TKGO=Torres,Kehmchandari,Gamermann,Oset AN=Albuquerque,Nielsen

GH(H)M=Guo,(Haidenbauer),Hanhart,Meissner

b Exotics above threshold - Belle

MeV	$Z_b(10610)$	$Z_b(10650)$	$Y_b(10888)$
mass	10608.1 ± 1.7	10653.3 ± 1.5	10888.4 ± 3.0
width	15.5 ± 2.4	14.0 ± 2.8	$30.7^{+8.0}_{-7.7}$
mode	$\Upsilon(nS)\pi^+\pi^-$ $n = 1, 2, 3$ $h_b(mP)\pi^+\pi^-$ $m = 1, 2$	$\Upsilon(nS)\pi^+\pi^-$ $n = 1, 2, 3$ $h_b(mP)\pi^+\pi^-$ $m = 1, 2$	$\Upsilon(nS)\pi^+\pi^-$ $n = 1, 2, 3$

Explanations:

$Y_b(1^{--})$ could be analog of $Y(4260)$

hybrid $b\bar{b}g$

disturbed $\Upsilon(5S)$

$Z_b: \; I^G = 1^+ \; J^P = 1^+$ This conference : A.Kuzmin

charged : cannot be $\bar{b}b$ alone

tetraquarks: Karliner/Lipkin prediction

$$\Upsilon(nS) \to \pi^{\pm} T_{bb}^{\mp} \to \Upsilon(mS)\pi^-\pi^+$$

isovector charged tetraquark $\bar{b}b\bar{d}u$ $\bar{b}b\bar{u}d$

prediction : look for subthreshold $I = 0$ state

Molecular overlap: Bugg

$\overline{B}B^*$ threshold $= 10604.3 \pm 0.6$ MeV

$Z_b(10610)$ analogous to X(3872)?

$\overline{B}^*B^*$ threshold $= \overline{B}B^* + 46$ MeV

$Z_b(10650)$ analogous to X(3915)?

hypothesis : each is $\bar{\mathrm{b}}\mathrm{b} + \overline{\mathrm{B}}\mathrm{B}^{(*)}$

Voloshin: more molecules from heavy quark spin symmetry; also predicts decay ratios

$$1^-(0^+) = \frac{1}{2} 0^-_{b\bar{b}} \times 0^-_{lt} - \frac{\sqrt{3}}{2} \left(1^-_{b\bar{b}} \otimes 1^-_{lt} \right)_{J=0}$$

$$Z_b = 1^+(1^+) = \frac{1}{\sqrt{2}} \left(0^-_{b\bar{b}} \times 1^-_{lt} + 1^-_{b\bar{b}} \otimes 0^-_{lt} \right) \searrow$$

$$\Upsilon\pi, h_b\pi, \eta_b\rho$$

$$Z'_b = 1^+(1^+) = \frac{1}{\sqrt{2}} \left(0^-_{b\bar{b}} \times 1^-_{lt} - 1^-_{b\bar{b}} \otimes 0^-_{lt} \right) \nearrow$$

$$1^-(0^+) = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \times 0^-_{lt} + \frac{1}{2} \left(1^-_{b\bar{b}} \otimes 1^-_{lt} \right)_{J=0}$$

$$\rightarrow \eta_b\pi, \chi_b\pi, \Upsilon\rho$$

X(3872): molecular state?

$$\frac{1}{\sqrt{2}}\left(D^0\bar{D}^{0*}+\bar{D}^0D^{0*}\right)$$

Isospin issue:

$$\frac{\Gamma[\to J/\psi\pi^+\pi^-\pi^0]}{\Gamma[\to J/\psi\pi^+\pi^-]}=1.0\pm0.4\pm0.3$$

Belle 2005

$$\frac{\Gamma[\to J/\psi\omega]}{\Gamma[\to J/\psi\pi^+\pi^-]}=0.8\pm0.3$$

BaBar 2010

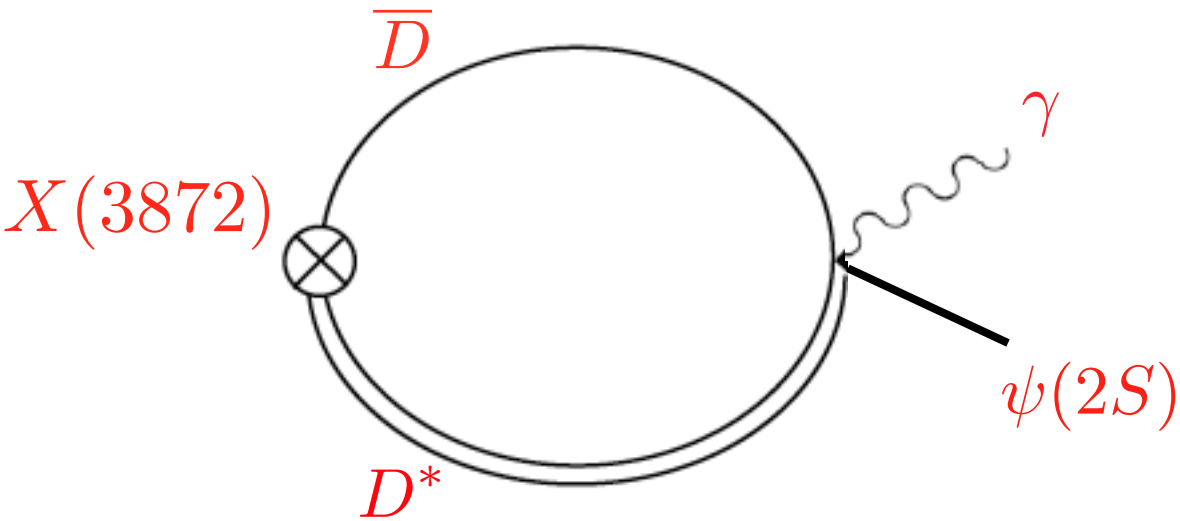
$$J^{PC}=1^{++}\text{ or }2^{-+}$$

multipole question

$$m_{D^0\bar{D}^{0*}}-m_{X(3872)}=0.42\pm0.39\ \text{MeV}$$

S-wave

X-Effective Field Theory: Fleming, Kusunoki, Mehen, van Kolck



Factorization theorems: Braaten/Kusunoki/Lu

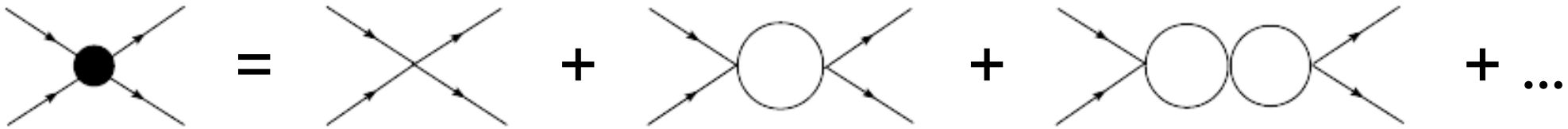
$$\text{Rate} = \frac{1}{3}\sum_{\lambda} |\langle 0|\frac{1}{\sqrt{2}}\epsilon_i(\lambda)\,(V^i\,\bar{P} + \bar{V}^i\,P)|X(3872,\lambda)\rangle|^2$$
$$\times\ (\text{phase space}) \times |\mathcal{C}\left(\overline{D}D^* \to f\right)|^2$$

Universal shallow-bound-state properties from effective range theory: Braaten/Voloshin...

$$\psi_{DD^*}(r) \propto \frac{e^{-\gamma r}}{r} \qquad B = \frac{1}{2\mu_{D^*D}a^2}$$

$$\gamma \sim 20\ \text{MeV}$$
$$a \sim 7\ \text{fm}$$
$$\langle r\rangle \sim 5\ \text{fm}$$

Compare Systematic NN treatment: NN-EFT (no pions)



$$A = \mathcal{C} + i\mathcal{C}^2 \frac{Mp}{4\pi} + \mathcal{C}^3 \left(\frac{Mp}{4\pi}\right)^2 + \cdots$$

$$A = \frac{4\pi}{M}[-a + ia^2 p + \frac{1}{2}(a^3 - a^2 r_0)p^2 + \cdots]$$

does not converge

$$a^{(^1S_0)} \sim -\frac{1}{8\ \mathrm{MeV}} \qquad a^{(^3S_1)} \sim \frac{1}{36\ \mathrm{MeV}}$$

Both S-wave scattering lengths anomalously large => momentum expansion fails => reorganize to treat C's nonperturbatively

$$A = -\frac{4\pi}{M}\frac{1}{1/a + ip} + \cdots$$

with effective range:

$$A = -\frac{4\pi}{M}\frac{1}{1/a - \frac{1}{2}rp^2 + ip} + \cdots$$

EM effects easily included

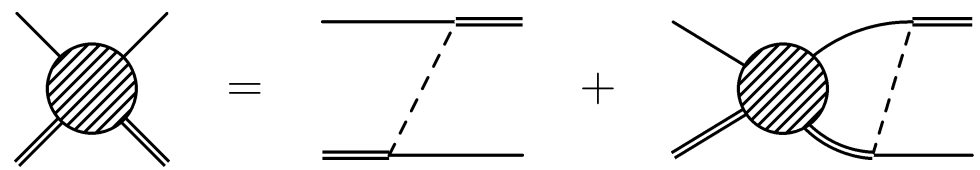
IF $$X(3872) \sim \frac{1}{\sqrt{2}}(D^0\overline{D}^{*0} + D^{*0}\overline{D}^0)$$

$$m_X = (3871.55 \pm 0.20) \ \text{Mev} \qquad E_X = (-0.26 \pm 0.41) \ \text{MeV}$$

$$a^{-1} \sim \sqrt{2\mu_X B_X}$$

$$\mathcal{L} = \sum_{j=D^0,D^{*0},\bar{D}^0,\bar{D}^{*0}} \psi_j^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_j} \right) \psi_j + \Delta X^\dagger X$$
$$- \frac{g}{\sqrt{2}} \left(X^\dagger (\psi_{D^0}\psi_{\bar{D}^{*0}} + \psi_{D^{*0}}\psi_{\bar{D}^0}) \ + \ \text{h.c.} \right) + \cdots$$

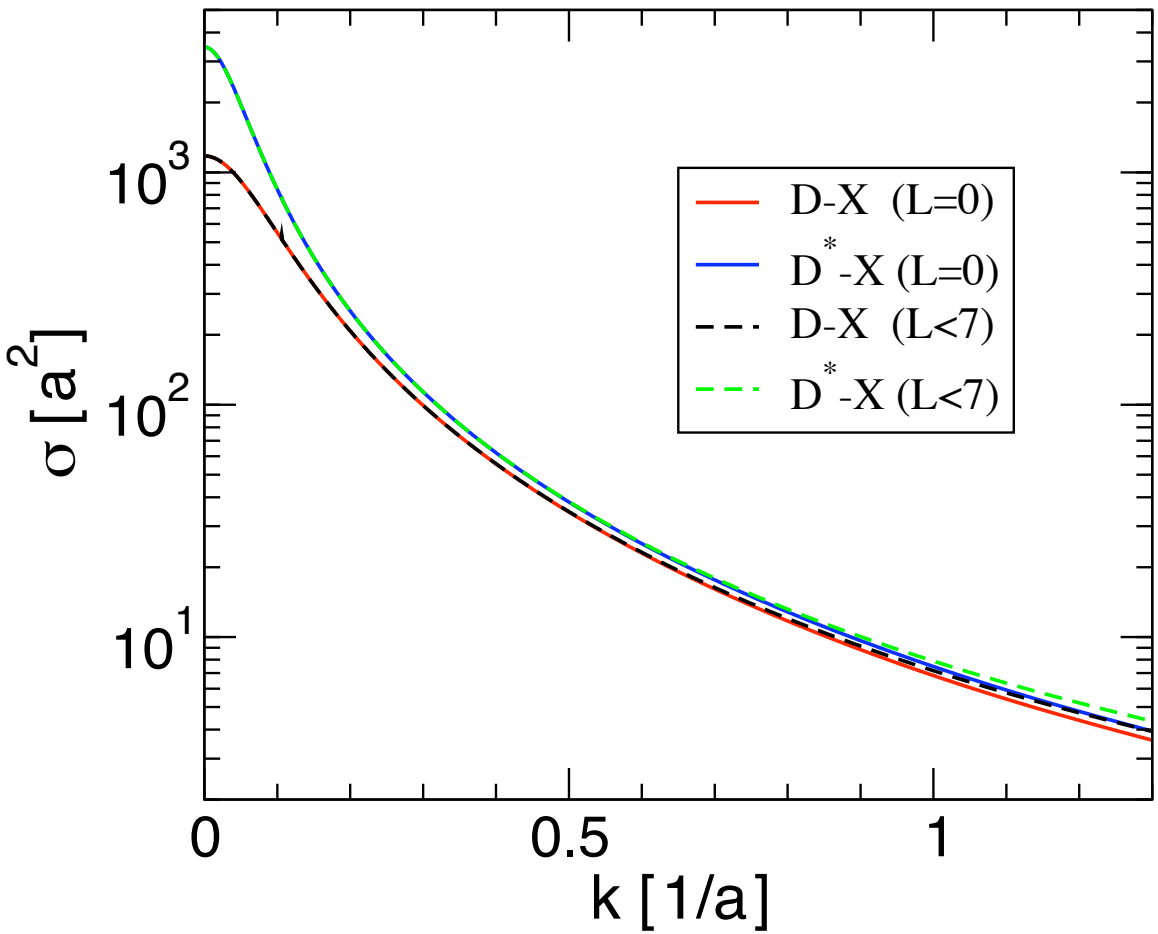
Integral equation:



Results depend only on scattering length

$$a_{D^0X} = -9.7a \qquad a_{D^{*0}X} = -16.6a$$

Three body cross section vs scattering length



LHC possibilities: $B_c \sim 10^7$ per week

$B\overline{B}$ final state interactions

$\sigma(b\bar{b}) \sim 0.4$ mb $\qquad$ $\sigma(b\bar{b}b\bar{b}) \sim 5$ fb

$X(3872) \to \psi(2S)\gamma$ factorization XEFT + HBChPT

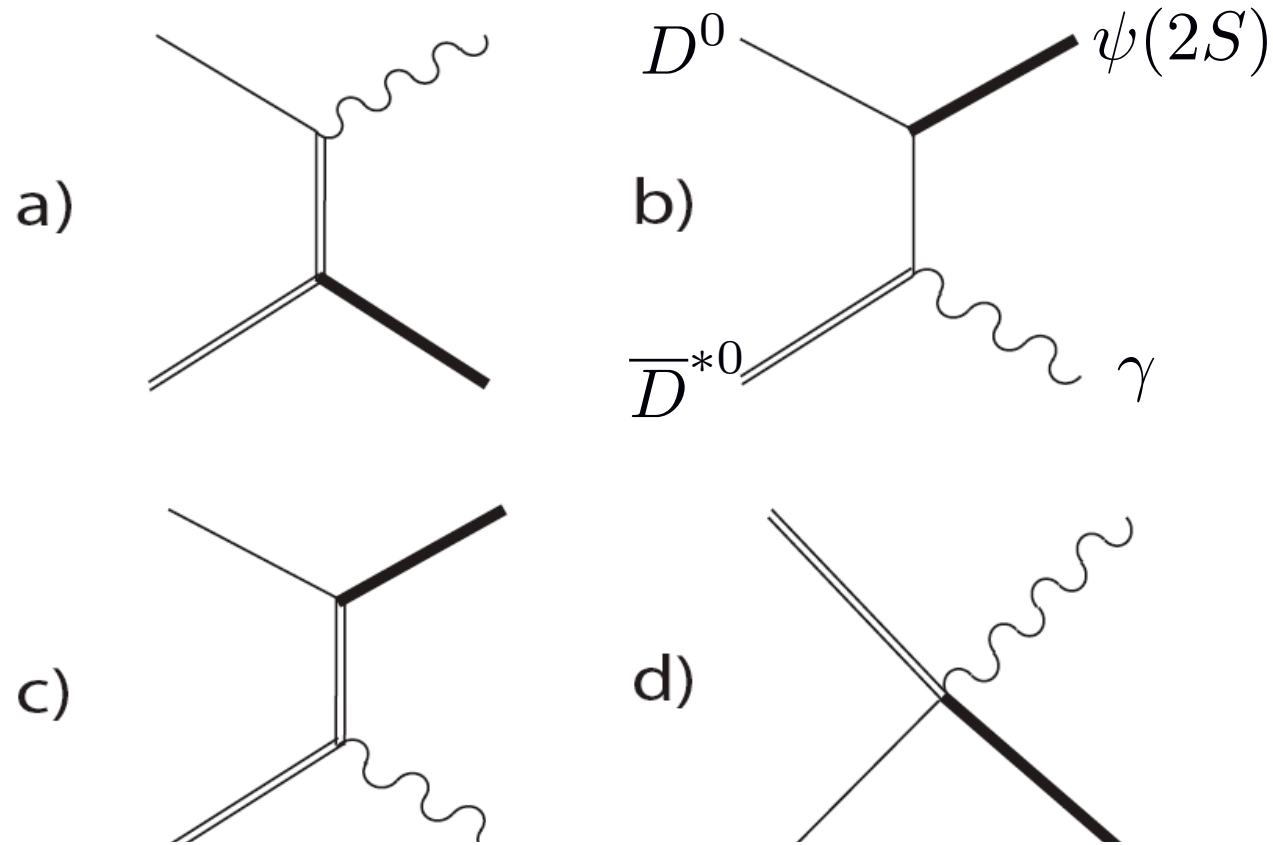
Mehen/RPS

$\beta^{-1} \sim 356$ MeV

Hu, Mehen

$g_2 \sim 0.81$ GeV$^{-3/2}$

Guo et al., 0907.0521



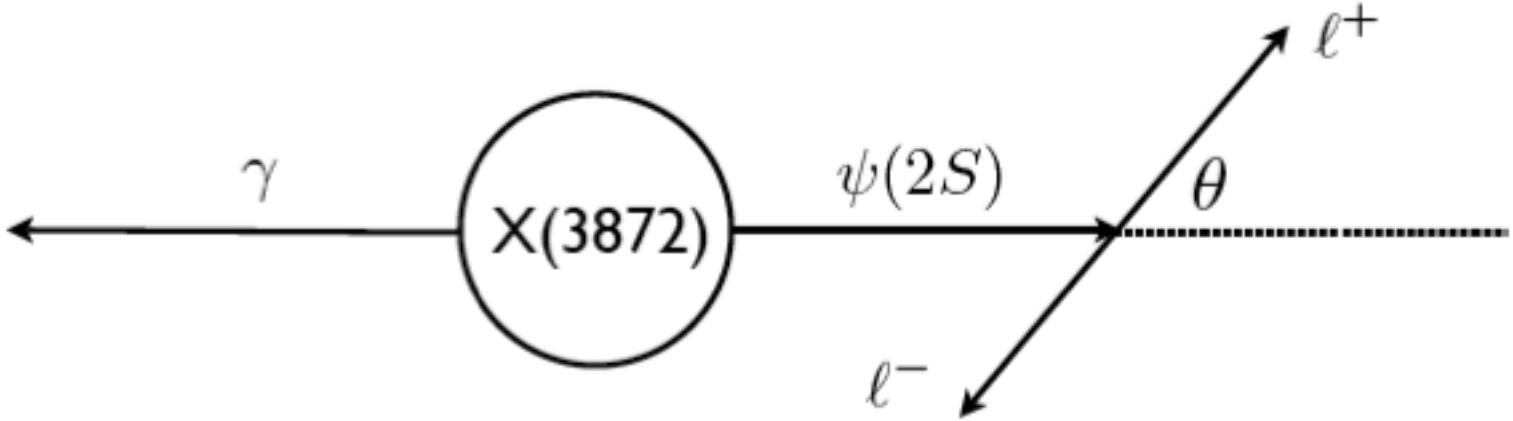
$$\mathcal{L} = \frac{e\beta}{2}\mathrm{Tr}[H_1^\dagger H_1\,\vec{\sigma}\cdot\vec{B}\,Q_{11}] + c.c. + i\frac{g_2}{2}\mathrm{Tr}[J^\dagger H_1\vec{\sigma}\cdot\overleftrightarrow{\partial}\,\bar{H}_1] + h.c.$$
$$+ i\frac{ec_1}{2}\mathrm{Tr}[J^\dagger H_1\vec{\sigma}\cdot\vec{E}\bar{H}_1] + h.c.$$

$$J = (\eta_c(2S), \psi(2S))$$

$$H_a \sim (D_a, D_a^*);\ a = 1, 2, 3$$

$$\frac{\Gamma(X(3872) \to \psi(2S)\gamma)}{\Gamma_{tot}} > 0.03 \text{ (BaBar, PDG)}$$

- Polarization $\psi(2S) \to \ell^+\ell^-$ $\boxed{\dfrac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos^2\theta}$ $\alpha = \dfrac{1-3f_L}{1+f_L}$



contact interaction

i) $g_2\beta \ll c_1$ d) only

$$f_L = \frac{1}{2}, \boxed{\alpha = -\frac{1}{3}}$$

$$\mathcal{M} \propto \vec{\epsilon}_X \cdot \vec{\epsilon}^{\,*}_\psi \times \vec{\epsilon}^{\,*}_\gamma$$

constituent decay

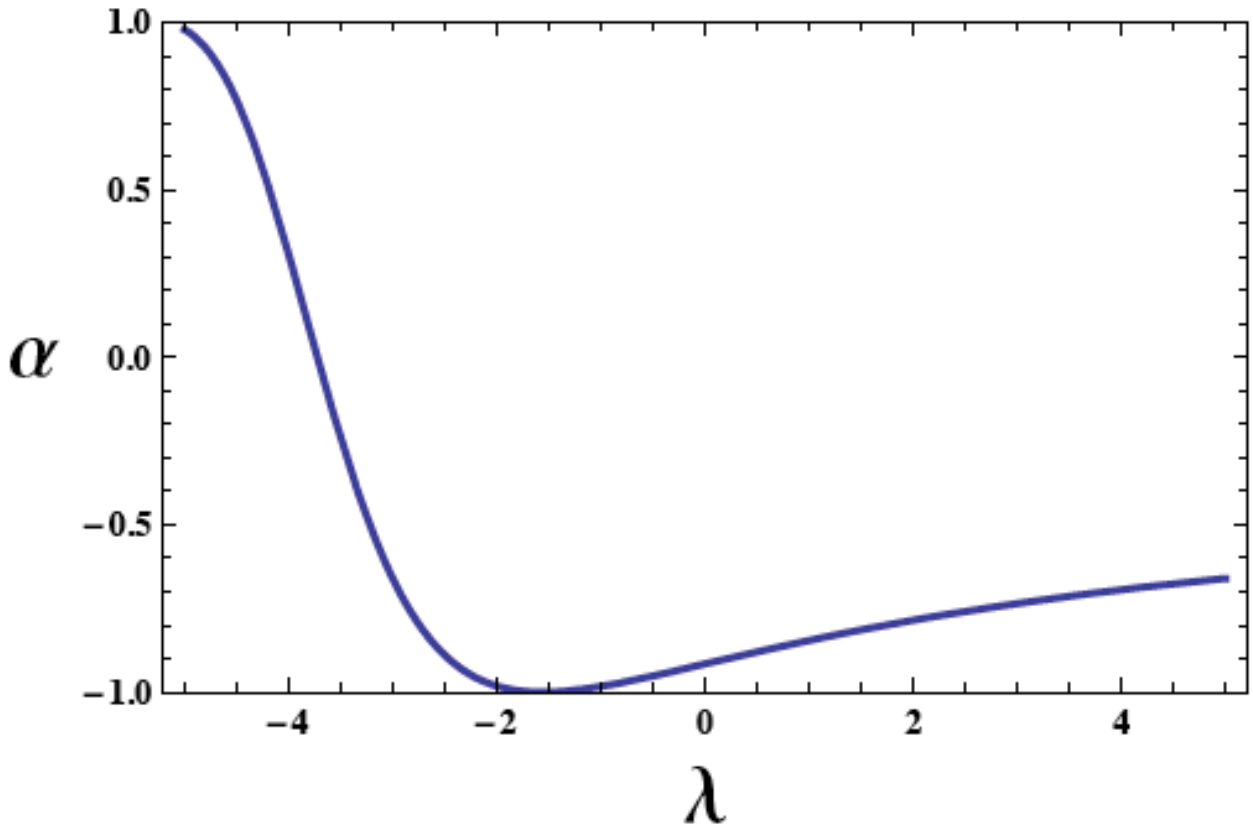
ii) $g_2\beta \gg c_1$ a-c) only b) dominate

$$f_L = \frac{4E_\gamma^4}{4E_\gamma^4 + (2E_\gamma + \Delta)^2(E_\gamma - \Delta)^2} = 0.92$$

$$\boxed{\alpha = -0.91}$$

- Polarization measurement would shed light on relative importance of decay mechanisms

- Polarization as function of $\lambda \equiv \dfrac{3c_1}{g_2\beta} \approx 1.3\,\dfrac{c_1}{\mathrm{GeV}^{-5/2}} \sim O(1)$



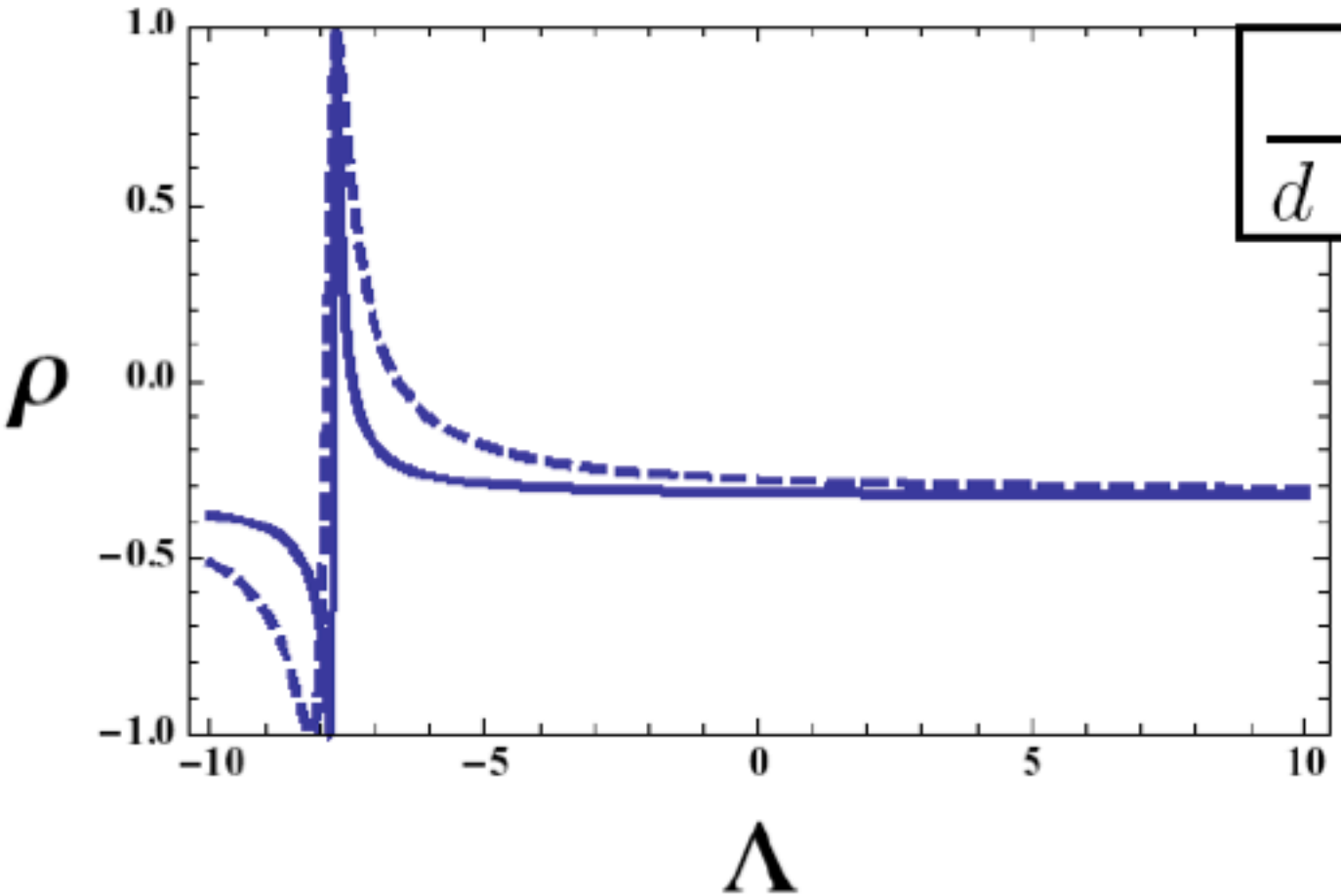
- Longitudinal Polarization $(\alpha < -0.5)$ for $-3.5 \leq \lambda \leq 5$

- $X(3872)$ as 2^{-+} : $\alpha = 0.08$

- $e^+e^- \to \psi(4040) \to X(3872)\gamma$ (BES?)

$\psi(4040)$ produced with polarization transverse to beam axis (LO)

same (crossed) graphs as $X(3872) \to \psi(2S)\gamma$



$$\frac{d\sigma}{d\cos\theta} \propto 1 + \rho\cos^2\theta$$

θ - angle from beam axis

$$\Lambda \equiv \frac{3\tilde{c}_1}{\tilde{g}_2\beta_+}$$

- $J^{PC} = 2^{-+}$ predicts $\rho = 0.08$

molecule predicts $\rho \approx -1/3$ for most of parameter space

Summary

Many new and interesting states in the charmonium "sector" that we do not understand

The exercise for theorists and experimentalists can only improve our understanding of QCD/spectra

The new results from the b-side may help clarify things -- or not

LHC has now seen the X(3872) (Y. Gao)

Better mass determination on D's coming from CLEO -- may clarify "binding" issue of X(3872)

Utilize polarization observables to probe X(3872) quantum numbers and "wavefunction" questions.

Additional Slides

Initial State Radiation $J^{PC} = 1^{--}$

(MeV)	Y(4660)	Y(4350)	Y(4260)
Mass	4664 ± 12	4361 ± 13	4263 ± 5
Width	48 ± 15	74 ± 18	108 ± 14
Mode	$\pi^+\pi^-\psi(2S)$	$\pi^+\pi^-\psi(2S)$	$\pi^+\pi^-J/\psi$

4360: BaBar 0610057

4260: BaBar 050608, 0808.1543; Cleo 06011021; Belle 0707.2541

4360,4660: Belle 0707.3699; Liu 0805.3560

MeV	$Z(4430)^+$	$Z_2(4250)^+$	$Z_1(4050)^+$
mass	4443^{+24}_{-18}	4248^{+185}_{-45}	4051^{+24}_{-23}
width	107^{+113}_{-71}	177^{+321}_{-72}	82^{+51}_{-55}
mode	$\pi^+\psi(2S)$	$\pi^+\chi_{c1}(1P)$	$\pi^+\chi_{c1}(1P)$

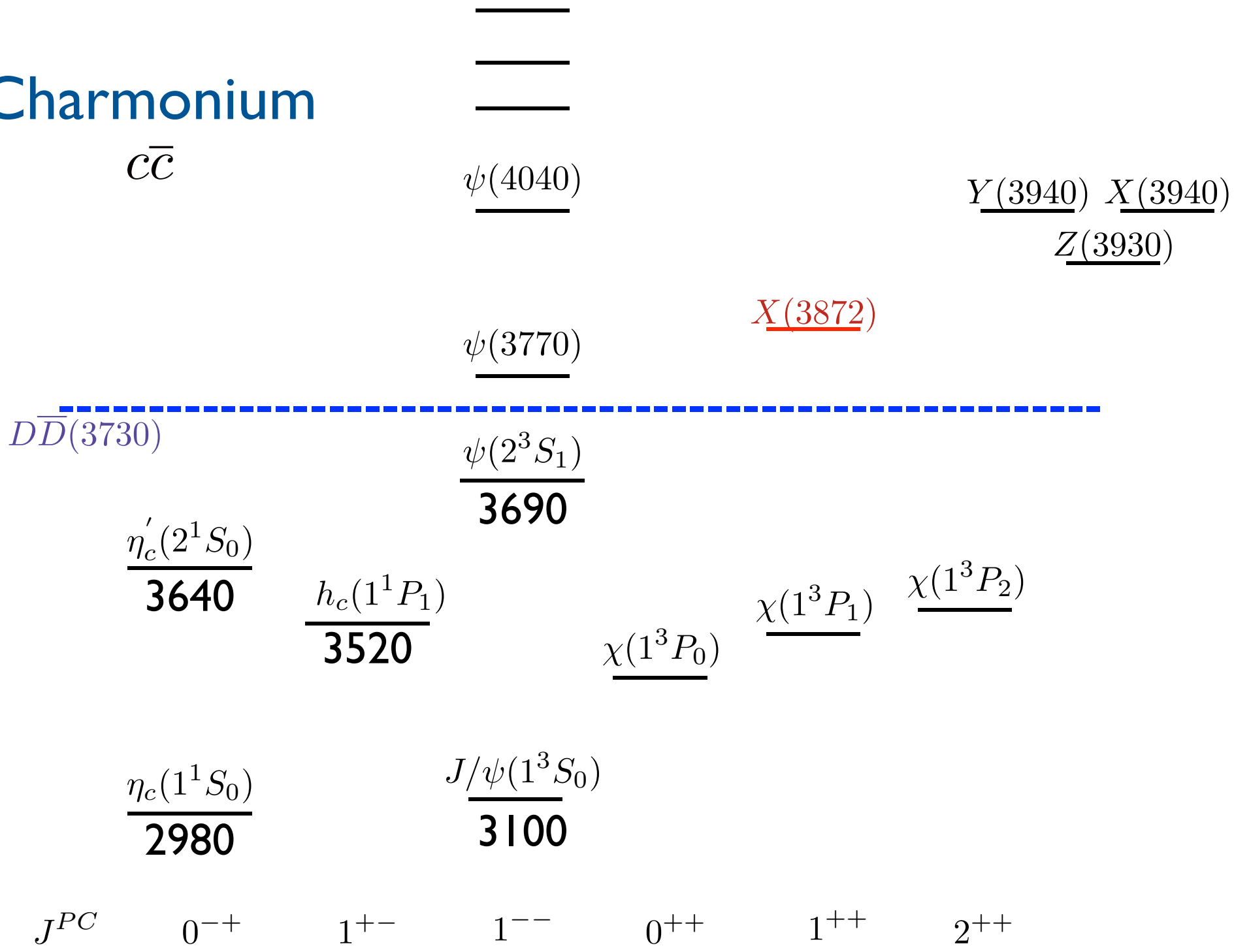
<u>cannot</u> be $c\bar{c}$

quark quantum numbers : $\bar{c}c\bar{d}u$

Hadroncharmonium? Dubynskiy/Voloshin

Charmonium

$c\bar{c}$



X(3872) Properties (Braaten)

$$\text{Belle (2003): } B \to K X(3872)$$

$$X(3872) \to \pi^+\pi^- J/\psi$$

$$\text{angular distribution } \Rightarrow \; 1^{++}$$

$$X(3872) \to J/\psi\gamma \Rightarrow C = +$$

$$M_X = 3871.55 \pm 0.20 \text{ MeV} \qquad \Gamma < 2.3 \text{ MeV}$$

$$M(X) - \left[M(D^{*0}) + M(D^0)\right] = -0.26 \pm 0.41 \text{ MeV} \Rightarrow \text{S} - \text{wave}$$

Threshold resonance universality (Braaten/Hammer) $\quad r \sim 5$ fm

$$\frac{\text{Br}(X \to J/\psi\pi^+\pi^-\pi^0)}{\text{Br}(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.5$$

Amplitudes

$$a) = -\frac{g_2\, e\, \beta}{3} \frac{1}{E_\gamma + \Delta} (\vec{k} \cdot \vec{\epsilon}_\psi^{\,*}\, \vec{\epsilon}_{D^*} \cdot \vec{k} \times \vec{\epsilon}_\gamma^{\,*} - \vec{k} \cdot \vec{\epsilon}_{D^*}\, \vec{\epsilon}_\psi^{\,*} \cdot \vec{k} \times \vec{\epsilon}_\gamma^{\,*})$$

$$b) = \frac{g_2\, e\, \beta}{3} \frac{1}{\Delta - E_\gamma}\, \vec{k} \cdot \vec{\epsilon}_\psi^{\,*}\, \vec{\epsilon}_{D^*} \cdot \vec{k} \times \vec{\epsilon}_\gamma^{\,*}$$

$$c) = \frac{g_2\, e\, \beta}{3} \frac{1}{E_\gamma}\, \vec{k} \cdot \vec{\epsilon}_{D^*}\, \vec{\epsilon}_\psi^{\,*} \cdot \vec{k} \times \vec{\epsilon}_\gamma^{\,*}$$

$$d) = -e\, c_1\, E_\gamma\, \vec{\epsilon}_{D^*} \cdot \vec{\epsilon}_\psi^{\,*} \times \vec{\epsilon}_\gamma^{\,*}$$

$$|\mathcal{M}|^2 = g_2^2 \beta^2 F_1(\Delta, E_\gamma) + g_2 \beta c_1 F_2(\Delta, E_\gamma) + c_1^2 F_3(E_\gamma)$$

$$|\mathcal{M}(\vec{\epsilon}_\psi)|^2 = \left(2 g_2^2 \beta^2 A^2 E_\gamma^4 + 4 g_2 \beta c_1 A C E_\gamma^2 + 2 c_1^2 C^2\right) |\hat{k} \cdot \vec{\epsilon}_\psi|^2 + \left(g_2^2 \beta^2 B^2 E_\gamma^4 - 2 g_2 \beta c_1 B C E_\gamma^2 + c_1^2 C^2\right) |\hat{k} \times \vec{\epsilon}_\psi|^2$$

$\Delta \sim 142$ MeV; $E_\gamma \sim 181$ MeV

$\psi(4040) \to X(3872)\gamma$

$E_\gamma \sim 165$ MeV

$g_2 \to \tilde{g}_2; \quad c_1 \to \tilde{c}_1$

$(g_2')^2 < 0.63$ GeV^{-3} from width of $\psi(4040)$

Γ to this channel $\sim 10^{-5}$

by using scattering length to get matrix element