Quarkonium-like States

- Observed spectrum of "exotic" states above DD (BB) threshold

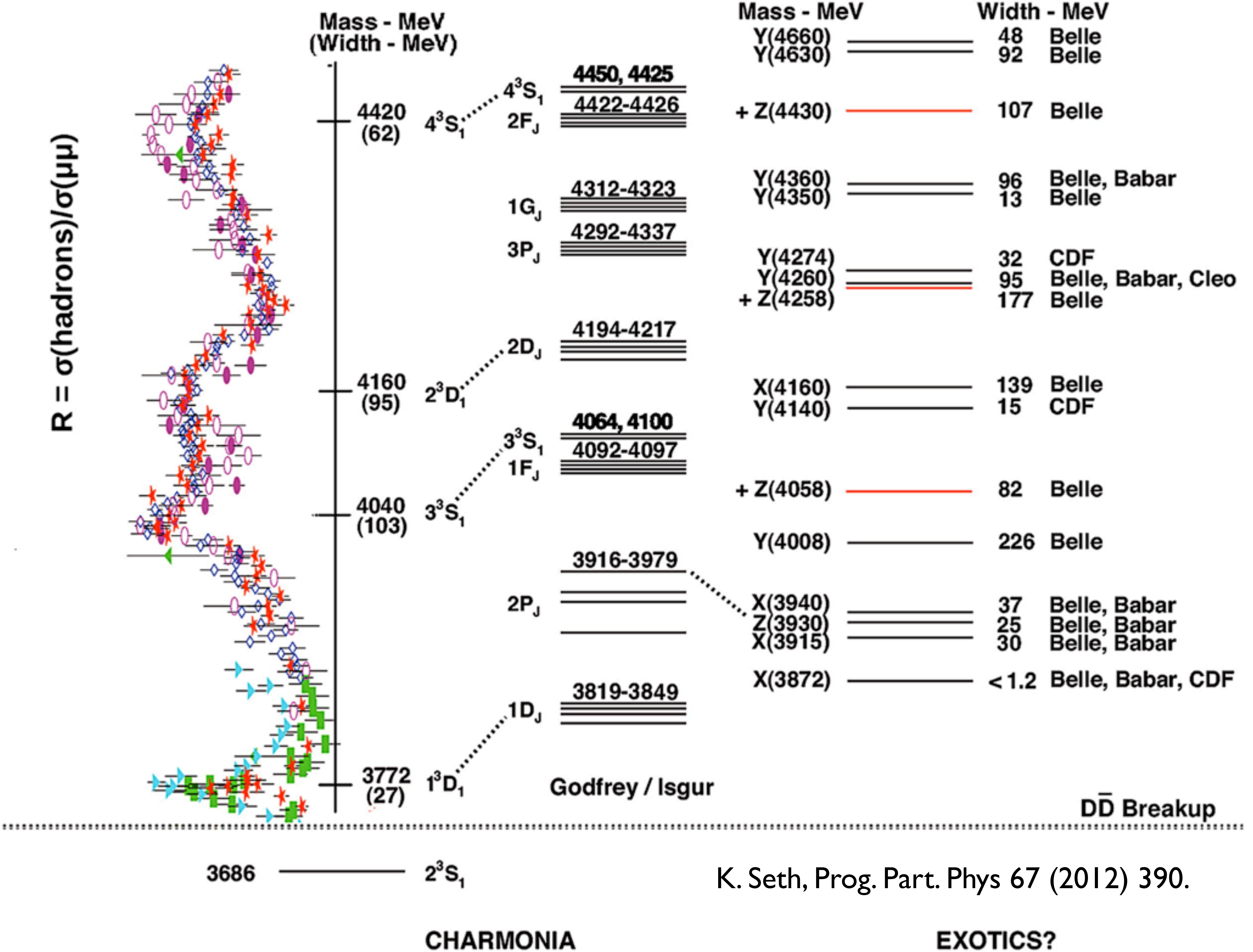
- Some proposed explanations

- Discussion of molecular hypothesis: X, Zb,...

Reviews: Voloshin 0711.4556; Brambilla et al.1010.5827; Eidelman, Heltsley, Hernandez-Rey, Navas, Patrignani 1205.4189

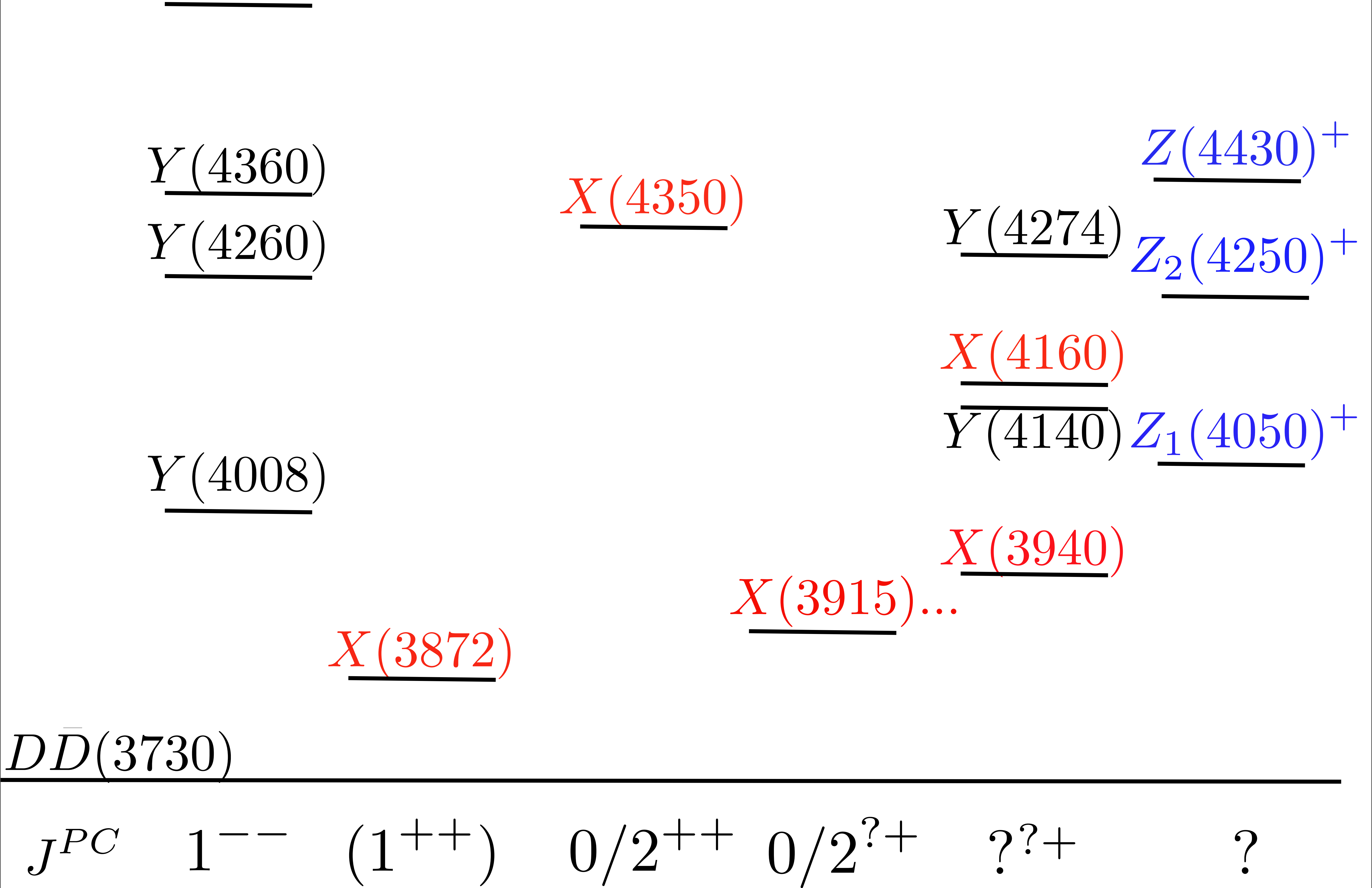
The Fourth Workshop on Hadron Physics in China and Opportunities in the US. Beijing, China 16-20 July 2012

R.P. Springer, Duke University



K. Seth, Prog. Part. Phys 67 (2012) 390.

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

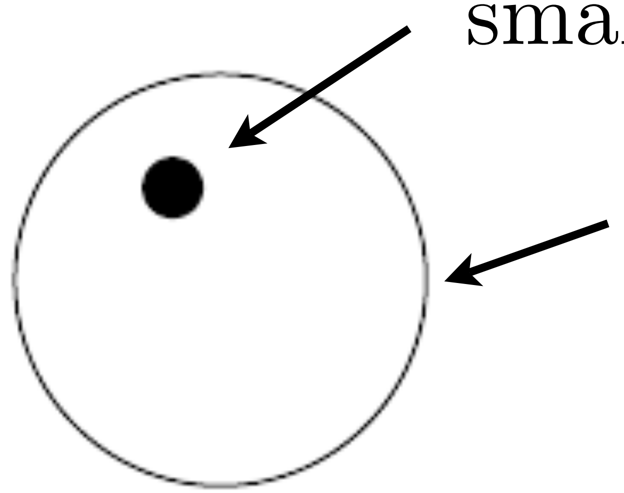
Hybrids

Coupled channels

Hadrocharmonium

Hadrocharmonium

$J/\psi, \psi(2S), \ldots$even Υ? affinity for light 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}
$Y(4260) \to \pi\pi J/\psi$	95 ± 14
$Y(4360) \to \pi^+\pi^-\psi(2S)$	74 ± 18
$Z(4430)^+ \to \pi^+\psi(2S)$	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] $[c\overline{q}]_1[\overline{c}q]_1;\ (S+V),(P+A)$

- **conventional** $c\bar{c}$ + **coupling to** $\omega\chi_{c0}$ [4]

[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

[4] Dai/Shi/Tang/Zheng

Molecules: do the constituents retain their identify as hadrons?

(more 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
$Y(4260)$	$D_0 \overline{D}^*, \psi(2S) f_0(980)$ $\Lambda_c \overline{\Lambda}_c, \chi_{c0}\rho, \chi_{c1}\omega, D_1 \overline{D}$	AN,TKGO Q,LZL,YWM,R
$Z(4430)^+$	$D^{*+} \overline{D}_1^0$	LMNN/BGL
$X(4630)$	$\psi(2S) f_0(980)$	GHHM
$Y(4660)$	$\psi(2S) f_0(980)$	GHM

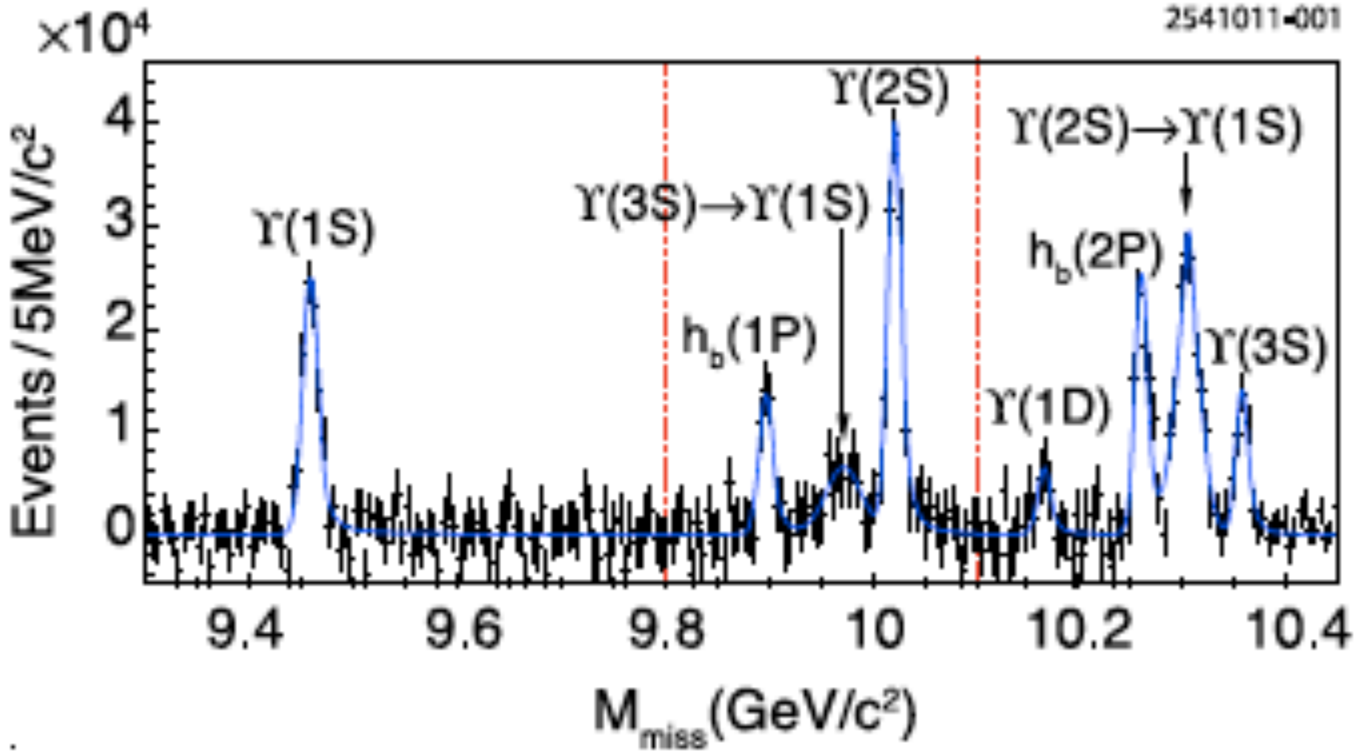
BGL=Branz,Gutsche,Lyubovitskij LMNN=Lee,Miharo,Navarro,Nielsen

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

Q=Qiao LZL=Liu,Zeng,Li YWM=Yuan,Wang,Mo R=Rosner

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

b Exotics above threshold - Belle 1103.3419



hybrid $b\bar{b}g$

disturbed $\Upsilon(5S)$

molecule

$Y_b(1^{--}) \sim Y(4260)$ analog

$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^+	$\Upsilon(5S) \to \pi^-(\pi^+[b\bar{b}])$
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^+	$\Upsilon(5S) \to \pi^-(\pi^+[b\bar{b}])$
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$

Eidelman, Heltsley, Hernandez-Rey, Navas, Patrignani 1205.4189

$Z_b: \ I^G = 1^+ \ J^P = 1^+$

$$\text{charged} \Rightarrow \ \text{cannot be } \bar{b}b \text{ alone}$$

Tetraquarks

Guo/Cao/Zhou/Chen 1106.2284
Ali 1108.2197
Cui/Liu/Huang 1107.1343

Karliner/Lipkin prediction

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

$$\text{isovector charged tetraquark} \qquad \bar{b}b\bar{d}u \quad \bar{b}b\bar{u}d$$

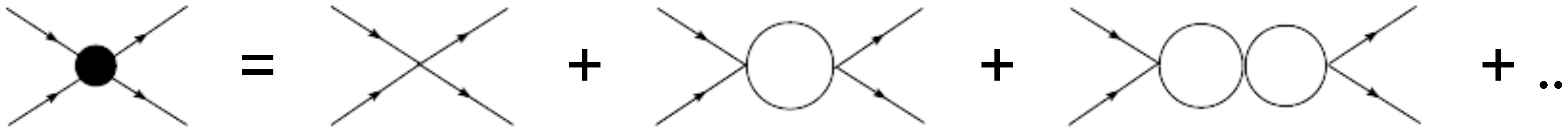
$$\text{prediction: look for subthreshold } I = 0 \text{ state}$$

Molecules: Bound states of B*B(*)

Liu/Liu/Deng/Zhu 0801.3540; Liu/Luo/Liu/Zhu 0808.0073;
Bondar/Garmash/Milstein/Mizuk/Voloshin 1105.4473;
Zhang/Zhong/Huang 1105.5472; Yang/Ping/Deng/Zong 1105.5935
Nieves/Valderrama 1106.0600; Sun/He/Liu/Luo 1106.2965

Like the Deuteron? Systematic NN treatment: NN-EFT (no pions)

Only now it is an infinite sum of $(\overline{D}D^* + cc)$ or $(\overline{B}^* B^{(*)} + cc)$ etc.



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

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

does not converge

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

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

X(3872) as molecule

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

Isospin issue:

(Objections about charged pieces noted)

$$\frac{\Gamma[X \to J/\psi\pi^+\pi^-\pi^0]}{\Gamma[X \to J/\psi\pi^+\pi^-]} =$$

Belle 2011 PRD 84, 052004

Hanhart et al 1111.6241

$$\frac{\Gamma[X \to J/\psi\omega]}{\Gamma[X \to J/\psi\pi^+\pi^-]} = 0.8 \pm 0.3$$

BaBar 2010

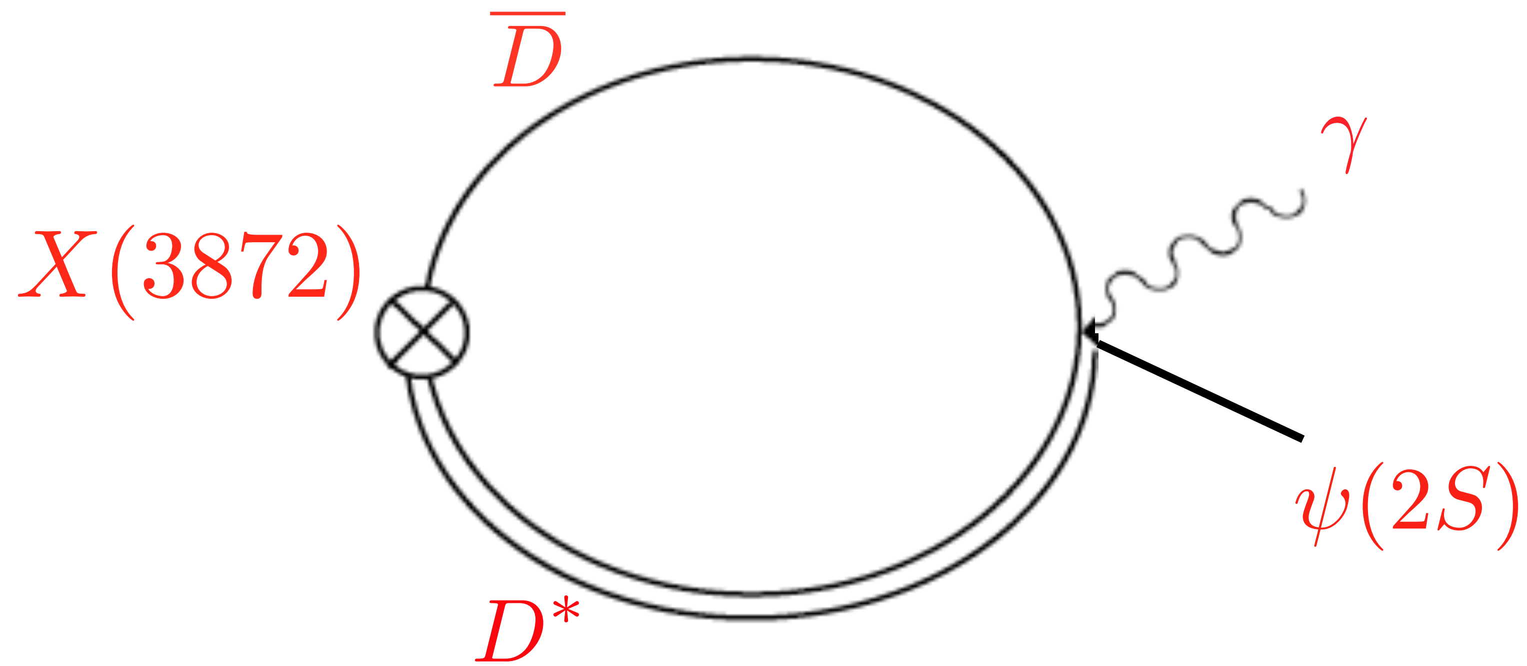
$$J^{PC} = 1^{++} \text{ or } 2^{-+}$$

multipole question

$$m_{D^0\bar{D}^{0*}} - m_{X(3872)} = 0.16 \pm 0.33 \text{ MeV}$$

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...

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

$$\gamma \sim 20 \text{ MeV}$$
$$a \sim 10 \text{ fm}$$
$$\langle r\rangle \sim 12 \text{ fm}$$

$X(3872) - D^{(*)}$ scattering Canham/Hammer/RPS

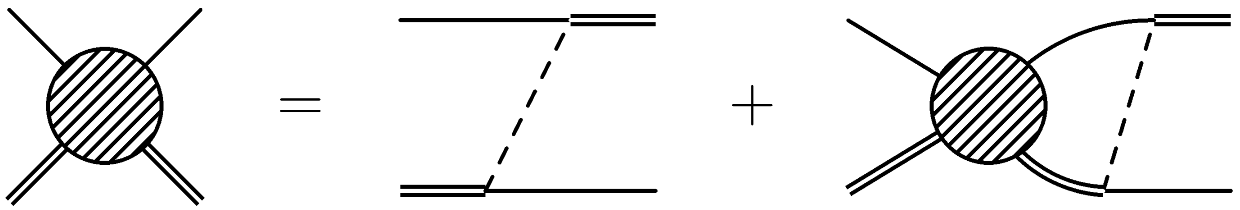
IF $X(3872) \sim \frac{1}{\sqrt{2}}(D^0\overline{D}^{*0} + D^{*0}\overline{D}^0)$

$m_X = (3871.68 \pm 0.17)$ MeV $B_X = (0.16 \pm 0.36)$ MeV

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

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

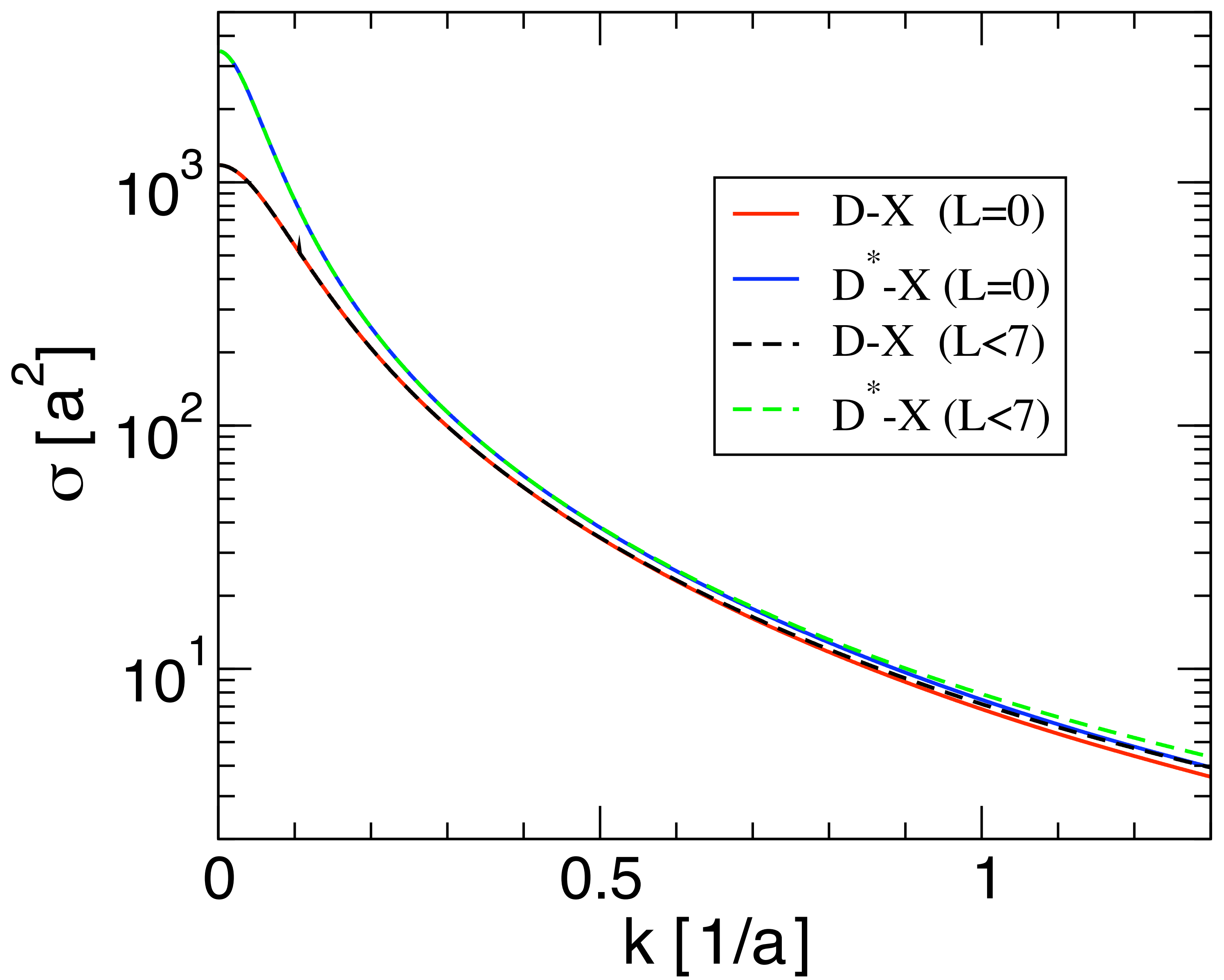
Integral equation:



Results depend only on scattering length

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

Three body cross section vs scattering length



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

$B\overline{B}$ final state interactions

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

$X(3872) \to \psi(2S)\gamma$

Mehen/RPS

factorization

XEFT + HBChPT

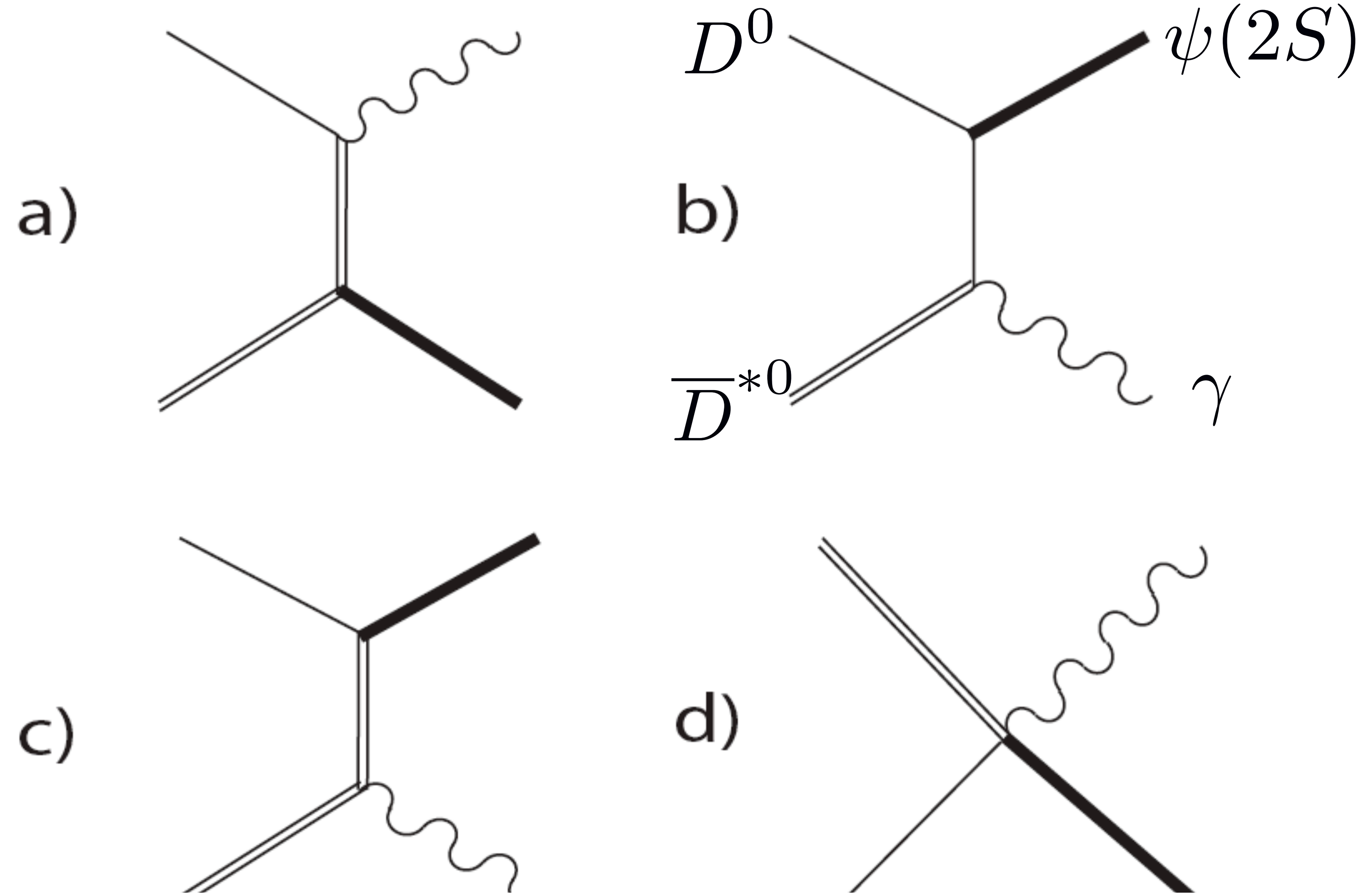
$\beta^{-1} \sim 356$ MeV

Hu, Mehen

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

Guo et al., 0907.0521

1002.2712



$D^{0(*)}$

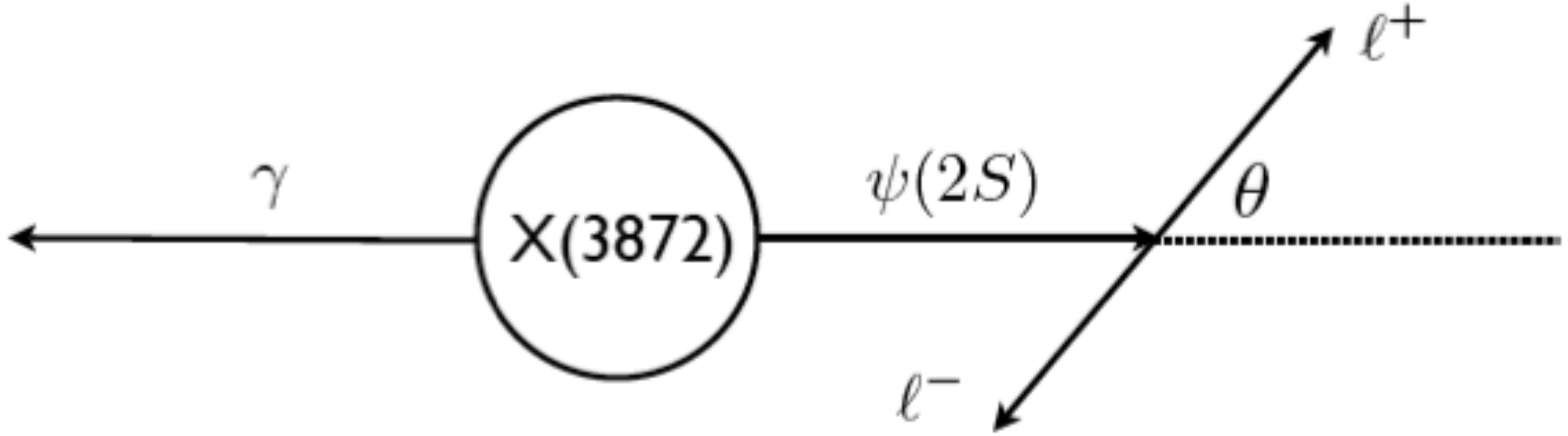
$$\mathcal{L} = \frac{e\beta}{2}\mathrm{Tr}[H_1^\dagger H_1\,\vec{\sigma}\cdot\vec{B}\,Q_{11}] + c.c. + i\frac{g_2}{2}\mathrm{Tr}[J^\dagger H_1\vec{\sigma}\cdot\overleftrightarrow{\partial}\,\bar{H}_1] + h.c. + i\frac{ec_1}{2}\mathrm{Tr}[J^\dagger H_1\vec{\sigma}\cdot\vec{E}\bar{H}_1] + h.c.$$

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

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

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

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



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

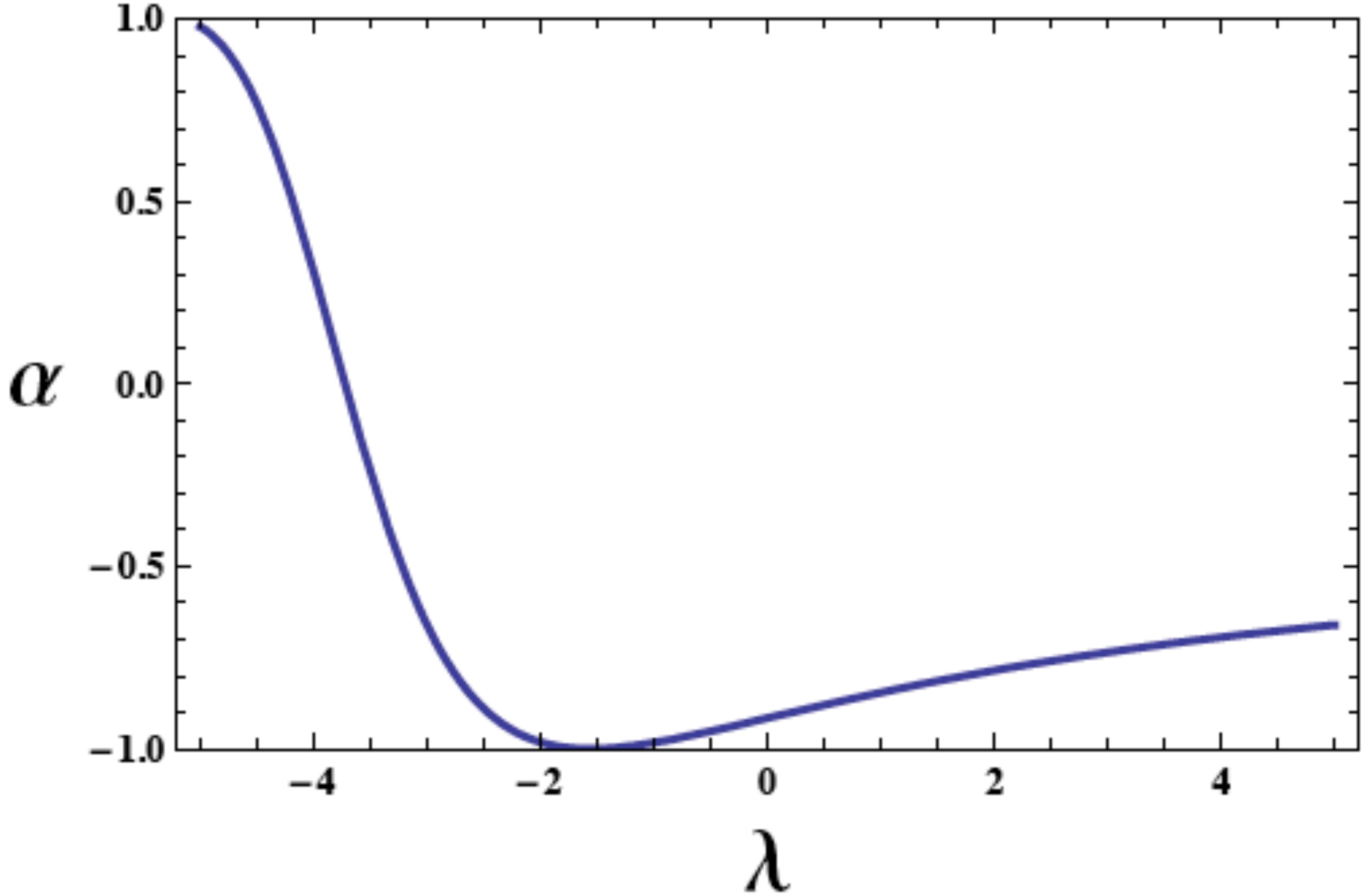
ii) $g_2\beta \gg c_1$ a-c) only b) dominate

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

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

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

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



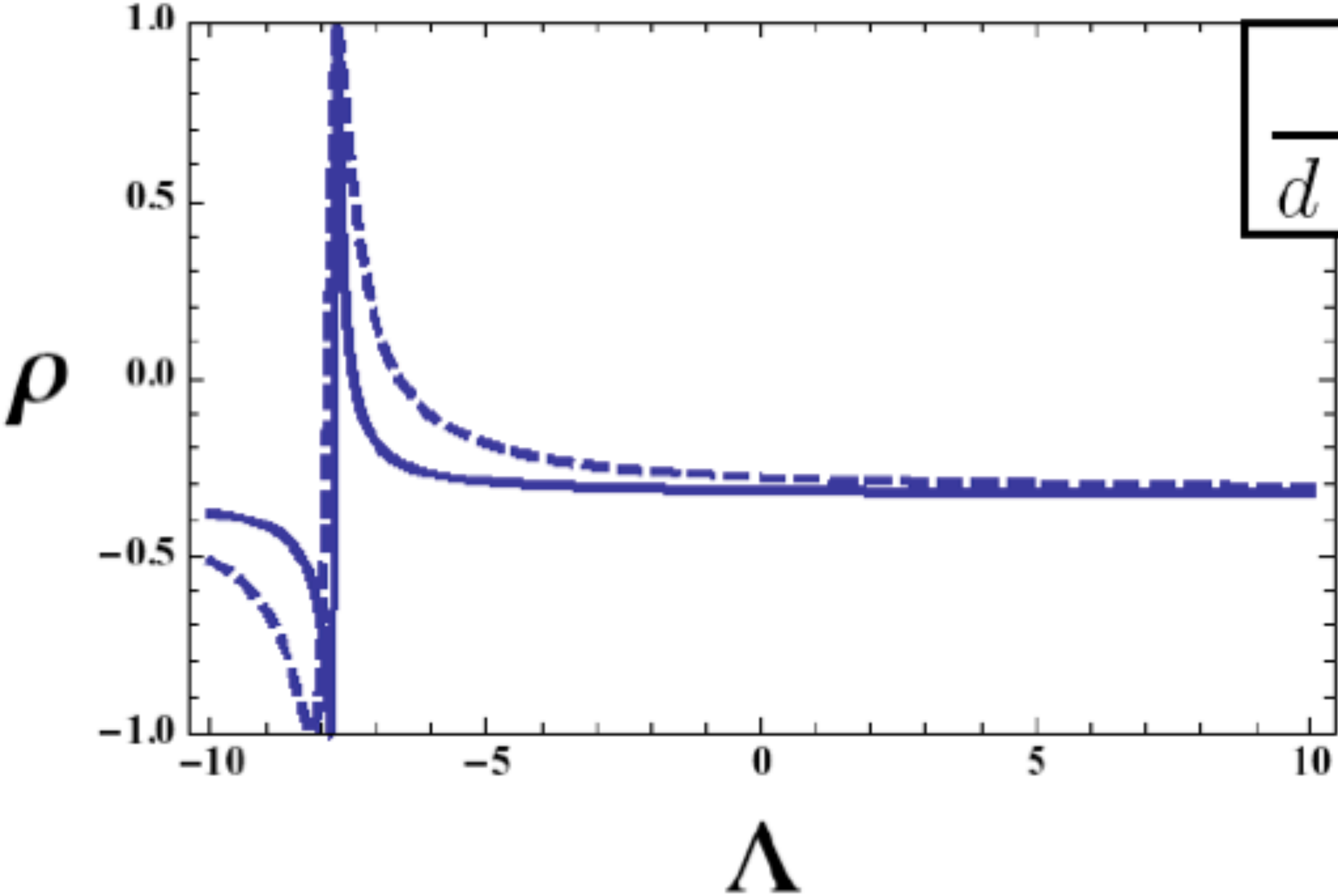
- Longitudinal Polarization $(\alpha < -0.5)$ for $-3.5 \leq \lambda \leq 5$

- $X(3872)$ 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

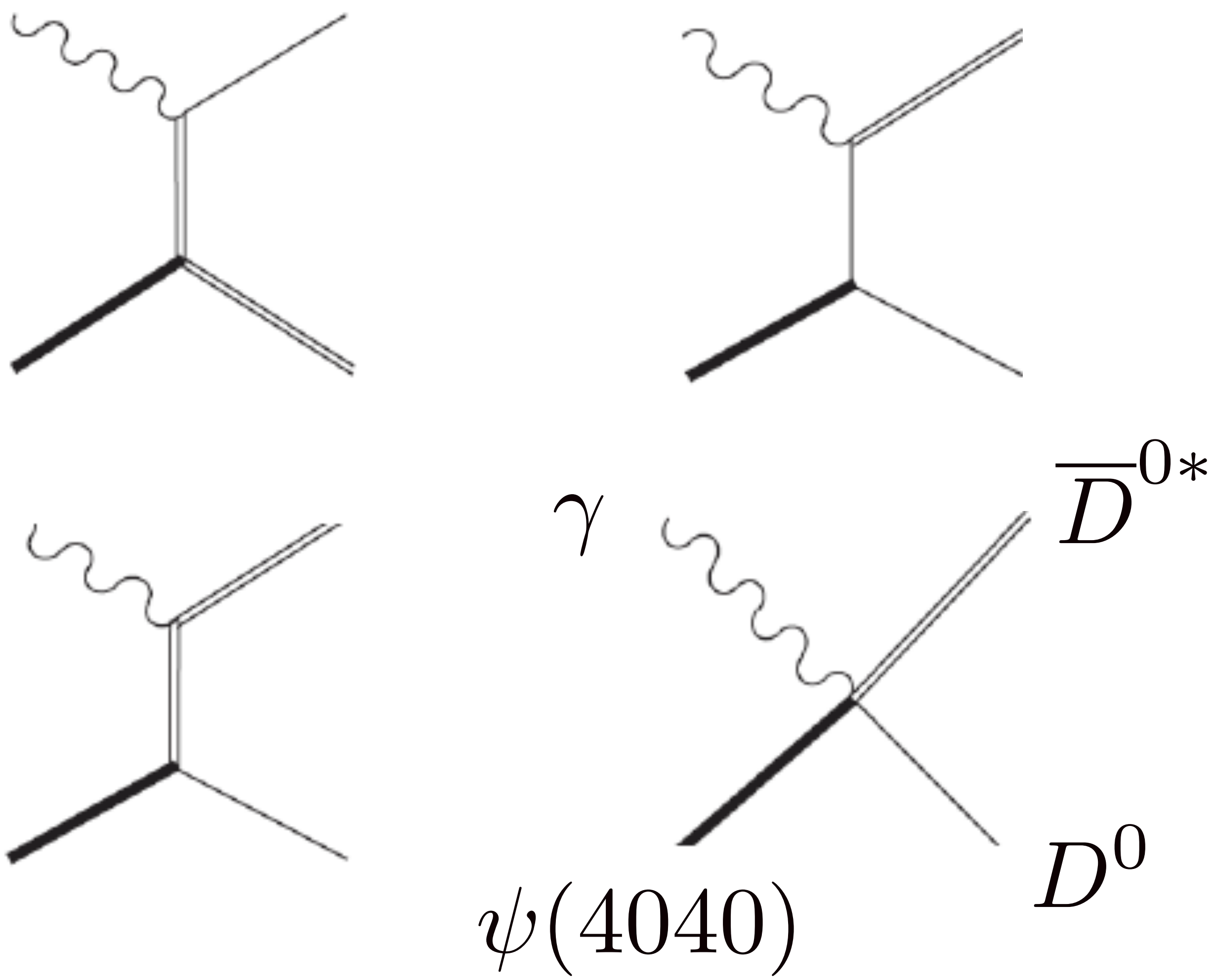
$\psi(4040) \to X(3872)\gamma$

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

$E_\gamma \sim 165 \text{ MeV}$

$(\tilde{g}_2)^2 < 0.63 \text{ GeV}^{-3}$

from width of $\psi(4040)$



Estimate rate by using scattering length to estimate matrix element

Z_b as a molecule

HQET predicts additional states (Voloshin...)

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

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

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

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

$$1^-(0^+) = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \times 0^-_{lt} + \frac{1}{2}\left(1^-_{b\bar{b}} \otimes 1^-_{lt}\right)_{J=0} \to \eta_b\pi, \chi_b\pi, \Upsilon\rho$$

Molecule treatment predicts decay ratios among them (Mehen/Powell)

$$\mathcal{L}_{eff} = \cdots - \frac{C_{10}}{4}\mathrm{Tr}[\bar{H}_a^\dagger \tau^A_{aa'} H^\dagger_{a'} H_b \tau^A_{bb'} \bar{H}_{b'}] + - \frac{C_{11}}{4}\mathrm{Tr}[\bar{H}_a^\dagger \tau^A_{aa'} \sigma^i H^\dagger_{a'} H_b \tau^A_{bb'} \sigma^i \bar{H}_{b'}].$$

$H_a = P_a + \vec{V} \cdot \vec{\sigma}$ now $B^{(*)}$ multiplet rather than $D^{(*)}$ multiplet

$$\Gamma[W_0 \to \chi_{b1}\ell]:\Gamma[W_0' \to \chi_{b1}\ell]:\Gamma[Z \to h_b\ell]:\Gamma[Z' \to h_b\ell] = \frac{3}{2}:\frac{1}{2}:1:1$$

Summary

Many new and interesting states living in the charmonium/ bottomonium "sector" that we (still) do not understand

Understanding them will be important progress towards understanding QCD and its bound states

Expected results from LHCb, BESIII, ... better masses, more decay information, etc. will clarify the character of "exotics"

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

Look for Zb type-ratios to check for molecular "status"