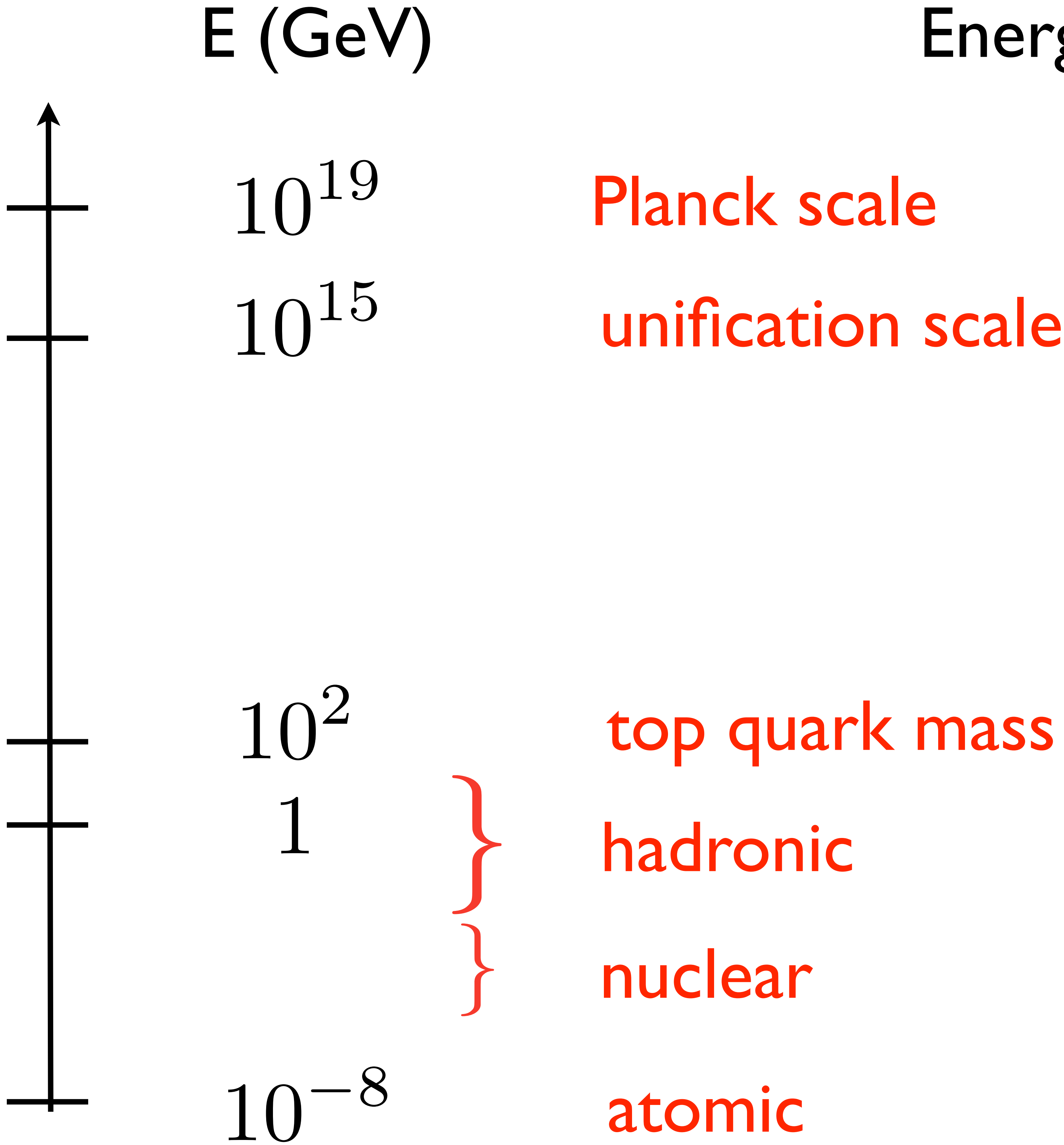
Attributes of molecule-like exotics in the heavy sector

- Interlude on EFTs
- The "Exotic" Spectrum $X(3872), Y,\ Z,\ \ldots$
- Observables that test the molecular hypothesis in
    - $X(3872) - \overset{(-)}{D}{}^{0,(*)}$ scattering
    - $X(3872) \to \psi(2S)\gamma$
    - $\psi(4040) \to X(3872)\gamma$
    - $\psi(4160) \to X(3872)\gamma$
- (Example of a thing that is probably not a molecule)
- Candidates for molecules in the b-sector

R.P. Springer Duke University

"Light Nuclei from First Principles" 4 Oct 2012

Energy Scales



Examples of Effective Theories

- Newton's laws
- Thermodynamics
- Fluid Dynamics
- Gravity
- Quantum Electrodynamics
- Standard Model of Nuclei and Particles

Attributes of Effective Field Theories (EFTs)

Utilize separation of scales => create small parameter

Based upon underlying (perhaps approximate) symmetries

Reliable error estimates from order of calculation

Systematically improvable

May be used to probe unknown underlying theory

May be used to simplify calculations in known theories

Typically contain unknown (by the EFT) coefficients that have to be fixed via experiment or other means

Coefficient fixed from any exp for which EFT is valid true for *all* observables in that EFT

Typically valid only in a limited energy window

An Effective Quantum Field Theory for low energy light-light scattering

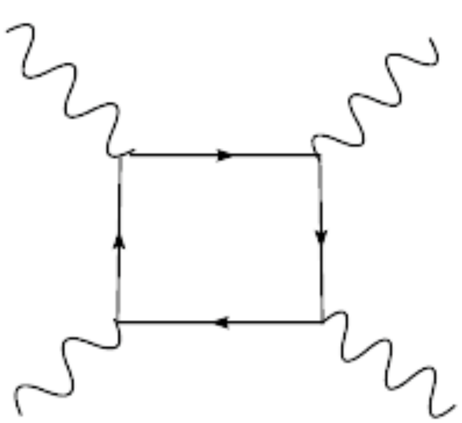
Scales: $m_e \sim 511\ \text{keV}$ $\quad E_\gamma << m_e$

Symmetry: Lorentz invariance $\quad \tilde{F}^{\mu\nu} = F_{\alpha\beta}\, \epsilon^{\mu\nu\alpha\beta}$

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{c_1}{m_e^4} (F^{\mu\nu} F_{\mu\nu})^2 + \frac{c_2}{m_e^4} (F^{\mu\nu} \tilde{F}_{\mu\nu})^2$$

$$F_{\mu\nu} = \frac{\partial A_\mu}{\partial x^\nu} - \frac{\partial A_\nu}{\partial x^\mu} \qquad c = 1 \Rightarrow [L] = [T]$$

$$\hbar = 1 \Rightarrow [E] = [T]^{-1} = [L]^{-1}$$

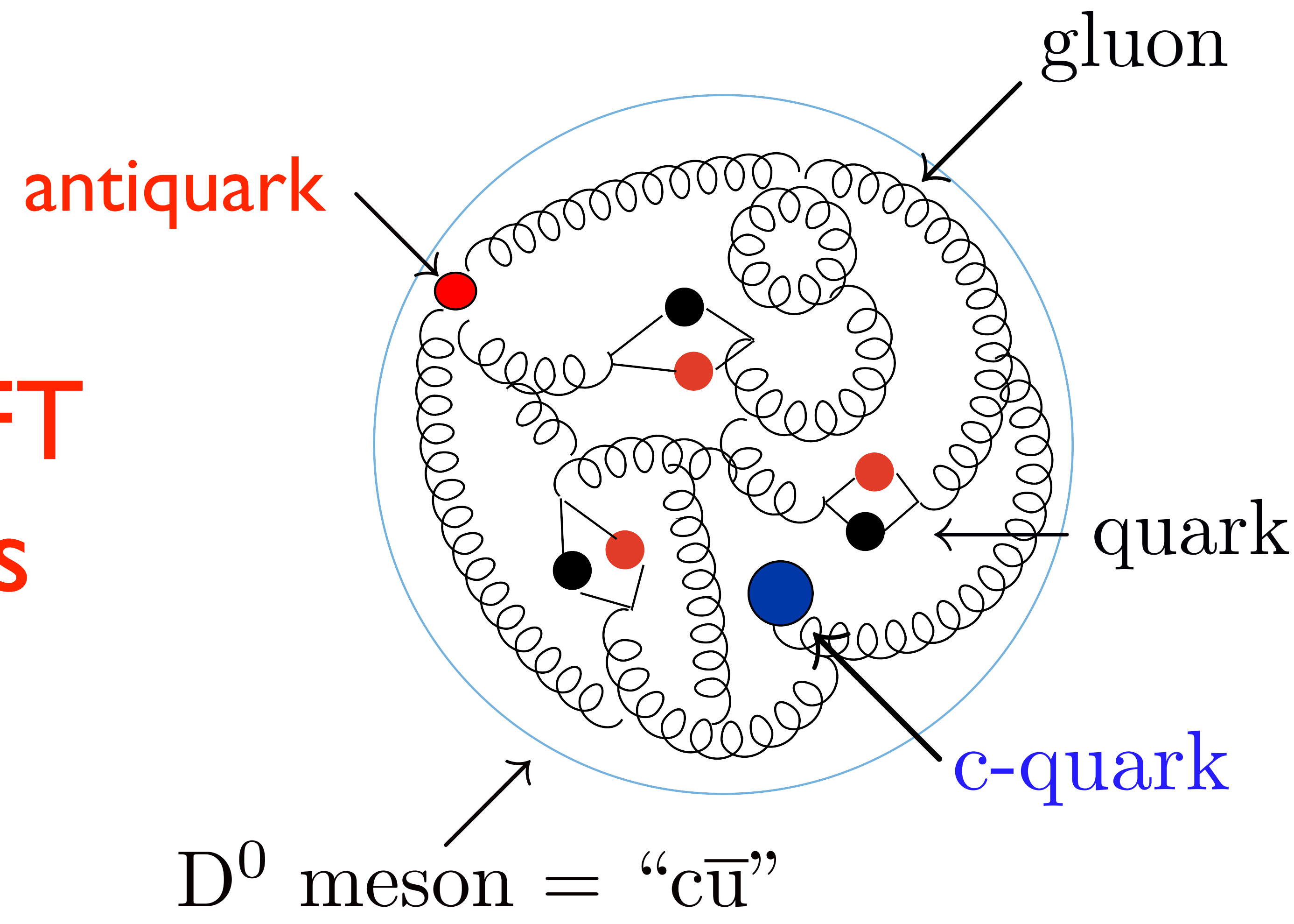


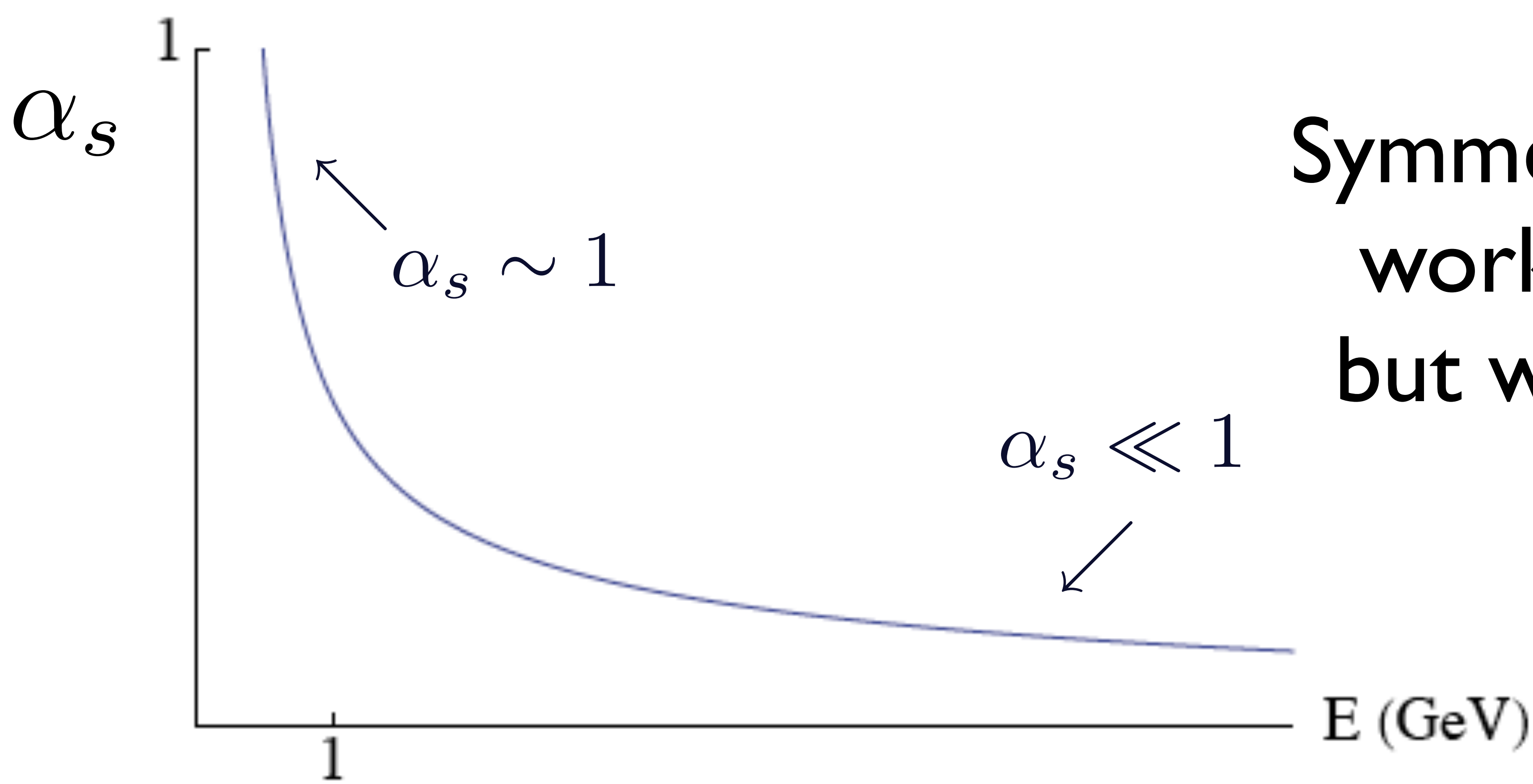
$$= c_1 \frac{E_\gamma^4}{m_e^4}$$

$$+ \cdots$$

(from J. Gasser, MENU 07)

In the absence of a solution to QCD, use EFT => contains predictions of QCD as a subset





Symmetry (group) structure works for ground states, but we need dynamics for excited states

Limits of QCD where symmetries are enhanced

$$0 \leftarrow m_u < m_d < m_s \,|\, m_c < m_b < m_t \rightarrow \infty$$

$\nwarrow \Lambda_{QCD}$

$$\mathcal{L}_{QCD}^{light} = \sum_i (\overline{q}_{iL} i\not{D} q_{iL} + \overline{q}_{iR} i\not{D} q_{iR})$$

$$- \sum_{ij} (\overline{q}_{iL} m_{ij} q_{jR} + \overline{q}_{iR} m_{ij} q_{jL})$$

$$m_q = diag(m_u, m_d, m_s)$$

$$q_{iL} \rightarrow L_{ij} q_{jL} \qquad q_{iR} \rightarrow R_{ij} q_{jR}$$

$$L \,\epsilon\, SU(3)_L \qquad R \,\epsilon\, SU(3)_R$$

$\Longrightarrow$ χPT $\qquad \dfrac{m_q, p}{\Lambda_\chi}$

$$\mathcal{L}_{QCD}^{heavy} = \overline{Q}(i\not{D} - m_Q)Q \;\; \rightarrow \overline{h}_v^{(Q)} iv.D h_v^{(Q)}$$

$$Q = e^{-im_Q v.x}(h_v^{(Q)} + \xi_v^{(Q)})$$

small

$$p_Q^\mu = m_Q v^\mu + k^\mu$$

Heavy Meson Multiplets

$c\overline{q}$

s_l and $s_Q = 1/2$ separately conserved

$$|D(0^-)\rangle = |00\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

light

$$|D(1^-)^\mu\rangle \sim |\uparrow\uparrow\rangle, \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle), |\downarrow\downarrow\rangle$$

$$\frac{k}{m_Q}$$

$HQET + \chi PT = HH\chi PT$

heavy

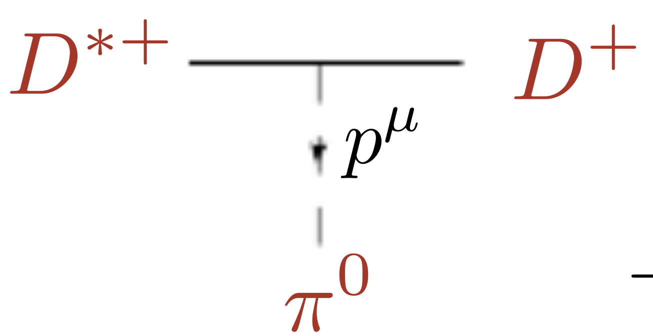
Collect into Supermultiplets

$$(D_0^{(0,+)}, D_{s0})$$

$$H_a = \frac{1+\not{v}}{2}[P_a^{*\mu}\gamma_\mu - P_a\gamma_5] \qquad S_a = \frac{1+\not{v}}{2}[\mathcal{P}_a^{*\mu}\gamma_\mu\gamma_5 - \mathcal{P}_a]$$

$$(D^{*(0,+)}, D_s^*) \qquad (D^{0,+}, D_s) \qquad (D_1^{(0,+)}, D_{s1})$$

$$\begin{aligned}\mathcal{L} \quad = \quad & -\mathrm{Tr}[\overline{H}_a(iv.D_{ab} - \delta_H)H_b] + Tr[\overline{S}_a(iv.D_{ab} - \delta_S)S_b] \\ & + g\,\mathrm{Tr}[\overline{H}_a H_b \not{A}_{ba}\gamma_5] + g'\,\mathrm{Tr}[\overline{S}_a S_b \not{A}_{ba}\gamma_5] \\ & + h\;(\mathrm{Tr}[\overline{H}_a S_b \not{A}_{ba}\gamma_5] + h.c.)\end{aligned}$$

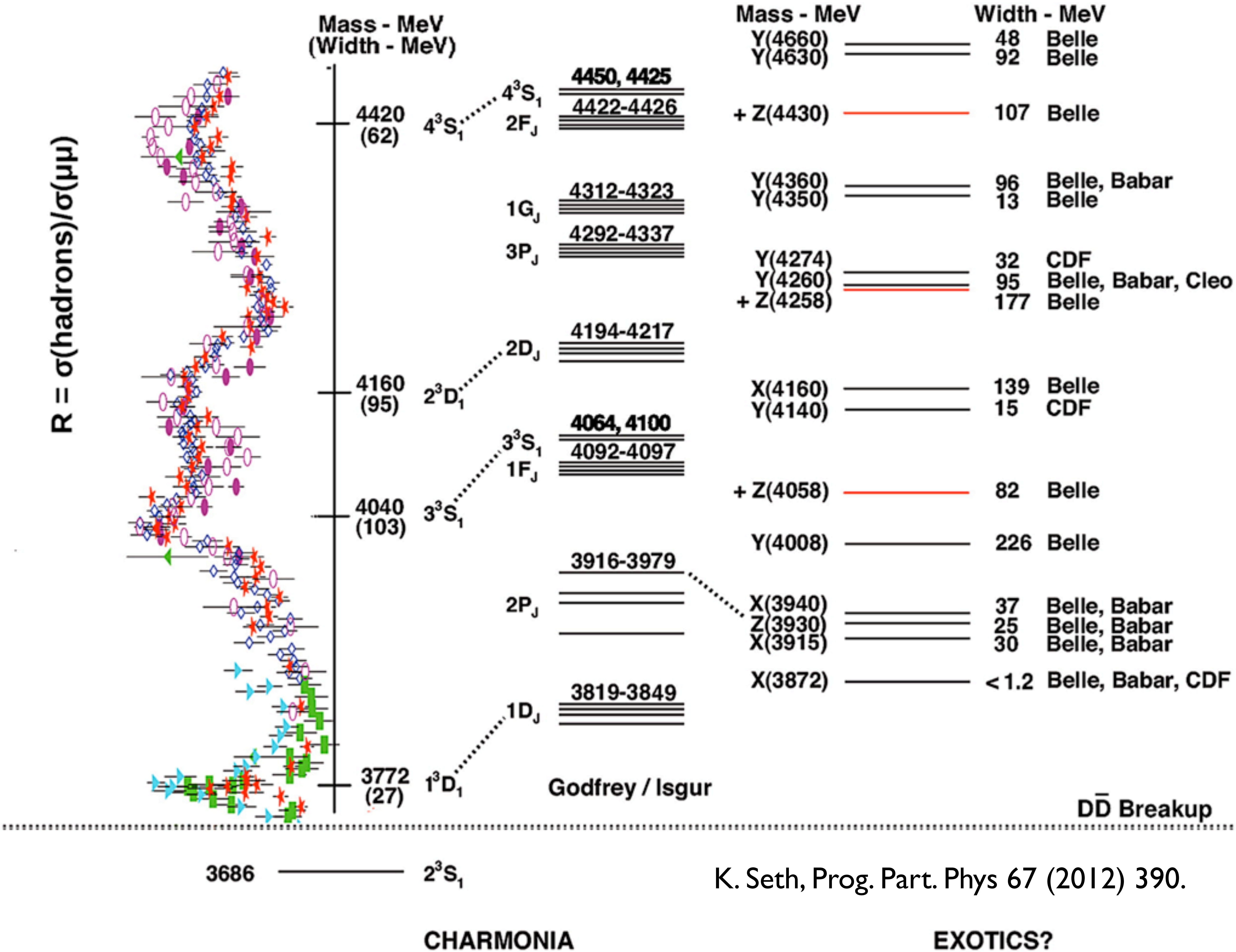


$$-\frac{g\ p.\epsilon}{f\sqrt{2}}$$

$$\xi = e^{iM/f} \qquad D^\mu = \partial^\mu + V^\mu$$

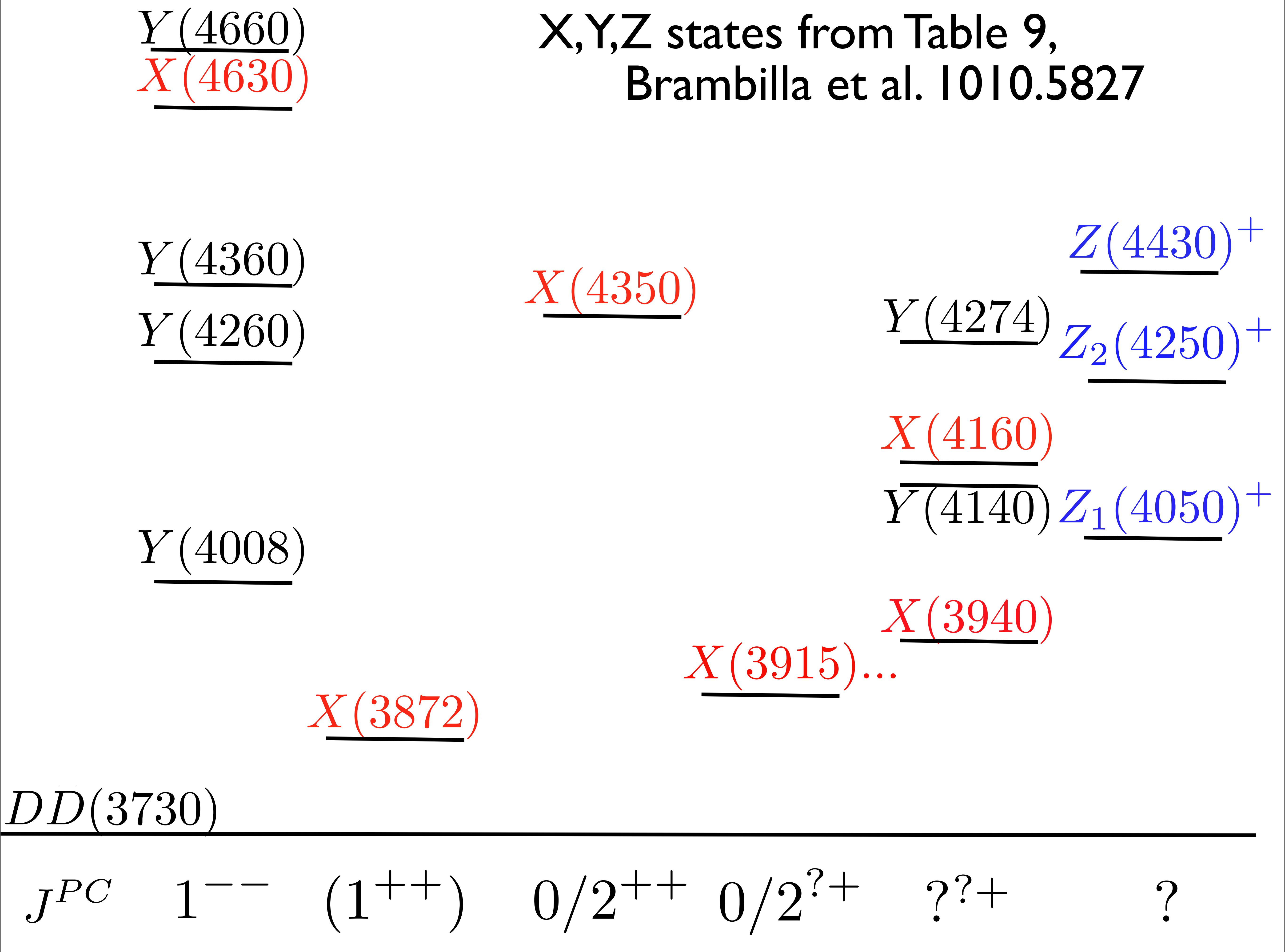
$$V^\mu = \frac{1}{2}(\xi\partial^\mu\xi^\dagger + \xi^\dagger\partial^\mu\xi)$$

$$A^\mu = \frac{i}{2}(\xi\partial^\mu\xi^\dagger - \xi^\dagger\partial^\mu\xi)$$



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

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

X(3872) as molecule

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

S-wave

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

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

$$\Gamma < 1.2 \text{ MeV}$$

Isospin issue:

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

Belle 2011 PRD 84, 052004
Hanhart et al 1111.6241

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

BaBar 2010

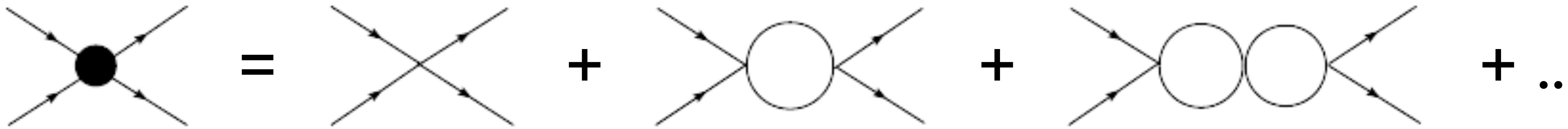
$$J^{PC}=1^{++} \text{ or } 2^{-+}$$

multipole question

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

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.



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

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

does not converge

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

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

Evidence that pionless EFT works in strong and EM sector

Chen,Rupak,Savage nucl-th/9902056v4

NN scattering phase shift:

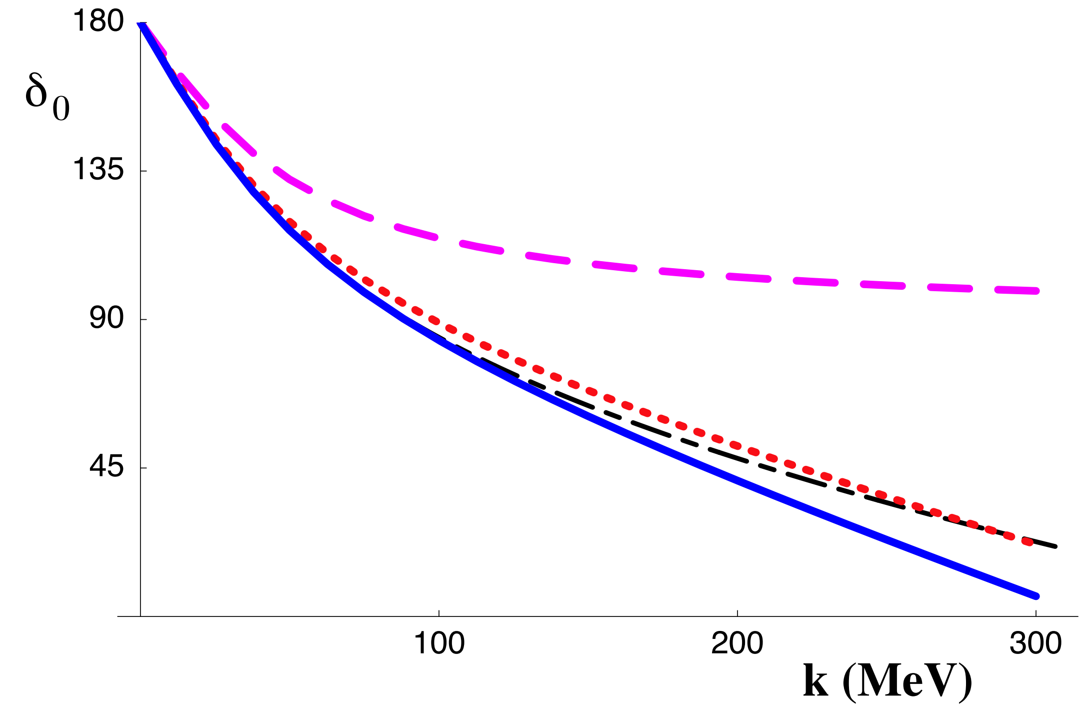
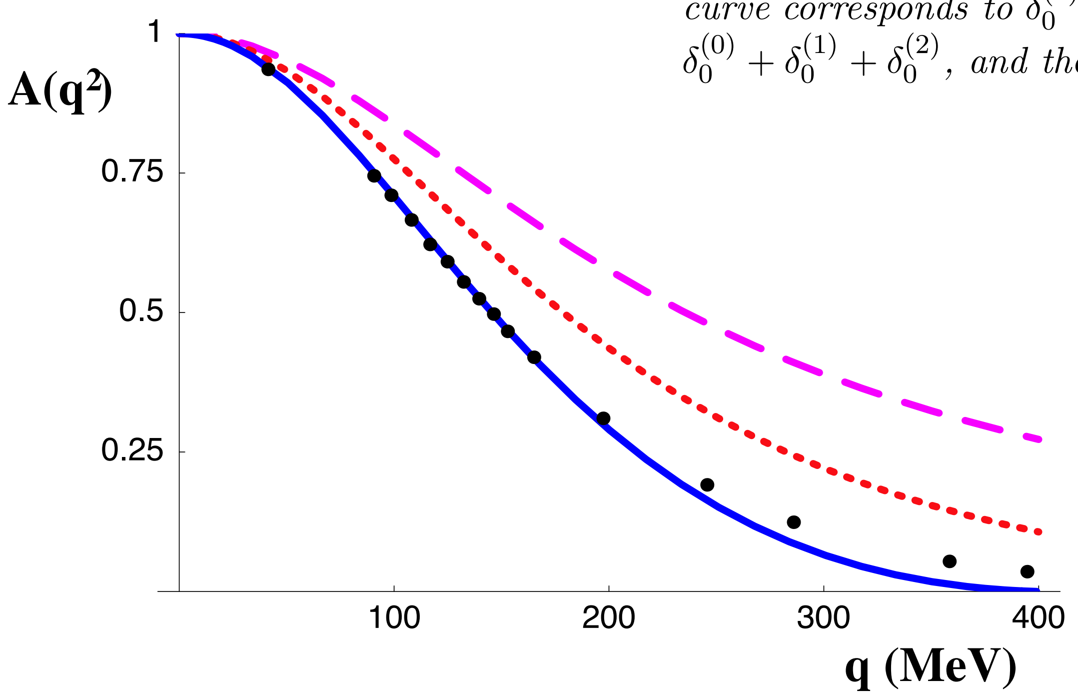


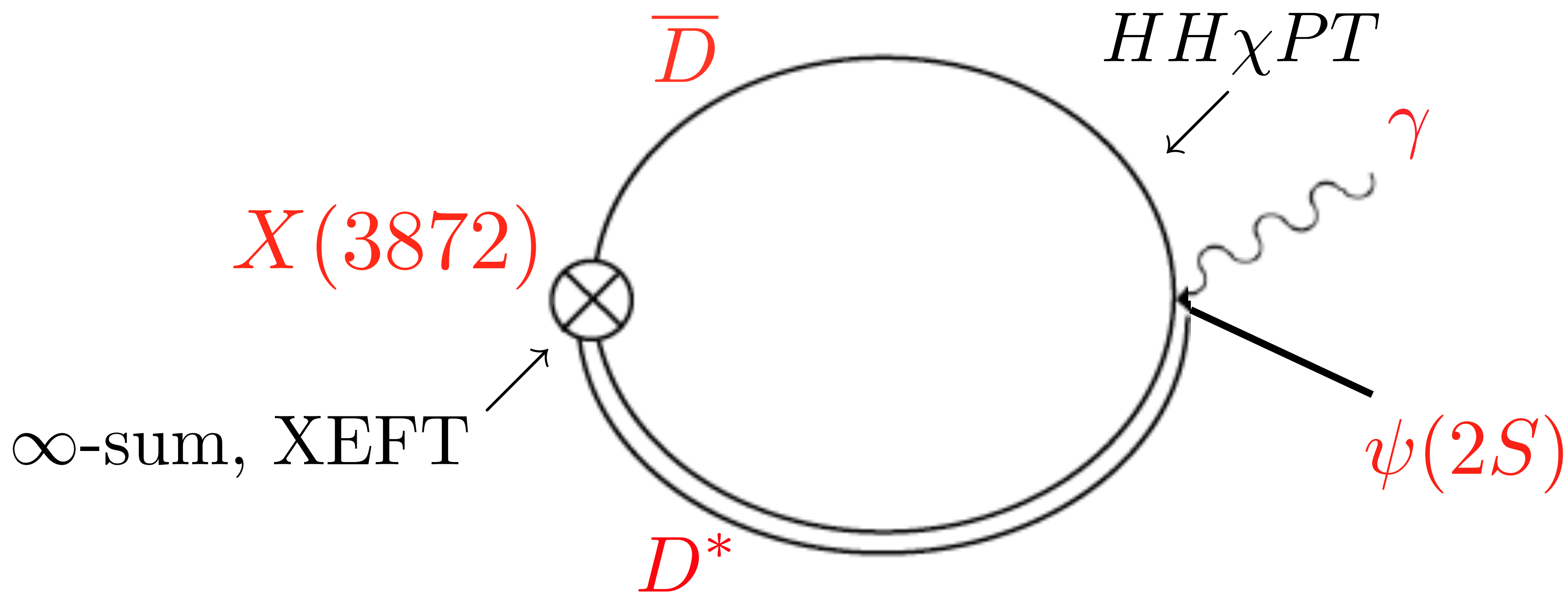
FIG. 1. *The phase shift* δ_0 *as a function of the center of mass momentum* $|\mathbf{k}|$. *The dashed curve corresponds to* $\delta_0^{(0)}$, *the dotted curve corresponds to* $\delta_0^{(0)} + \delta_0^{(1)}$, *the solid curve corresponds to* $\delta_0^{(0)} + \delta_0^{(1)} + \delta_0^{(2)}$, *and the dot-dashed curve is the Nijmegen partial wave analysis [35].*



:EM form factor of deuteron

FIG. 3. *The form factor* $A(q^2)$ *as a function of* $|\mathbf{q}| = \sqrt{-q^2}$. *The dashed curve corresponds to the leading order prediction, the dotted curve corresponds to the next-to-leading order prediction, and the solid curve corresponds to the next-to-next-to-leading order prediction, in* EFT($\not\pi$).

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...

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

$\gamma \sim 20$ MeV

$a \sim 10$ fm

$\langle r\rangle \sim 12$ fm

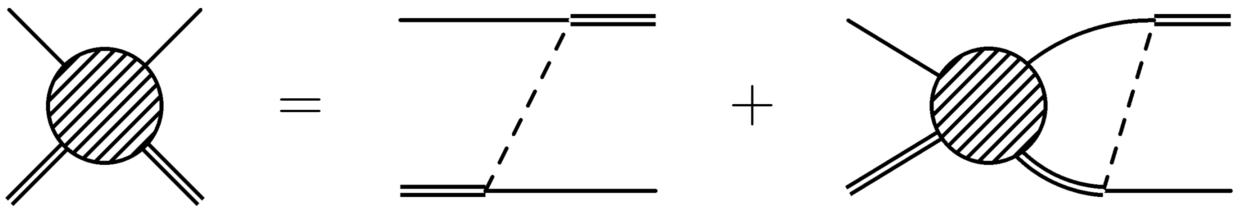
$X(3872) - D^{(*)}$ scattering   Canham/Hammer/RPS

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

$$m_X = (3871.68 \pm 0.17) \text{ MeV} \qquad B_X = (0.16 \pm 0.36) \text{ MeV}$$

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

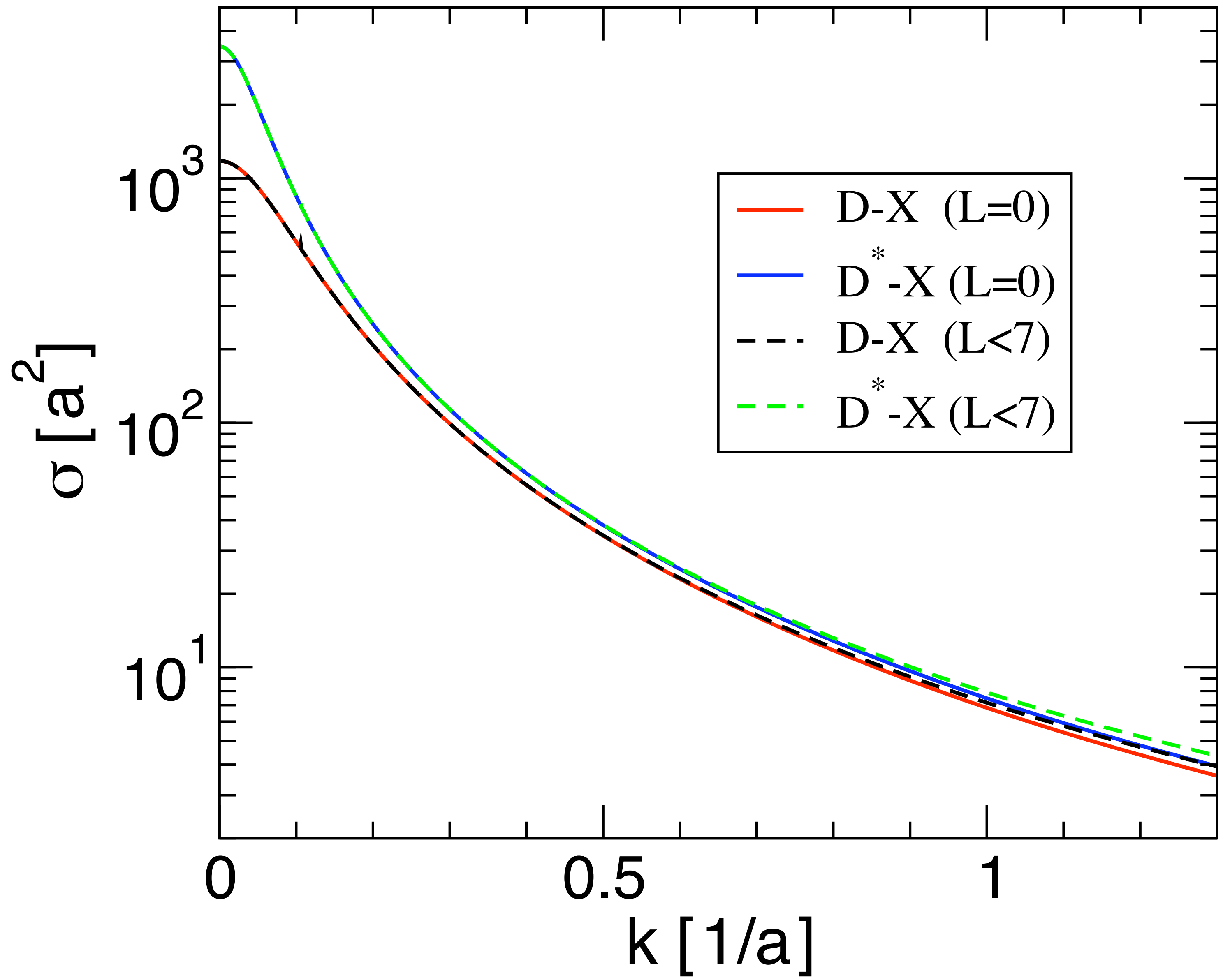
$$\mathcal{L} = \sum_{j=D^0, D^{*0}, \bar{D}^0, \bar{D}^{*0}} \psi_j^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_j}\right)\psi_j + \Delta X^\dagger X$$
$$- \frac{g}{\sqrt{2}}\left(X^\dagger(\psi_{D^0}\psi_{\bar{D}^{*0}} + \psi_{D^{*0}}\psi_{\bar{D}^0}) + \text{ h.c.}\right) + \cdots$$

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

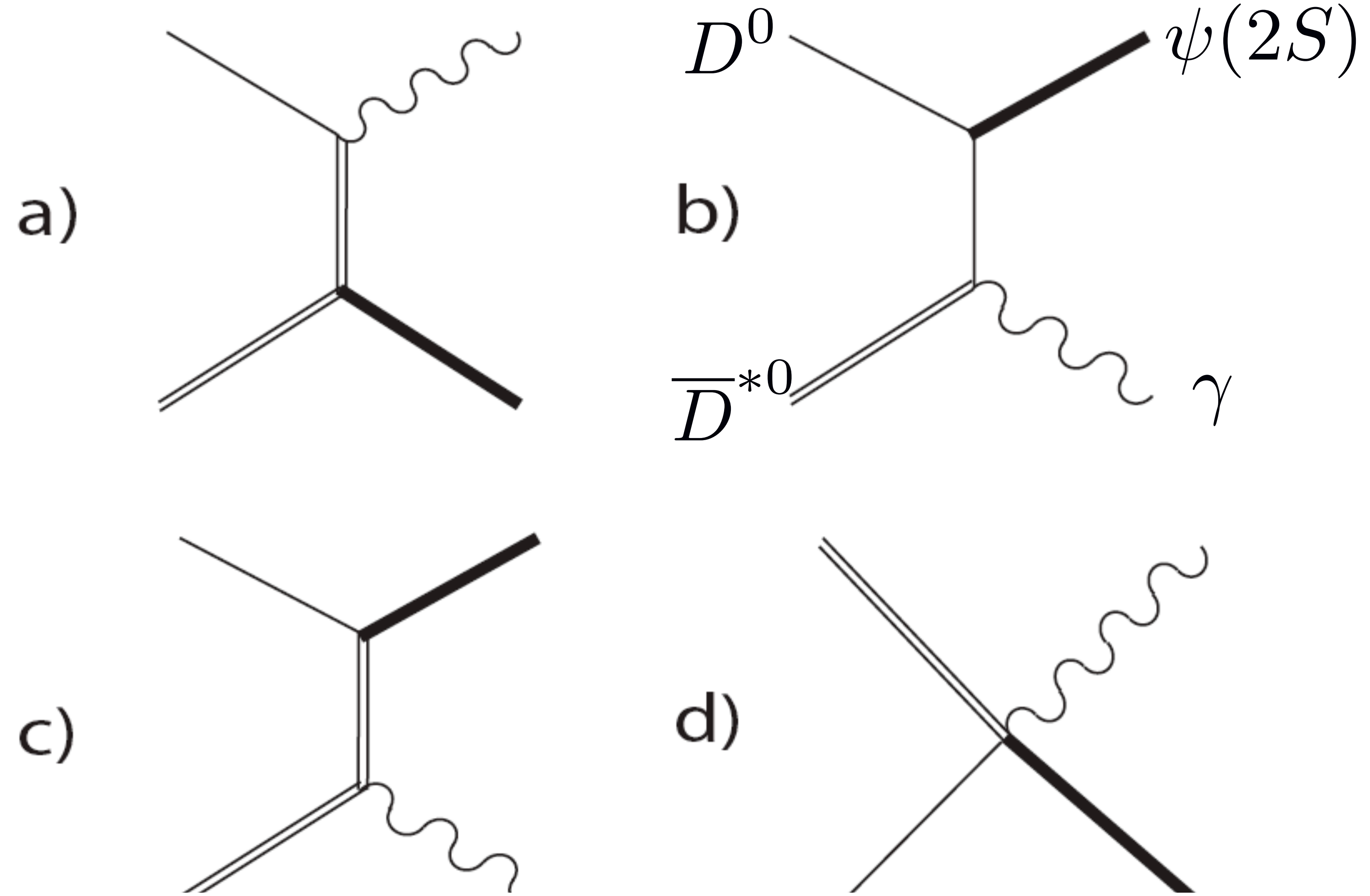
$B\overline{B}$ final state interactions

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

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

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

$D^{0(*)}$

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

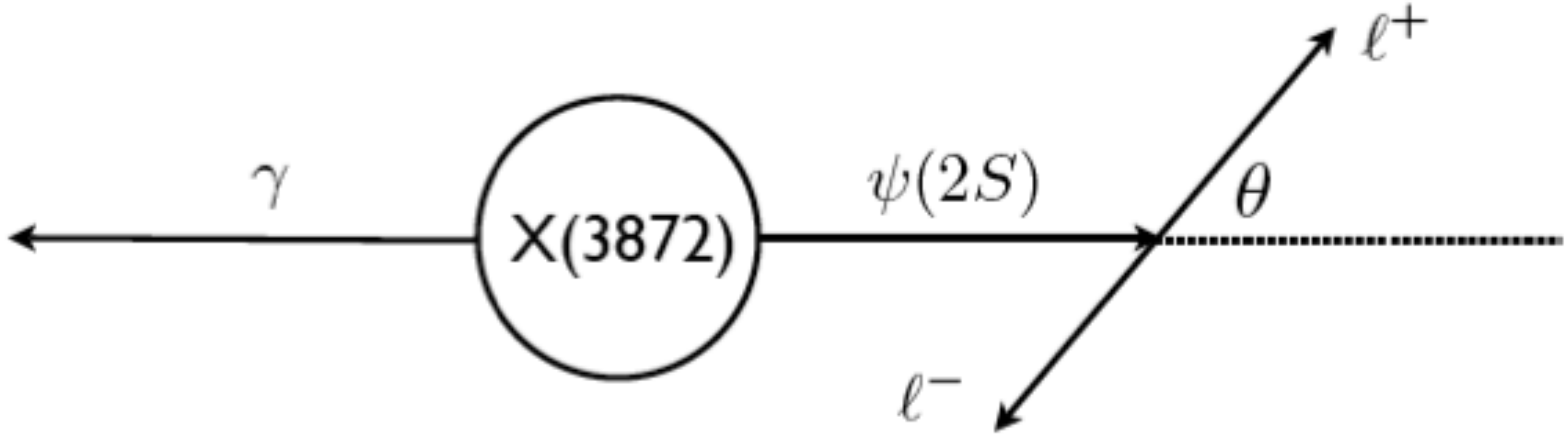
$J = (\eta_c(2S), \psi(2S))$

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

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

$\Rightarrow \Gamma(X(3872) \to \psi(2S)\gamma) > 0.04$ MeV

- 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

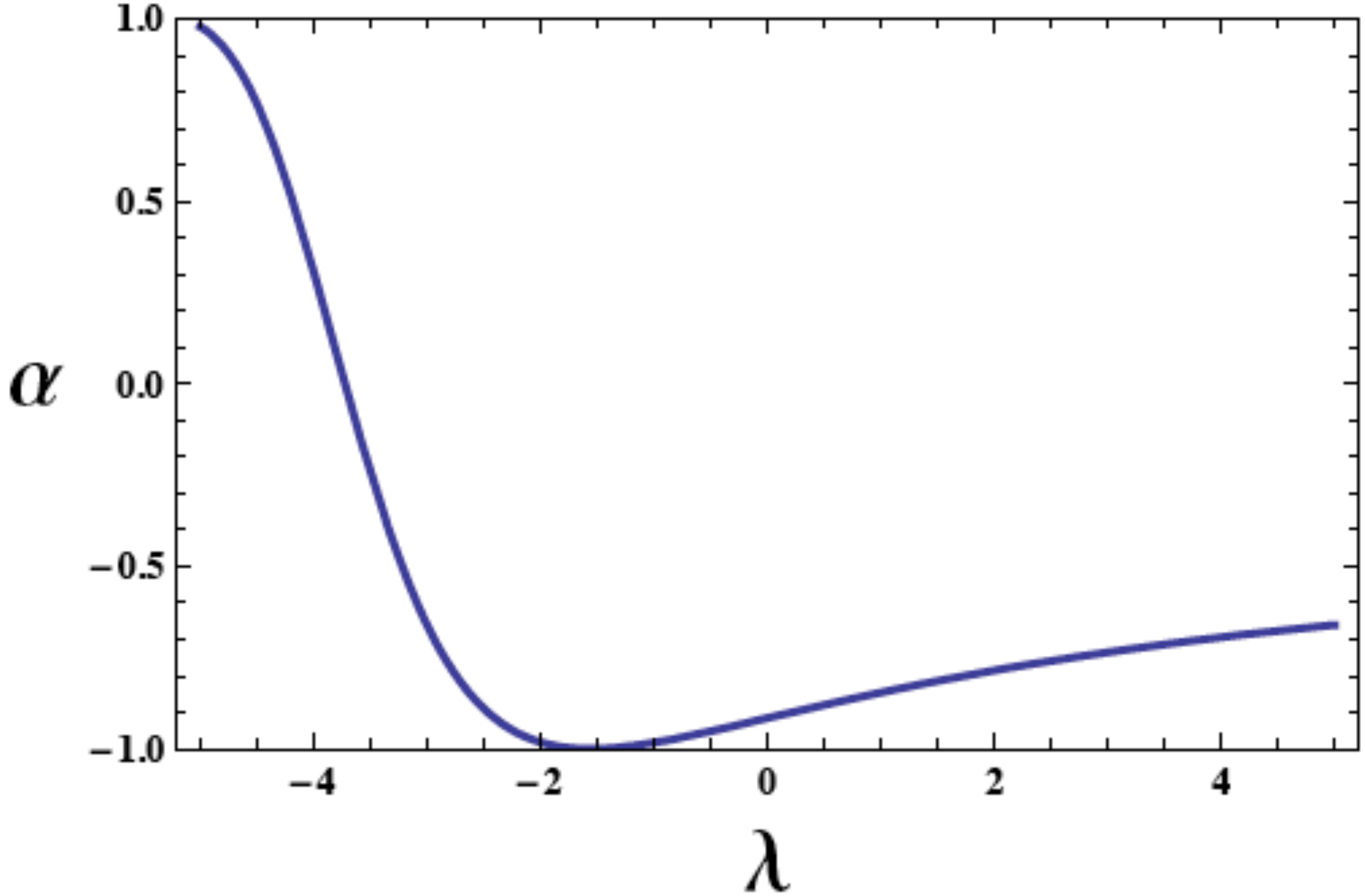
ii) $g_2\beta \gg c_1$ a-c) only b) dominate

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

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

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

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



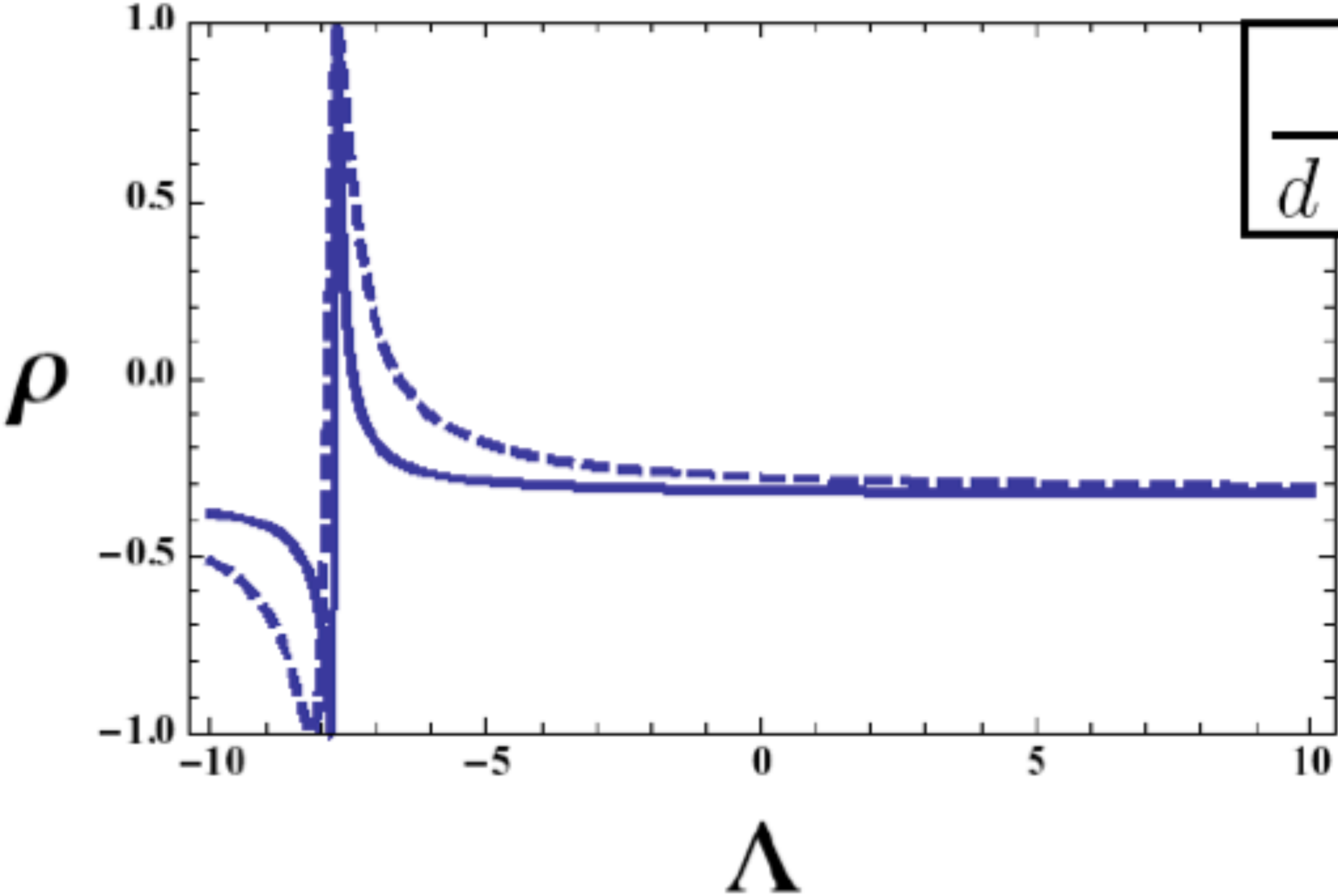
- Longitudinal Polarization $(\alpha < -0.5)$ for $-3.5 \leq \lambda \leq 5$

- $X(3872)$ 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

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

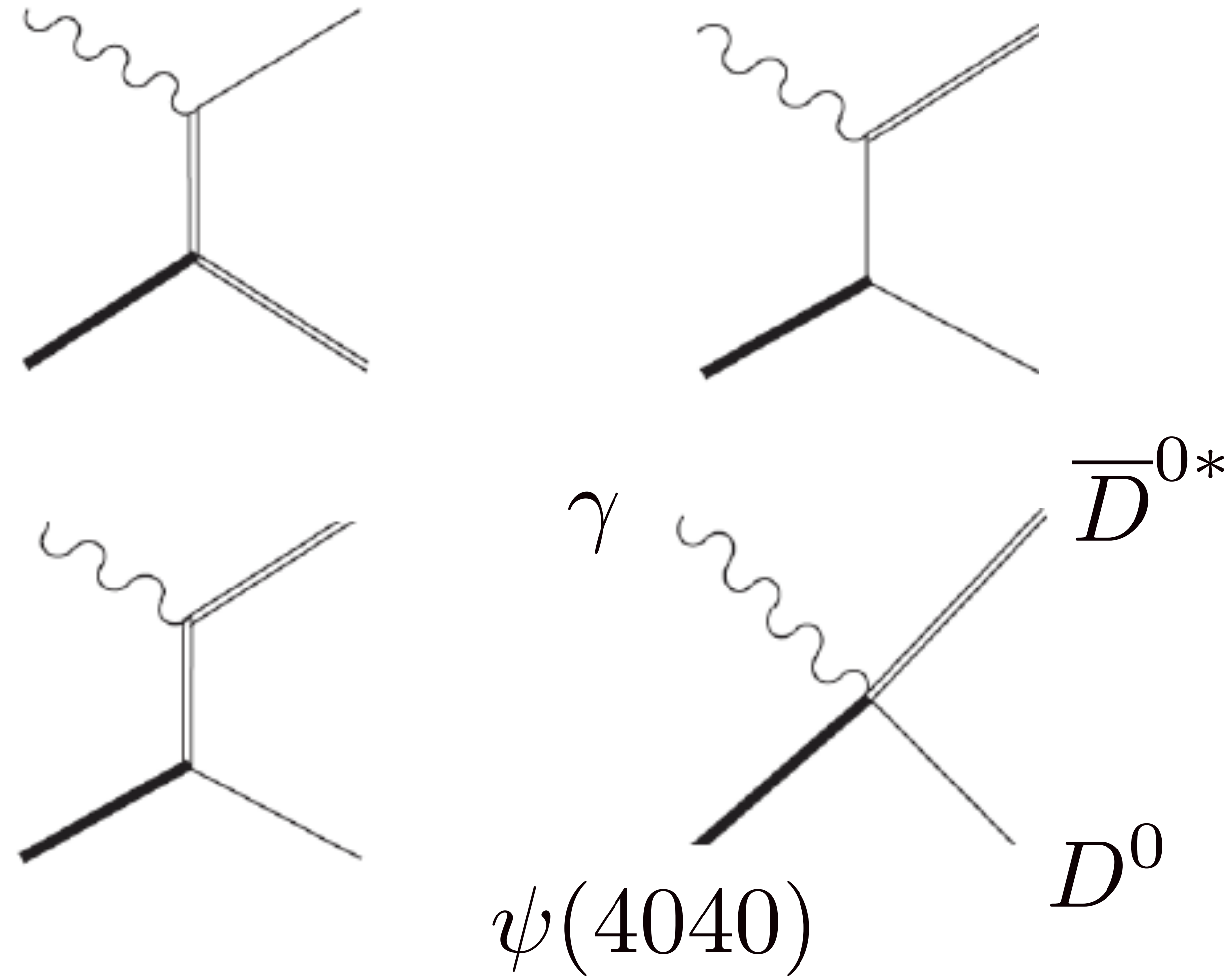
- $J^{PC} = 2^{-+}$ predicts $\rho = 0.08$

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

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

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

$E_\gamma \sim 165$ MeV



Suppose g-like terms dominate:

$|M(X)|^2 > 0.09 \text{ GeV}^3$

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

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

from width of $\psi(4040)$

$(\tilde{g}_2)^2 \sim 0.17 \text{ GeV}^{-3}$

from quark model hep-ph/0511179

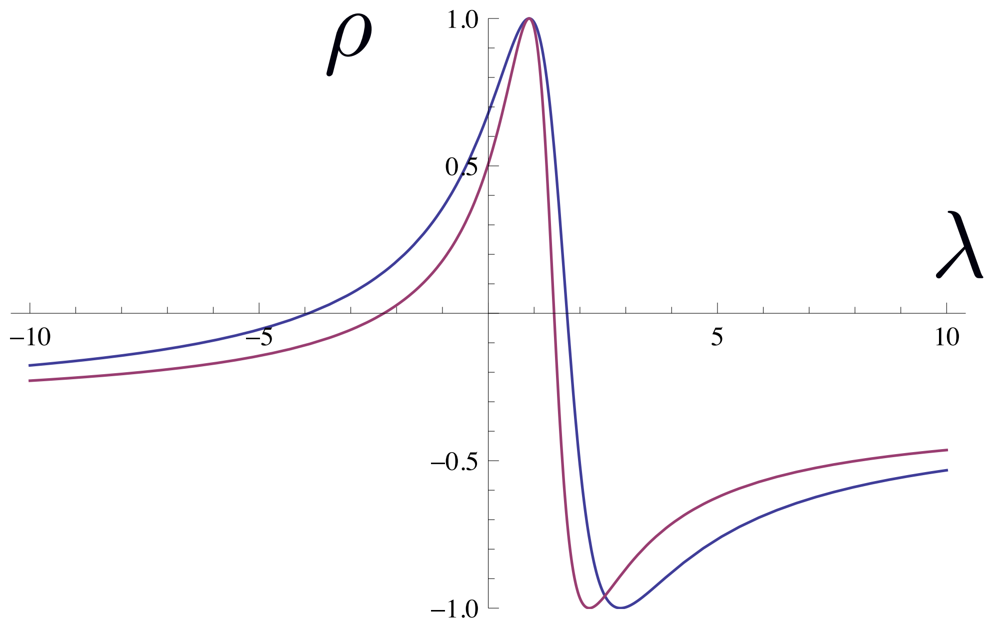
$\Rightarrow \Gamma[\psi(4040) \to X(3872)\gamma]$
$\sim (0.005 - 0.02)$ MeV

$$\psi(4160) \to X(3872)\gamma$$

$$n^{(2s+1)}L_J = 1^3D_1 \qquad J^{PC} = 1^{--}$$

$$J^{ij} = \frac{1}{2}\sqrt{\frac{3}{5}}\left(\sigma^i\psi^j + \sigma^j\psi^i - \frac{2}{3}\delta^{ij}\sigma\cdot\psi\right) + \cdots$$

$$\mathcal{L} = i\frac{\bar{g}}{2}\mathrm{Tr}\left[J^{ij}\bar{H}^\dagger\sigma^i\overleftrightarrow{\partial}^j H^\dagger\right] + \frac{\bar{c}}{2}\mathrm{Tr}\left[J^{ij}\bar{H}^\dagger\sigma^i E^j H^\dagger\right] + \mathrm{h.c.}$$



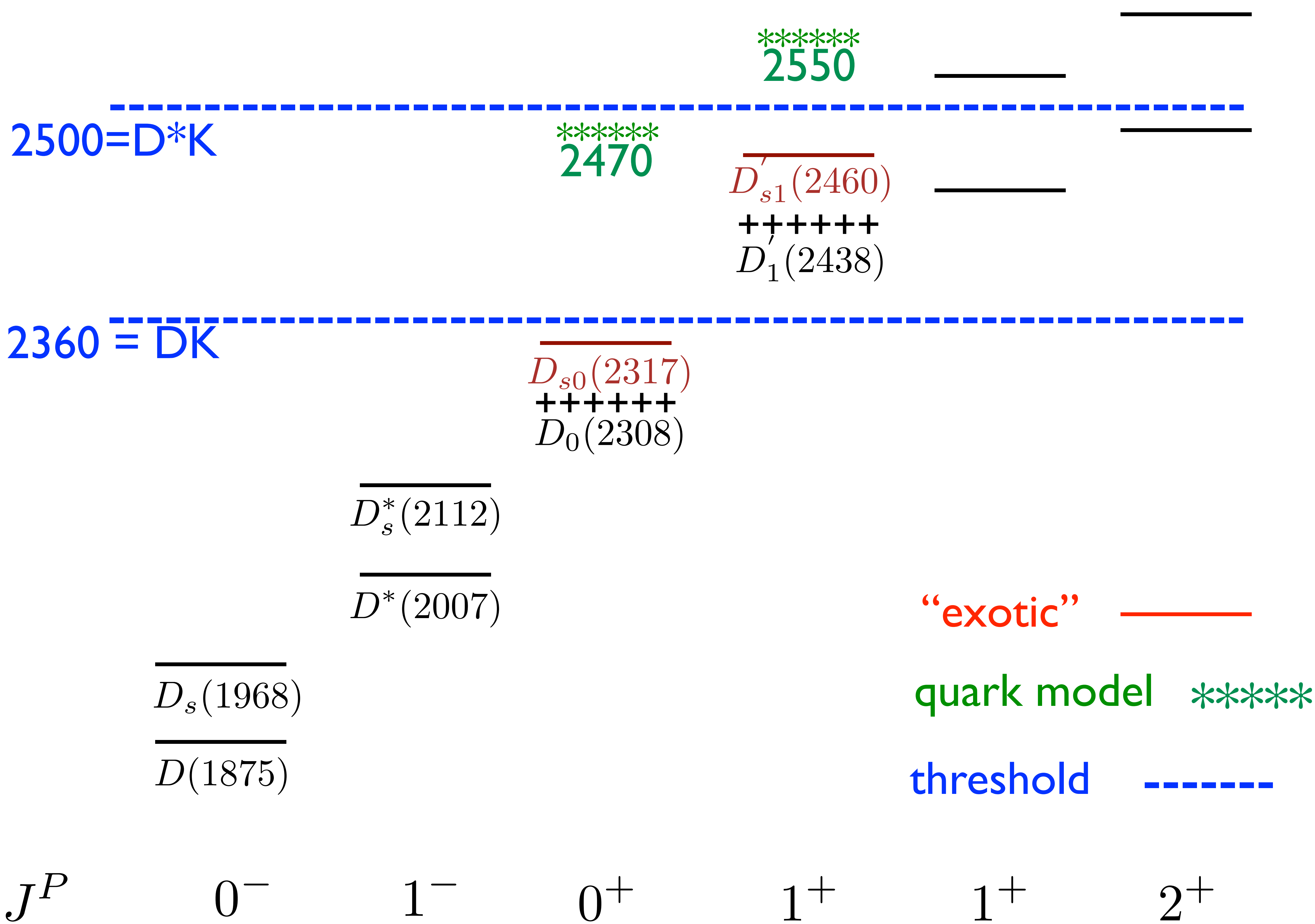
$$\lambda = \frac{3\bar{c}}{\bar{g}\beta}$$

Preliminary

Margaryan
Mehen
RPS

An example of possible “exotics ” that appear *not* to be molecules

Open Charm $c\bar{u}, c\bar{d}, c\bar{s}$



$1^+, 2^+$ — $D_1^{(0,+)}$ D_{s1} $D_2^{(0,+)}$ D_{s2}

$m_c \rightarrow \infty$

$0^+, 1^+$ — $D_0^{(0,+)}$ D_{s0} $D_1'^{(0,+)}$ D'_{s1}

$m_u,\, m_d,\, m_s \rightarrow 0$

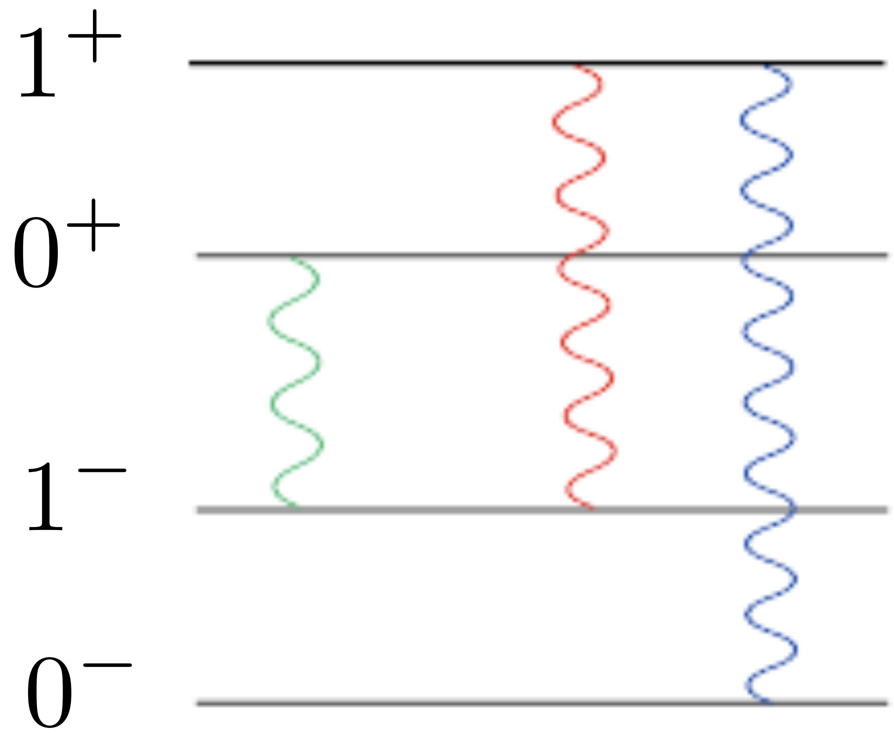
$0^-, 1^-$ — $D^{(0,+)}$ D_s $D^{*(0,+)}$ D_s^*

$$\text{Corrections}: \; \frac{(m_q, p)}{(\Lambda_\chi, m_Q)}$$

$SU(3)$?

$$D^* - D \sim D_s^* - D_s \sim D'_{s1} - D_{s0} \sim 140 MeV$$

Electromagnetic Decays of 0_s^+ and 1_s^+



$$\frac{D_{s0}(2317) \to D_s^* \gamma}{D_{s0}(2317) \to D_s \pi^0} < 0.059$$

(CLEO)

$$\frac{D'_{s1}(2460) \to D_s^* \gamma}{D'_{s1}(2460) \to D_s^* \pi^0} < 0.16$$

$$\frac{D'_{s1}(2460) \to D_s \gamma}{D'_{s1}(2460) \to D_s^* \pi^0} = 0.55 - 0.38 \quad \text{(Belle)}$$

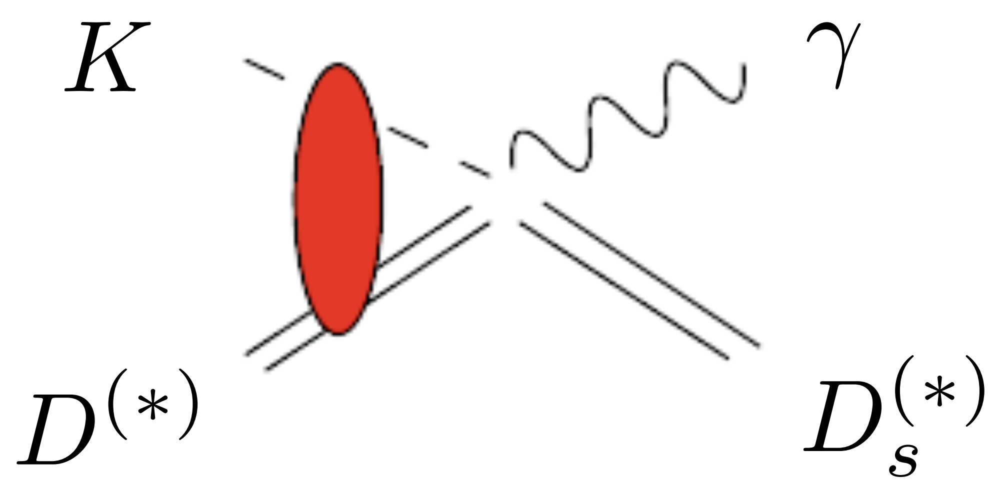
$$0.38 - 0.27 \quad \text{(BaBar)}$$

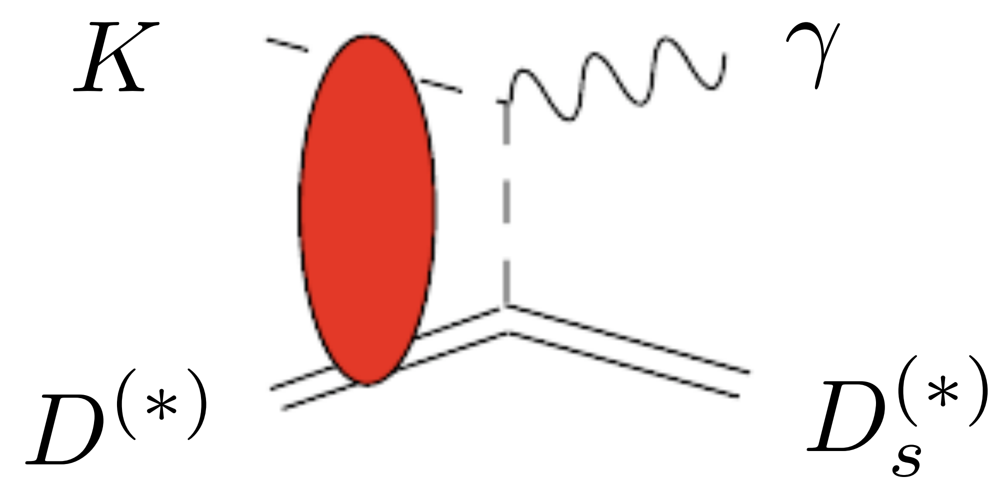
$$\mathcal{L}_{em} = \frac{e}{4} \tilde{\beta} \, [\overline{H}_a S_b \sigma^{\mu\nu} F_{\mu\nu} Q^{\xi}_{ba}]$$

$$Q^{\xi} = \frac{1}{2}(\xi Q \xi^{\dagger} + \xi^{\dagger} Q \xi)$$

corrections : $\frac{\Lambda_{QCD}}{m_c} \sim \frac{m_s}{\Lambda_\chi} \sim 30\%$

$D_{s0},\ D'_{s1}$ as molecules?





$$\Gamma(D_{s1} \to D_s^*\gamma) = \frac{8g^2\alpha^2}{3f^2}\frac{m_{D^*}m_{D_s^*}}{m_{Ds1}^3}|\Psi_{D^*K}(0)|^2 E_\gamma$$

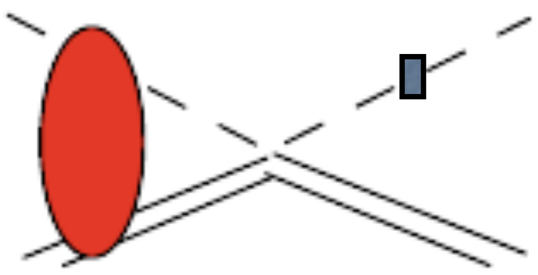
$$\Gamma(D_{s1} \to D_s\gamma) = \frac{4g^2\alpha^2}{3f^2}\frac{m_{D^*}m_{D_s}}{m_{Ds1}^3}|\Psi_{D^*K}(0)|^2 E_\gamma$$

$$\Gamma(D_{s0} \to D_s^*\gamma) = \frac{4g^2\alpha^2}{f^2}\frac{m_{D}m_{D_s^*}}{m_{Ds0}^3}|\Psi_{DK}(0)|^2 E_\gamma$$

$m_Q \to \infty \quad 2:1:3$ phase space $1.57 : 1 : R_\Psi 1.58$

cf. to exp. limits

Strong Decay of Molecules



Predicts $(\pm 30\%)$:

$$\frac{D_{s1} \to D_s^* \gamma}{D_{s1} \to D_s^* \pi^0} = 3.23 \qquad (\exp < 0.16)$$

problem ratios

$\to$ molecular hypothesis

disfavored

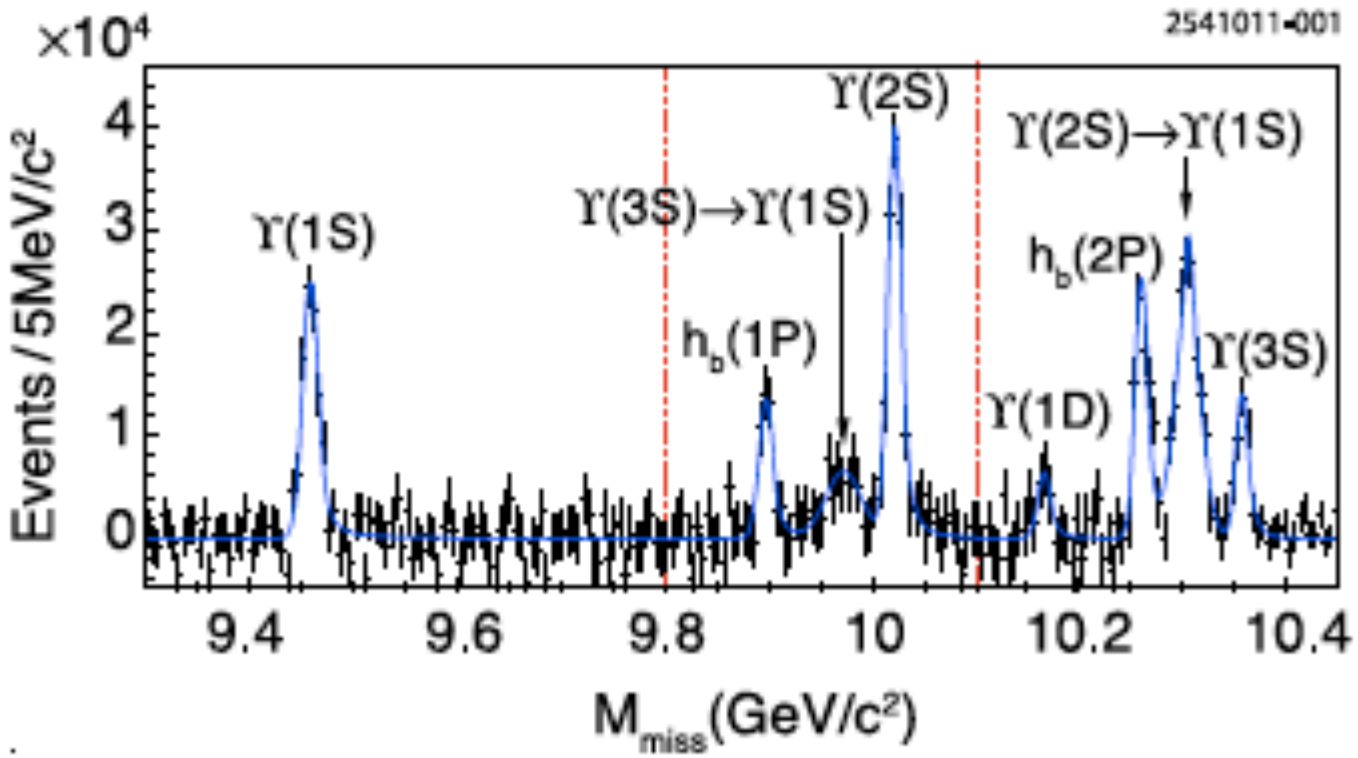
$$\frac{D_{s1} \to D_s \gamma}{D_{s1} \to D_s^* \pi^0} = 2.21 \qquad (\exp \sim 0.44)$$

$$\frac{D_{s0} \to D_s^* \gamma}{D_{s0} \to D_s \pi^0} = 2.96 \qquad (\exp < 0.059)$$

$$\Gamma(D_{s1} \to D_s^* \pi^0) = \frac{3(m_K + E_{\pi^0})^2}{4\pi f^4} \theta^2 \frac{m_{D^*} m_{D_s^*}}{m_{Ds1}^3} |\Psi_{D^*K}(0)|^2 |\vec{p}_{\pi^0}|$$

$$\Gamma(D_{s0} \to D_s \pi^0) = \frac{3(m_K + E_{\pi^0})^2}{4\pi f^4} \theta^2 \frac{m_D m_{D_s}}{m_{D_{s0}}^3} |\Psi_{DK}(0)|^2 |\vec{p}_{\pi^0}|$$

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 as a molecule

HQET predicts additional states (Voloshin...)

$$W_0 = \; 1^-(0^+) = \frac{1}{2} 0^-_{b\bar{b}} \times 0^-_{lt} - \frac{\sqrt{3}}{2} \left(1^-_{b\bar{b}} \otimes 1^-_{lt} \right)_{J=0}$$

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

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

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

$$W'_0 = \; 1^-(0^+) = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \times 0^-_{lt} + \frac{1}{2} \left(1^-_{b\bar{b}} \otimes 1^-_{lt} \right)_{J=0} \rightarrow \eta_b\pi, \chi_b\pi, \Upsilon\rho$$

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

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

$H_a = P_a + \vec{V} \cdot \vec{\sigma}$ 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 "exotic" unexpected particles discovered at B factories

X(3872) may be a molecular bound state of the D^0 and $\overline{D}^{0*}$ mesons.

If so, it *must* have $J^{PC} = 1^{++}$

Measurements needed to check molecular hypothesis:

a. $D^{0(*)}$, $\overline{D}^{0(*)}$ scattering enhancement

b. polarization of $\psi(2S)$ in decay

c. polarization of $X(3872)$ in creation

Possible analogues seen in bottomonium-like system

Again, additional data needed to prove or disprove character

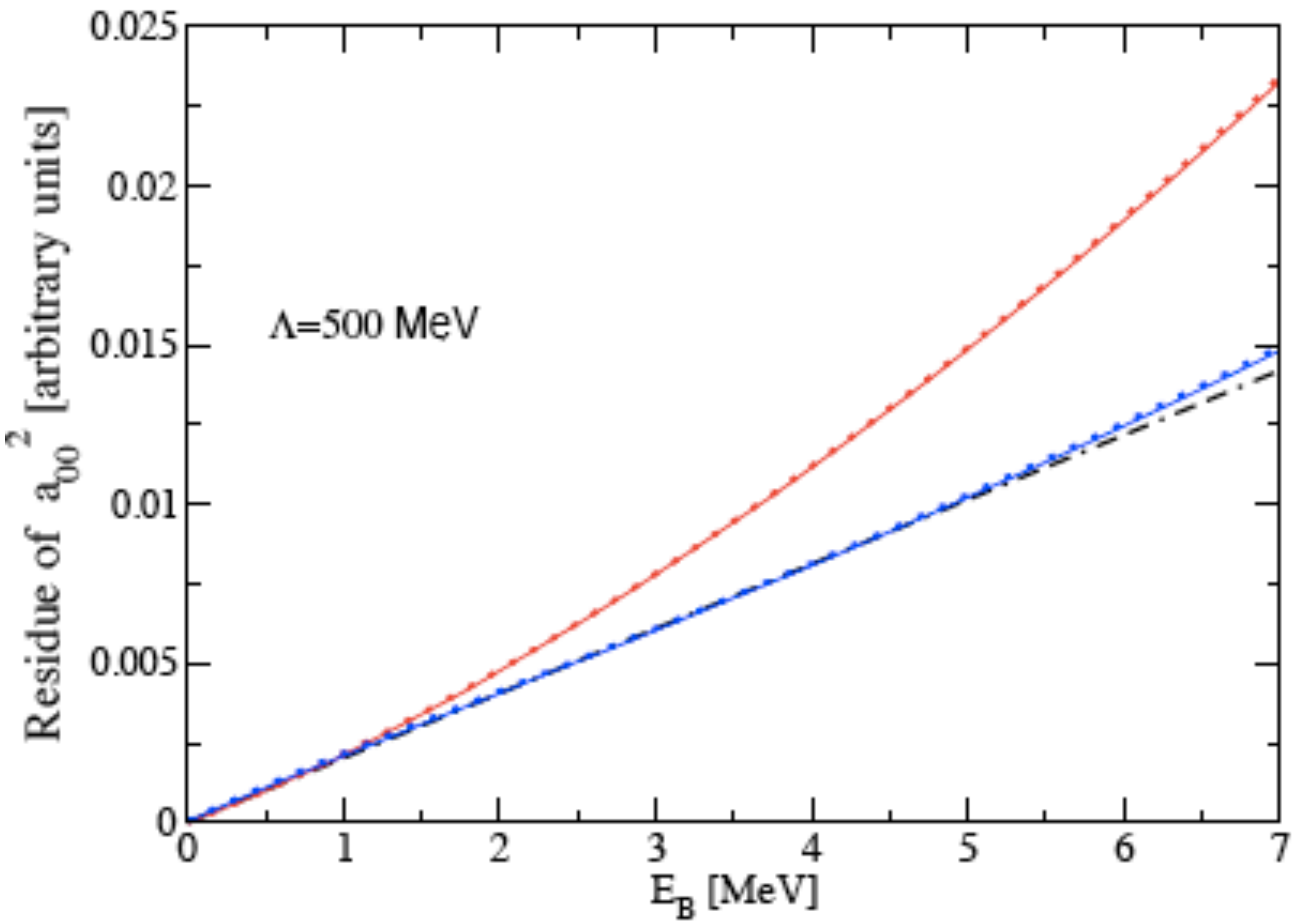
LHC, BESIII, ... exciting times ahead for heavy quark spectroscopy

and our ability to understand bound states of QCD

Will this "cleaner" system shed light on nuclear bound states?

Additional Slides

Baru et al 1108.5644



Amplitudes

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

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

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

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

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

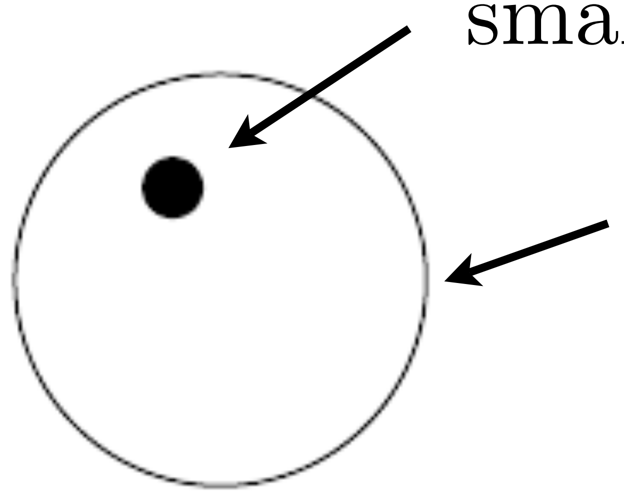
$$|\mathcal{M}(\vec{\epsilon}_\psi)|^2 = \left(2 g_2^2 \beta^2 A^2 E_\gamma^4 + 4 g_2 \beta c_1 A C E_\gamma^2 + 2 c_1^2 C^2\right) |\hat{k} \cdot \vec{\epsilon}_\psi|^2 + \left(g_2^2 \beta^2 B^2 E_\gamma^4 - 2 g_2 \beta c_1 B C E_\gamma^2 + c_1^2 C^2\right) |\hat{k} \times \vec{\epsilon}_\psi|^2$$

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

Hadrocharmonium

$J/\psi, \psi(2S), \ldots$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}
$Y(4260) \to \pi\pi J/\psi$	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

Strong Interaction Terms

$$\mathcal{L} = N^\dagger(i\partial_0 + \frac{\vec{\nabla}^2}{2M})N - \frac{1}{8}\mathcal{C}_0^{(^1S_0)}(N^T\tau_2\tau_a\sigma_2 N)^\dagger(N\tau_2\tau_a\sigma_2 N)$$
$$-\frac{1}{8}\mathcal{C}_0^{(^3S_1)}(N^T\tau_2\sigma_2\sigma_i N)^\dagger(N\tau_2\sigma_2\sigma_i N) + \ldots,$$

$$P_a(^1S_0) = \frac{1}{\sqrt{8}}\tau_2\tau_a\sigma_2 \ ; \qquad P_i(^3S_1) = \frac{1}{\sqrt{8}}\tau_2\sigma_2\sigma_i$$

$$\mathcal{L} = N^\dagger\left(i\partial_0 + \frac{\vec{\nabla}^2}{2M}\right)N - t_i^\dagger\left(i\partial_0 + \frac{\nabla^2}{4M} - \Delta_{(^3S_1)}\right)t_i$$
$$-g_{(^3S_1)}\left[t_i^\dagger N^T P_i(^3S_1)N + \text{h.c.}\right]$$
$$-s_a^\dagger\left(i\partial_0 + \frac{\nabla^2}{4M} - \Delta_{(^1S_0)}\right)s_a$$
$$-g_{(^1S_0)}\left[s_a N^T P_a(^1S_0)N + \text{h.c.}\right]$$

"dibaryon" treatment