XYZ States and Hadronic Transitions

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Outline:
- Brief review quarkonium physics below threshold

- Surprises above threshold

  - Hadronic transitions

  - XYZ states

- Disentangling the XYZ states

- New dynamics for hadronic transitions above threshold

- Summary and Requests

Modern Exotic Hadrons
Nov. 2-13, 2015
Institute for Nuclear Theory
University of Washington, Seattle

Quarkonium physics below threshold

- Qualitative predictions of QCD inspired potential models reproduce the spectrum and EM transitions well
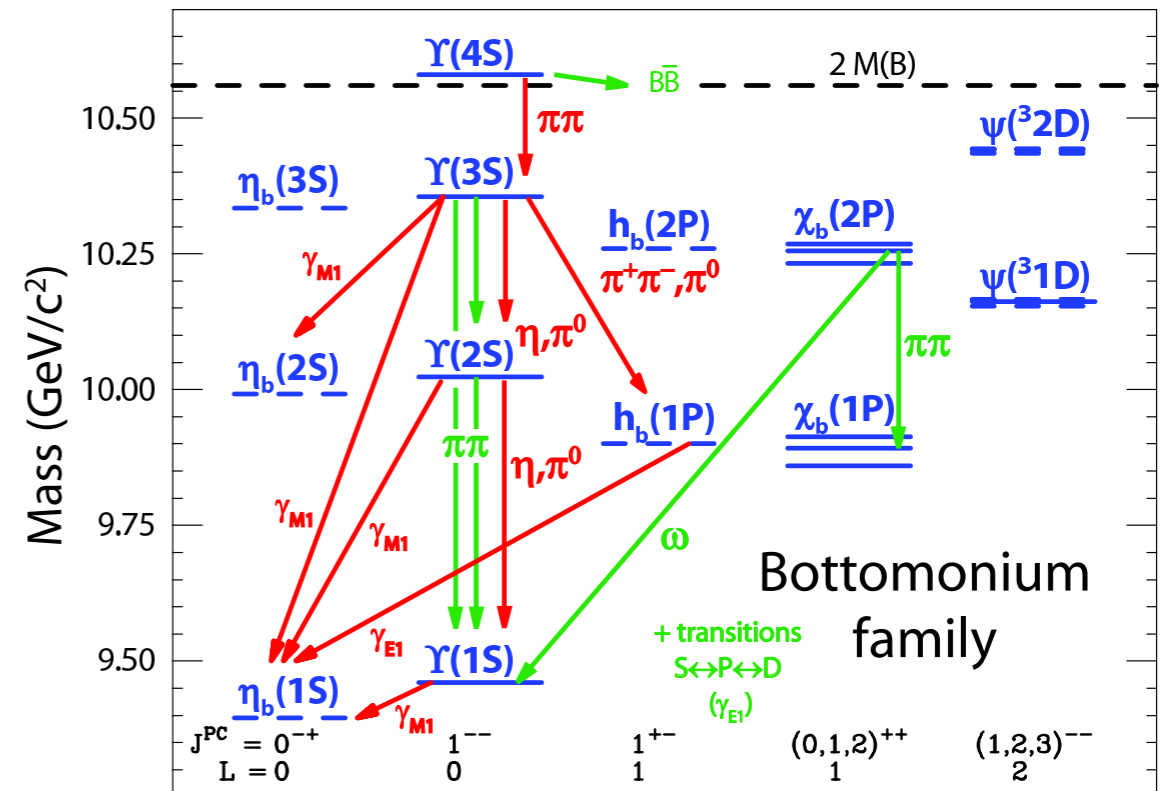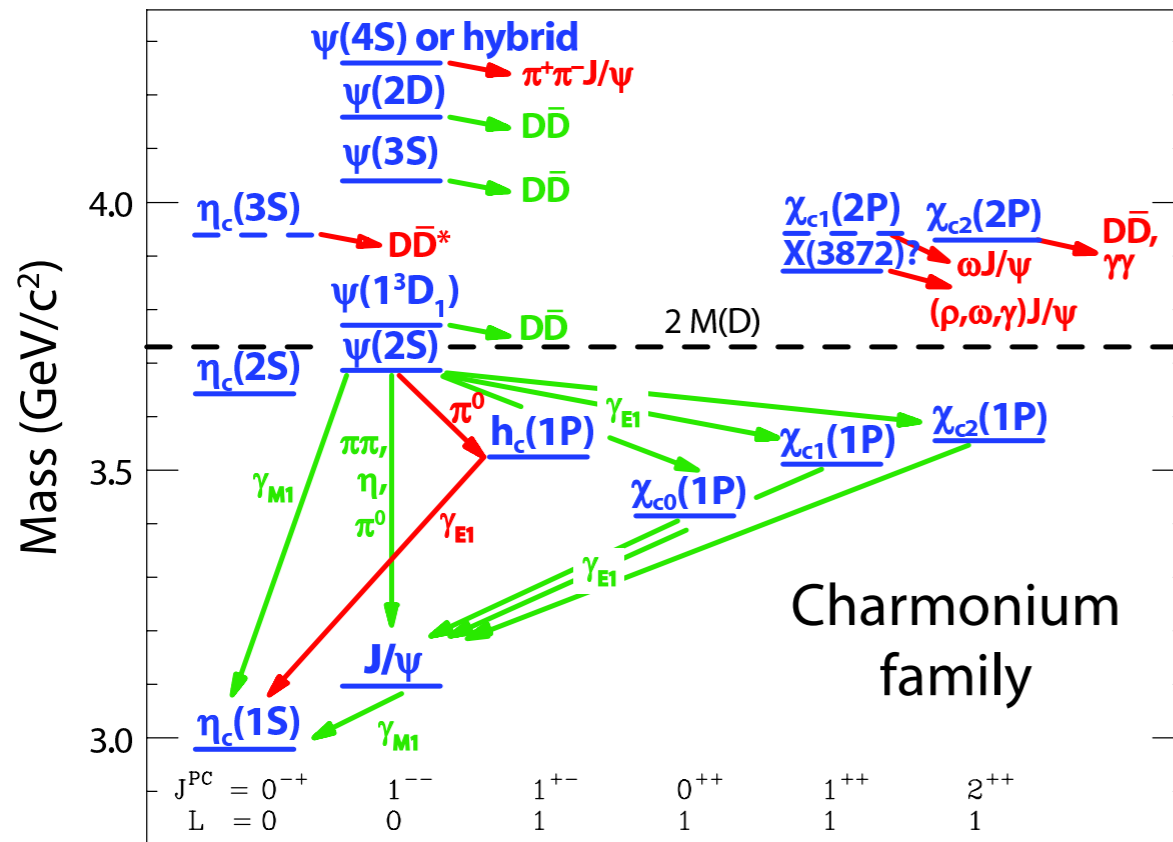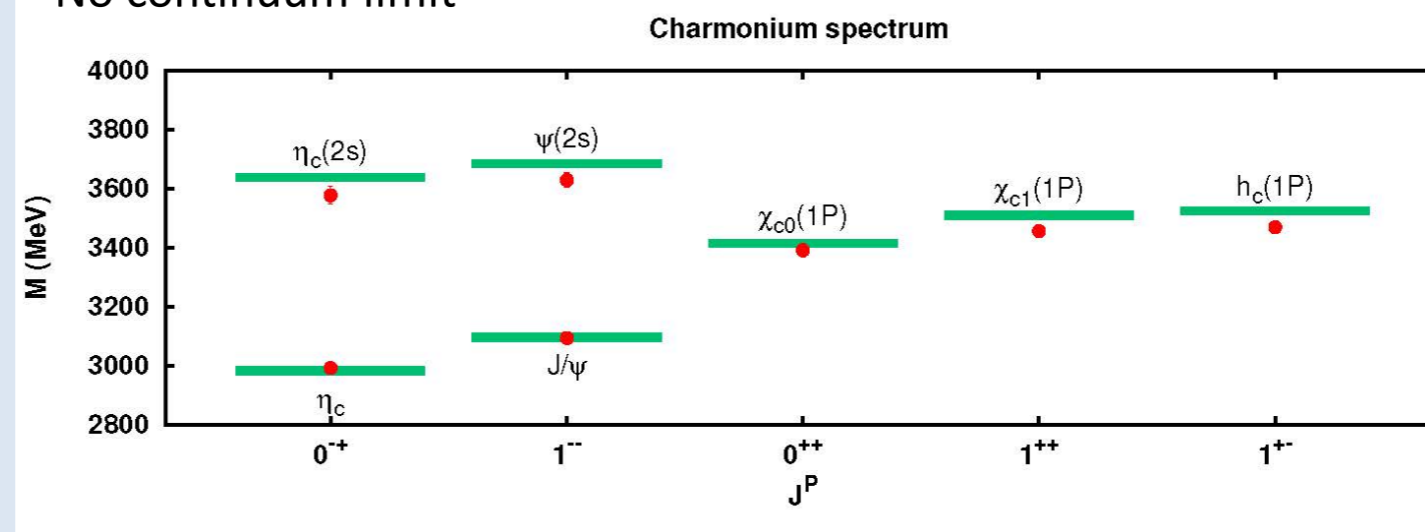
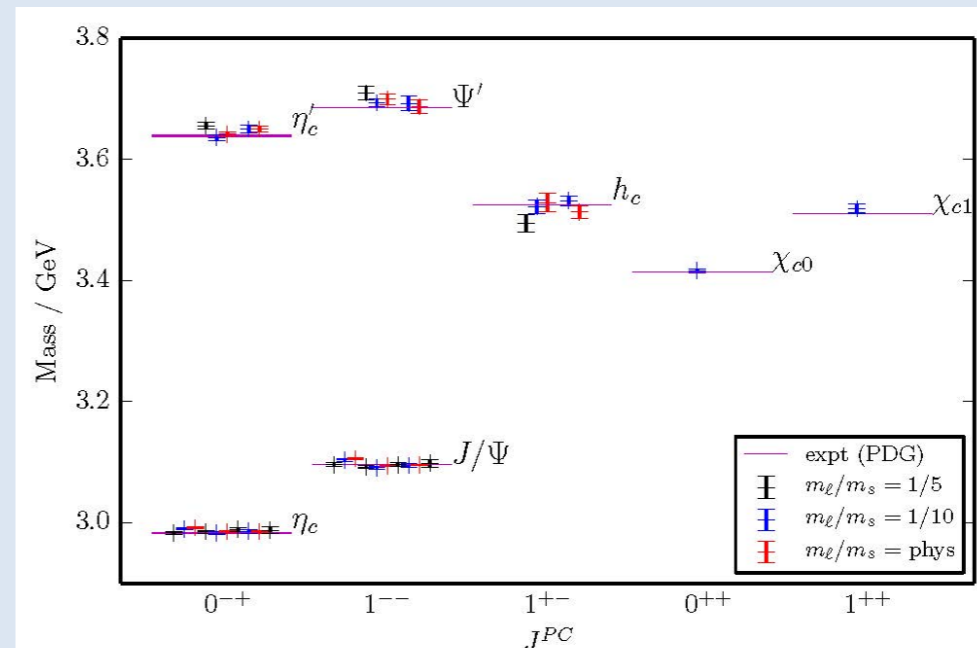# Quarkonium physics below threshold

- Now superseded by lattice calculations for the spectrum

Low lying charmonium levels

Reasonably well understood

Glasgow 1411.1318
Continuum limit,
Physical quark masses

Regensburg 1503.08440
No continuum limit

C. DeTar, Lepton-Photon 2015

Hadronic Transitions

- Below threshold the QCD multipole expansion works well to describe the hadronic transitions.

- The transition rates are small.

- Heavy-quark symmetry (HQS) dictates that the leading transitions do not flip the spin of the heavy quarks (as with the usual EM transitions in non-relativistic systems E1, M1, E2, …).

- Isospin breaking is suppressed.

- But detailed results rely on a specific phenomenological model of Kuang-Yan.

- A few puzzles remain.

Transition	$\Gamma_{\mathrm{partial}}$ (keV) (Experiment)	$\Gamma_{\mathrm{partial}}$ (keV) (KY Model)
$\psi(2S)$		
$\rightarrow J/\psi + \pi^+\pi^-$	102.3 ± 3.4	input $(|C_1|)$
$\rightarrow J/\psi + \eta$	10.0 ± 0.4	input (C_3/C_1)
$\rightarrow J/\psi + \pi^0$	0.411 ± 0.030 [446]	0.64 [522]
$\rightarrow h_c(1P) + \pi^0$	0.26 ± 0.05 [47]	0.12-0.40 [527]
$\psi(3770)$		
$\rightarrow J/\psi + \pi^+\pi^-$	52.7 ± 7.9	input (C_2/C_1)
$\rightarrow J/\psi + \eta$	24 ± 11	
$\psi(3S)$		
$\rightarrow J/\psi + \pi^+\pi^-$	< 320 (90% CL)	
$\Upsilon(2S)$		
$\rightarrow \Upsilon(1S) + \pi^+\pi^-$	5.79 ± 0.49	8.7 [528]
$\rightarrow \Upsilon(1S) + \eta$	$(6.7 \pm 2.4) \times 10^{-3}$	0.025 [521]
$\Upsilon(1^3D_2)$		
$\rightarrow \Upsilon(1S) + \pi^+\pi^-$	0.188 ± 0.046 [63]	0.07 [529]
$\chi_{b1}(2P)$		
$\rightarrow \chi_{b1}(1P) + \pi^+\pi^-$	0.83 ± 0.33 [523]	0.54 [530]
$\rightarrow \Upsilon(1S) + \omega$	1.56 ± 0.46	
$\chi_{b2}(2P)$		
$\rightarrow \chi_{b2}(1P) + \pi^+\pi^-$	0.83 ± 0.31 [523]	0.54 [530]
$\rightarrow \Upsilon(1S) + \omega$	1.52 ± 0.49	
$\Upsilon(3S)$		
$\rightarrow \Upsilon(1S) + \pi^+\pi^-$	0.894 ± 0.084	1.85 [528]
$\rightarrow \Upsilon(1S) + \eta$	$< 3.7 \times 10^{-3}$	0.012 [521]
$\rightarrow \Upsilon(2S) + \pi^+\pi^-$	0.498 ± 0.065	0.86 [528]
$\Upsilon(4S)$		
$\rightarrow \Upsilon(1S) + \pi^+\pi^-$	1.64 ± 0.25	4.1 [528]
$\rightarrow \Upsilon(1S) + \eta$	4.02 ± 0.54	
$\rightarrow \Upsilon(2S) + \pi^+\pi^-$	1.76 ± 0.34	1.4 [528]

Basics of the QCDME

- QCD multipole expansion (QCDME) in a nutshell

  – Analogous to the QED multipole expansion with gluons replacing photons.

$$H_{\text{QCD}}^{\text{eff}} = H_{\text{QCD}}^{(0)} + H_{\text{QCD}}^{(1)} + H_{\text{QCD}}^{(2)} \qquad H_{\text{QCD}}^{(1)} \equiv Q_a A_0^a(\mathbf{X}, t)$$
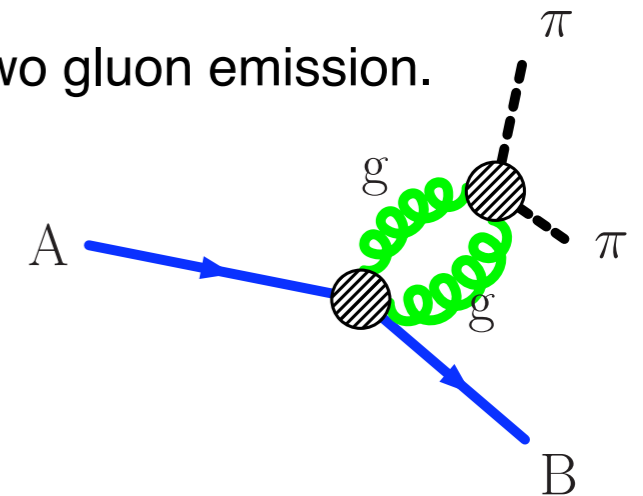
  zero for color singlet

$$H_{\text{QCD}}^{(2)} \equiv -\mathbf{d}_a \cdot \mathbf{E}^a(\mathbf{X}, \mathbf{t}) - \mathbf{m_a} \cdot \mathbf{B^a}(\mathbf{X}, \mathbf{t}) + \cdots$$

  E1   M1   ...

  – color singlet physical states means lowest order terms involve two gluon emission.
  So lowest multipoles E1 E1, E1 M1, E1 E2, ...

  – factorize the heavy quark and light quark dynamics

$$\mathcal{M}(\Phi_i \to \Phi_f + h) =$$
$$\frac{1}{24} \sum_{KL} \frac{\langle f|d_m^{ia}|KL\rangle \langle|KL|d_{ma}^{j}|i\rangle}{E_i - E_{KL}} \langle h|\mathbf{E}^{ai}\mathbf{E}_a^j|0\rangle \qquad \text{+ higher order multipole terms.}$$

  – assume a model for the heavy quarkonium states Φ_i, Φ_f and a model for the intermediate states |KL> hybrid states.

  – use chiral effective lagrangians to parameterize the light hadronic system.

Remaining puzzles

- QCDME n $^3S_1$ -> m $^3S_1$ + π π transitions:

  Bottomonium

  – E1E1 dominates

  $$\mathcal{M}_{if}^{gg} = \frac{1}{16} < B|\mathbf{r_i}\xi^a\mathcal{G}\mathbf{r_j}\xi^a|A> \quad \frac{g_E^2}{6} < \pi_\alpha\pi_\beta|Tr(\mathbf{E^i E}^j)|0 >$$

  α_{AB}^{EE}

  – Chiral symmetry

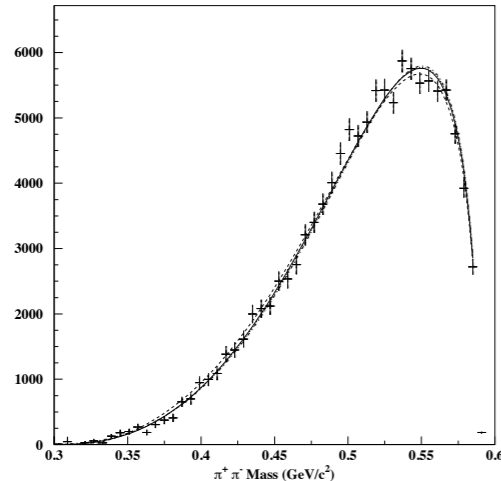 S-wave   D-wave

  $$\frac{\delta_{\alpha\beta}}{\sqrt{(2\omega_1)(2\omega_2)}}\left[C_1\delta_{kl}q_1^\mu q_{2\mu} + C_2\left(q_{1k}q_{2l} + q_{1l}q_{2k} - \frac{2}{3}\delta_{kl}\ (q_1 \cdot q_2)\right)\right]$$

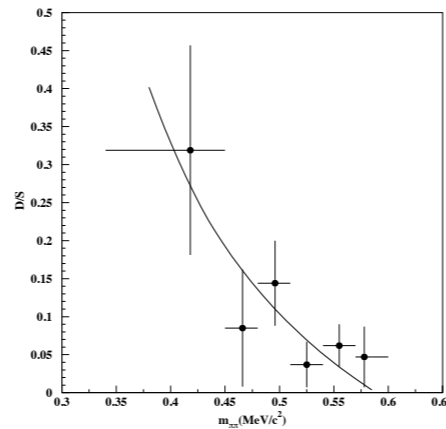 Charmonium   2->1   D/S wave   J. Z. Bai, et al (BES)
  Phys.Rev. D62 (2000) 032002

  D. Cronin-Hennessy, et al
  PRD76:072001,2007 (CLEO III)

  (BABAR) B. Aubert, el al
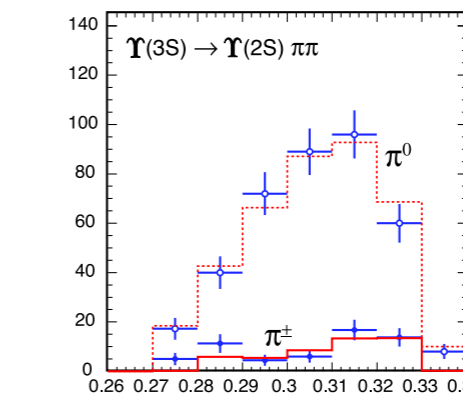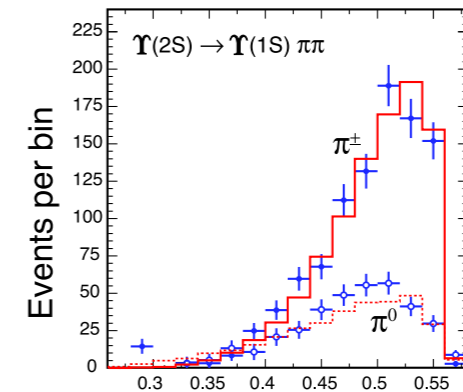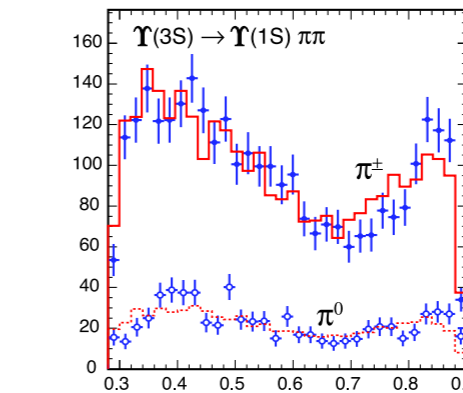 PRL96:232001,2006.

  – 3 ->1 and 4 -> 2   puzzling behavior

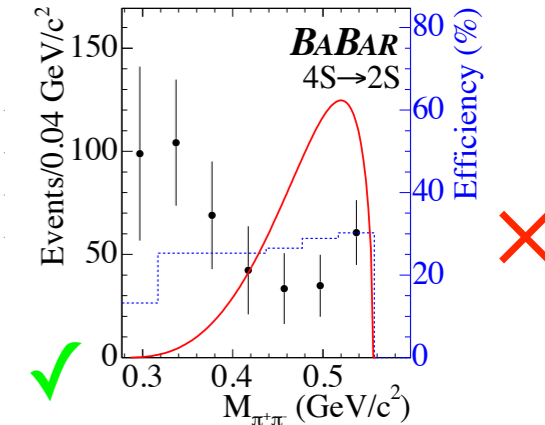   – dynamical cancellations: M. Voloshin [arXiv:hep-ph/0606258]

    – final state (π π) interactions: Y. Surovtsev, el al[arXiv:1506.0306]
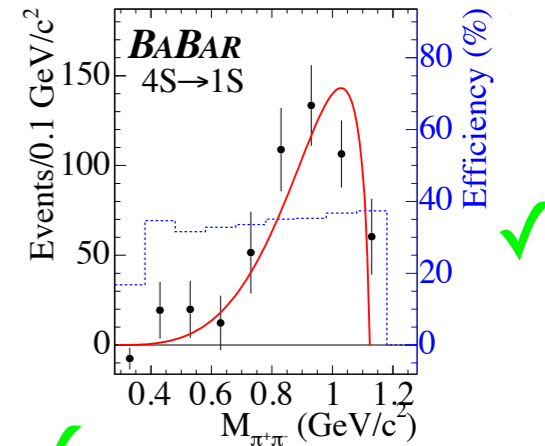
Remaining puzzles / QCDME

$$S_{if}^{M} = 6(2s+1)(2s'+1)\left\{\begin{matrix}1 & \mathcal{Y} & 1 \\ \tfrac{1}{2} & \tfrac{1}{2} \end{matrix}\right\}\left\{\begin{matrix} \\ s' & \ell & s \end{matrix}\right\}\left\{\begin{matrix} \\ \tfrac{1}{2} & s' & s \end{matrix}\right\}.\tag{9}$$

For $\ell = 0$ transitions, $S_{if}^{M} = 1$.

- ## QCDME η transitions:

  - **E1-M2 dominates:** $\mathcal{M}_{if}^{gg} = \dfrac{1}{16}<B|\mathbf{r_i}\xi^a \mathcal{G}\mathbf{r_j}\xi^a|A> \dfrac{g_e g_M}{6}\langle\eta|\mathbf{E}_i\partial_j\mathbf{B}_k|0\rangle\dfrac{(\epsilon_B^* \times \epsilon_A)_k}{3m_Q}$

    α_{AB}^{EE}

  - **Ratio of η to ππ transitions:** same initial and final quarkonium states at $(M_{\pi\pi} = M_\eta)$

    $$R_{Q\bar{Q}}(n \to m) \equiv \frac{\Gamma(n^3S_1 \to m^3 S_1 \eta)}{\Gamma(n^3 S_1 \to m^3 S_1 \pi \pi)} \quad\quad (14)$$

    is independent of the details of the intermediate states

    [kinematic factor]

  - **Comparing theory (KY) and experiment**

$R_{\eta/\pi\pi}(^3S_1(n) \to\ ^3S_1(m))$ $(Q\bar{Q})n \to m$	theory	experiment
$(c\bar{c}): 2 \to 1$	3.39×10^{-3}	1.0×10^{-1}
$(c\bar{c}): 3 \to 1$	6.35×10^{-3}	1.0
$(b\bar{b}): 2 \to 1$	1.99×10^{-2}	1.99×10^{-2}
$(b\bar{b}): 3 \to 1$	4.57×10^{-3}	$< 2.3 \times 10^{-2}$
$(b\bar{b}): 4 \to 1$	2.23×10^{-3}	24
$(b\bar{b}): 5 \to 1$	9.58×10^{-4}	4.8
$(b\bar{b}): 5 \to 2$	5.33×10^{-3}	1.6

~ 30 > model
~ 150 > model
sets C_3/C_1 = 0.143 ± 0.024
~ 1000 > model
~ 2000 > model
~ 300 > model

$C_2/C_1 = 1.32^{+0.35}_{-0.45}$

- – Transitions near and above threshold violate expectations of QCDME and sizable rates require large SU(3) breaking.
- – We will see this is associated with the large SU(3) breaking in virtual and real heavy-light meson pair contributions to the states.

Why does it work so well?

- When should the QCDME work?

  – Transitions between tightly bound quarkonium states

  – Small radius ($R \ll \Lambda_{QCD}$)

    • bottomonium 1S, 1P, 2S, 1D, 2P, 3S, ...

    • charmonium 1S, 1P, ...

  – Small contributions from excitations involving QCD additional degrees of freedom.

    • This is essential to the factorization assumption !

- Above threshold

  – light quark pairs

    • $\overline{D}^{(*)} D^{(*)}$ thresholds in 1D to 3S region

    • $\overline{B}^{(*)} B^{(*)}$ thresholds in 4S region

  – gluonic string excitations

    • Hybrid states associated with the potentials Π_u, ...

    • In the static limit this occurs at separation r ≈ 1.2 fm.

      • Between the 3S and 4S in (cc) system

      • Just above the 5S in the (bb) system

- New mechanisms can be expected for hadronic transitions above threshold.

Cornell Potential Model
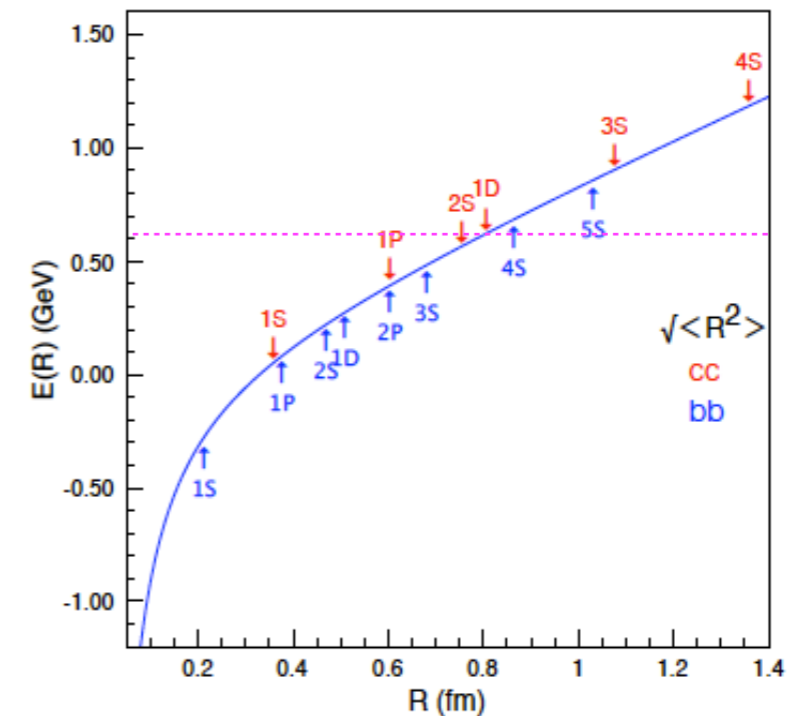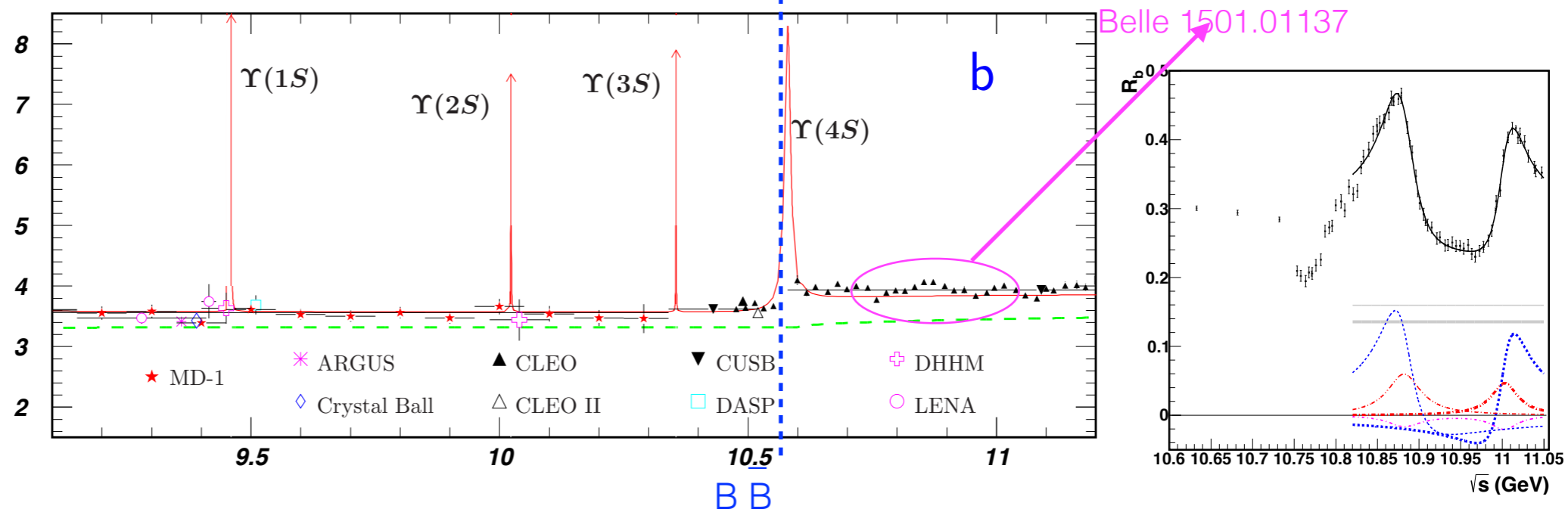
$\overline{DD}, \overline{BB}$
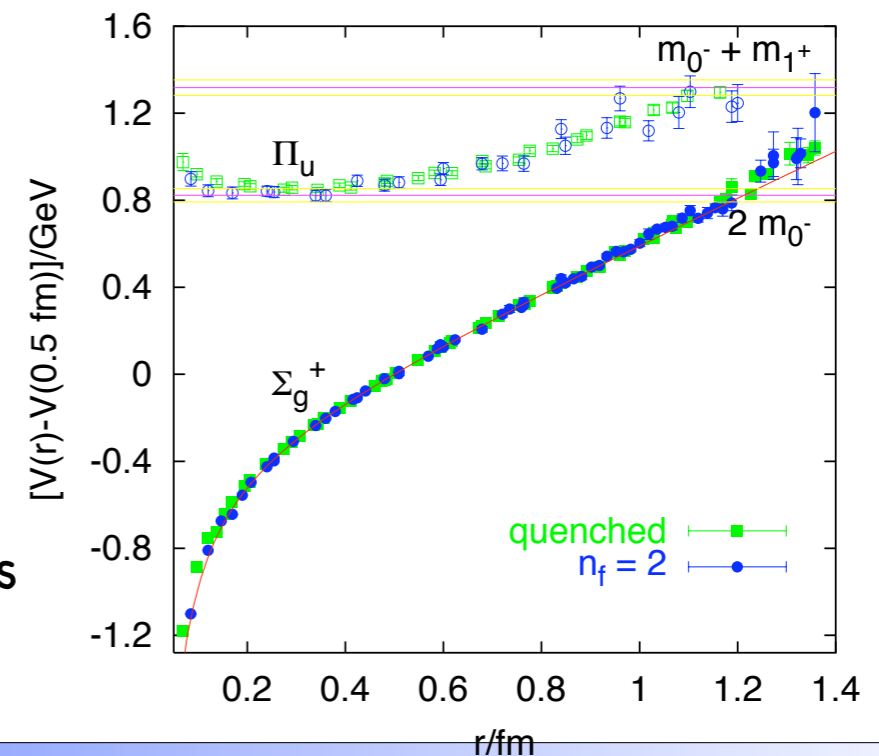
The Threshold Region

- $R = \sigma(e+e- \to \gamma^* \to \text{hadrons})/\sigma(e+e- \to \gamma^* \to \mu+\mu-)$ $J^{PC} = 1^{--}$

  - Resonance region: $(\sqrt{s} - 2m_H) \lesssim 1$ GeV

  - Two body decays

    - D0 = (cu), D+ = (cd)

    - $M(D^0 D^0) = 3,729.72$ MeV

    - $M(D^+ D^-) = 3,739.26$ MeV

    - B- = (bu), B0 = (bd)

    - $M(B^+ B^-) = 10,578.52$ MeV

    - $M(B^0 B^0) = 10,579.16$ MeV

  - $e_c = 2/3$; $e_b = -1/3$
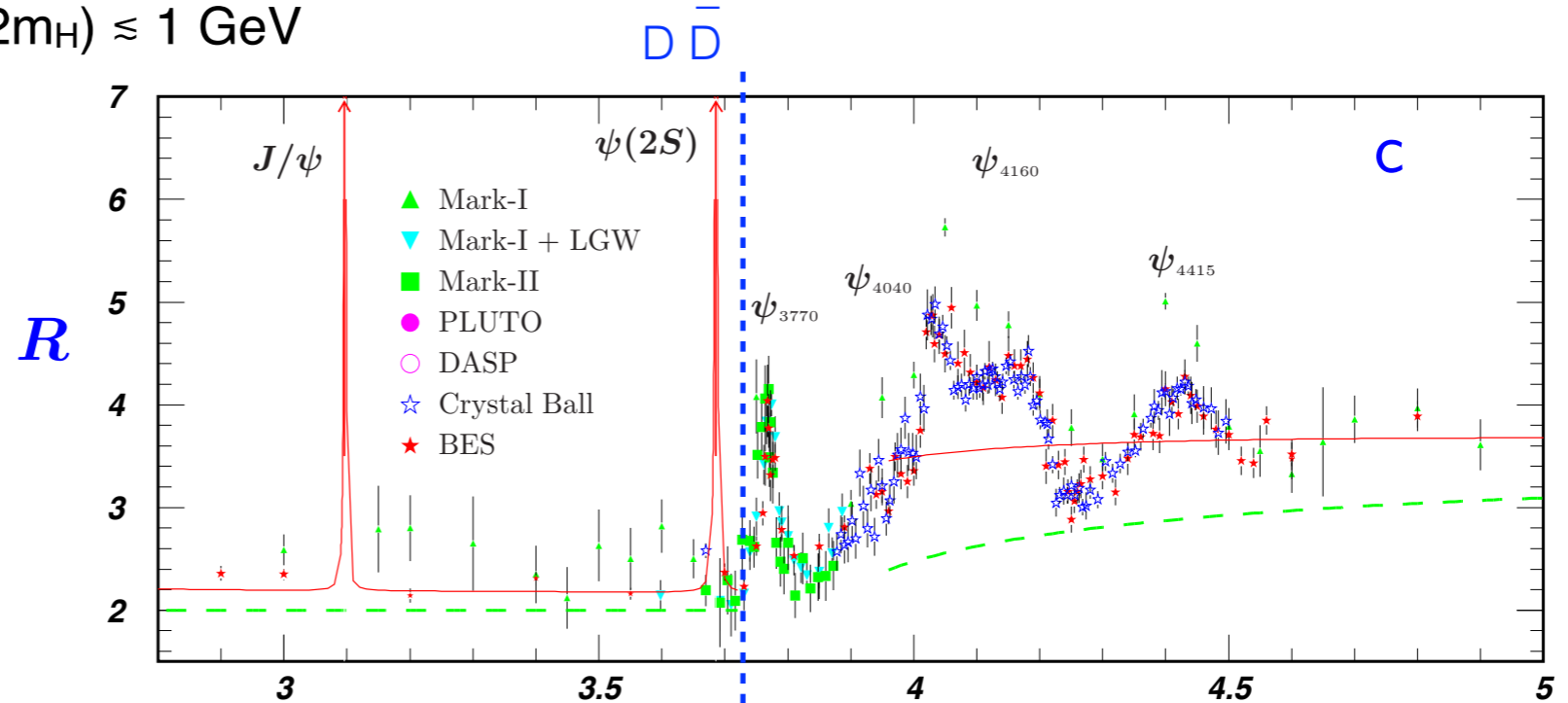
- Two pictures of R
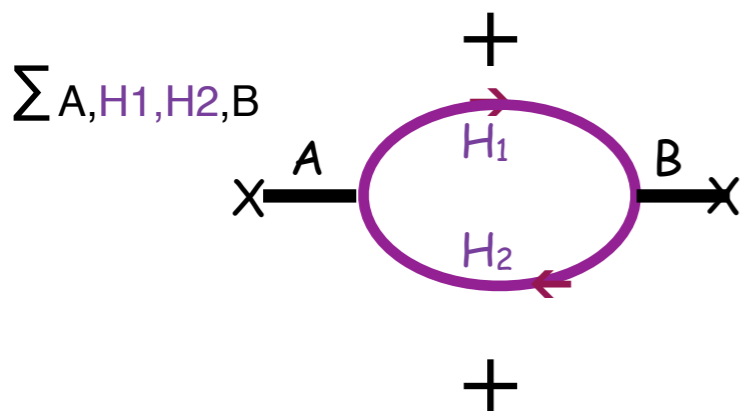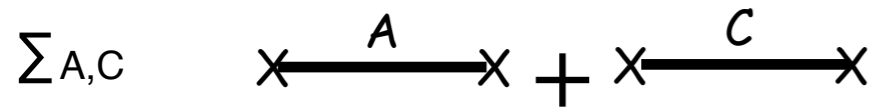
$$\Delta R(W) = \frac{6\pi}{W^2} \rho_c(W) \qquad -(g_{\mu\nu}q^2 - q_\mu q_\nu)\rho_c(W)$$

$$= \int d^4x \, e^{iqx} \langle 0 | j_\mu(x) j_\nu(0) | 0 \rangle \Big|_{\text{charm}} .$$

QCD - hadronic
A,B (QQ) , C (QQg)
H₁,H₂(Qq)

QCD - perturbative
Q, g

$\sum$A,C

$\sum$A,H1,H2,B

$\equiv$

Simple expansion
near threshold.
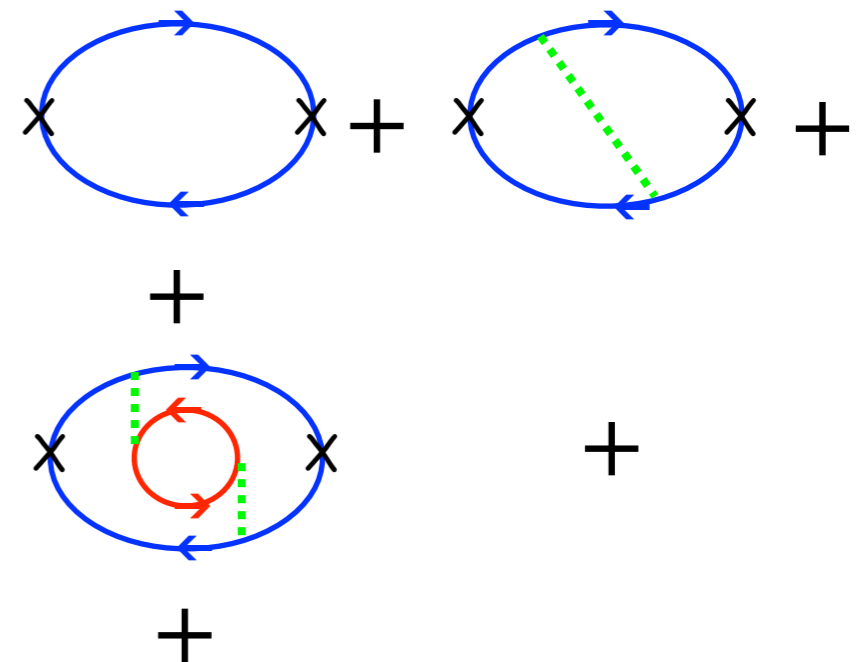
Simple expansion far
above threshold.

Heavy-Light Mesons

- Observed low-lying (1S, 1P, and 1D) charm and bottom mesons:

  – Very similar excitation spectrum - HQS

Charm Meson Spectrum

Bottom Meson Spectrum

  – There are 9 narrow (< 2 MeV) charm meson states [and 10 bottom mesons states].
    Any pair of these might have a cusp at S-wave threshold.

  – The wide states can originate sequential decay chains.

Light quarks effects

- **Light quark loops**

  – **Corrections even below threshold**

  C. T. H. Davies et al.
  [HPQCD, Fermilab Lattice, MILC, and UKQCD Collaborations],
  Phys. Rev. Lett. 92, 022001 (2004) [arXiv:hep-lat/0304004].

- **Above threshold: Zweig allowed strong decay**

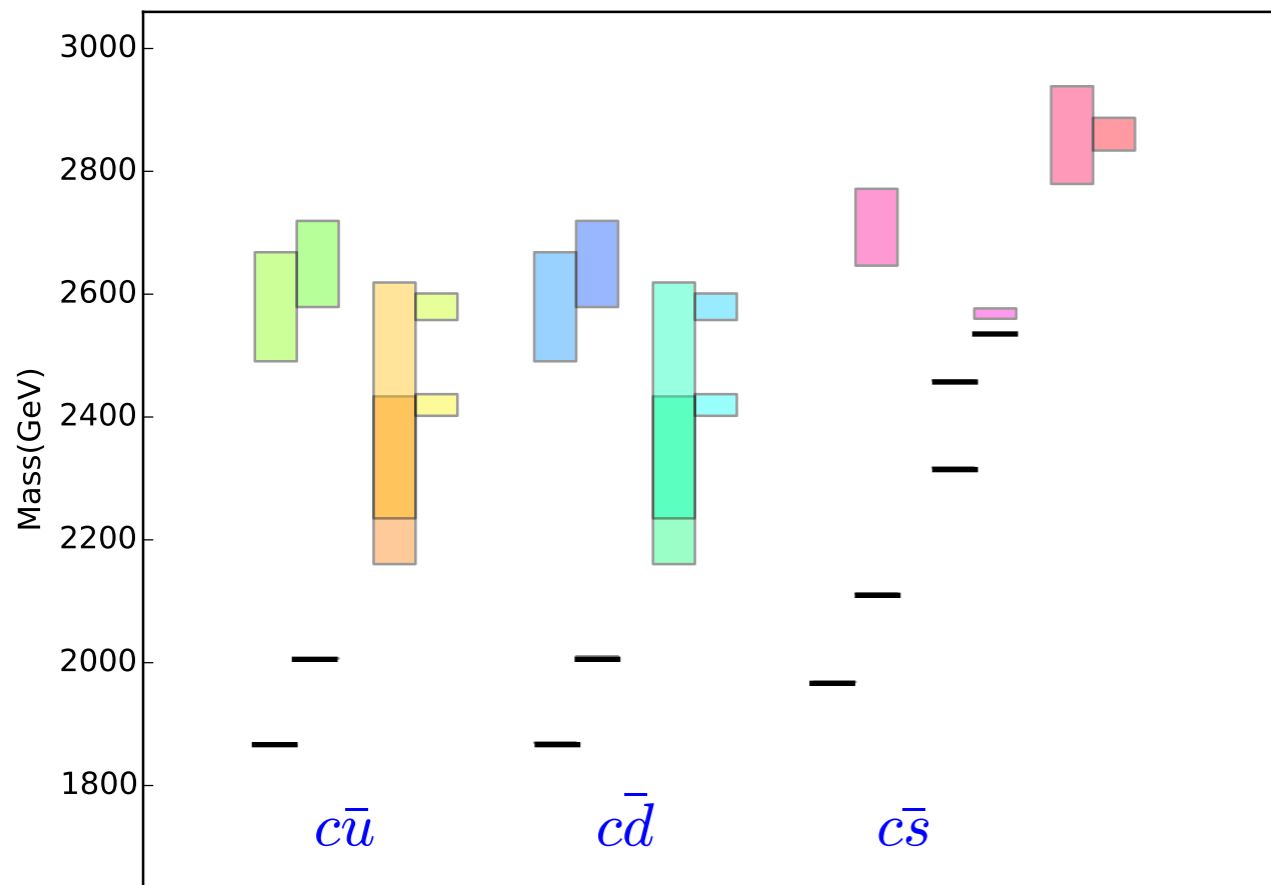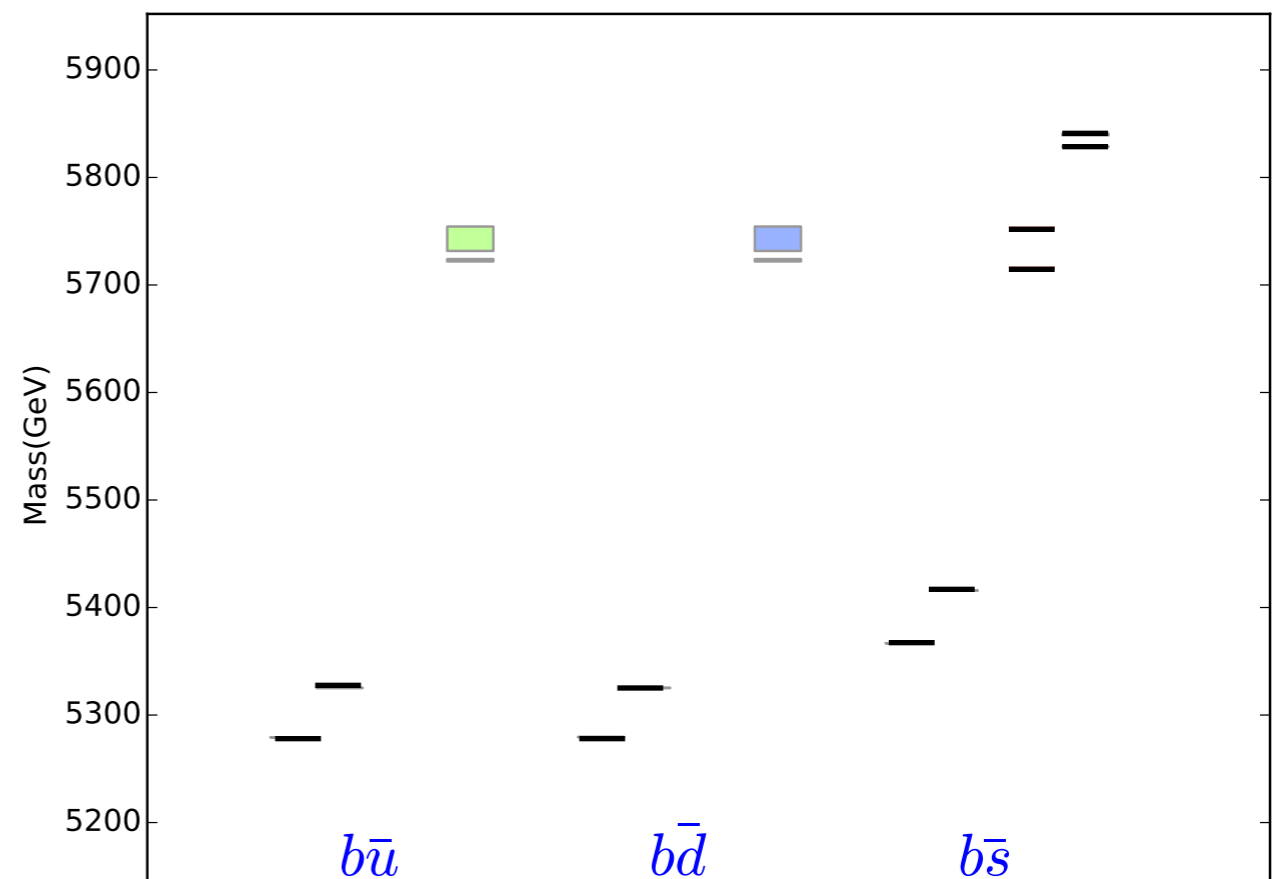$$[\mathcal{H}_0 + \mathcal{H}_2 + \mathcal{H}_I]\psi = \omega\psi$$

$\mathcal{H}_0$: $Q\bar{Q}$ NRQCD (without light quarks)

$\mathcal{H}_I$ $Q\bar{Q} \Rightarrow Q\bar{q}+q\bar{Q}$ light quark pair creation

Cornell model (CCCM)

$$\mathcal{H}_I = \frac{3}{8}\sum_a \int\, :\rho_a(\mathbf{r})V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}'): d^3r\, d^3r'$$

Vacuum Pair Creation model (QPC)

$$\mathcal{H}_I = \gamma \int \bar{\psi}\psi(\mathbf{r})d^3r$$

$\mathcal{H}_2$ $Q\bar{q}+q\bar{Q}$ Heavy-Light meson pair interactions
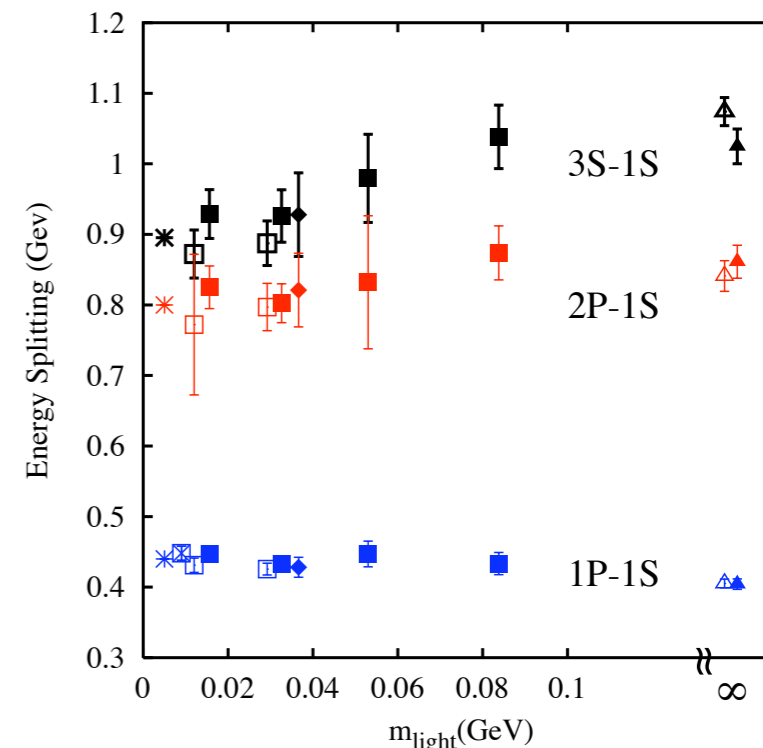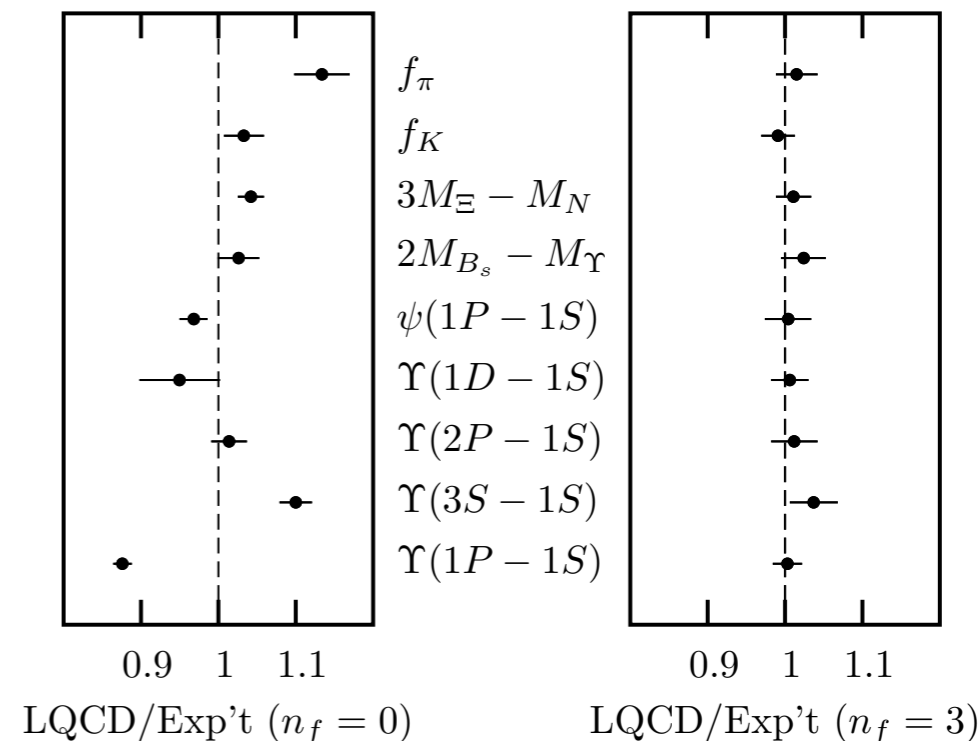
Threshold Formalism

- Two set of states near threshold in each J^{PC} channel

Charmonium bound states   Charmed meson pair states

$\psi(4160)$

$\psi(4040)$

D*D*

$\psi(3770)$

$\psi'(3686)$

DD*+D*D

DD

H_0 H_I H_2

1--

J/ψ
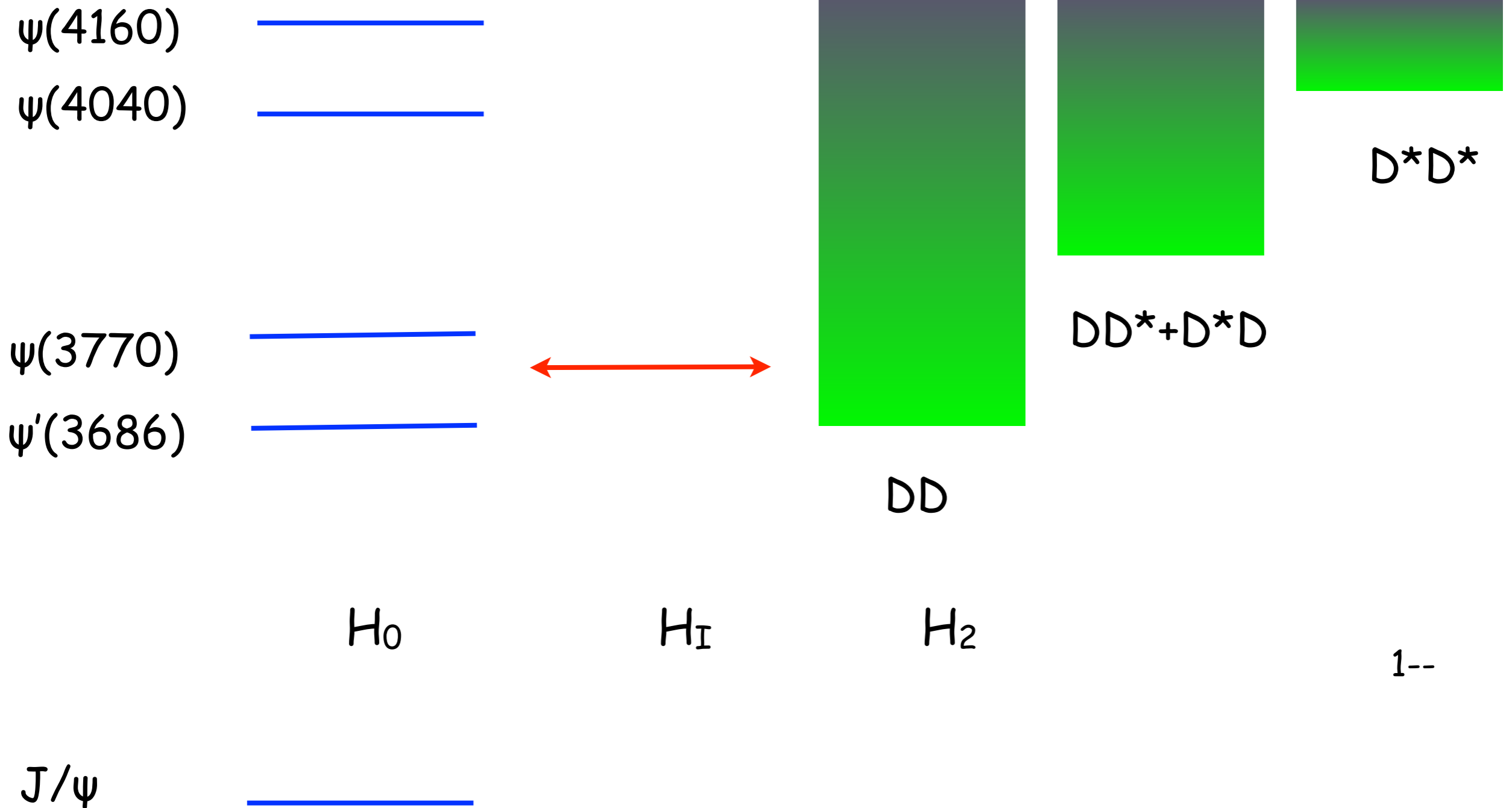
Threshold Formalism

- Coupled channel problem

$$\begin{pmatrix} \mathcal{H}_0 & \mathcal{H}_I^\dagger \\ \mathcal{H}_I & \mathcal{H}_2 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = z \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

- Formally eliminate ψ_2

defines $\Omega(z)$

$$\left(\mathcal{H}_0 + \mathcal{H}_I^\dagger \frac{1}{z - \mathcal{H}_2} \mathcal{H}_I \right) \psi_1 = z\psi_1$$

- Decay amplitude $<DD|H_I|\psi>$
- Simplifying assumptions

  - H_2 - free meson pairs no final state interactions
  - H_0 - charmonium states are a complete basis - no hybrids

$$< n|\mathcal{G}(z)|m> = < n|\frac{1}{z - \mathcal{H}_0 - \Omega(z)}|m>$$

- Assuming vector meson dominance. Can compute R_c

$$R_Q \sim \frac{1}{s} \sum_{nm} \lim_{r \to 0} \psi_n^*(r) \mathrm{Im}\mathcal{G}_{nm}(W + i\epsilon)\psi_m(r)$$

Decay Amplitudes

- **Cornell Coupled Channel Model**

  - ψ_n potential model wavefunction

  - Final mesons: $\phi(x) \sim \exp(-x^2 \beta_S)$ $[\beta_S = \dfrac{1}{2a^2}(\dfrac{4\mu a}{3\sqrt{(\pi)}})^{2/3}]$

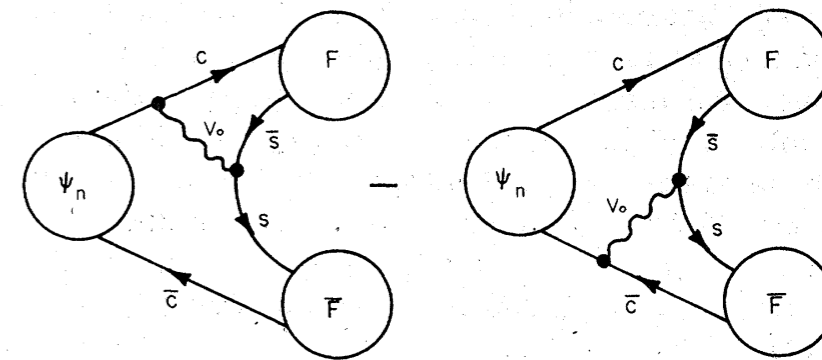$$\langle C_1(\vec{\mathrm{P}}\lambda_1)\overline{C}_2(\vec{\mathrm{P}}'\lambda_2)|H_I|\psi_n\rangle = -i(2\pi)^{-3/2}\delta^3(\vec{\mathrm{p}}+\vec{\mathrm{p}}')3^{-1/2}A_{12}(\vec{\mathrm{P}}\lambda_1\lambda_2;n),$$

E. Eichten, K. Gottfried, T. Kinoshita, K. Lane and T.M. Yan
PR D17, 3090 (1978)

where

$$A_{12}(\vec{\mathrm{P}}\lambda_1\lambda_2;n) = \frac{1}{m_q}\sum_{\{s\}}\int d^3x\, d^3y\,[\chi^\dagger(s_2')\vec{\sigma}\cdot\hat{x}\chi(-s_1')]\frac{dV(|\vec{\mathrm{x}}|)}{d|\vec{\mathrm{x}}|}\phi_1^*(\vec{\mathrm{x}}s_1s_1')\phi_2^*(\vec{\mathrm{x}}-\vec{\mathrm{y}},s_2s_2')\psi_n(\vec{\mathrm{y}}s_1s_2)e^{-i\mu_c\vec{\mathrm{p}}\cdot\vec{\mathrm{y}}}$$

- $dV(x)/dx = 1/a^2 + \kappa/x^2$ => no free parameters
  setting $\kappa = 0$ => same form as the vacuum pair creation model ($^3P_0$)

Hence $$\Omega_{nL,\,mL'}(W) = \sum_i \int_0^\infty P^2\,dP\,\frac{H_{nL,\,mL'}^i(P)}{W - E_1(P) - E_2(P) + i0}$$

where $$H_{nL,\,mL'}^i(P) = f^2 \sum_l C(JLL';l)I_{nL}^l(P)\,I_{mL'}^l(P)$$

Statistical factor

Reduced decay amplitudes I(p)

Decay Model

$$I_{nL}^{l}(P) = \int_{0}^{\infty} dt \, \Phi(t) R_{nL}(t\beta^{-1/2}) j_{l}(\mu_c \beta^{-1/2} Pt)$$

Key point: The only part of I(p) that depends on the pair production model is the function Φ(t):

For the CCCM (κ=0): $(t = y\sqrt{\beta_S})$

$$\Phi(t) = te^{-t^2} + (\pi/2)^{1/2}(t^2 - 1)e^{-t^2/2} \mathbf{erf}(t/\sqrt{2})$$

Using HQET this function Φ(t) is the same for all final states in a j_l^P multiplet.

Apart from overall light quark mass factors Φ(t) is approximately SU(3) invariant. So independent of light quark flavor (u,d,s).

One universal function, Φ(t), determines R_Q in the threshold region.

Sample decay amplitudes I(p)

$I^{l=1}{}_{3S}(p)$ cc,bb

Id_3S_1 (cc)
Id_3S_1 (bb)

p(GeV)

$I^{l=1}{}_{\Upsilon(4S)}(p)$ d,s

Id_4S_1
Is_4S_1

p(GeV)
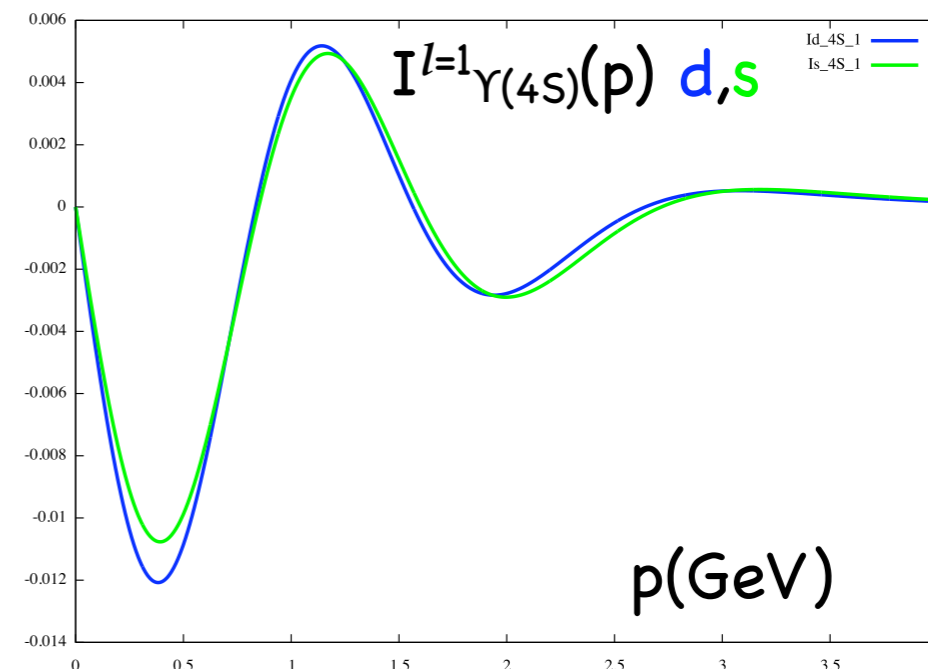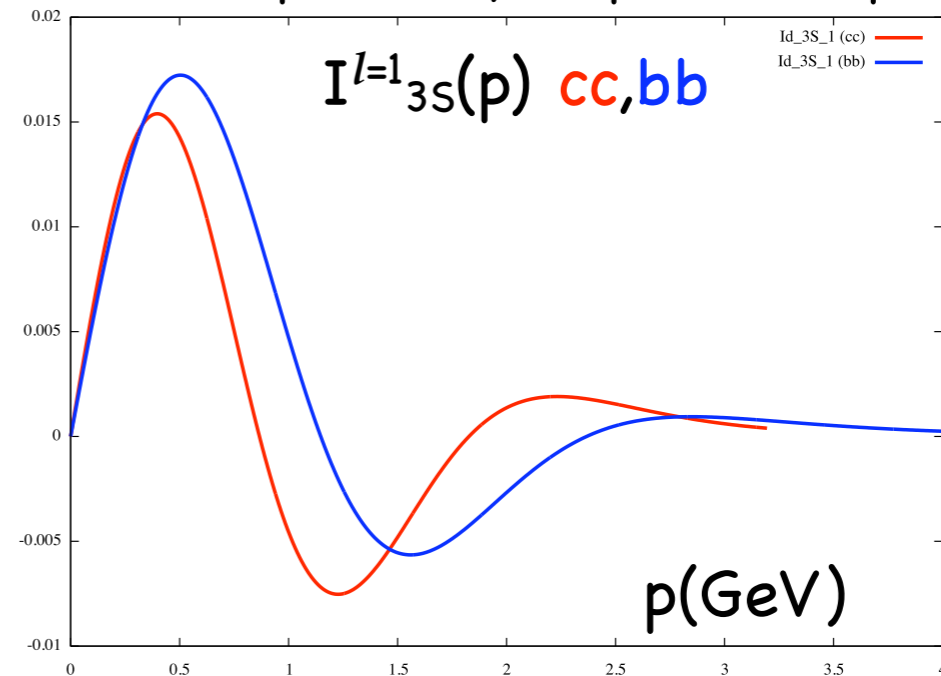
Complicated Decay Amplitudes

- For resonances (with no radial nodes) as expected:

$$1S \rightarrow D^{(*)} \bar{D}^{(*)} \text{ P-wave}$$

$$1S \rightarrow D_1 \bar{D}^{(*)} \text{ S-wave}$$
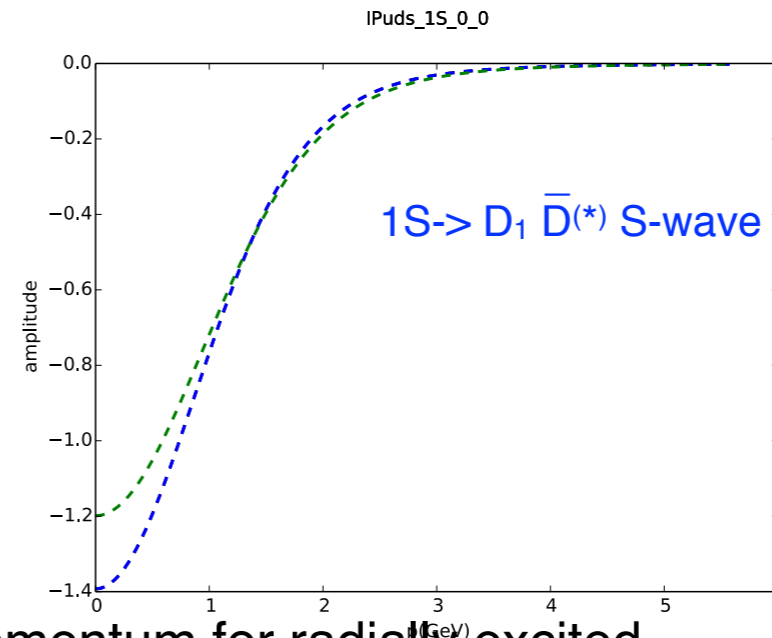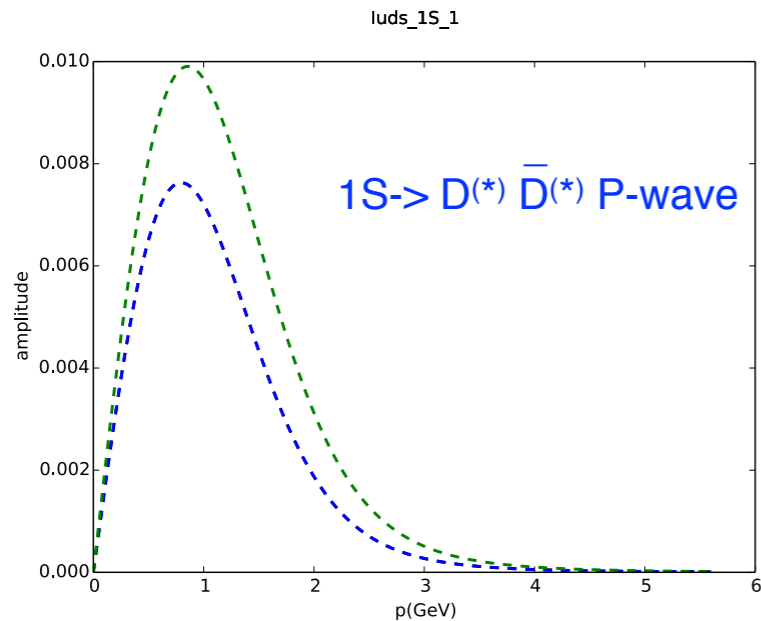
- But complicated dependence on heavy-light momentum for radially excited resonances.

$$3S \rightarrow D^{(*)} \bar{D}^{(*)} \text{ P-wave}$$

$$4S \rightarrow D_1 \bar{D}^{(*)} \text{ S-wave}$$
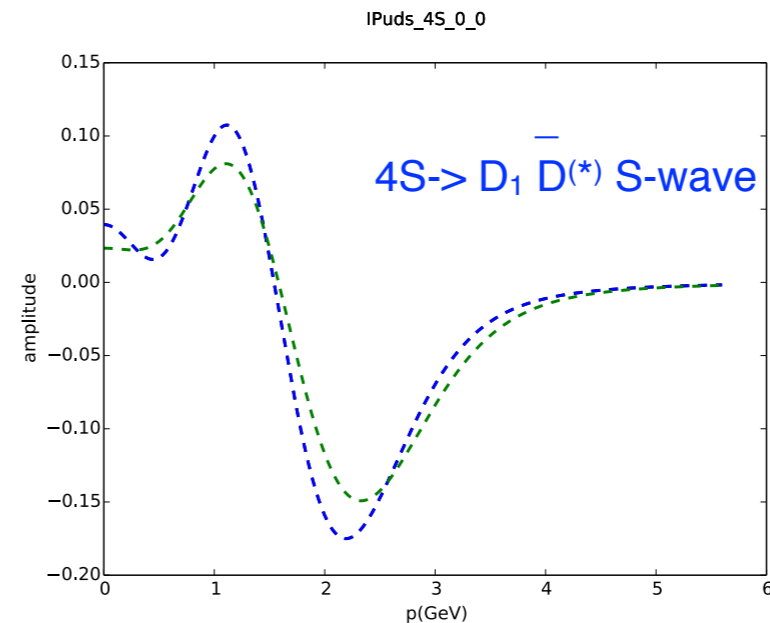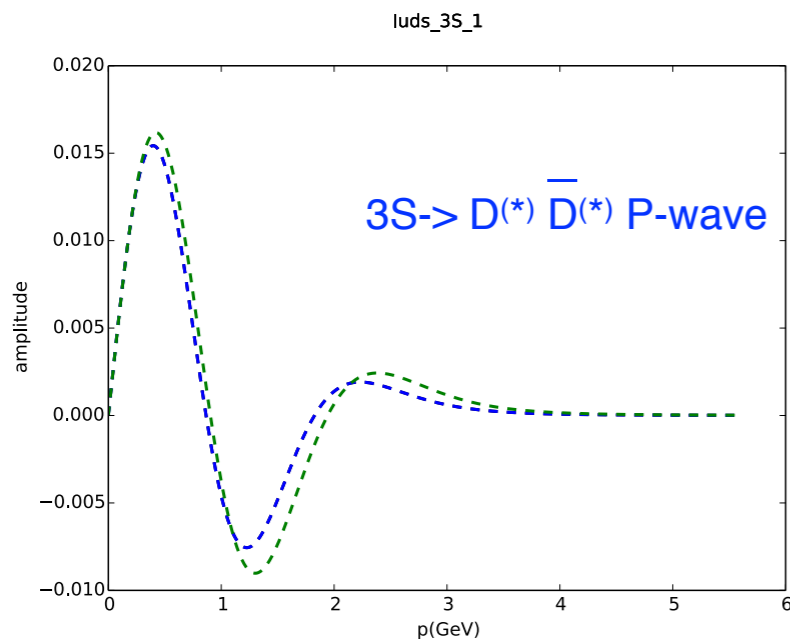
- $\Delta E = E - m_1 - m_2 = \sqrt{(m_1^2 + p^2)} + \sqrt{(m_2^2 + p^2)} - m_1 - m_2 \approx (m_1 + m_2) p^2 / (2 m_1 m_2)$

Effects of HQS Breaking Masses

- The differences between the exclusive channels arises from the mass splittings of of the D and D*

luds_3S_1   3S-> D$^{(*)}$ D$^{(*)}$ P-wave

Legend:
- D D (red)
- D D* (green)
- D*D* (blue)
- D$_s$ D$_s$ (violet)
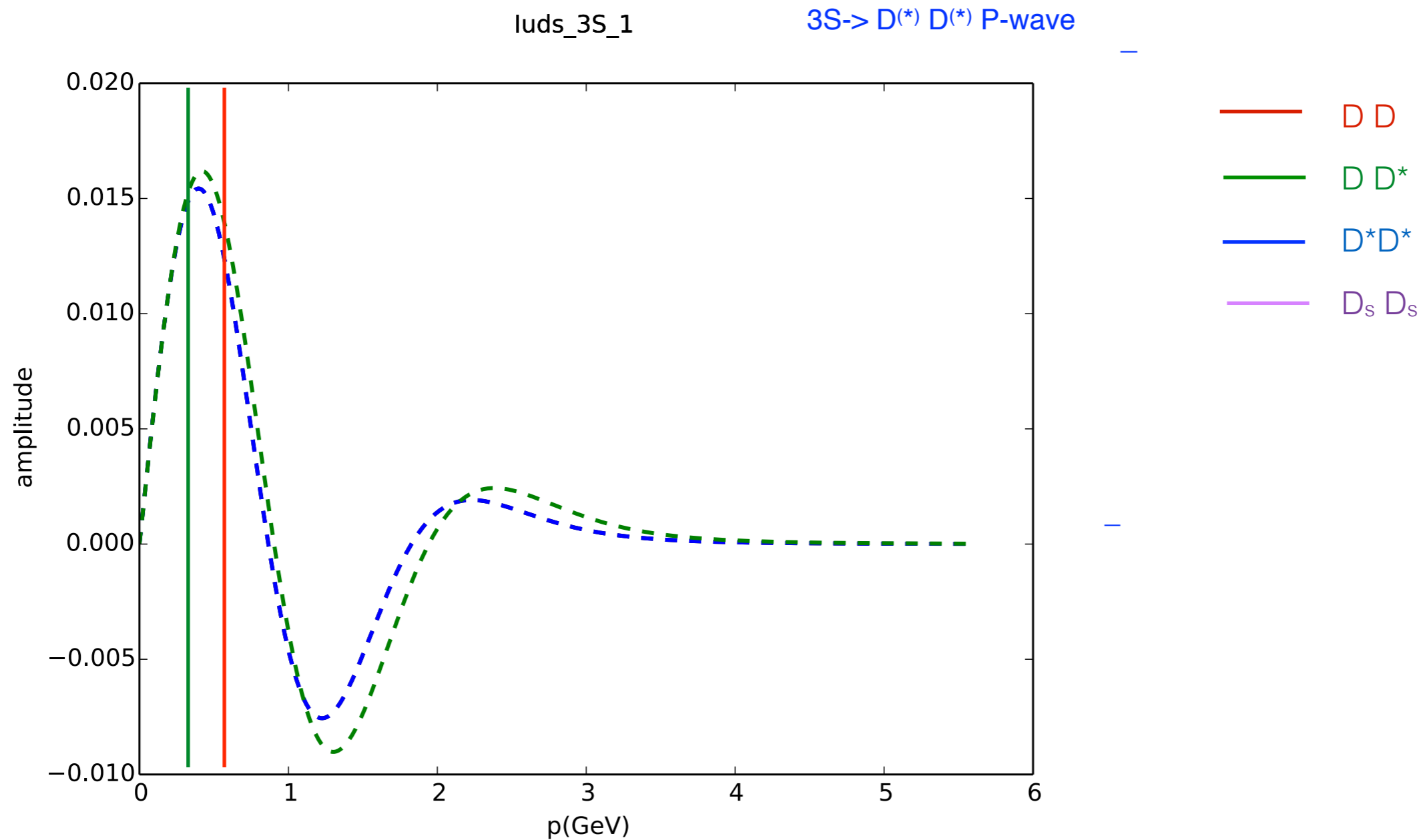
- p(DD) = 590 MeV; p(DD*) = 288 MeV;

E = 4.000 GeV

Effects of HQS Breaking Masses

- The differences between the exclusive channels arises from the mass splittings of of the D and D*

luds_3S_1   3S-> D$^{(*)}$ D$^{(*)}$ P-wave

Legend:
- D D
- D D*
- D*D*
- D$_s$ D$_s$
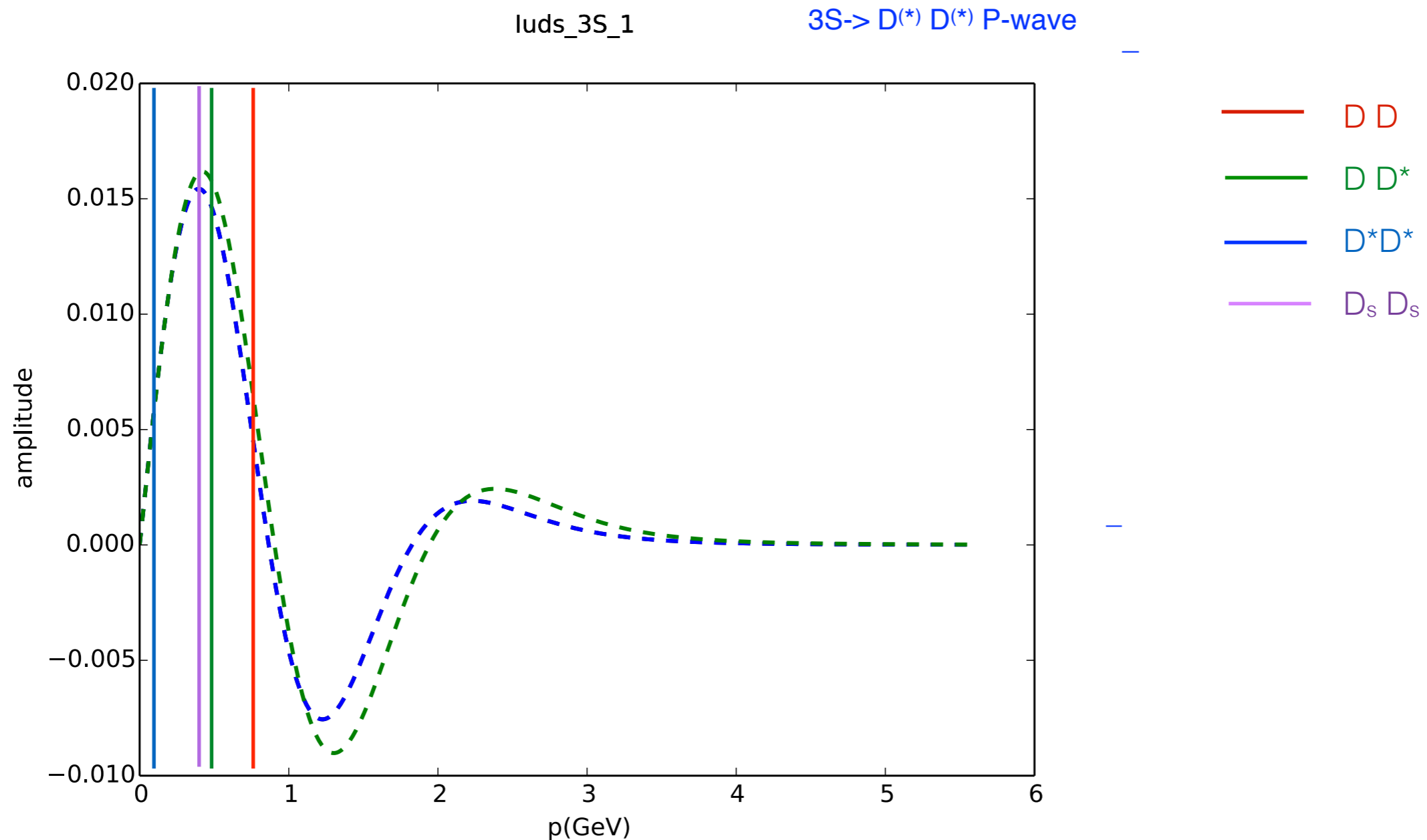
- p(DD) = 740 MeV; p(DD*) = 530 MeV; p(D*D*) = 085 MeV; p(D$_s$D$_s$) = 406 MeV   E = 4.020 GeV

Effects of HQS Breaking Masses

- The differences between the exclusive channels arises from the mass splittings of of the D and D*

luds_3S_1   3S-> D$^{(*)}$ D$^{(*)}$ P-wave
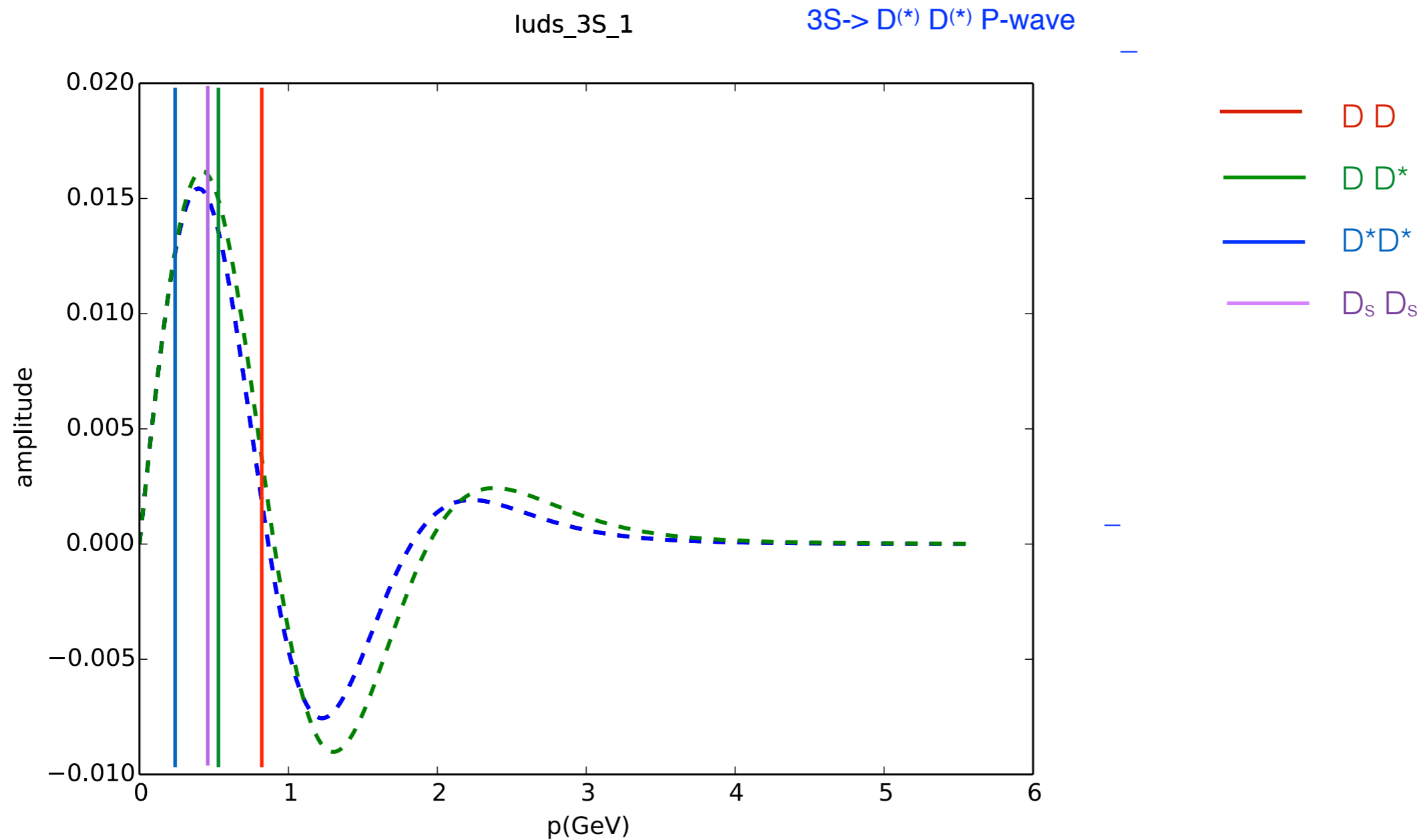
- p(DD) = 766 MeV; p(DD*) = 567 MeV; p(D*D*) = 218 MeV; p(D$_s$D$_s$) = 453 MeV   E = 4.040 GeV

Individual Decay Channels Above Threshold

- Ψ(3S)

  - M = 4039 ± 1 MeV   Γ = 80 ± 10 MeV;

  - Open decay channels:

    - $M(\bar{D}^0 D^0) = 3{,}729.72$ MeV, $M(D^+ D^-) = 3{,}739.26$ MeV

    - $M(\bar{D}^0 D^{*0}) = 3{,}871.85$ MeV, $M(D^+ D^{*-}) = 3{,}879.92$ MeV

    - $M(\bar{D}_s^+ D_s^-) = 3{,}937.$ MeV

    - $M(\bar{D}^{*0} D^{*0}) = 4{,}013.98$ MeV, $M(D^{*+} D^{*-}) = 4{,}020.58$ MeV

Charm threshold region has very large induced HQS breaking effects due to spin splitting in j_l heavy-light multiplets

Table 4: Selected $\psi(3S)$ decays.

Decay Mode	Branching Rate
$D * \bar{D} *$	
$D_s^+ D_s^- * + c.c.$	
$DD*$	$\frac{\Gamma(D*\bar{D}+c.c.)}{\Gamma(D*\bar{D}*)} = 0.34 \pm 0.14 \pm 0.05$
$D\bar{D}$	$\frac{\Gamma(D*\bar{D}+c.c.)}{\Gamma(D*\bar{D}*)} = 0.02 \pm 0.03 \pm 0.02$
$\psi(1S)\,\eta$	$(5.2 \pm 0.7) \times 10^{-3}$

Evidence of strong production of $D^{(*)} D_P$ at the ψ(4160)
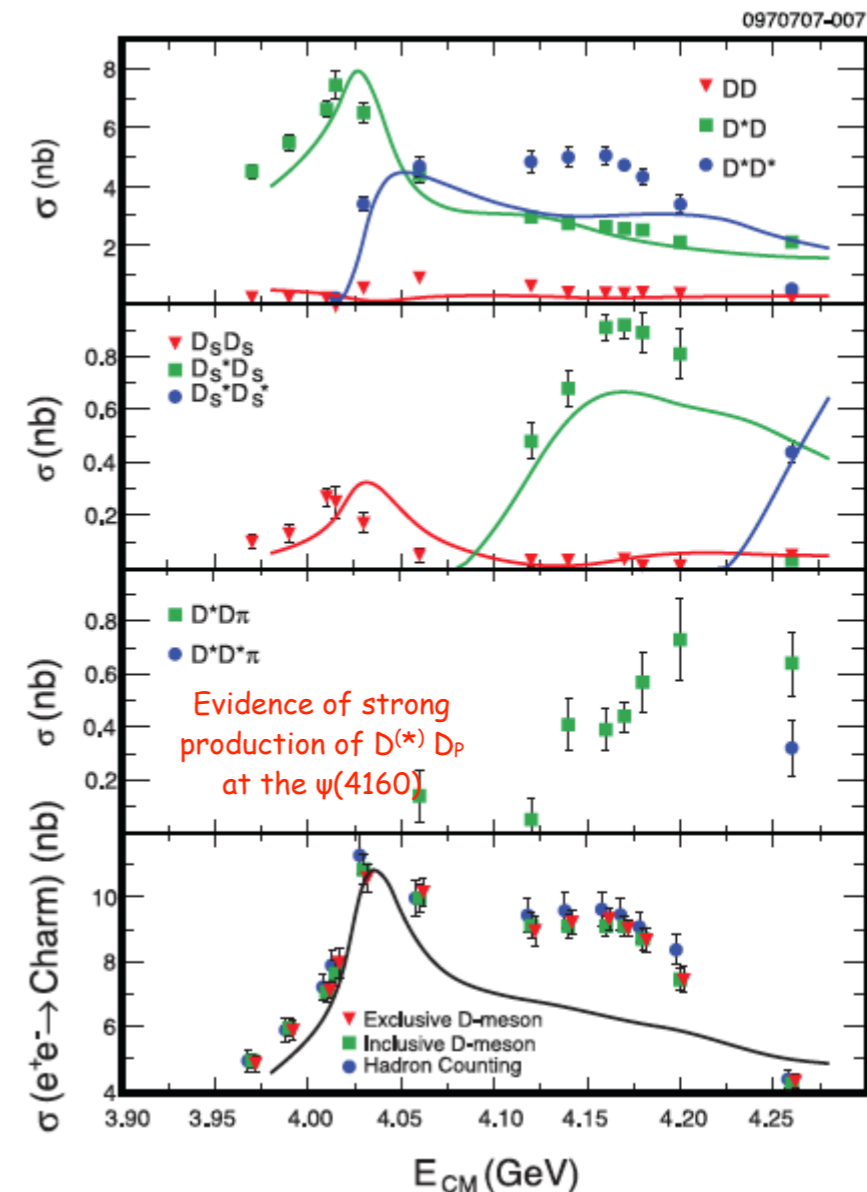
Virtual Loop Effects

- Effects of heavy-light meson virtual loops

  – Shift masses and properties of states near threshold. Because the lowest quarkonium states feel more of the short distance (Coulomb) interaction they are least affected by the large loop effects.

  – Lattice calculations (some already in hand) could provide valuable information on the meson loop effects. The variation of quarkonium masses as a function of light quark masses (physical values $< m_q < \Lambda_{QCD}$) is directly related to the meson loops contributions.

  – Couplings are independent of the particular mesons in the loop within a heavy-light multiplet (up to CG coefficients) and are approximately SU(3) flavor invariant.

  – SU(3) breaking and HQS Spin breaking in quarkonium masses and transitions are induced by the mass splittings of physical heavy-light mesons. These effects are only large near the relevant threshold. For example isospin splitting is only important for the X(3872).

- Notation

  - Y denotes states observed directly in the charm contribution to e^+e^- -> hadrons:

    $\Rightarrow$ $J^{PC} = 1^{--}$ and $I = 0$

    - $Y_c(4260)$, $Y_c(4360)$, $Y_c(4650)$

  - Z denotes states with $I = 1$
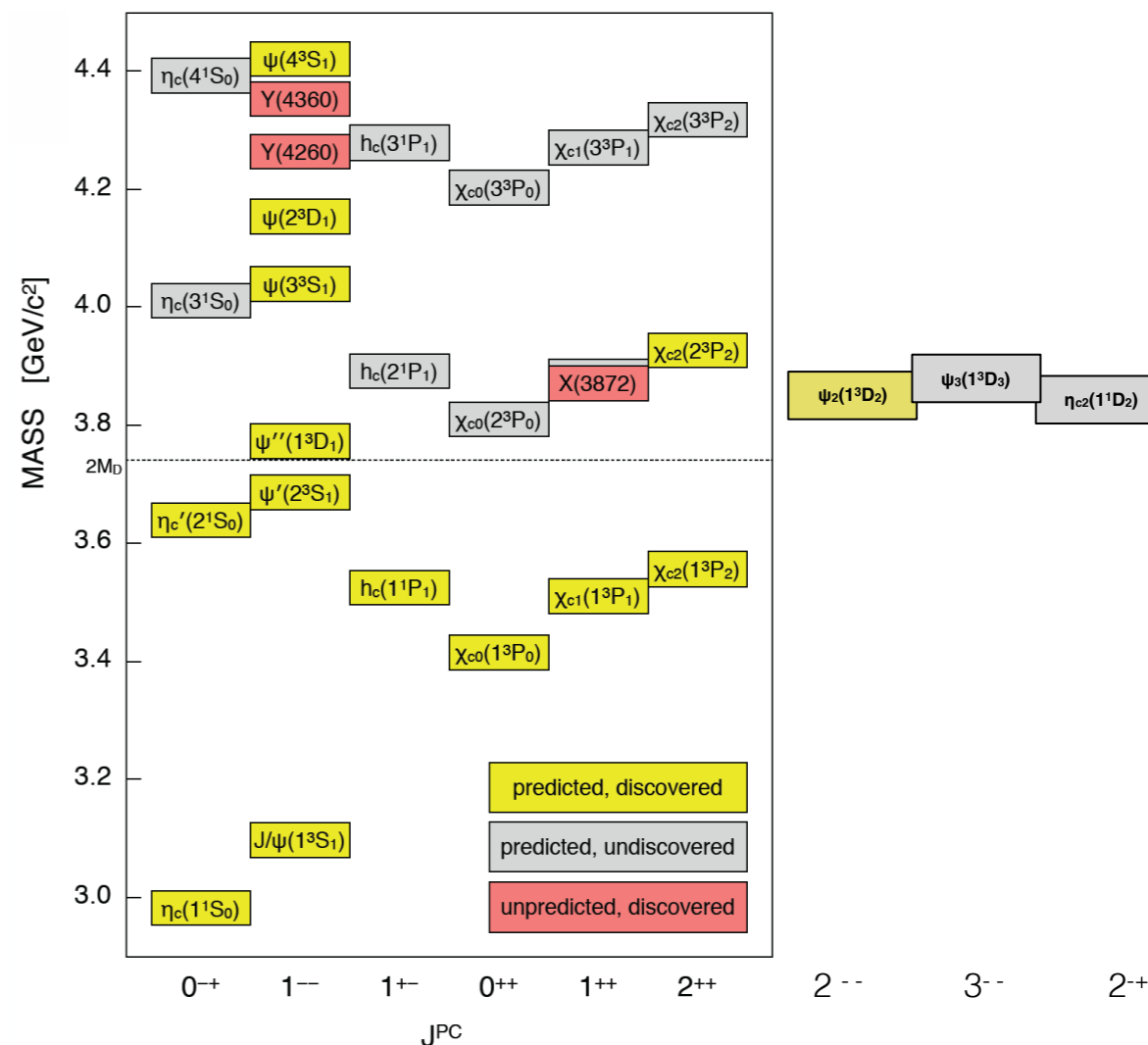
    - $Z^+_c(3885)$, $Z^+_c(4025)$

    - $Z^+_b(10610)$, $Z^+_b(10650)$

      HQS

    - $Z^+_c(4430)$

  - X denotes anything else

    - $X_c(3872)$, … $\Rightarrow$ see PDG table

    - Pentaquarks: $X(4450)$ ($J^P = 5/2^+$), …

Additional XYZ Candidates

- Updated from PDG - other X states need more information

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year
$\chi_{c0}(3915)$	3917.4 ± 2.7	$28^{+10}_{-\ 9}$	0^{++}	$B \to K(\omega J/\psi)$	Belle (8.1), BABAR (19)	2004
				Close to $\chi_{c2}(3927)$. Are the quantum numbers correct?		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle(6.0)	2007
				$e^+e^- \to J/\psi(...)$	Belle (5.0)	
				Candidate for $\eta_c(3S)$, but to far below $\psi(3S)$		
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle(7.4)	2007
				Two BW peak fit better than only the Y(4260).		
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?$	$B \to K(\pi^+\chi_{c1}(1P))$	Belle(5.0), BABAR (1.1)	2008
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF (3.1), Belle (1.9) LHCb (1.4), CMS (> 5) D0 (3.1)	2008
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle(5.5)	2007
$Z_2(4250)^+$	4248 ± 20	35 ± 16	$?$	$B \to K(\pi^+\chi_{c1}(1P))$	Belle(5.0), BABAR (2.0)	2008
$Y(4274)$	$4293^{+121}_{-\ 49}$	226 ± 97	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF (3.1), LHCb (1.0) CMS (> 3), D0 (np)	2007
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle(3.2)	2009
				Observable in LHCb, CMS, Atlas ?		
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle (8.2)	2007

Y(4260)

- Y(4260) - not standard charmonium state. $J^{PC} = 1^{--}$ $M = 4259 \pm 9$ $\Gamma = 120 \pm 12$ MeV

  – Decays observed:

$$J/\psi\,\pi^+\pi^-$$
$$J/\psi\,f_0(980), \quad f_0(980) \to \pi^+\pi^-$$
$$X(3900)^\pm\pi^\mp, \quad X^\pm \to J/\psi\,\pi^\pm$$
$$J/\psi\,\pi^0\pi^0$$
$$J/\psi\,K^+K^-$$
$$X(3872)\,\gamma$$

ZHU S L. Phys. Lett. B, 2005, **625**: 212
Kou E and Pene O. Phys. Lett. B, 2005, **631**: 164
Close F E and Page P R. Phys. Lett. B, 2005, **628**: 215

DING G J, Zhu J J and YAN M L. Phys. Rev. D, 2008, **77**: 014033
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WANG Q, Hanhart C and ZHAO Q. Phys. Rev. Lett., 2013, **111**: 132003

Voloshin M B. Prog. Part. Nucl. Phys., 2008, **61**: 455
S. Dubynskiy and Voloshin M B. Phys. Lett. B, 2008, **666**: 344
LI X and Voloshin M B. Phys. Rev. D, 2013, **588**: 034012

Maiani L, Riquer V, Piccinini F and Polosa A D. Phys. Rev. D, 2005, **72**: 031502

Beveren E van and Rupp G. arXiv:0904.4351 [hep-ph]
Beveren E van and Rupp G. Phys. Rev. D, 2009, **79**: 111501
Beveren E van, Rupp G and Segovia J. Phys. Rev. Lett., 2010, **105** 102001
CHEN D Y, HE J and LIU X. Phys. Rev. D, 2011, **83** 054021

  – Many models:

1. Charmonium hybrid
2. D_1 D molecule
3. Hadrocharmonium
4. Tetraquark (ccss)
5. Cusp/nonresonance
…

  – Lattice results from the hadron spectroscopy collaboration suggest the possibility of a hybrid

  – HQS expectations require to see an analog state in the bottomonium system

  - 1. Using the static potential of the excited string Π_u : Hybrid state should be ~ 10,870 MeV

  - 2. At threshold of B_1 B : 11,000 MeV

  - 3. Deeper bound systems :

Charmonium on the lattice

- L. Liu et al (HSC) [arXiv:1204.5425]

Hybrid (c̄cg)

4S(cc̄)

3S(cc̄)
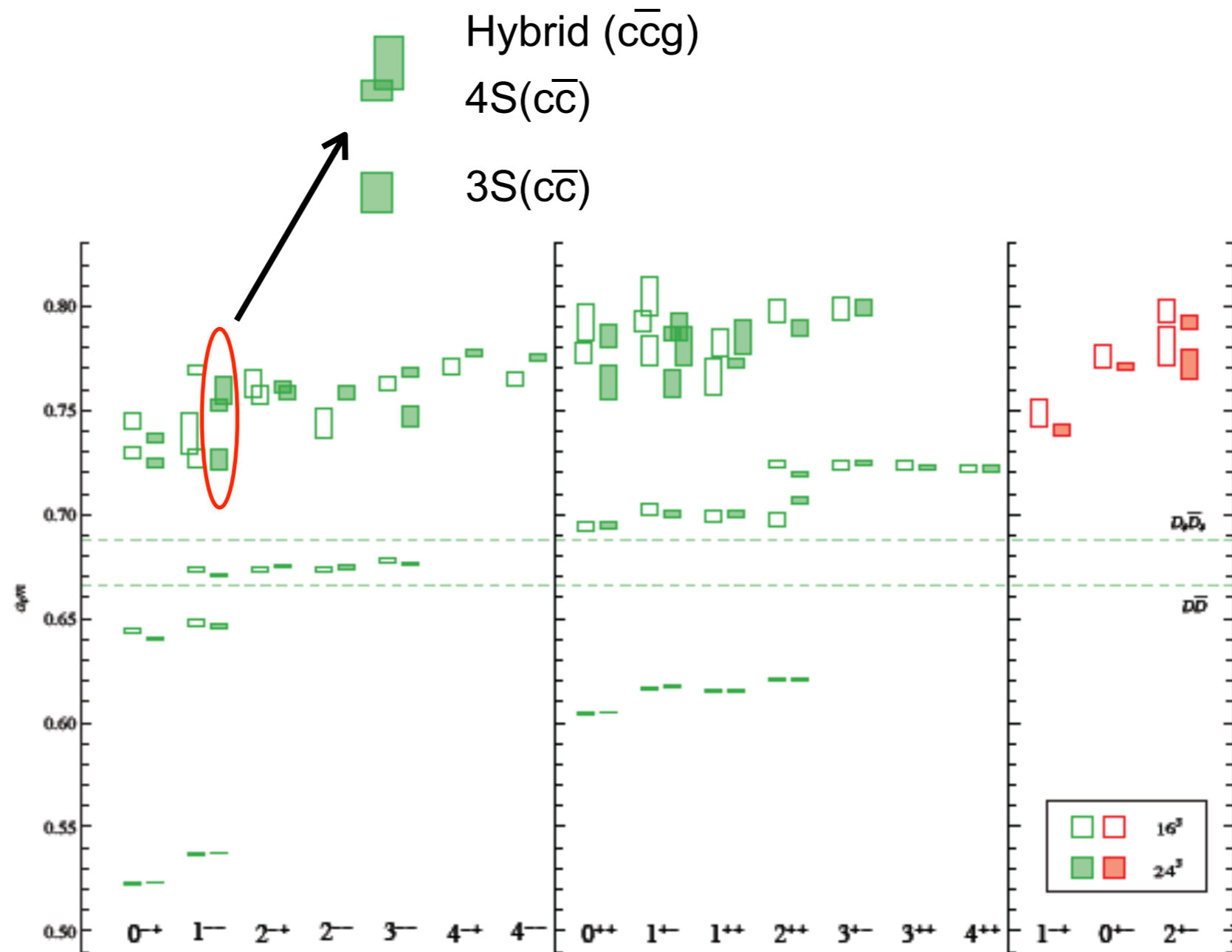
X(3872)

- X(3872) - $J^{PC} = 1^{++}$ M= 3871.69 ± 0.16 ± 0.19 Γ < 1.2 MeV   from J/ψ $\pi\pi$ mode

  – Decays observed:

$\pi^+\pi^- J/\psi(1S)$	> 2.6 %
$\rho^0 J/\psi(1S)$	
$\omega J/\psi(1S)$	> 1.9 %
$D^0 \overline{D}^0 \pi^0$	>32 %
$\overline{D}^{*0} D^0$	>24 %
$\gamma \psi(2S)$	[a] > 3.0 %

  large Isospin violation

  – LHCb [arXiv:1404.0275]

  $$\frac{\mathcal{B}(\text{X}(3872) \to \psi(2S)\gamma)}{\mathcal{B}(\text{X}(3872) \to \text{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$ suggests 2P state

  – M_X - M_D - M_{D^*} = - 0.11 ± 0.23 MeV

  suggests molecule

  – Two primary models:

  1. $\chi_{c1}'(2^3P_1)$ state
  2. $D^0 \overline{D}^0{}^*$ molecule

  M. Suzuki, hep-ph/0307118.

  DeRujula, Georgi, Glashow, PRL 38(1997)317
  F. Close and P. Page, Phys. Lett. B578 (2004) 119
  M. Voloshin, Phys. Letts. B579 (2004) 316.
  …
  E. Braaten [arXiv1503.04791]

  – Mixed state with sizable quarkonium component likely.

  – For LQCD: Where is the $\chi_{c0}'(2^3P_0)$ state?

X(3872)

- B -> X(3872) K -> ($D^0\overline{D}^{0*}$) K

- Strong peaking at threshold for S-wave observed experimentally.
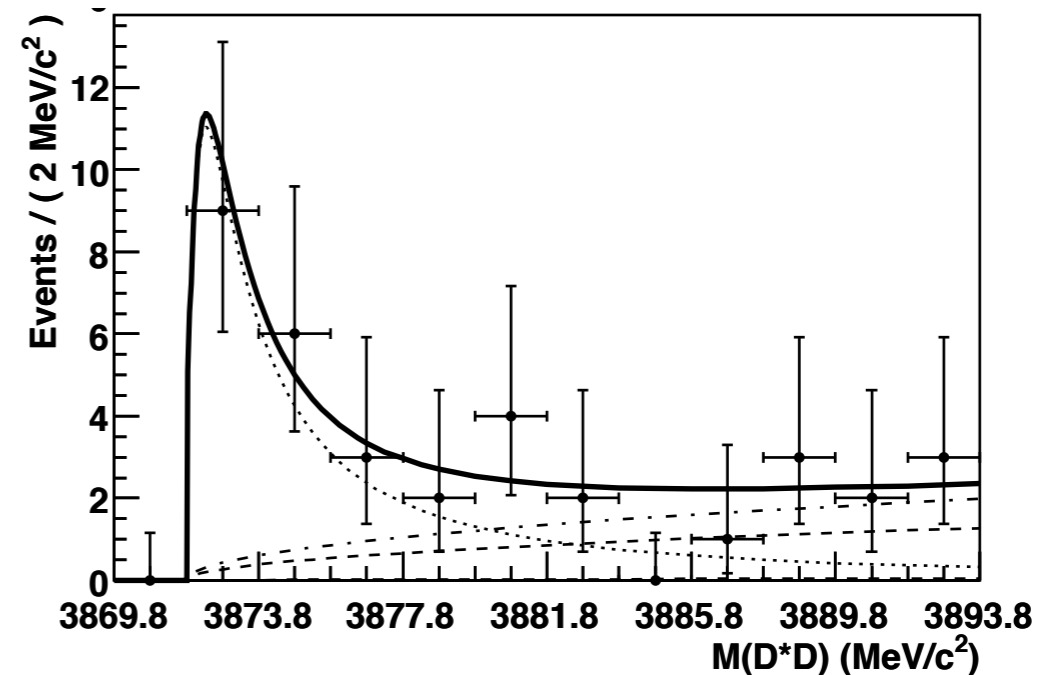
- Lattice calculations:

  – `A pole appears just below threshold in the $J^{PC} = 1^{++}$ I = 0 channel.

  – But requires both the ($\overline{c}c$) and the D$\overline{D}^*$ components.

  – Suggests there is a significant ($\overline{c}c$) component of the X(3872)

  – No pole observed in the I = 1 channel.

B. A. Galloway, P. Knecht, J. Koponen, C. T. H. Davies, and G. P. Lepage, PoS **LATTICE2014**, 092 (2014), 1411.1318.

S. Prelovsek and L. Leskovec, Phys.Rev.Lett. **111**, 192001 (2013), 1307.5172.

Fermilab Lattice, MILC, S.-h. Lee, C. DeTar, H. Na, and D. Mohler, (2014) 1411.1389.

M. Padmanath, C. B. Lang, and S. Prelovsek, Phys. Rev. **D92**, 034501 (2015), 1503.03257.

X(3872)

- Xb(10604) ??

  - No isospin breaking: X is I=0 => G-parity forbids the decay X -> ππϒ(1S).

  - Dominate decay X -> ωϒ(1S)?

  - M(χ_{b1}(3P)) – M(B) - M(B*) ≈ -75 MeV

  - So the (bb) state is decoupled.

- Expect no analogy of the X(3872) in the bottomonium system
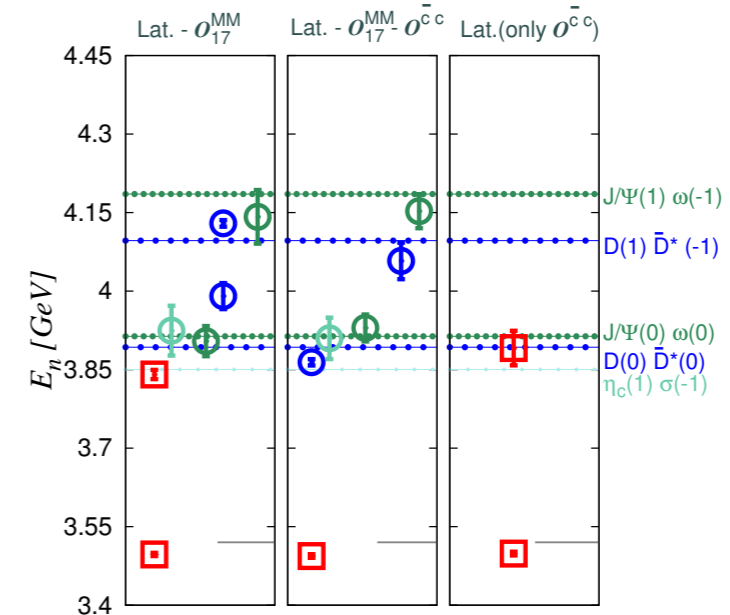
FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note that candidate for $X(3872)$ disappears when removing $\bar{c}c$ operators although diquark-antidiquark operators are present in the basis, while it is not clear to infer on the dominant nature of this state just from the third panel. The $O_{17}^{MM} = \chi_{c1}(0)\sigma(0)$ is excluded from the basis to achieve better signals and clear comparison.

arXiv:1411.1389
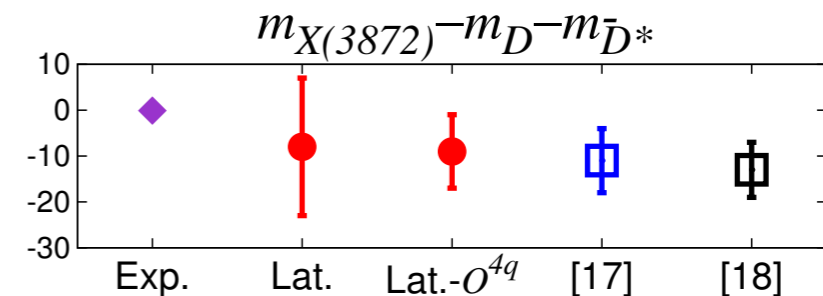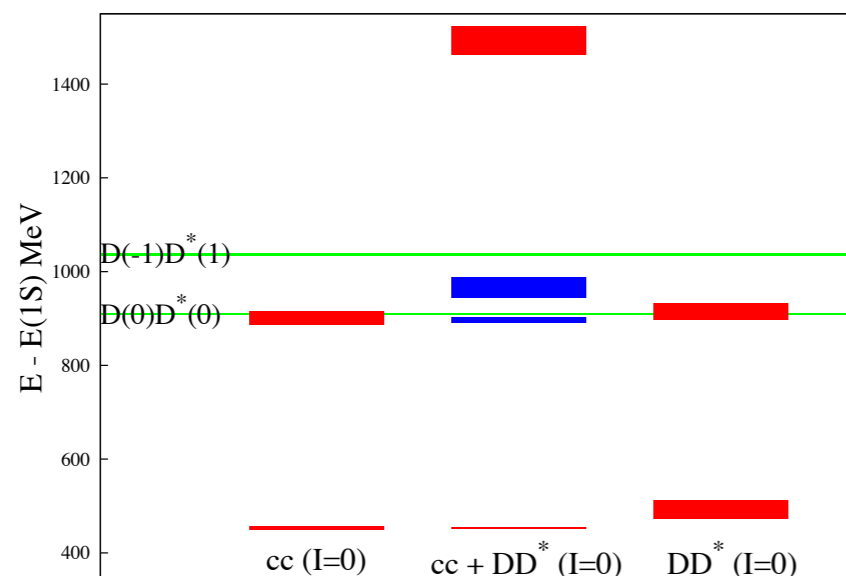
Hadronic Transitions Above Threshold

- With BaBar, BES III, LHCb, BELLE and (CMS, ATLAS, CDF/D0) many new details of hadronic transitions have been observed.

- A clearer theoretical understanding hadronic transitions for quarkonium-like states above threshold should now be possible.

- However there are many the questions which arise as well:

    – The QCD Multipole Expansion fails above threshold. Why and how?

    – What are the remaining constraints of Heavy Quark Symmetry?

    – What explains the large rate of transitions for some states above threshold?

    – Can the pattern of transitions be understood?

    – Can detailed predictions be made?

- First let's look at the details of the transitions.

Hadronic Transitions Above Threshold

- Bottomonium systems:

- $\Upsilon(4S)$

    - M = 10,579.4 ± 1.2 MeV Γ = 20.5 ± 2.5 MeV;

    - Open decay channels:

        - M(B⁺B⁻) = 10,578.52 MeV,   M(B⁰B̄⁰) = 10,579.16 MeV

        - Essentially no isospin breaking in the masses.

    - Normal pattern of 2π decays, large η decays:

$\Upsilon(4S)$ nearby thresholds

Table 1: Selected $\Upsilon(4S)$ decays.

Decay Mode	Branching Rate
$B^+ B^-$	$(51.4 \pm 0.6)\%$
$B^0 \bar{B}^0$	$(48.6 \pm 0.6)\%$
total $B\bar{B}$	$> 96\%$
$\Upsilon(1S)\,\pi^+\pi^-$	$(8.1 \pm 0.6) \times 10^{-5}$
$\Upsilon(2S)\,\pi^+\pi^-$	$(8.6 \pm 1.3) \times 10^{-5}$
$h_b(1P)\,\pi^+\pi^-$	(not seen)
$\Upsilon(1S)\quad \eta$	$(1.96 \pm 0.28) \times 10^{-4}$
$h_b(1P)\quad \eta$	$(1.83 \pm 0.23) \times 10^{-4}$

⟶ partial rate = 1.66 ± 0.23 keV

⟶ partial rate = 4.02 ± 0.89 keV
⟶ partial rate = 3.75 ± 0.73 keV

SU(3) violating
HQS violating
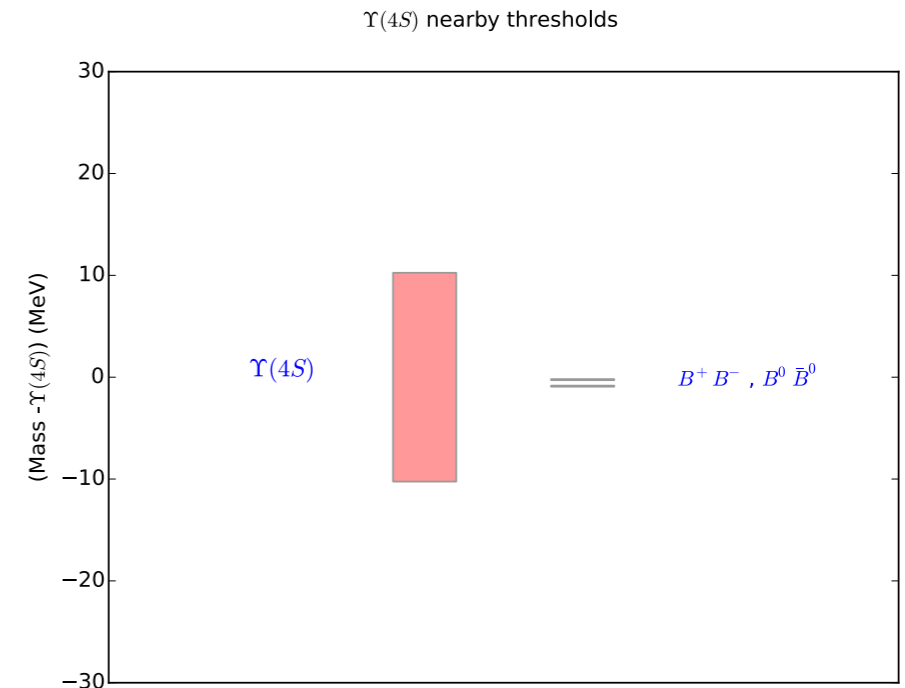
Heavy Quark Spin Symmetry

- Large heavy quark spin symmetry breaking induced by the B*- B mass splitting. [Same for D*-D and D_s*-D_s]

  - Coupled channel calculations show a large virtual B B component to the Υ(4S). This accounts for the observed violation of the spin-flip rules of the usual QCDME.

  - $J^{PC} = 1^{--}$ in terms of B(*), B(*) mass eigenstates:

    Voloshin [arXiv:1201.1222]

    - $J_{SLB} = j_{SLB} + L$

    $$B\bar{B} \quad : \quad \frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01} \ ;$$

    $$\frac{B^*\bar{B} - \bar{B}^*B}{\sqrt{2}} \quad : \quad \frac{1}{\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} \ ;$$

    $$(B^*\bar{B}^*)_{S=0} \quad : \quad -\frac{1}{6}\psi_{10} - \frac{1}{2\sqrt{3}}\psi_{11} - \frac{\sqrt{5}}{6}\psi_{12} + \frac{\sqrt{3}}{2}\psi_{01} \ ;$$

    $$(B^*\bar{B}^*)_{S=2} \quad : \quad \frac{\sqrt{5}}{3}\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{11} + \frac{1}{6}\psi_{12} \ .$$

    $$\psi_{10} = 1_H^{--} \otimes 0_{SLB}^{++}, \quad \psi_{11} = 1_H^{--} \otimes 1_{SLB}^{++}, \quad \psi_{12} = 1_H^{--} \otimes 2_{SLB}^{++}, \quad \text{and} \quad \psi_{01} = 0_H^{-+} \otimes 1_{SLB}^{+-}.$$

  - $I^G (J^P) = 1^- (1^+)$

    - S-wave (L=0)

    $$(B^*\bar{B} - \bar{B}^*B) \sim \frac{1}{\sqrt{2}}\left(0_H^- \otimes 1_{SLB}^- + 1_H^- \otimes 0_{SLB}^-\right)$$

    $$B^*\bar{B}^* \sim \frac{1}{\sqrt{2}}\left(0_H^- \otimes 1_{SLB}^- - 1_H^- \otimes 0_{SLB}^-\right) \ ,$$

Strange heavy-light meson thresholds

- What about SU(3) ?

  - If there was no SU(3) breaking: only SU(3) singlet light hadron states could be produced. So single light hadron production (except the η') would be forbidden.

  $$U = \exp\left(i\gamma_5 \frac{\varphi_a \lambda_a}{f_\pi}\right)$$

  $$\varphi_a \lambda_a = \sqrt{2}\begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}}, & \pi^+, & K^+ \\ \pi^-, & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}}, & K^0 \\ K^-, & \bar{K}^0, & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

  - BUT: SU(3) breaking is induced by the mass splitting of the (Q q) mesons with q=u,d (degenerate if no isospin breaking) and q = s.

  - These splittings are large (~100 MeV) so there is large SU(3) breaking in the threshold dynamics.

  - This leads to large effects in the threshold region.

  - This greatly enhances the final states with η + (Q$\bar{\text{Q}}$).
    Yu.A. Simonov and A.I. Veselov [arXiv:0810.0366]

  - Similarly important in ω and φ production.

Hadronic Transitions Above Threshold

- **Υ(5S) hadronic transitions**

  - $M = 10{,}876 \pm 11$ MeV $\Gamma = 55 \pm 26$ MeV;

  - Open Ground State ($j^p = \tfrac{1}{2}^-$) Decay Channels:

    - $M(B\overline{B}) = 10{,}559$ MeV, $M(B^*\overline{B}) = 10{,}604$ MeV, $M(B^*\overline{B}^*) = 10{,}650$ MeV

    - $M(B_s\overline{B}_s) = 10{,}734$ MeV, $M(B^*_s\overline{B}_s) = 10{,}782$ MeV, $M(B^*_s\overline{B}^*_s) = 10{,}831$ MeV

  - Also some P state ($j^p = \tfrac{1}{2}^+$) Decay Channels are essentially open

    - $M(B[1^{\frac{1}{2}+}P_0]\overline{B}^*) = 11{,}055$ MeV   (notation: $n^{jP}L_J$)

    - $M(B[1^{\frac{1}{2}+}P_1]\overline{B}) = 11{,}045$ MeV, $M(B[1^{\frac{1}{2}+}P_1]\overline{B}^*) = 11{,}091$ MeV

  - I have assumed: $\Gamma(B[1^{\frac{1}{2}+}P_{\{0,1\}}]) \sim 300$ MeV (wide); $\Gamma(B[1^{3/2+}P_{\{1,2\}}])$ are narrow

B B_s

Hadronic Transitions Above Threshold

- **ϒ(5S) hadronic transitions**

  - M = 10,876 ± 11 MeV Γ = 55 ± 26 MeV;

  - Open Ground State (j^p = ½⁻) Decay Channels:

    - M(BB) = 10,559 MeV, M(B*B) = 10,604 MeV,

    - M(B*B*) = 10,650 MeV

    - M(B_sB_s) = 10,734 MeV, M($B*_sB_s$) = 10,782 MeV,

    - M($B*_sB*_s$) = 10,831 MeV

  - Also some P state (j^p = ½⁺) decay channels
    are essentially open

    - M(B[1^{½+}P_0]B*) = 11,055 MeV   (notation: $n^{j^P}L_J$)

    - M(B[1^{½+}P_1]B) = 11,045 MeV,

    - M(B[1^{½+}P_1]B*) = 11,091 MeV

  - I have assumed: Γ(B[1^{½+}P_{{0,1}}]) ~ 300 MeV (wide); Γ(B[1^{3/2+}P_{{1,2}}]) < few MeV (narrow)

ϒ(5S) nearby thresholds

Low-lying thresholds

Low-lying (Narrow) Bottom Meson Pair Thresholds

Threshold (GeV)

$B_s^* B_s(1P_1)$, $B_s^* B_s(1P_2)$

$B_s B_s(1P_1)$, $B_s B_s(1P_2)$

$B(1P_1)B_s^*$, $B^* B_s(1P_1)$, $B(1P_2)B_s^*$, $B^* B_s(1P_2)$

$B(1P_1)B_s$, $BB_s(1P_1)$, $B(1P_2)B_s$, $BB_s(1P_2)$

$B^* B(1P_1)$, $B^* B(1P_2)$

$BB(1P_1)$, $BB(1P_2)$

$B_s^* B_s^*$

$B_s B_s^*$

$B^* B_s^*$ $B_s B_s$

$B^* B_s$, BB_s^*

$B^* B^*$ BB_s

BB^*

BB

Narrow-Wide Thresholds

$B_s^* B(P_1)$

$B_s^* B(P_0)$; $B_s B(P_1)$

$B^* B(P_1)$; $B_s B(P_0)$

$B^* B(P_0)$, $B B(P_1)$

$B B(P_0)$
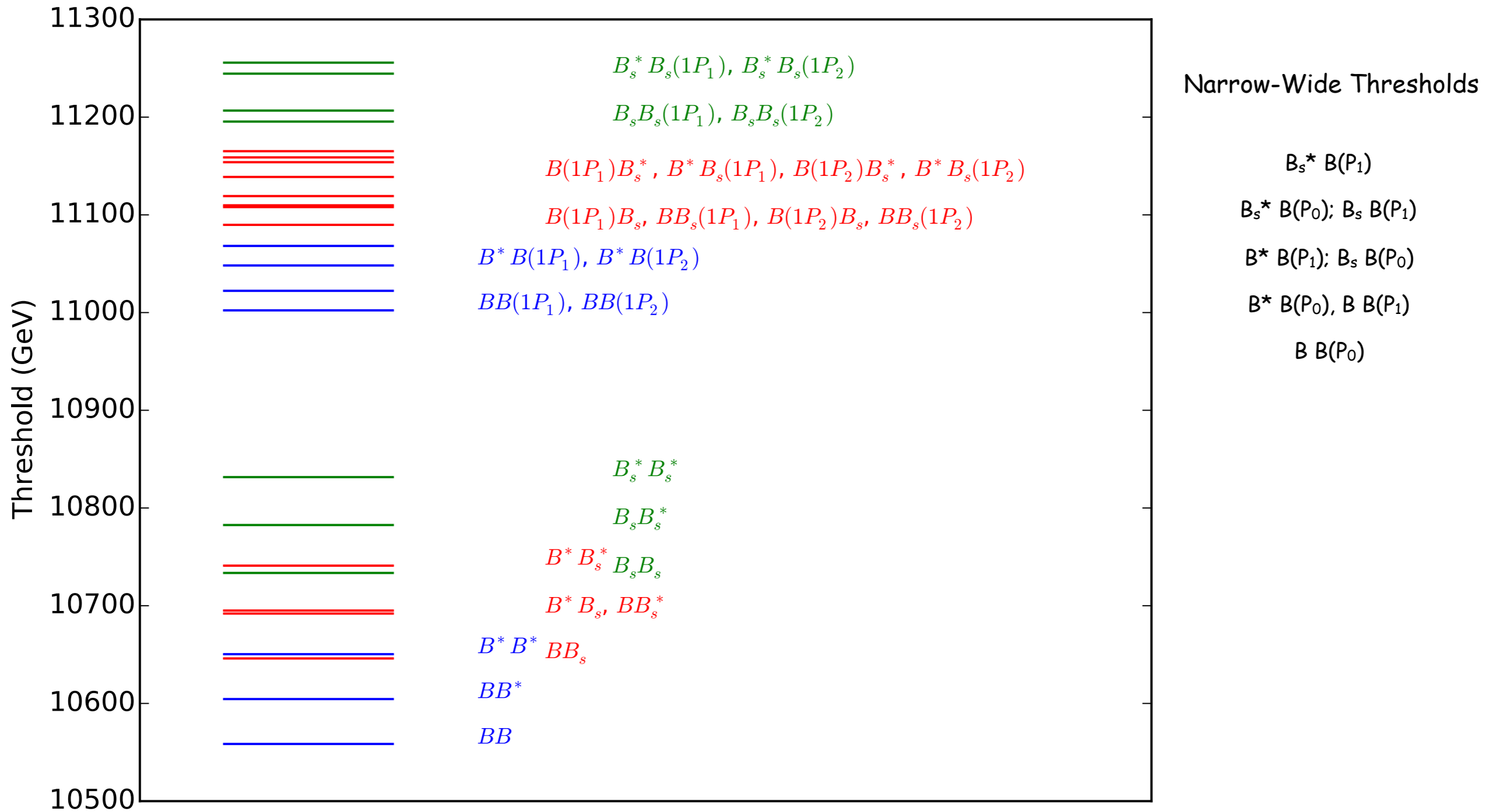
Hadronic Transitions Above Threshold

- **Υ(5S) decay pattern:**

Table 2: Selected $\Upsilon(5S)$ decays.

Decay Mode	Branching Rate		Decay Mode	Branching Rate	
$B\bar{B}$	$(5.5 \pm 1.0)\%$		$\Upsilon(1S)\,\pi^+\pi^-$	$(5.3 \pm 0.6) \times 10^{-3}$	→ partial rate = 0.29 ± 0.13 MeV
$B\bar{B}^* + c.c.$	$(13.7 \pm 1.6)\%$		$\Upsilon(2S)\,\pi^+\pi^-$	$(7.8 \pm 1.3) \times 10^{-3}$	
$B^*\bar{B}^*$	$(38.1 \pm 3.4)\%$		$\Upsilon(3S)\,\pi^+\pi^-$	$(4.8\,{}^{+1.9}_{-1.7}) \times 10^{-3}$	
			$\Upsilon(1S)K\bar{K}$	$(6.1 \pm 1.8) \times 10^{-4}$	
$B_s\bar{B}_s$	$(5 \pm 5) \times 10^{-3}$		$h_b(1P)\pi^+\pi^-$	$(3.5\,{}^{+1.0}_{-1.3}) \times 10^{-3}$	
$B_s\bar{B}_s^* + c.c.$	$(1.35 \pm 0.32)\%$		$h_b(1P)\pi^+\pi^-$	$(6.0\,{}^{+2.1}_{-1.8}) \times 10^{-3}$	
$B_s^*\bar{B}_s^*$	$(17.6 \pm 2.7)\%$	χ_{b1}	$\pi^+\pi^-\pi^0$ (total)	$(1.85 \pm 0.33) \times 10^{-3}$	→ partial rate = 86 ± 41 keV
$B\bar{B}\pi$	$(0.0 \pm 1.2)\%$	χ_{b2}	$\pi^+\pi^-\pi^0$ (total)	$(1.17 \pm 0.30) \times 10^{-3}$	
$B^*\bar{B}\pi + B\bar{B}^*\pi$	$(7.3 \pm 2.3)\%$		$\chi_{b1}\;\;\omega$	$(1.57 \pm 0.32) \times 10^{-3}$	
$B^*\bar{B}^*\pi$	$(1.0 \pm 1.4)\%$		$\chi_{b2}\;\;\omega$	$(0.60 \pm 0.27) \times 10^{-3}$	
$B\bar{B}\pi\pi$	$< 8.9\%$		$\Upsilon(1S)\eta$	$(0.73 \pm 0.18) \times 10^{-3}$	
			$\Upsilon(2S)\eta$	$(2.1 \pm 0.8) \times 10^{-3}$	
			$\Upsilon(1D)\eta$	$(2.8 \pm 0.8) \times 10^{-3}$	→ partial rate = 0.15 ± 0.08 MeV
total $B\bar{B}$X	$(76.2\,{}^{+2.7}_{-4.0})\%$				

- Very large 2π hadronic transitions [> 100 times **Υ**(4S) rates]

- Very large η (single light hadron) transitions.   Related to nearby $B_s^*B_s^*$ threshold?

$Z_b^{\pm}(10,610)$ and $Z_b^{\pm}(10,650)$

- BELLE observed two new charged states in the $Y(5S) \to Y(nS) + \pi^+\pi$ (n=1,2,3) and the $Y(5S) \to h_b(nP) + \pi^+\pi$ (n=1,2)

TABLE 1. Masses, widths, and relative phases of peaks observed in $h_b\pi$ and $Y\pi$ channels, from fits described in text.

	$h_b(1P)\pi^\pm\pi^\mp$	$h_b(2P)\pi^\pm\pi^\mp$	$Y(1S)\pi^\pm\pi^\mp$	$Y(2S)\pi^\pm\pi^\mp$	$Y(3S)\pi^\pm\pi^\mp$	Average
M_1 (MeV/c^2)	$10605.1\pm2.2^{+3.0}_{-1.0}$	$10596\pm7^{+5}_{-2}$	$10609\pm3\pm2$	$10616\pm2^{+3}_{-4}$	$10608\pm2^{+5}_{-2}$	10608 ± 2.0
Γ_1 (MeV)	$11.4^{+4.5}_{-3.9}{}^{+2.1}_{-1.2}$	$16^{+16}_{-10}{}^{+13}_{-14}$	$22.9\pm7.3\pm2$	$21.1\pm4^{+2}_{-3}$	$12.2\pm1.7\pm4$	15.6 ± 2.5
M_2 (MeV/c^2)	$10654.5\pm2.5^{+1.0}_{-1.9}$	$10651\pm4\pm2$	$10660\pm6\pm2$	$10653\pm2\pm2$	$1-652\pm2\pm2$	10653 ± 1.5
Γ_2 (MeV)	$20.9^{+5.4}_{-1.7}{}^{+2.1}_{-5.7}$	$12^{+11}_{-9}{}^{+8}_{-2}$	$12\pm10\pm3$	$16.4\pm3.6^{+4}_{-6}$	$10.9\pm2.6^{+4}_{-2}$	14.4 ± 3.2
ϕ (°)	$188^{+44}_{-58}{}^{+4}_{-9}$	$255^{+56}_{-72}{}^{+12}_{-183}$	$53\pm61^{+5}_{-50}$	$-20\pm18^{+14}_{-9}$	$6\pm24^{+23}_{-59}$	–

- Explicitly violates the factorization assumption of the QCDME.

- The $Z_b^{\pm}$ (10610) is a narrow state (Γ= 15.6 ± 2.5 MeV) at the $B\bar{B}^*$ threshold (10605).

- The $Z_b^{\pm}$ (10650) is a narrow state (Γ= 14.4 ± 3.2 MeV) at the $B^*\bar{B}^*$ threshold (10650).

$Z_b^+(10610)$ $Z_b^+(19650)$

- **Strong threshold dynamics**

  – Strong peaking at threshold BB* and B*B*

  – Z+(10610) and Z+(10650) states
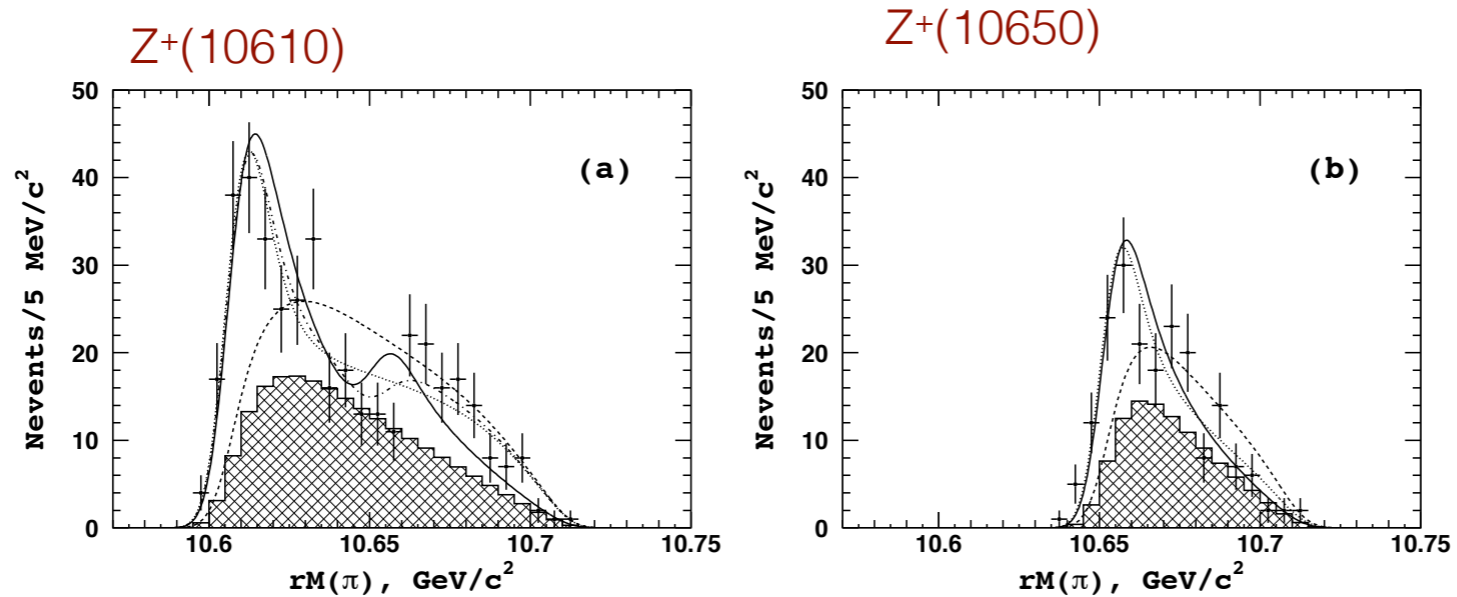
$$\frac{\mathcal{B}(Z_b(10610) \to BB^*)}{\sum_n \mathcal{B}(Z_b(10610) \to \Upsilon(nS)\pi) + \sum_m Z_b(10610) \to h_b(mP)} = 6.2 \pm 0.7 \pm 1.3^{+0.0}_{-1.8}$$

and

$$\frac{\mathcal{B}(Z_b(10650) \to B^*B^*)}{\sum_n \mathcal{B}(Z_b(10650) \to \Upsilon(nS)\pi) + \sum_m Z_b(10650) \to h_b(mP)} = 2.8 \pm 0.4 \pm 0.6^{+0.0}_{-0.4}.$$

  – HQS implies that the same mechanism applies for charmonium-like states

New Dynamics for Hadronic Transitions

– Contributions of P-state decays:

- $n^3S_1(\overline{Q}Q) \rightarrow 1^{\frac{1}{2}+}P_J(\overline{Q}q) + 1^{\frac{1}{2}-}S_{J'}(\overline{q}Q)$:

S-wave decays

$C(J, J')$	$J' = 0$	$J' = 1$
$J = 0$	0	$2/3$
$J = 1$	$2/3$	$4/3$

- $1^{\frac{1}{2}+}P_J(\overline{Q}q) \rightarrow 1^{\frac{1}{2}-}S_{J'}(\overline{Q}q') + {}^1S_0(\overline{q}q')$ for S-wave J=J'

- Dominant two body decays of the $\Upsilon(5S)$

Example

$\Upsilon(5S)$, $B_1(1P)$, π, B^*, π, $\overline{B}^{(*)}$, $\Upsilon(1S)$
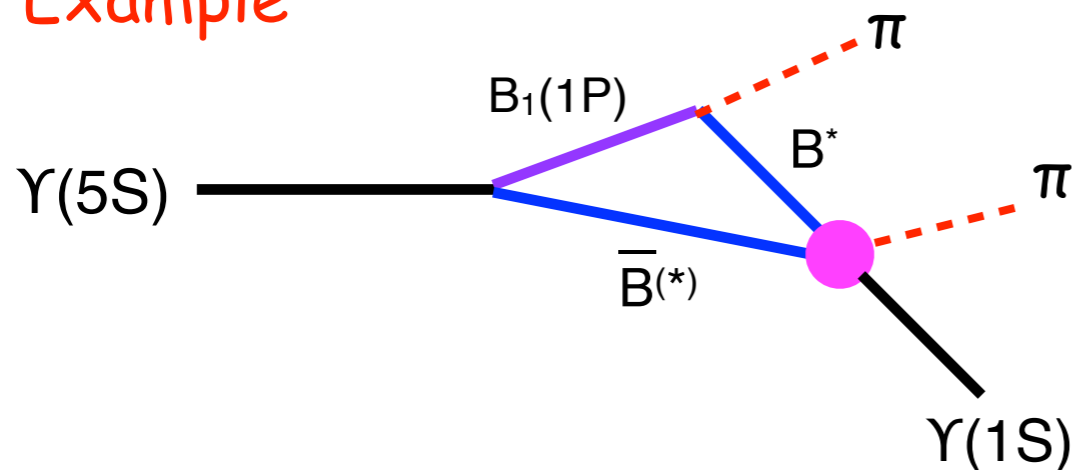
Remarks:
(1) $\Upsilon(5S)$ strong decay is S-wave
(2) The large width of the $B_1(1P)$ implies that the first π is likely emitted while the $B_1(1P)$ and $B^{(*)}$ are still nearby.
(3)   The $B_1(1P)$ decay is S-wave
(4) Therefore the $B^{(*)}$ B^* system is in a relative S-wave and near threshold.
(5)   No similar BB system is possible.

New Dynamics for Hadronic Transitions

- A new factorization for hadronic transitions above threshold.

  - Production of a pair of heavy-light mesons ($H'_1 H_2$) near threshold.
    Where $H'_1 = H_1$ or H'_1 decays rapidly to H_1 + light hadrons (h_b),
    yielding $H_1 H_2 <h_b>$

  - Followed by recombination of this ($H_1 H_2$) state into a narrow
    quarkonium state (ϕ_f) and light hadrons (h_a).

$$\mathcal{M}(\Phi_i \to \Phi_f + h >=$$
$$\sum_{H_1 H_2} \sum_{p_1,p_2} \langle \Phi_f h_a | \mathcal{H}'_I | H_1(p_1) \bar{H}_2(p_2) \rangle \frac{1}{(E_f + E_a) - (E_1 + E_2)} \langle H_1 \bar{H}_2[h_b] | \mathcal{H}_I || \phi_i \rangle$$
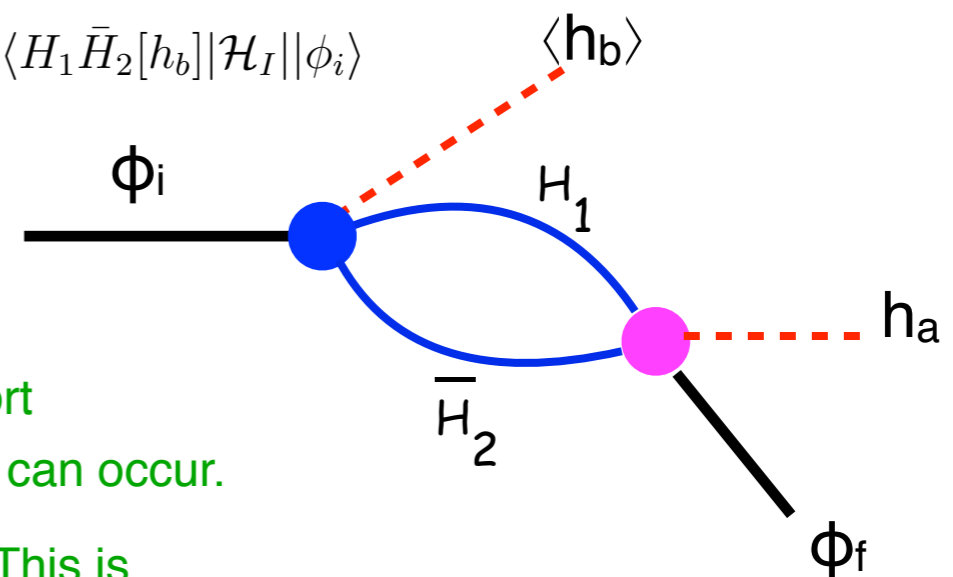
  - The time scale of the production process has to be short
    relative to the time scale over which $H_1 H_2$ rescattering can occur.

  - The relative velocity in the $H_1 H_2$ system must be low. This is
    only possible near threshold.

  - Here we need not speculate on whether the observed rescattering is
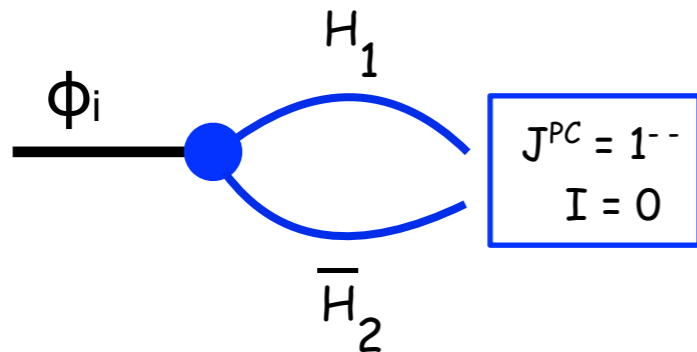   caused by a threshold bound state, cusp, or other dynamical effect.

  F.K. Gao, C. Hanhart, Q. Wang, Q. Zhao [arXiv:1411.5584]

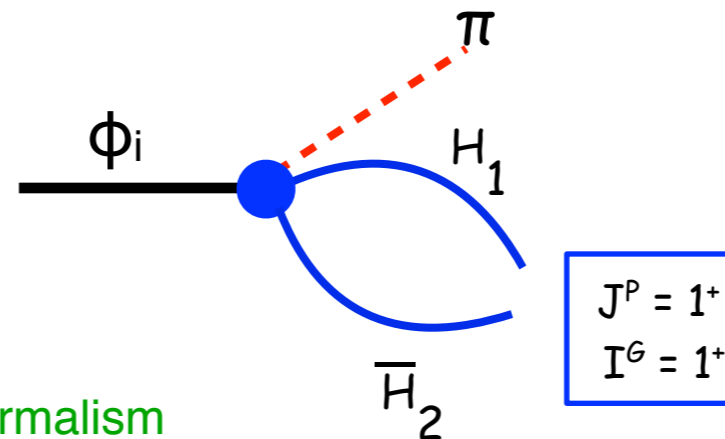# New Dynamics for Hadronic Transitions

- **Production modes**

  - e+e-

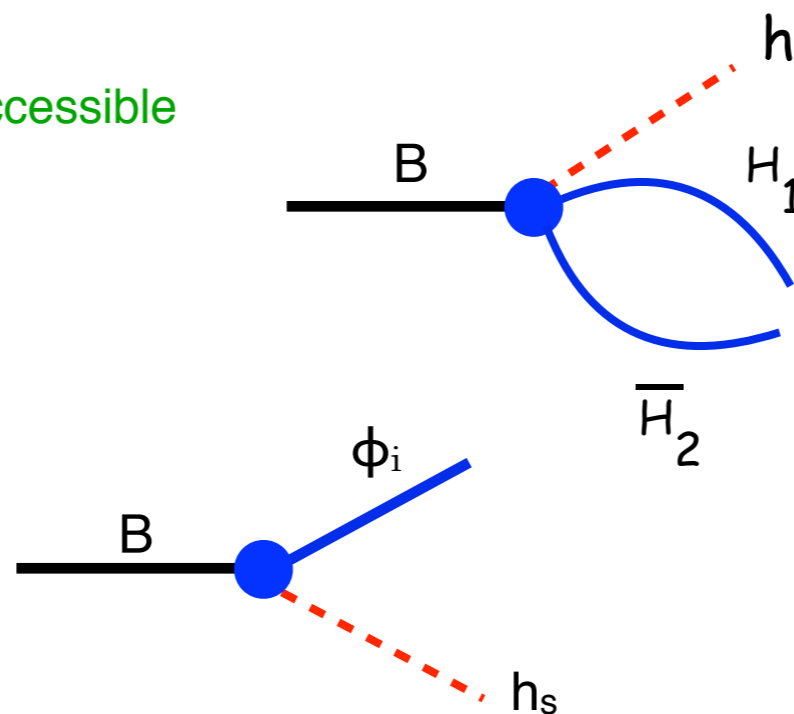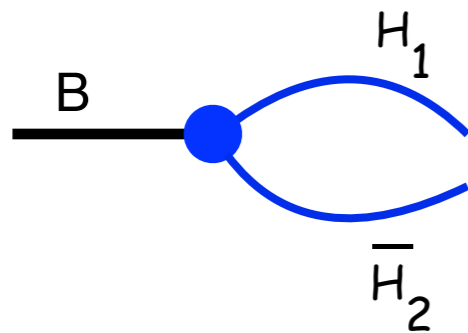   - direct   sequential (dominate terms)

    - Can compute using coupled channel formalism

  - B decays

    - More quantum numbers accessible

New Dynamics for Hadronic Transitions

- **Physical Expectations for Threshold Dynamics:**

  1. There is a large rescattering probability into light hadrons and quarkonium states for two heavy light mesons both near threshold and nearby in position.

  2. For direct decays of a quarkonium resonance: New S-wave channels peak rapidly near threshold. This is an expected property of the decay amplitudes into two narrow two heavy mesons and is an explicit feature of coupled channel calculations.

  3. For sequential decays: the strong scattering dynamics of two narrow heavy-light mesons is peaked near threshold for S-wave initial states.
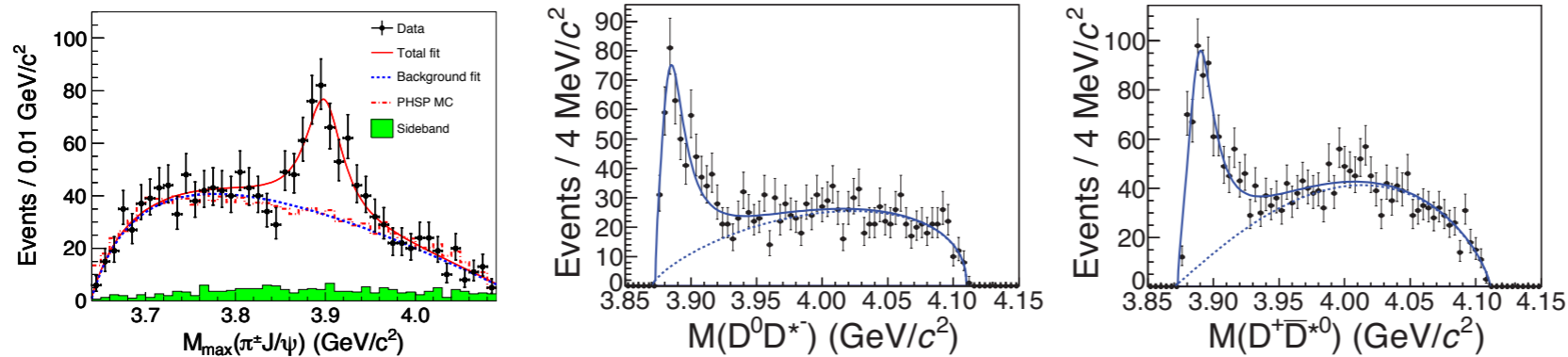
B^* π

$B^{(*)}$ $\Upsilon(nS)$

B^* B^*

$B^{(*)}$ $B^{(*)}$
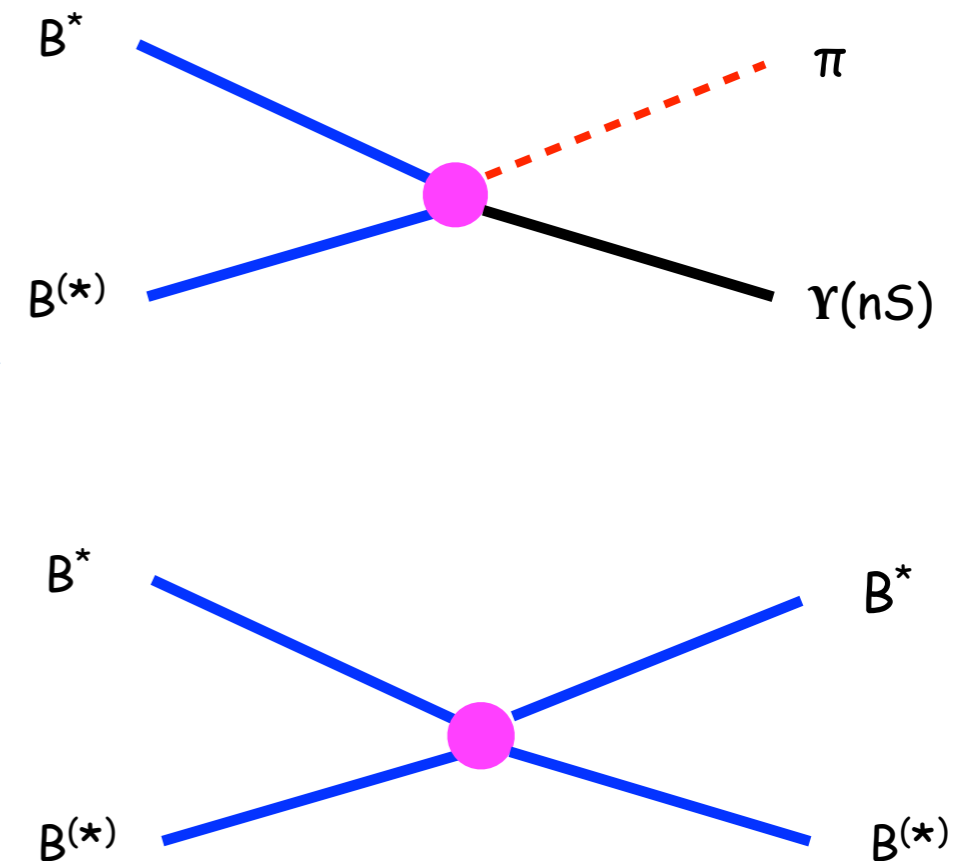
Ratios determined by LQCD calculations and judicious use of SU(3).
M. Padmanath, C. B. Lang and S. Prelovsek
[arXix:1503.03257]

Heavy Quark Symmetry

- Charmonium-like states: $e^+e^- \longrightarrow \pi^+ \pi^- J/\psi$ at $\sqrt{s}$ = 4.26 GeV   [Y(4260)]

- $Z_c(3885)$, $Z_c(4020)$ both have $I^G(J^P) = 1^-(1^+)$.

- As expected by HQS between the bottomonium and charmonium systems

M(D^0+D^{*-}) = 3.8752

$M_{pole} = 3883.9 \pm 1.5 \pm 4.2$ MeV

$\Gamma_{pole} = 24.8 \pm 3.3 \pm 11.0$ MeV.

$$\frac{\Gamma[Z_c(3900) \to DD^*]}{\Gamma[Z_c(3900) \to \pi J/\psi]} = 6.2 \pm 1.1_{stat} \pm 2.7_{sys}.$$

BESIII Z. Lin

[arXiv:1504.06102]
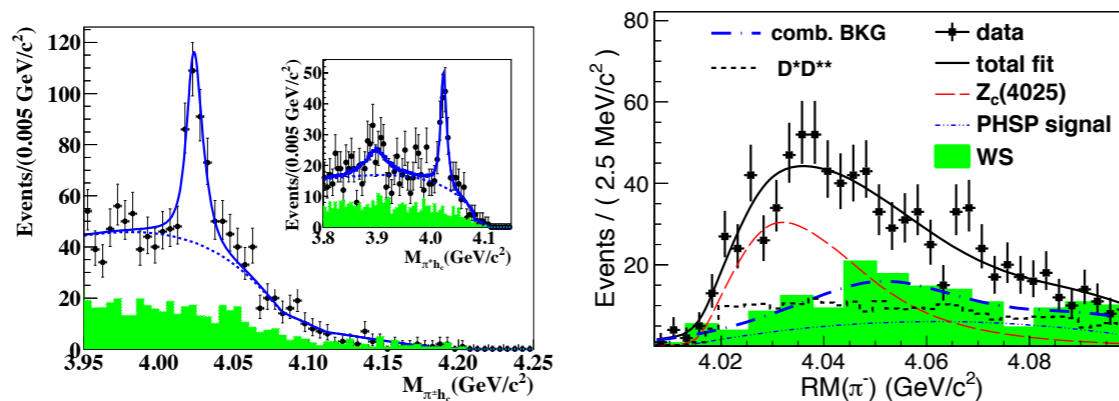
$M = 4022.9 \pm 0.8 \pm 2.7$ MeV

$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

M(D^{*0}+D^{*-}) = 4.0178

$$\frac{\Gamma[Z_c(4025) \to D^*D^*]}{\Gamma[Z_c(4020) \to \pi h_c]} \sim 9.$$

More States and Transitions

- Charmonium systems:

- $\Psi(1D)$

  - M = 3773.15 ± 0.33 MeV   Γ = 27.2 ± 1.1 MeV;

  - Open decay channels:

    - $M(\overline{D}^0 D^0)$ = 3,729.72 MeV, $M(D^+ D^-)$ = 3,739.26 MeV

  - Normal pattern

Decay Mode	Branching Rate
$D^0 \bar{D}^0$	$(52 \pm 5)\%$
$D^+ D^-$	$(41 \pm 4)\%$
total $D\bar{D}$	$93^{+8}_{-9}\%$
$\psi(1S)\,\pi^+\pi^-$	$(1.93 \pm 0.28) \times 10^{-3}$
$\psi(1S)\,\eta$	$(9 \pm 4) \times 10^{-4}$

—> partial rate = 52.5 ± 7.6 keV

  - Puzzle is the total $\overline{DD}$ branching fraction

Ψ(3770), Ψ(4040)

- Only ground state heavy-light meson pair decays allowed
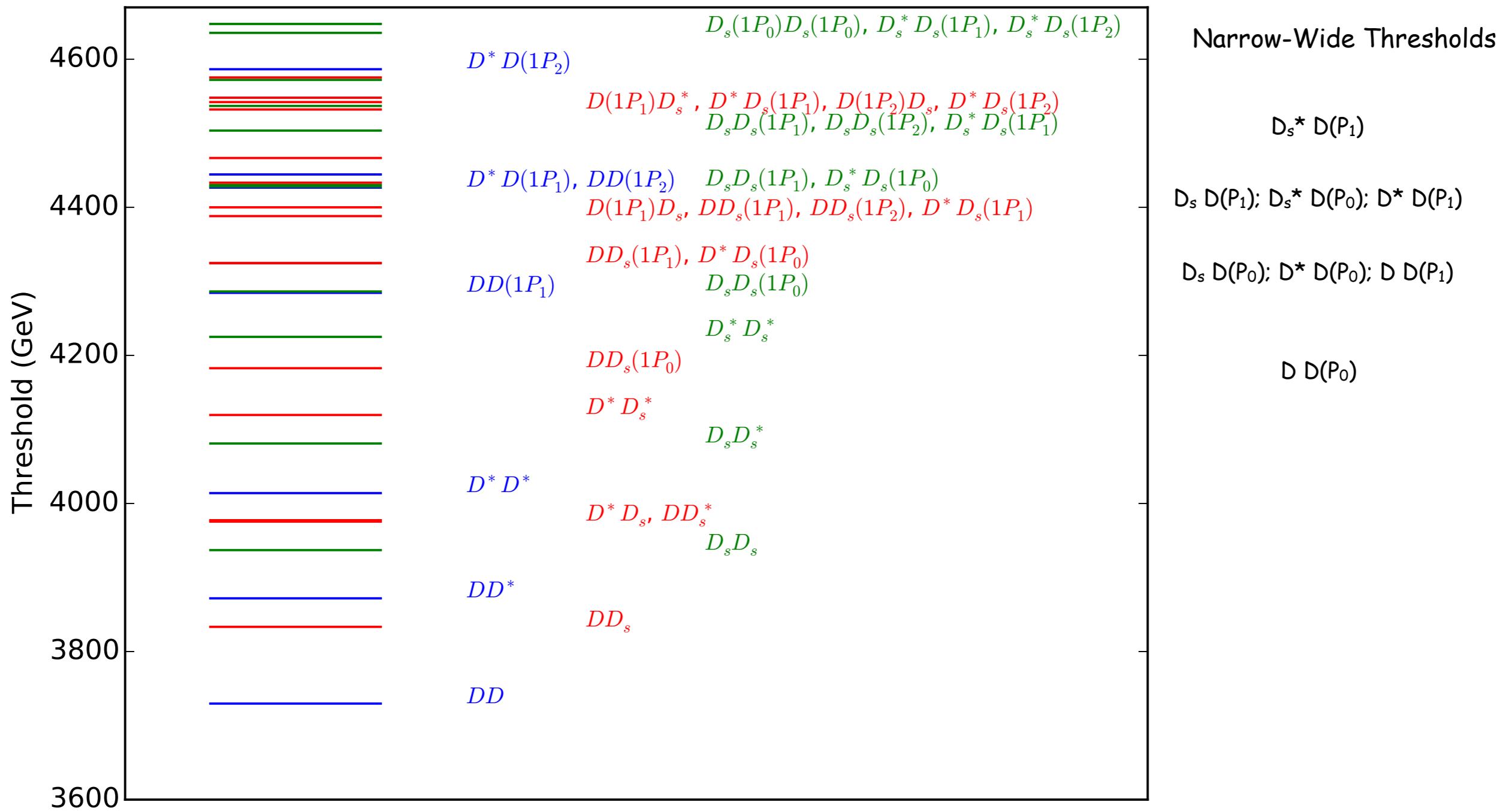
$\psi(3770)$ nearby thresholds
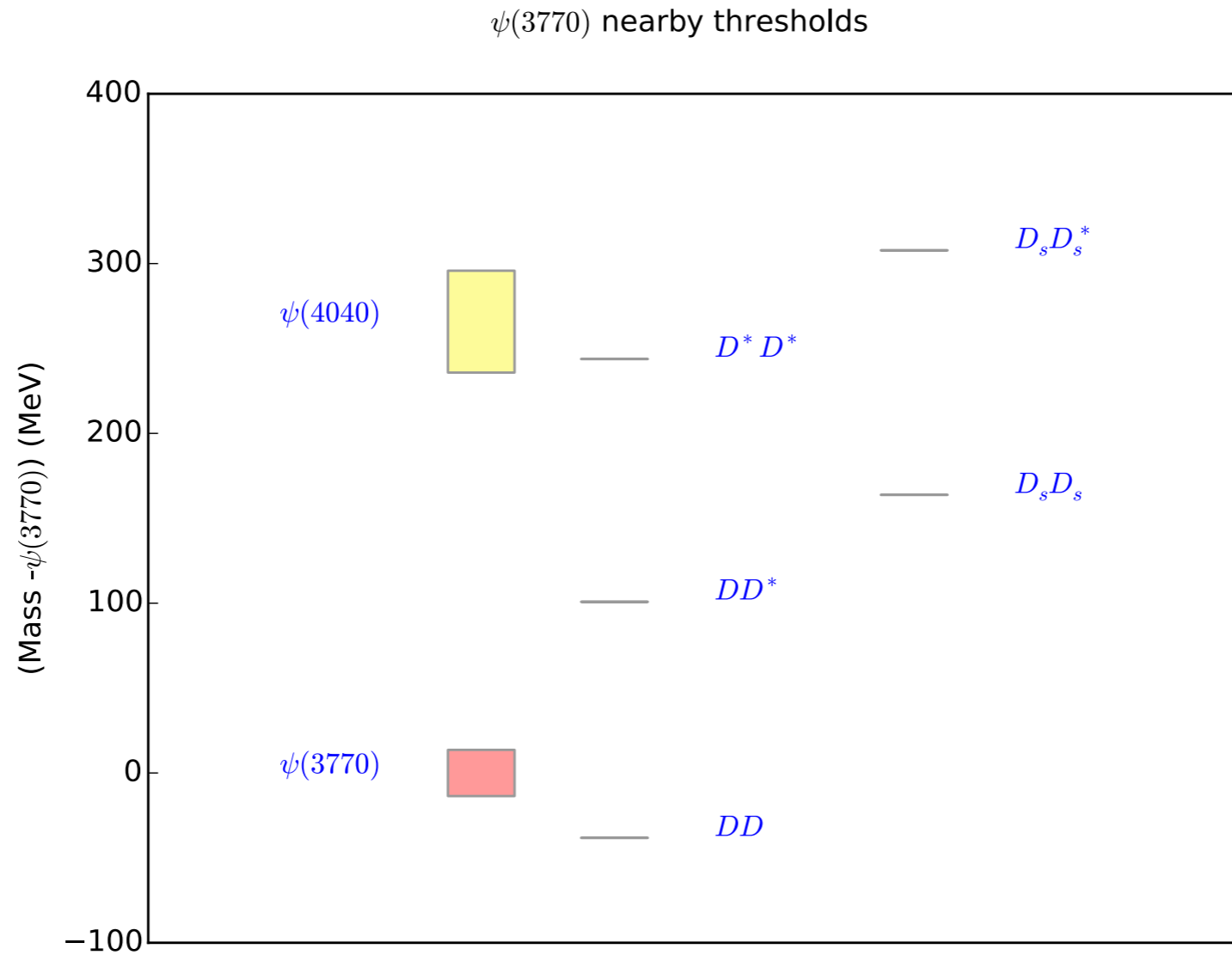
Systematics: ψ(4040) and Below

- Charmonium-like state transitions for masses at or below the ψ(3S)

State	Mass Transition Observed	Width Branching Fraction	J^{PC}	Comments
$\psi(3770)$	3773.15 ± 0.33	27.2 ± 1.0	1^{--}	1^3D_1
	$\pi^+\pi^- J/\psi$	$(1.93 \pm 0.28) \times 10^{-3}$		
	$\pi^0\pi^0 J/\psi$	$(8.0 \pm 3.0) \times 10^{-4}$		
	$\eta J/\psi$	$(9 \pm 4) \times 10^{-4}$		
$X(3872)$	3871.68 ± 0.17	< 1.2 MeV	1^{++}	
	$\pi^+\pi^- J/\psi$			large ρ component
	$\omega J/\psi$			off shell
	$D^0\bar{D}^0\pi^0$			
	$D^{*0}\bar{D}^0$			
$X(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	2^3P_0
	$\omega J/\psi$			
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	2^3P_2
$Z(3900)^+$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	1^+	$e^+e^-(4260) \to \pi^+\pi^- J/\psi$
	$\pi^+ J/\psi$	$\left(\frac{Z_c(3885)\to D\bar{D}^*}{Z_c\to\pi J/\psi}\right) = 6.2 \pm 1.1 \pm 2.7$	1^+	
$Z(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.2 \pm 3.3 \pm 11$	1^+	
	$\pi^0 J/\psi$			$I = 1$
$X(3940)$	$3942 \pm 7/6 \pm 6$	$37 \pm 26/15 \pm 8$	$?$	
	$\omega J/\psi$			
$Z(4020)^+$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	1^+	$e^+e^-(4260) \to \pi^+\pi^- h_c$
	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	1^+	$e^+e^-(4260) \to \pi^\pm(D^*\bar{D}^*)^\mp$
$Z(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed to Z^+		$I = 1$
$\psi(4040)$	4039 ± 1	60 ± 10	1^{--}	3^3S_1
	$\eta J/\psi$	$(5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$		

Low-lying thresholds

Low-lying (Narrow) Charm Meson Pair Thresholds

$D_s(1P_0)D_s(1P_0)$, $D_s^* D_s(1P_1)$, $D_s^* D_s(1P_2)$

$D^* D(1P_2)$

$D(1P_1)D_s^*$, $D^* D_s(1P_1)$, $D(1P_2)D_s$, $D^* D_s(1P_2)$
$D_s D_s(1P_1)$, $D_s D_s(1P_2)$, $D_s^* D_s(1P_1)$

$D^* D(1P_1)$, $DD(1P_2)$ $D_s D_s(1P_1)$, $D_s^* D_s(1P_0)$
$D(1P_1)D_s$, $DD_s(1P_1)$, $DD_s(1P_2)$, $D^* D_s(1P_1)$

$DD_s(1P_1)$, $D^* D_s(1P_0)$

$DD(1P_1)$ $D_s D_s(1P_0)$

$D_s^* D_s^*$

$DD_s(1P_0)$

$D^* D_s^*$

$D_s D_s^*$

$D^* D^*$

$D^* D_s$, DD_s^*
$D_s D_s$

DD^*

DD_s

DD

Threshold (GeV) (y-axis): 3600, 3800, 4000, 4200, 4400, 4600

Narrow-Wide Thresholds

$D_s^* D(P_1)$

$D_s D(P_1)$; $D_s^* D(P_0)$; $D^* D(P_1)$

$D_s D(P_0)$; $D^* D(P_0)$; $D D(P_1)$

$D D(P_0)$

- Many open channels for heavy-light meson pair decays.

$\psi(4160)$ nearby thresholds

- Ψ(4S)
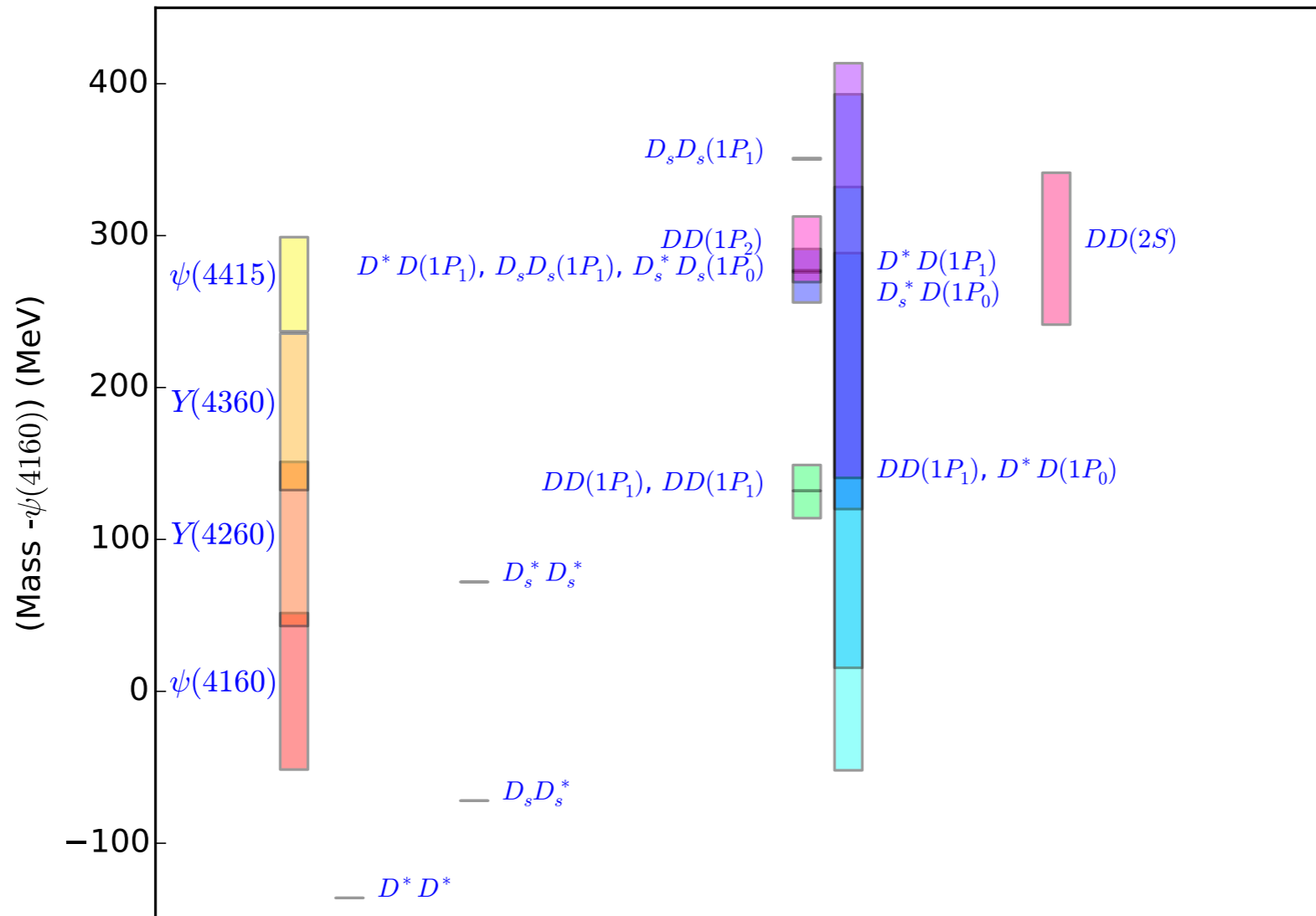
  – M = 4421 ± 4 MeV   Γ = 62 ± 20 MeV;

  – Open decay channels:

    • Many

Decay Mode	Branching Rate
$D^* \bar{D}$ + cc	$\frac{\Gamma(D^* \bar{D})}{\Gamma(D^* \bar{D}^*)} = 0.17 \pm 0.25 \pm 0.03$
$D^* \bar{D}^*$	seen
$D_s^{+*} D_s^-$	seen
$D D_2^*(\bar{2}460)$	$(10 \pm 4)\%$
$\eta J/\psi$	$< 6 \pm 10^{-3}$

Systematics: Ψ(4160), Ψ(4415)

- Charmonium-like state transitions for masses above the ψ(3S)

| State	Mass Transition Observed	Width Branching Fraction	J^{PC}	Comments
$X(4140)$	$4148.0 \pm 3.9 \pm 6.3$	$28 \pm 15 \pm 19$	?	
	$\phi J/\psi$			
$X(4160)$	$4156 \pm 25/20 \pm 15$	$139 \pm 111/61 \pm 21$	?	
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$2^3 D_1$
	$\eta J/\psi$			
$Z(4200)^+$	$4196\,^{81}_{-29}\,^{+17}_{-13}$	$370 \pm 70\,^{+70}_{-132}$	1^+	
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	
	$\pi^+\pi^- J/\psi$			
	$\pi^0\pi^0 J/\psi$			
	$K^+ K^- J/\psi$			
	$\gamma X(3872)$			
$X(4350)$	$4350.6 \pm 4.6/5.1 \pm 0.7$	$13 \pm 18/9 \pm 4$	$2^{++}/0^{++}$	$3^3 P_2$
	$\phi J/\psi$			
$Y(4360)$	$4337 \pm 6 \pm 3$	$103 \pm 9 \pm 5$	1^{--}	
	$\pi^+\pi^- \psi(2S)$			
	$\eta J/\psi$			
	$\pi^\pm (D\bar{D}^*)^\mp$			
	$\pi^+ \psi(2S)$			
$\psi(4415)$	4421 ± 4	62 ± 20	1^{--}	$4^3 S_1$
$Z(4430)^+$	$4475 \pm 7\,^{`+15}_{-25}$	$172 \pm 13 +^{+37}_{-34}$	1^+	
	$\pi^+ \psi(2S)$			
	$\pi^+ J/\psi$			
$Y(4660)$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$	1^{--}	
	$\pi^+\pi^- \psi(2S)$			
	$\eta J/\psi$			
	$\pi^\pm (D\bar{D}^*)^\mp$			

Strange heavy-light meson thresholds

- What happens at strange heavy-light meson thresholds ?

  - There should be threshold enhancements for strange heavy-light meson pair production leading to sizable production of single η and φ light hadrons.

Belle Pakhlova et.al [arXiv:1011.4397]
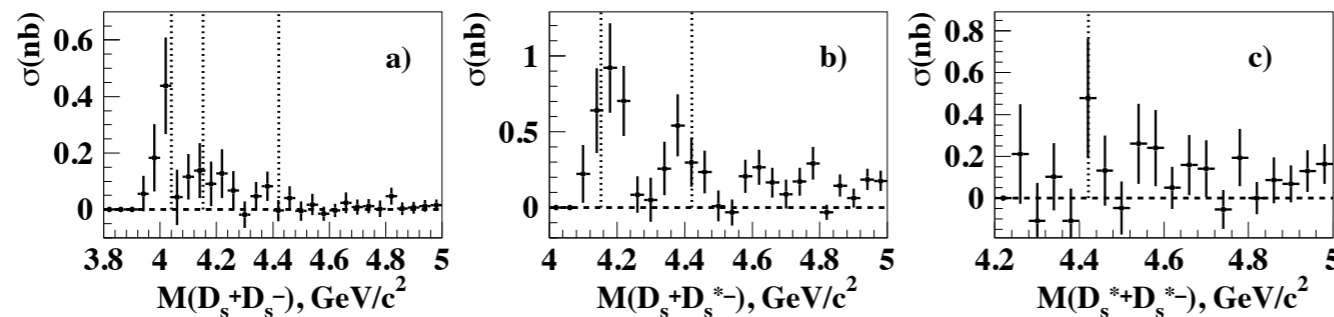
  - No wide P-states -> no sequential transitions with these states.

  - $M(D_s^+ D_s^{-*}) = 4,081$ MeV, $M(D_s^{+*}D_s^{-*}) = 4,225$ MeV; $M(3^3P_1) = 4,310$ MeV -> no analogy of X(3872)

  - Direct transitions?

  - Narrow D(½+P) + D(½-S) thresholds? (and B analogs)

  - At higher energies the $D_s(2S)$ wide states could play a role in sequential transitions.
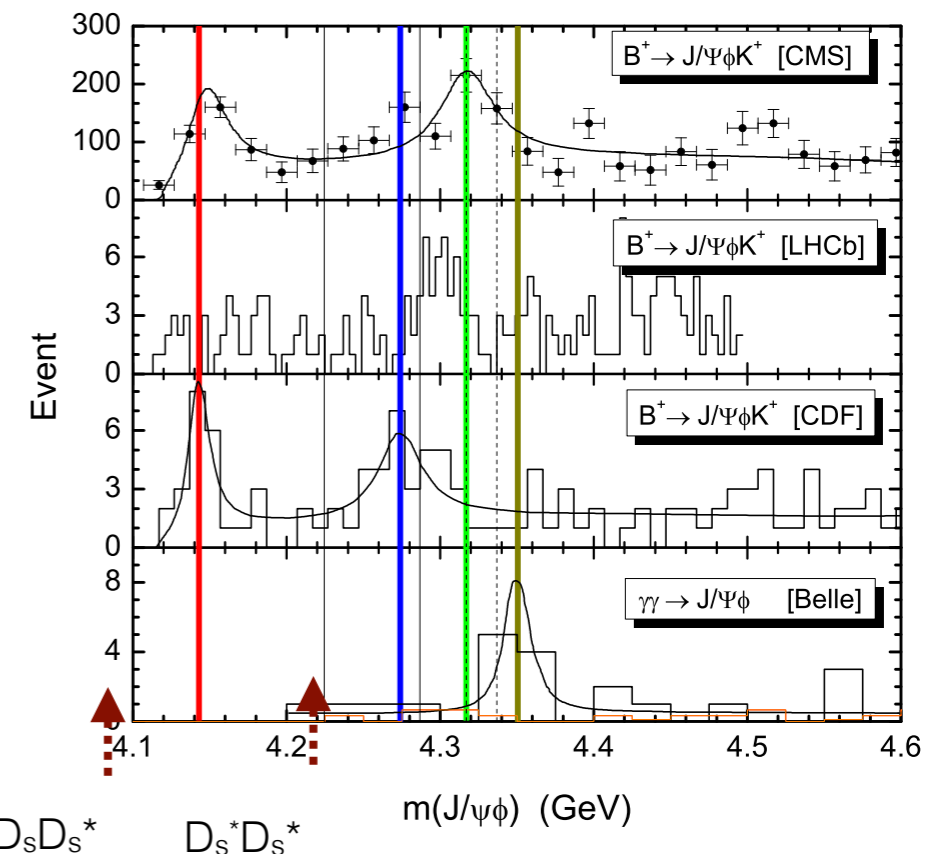
Summary

- Near threshold the effects of heavy-light meson loops on quarkonium transiton rates are pronounced.

  - Hadronic transition rates are much larger than then usual QCDME.

  - The SU(3) breaking and Heavy Quark Spin Symmetry violation seen in these transitions are induced by the HL meson mass differences of nearby threshold

  - The factorization assumption fails. Heavy quark and light hadronic dynamics interact strongly due to heavy flavor meson pair (four quark) contributions to the quarkonium wavefunctions.

  - A new mechanism, in which the dynamics is factored differently, is purposed. HQS as well as the usual SU(3) and chiral symmetry expectations are recovered for amplitudes. Magnetic transitions not suppressed. The puzzles in η transitions are resolved.

- The known X and Z states are associated with threshold S-wave scattering of narrow HL state meson pairs. The Y(4260) may be a hybrid state.

- With BES III and LHCb and soon BELLE 2. I expect even more progress in understanding hadronic transitions and XYZ states in the near future.

- Lattice QCD can play an important role in disentangling this situation

Requests to Experimentalists

- Confirm/Refute the X,Y,Z states seen in only one experiment: X(3740), Y(4008), $Z_1(4050)^+$, $Z_2(4250)^+$.

- The $\chi_{c0}(3917)$ has a very small separation from the $\chi_{c2}(3927)$. Why?

- As many decay modes of the Y(4260) as possible. Look for partners of this state.

- Look for quasi two body exclusive channels with a ground state heavy-light meson and a P-wave ($J^P = 1/2^+$ or $3/2^+$) heavy-light meson.

- Are there any I=0 threshold associated with the I=1 states? This will help understand the mechanism of the Z states.

- What about strange light quarks? Y(4140), Y(4274), X(4350),.. Clearly states decaying into ($\phi\psi$) can have $J^{PC} = 0^{++}$ or 2^{++}. Can be produced in hadron collisions.

Requests to lattice theorists

- Calculate the quarkonium spectrum (and transitions) as a function of the light quark masses for masses $\lesssim \Lambda_{QCD}$. This provides model independent insight into the role of meson loops.

- Calculate the behavior of scattering of heavy-light meson pairs in the threshold region.

  – Consider S-wave amplitudes

  – Include the mixing between two HL mesons and quarkonium + a single light hadron.

  – Can use the HQSS and approximate SU(3) of the amplitudes to greatly simplify the task.

  – This is an difficult challenge but initial progress is very encouraging.

Backup Slides

Pentaquarks

- X(4450) F. K. Guo et al [arXiv:1507.04950]

  – Resonance is at threshold of χ_{c1} p = 3510.66 + 938.27 = 4448.93 MeV

  – Also triangle diagram involving the Λ(1890) can give a leading Laudau singularity which would appear at χ_{c1} P threshold.
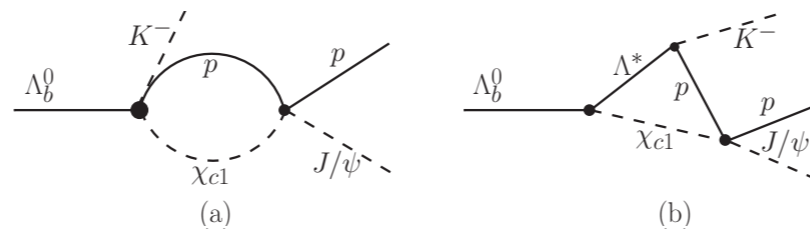
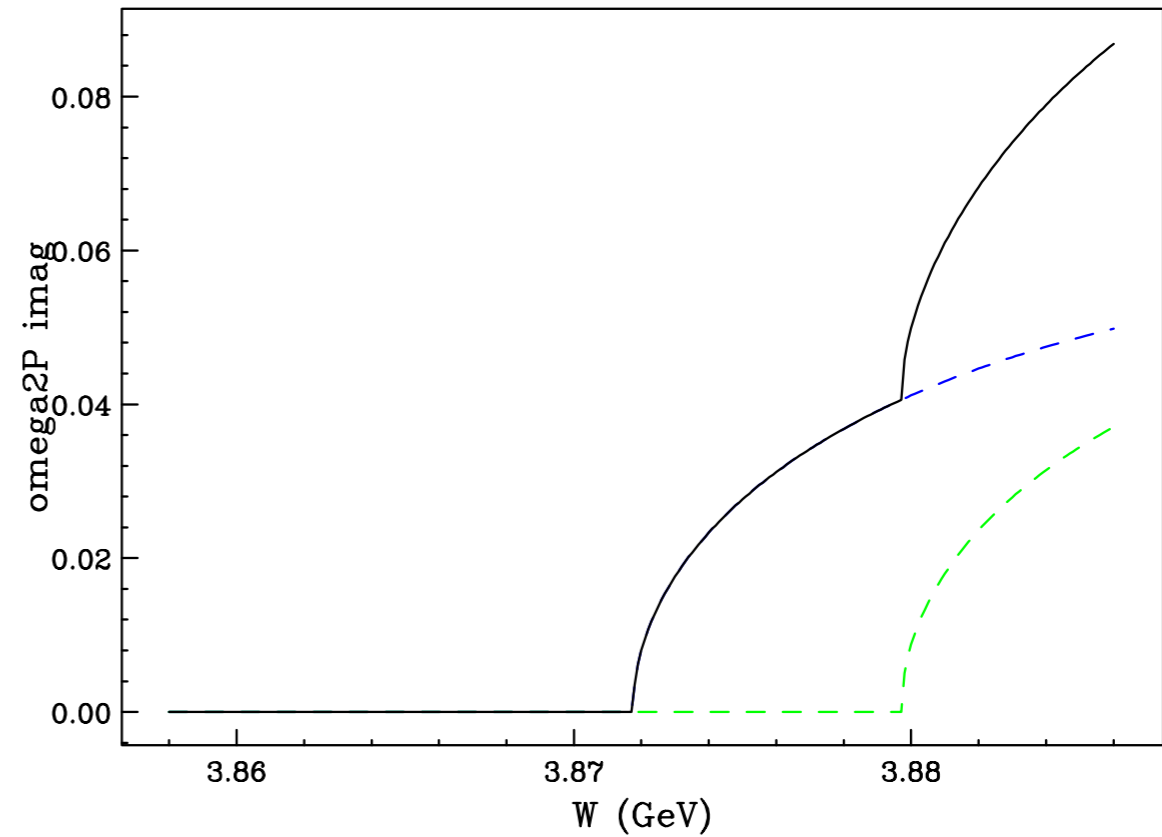 – Purpose tests in: Λb -> K χ_{c1} p and Y(1S) -> J/Ψ p $\overline{p}$
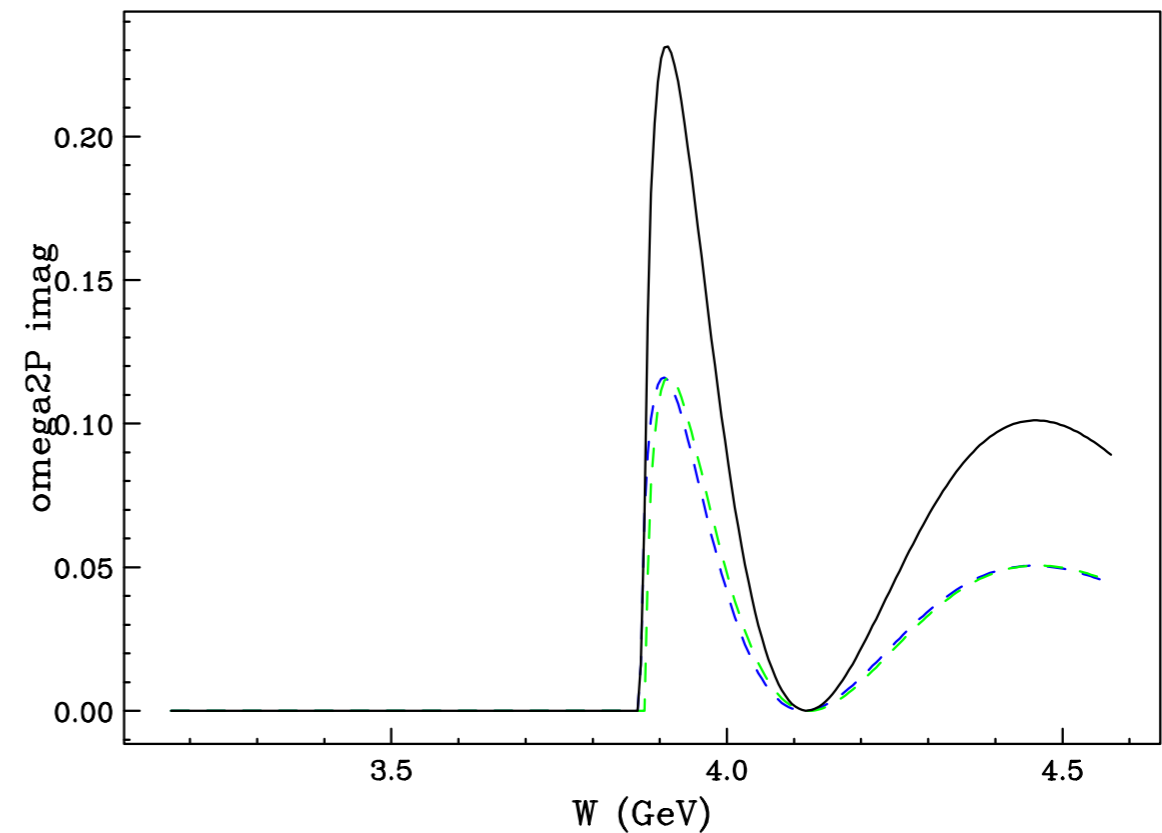
- 2 $^3P_1(c\bar{c})$

  - Strong S-wave decay

  - Large width attained quickly
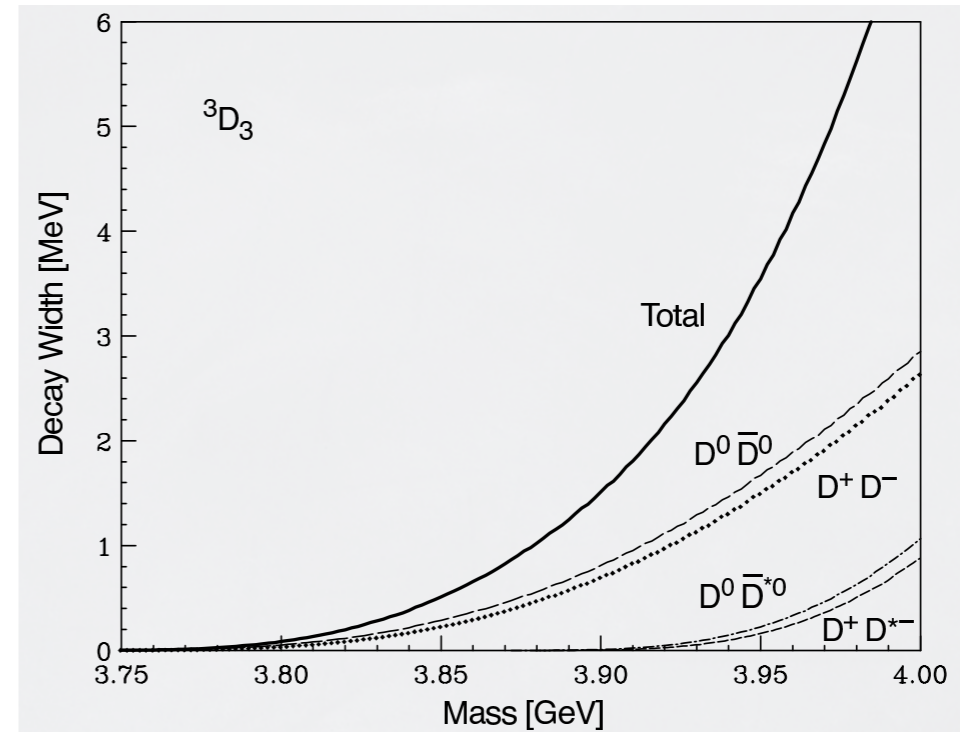
$\Gamma(\text{GeV})$

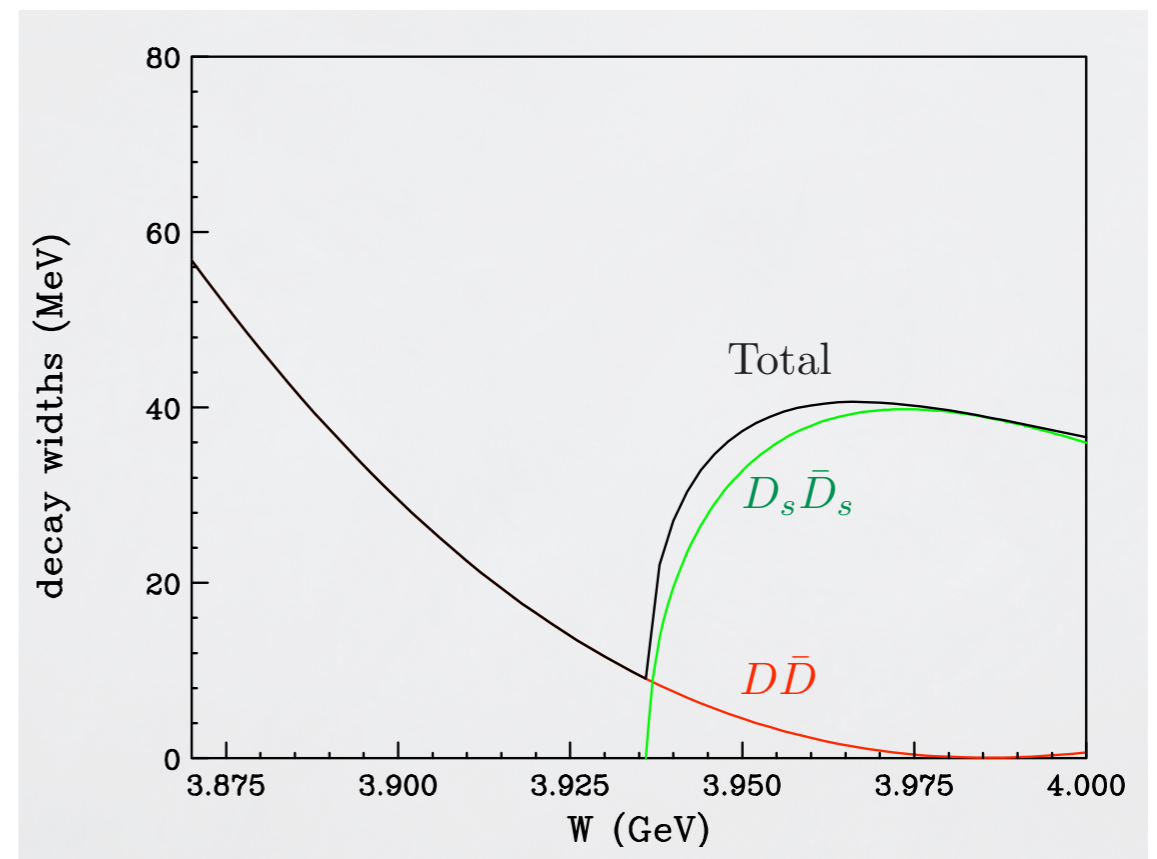$\Gamma(\text{GeV})$

Other Decay Structures

- 1 $^3D_3$ (cc)

  - very small decay width

  - How to observe?

- 2^3P_0 (cc)

  - wide state but complex structure in line shape.

  - $M(D_s^+ + D_s^-) = 3{,}937$ MeV

  - large SU(3) breaking

  - hadronic transitions observable near dip.

- Decays Near Threshold in e+e-

Partial Wave (L) of Two Body Decay to Heavy-Light Meson Pairs

$[n^3S_1]$	$j_l^P=1/2^-$	$j_l^P=1/2^+$	$j_l^P=3/2^+$	$j_l^P=3/2^-$	$j_l^P=5/2^-$
$j_l^P=1/2^-$	L=1	L=0	L=2	L=1	-
$j_l^P=1/2^+$	L=0	L=1	L=1	L=2	-
$j_l^P=3/2^+$	L=2	L=1	L=1,3	L=0,2	L=1,3
$j_l^P=3/2^-$	L=1	L=2	L=0,2	L=1,3	L=2,4
$j_l^P=5/2^-$	-	-	L=1,3	L=2,4	L=1,3,5

$[n^3D_1]$	$j_l^P=1/2^-$	$j_l^P=1/2^+$	$j_l^P=3/2^+$	$j_l^P=3/2^-$	$j_l^P=5/2^-$
$j_l^P=1/2^-$	L=1,3	L=2	L=0,2,4	L=1,3	L=1,3,5
$j_l^P=1/2^+$	L=2	L=1,3	L=1,3	L=0,2,4	L=0,2,4
$j_l^P=3/2^+$	L=0,2,4	L=1,3	L=1,3,5	L=0,2,4	L=0,2,4,6
$j_l^P=3/2^-$	L=1,3	L=0,2,4	L=0,2,4	L=1,3,5	L=1,3,5
$j_l^P=5/2^-$	L=1,3,5	L=0,2,4	L=0,2,	L=1,3,5	L=1,3,

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- Ψ(3S) in exclusive channels (2006 CCM)
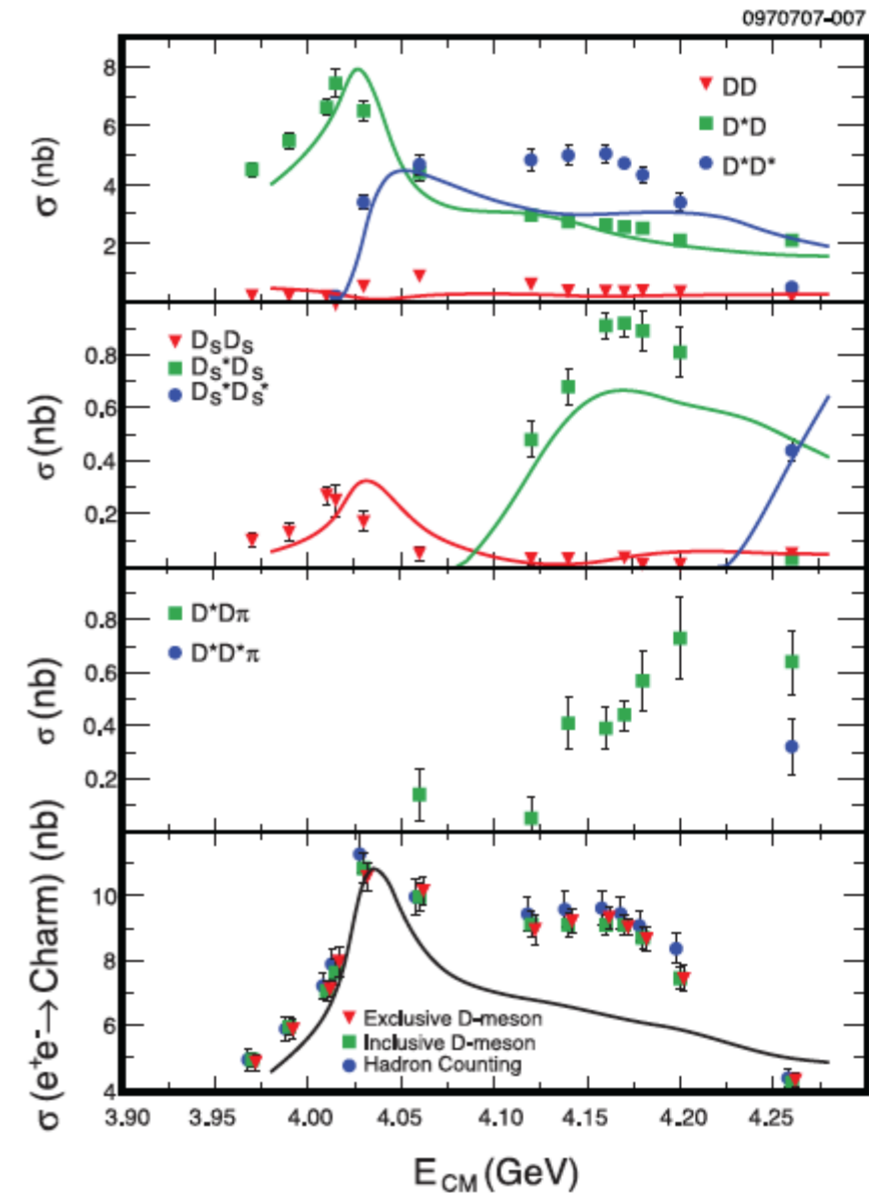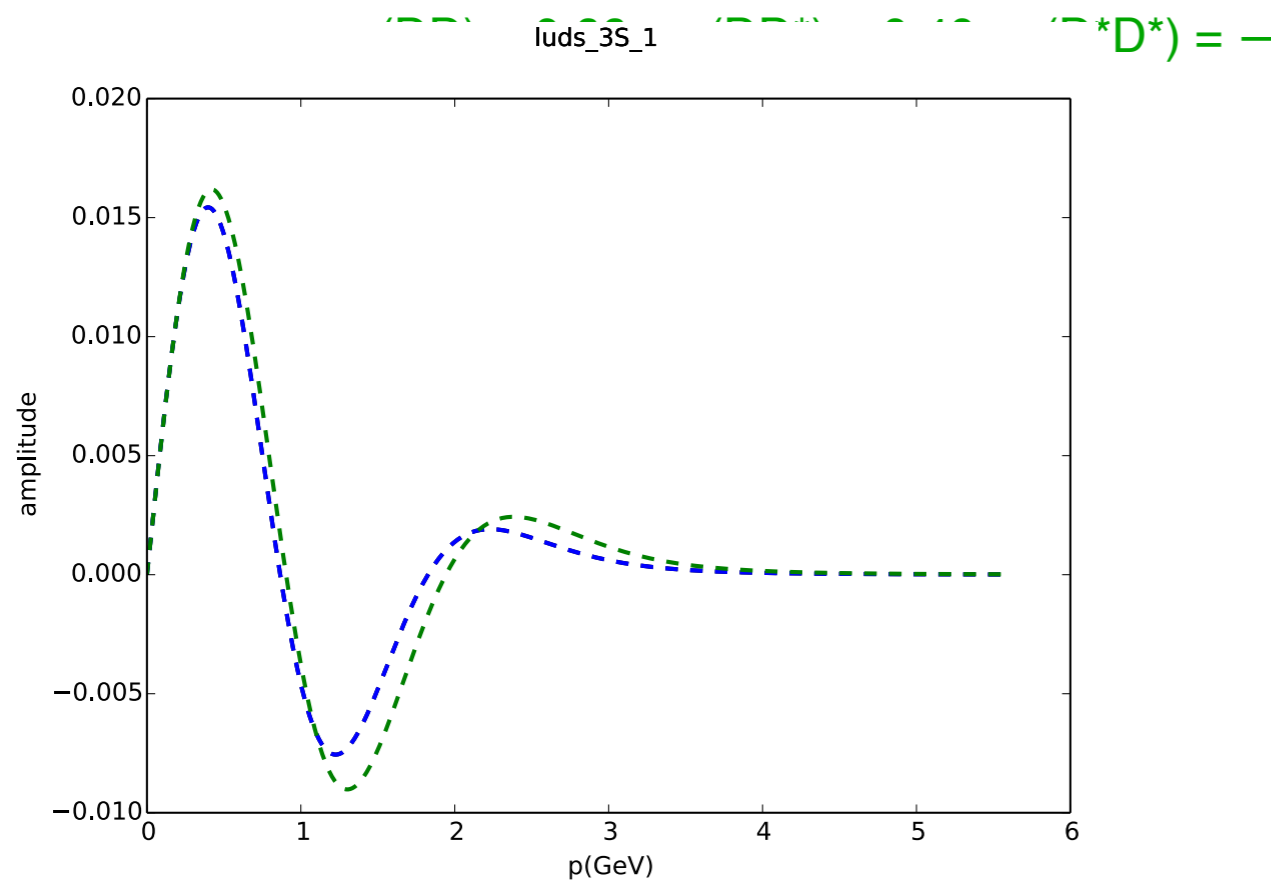
  - At 4.04 GeV:

    - p(DD) = 0.77 ; p(DD*) = 0.57 ; p(D*D*) = 0.20

  - At 4.00 GeV:

    - p(DD) = 0.72 ; p(DD*) = 0.49 ; p(D*D*) = 0.0

  - At 3.96 GeV:

    (DD) — 0.68   (DD*) — 0.40   (D*D*) = —
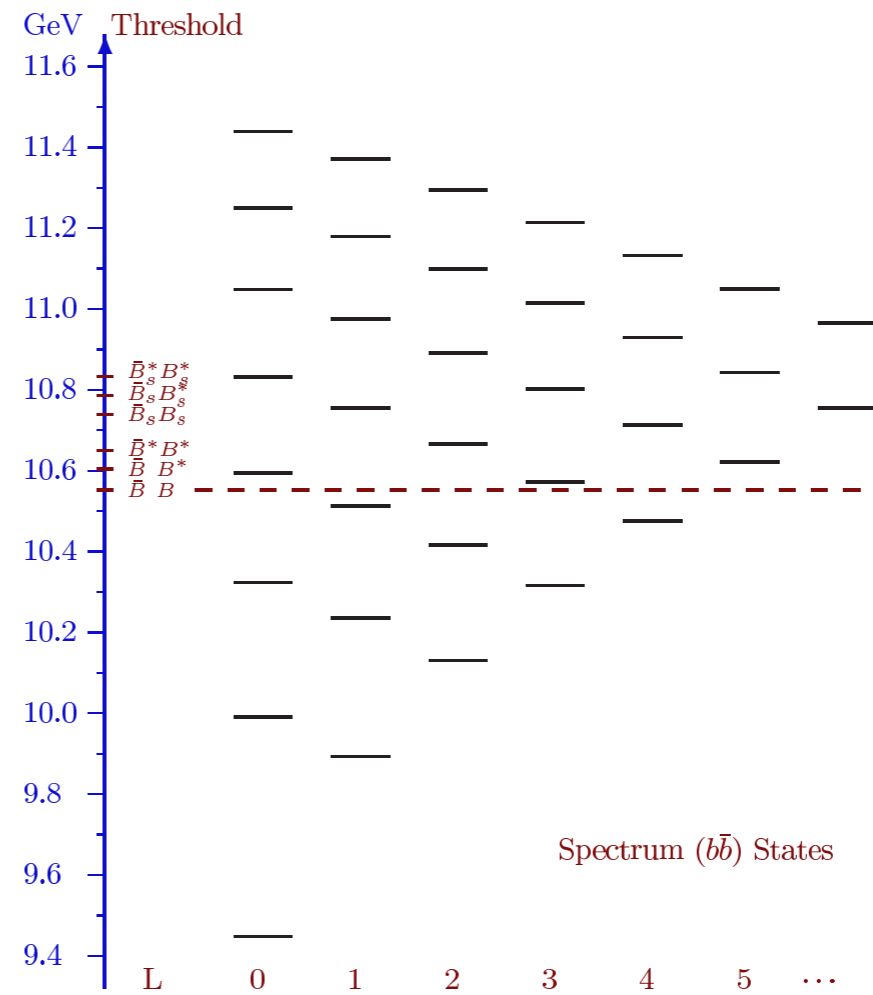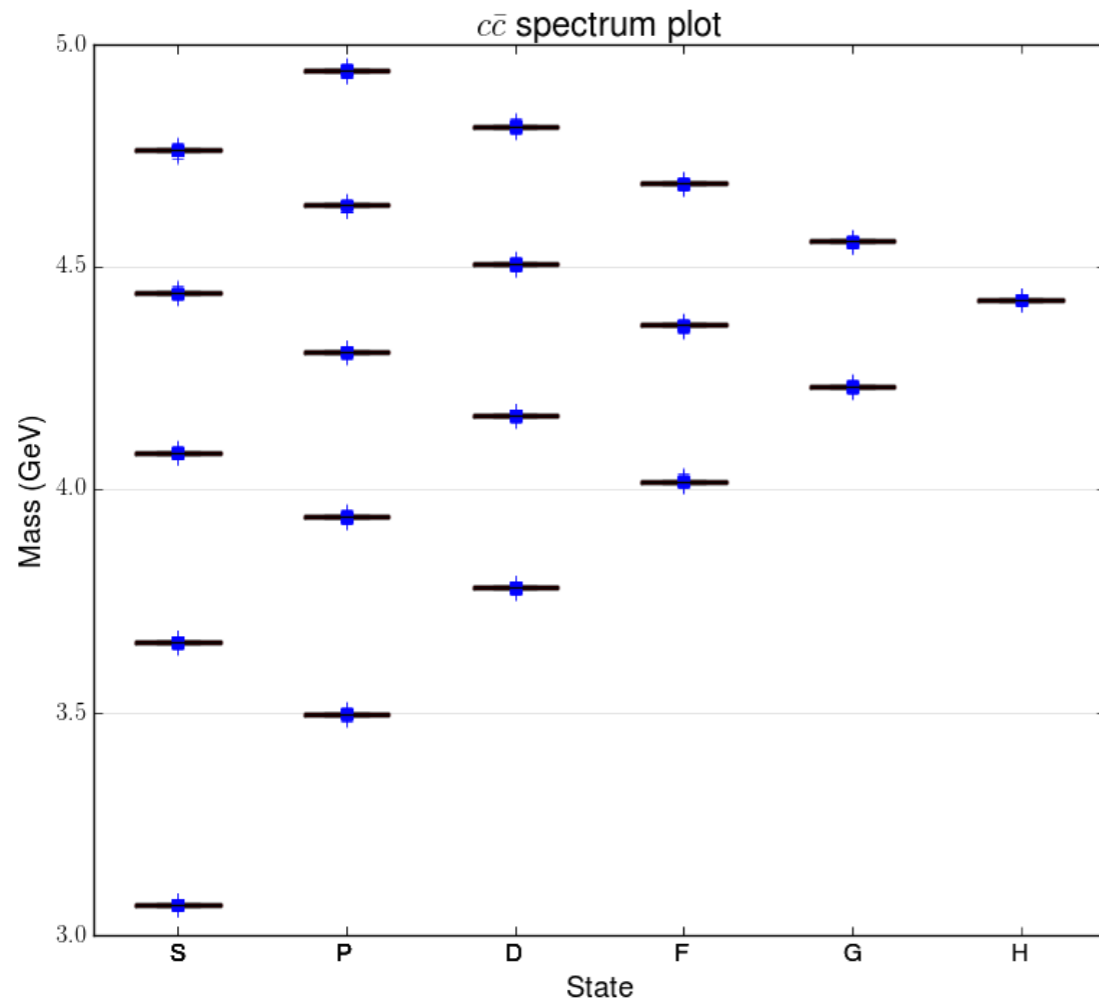
luds_3S_1

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Decay Couplings

TABLE II: Statistical recoupling coefficients C, defined by Eq. D19 of Ref. [10], that enter the calculation of charmonium decays to pairs of charmed mesons. Paired entries correspond to $\ell = L - 1$ and $\ell = L + 1$.

State	$D\bar{D}$	$D\bar{D}^*$	$D^*\bar{D}^*$
$^1S_0$	$-:0$	$-:2$	$-:2$
$^3S_1$	$-:\frac{1}{3}$	$-:\frac{4}{3}$	$-:\frac{7}{3}$
$^3P_0$	$1:0$	$0:0$	$\frac{1}{3}:\frac{8}{3}$
$^3P_1$	$0:0$	$\frac{4}{3}:\frac{2}{3}$	$0:2$
$^1P_1$	$0:0$	$\frac{2}{3}:\frac{4}{3}$	$\frac{2}{3}:\frac{4}{3}$
$^3P_2$	$0:\frac{2}{5}$	$0:\frac{6}{5}$	$\frac{4}{3}:\frac{16}{15}$
$^3D_1$	$\frac{2}{3}:0$	$\frac{2}{3}:0$	$\frac{4}{15}:\frac{12}{5}$
$^3D_2$	$0:0$	$\frac{6}{5}:\frac{4}{5}$	$\frac{2}{5}:\frac{8}{5}$
$^1D_2$	$0:0$	$\frac{4}{5}:\frac{6}{5}$	$\frac{4}{5}:\frac{6}{5}$
$^3D_3$	$0:\frac{3}{7}$	$0:\frac{8}{7}$	$\frac{8}{5}:\frac{29}{35}$
$^3F_2$	$\frac{3}{5}:0$	$\frac{4}{5}:0$	$\frac{11}{35}:\frac{16}{7}$
$^3F_3$	$0:0$	$\frac{8}{7}:\frac{6}{7}$	$\frac{4}{7}:\frac{10}{7}$
$^1F_3$	$0:0$	$\frac{6}{7}:\frac{8}{7}$	$\frac{6}{7}:\frac{8}{7}$
$^3F_4$	$0:\frac{4}{9}$	$0:\frac{10}{9}$	$\frac{12}{7}:\frac{46}{63}$
$^3G_3$	$\frac{4}{7}:0$	$\frac{6}{7}:0$	$\frac{22}{63}:\frac{20}{9}$
$^3G_4$	$0:0$	$\frac{10}{9}:\frac{8}{9}$	$\frac{2}{3}:\frac{4}{3}$
$^1G_4$	$0:0$	$\frac{8}{9}:\frac{10}{9}$	$\frac{8}{9}:\frac{10}{9}$
$^3G_5$	$0:\frac{5}{11}$	$0:\frac{12}{11}$	$\frac{16}{9}:\frac{67}{99}$

Potential model states

Transitions

Transition	Γ_{partial} (keV) (Experiment)	Γ_{partial} (keV) (KY Model)
$\psi(2S)$		
$\to J/\psi + \pi^+\pi^-$	102.3 ± 3.4	input $(|C_1|)$
$\to J/\psi + \eta$	10.0 ± 0.4	input (C_3/C_1)
$\to J/\psi + \pi^0$	0.411 ± 0.030 [446]	0.64 [522]
$\to h_c(1P) + \pi^0$	0.26 ± 0.05 [47]	$0.12\text{-}0.40$ [527]
$\psi(3770)$		
$\to J/\psi + \pi^+\pi^-$	52.7 ± 7.9	input (C_2/C_1)
$\to J/\psi + \eta$	24 ± 11	
$\Upsilon(2S)$		
$\to \Upsilon(1S) + \pi^+\pi^-$	5.79 ± 0.49	8.7 [528]
$\to \Upsilon(1S) + \eta$	$(6.7 \pm 2.4) \times 10^{-3}$	0.025 [521]
$\Upsilon(1^3D_2)$		
$\to \Upsilon(1S) + \pi^+\pi^-$	0.188 ± 0.046 [63]	0.07 [529]
$\chi_{b1}(2P)$		
$\to \chi_{b1}(1P) + \pi^+\pi^-$	0.83 ± 0.33 [523]	0.54 [530]
$\to \Upsilon(1S) + \omega$	1.56 ± 0.46	
$\chi_{b2}(2P)$		
$\to \chi_{b2}(1P) + \pi^+\pi^-$	0.83 ± 0.31 [523]	0.54 [530]
$\to \Upsilon(1S) + \omega$	1.52 ± 0.49	
$\Upsilon(3S)$		
$\to \Upsilon(1S) + \pi^+\pi^-$	0.894 ± 0.084	1.85 [528]
$\to \Upsilon(1S) + \eta$	$< 3.7 \times 10^{-3}$	0.012 [521]
$\to \Upsilon(2S) + \pi^+\pi^-$	0.498 ± 0.065	0.86 [528]
$\Upsilon(4S)$		
$\to \Upsilon(1S) + \pi^+\pi^-$	1.64 ± 0.25	4.1 [528]
$\to \Upsilon(1S) + \eta$	4.02 ± 0.54	
$\to \Upsilon(2S) + \pi^+\pi^-$	1.76 ± 0.34	1.4 [528]

Heavy quarkonium: progress, puzzles, and opportunities
N. Brambilla et.al. [arXiv:1010.5827]

- Putting the ends together

- Toy model - minimal parameters

$$V_n(R) = \frac{\alpha_s}{6R} + \sigma R \sqrt{1 + \frac{2\pi}{\sigma R^2}\left(n(R) - \frac{1}{24}(d-2)\right)} + V_0 \quad (n > 0)$$

$$V_{\Sigma_g^+}(R) = -\frac{4\alpha_s}{3R} + \sigma R + V_0 \quad (n = 0)$$

Fixes Mc = 1.84 GeV, √σ = .427 GeV, α_s = 0.39

n(R) = [n] (string level) if no level crossing
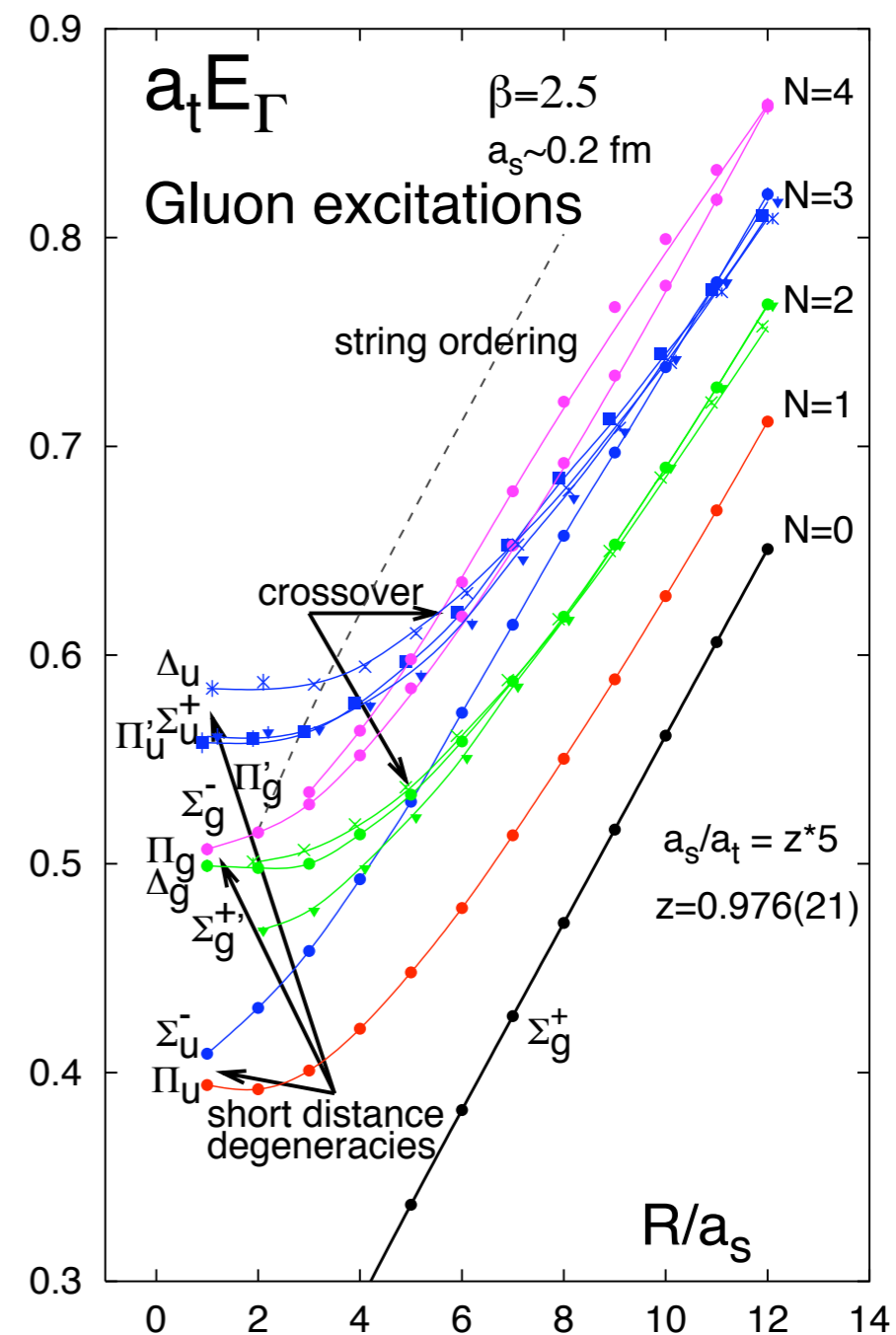
[n – 2 tanh(R₀/R)] for Σ_u potential (n=3)

FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.
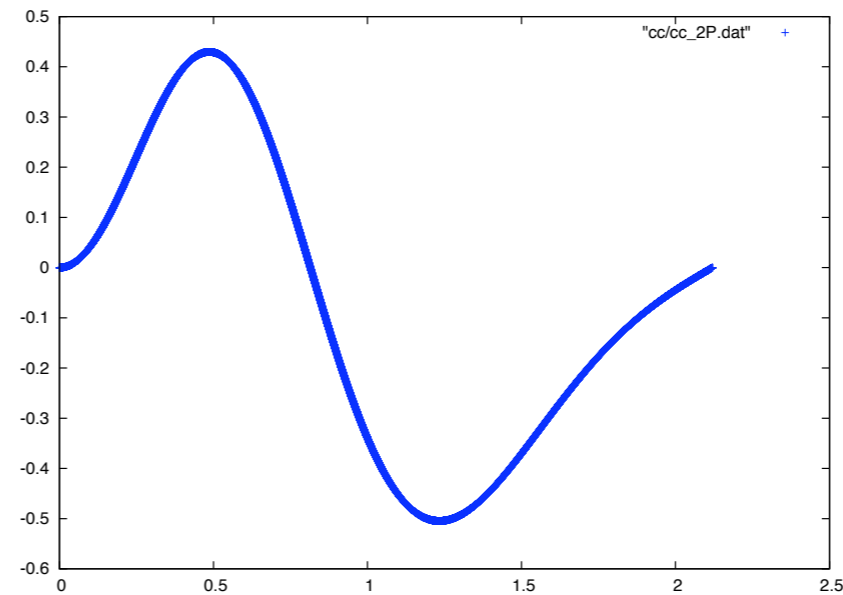
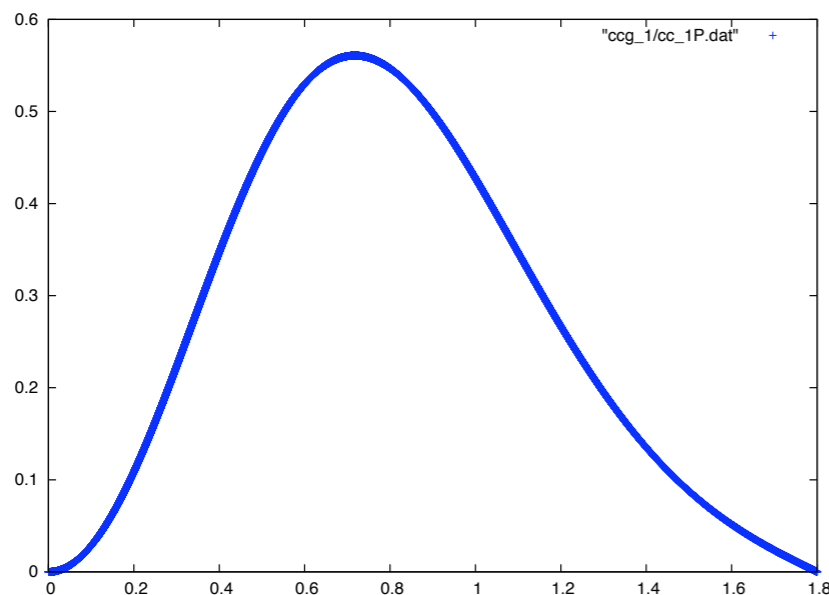# Spectrum of Low-Lying Hybrid States

- Only interested in states below 4.8 GeV for cc system.

  Unlikely higher states will be narrow (DD, glueball+J/ψ, *etc*)
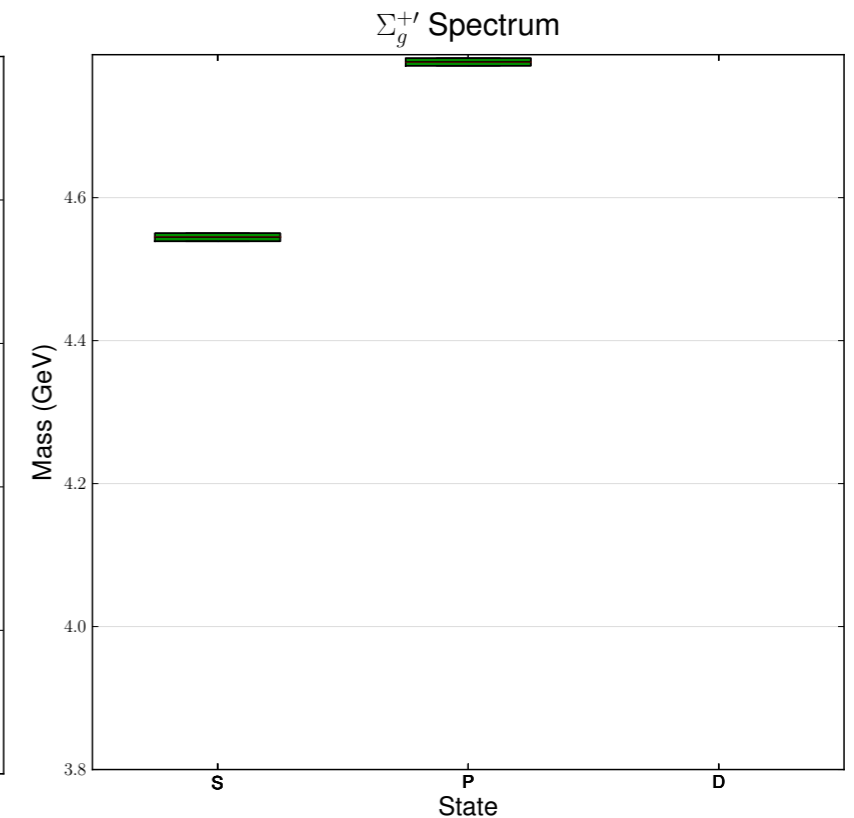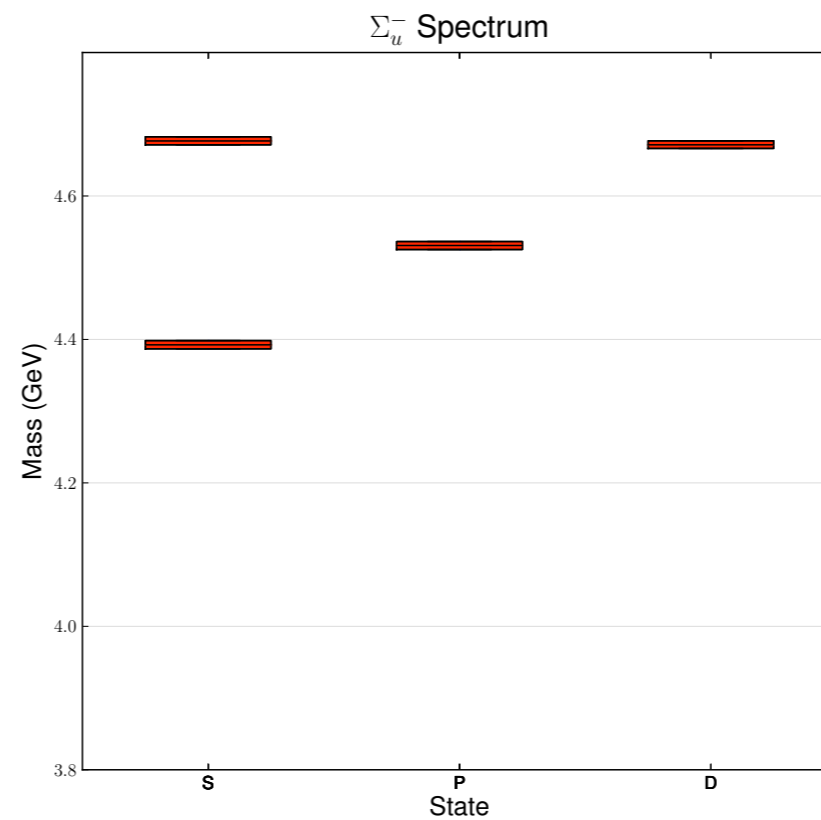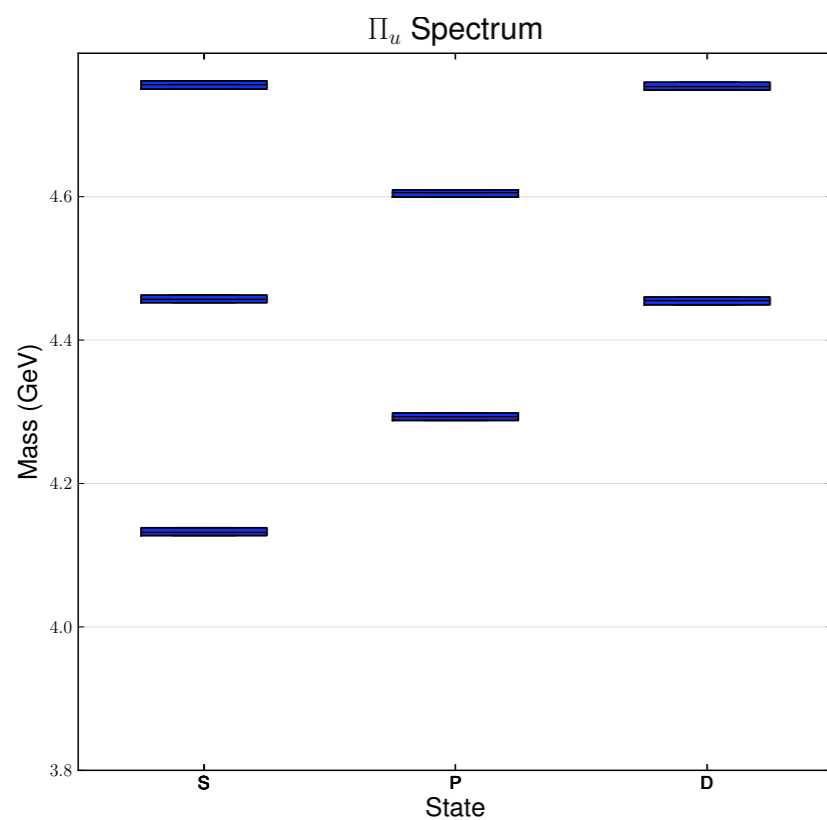
- Only Π_u, Σ_u^-, and $\Sigma_g^{+'}$ systems have sufficiently light states.

Spectrum of Low-Lying Hybrid States

- Π_u (1S)   m = 4.132 GeV Π_u (2S)   m = 4.465 GeV $J^{PC} = 0^{++}, 0^{--}, 1^{+-}, 1^{-+}$

  Π_u (1P)   m = 4.445 GeV Π_u (2P)   m = 4.773 GeV $J^{PC} = 1^{--}, 1^{++}, 0^{-+}, 0^{+-}, 1^{+-}, 1^{-+}, 2^{+-}, 2^{-+}$

- $\Sigma_g^{+\prime}$(1S)   m = 4.547 GeV $J^{PC} = 0^{-+}, 1^{--}$

- The Π_u (1P), Π_u (2P) and $\Sigma_g^{+\prime}$(1S) have 1^{--} states with spacing seen in the Y(4260) system

- Σ_u^{-}(1S)   m = 4.292 GeV Σ_u^{-}(1P)   m = 4.537 GeV Σ_u^{-}(2S)   m = 4.772 GeV

- Numerous states with C=+ in the 4.2 GeV region.

Spectrum of Low-Lying Hybrid States

- The spectrum of bottomonium hybrids is completely predicted as well

- For the Π_u states

(cc)	L	n	mass(GeV)
	0	1	4.132580
	0	2	4.454556
	0	3	4.752947
	0	4	5.032962
	0	5	5.298250
	0	6	5.551412
✓	1	1	4.293717
	1	2	4.604123
	1	3	4.893249
	1	4	5.165793
	1	5	5.424925
	2	1	4.454768
	2	2	4.753368
	2	3	5.033384

(bb)	L	n	mass(GeV)
	0	1	10.783900
	0	2	10.982855
	0	3	11.172408
	0	4	11.353469
	0	5	11.527274
	0	6	11.694851
	0	7	11.856977
	0	8	12.014256
✓	1	1	10.877928
	1	2	11.073672
	1	3	11.259766
	1	4	11.437735
	1	5	11.608810
	1	6	11.773931
	1	7	11.933823
	2	1	10.976071
	2	2	11.167070
	2	3	11.349124
	2	4	11.523652
	2	5	11.691737
	2	6	11.854216

Systematics: Other States

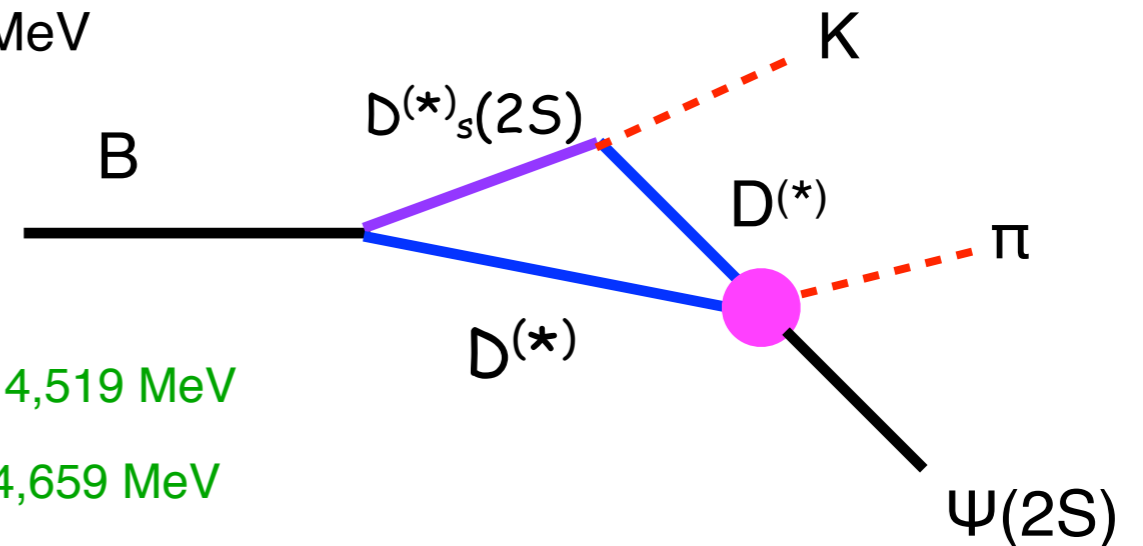- Same mechanism in B-decays with $2S_{\{0,1\}}(D_s)$ states: $Z^+(4430)$ P. Pakhlov [arXiv:1105.2945]

  - $D_s^*(2S)$ M = 2,709 ± 4 MeV   Γ = 117 ± 13 MeV

  - $D_s(2S)$ M = 2,610-2660 MeV

  - Relevant open thresholds:

    - M(D D(2S)) = 4,449 MeV;   M(D D*(2S)) = 4,519 MeV

    - M(D*D(2S)) = 4,586 MeV;   M(D*D*(2S)) = 4,659 MeV

P. Pakhlov and T. Uglov

[arXiv:1408.5295]