Lecture 2: Crossing the Threshold

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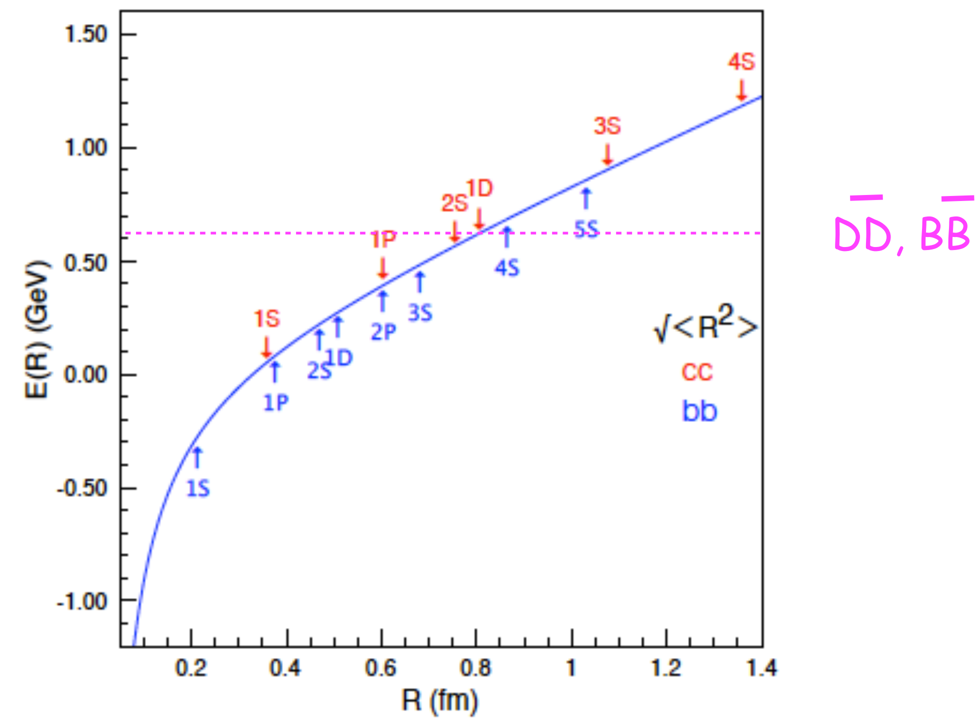
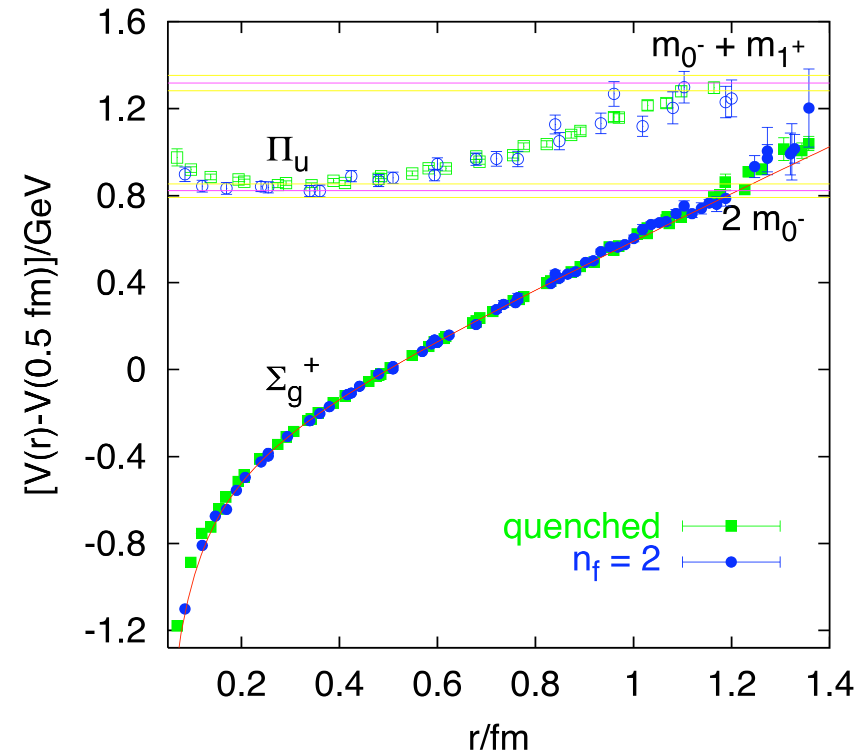
- QCD Dynamics Above Thresholds
  - Coupling to H-L meson pairs
  - New States possible: Hybrids, 4Q
- Effects On Hadronic Transitions
  - Unexpectedly large rates.
  - Understanding HSQ and SU(3) violations
- New Approach Above Threshold
  - A possible new factorization.
  - Systematics and expectations.

The Threshold Region

- 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 $r \approx 1.2$ 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.

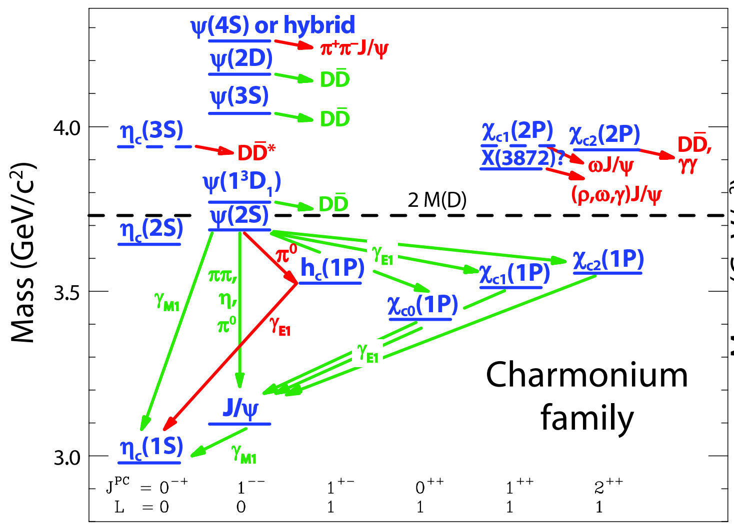
Cornell
Potential Model

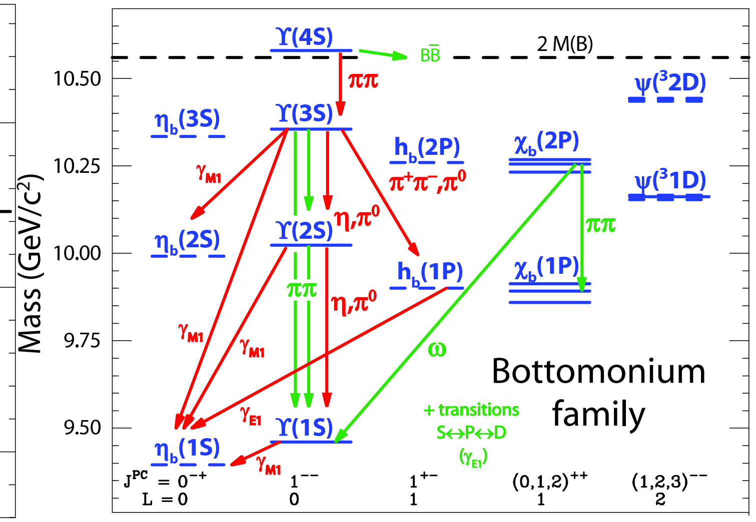




QCD Multipole Expansion

- Below threshold this theory 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 it is for the usual EM transitions in non-relativistic systems).
- Isospin breaking is suppressed.
- A few puzzles remain.

N. Brambilla, et al.,Eur.Phys.J. C71 (2011) 1534

Transition	$\Gamma_{\rm partial}$ (keV) (Experiment)	$\Gamma_{\rm partial}$ (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]	0.12-0.40 [527]
$\psi(3770)$		
$\to J/\psi + \pi^+\pi^-$	52.7 ± 7.9	input (C_2/C_1)
$\to J/\psi + \eta$	24 ± 11	
$\psi(3S)$		
$\to J/\psi + \pi^+\pi^-$	< 320 (90% CL)	
$\Upsilon(2S)$		
$\to \Upsilon(1S) + \pi^+\pi^-$	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]

η Transitions

- QCDME
  - E1-M2 dominates:

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

α_{AB}^{EE} $\quad$ $: i(2\pi)^{3/2}C_3 q_k$

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

$$R_{Q\bar{Q}}(n \to m) \equiv \frac{\Gamma(n^3S_1 \to m^3S_1 + \eta)}{\Gamma(n^3S_1 \to m^3S_1 + \pi^+\pi^-)} = \frac{8\pi^2}{27}\frac{1}{m_Q^2}(\frac{C_3}{C_1})^2[\frac{[(M_i+M_f)^2 - M_\eta^2)((M_i-M_f)^2 - M_\eta^2)]^{3/2}}{G}]$$

is independent of the details of the intermediate states. [kinematic factor]

  - Comparing theory (KY model) and experiment.

Ratio	theory	experiment
$R^{c\bar{c}}(2 \to 1)$	3.29×10^{-3}	9.78×10^{-2}
$R^{b\bar{b}}(2 \to 1)$	1.16×10^{-3}	1.16×10^{-3}
$R^{b\bar{b}}(3 \to 1)$	4.57×10^{-3}	$< 4.13 \times 10^{-3}$
$R^{b\bar{b}}(4 \to 1)$	2.23×10^{-3}	2.45
$R^{b\bar{b}}(4 \to 2)$	5.28×10^{-4}	

~ 30 > theory
sets $C_3/C_1 = 0.143 \pm 0.024$
related to ππ suppression

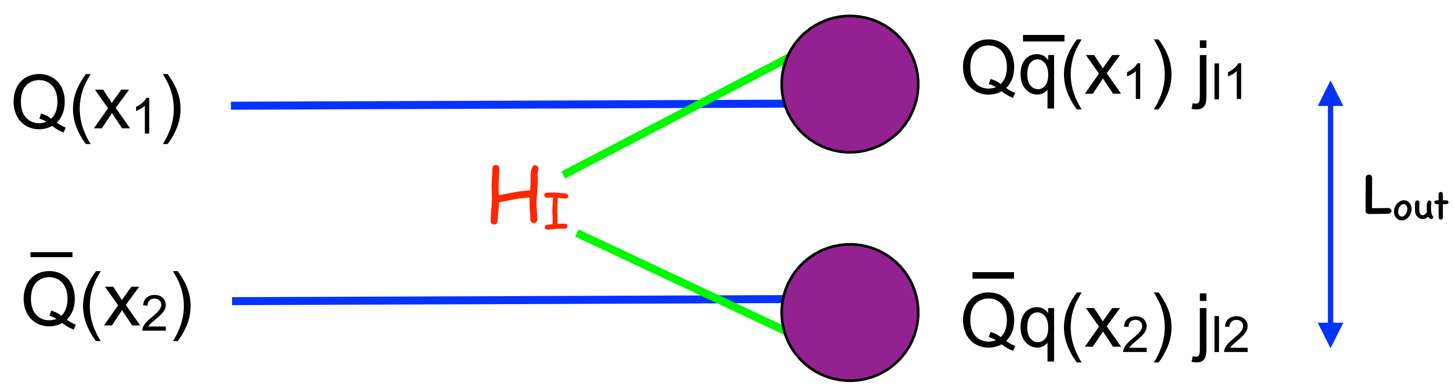
~ 1000 > theory

  - 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.

The Threshold Region

- Three effects of including light quark pairs on the properties of quarkonium states.
  - Strong decay channels open up.

First



  - For heavy light mesons: $J = S_Q + j_l$, where is the total angular momentum of the light degrees of freedom $j_l = s_q + l_q$
  - The heavy-light ground state $j_l^P = \frac{1}{2}^-$ mesons are:

D masses (GeV)		B masses (GeV)	
D^0 = 1.8649	4.77 MeV	B^0 = 5.2796	-0.32 MeV
D^+ = 1.8696		B^+ = 5.2793	
D^{*0} = 2.0070		B^{*0} = 5.3248	
D^{*+} = 2.0103		B^{*+} = 5.3248	
D_s = 1.9683		B_s = 5.3668	
D_s^* = 2.1121		B_s^* = 5.4154	

Heavy-Light mesons

- The low-lying spectrum for heavy-light mesons

$\bar{H}_L^j = (Qq)(L,j)$

$H_d^{5/2} = \{H_d(2^-), H_d(3^-)\}$

$H_d^{3/2} = \{H_d(1^-), H_d(2^-)\}$

$H'^{1/2}_s = \{H'_s(0^-), H'^*_s(1^-)\}$

$H_P^{3/2} = \{H(1^+), H(2^+)\}$

$H_P^{1/2} = \{H(0^+), H(1^+)\}$

$H_s^{1/2} = \{H_s(0^-), H^*_s(1^-)\}$

- The doublet degeneracy is split by $1/m_Q$ terms:

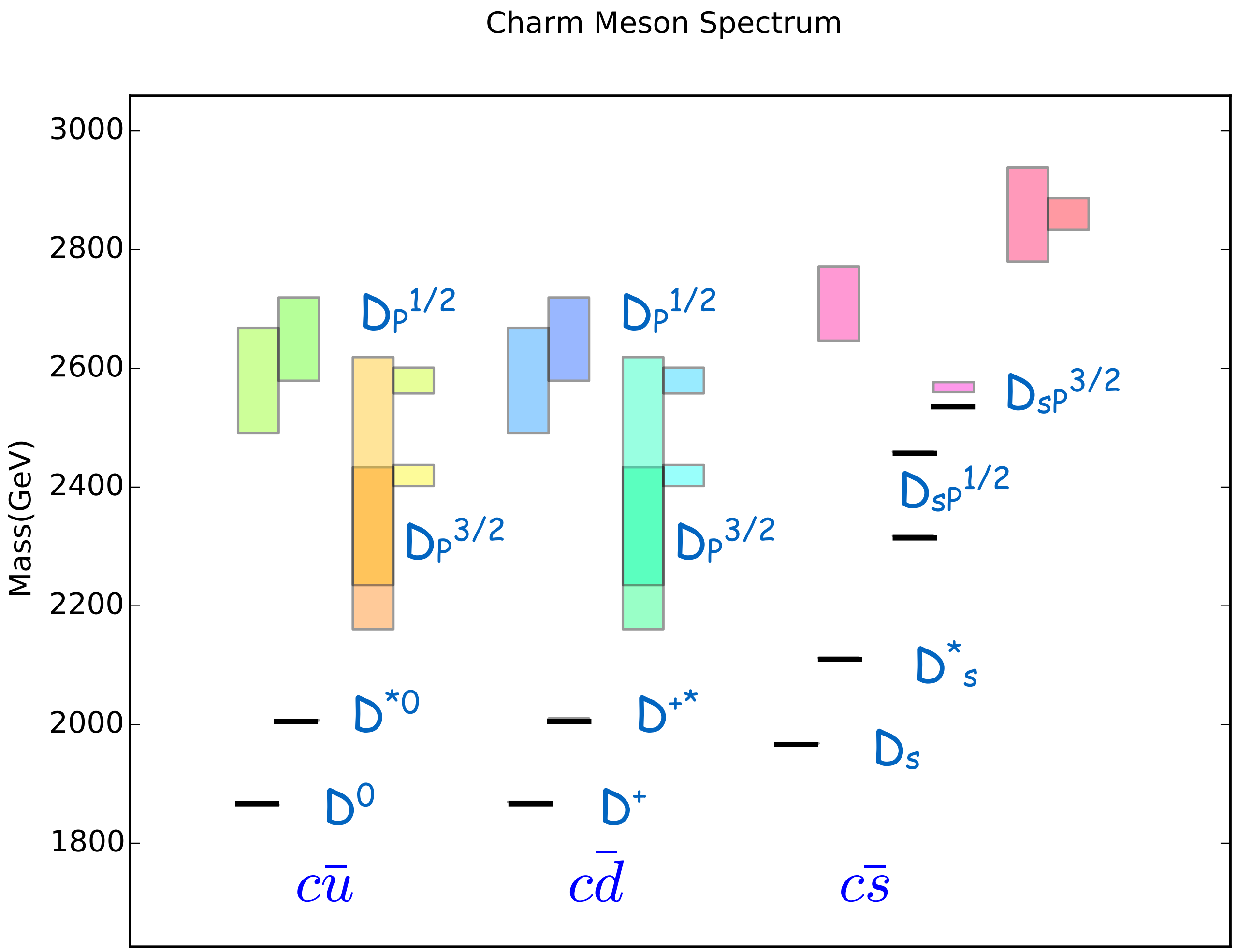
$H_L^j \rightarrow$ $H_L([J=j+1/2]^P)$, $H_L([J=j-1/2]^P)$

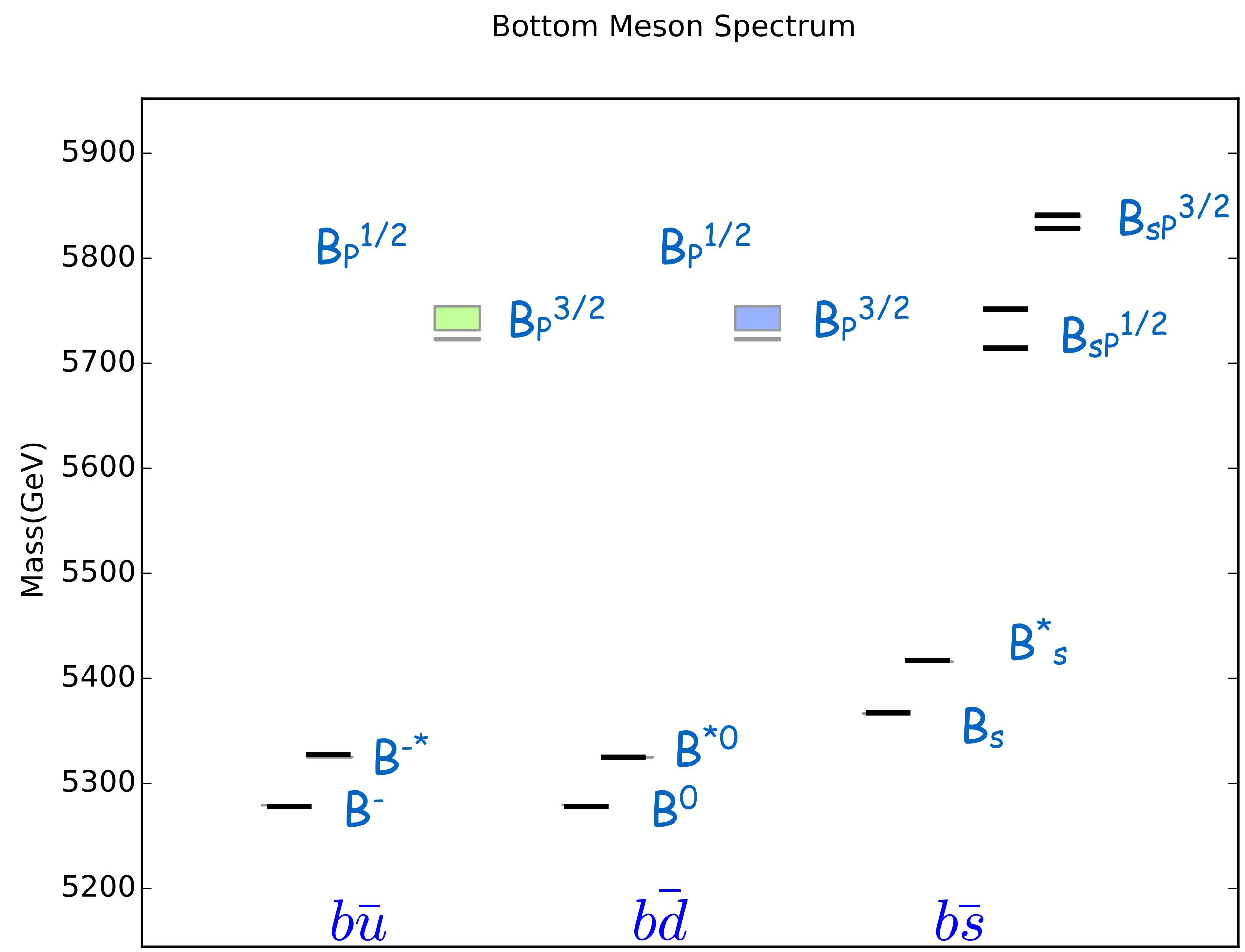
- Transition branching ratios $H_1 \to H_2 + (\pi, K, \ldots)$ predicted by HQET

M. Di Pierro and E. Eichten, Phys. Rev. D **64**, 114004 (2001).

Heavy-Light Mesons

- Observed low-lying (1S, 1P, and 1D) charm and bottom mesons:
  - Very similar excitation spectrum - HQS





  - 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 P states: $j_l^P = 1/2^+$ can be wide, while the $j_l^P = 3/2^+$ are narrow
  - The wide states can originate sequential decay chains.

- For example, the two body charmed meson threshold in e+e- channel

Narrow Thresholds

$D\bar{D}$	$3729.7(+9.56)$	P-wave
$D\bar{D}^* + D^*\bar{D}$	$3,871.8(+8.08)$	P-wave
$D_s\bar{D}_s$	$3,937.0$	P-wave
$D^*\bar{D}^*$	$4,013.9(+6.6)$	P-wave
$D_s\bar{D}_s^* + \bar{D}_s D_s^*$	$4,080.8$	
$D_s^*\bar{D}_s^*$	$4,224.6$	
$D\bar{D}(1^+) + D(1^+)\bar{D}$	$4,287.1(+5.9)$	D-wave
$D\bar{D}(2^+) + D(2^+)\bar{D}$	$4,325.9(+3.8)$	D-wave
$D^*\bar{D}(1^+) + D(1^+)\bar{D}^*$	$4,429.3(+4.4)$	D-wave
$D^*\bar{D}(2^+) + D(2^+)\bar{D}^*$	$4,468.1(+2.3)$	
$D_s\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s$	$4,428.1$	S-wave
$D_s^*\bar{D}_s(0^+) + D_s(0^+)\bar{D}_s^*$	$4,430.1$	S-wave
$D_s^*\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s^*$	$4,571.9$	S-wave
$D_s\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s$	$4,540.9$	D-wave
$D_s\bar{D}_s(2^+) + D_s(2^+)\bar{D}_s$	$4,541.1$	D-wave
$D_s^*\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s^*$	$4,647.7$	D-wave
$D_s^*\bar{D}_s(2^+) + D_s(2^+)\bar{D}_s^*$	$4,684.9$	
...		

Broad Thresholds

*D*D(0+)*	4,270	S-wave
D D'(1+)	4,270	S-wave
*D*D'(1+)*	4,430	S-wave
...		

Threshold Formalism

- How to compute the decays of quarkonium states into pairs of heavy light mesons? (Zweig allowed strong decays)

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

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

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

Cornell model (CCCM)

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

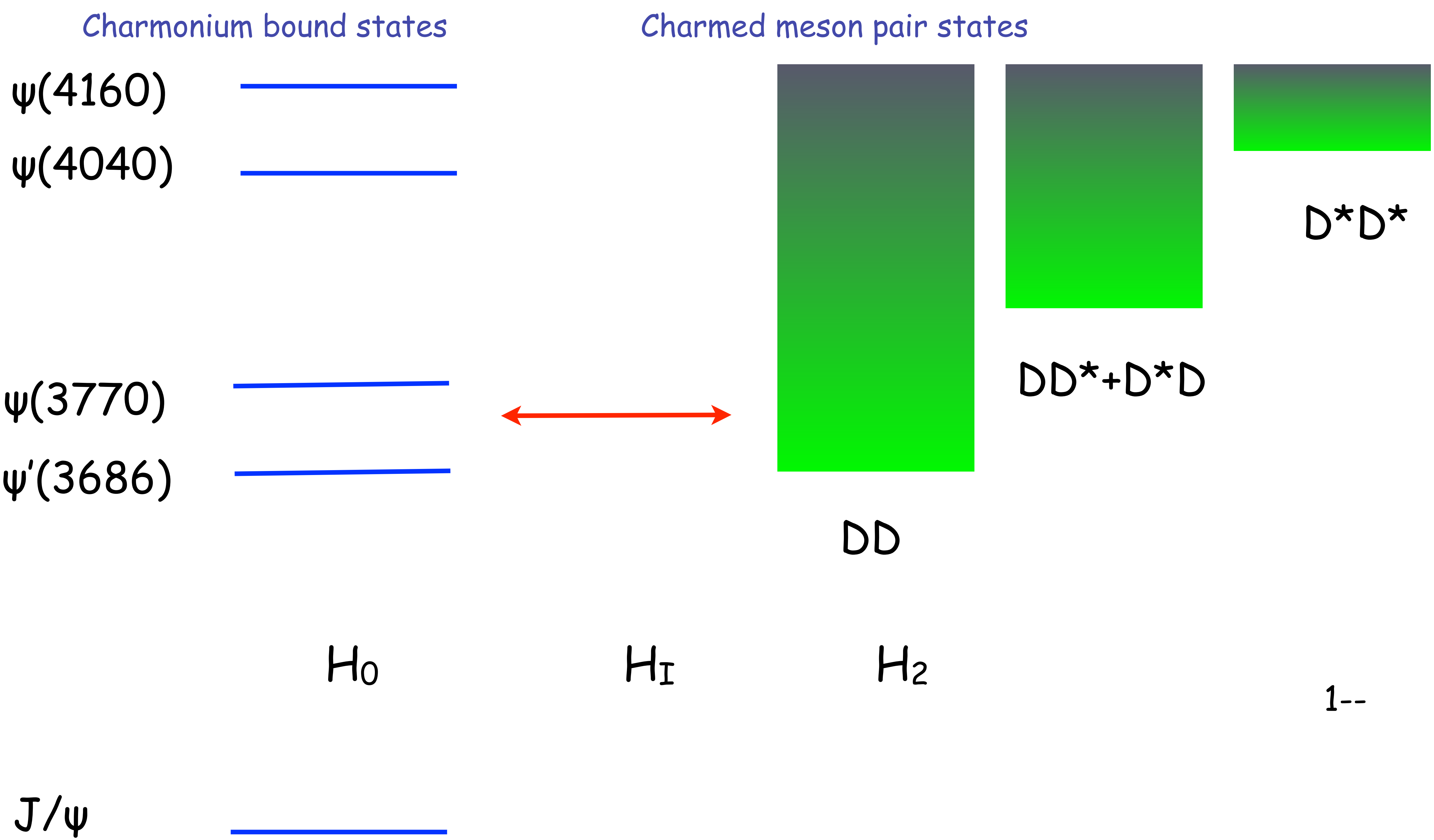
Vacuum Pair Creation model (QPC)

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

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

Threshold Formalism

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



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 $\langle DD|H_I|\psi\rangle$
- Simplifying assumptions
  - H_2 - free meson pairs no final state interactions
  - H_0 - charmonium states are a complete basis - no hybrids

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

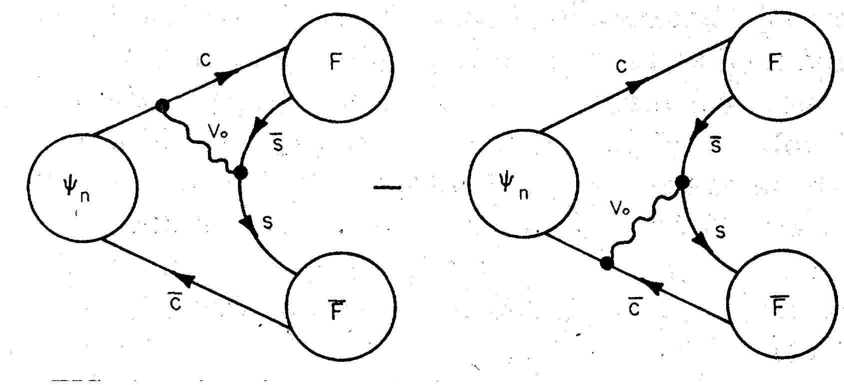
- Assuming vector meson dominance. Can compute R_c

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

Decay Amplitudes

- Cornell Coupled Channel Model
  - ψ_n potential model wavefunction
  - Final mesons:

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



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

where

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

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

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

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

where $$H^i_{nL,mL'}(P) = f^2 \sum_l C(JLL';l) I^l_{nL}(P) I^l_{mL'}(P)$$

Statistical factor, C

Reduced decay amplitudes I(p)

C

$H = (Q\bar{q})$

$H_s = \{H, H^*, H_s\}$

$H_P^{1/2} = \{H(0^+), H(1^+), H_s(0^+), H_s(1^+)\}$

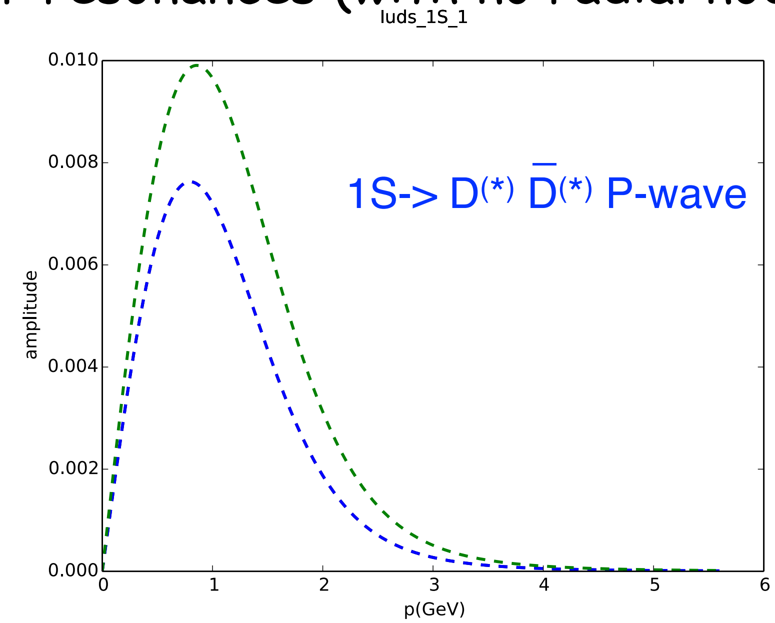
$H_P^{3/2} = \{H(1^+), H(2^+), H_s(1^+), H_s(2^+)\}$

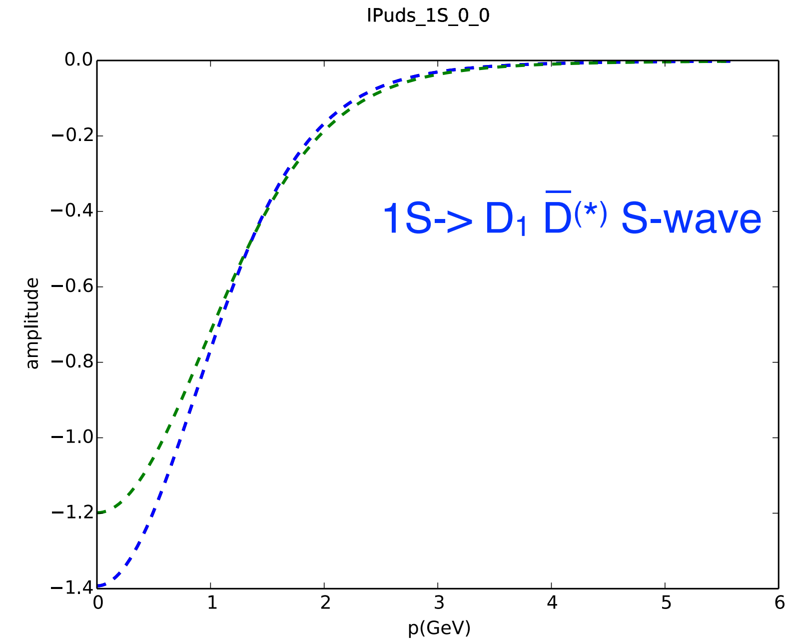
TABLE II: Statistical recoupling coefficients C, defined by Eq. D19 of Ref. [10], that enter the calculation of charmonium decays to pairs of charmed mesons. Paired entries correspond to $\ell = L - 1$ and $\ell = L + 1$.

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

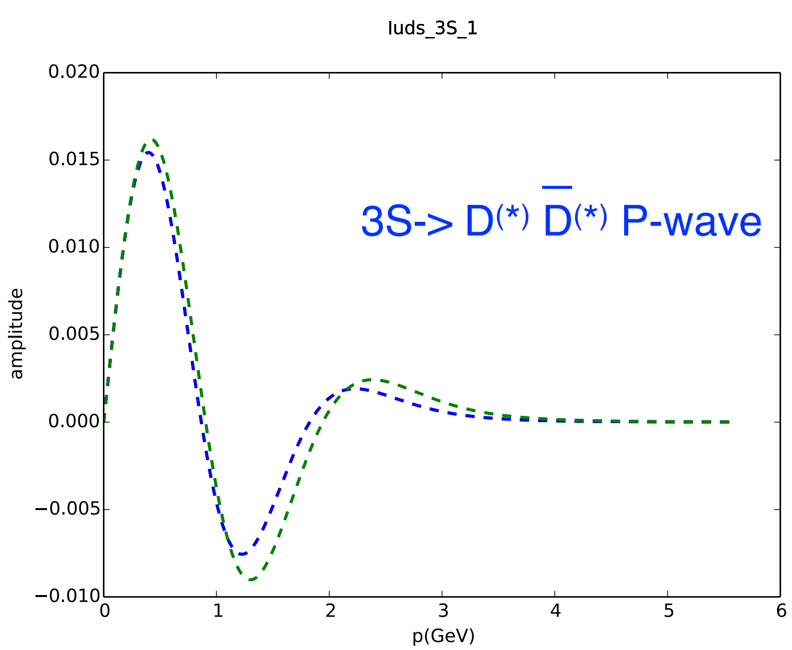
Complicated Decay Amplitudes

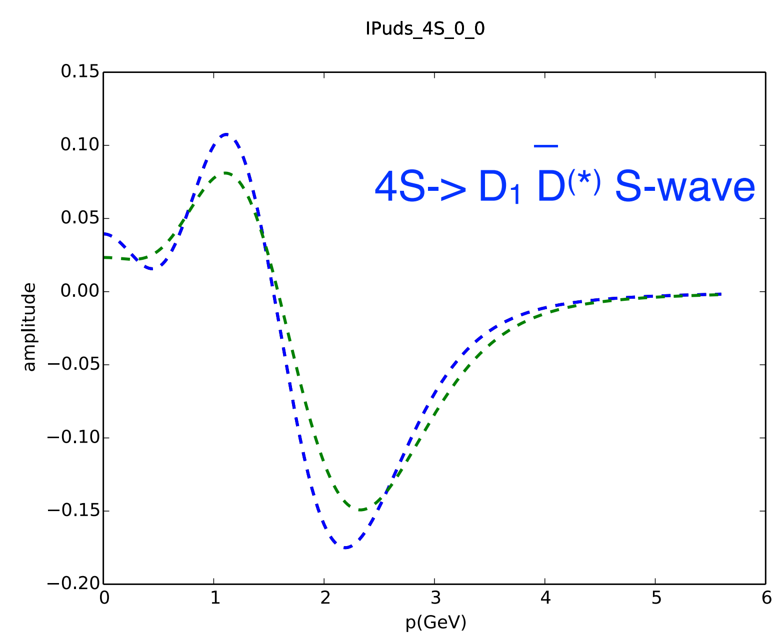
- For resonances (with no radial nodes) as expected:





- But complicated dependence on heavy-light momentum for radially excited resonances.

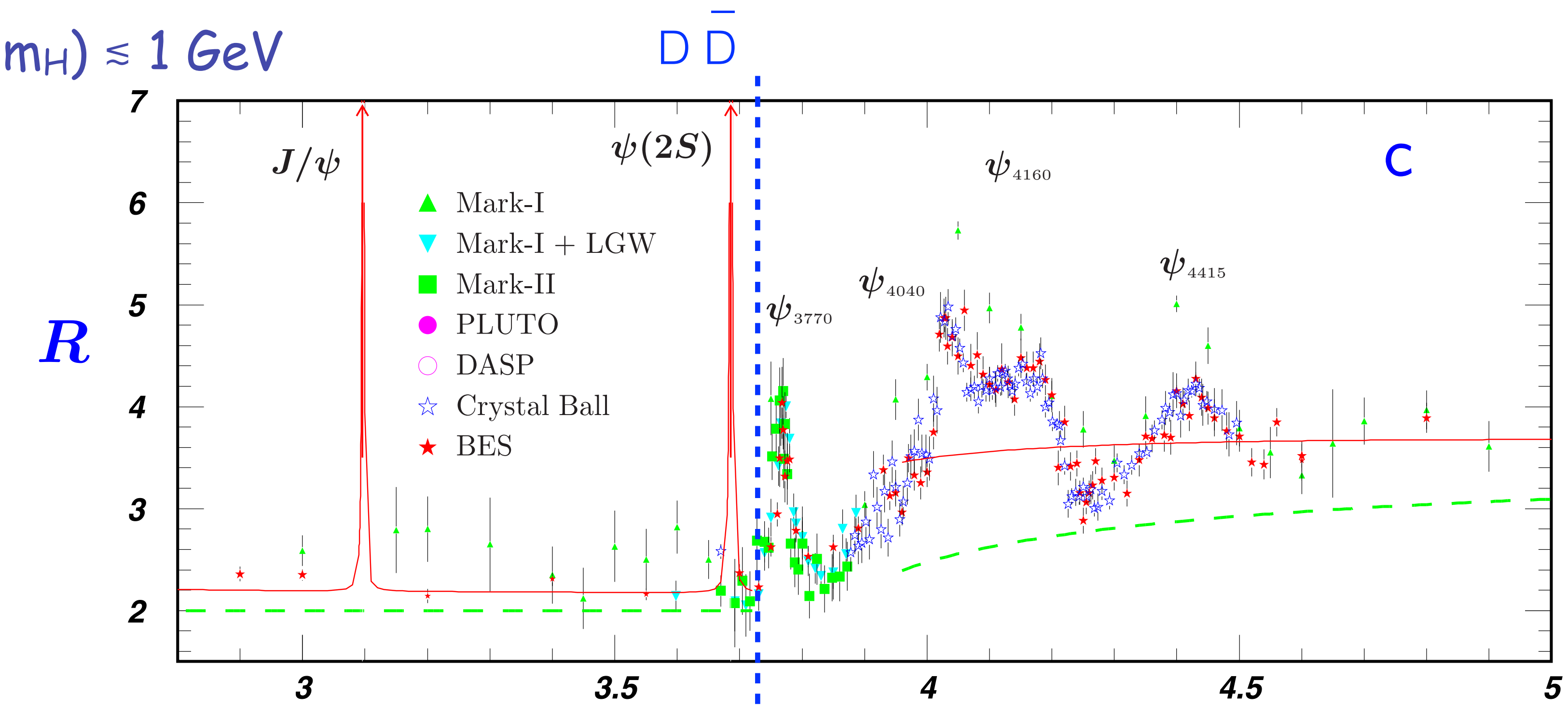


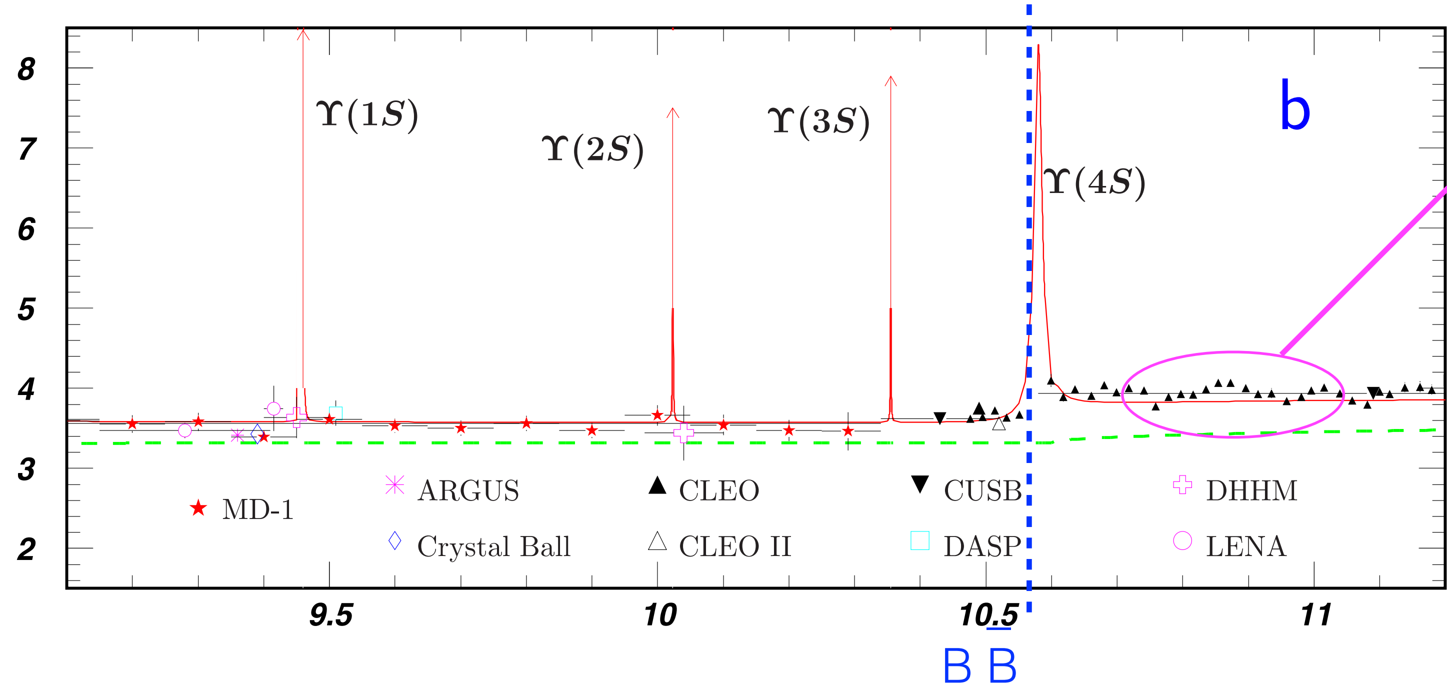


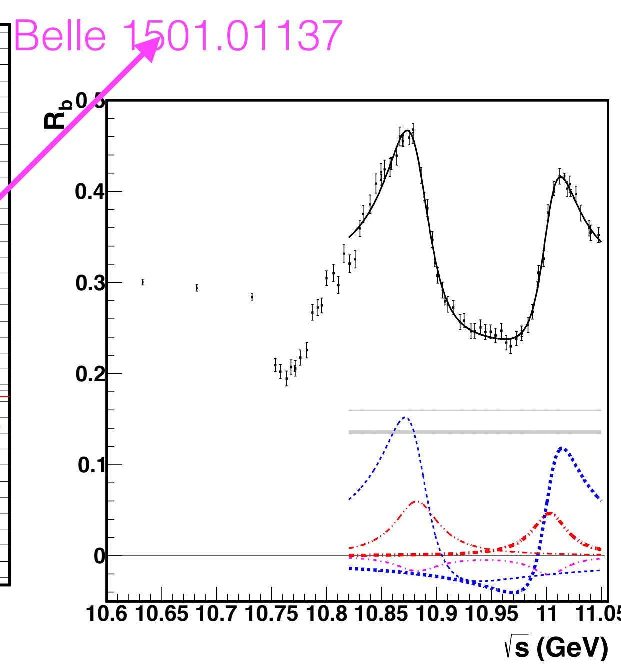
- $\Delta E = E - m_1 - m_2 = \sqrt{(m_1^2+p^2)} + \sqrt{(m_2^2+p^2)} - m_1 - m_2 \approx (m_1+m_2)\, p^2/(2m_1m_2)$

The Threshold Region

- R = σ(e+e- -> γ* -> hadrons)/σ(e+e- -> γ*-> μ+μ-) $J^{PC} = 1^{--}$
  - Resonance region: ($\sqrt{s}$ - $2m_H$) ≲ 1 GeV
  - Two body decays
    - D0 = (cu), D+ = (cd)
    - $M(D^0D^0)$ = 3,729.72 MeV
    - $M(D^+D^-)$ = 3,739.26 MeV
    - B- = (bu), B0 = (bd)
    - $M(B^+B^-)$ = 10,578.52 MeV
    - $M(B^0B^0)$ = 10,579.16 MeV
  - $e_c = 2/3$; $e_b = -1/3$







The Threshold Region

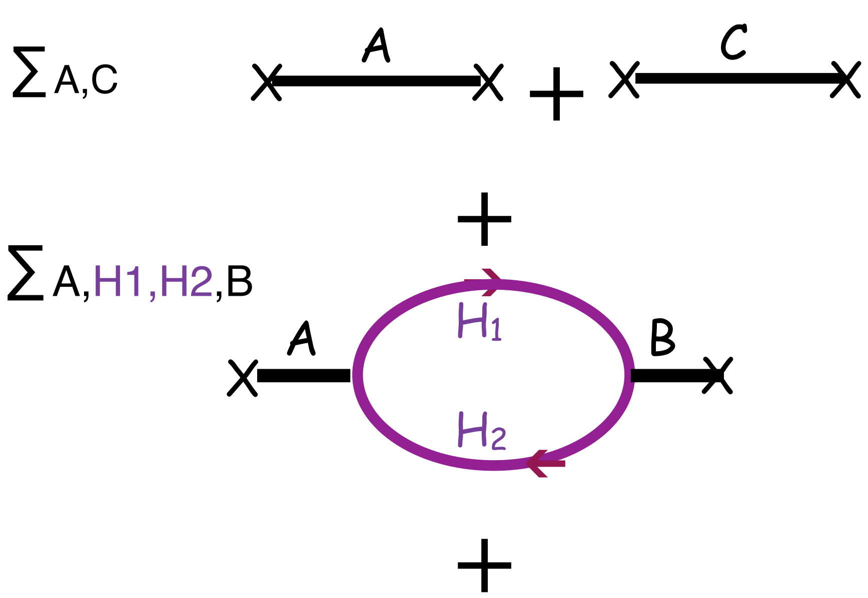
- Quark-hadron duality

$$-(g_{\mu\nu} q^2 - q_\mu q_\nu)\rho_c(W)$$

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

$$\Delta R(W) = \frac{6\pi}{W^2} \rho_c(W)$$

QCD - hadronic
A,B (QQ) , C (QQg)
H_1,H_2(Qq)



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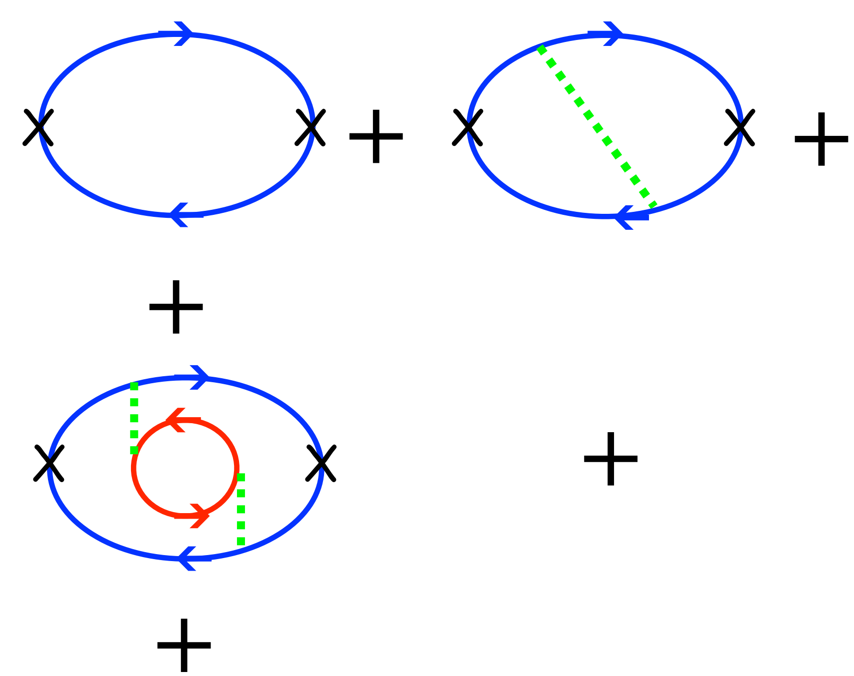
QCD - perturbative
Q, g



Simple expansion near threshold.

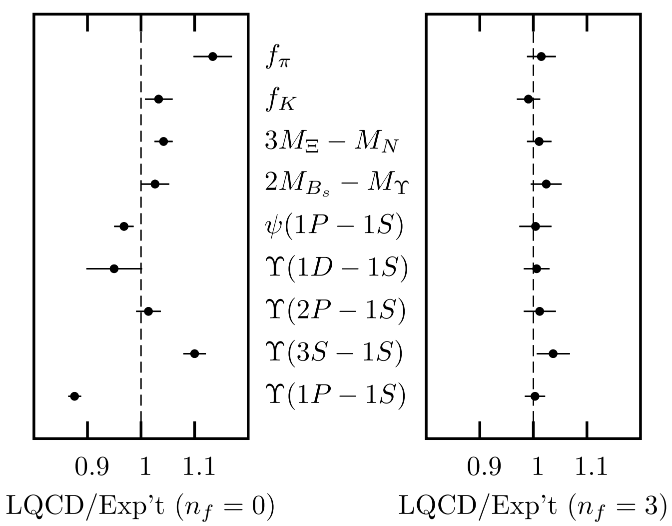
Simple expansion far above threshold.

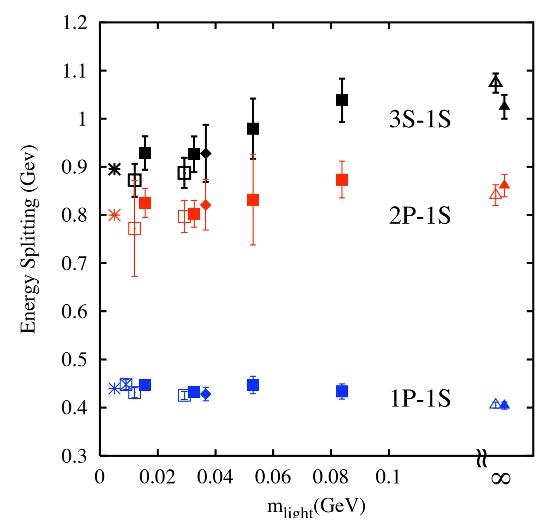
The Threshold Region

- Effects of heavy-light meson virtual loops
  - Effects of light quark loops can be computed in LQCD

Second

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





State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	-90.5^e	$+2.8$
1^3S_1	$3\,096.9^a$		$+30.2^e$	-0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	$+5.9$
1^3P_1	$3\,510.5^a$		-11.6^e	-2.0
1^1P_1	$3\,524.4^f$		$+0.6^e$	$+0.5$
1^3P_2	$3\,556.2^a$		$+31.9^e$	-0.3
2^1S_0	$3\,638^a$	$3\,674^b$	-50.1^e	$+15.7$
2^3S_1	$3\,686.0^a$		$+16.7^e$	-5.2
1^3D_1	$3\,769.9^a$	$(3\,815)^d$	-40	-39.9
1^3D_2	$3\,830.6$		0	-2.7
1^1D_2	$3\,838.0$		0	$+4.2$
1^3D_3	$3\,868.3$		$+20$	$+19.0$
2^3P_0	$3\,881.4$	$(3\,922)^d$	-90	$+27.9$
2^3P_1	$3\,920.5$		-8	$+6.7$
2^1P_1	$3\,919.0$		0	-5.4
2^3P_2	$3\,931^g$		$+25$	-9.6
3^1S_0	$3\,943^h$	$(4\,015)^i$	-66^e	-3.1
3^3S_1	$4\,040^a$		$+22^e$	$+1.0$

  - Shift masses and properties of states near threshold obtained by coupled channel models. Because the lowest quarkonium states are more deeply bound they are least affected by the large loop effects.

- States have modified wavefuctions

$$\Psi(1^1\mathrm{S}_0) = 0.986\,|1^1\mathrm{S}_0\rangle - 0.042\,|2^1\mathrm{S}_0\rangle - 0.008\,|3^1\mathrm{S}_0\rangle - 0.002\,|4^1\mathrm{S}_0\rangle - 0.001\,|5^1\mathrm{S}_0\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.974$$

$$\Psi(1^3\mathrm{S}_1) = 0.983\,|1^3\mathrm{S}_1\rangle - 0.050\,|2^3\mathrm{S}_1\rangle - 0.009\,|3^3\mathrm{S}_1\rangle - 0.003\,|4^3\mathrm{S}_1\rangle + -0.001\,|5^3\mathrm{S}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.968$$

$$\Psi(1^3\mathrm{P}_0) = 0.919\,|1^3\mathrm{P}_0\rangle - 0.067\,|2^3\mathrm{P}_0\rangle - 0.014\,|3^3\mathrm{P}_0\rangle - 0.005\,|4^3\mathrm{P}_0\rangle - 0.002\,|5^3\mathrm{P}_0\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.850$$

$$\Psi(1^3\mathrm{P}_1) = 0.914\,|1^3\mathrm{P}_1\rangle - 0.075\,|2^3\mathrm{P}_1\rangle - 0.015\,|3^3\mathrm{P}_1\rangle - 0.005\,|4^3\mathrm{P}_1\rangle - 0.002\,|5^3\mathrm{P}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.841$$

$$\Psi(1^1\mathrm{P}_1) = 0.918\,|1^1\mathrm{P}_1\rangle - 0.077\,|2^1\mathrm{P}_1\rangle - 0.015\,|3^1\mathrm{P}_1\rangle - 0.005\,|4^1\mathrm{P}_1\rangle - 0.002\,|5^1\mathrm{P}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.845$$

$$\Psi(1^3\mathrm{P}_2) = 0.920\,|1^3\mathrm{P}_2\rangle - 0.080\,|2^3\mathrm{P}_2\rangle - 0.015\,|3^3\mathrm{P}_2\rangle - 0.005\,|4^3\mathrm{P}_2\rangle - 0.002\,|5^3\mathrm{P}_2\rangle - 0.002\,|1^3\mathrm{F}_2\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.854$$

$$\Psi(2^1\mathrm{S}_0) = 0.087\,|1^1\mathrm{S}_0\rangle + 0.883\,|2^1\mathrm{S}_0\rangle - 0.060\,|3^1\mathrm{S}_0\rangle - 0.016\,|4^1\mathrm{S}_0\rangle - 0.007\,|5^1\mathrm{S}_0\rangle - 0.003\,|6^1\mathrm{S}_0\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.791$$

$$\Psi(2^3\mathrm{S}_1) = 0.103\,|1^3\mathrm{S}_1\rangle + 0.838\,|2^3\mathrm{S}_1\rangle - 0.085\,|3^3\mathrm{S}_1\rangle - 0.017\,|4^3\mathrm{S}_1\rangle - 0.007\,|5^3\mathrm{S}_1\rangle - 0.002\,|6^3\mathrm{D}_1\rangle$$
$$+0.040\,|1^3\mathrm{D}_1\rangle - 0.008\,|2^3\mathrm{D}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.723$$

$$\Psi(1^3\mathrm{D}_1) = 0.694\,|1^3\mathrm{D}_1\rangle + 0.097\,e^{0.935i\pi}\,|2^3\mathrm{D}_1\rangle + 0.008\,e^{-0.668i\pi}\,|3^3\mathrm{D}_1\rangle + 0.006\,e^{0.904i\pi}\,|4^3\mathrm{D}_1\rangle$$
$$+0.013\,e^{0.742i\pi}\,|1^3\mathrm{S}_1\rangle + 0.168\,e^{0.805i\pi}\,|2^3\mathrm{S}_1\rangle + 0.014\,e^{0.866i\pi}\,|3^3\mathrm{S}_1\rangle + 0.012\,e^{-0.229i\pi}\,|4^3\mathrm{S}_1\rangle$$
$$+0.001\,e^{0.278i\pi}\,|5^3\mathrm{S}_1\rangle + 0.001\,e^{-0.267i\pi}\,|6^3\mathrm{S}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.520$$

$$\Psi(1^3\mathrm{D}_2) = 0.754\,|1^3\mathrm{D}_2\rangle - 0.084\,|2^3\mathrm{D}_2\rangle - 0.011\,|3^3\mathrm{D}_2\rangle - 0.006\,|4^3\mathrm{D}_2\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.576$$

$$\Psi(1^1\mathrm{D}_2) = 0.770\,|1^1\mathrm{D}_2\rangle - 0.083\,|2^1\mathrm{D}_2\rangle - 0.012\,|3^1\mathrm{D}_2\rangle - 0.006\,|4^1\mathrm{D}_2\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.600$$

$$\Psi(1^3\mathrm{D}_3) = 0.812\,|1^3\mathrm{D}_3\rangle + 0.086\,e^{0.990i\pi}\,|2^3\mathrm{D}_3\rangle + 0.013\,e^{-0.969i\pi}\,|3^3\mathrm{D}_3\rangle + 0.007\,e^{0.980i\pi}\,|4^3\mathrm{D}_3\rangle$$
$$+0.016\,e^{0.848i\pi}\,|1^3\mathrm{G}_3\rangle + 0.003\,e^{-0.291i\pi}\,|2^3\mathrm{G}_3\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.667$$

$$\Psi(2^3\mathrm{P}_0) = 0.040\,e^{-0.454i\pi}\,|1^3\mathrm{P}_0\rangle + 0.532\,|2^3\mathrm{P}_0\rangle + 0.024\,e^{-0.889i\pi}\,|3^3\mathrm{P}_0\rangle + 0.010\,e^{0.867i\pi}\,|4^3\mathrm{P}_0\rangle$$
$$+0.006\,e^{-0.976i\pi}\,|5^3\mathrm{P}_0\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.286$$

$$\Psi(2^3\mathrm{P}_1) = 0.218\,e^{-0.456i\pi}\,|1^3\mathrm{P}_1\rangle + 0.821\,|2^3\mathrm{P}_1\rangle + 0.058\,e^{0.516i\pi}\,|3^3\mathrm{P}_1\rangle + 0.032\,e^{0.976i\pi}\,|4^3\mathrm{P}_1\rangle$$
$$+0.008\,e^{0.986i\pi}\,|5^3\mathrm{P}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.726$$

$$\Psi(2^1\mathrm{P}_1) = 0.216\,e^{-0.226i\pi}\,|1^1\mathrm{P}_1\rangle + 0.852\,|2^1\mathrm{P}_1\rangle + 0.079\,e^{0.780i\pi}\,|3^1\mathrm{P}_1\rangle + 0.023\,e^{-0.890i\pi}\,|4^1\mathrm{P}_1\rangle$$
$$0.007\,e^{0.985i\pi}\,|5^1\mathrm{P}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.883$$

$$\Psi(2^3\mathrm{P}_2) = 0.234\,e^{-0.046i\pi}\,|1^3\mathrm{P}_2\rangle + 0.754\,|2^3\mathrm{P}_2\rangle + 0.097\,e^{0.876i\pi}\,|3^3\mathrm{P}_2\rangle + 0.016\,e^{-0.743i\pi}\,|4^3\mathrm{P}_2\rangle$$
$$0.007\,e^{0.898i\pi}\,|5^3\mathrm{P}_2\rangle + 0.370\,e^{0.775i\pi}\,|1^3\mathrm{F}_2\rangle + 0.035\,e^{-0.317i\pi}\,|2^3\mathrm{F}_2\rangle + 0.002\,e^{0.097i\pi}\,|3^3\mathrm{F}_2\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.771$$

$$M = 3872\ \mathrm{MeV}: \ \Psi(1^3\mathrm{D}_2) = 0.596\,|1^3\mathrm{D}_2\rangle - 0.108\,|2^3\mathrm{D}_2\rangle - 0.004\,|3^3\mathrm{D}_2\rangle - 0.006\,|4^3\mathrm{D}_2\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.367$$

$$M = 3872\ \mathrm{MeV}: \ \Psi(1^3\mathrm{D}_3) = 0.813\,|1^3\mathrm{D}_3\rangle + 0.089\,e^{0.989i\pi}\,|2^3\mathrm{D}_3\rangle + 0.013\,e^{-0.965i\pi}\,|3^3\mathrm{D}_3\rangle + 0.007\,e^{0.978i\pi}\,|4^3\mathrm{D}_3\rangle$$
$$+0.017\,e^{0.837i\pi}\,|1^3\mathrm{G}_3\rangle + 0.003\,e^{-0.305i\pi}\,|2^3\mathrm{G}_3\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.669$$

$$M = 3872\ \mathrm{MeV}: \ \Psi(2^1\mathrm{P}_1) = 0.134\,e^{-0.004i\pi}\,|1^1\mathrm{P}_1\rangle + 0.374\,|2^1\mathrm{P}_1\rangle + 0.035\,e^{0.993i\pi}\,|3^1\mathrm{P}_1\rangle + 0.003\,e^{-0.981i\pi}\,|4^1\mathrm{P}_1\rangle$$
$$+0.004\,e^{0.996i\pi}\,|5^1\mathrm{P}_1\rangle; \quad \mathcal{Z}_{c\bar{c}} = 0.159$$

- 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).

The Threshold Region

Third

- There be new states formed of the extra degrees of freedom
  - Add gluons - Hybrid states
  - Add light quark pair - $Q\bar{Q}q\bar{q}$ states

- Many such candidates have been observed. These are the so called XYZ states

Known XYZ States

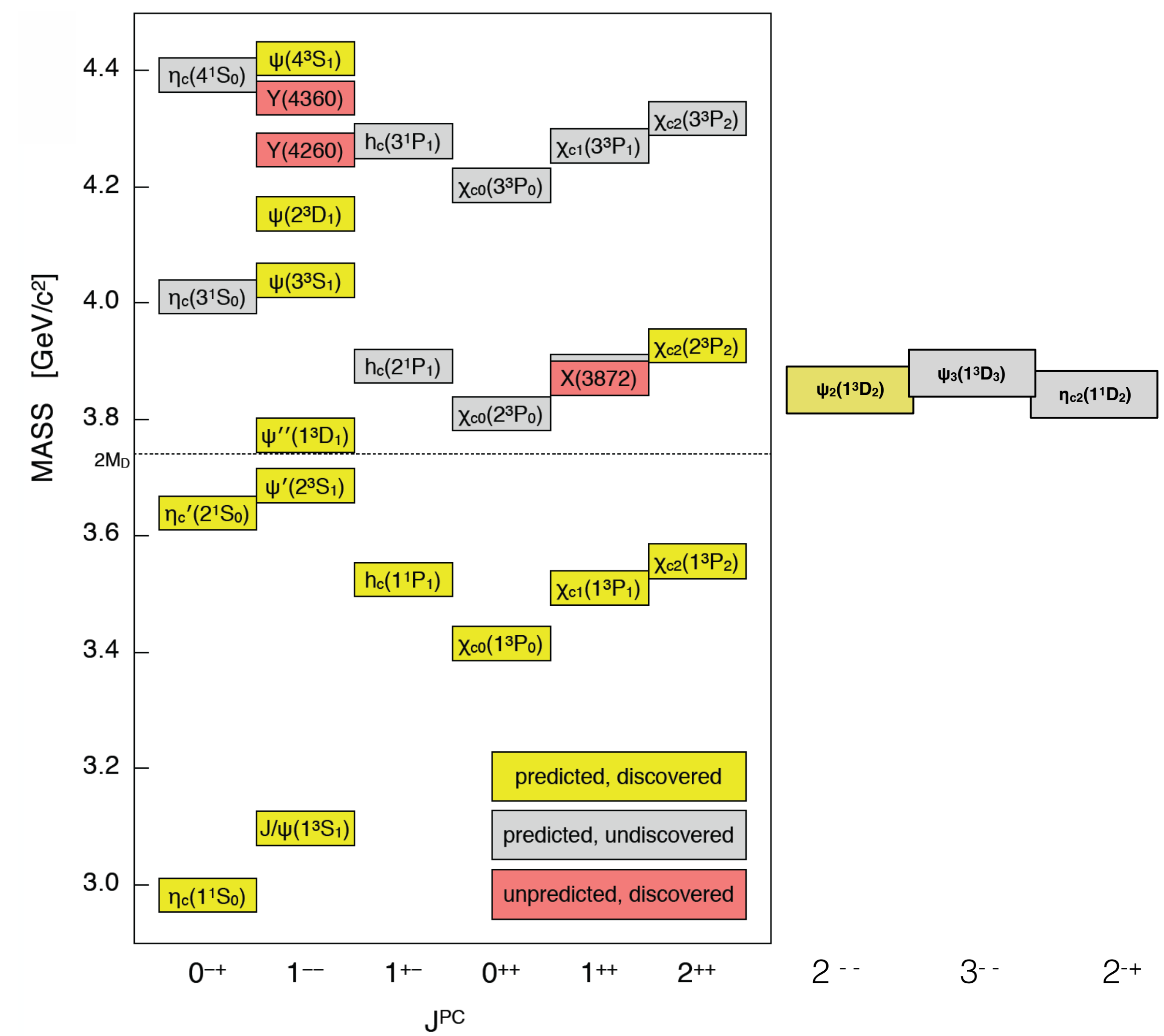
- Notation
  - Y denotes states observed directly in the charm contribution to e^+e^- -> hadrons:

    ⇒ $J^{PC} = 1^{--}$ 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
    - $X_c(3872)$, … ⇒ see PDG table
    - Pentaquarks: X(4450) ($J^P = 5/2^+$), …



Additional XYZ Candidates

- From PDG - other X states with undetermined quantum numbers

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$\chi_{c0}(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K(\omega J/\psi)$	Belle [66] (8.1), BABAR [67,65] (19)	2004	OK
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [68] (5.3), BABAR [69,45] (5.8)	2005	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [70] (7.7), BABAR [45] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\overline{D}^*)$	Belle [71] (6.0)	2007	NC!
				$e^+e^- \to J/\psi(...)$	Belle [21] (5.0)		
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [72] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [73] (5.0), BABAR [74] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [75,76](5.0), Belle [77](1.9), LHCb [78](1.4), CMS [79](>5) D0 [80](3.1)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\overline{D}^*)$	Belle [71] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [73] (5.0), BABAR [74] (2.0)	2008	NC!
$Y(4260)$	4263^{+8}_{-9}	95±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [81,82] (8.0) CLEO [83] (5.4), Belle [72] (15)	2005	OK
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [84] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [84] (5.1)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [85](np), Belle [57](np)	2012	OK
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BESIII [56](8), Belle [57](5.2)	2013	OK
				$e^+e^- \to (\gamma X(3872))$	BESIII [86](5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [76](3.1), LHCb [78](1.0), CMS [79](>3), D0 [80](np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [87] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [88] (np), Belle [89] (8.0)	2007	OK
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [90,91,92](6.4), BaBar [93](2.4)	2007	OK
				$B^0 \to \psi(2S)\pi^- K^+$	LHCb [94](13.9)		
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [95] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [89] (5.8)	2007	NC!
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [96]	1985	OK
				$e^+e^- \to (\pi\pi\Upsilon(1S,2S,3S))$	Belle [97,62,63](>10)	2007	OK
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [62,63](>5)	2011	OK
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [62,63](>10)	2011	OK
				$e^+e^- \to (\eta\Upsilon(1S,2S))$	Belle [98](10)	2012	OK
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [98](9)	2012	OK
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [99](2.3)	2008	NC!

Y(4260)

- Y(4260) - not standard charmonium state. $J^{PC} = 1^{--}$ M= 4259 ± 9 Γ= 120 ± 12 MeV
  - Decays observed: $J/\psi\pi^+\pi^-$
    - $J/\psi f_0(980)$, $f_0(980) \to \pi^+\pi^-$
    - $X(3900)^\pm\pi^\mp$, $X^\pm \to J/\psi\pi^\pm$
    - $J/\psi\pi^0\pi^0$
    - $J/\psi K^+K^-$
    - $X(3872)\gamma$
  - Many models:
    1. Charmonium hybrid → 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
    2. D_1 D molecule → DING G J, Zhu J J and YAN M L. Phys. Rev. D, 2008, **77**: 014033; Ding G J. Phys. Rev. D, 2009, **79**: 014001; WANG Q, Hanhart C and ZHAO Q. Phys. Rev. Lett., 2013, **111**: 132003
    3. Hadrocharmonium → 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
    4. Tetraquark (ccss) → Maiani L, Riquer V, Piccinini F and Polosa A D. Phys. Rev. D, 2005, **72**: 031502
    5. Cusp/nonresonance → 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

    ...
  - 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 :

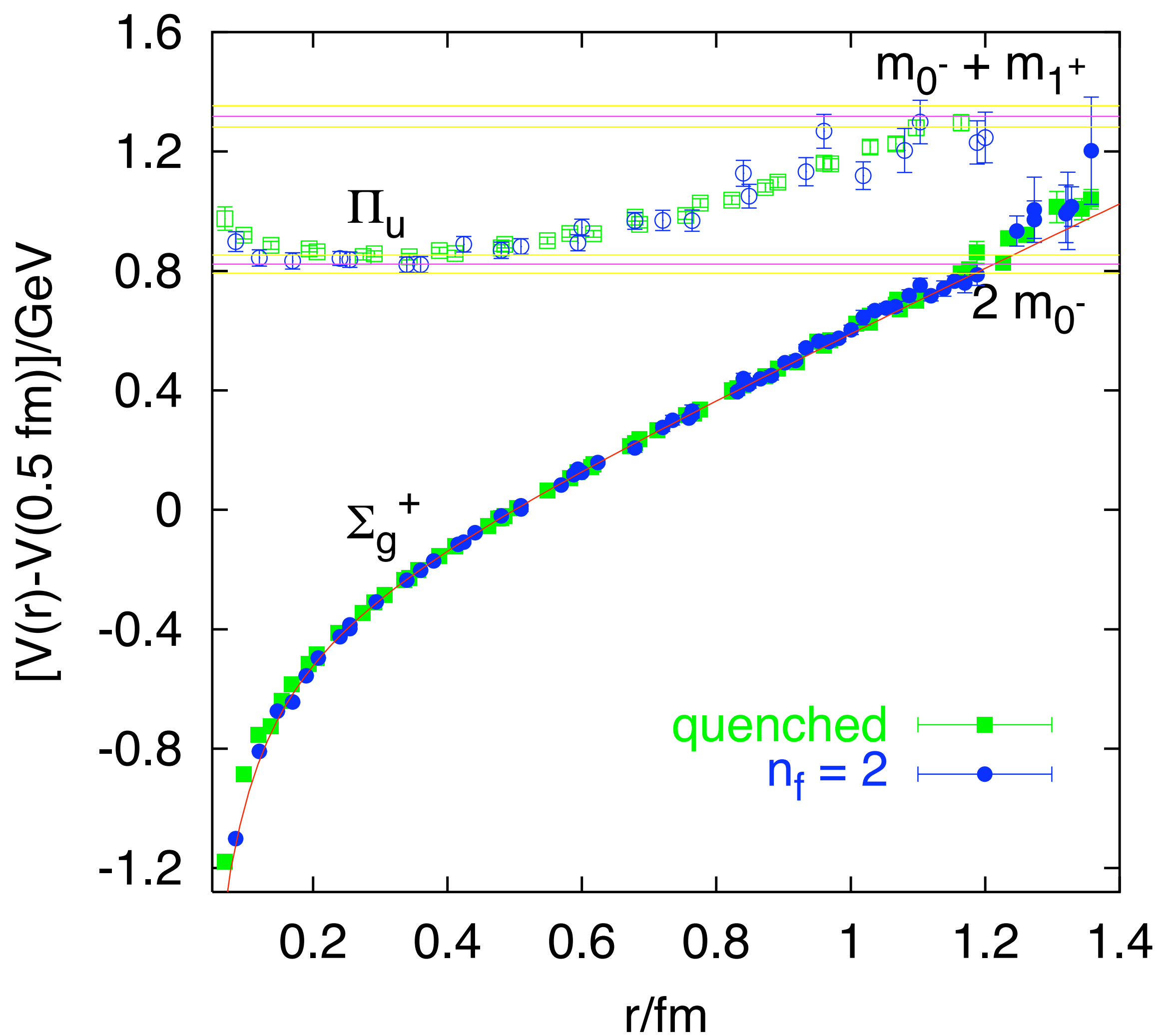
QCD Dynamics for Hybrids

- Lattice calculation V(R), then SE

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\,u(r)$$

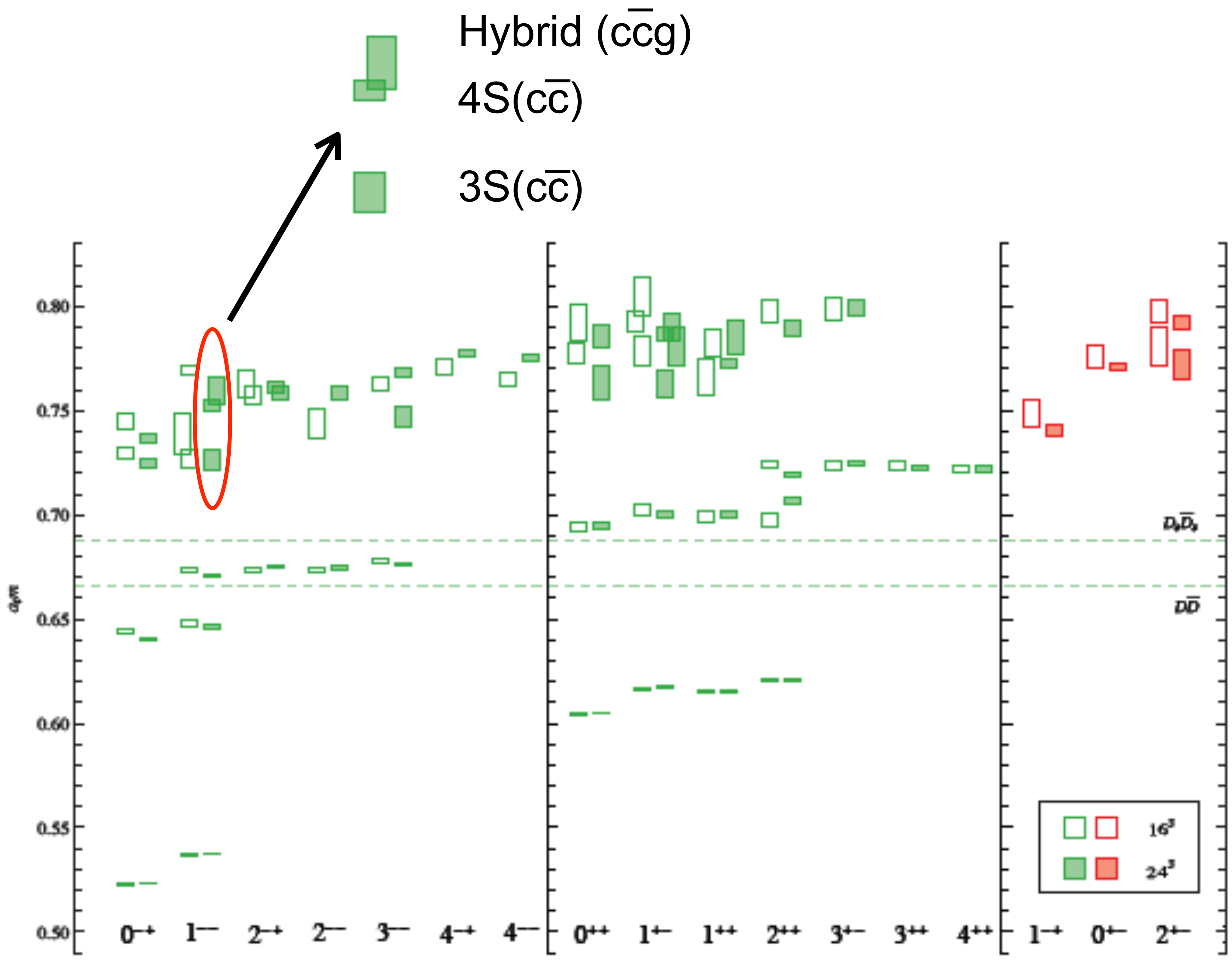
- What about the gluon and light quark degrees of freedom of QCD?
- Two thresholds:
  - Usual $(Q\bar{q})+(q\bar{Q})$ decay threshold
  - Excite the string - hybrids
- Hybrid states will appear in the spectrum associated with the potential Π_u, ...
- In the static limit this occurs at separation: r ≈ 1.2 fm. Between 3S-4S in $(c\bar{c})$; just above the 5S in $(b\bar{b})$.

LQCD calculation of static energy



Charmonium on the lattice

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



X(3872)

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

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

  - LHCb [arXiv:1404.0275]

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

suggests 2P state

  - $M_X - M_D - M_{D^*} = -0.11 \pm 0.23$ MeV

suggests molecule

  - Two primary models:
    1. $\chi_{c1}'(2^3P_1)$ state → M. Suzuki, hep-ph/0307118.
    2. $D^0 \overline{D}^{0*}$ molecule → 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]

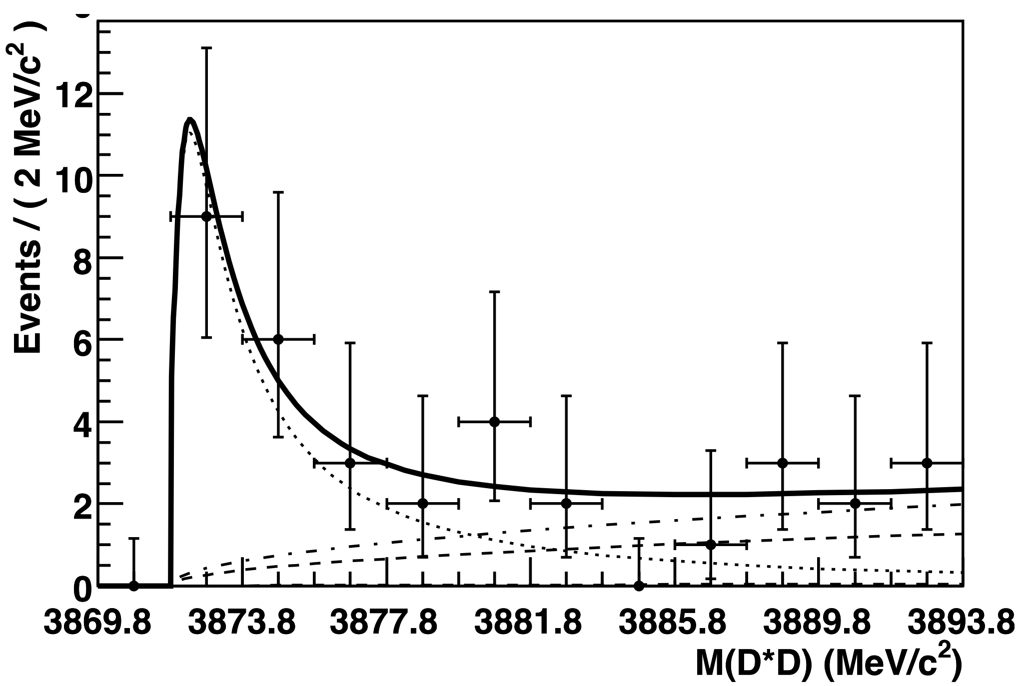
  - Mixed state with sizable quarkonium component likely.

  - 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.

Belle Phys.Rev. D81 (2010) 031103



- Lattice calculations:
  - \`A pole appears just below threshold in the J^{PC} =1^{++} I = 0 channel.
  - But requires both the ($\bar{c}c$) and the $\overline{D}$D* components.
  - Suggests there is a significant ($\bar{c}c$) 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.

Analogy of X(3872) in Bottomonium?

- $X_b(10604)$??
  - No isospin breaking: X is I=0 => G-parity forbids the decay X -> $\pi\pi\Upsilon(1S)$.
  - Dominate decays: X -> $\omega\Upsilon(1S)$, $\pi\pi\ \chi_{b1}(1P)$
  - $M(\chi_{b1}(3P)) - M(B) - M(B^*) \approx -75$ MeV
  - So the (bb) state is decoupled.
- Expect no analogy of the X(3872) in the bottomonium system

arXiv:1503.03257

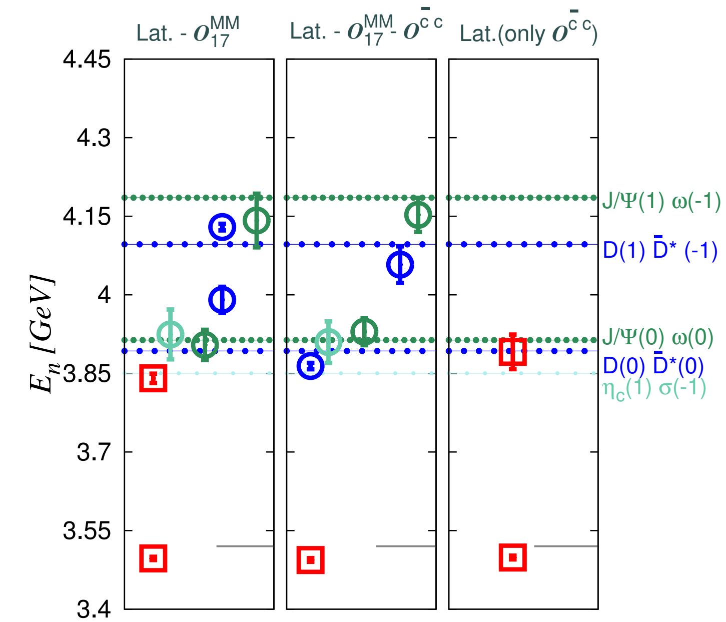
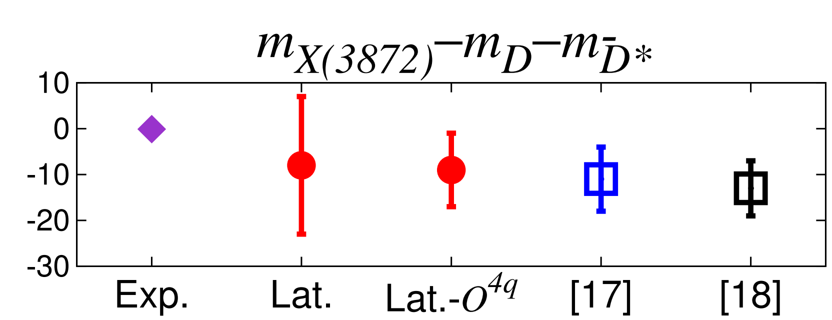
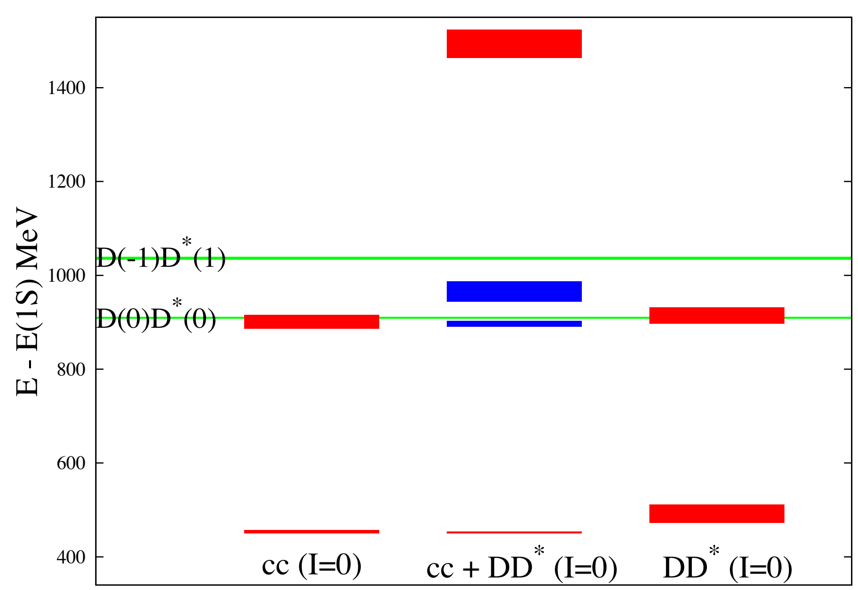


FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note 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:
- ϒ(4S)
  - M = 10,579.4 ± 1.2 MeV Γ = 20.5 ± 2.5 MeV;
  - Open decay channels:
    - $M(B^+B^-)$ = 10,578.52 MeV, $M(B^0\bar{B}^0)$ = 10,579.16 MeV
    - Essentially no isospin breaking in the masses.
  - Normal pattern of 2π decays, large η decays:

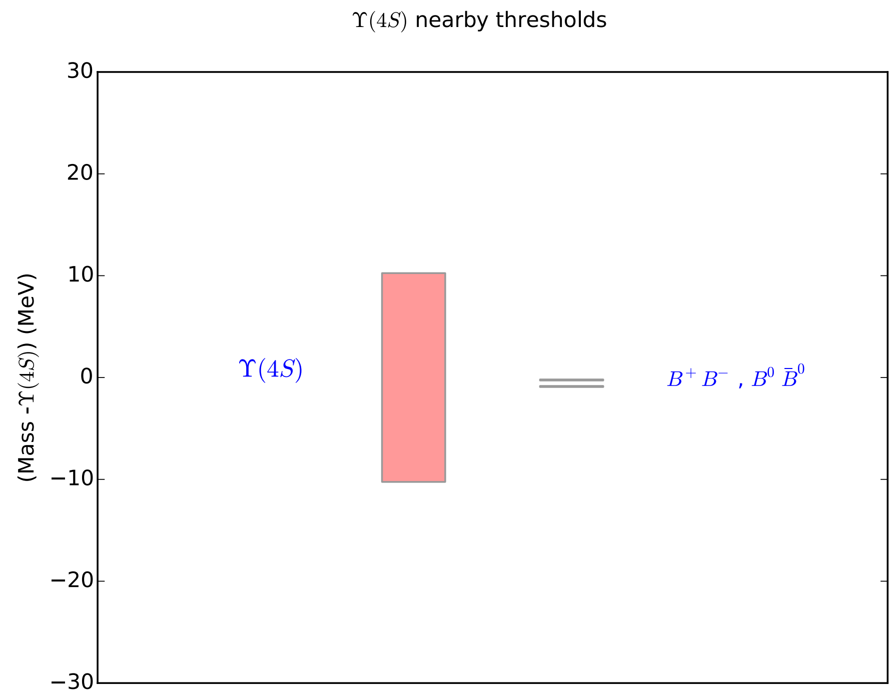


Table 1: Selected $\Upsilon(4S)$ decays.

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)
$\Upsilon(1S)\ \eta$	$(1.96 \pm 0.28) \times 10^{-4}$
$h_b(1P)\ \eta$	$(1.83 \pm 0.23) \times 10^{-3}$

—> partial rate = 1.66 ± 0.23 keV

—> partial rate = 4.02 ± 0.89 keV SU(3) violating

—> partial rate = 37.5 ± 7.3 keV HSQ violating

Heavy Quark 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]

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

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

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

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

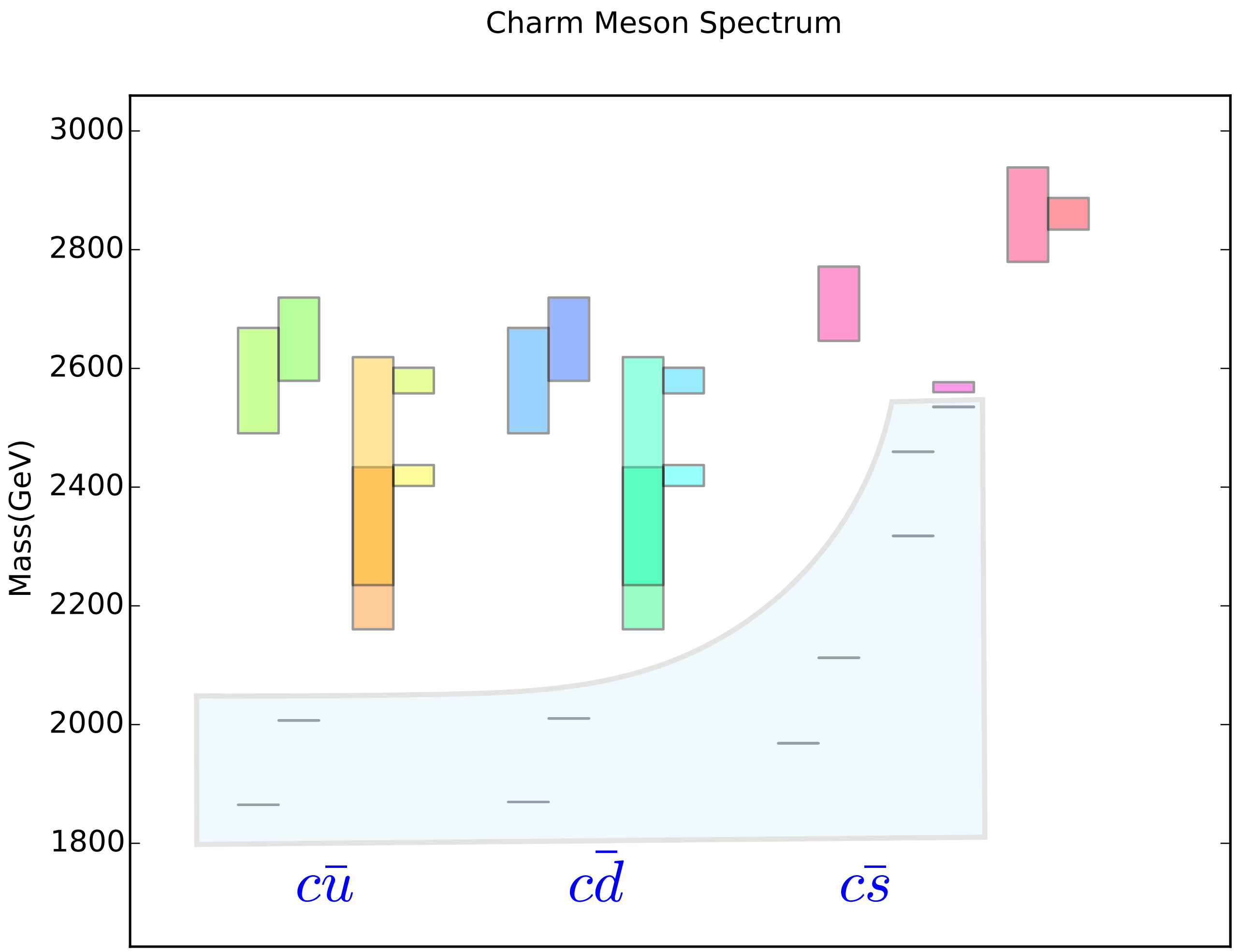
$$U = \exp\left(i\gamma_5 \frac{\varphi_a \lambda_a}{f_\pi}\right)$$

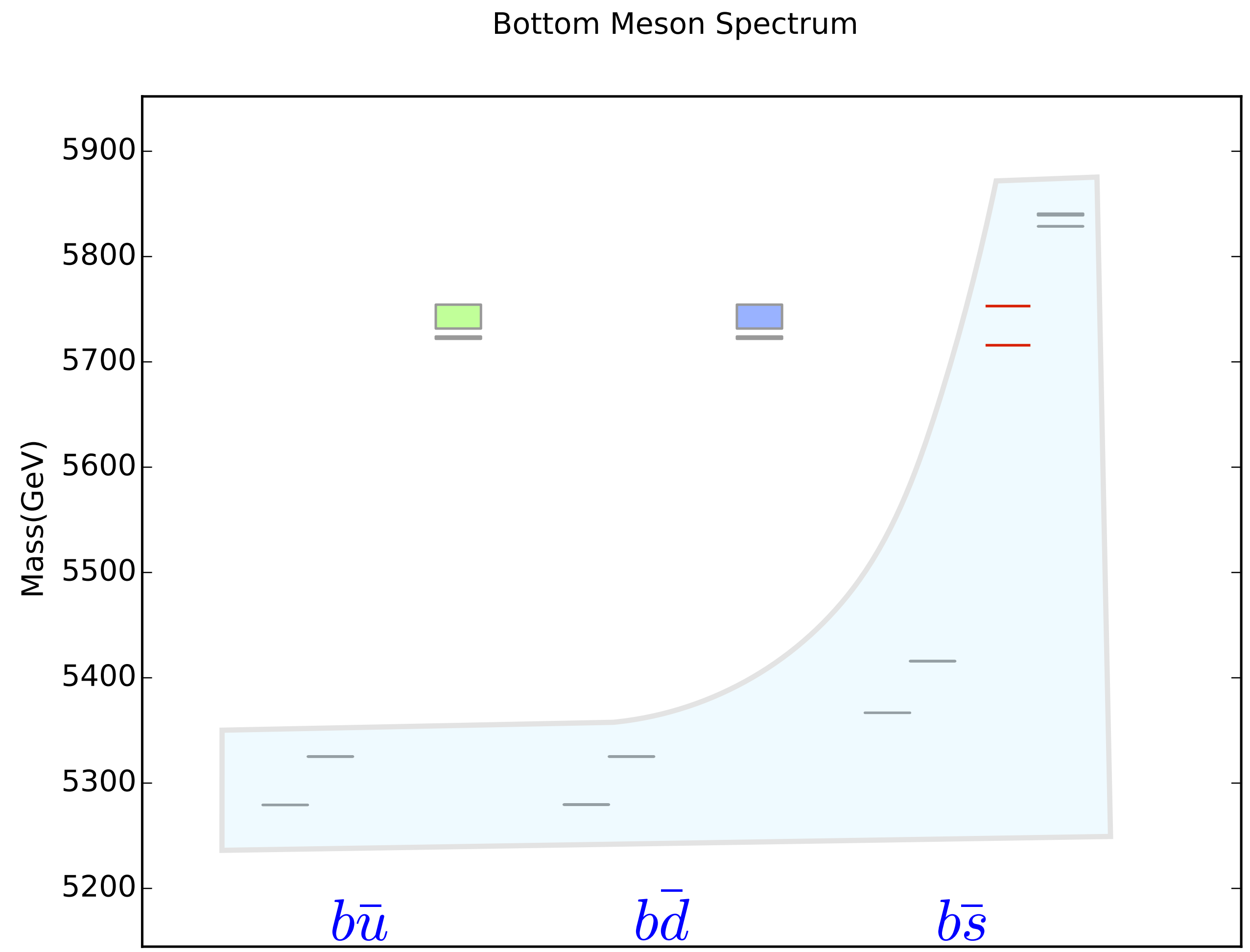
$$\varphi_a \lambda_a = \sqrt{2}\begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}}, & \pi^+, & K^+ \\ \pi^-, & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}}, & K^0 \\ K^-, & \bar{K}^0, & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

  - 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 greatly enhances the final states with η + (QQ̄). Yu.A. Simonov and A.I. Veselov [arXiv: 0810.0366]
  - This leads to large effects in the threshold region.
  - Similarly important in ω and ϕ production.

Heavy-Light Mesons

- Observed low-lying (1S, 1P, and 1D) charm and bottom mesons:
  - Very similar excitation spectrum - HQS

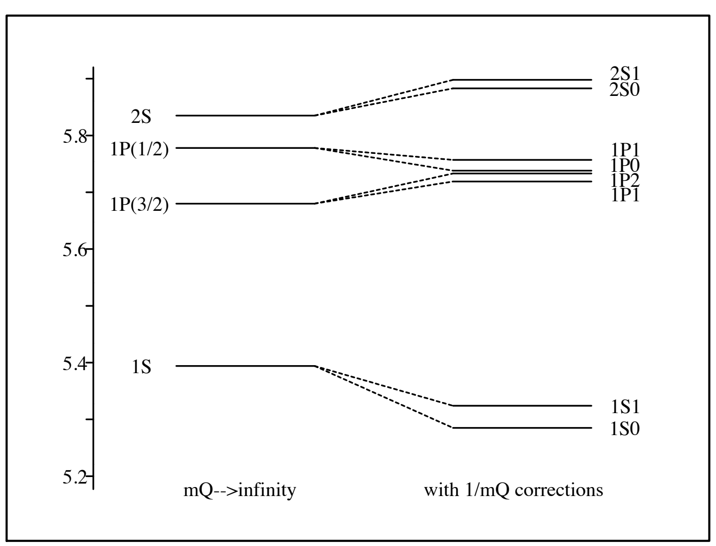




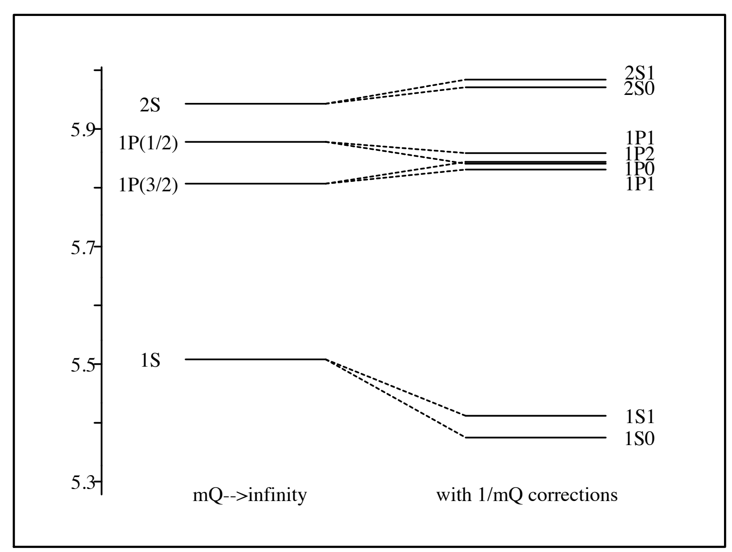
  - There are 9 narrow (< 2 MeV) charm meson states [and 10 bottom mesons states]. Any pair of these might have a cusp at S-wave threshold.

Hadronic Transitions Above Threshold

- $\Upsilon(5S)$ hadronic transitions
  - $M = 10{,}876 \pm 11$ MeV $\Gamma = 55 \pm 26$ MeV;
  - Open Ground State ($j^p = \frac{1}{2}^-$) Decay Channels:
    - $M(B\bar{B}) = 10{,}559$ MeV, $M(B^*\bar{B}) = 10{,}604$ MeV, $M(B^*\bar{B}^*) = 10{,}650$ MeV
    - $M(B_s\bar{B}_s) = 10{,}734$ MeV, $M(B^*_s\bar{B}_s) = 10{,}782$ MeV, $M(B^*_s\bar{B}^*_s) = 10{,}831$ MeV
  - Also some P state ($j^p = \frac{1}{2}^+$) Decay Channels are essentially open
    - $M(B[1^{\frac{1}{2}+}P_0]\bar{B}^*) = 11{,}055$ MeV   (notation: $n^{jP}L_J$)
    - $M(B[1^{\frac{1}{2}+}P_1]\bar{B}) = 11{,}045$ MeV, $M(B[1^{\frac{1}{2}+}P_1]\bar{B}^*) = 11{,}091$ 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

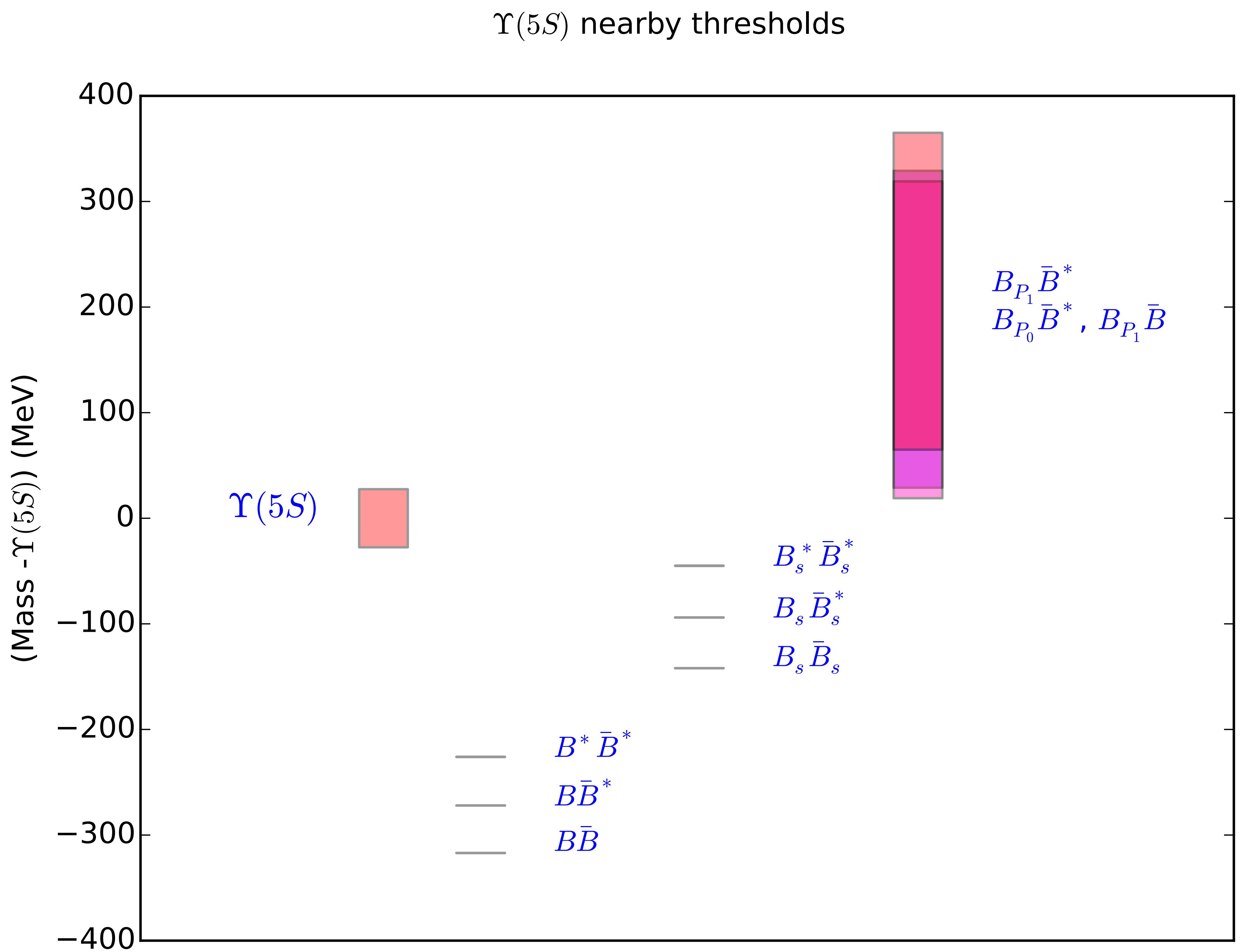


B

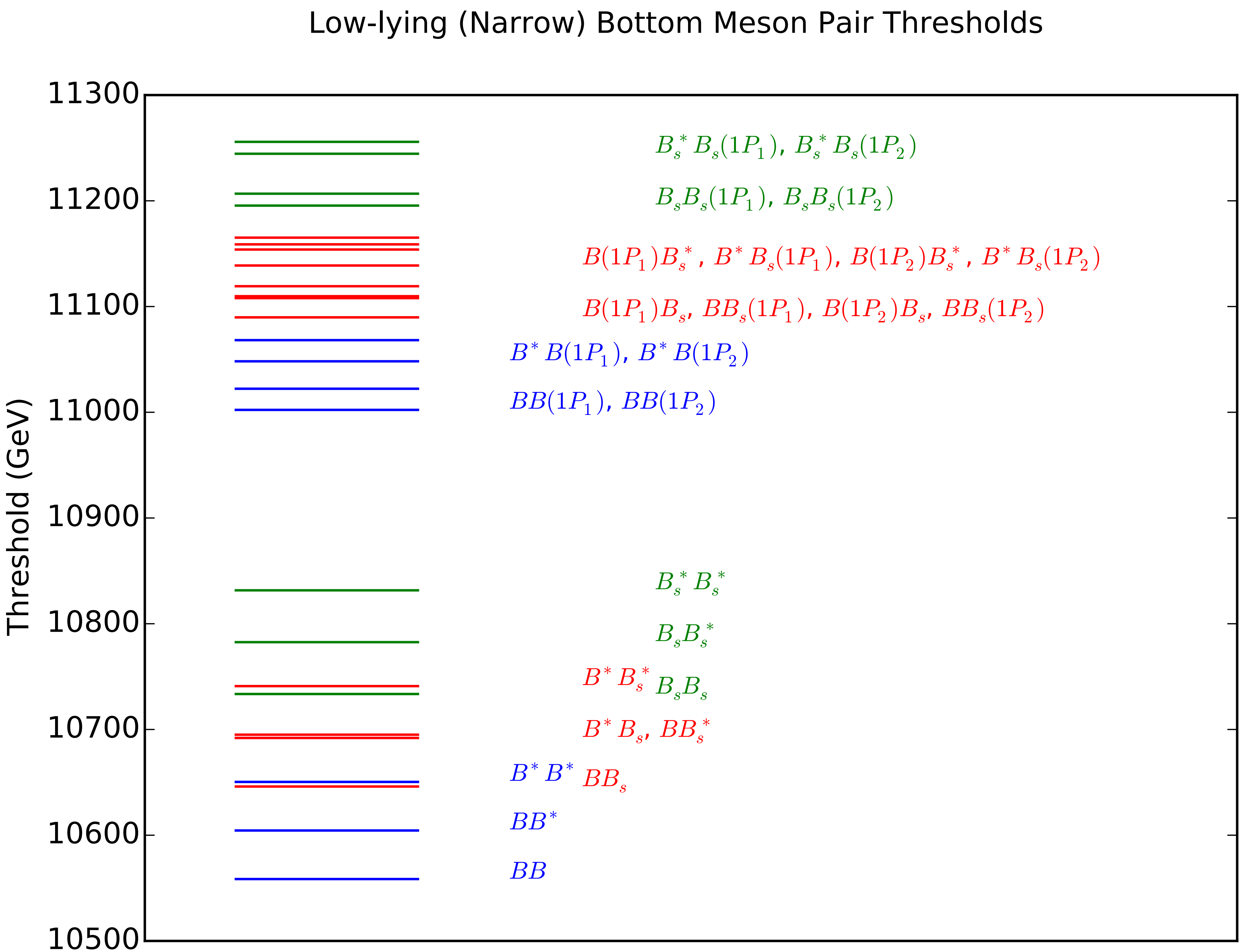


B_s

Hadronic Transitions Above Threshold



Low-lying thresholds



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 $B(P_0)$

Hadronic Transitions Above Threshold

- $\Upsilon(5S)$ decay pattern:

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

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

—> partial rate = 0.29 ± 0.13 MeV

—> partial rate = 86 ± 41 keV

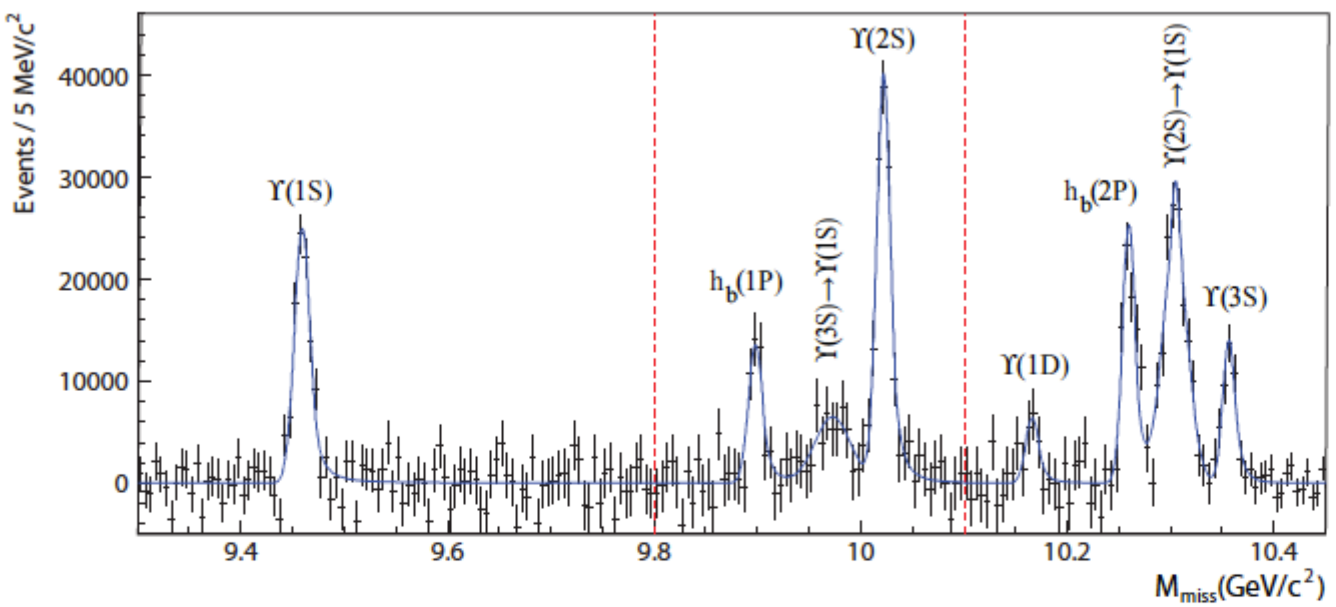
—> partial rate = 0.15 ± 0.08 MeV

- Very large 2π hadronic transitions [> 100 times $\Upsilon(4S)$ rates]

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

- Large rates
  - Y(5S): m=10,876 ± 11 MeV and Γ= 55 ± 23 MeV
  - BR(Y 5S) -> Y(2S) + $\pi^+\pi^-$) = (0.78 ± 0.13) %

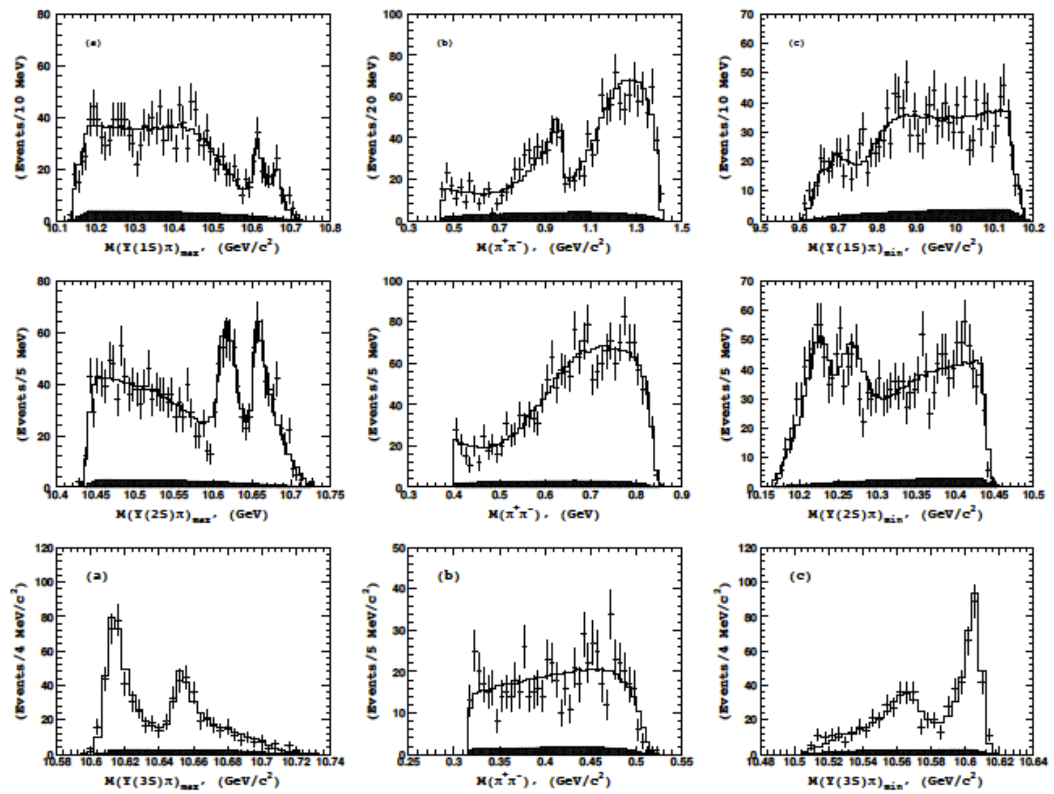
BELLE [arXiv:1103.3419]



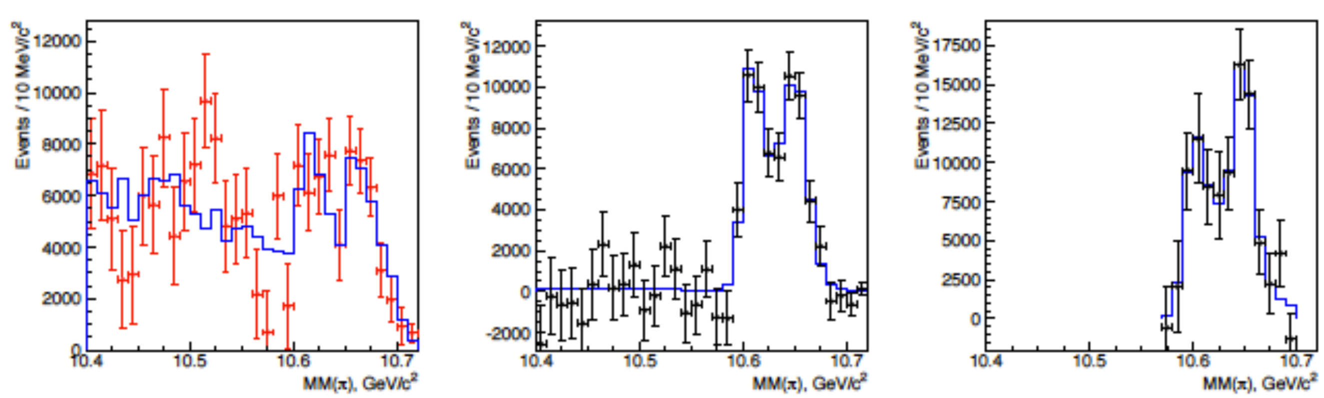
  - $\pi^+\pi^-$ system I= 0
  - total branching ratio for known hadronic transitions (3.9 ± 0.7)% => Γ = 2.1 ± 0.9 MeV
- Clear violation of QCDME expectations:
  - the transitions Y(5S) -> h_b(1P,2P) + $\pi^+\pi^-$ requires a heavy quark spin flip (M1)(E1)
- The usual formulation of QCDME needs modification, Structure in the transition amplitudes not found in the usual (KY) model.

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

- $\Upsilon(5S) \to \pi^- + Z_b^+ \to \Upsilon(nS) + \pi^+\pi^-$ (n=1,2,3)



- Zb in $\Upsilon(2S)$, $h_b(1P)$ and $h_b(2P)$ pion transitions



- Explicitly violates the factorization assumption of QCDME

Hadronic Transitions Above Threshold

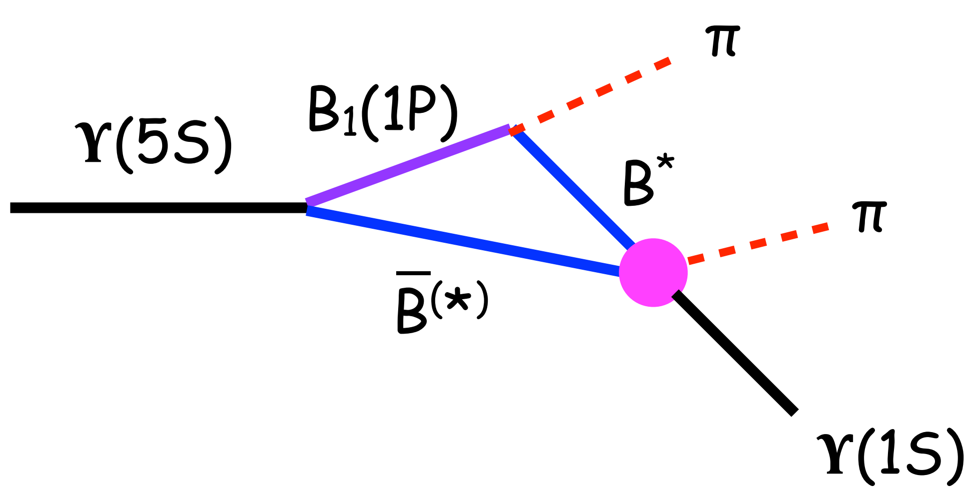
- Contributions of P-state decays:
  - $n^3S_1(Q\bar{Q}) \to 1^{\frac{1}{2}+}P_J(Q\bar{q}) + 1^{\frac{1}{2}-}S_{J'}(q\bar{Q})$:
  - $1^{\frac{1}{2}+}P_J(Q\bar{q}) \to 1^{\frac{1}{2}-}S_{J'}(Q\bar{q}) + {}^1S_0\,(q\bar{q})$ for S-wave J=J'

S-wave decays

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

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

Example



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

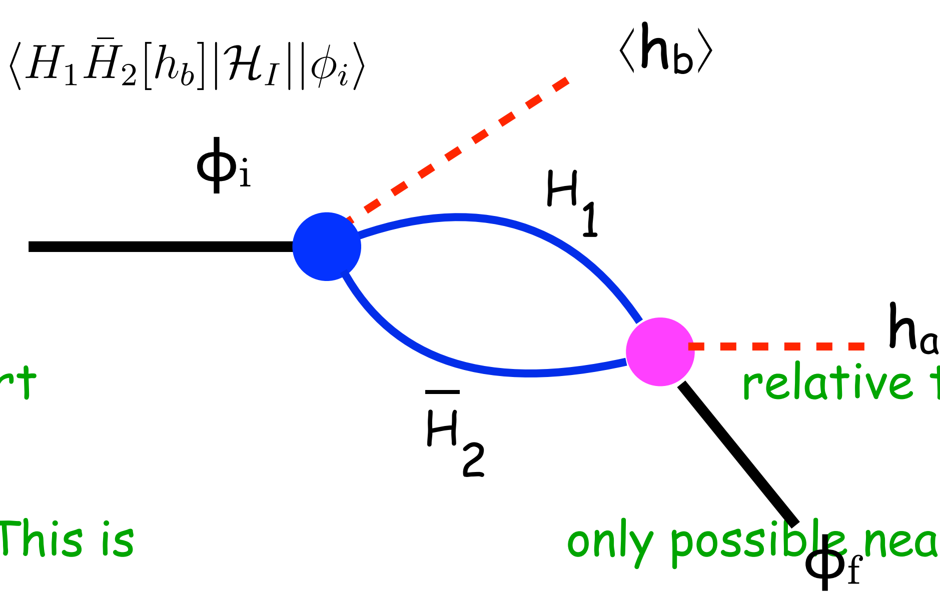
(4) Therefore the $B^{(*)}$ B^* system is in a relative S-wave and near threshold.

(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).

$$\mathcal{M}(\Phi_i \to \Phi_f + h >= \sum_{H_1 H_2} \sum_{p_1, p_2} \langle \Phi_f h_a | \mathcal{H}'_I | H_1(p_1) \bar{H}_2(p_2) \rangle \frac{1}{(E_f + E_a) - (E_1 + E_2)} \langle H_1 \bar{H}_2 [h_b] | \mathcal{H}_I | | \phi_i \rangle$$



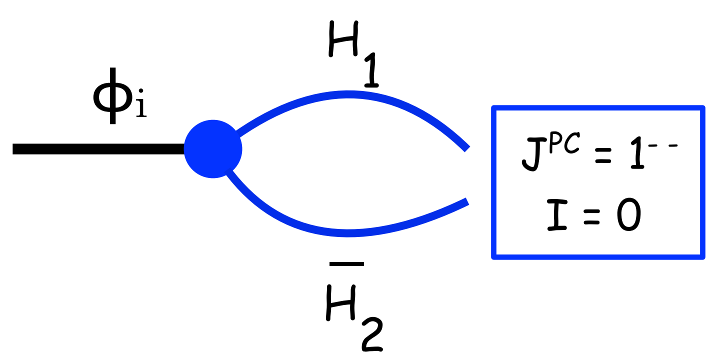
  - The time scale of the production process has to be short relative to the time scale over which H_1 H_2 rescattering can occur.
  - The relative velocity in the H_1 H_2 system must be low. This is only possible near threshold.

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

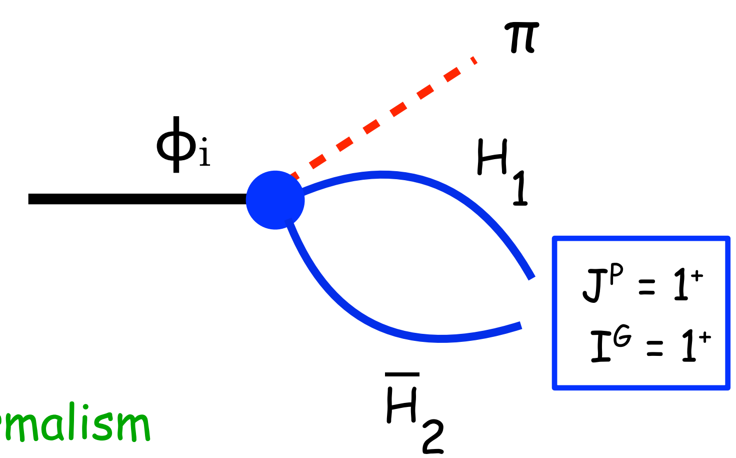
F.K. Gao, C. Hanhart, Q. Wang, Q. Zhao [arXiv:1411.5584]

New Dynamics for Hadronic Transitions

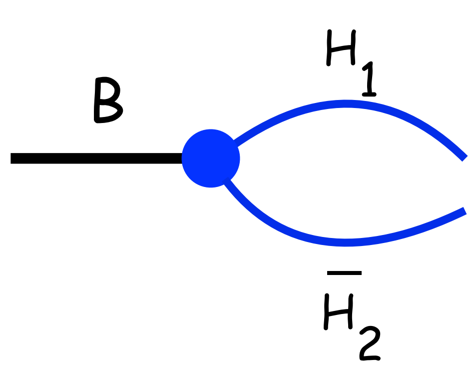
- Production modes
  - e+e-
    - direct

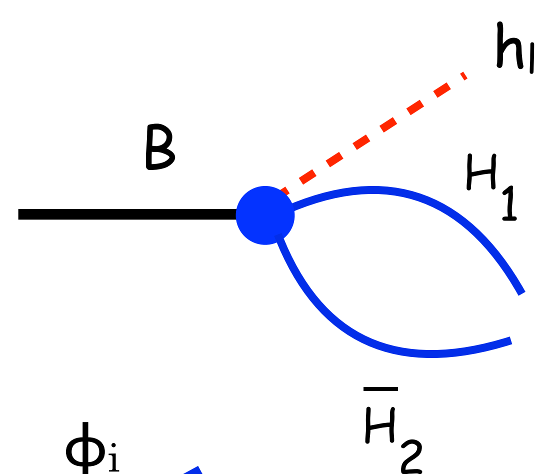


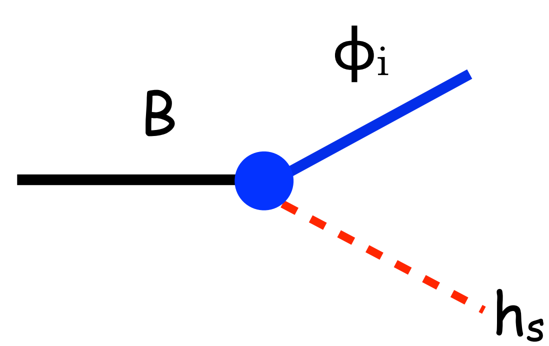
sequential (dominate terms)



    - Can compute using coupled channel formalism
  - B decays
    - More quantum numbers accessible







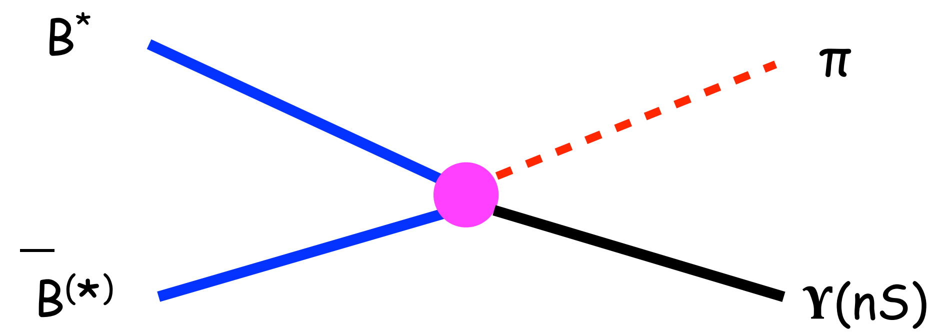
New Dynamics for Hadronic Transitions

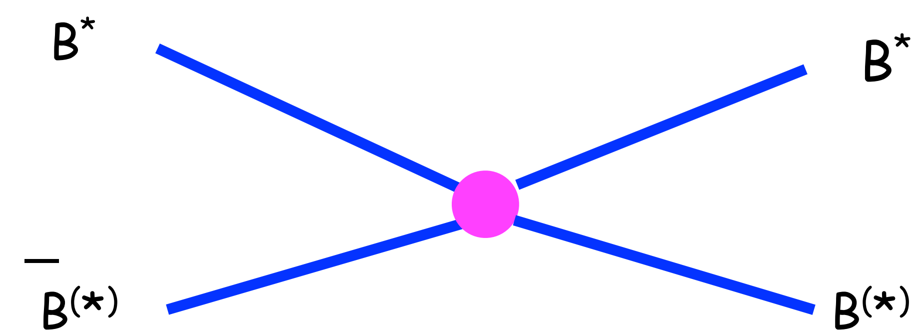
- Physical Expectations for Threshold Dynamics:

1. There is a large rescattering probability per unit time 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.

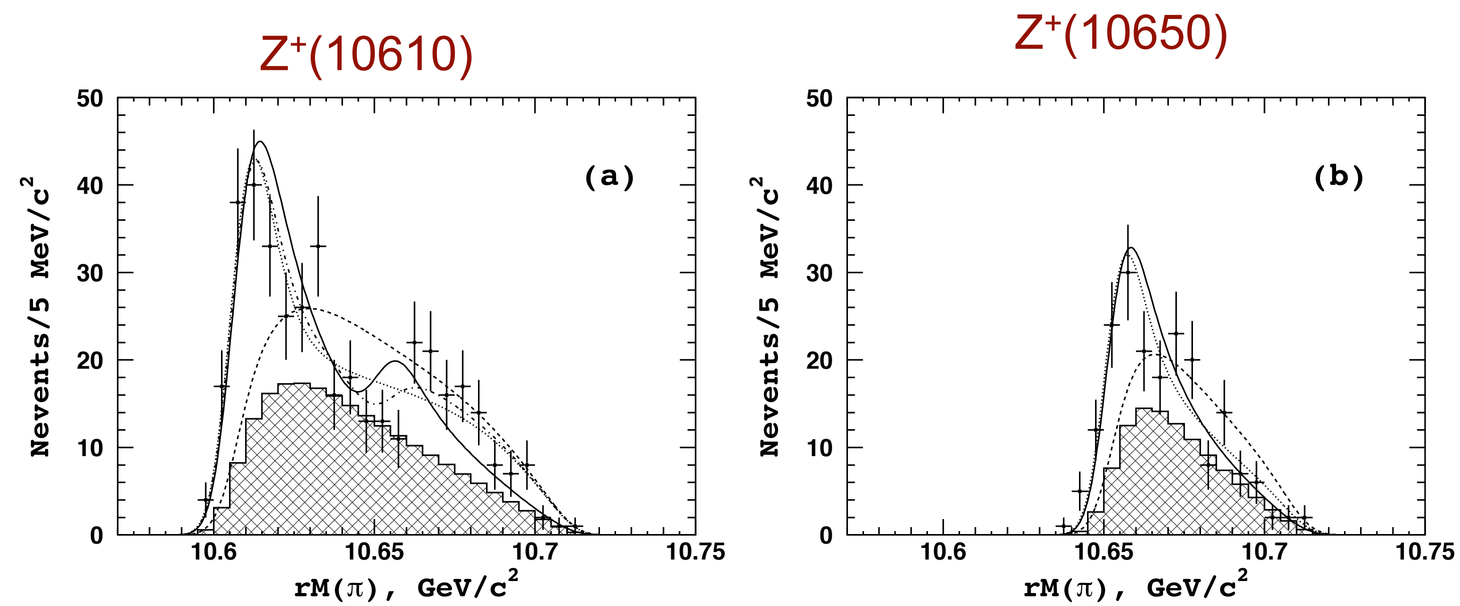




Ratios determined by LQCD calculations and judicious use of SU(3).
M. Padmanath, C. B. Lang and S. Prelovsek [arXix:1503.03257]

New Dynamics for Hadronic Transitions

- Strong threshold dynamics
  - Strong peaking at threshold BB* and B*B*
  - Z+(10610) and Z+(10650) states



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

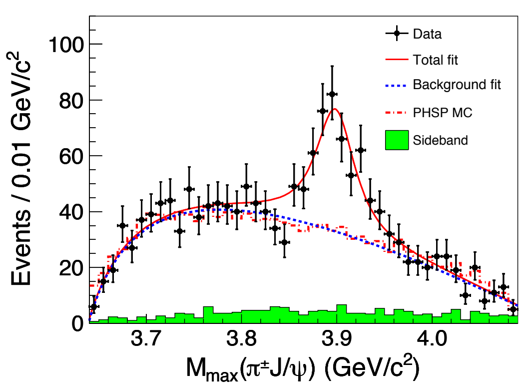
and

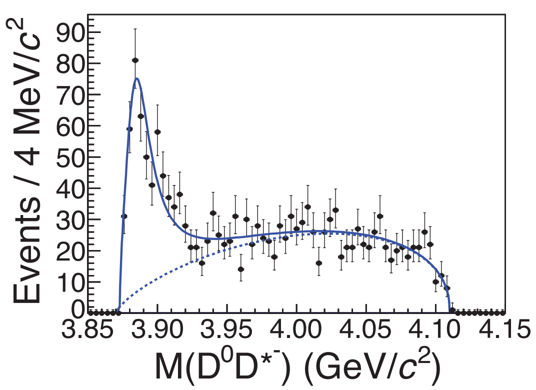
$$\frac{\mathcal{B}(Z_b(10650)\to B^*B^*)}{\sum_n \mathcal{B}(Z_b(10650)\to \Upsilon(nS)\pi)+\sum_m Z_b(10650)\to h_b(mP)} = 2.8\pm 0.4\pm 0.6^{+0.0}_{-0.4}.$$

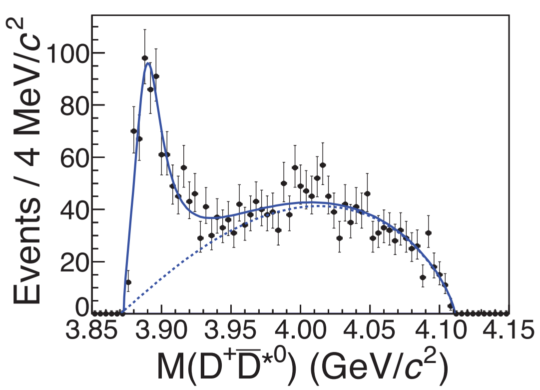
  - HQS implies that the same mechanism applies for charmonium-like states

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







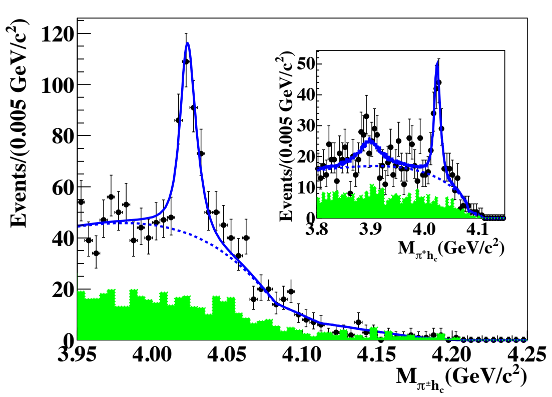
$$\frac{\Gamma[Z_c(3900) \to D D^*]}{\Gamma[Z_c(3900) \to \pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}.$$

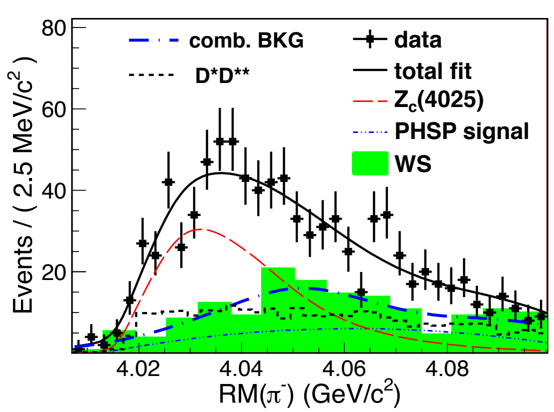
M(D^0+D^{*-}) = 3.8752

$$M_{\rm pole} = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$$
$$\Gamma_{\rm pole} = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$$

BESIII Z. Lin

[arXiv:1504.06102]





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

$$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}$$
$$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$

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

Hadronic Transitions Above Threshold

- Charmonium systems:
- Ψ(1D)
  - M = 3773.15 ± 0.33 MeV Γ = 27.2 ± 1.1 MeV;
  - Open decay channels:
    - $M(D^0 \bar{D}^0)$ = 3,729.72 MeV, $M(D^+D^-)$ = 3,739.26 MeV
  - Normal pattern

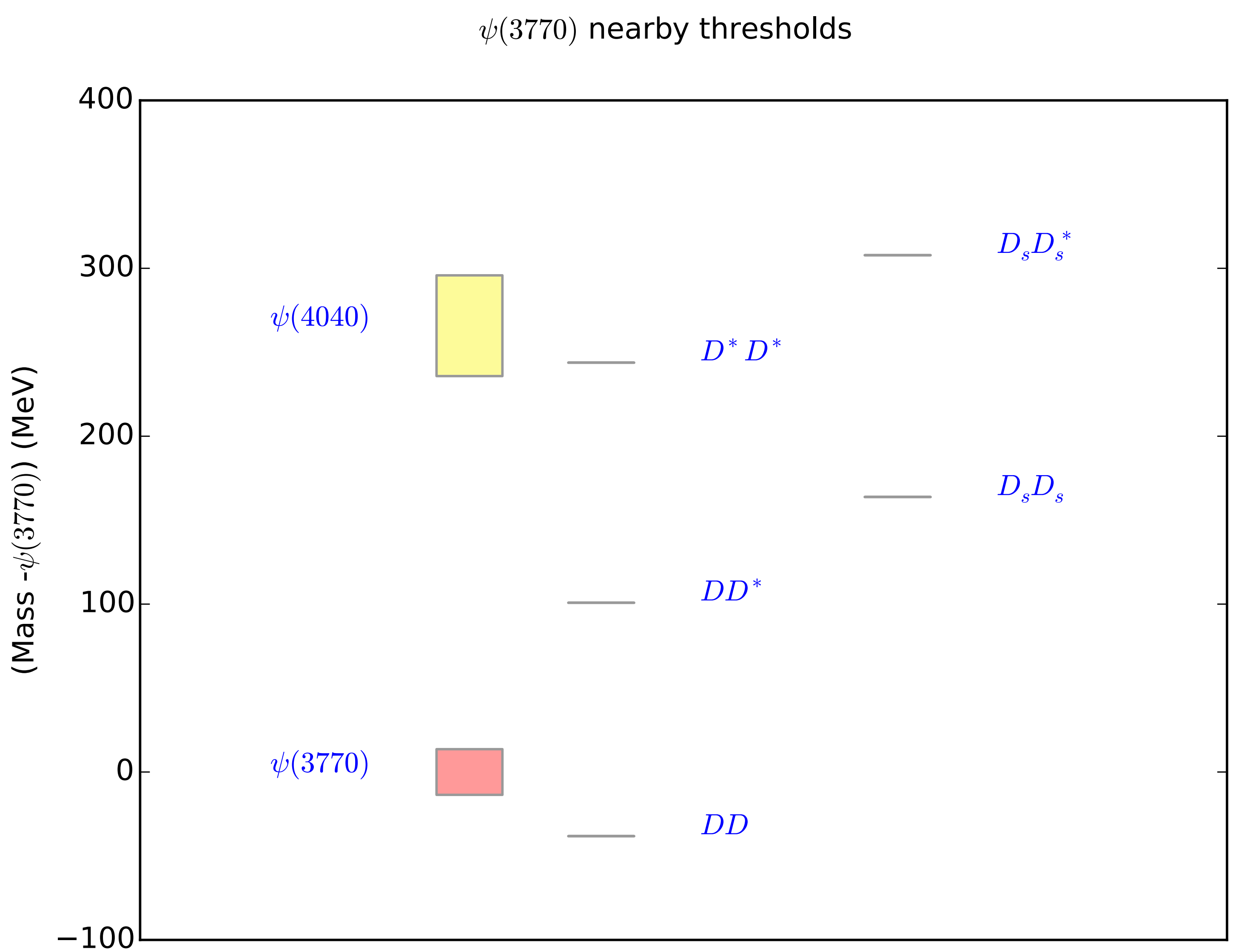
Decay Mode	Branching Rate
$D^0\bar{D}^0$	$(52 \pm 5)\%$
D^+D^-	$(41 \pm 4)\%$
total $D\bar{D}$	$93^{+8}_{-9}\%$
$\psi(1S)\ \pi^+\pi^-$	$(1.93 \pm 0.28) \times 10^{-3}$
$\psi(1S)\ \eta$	$(9 \pm 4) \times 10^{-4}$

—> partial rate = 52.5 ± 7.6 keV

  - Puzzle is the total $D\bar{D}$ branching fraction

Ψ(3770), Ψ(4040)

- Only ground state heavy-light meson pair decays allowed



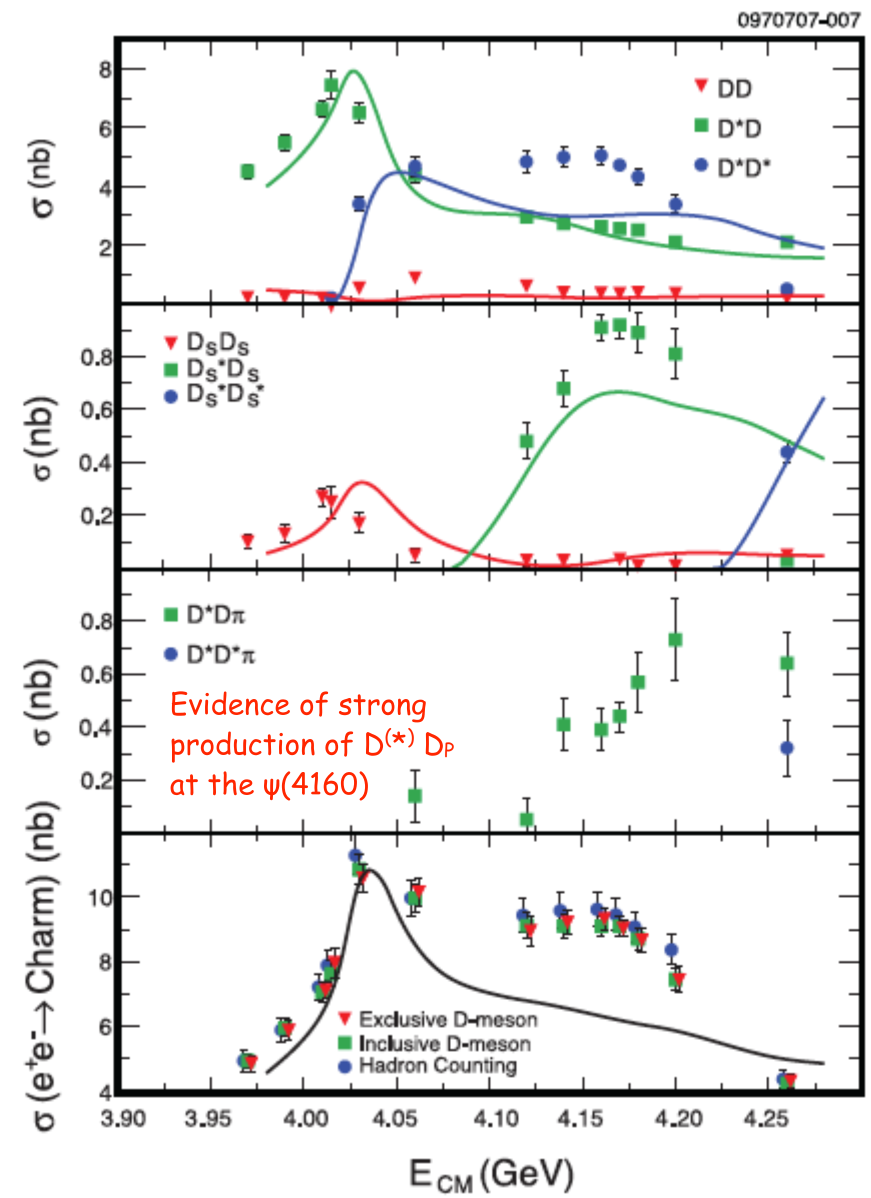
Hadronic Transitions Above Threshold

- Ψ(3S)
  - M = 4039 ± 1 MeV   Γ = 80 ± 10 MeV;
  - Open decay channels:
    - $M(D^0\overline{D}^0)$ = 3,729.72 MeV, $M(D^+D^-)$ = 3,739.26 MeV
    - $M(D^0\overline{D}^{*0})$ = 3,871.85 MeV, $M(D^+D^{*-})$ = 3,879.92 MeV
    - $M(D_s^+D_s^-)$ = 3,937. MeV
    - $M(D^{*0}\overline{D}^{*0})$ = 4,013.98 MeV, $M(D^{*+}D^{*-})$ = 4,020.58 MeV

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

Decay Mode	Branching Rate
$D*\bar{D}*$	
$D_s^+D_s^- * +c.c.$	
$DD*$	$\frac{\Gamma(D*\bar{D}+c.c.)}{\Gamma(D*\bar{D}*}=0.34\pm0.14\pm0.05$
$D\bar{D}$	$\frac{\Gamma(D*\bar{D}+c.c.)}{\Gamma(D*\bar{D}*)}=0.02\pm0.03\pm0.02$
$\psi(1S)\ \eta$	$(5.2\pm0.7)\times10^{-3}$

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

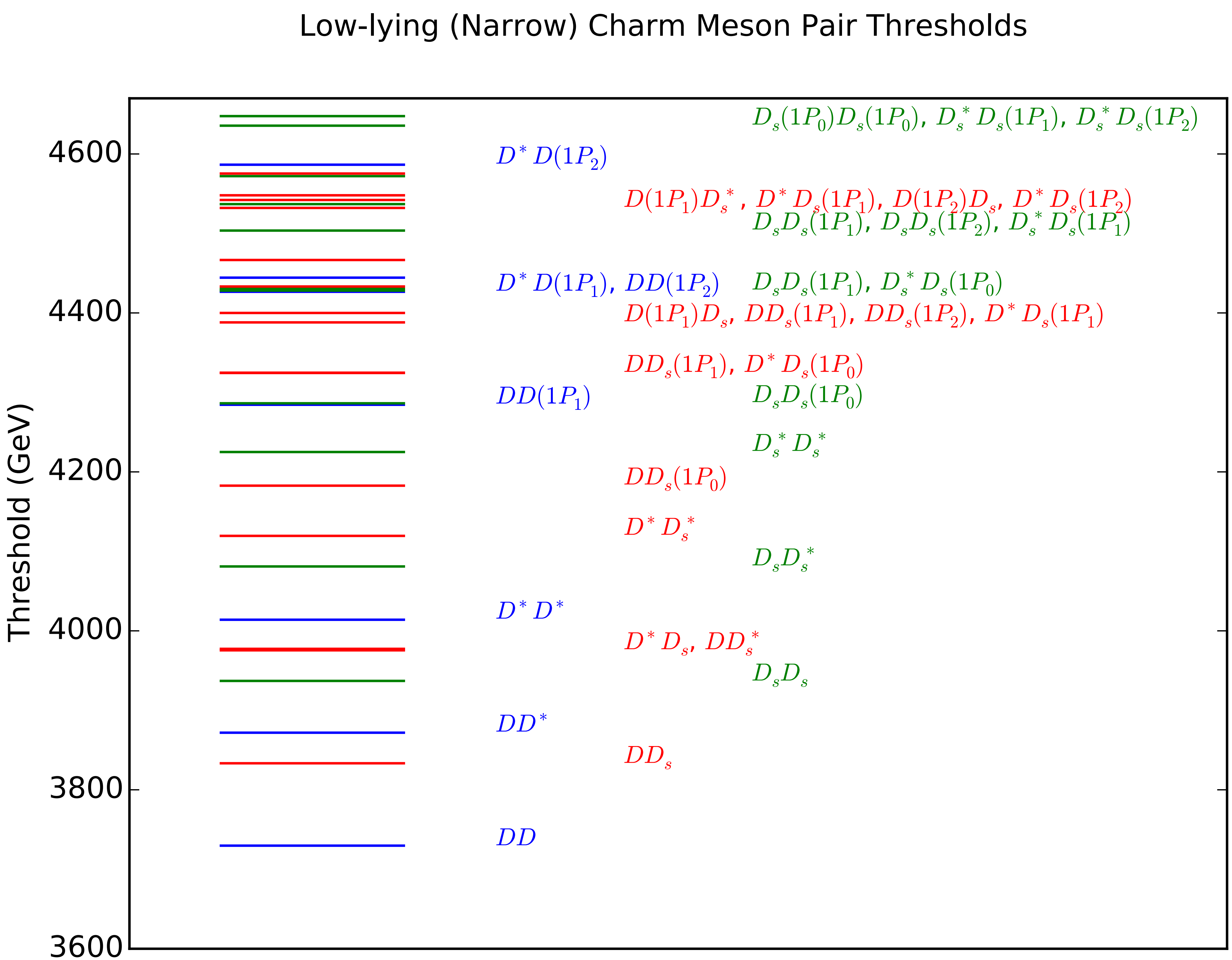


Systematics: ψ(4040) and Below

- 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



Narrow-Wide Thresholds

D_s^* $D(P_1)$

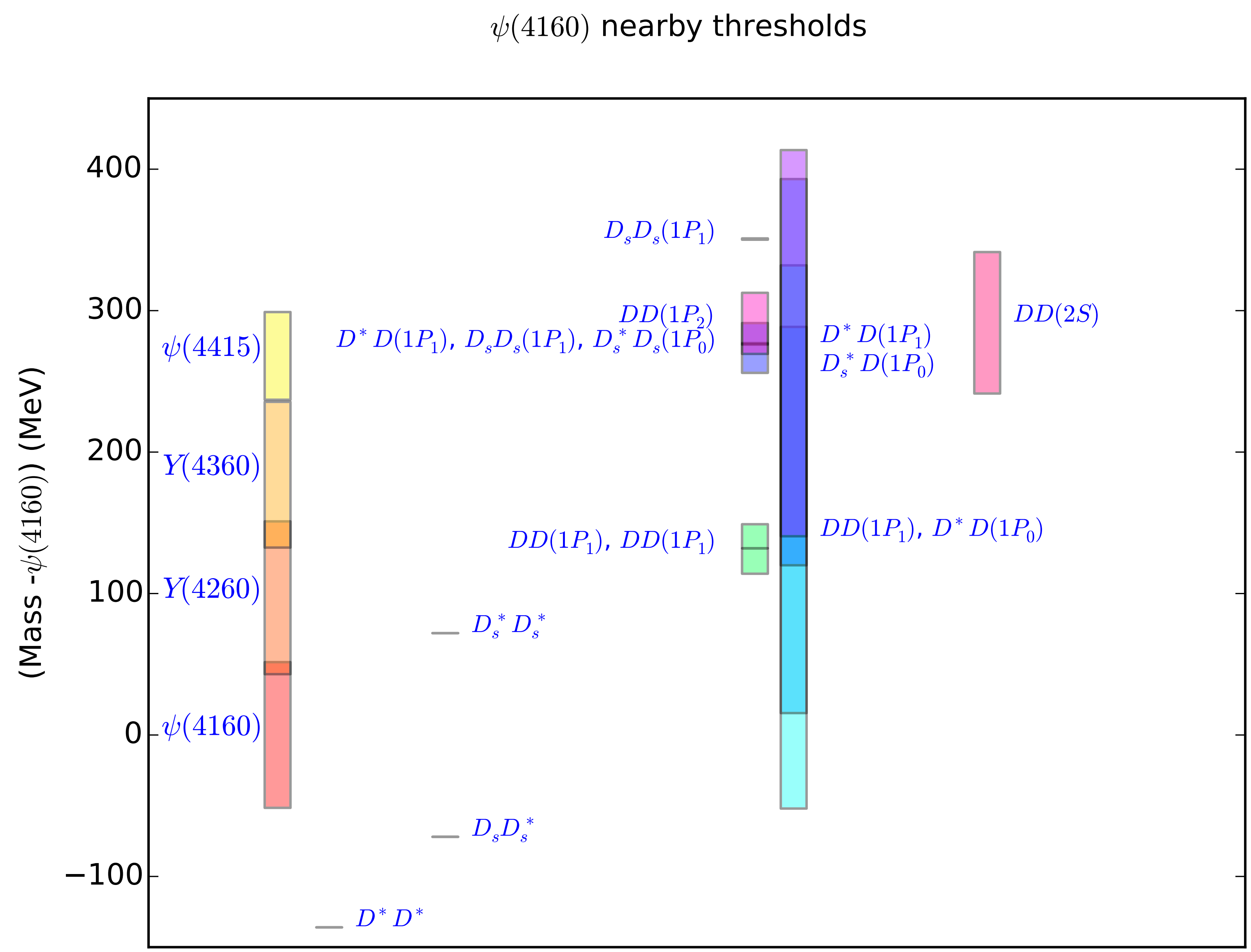
D_s $D(P_1)$; D_s^* $D(P_0)$

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

D $D(P_0)$

Systematics: Ψ(4160), Ψ(4415)

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



Hadronic Transitions Above Threshold

- 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
$DD_2^*(\bar{2}460)$	$(10 \pm 4)\%$
$\eta J/\psi$	$< 6 \pm 10^{-3}$

  - Would be nice to see more study here.

Systematics: Ψ(4160), Ψ(4415)

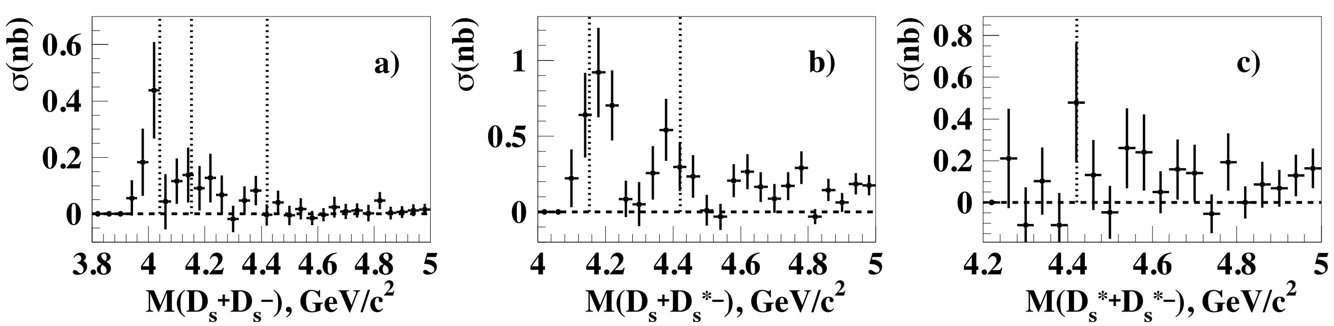
- Charmonium-like state transitions for masses above the ψ(3S)

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^{--}	2^3D_1
	$\eta J/\psi$			
$Z(4200)^+$	$4196\ {}^{81}_{-29}\ {}^{+17}_{-13}$	$370 \pm 70\ {}^{+70}_{-132}$	1^+	
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	
	$\pi^+\pi^- J/\psi$			
	$\pi^0\pi^0 J/\psi$			
	$K^+\ K^- J/\psi$			
	$\gamma X(3872)$			
$X(4350)$	$4350.6 \pm 4.6/5.1 \pm 0.7$	$13 \pm 18/9 \pm 4$	$2^{++}/0^{++}$	3^3P_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^{--}	4^3S_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^{--}	
	$\pi^+\pi^-\psi(2S)$			
	$\eta J/\psi$			
	$\pi^\pm(D\bar{D}^*)^\mp$			

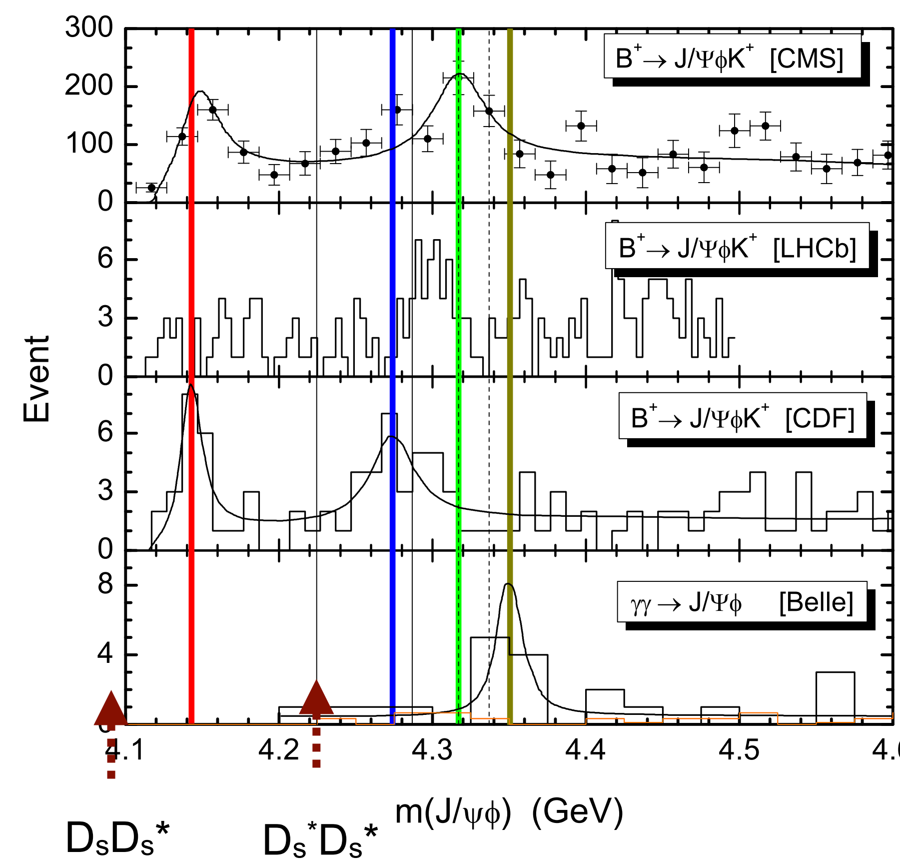
Strange heavy-light meson thresholds

- 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]



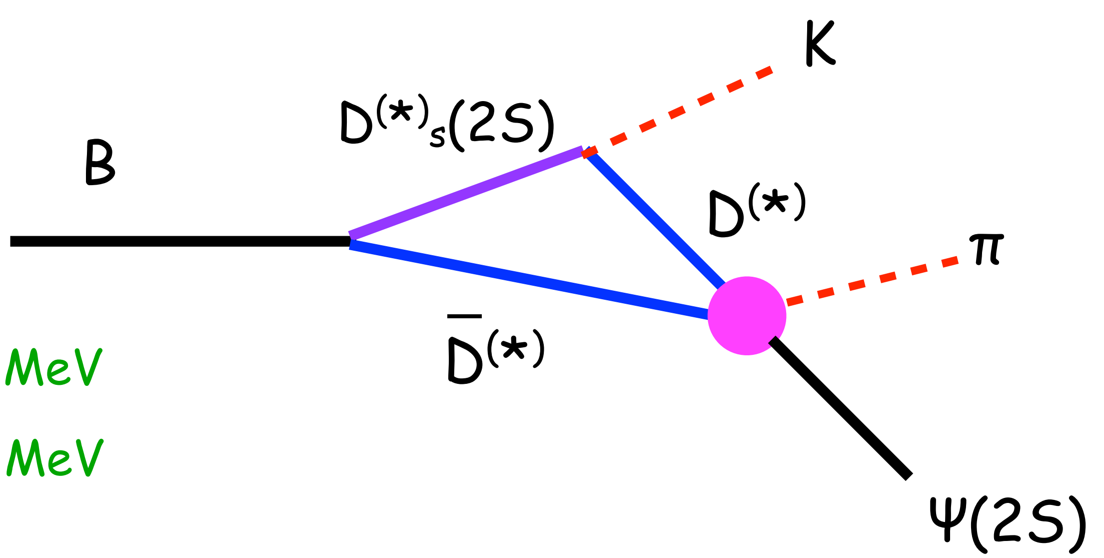
  - No wide P-states -> no sequential transitions with these states.
  - $M(D_s^+ D_s^{-*})$ = 4,081 MeV, $M(D_s^{+*} D_s^{-*})$ =4,225 MeV; $M(3^3P_2)$ = 4,315 MeV
  - Direct transitions?
  - Narrow D($\frac{1}{2}^+$P) + D($\frac{1}{2}^-$S) thresholds? (and B analogs)
  - At higher energies the D_s(2S) wide states could play a role in sequential transitions.



Systematics: Other States

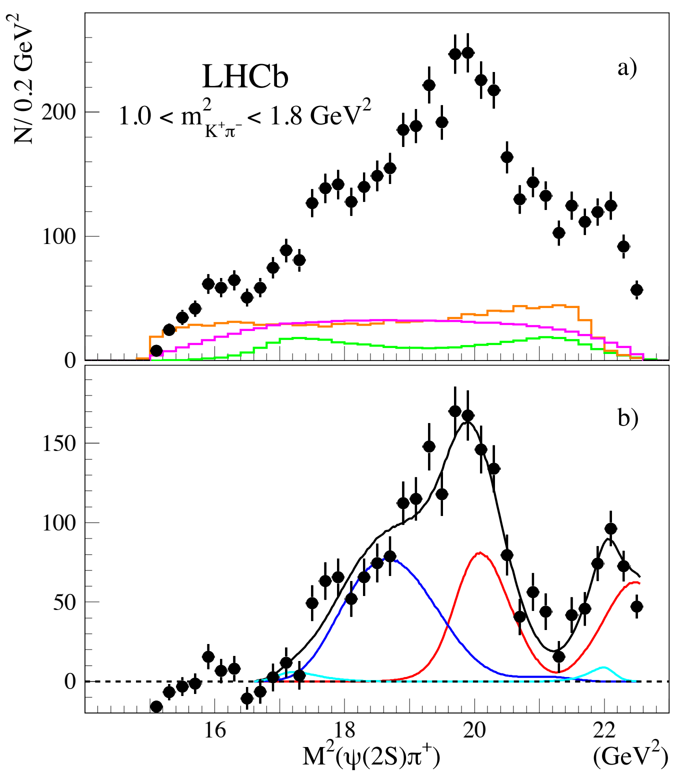
- Same mechanism in B-decays with $2S_{\{0,1\}}(D_s)$ states: $Z^+(4430)$
  - $D_s^*(2S)$ M = 2,709 ± 4 MeV Γ = 117 ± 13 MeV
  - $D_s(2S)$ M = 2,610-2660 MeV
  - Relevant open thresholds:
    - M(D D(2S)) = 4,449 MeV; M(D D*(2S)) = 4,519 MeV
    - M(D*D(2S)) = 4,586 MeV; M(D*D*(2S)) = 4,659 MeV

P. Pakhlov [arXiv:1105.2945]



P. Pakhlov and T. Uglov

[arXiv:1408.5295]



Summary

- Many new features appear above heavy flavor production threshold: Strong decays, new states and surprising hadronic transitions.
- The usual QCDME fails.
  - The transitions rate are much larger than expected.
  - 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. Magnetic transitions not suppressed.
  - A new mechanism for hadronic transitions is required.
- A new mechanism, in which the dynamics is factored differently, is proposed.
  - It requires an intermediate state containing two narrow heavy-light mesons nearby and near threshold (v -> zero). This is the factor. Other light hadrons may be present or not.
    - The production of this state from the initial state is calculated using familiar strong dynamics of coupled channels.
    - The evolution of this threshold system into the final quarkonium state and light hadrons requires a new threshold dynamics.
- HQS as well as the usual SU(3) and chiral symmetry expectations are recovered.
- The puzzles in η transitions resolved.
- With BES III and LHCb and soon BELLE 2. I expect even more progress in understanding hadronic transitions in the near future.