Hadronic Transitions and Quarkonium-like States Near Threshold

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Outline:

- Revisiting the QCD Multipole Expansion
- Hadronic Transitions Above Threshold
- New Dynamics for Hadronic Transitions
- Systematics and Expectations
- Summary

6th Workshop of the APS Topical
Group on Hadronic Physics

April 8-10, 2015, Baltimore, MD

Revisiting the QCDME Assumptions

- QCD multipole expansion (QCDME) in a nutshell
  - *Analogous to the QED multipole expansion with gluons replacing photons.*

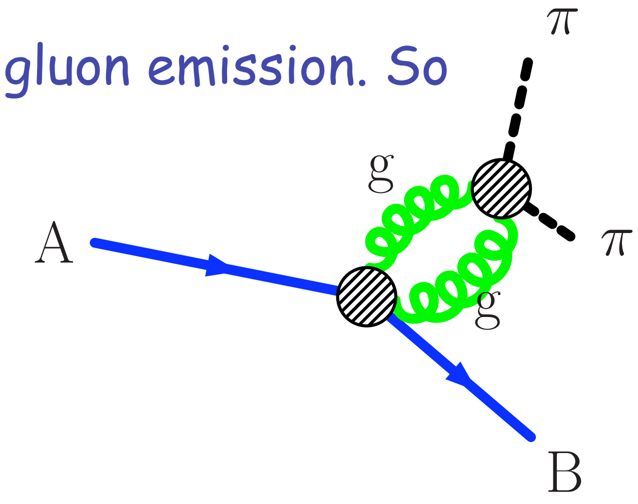
$$H^{\rm eff}_{\rm QCD} = H^{(0)}_{\rm QCD} + H^{(1)}_{\rm QCD} + H^{(2)}_{\rm QCD} \qquad H^{(1)}_{\rm QCD} \equiv Q_a A^a_0(\mathbf{X}, t)$$

zero for color singlet

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

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

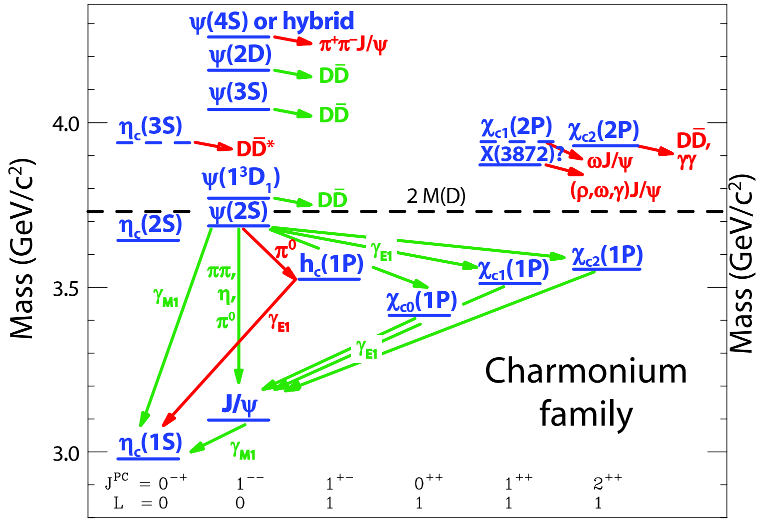
$$\mathcal{M}(\Phi_i \to \Phi_f + h) = \frac{1}{24}\sum_{KL} \frac{\langle f|d^{ia}_m|KL\rangle\langle|KL|d^j_{ma}|i\rangle}{E_i - E_{KL}} \langle h|\mathbf{E}^{ai}\mathbf{E}^j_a|0\rangle$$

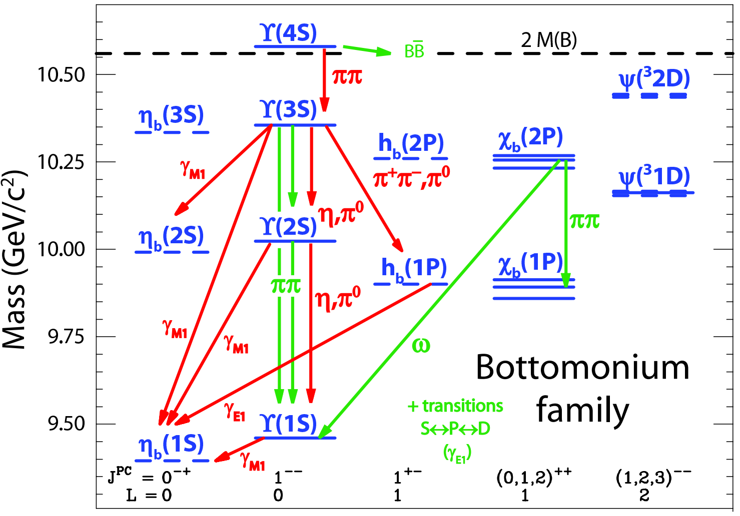
+ higher order multipole terms.

  - assume a model for the heavy quarkonium states Φi, Φf and a model for the intermediate states |KL> hybrid states.
  - use chiral effective lagrangians to parameterize the light hadronic system.

QCD Multipole Expansion

- Below threshold this theory works well to describe the hadronic transitions.





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

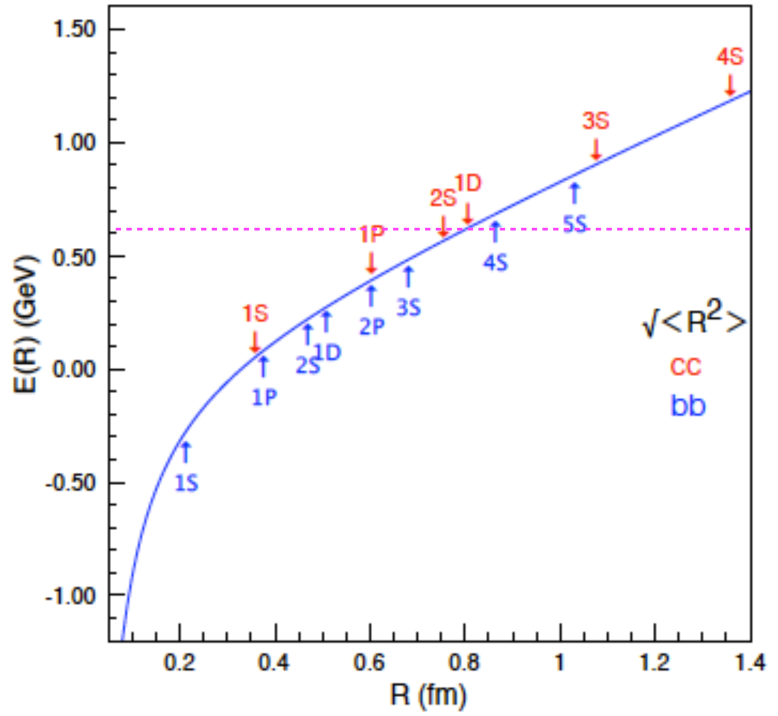
Transition	Γ_{partial} (keV) (Experiment)	Γ_{partial} (keV) (KY Model)
$\psi(2S)$		
$\to J/\psi + \pi^+\pi^-$	102.3 ± 3.4	input ($\lvert C_1 \rvert$)
$\to J/\psi + \eta$	10.0 ± 0.4	input (C_3/C_1)
$\to J/\psi + \pi^0$	0.411 ± 0.030 [446]	0.64 [522]
$\to h_c(1P) + \pi^0$	0.26 ± 0.05 [47]	0.12-0.40 [527
$\psi(3770)$		
$\to J/\psi + \pi^+\pi^-$	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]

- 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.

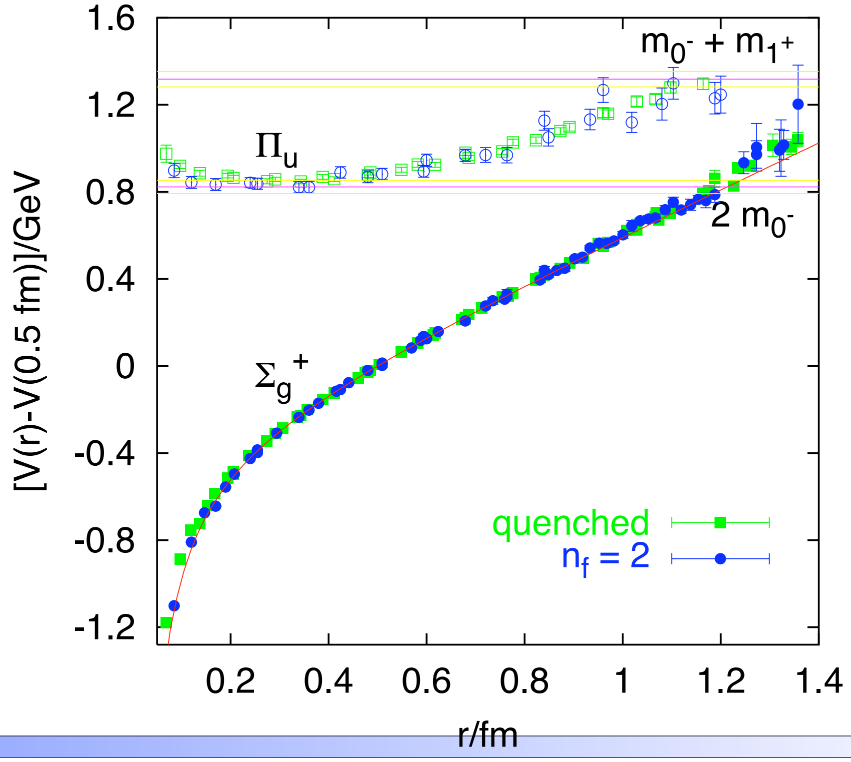
QCD Multipole Expansion (QCDME)

- When should the QCDME work well ?
  - Transitions between tightly bound quarkonium states
  - Small radius ($R \ll \Lambda_{QCD}$)
    - bottomium 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
    - $D^{(*)}\,\overline{D}^{(*)}$ thresholds in 1D to 3S region
    - $B^{(*)}\,\overline{B}^{(*)}$ thresholds in 4S region
  - gluonic string excitations
    - Hybrid states will appear in the spectrum 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



$D\overline{D}$, $B\overline{B}$



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, $M(B^0\bar{B}^0)$ = 10,579.16 MeV
    - Essentially no isospin breaking in the masses.
  - Normal pattern of 2π decays, large η decays:

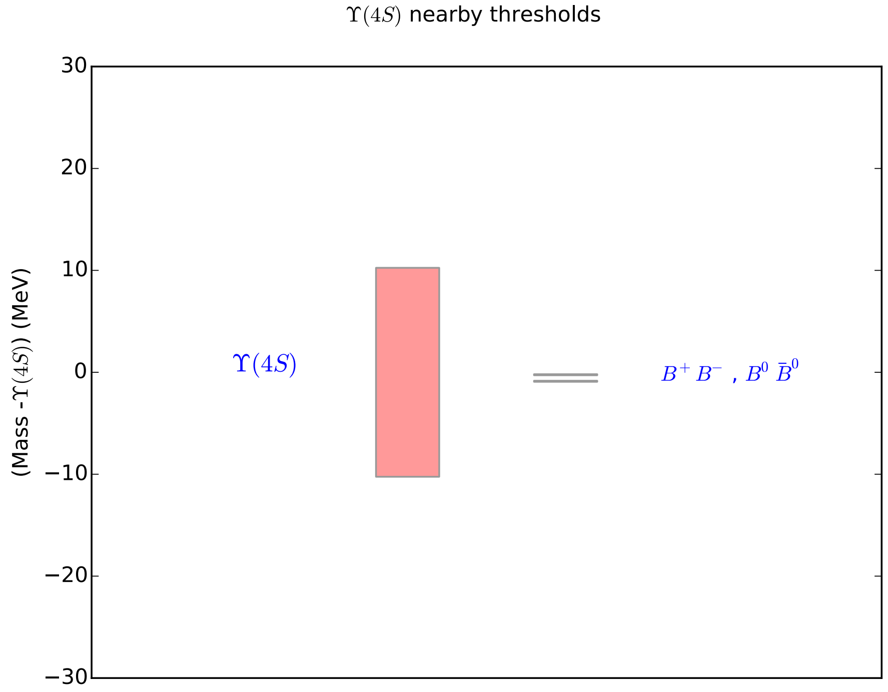


Table 1: Selected $\Upsilon(4S)$ decays.

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

—> partial rate = 1.66 ± 0.23 keV

—> partial rate = 37.5 ± 7.3 keV

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]

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

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

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

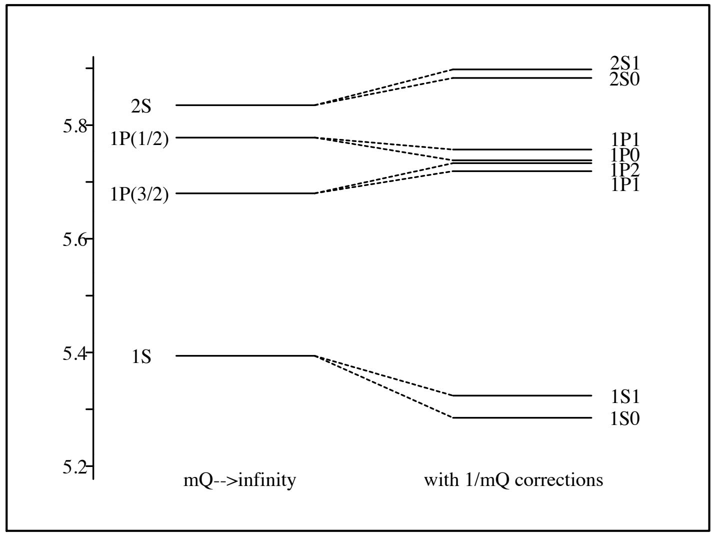
  - $I^G\,(J^P) = 1^-\,(1^+)$
    - S-wave (L=0)

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

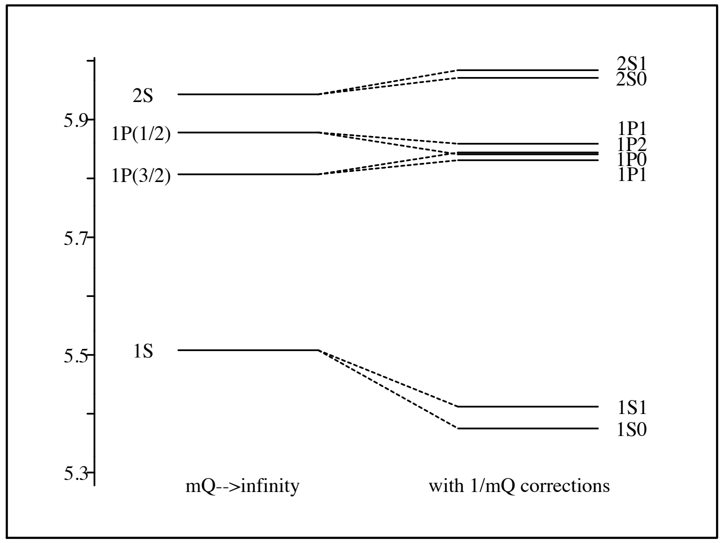
$$
B^*\bar{B}^* \sim \frac{1}{\sqrt{2}}\left(0_H^- \otimes 1_{SLB}^- - 1_H^- \otimes 0_{SLB}^-\right)\ ,
$$

Hadronic Transitions Above Threshold

- $\Upsilon(5S)$ hadronic transitions
  - M = 10,876 ± 11 MeV Γ = 55 ± 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
    - $M(B[1^{\frac{1}{2}+}P_0]B^*) = 11{,}055$ MeV (notation: $n^{j^P}L_J$)
    - $M(B[1^{\frac{1}{2}+}P_1]B) = 11{,}045$ MeV, $M(B[1^{\frac{1}{2}+}P_1]B^*) = 11{,}091$ MeV
  - I have assumed: $\Gamma(B[1^{\frac{1}{2}+}P_{\{0,1\}}])$ ~ 300 MeV (wide); $\Gamma(B[1^{3/2+}P_{\{1,2\}}])$ are narrow

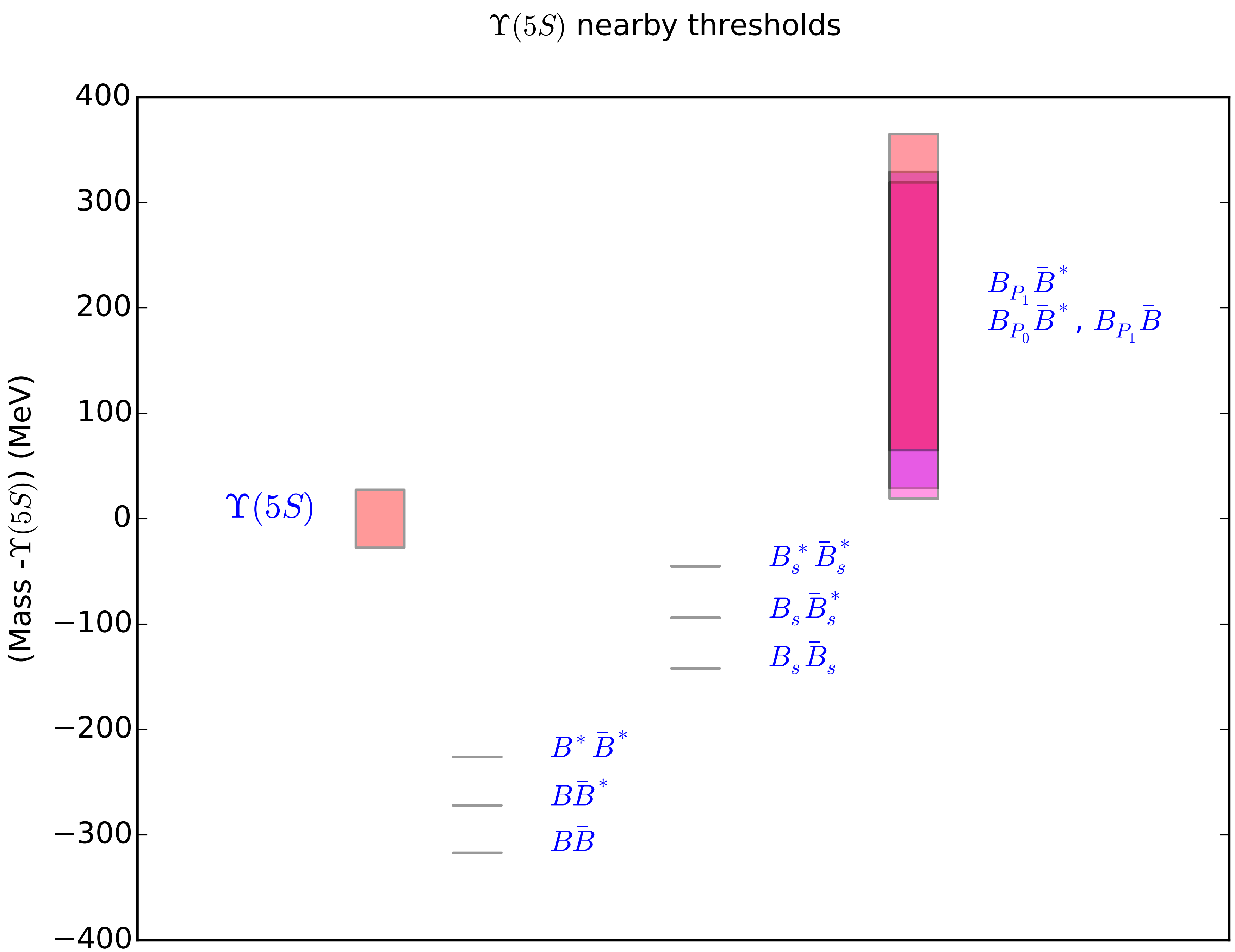


B



B_s

Hadronic Transitions Above Threshold



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?

Hadronic Transitions Above Threshold

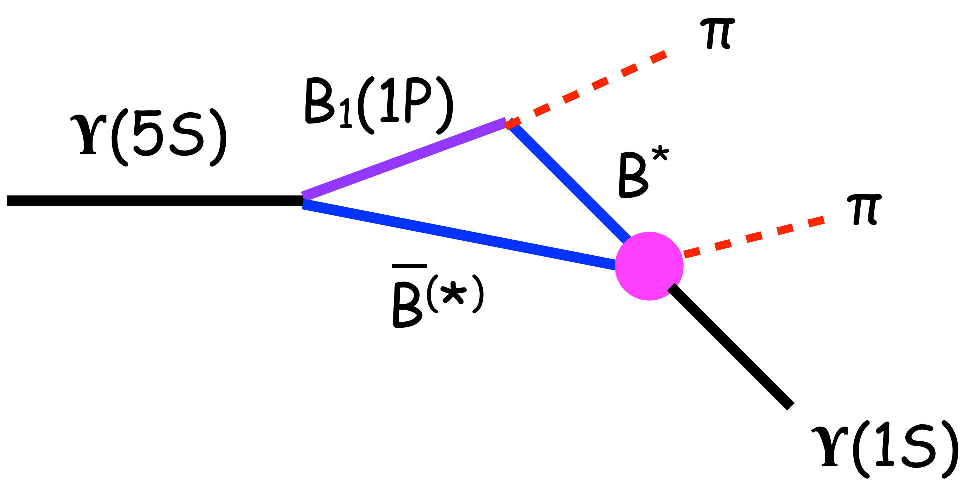
- Contributions of P-state decays:
  - $n^3S_1(Q\overline{Q})$ -> $1^{\frac{1}{2}+}P_J(Q\overline{q})$ + $1^{\frac{1}{2}-}S_{J'}(q\overline{Q})$:

S-wave decays

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

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

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

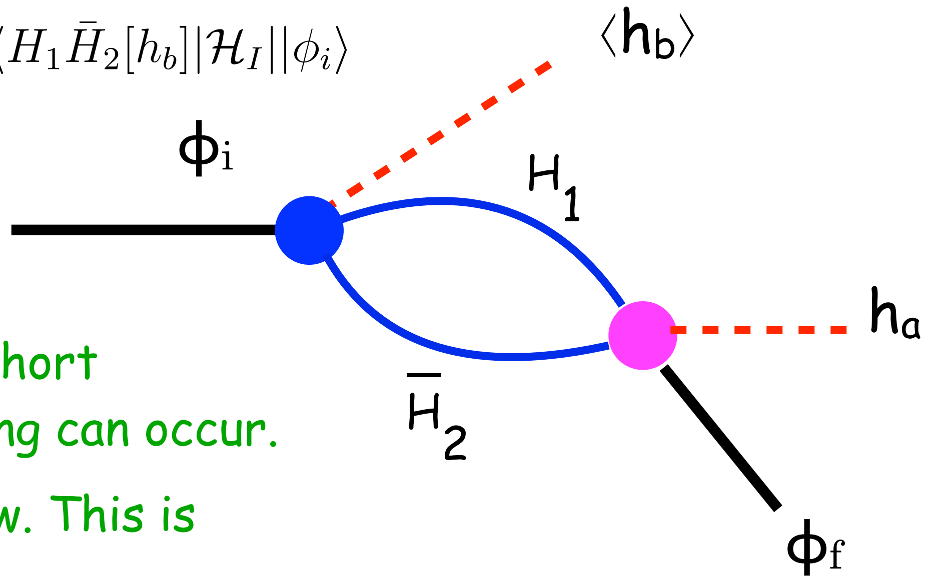
(4) Therefore the $B^{(*)}$ B^* system is in a relative S-wave and near threshold.

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

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



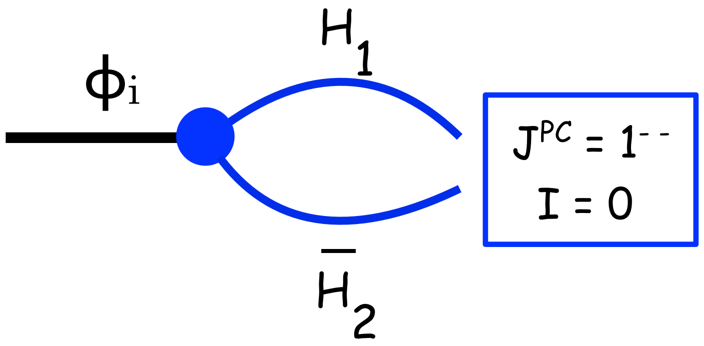
  - The time scale of the production process has to be short relative to the time scale over with H_1 H_2 rescattering can occur.
  - The relative velocity in the H_1 H_2 system must be low. This is only possible near threshold.

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

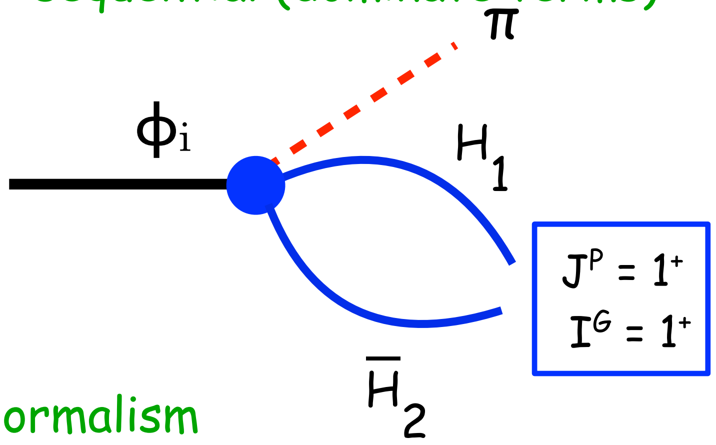
F.K. Gao, C. Hanhart, Q. Wang, Q. Zhao [arXiv:1411.5584]

New Dynamics for Hadronic Transitions

- Production modes
  - e+e-
    - direct

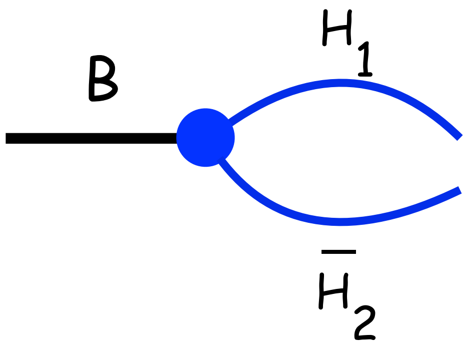


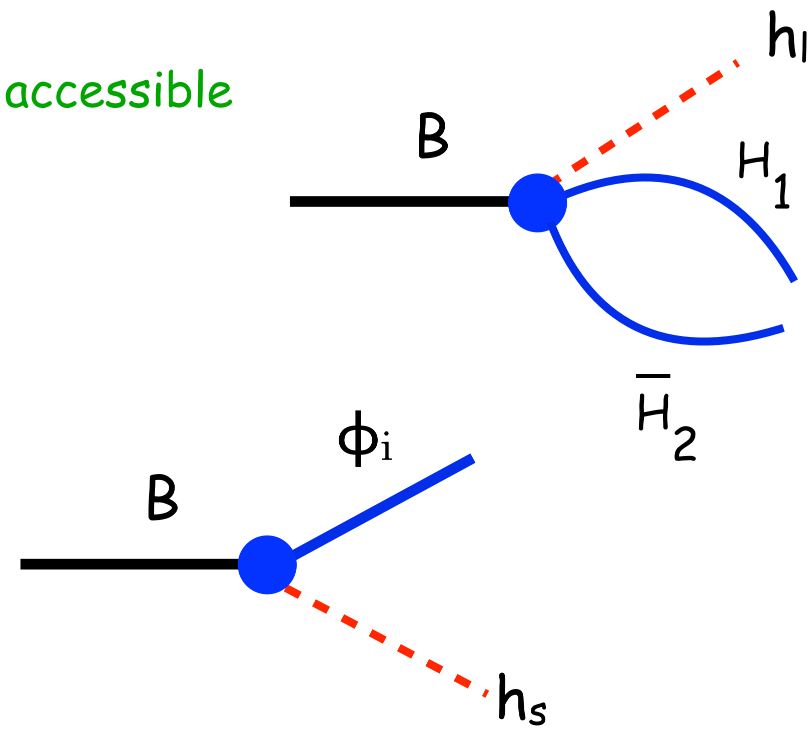
sequential (dominate terms)



- Can compute using coupled channel formalism

  - B decays
    - More quantum numbers accessible





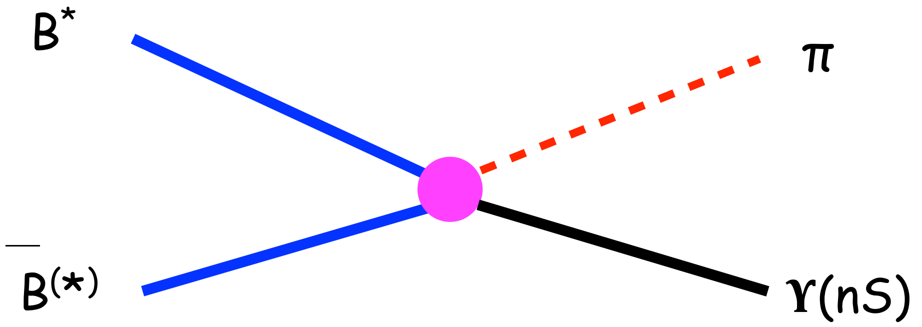
New Dynamics for Hadronic Transitions

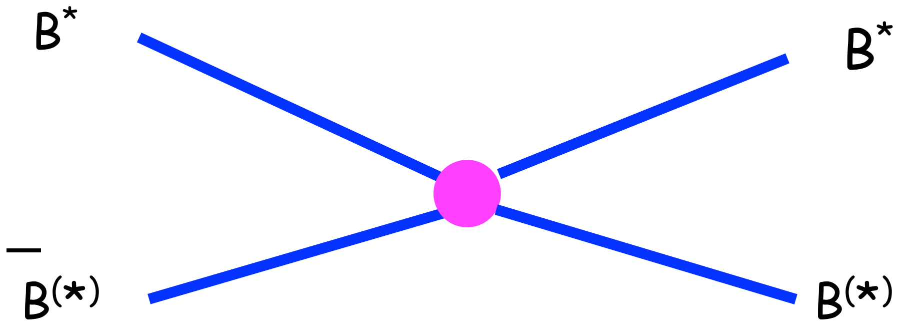
- Physical Expectations for Threshold Dynamics:

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.

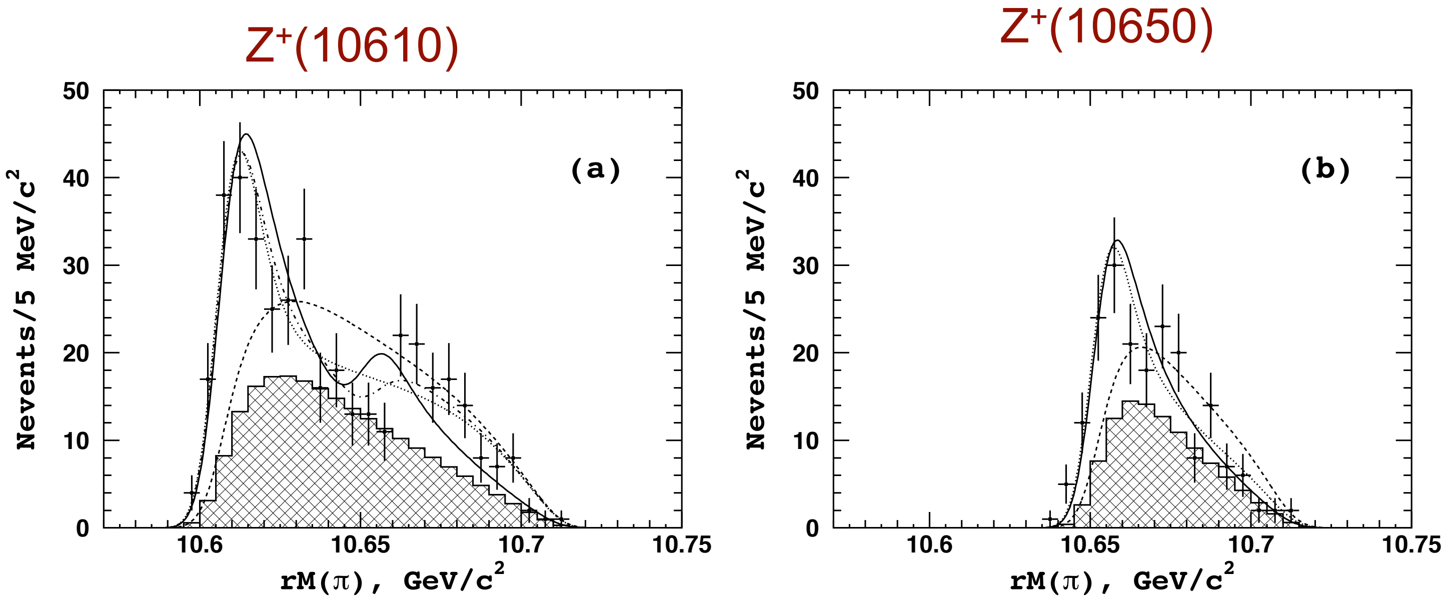
3. For sequential decays: the strong scattering dynamics of two narrow heavy-light mesons is peaked near threshold for S-wave initial states.





New Dynamics for Hadronic Transitions

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



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

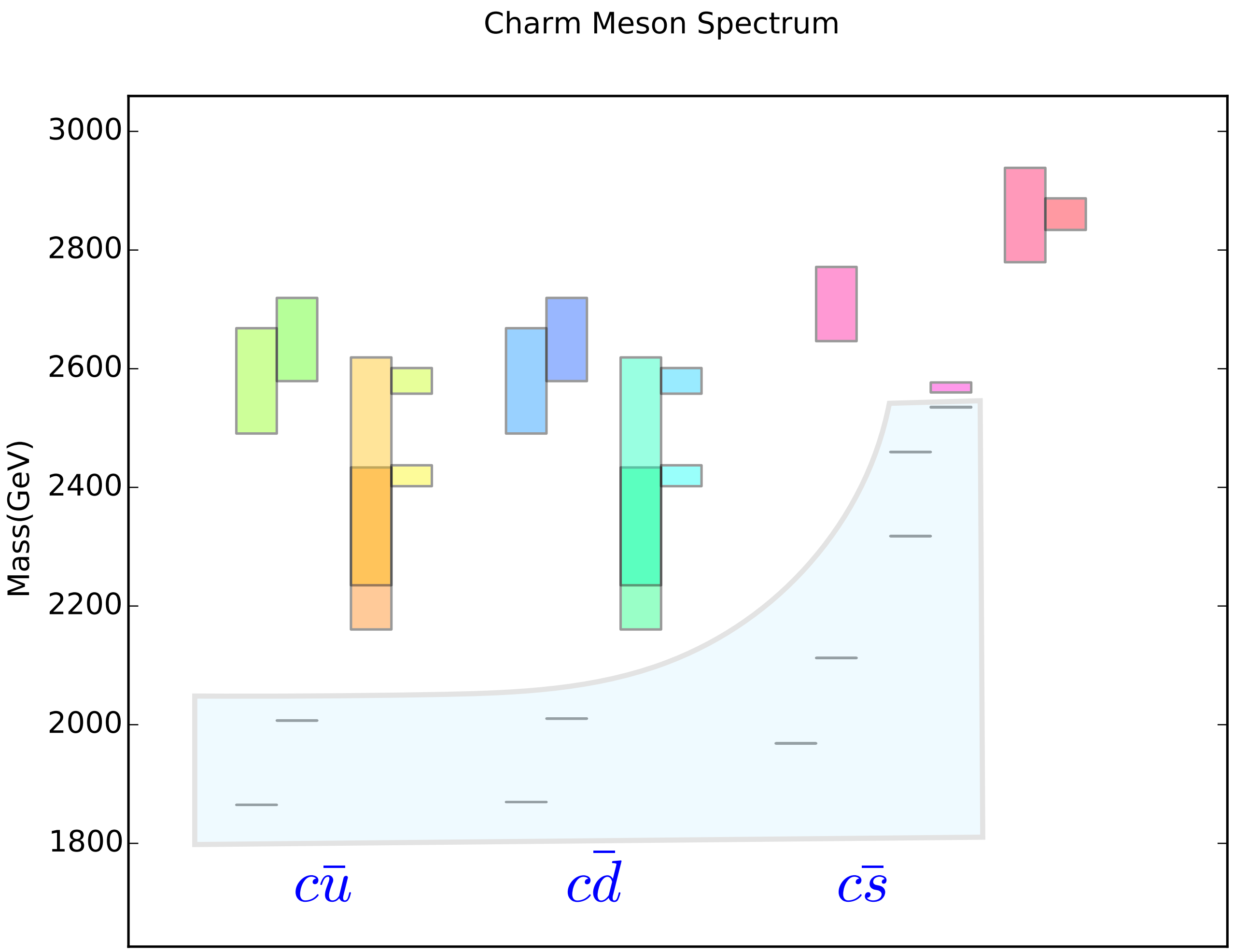
and

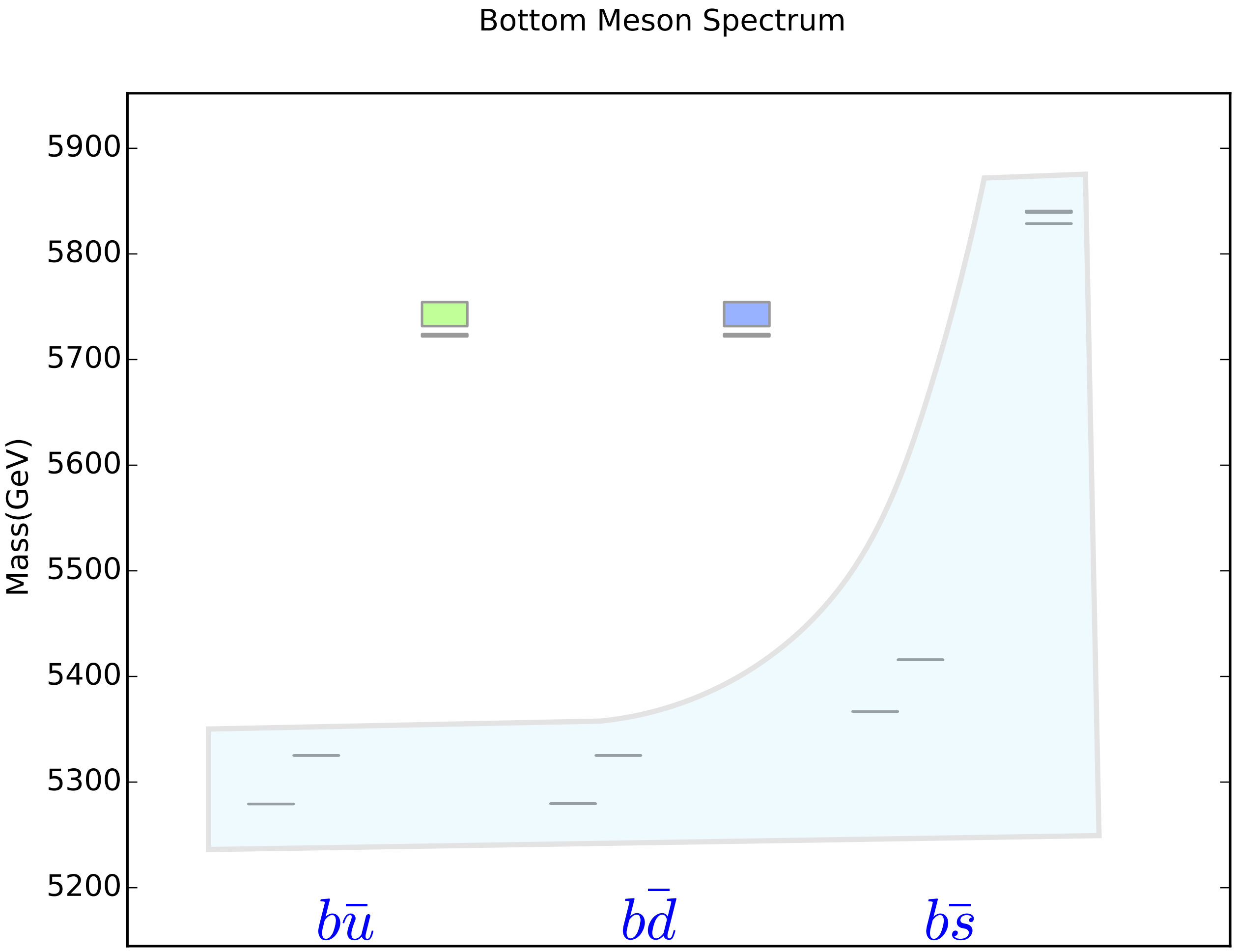
$$\frac{\mathcal{B}(Z_b(10650)\to B^*B^*)}{\sum_n \mathcal{B}(Z_b(10650)\to \Upsilon(nS)\pi)+\sum_m Z_b(10650)\to h_b(mP)} = 2.8\pm 0.4\pm 0.6^{+0.0}_{-0.4}.$$

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

Heavy-Light Mesons

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

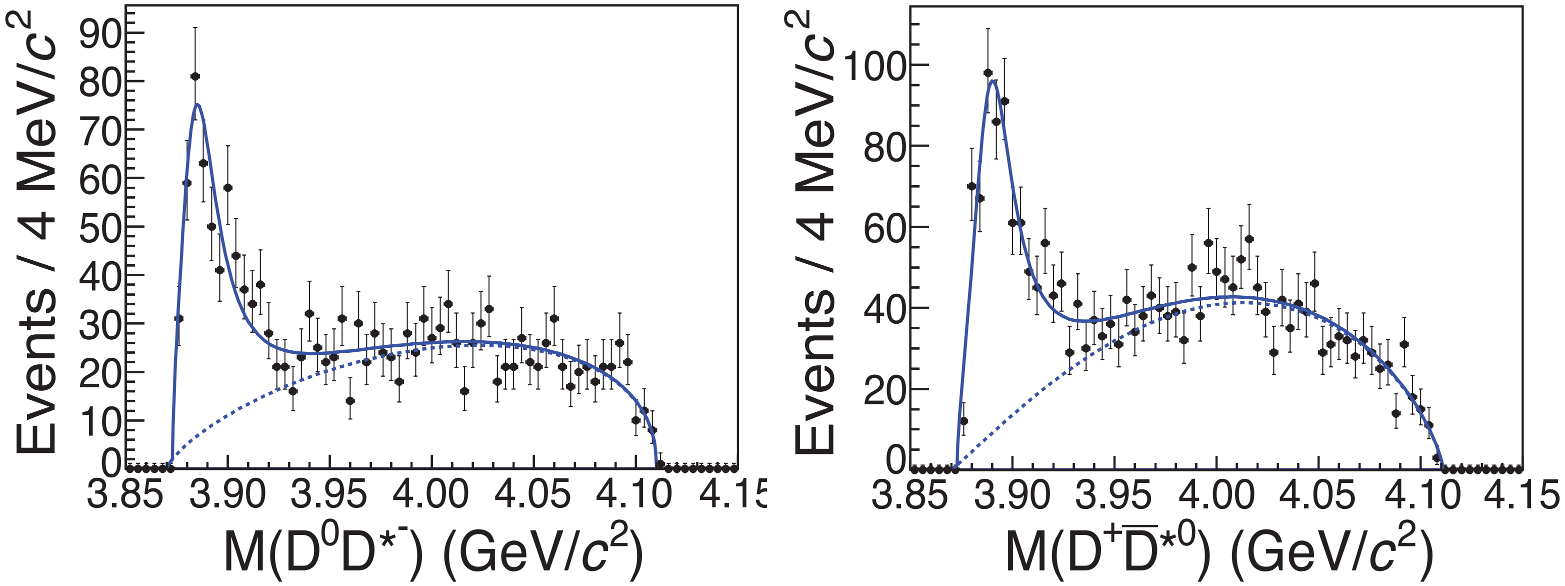




- There are 9 narrow (< 2 MeV) charm meson states [and 10 bottom mesons states]. Any pair of these might have a cusp at S-wave threshold.
- The wide states can originate sequential decay chains.

Systematics and Expectations

- 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



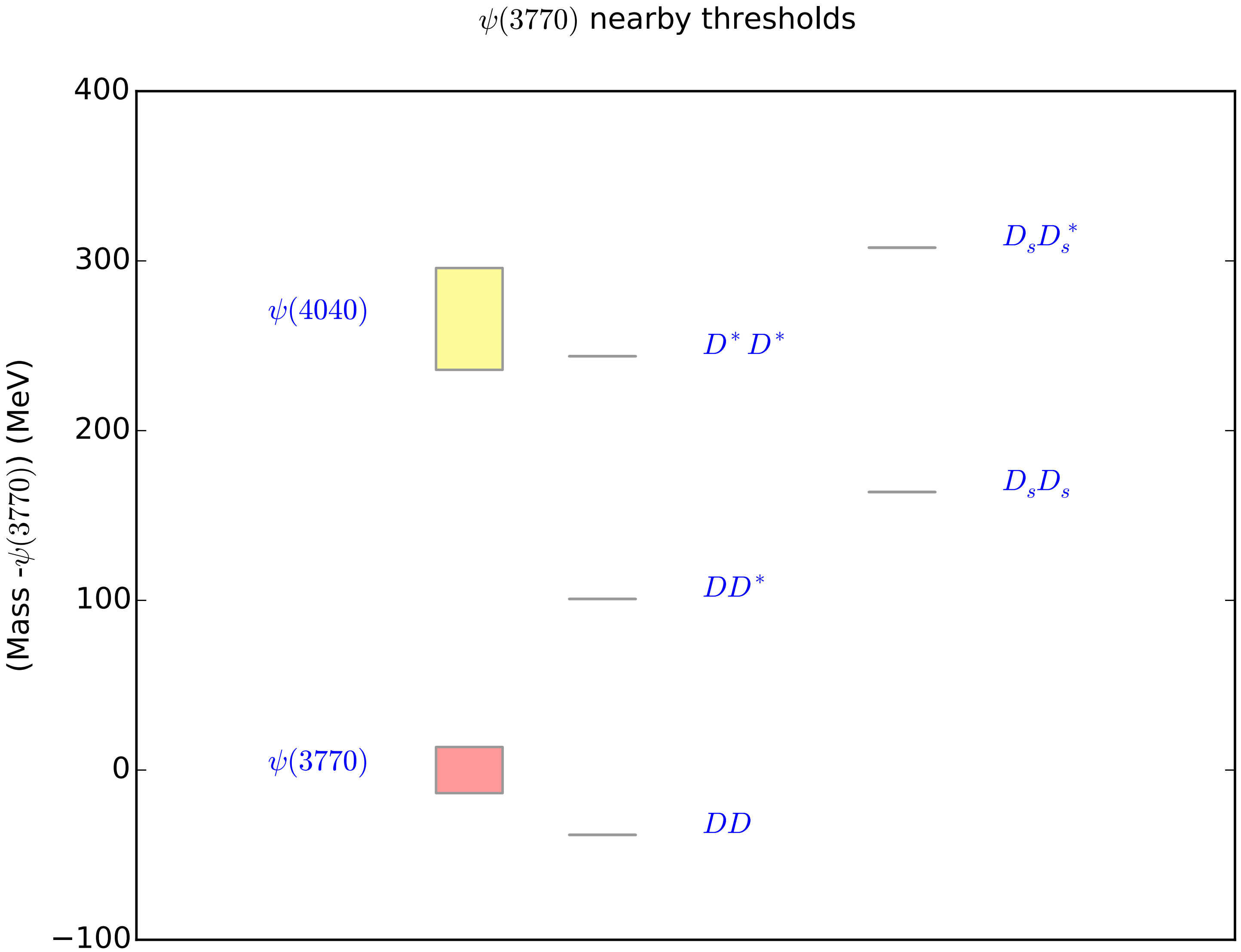
BES III

[arXiv:1310.1163]

$$\frac{\Gamma(Z_c(3885) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 1.1 \ \ \pm 2.7$$

Ψ(3770), Ψ(4040)

- Only ground state heavy-light meson pair decays allowed



Systematics and Expectations

- Charmonium systems:
- Ψ(1D)
  - M = 3773.15 ± 0.33 MeV   Γ = 27.2 ± 1.1 MeV;
  - Open decay channels:
    - M($D^0\overline{D^0}$) = 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 $D\overline{D}$ branching fraction

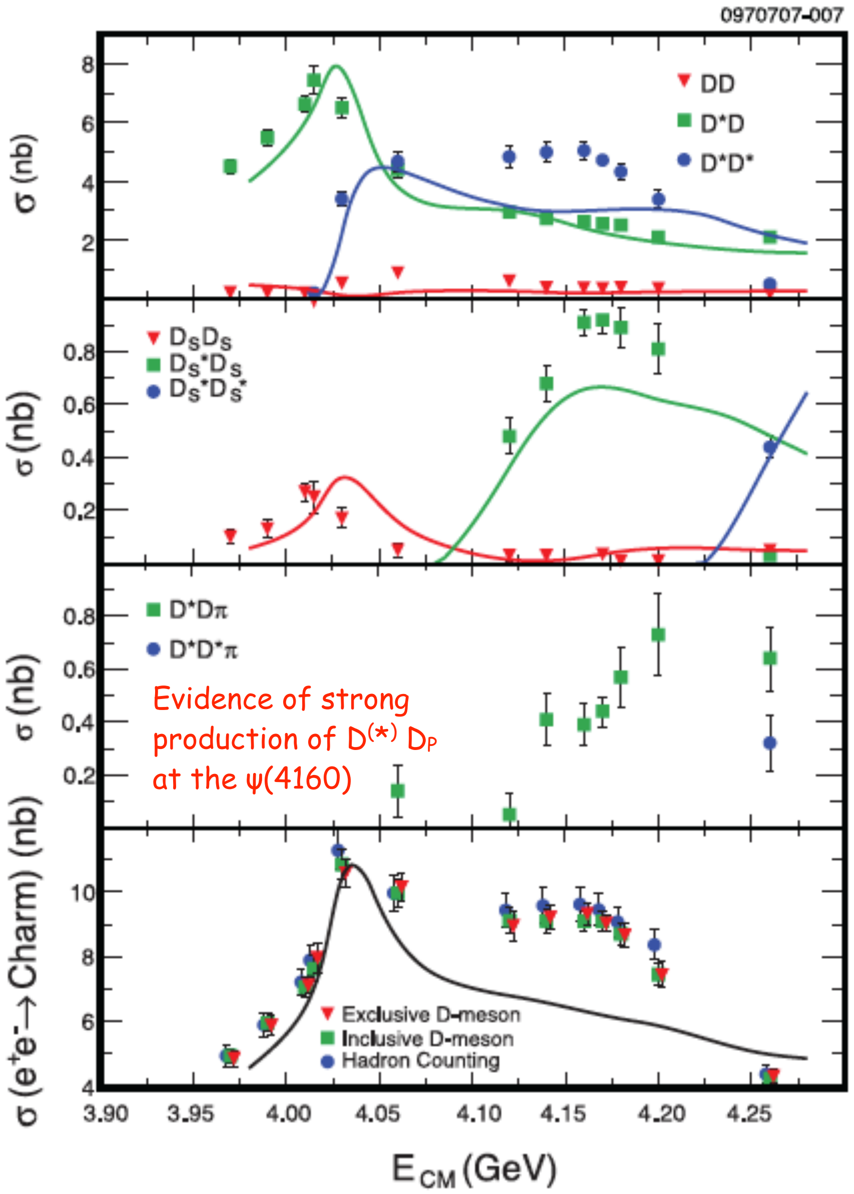
Systematics and Expectations

- 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

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)

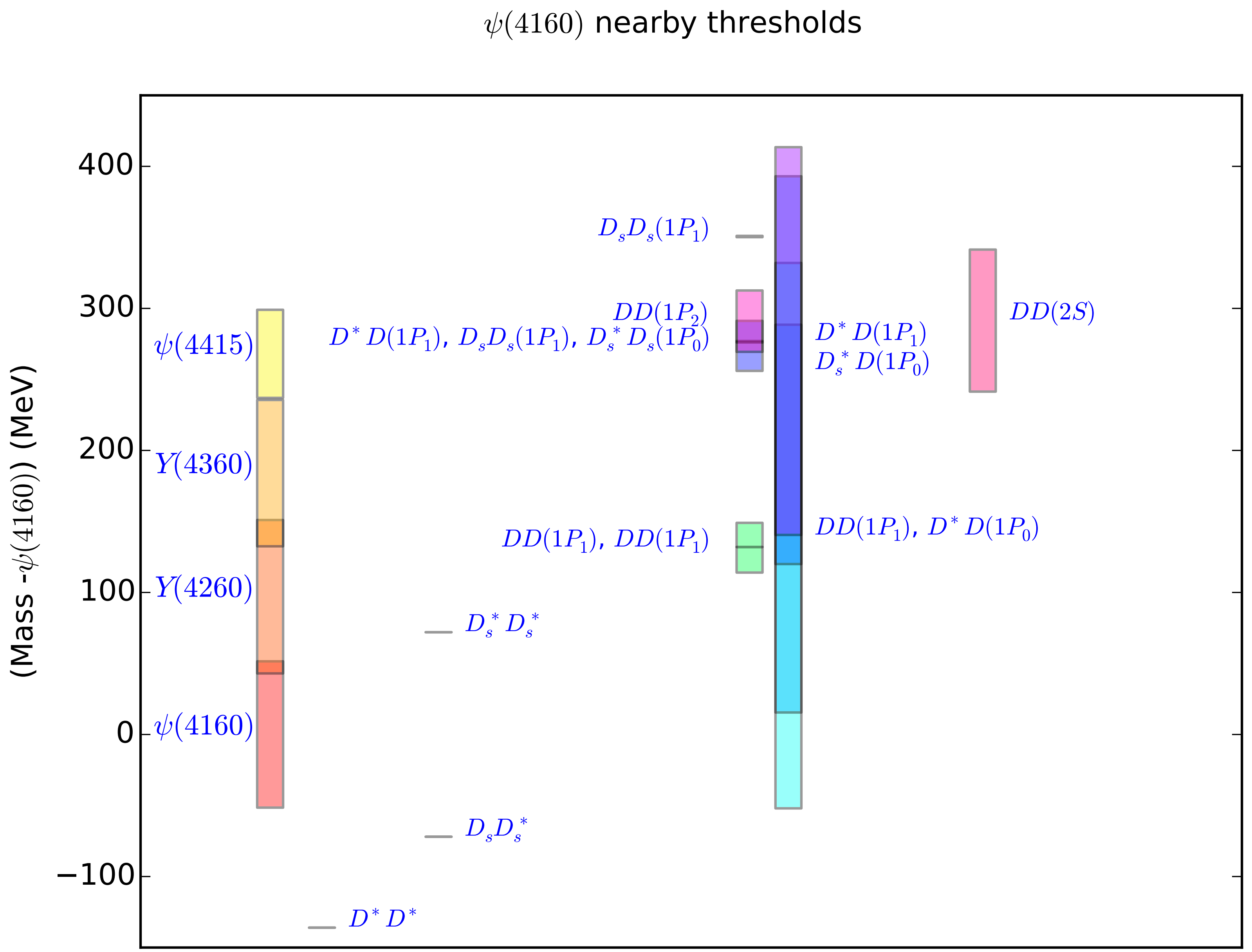
Systematics: ψ(4040) and Below

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

State	Mass	Width	J^{PC}	Comments
	Transition Observed	Branching Fraction		
$\psi(3770)$	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^+	$e^+e^-(4260) \to \pi^+\pi^- J/\psi$
	$\pi^+ J/\psi$	$(\frac{Z_c(3885) \to D\bar{D}^*}{Z_c \to \pi J/\psi}) = 6.2 \pm 1.1 \pm 2.7$	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
	$\eta J/\psi$	$(5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$		

Systematics: Ψ(4160), Ψ(4415)

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



Systematics and Expectations

- Ψ(4S)
  - M = 4421 ± 4 MeV   Γ = 62 ± 20 MeV;
  - Open decay channels:
    - Many

Decay Mode	Branching Rate
$D^*\bar{D} + \mathrm{cc}$	$\frac{\Gamma(D^*\bar{D})}{\Gamma(D^*\bar{D}^*)} = 0.17 \pm 0.25 \pm 0.03$
$D^*\bar{D}^*$	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
$Z(4430)^+$	$4475 \pm 7\text{‘}^{+15}_{-25}$	$172 \pm 13+^{+37}_{-34}$	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 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.

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

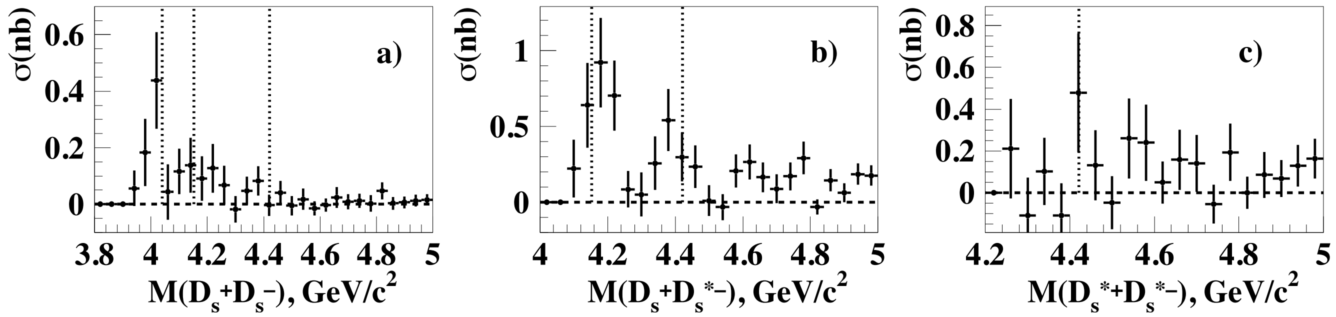
$$\varphi_a \lambda_a = \sqrt{2}\begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}}, & \pi^+, & K^+ \\ \pi^-, & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}}, & K^0 \\ K^-, & \bar{K}^0, & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

  - **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 + (Q$\bar{Q}$).
    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.

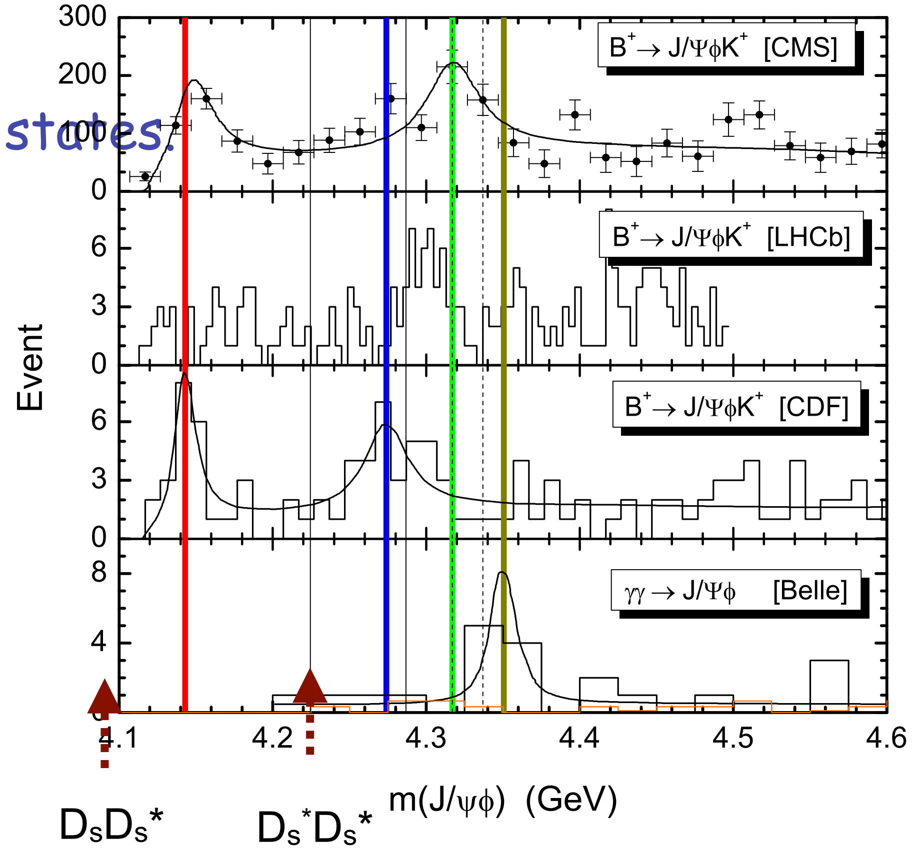
Strange heavy-light meson thresholds

- 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]



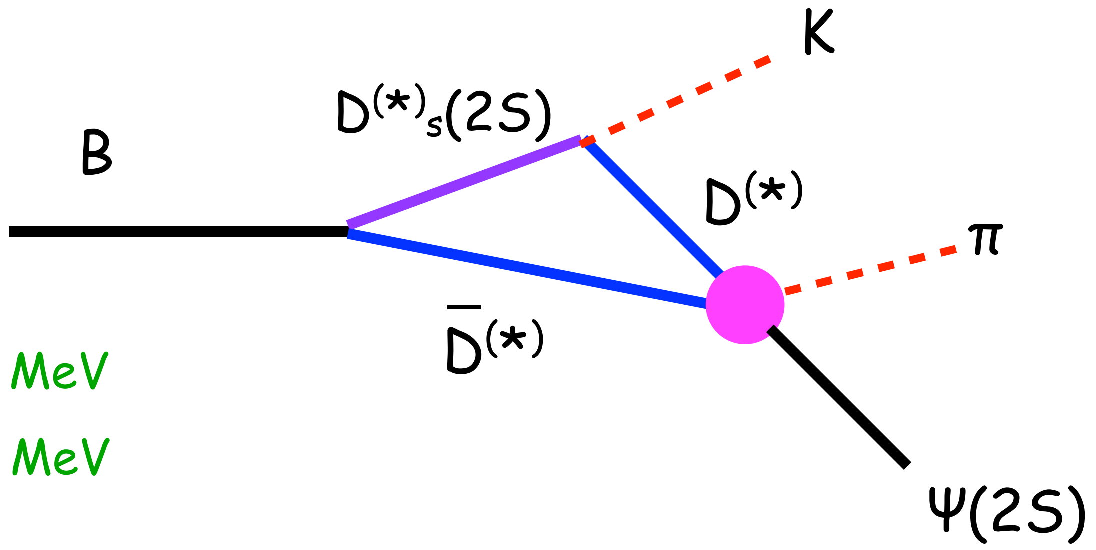
  - No wide P-states -> no sequential transitions with these states.
  - $M(D_s^+ D_s^{-*}) = 4{,}081$ MeV, $M(D_s^{+*} D_s^{-*}) = 4{,}225$ MeV; $M(3^3P_2) = 4{,}315$ MeV
  - Direct transitions?
  - At higher energies the $D_s(2S)$ wide states could play a role in sequential transitions.



Systematics: Other States

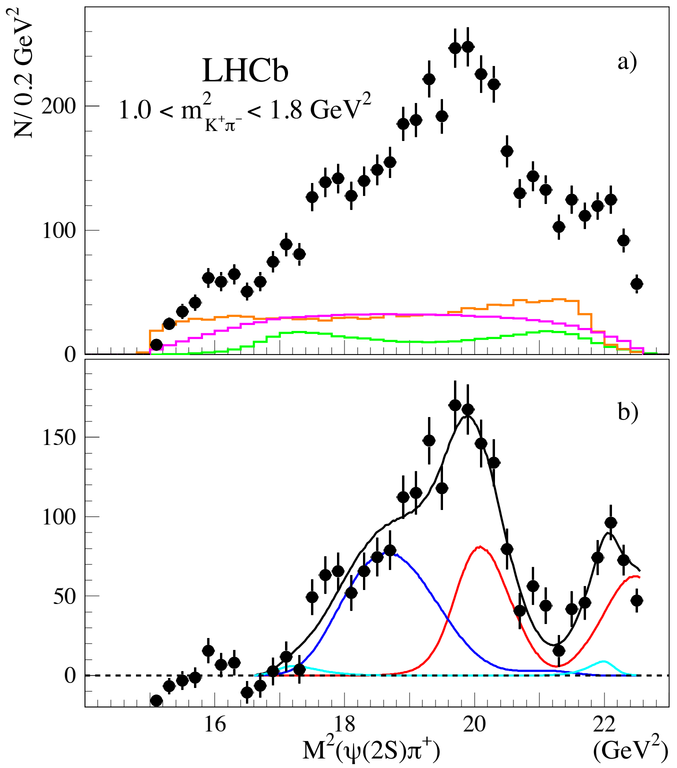
P. Pakhlov [arXiv:1105.2945]

- 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 and T. Uglov

[arXiv:1408.5295]

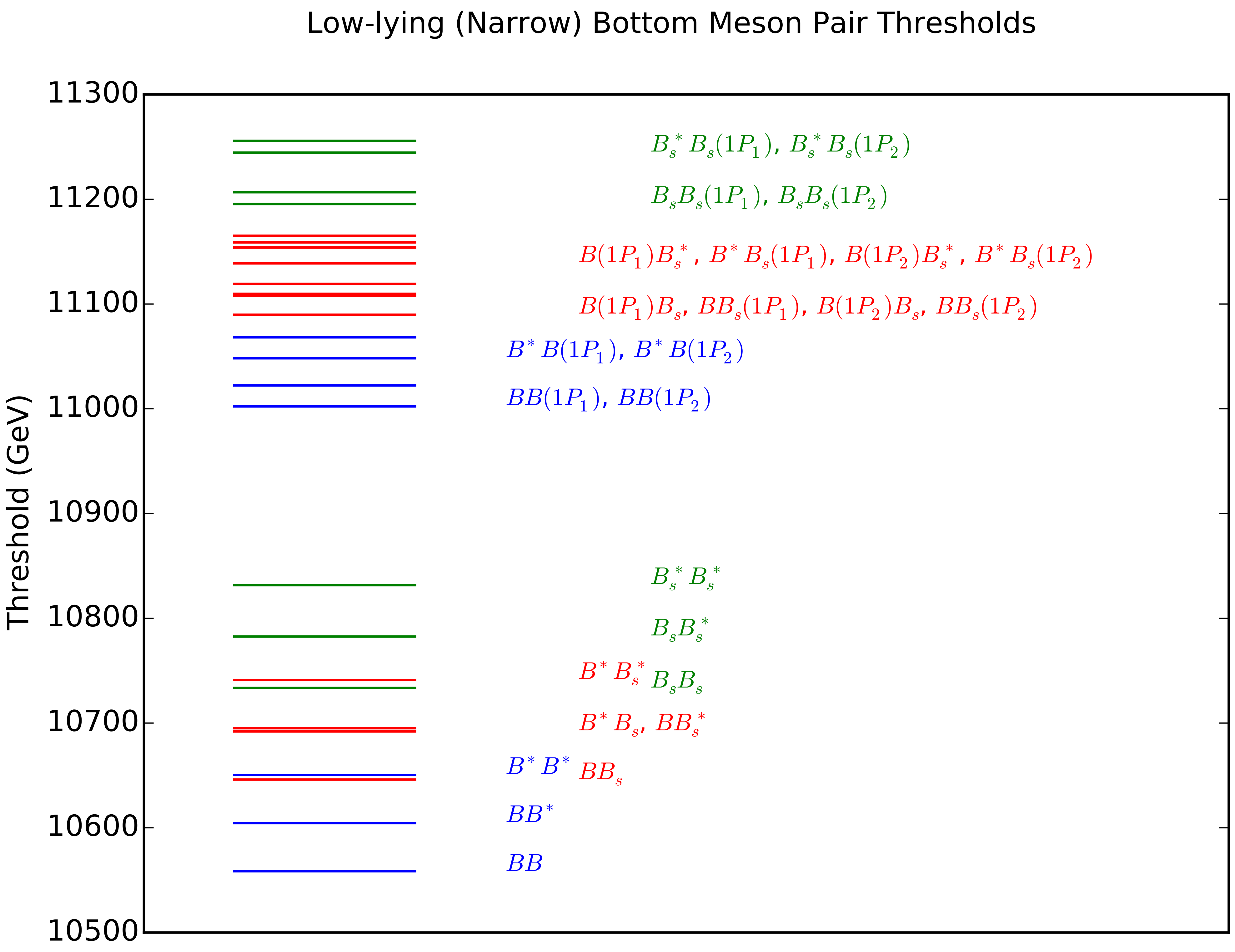


Summary

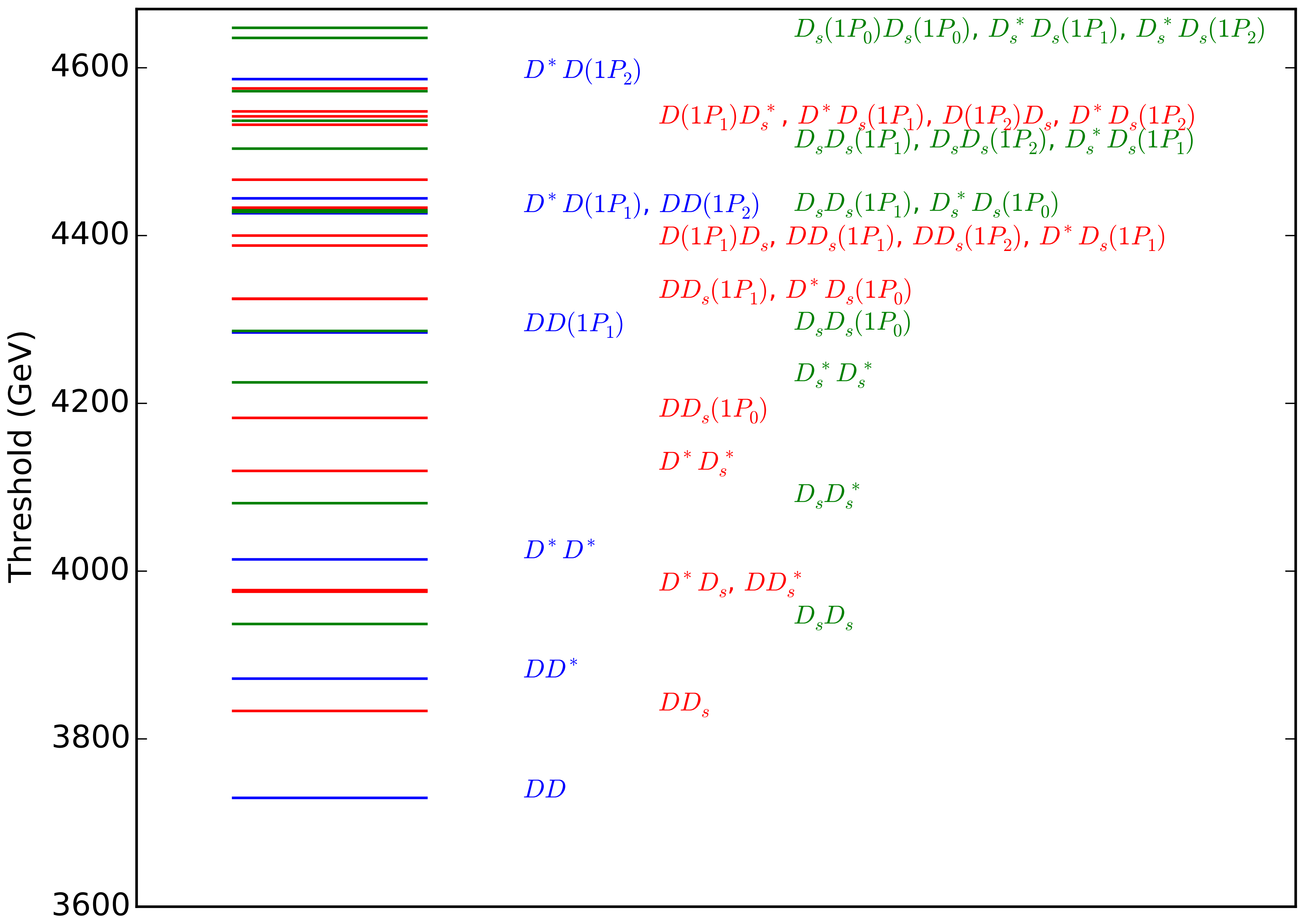
- Above heavy flavor production threshold the usual QCDME fails.
  - The transitions rate are much larger than expected.
  - The factorization assumption fails. Heavy quark and light hadronic dynamics interact strongly due to heavy flavor meson pair (four quark) contributions to the quarkonium wavefunctions. Magnetic transitions not suppressed.
  - A new mechanism for hadronic transitions is required.
- A new mechanism, in which the dynamics is factored differently, is purposed.
  - 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. This dynamics involves non-relativistic heavy systems and should respect HQS as well as the usual SU(3) and chiral symmetry expectations.
- With BES III and LHCb and soon BELLE 2. I expect even more progress in understanding hadronic transitions in the near future.

Backup Slides

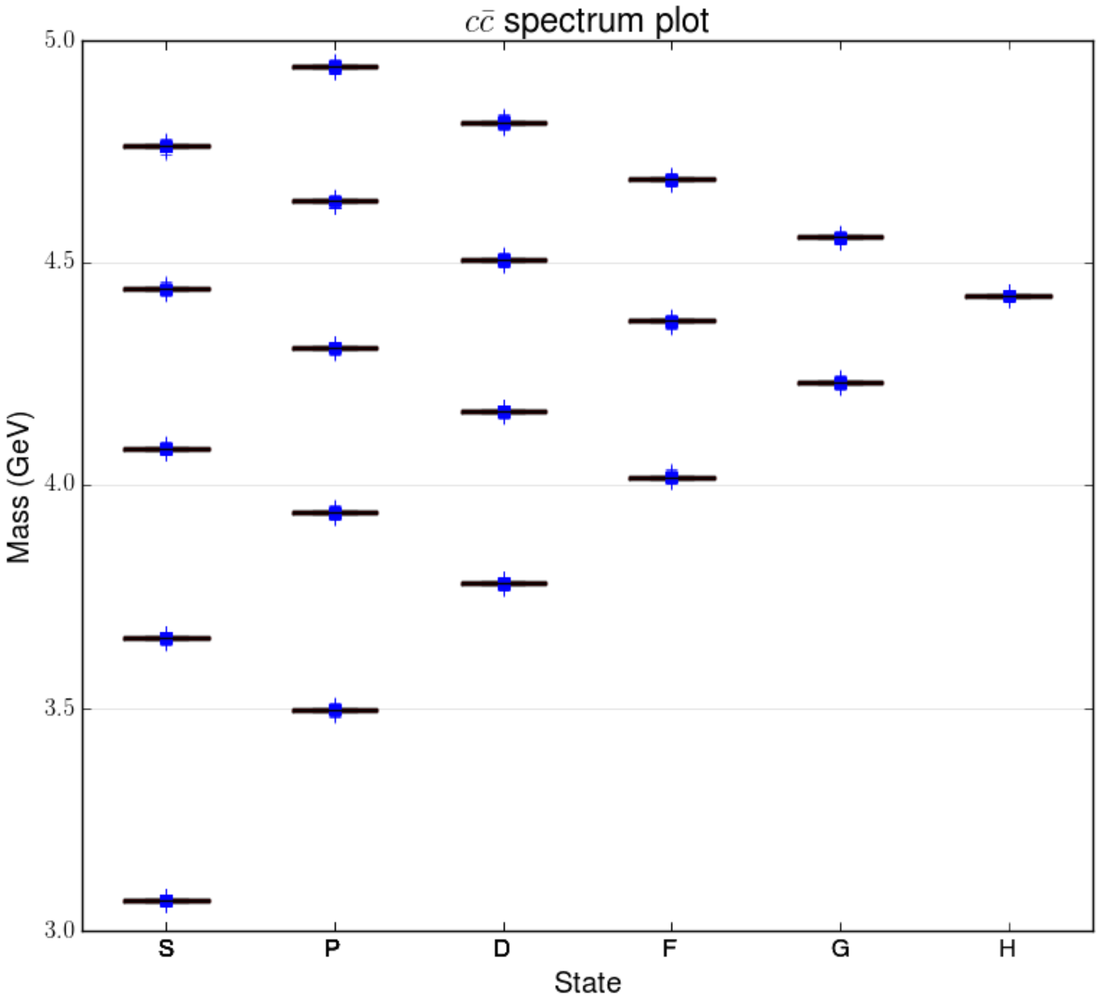
Low-lying thresholds

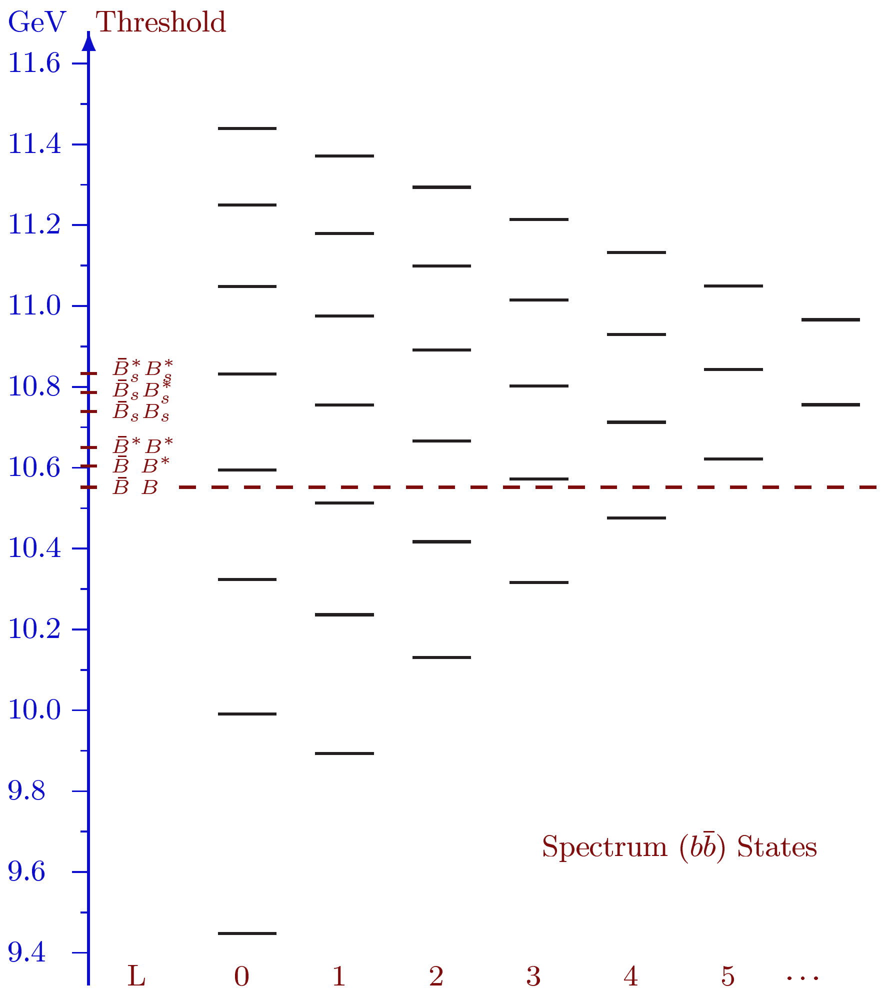


Low-lying thresholds


Low-lying (Narrow) Charm Meson Pair Thresholds

Potential model states





Decay Couplings

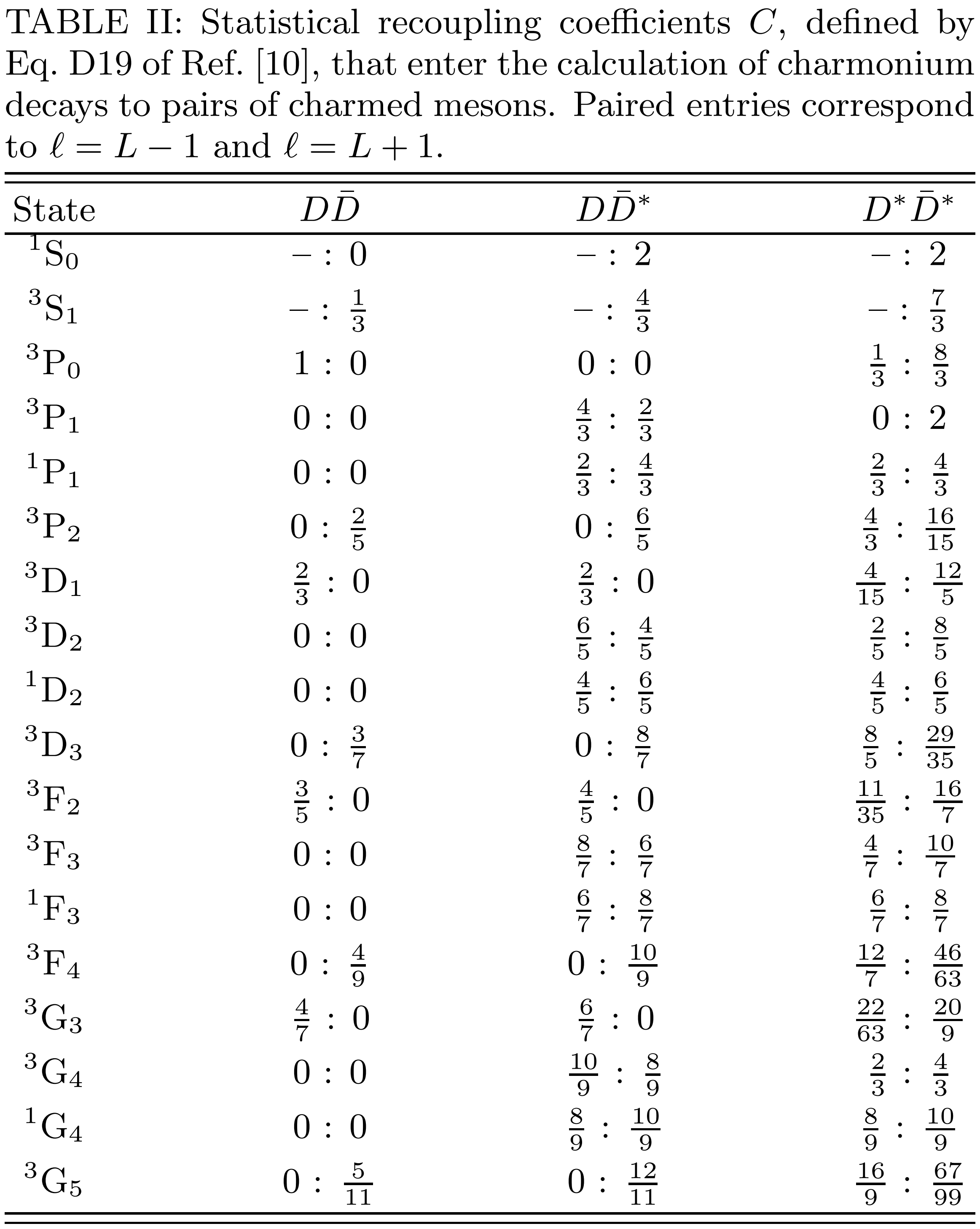
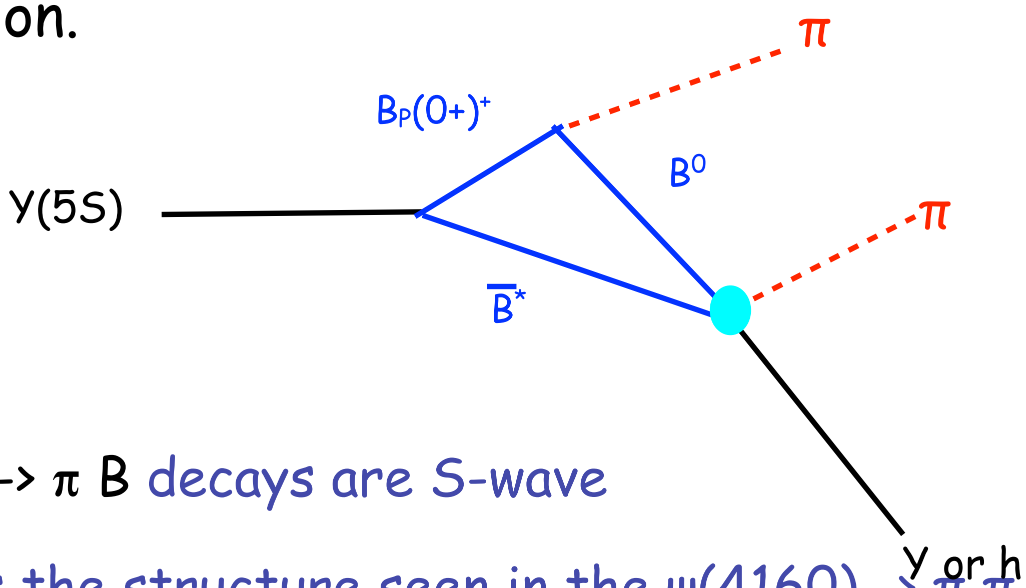


TABLE II: Statistical recoupling coefficients C, defined by Eq. D19 of Ref. [10], that enter the calculation of charmonium decays to pairs of charmed mesons. Paired entries correspond to $\ell = L - 1$ and $\ell = L + 1$.

State	$D\bar{D}$	$D\bar{D}^*$	$D^*\bar{D}^*$
^{1}S$_0$	$- : 0$	$- : 2$	$- : 2$
^{3}S$_1$	$- : \frac{1}{3}$	$- : \frac{4}{3}$	$- : \frac{7}{3}$
^{3}P$_0$	$1 : 0$	$0 : 0$	$\frac{1}{3} : \frac{8}{3}$
^{3}P$_1$	$0 : 0$	$\frac{4}{3} : \frac{2}{3}$	$0 : 2$
^{1}P$_1$	$0 : 0$	$\frac{2}{3} : \frac{4}{3}$	$\frac{2}{3} : \frac{4}{3}$
^{3}P$_2$	$0 : \frac{2}{5}$	$0 : \frac{6}{5}$	$\frac{4}{3} : \frac{16}{15}$
^{3}D$_1$	$\frac{2}{3} : 0$	$\frac{2}{3} : 0$	$\frac{4}{15} : \frac{12}{5}$
^{3}D$_2$	$0 : 0$	$\frac{6}{5} : \frac{4}{5}$	$\frac{2}{5} : \frac{8}{5}$
^{1}D$_2$	$0 : 0$	$\frac{4}{5} : \frac{6}{5}$	$\frac{4}{5} : \frac{6}{5}$
^{3}D$_3$	$0 : \frac{3}{7}$	$0 : \frac{8}{7}$	$\frac{8}{5} : \frac{29}{35}$
^{3}F$_2$	$\frac{3}{5} : 0$	$\frac{4}{5} : 0$	$\frac{11}{35} : \frac{16}{7}$
^{3}F$_3$	$0 : 0$	$\frac{8}{7} : \frac{6}{7}$	$\frac{4}{7} : \frac{10}{7}$
^{1}F$_3$	$0 : 0$	$\frac{6}{7} : \frac{8}{7}$	$\frac{6}{7} : \frac{8}{7}$
^{3}F$_4$	$0 : \frac{4}{9}$	$0 : \frac{10}{9}$	$\frac{12}{7} : \frac{46}{63}$
^{3}G$_3$	$\frac{4}{7} : 0$	$\frac{6}{7} : 0$	$\frac{22}{63} : \frac{20}{9}$
^{3}G$_4$	$0 : 0$	$\frac{10}{9} : \frac{8}{9}$	$\frac{2}{3} : \frac{4}{3}$
^{1}G$_4$	$0 : 0$	$\frac{8}{9} : \frac{10}{9}$	$\frac{8}{9} : \frac{10}{9}$
^{3}G$_5$	$0 : \frac{5}{11}$	$0 : \frac{12}{11}$	$\frac{16}{9} : \frac{67}{99}$

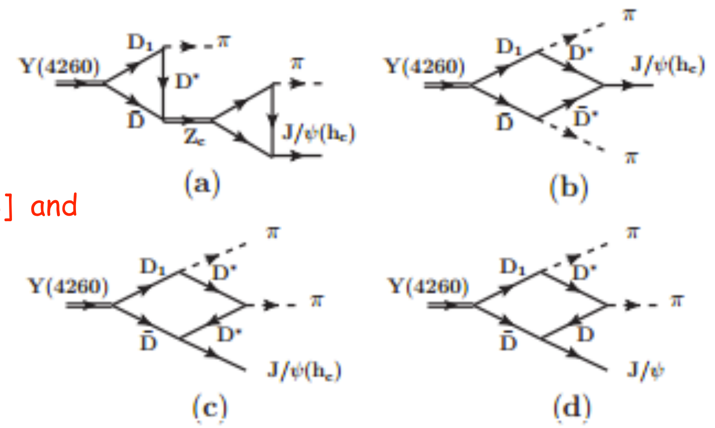
Structure in two pion transitions

- For example, the Υ(5S) has a $B(1/2^-)$ + $B_P(1/2^+)$ component. The $B_P(1/2^+)$ state decays rapidly into a B meson and pion, leaving a $B(1/2^-)$ + $B(1/2^-)$ nearly at rest. They then recombine into the final (Υ or h_b) and pion.



Υ(5S) -> Bp(0+) B* -> π B B*
and Bp(1+) B -> π B B*
and Bp(1+) B* -> π B*B*

  - Both the Υ(5S) -> Bp(0+) B* and Bp(0+) -> π B decays are S-wave
  - The analogy in the charmonium system is the structure seen in the ψ(4160) -> π π J/ψ transition.
  - This provides a dynamical mechanism for the Meson Loop and ISPE models.



Meson Loop Models: [1303.6355}, [1304.4458] and references therein

ISPE Model: [1303.6842] and references therein