Hadronic Transitions For Quarkonium States Above Threshold

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Outline:

- Revisiting the QCD Multipole Expansion
- Hadronic Transitions Below Threshold
- New Dynamics for Hadronic Transitions At Threshold
- Systematics and Expectations
- ΔR_Q in the Threshold Region
- Summary

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Revisiting the QCDME Assumptions

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

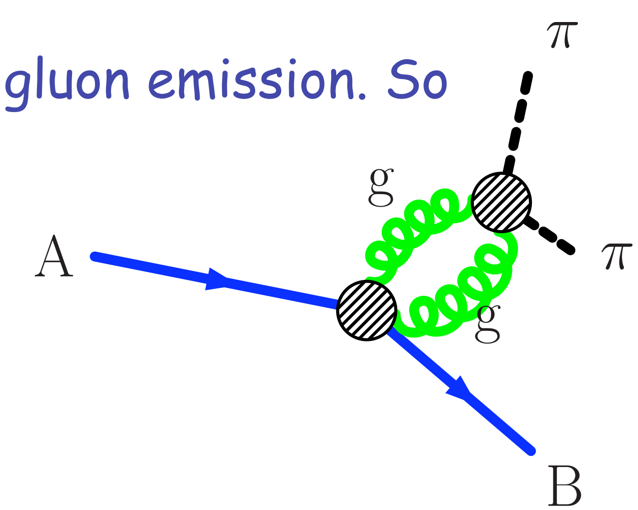
$$H^{\rm eff}_{\rm QCD} = H^{(0)}_{\rm QCD} + H^{(1)}_{\rm QCD} + H^{(2)}_{\rm QCD} \qquad H^{(1)}_{\rm QCD} \equiv Q_a A^a_0(\mathbf{X}, t)$$

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

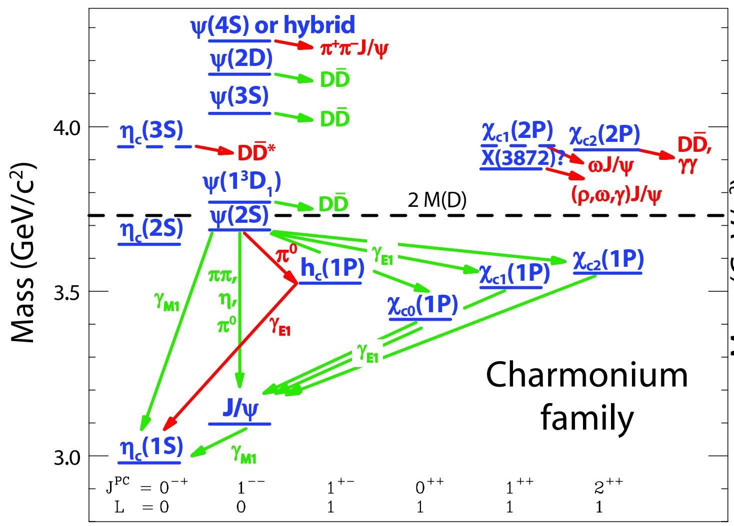
$$\mathcal{M}(\Phi_i \to \Phi_f + h) = \frac{1}{24} \sum_{KL} \frac{\langle f | d^{ia}_m | KL \rangle \langle | KL | d^j_{ma} | i \rangle}{E_i - E_{KL}} \langle h | \mathbf{E}^{ai} \mathbf{E}^j_a | 0 \rangle$$

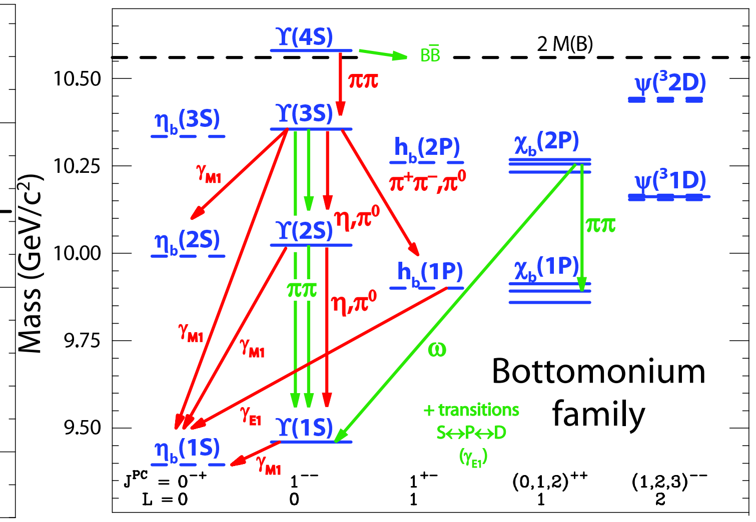
+ higher order multipole terms.

  - 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	$\Gamma_{\rm partial}$ (keV) (Experiment)	$\Gamma_{\rm partial}$ (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]
$\to\Upsilon(1S)+\eta$	$(6.7\pm2.4)\times10^{-3}$	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]
$\to\Upsilon(1S)+\eta$	$<3.7\times10^{-3}$	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.

η Transitions

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

    α_{AB}^{EE}

    $: i(2\pi)^{3/2}C_3 q_k$
  - 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) 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.

Υ(3S)->Υ(1S) + ππ

- Suppressed overlaps Υ((n+2)S) -> Υ(nS) + h or χ_b(nP) + γ:
  - E1 photon transitions: Υ(3S) -> χ_b(1P) + γ highly suppressed
  - Υ(3S) = Υ(1S) + ππ: (leading term dynamically suppressed?)
  - Same for η transition?
- Measure ratios:
  - $R_\eta = R_{bb}(3\to1)/R_{bb}(2\to1)$
  - $R_{\pi\pi} = \Gamma(\Upsilon(3S) \to h_b + \pi\pi)/\Gamma(\Upsilon(3S) \to \Upsilon(1S) + \pi\pi)$
  - No new physics: $R_\eta \sim 1$, $R_{\pi\pi} \sim O(v^4) \sim$ small
  - Significant coupled channel contributions: $R_\eta \gg 1$
  - If Z^+(10610) dominated: $R_{\pi\pi} \sim 1$

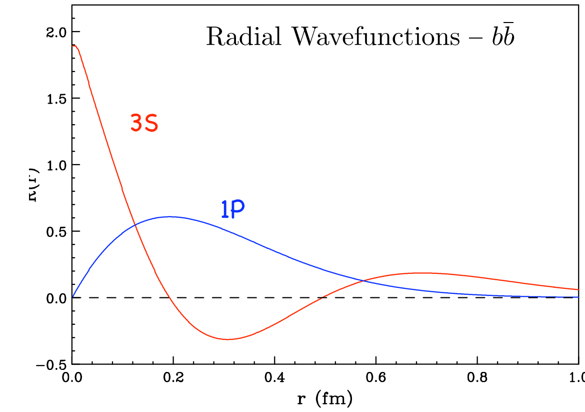
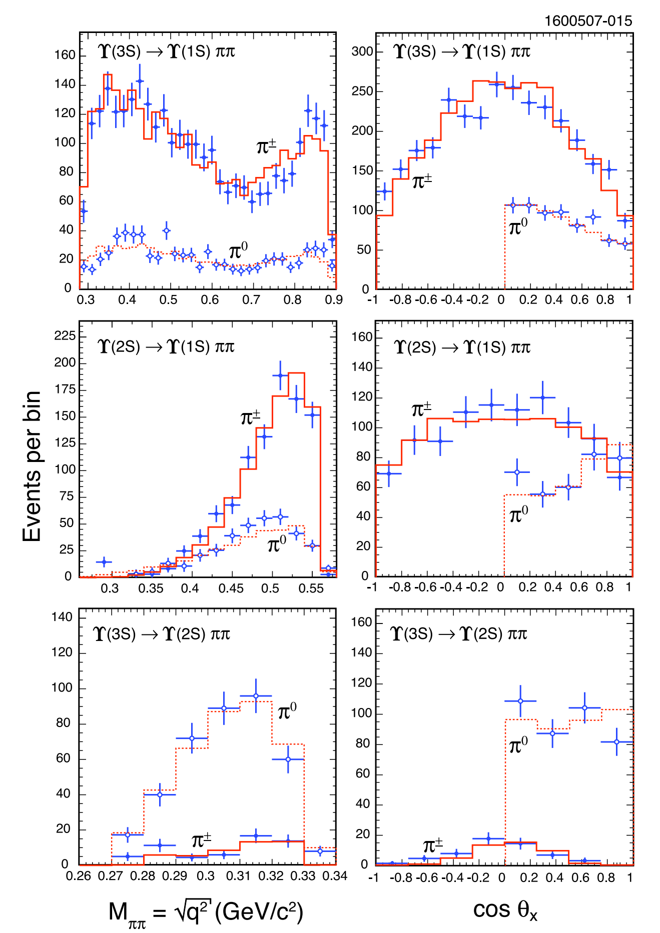


Table 1: Cancellations in $\mathcal{E}_{if}$ by node regions.

$b\bar{b}$	initial state node			
Transition	< 1	1 to 2	2 to 3	total
$2S \to 1P$	0.07	−1.68		−1.61
$3S \to 2P$	0.04	−0.12	−2.43	−2.51
$3S \to 1P$	0.04	−0.63	0.65	0.06

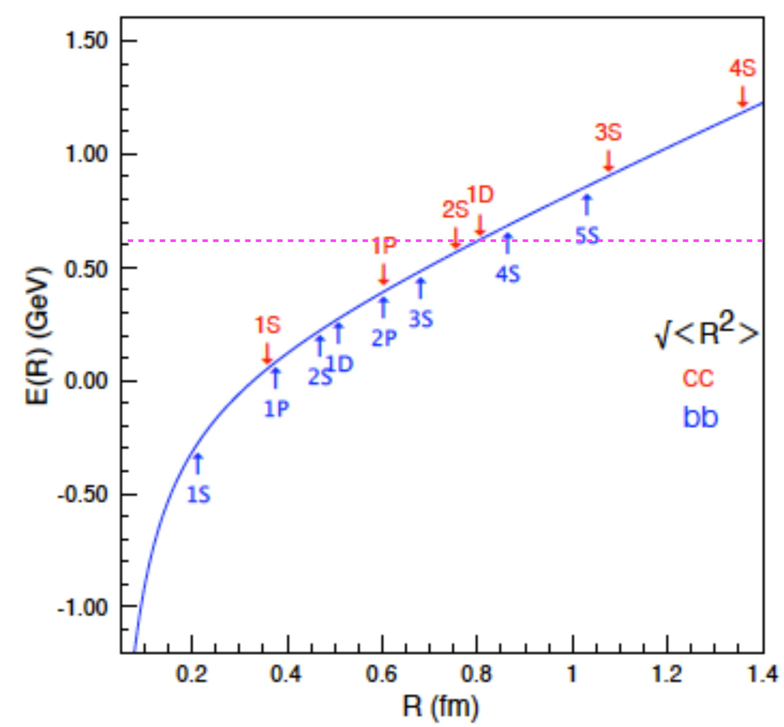


CLEO [arXiv:0706.2317]

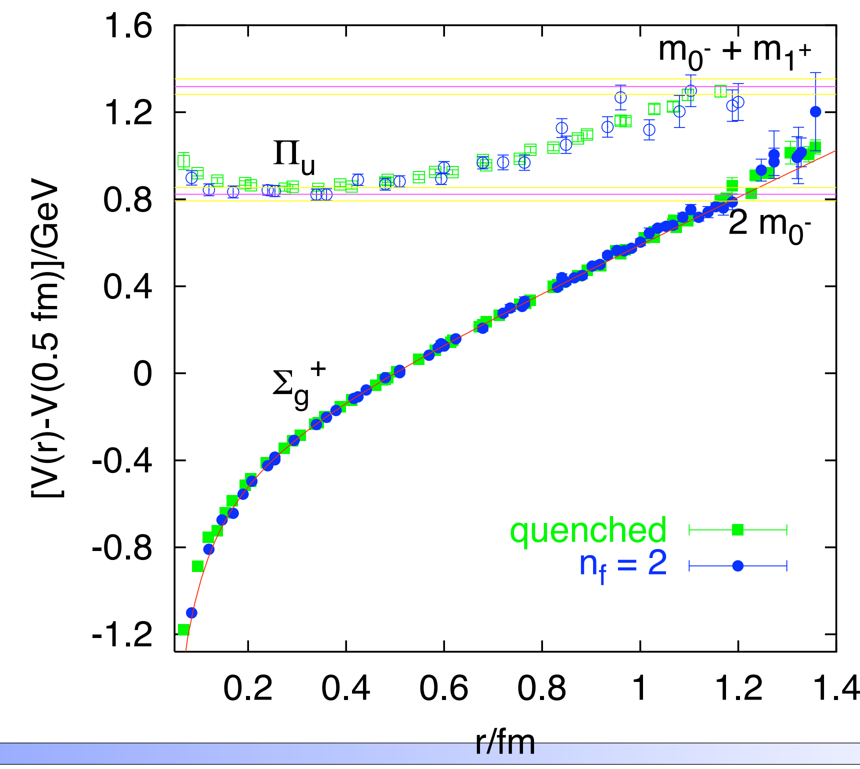
QCD Multipole Expansion (QCDME)

- 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:
- 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:

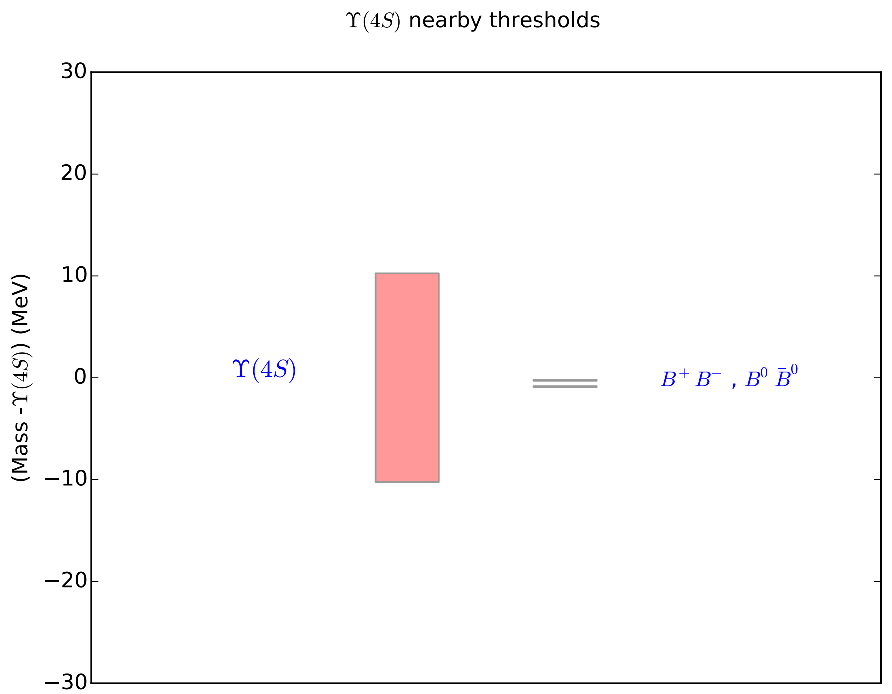


Table 1: Selected $\Upsilon(4S)$ decays.

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

—> partial rate = 1.66 ± 0.23 keV

—> partial rate = 4.02 ± 0.89 keV
—> partial rate = 3.75 ± 0.73 keV

SU(3) violating
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.

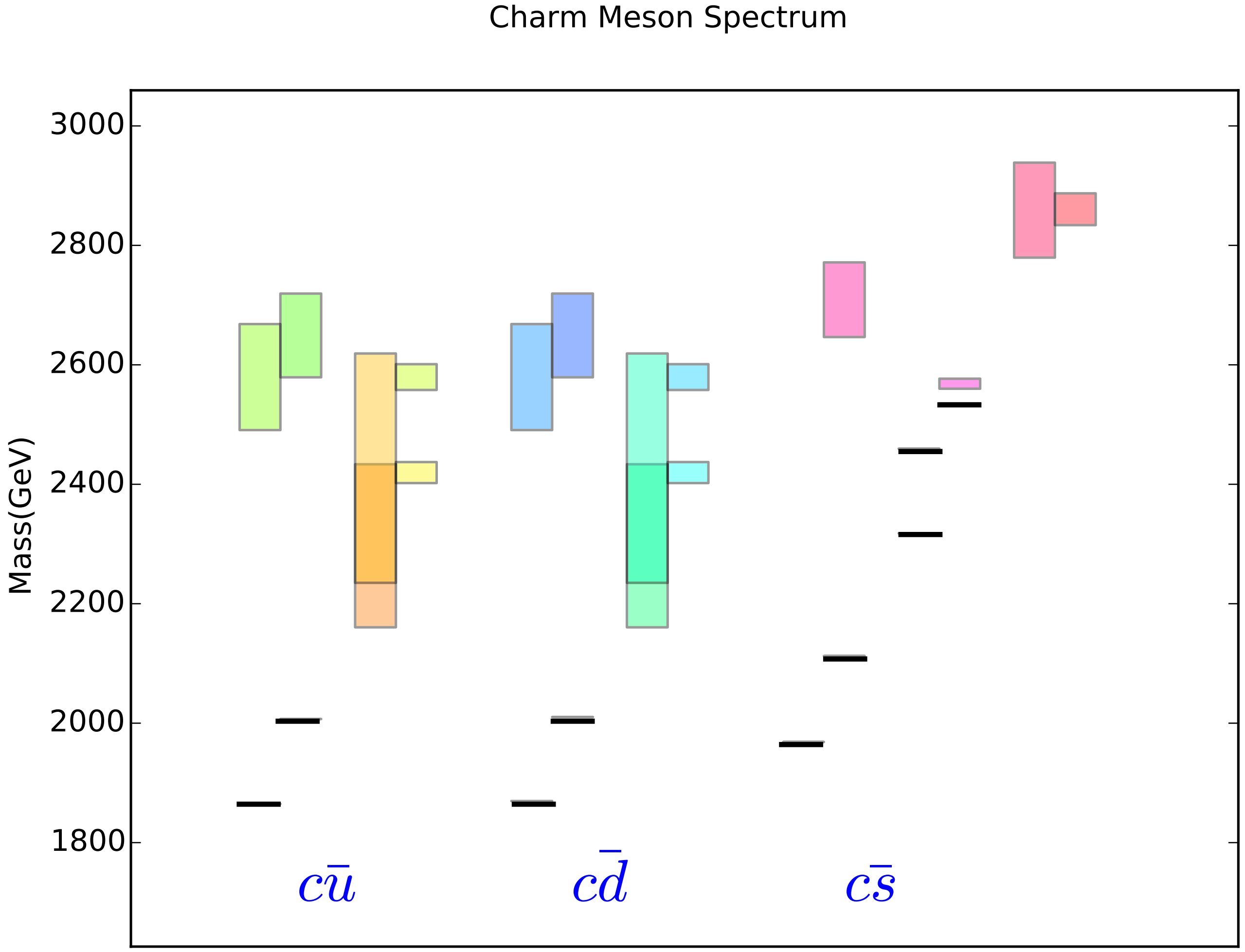
$$U = \exp\left(i\gamma_5 \frac{\varphi_a \lambda_a}{f_\pi}\right)$$

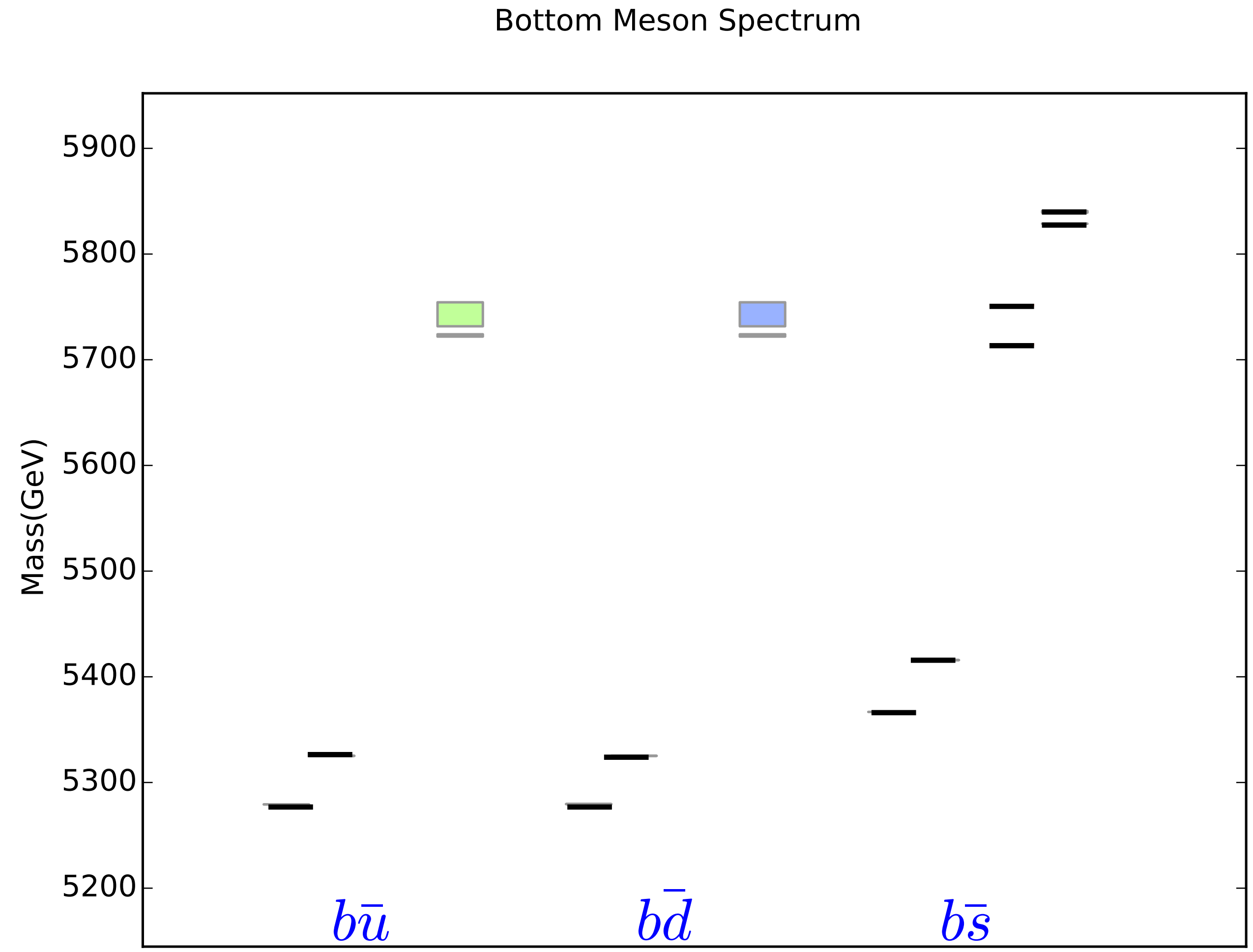
$$\varphi_a \lambda_a = \sqrt{2}\begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}}, & \pi^+, & K^+ \\ \pi^-, & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}}, & K^0 \\ K^-, & \bar{K}^0, & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

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

Heavy-Light Mesons

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

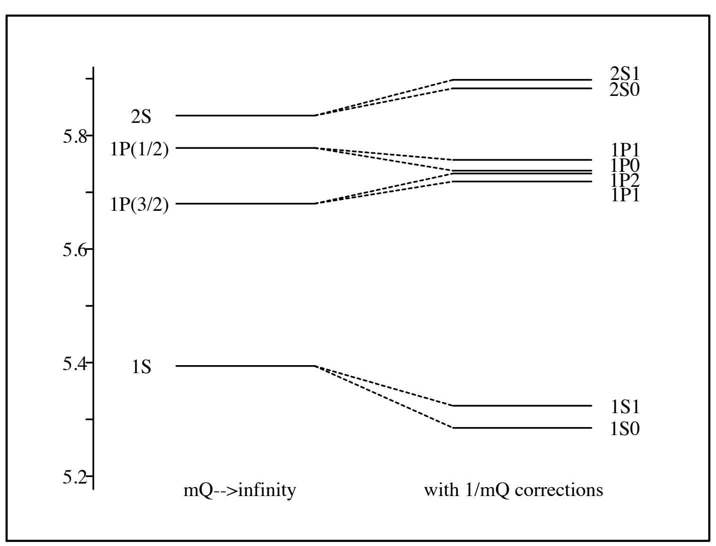




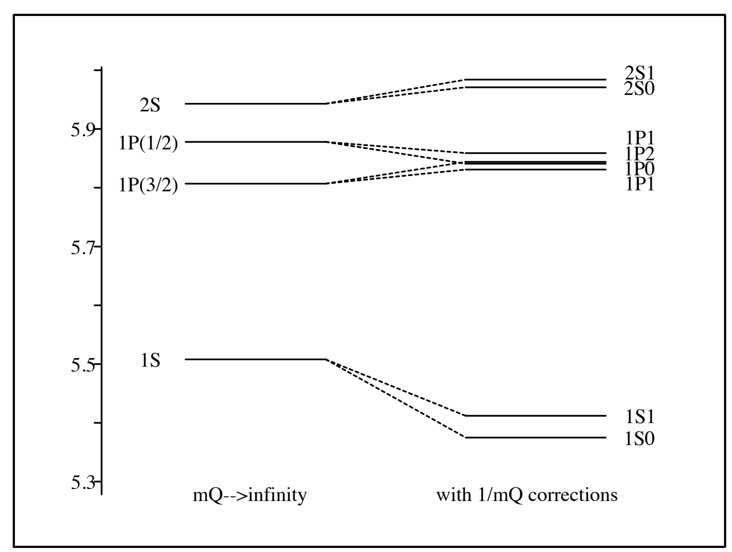
  - There are 9 narrow (< 2 MeV) charm meson states [and 10 bottom mesons states]. Any pair of these might have a cusp at S-wave threshold.

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: $n^{j^P}L_J$)
    - $M(B[1^{\frac{1}{2}+}P_1]\bar{B}) = 11{,}045$ 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

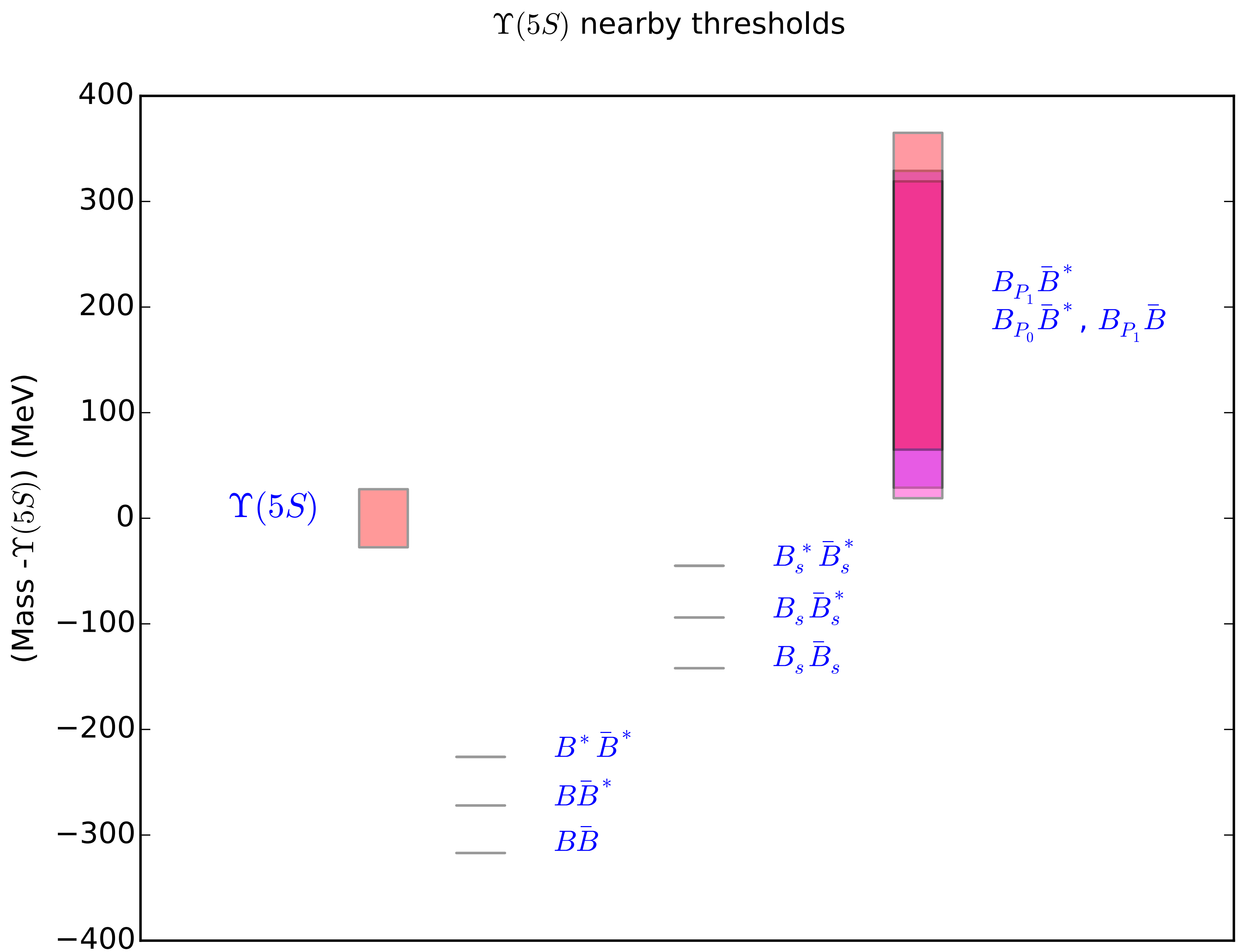


B

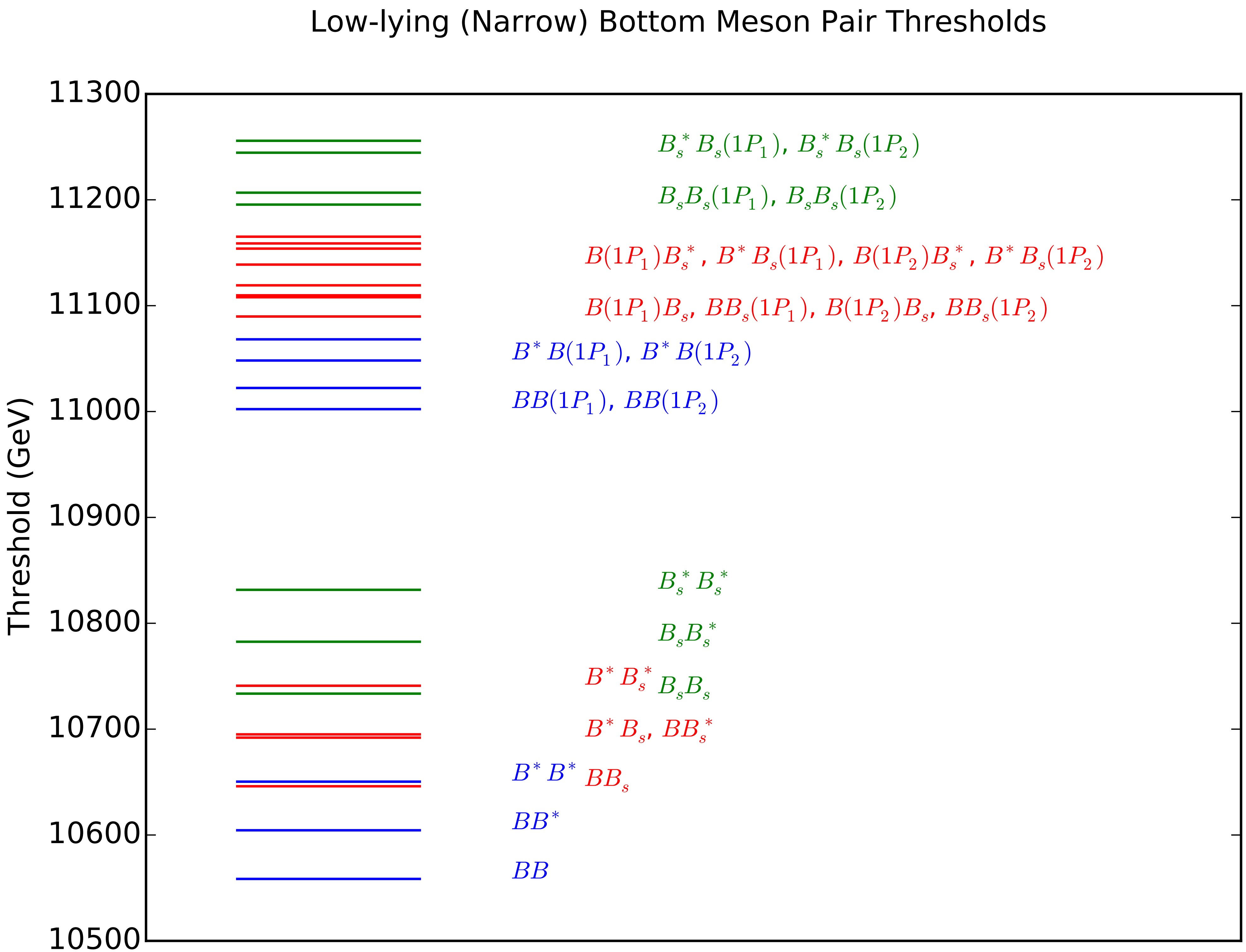


B_s

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?

Hadronic Transitions Above Threshold

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

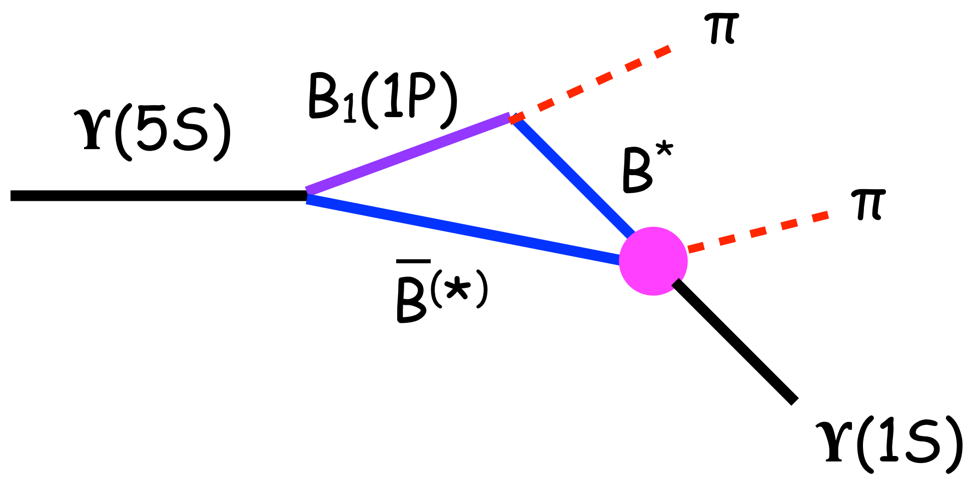
S-wave decays

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

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

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

Example

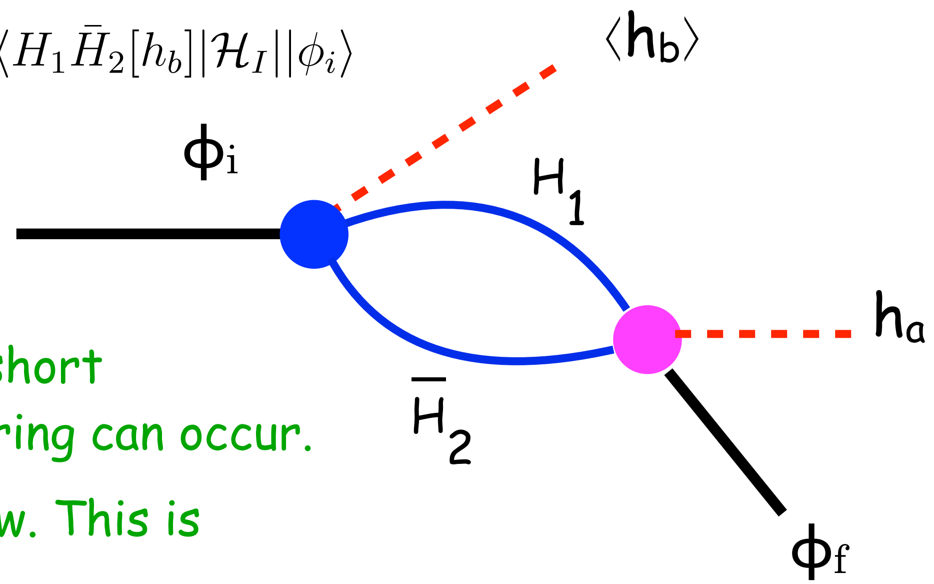


Remarks:
(1) $\Upsilon(5S)$ strong decay is S-wave
(2) The large width of the $B_1(1P)$ implies that the first π is likely emitted while the $B_1(1P)$ and $B^{(*)}$ are still nearby.
(3) The $B_1(1P)$ decay is S-wave
(4) Therefore the $B^{(*)}$ B^* system is in a relative S-wave and near threshold.
(5) 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).

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



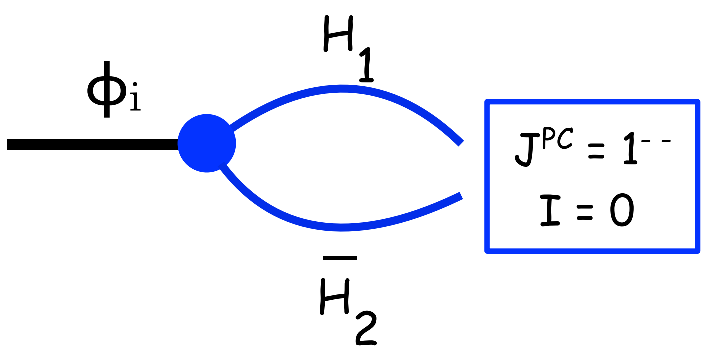
  - The time scale of the production process has to be short relative to the time scale over which H_1 H_2 rescattering can occur.
  - The relative velocity in the H_1 H_2 system must be low. This is only possible near threshold.

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

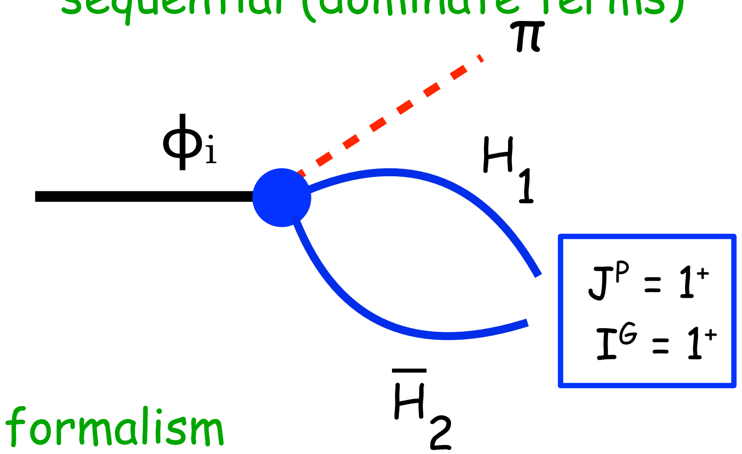
F.K. Gao, C. Hanhart, Q. Wang, Q. Zhao [arXiv:1411.5584]

New Dynamics for Hadronic Transitions

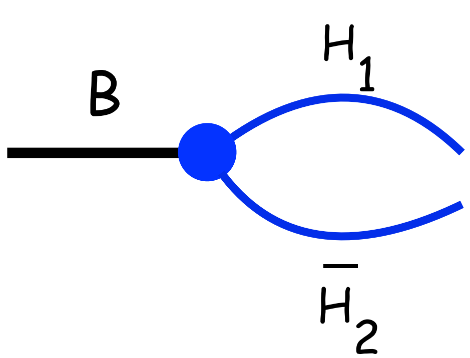
- Production modes
  - e+e-
    - direct

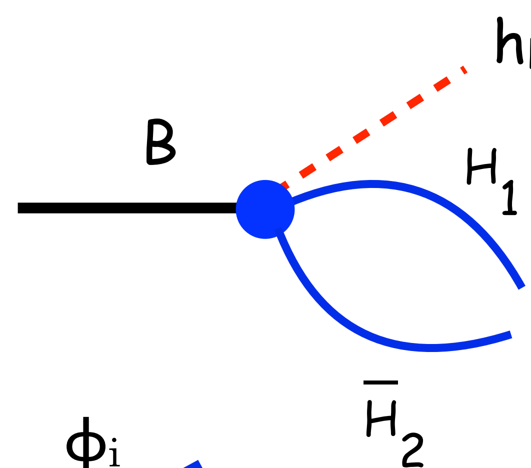


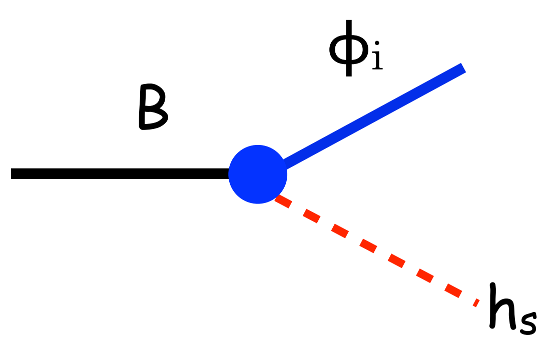
sequential (dominate terms)



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







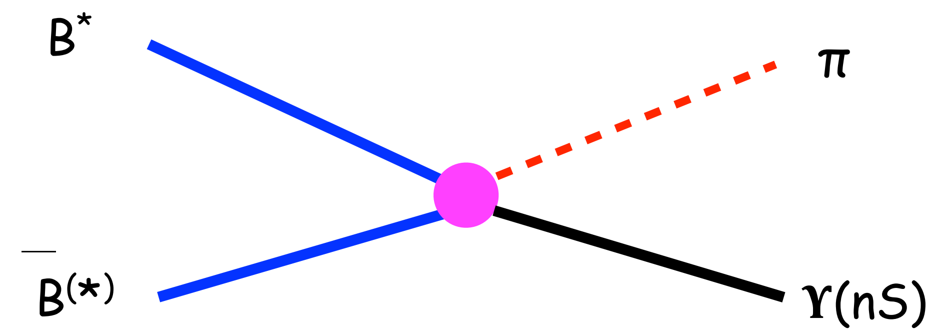
New Dynamics for Hadronic Transitions

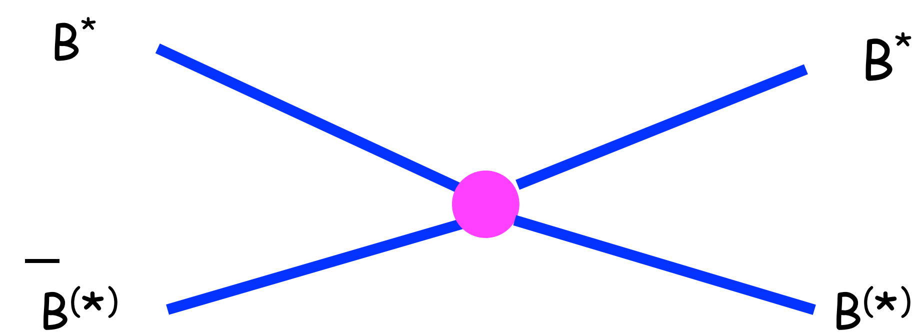
- Physical Expectations for Threshold Dynamics:

  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.

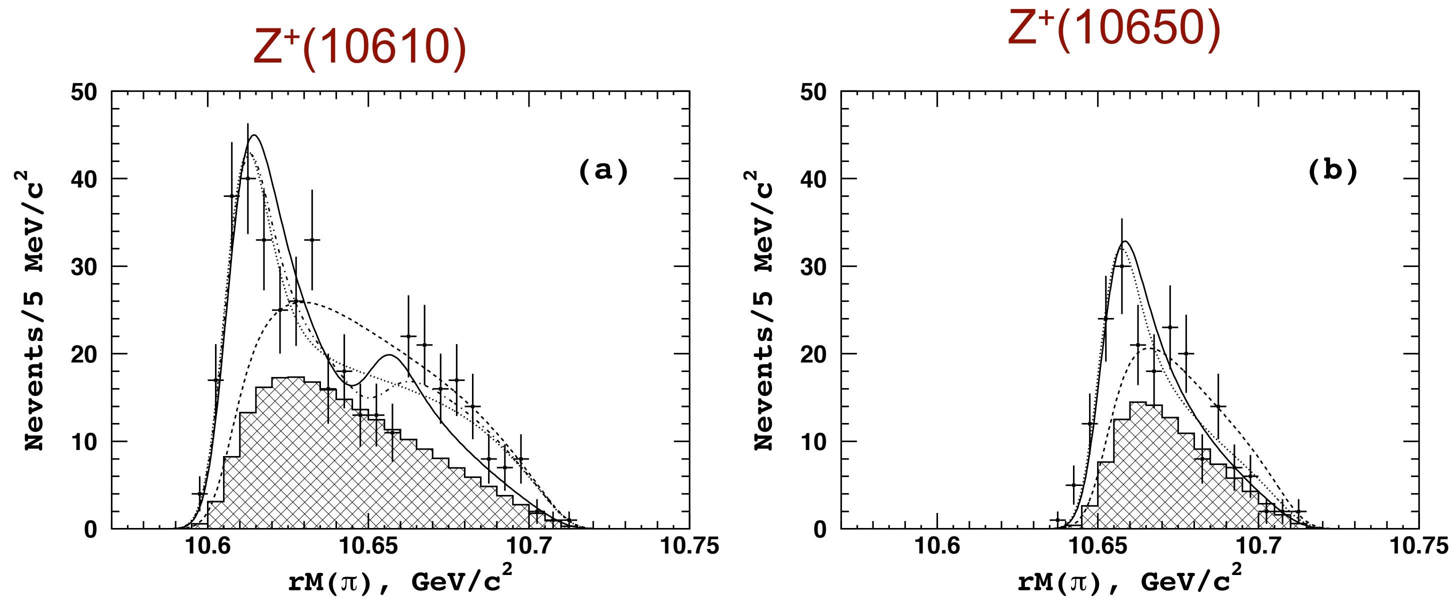




Ratios determined by LQCD calculations and judicious use of SU(3).
M. Padmanath, C. B. Lang and S. Prelovsek [arXix:1503.03257]

New Dynamics for Hadronic Transitions

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



$$\frac{\mathcal{B}(Z_b(10610)\to BB^*)}{\sum_n \mathcal{B}(Z_b(10610)\to\Upsilon(nS)\pi)+\sum_m Z_b(10610)\to h_b(mP)} = 6.2\pm0.7\pm1.3^{+0.0}_{-1.8}$$

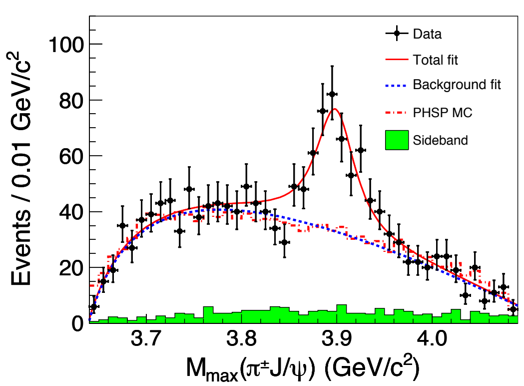
and

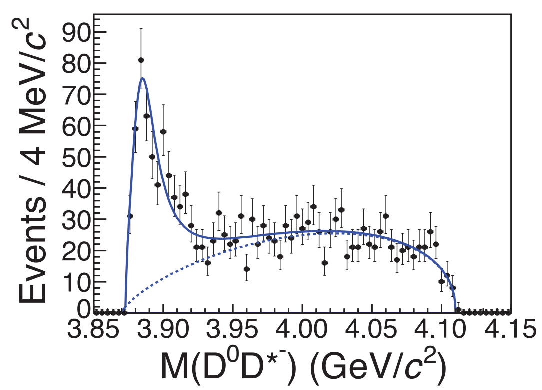
$$\frac{\mathcal{B}(Z_b(10650)\to B^*B^*)}{\sum_n \mathcal{B}(Z_b(10650)\to\Upsilon(nS)\pi)+\sum_m Z_b(10650)\to h_b(mP)} = 2.8\pm0.4\pm0.6^{+0.0}_{-0.4}.$$

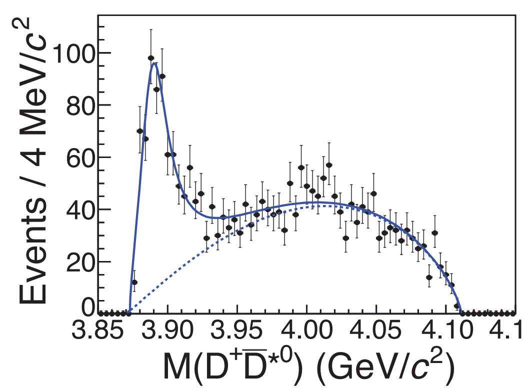
  - HQS implies that the same mechanism applies for charmonium-like states

Systematics and Expectations

- Charmonium-like states: $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$ 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







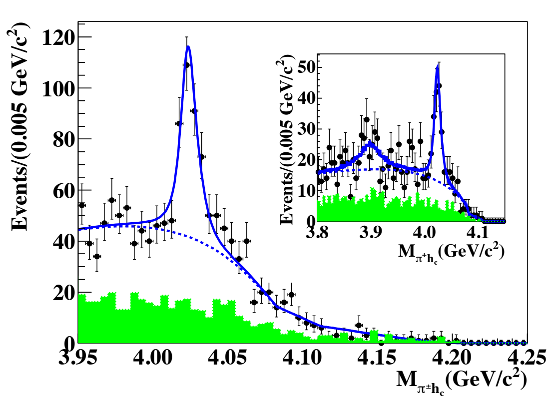
$$\frac{\Gamma[Z_c(3900)\to D D^*]}{\Gamma[Z_c(3900)\to \pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}.$$

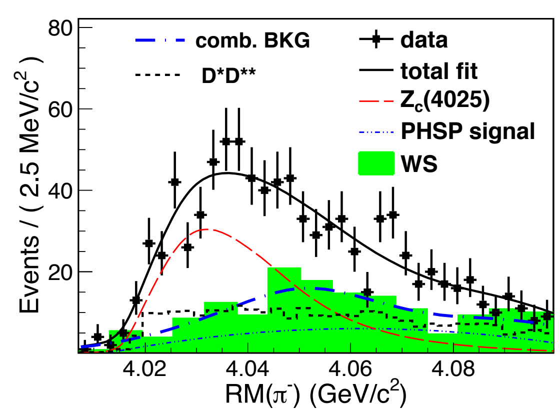
BESIII Z. Lin

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

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

[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

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

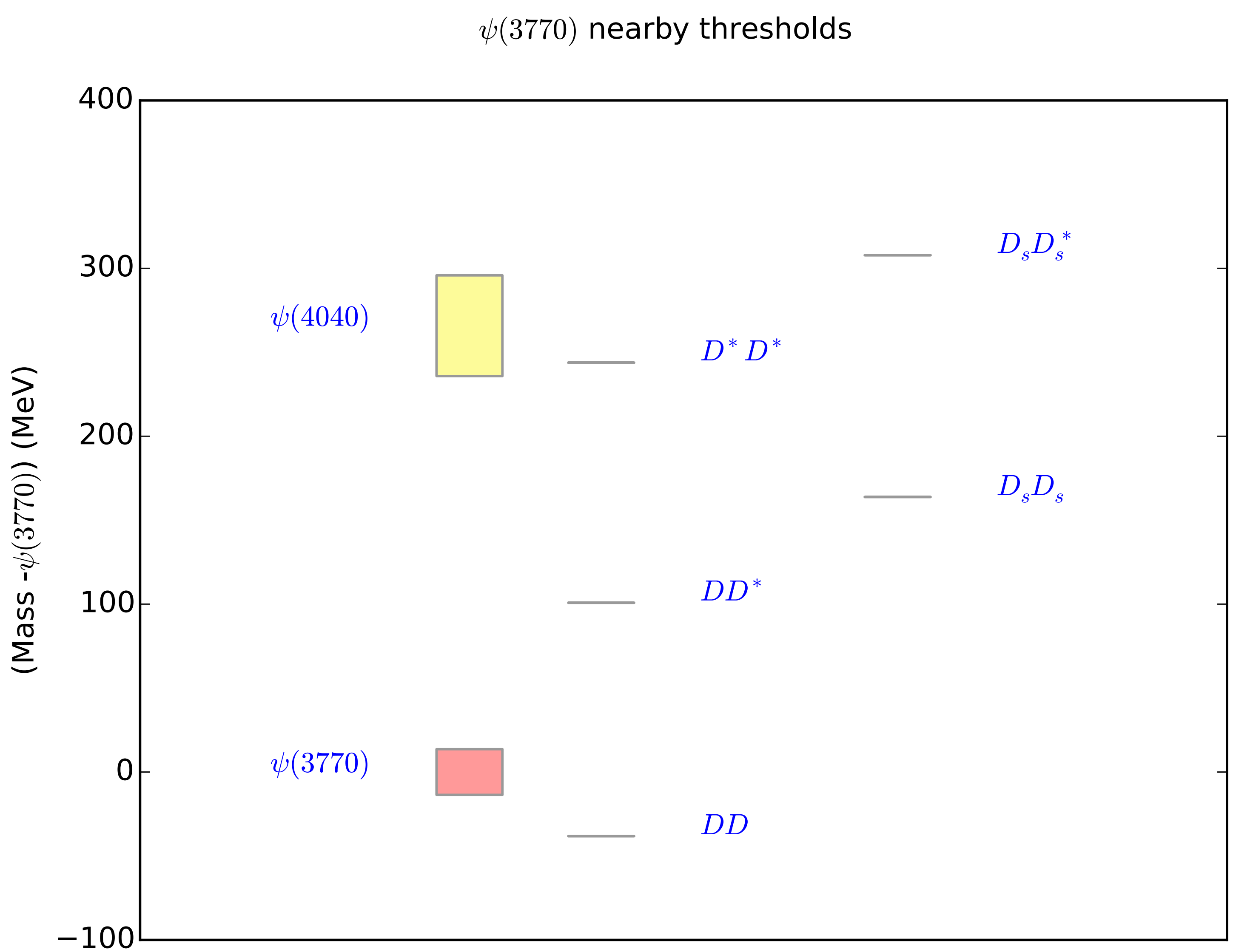
Decay Mode	Branching Rate
$D^0\bar{D}^0$	$(52 \pm 5)\%$
D^+D^-	$(41 \pm 4)\%$
total $D\bar{D}$	$93^{+8}_{-9}\%$
$\psi(1S)\ \pi^+\pi^-$	$(1.93 \pm 0.28) \times 10^{-3}$
$\psi(1S)\ \eta$	$(9 \pm 4) \times 10^{-4}$

$\longrightarrow$ partial rate = 52.5 ± 7.6 keV

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

Ψ(3770), Ψ(4040)

- Only ground state heavy-light meson pair decays allowed



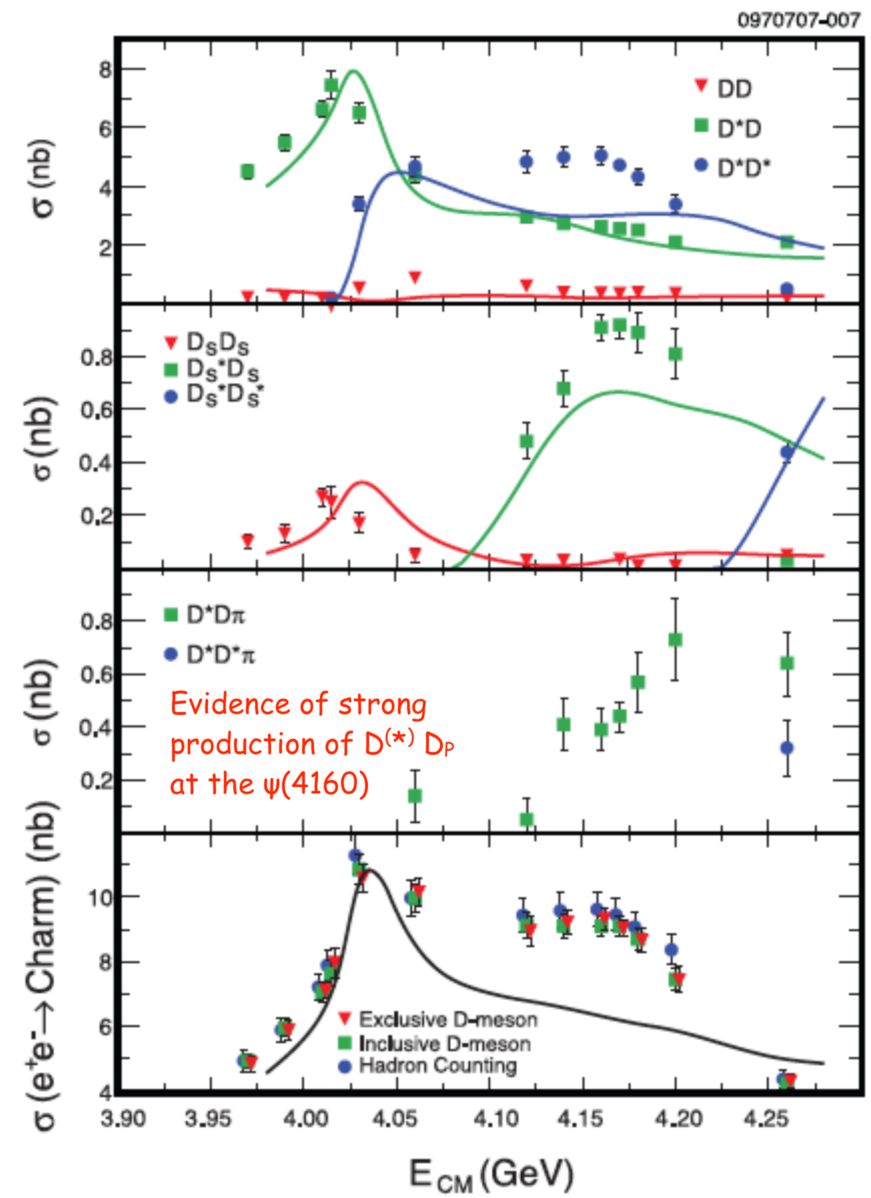
Systematics and Expectations

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

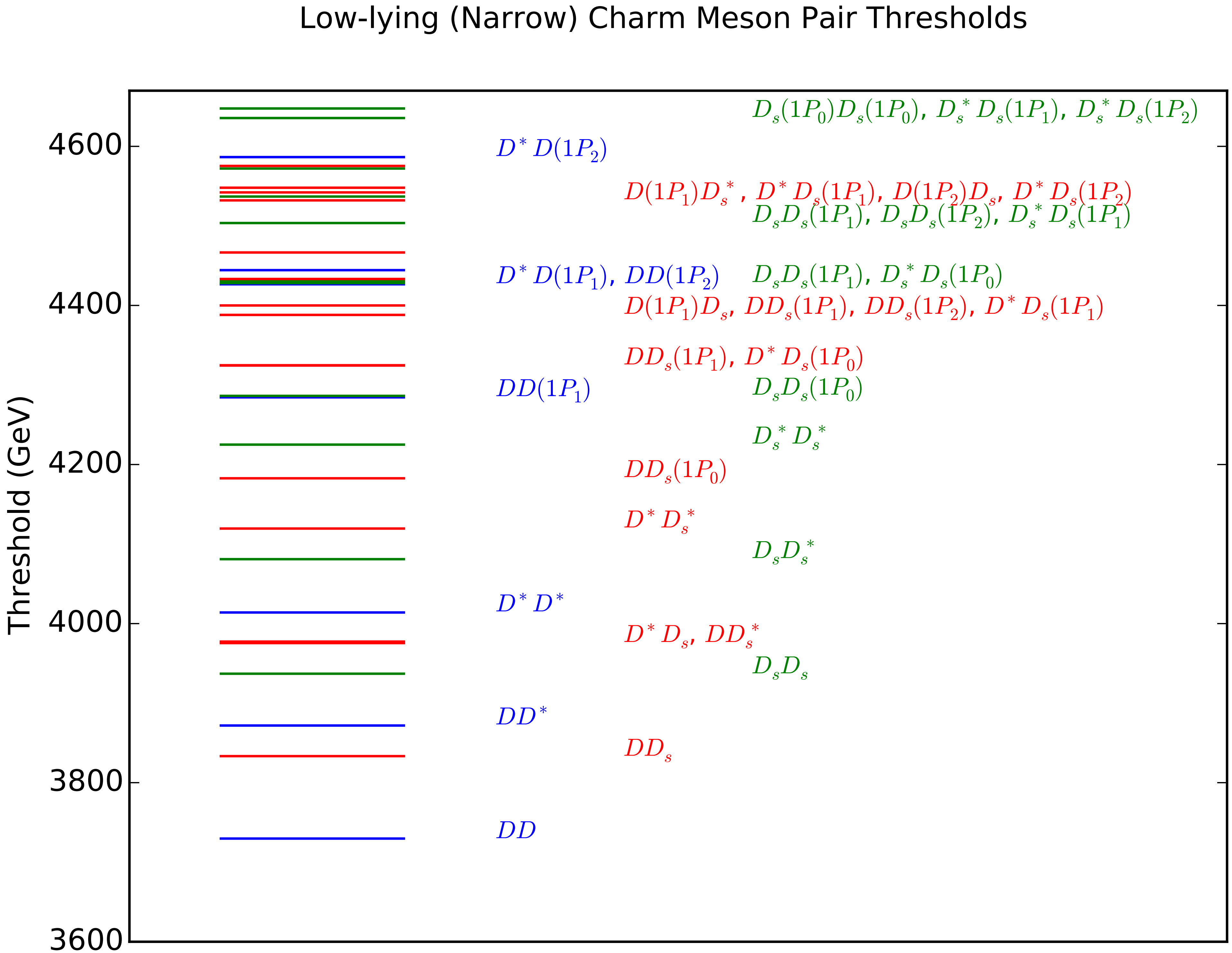


Systematics: ψ(4040) and Below

- 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^* $D(P_1)$

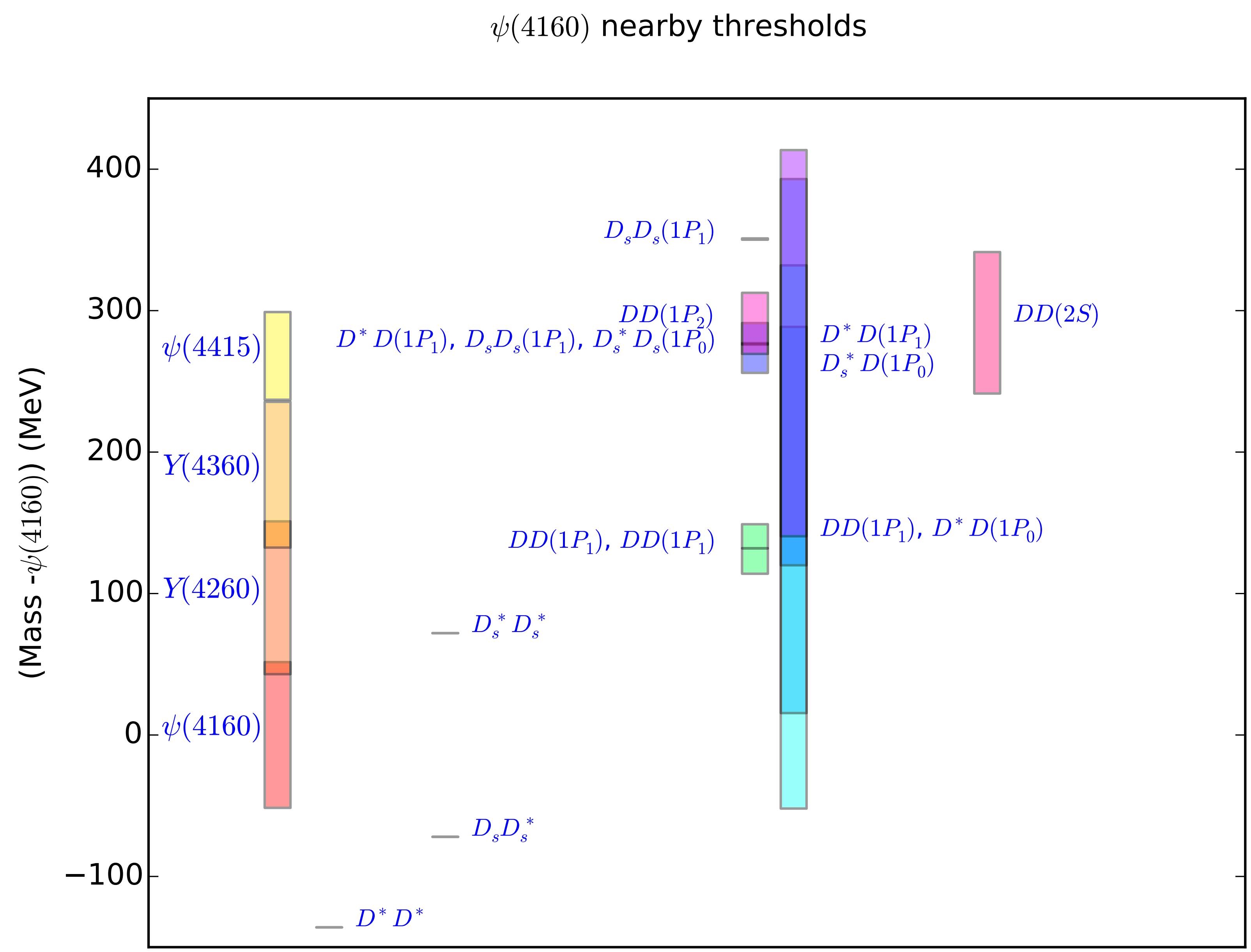
D_s $D(P_1)$; D_s^* $D(P_0)$

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.



Systematics and Expectations

- 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)

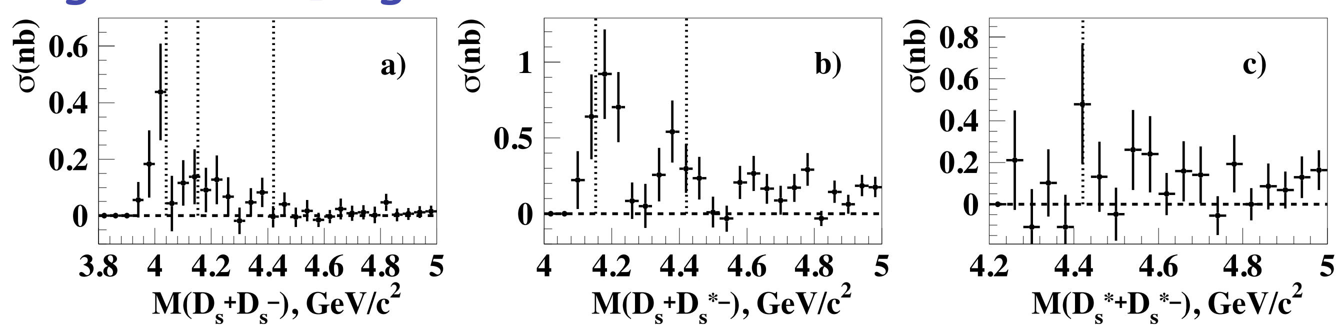
- Charmonium-like state transitions for masses above the ψ(3S)

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^{--}	
	$\pi^+\pi^-\psi(2S)$			
	$\eta J/\psi$			
	$\pi^\pm(D\bar{D}^*)^\mp$			

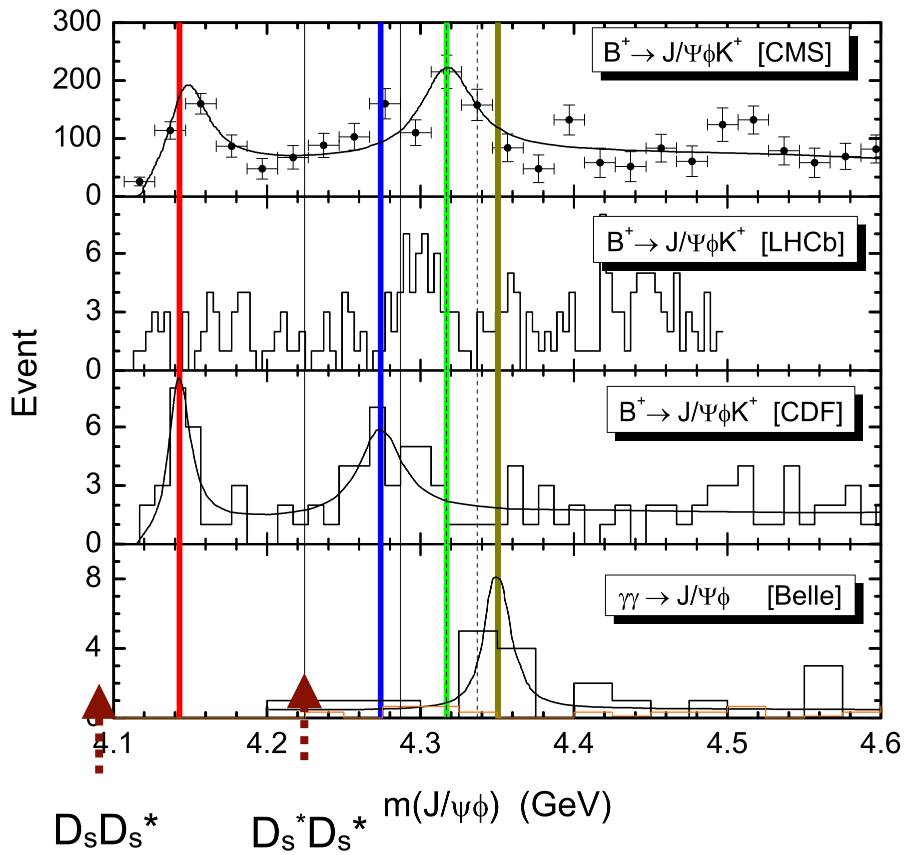
Strange heavy-light meson thresholds

- 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]

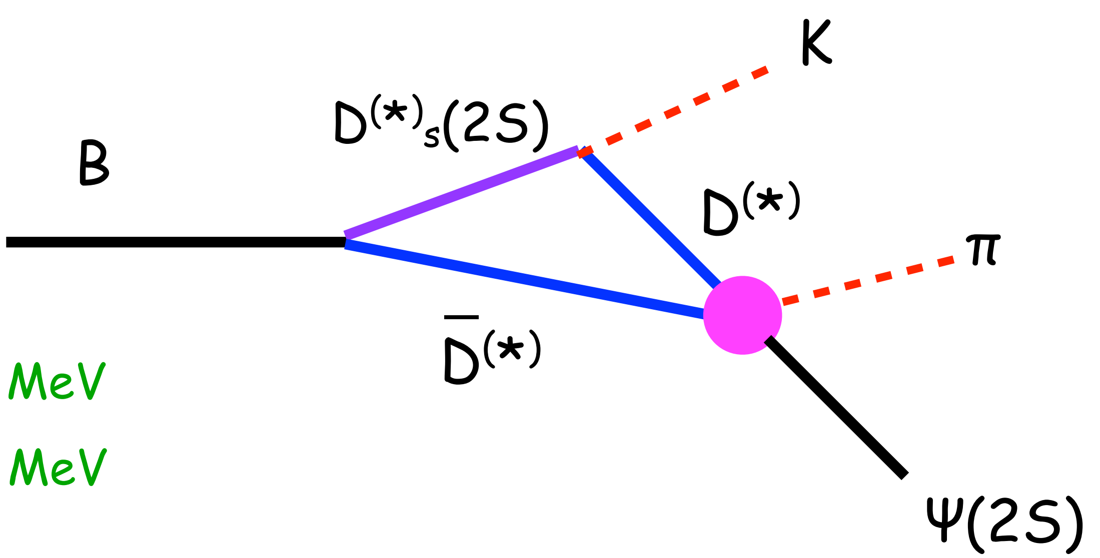


  - No wide P-states -> no sequential transitions with these states.
  - $M(D_s^+ D_s^{-*})$ = 4,081 MeV, $M(D_s^{+*} D_s^{-*})$ =4,225 MeV; $M(3^3P_2)$ = 4,315 MeV
  - Direct transitions?
  - Narrow $D(\frac{1}{2}^+P) + D(\frac{1}{2}^-S)$ thresholds? (and B analogs)
  - At higher energies the $D_s(2S)$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



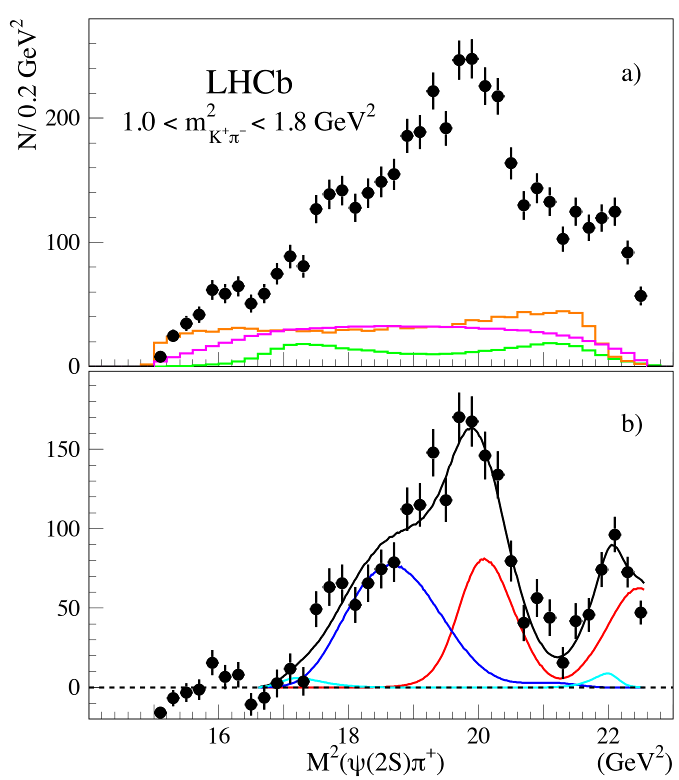
Systematics: Other States

- Same mechanism in B-decays with $2S_{\{0,1\}}(D_s)$ states: $Z^+(4430)$ 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



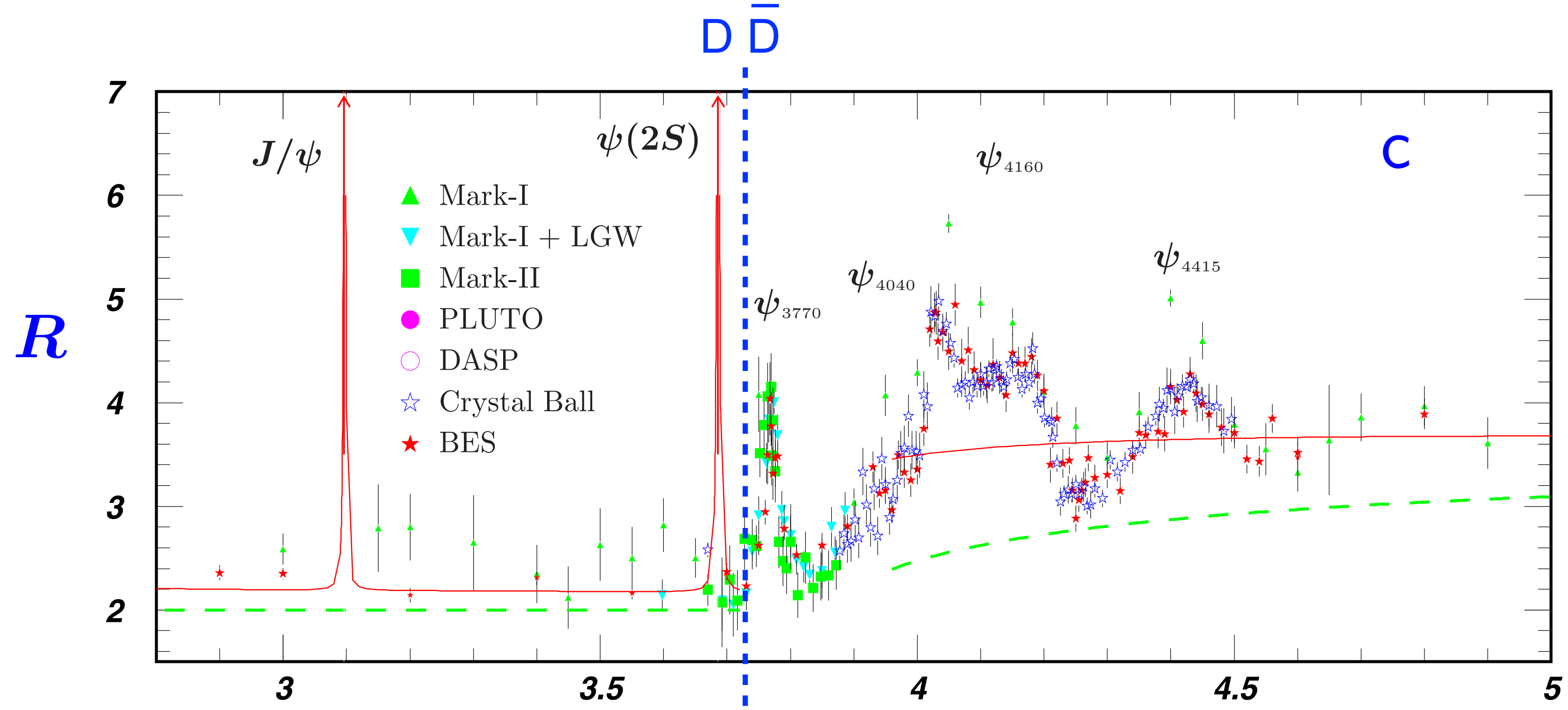
P. Pakhlov and T. Uglov

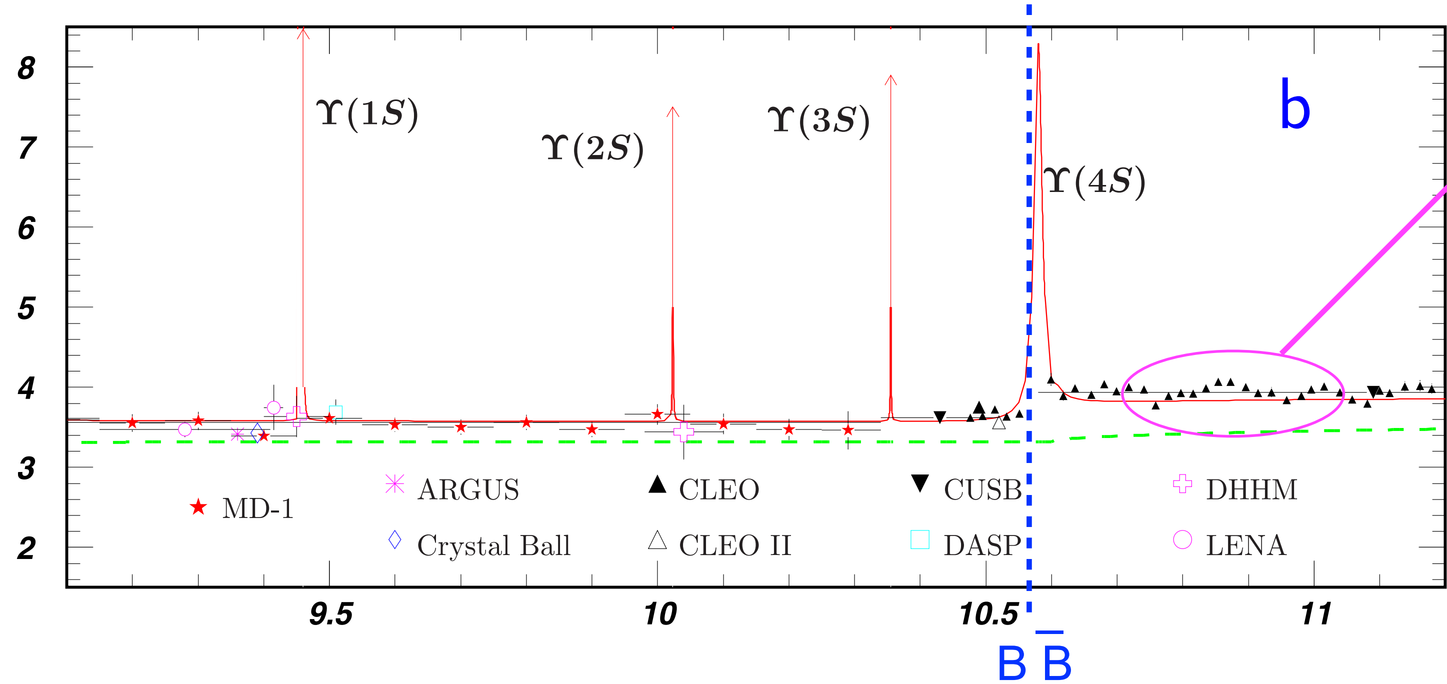
[arXiv:1408.5295]

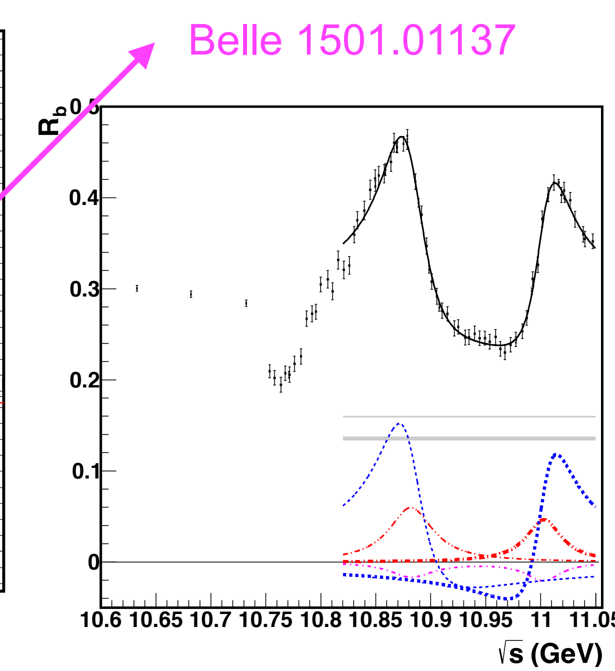


ΔR_Q in the Threshold Region

- R = σ(e+e- -> γ* -> hadrons)/σ(e+e- -> γ*-> μ+μ-) $J^{PC} = 1^{--}$
  - Resonance region ~ 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
  - $e_c = 2/3$; $e_b = -1/3$





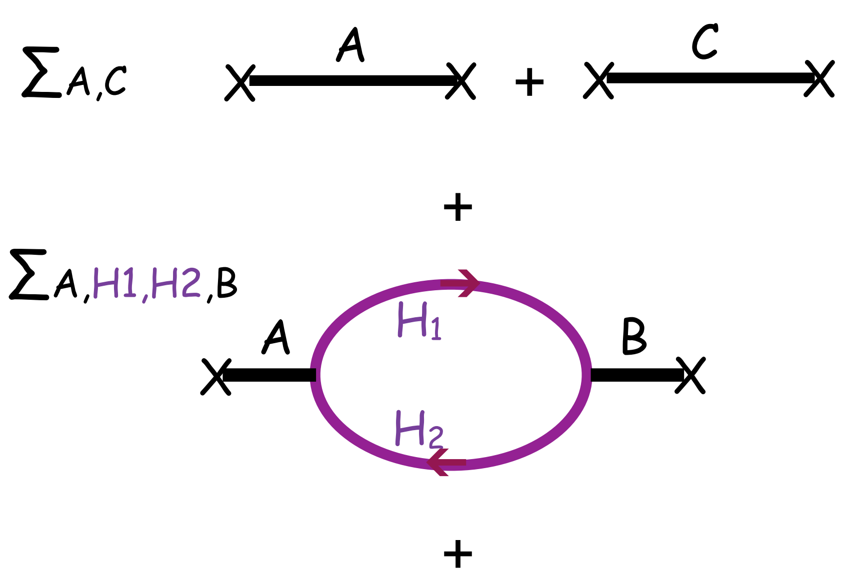


Quark-Hadron Duality

- Two pictures of R

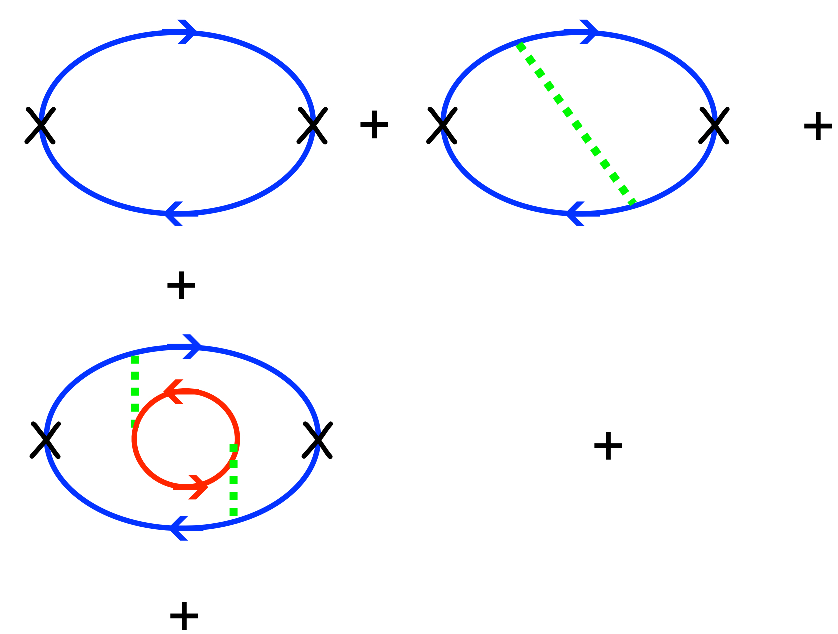
$$\Delta R(W) = \frac{6\pi}{W^2}\,\rho_c(W) \qquad -(g_{\mu\nu}q^2 - q_\mu q_\nu)\rho_c(W) = \int d^4x\, e^{iqx}\langle 0|j_\mu(x) j_\nu(0)|0\rangle\Big|_{\text{charm}}.$$

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



$\equiv$

QCD - perturbative
Q, g

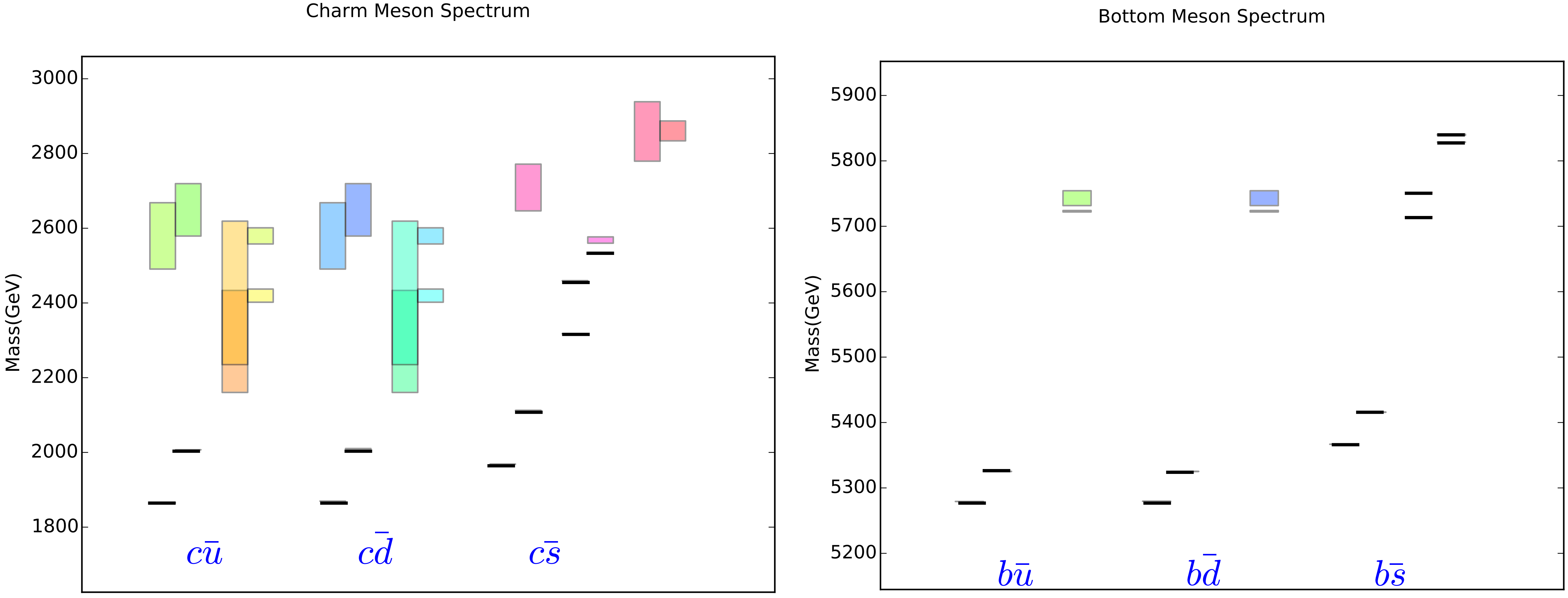


Simple expansion near threshold.

Simple expansion far above threshold.

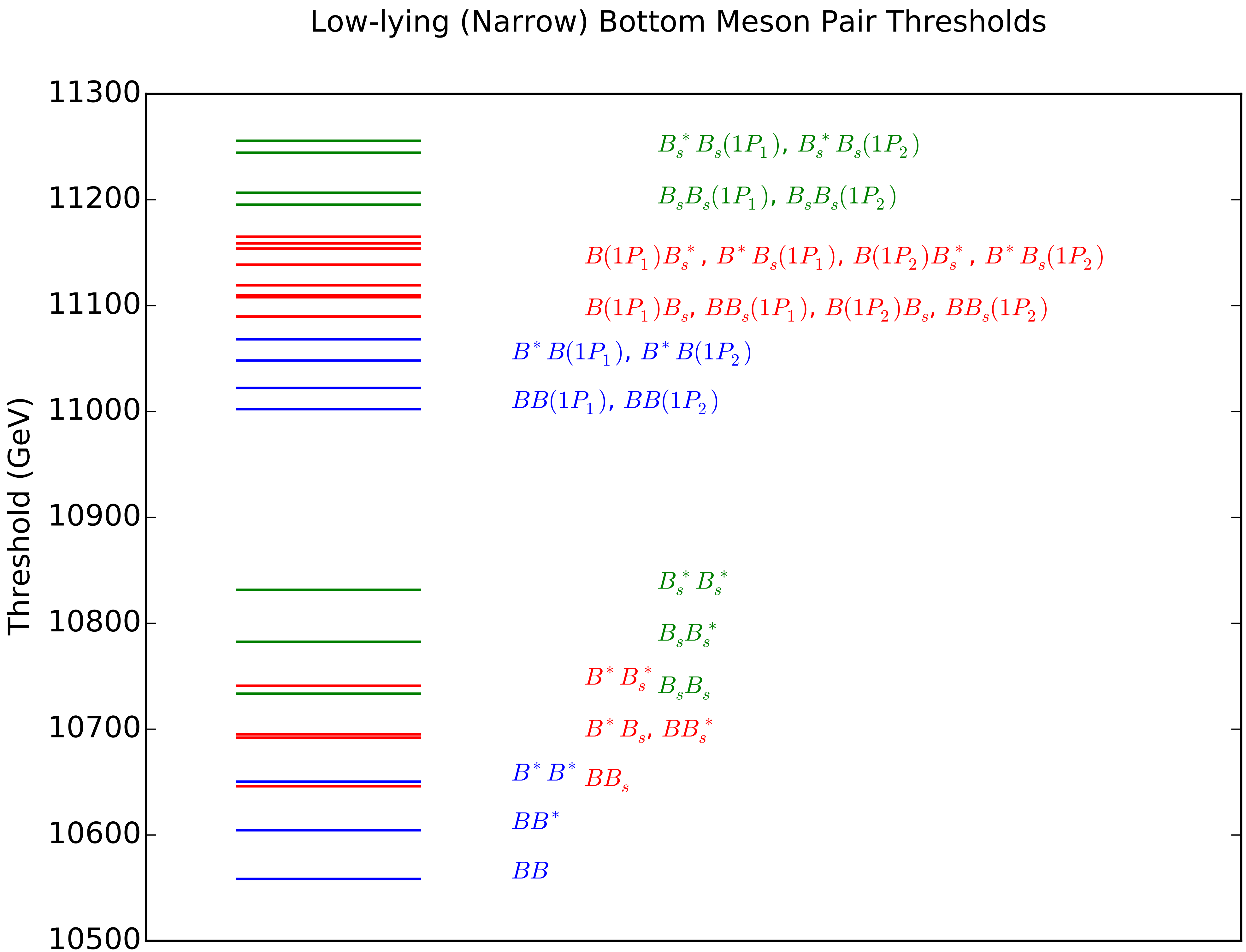
Heavy-Light Mesons

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



  - 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.

Low-lying thresholds



Narrow-Wide Thresholds

B_s* $B(P_1)$

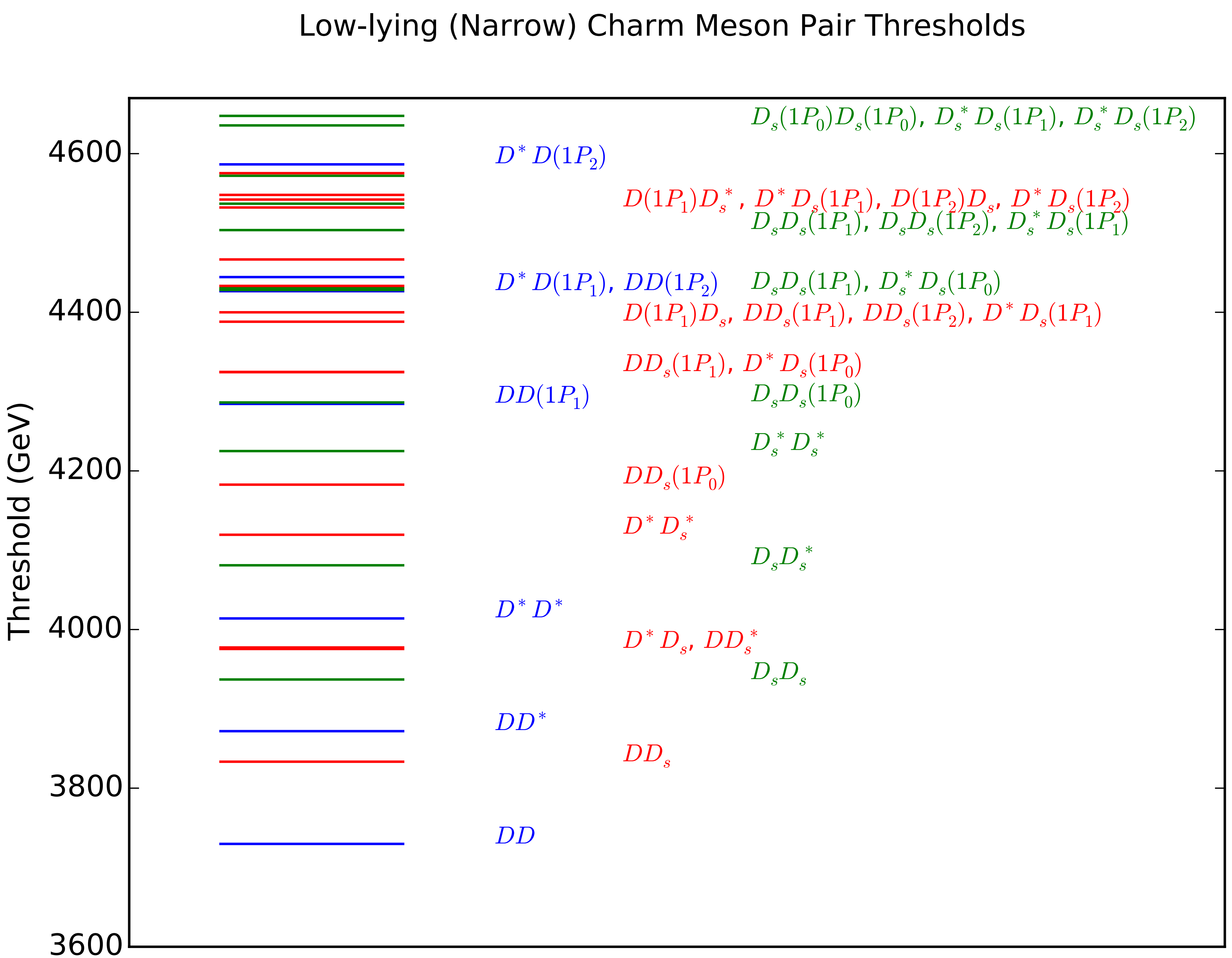
B_s* $B(P_0)$; B_s $B(P_1)$

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

B* $B(P_0)$

B $B(P_0)$

Low-lying thresholds



Narrow-Wide Thresholds

D_s^* $D(P_1)$

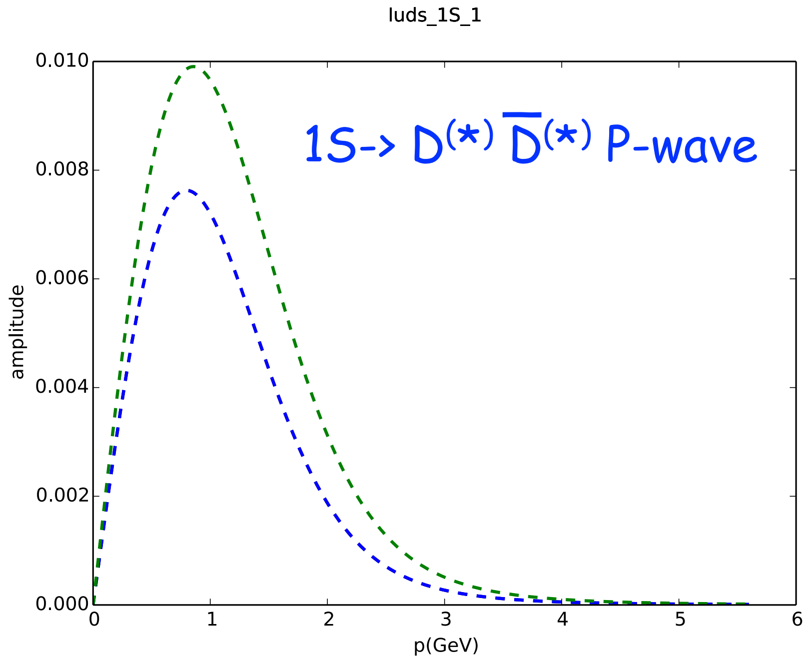
D_s $D(P_1)$; D_s^* $D(P_0)$

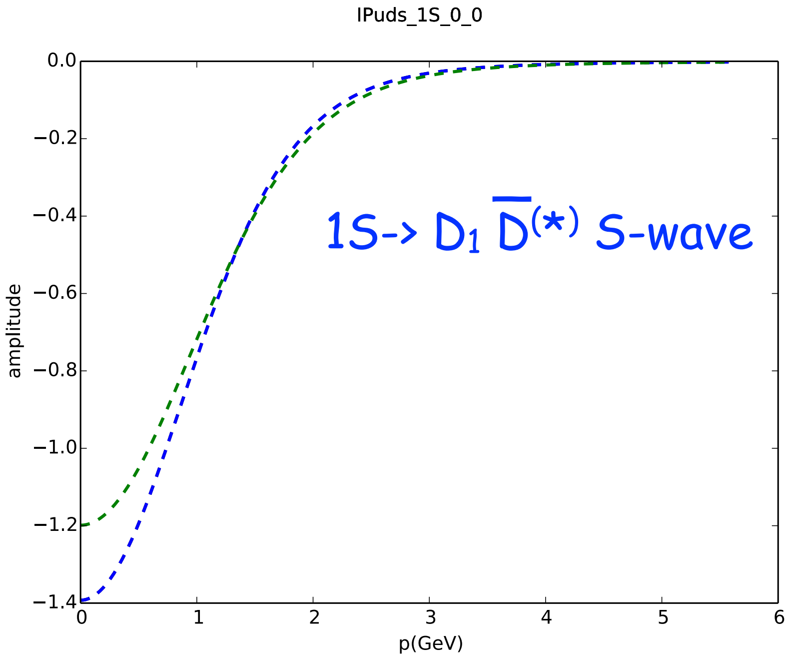
D_s $D(P_0)$; D^* $D(P_0)$; D $D(P_1)$

D $D(P_0)$

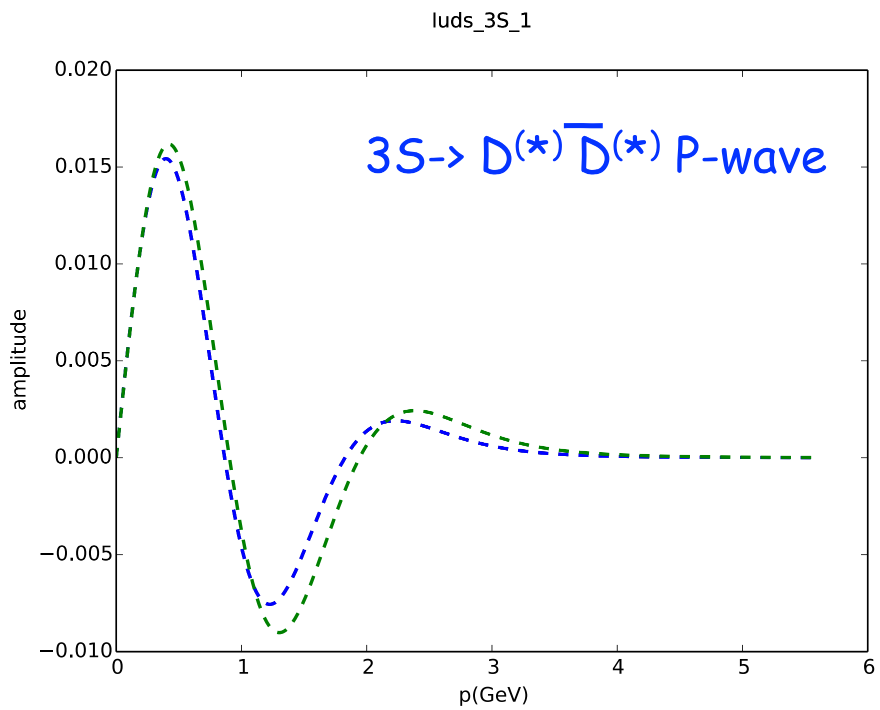
Decay Amplitudes

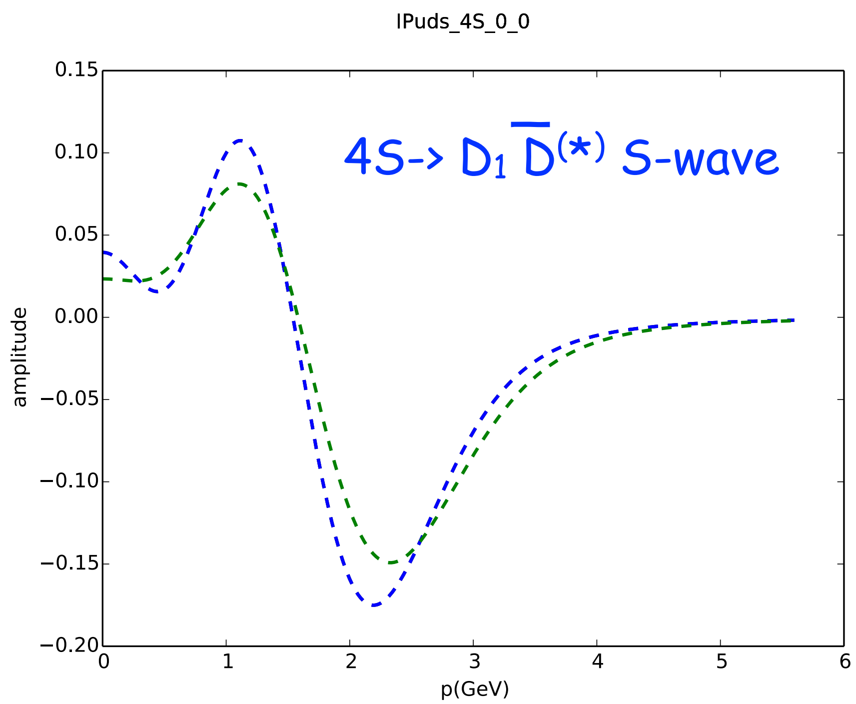
- For resonances (with no radial nodes) as expected:





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

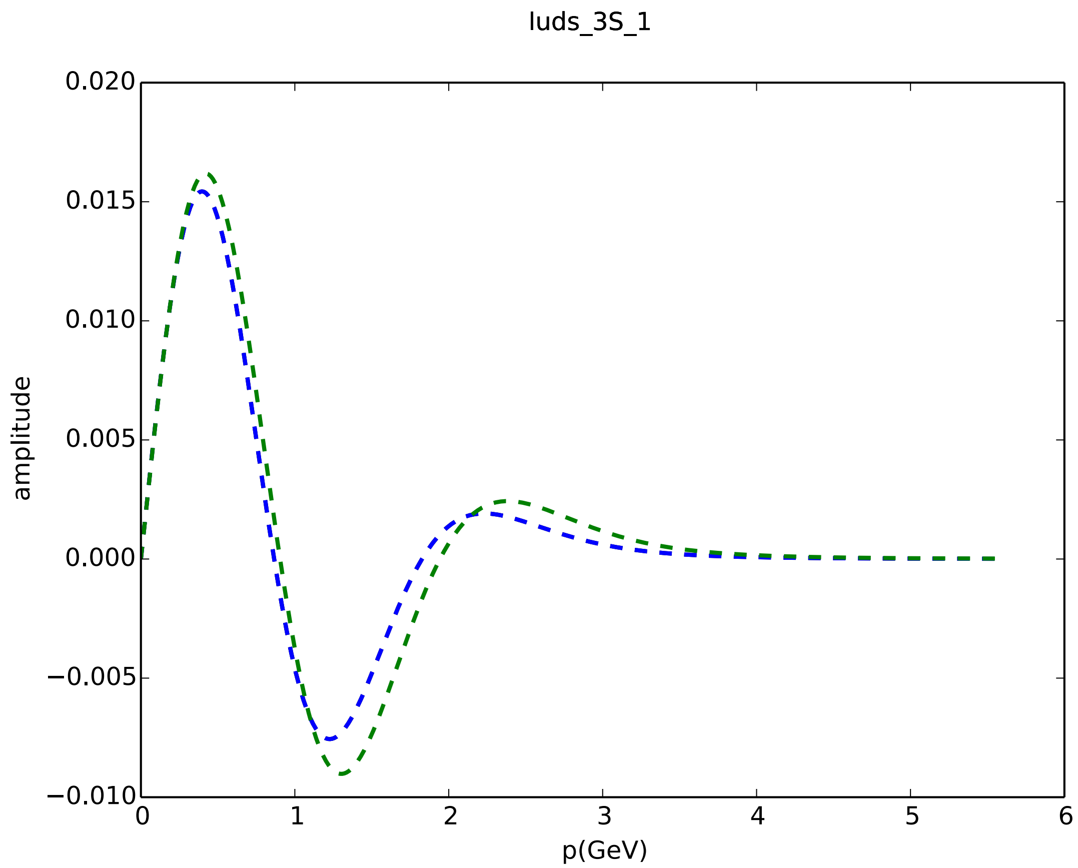


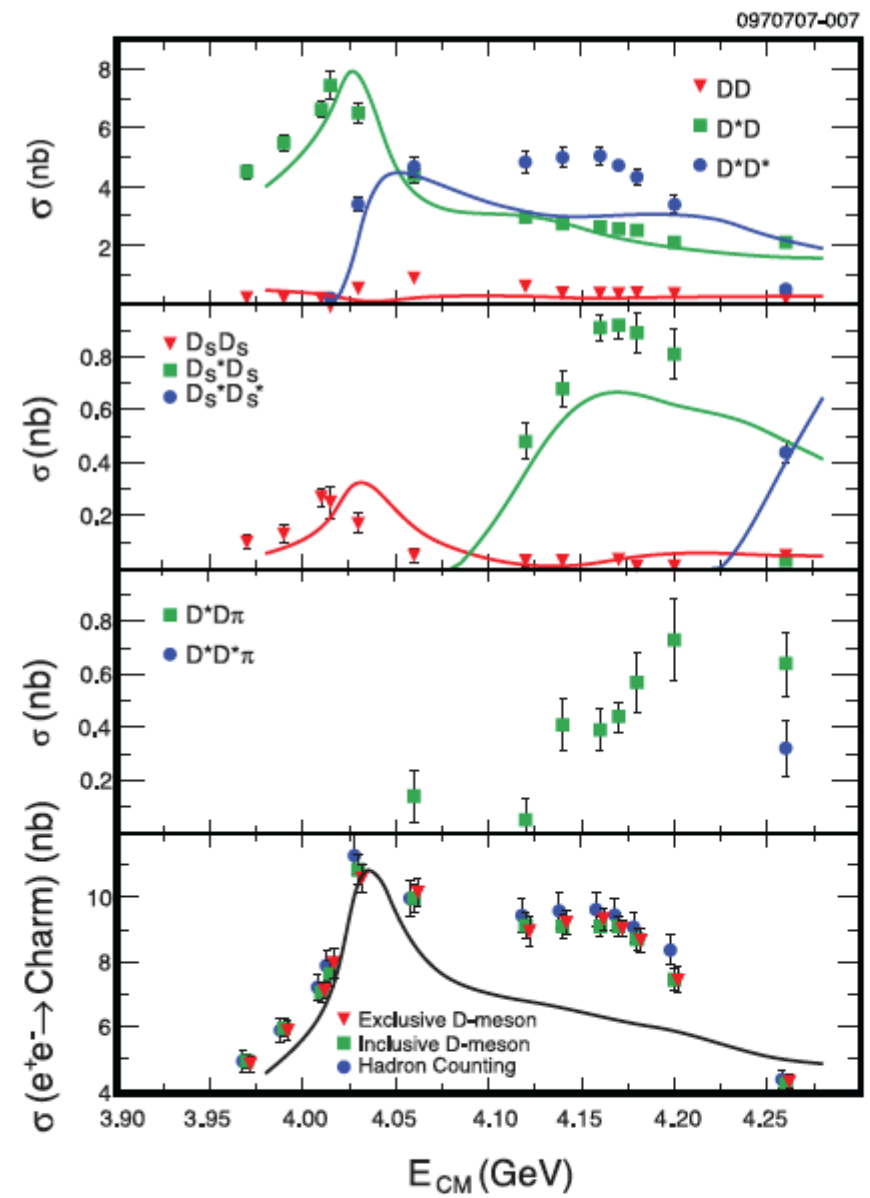


- $\Delta E = E - m_1 - m_2 = \sqrt{(m_1^2+p^2)} + \sqrt{(m_2^2+p^2)} - m_1 - m_2$

Complicated pattern in ΔR_c

- 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:
    - p(DD) = 0.66 ; p(DD*) = 0.40 ; p(D*D*) = —





Two requests

- To BES: Measure the line shape ΔR_c in the threshold region. Give results for each individual channel for:
  - pairs of narrow states of the heavy-light systems + pions
  - Quarkonium bound states + light hadrons.
  - It is the theorist challenge to make their model fit the data.

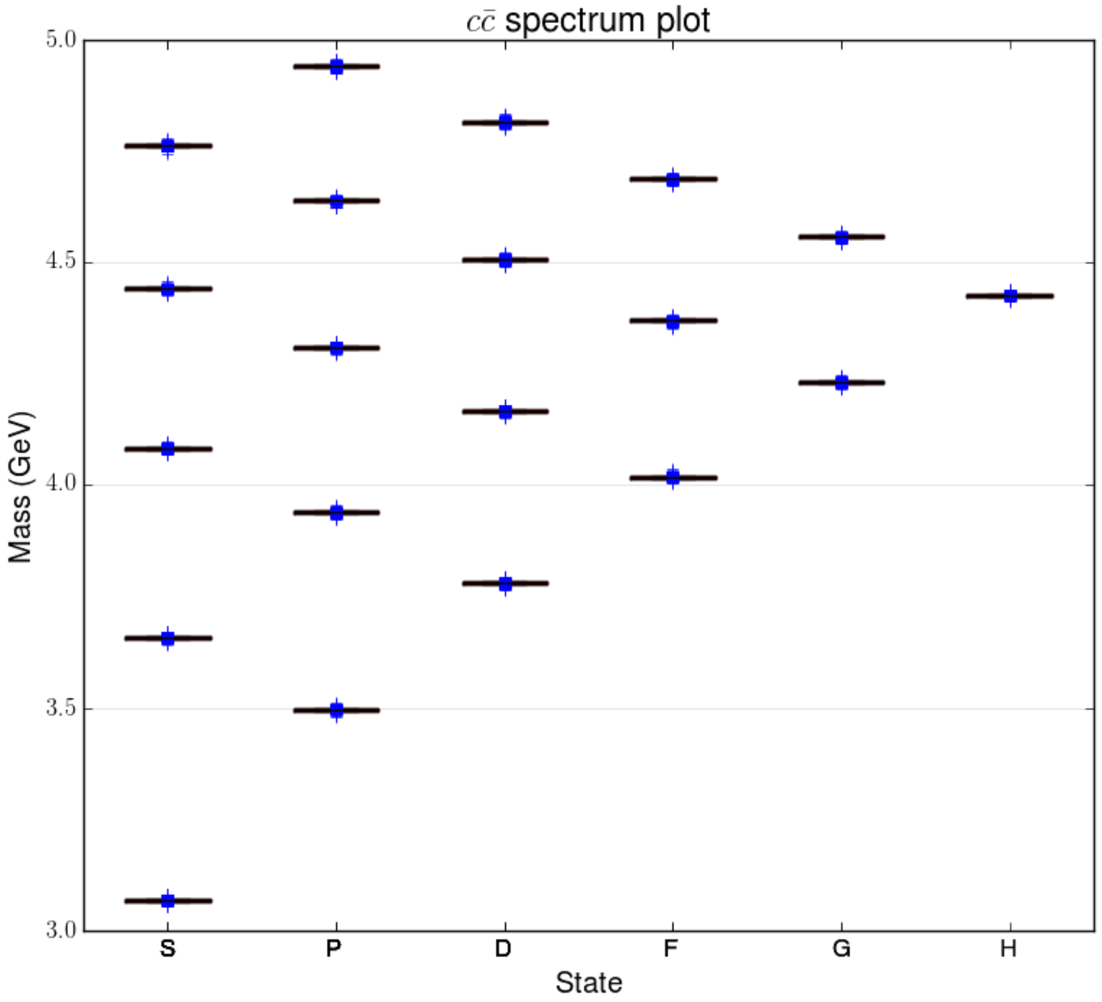
- To Lattice QCD: Calculate the behavior of scattering of heavy-light meson pairs in the threshold region.
  - Consider S-wave amplitudes (at first)
  - Include the mixing between two HL mesons and quarkonium + a single light hadron.
  - This is an difficult but not impossible challenge.

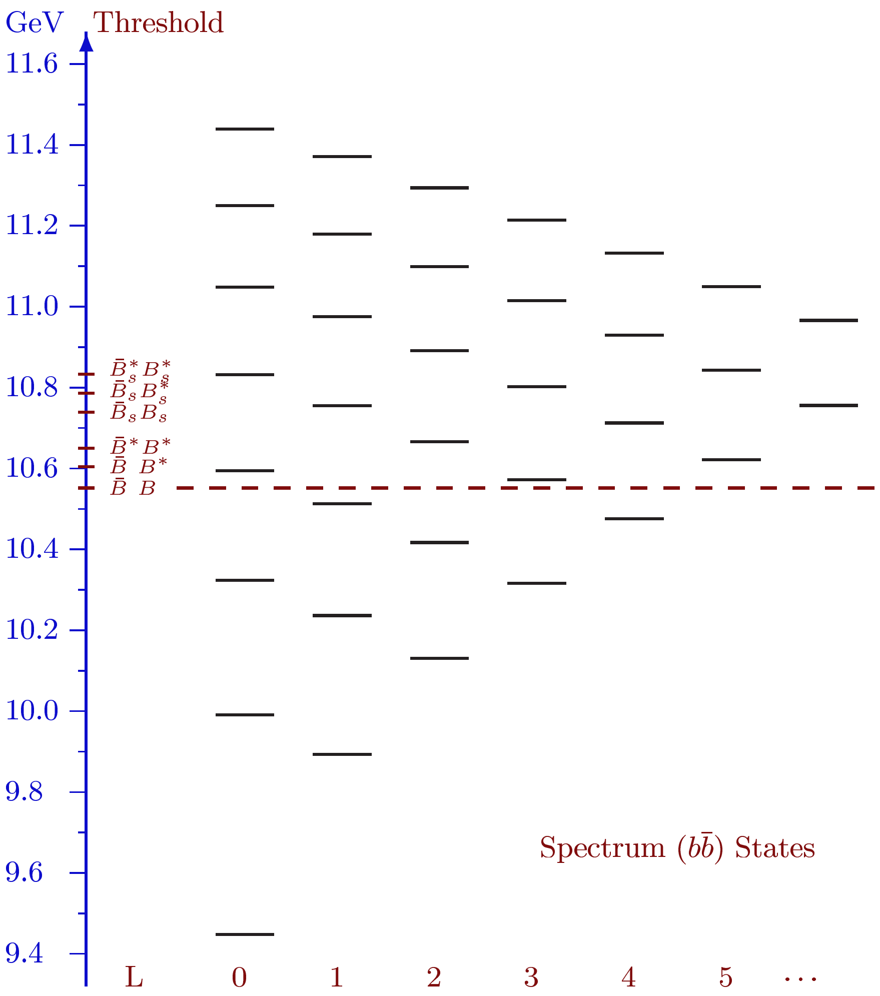
Summary

- 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.
- HQS as well as the usual SU(3) and chiral symmetry expectations are recovered.
- Resolves the puzzles in η transitions.
- With BES III and LHCb and soon BELLE 2. I expect even more progress in understanding hadronic transitions in the near future.

Backup Slides

Potential model states





Partial Waves for Various Decays

- Decays Near Threshold in e+e-

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

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

	$j_l^P=0^-$ [n^3D_1]	$j_l^P=1/2^-$	$j_l^P=1/2^+$	$j_l^P=3/2^+$	$j_l^P=3/2^-$	$j_l^P=5/2^-$
S	$j_l^P=1/2^-$	L=1,3	L=2	L=0,2,4	L=1,3	L=1,3,5
P	$j_l^P=1/2^+$	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
D	$j_l^P=3/2^-$	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=0,2,4,6	L=1,3,5	L=1,3,5,7
		S	P		D	

Decay Couplings

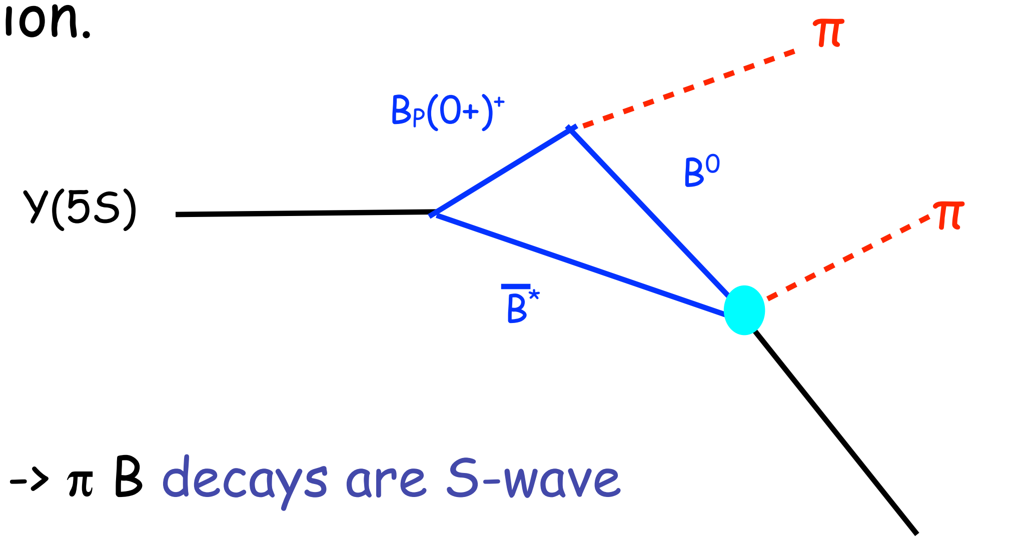
TABLE II: Statistical recoupling coefficients C, defined by Eq. D19 of Ref. [10], that enter the calculation of charmonium decays to pairs of charmed mesons. Paired entries correspond to $\ell = L - 1$ and $\ell = L + 1$.

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

Structure in two pion transitions

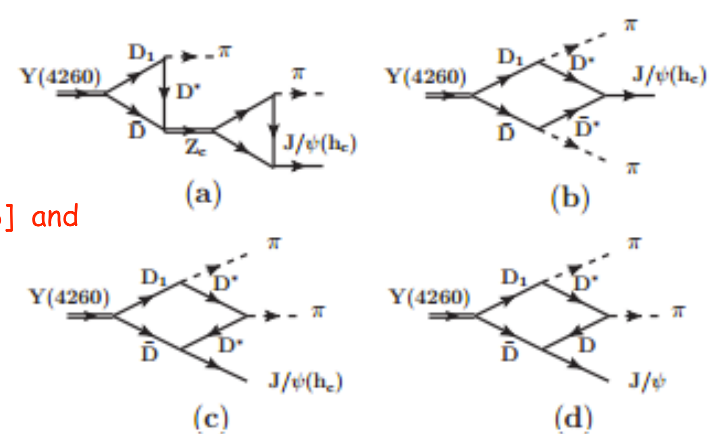
- For example, the Υ(5S) has a $B(1/2^-) + B_P(1/2^+)$ component. The $B_P(1/2^+)$ state decays rapidly into a B meson and pion, leaving a $B(1/2^-) + B(1/2^-)$ nearly at rest. They then recombine into the final (Υ or h_b) and pion.

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

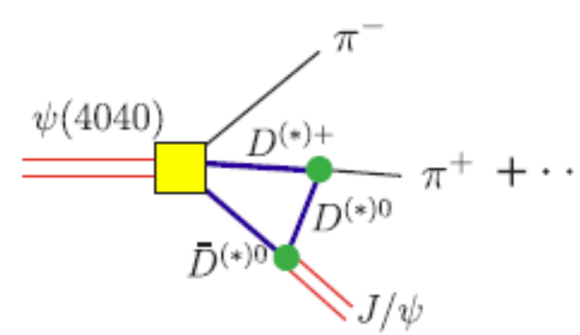


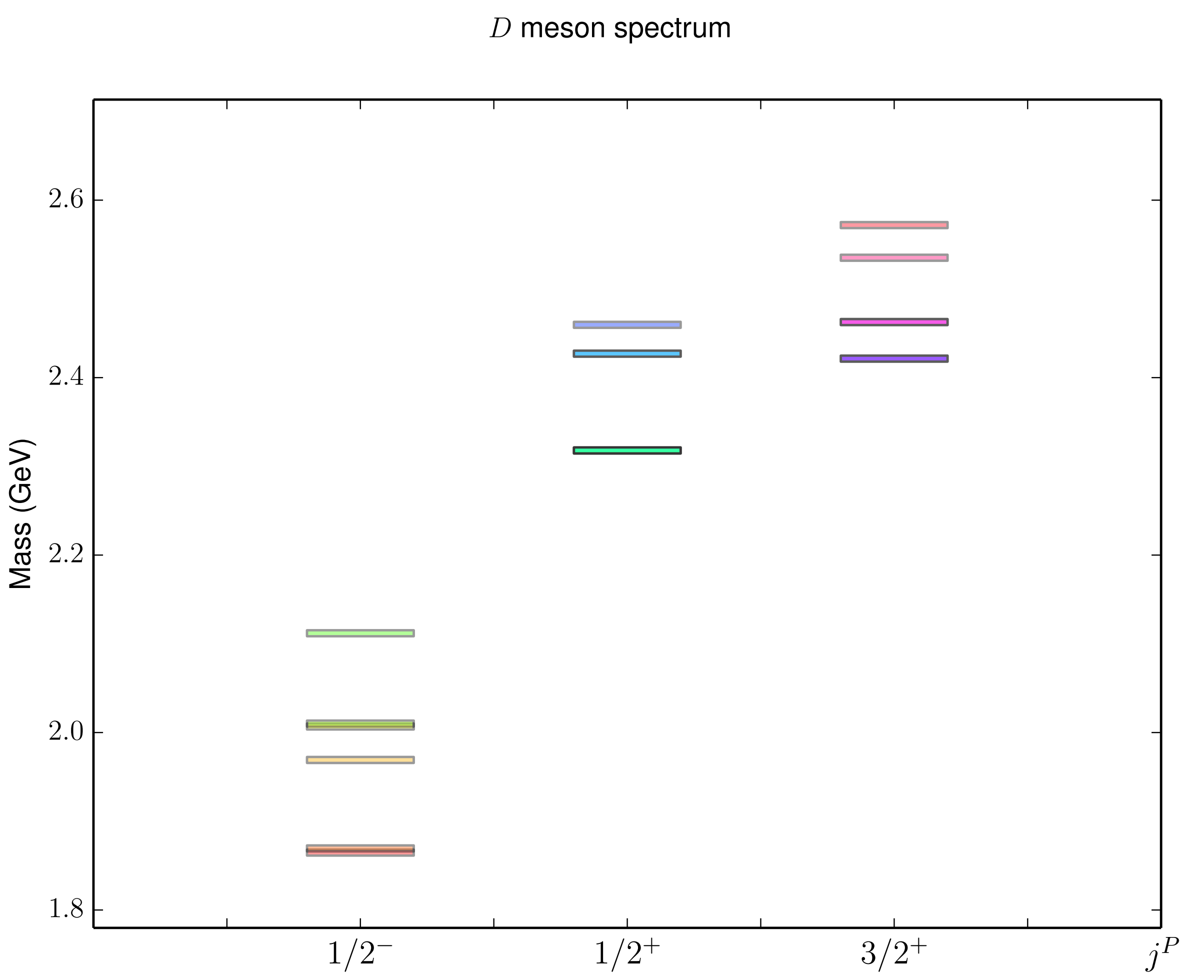
  - Both the Υ(5S) -> Bp(0+) B* and Bp(0+) -> π B decays are S-wave
  - The analogy in the charmonium system is the structure seen in the ψ(4160) -> π π J/ψ transition.
  - This provides a dynamical mechanism for the Meson Loop and ISPE models.

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

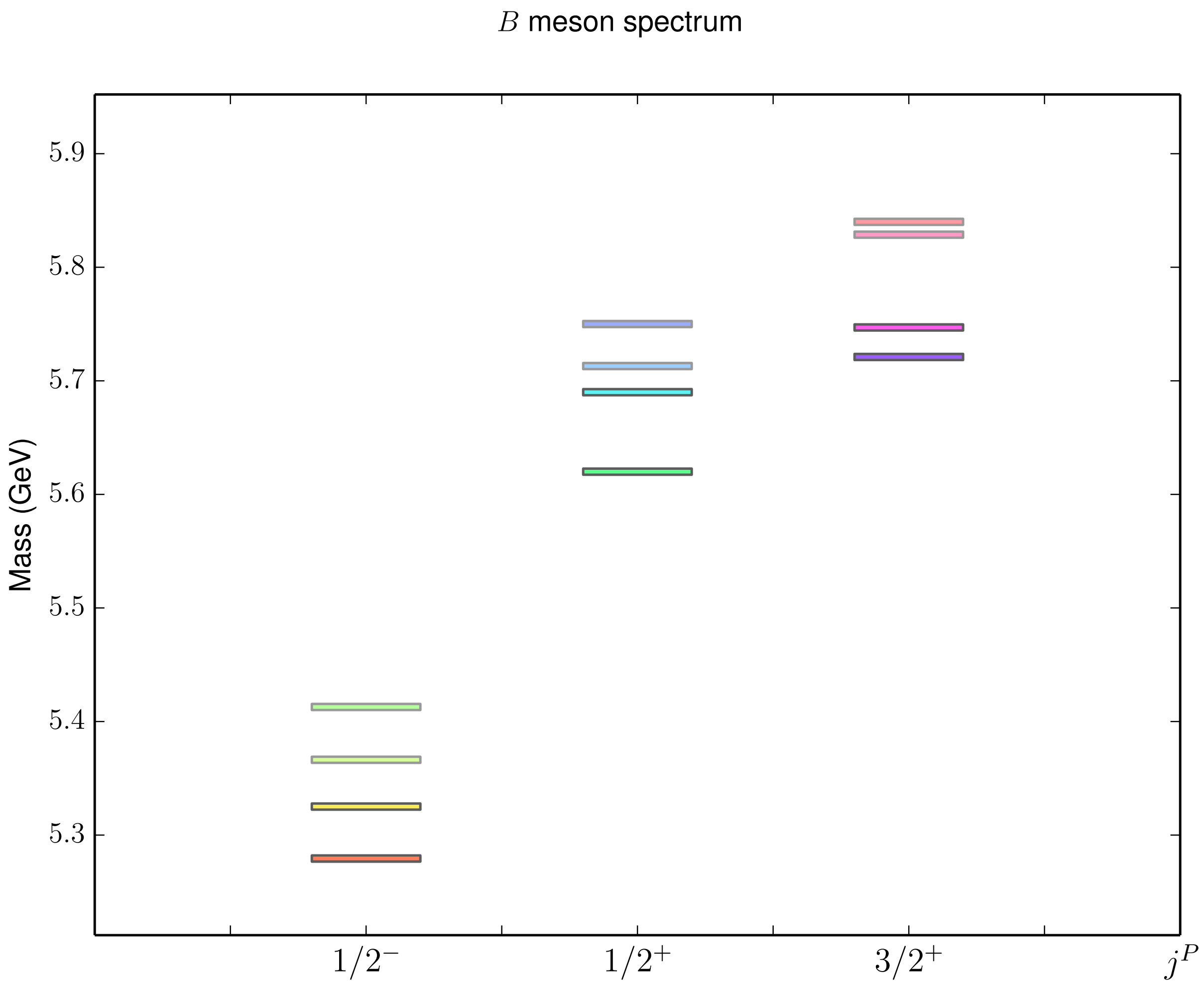


ISPE Model: [1303.6842] and references therein





D meson spectrum
Mass (GeV)
2.6
2.4
2.2
2.0
1.8
$1/2^-$
$1/2^+$
$3/2^+$
j^P



B meson spectrum
Mass (GeV)
5.9
5.8
5.7
5.6
5.5
5.4
5.3
$1/2^-$
$1/2^+$
$3/2^+$
j^P

Transitions

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	
$\Upsilon(2S)$		
$\to \Upsilon(1S) + \pi^+\pi^-$	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]

Determining the Hybrid Potentials

- 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, $\sqrt{\sigma}$ = .427 GeV, α_s = 0.39

n(R) = [n] (string level) if no level crossing

[n - 2 tanh(R_0/R)] for Σ_u potential (n=3)

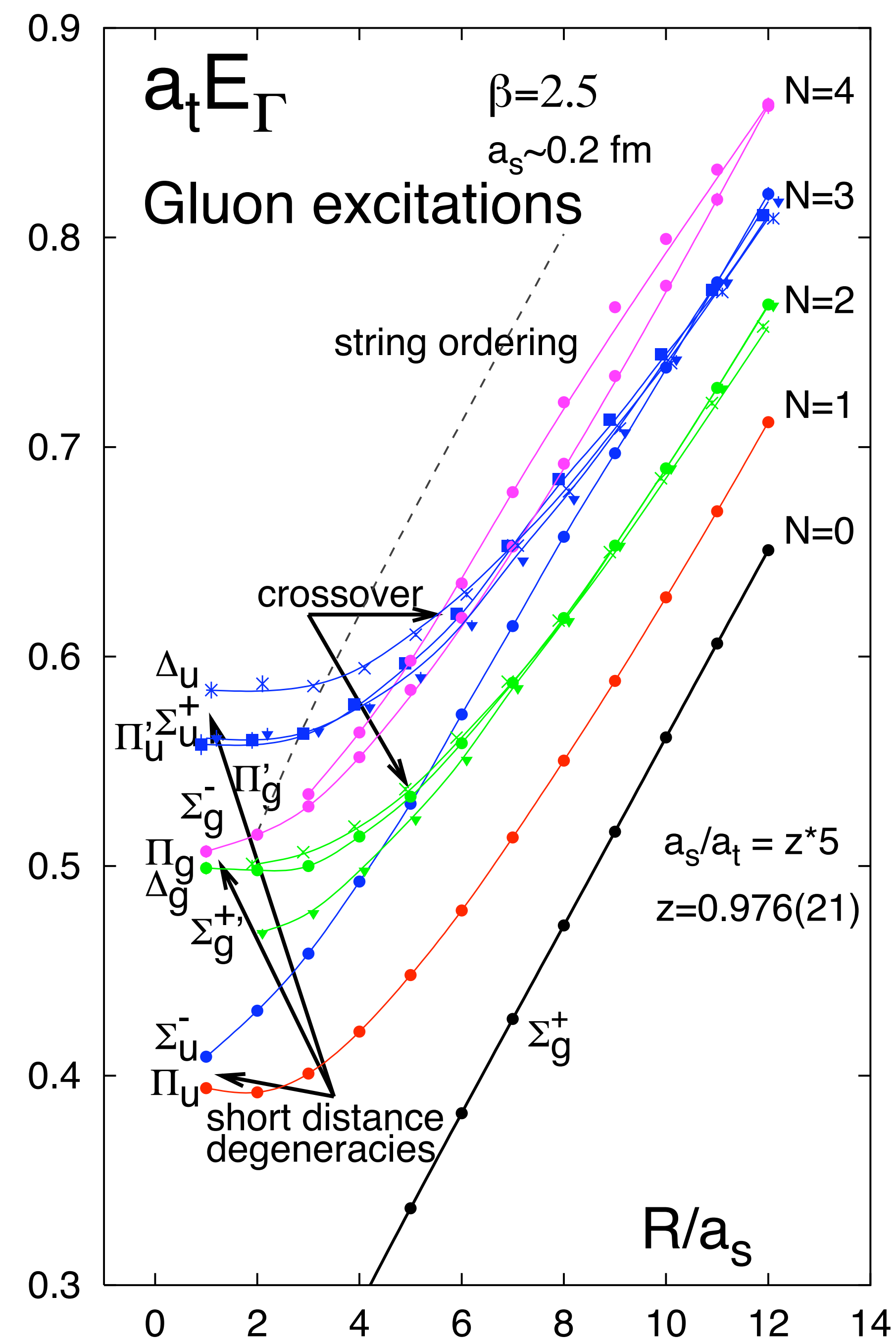
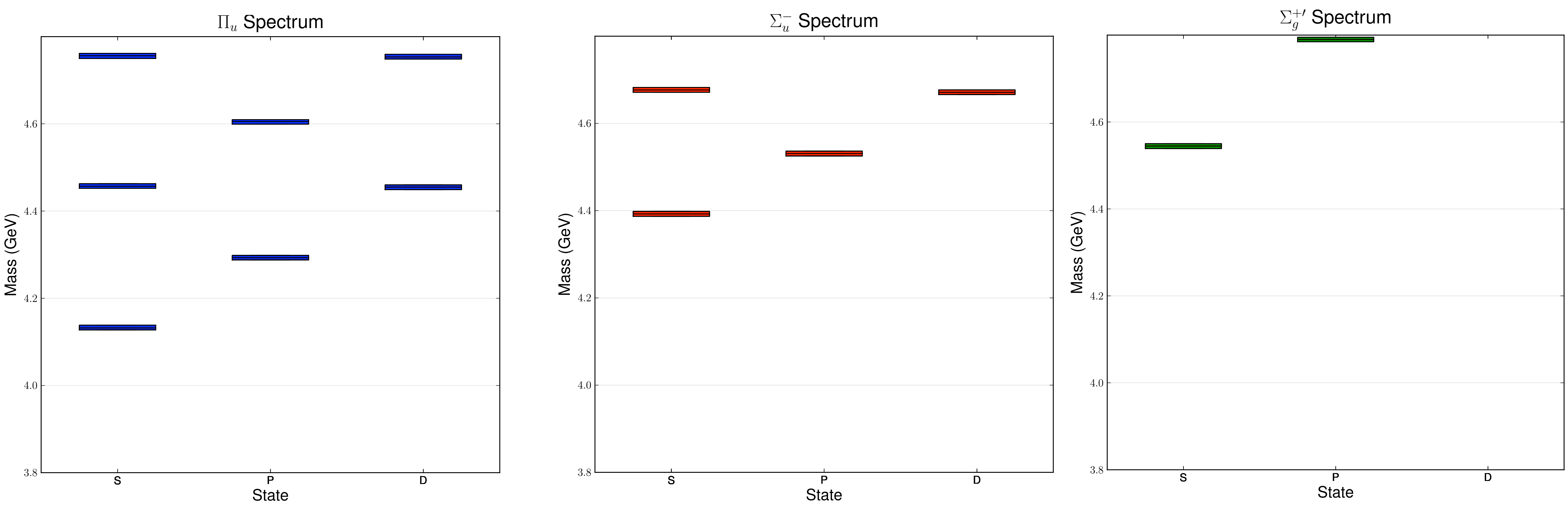


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Spectrum of Low-Lying Hybrid States

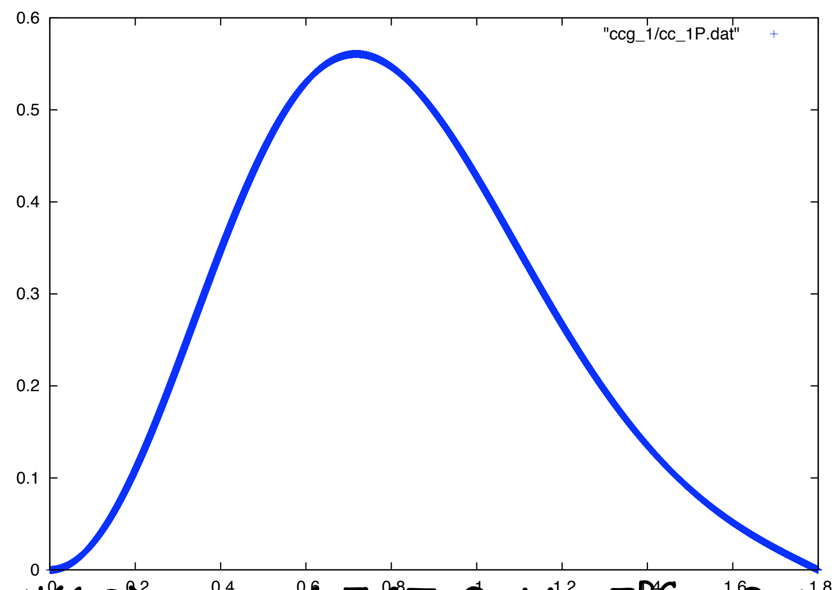
- Only interested in states below 4.8 GeV for cc system.
  Unlikely higher states will be narrow (DD, glueball+J/ψ, etc)

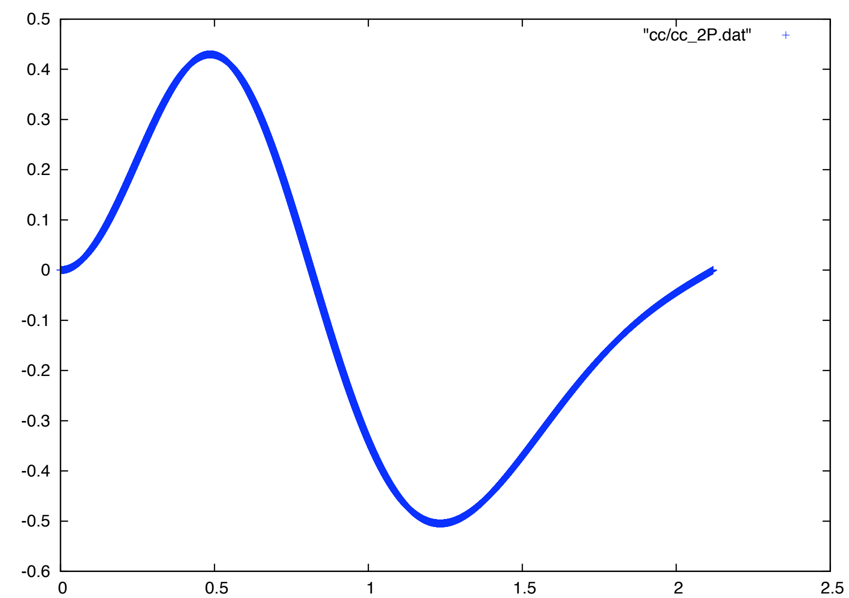


- Only Π_u, Σ_u^- , and$\Sigma_g^{+\prime}$ systems have sufficiently light states.

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

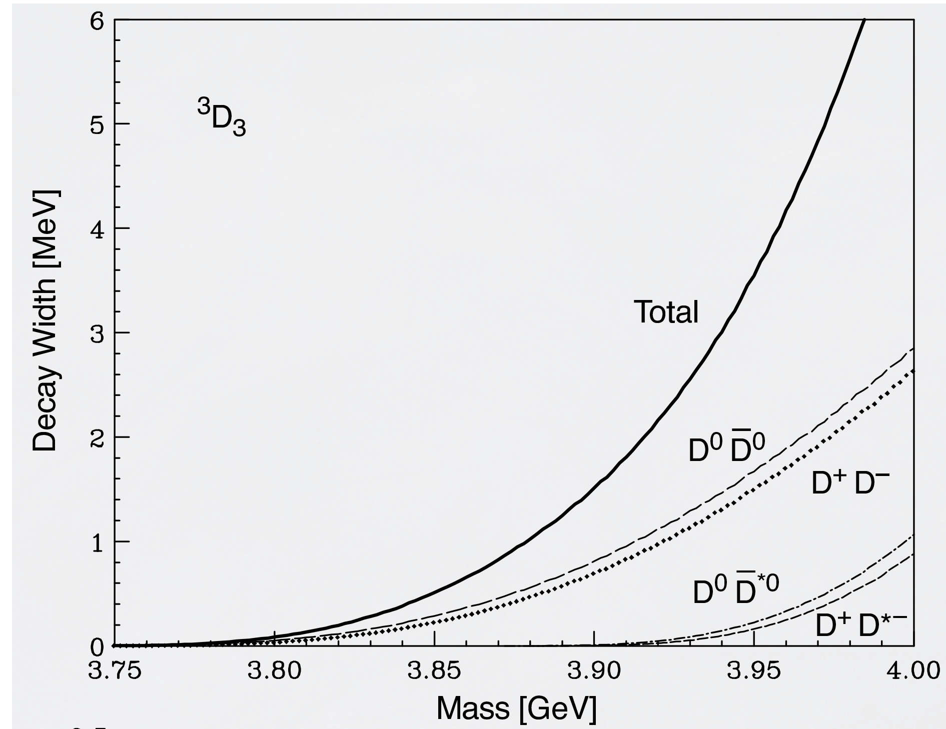
- The spectrum of bottomonium hybrids is completely predicted as well
- For the Π_u states

(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

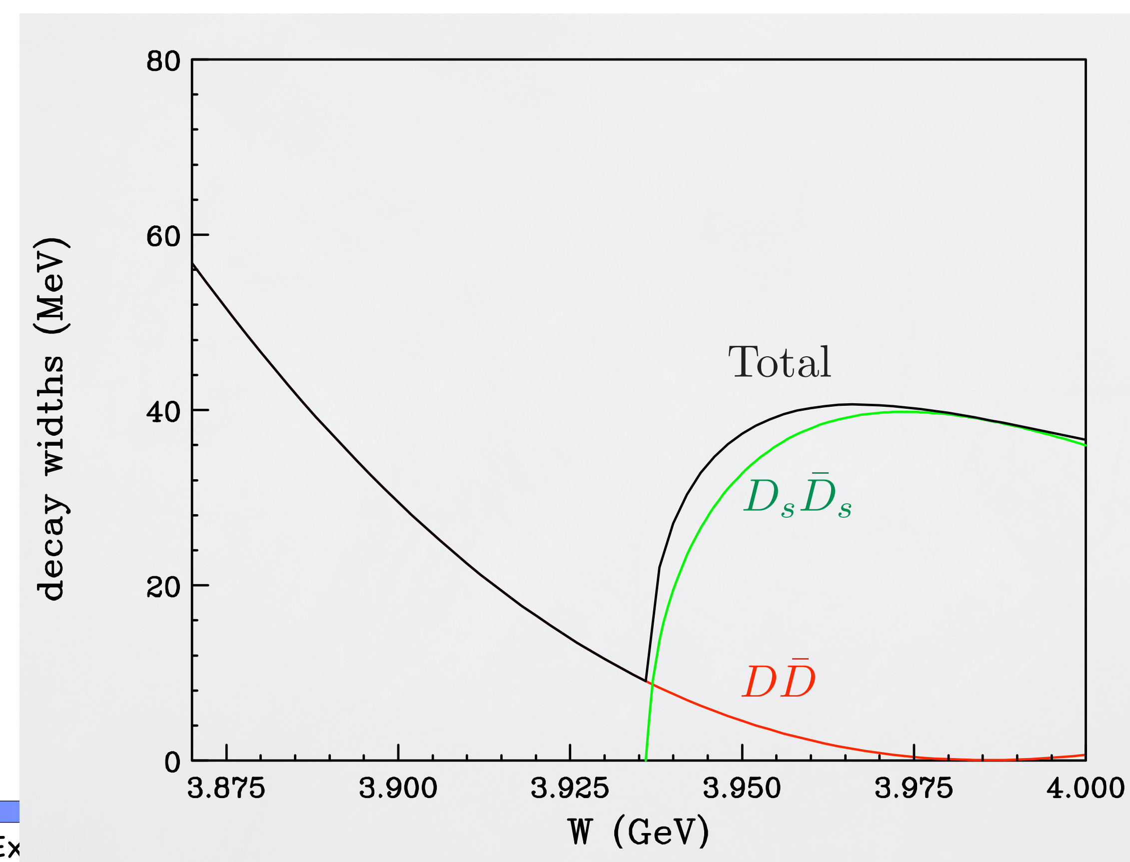
(bb)	L	n	mass(GeV)
	0	1	10.783900
	0	2	10.982855
	0	3	11.172408
	0	4	11.353469
	0	5	11.527274
	0	6	11.694851
	0	7	11.856977
	0	8	12.014256
✓	1	1	10.877928
	1	2	11.073672
	1	3	11.259766
	1	4	11.437735
	1	5	11.608810
	1	6	11.773931
	1	7	11.933823
	2	1	10.976071
	2	2	11.167070
	2	3	11.349124
	2	4	11.523652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

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.



QCDME

- QCD multipole expansion (basics)
  - Factorize heavy quark dynamics and light hadron production.

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

+ higher order multipole terms.

  - Assume models for spectrum of $H^{(0)}$ (potential model) and intermediate states |KL> (QCS Buchmueller-Tye)

where |KL> are a complete set of intermediate states.

$$\langle f\ h|H_2 \mathcal{G}(E_i) H_2|i\rangle = \sum_{KL} \langle f\ h|H_2|KL\rangle \frac{1}{E_i - E_{KL}} \langle KL|H_2|i\rangle$$

  - Chiral effective lagrangian to parameterize light hadron matrix elements.

with

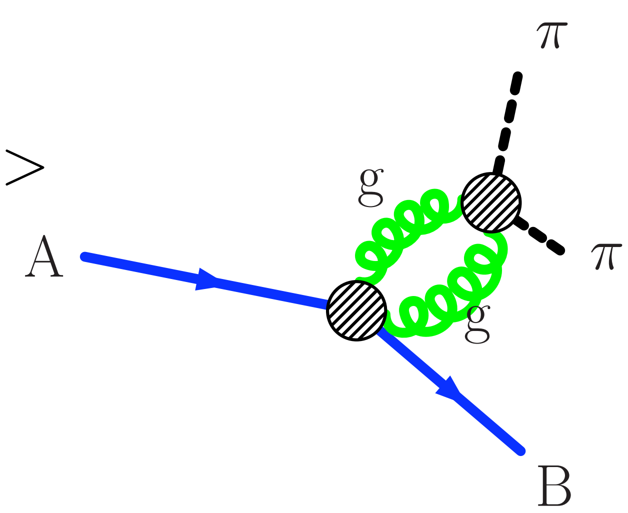
$$\mathcal{G}(E) = \frac{1}{E - H^{(0)}_{\rm QCD} + i\partial_0 - H^{(1)}_{\rm QCD} + i\epsilon}$$

QCDME

- two pion transitions (E1-E1) (C$C_A C_B = +1$)
  - Factorization

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

α_{AB}^{EE}



  - Chiral symmetry

Hadronize

S-wave D-wave

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

  - Explicit model - Kuang & Yan (PR D24, 2874 (1981)

$$d\Gamma \sim K \sqrt{1 - \frac{4m_\pi^2}{M_{\pi\pi}^2}} (M_{\pi\pi}^2 - 2m_\pi^2)^2 \; dM_{\pi\pi}^2 \qquad K \equiv \frac{\sqrt{(M_A + M_B)^2 - M_{\pi\pi}^2} \sqrt{(M_A - M_B)^2 - M_{\pi\pi}^2}}{2M_A}$$

S state -> S state

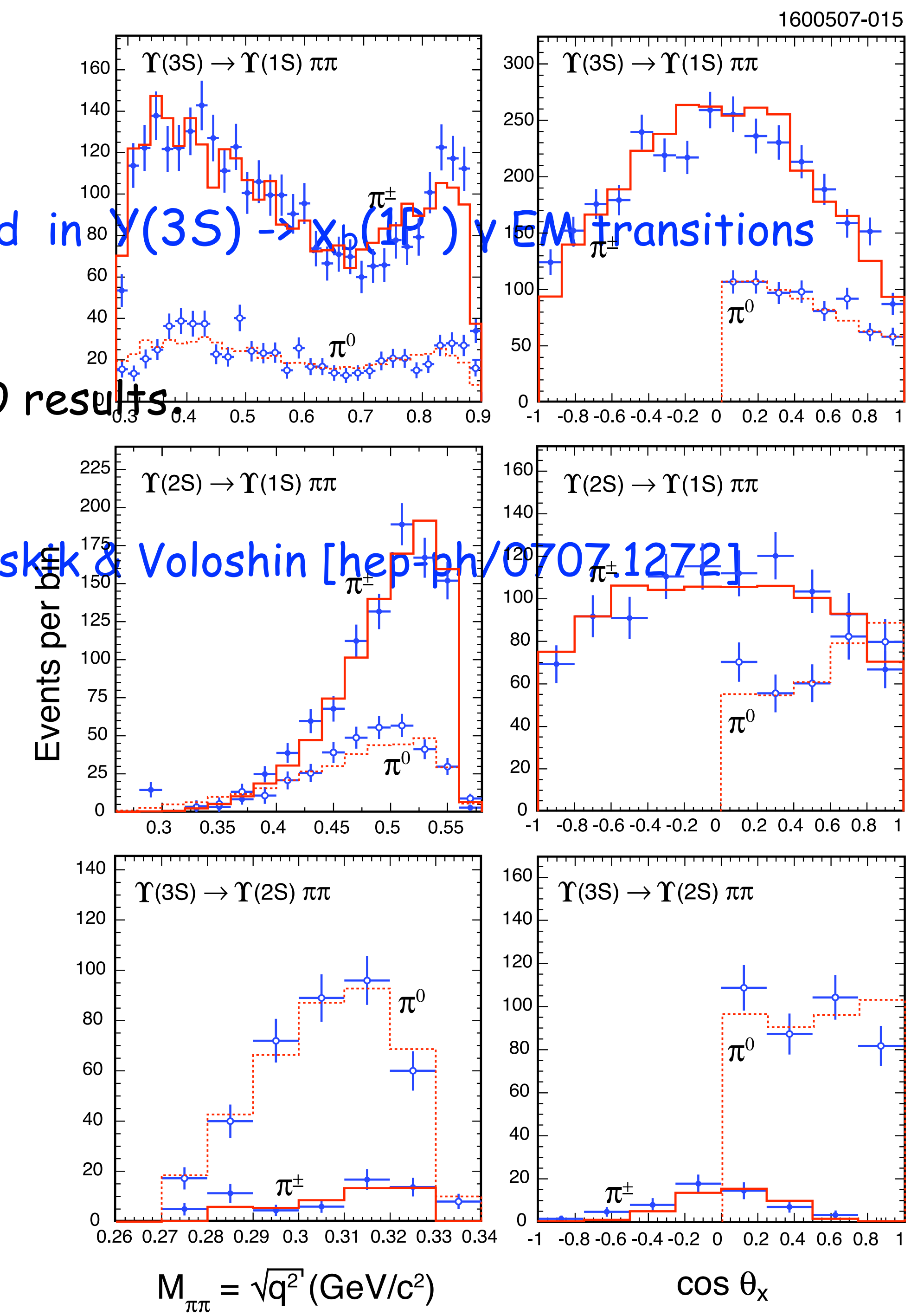
$$\Gamma = \mathrm{G} \; |\alpha_{\mathrm{AB}}^{\mathrm{EE}} \; \mathrm{C}_1|^2$$

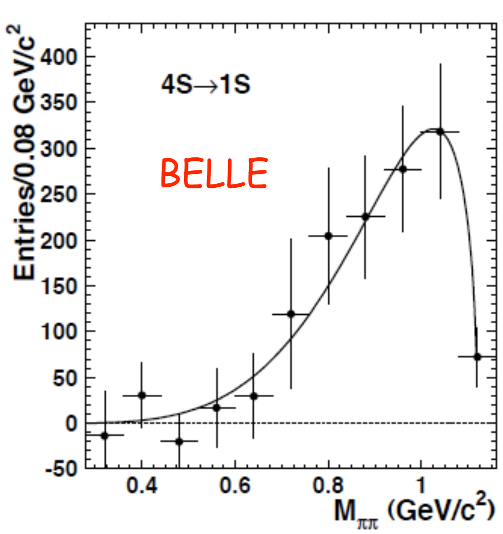
Phase Space

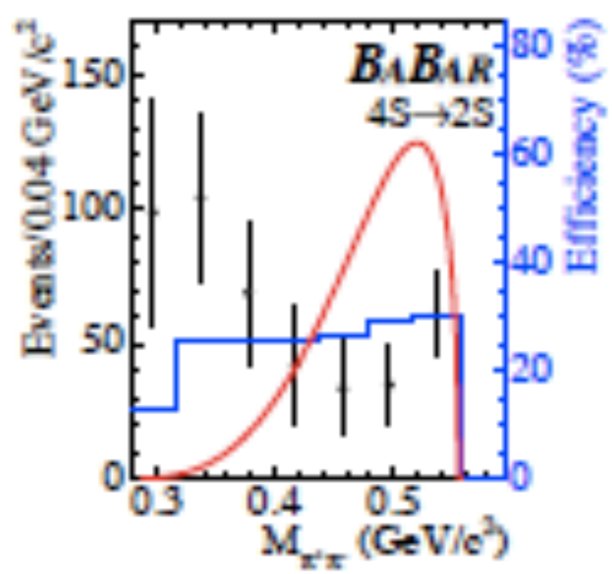
Overlap - Buchmuller-Tye string inspired model)

Some Puzzles / Remaining Puzzles

- $\Upsilon(3S) \to \Upsilon(1S)\ \pi\pi$ and $\Upsilon(4S) \to \Upsilon(2S)\ \pi\pi$ transitions
  - $M_{\pi\pi}$ distributions NOT the expected S-wave behaviour
  - Likely explanation - same as overlap dynamically suppressed in $\Upsilon(3S) \to \chi_b(1P)\ \gamma$ EM transitions
  - CLEO detailed study [arXiv:0706.2317]
    - Hindered M1-M1 term => C≈0. Consistent with CLEO results.
    - Small D-wave contributions
  - Further study would be useful. Look at polarization. Dubynskiy & Voloshin [hep-ph/0707.1272]







QCDME

- eta transitions (E1-M2, M1-M1) (C$_A$C$_B$ = +1) O(v^2)
  - E1-M2 expected to dominate
  - Factorization

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

  - Ch

Hadronize

$$i(2\pi)^{3/2}C_3 q_k$$

  - Relation to other single pseudoscalar transitions

Chiral symmetry breaking - Chiral effective lagrangian

$$\tilde{\pi}^0 = \pi^0 + \epsilon\eta + \epsilon'\eta' \qquad \tilde{\eta} = \eta - \epsilon\pi^0 + \theta\eta' \qquad \tilde{\eta}' = \eta' - \theta\eta - \epsilon'\pi^0,$$

$$\epsilon = \frac{(m_d - m_u)\sqrt{3}}{4(m_s - \dfrac{m_u + m_d}{2})}, \qquad \epsilon' = \frac{\tilde{\lambda}(m_d - m_u)}{\sqrt{2}(m_{\eta'}^2 - m_{\pi^0}^2)}, \qquad \theta = \sqrt{\frac{2}{3}}\ \frac{\tilde{\lambda}\left(m_s - \dfrac{m_u + m_d}{2}\right)}{m_{\eta'}^2 - m_\eta^2}.$$

ϒ(6S)

- Belle [arXiv:1501.01137]

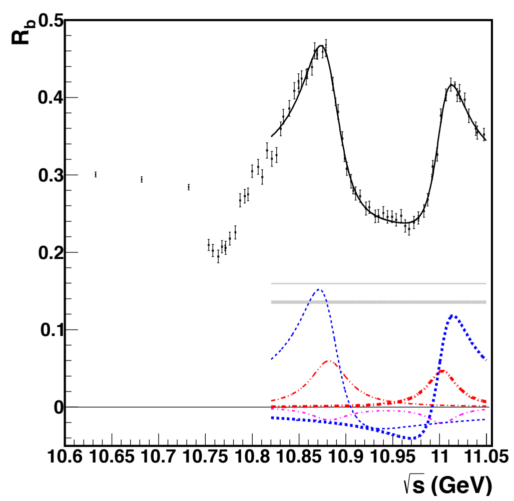


FIG. 1. R'_b, data with components of fit: total (solid curve), constants $|A_{\rm nr}|^2$ (thin), $|A_{\rm r}|^2$ (thick); for Υ(5S) (thin) and Υ(6S) (thick), $|f|^2$ (dot-dot-dash), cross terms with $A_{\rm r}$ (dashed), and two-resonance cross term (dot-dash). Error bars are statistical only.

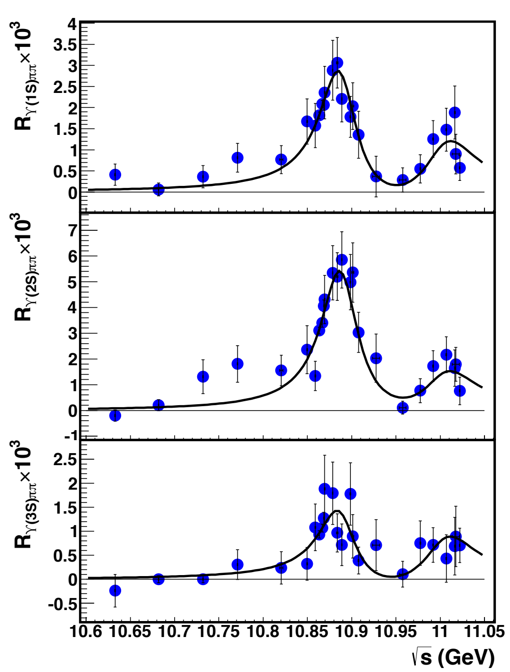


FIG. 2. $R_{\Upsilon\pi\pi}$ data for Υ(1S) (top), Υ(2S) (center), and Υ(3S) (bottom), with results of fit C. Error bars are statistical only.