XYZ States and Hadronic Transitions

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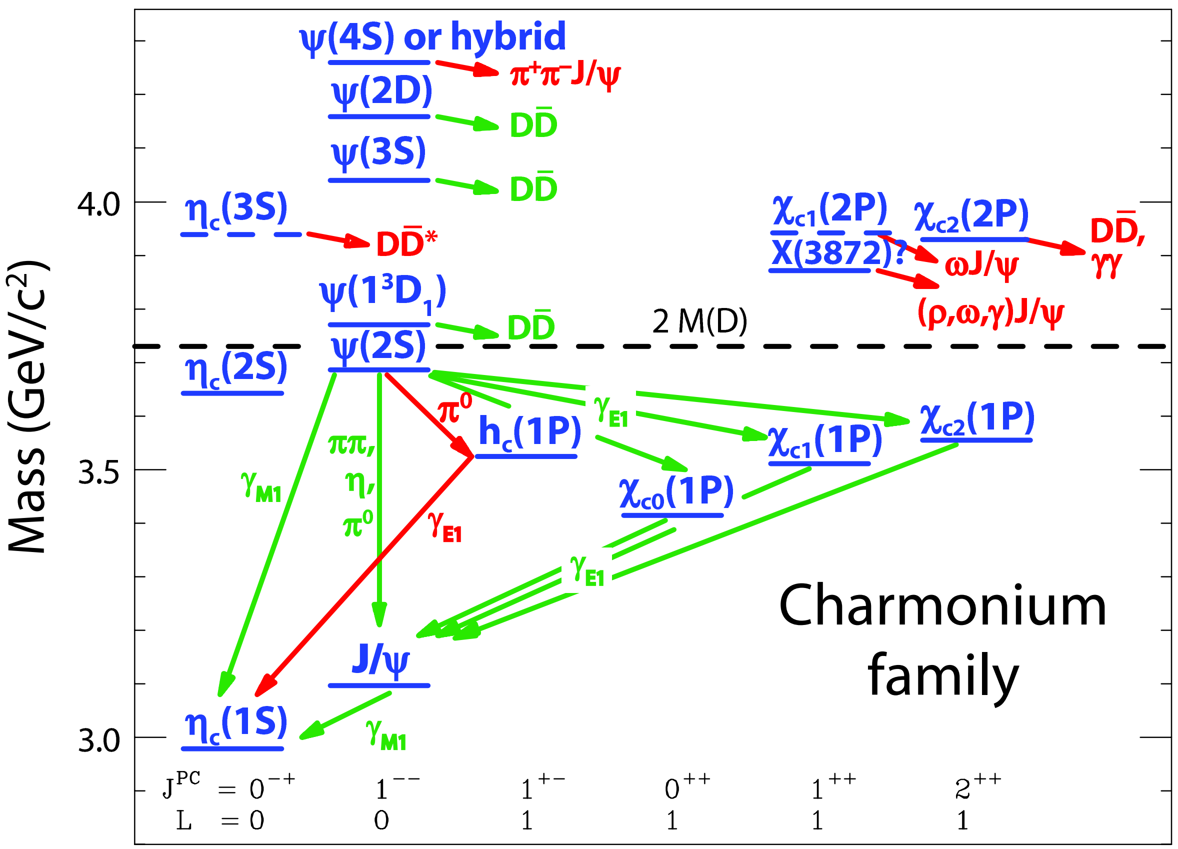
Outline:

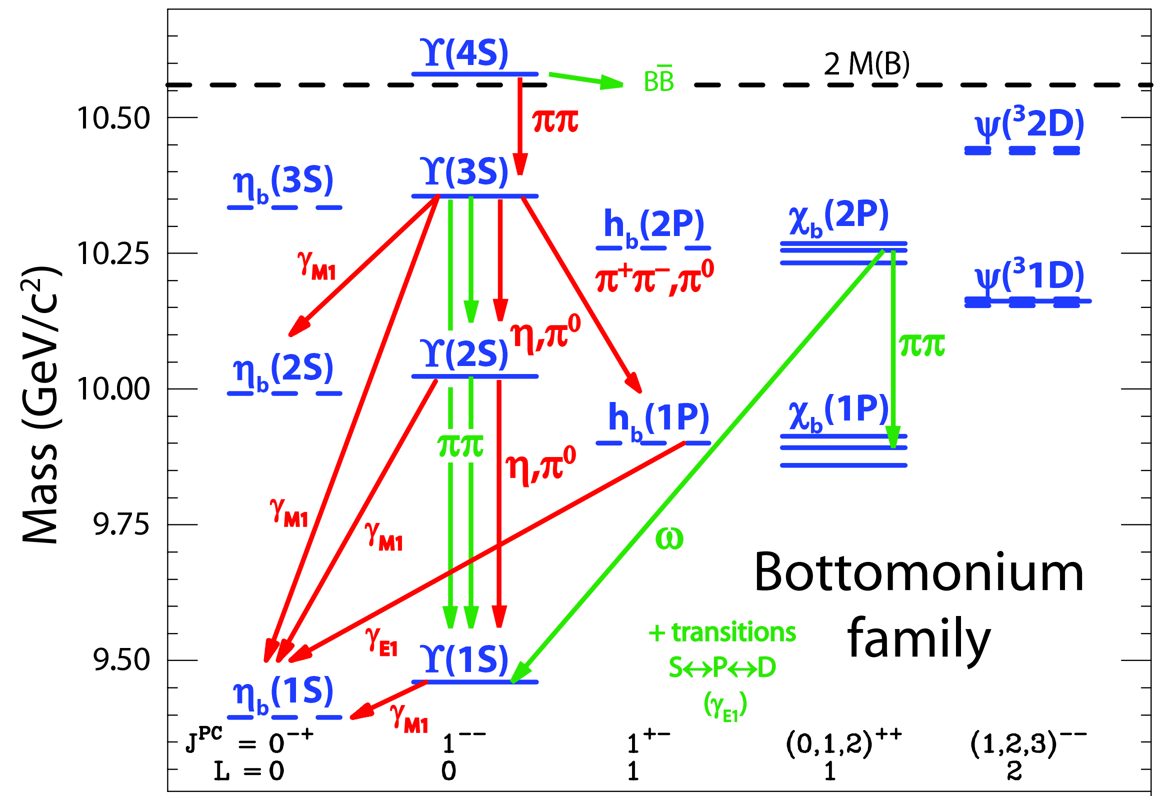
- Quarkonium physics below threshold
- Surprises above threshold
  - Hadronic transitions
  - XYZ states
- Disentangling the XYZ states
- New dynamics for hadronic transitions above threshold
- Role for Lattice QCD

Workshop on Lattice Gauge Theory
for the LHC and Beyond
Aug 3-Sept 25, 2015
KITP Santa Barbara

Quarkonium physics below threshold

- Qualitative predictions of QCD inspired potential models reproduce the spectrum and EM transitions well





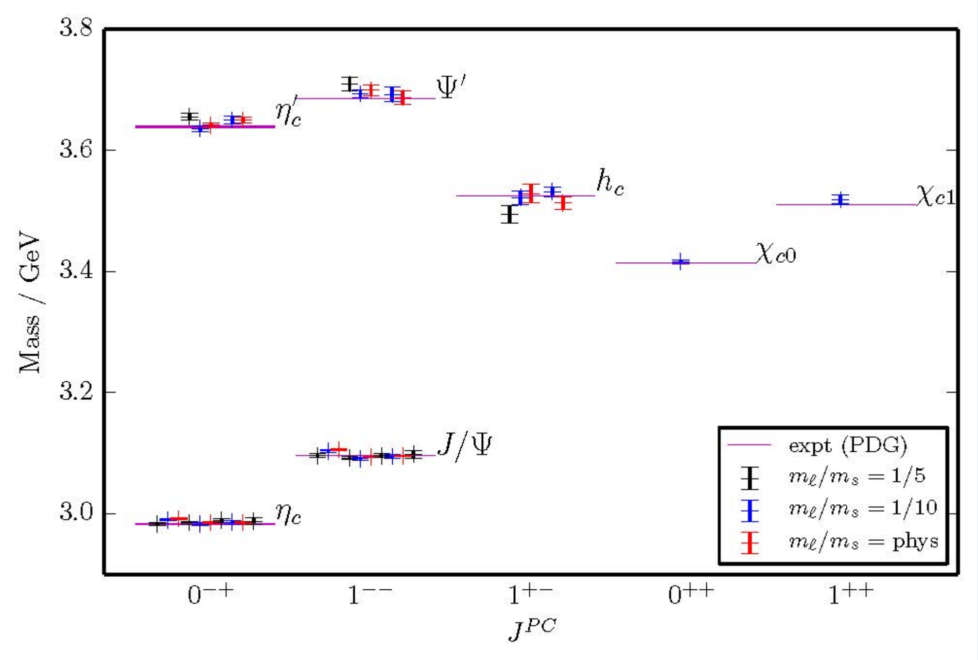
Quarkonium physics below threshold

- Now superseded by lattice calculations for the spectrum

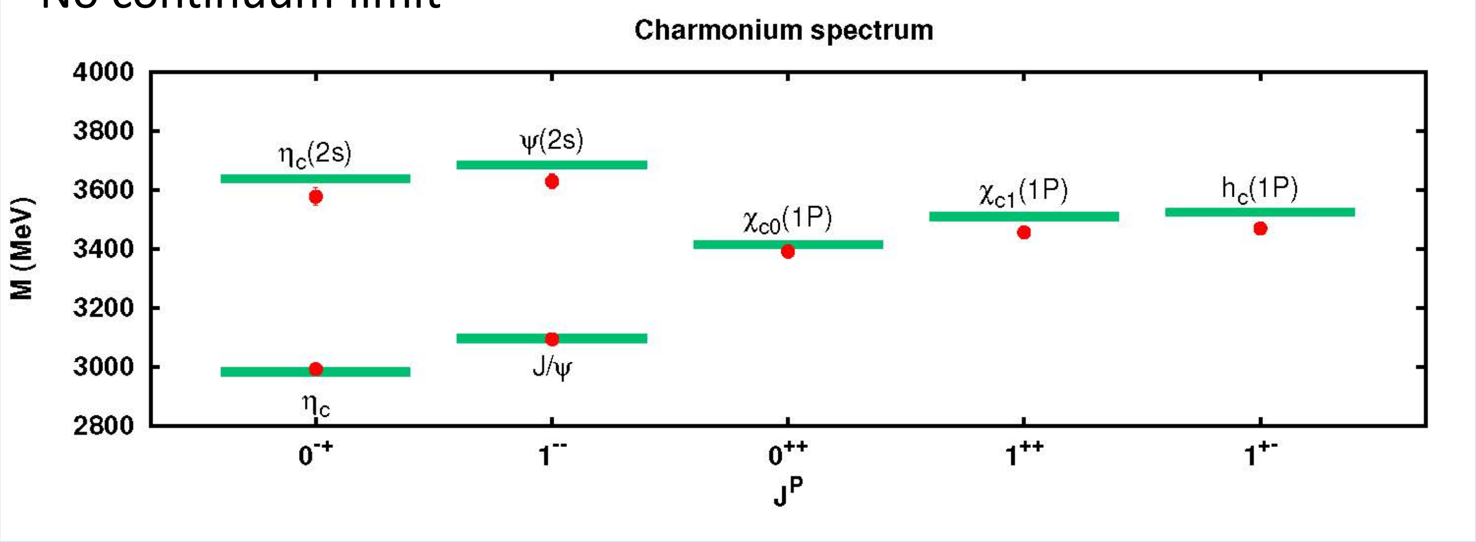
Low lying charmonium levels

Reasonably well understood

Glasgow 1411.1318
Continuum limit,
Physical quark masses



Regensburg 1503.08440
No continuum limit



C. DeTar, Lepton-Photon 2015

Hadronic Transitions

- Below threshold the QCD multipole expansion works well to describe the hadronic transitions.
- The transition rates are small.
- Heavy-quark symmetry (HQS) dictates that the leading transitions do not flip the spin of the heavy quarks (as with the usual EM transitions in non-relativistic systems E1, M1, E2, …).
- Isospin breaking is suppressed.
- But detailed results rely on a specific phenomenological model of Kuang-Yan.
- A few puzzles remain.

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]

Basics of the QCDME

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

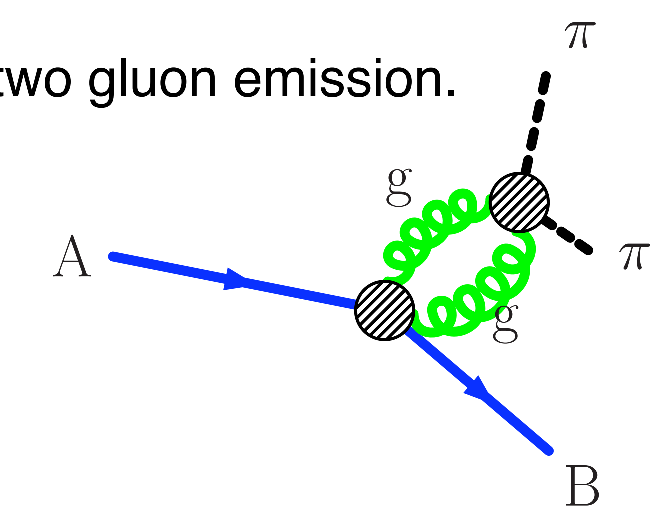
$$H^{\rm eff}_{\rm QCD} = H^{(0)}_{\rm QCD} + H^{(1)}_{\rm QCD} + H^{(2)}_{\rm QCD} \qquad H^{(1)}_{\rm QCD} \equiv Q_a A^a_0(\mathbf{X},t)$$

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 Φ_i, Φ_f and a model for the intermediate states |KL> hybrid states.
  - use chiral effective lagrangians to parameterize the light hadronic system.

Remaining puzzles

- QCDME n $^3S_1$ -> m $^3S_1$ + π π transitions:
  - E1E1 dominates

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

α_{AB}^{EE}

  - Chiral symmetry

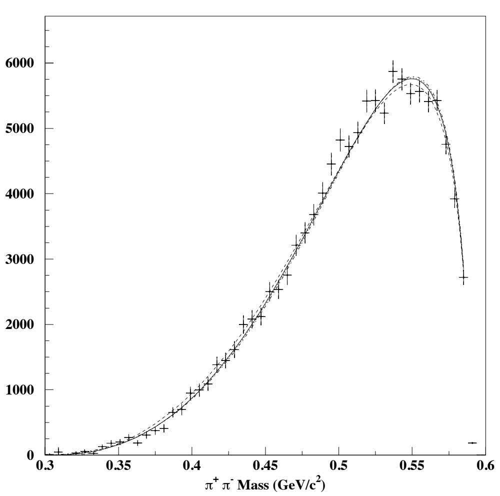
S-wave D-wave

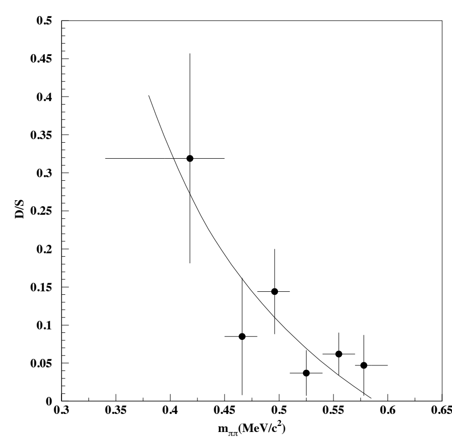
$$\frac{\delta_{\alpha\beta}}{\sqrt{(2\omega_1)(2\omega_2)}}\left[C_1\delta_{kl}q_1^\mu q_{2\mu} + C_2\left(q_{1k}q_{2l} + q_{1l}q_{2k} - \frac{2}{3}\delta_{kl}\ (q_1\cdot q_2)\right)\right]$$

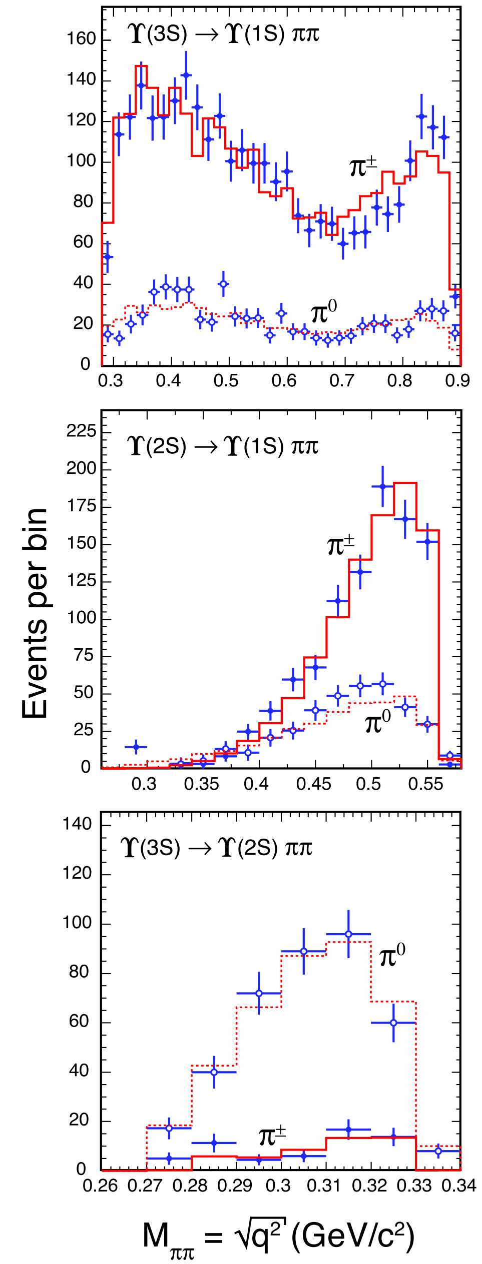
Bottomonium

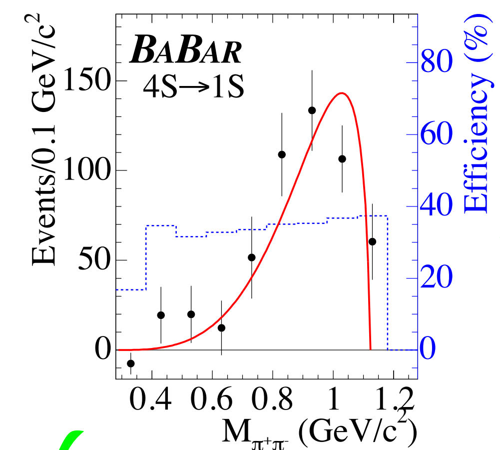
Charmonium 2->1 D/S wave

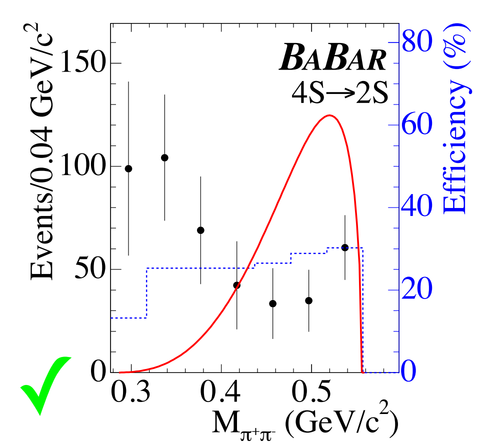
J. Z. Bai, et al (BES)
Phys.Rev. D62 (2000) 032002











  - 3 ->1 and 4 -> 2 puzzling behavior
    - dynamical cancellations: M. Voloshin [arXiv:hep-ph/0606258]
    - final state (π π) interactions: Y. Surovtsev, el al[arXiv:1506.0306]

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

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

Remaining puzzles

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

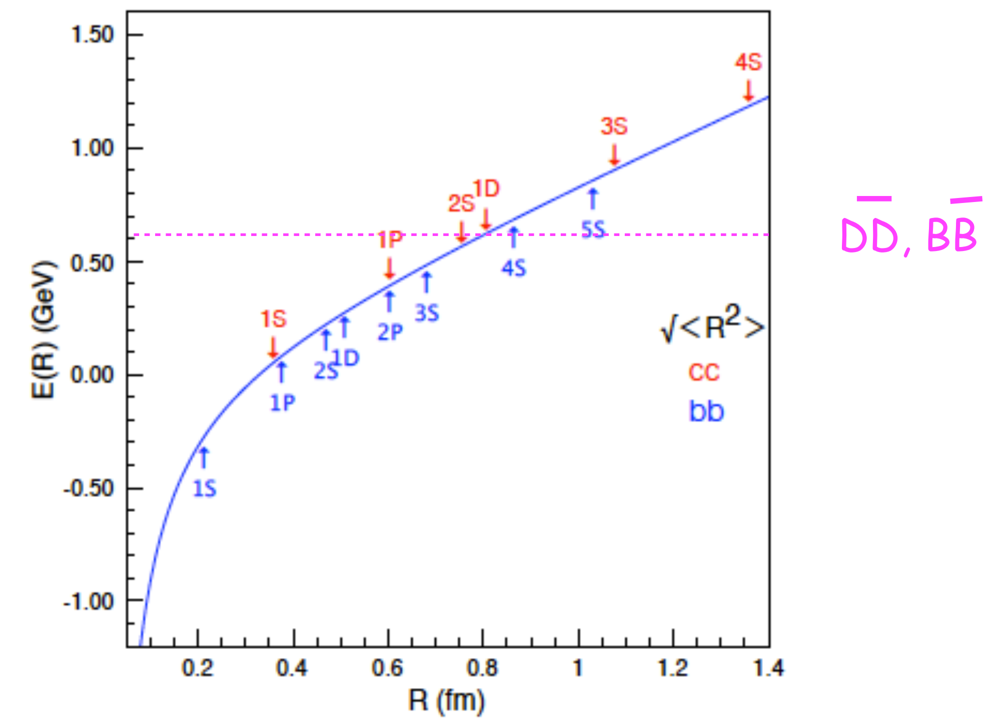
$R_{\eta/\pi\pi}(^3S_1(n) \to ^3S_1(m))$ $(Q\bar{Q}) n \to m$	theory	experiment	
$(c\bar{c}) : 2 \to 1$	3.39×10^{-3}	1.0×10^{-1}	~ 30 > model
$(c\bar{c}) : 3 \to 1$	6.35×10^{-3}	1.0	~ 150 > model
$(b\bar{b}) : 2 \to 1$	1.99×10^{-2}	1.99×10^{-2}	sets $C_3/C_1 = 0.143 \pm 0.024$
$(b\bar{b}) : 3 \to 1$	4.57×10^{-3}	$< 2.3 \times 10^{-2}$	
$(b\bar{b}) : 4 \to 1$	2.23×10^{-3}	24	~ 1000 > model
$(b\bar{b}) : 5 \to 1$	9.58×10^{-4}	4.8	~ 2000 > model
$(b\bar{b}) : 5 \to 2$	5.33×10^{-3}	1.6	~ 300 > model

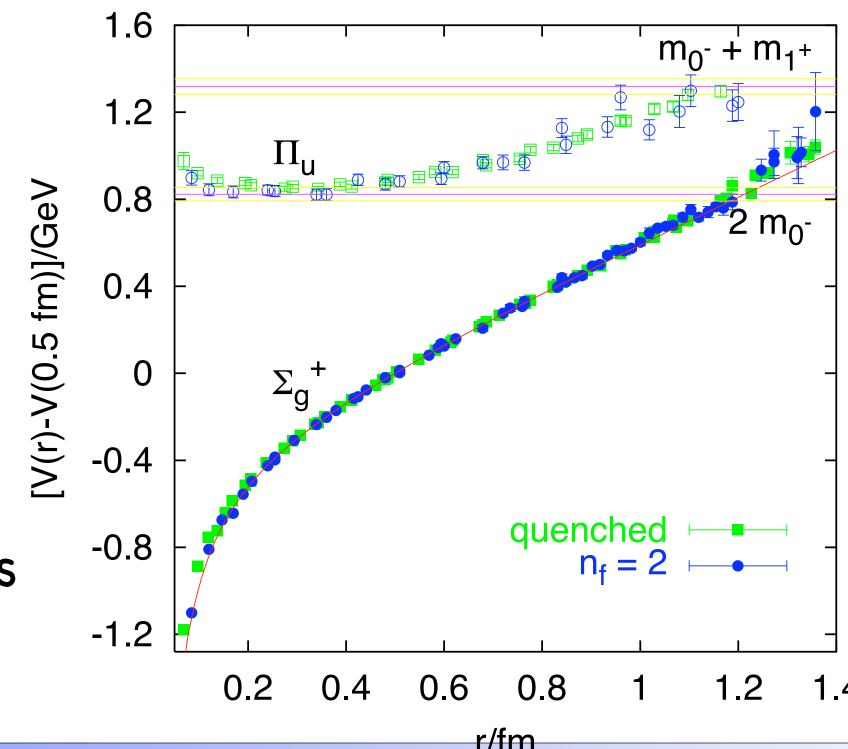
  - Transitions near and above threshold violate expectations of QCDME and sizable rates require large SU(3) breaking.
  - We will see this is associated with the large SU(3) breaking in virtual and real heavy-light meson pair contributions to the states.

Why does it work so well?

- When should the QCDME work?
  - Transitions between tightly bound quarkonium states
  - Small radius ($R << \Lambda_{QCD}$)
    - 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.

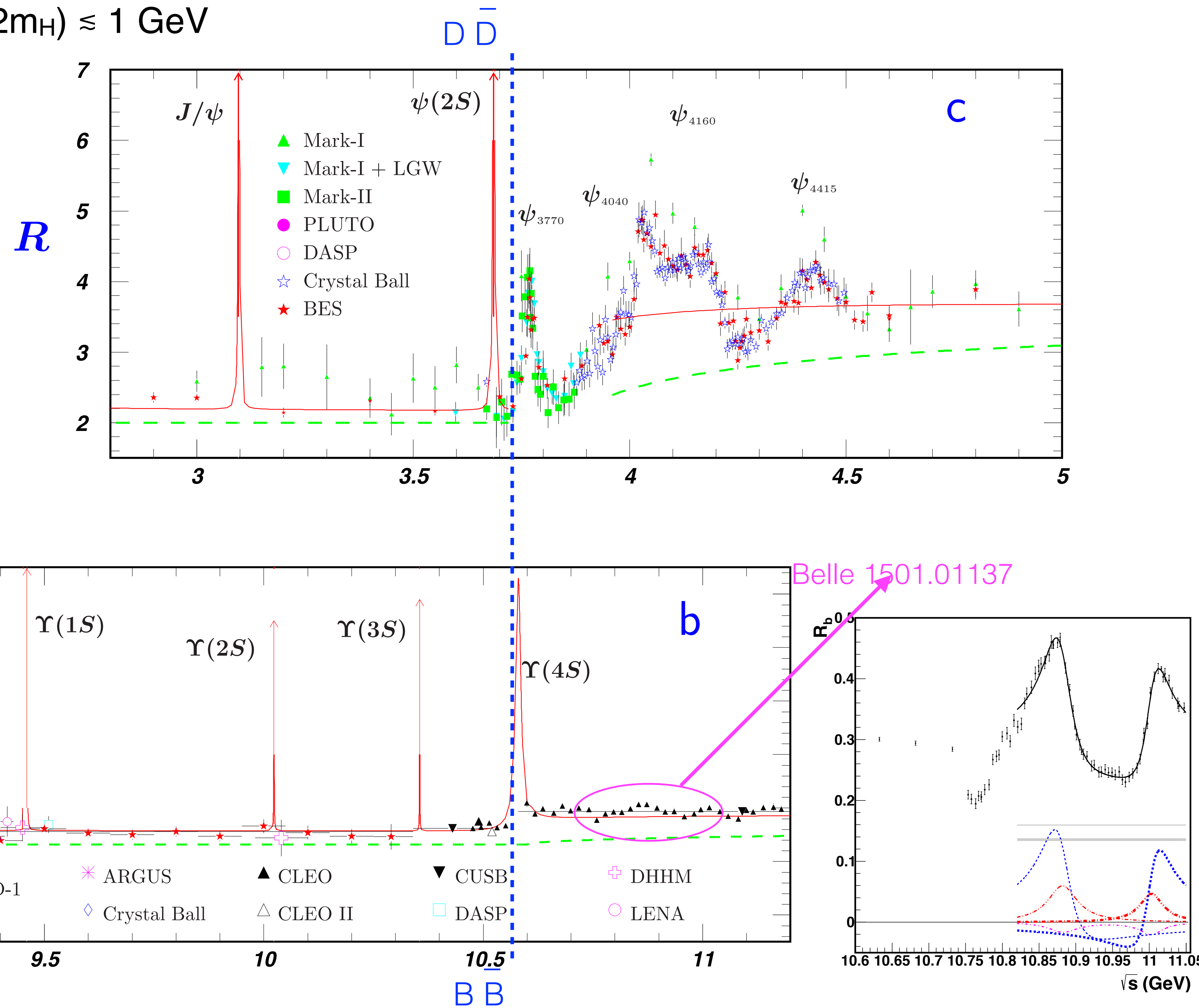
Cornell
Potential Model





The Threshold Region

- R = σ(e+e- -> ɣ* -> hadrons)/σ(e+e- -> ɣ*-> 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

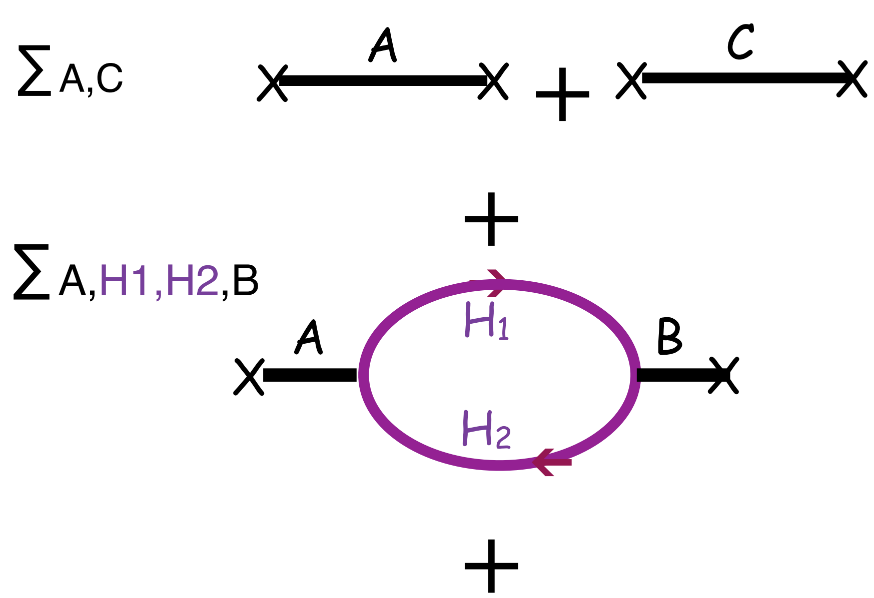
- Two pictures of R

$$\Delta R(W) = \frac{6\pi}{W^2}\rho_c(W) \qquad -(g_{\mu\nu}q^2 - q_\mu q_\nu)\rho_c(W)$$

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

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

QCD - perturbative
Q, g



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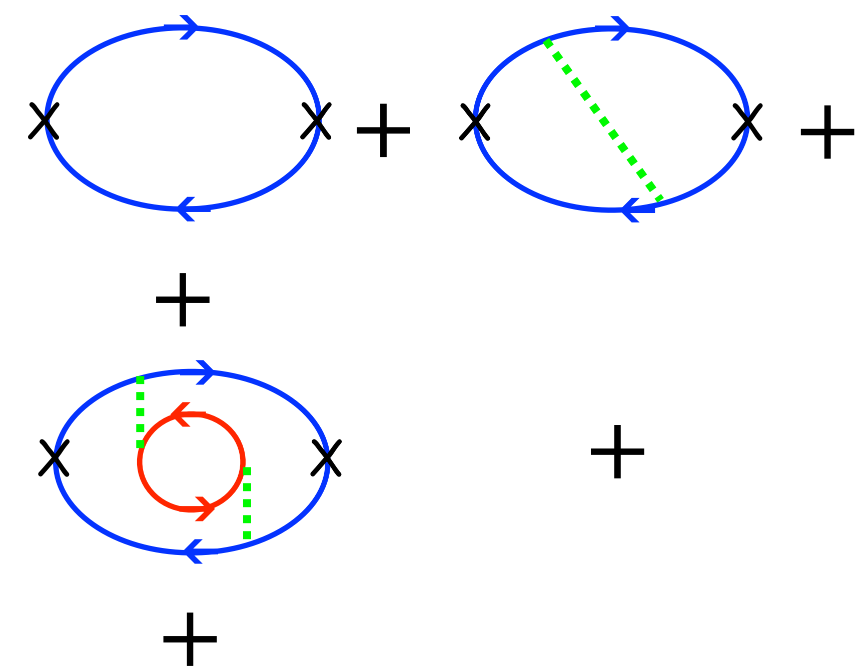


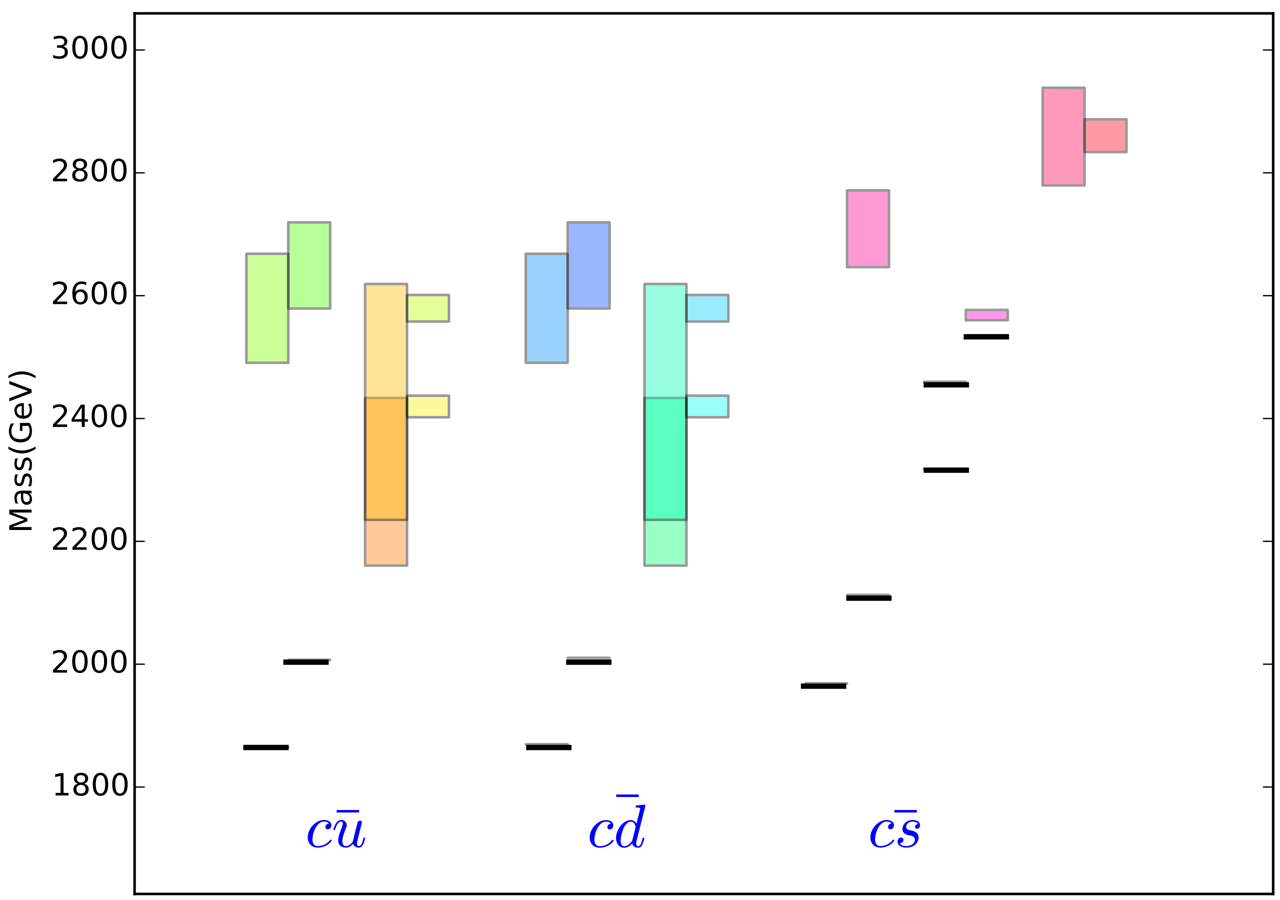
Simple expansion near threshold.

Simple expansion far above threshold.

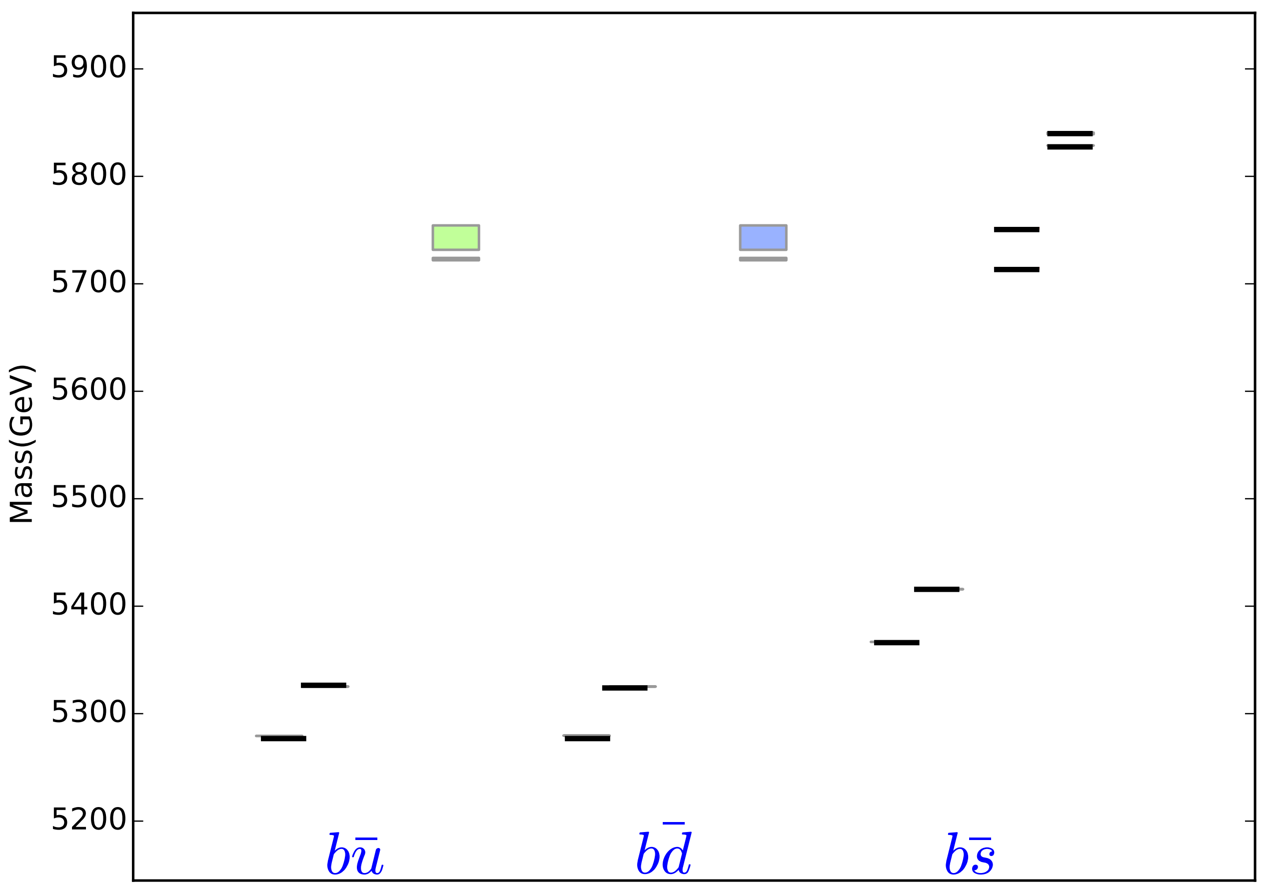
Heavy-Light Mesons

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

Charm Meson Spectrum



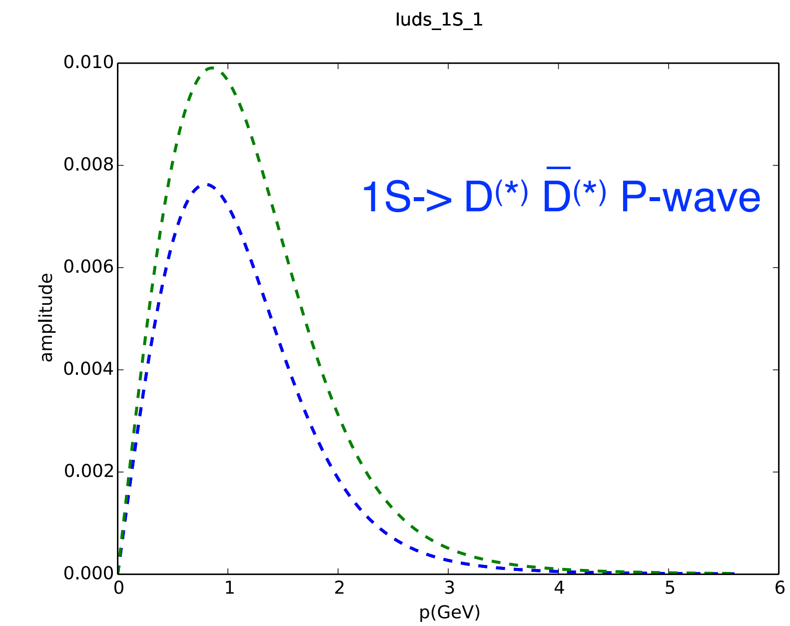
Bottom Meson Spectrum

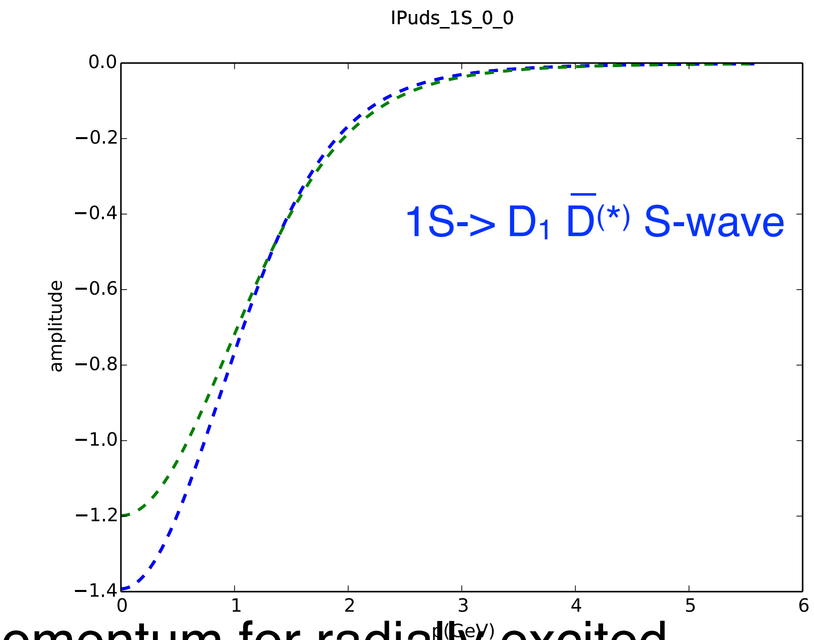


  – There are 9 narrow (< 2 MeV) charm meson states [and 10 bottom mesons states]. Any pair of these might have a cusp at S-wave threshold.
  – The wide states can originate sequential decay chains.

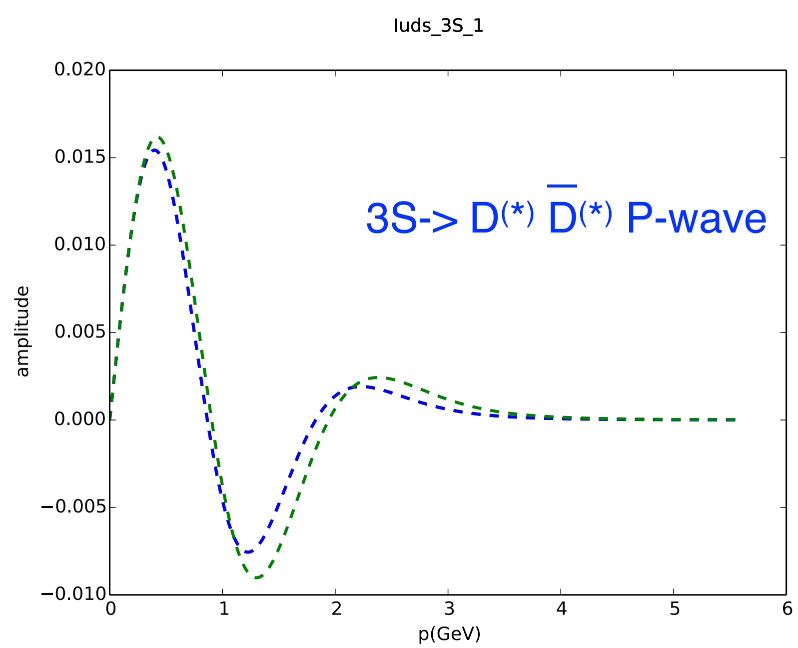
Complicated Decay Amplitudes

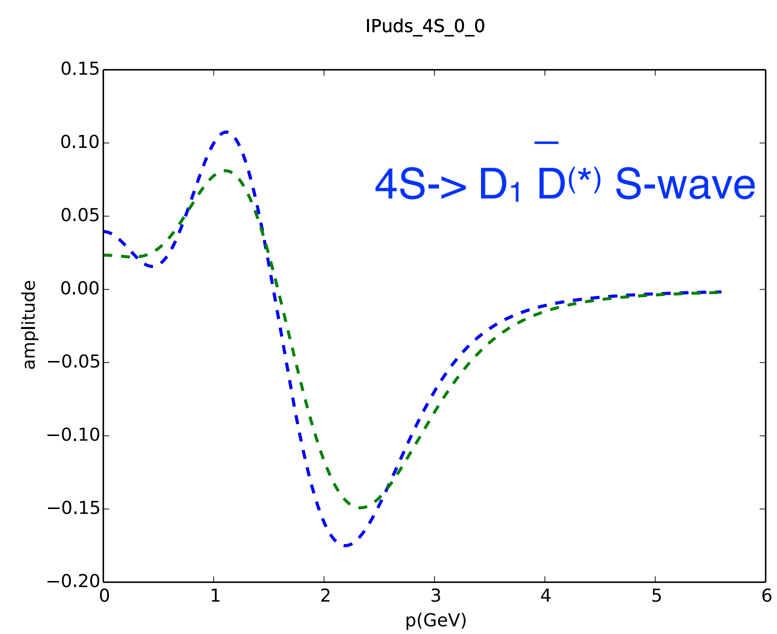
- For resonances (with no radial nodes) as expected:





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





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

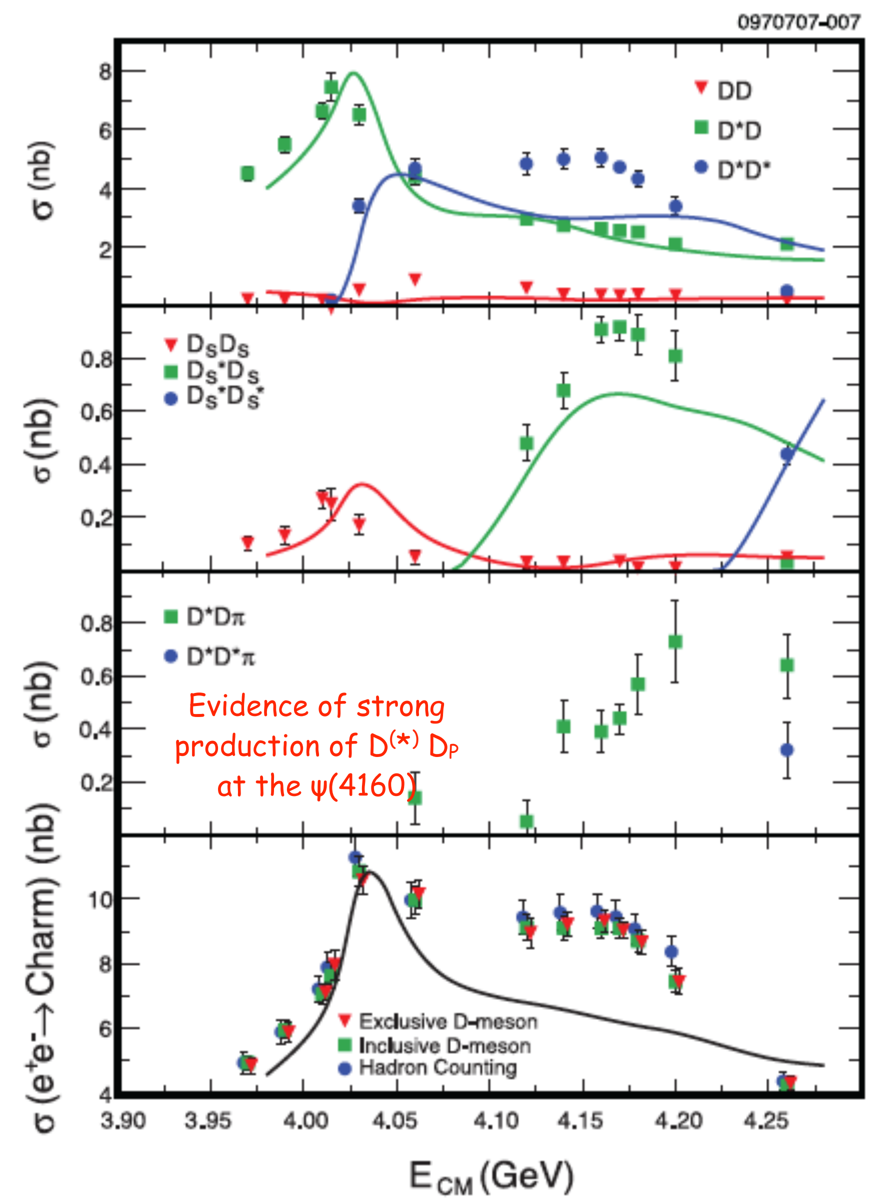
Individual Decay Channels Above Threshold

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

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

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

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



The Threshold Region

- Effects of heavy-light meson virtual loops
  - Shift masses and properties of states near threshold. Because the lowest quarkonium states feel more of the Coulomb interaction they are least affected by the large loop effects.
  - Lattice calculations (some already in hand) could provide valuable information on the meson loop effects. The variation of quarkonium masses as a function of light quark masses (physical values $< m_q < \Lambda_{QCD}$) is directly related to the meson loops contributions.
  - Couplings are independent of the particular mesons in the loop within a heavy-light multiplet (up to CG coefficients) and are approximately SU(3) flavor invariant.
  - SU(3) breaking and HQS Spin breaking in quarkonium masses and transitions are induced by the mass splittings of physical heavy-light mesons. These effects are only large near the relevant threshold. For example isospin splitting is only important for the X(3872).

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

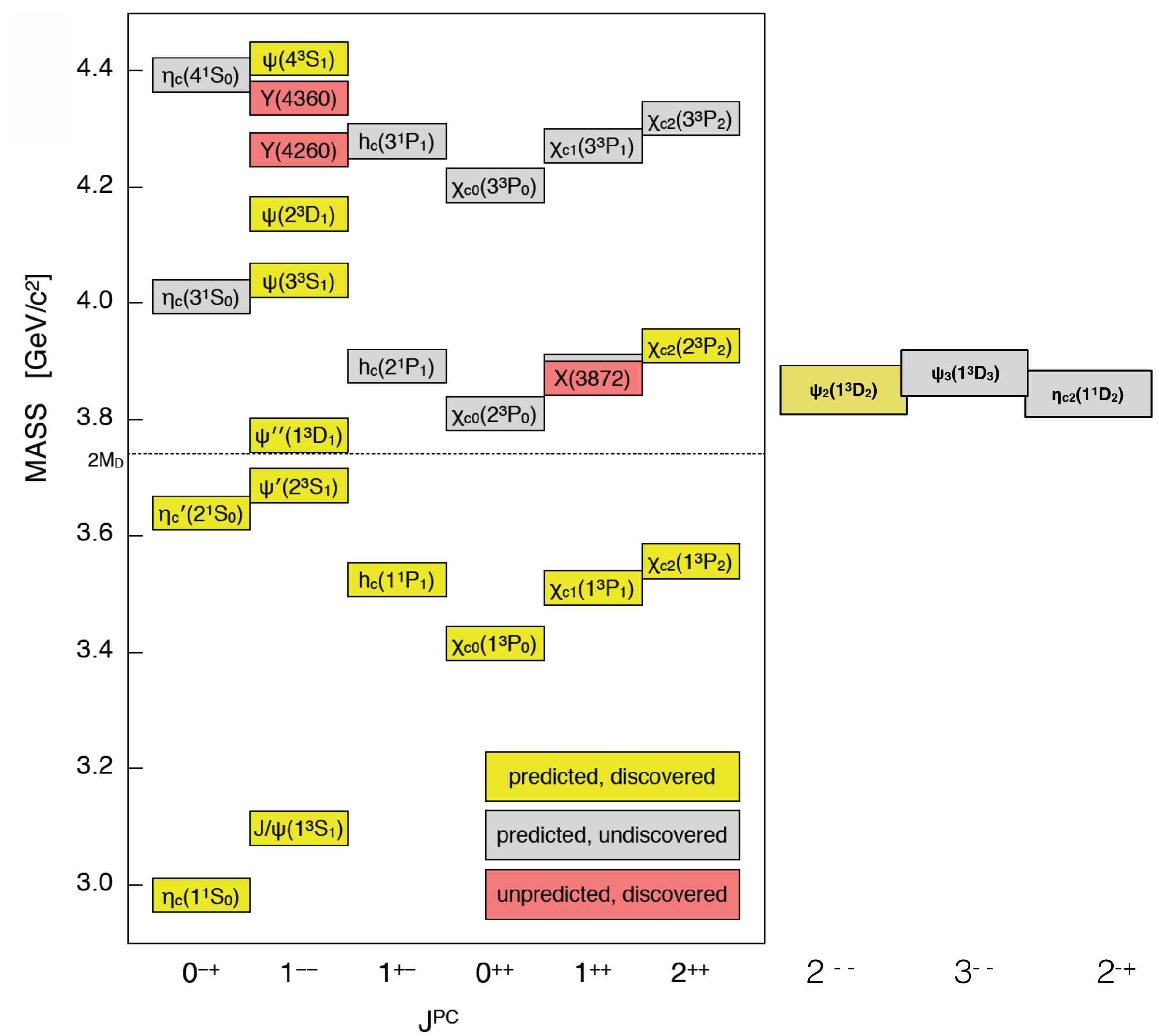
    - $Z^+_c(3885)$, $Z^+_c(4025)$
    - $Z^+_b(10610)$, $Z^+_b(10650)$

    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),	2009	NC!
					LHCb [78](1.4), CMS [79](>5)		
					D0 [80](3.1)		
$X(4160)$	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)	2005	OK
					CLEO [83] (5.4), Belle [72] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	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),	2011	NC!
					CMS [79](>3), D0 [80](np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	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!

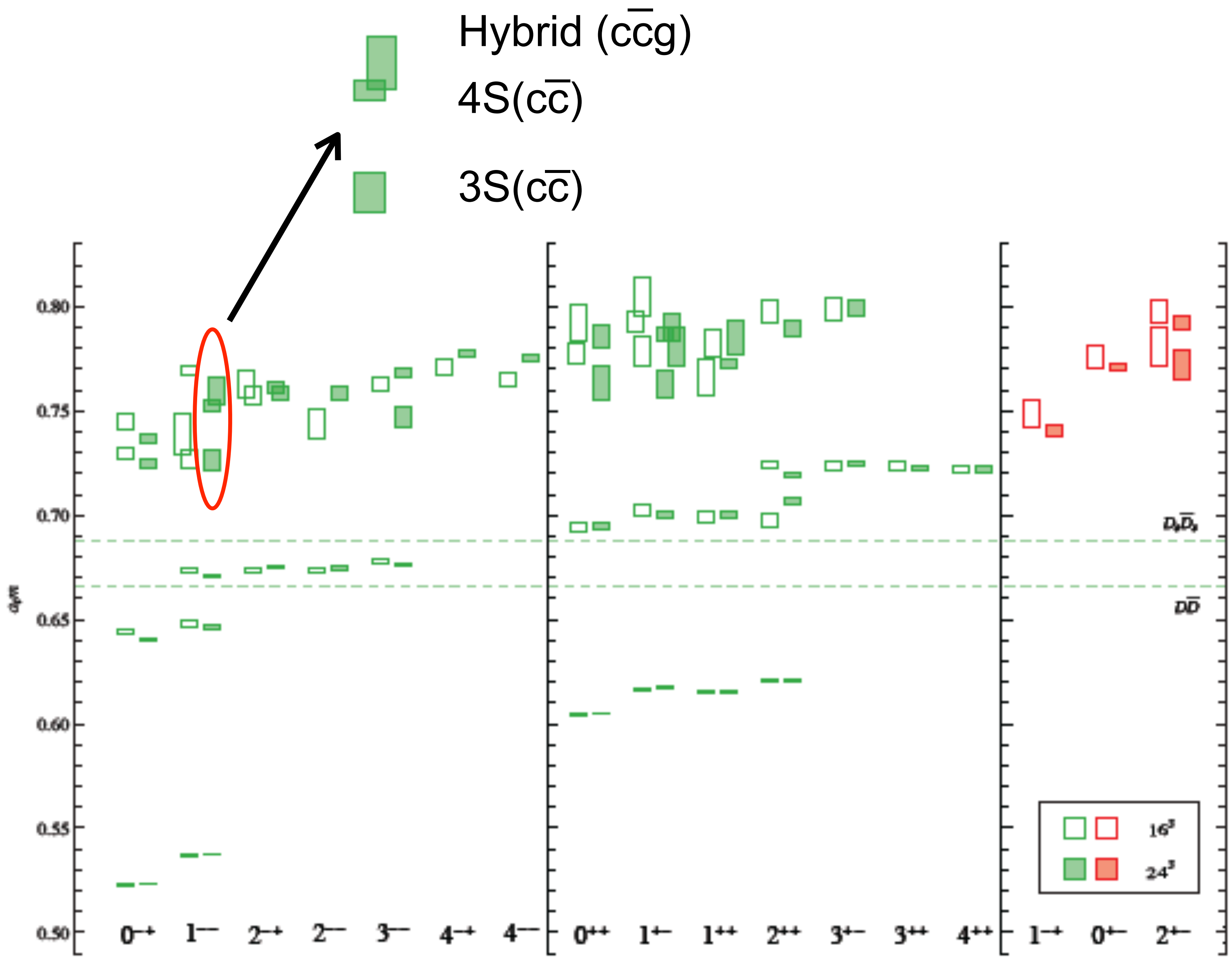
Y(4260)

- 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 :

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:

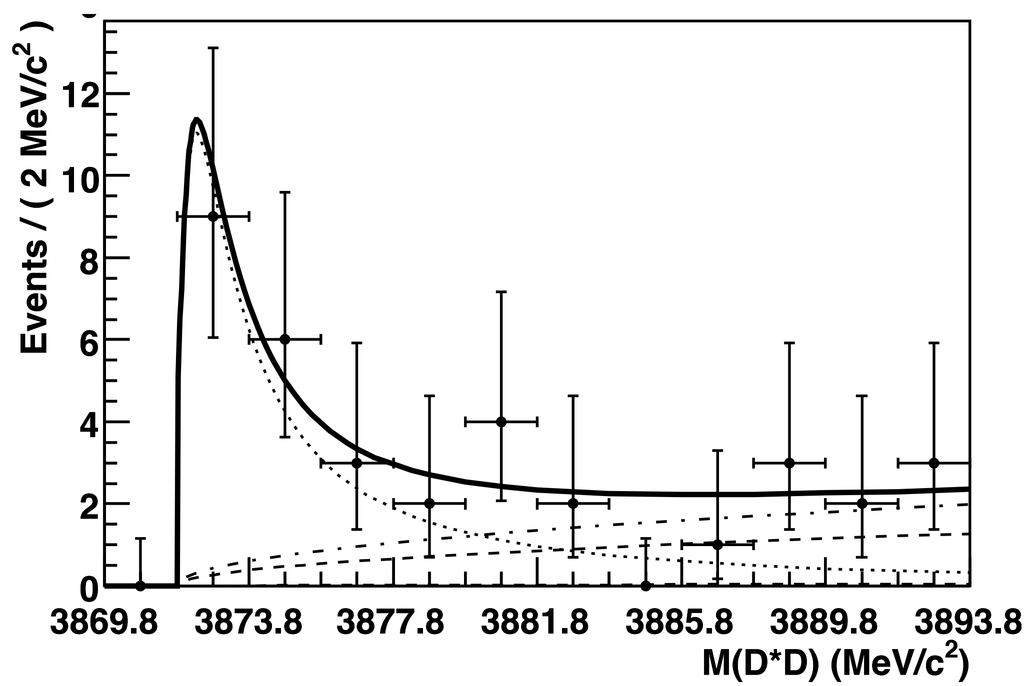
$\pi^+\pi^- J/\psi(1S)$	> 2.6 %	
$\rho^0 J/\psi(1S)$		large Isospin violation
$\omega J/\psi(1S)$	> 1.9 %	
$D^0 \overline{D}{}^0 \pi^0$	>32 %	
$\overline{D}{}^{*0} D^0$	>24 %	
$\gamma\psi(2S)$	[a] > 3.0 %	

  - 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 ± 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 -> ($D^0\bar{D}^{0*}$) 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 $D\bar{D}^*$ 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.

X(3872)

- $X_b(10604)$??
  - No isospin breaking: X is I=0 => G-parity forbids the decay X -> ππϒ(1S).
  - Dominate decay X -> ωϒ(1S)
  - M(χ_{b1}(3P)) - M(B) - M(B*) ≈ - 75 MeV
  - So the (bb) state is decoupled.
- Expect no analogy of the X(3872) in the bottomonium system

arXiv:1503.03257

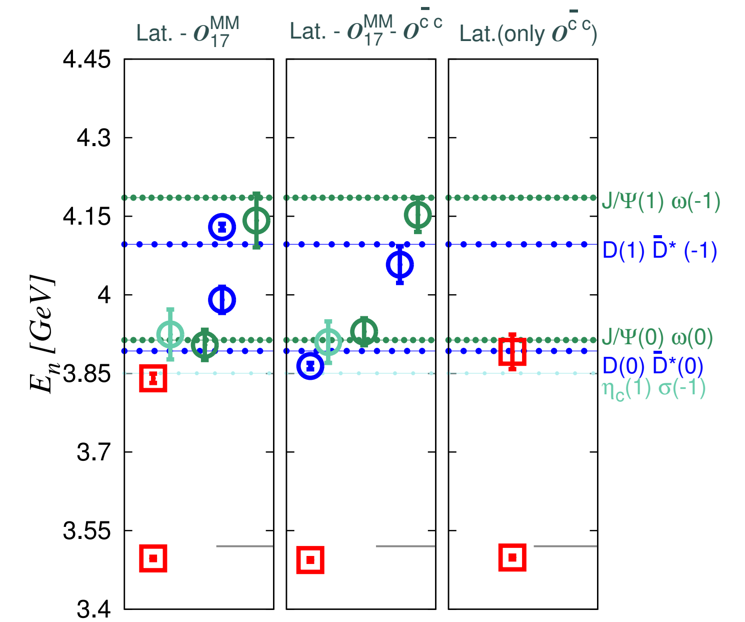
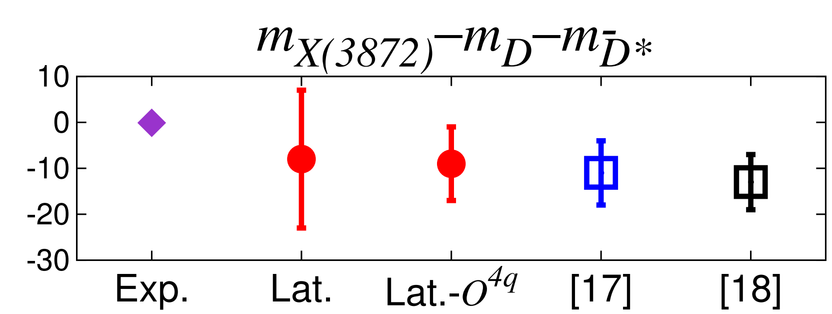
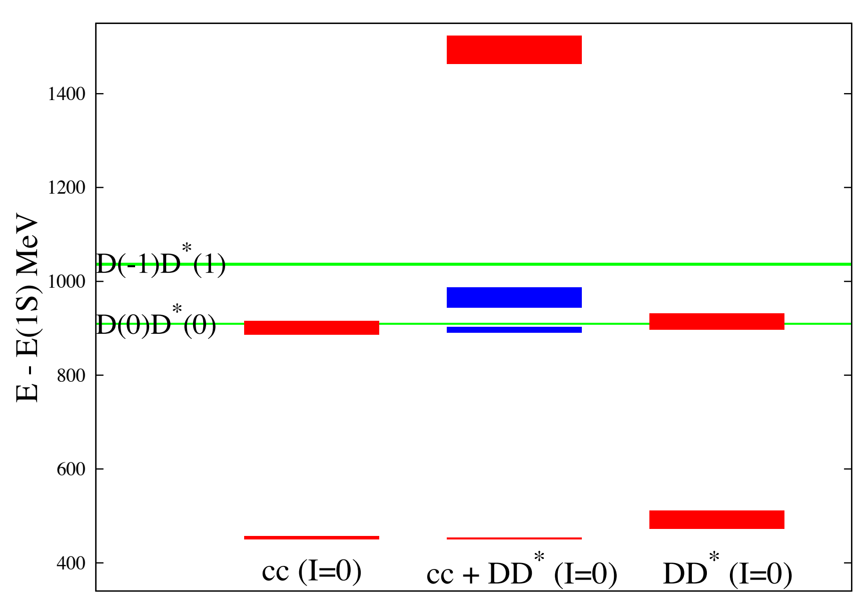


FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note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

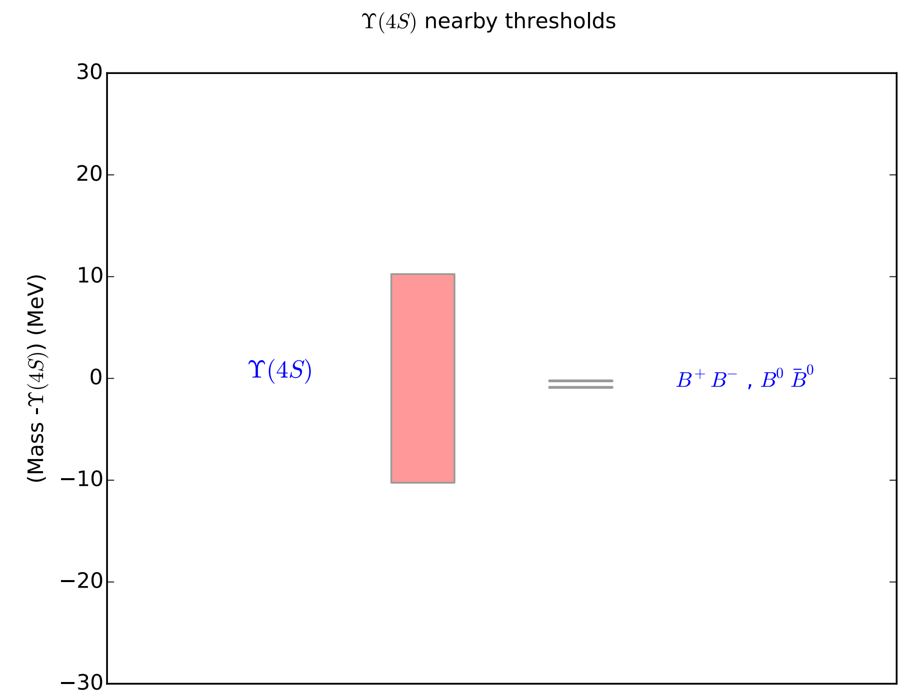


Table 1: Selected $\Upsilon(4S)$ decays.

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
HQS violating

Heavy Quark Spin Symmetry

- Large heavy quark spin symmetry breaking induced by the B*- B mass splitting. [Same for D*-D and D_s*-D_s]
  - Coupled channel calculations show a large virtual B B component to the ϒ(4S). This accounts for the observed violation of the spin-flip rules of the usual QCDME.
  - $J^{PC} = 1^{--}$ in terms of B(*), B(*) mass eigenstates:

Voloshin [arXiv:1201.1222]

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

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

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

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

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

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

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

- S-wave (L=0)

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

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

Strange heavy-light meson thresholds

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

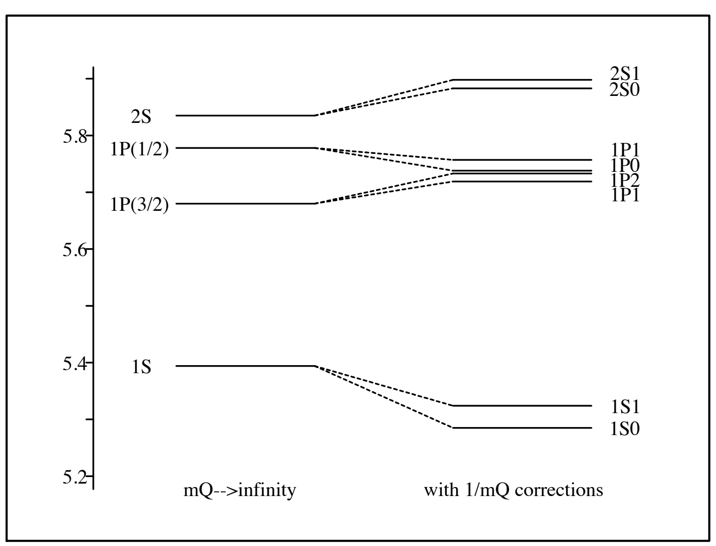
$$U = \exp\left(i\gamma_5 \frac{\varphi_a \lambda_a}{f_\pi}\right)$$

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

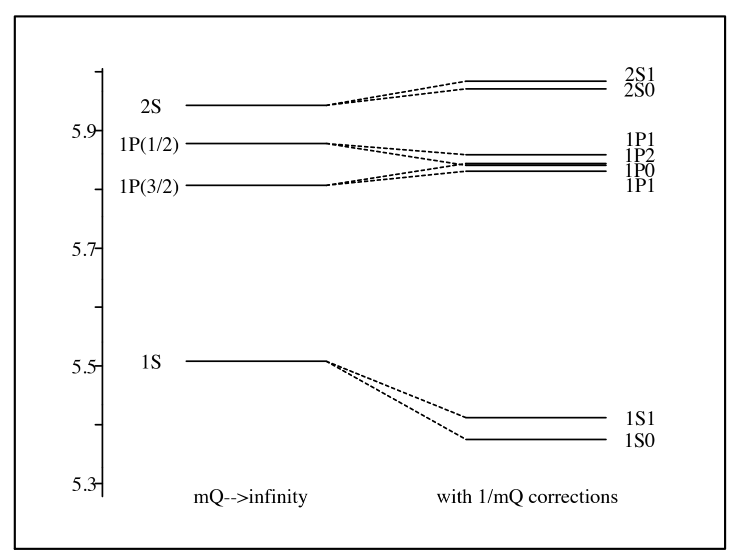
  - BUT: SU(3) breaking is induced by the mass splitting of the (Q q) mesons with q=u,d (degenerate if no isospin breaking) and q = s.
  - These splittings are large (~100 MeV) so there is large SU(3) breaking in the threshold dynamics.
  - This leads to large effects in the threshold region.
  - This greatly enhances the final states with η + ($\bar{Q}$Q).
    Yu.A. Simonov and A.I. Veselov [arXiv:0810.0366]
  - Similarly important in ω and ϕ production.

Hadronic Transitions Above Threshold

- Υ(5S) hadronic transitions
  - M = 10,876 ± 11 MeV Γ = 55 ± 26 MeV;
  - Open Ground State ($j^p = ½^-$) Decay Channels:
    - $M(B\overline{B})$ = 10,559 MeV, $M(B^*\overline{B})$ = 10,604 MeV, $M(B^*\overline{B}^*)$ = 10,650 MeV
    - $M(B_s\overline{B}_s)$ = 10,734 MeV, $M(B^*_s\overline{B}_s)$ = 10,782 MeV, $M(B^*_s\overline{B}^*_s)$ = 10,831 MeV
  - Also some P state ($j^p = ½^+$) Decay Channels are essentially open
    - $M(B[1^{½+}P_0]\overline{B}^*)$ = 11,055 MeV   (notation: $n^{jP}L_J$)
    - $M(B[1^{½+}P_1]\overline{B})$ = 11,045 MeV, $M(B[1^{½+}P_1]\overline{B}^*)$ = 11,091 MeV
  - I have assumed: $\Gamma(B[1^{½+}P_{\{0,1\}}])$ ~ 300 MeV (wide); $\Gamma(B[1^{3/2+}P_{\{1,2\}}])$ are narrow



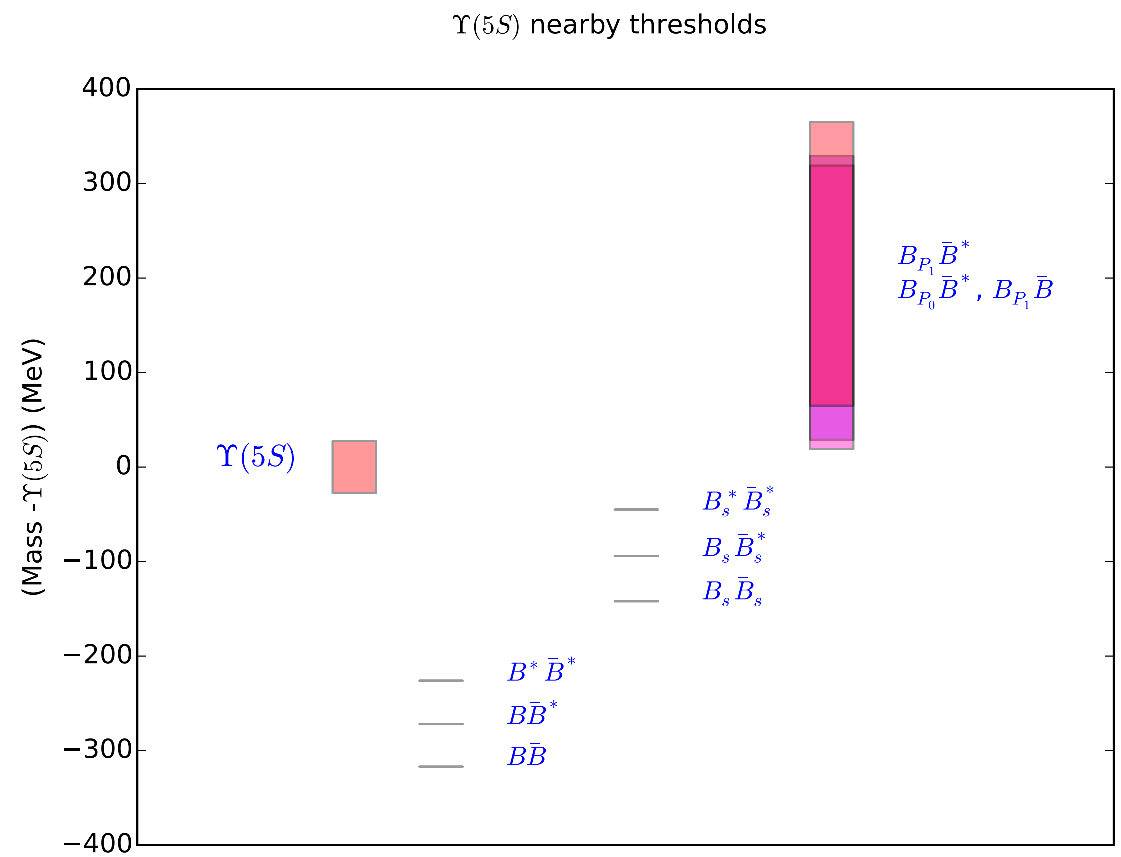
B



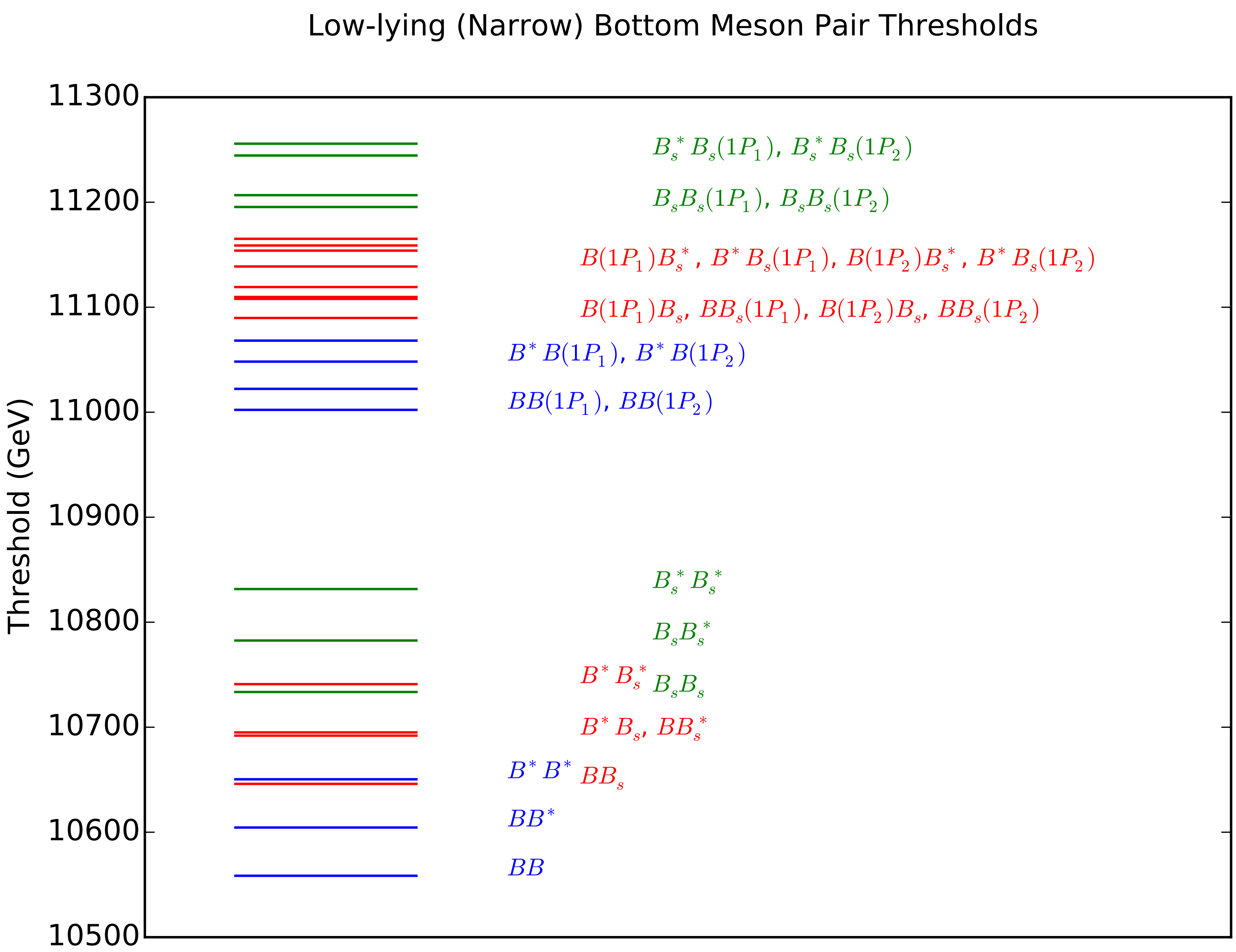
B_s

Hadronic Transitions Above Threshold

- Υ(5S) hadronic transitions
  - M = 10,876 ± 11 MeV Γ = 55 ± 26 MeV;
  - Open Ground State ($j^p = ½^-$) Decay Channels:
    - M(BB) = 10,559 MeV, M(B*B) = 10,604 MeV,
    - M(B*B*) = 10,650 MeV
    - M(B_sB_s) = 10,734 MeV, M($B^*_sB_s$) = 10,782 MeV,
    - M($B^*_sB^*_s$) = 10,831 MeV
  - Also some P state ($j^p = ½^+$) decay channels are essentially open
    - M(B[$1^{½+}P_0$]B*) = 11,055 MeV   (notation: $n^{jP}L_J$)
    - M(B[$1^{½+}P_1$]B) = 11,045 MeV,
    - M(B[$1^{½+}P_1$]B*) = 11,091 MeV
  - I have assumed: Γ(B[$1^{½+}P_{\{0,1\}}$]) ~ 300 MeV (wide); Γ(B[$1^{3/2+}P_{\{1,2\}}$]) < few MeV (narrow)



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 $B(P_1)$

B $B(P_0)$

Hadronic Transitions Above Threshold

– Υ(5S) decay pattern:

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

Decay Mode	Branching Rate	Decay Mode	Branching Rate
$B\bar{B}$	$(5.5 \pm 1.0)\%$	$\Upsilon(1S)\ \pi^+\pi^-$	$(5.3 \pm 0.6) \times 10^{-3}$
$B\bar{B}^* + c.c.$	$(13.7 \pm 1.6)\%$	$\Upsilon(2S)\ \pi^+\pi^-$	$(7.8 \pm 1.3) \times 10^{-3}$
$B^*\bar{B}^*$	$(38.1 \pm 3.4)\%$	$\Upsilon(3S)\ \pi^+\pi^-$	$(4.8\ ^{+1.9}_{-1.7}) \times 10^{-3}$
		$\Upsilon(1S)K\bar{K}$	$(6.1 \pm 1.8) \times 10^{-4}$
$B_s\bar{B}_s$	$(5 \pm 5) \times 10^{-3}$	$h_b(1P)\pi^+\pi^-$	$(3.5\ ^{+1.0}_{-1.3}) \times 10^{-3}$
$B_s\bar{B}_s^* + c.c.$	$(1.35 \pm 0.32)\%$	$h_b(1P)\pi^+\pi^-$	$(6.0\ ^{+2.1}_{-1.8}) \times 10^{-3}$
$B_s^*\bar{B}_s^*$	$(17.6 \pm 2.7)\%$	$\chi_{b1}\ \ \pi^+\pi^-\pi^0$ (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 Υ(4S) rates]

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

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

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

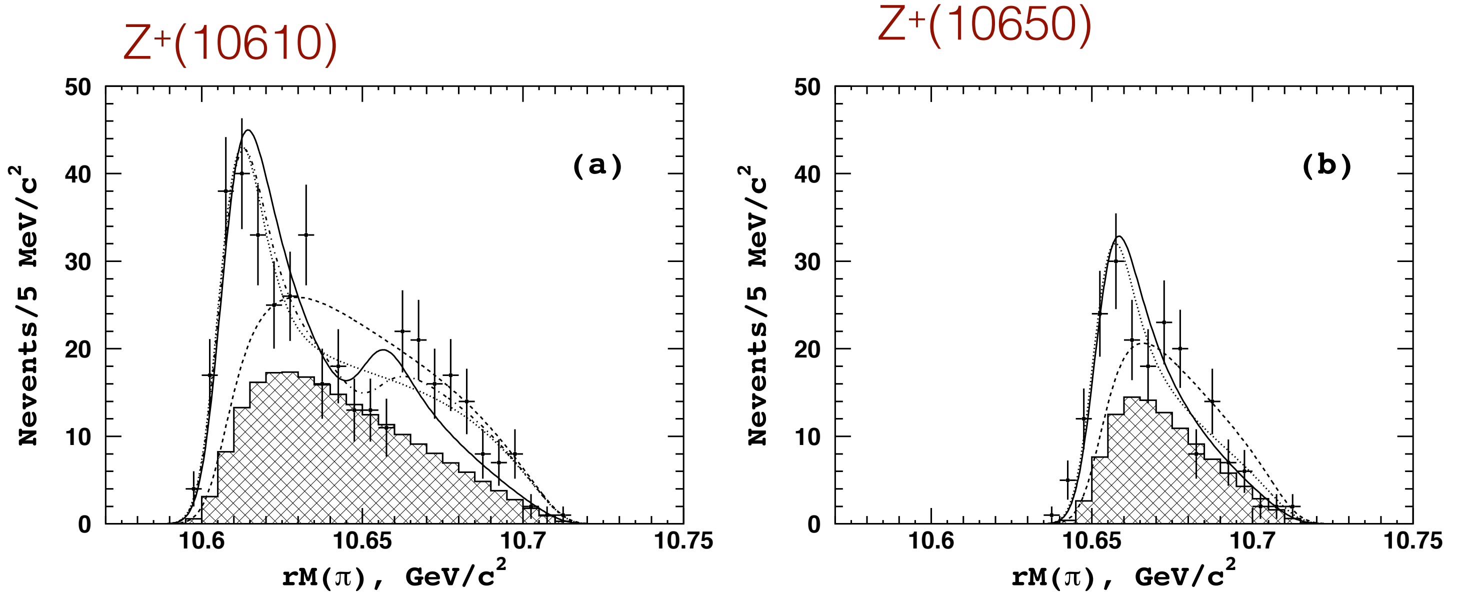
TABLE 1. Masses, widths, and relative phases of peaks observed in $h_b\pi$ and $\Upsilon\pi$ channels, from fits described in text.

	$h_b(1P)\pi^\pm\pi^\mp$	$h_b(2P)\pi^\pm\pi^\mp$	$\Upsilon(1S)\pi^\pm\pi^\mp$	$\Upsilon(2S)\pi^\pm\pi^\mp$	$\Upsilon(3S)\pi^\pm\pi^\mp$	Average
M_1 (MeV/c^2)	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$	$10609 \pm 3 \pm 2$	$10616 \pm 2^{+3}_{-4}$	$10608 \pm 2^{+5}_{-2}$	10608 ± 2.0
Γ_1 (MeV)	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-14}	$22.9 \pm 7.3 \pm 2$	$21.1 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$	15.6 ± 2.5
M_2 (MeV/c^2)	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$1-652 \pm 2 \pm 2$	10653 ± 1.5
Γ_2 (MeV)	$20.9^{+5.4+2.1}_{-1.7-5.7}$	12^{+11+8}_{-9-2}	$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$	14.4 ± 3.2
ϕ (°)	188^{+44+4}_{-58-9}	$255^{+56+12}_{-72-183}$	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	–

- Explicitly violates the factorization assumption of the QCDME.
- The $Z_b^{\pm}$ (10610) is a narrow state (Γ= 15.6 ± 2.5 MeV) at the $B\bar{B}^*$ threshold (10605).
- The $Z_b^{\pm}$ (10650) is a narrow state (Γ= 14.4 ± 3.2 MeV) at the $B^*\bar{B}^*$ threshold (10650).

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

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



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

and

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

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

New Dynamics for Hadronic Transitions

– Contributions of P-state decays:

- $n^3S_1(\bar{Q}Q)$ -> $1^{½+}P_J(\bar{Q}q)$ + $1^{½-}S_{J'}(\bar{q}Q)$:

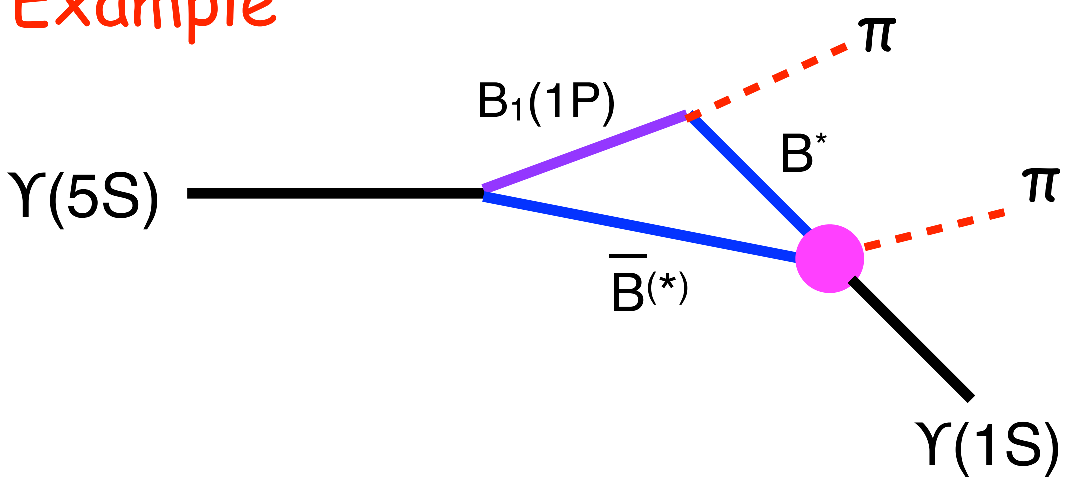
S-wave decays

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

- $1^{½+}P_J(\bar{Q}q)$ -> $1^{½-}S_{J'}(\bar{Q}q')$ + $^1S_0$ $(\bar{q}q')$ for S-wave J=J'

- Dominant two body decays of the ϒ(5S)

Example



Remarks:

(1) ϒ(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

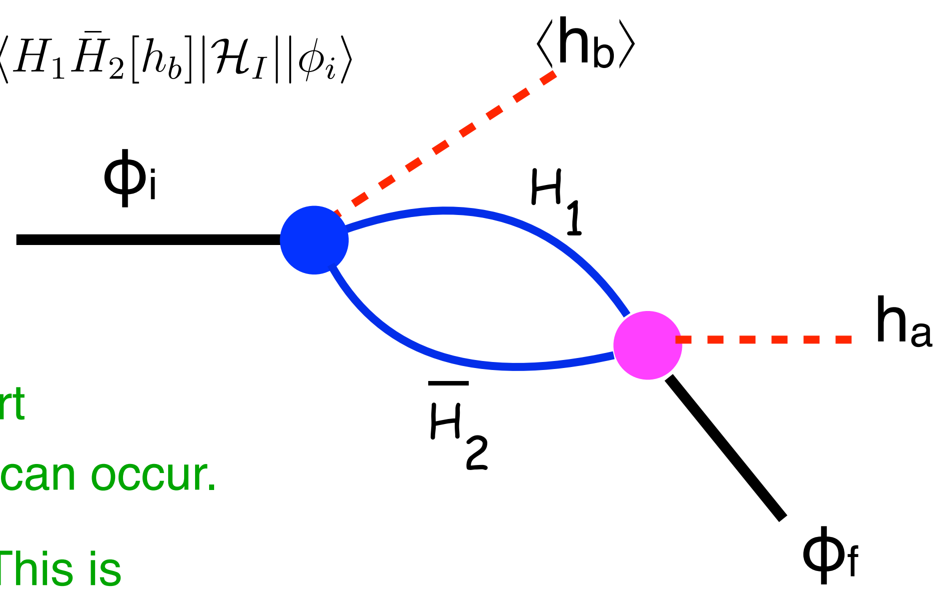
(4) Therefore the $B^{(*)}$ B^* system is in a relative S-wave and near threshold.

(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).

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

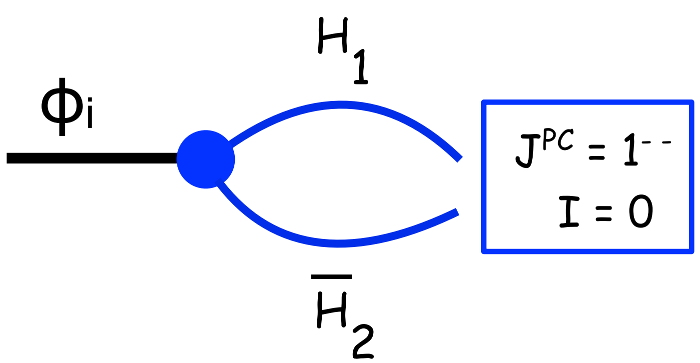


  - The time scale of the production process has to be short relative to the time scale over which H_1 H_2 rescattering can occur.
  - The relative velocity in the H_1 H_2 system must be low. This is only possible near threshold.
- Here we need not speculate on whether the observed rescattering is caused by a threshold bound state, cusp, or other dynamical effect.

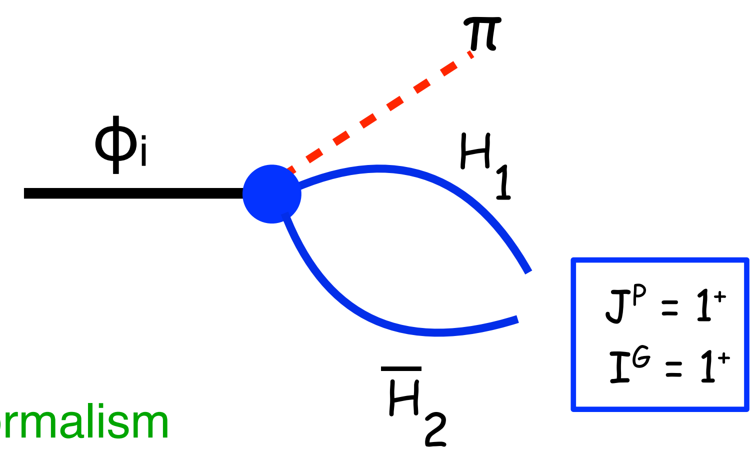
F.K. Gao, C. Hanhart, Q. Wang, Q. Zhao [arXiv:1411.5584]

New Dynamics for Hadronic Transitions

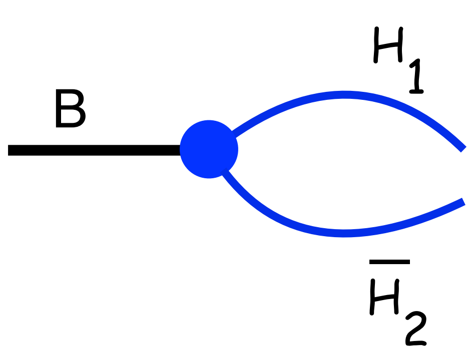
- Production modes
  - e+e-
    - direct

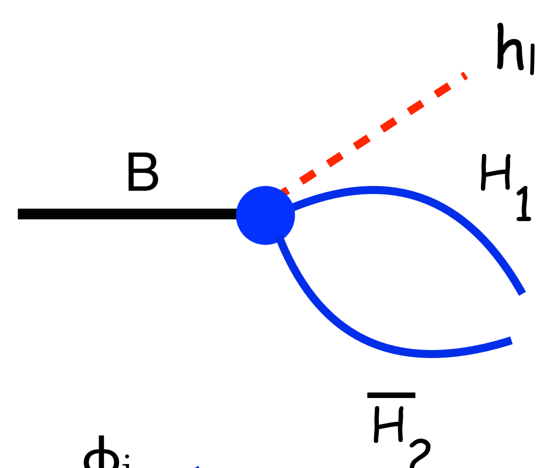


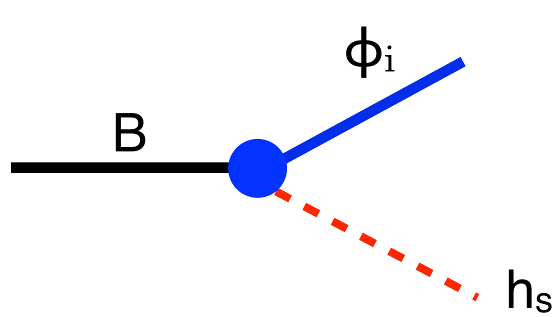
sequential (dominate terms)



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







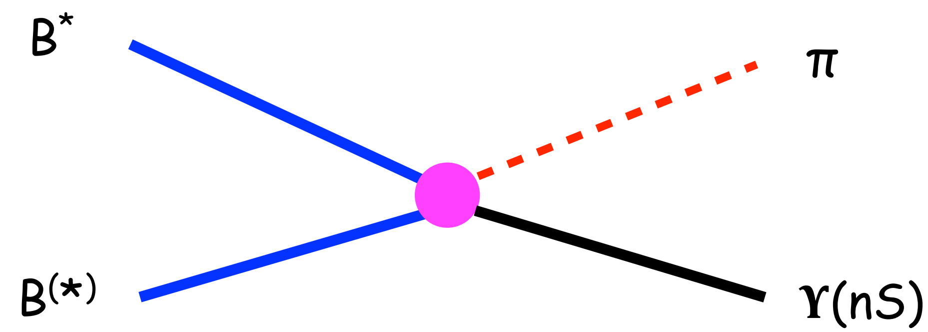
New Dynamics for Hadronic Transitions

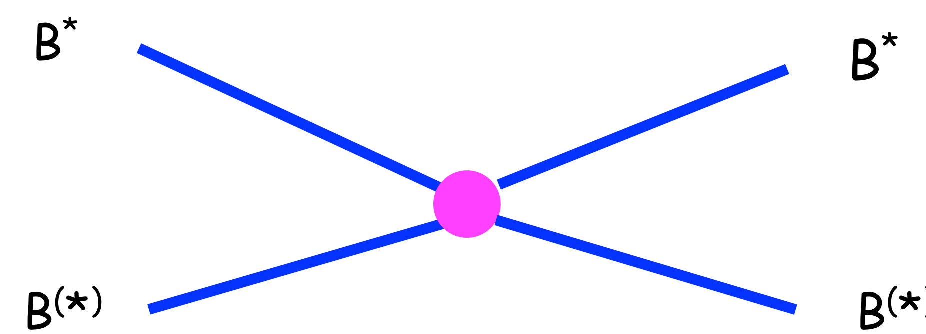
- Physical Expectations for Threshold Dynamics:

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

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

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



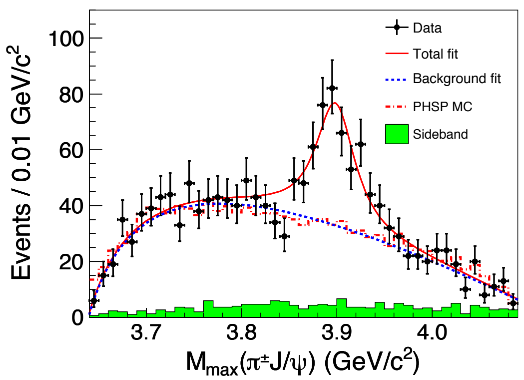


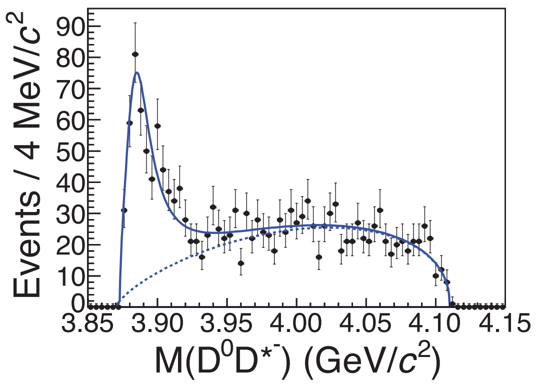
Ratios determined by LQCD calculations and judicious use of SU(3).

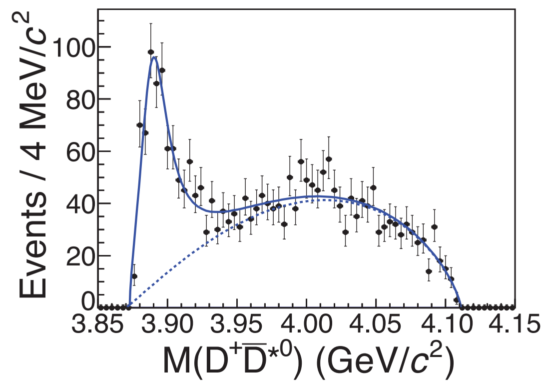
M. Padmanath, C. B. Lang and S. Prelovsek [arXix:1503.03257]

Heavy Quark Symmetry

- Charmonium-like states: $e^+e^- \longrightarrow \pi^+\pi^- J/\psi$ at $\sqrt{s}$ = 4.26 GeV [Y(4260)]
- $Z_c(3885)$, $Z_c(4020)$ both have $I^G(J^P) = 1^-(1^+)$.
- As expected by HQS between the bottomonium and charmonium systems







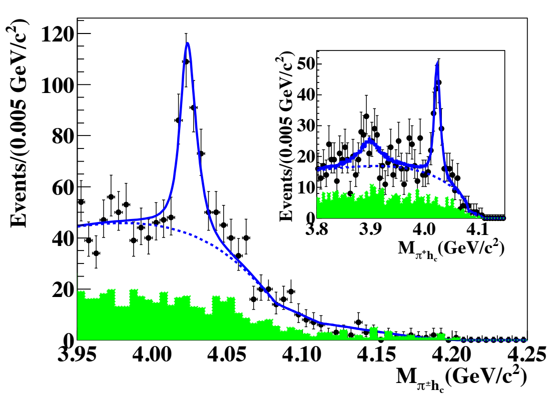
$$\frac{\Gamma[Z_c(3900)\to D D^*]}{\Gamma[Z_c(3900)\to \pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}.$$

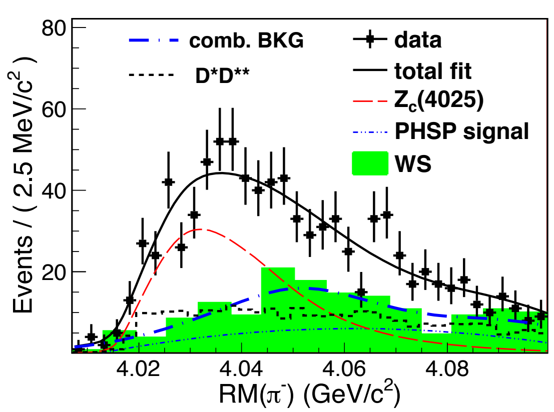
M(D⁰+D*⁻) = 3.8752

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

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

More States and Transitions

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

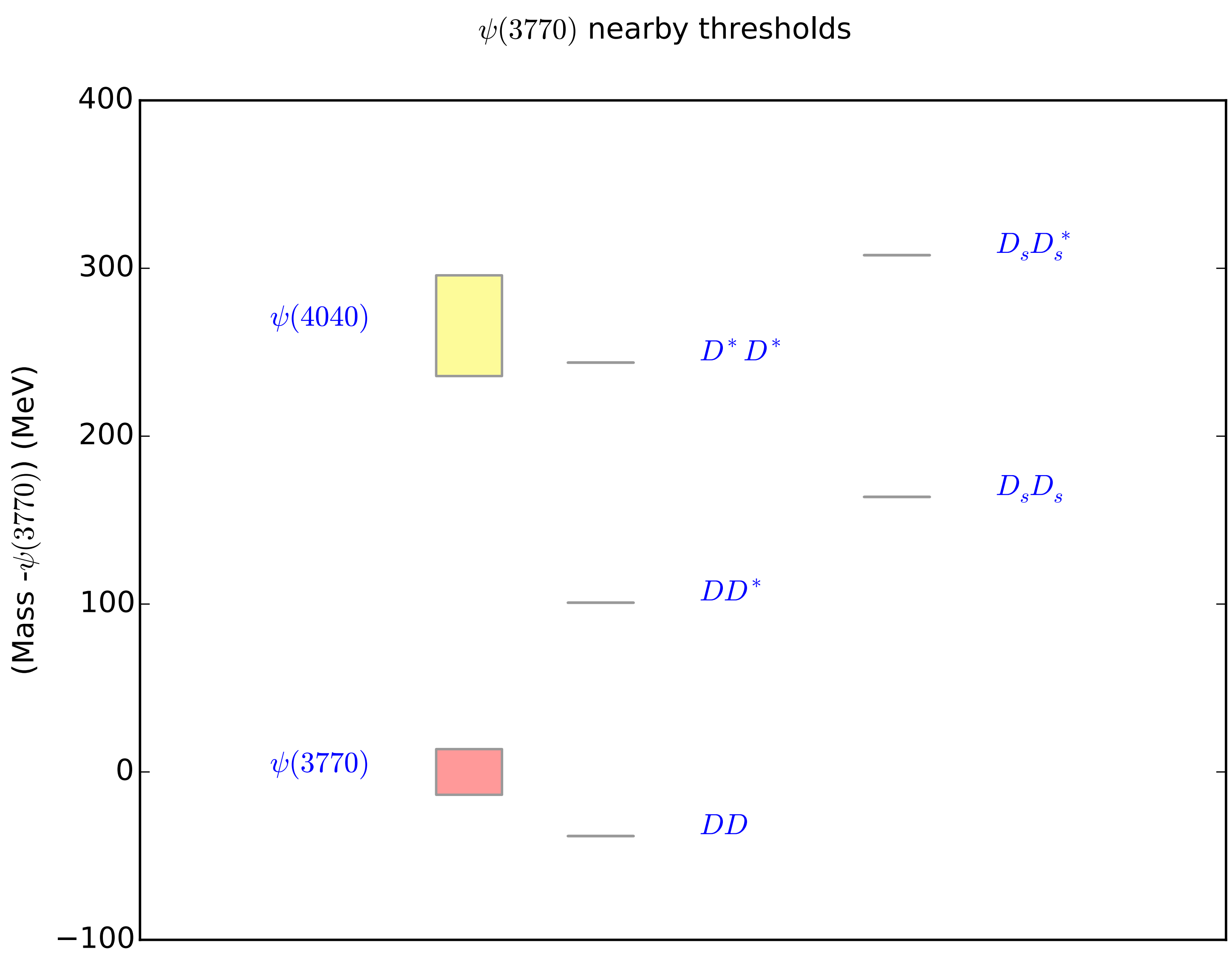
Decay Mode	Branching Rate
$D^0 \bar{D}^0$	$(52 \pm 5)\%$
$D^+ D^-$	$(41 \pm 4)\%$
total $D\bar{D}$	$93^{+8}_{-9}\%$
$\psi(1S)\ \pi^+\pi^-$	$(1.93 \pm 0.28) \times 10^{-3}$
$\psi(1S)\ \eta$	$(9 \pm 4) \times 10^{-4}$

—> partial rate = 52.5 ± 7.6 keV

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

Ψ(3770), Ψ(4040)

- Only ground state heavy-light meson pair decays allowed

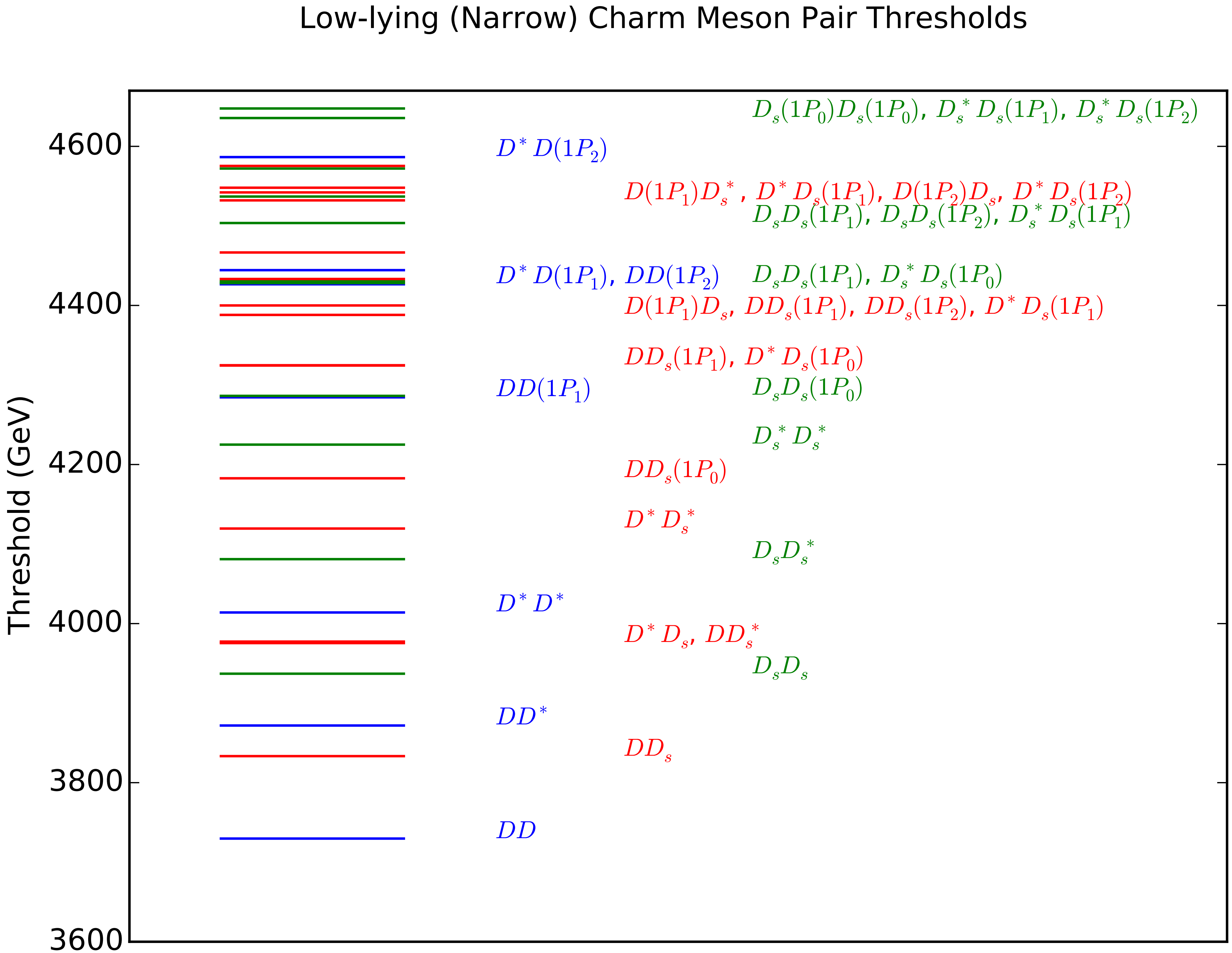


Systematics: ψ(4040) and Below

- 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^+	$e^+e^-(4260) \to \pi^+\pi^- J/\psi$
	$\pi^+ J/\psi$	$(\frac{Z_c(3885)\to D\bar{D}^*}{Z_c \to \pi J/\psi}) = 6.2 \pm 1.1 \pm 2.7$	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
	$\eta J/\psi$	$(5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$		

Low-lying thresholds



Narrow-Wide Thresholds

D_s^* $D(P_1)$

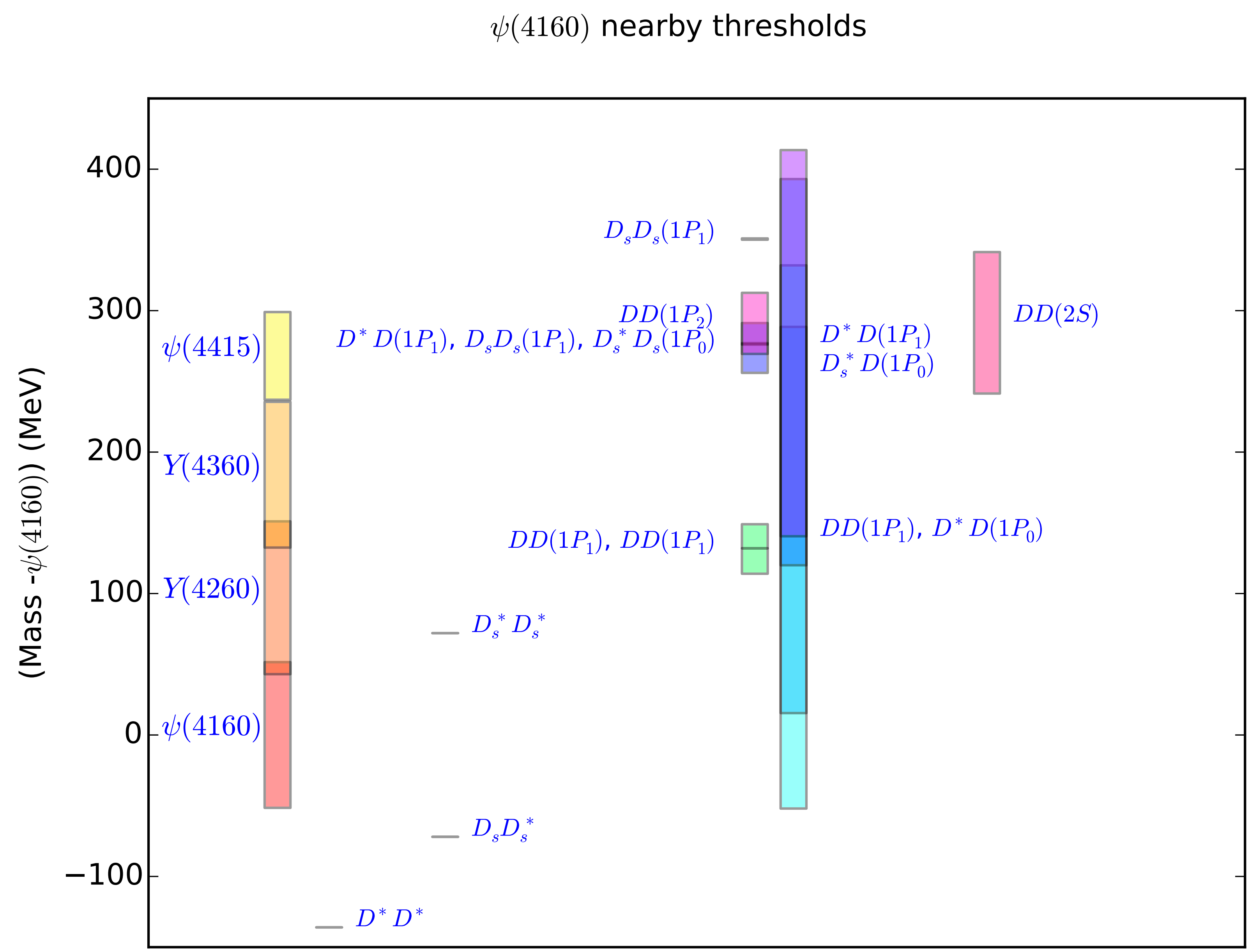
D_s $D(P_1)$; D_s^* $D(P_0)$; D^* $D(P_1)$

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

D $D(P_0)$

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

Systematics: Ψ(4160), Ψ(4415)

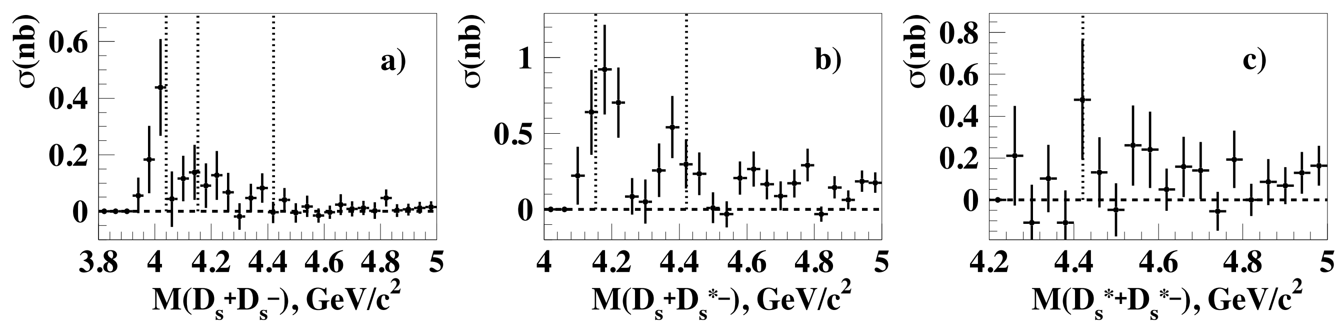
- Charmonium-like state transitions for masses above the ψ(3S)

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

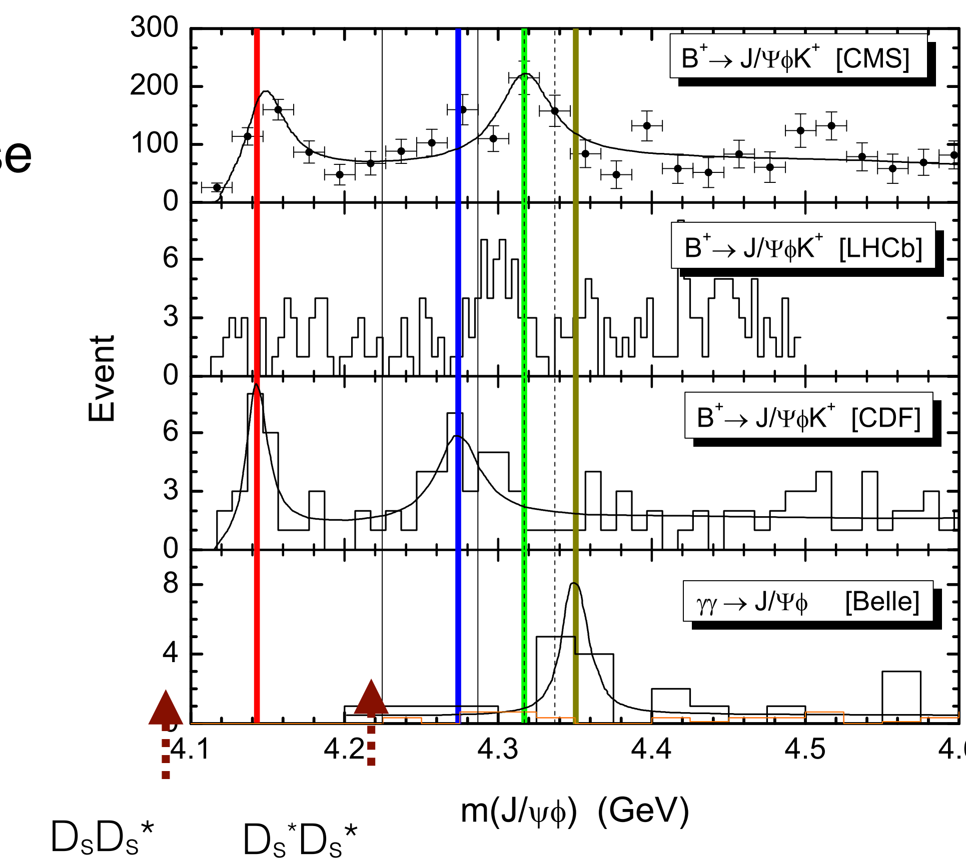
Strange heavy-light meson thresholds

- 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]

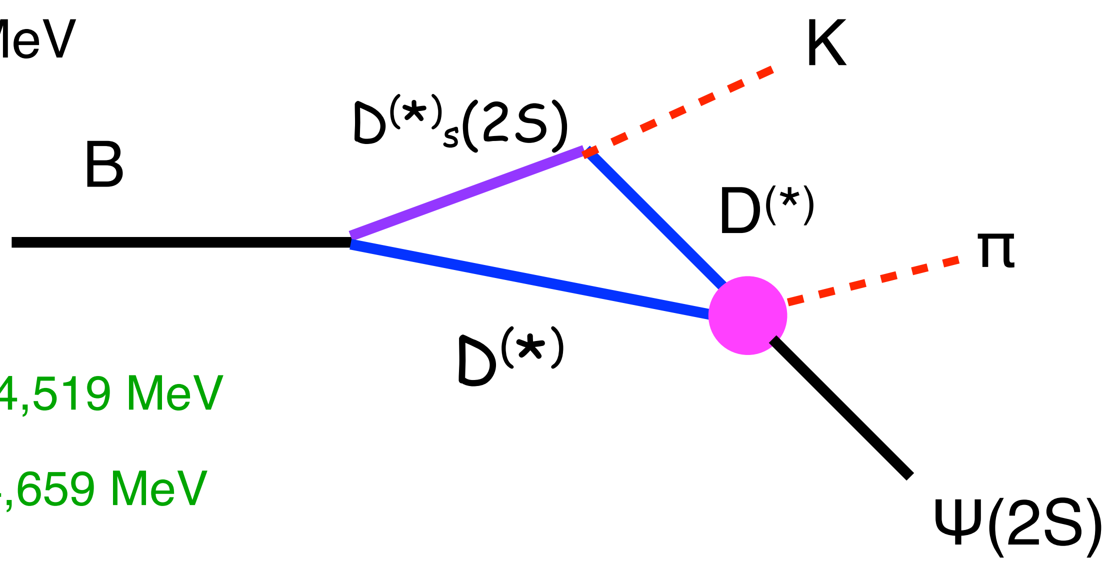


  - No wide P-states -> no sequential transitions with these states.
  - M($D_s^+ D_s^{-*}$) = 4,081 MeV, M($D_s^{+*}D_s^{-*}$) =4,225 MeV; M(3^3P_1) = 4,310 MeV -> no analogy of X(3872)
  - Direct transitions?
  - Narrow D($\frac{1}{2}^+$P) + D($\frac{1}{2}^-$S) thresholds? (and B analogs)
  - At higher energies the $D_s(2S)$ wide states could play a role in sequential transitions.



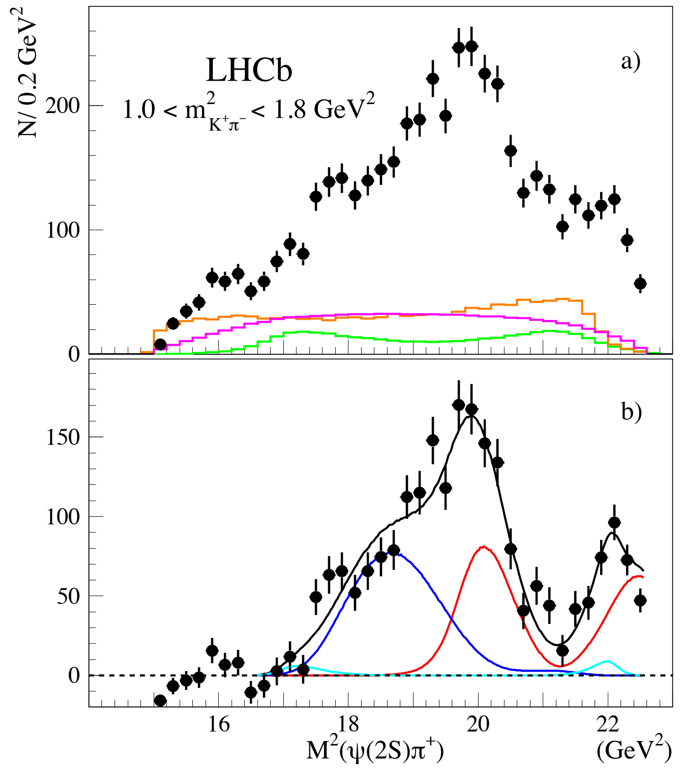
Systematics: Other States

- 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]



Summary

- Near threshold of the effects of heavy-light meson loops on quarkonium transiton rates are pronounced.
  - Hadronic transition rates are much larger than then usual QCDME.
  - The SU(3) breaking and Heavy Quark Spin Symmetry violation seen in these transitions are induced by the HL meson mass differences of nearby threshold
  - The factorization assumption fails. Heavy quark and light hadronic dynamics interact strongly due to heavy flavor meson pair (four quark) contributions to the quarkonium wavefunctions.
  - A new mechanism, in which the dynamics is factored differently, is purposed. HQS as well as the usual SU(3) and chiral symmetry expectations are recovered for amplitudes. Magnetic transitions not suppressed. The puzzles in η transitions are resolved.
- The known X and Z states are associated with threshold S-wave scattering of narrow HL state meson pairs. The Y(4260) may be a hybrid state.
- With BES III and LHCb and soon BELLE 2. I expect even more progress in understanding hadronic transitions and XYZ states in the near future.
- Lattice QCD can play an important role in disentangling this situation

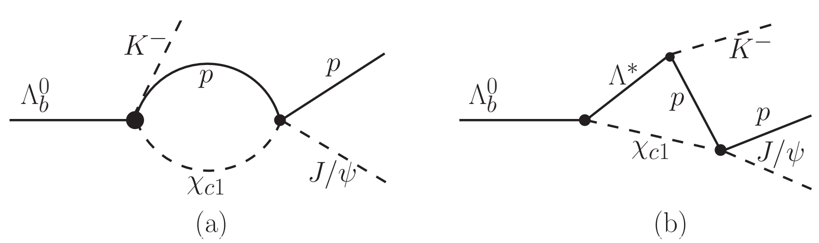
Two requests for LQCD

- Calculate the quarkonium spectrum (and transitions) as a function of the light quark masses for masses $\lesssim \Lambda_{QCD}$. This provides model independent insight into the role of meson loops.
- Calculate the behavior of scattering of heavy-light meson pairs in the threshold region.
  - Consider S-wave amplitudes
  - Include the mixing between two HL mesons and quarkonium + a single light hadron.
  - Can use the HQSS and approximate SU(3) of the amplitudes to greatly simplify the task.
  - This is an difficult challenge but initial progress is very encouraging.

Backup Slides

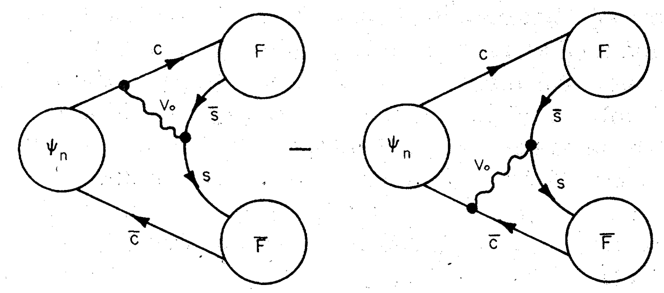
Pentaquarks

- X(4450) F. K. Guo et al [arXiv:1507.04950]
  - Resonance is at threshold of χ_{c1} p = 3510.66 + 938.27 = 4448.93 MeV
  - Also triangle diagram involving the Λ(1890) can give a leading Laudau singularity which would appear at χ_{c1} P threshold.



  - Purpose tests in: Λb -> K χ_{c1} p and Y(1S) -> J/Ψ p $\overline{p}$

Decay Amplitudes



Cornell Model:

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

where

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

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

$dV(x)/dx = 1/a^2 + \kappa/x^2$ -> ignoring κ term

similar form as vacuum pair creation (QPC) model

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

Decay amplitudes I(p)

Decay Model

$$I^l_{nL}(P) = \int_0^\infty dt\, \Phi(t) R_{nL}(t\beta^{-1/2}) j_l(\mu_c \beta^{-1/2} P t)$$

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

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

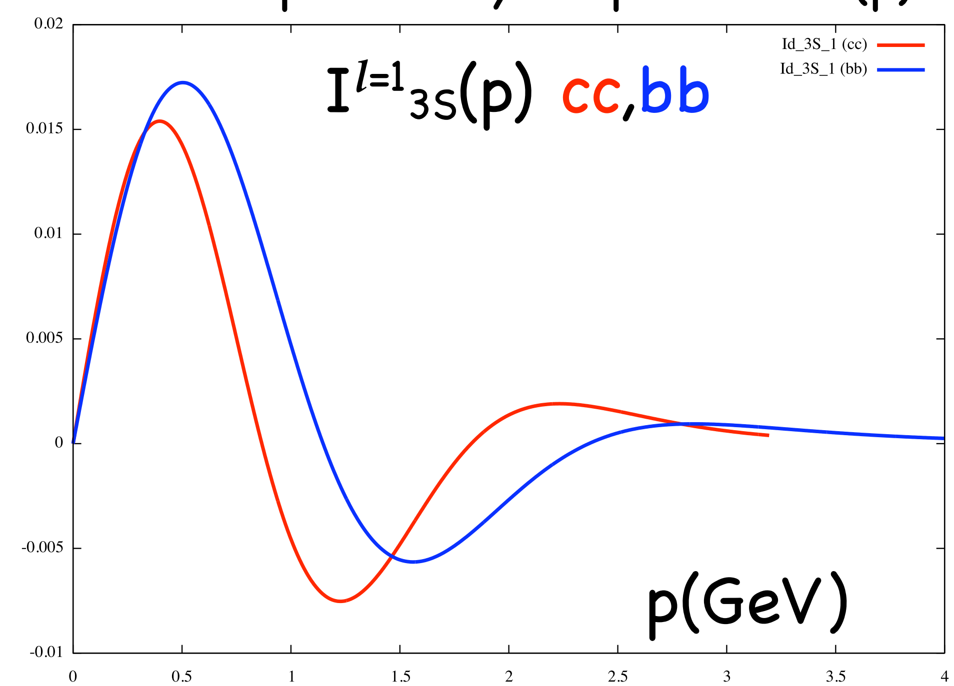
$$\Phi(t) = t e^{-t^2} + (\pi/2)^{1/2}(t^2 - 1) e^{-t^2/2} \operatorname{erf}(t/\sqrt{2})$$

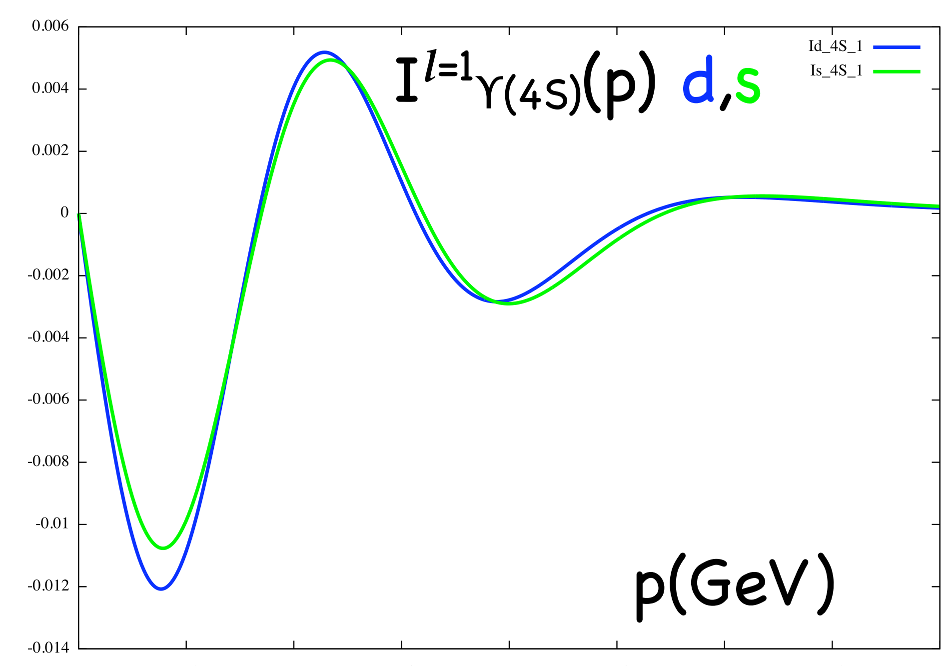
Using HQET this function Φ(t) is the same for all final states in a j_l^P multiplet.

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

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

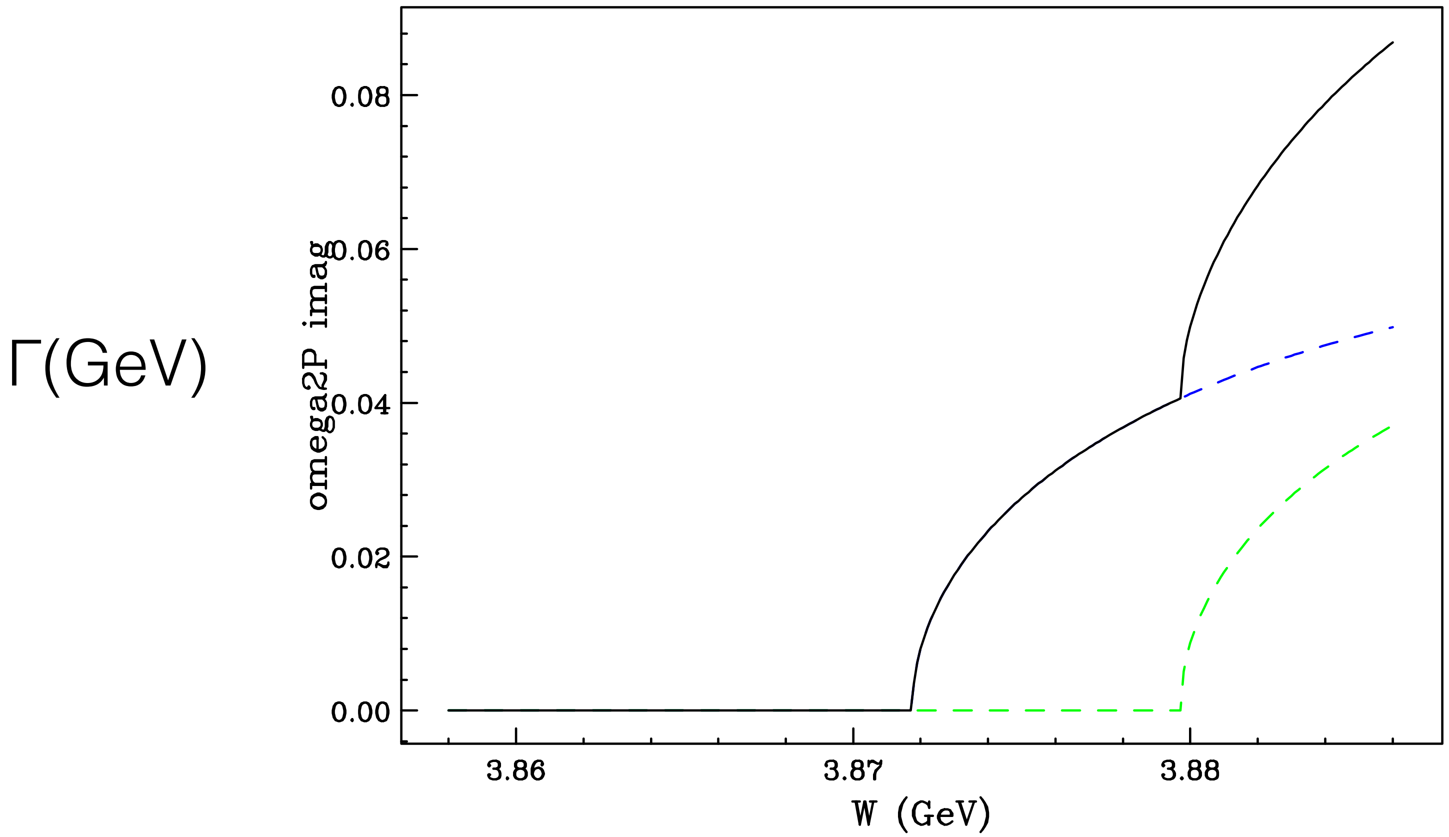
Sample decay amplitudes I(p)

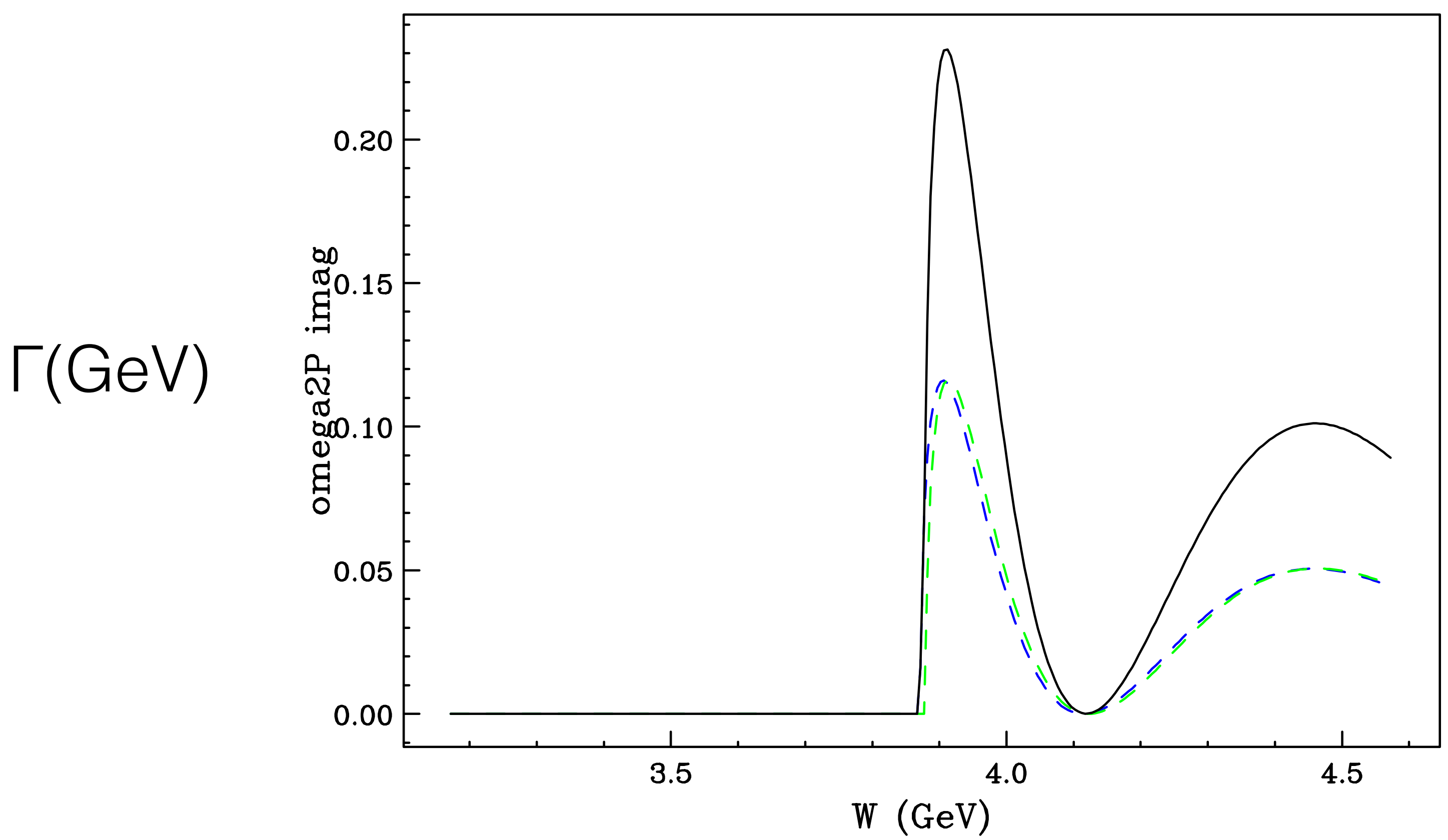




Other Decay Structures

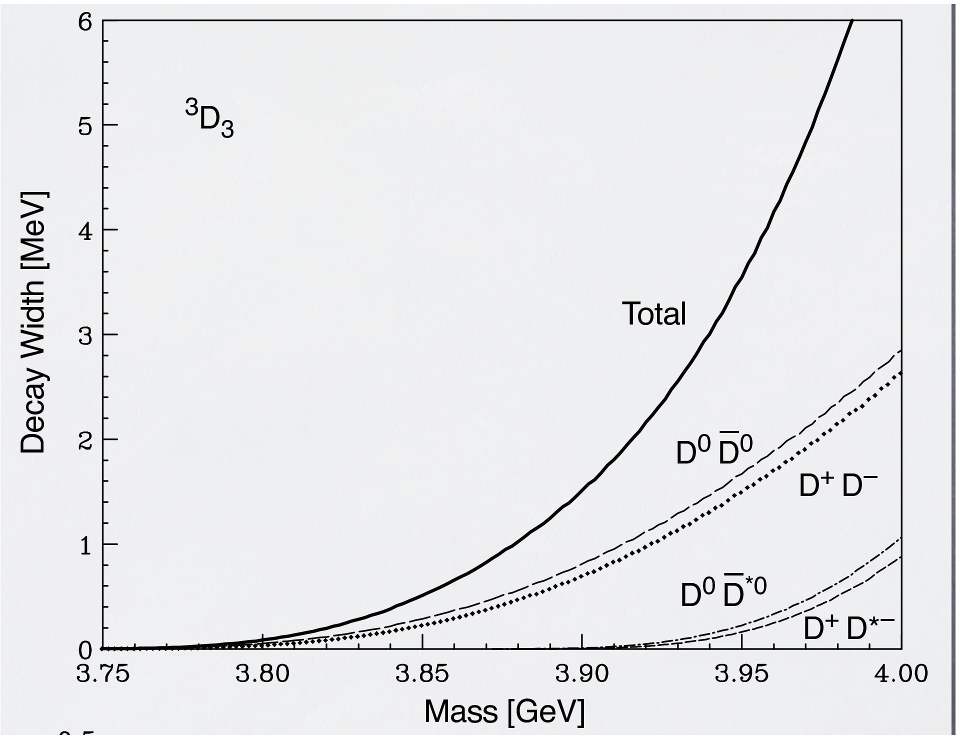
- $2\,^3P_1(c\bar{c})$
  - Strong S-wave decay
  - Large width attained quickly



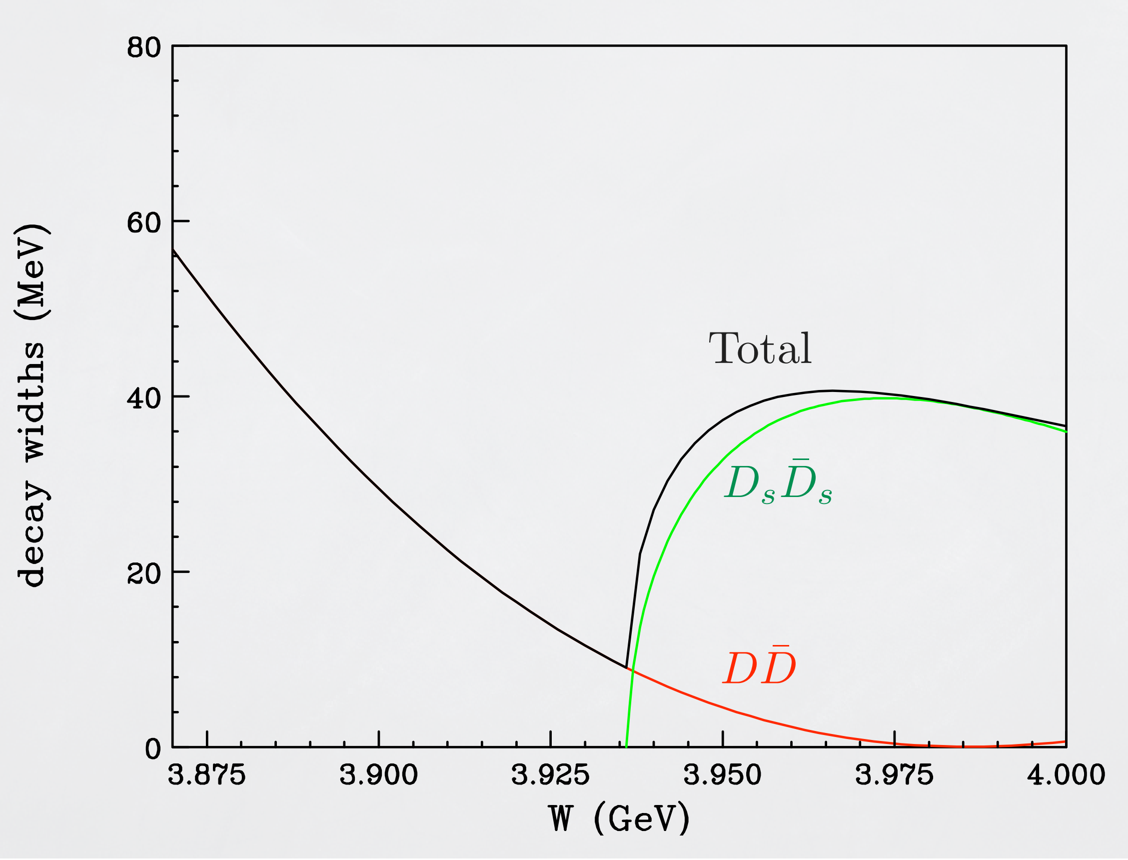


Other Decay Structures

- 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.



Partial Waves for Various Decays

- Decays Near Threshold in e+e-

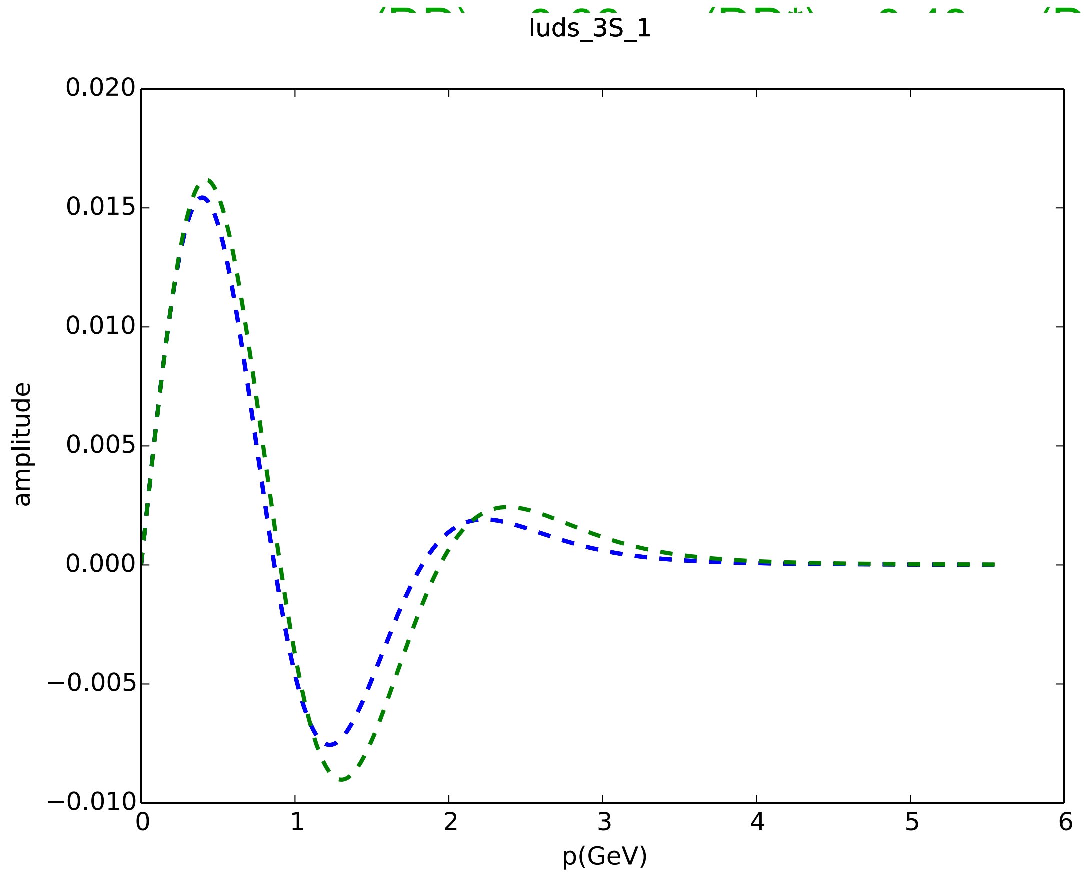
Partial Wave (L) of Two Body Decay to Heavy-Light Meson Pairs

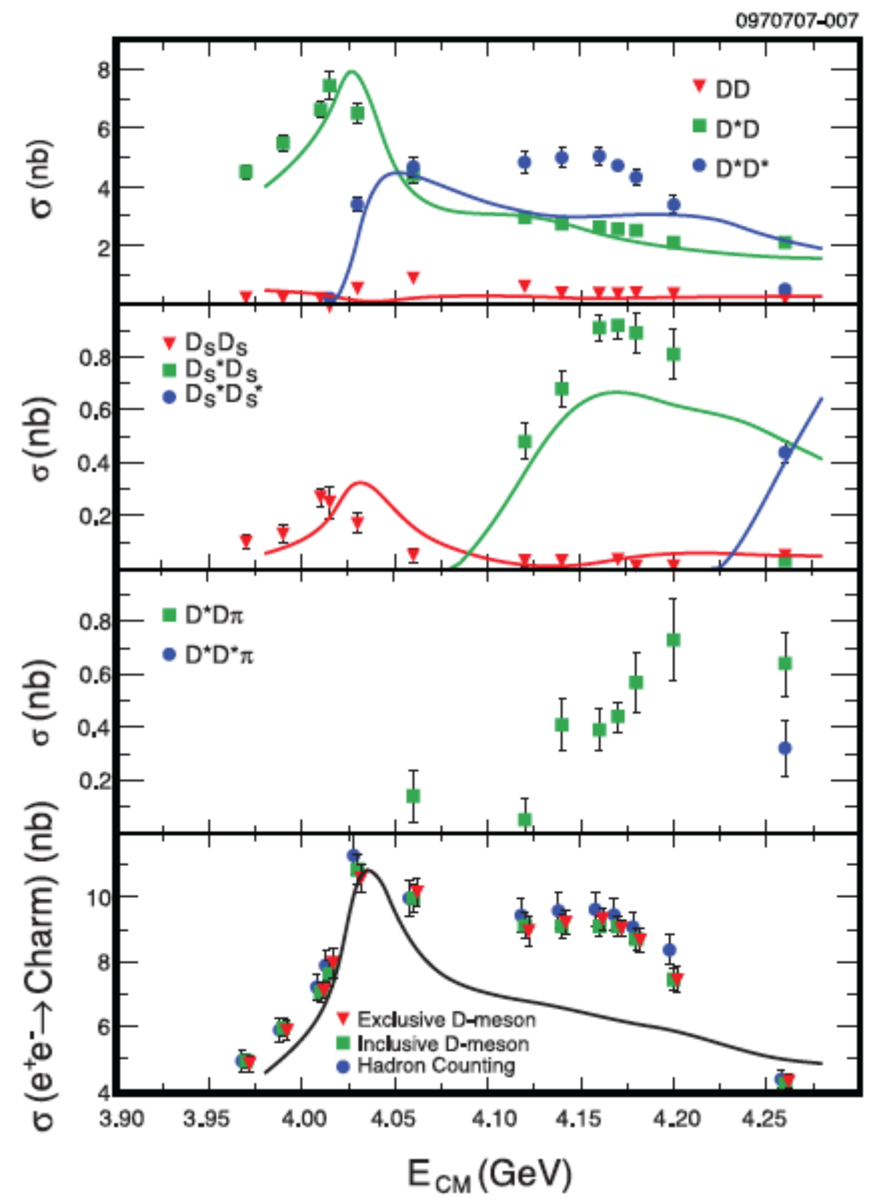
	$j_l^P=0^-$ [n^3S_1]	$j_l^P=1/2^-$	$j_l^P=1/2^+$	$j_l^P=3/2^+$	$j_l^P=3/2^-$	$j_l^P=5/2^-$
S	$j_l^P=1/2^-$	L=1	L=0	L=2	L=1	-
P	$j_l^P=1/2^+$	L=0	L=1	L=1	L=2	-
P	$j_l^P=3/2^+$	L=2	L=1	L=1,3	L=0,2	L=1,3
D	$j_l^P=3/2^-$	L=1	L=2	L=0,2	L=1,3	L=2,4
D	$j_l^P=5/2^-$	-	-	L=1,3	L=2,4	L=1,3,5

	$j_l^P=0^-$ [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
P	$j_l^P=3/2^+$	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
D	$j_l^P=5/2^-$	L=1,3,5	L=0,2,4	L=0,2,	L=1,3,5	L=1,3,
		S	P	P	D	D

Complicated pattern in ΔR_c

- $\Psi(3S)$ 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:
    - *D*) = —



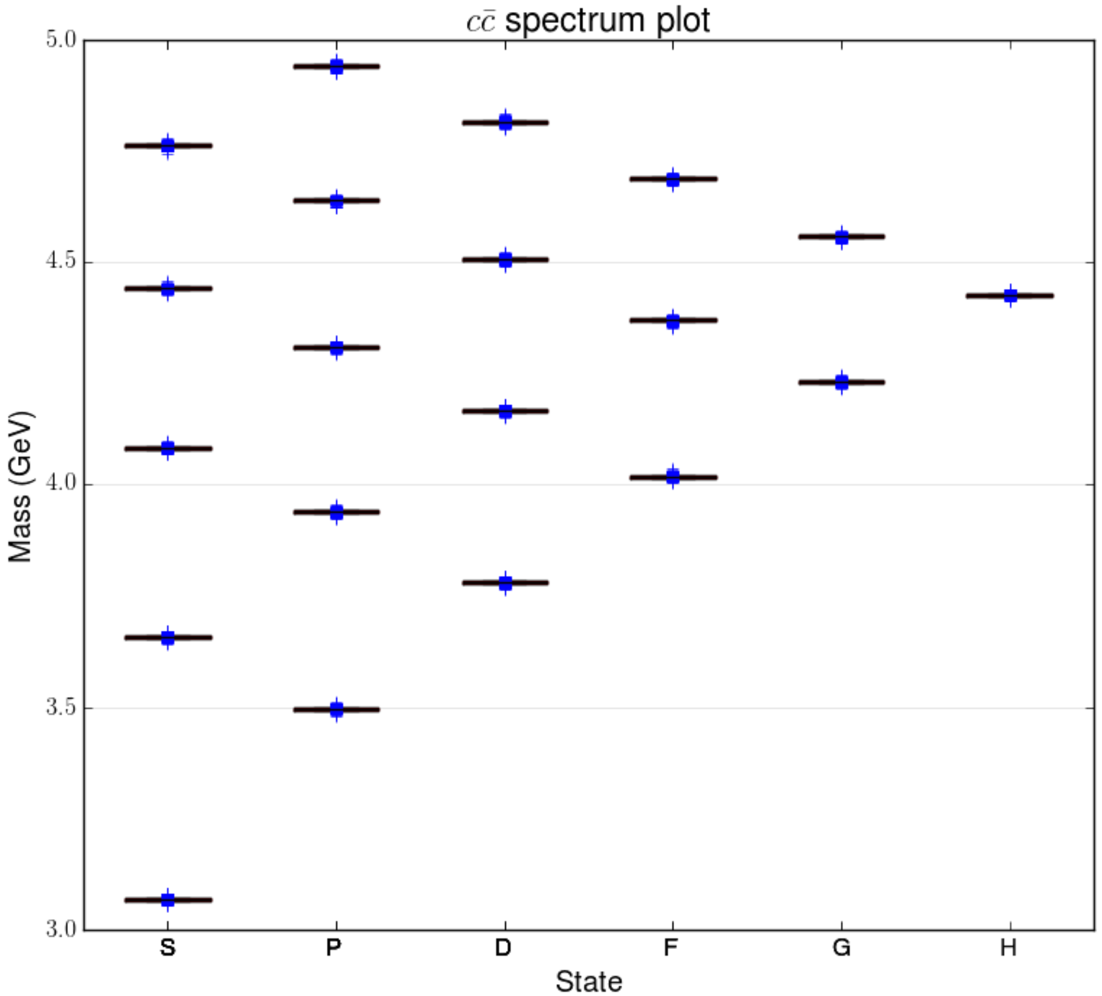


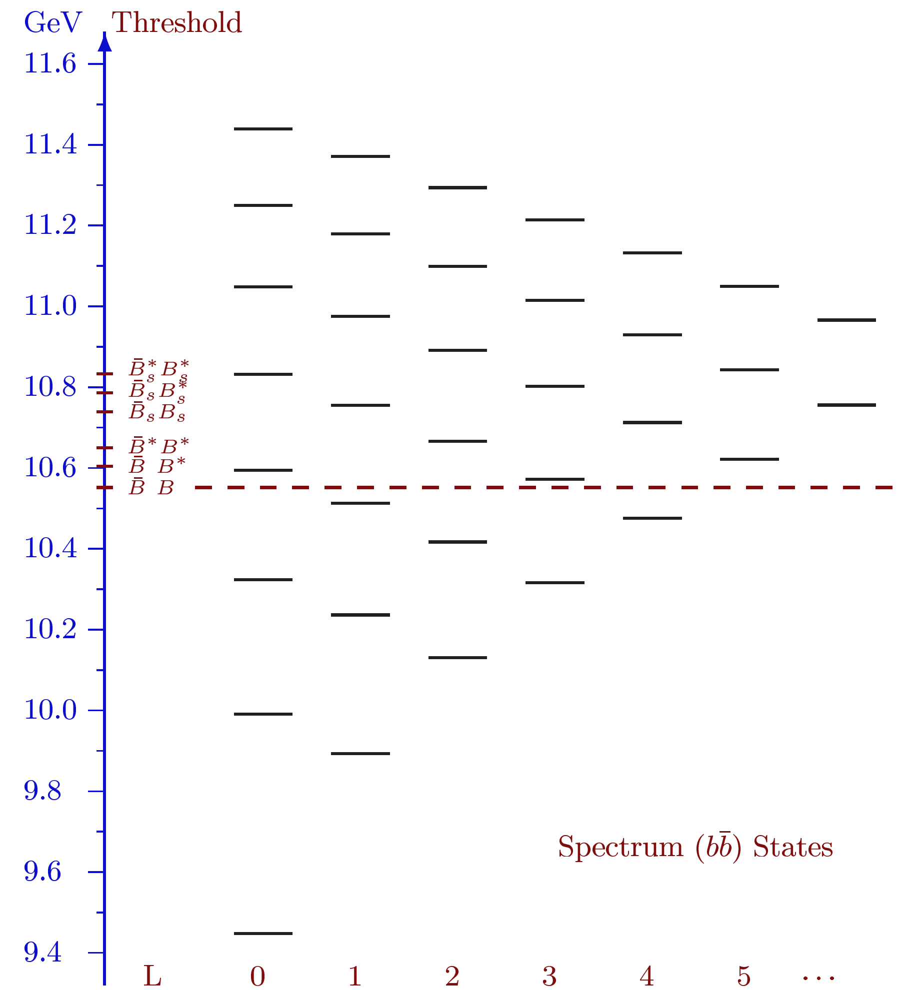
Decay Couplings

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

Potential model states





Transitions

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

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)

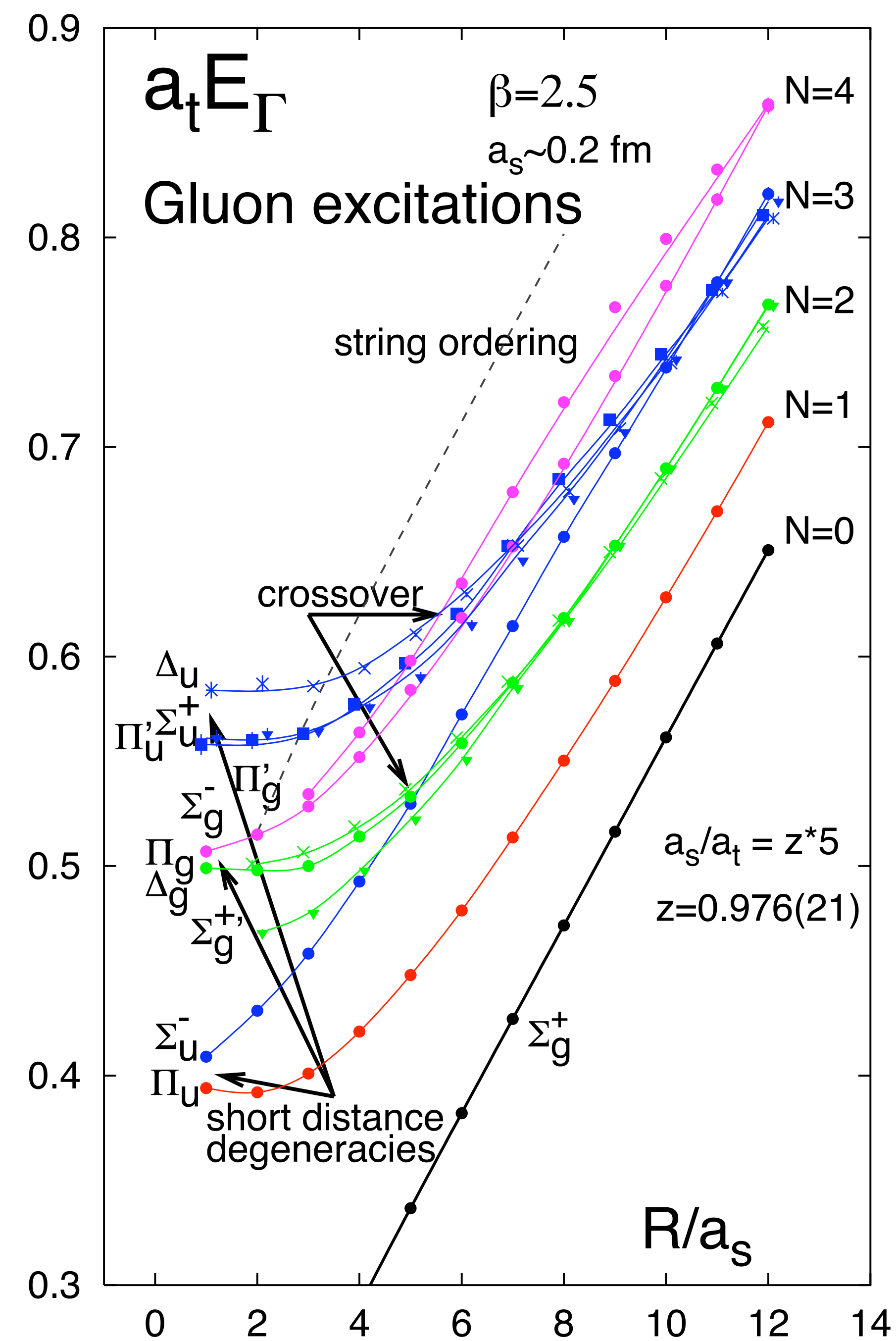
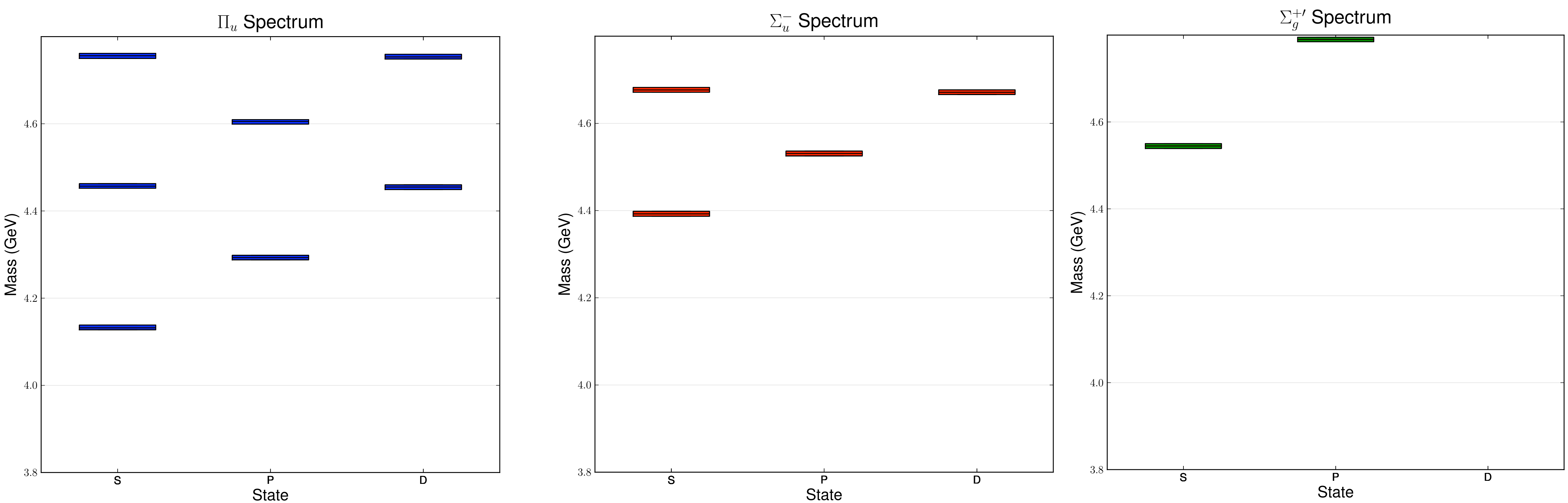


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Spectrum of Low-Lying Hybrid States

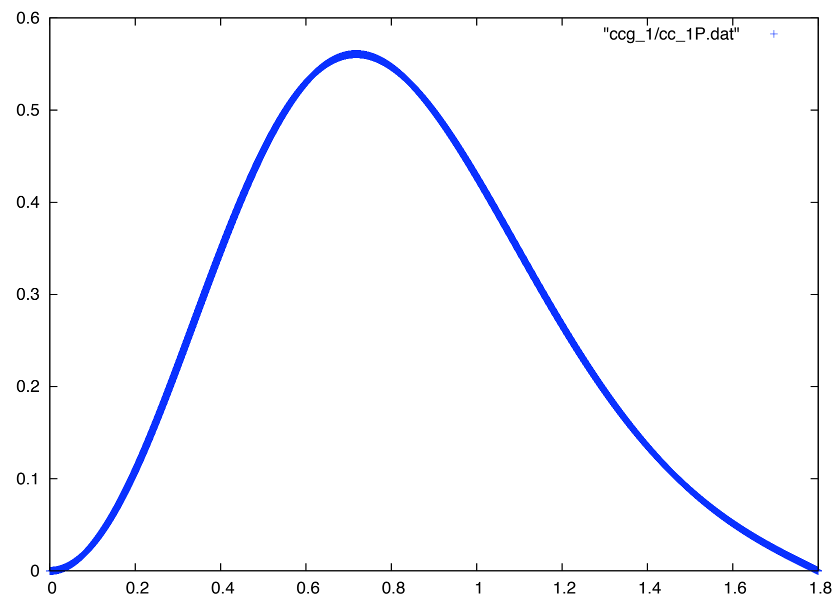
- Only interested in states below 4.8 GeV for cc system. Unlikely higher states will be narrow (DD, glueball+J/ψ, etc)

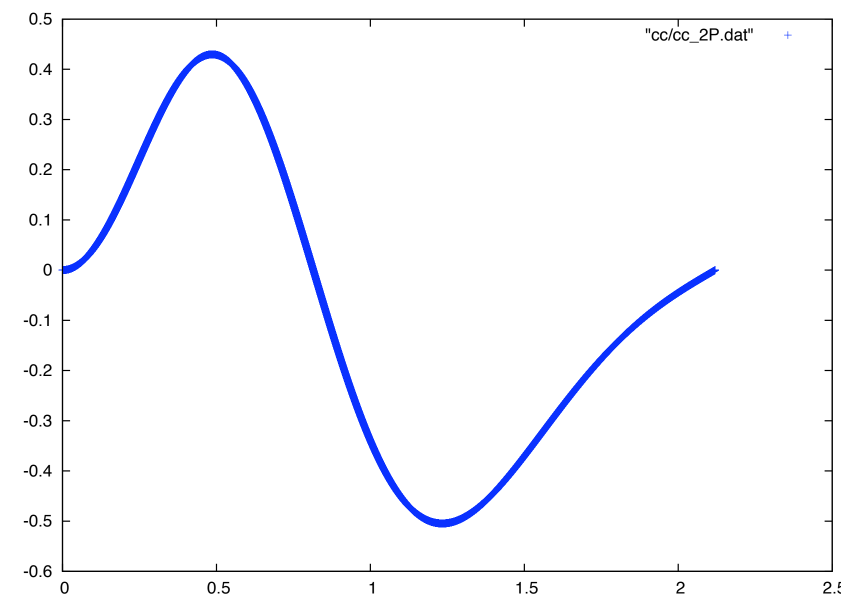


- Only Π_u, Σ_u^-, and $\Sigma_g^{+\prime}$ systems have sufficiently light states.

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