Resolving the Puzzles of Quarkonium Transitions

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- Basic QCDME
- Puzzles in hadronic transitions
  - Two pion transitions
  - Single hadron transitions
- Hadronic transitions above threshold
  - Eta transitions
  - Structure in two pion transitions
- Summary

QCD Multipole Expansion (QCDME)

- Basic Idea
  - Analogous to the QED multipole expansion with gluons replacing photons.

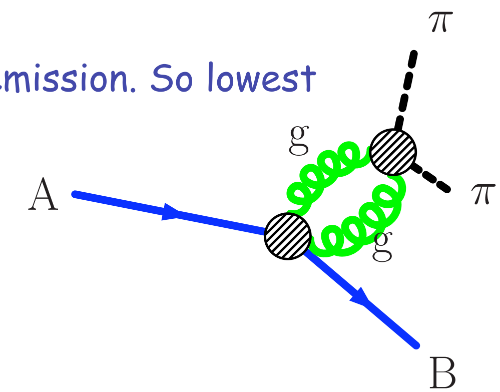
$$H^{\rm eff}_{\rm QCD} = H^{(0)}_{\rm QCD} + H^{(1)}_{\rm QCD} + H^{(2)}_{\rm QCD} \qquad H^{(1)}_{\rm QCD} \equiv Q_a A^a_0(\mathbf{X}, t)$$

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.

Model: Kuang & Yan [PR D24, 2874 (1981)]

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

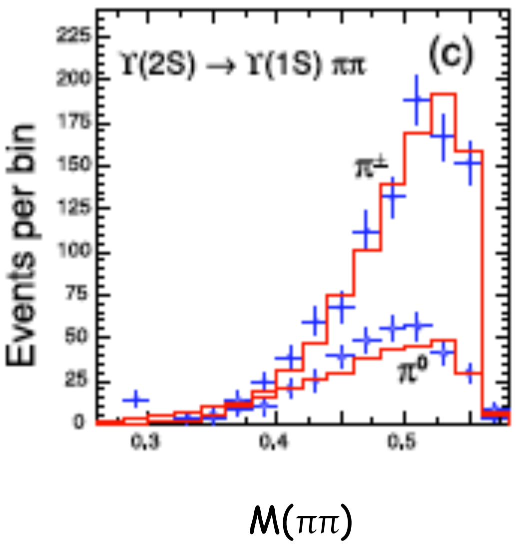
QCD Multipole Expansion (QCDME)

- Two pion transitions: (E1-E1), ... $C_A C_B = +1$

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

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

S-wave   D-wave



- nS -> mS transitions

$$d\Gamma \sim K\sqrt{1 - \frac{4m_\pi^2}{M_{\pi\pi}^2}}(M_{\pi\pi}^2 - 2m_\pi^2)^2 dM_{\pi\pi}^2$$

$$K \equiv \frac{\sqrt{(M_A + M_B)^2 - M_{\pi\pi}^2}\sqrt{(M_A - M_B)^2 - M_{\pi\pi}^2}}{2M_A}$$

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

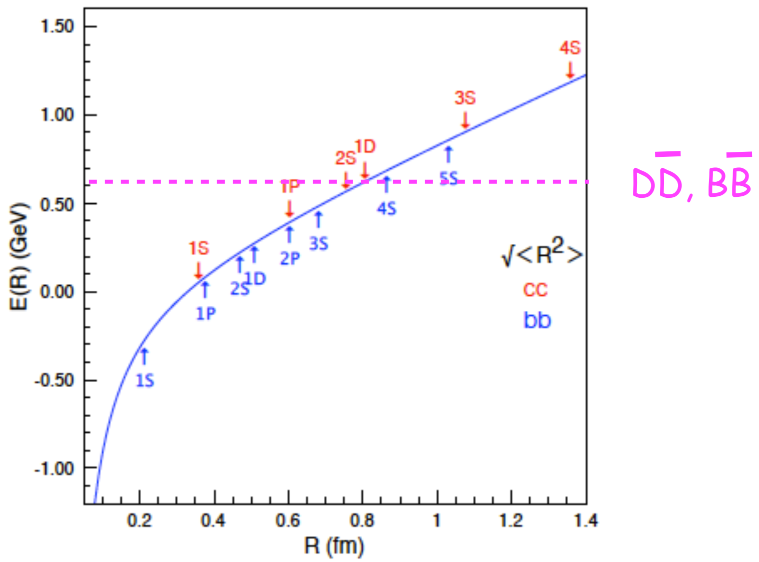
Phase Space   Overlap - Vibrating String Model

- Higher order transitions: (E1-M2), (M1-M1), ... $C_A C_B = +1$
  - Combine chiral symmetry and SU(3) symmetry breaking to relate (π^0, η, η') transitions
- 3 gluons $C_A C_B = -1$ (ω, ...)

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, …

Cornell Potential Model



  - Small contributions from excitations involving QCD additional degrees of freedom.
    - This is essential to the factorization assumption !
  - light quark pairs
    - $D^{(*)}\,\bar{D}^{(*)}$ thresholds in 1D to 3S region
    - $B^{(*)}\,\bar{B}^{(*)}$ thresholds in 4S region
  - gluonic excitations ?

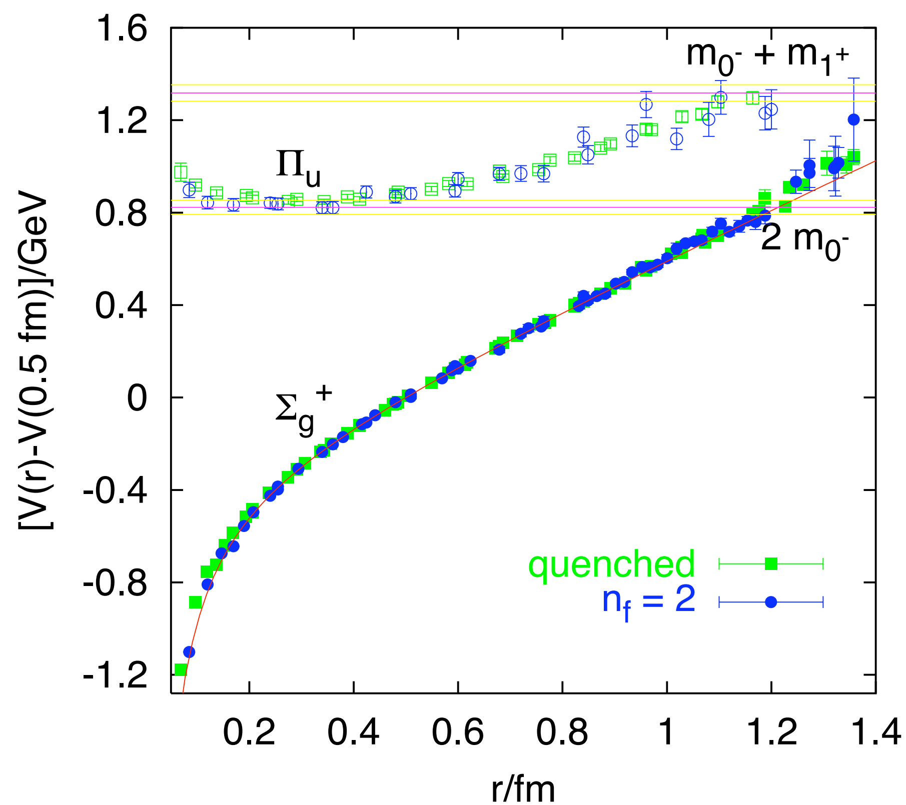
QCD Multipole Expansion (QCDME)

- Lattice calculation V(r), then SE

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

  - What about the gluon and light quark degrees of freedom in QCD?
  - Two thresholds
    - Usual $(Q\bar{q})$ + $(q\bar{Q})$ decay thresholds
    - Exciting the string - hybrids
  - 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 $(c\bar{c})$ system
    - Just above the 5S in the $(b\bar{b})$ system
- Should have expected trouble for QCDME above the 3S $(c\bar{c})$ and 4S $(b\bar{b})$

LQCD calculation of static energy



Two pion Transitions

Table 1: Partial widths for observed two pion transitions.

Initial State → Final State	Γ_{total} (MeV)	Branching Fraction (10^{-3})	$\Gamma_{partial}$ (keV)
$\psi' \to J/\psi + \pi^+\pi^-$	0.304 ± 0.009	336 ± 4	102 ± 3.3
$\psi(1D) \to J/\psi + \pi^+\pi^-$	27.2 ± 1.0	1.93 ± 0.28	52.5 ± 7.9
$\psi(3S) \to J/\psi + \pi^+\pi^-$	80 ± 10	5.2 ± 0.73	416 ± 78
$\psi(2D) \to J/\psi + \pi^+\pi^-$	103 ± 8 (8.2 nb)	1.92 ± 0.52	197 ± 52
$\Upsilon(2S) \to \Upsilon(1S) + \pi^+\pi^-$	$(31.98 \pm 2.63) \times 10^{-3}$	179.2 ± 2.6	5.73 ± 0.48
$\Upsilon(1D) \to \Upsilon(1S) + \pi^+\pi^-$	28.5×10^{-3}	6.6 ± 1.6	0.188 ± 0.045
$\chi_{b1}(2P) \to \chi_{b1}(1P) + \pi^+\pi^-$	0.096 ± 0.016	9.1 ± 1.3	0.87 ± 0.19
$\chi_{b2}(2P) \to \chi_{b2}(1P) + \pi^+\pi^-$	0.138 ± 0.019	5.1 ± 0.9	0.70 ± 0.16
$\Upsilon(3S)$	$(20.32 \pm 1.85) \times 10^{-3}$		
$\to \Upsilon(2S) + \pi^+\pi^-$		28.2 ± 1.8	0.573 ± 0.064
$\to \Upsilon(1S) + \pi^+\pi^-$		43.7 ± 0.8	0.888 ± 0.082
$\Upsilon(4S)$	20.5 ± 2.5		
$\to \Upsilon(2S) + \pi^+\pi^-$		$(8.6 \pm 1.3) \times 10^{-2}$	1.76 ± 0.34
$\to \Upsilon(1S) + \pi^+\pi^-$		$(8.1 \pm 0.6) \times 10^{-2}$	1.66 ± 0.24
$\Upsilon(5S)$	55 ± 28		
$\to \Upsilon(3S) + \pi^+\pi^-$		2.88 ± 0.41 [25]	158 ± 84
$\to \Upsilon(2S) + \pi^+\pi^-$		7.97 ± 1.00 [25]	438 ± 230
$\to \Upsilon(1S) + \pi^+\pi^-$		4.45 ± 0.35 [25]	245 ± 126
$\to h_b(2P) + \pi^+\pi^-$		$6.0^{+2.1}_{-1.8}$	330^{+204}_{-195}
$\to h_b(1P) + \pi^+\pi^-$		$3.5^{+1.0}_{-1.3}$	192^{+112}_{-121}
$\to \Upsilon_2(1D) + \pi^+\pi^-$		0.10 ± 0.028 [1]	5.5 ± 3.2

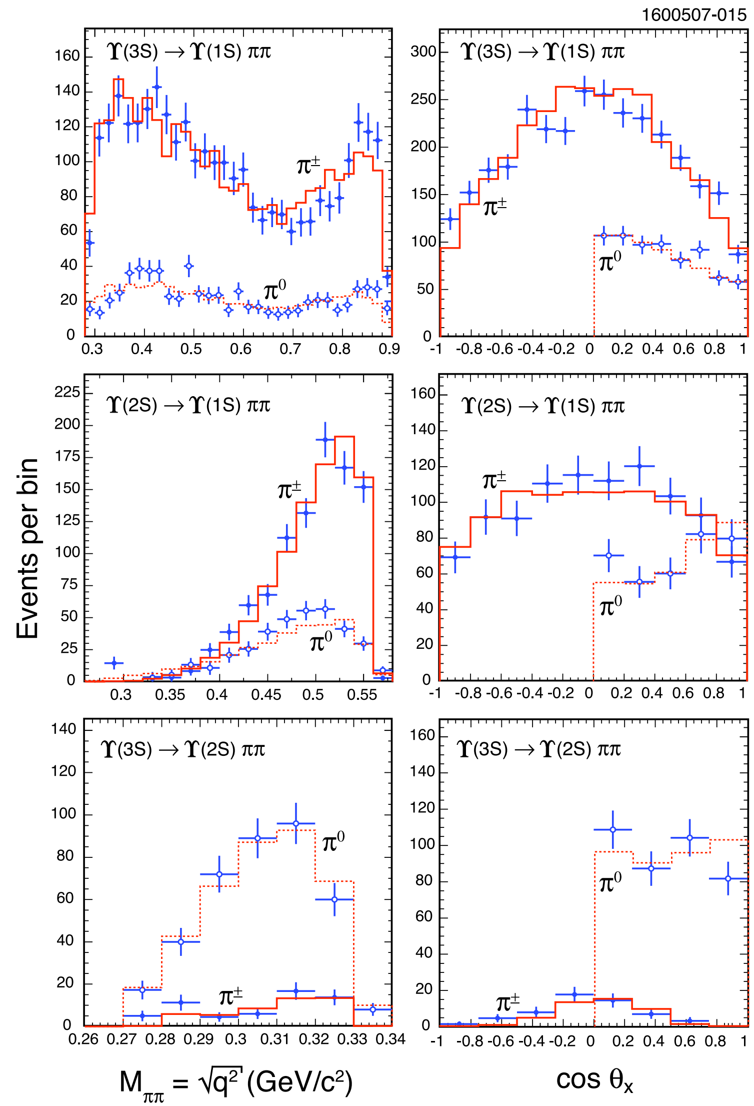
- Comments:
  - Chosing $|C_1| = 10.2 \pm 0.2$, $|C_2/C_1| = 1.25 \pm 0.14$ from the $(c\bar{c})$ system.
  - Ratio of charged to neutral pion pair production consistent with I=0
  - For the $^3D_2$ $(b\bar{b})$ state the theoretical total width is used.
  - The $\Upsilon(5S)$ transitions are strikingly large. Partial rates over 100 times the rates of lower states.
  - A number of quarkonium-like states have been first discovered in hadron transitions. X(3872), Y(4260), … and charged states $Z_b^{\pm}(10,610)$, $Z_b^{\pm}(10,650)$, … Discussion these states postponed.

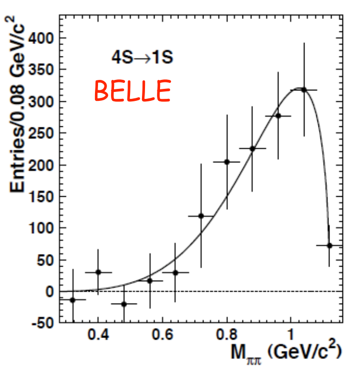
Unresolved Puzzles

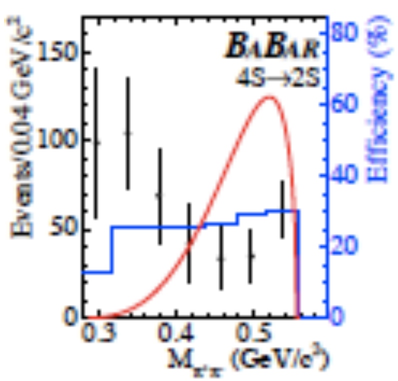
- The experimental transitions rates (for states below threshold) are in reasonable agreement with the simple KY model.
- $\Upsilon(3S) \to \Upsilon(1S)\ \pi\pi$ and $\Upsilon(4S) \to \Upsilon(2S)\ \pi\pi$ transitions
  - $M_{\pi\pi}$ distributions NOT the expected S-wave behaviour.
  - Transitions not expected to have any large violation of QCDME assumptions due to light quark pairs. [Unlike the $\Upsilon(5S) \to \Upsilon(nS)\ \pi\pi$]
  - Possible explanation - same as overlap dynamically suppressed in $\Upsilon(3S) \to \chi_b(1P)\ \gamma$ EM transitions.

    [The KY model has such a dynamical suppression.]
  - Further study at Belle 2 would be useful. Look at polarization.

CLEO

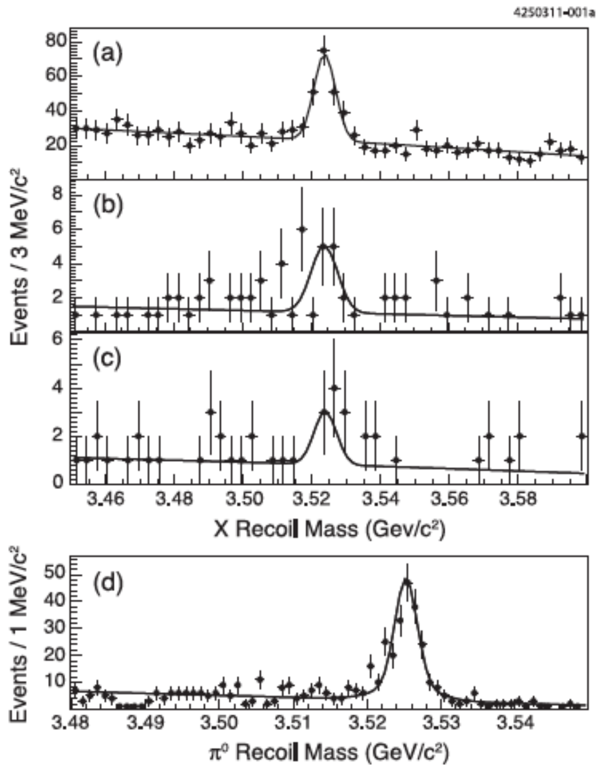




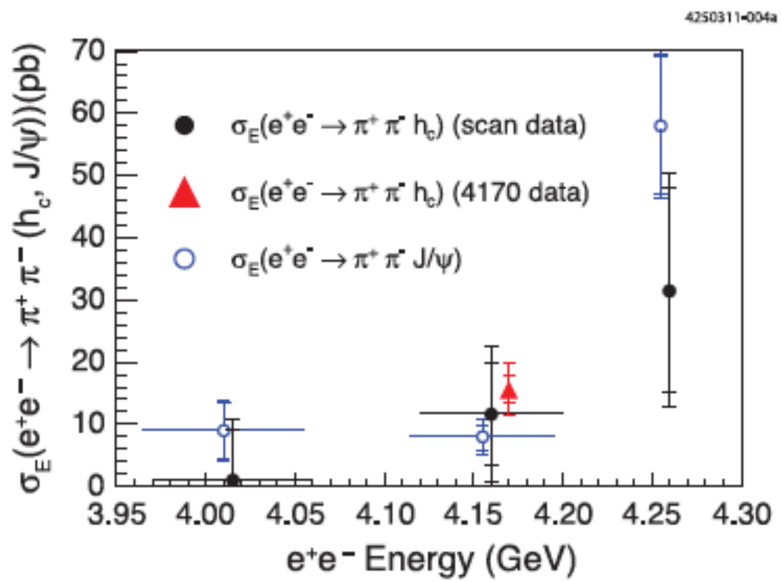


Unresolved Puzzles

- The $\psi(4160) \to h_c(1P) + \pi^+\pi^-$ transition.



T.K. Pedlar et.al [CLEO Collaboration]
PRL 107, 041803 (2011) [arXiv:1104.2025]



- $\psi(4160)$ is the 2^3D_1 charmonium state.
- Spin flip transition (E1-M1) expected to be too small to observe but the transition is clearly seen.
- Gross violation of QCDME for hadronic transitions !

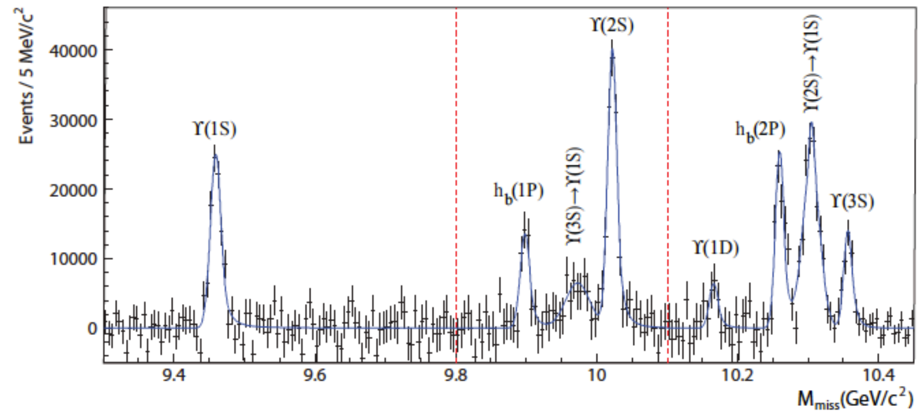
- The $\Upsilon(5S) \to \Upsilon(2S) + \pi^+\pi^-$ transitions

BELLE [arXiv:1103.3419]

  - $\Upsilon(5S)$: m=10,876 ± 11 MeV and Γ = 55 ± 23 MeV
  - PRL100,112001(2008)

PRL100,112001(2008)	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2



  - $\pi^+\pi^-$ system I= 0
  - total branching ratio for known hadronic transitions (3.9 ± 0.7)% => Γ = 2.1 ± 0.9 MeV
  - Clear violation of QCDME expectations. (E1-M1/E1-E1) shoud be small but
    - the transitions $\Upsilon(5S) \to h_b(1P,2P) + \pi^+\pi^-$ requires a heavy quark spin flip (M1)(E1)

$$\frac{\sigma(h_b(nP)\pi^+\pi^-)}{\sigma(\Upsilon(2S)\pi^+\pi^-)} \equiv R = 0.46 \pm 0.08^{+0.07}_{-0.12} \quad \text{(n=1)} \qquad R = 0.77 \pm 0.08^{+0.22}_{-0.17} \quad \text{(n=2)}$$

  - Striking failure of the QCDME above threshold

Single Light Hadron Transitions

- Eta transitions (E1-M2, M1-M1) (C_AC_B = +1) $O(v^2)$
  - E1-M2 expected to dominate
  - Factorization

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

α_{AB}^{EE} Hadronize

  - Chiral symmetry: $i(2\pi)^{3/2}C_3 q_k$
  - α^{EE} same factor of heavy quark dynamics as in two pion case. So cancels in ratio $R_{\eta/\pi\pi}$ at $q^2 = m_\eta^2$

- Relation to other single pseudoscalar transitions

Chiral symmetry breaking - Chiral effective lagrangian

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

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

Single light hadron Transitions

Table 2: Partial widths for observed single π^0, η, or ω transitions.

Initial State → Final State	Γ_{total} (MeV)	Branching Fraction (10^{-3})	$\Gamma_{partial}$ (keV)
ψ'	0.304 ± 0.009		
$\to J/\psi + \eta$		33.75 ± 0.88 [23]	10.26 ± 0.40
$\to J/\psi + \pi^0$		1.26 ± 0.04 [23]	0.383 ± 0.017
$\to h_c(1P) + \pi^0$		0.86 ± 0.13	0.26 ± 0.04
$\psi(1D)$	27.2 ± 1.0		
$\to J/\psi + \eta$		0.87 ± 0.4	23.7 ± 10.8
$\to J/\psi + \pi^0$		< 0.28	< 7.6
$\psi(3S)$	80 ± 10		
$\to J/\psi + \eta$		5.2 ± 0.74 [22]	416 ± 79
		5.6 ± 2.0 [26]	450 ± 170
$\to J/\psi + \pi^0$		< 0.28 [22]	< 22
$\psi(2D)$	103 ± 3		
$\to J/\psi + \eta$		4.8 ± 2.0 [26]	500 ± 210
$\Upsilon(2S)$	$(31.98 \pm 2.63) \times 10^{-3}$		
$\to \Upsilon(1S) + \eta$		0.357 ± 0.033 [24]	0.114 ± 0.014
$\to \Upsilon(1S) + \pi^0$		< 0.041 [24]	< 0.013
$\chi_{b1}(2P) \to \Upsilon(1S) + \omega$	0.096 ± 0.016	$1.63^{+0.40}_{-0.34}$	$1.56^{+0.46}_{-0.42}$
$\chi_{b2}(2P) \to \Upsilon(1S) + \omega$	0.138 ± 0.019	$1.10^{+0.34}_{-0.30}$	$1.52^{+0.51}_{-0..46}$
$\Upsilon(3S)$	$(20.32 \pm 1.85) \times 10^{-3}$		
$\to \Upsilon(1S) + \eta$		< 0.1	< 2
$\Upsilon(4S)$	20.5 ± 2.5		
$\to \Upsilon(1S) + \eta$		0.196 ± 0.011	4.02 ± 0.54
$\Upsilon(5S)$	55 ± 28		
$\to \Upsilon(2S) + \eta$		3.8 ± 0.8	209 ± 115
$\to \Upsilon(1S) + \eta$		0.73 ± 0.20	40.2 ± 23.2

Single light hadron Transitions

- Ratios of transitions:
  - The ratio of eta to two pion transitions at $M_{\pi\pi} = M_\eta$ is independent of the details of the intermediate octet ($Q\bar{Q}$) states:

[kinematic factor]

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

  - The ratio of eta to neutral pion transitions are given by chiral perturbation theory,
  - The present experimenta status is shown in Table 3.

Table 3: Ratios of hadronic transitions. $R_{\eta/\pi\pi}$ is ratio of eta to two pion and $R_{\eta/\pi\pi}$ is ration of neutral pion to eta. All other notation as in Table 2.

Initial State	Final State	$R_{\eta/\pi\pi}$(in units 10^{-1})	$R_{\pi^0/\eta}$(in units 10^{-2})
ψ'	J/ψ	1.00 ± 0.02	$3.74 \pm 0.17(stat) \pm 0.04(syst)$ [23]
ψ(1D)	J/ψ	4.5 ± 2.2	< 32
$\psi(3S)$	J/ψ	10 ± 2	
Υ(2S)	Υ(1S)	$0.199 \pm 0.018(stat) \pm 0.11(syst)$ [24]	< 13 [24]
Υ(3S)	Υ(1S)	< 0.023	
Υ(4S)	Υ(1S)	24.0 ± 2.2	
Υ(5S)	Υ(2S)	4.8 ± 1.2	
	Υ(1S)	1.6 ± 0.5	

More puzzles

- Within the KY model the ratio $R_{\eta/\pi\pi}$ is fixed for all transitions (n->m) once one is fixed.

  From the $\Upsilon(2S)$ -> $\Upsilon(1S)$ transitions set the value of $|C3/C1|$ = 0.143 ± 0.024 0.143 ± 0.024

Table 4: Comparison of theory (KY model) nd experiment for $R_{\eta/\pi\pi}$

$R_{\eta/\pi\pi}(^3S_1(n) \rightarrow ^3S_1(m))$ $(Q\bar{Q})n \rightarrow m$	theory	experiment	
$(c\bar{c}) : 2 \rightarrow 1$	3.39×10^{-3}	1.0×10^{-1}	~ 30 x theory
$(c\bar{c}) : 3 \rightarrow 1$	6.35×10^{-3}	1.0	
$(b\bar{b}) : 2 \rightarrow 1$	1.99×10^{-2}	1.99×10^{-2}	input
$(b\bar{b}) : 3 \rightarrow 1$	4.57×10^{-3}	$< 2.3 \times 10^{-2}$	suppressed ?
$(b\bar{b}) : 4 \rightarrow 1$	2.23×10^{-3}	24	~ 1000 theory
$(b\bar{b}) : 5 \rightarrow 1$	9.58×10^{-4}	4.8	~ 2000 x theory
$(b\bar{b}) : 5 \rightarrow 2$	5.33×10^{-3}	1.6	~ 300 x theory

- The eta transitions are very poorly described by this model if initial state is near or above threshold.

Hadronic Transitions Above Threshold

- Quarkonium states above threshold have strong decays to pairs of heavy flavor mesons H + $\overline{\text{H}}$'
  - The thresholds

L=0 $b\bar{q}\ [j_l^P = \frac{1}{2}^-]$

Meson	Mass (MeV/c^2)	Width (eV)
B^-	5279.15 ± 0.31	$(4.02 \pm 0.03) \times 10^{-4}$
$\bar{B}^0$	5279.53 ± 0.33	$(4.30 \pm 0.03) \times 10^{-4}$
$\bar{B}_s^0$	5366.3 ± 0.6	$(4.48 \pm 0.08) \times 10^{-4}$
B^{*-}	5325.1 ± 0.5	780 [21]
$\bar{B}^{*0}$		240 [21]
$\bar{B}_s^{*0}$	5412.8 ± 1.3	150 [21]

L=1 $b\bar{q}\ [j_l^P = \frac{1}{2}^+]$

Meson (J^P)	Mass (MeV/c^2)	Width (MeV)
$B^{*-}(0^+)$	5730 (a)	270 (a)
$\bar{B}^{*0}(0^+)$	5730 (a)	270(a)
$\bar{B}_s^{*0}(0^+)$	5716	0.080 [21]
$B^-(1^+)$	5740 (a)	270 (a)
$\bar{B}^0(1^+)$	5740 (a)	270 (a)
$\bar{B}_s^0(1^+)$	5763	0.118 [21]

$b\bar{q}\ [j_l^P = \frac{3}{2}^+]$

Meson (J^P)	Mass (MeV/c^2)	Width (MeV)
$B^-(1^+)$	5725.3	15 (a)
$\bar{B}^0(1^+)$	$5725.3\ ^{+2.1}_{-2.7}$ [22]	15 (a)
$\bar{B}_s^0(1^+)$	5829.4 ± 0.7	0.002 (a)
$B^{*-}(2^+)$	5740.2	22.7
$\bar{B}^{*0}(2^+)$	$5740.2\ ^{+1.9}_{-2.0}$ [22]	$22.7\ ^{+5.0}_{-10.7}$ [22]
$\bar{B}_s^{*0}(2^+)$	5839.7 ± 0.6	$1.1(a)$

Narrow Thresholds

$B\bar{B}$	10,558	
$B\bar{B}^* + B^*\bar{B}$	10,606	
$B^*\bar{B}^*$	10,650	
$B_s\bar{B}_s$	10,733	F
$B_s\bar{B}_s^* + \bar{B}_s B_s^*$	10,779	
$B_s^*\bar{B}_s^*$	10,825	
$B\bar{B}(1^+) + B(1^+)\bar{B}$	11,004	
$B\bar{B}(2^+) + B(2^+)\bar{B}$	11,019	D
$B^*\bar{B}(1^+) + B(1^+)\bar{B}^*$	11,050	
$B^*\bar{B}(2^+) + B(2^+)\bar{B}^*$	11,065	
$B_s\bar{B}_s(1^+) + B_s(1^+)\bar{B}_s$	11,129	
$B_s^*\bar{B}_s(0^+) + B_s(0^+)\bar{B}_s^*$	11,129	S
$B_s^*\bar{B}_s(1^+) + B_s(1^+)\bar{B}_s^*$	11,176	
$B_s\bar{B}_s(1^+) + B_s(1^+)\bar{B}_s$	11,196	
$B_s\bar{B}_s(2^+) + B_s(2^+)\bar{B}_s$	11,206	D
$B_s^*\bar{B}_s(1^+) + B_s(1^+)\bar{B}_s^*$	11,232	
$B_s^*\bar{B}_s(2^+) + B_s(2^+)\bar{B}_s^*$	11,253	
...		

wide $B^*B(0^+)$,$B^{(*)}B'(1^+)$,... S

Narrow Thresholds

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

Broad Thresholds

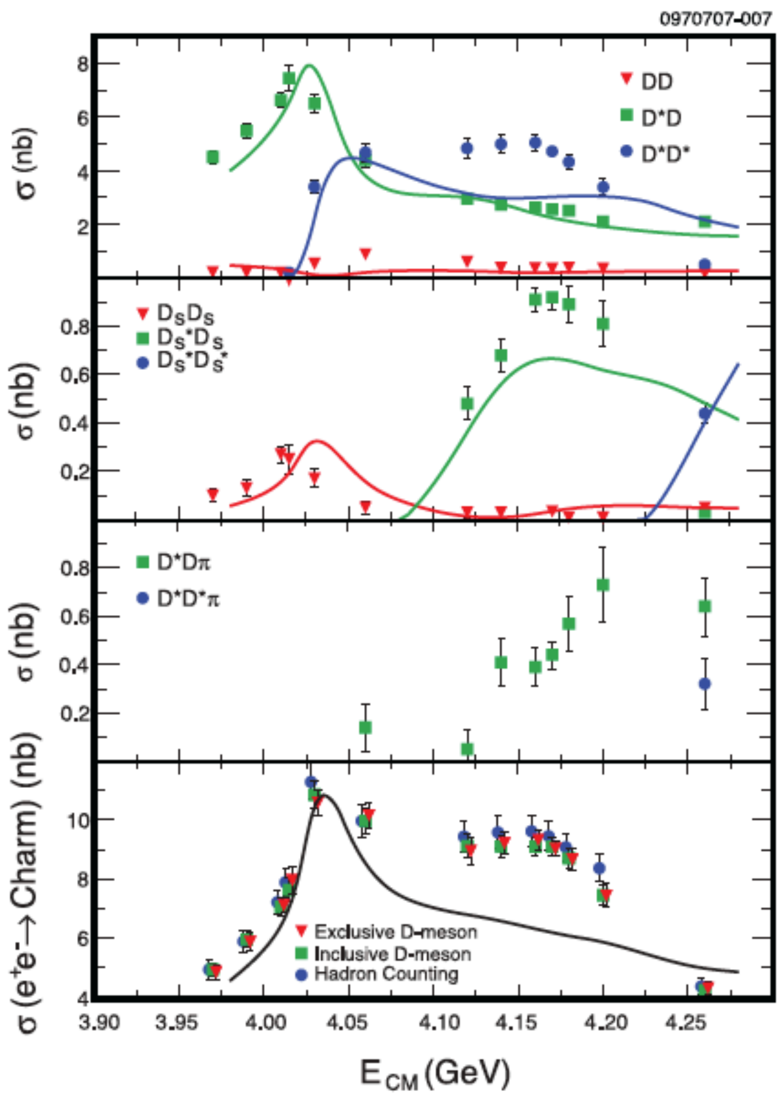
*D*D(0+)*	4,270	
D D'(1+)	4,270	S-wave
*D*D'(1+)*	4,430	
...		

Hadronic Transitions Above Threshold

- The physical states are mixtures of the naive quarkonium (QQ) and the four quark states ($\bar{Q}q\bar{q}Q$)
  - Above threshold the fraction of time the state is in the virtual four quark sector is large and therefore hadronic transitions from these system must be considered.
  - For hadronic transitions this is a critical difference.
  - The four quark system dominated by the H+H' configuration at least for large QQ separation. For smaller QQ separation dynamics more complicated.
  - Need a model of the detailed contributions of various H+H' states. (Cornell model for me).
- Effect on the QCDME expansion
  - In the heavy quark symmetry limit, the H + H' states would not violate the expectation that (E1-M1) and (E1-M2) transitions are suppressed. (general theorem)
  - BUT the spin splitting within a HQS multiplet induces a large heavy quark spin flip contribution. Invalidates the QCDME. No suppression.
  - The general conclusion is not model dependent: For H $(1/2)^-$ ground states (D,D*) and (B,B*). In HQS limit HH, HH*+H*H, H*H* decay ratios are 1:4:7 (0.083: 0.33: 0.58)
    - measured ratio at the $\Upsilon(5S)$: 0.096:0:24.66 (B) 0.0:0.08;0.92 (B_s)
    - measured ratios in the charm threshold region studied in detail (see figure)
- Eta transitions not suppressed relative to two pion transitions above threshold.

Hadronic Transitions Above Threshold

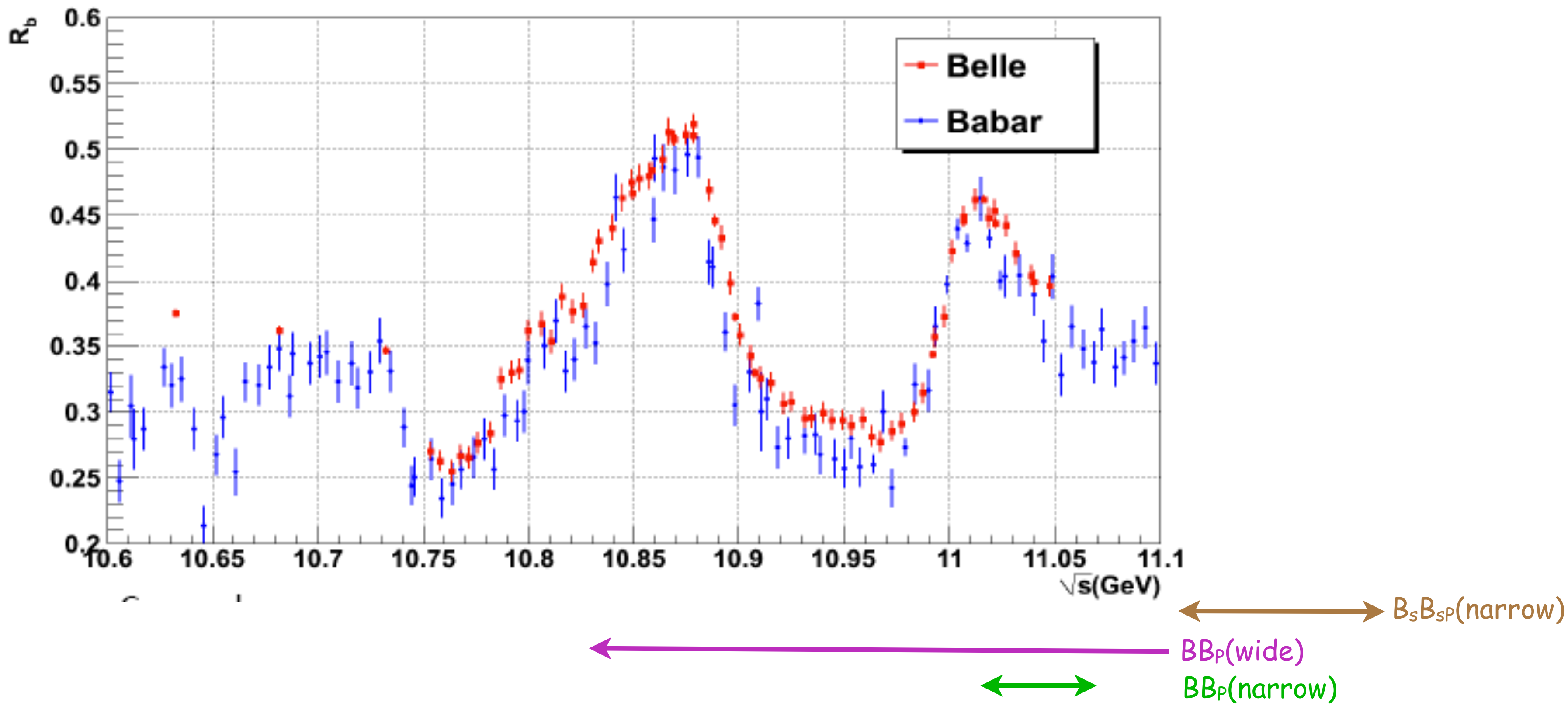
- Charm threshold region has very large induced HQS breaking effects



Evidence of strong production of $D^{(*)} D\rho$ at the $\psi(4160)$

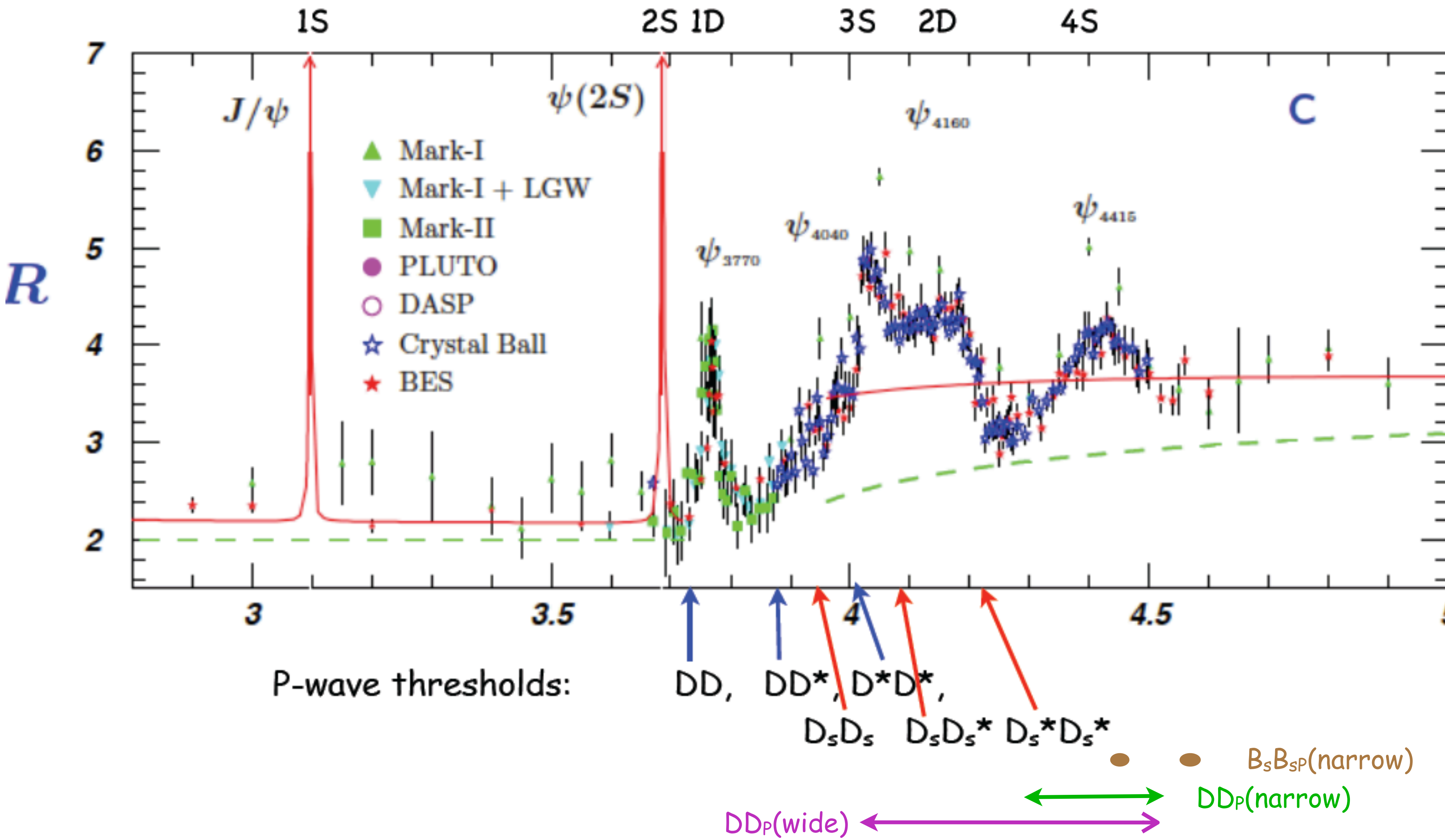
Structure in two pion transitions

- What happened to decays into heavy-light P state H(1P) $j^P=(1/2, 3/2)^+$ and a ground state H(1S) $j^P=(1/2)^-$?
  - For the bottomium region the narrow B(1P) states have thresholds in the $\Upsilon(6S)$ while the influence of the wide states entend into the $\Upsilon(5S)$ region and above.



Structure in two pion transitions

- For the charm threshold region the narrow D(1P) states have thresholds around 4260 MeV to the ψ(4S) region, while influence of the wide states extends down to the ψ(3S)



Structure in two pion transitions

- S-wave decays should be very strong near threshold. D-wave decays weaker.

TABLE VI. Systematics for decays containing charmed P states. Here j_L is the total angular momentum of the light-quark constituent of D_P as seen in the rest frame of c.

Final state	Threshold behavior	Statistical factor
$D\bar{D}_{P_0}$	Forbidden	...
$D\bar{D}_{P_1}$ $(j_L=\frac{1}{2})$	S-wave	$\frac{2}{3}$
$D^*\bar{D}_{P_0}$	S-wave	$\frac{2}{3}$
$D^*\bar{D}_{P_1}$ $(j_L=\frac{1}{2})$	S-wave	$\frac{4}{3}$
$D\bar{D}_{P_2}$	D-wave	$\frac{2}{3}$
$D\bar{D}_{P_1}$ $(j_L=\frac{3}{2})$	D-wave	$\frac{2}{3}$
$D^*\bar{D}_{P_1}$ $(j_L=\frac{3}{2})$	D-wave	$\frac{4}{3}$
$D^*\bar{D}_{P_2}$	D-wave	$\frac{8}{3}$

Eichten, et.al,
PR D17, 3090 (1978)

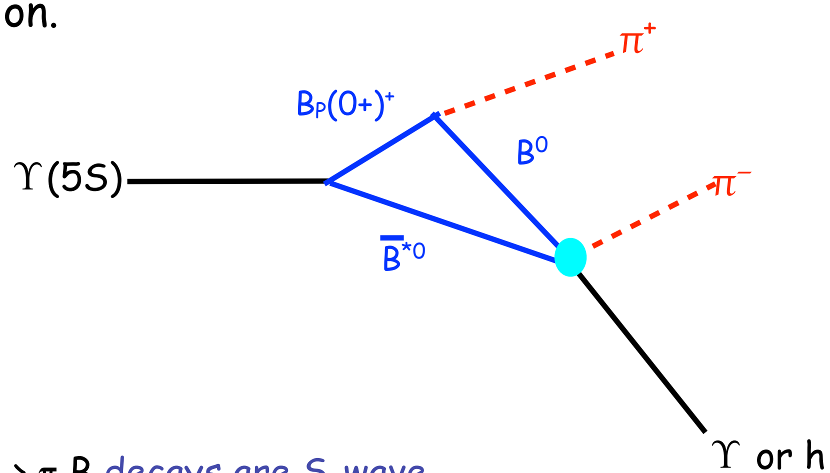
Structure in two pion transitions

- For example, the $\Upsilon(5S)$ 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.

$\Upsilon(5S) \to Bp(0+)\ B^* \to \pi\ B\ B^*$

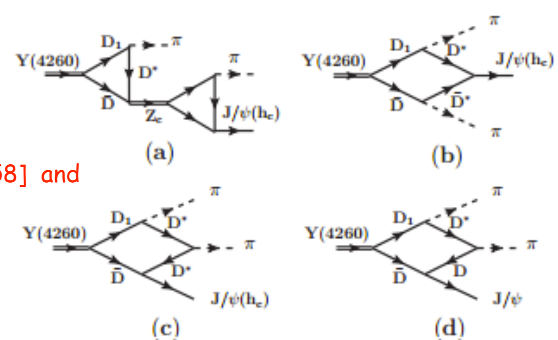
and $Bp(1+)\ B \to \pi\ B\ B^*$

and $Bp(1+)\ B^* \to \pi\ B^* B^*$

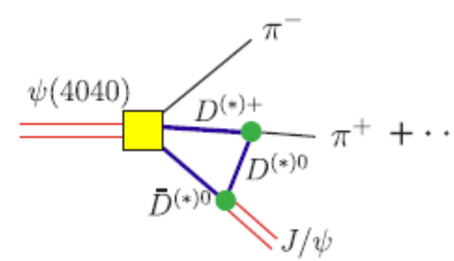


  - Both the $\Upsilon(5S) \to Bp(0+)\ B^*$ and $Bp(0+) \to \pi\ B$ decays are S-wave
  - The analogy in the charmonium system is the structure seen in the $\psi(4160) \to \pi\ \pi\ J/\psi$ transition.
  - This provides a dynamical mechanism for the Meson Loop and ISPE models.

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



ISPE Model: [1303.6842] and references therein

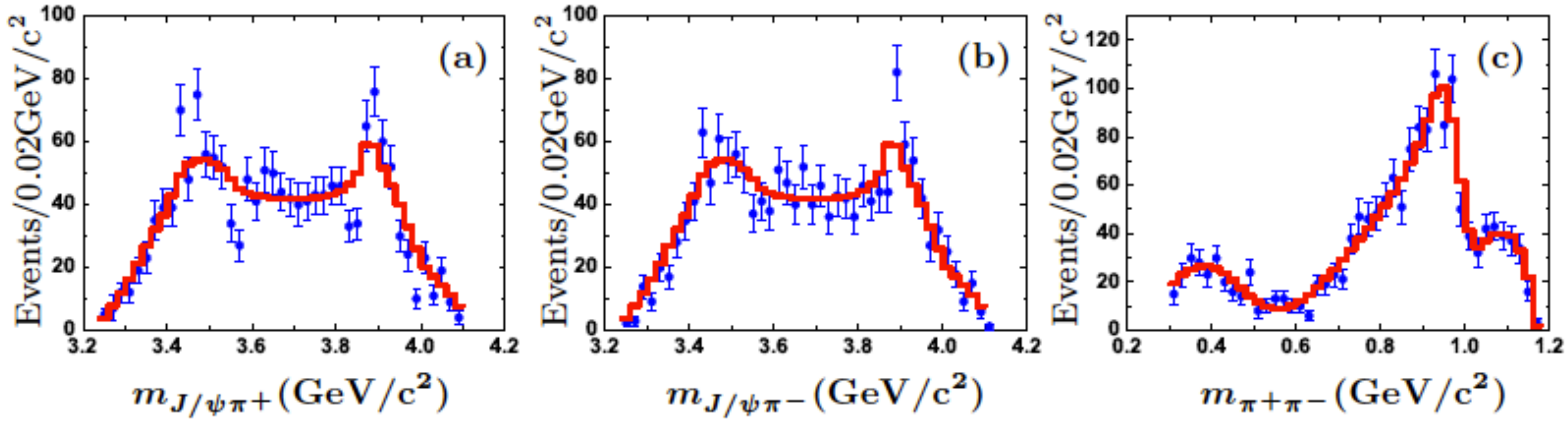


Structure in two pion transitions

- Chen, Lui and Matsuki applied the ISPE model to the Y(4260) -> $\pi\,\pi\,\psi$ transition.

- They were able to reproduce the structure observed in those transitions.

D.Y. Chen, X, Lui and T. Matsuki [1304.5845]



- Thus the nature (cusp or molecule) of the $Z^+(10610)$, $Z+(10650)^+$ and newly observed $Z^+(3900)$ state is open.

- There is an extraordinary rich structure of decays into a heavy-light P state $H_q(1P)$ $j^P=(1/2, 3/2)^+$ and a ground state $H_q(1S)$ $j^P=(1/2)^-$ (q=u,d,s) at and above the ψ(4S) in the charm sstem and Υ(6S) in the bottom system.

- The study of these channels will provide detailed information about the decay strengths and the associated hadronic transitions.

Summary

- The hadronic transitions for states below strong decay threshold are well described by the usual QCD Multipole Expansion except for:
  - The $\Upsilon(3S) \to \Upsilon(1S)\ \pi\pi$ and $\Upsilon(4S) \to \Upsilon(2S)\ \pi\pi$ transitions. Here It is not understood why the $M_{\pi\pi}$ distributions not the expected S-wave behaviour.
- Above heavy flavor production threshold the QCDME fails.
  - 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 surpressed.
  - A new mechanism for hadronic transitions is required.to explain the large rates
- For 1^{--} quarkonium states above threshold the opening of strong S-wave decays into a ground state $\frac{1}{2}^-$ $(0^-, 1^-)$ and a excited P-wave $\frac{1}{2}^+$ $(0^+, 1^+)$ heavy-light mesons needs to be taken into account to understand the structure of hadronic transitions. This occurs around the
  - $\psi(2D)$ in the $(c\bar{c})$ system.
  - $\Upsilon(5S)$ in the $(b\bar{b})$ system
- With BES III and LHCb and soon BELLE 2. I expect much progress in understanding hadronic transitions in the near future.

BACKUP SLIDES

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

- BELLE has 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) transitions [arXiv:1105.4583]

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}	$255^{+56+12}_{-72-183}$	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	–

- $\Upsilon(5S) \to Z_b^+ + \pi^-$ and $Z_b \to h_b(nP) + \pi^+$.
- Explicitly violates the factorization assumption of the QCDME.
- Clear evidence for four quark molecular states if confirmed
- The $Z_b^{\pm}$ (10610) is a narrow state (Γ = 15.6 ± 2.5 MeV) at the BB* threshold (10605).
- The $Z_b^{\pm}$ (10650) is a narrow state (Γ = 14.4 ± 3.2 MeV) at the B*B* threshold (10650).