

Spectroscopy Theory: Surprises and Opportunities

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Flavor Physics and *CP* Violation
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Outline

- The Threshold Region:
 - $(c\bar{c})$ and $(b\bar{b})$ states
 - Strong Decays Near Threshold
- New states, XYZ, ...
- Unexplored Territory
- Conclusions

QCD with Heavy Quarks

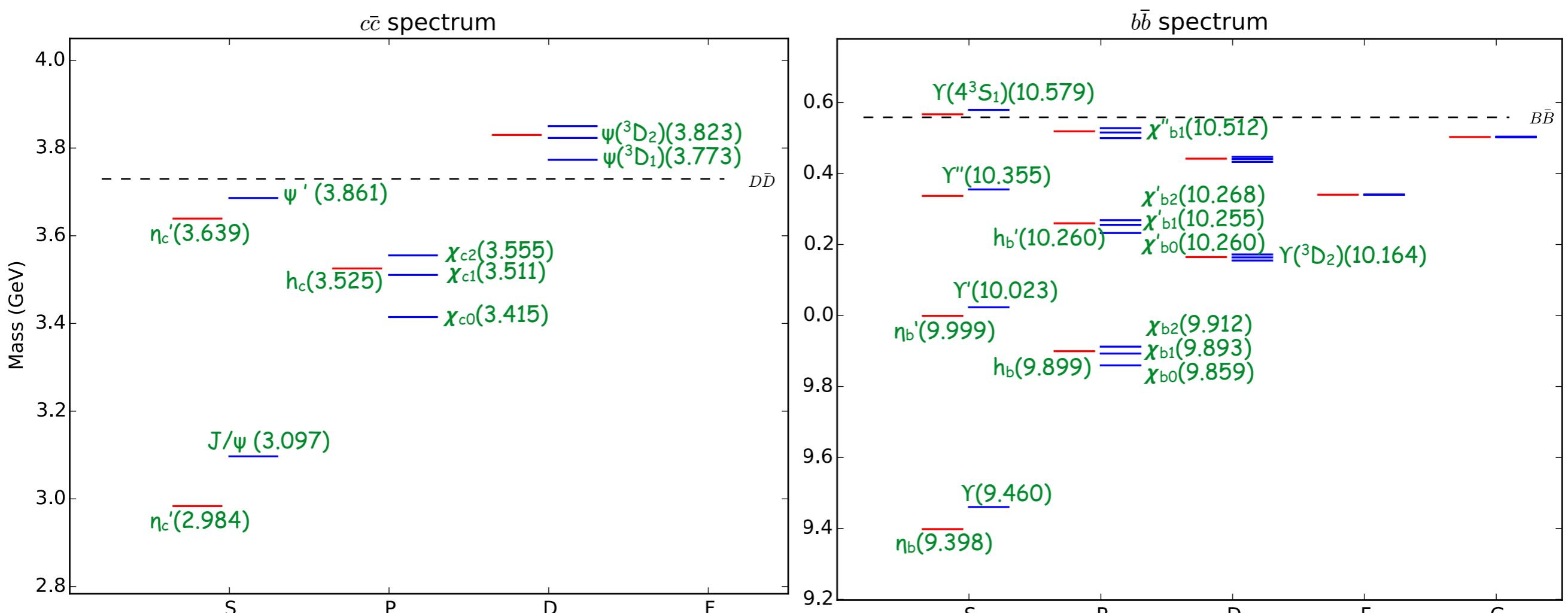
- QCD dynamics greatly simplifies for heavy quarks ($m_Q \gg \Lambda_{\text{QCD}}$)
- For systems with heavy quarks and light quarks:
 - HQET: systematic expansion in powers of Λ_{QCD}/m_Q
 - Heavy-light systems: $(c\bar{q})$, $(b\bar{q})$, (cqq) , (bqq) , (ccq) , (cbq) , (bbq) for $q=u,d$ or s
 - HQS relations between excitation spectrum in $[(c\bar{q}), (b\bar{q}), (ccq), (bcq) \text{ and } (bbq)]$ and between $[(cqq) \text{ and } (bqq)]$
 - QED analog - hydrogen atom (e^-p)
- For nonrelativistic ($Q\bar{Q}$): bound states form with masses M near $2m_Q$:
 - NRQCD: systematic expansion in powers of v/c
 - Quarkonium systems: $(c\bar{c})$, $(b\bar{b})$, $(b\bar{c})$
 - heavy quark velocity: $p_Q/m_Q \approx v/c \ll 1$
 - binding energy: $2m_Q - M \approx m_Q v^2/c^2$
 - QED analogs - positronium (e^+e^-), (true) muonium ($\mu^-\mu^+$), muonium ($e^-\mu^+$)

Narrow States Below Threshold

- expected spectrum below threshold:

- Observed states (labeled)

S=0 —————
S=1 —————



- 2 narrow states still unobserved

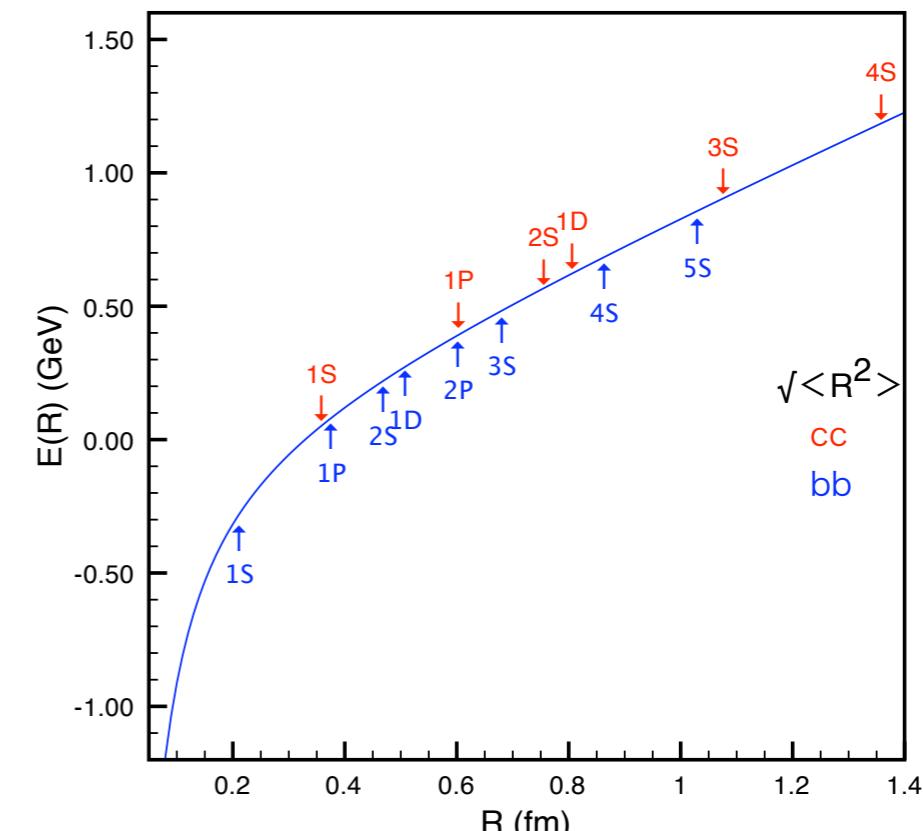
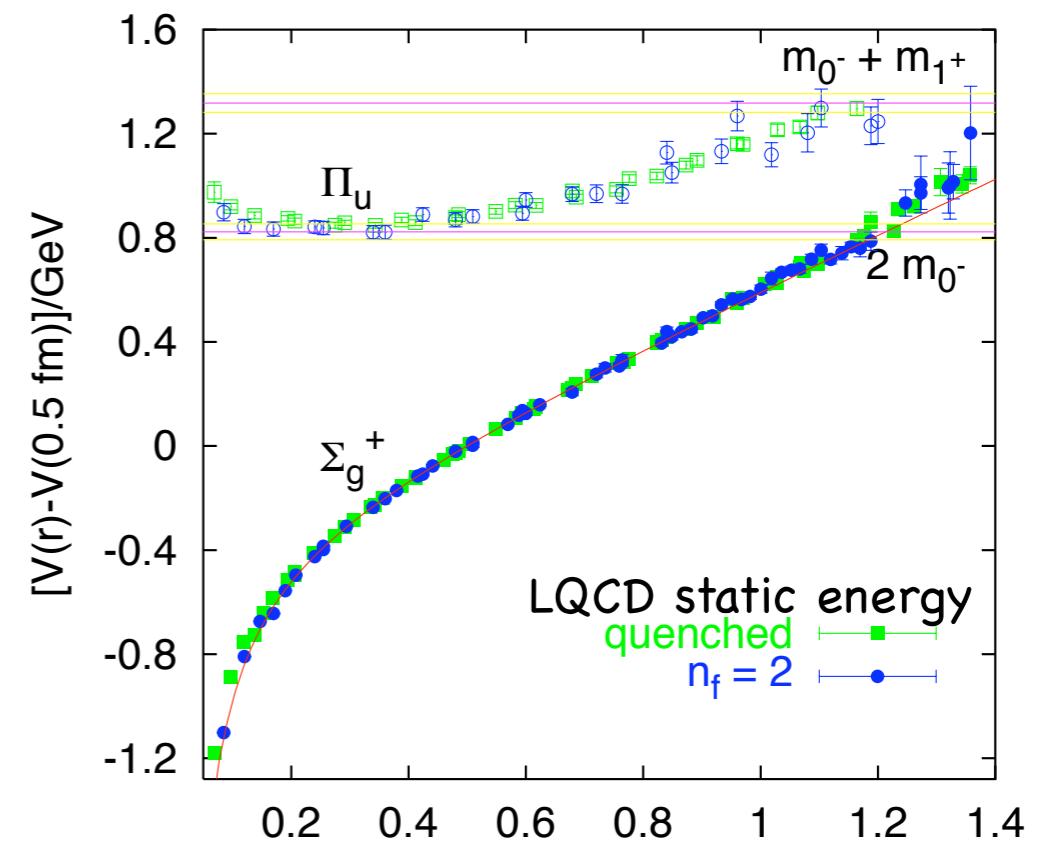
- 18 narrow states still unobserved

Why it works so well

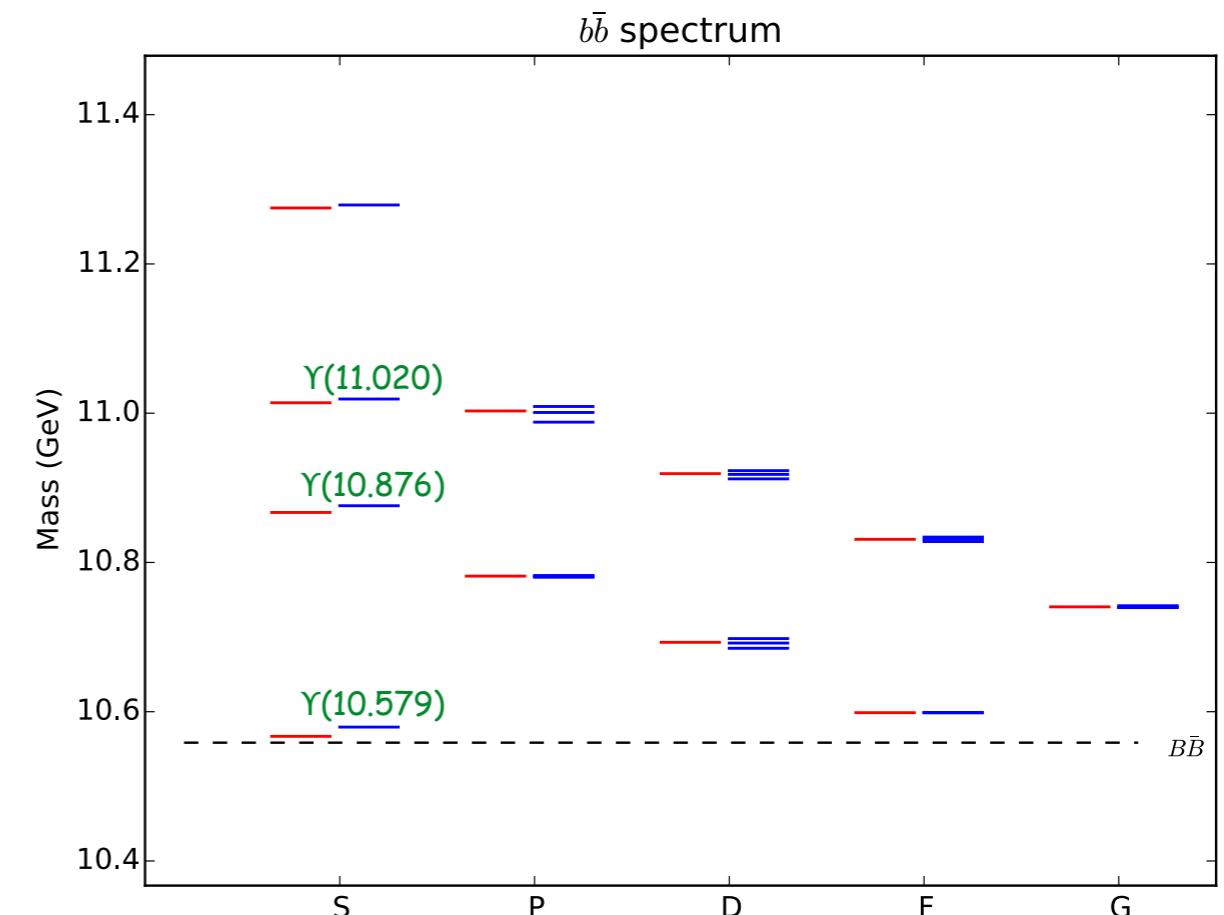
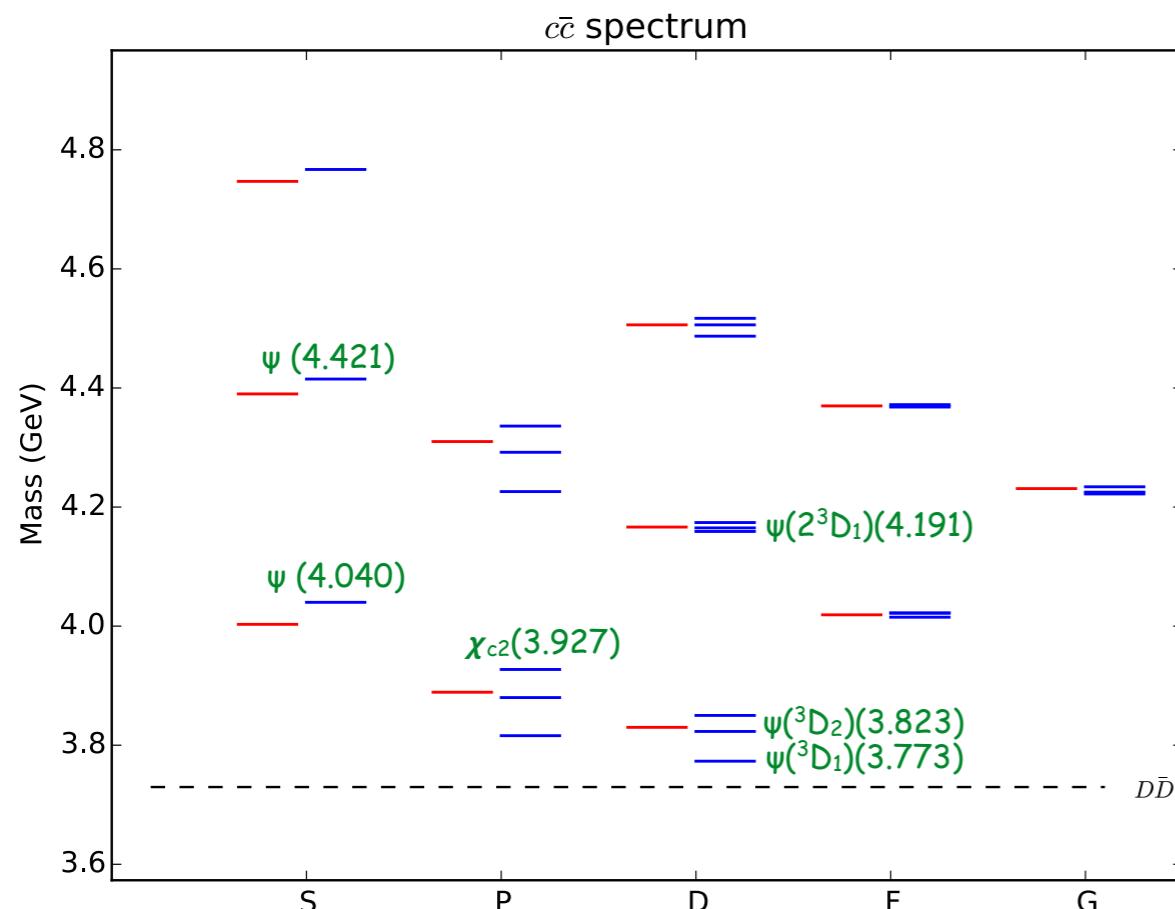
- Lattice calculation $V(r)$, then SE

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

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



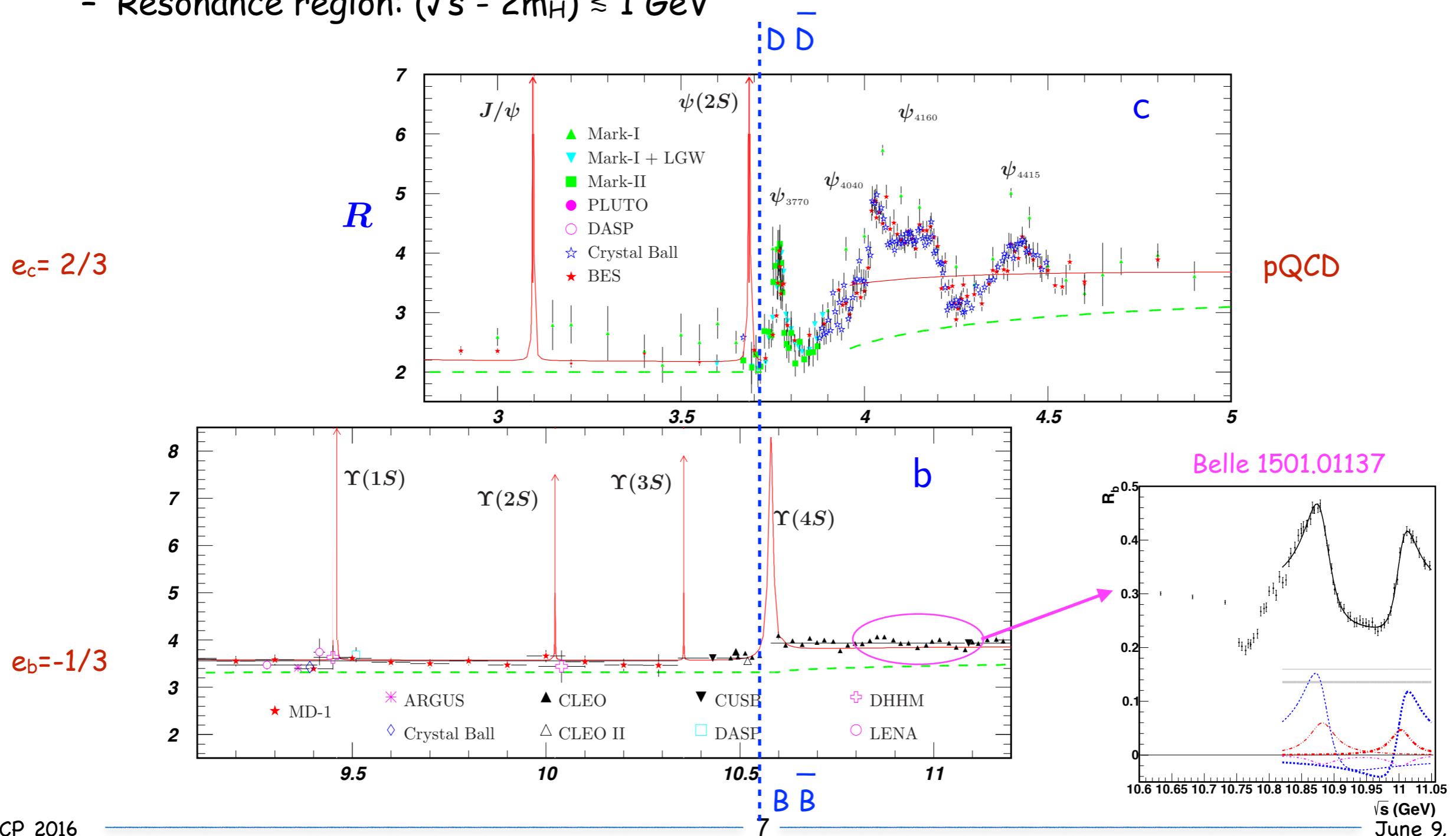
- Observed quarkonium states above threshold



Crossing the Threshold

1. Strong decays - resonances become wide and eventually hard to extract.

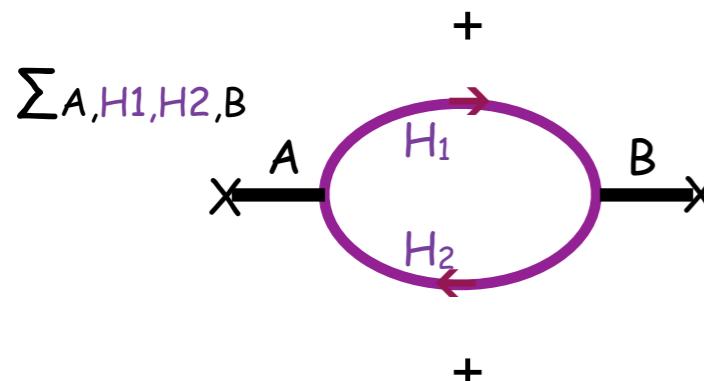
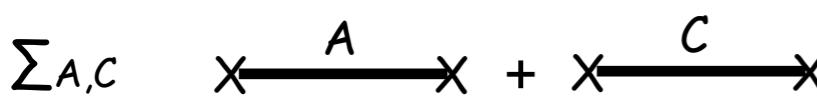
- $R = \sigma(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)$ $J^{PC} = 1^{--}$
- Resonance region: $(\sqrt{s} - 2m_H) \lesssim 1 \text{ GeV}$



- Two pictures of R: Quark-Hadron Duality

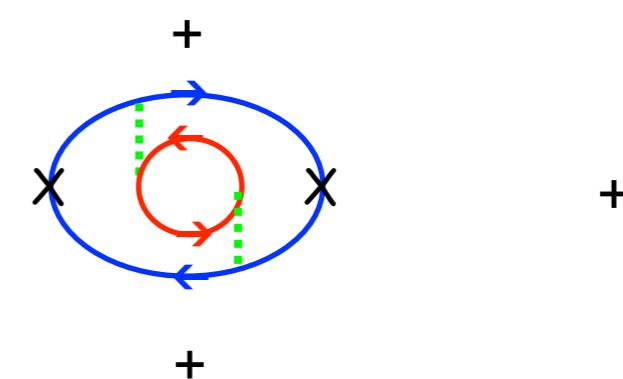
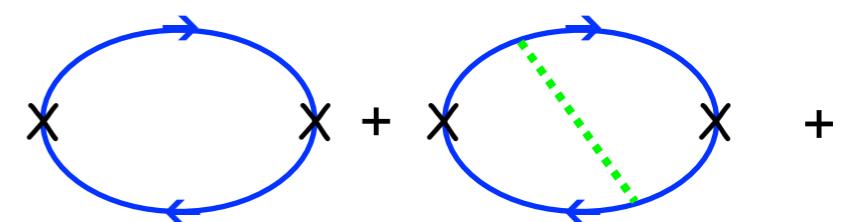
$$\begin{aligned}
 - \Delta R(W) = \frac{6\pi}{W^2} \rho_c(W) : & -(g_{\mu\nu} q^2 - q_\mu q_\nu) \rho_c(W) \\
 & = \int d^4x e^{iqx} \langle 0 | j_\mu(x) j_\nu(0) | 0 \rangle \Big|_{\text{charm}}
 \end{aligned}$$

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



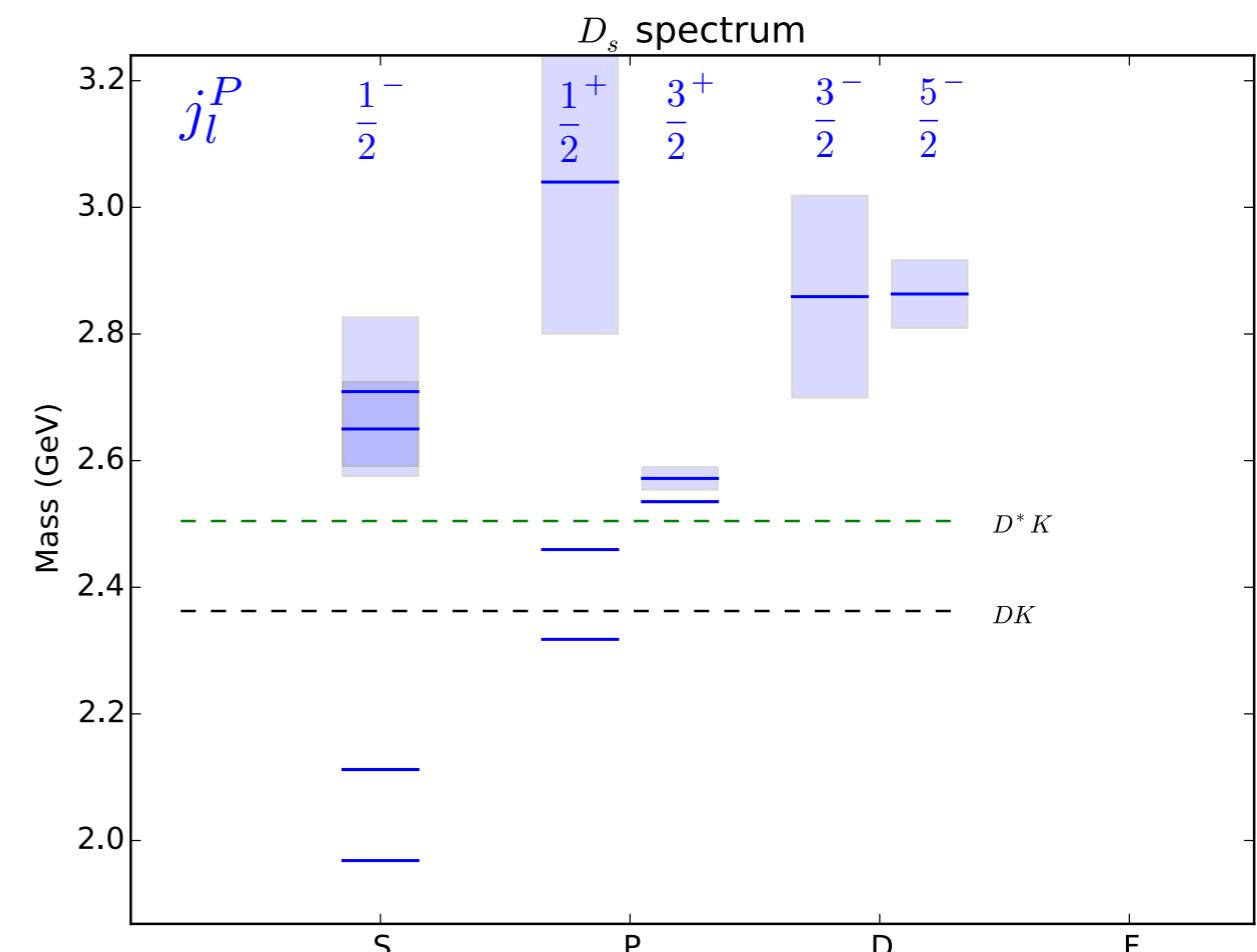
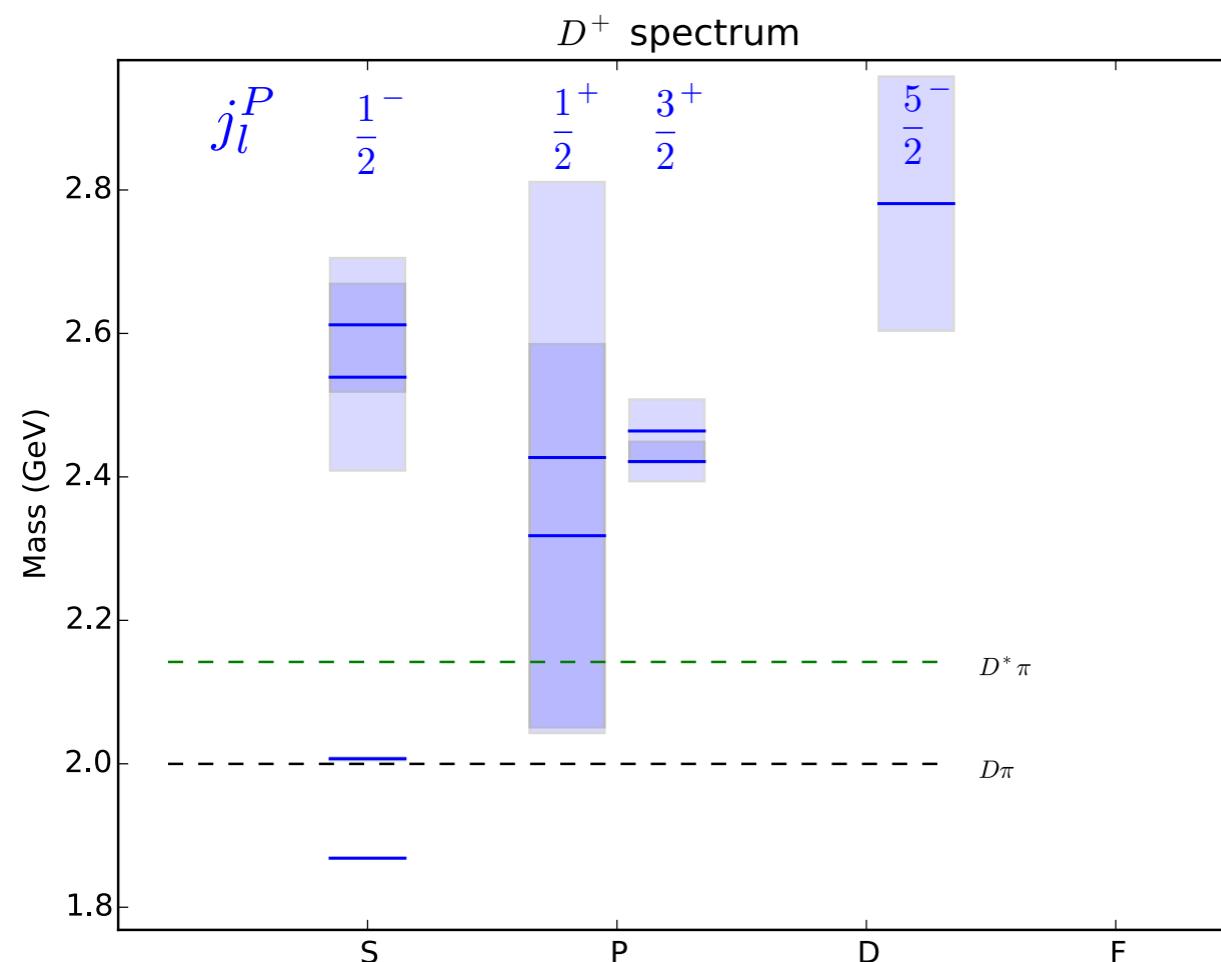
Simple expansion
near threshold.

QCD - perturbative
 Q, g



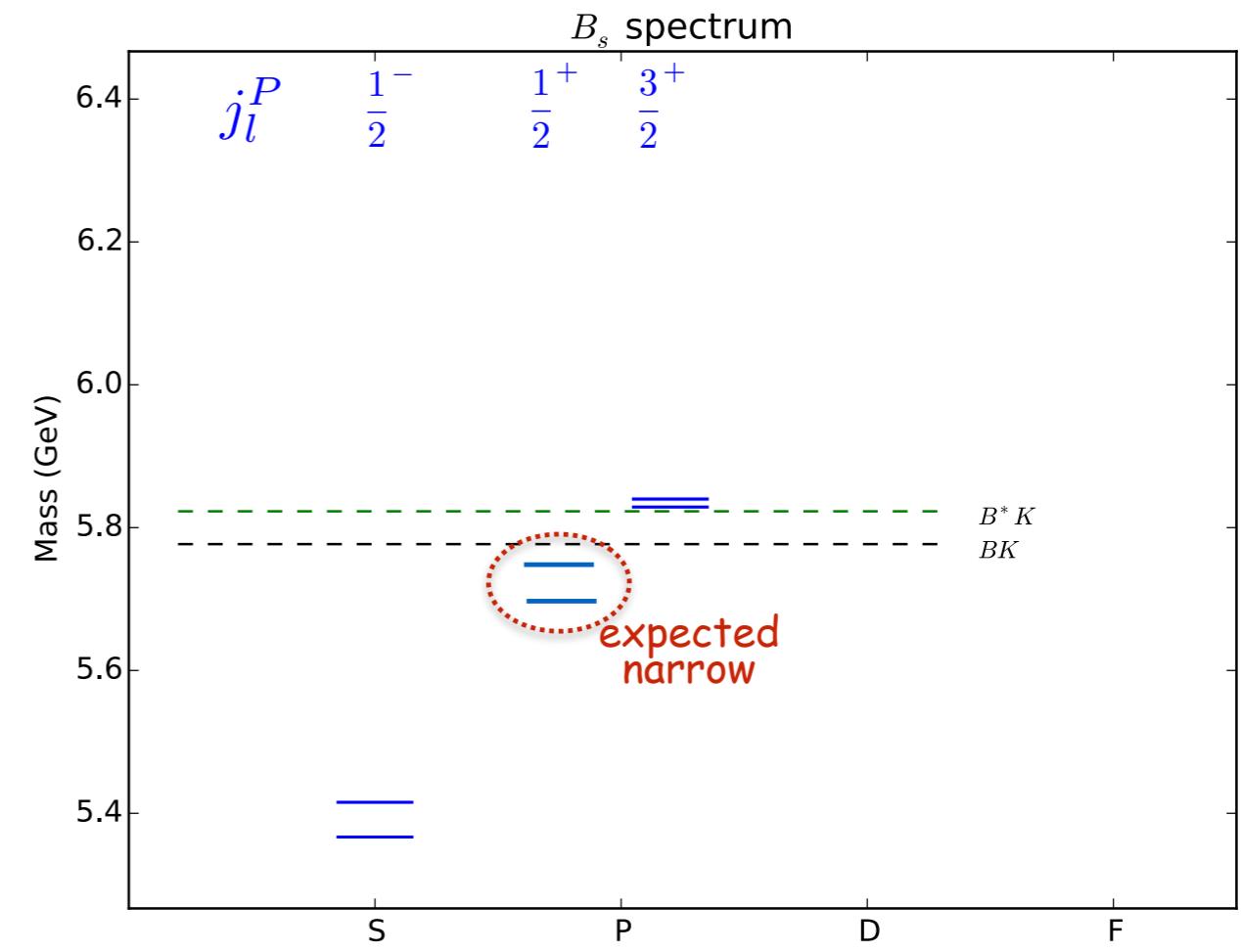
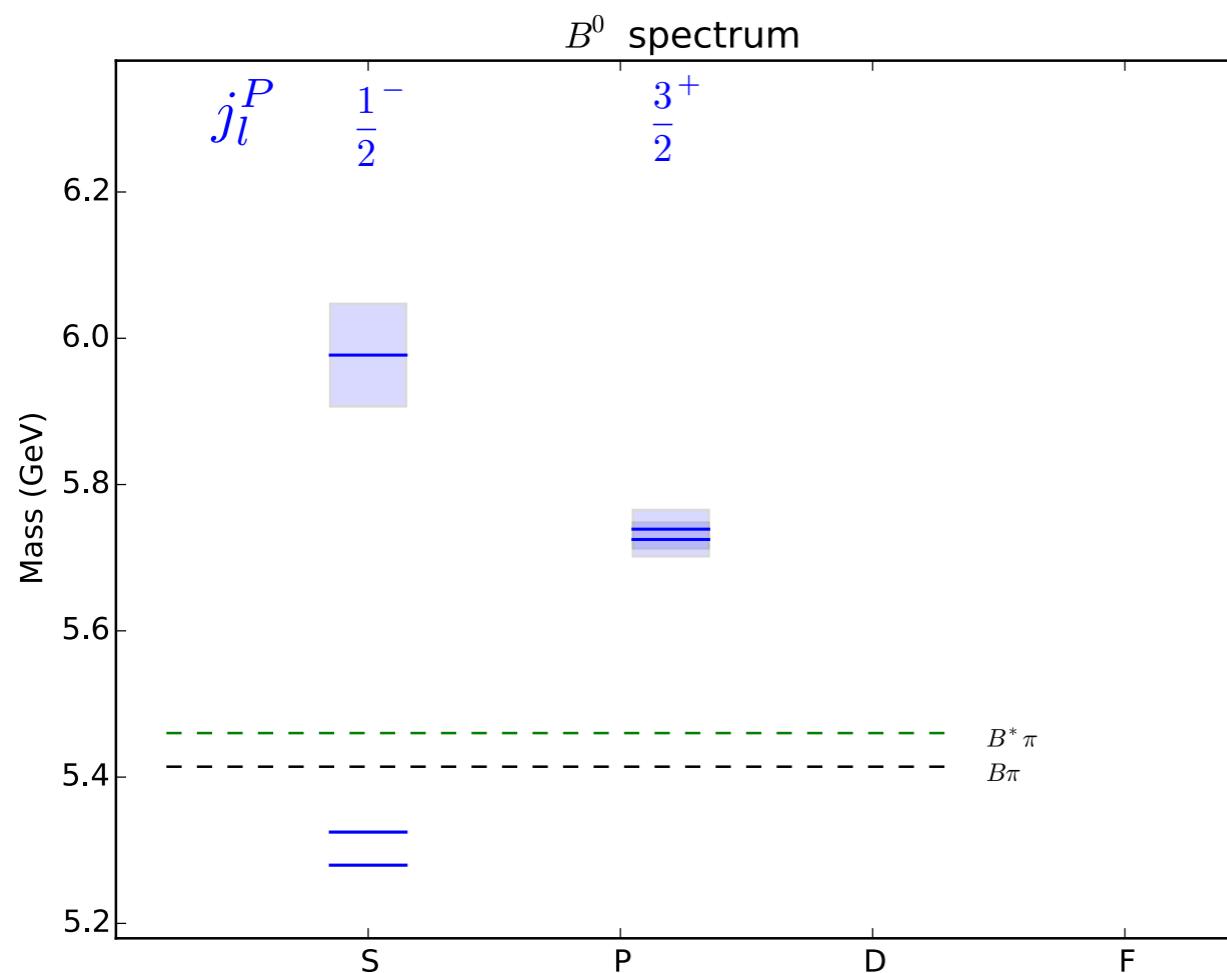
Simple expansion far
above threshold.

- Observed states in D meson systems:



- HQS determines the ratios of hadronic transitions - very useful in distinguishing excited states
- Various proposals for the shifts of the $D_s^*(2317)$ and $D_s(2460)$:
 - Influence of the nearby decay channels.
 - Chiral multiplets ($0^-, 0^+$).
 - Threshold bound states of DK and D^*K respectively.

- Observed states in the B meson systems

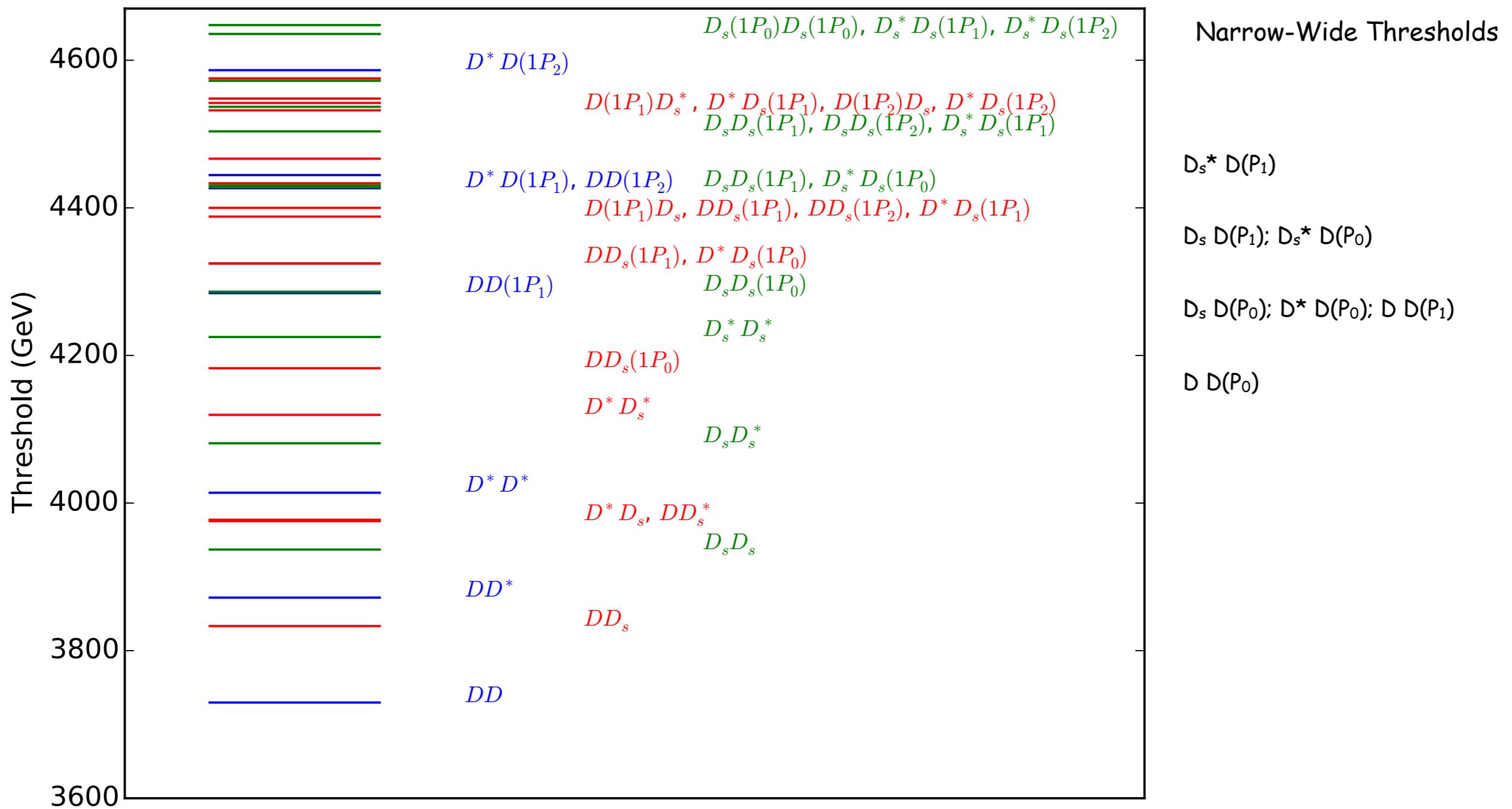


- HQS relates the excitation spectrum in the D system to the B system.
- Various models will be disentangled when the narrow B_s ($j^P = \frac{1}{2}^+$) states are observed.

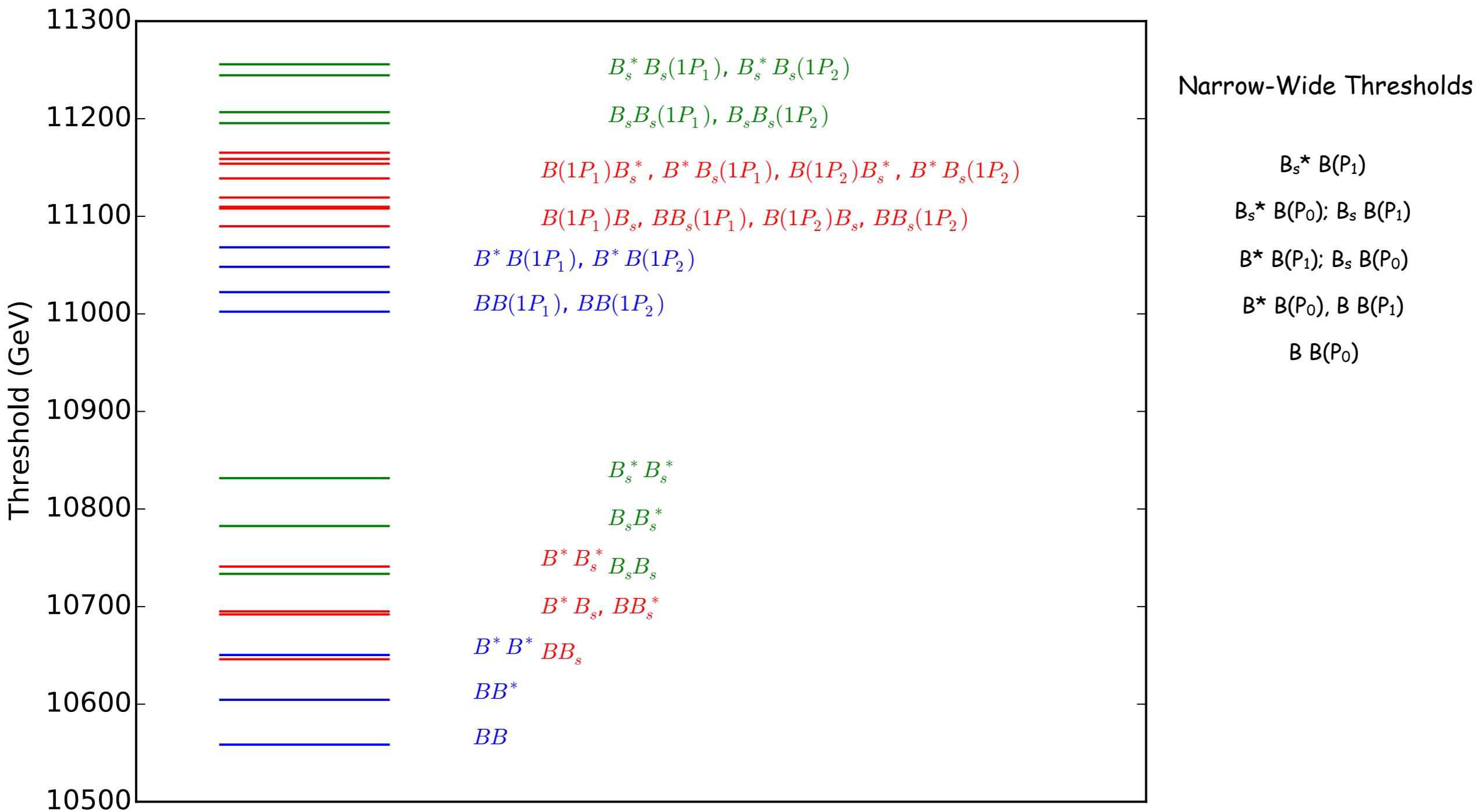
Important to observe the B_s ($j^P = \frac{1}{2}^+$) states

Low-lying thresholds

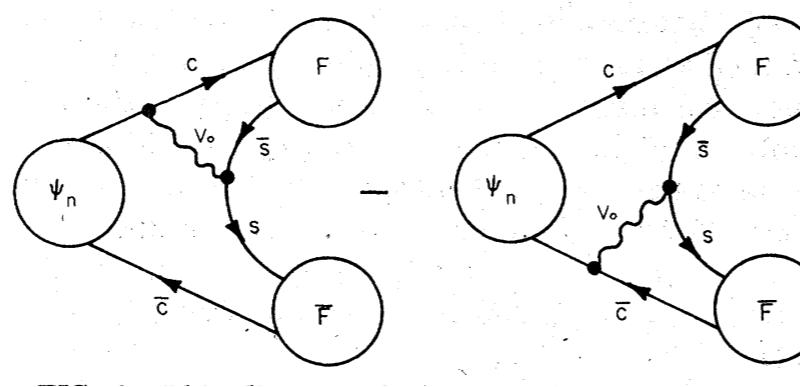
Low-lying (Narrow) Charm Meson Pair Thresholds



Low-lying (Narrow) Bottom Meson Pair Thresholds



- Coupled Channel Models
 - ψ_n potential model wavefunction
 - Final mesons - simple harmonic oscillator wave functions



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

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

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

where $H_{nL, mL'}^i(P) = f^2 \sum_l C(JLL'; l) I_{nL}^l(P) I_{mL'}^l(P)$

Statistical factor

Reduced decay amplitudes $I(p)$

- Reduced decay amplitudes $I(p)$

$$I_{nL}^l(P) = \int_0^\infty dt \Phi(t) R_{nL}(t\beta^{-1/2}) j_l(\mu_c \beta^{-1/2} Pt)$$

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

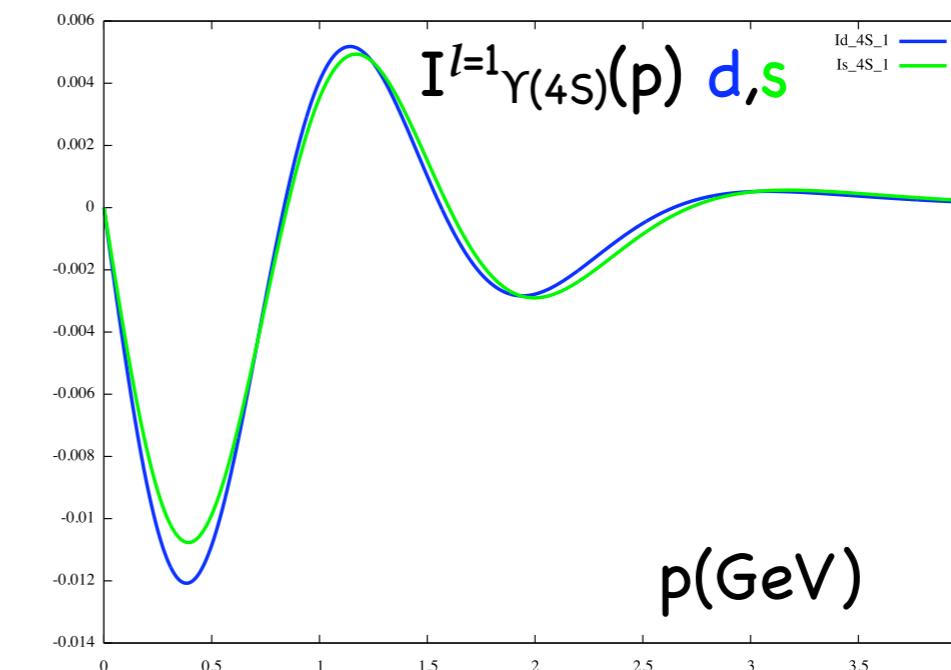
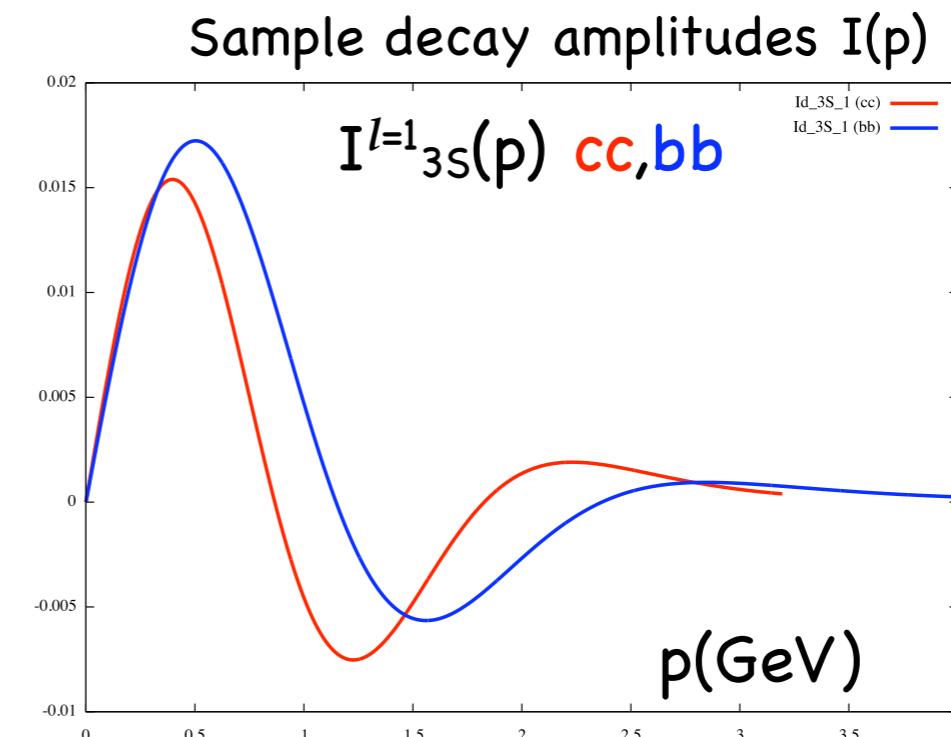
For the CCCM ($\kappa=0$): $(t = y\sqrt{\beta_S})$

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

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

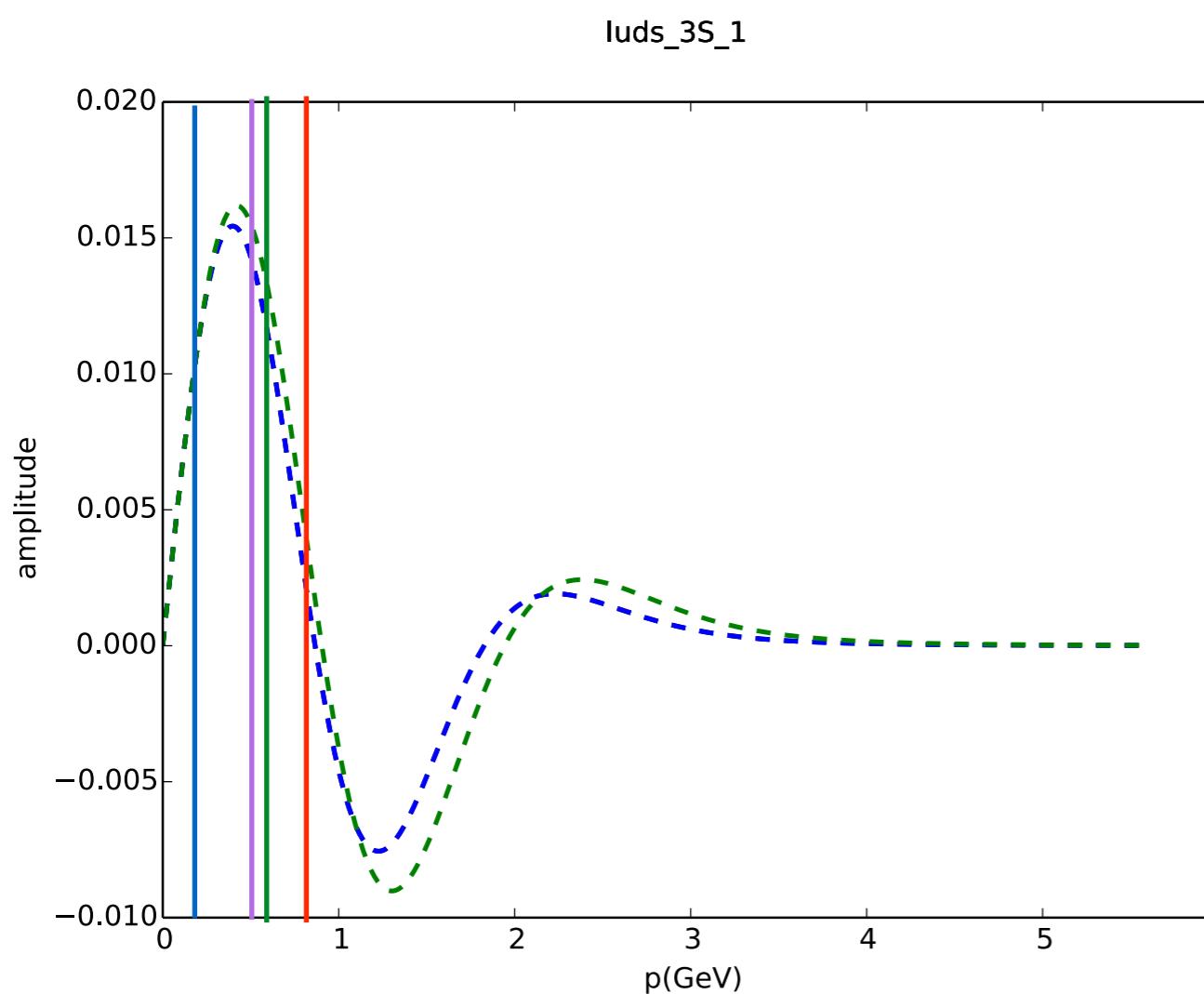
Apart from overall light quark mass factors $\Phi(t)$ is approximately SU(3) invariant. So independent of light quark flavor (u,d,s).

One universal function, $\Phi(t)$, determines R_Q in the threshold region.



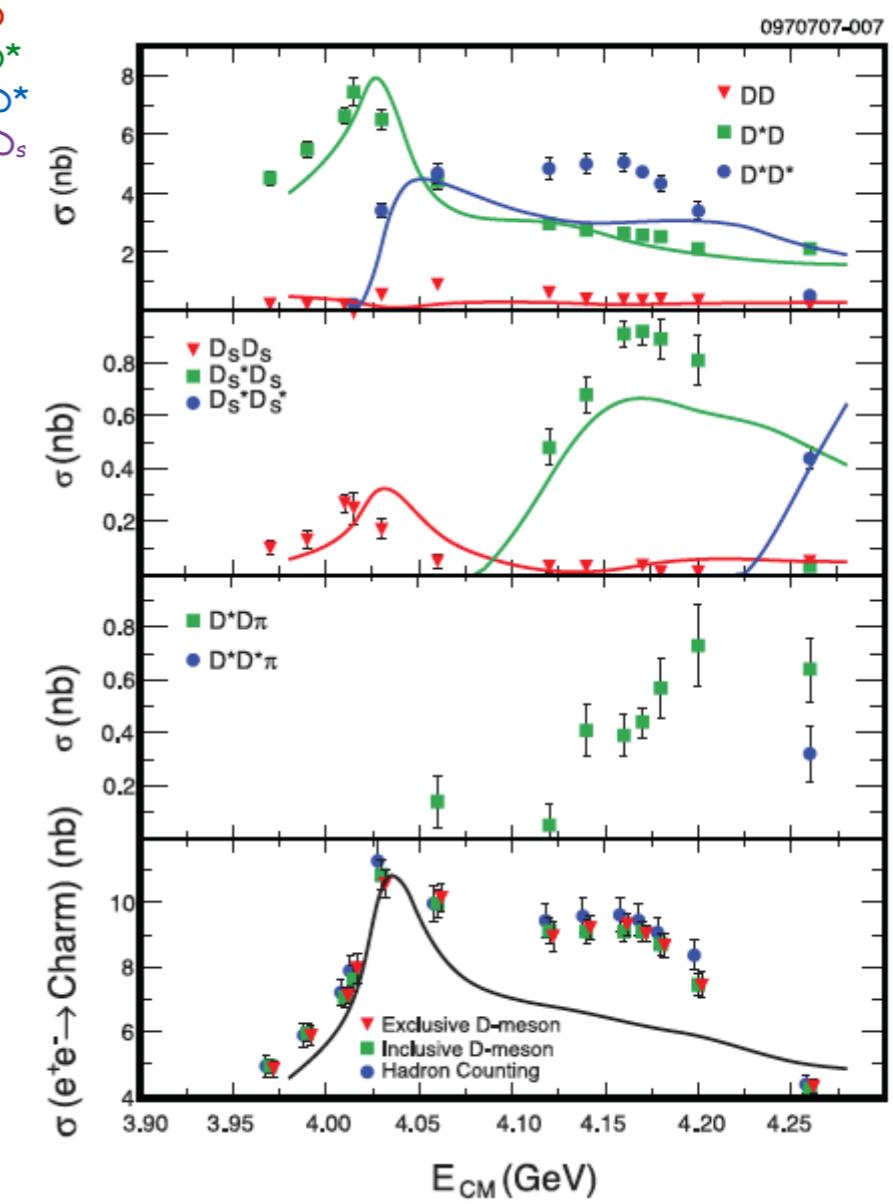
- The mass differences of heavy-light mesons produces large effects in the decay amplitudes to exclusive channels.

- $E = 4.04 \text{ GeV}$



- $p(DD) = 766 \text{ MeV}; p(D\bar{D}^*) = 567 \text{ MeV};$
 $p(D^*\bar{D}^*) = 218 \text{ MeV}; p(D_s\bar{D}_s) = 453 \text{ MeV}$

Observed exclusive channel rates



Hadronic Transitions Above Threshold

- There were two surprises in the decays of quarkonium states above threshold
 1. Hadronic transitions violate naive expectations. Spin flip transitions not suppressed (HQSS) and large SU(3) violation. For example, $\Upsilon(4S)$:

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 $B\bar{B}$	$> 96\%$		
$\Upsilon(1S) \pi^+\pi^-$	$(8.1 \pm 0.6) \times 10^{-5}$	→ partial rate = 1.66 ± 0.23 keV	expected rates
$\Upsilon(2S) \pi^+\pi^-$	$(8.6 \pm 1.3) \times 10^{-5}$		
$h_b(1P) \pi^+\pi^-$	(not seen)		
$\Upsilon(1S) \eta$	$(1.96 \pm 0.28) \times 10^{-4}$	→ partial rate = 4.02 ± 0.89 keV	SU(3) violating
$h_b(1P) \eta$	$(1.83 \pm 0.23) \times 10^{-3}$	→ partial rate = 37.5 ± 7.3 keV	HQS violating

- Large heavy quark spin symmetry (HQSS) breaking is 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 $\Upsilon(4S)$. This accounts for the observed violation of the spin-flip rules in hadronic transitions

- What about SU(3) ?

- SU(3) breaking is induced by the mass splitting of the ($Q\bar{q}$) mesons with $q=(u,d)$ 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 $\eta + (QQ)$.
- Similarly important in ω and ϕ production.

—
Yu.A. Simonov and A. I. Veselov
[arXiv:0810.0366]

The observed HQSS and SU(3) violation in hadronic decays of quarkonium states near threshold is induced by the symmetry breaking in the heavy-light meson masses

2. Second surprise is the large size of the hadronic transitions for some states above threshold.

- $\Upsilon(10860)$

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

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

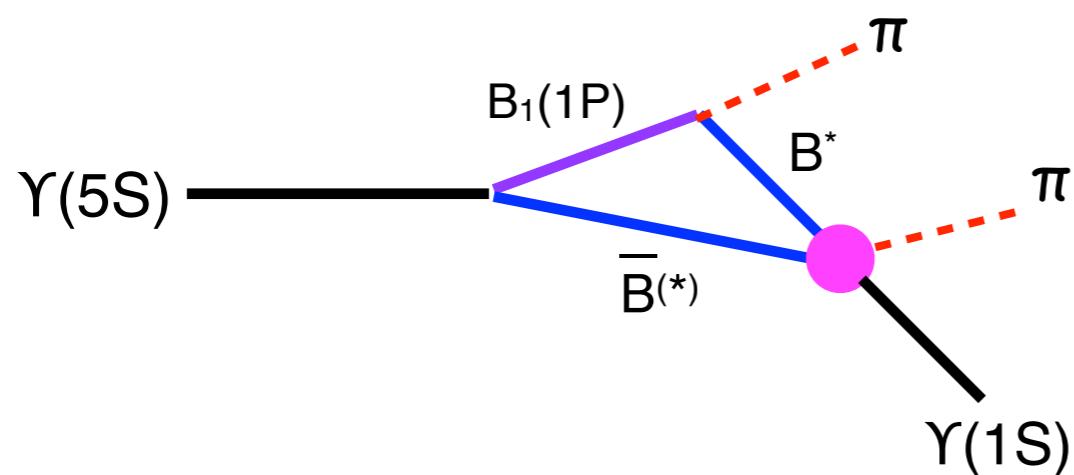
- Requires new mechanism for hadronic transitions

- Dominant two body decays of the $\Upsilon(5S)$
- Decays involving P-state heavy-light mesons:

- $n^3S_1(Q\bar{Q}) \rightarrow 1^{\frac{1}{2}+}P_J(\bar{Q}\bar{q}) + 1^{\frac{1}{2}-}S_{J'}(q\bar{Q})$ then
- $1^{\frac{1}{2}+}P_J(\bar{Q}\bar{q}) \rightarrow 1^{\frac{1}{2}-}S_{J'}(Q\bar{q}') + {}^1S_0(q\bar{q}')$ for S-wave $J=J'$

S-wave decays

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



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.

- These hadronic transitions seen at both the $\Upsilon(5S)$ and $\Upsilon(6S)$

HHChPT

$$H_a = \frac{1 + \gamma}{2} [\mathcal{D}_{a\mu}^* \gamma^\mu - \mathcal{D}_a \gamma_5],$$

$$S_a = \frac{1 + \gamma}{2} [\mathcal{D}'_\mu^{1a} \gamma_\mu \gamma_5 - \mathcal{D}_0^* a],$$

$$\mathcal{L}_S = i h \text{Tr}[\bar{H}_a S_b \gamma_\mu \gamma_5 A_{ba}^\mu] + h.c.$$

$$\mathcal{A}_\mu = \frac{1}{2} (\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger) \quad \xi = e^{i \mathcal{M}/f_\pi}$$

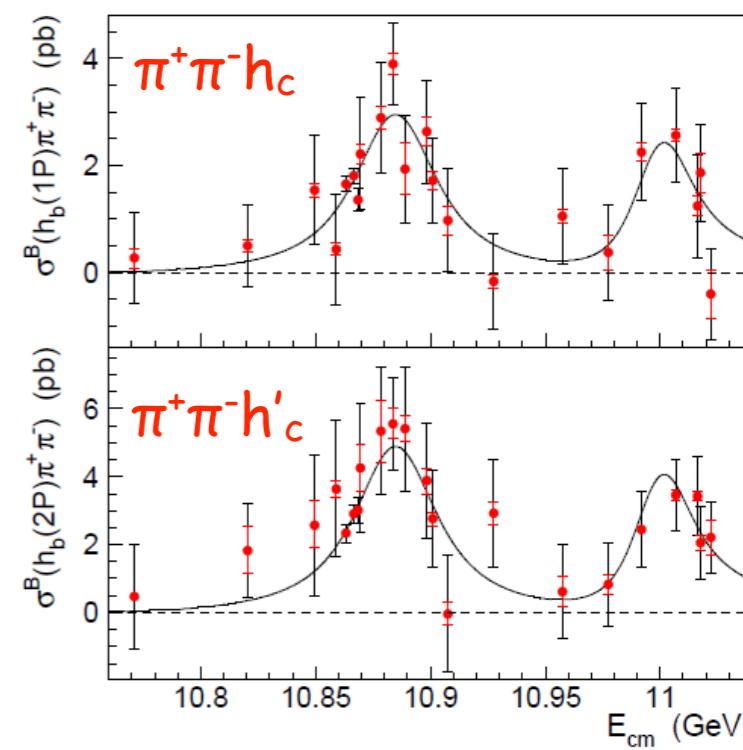
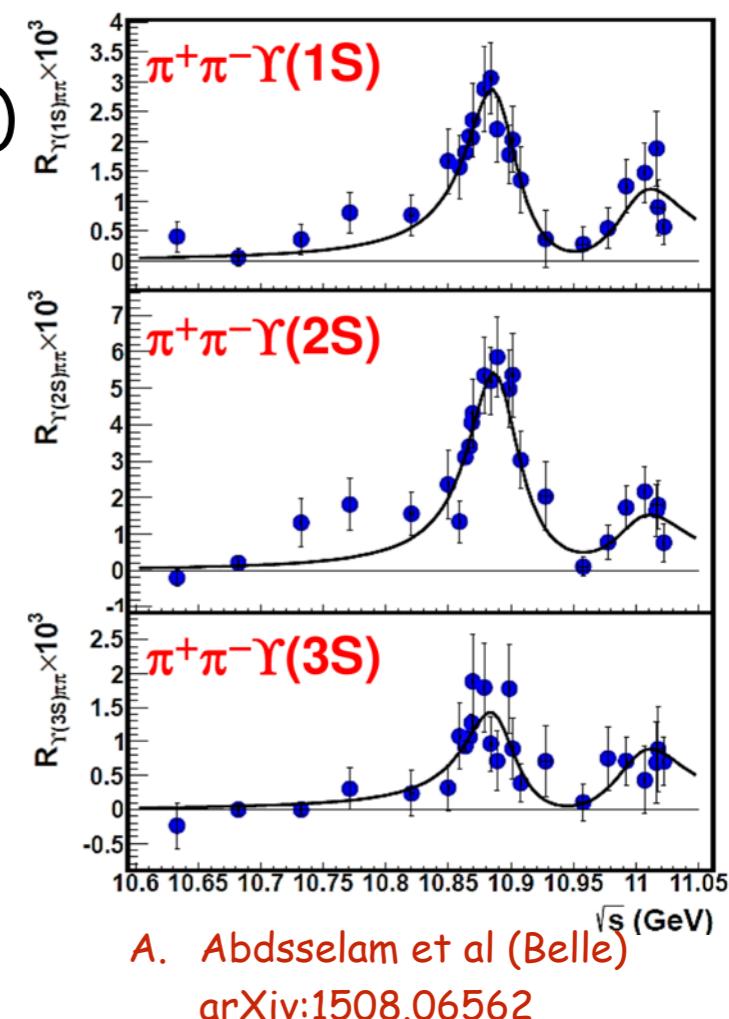
$$\mathcal{M} = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

- Using the masses and widths of the $j^p = 1^+$ B mesons

TABLE II. Summary of results on three-body cross sections.
The first (or sole) uncertainty is statistical; the second is systematic.

Parameter	$BB\pi$	$BB^*\pi$	$B^*B^*\pi$
Yield, Events	13 ± 25	357 ± 30	161 ± 21
$\mathcal{B}_f, 10^{-6}$	293 ± 22	276 ± 21	223 ± 17
η	1.0	1.066	1.182
$\sigma_{\text{vis}}, \text{pb}$	< 2.1	$11.2 \pm 1.0 \pm 1.2$	$5.61 \pm 0.73 \pm 0.66$

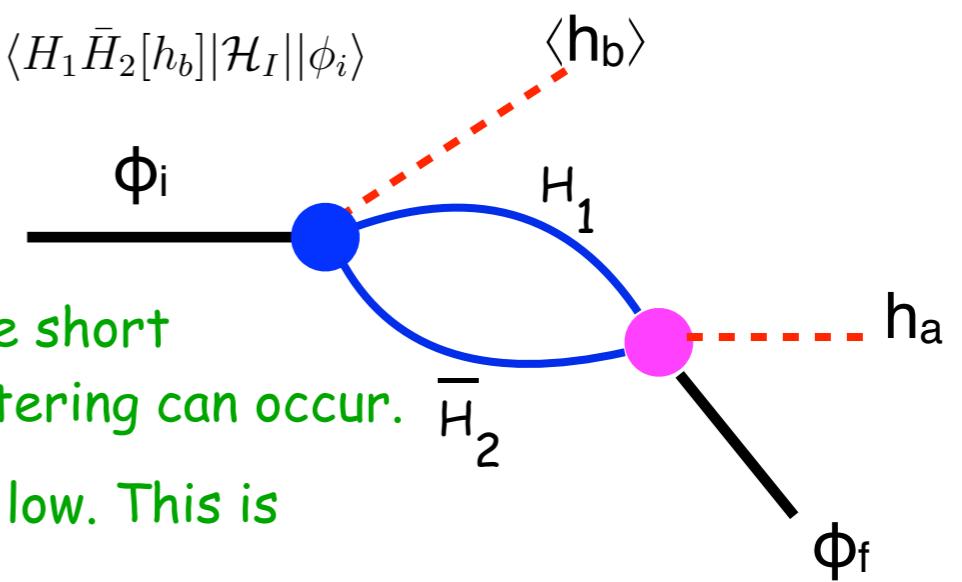
Good Agreement



- 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 $H_1 + \text{light hadrons } (h_b)$, 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).

$$\mathcal{M}(\Phi_i \rightarrow \Phi_f + h) =$$

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



- 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.

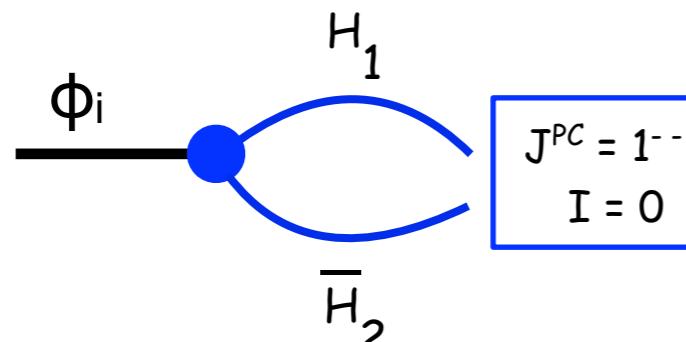
F.K. Gao, C. Hanhart, Q. Wang, Q. Zhao [arXiv:1411.5584]

Four Quark States May Be Easily Produced at Two Heavy-Light Mesons S-wave Thresholds

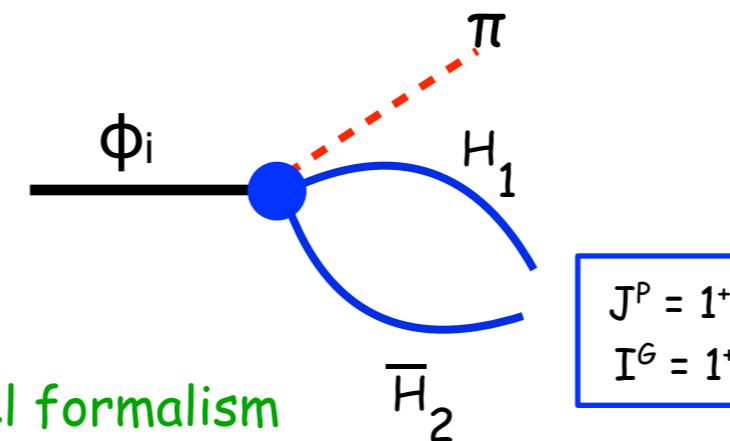
- Production modes: (Where to look for new surprises)

- e^+e^- processes

- direct



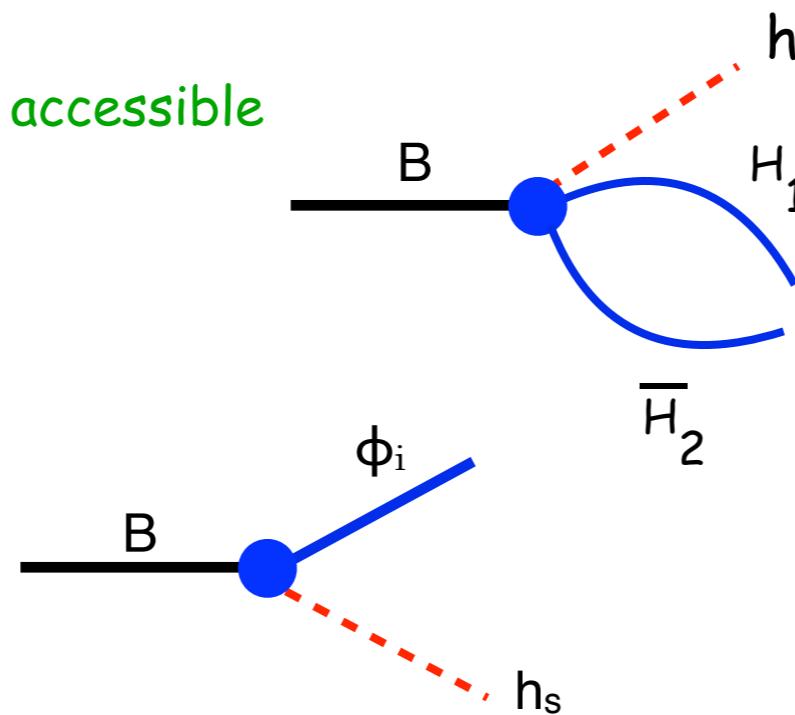
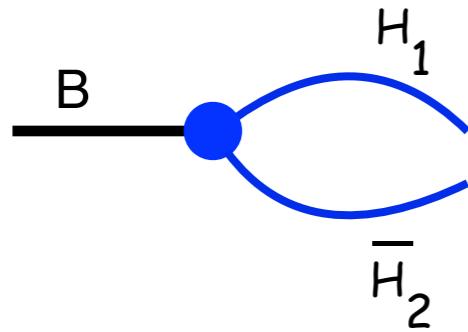
sequential (dominant terms)



• Can compute using coupled channel formalism

- B weak decays

- More quantum numbers accessible



Biggest Surprise:
Resonances are seen at these
thresholds

XYZ States

- **X(3872)** - the first surprising new state
 - A molecule? $M(X) - M(D^0) - M(D^{*0}) = -0.11 \pm 0.23$ MeV
 - Observed decays: $\pi^+\pi^- J/\psi; \rho^0 J/\psi; \omega J/\psi; \bar{D}^0 D^0 \pi^0; \bar{D}^{*0} D^0$
 - $I = 0$ (but significant isospin breaking) $\Gamma(\omega J/\psi(1S))/\Gamma(\pi^+ \pi^- J/\psi(1S)) = 0.8 \pm 0.2$
 - A 2^3P_1 charmonium state? $\frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$

- **Y(4260)** - another surprise
 - $J^{PC} = 1^{--}$ Produced in e^+e^- collisions with very small ΔR
 - Also Y(4360), Y(4660)
 - Possible decay: $\chi X(3872)$

- **$Z^+_b(10607), Z^+_b(10652)$ and $Z^+_c(3889), Z^+_c(4024)$** - third surprises
 - A. Bondar et al. [Belle] (271 cites)
PRL 108 (2012) 122001 [arXiv:1110.2251]
 - M. Ablikim et al. [BESIII] (175 cites)
PRL 111 (2013) 242001 [arXiv:1309.1896]
 - $I = 1$ isospin triplets \rightarrow must have valence light quarks.
 - $I^G(J^P) = 1^+(1^+)$
 - near thresholds for \bar{B}^*B, \bar{B}^*B^* and \bar{D}^*D, \bar{D}^*D^* production respectively

- Notation

- Y denotes states observed directly in the charm contribution to $e^+e^- \rightarrow$ hadrons:

$$\Rightarrow J^{PC} = 1^{--} \text{ and } I = 0$$

- $Y_c(4260), Y_c(4360), Y_c(4650)$

- Z denotes states with $I = 1$

- $Z_c^+(3885), Z_c^+(4025)$

- $Z_b^+(10610), Z_b^+(10650)$

- $Z_c^+(4430)$

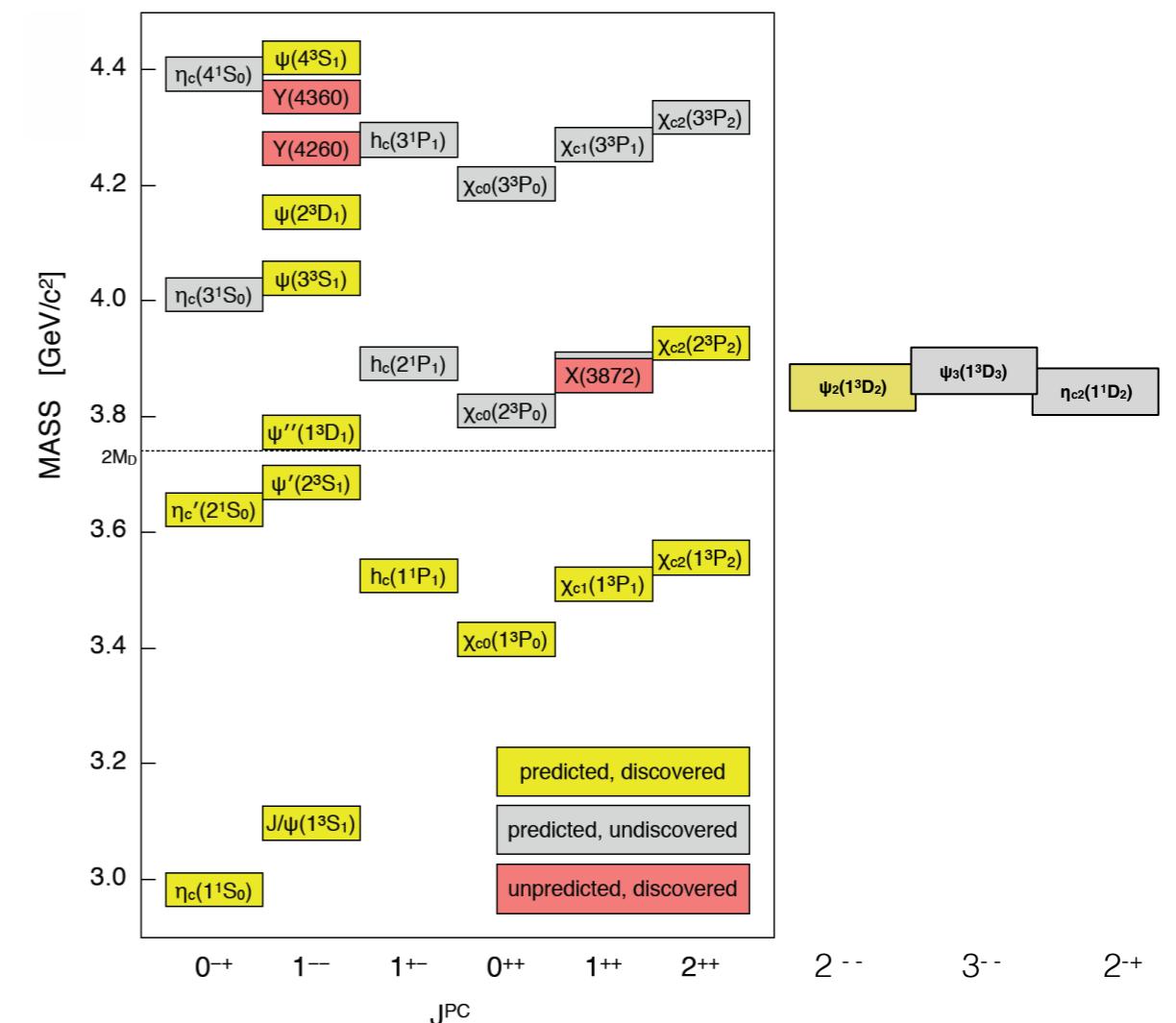
HQS

- X denotes anything else

- $X_c(3872), \dots$

\Rightarrow see PDG table

- Pentaquarks: $X(4450)$ ($J^P = 5/2^+$), ...

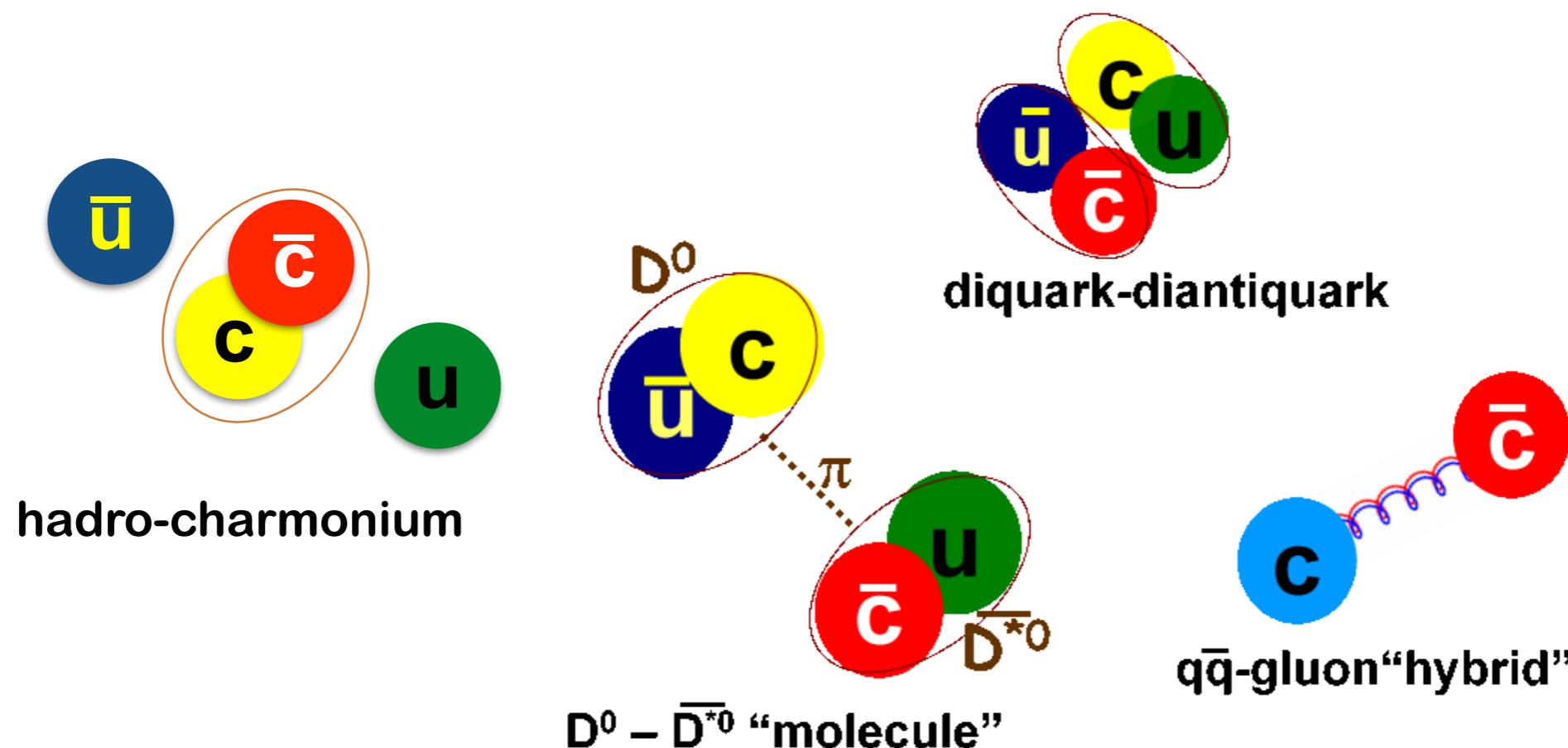


- Updated from PDG - other X states need more information

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (# σ)	Year
$\chi_{c0}(3915)$	3917.4 ± 2.7	28_{-9}^{+10}	0^{++}	$B \rightarrow K(\omega J/\psi)$	Belle (8.1), BABAR (19)	2004
				Close to $\chi_{c2}(3927)$. Are the quantum numbers correct?		
$X(3940)$	3942_{-8}^{+9}	37_{-17}^{+27}	$?^{?+}$	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$ $e^+e^- \rightarrow J/\psi(...)$	Belle(6.0) Belle (5.0)	2007
				Candidate for $\eta_c(3S)$, but too far below $\psi(3S)$		
$Y(4008)$	4008_{-49}^{+121}	226 ± 97	1^{--}	$e^+e^- \rightarrow \gamma(\pi^+\pi^-J/\psi)$	Belle(7.4)	2007
				Two BW peak fit better than only the Y(4260).		
$Z_1(4050)^+$	4051_{-43}^{+24}	82_{-55}^{+51}	?	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle(5.0), BABAR (1.1)	2008
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B \rightarrow K(\phi J/\psi)$	CDF (3.1), Belle (1.9) LHCb (1.4), CMS (> 5) D0 (3.1)	2008
$X(4160)$	4156_{-25}^{+29}	139_{-65}^{+113}	$?^{?+}$	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle(5.5)	2007
$Z_2(4250)^+$	4248 ± 20	35 ± 16	?	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle(5.0), BABAR (2.0)	2008
$Y(4274)$	4293_{-49}^{+121}	226 ± 97	$?^{?+}$	$B^+ \rightarrow K^+(\phi J/\psi)$	CDF (3.1), LHCb (1.0) CMS (> 3), D0 (np)	2007
$X(4350)$	$4350.6_{-5.1}^{+4.6}$	$13.3_{-10.0}^{+18.4}$	$0/2^{++}$	$e^+e^- \rightarrow e^+e^-(\phi J/\psi)$	Belle(3.2)	2009
				Observable in LHCb, CMS, Atlas ?		
$X(4630)$	4634_{-11}^{+9}	92_{-32}^{+41}	1^{--}	$e^+e^- \rightarrow \gamma(\Lambda_c^+\Lambda_c^-)$	Belle (8.2)	2007

What is the QCD dynamics of these new states?

- Threshold Effects, Hybrids, Tetraquark States:



S. Godfrey+S. Olsen
arXiv:0801.3867

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

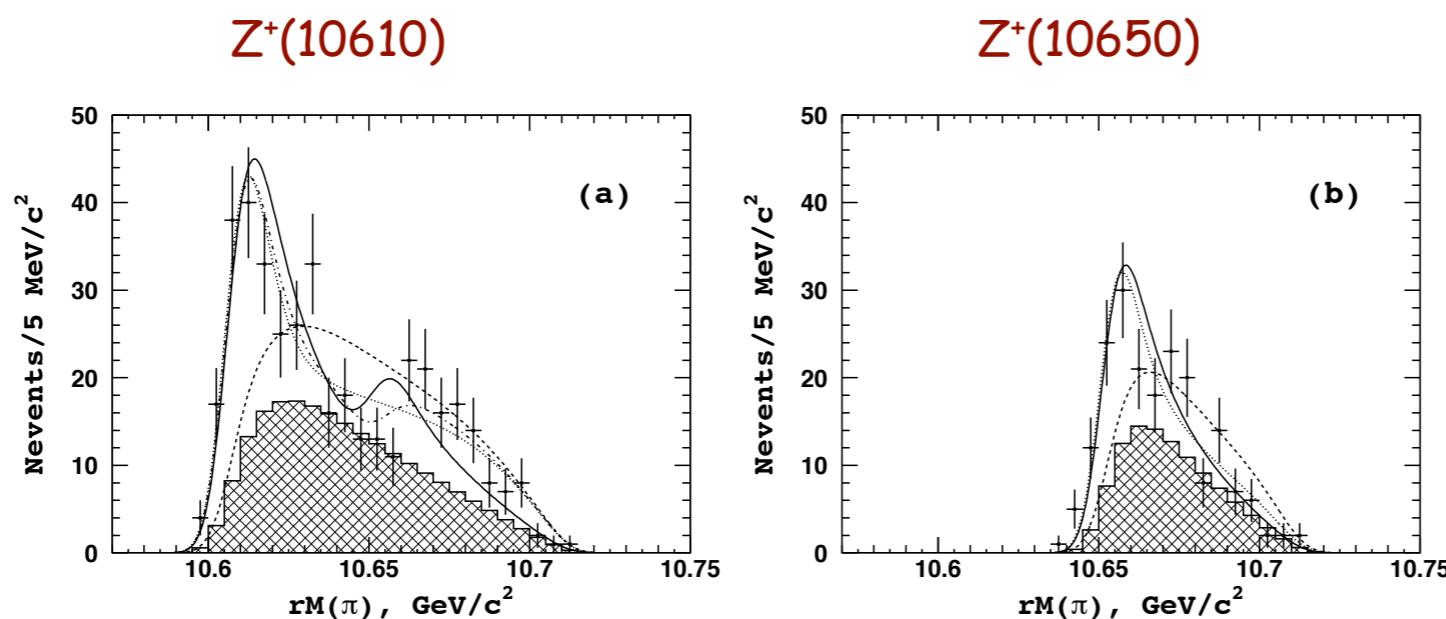
- BELLE observed two new charged states in the $\Upsilon(5S) \rightarrow \Upsilon(nS) + \pi^+ \pi^-$ ($n=1,2,3$) and the $\Upsilon(5S) \rightarrow h_b(nP) + \pi^+ \pi^-$ ($n=1,2$)

TABLE I. 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)	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$10652 \pm 2 \pm 2$	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}	$255^{+56+12}_{-72-183}$	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	—

- $\Upsilon(5S) \rightarrow Z_b^\pm + \pi^-$ and $Z_b \rightarrow h_b(nP) + \pi^+$.
- Explicitly violates the factorization assumption of the QCDME but consistent with the new mechanism for hadronic transitions above threshold
- The $Z_b^\pm(10610)$ is a narrow state ($\Gamma = 15.6 \pm 2.5$ MeV) at the $\bar{B}\bar{B}^*$ threshold (10605).
- The $Z_b^\pm(10650)$ is a narrow state ($\Gamma = 14.4 \pm 3.2$ MeV) at the B^*B^* threshold (10650).

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



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

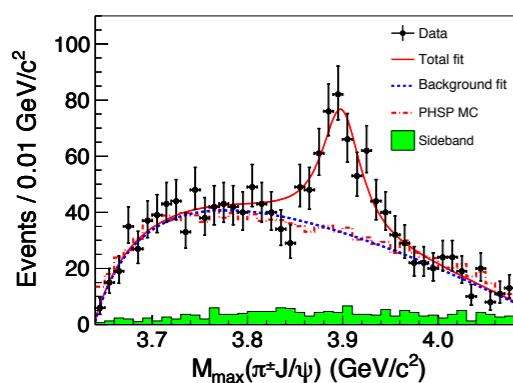
and

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

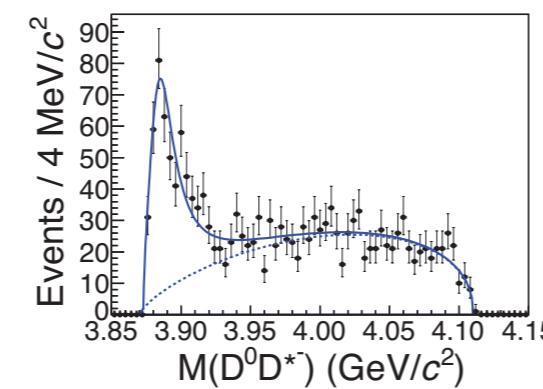
- HQS implies that the same mechanism applies for charmonium-like states

$Z_c^+(3885)$ and $Z_c^+(4020)$

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

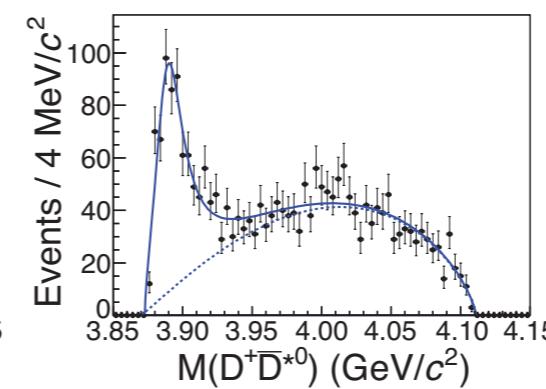


$$M(D^0 + D^{*-}) = 3.8752$$



$$M_{\text{pole}} = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$$

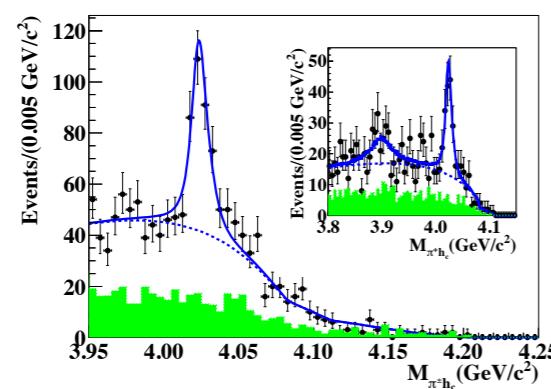
$$\Gamma_{\text{pole}} = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$$



$$\frac{\Gamma[Z_c(3900) \rightarrow DD^*]}{\Gamma[Z_c(3900) \rightarrow \pi J/\psi]} = 6.2 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys}}$$

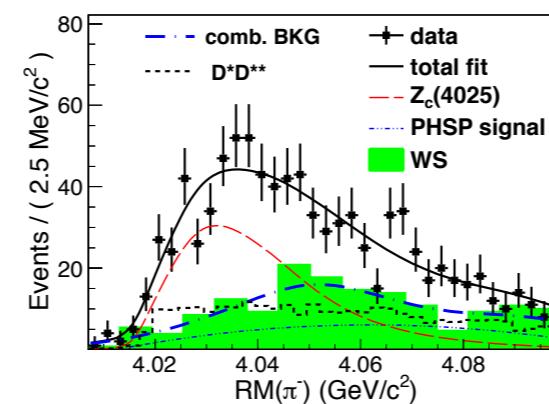
BESIII Z. Lin

[arXiv:1504.06102]



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

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



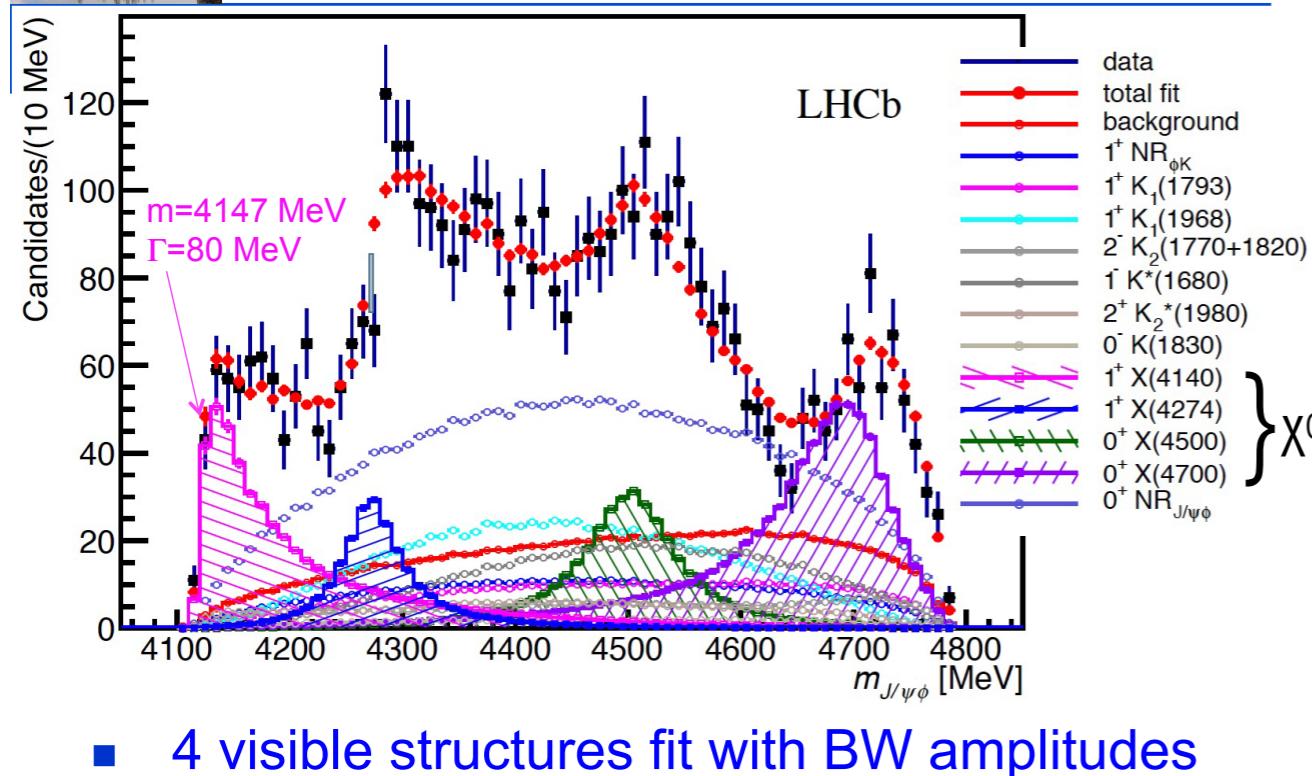
$$M(D^{*0} + D^{*-}) = 4.0178$$

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

- LHCb - T. Skwarnicki talk Meson 2016 - light quarks \rightarrow strange quarks



Results of fit: $m(J/\psi\phi)$



Results of fit

- J^P also measured all with $>4\sigma$ significances

Particle	J^P	Significance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	1^+	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	0^+	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
X(4700)	0^+	5.6σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$
NR	0^+	6.4σ			$46 \pm 11^{+11}_{-21}$

28 Rencontres de Blois, June 2, 2016

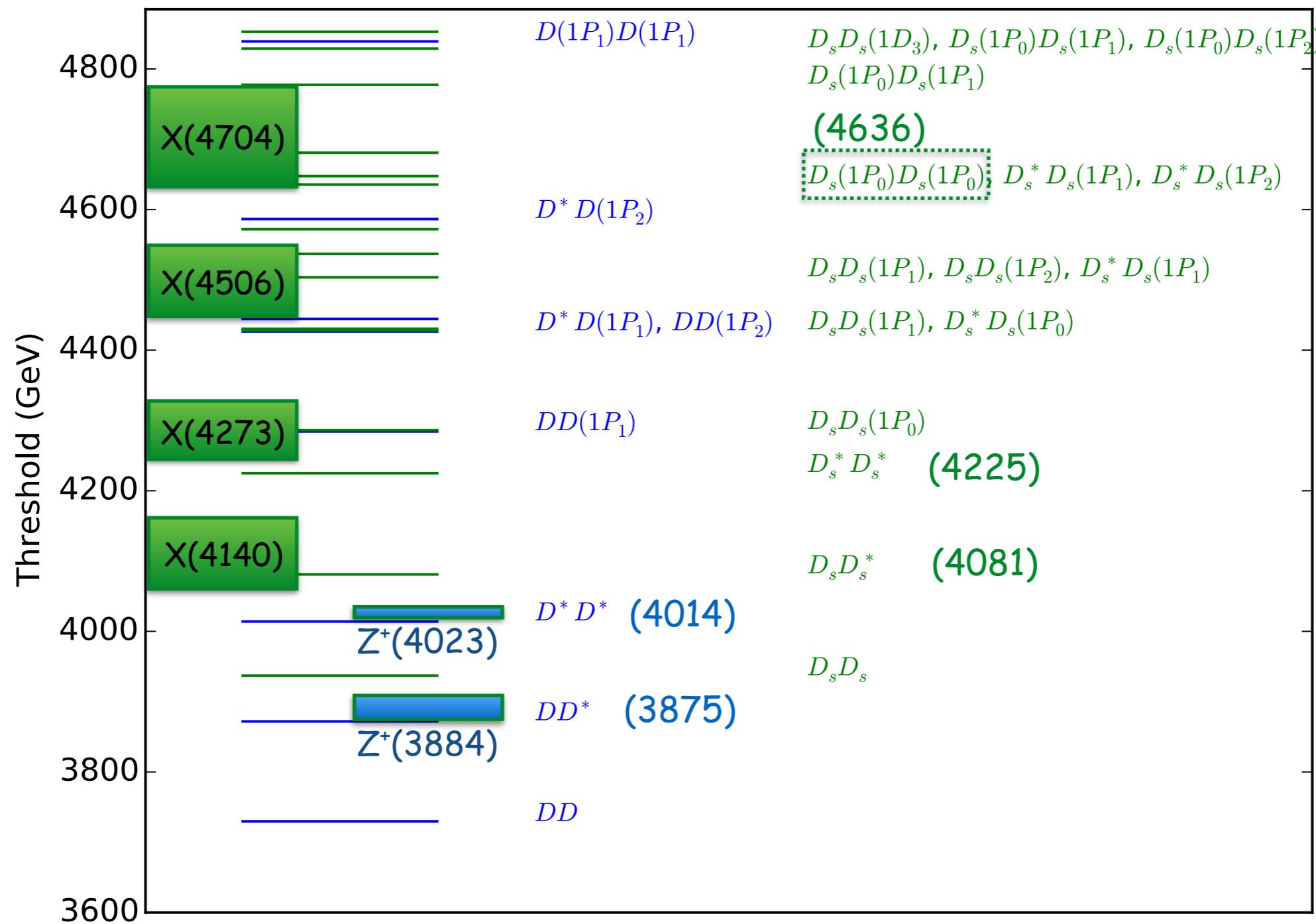
28 Rencontres de Blois, June 2, 2016

36

37

- strangeness zero states - charmonium
- ($\bar{c}\bar{s}s\bar{c}$) structures

$B \rightarrow X K: M_X < 4785 \text{ MeV}$



$\Upsilon(4260)$

- $\Upsilon(4260)$ - not standard charmonium state. $JPC = 1- -$ $M = 4259 \pm 9$ $\Gamma = 120 \pm 12$ MeV

- Decays observed:

$$J/\psi \pi^+ \pi^-$$

$$J/\psi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-$$

$$X(3900)^\pm \pi^\mp, X^\pm \rightarrow J/\psi \pi^\pm$$

$$J/\psi \pi^0 \pi^0$$

$$J/\psi K^+ K^-$$

$$X(3872) \gamma$$

- Many models:

1. Charmonium hybrid

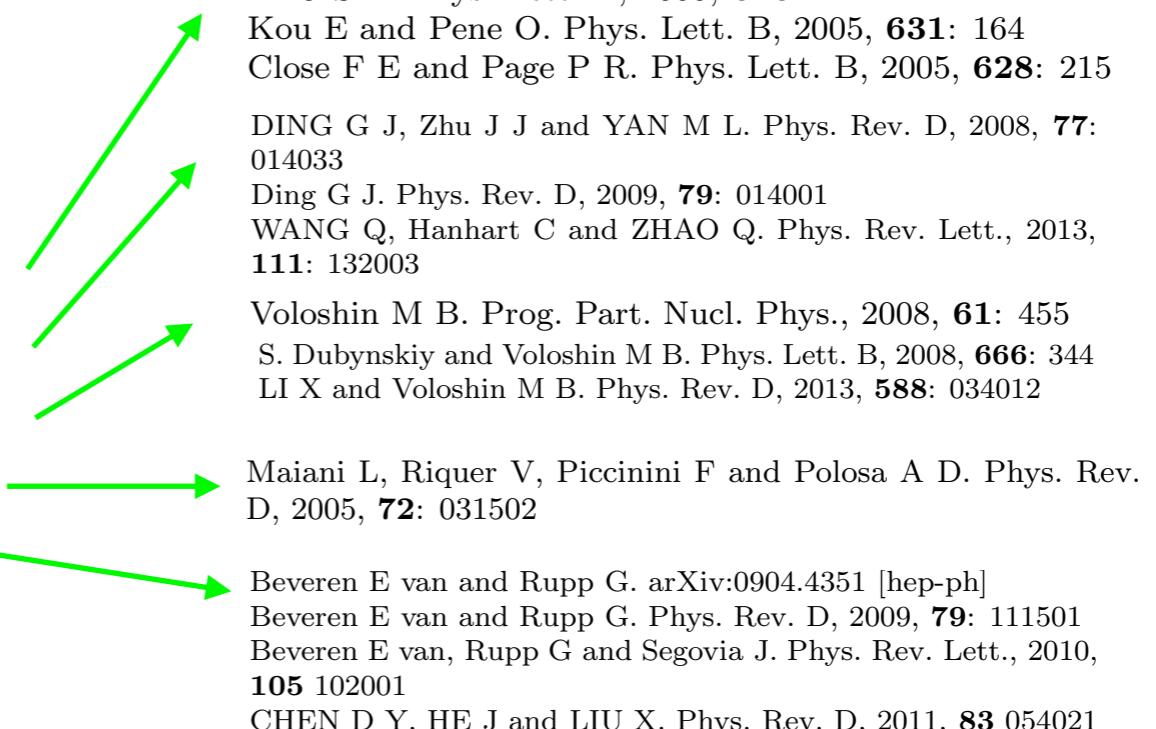
2. D₁ D molecule

3. Hadrocharmonium

4. Tetraquark (ccss)

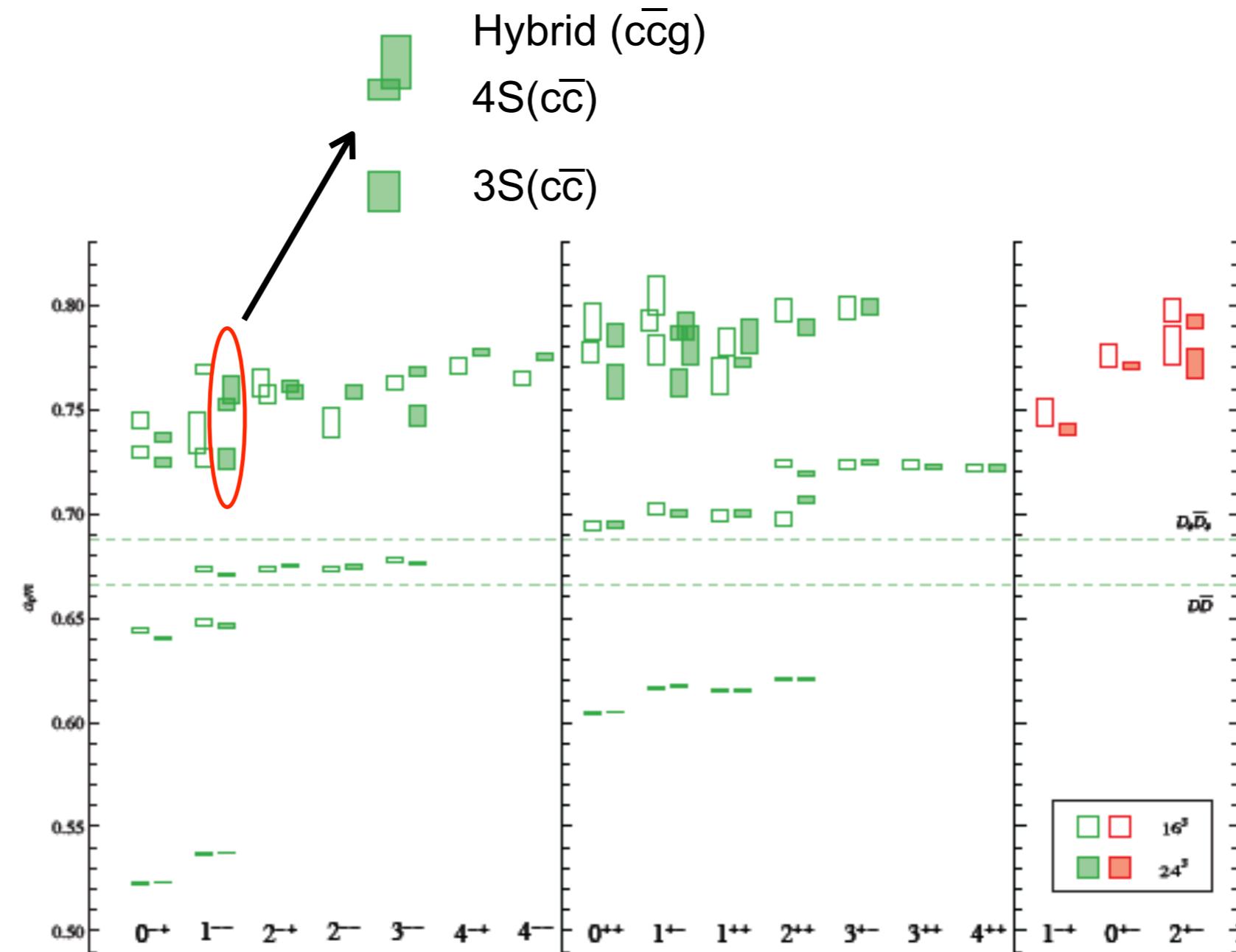
5. Cusp/nonresonance

...



- 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 Πu : Hybrid state should be $\sim 10,870$ MeV
 - 2. At threshold of $B_1 B$: 11,000 MeV

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



- These preliminary results (quenched) support the identification of the $\Upsilon(4260)$ as a hybrid meson.

X(3872)

- $X(3872) - J^{PC} = 1^{++}$ $M = 3871.69 \pm 0.16 \pm 0.19$ $\Gamma < 1.2$ MeV from $J/\psi \pi\pi$ mode

- Decays observed:

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

large Isospin violation

- LHCb [arXiv:1404.0275]

$$\frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29. \quad \text{suggests 2P state}$$

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

suggests molecule

- Two primary models:

1. $\chi_{c1}'(2^3P_1)$ state

2. $D^0 \bar{D}^{*0}$ molecule

M. Suzuki, hep-ph/0307118.

DeRujula, Georgi, Glashow, PRL 38(1997)317
F. Close and P. Page, Phys. Lett. B578 (2004) 119
M. Voloshin, Phys. Letts. B579 (2004) 316.
...

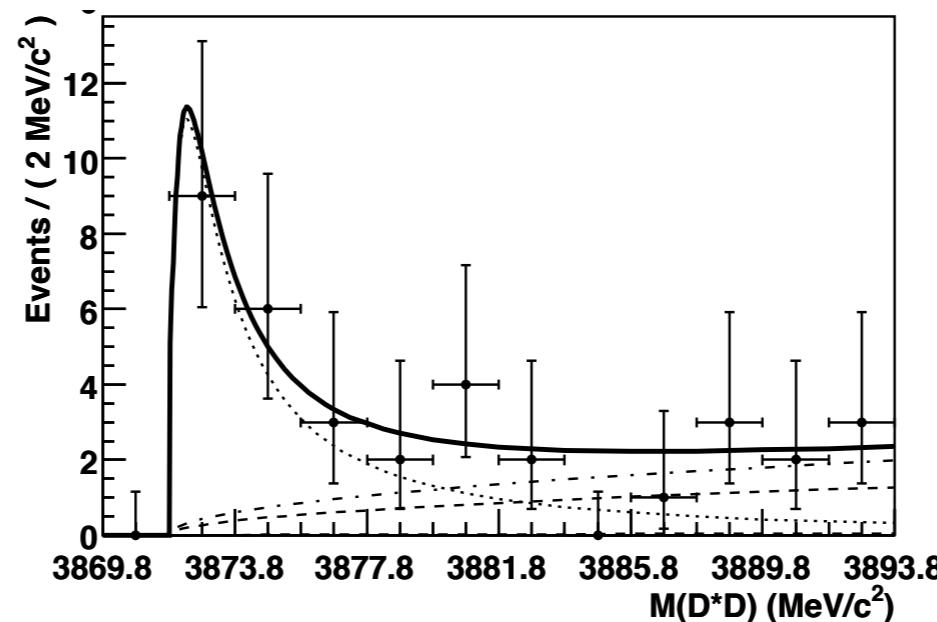
E. Braaten [arXiv:1503.04791]

- Mixed state with sizable quarkonium component likely.

- For LQCD: Where is the $\chi_{c0}'(2^3P_0)$ state?

- $B \rightarrow X(3872) K \rightarrow (D^0 \bar{D}^{0*}) K$
- 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 $(c\bar{c})$ and the $D\bar{D}^*$ components.
- Suggests there is a significant $(c\bar{c})$ component of the $X(3872)$.
- No pole observed in the $I = 1$ channel.

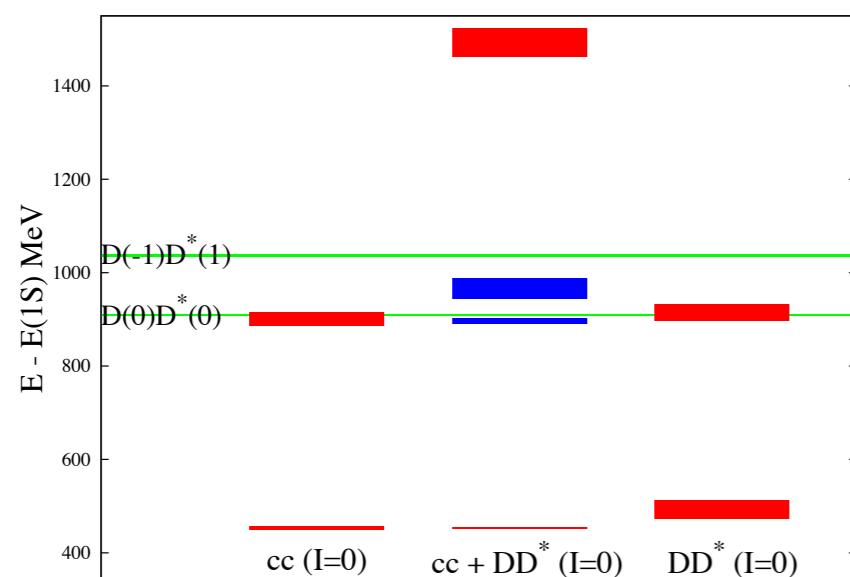
B. A. Galloway, P. Knecht, J. Koponen, C. T. H. Davies, and G. P. Lepage, PoS LATTICE2014, 092 (2014), 1411.1318.

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.

arXiv:1411.1389



arXiv:1503.03257

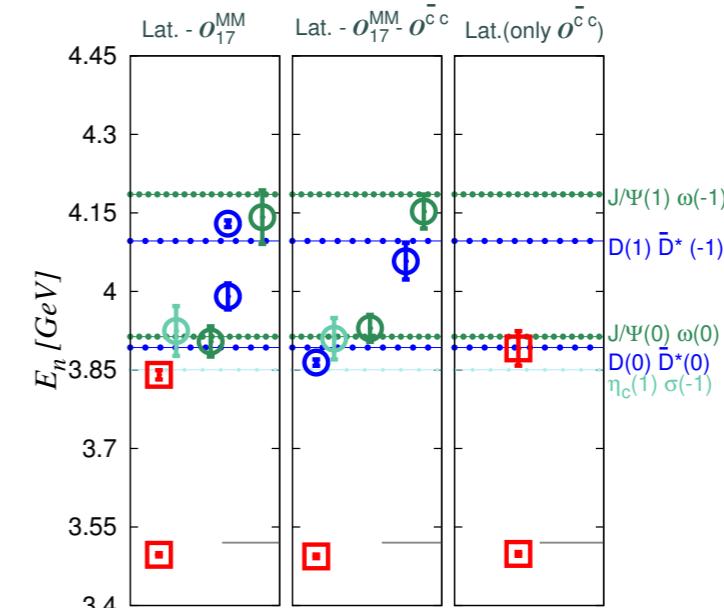
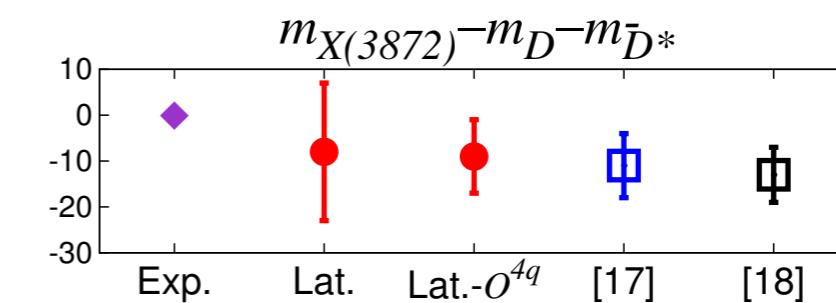


FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note 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.



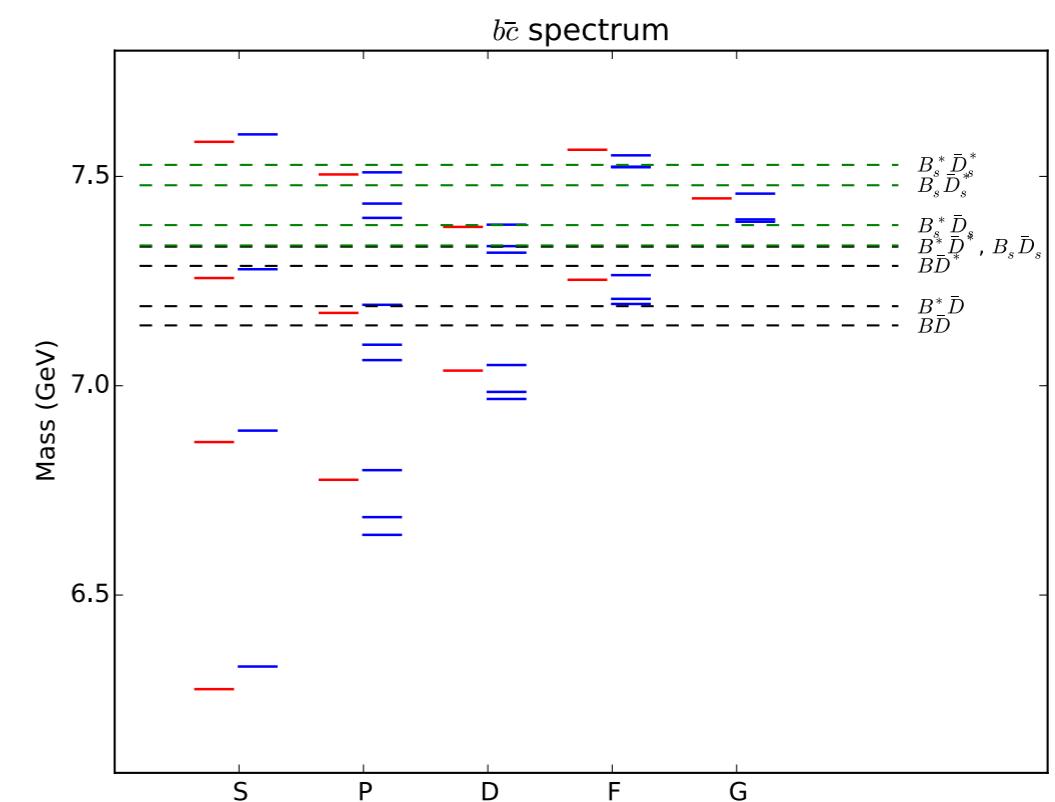
- $X_b(10604) ??$
 - No isospin breaking: X is $I=0 \Rightarrow G$ -parity forbids the decay $X \rightarrow \pi\pi\Upsilon(1S)$.
 - Dominate decay $X \rightarrow \omega\Upsilon(1S) ?$
 - $M(X_{b1}(3P)) - M(B) - M(B^*) \approx -75$ MeV
 - So the (bb) state is decoupled.

Expect no analog of the $X(3872)$
in the bottomonium system

Unexplored Territory

Many surprises still ahead?

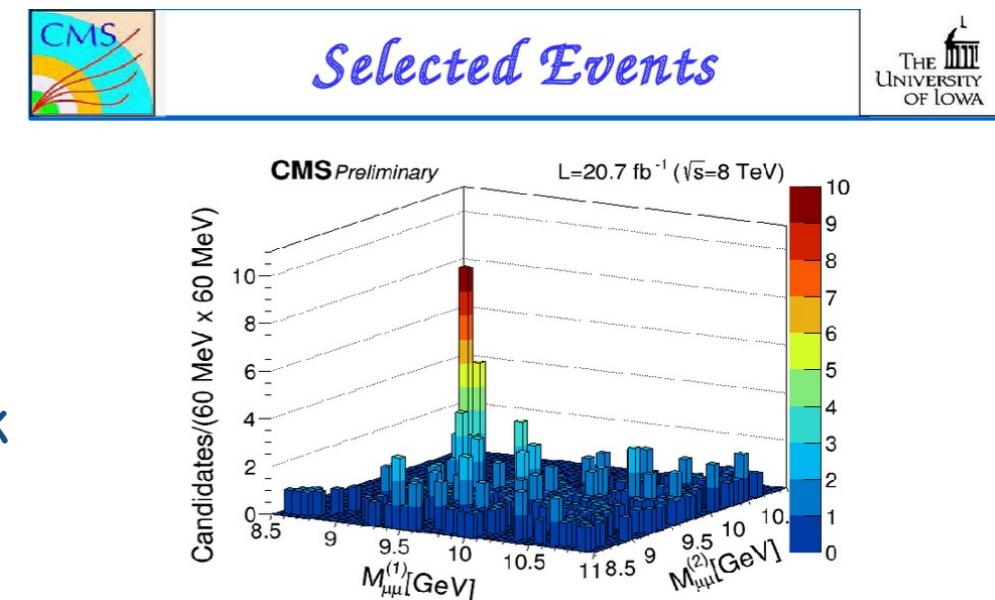
- Double heavy baryons - (ccq), (cbq), (bbq). Both HQET and NRQCD play a role in the excitation spectra.
 - double expansion
 - NRQCD for the two heavy quarks and HQET expansion for the heavy core (QQ) - light quark system.
 - In leading order in $1/m_Q$: Excitation spectrum for the light quark is same as for heavy-light mesons (HQET)
- B_c - a rich excitation spectrum of states.
 - Atlas observed: $B_c(2S) \rightarrow B_c(1S) + \pi\pi$. radially excited state.
 - Many states observable at the LHC and TevaZ factory.
 - B_c is the unique heavy-heavy meson that weak direct decays.
 - Opportunities to study CKM and BSM physics.



- CMS at $\sqrt{s} = 8$ TeV observes double Υ production in the $\mu^+ \mu^- \mu^+ \mu^-$ final state:
 - $\sigma(\bar{p}p \rightarrow \Upsilon \Upsilon) = 68.8 \pm 12.7$ (stat) ± 7.4 (syst) pb for $|y| < 2.0$ and $p_T^\Upsilon < 50$ GeV
 - Possible to search for heavy quark hadrons ($c\bar{c}c\bar{c}$), ($c\bar{b}b\bar{c}$), ($b\bar{b}b\bar{b}$)
 - Quarkonium states increasingly bound as heavy quark mass increases. What about tetraquark states?

Are there any narrow deeply bound tetraquark states?

Maksat Haymyradov: APS April meeting



Two dimensional scatter plot of selected events.
Significant excess of events around ~ 9.5 GeV.

10

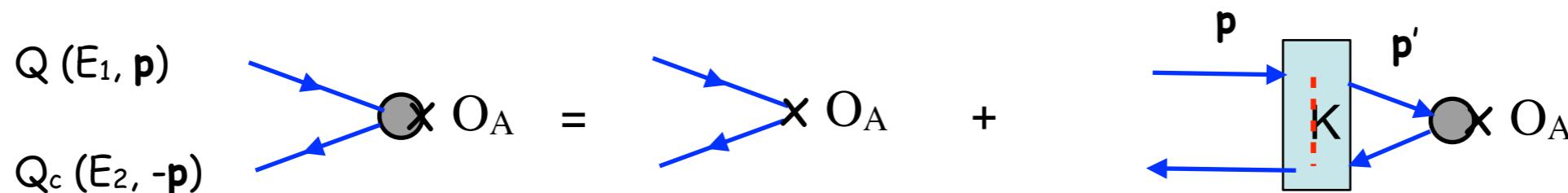
Conclusions

- Heavy quark states are ideal systems to study QCD strong dynamics.
- In the threshold region for decays to open heavy flavor states QCD dynamics is more complicated. There have been many surprises and a still incomplete picture of the dynamics:
 - Large hadronic transition rates. New transition contributions with two open flavor intermediate states.
 - Large violations of heavy quark spin symmetry and SU(3) expectations. Likely induced by the symmetry breaking of the heavy-light mesons masses coupled to the rapid energy variation of the decay amplitudes.
 - New states with additional degrees of freedom: Threshold effects, hybrid states, tetraquarks, pentaquark provide a multitude of possibilities. More clues from BESIII, Belle2, LHCb, PANDA,... coupled with Lattice QCD calculations are needed.
- Many heavy quark systems remain essentially unexplored; more surprises may await.

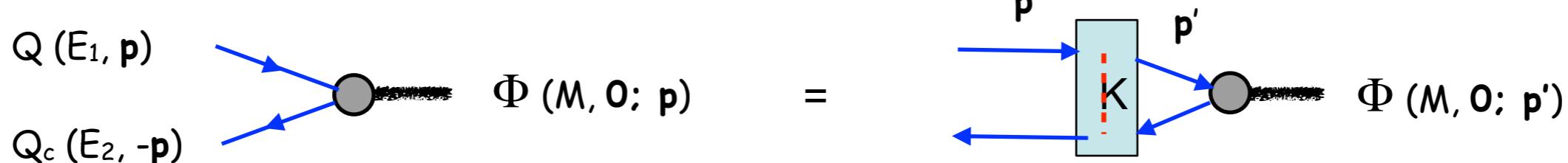
BACKUP SLIDES

Quarkonium States

- Threshold bound states
 - let O_A be a local operator coupling to QQ_c with bare vertex Γ the full vertex function satisfies the equation:



- where K is the two body irreducible kernel
- if a bound state exists in this channel then for $E_1 + E_2$ near the mass M of the bound state the pole should dominate.
- So the bound state equation becomes



- In QED to leading order in $(1/m)$
 - the kernel K is just the Coulomb exchange



$$\Phi(M, \mathbf{0}, \mathbf{p}) = -\frac{\alpha_{EM}}{2\pi^2} \int d^3 p' \frac{1}{(\mathbf{p} - \mathbf{p}')^2} \left[\frac{1}{\sqrt{m_1^2 + \mathbf{p}'^2} + \sqrt{m_2^2 + \mathbf{p}'^2} - M} \right] \Phi(M, \mathbf{0}, \mathbf{p}')$$

- But $\alpha_{EM} \ll 1 \rightarrow$ no solutions unless:

$$\sqrt{m_1^2 + \mathbf{p}'^2} + \sqrt{m_2^2 + \mathbf{p}'^2} - M = (m_1 + m_2 - M) + \frac{\mathbf{p}^2}{\mu_R} + \dots \ll m_1 + m_2$$

$$E(\text{binding}) \sim \frac{v_{\text{rel}}^2}{2\mu_R}$$

$$\mathbf{p}, \mathbf{p}' \sim v_{\text{rel}} \mu_R$$

- Non relativistic states with natural expansion in $v/c \approx \alpha_{EM}$
- Schrödinger Equation:

$$\Psi(M, \mathbf{0}, \mathbf{p}) \equiv \sqrt{m_1^2 + \mathbf{p}^2} + \sqrt{m_2^2 + \mathbf{p}^2} - M \Phi(M, \mathbf{0}, \mathbf{p})$$

$$\left[-\frac{\vec{\nabla}^2}{2\mu_R} - \frac{\alpha_{EM}}{r} \right] \Psi(M, \mathbf{x}) = M \Psi(M, \mathbf{x})$$

with

$$\begin{aligned} \mu_R &= \frac{m_1 m_2}{m_1 + m_2} \\ r &= |\mathbf{x}| \end{aligned}$$

- In NRQCD - the same behavior but the kernel is given by the static energy (potential)

$$\mathcal{H}_{\text{QCD}}^{\text{eff}} = \frac{1}{g^2} \int d^3x [\text{Tr}(\mathbf{E}^2) + \text{Tr}(\mathbf{B}^2)] + \sum_{Q=c,b,t} [\mathcal{H}_Q + \mathcal{H}_{Q_c}]$$

$$+ \frac{g^2}{4\pi} \int d^3x \int d^3y \{ J_a^0(x) \mathcal{G}(\mathbf{x}, \mathbf{y})_{ab} J_b^0(y) \}$$

Potential

Relativistic corrections	$\mathcal{H}_Q = \int d^3x Q^\dagger \left((m_Q + \delta m_Q) - \frac{\mathbf{D}^2}{2m_Q} \right) Q$ $- \int d^3x Q^\dagger \left[c_4 \frac{1}{8m_Q^3} (\mathbf{D}^2)^2 + c_d \frac{1}{8m_Q^2} (\mathbf{D} \cdot \mathbf{E} - \mathbf{E} \cdot \mathbf{D}) \right] Q$ $- \int d^3x Q^\dagger \left[c_f \frac{1}{2m_Q} \sigma \cdot \mathbf{B} + c_s \frac{i}{8m_Q^2} \sigma \cdot (\mathbf{D} \times \mathbf{E} + \mathbf{E} \times \mathbf{D}) \right] Q + \dots$	Darwin	Kinetic
	Magnetic	Spin- Orbit	Spin Independent

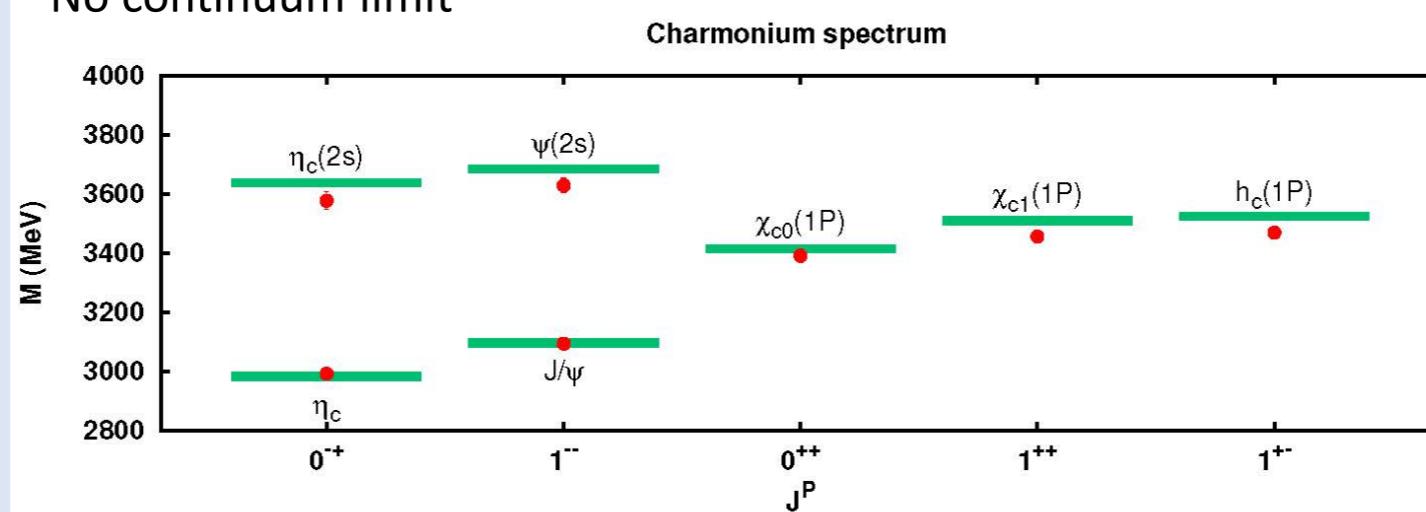
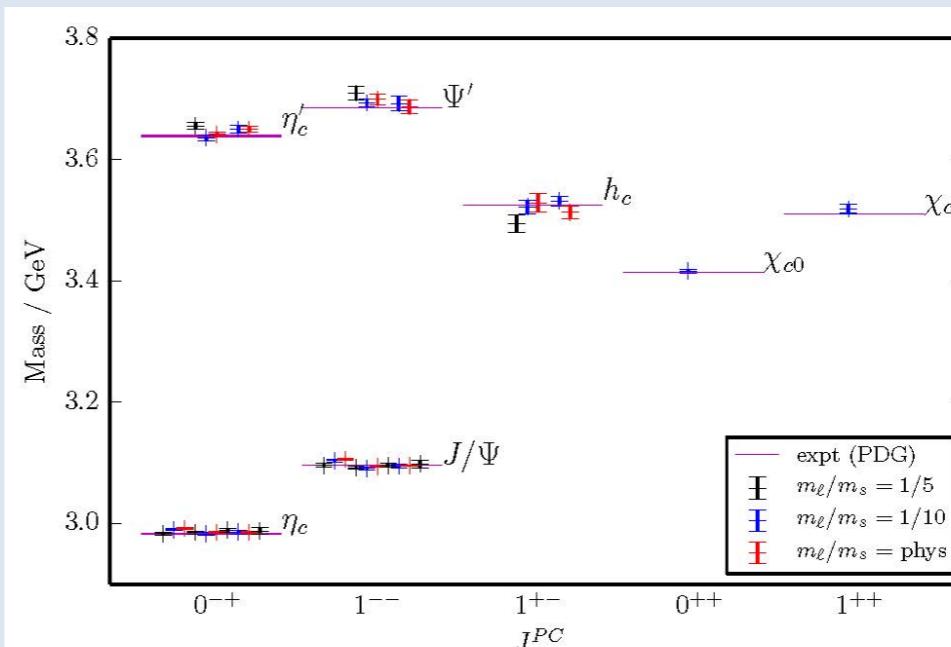
- Now superseded by lattice calculations for the low-lying spectrum

Low lying charmonium levels

Reasonably well understood

Glasgow 1411.1318
Continuum limit,
Physical quark masses

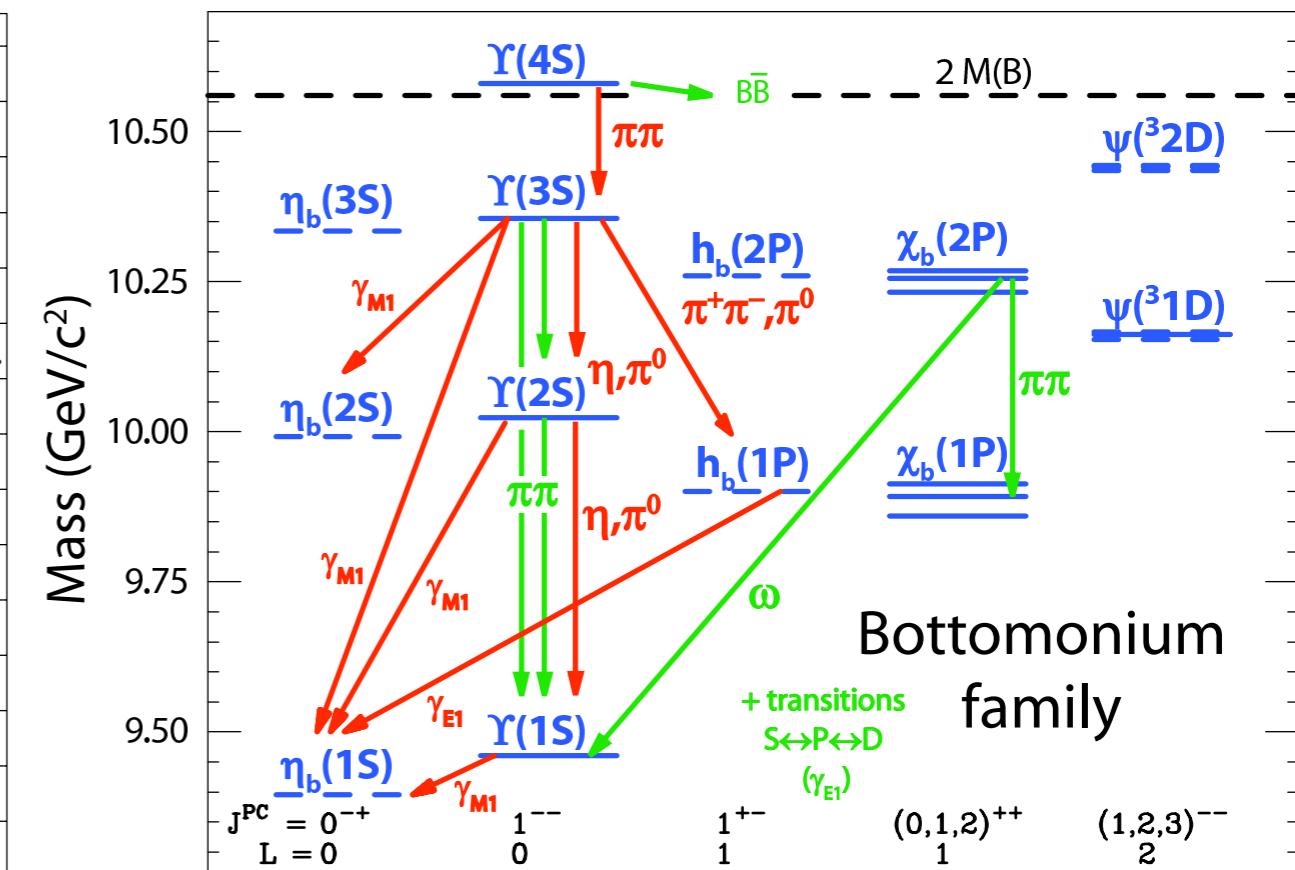
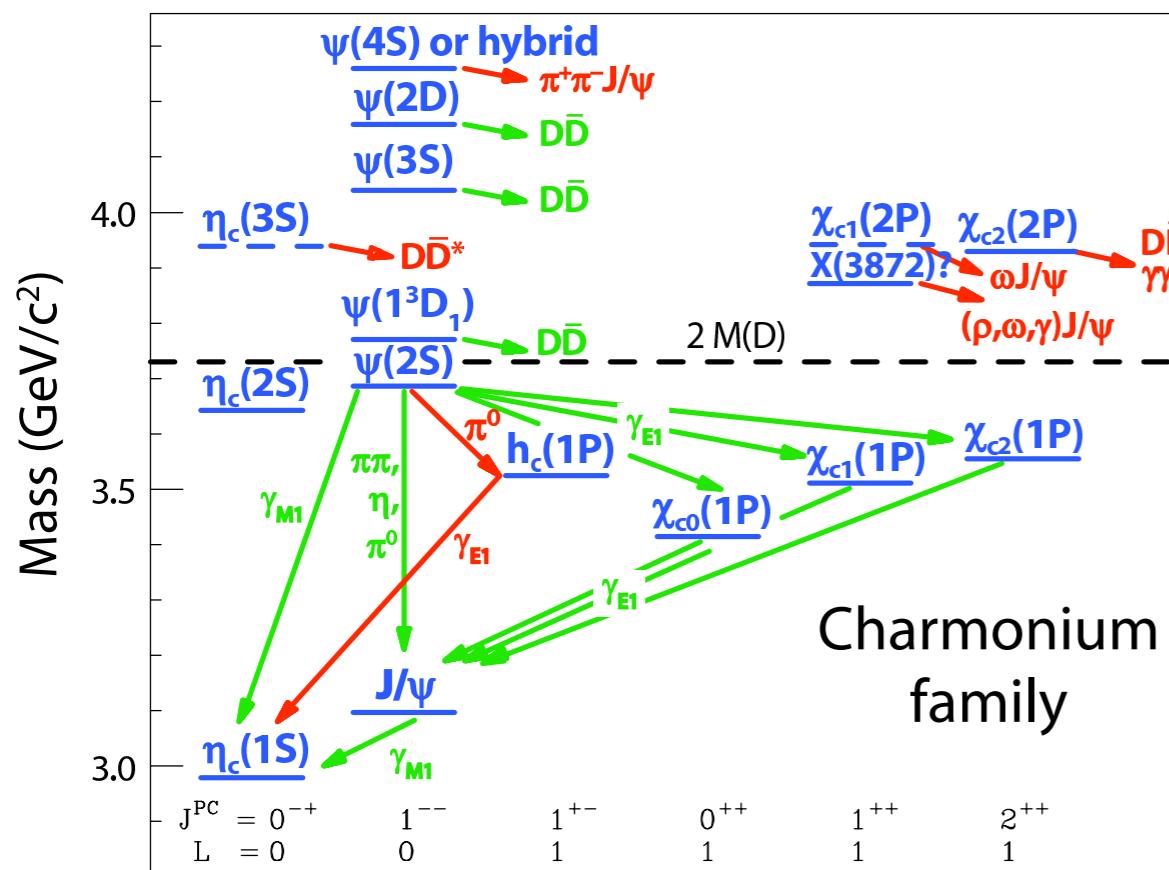
Regensburg 1503.08440
No continuum limit



C. DeTar, Lepton-Photon 2015

- Hadronic and EM transitions

- EM transitions - Standard multipole expansion for photon emission
- Hadronic transitions - QCDME - multipole expansion in gluons followed by hadronization. into light hadrons.
- Some hadronic and EM transitions



Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E. [Rev. Mod. Phys. 80, 1161 (2008)]

- Coupled channel problem

$$\mathcal{H}_0 \cdot Q\bar{Q}$$

NRQCD (without light quarks)

$$\mathcal{H}_I \quad Q\bar{Q} \xrightarrow{\text{light quark pair creation}} Q\bar{q} + q\bar{Q}$$

heavy-light meson pair interactions

$$\mathcal{H}_2 \quad Q\bar{q} + q\bar{Q}$$

heavy-light meson pair interactions

$$\begin{pmatrix} \mathcal{H}_0 & \mathcal{H}_I^\dagger \\ \mathcal{H}_I & \mathcal{H}_2 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = z \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

- Formally eliminate Ψ_2

defines $\Omega(z)$

$$\left(\mathcal{H}_0 + \mathcal{H}_I^\dagger \frac{1}{z - \mathcal{H}_2} \mathcal{H}_I \right) \psi_1 = z\psi_1$$

- Decay amplitude $\langle DD | \mathcal{H}_I | \psi \rangle$

- Simplifying assumptions

- \mathcal{H}_2 - free meson pairs no final state interactions

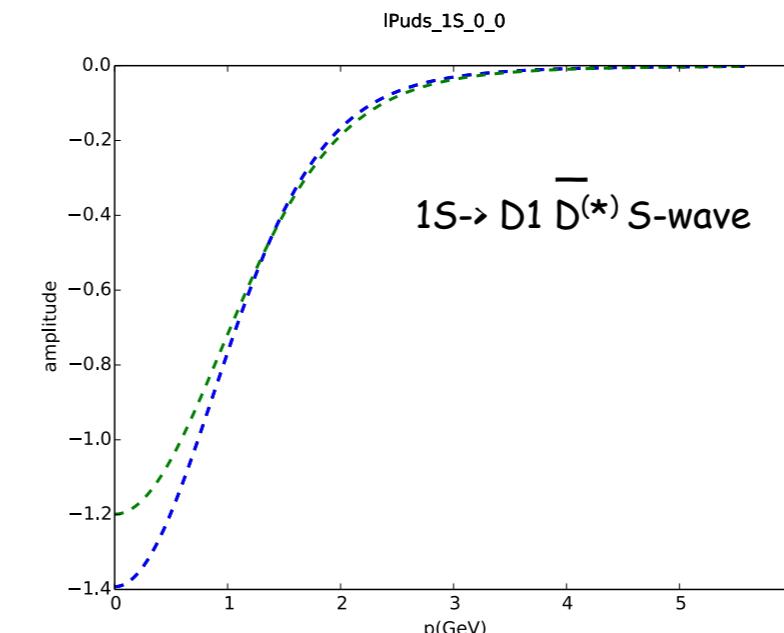
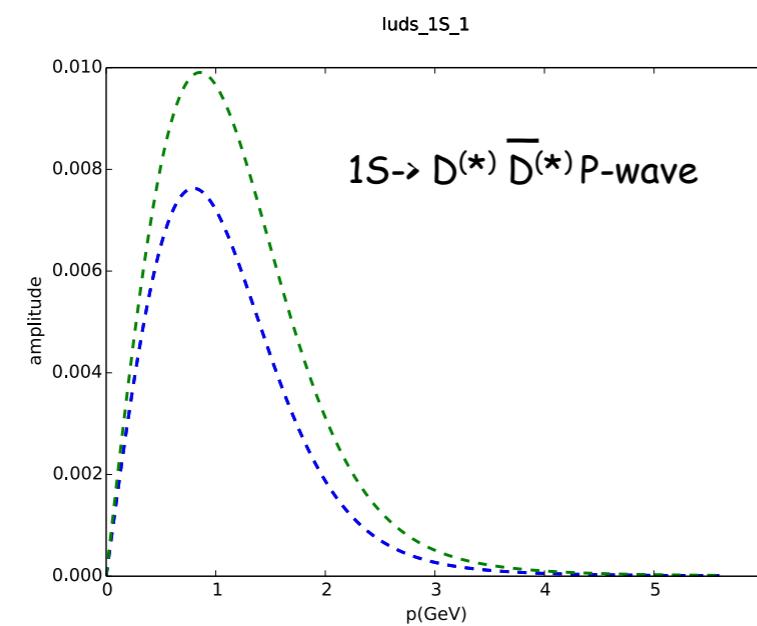
- \mathcal{H}_0 - charmonium states are a complete basis - no hybrids

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

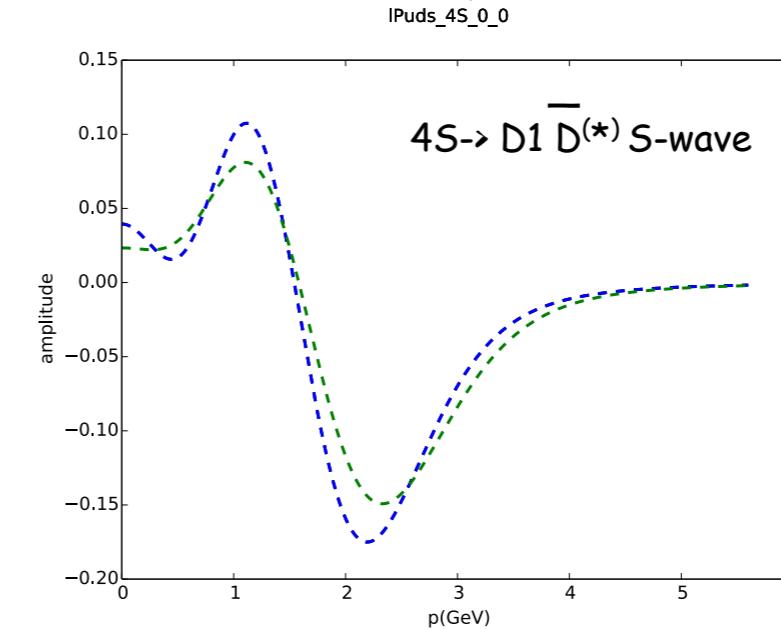
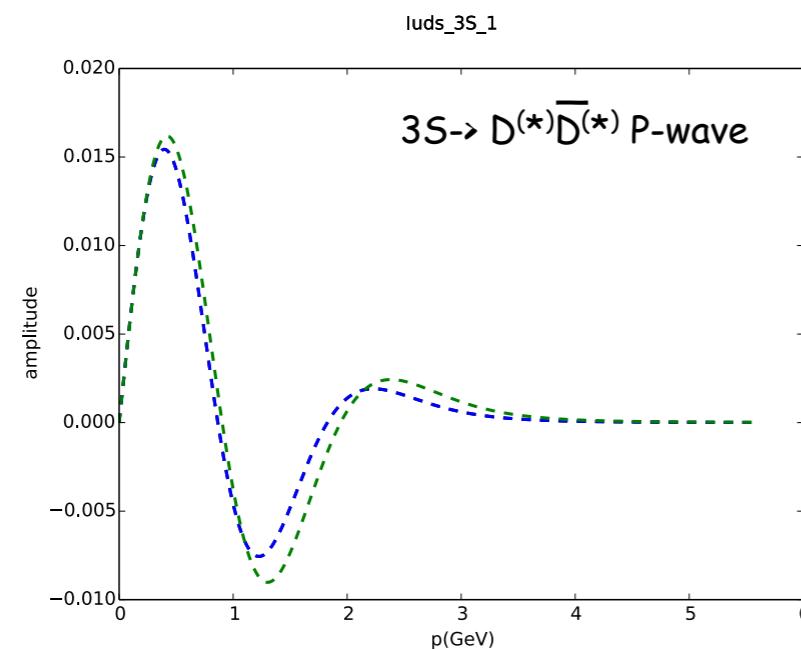
- Assuming vector meson dominance. Can compute R_c

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

- General features of decays to low-lying heavy-light mesons:
 - Unlike light meson systems, these decays are from highly excited QQ states:
 - Ground state decay amplitudes :



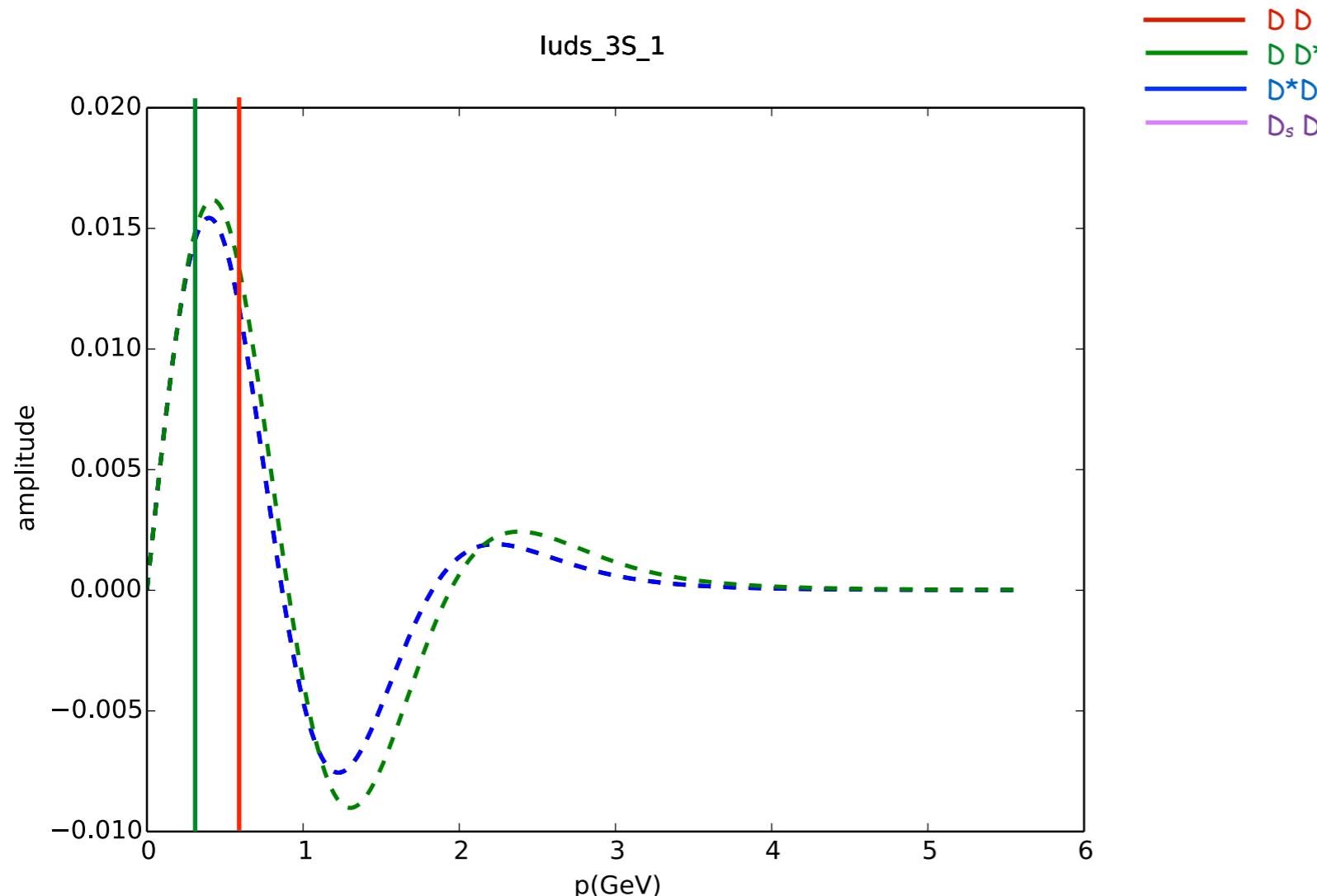
- Second (third) radial excited state: $\psi(4040)$ ($\psi(4415)$) decay



- Have complicated energy dependence.

- The mass differences of heavy-light mesons produces large effects in the decay amplitudes to exclusive channels.

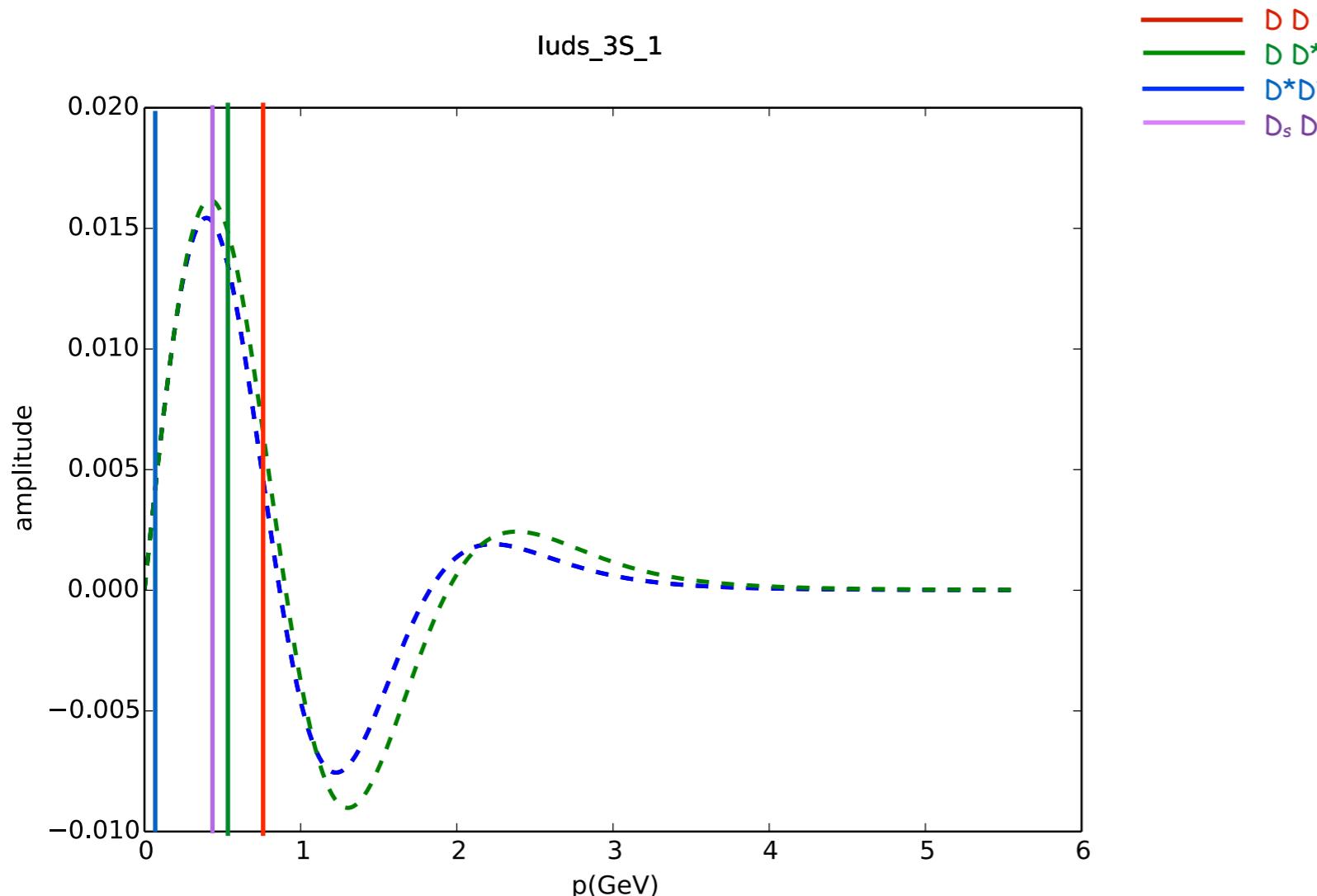
- $E = 4.00 \text{ GeV}$



- $p(\text{DD}) = 590 \text{ MeV}; p(\text{DD}^*) = 288 \text{ MeV}$

- The mass differences of heavy-light mesons produces large effects in the decay amplitudes to exclusive channels

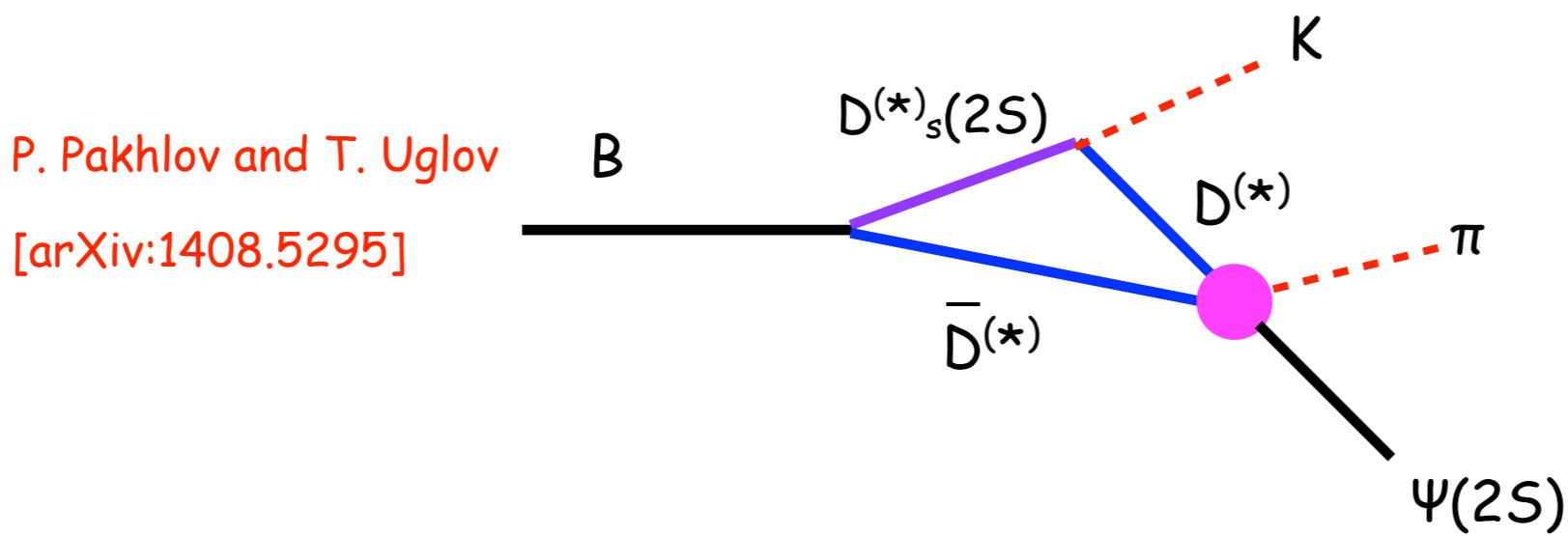
- $E = 4.02 \text{ GeV}$



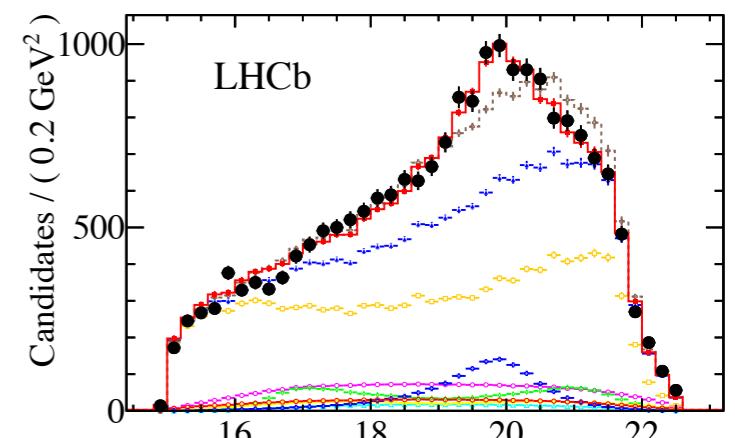
- $p(\text{DD}) = 740 \text{ MeV}; p(\text{DD}^*) = 530 \text{ MeV};$
 $p(\text{D}^*\text{D}^*) = 85 \text{ MeV}; p(\text{D}_s\text{D}_s) = 406 \text{ MeV}$

Systematics: Other States

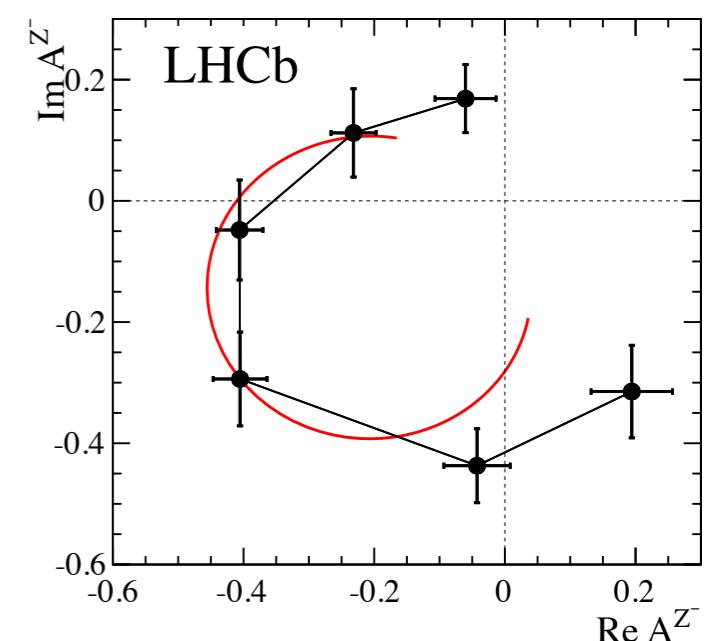
- $Z^-(4430)$: seen in $B^0 \rightarrow K^+ \pi^- \psi'$
 - $J^P = 1^+$; $M = (4,475 \pm 7 \pm [15/25]) \text{ MeV}$; $\Gamma = (172 \pm 13 \pm [37/34]) \text{ MeV}$
 - Resonance behavior observed.
 - Same mechanism in B-decays with $D_s(2S)$ states?
 - $D_s^*(2S)$ $M = 2,709 \pm 4 \text{ MeV}$ $\Gamma = 117 \pm 13 \text{ MeV}$
 - $B \rightarrow D_s(2^3S_1) D^*$, $D_s(2^1S_0) D^*$, or $D_s(2^3S_1) D$ then
 - $D_s(2^3S_1) \rightarrow K^+ D^{*-}$ or $K^+ D^-$; $D_s(2^1S_0) \rightarrow K^+ D^{*-}$
 - Possible rescattering explanation



- $X(5568)$: decaying into $B_s \pi^+$
 - by observed by Dzero but not confirmed by LHCb

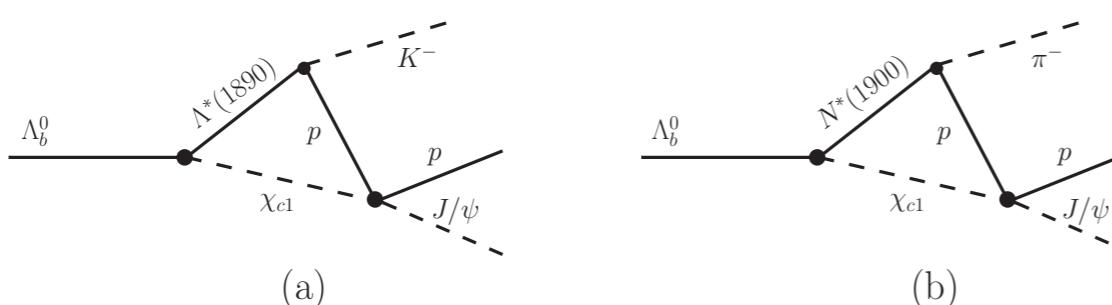


LHCb [arXiv:1404.1903]



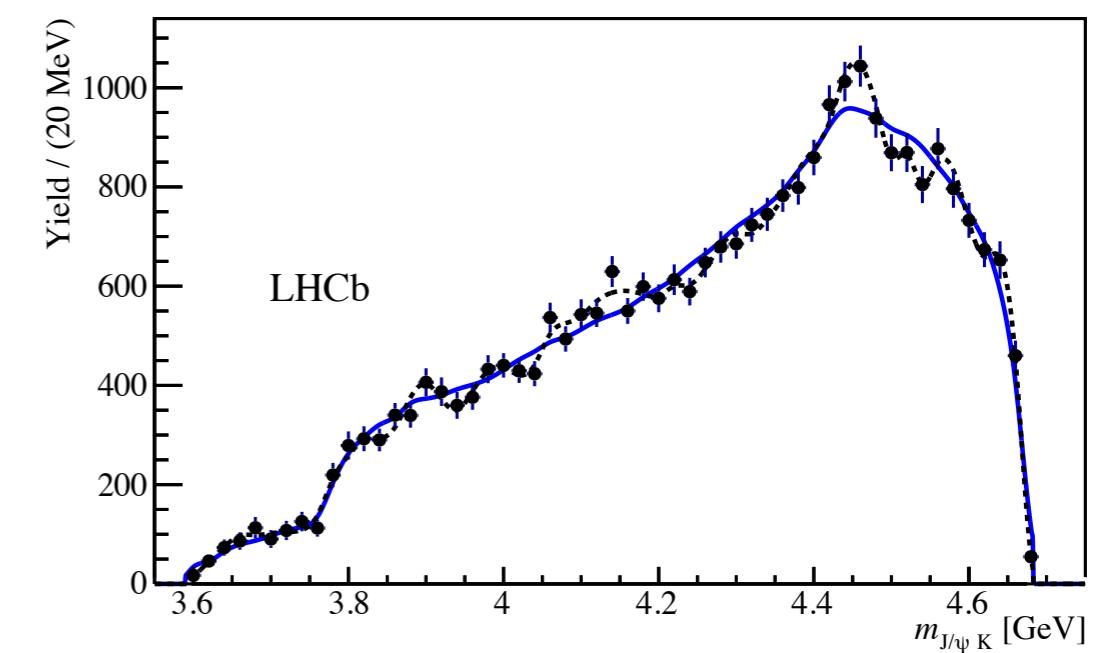
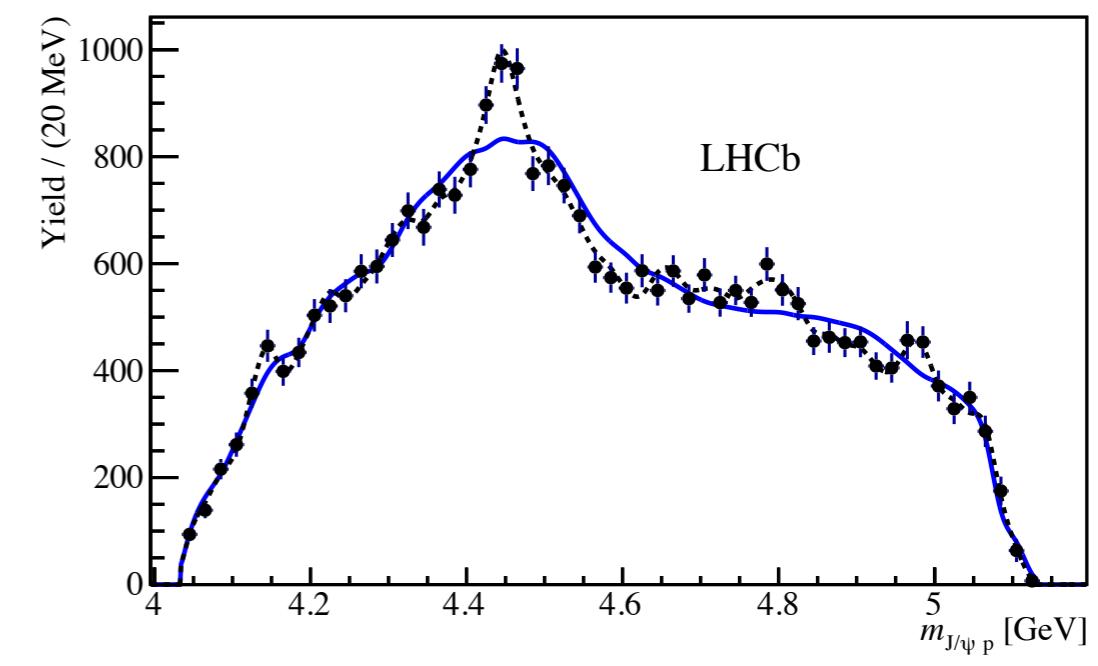
- Pentaquarks: $[\Lambda_b \rightarrow p J/\psi K]$ weak decay]

- $P_c(4450)$ - $J^P = 5/2^+$; $M = (4,449.8 \pm 1.7 \pm 2.5) \text{ MeV}$; $\Gamma = (39 \pm 5 \pm 19) \text{ MeV}$
- $P_c(4380)$ - $J^P = 3/2^-$; $M = (4,380 \pm 8 \pm 29) \text{ MeV}$; $\Gamma = (205 \pm 18 \pm 86) \text{ MeV}$
- complicated analysis required.
- possible $J/\psi K$ state investigated also
- Note nearby thresholds
 - χ_{c1} p threshold 4,448 MeV
 - Maybe a cusp effect?

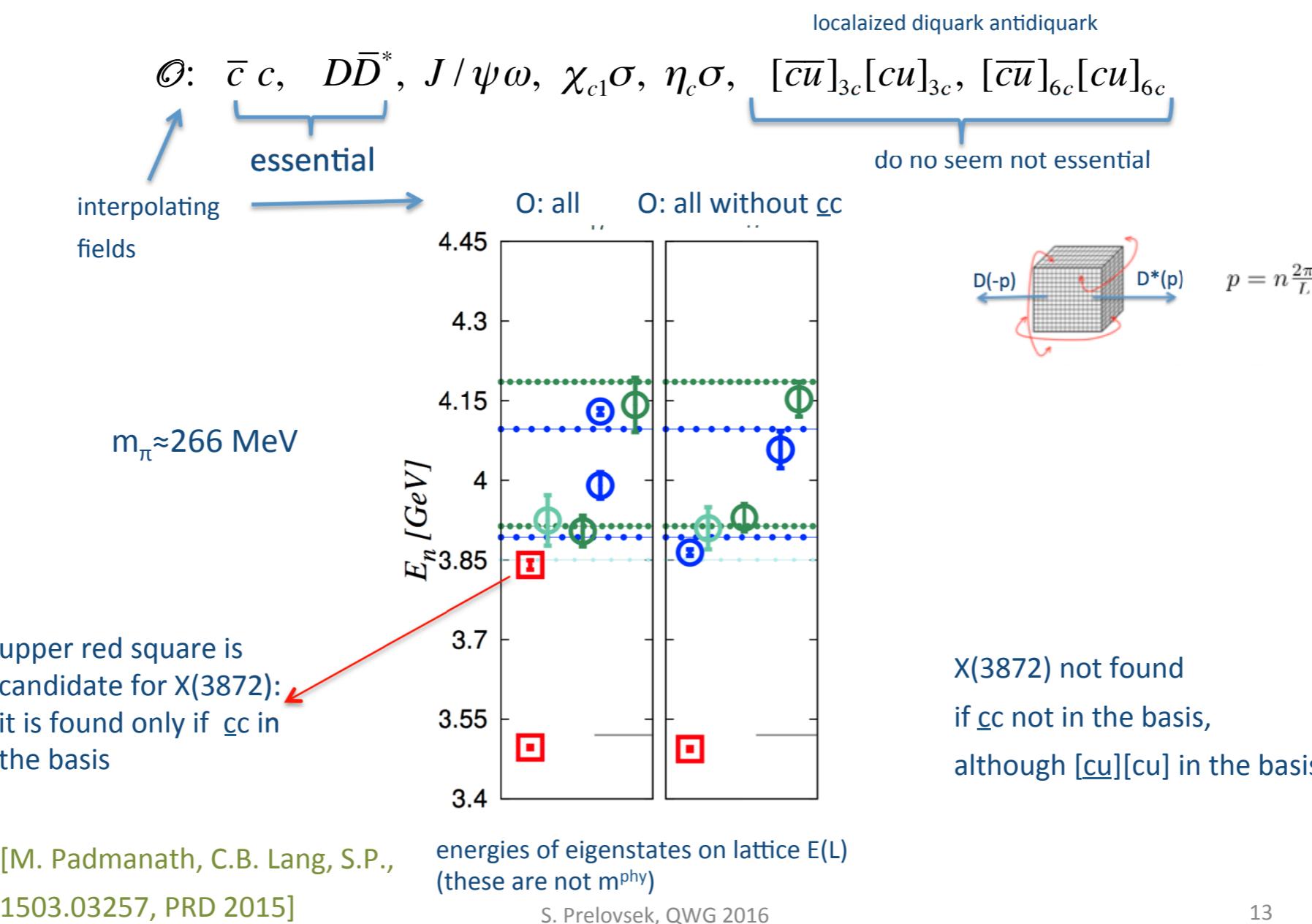


F.-K. Guo, U.-G. Meißner, W. Wang and Z. Yang
[\[arXiv:1507.04950\]](https://arxiv.org/abs/1507.04950)
 F.-K. Guo, U.-G. Meißner, J. Nieves and Z. Yang
[\[arXiv:1605.05113\]](https://arxiv.org/abs/1605.05113)

LHCb: [arXiv:507.03414, 1604.05708]



Which Fock components are essential for X(3872) with $I=0$?



Many surprises still ahead?

- The dynamics of the new states is likely a cocktail of the models so far proposed. Lattice QCD may provide some answers. More experimental data will also clarify the situation:
 - Resolve the status of (cc) new exotic states only seen by one experiment.
 - HQS predicts the expectations (cc) \rightarrow (bb) within a given model. Provides a test for various models.
- We see enhancements (resonances) at two heavy-light meson thresholds for I=1 channels. What about the rest of the SU(3) nonet?
 - For strange heavy-light meson pair thresholds: Resonances and hadronic transitions with single η and ϕ light hadrons?
 - No wide $j^P = \frac{1}{2}^+$ heavy-light mesons in charm or bottom systems \rightarrow no sequential transitions (as in the $\Upsilon(5S)$ system).
 - $M(D_s^+ D_s^{-*}) = 4,081$; $M(D_s^{+*} D_s^{-*}) = 4,225$; $M(2^3P_1) = 4,310$ MeV \rightarrow no analogy of $X(3872)$.
 - Narrow $D_P(\frac{1}{2}^+) + D_S(\frac{1}{2}^-)$ thresholds? (and B analogs) - This is answered now
 - Also possible in decays of B mesons - $D D_s^*$, $D^* D_s$, $D^* D_s^*$ states.