Opportunities in Quarkonia

Estia Eichten
Fermilab

XIV International Workshop on
Hadron Structure and Spectroscopy
Cortona, Italy
2-5 April, 2017

Outline

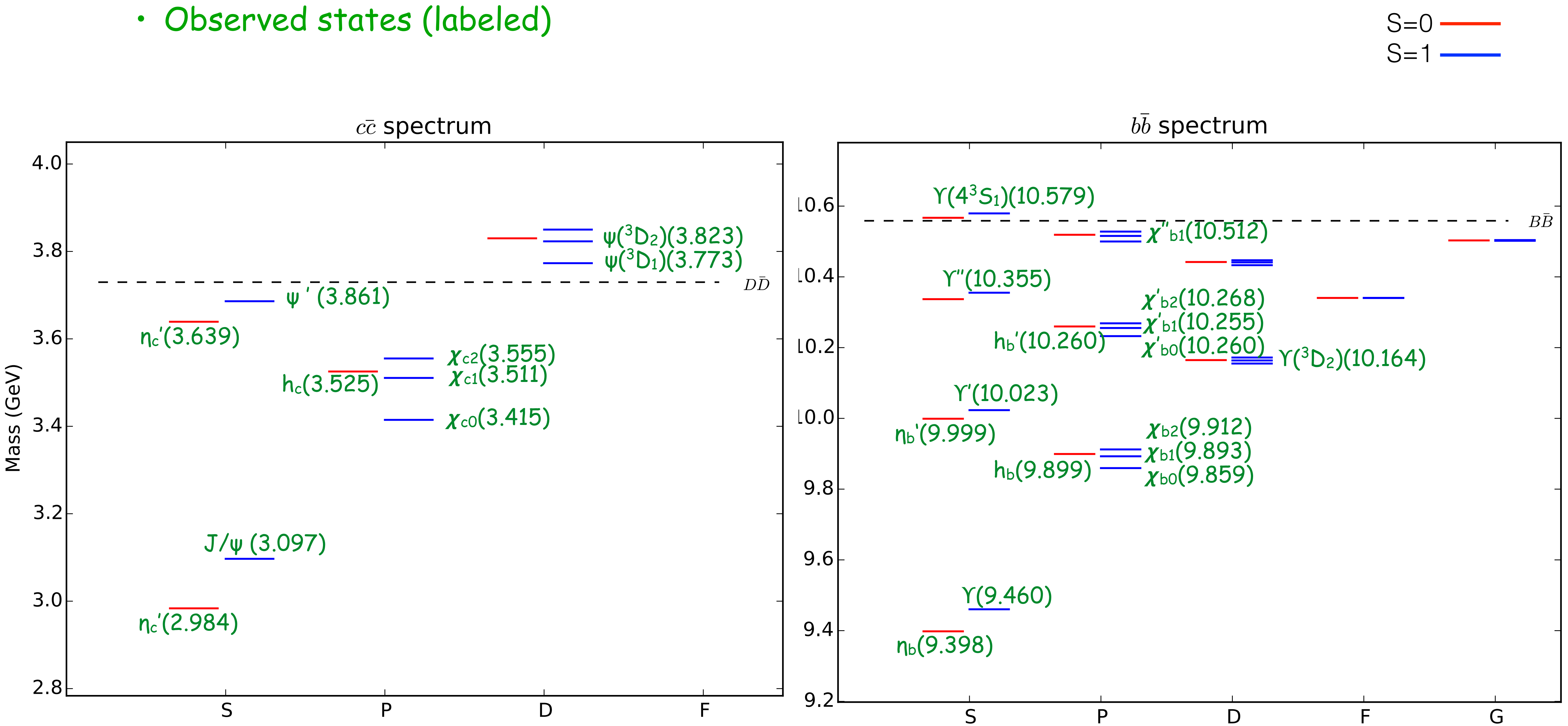
- The Threshold Region:
  - $(c\bar{c})$ and $(b\bar{b})$ states
  - Strong Decays Near Threshold
- New states, XYZ, Tetraquarks
- Unexplored Territory
- Conclusions

QCD with Heavy Quarks

- QCD dynamics greatly simplifies for heavy quarks ($m_Q \gg \Lambda_{QCD}$)
- 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) and (bbq)] and between [(cqq) and (bqq)]
  - QED analog - hydrogen atom (e^-p)
- For non relativistic ($Q\bar{Q}$): 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)



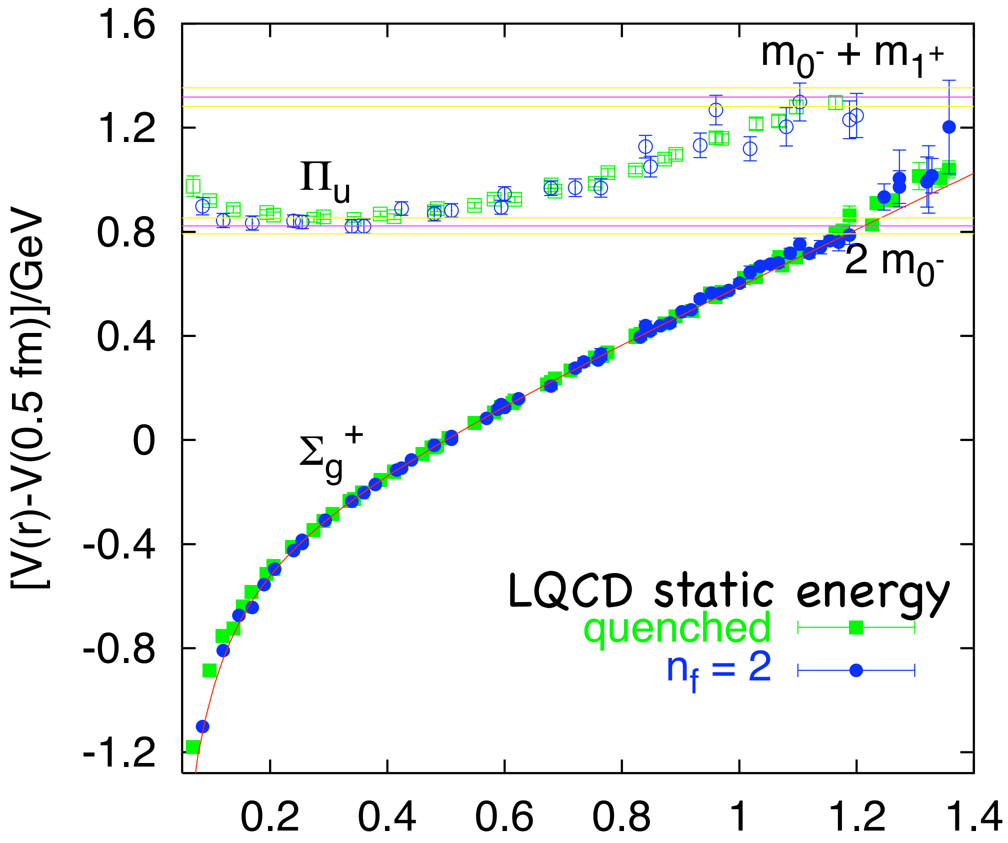
- 2 narrow states still unobserved

18 narrow states still unobserved

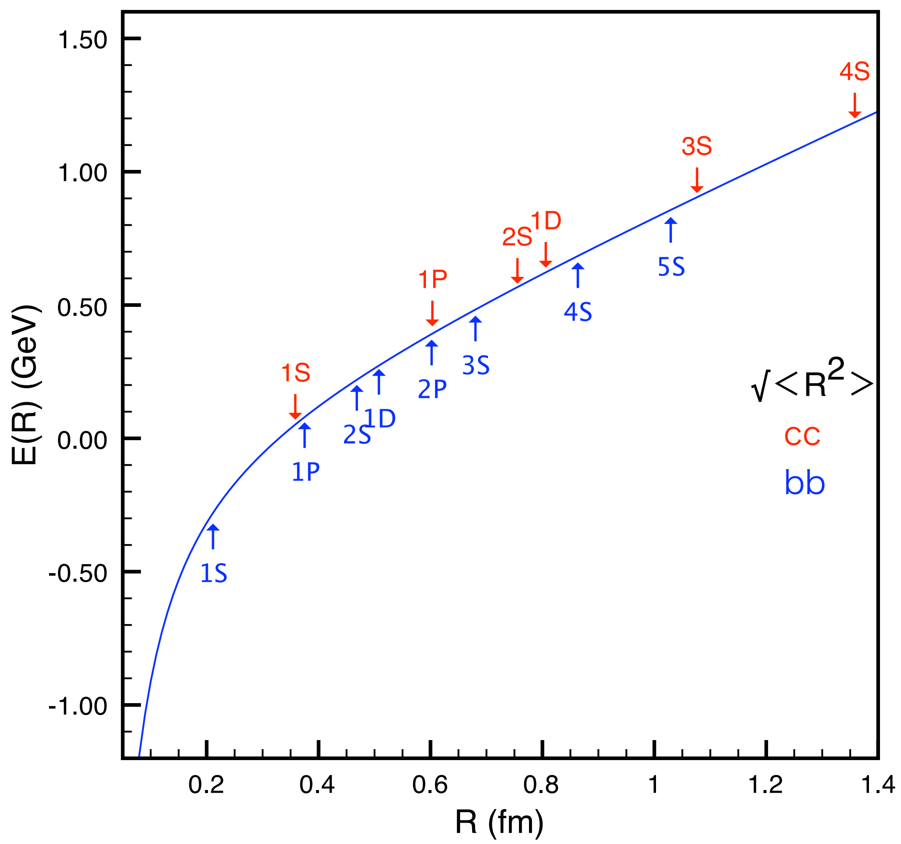
Why it works so well

- Lattice calculation V(r), then SE

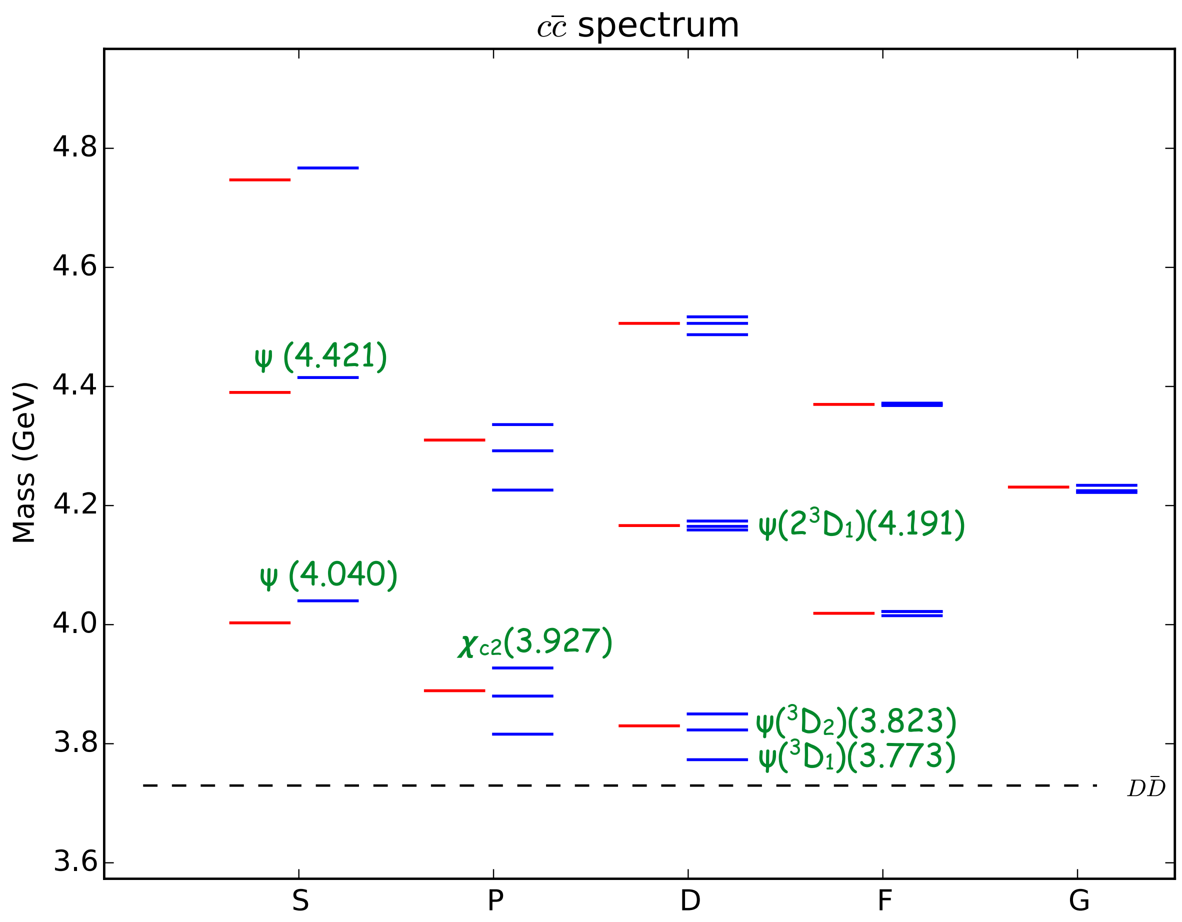
$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}_{Q\bar{Q}}^2\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\,u(r)$$

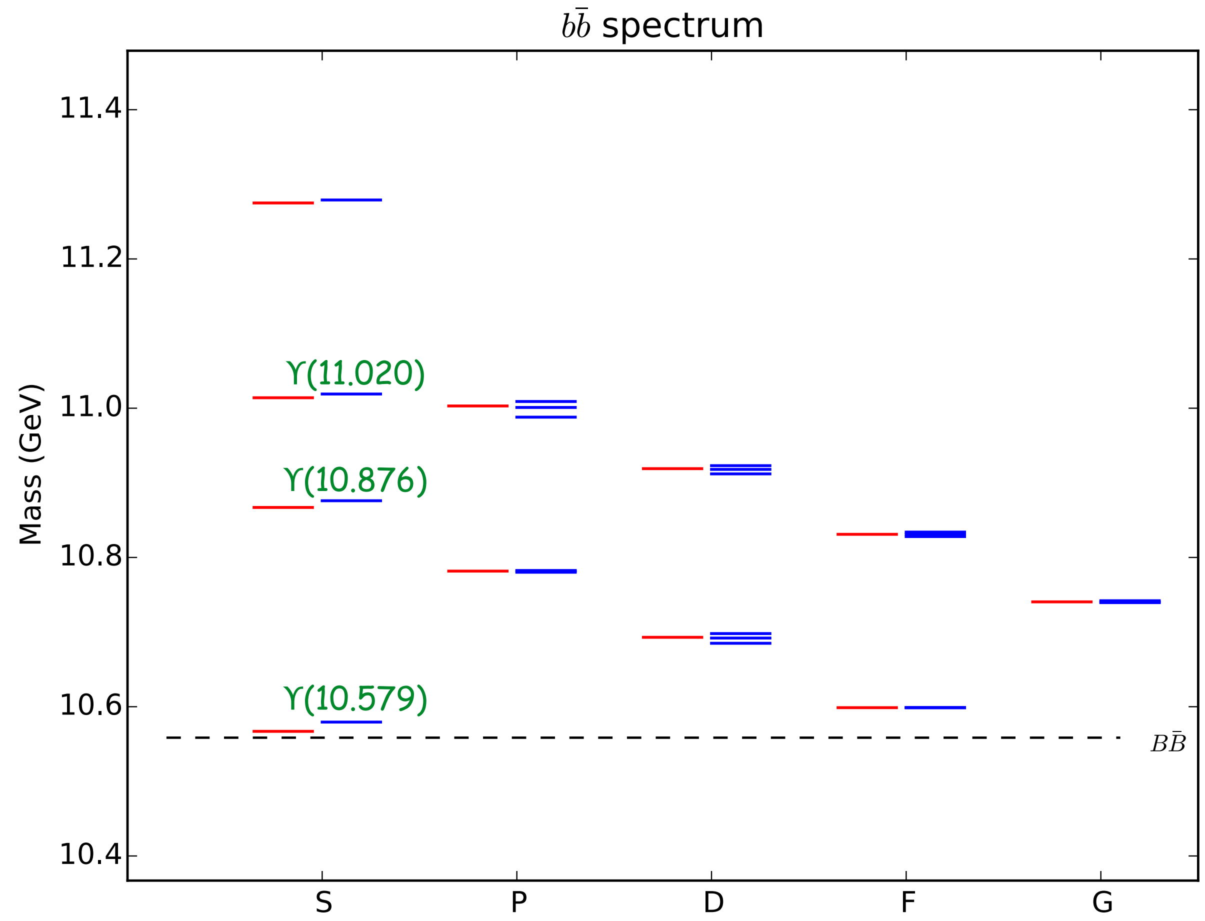


- What about the gluon and light quark degrees of freedom of QCD?
- Two thresholds:
  - Usual $(Q\bar{q})+(q\bar{Q})$ decay threshold
  - Excite the string - hybrids
- Hybrid states will appear in the spectrum associated with the potential Π_u, ...
- In the static limit this occurs at separation: r ≈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



- Observed quarkonium states above threshold

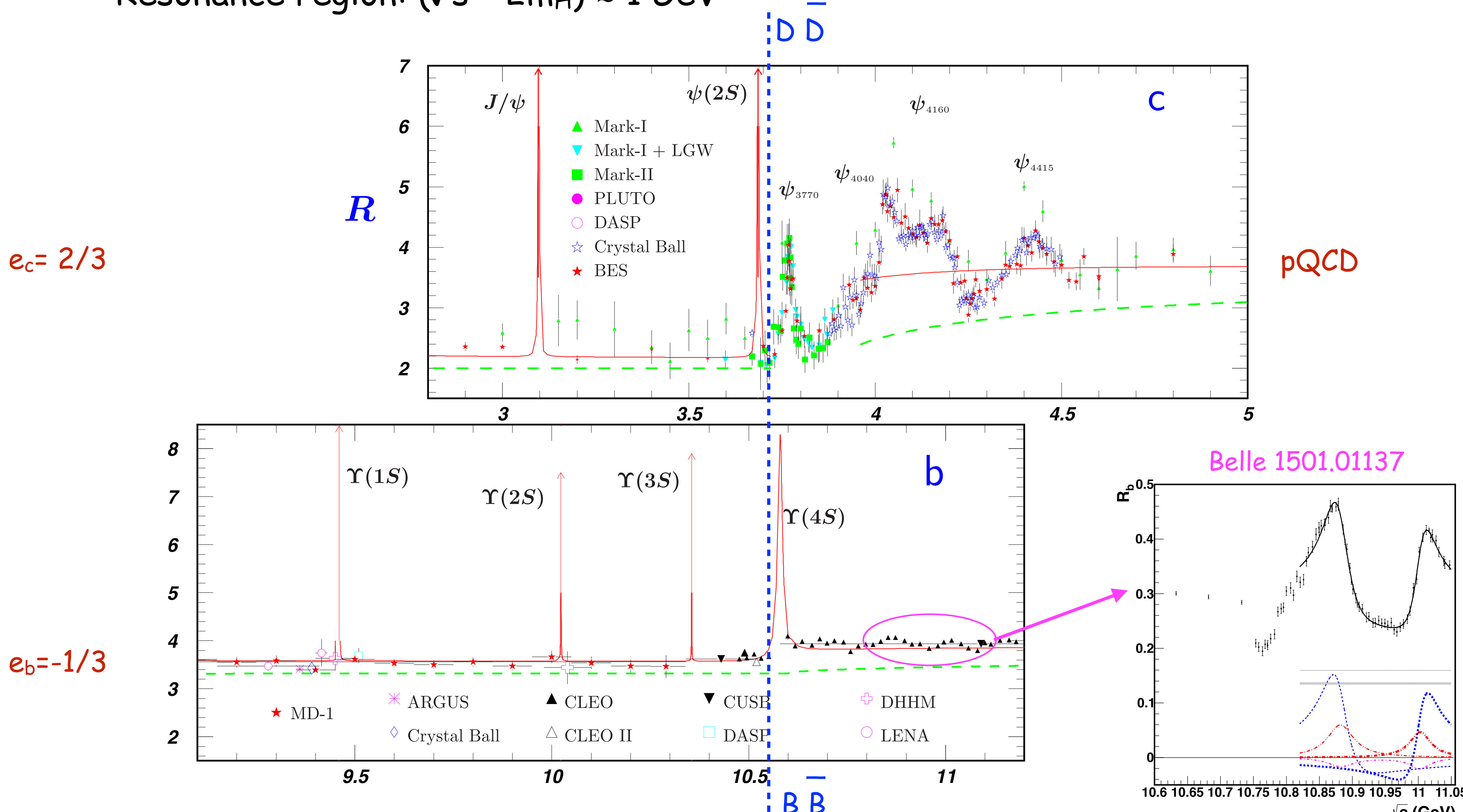




Crossing the Threshold

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

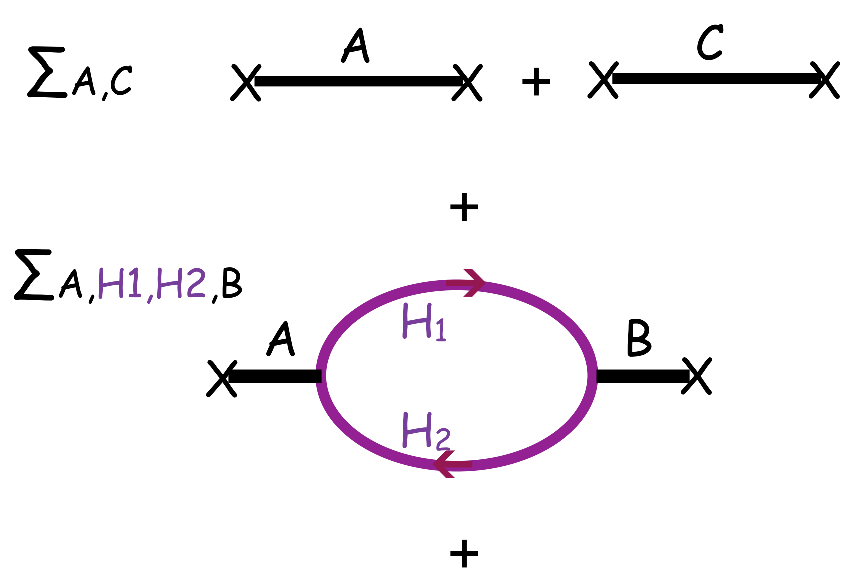
- $R = \sigma(e^+e^- \to \gamma^* \to \text{hadrons})/\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)$ $J^{PC} = 1^{--}$
  - Resonance region: $(\sqrt{s} - 2m_H) \lesssim 1$ GeV



- Two pictures of R: Quark-Hadron Duality
  - $\Delta R(W) = \frac{6\pi}{W^2}\,\rho_c(W)$: $-(g_{\mu\nu}q^2 - q_\mu q_\nu)\rho_c(W)$

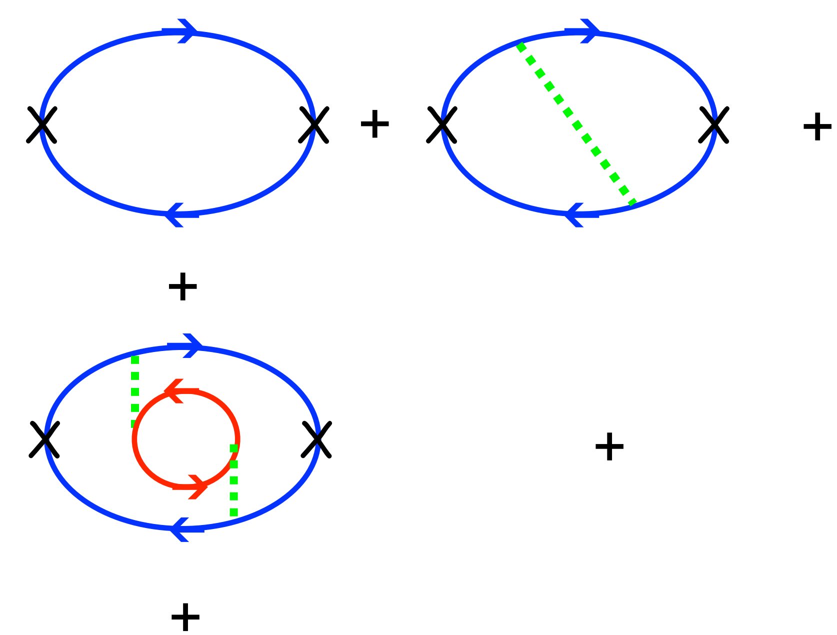
$$= \int d^4x\, e^{iqx}\langle 0|j_\mu(x)j_\nu(0)|0\rangle\Big|_{\text{charm}}\,'$$

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



≡

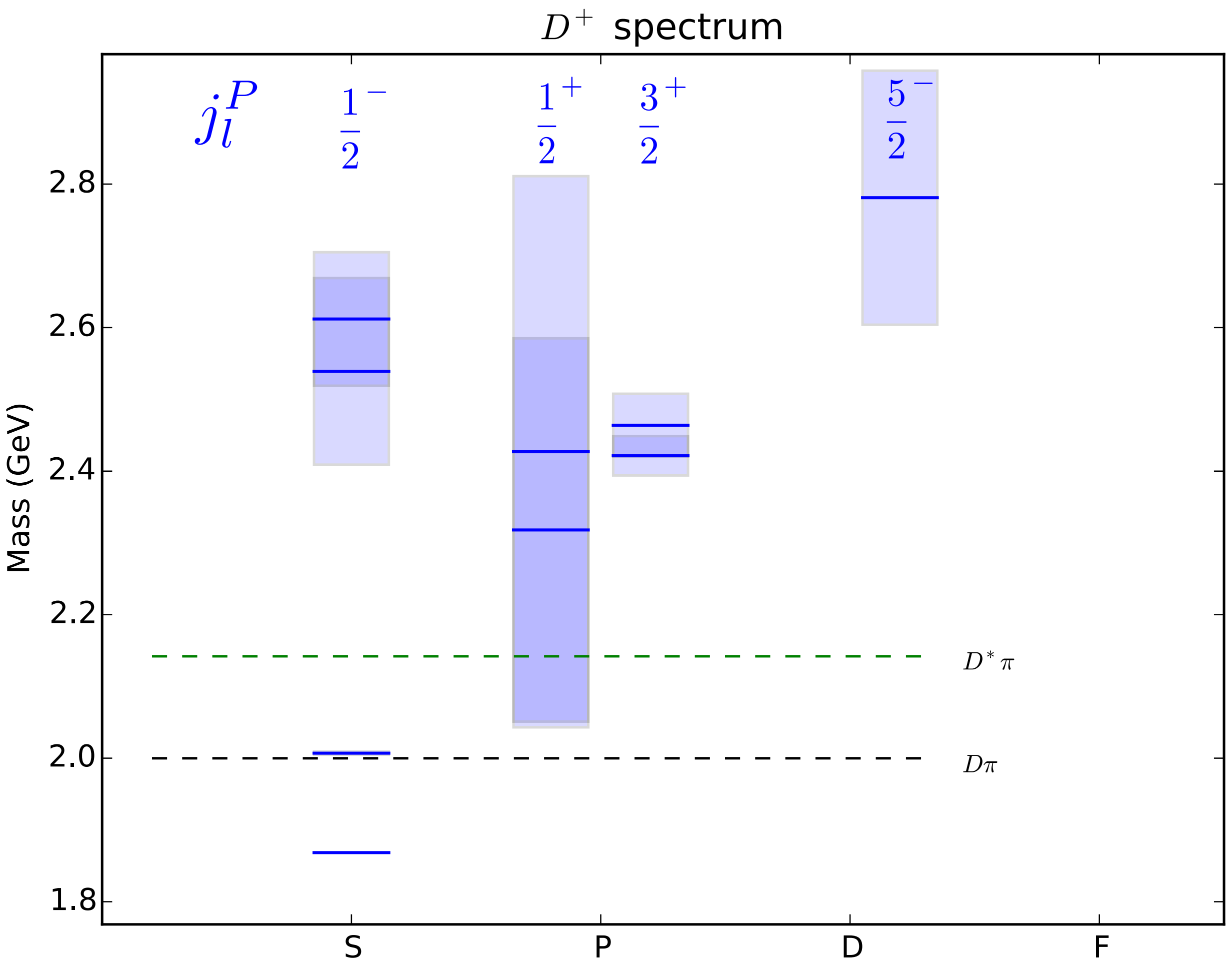
QCD - perturbative
Q, g

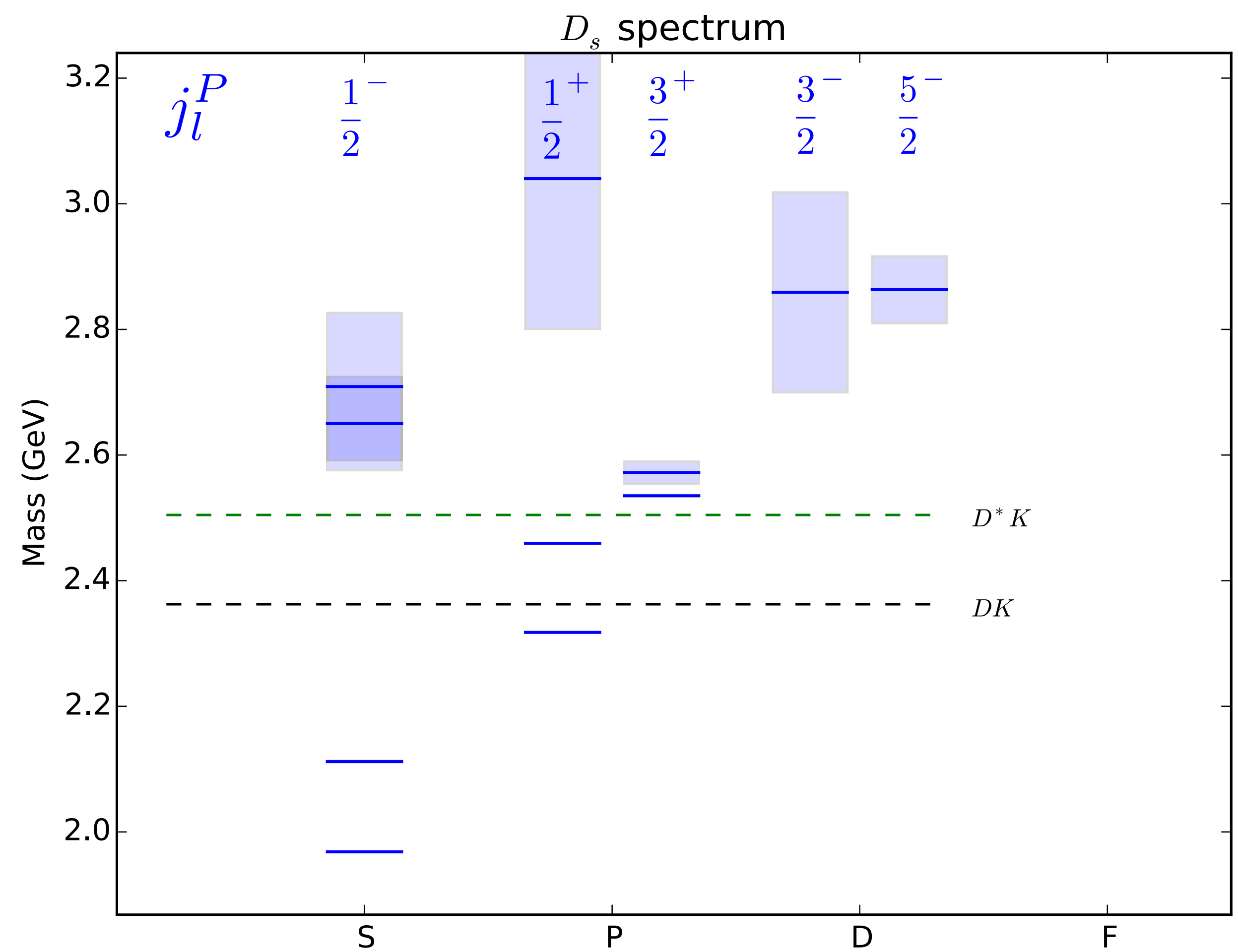


Simple expansion near threshold.

Simple expansion far above threshold.

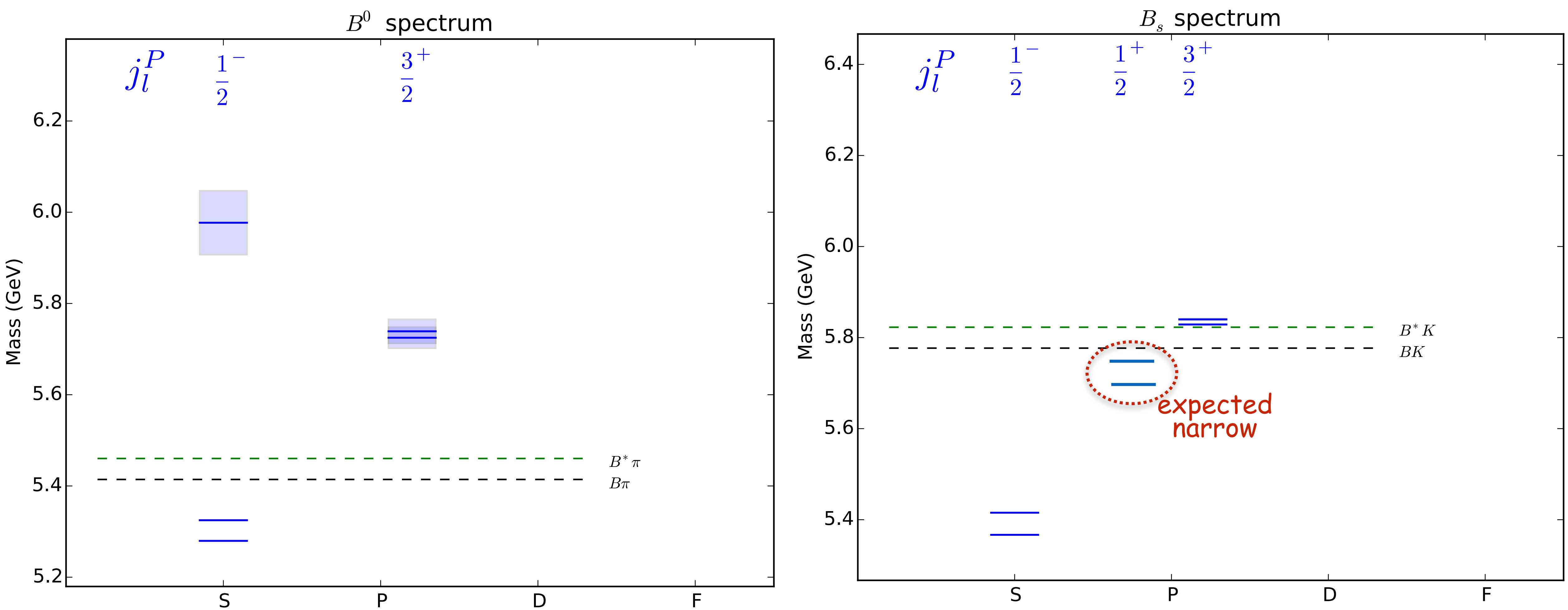
- Observed states in D meson systems:





- 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

- Lattice expectations:

Table 5: Comparison of masses from this work to results from various model based calculations; all masses in MeV.

J^P	0^+	1^+
Covariant (U)ChPT [24]	5726(28)	5778(26)
NLO UHMChPT [19]	5696(20)(30)	5742(20)(30)
LO UChPT [17, 18]	5725(39)	5778(7)
LO χ-SU(3) [16]	5643	5690
HQET + ChPT [20]	5706.6(1.2)	5765.6(1.2)
Bardeen, Eichten, Hill [15]	5718(35)	5765(35)
rel. quark model [5]	5804	5842
rel. quark model [22]	5833	5865
rel. quark model [23]	5830	5858
HPQCD [30]	5752(16)(5)(25)	5806(15)(5)(25)
this work	5713(11)(19)	5750(17)(19)

C. B. Lang, Daniel Mohler, Sasa Prelovsek, R. M. Woloshyn [arXiv:1501.01646]

LQCD calculation includes the mixing of the two meson thresholds.

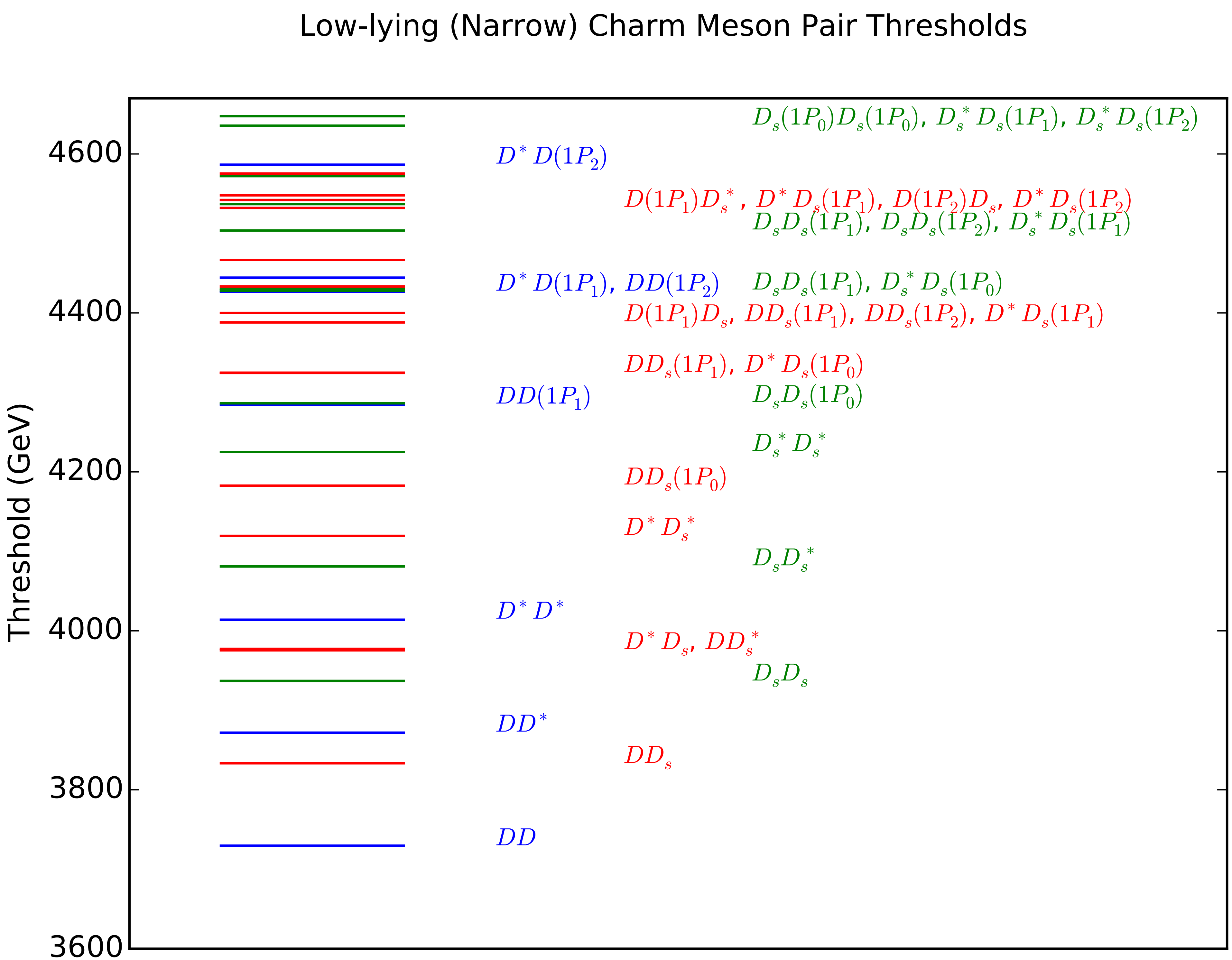
- Branching fractions:

system	transition	Q(keV)	overlap	dependence	Γ (keV)
$(b\bar{s})$	$0^+ \to 1^- + \gamma$	293	2.536	$r_{\bar{b}s}$	58.3
	$0^+ \to 0^- + \pi^0$	297		$G_A\delta_{\eta\pi 0}$	21.5
	total				79.8
$(b\bar{s})$	$1^+ \to 0^+ + \gamma$	47	0.998	$r'_{\bar{b}s}$	0.061
	$1^+ \to 1^- + \gamma$	335	2.483	$r_{\bar{b}s}$	56.9
	$1^+ \to 0^- + \gamma$	381	2.423	$r_{\bar{b}s}$	39.1
	$1^+ \to 1^- + \pi^0$	298		$G_A\delta_{\eta\pi 0}$	21.5
	$1^+ \to 0^- + 2\pi$	125		$g_A\delta_{\sigma_1\sigma_3}$	0.12
	total				117.7

W.Bardeen, E.E., C. Hill PR D68 054024 (2003) [hep-ph/0305049]

- Requires identifying low momentum photons and π^0 s.

Low-lying thresholds



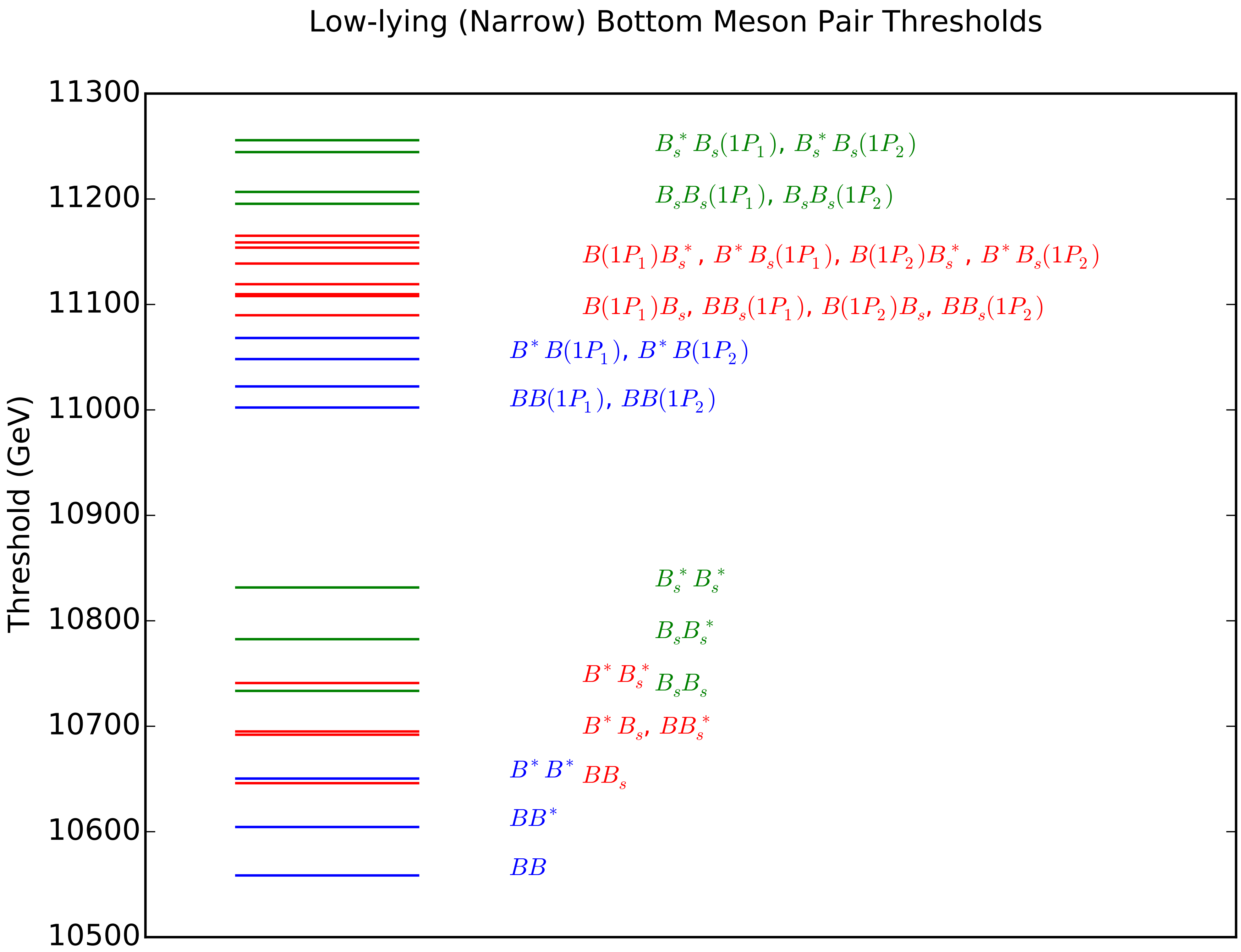
Narrow-Wide Thresholds

D_s^* $D(P_1)$

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

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

D $D(P_0)$



Narrow-Wide Thresholds

B_s^* $B(P_1)$

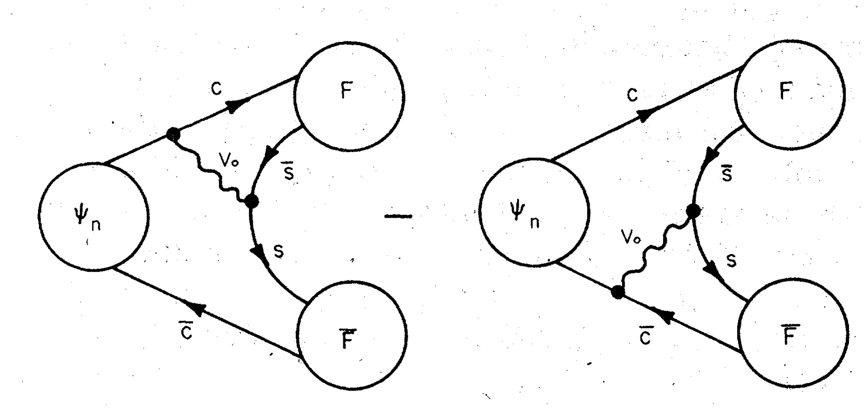
B_s^* $B(P_0)$; B_s $B(P_1)$

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

B^* $B(P_0)$, B $B(P_1)$

B $B(P_0)$

- 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)

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

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

where $$\Omega^i_{nL,mL'}(W) = \sum_l \int_0^\infty P^2 dP \frac{H^i_{nL,mL'}(P)}{W - E_1(P) - E_2(P) + i0}$$

$$H^i_{nL,mL'}(P) = f^2 \sum_l C(JLL';l) I^l_{nL}(P) I^l_{mL'}(P)$$

Statistical factor

Reduced decay amplitudes I(p)

- Reduced decay amplitudes I(p)

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

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): $(t = y\sqrt{\beta_S})$

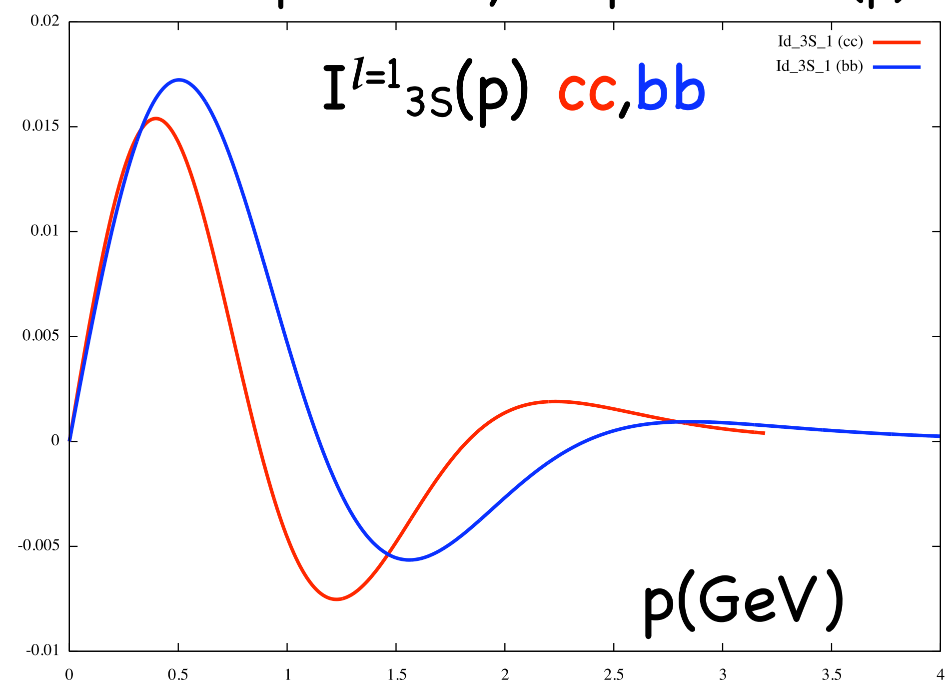
$$\Phi(t) = te^{-t^2} + (\pi/2)^{1/2}(t^2 - 1)e^{-t^2/2}\,\mathrm{erf}(t/\sqrt{2})$$

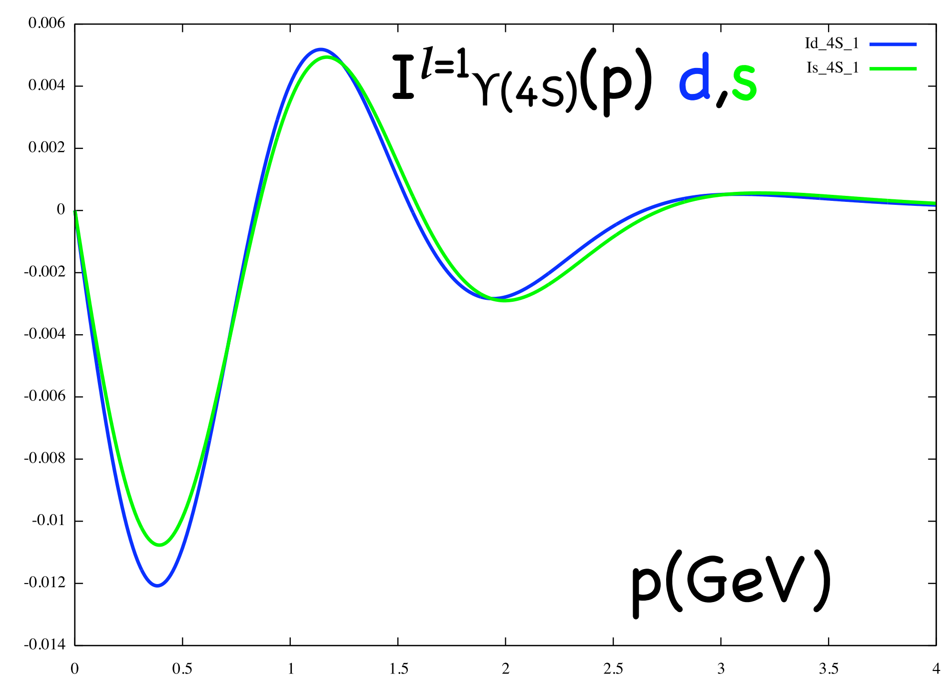
Using HQET this function Φ(t) is the same for all final states in a j_l^P multiplet.

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.

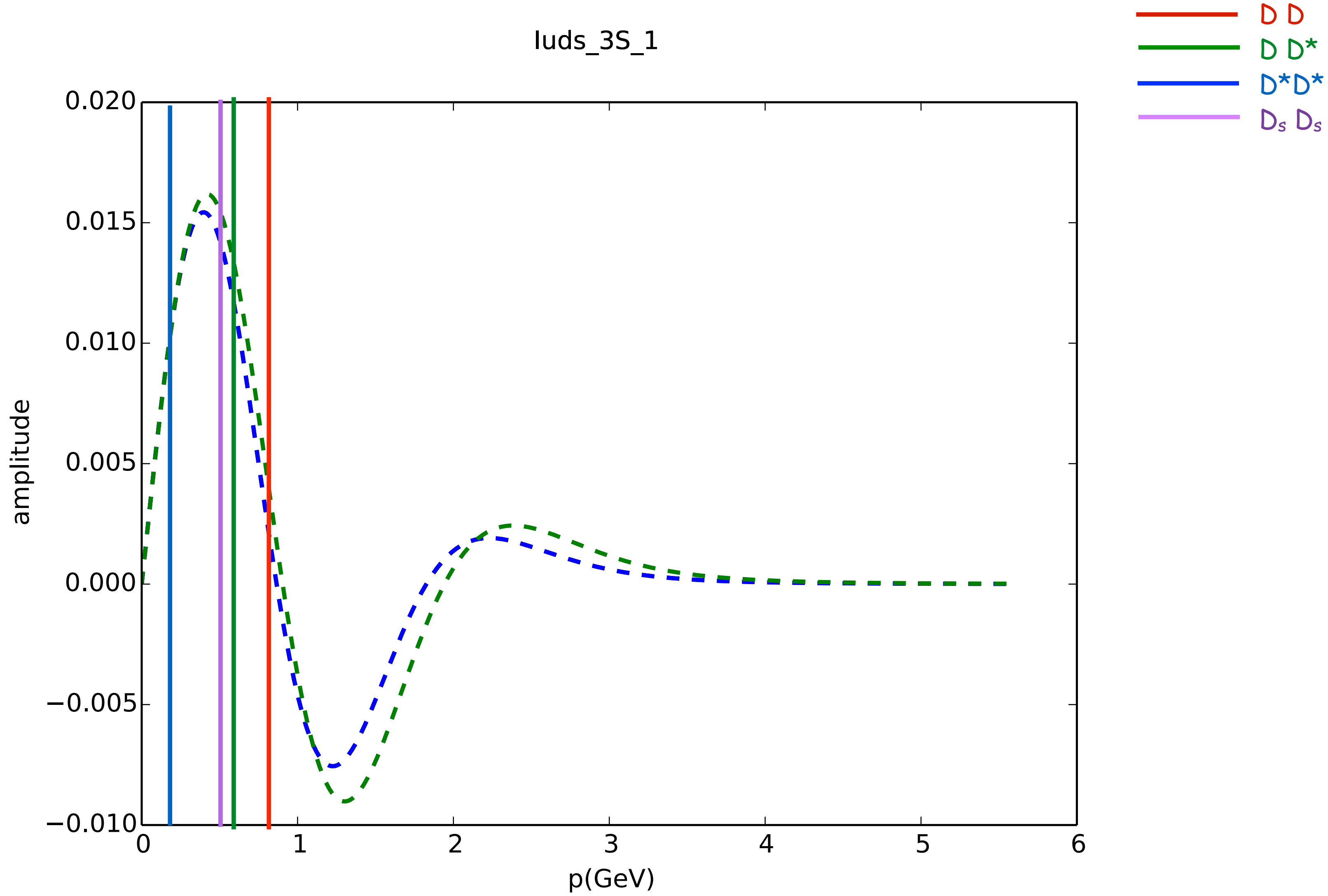
Sample decay amplitudes I(p)



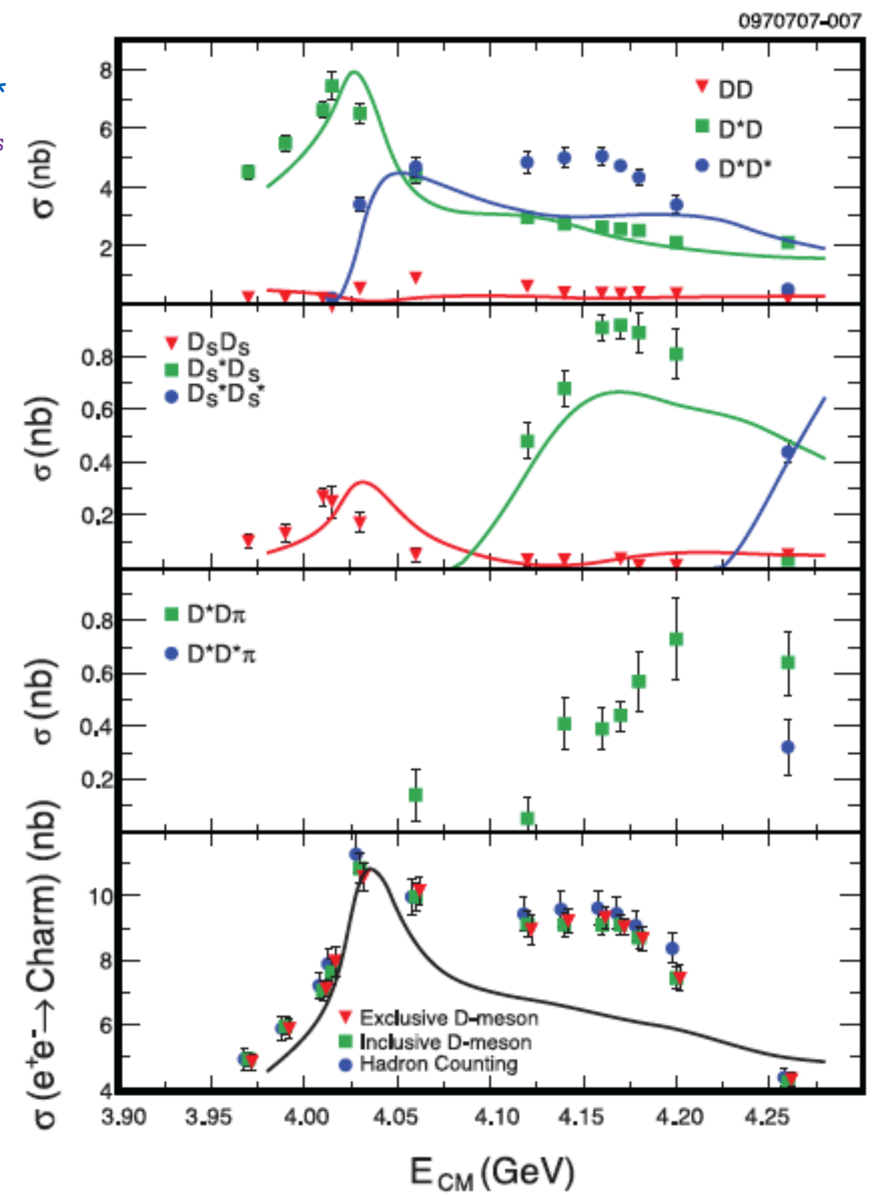


- The mass differences of heavy-light mesons produces large effects in the decay amplitudes to exclusive channels.

• E = 4.04 GeV

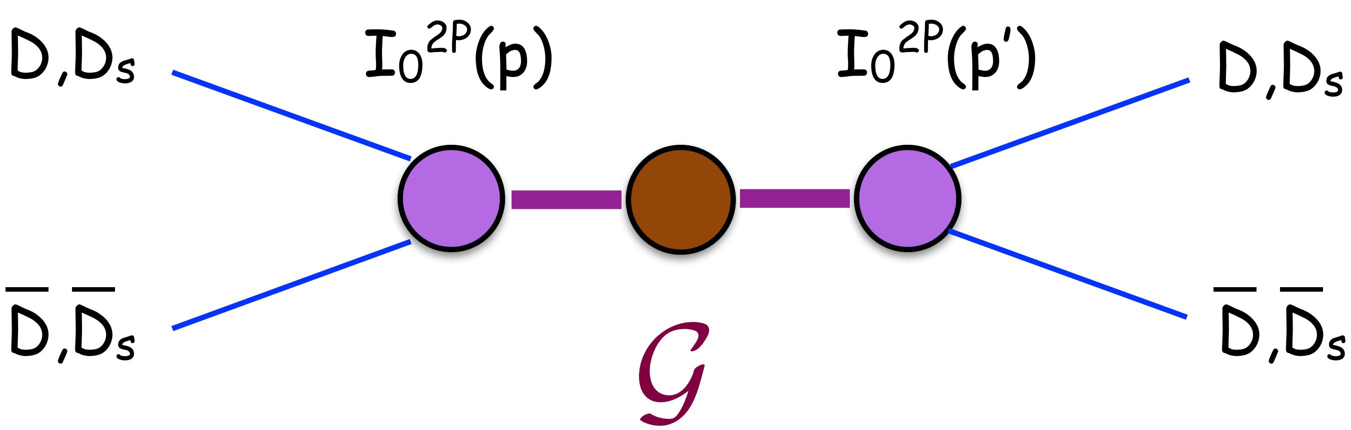


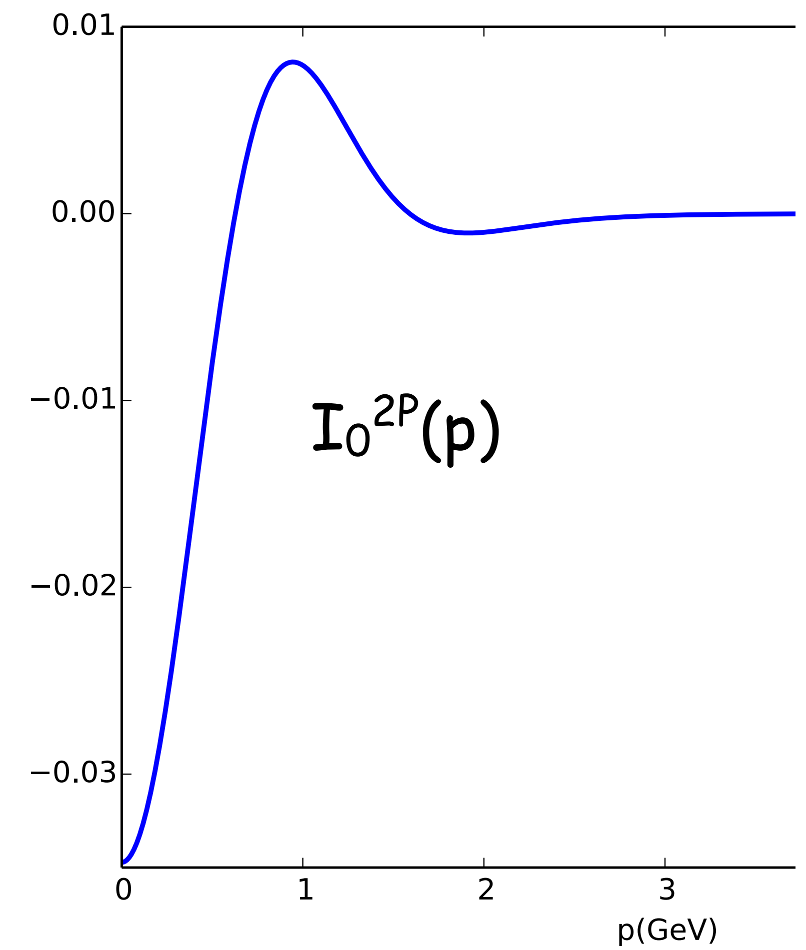
Observed exclusive channel rates



• p(DD) = 766 MeV; p(DD*) = 567 MeV; p(D*D*) = 218 MeV; p(D_sD_s) = 453 MeV

- These same reduced decay amplitudes I(p) determine the heavy-light meson two-body scattering amplitudes.
- Predict leading behavior of the T and K matrices in the threshold region.
- Example - S-wave $D_{(u,d,s)}\,\overline{D}^{(*)}_{(u,d,s)}$ scattering amplitude:





- For 2M(D) < W < 2M(D*) in the $J^{PC} = 0^{++}$ channel the cc(2^3P^0) state dominates. Elastic scattering below the Ds Ds threshold and two channels below 2M(D*).
- For M(D) + M(D*) < W < 2M(D*) in the $J^{PC} = 1^{++}$ channel the cc(2^3P_1) state dominates. Study the need for additional molecular X(3872).

Hadronic Transitions Above Threshold

- There are 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 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 $\eta + (Q\bar{Q})$.
  - Similarly important in ω and ϕ production.

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

Mass Splittings: $[[\{D^0, D^{0*}\}, \{D^+ D^{+*}\}], \{D_s, D_s^*\}]$

Degeneracies: {}: $1/m_c \to 0$, []:SU(3), []: isospin

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.

- ϒ(10860)

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

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

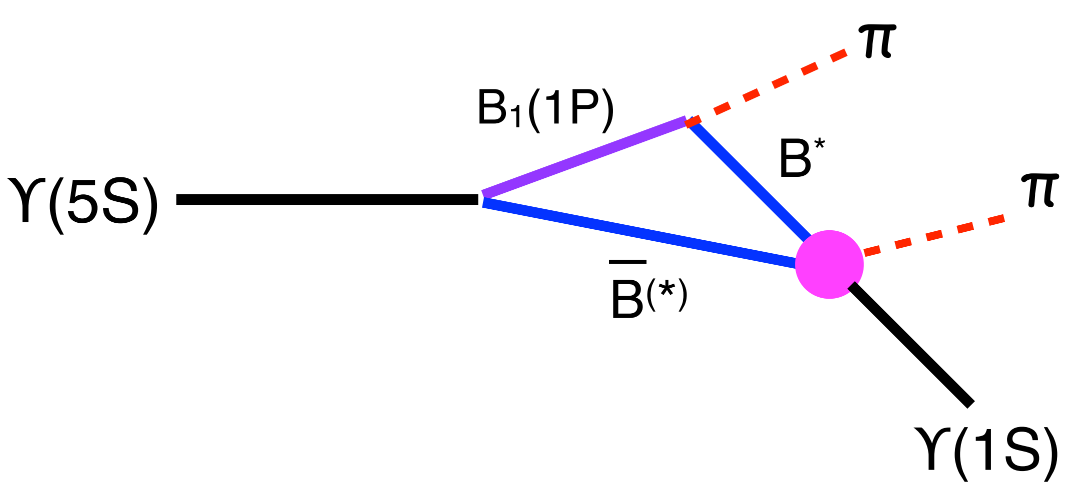
—> partial rate = 0.15 ± 0.08 MeV

- 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?

- Requires new mechanism for hadronic transitions
  - Dominant two body decays of the $\Upsilon(5S)$
  - Decays involving P-state heavy-light mesons:
    - $n^3S_1(Q\bar{Q})$ -> $1^{\frac{1}{2}+}P_J(Q\bar{q})$ + $1^{\frac{1}{2}-}S_{J'}(q\bar{Q})$ then
    - $1^{\frac{1}{2}+}P_J(Q\bar{q})$ -> $1^{\frac{1}{2}-}S_{J'}(Q\bar{q}')$ + ${}^1S_0$ $(q\bar{q}')$ 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.

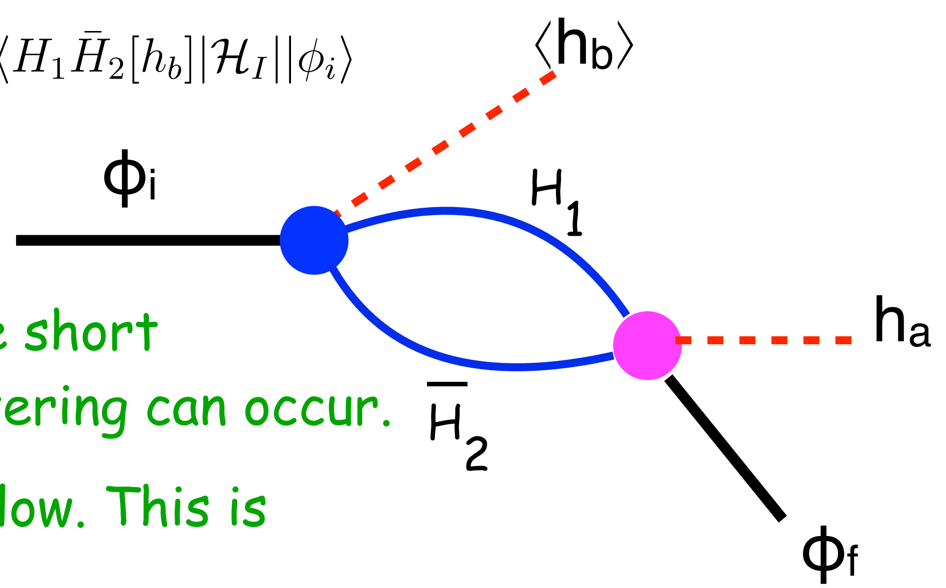
(3) The $B_1(1P)$ decay is S-wave

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

(5) No similar BB system is possible.

- 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).

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

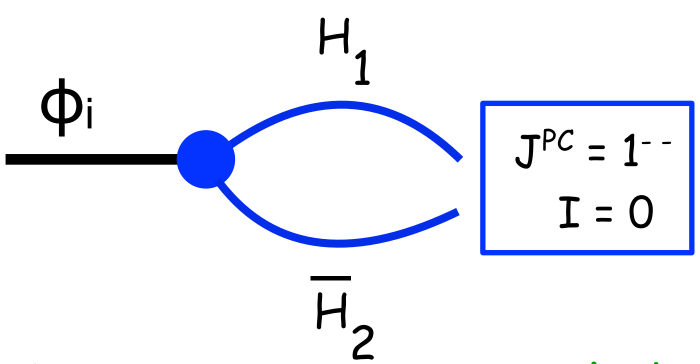


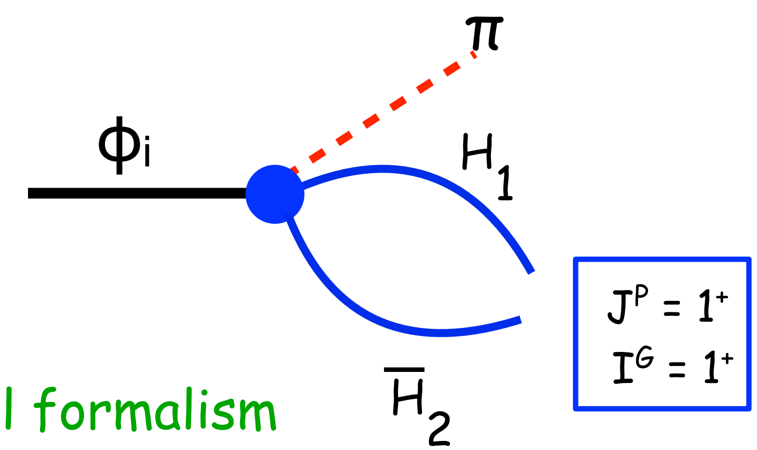
  - The time scale of the production process has to be short relative to the time scale over which H_1 H_2 rescattering can occur.
  - The relative velocity in the H_1 H_2 system must be low. This is only possible near threshold.
- Here we need not speculate on whether the observed rescattering is caused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

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

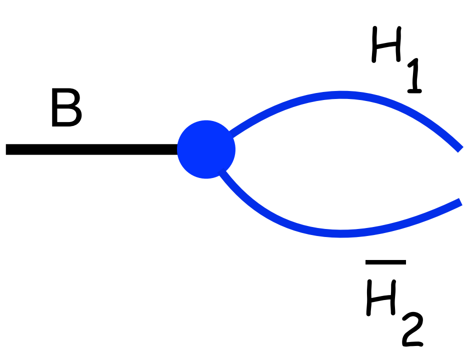
Four Quark States May Be Easily Produced at Two Heavy-Light Mesons S-wave Thresholds

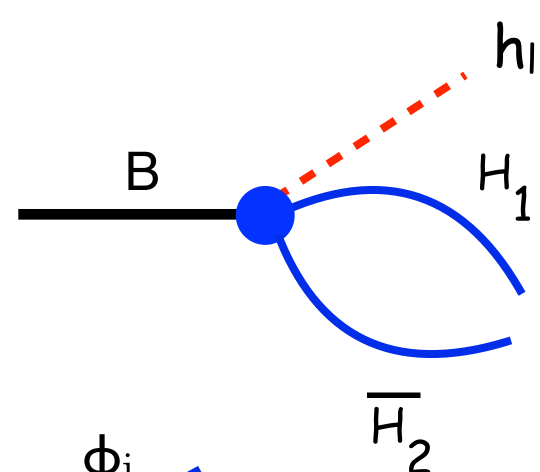
- Production modes: (Where to look for new surprises)
  - e+e- processes
    - direct sequential (dominant terms)

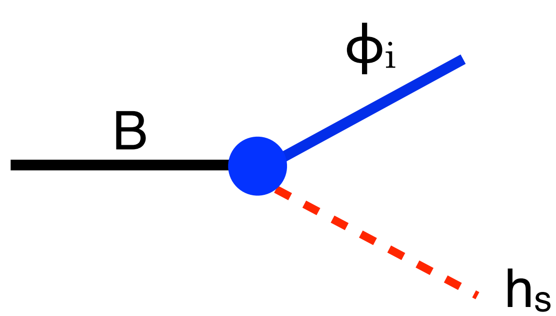




    - Can compute using coupled channel formalism
  - B weak decays
    - More quantum numbers accessible







Biggest Surprise:

Resonances are seen at these thresholds

XYZ States

- $X(3872)$ - the first surprising new state

S.-K. Choi et al. [Belle] (1287 cites)
PRL 91 (2003)262001 [hep-ex/0309032]

  - 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? $\dfrac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 2.46 \pm 0.64 \pm 0.29$

- $Y(4260)$- another surprise

B. Aubert et al. [BaBar] (653 cites)
PRL 95 (2005) 142001 [hep-ex/0506081]

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

- $Z^+_b(10607)$, $Z^+_b(10652)$ and $Z^+_c(3889)$, $Z^+_c(4024)$ - third surprises

A. Bondar et al. [Belle] (335 cites)
PRL 108 (2012) 122001 [arXiv:1110.2251]

M. Ablikim et al. [BESIII] (214 cites)
PRL 111 (2013) 242001 [arXiv:1309.1896]

  - $I = 1$ isospin triplets -> 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

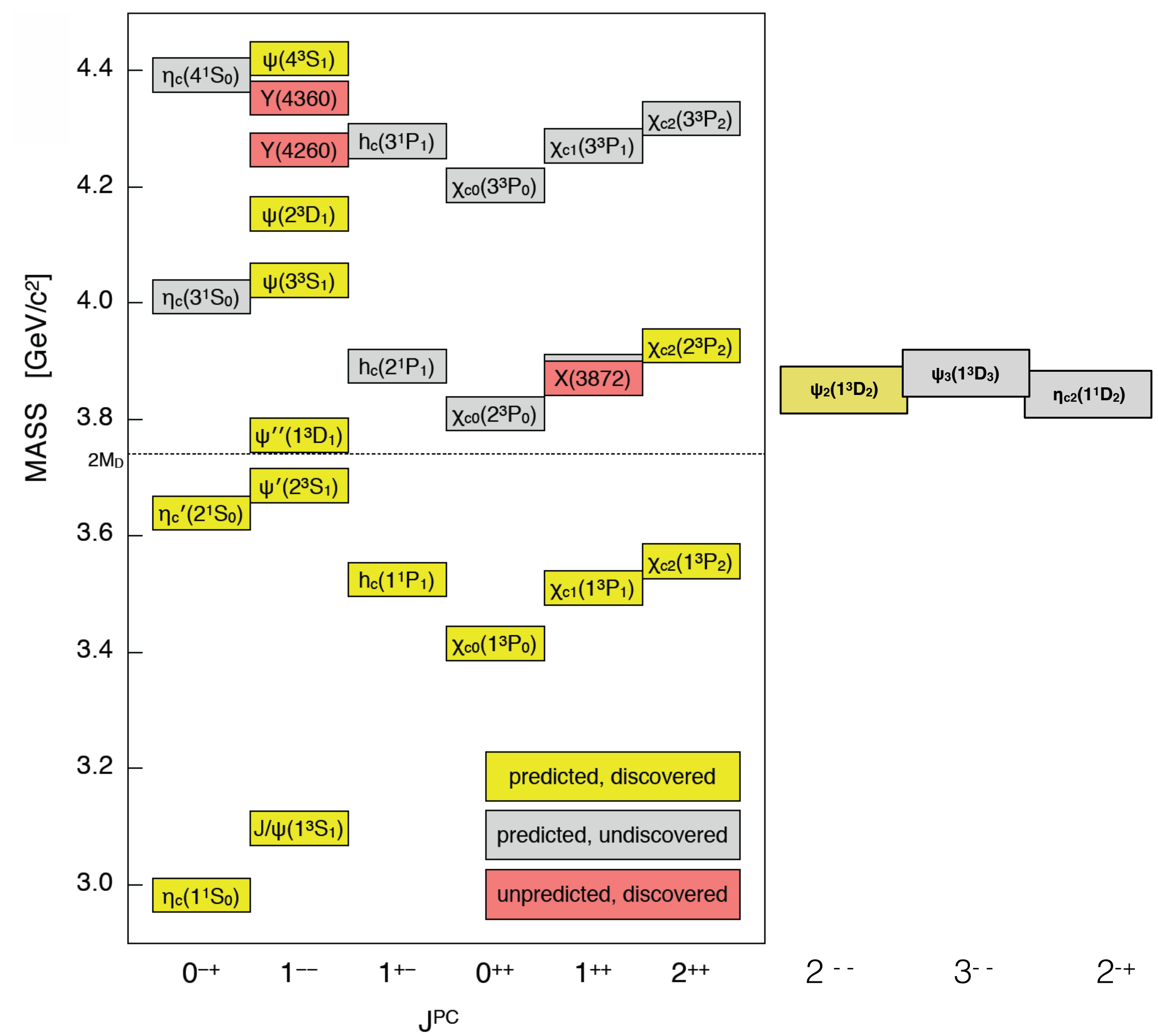
- Notation
  - Y denotes states observed directly in the charm contribution to e^+e^- -> hadrons:

    ⇒ $J^{PC} = 1^{--}$ 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) ($J^P = 5/2^+$), …

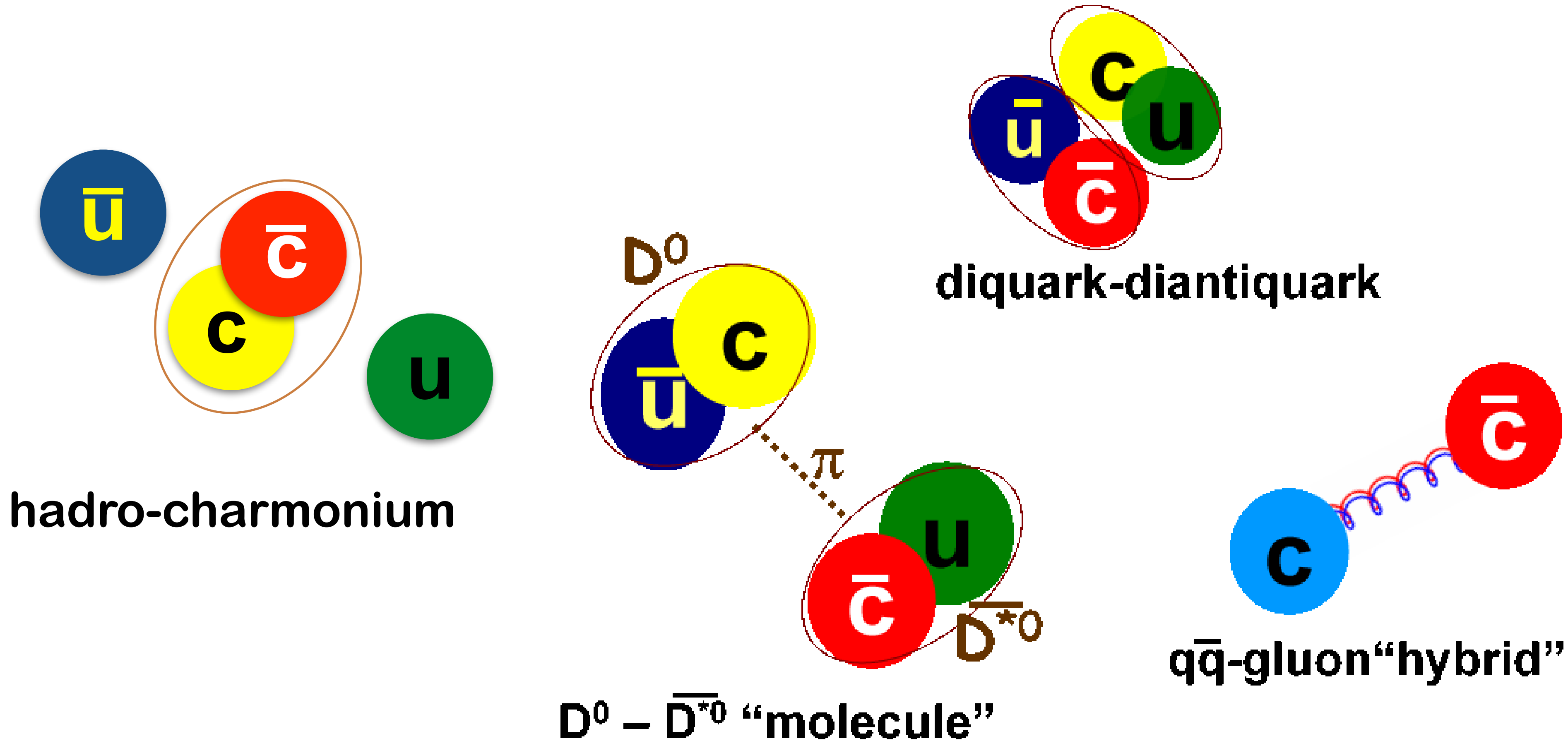


- Updated from PDG - other X states need more information

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

- Proof of Existence of Bound Tetraquarks in the Heavy Quark Limit

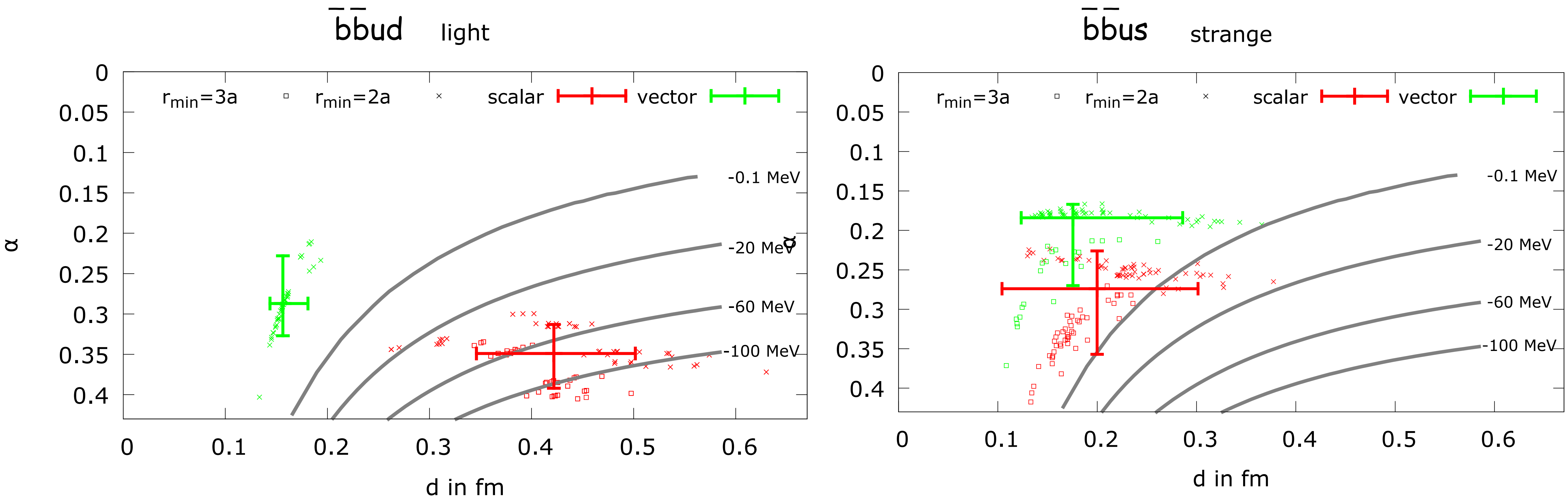
  - Consider a tetraquark system $(\bar{Q}\bar{Q}q_1q_2)$ with two light quarks q_1, q_2 and two heavy quarks Q with mass M.
  - For $(\bar{Q}\bar{Q})$ in color 3. For sufficiently heavy quarks:
    - $V_{\bar{Q}\bar{Q}} = 1/2\, V_{Q\bar{Q}}$
    - Is attractive binding $-(2/3)\,[\alpha^2 M_Q/2]$
  - SO $m(\bar{Q}\bar{Q}q_1q_2) - [m(\bar{Q}q_1) + m(\bar{Q}q_2)] = \Delta(q_1q_2) - 2/3\, a^2 M_Q/2 + O(1/M_Q) \ll 0$
  - The other possible decay channel is: $(\bar{Q}\bar{Q}q_1q_2) \to (\bar{Q}\bar{Q}\bar{q}_3) + (q_1q_2q_3)$

    BUT in the heavy quark limit:

    $m(\bar{Q}\bar{Q}q_1q_2) - m(\bar{Q}\bar{Q}\bar{q}_3) = m(Qq_1q_2) - m(Q\bar{q}_3) \sim m(\Lambda_b) - m(B) = 341$ MeV

    and $m(q_1q_2q_3) = m(P) = 938$ MeV
  - SO $m(\bar{Q}\bar{Q}q_1q_2) - [(m(\bar{Q}\bar{Q}\bar{q}_3) + m(q_1q_2q_3)] \sim -597$ MeV
  - NO STRONG DECAYS ARE POSSIBLE
  - $(\bar{Q}\bar{Q}q_1q_2)$ must be bound for sufficiently heavy quarks Q

- Lowest states:
  - [q_1 = (u,d) q_2 = (u,d) I=0]: S=0, l=0, j=0, $S_{\{QQ\}}$ = 0, L = 0
    -> $J^P = 0^+$
- Lattice results and phenomenological estimates conclusions agree:
  - Q = b heavy enough for at least one narrow tetraquark state
  - Q = c marginal



Peters, P. Bicudo, K. Cichy, B. Wagenbach, M Wagner [arXiv:1508.00343]

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

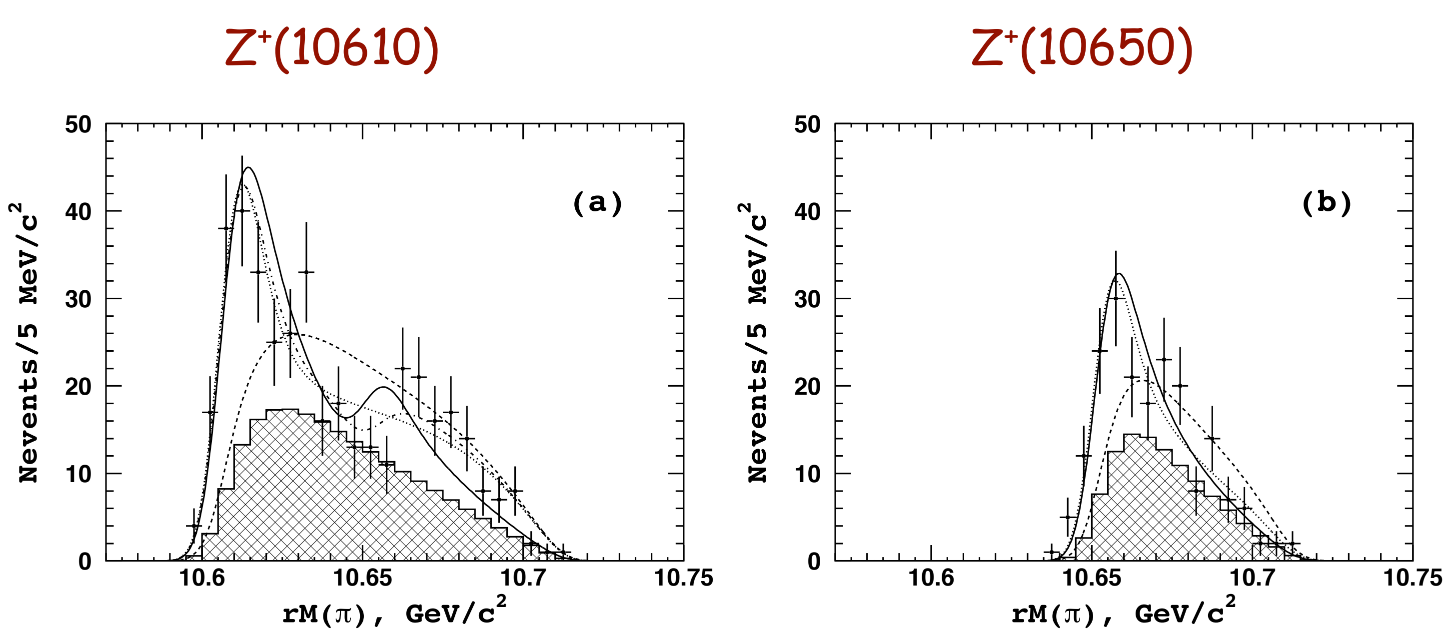
- BELLE observed two new charged states in the $\Upsilon(5S) \to \Upsilon(nS) + \pi^+\pi^-$ (n=1,2,3) and the $\Upsilon(5S) \to h_b(nP) + \pi^+\pi^-$ (n=1,2)

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

- $\Upsilon(5S) \to Z_b^+ + \pi^-$ and $Z_b \to h_b(nP) + \pi^+$.
- 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 (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^*B^* threshold (10650).

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



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

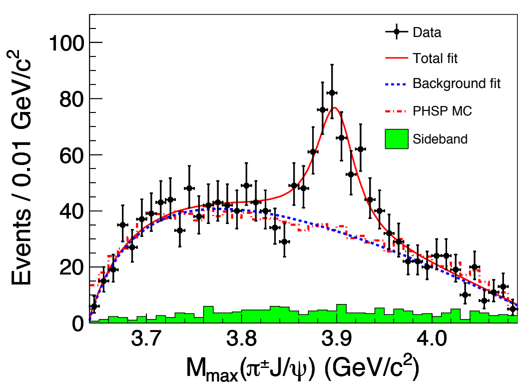
and

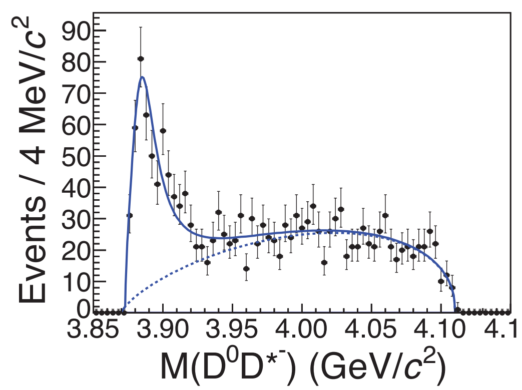
$$\frac{\mathcal{B}(Z_b(10650) \to B^*B^*)}{\sum_n \mathcal{B}(Z_b(10650) \to \Upsilon(nS)\pi) + \sum_m Z_b(10650) \to h_b(mP)} = 2.8 \pm 0.4 \pm 0.6^{+0.0}_{-0.4}.$$

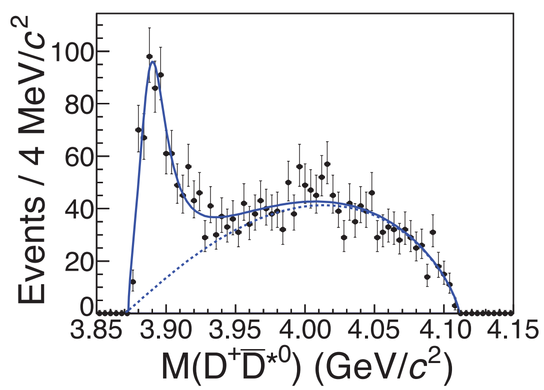
  - HQS implies that the same mechanism applies for charmonium-like states

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

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







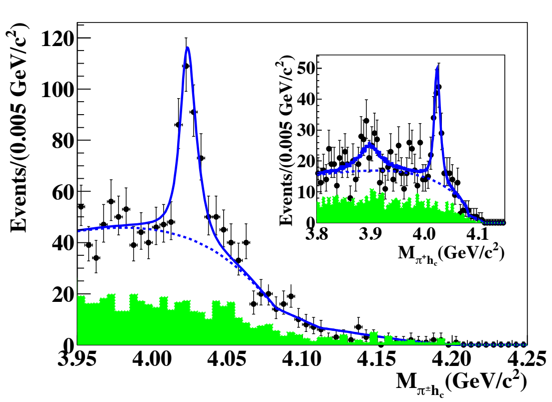
$$\frac{\Gamma[Z_c(3900)\to D D^*]}{\Gamma[Z_c(3900)\to \pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}.$$

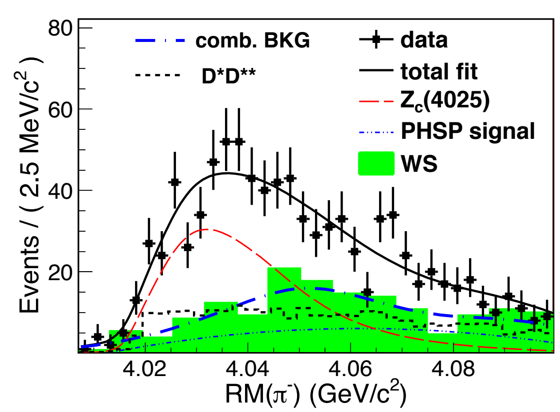
$M(D^0 + D^{*-}) = 3.8752$

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

BESIII Z. Lin

[arXiv:1504.06102]





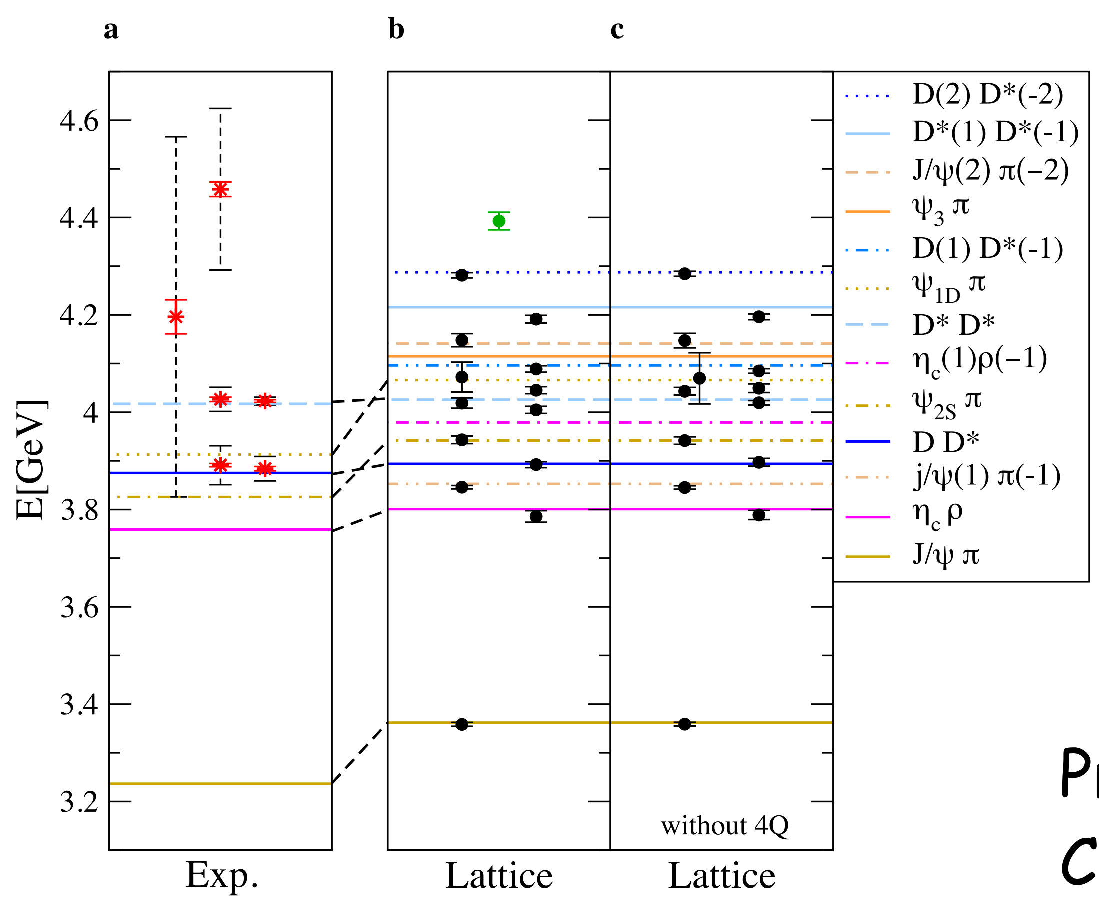
$$\frac{\Gamma[Z_c(4025)\to D^* D^*]}{\Gamma[Z_c(4020)\to \pi h_c]} \sim 9.$$

$$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}$$
$$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$

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

- No evidence for the isospin 1 $(\bar{c}c u \bar{d})$ $J^{PC} = 1^{+-}$ states from preliminary lattice studies:

Alexandrou et al. arXiv:1212.1418
Prelovsek et al. arXiv:1405.7623 *
Guerrieri et al. arXiv:1411.2247
Padmanath et al. arXiv:1503.03257
Francis et al. arXiv:1607.05214

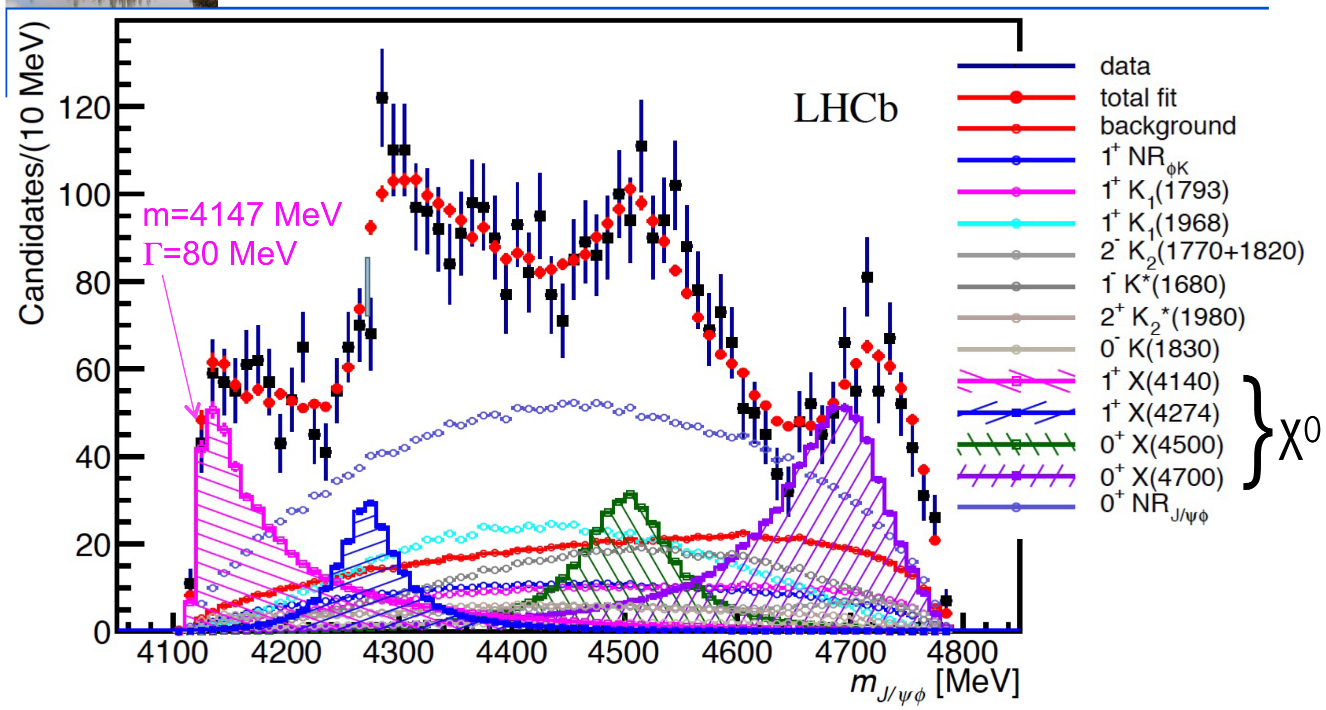


Prelovsek et al. arXiv:1405.7623
Caveats:
(1) m_π = 266 MeV
(2) limited spacings and volumes
(3) must include all states below and in region of possible new 4Q states

- Light quarks -> strange quarks

Meson 2016 (T. Skwarnicki)

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



- 4 visible structures fit with BW amplitudes

28 Recontres de Blois, June 2, 2016

36

Results of fit

- J^P also measured all with >4σ significances

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

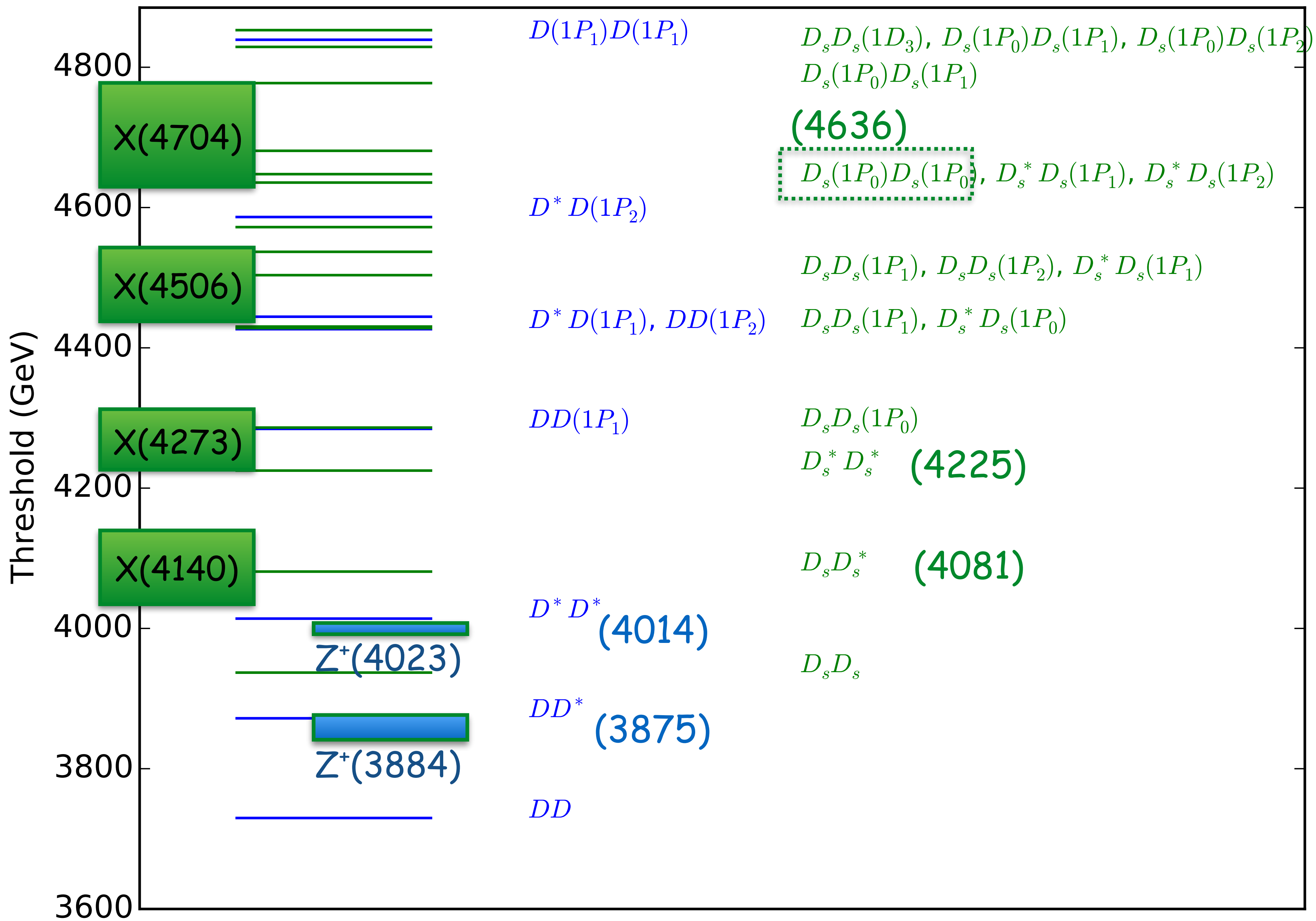
28 Recontres de Blois, June 2, 2016

37

LHCb - [arXiv:1606.07895]

- strangeness zero states - charmonium ($c\bar{s}\bar{s}c$) structures
- SU(3) symmetry suggests new X_s states near the thresholds: $D D_s^*$, $D_s D^*$, $D_s^* D_s^*$: observable in B decays?

B -> X K: M_X < 4785 MeV



- No evidence in preliminary LQCD studies for ($c\bar{s}\bar{s}c$) tetraquark states.

Y(4260)

- Y(4260) - not standard charmonium state. $J^{PC} = 1^{--}$ M= 4259 ± 9 Γ= 120 ± 12 MeV
  - Decays observed:

$$J/\psi \pi^+ \pi^-$$
$$J/\psi f_0(980)\ ,\quad f_0(980) -> \pi^+\pi^-$$
$$J/\psi X(3900)^{\pm}\pi^{\mp},\quad X(3900) -> J/\psi + \pi^{\pm}$$
$$J/\psi \pi^0 \pi^0$$
$$J/\psi K^+ K^-$$
$$X(3872)\gamma$$
$$h_c \pi^+ \pi^-$$

  - Many models:

1. Charmonium hybrid
2. D_1 D molecule
3. Hadrocharmonium
4. Tetraquark (ccss)
5. Cusp/nonresonance

...

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

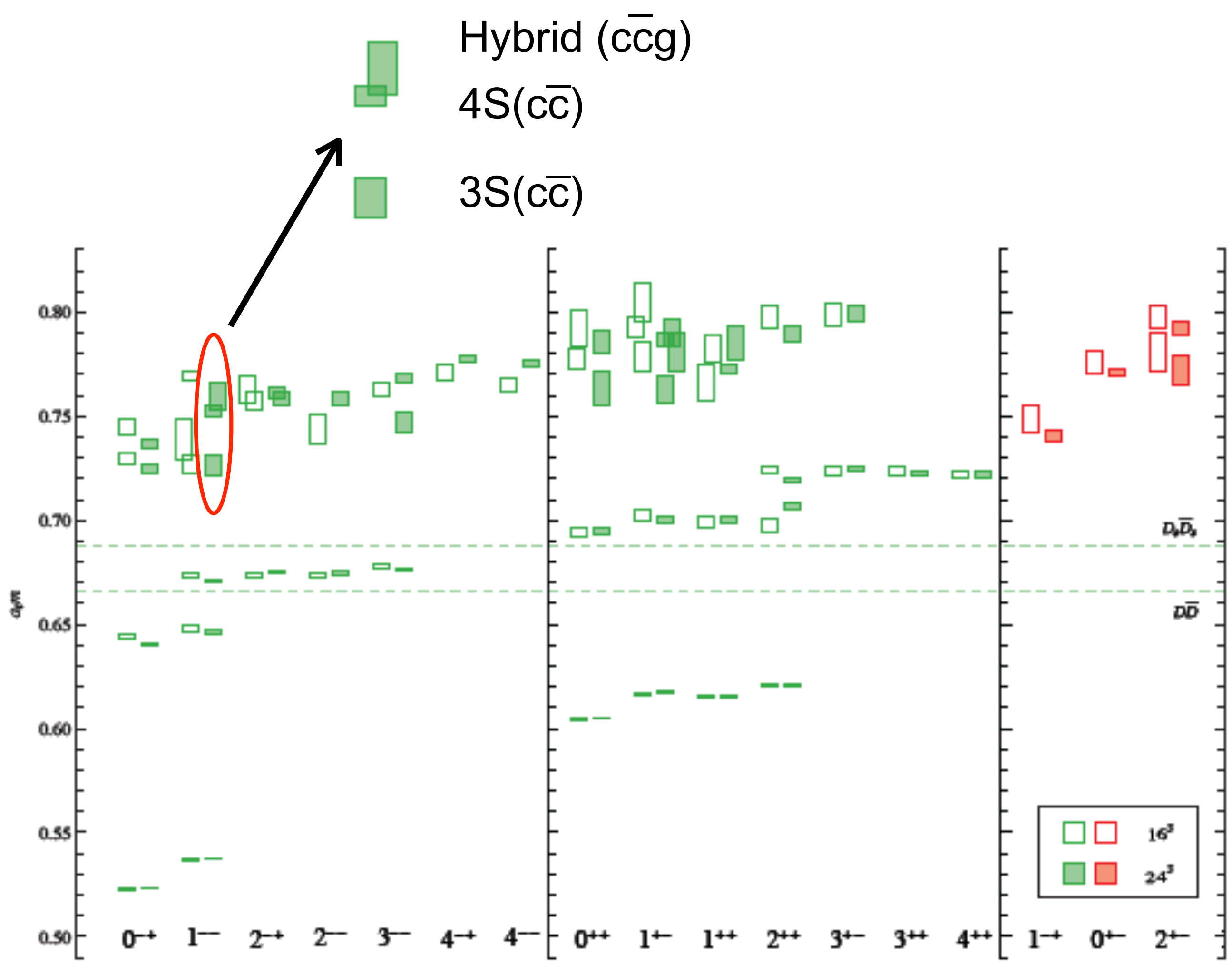
DING G J, Zhu J J and YAN M L. Phys. Rev. D, 2008, **77**: 014033
Ding G J. Phys. Rev. D, 2009, **79**: 014001
WANG Q, Hanhart C and ZHAO Q. Phys. Rev. Lett., 2013, **111**: 132003

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

Maiani L, Riquer V, Piccinini F and Polosa A D. Phys. Rev. D, 2005, **72**: 031502

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

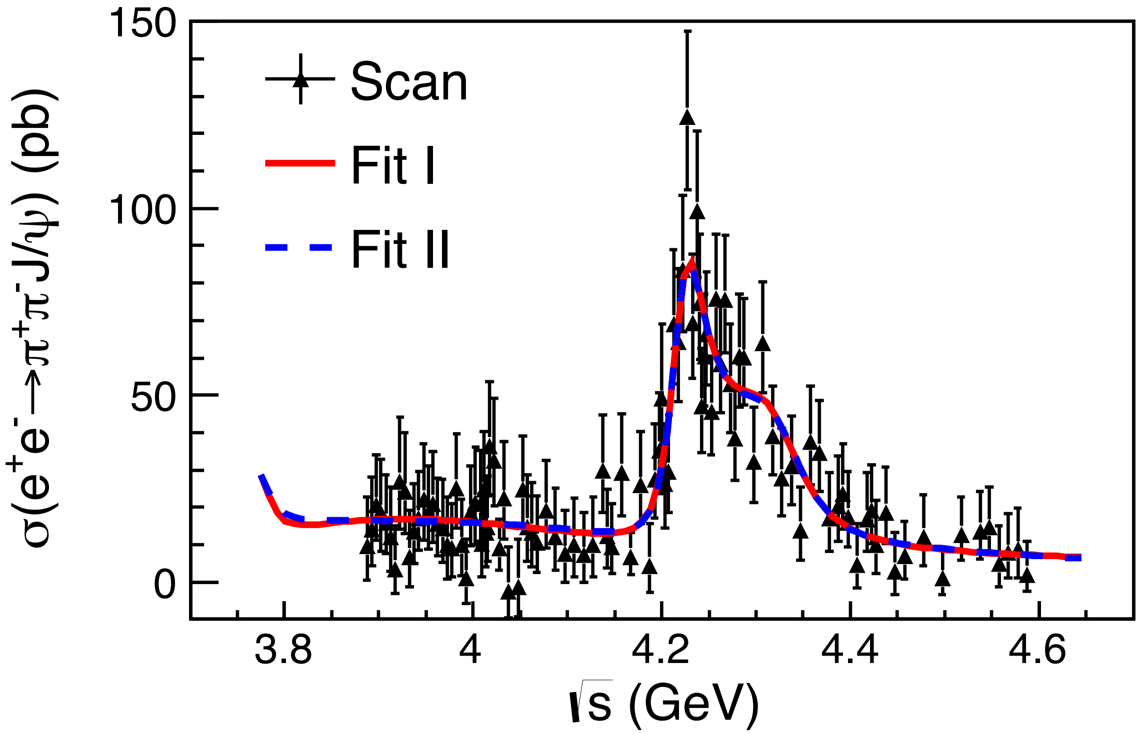
- Lattice results support the identification of the Y(4260) as a hybrid meson.
  : 2+1 results (m_π =391)
  - L. Liu et al (HSC) [arXiv:1204.5425], G. Moir et al (HSC) [arXiv:1312.1361]

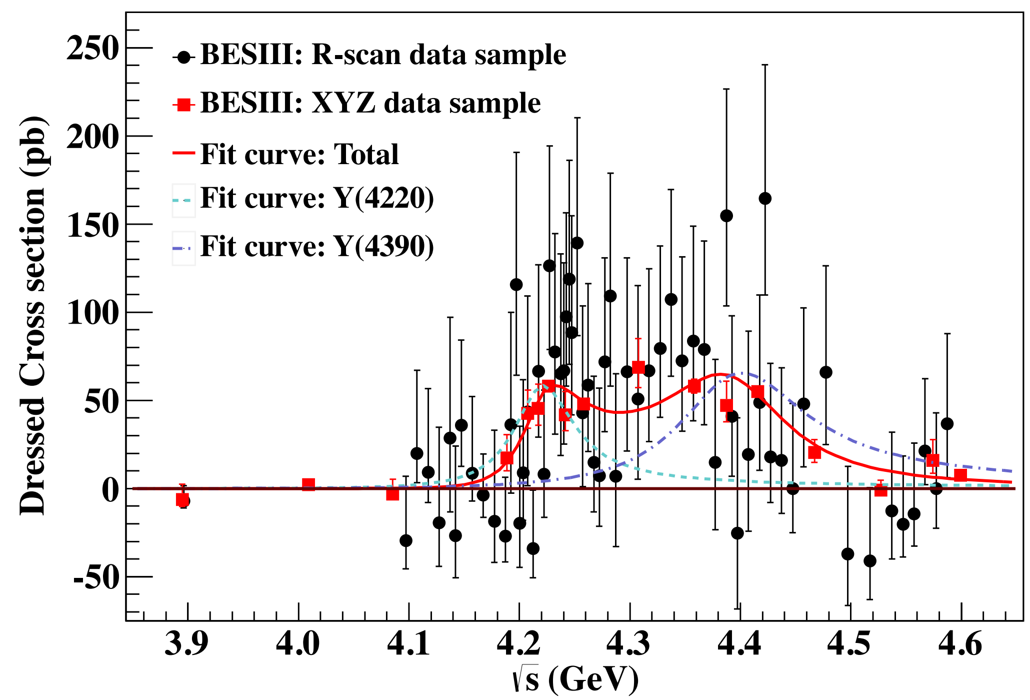


- No additional state below 4200 seen.

- New detailed results from BESIII
  - Rscan in the $\pi^+\pi^- \psi$ final state; Rscan in the $\pi^+\pi^- h_c$ final state

M. Ablikim et al. (BESIII) - [arXiv:1611.01317] M. Ablikim et al. (BESIII) - [arXiv:1611.01317]





- Fit to two Breit-Wigner functions

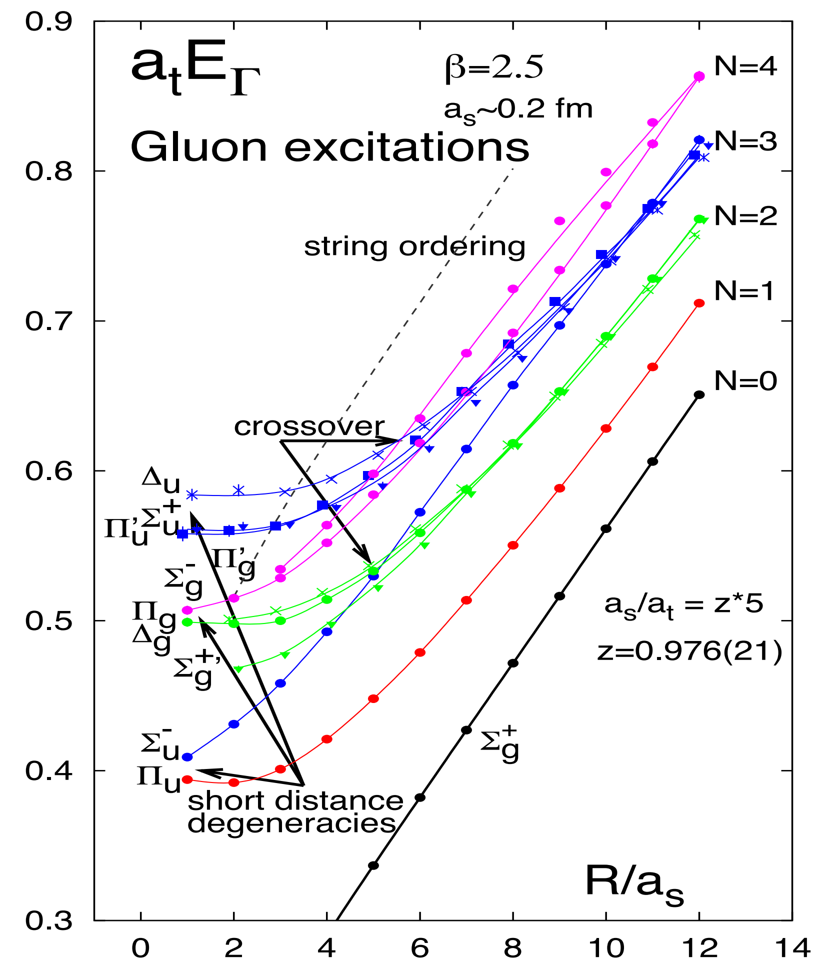
Channel	Mass	Width	Mass	Width
$\pi^+\pi^-\psi$	$4222.0 \pm 3.1 \pm 1.4$	$44.1 \pm 4.3 \pm 2.0$	$4320.0 \pm 10.4 \pm 7.0$	$101.4^{+25.3}_{-19.7} \pm 10.2$
$\pi^+\pi^-h_c$	$4218.4 \pm 4.0 \pm 0.9$	$66.0 \pm 9.0 \pm 0.4$	$4391.6 \pm 6.3 \pm 1.0$	$139.5 \pm 16.1 \pm 0.6$
	State 1		State 2	

- Need a better theoretical understanding of decay amplitude structures.
- D $D_P(1^+)$ threshold 4280

- Can model the hybrid potentials Π_u, … and solve the SE as models did for Σ^+_g (e.g. Cornell potential):
- pNRQCD calculations
  - lowest lying 1^{--} states

R. Oncala & J. Soto [arXiv:1702.03900]

NL_J	w-f	$M_{c\bar{c}}$	$M_{c\bar{c}g}$	$S=0$ $\mathcal{J}^{PC}$	$S=1$ $\mathcal{J}^{PC}$	Λ^ϵ_η
$1p$	S	3494		1^{+-}	$(0,1,2)^{++}$	Σ^+_g
$2p$	S	3968		1^{+-}	$(0,1,2)^{++}$	Σ^+_g
$1(s/d)_1$	P^{+-}		4011	1^{--}	$(0,1,2)^{-+}$	$\Pi_u\Sigma^-_u$
$1p_1$	P^0		4145	1^{++}	$(0,1,2)^{+-}$	Π_u
$2(s/d)_1$	P^{+-}		4355	1^{--}	$(0,1,2)^{-+}$	$\Pi_u\Sigma^-_u$
$3p$	S	4369		1^{+-}	$(0,1,2)^{++}$	Σ^+_g
$2p_1$	P^0		4511	1^{++}	$(0,1,2)^{+-}$	Π_u
$3(s/d)_1$	P^{+-}		4692	1^{--}	$(0,1,2)^{-+}$	$\Pi_u\Sigma^-_u$
$4(s/d)_1$	P^{+-}		4718	1^{--}	$(0,1,2)^{-+}$	$\Pi_u\Sigma^-_u$
$4p$	S	4727		1^{+-}	$(0,1,2)^{++}$	Σ^+_g
$3p_1$	P^0		4863	1^{++}	$(0,1,2)^{+-}$	Π_u
$5(s/d)_1$	P^{+-}		5043	1^{--}	$(0,1,2)^{-+}$	$\Pi_u\Sigma^-_u$
$5p$	S	5055		1^{+-}	$(0,1,2)^{++}$	Σ^+_g



- HQS expectations require to see analog states 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

X(3872)

- X(3872) - $J^{PC} = 1^{++}$ M= 3871.69 ± 0.16 ± 0.19 Γ< 1.2 MeV from $J/\psi\ \pi\pi$ mode
  - Decays observed:

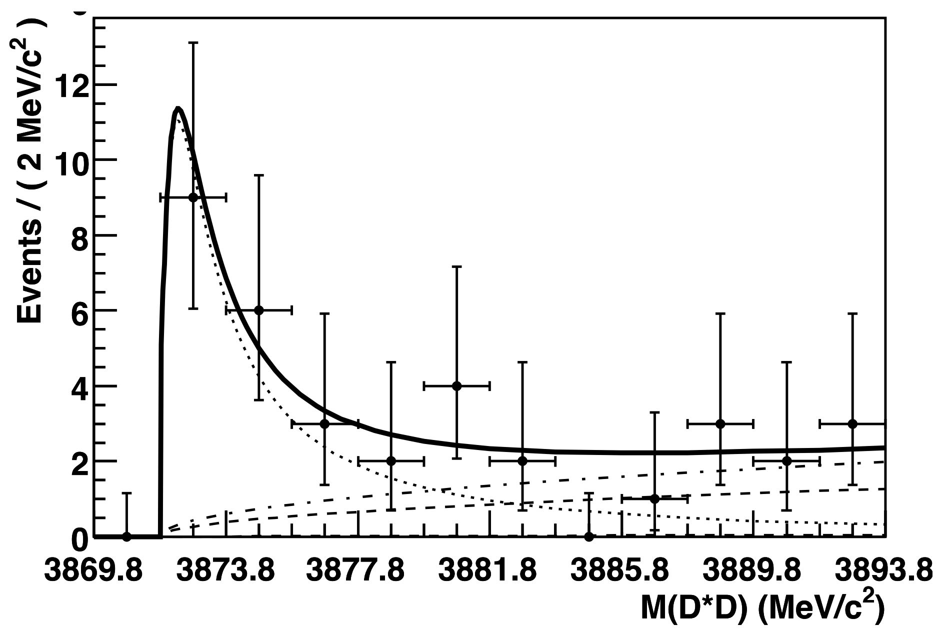
$\pi^+\pi^- J/\psi(1S)$	$>$ 2.6 %
$\rho^0 J/\psi(1S)$	
$\omega J/\psi(1S)$	$>$ 1.9 %
$D^0 \overline{D}{}^0 \pi^0$	>32 %
$\overline{D}{}^{*0} D^0$	>24 %
$\gamma\psi(2S)$	[a] $>$ 3.0 %

large Isospin violation

  - 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?

- $B \to X(3872)\ K \to (D^0\bar{D}^{0*})\ K$
- 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.

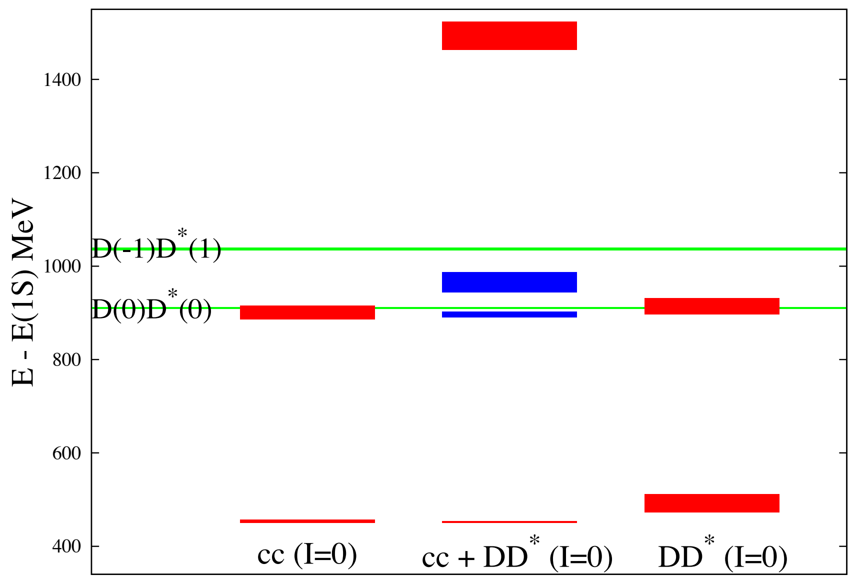
B. A. Galloway, P. Knecht, J. Koponen, C. T. H. Davies, and G. P. Lepage, PoS **LATTICE2014**, 092 (2014), 1411.1318.

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

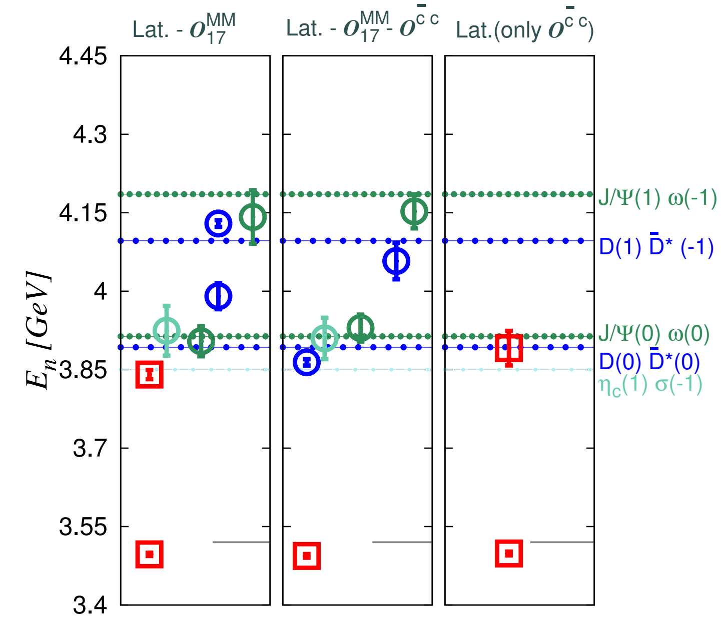
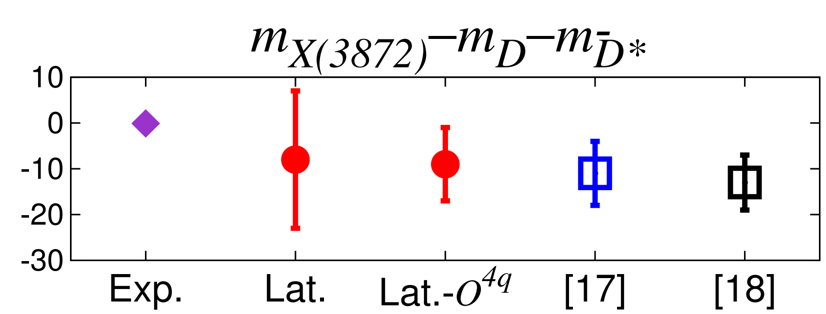


FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note 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 => G-parity forbids the decay X-> ππϒ(1S)
  - Dominate decay X -> ω ϒ(1S)?
  - $M(\chi_{b1}(3P)) - M(B) - M(B^*) \approx -75$ MeV
  - So the (bb) state is decoupled.

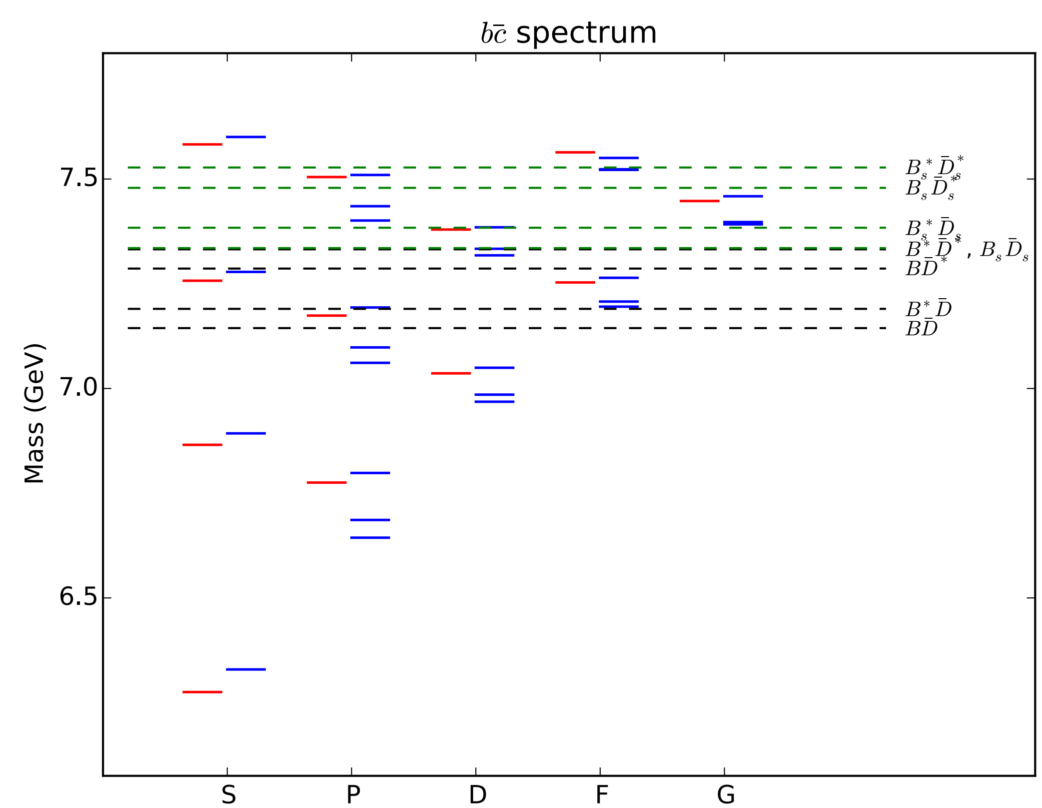


Expect no analog of the X(3872) in the bottomonium system

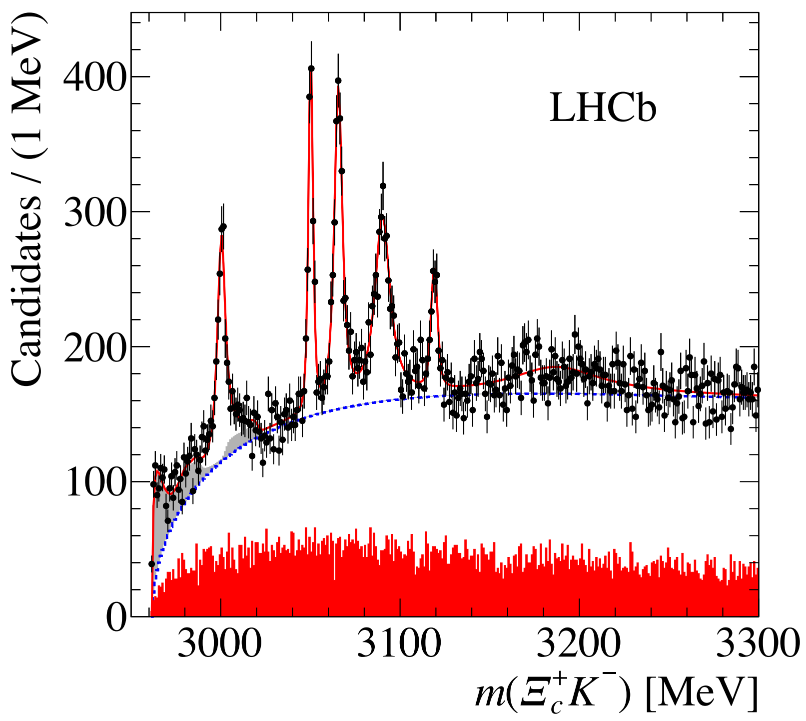
Unexplored Territory

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: Bc(2S) -> Bc(1S) +ππ. 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.



- Charmed Baryons - P waves Ω_c - LHCb

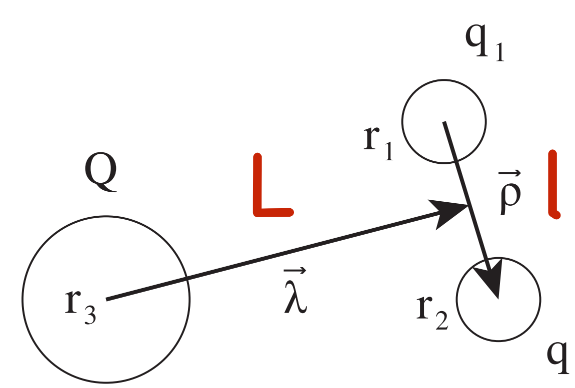


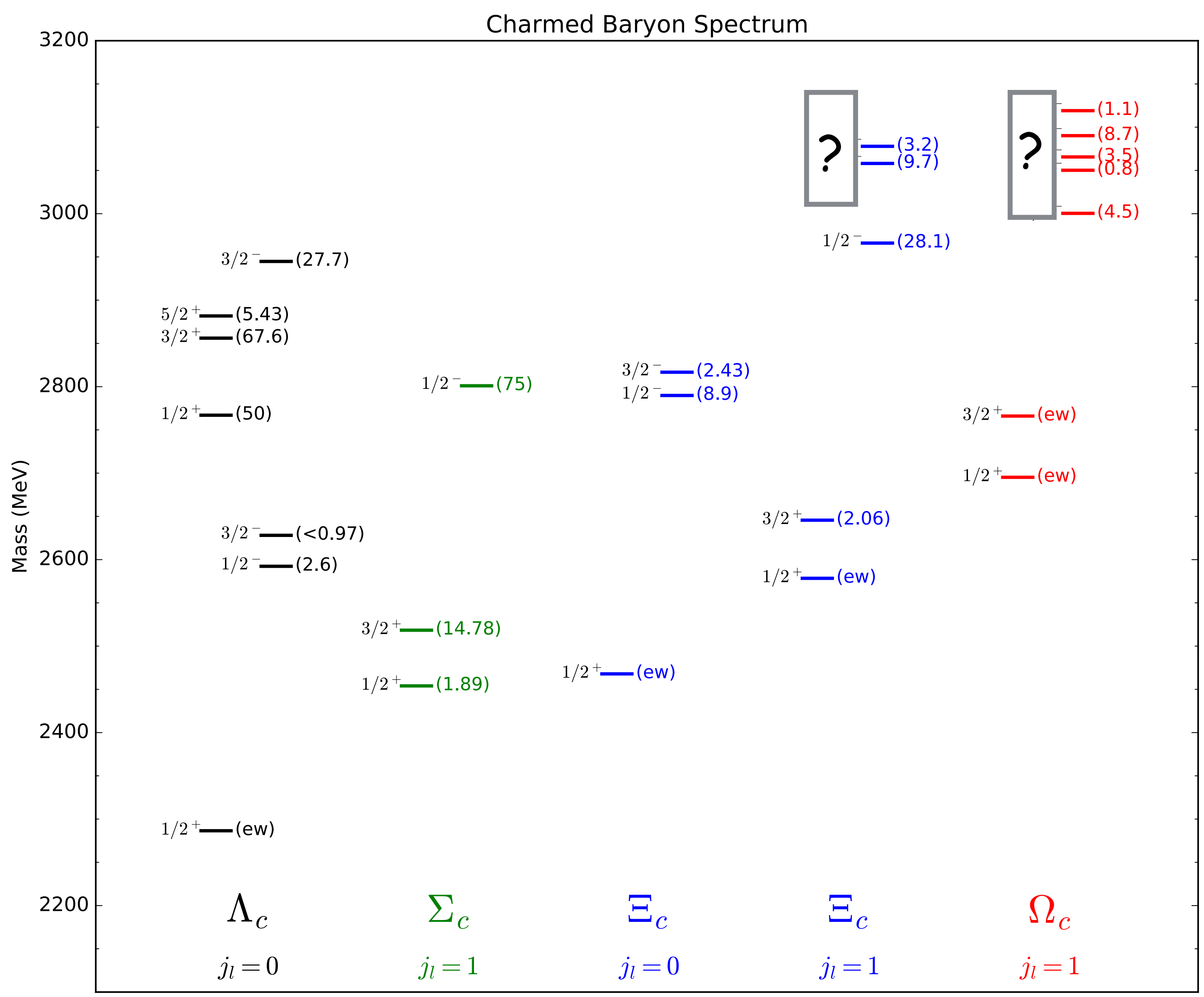
arXiv:1703.04639

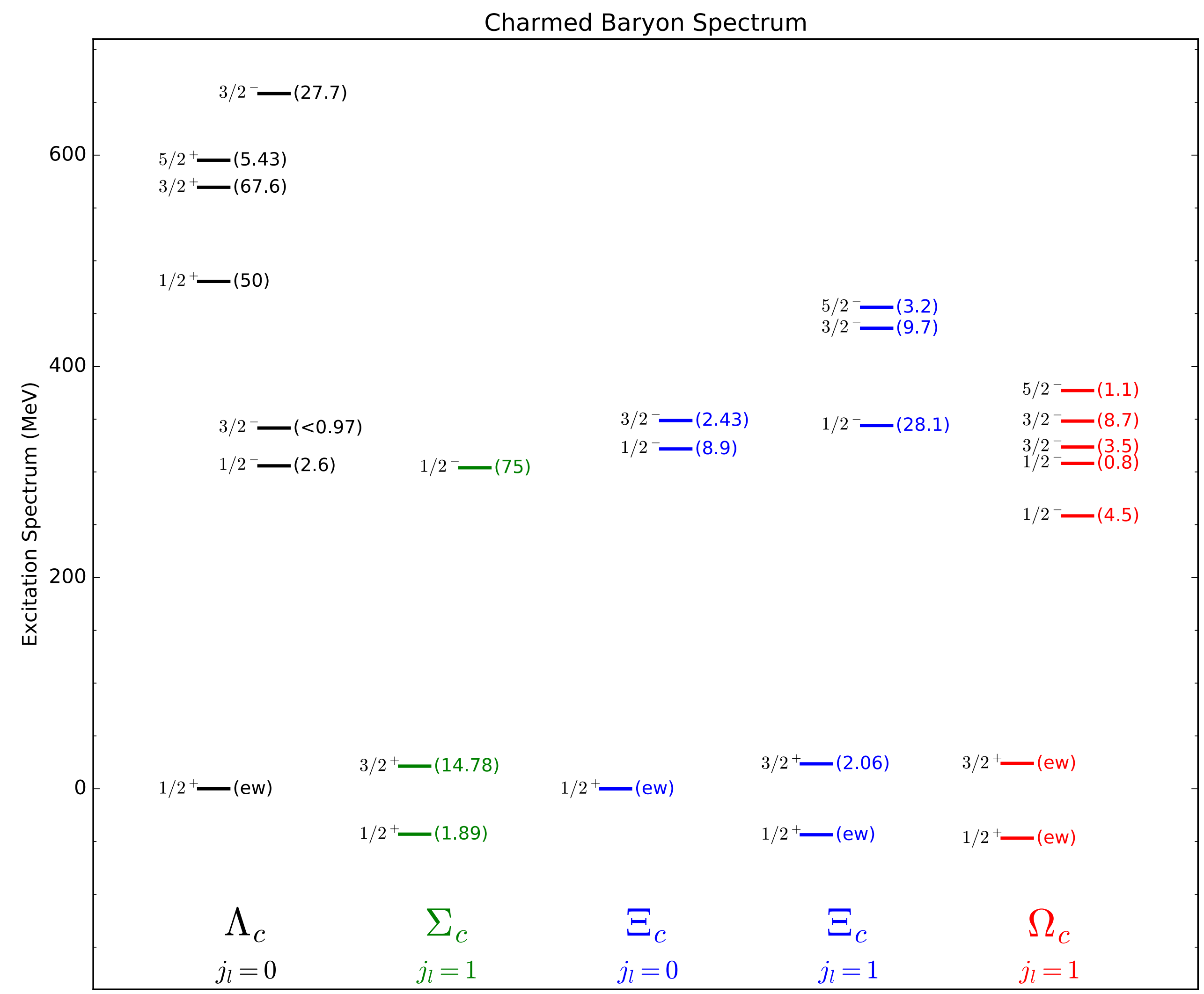
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\text{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\text{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

- Many models of baryon excitations and transitions - diquarks, potential models, psuedoscalar transitions.
- Extraordinary opportunity to resolve some long standing issues.
- Already new theory papers: [1703.07774] (pot), [1703.07091] (sum rules), [1703.08845] (pentaquarks), [1703.09130] (using decays),…

- Charmed Baryons - P wave excitation spectrum
  - (q_1 q_2) spin=0, flavor symmetric, l=0, L=1
    - (Λ_c, $\Xi_c^{(a)}$)
  - (q_1 q_2) spin=1, flavor antisymmetric, l=0, L=1
    - (Σ_c, $\Xi_c^{(s)}$, Ω_c)







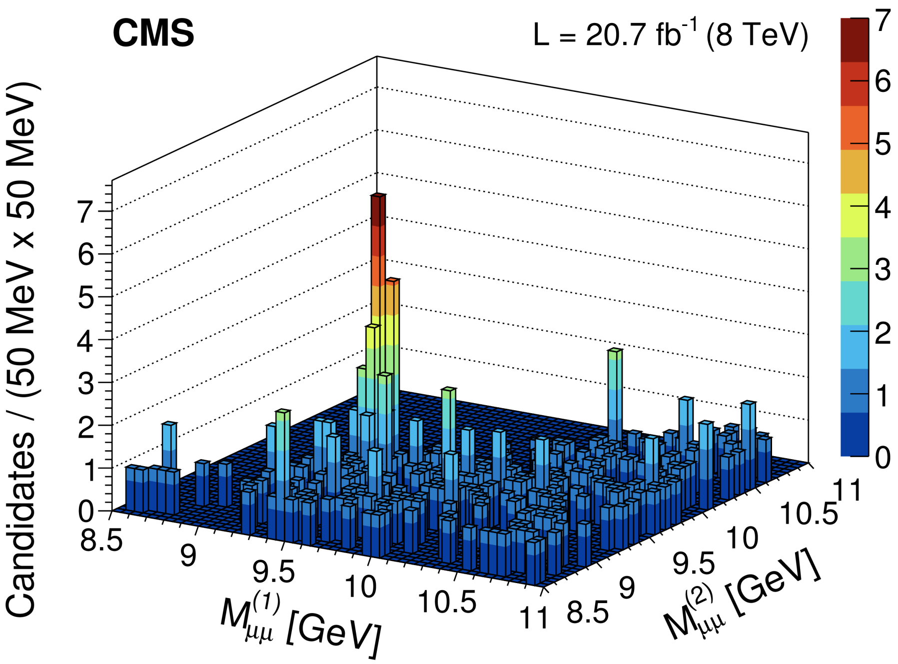
EE, C. Hill, C. Quigg (HQET)

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

Are there any narrow deeply bound all heavy tetraquark states?

  - Potential models suggest this may be possible.

CMS [arXiv:1610.07095]



A. V. Berezhnoy et. al. [PR D84,09023(2011)]; Berezhnoy, Lucninsky & Novoselov [PR D86,034004(2012)]
W. Heupel, G. Eichmann & C. S. Fischer [PL B718, 545 (2012)]
J. Wu et. al.[arXiv:1605.01134]; W. Chen et al. [arXiv:1605.01647]
M. Karliner, S. Nussinov & J. Rosner [arXiv:1611.00348]; Y. Bai, S. Lu & J. Osborne [arXiv:1612.00012]

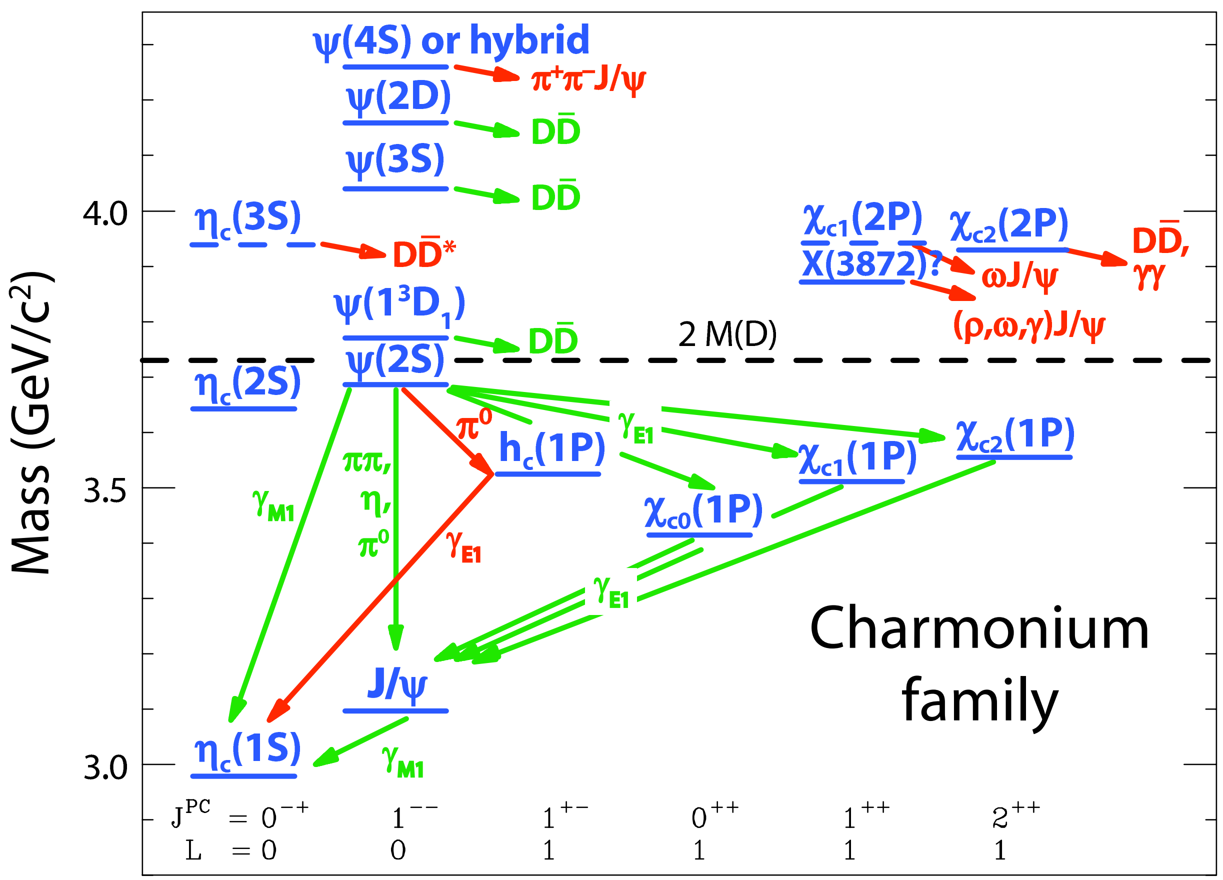
Conclusions

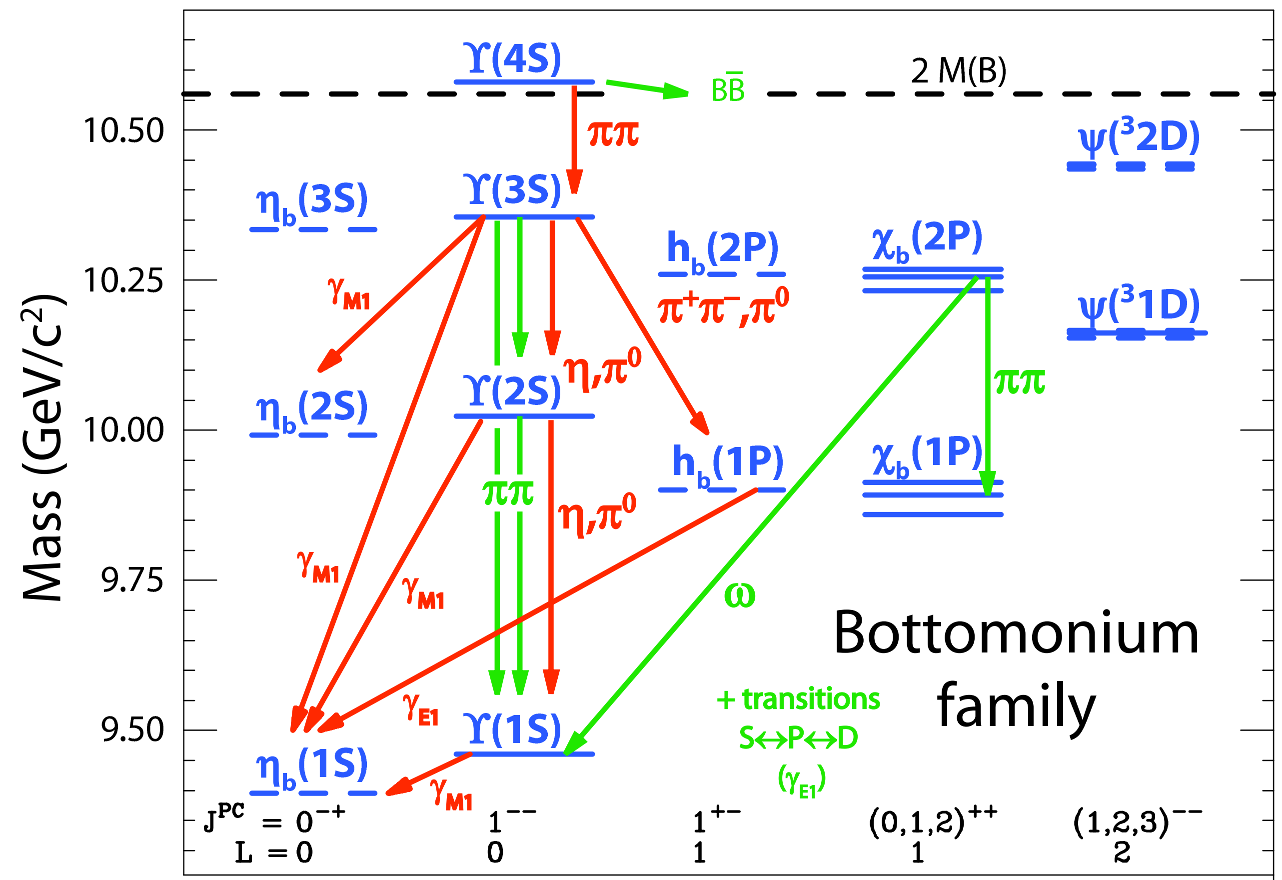
- Heavy quark states are ideal systems to study QCD strong dynamics.
- In the threshold region for decays to open heavy flavor states QCD dynamics is more complicated. There have been many surprises and a still incomplete picture of the dynamics:
  - Large violations of heavy quark spin symmetry and 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.
  - Large hadronic transition rates. New transition contributions with two open flavor intermediate states near threshold.
  - Does the resonance-like behavior seen for two heavy-light mesons at S-wave threshold respect approximate HQSS and SU(3) symmetry?
  - 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

- 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

  $\mathcal{H}_0$ $Q\bar{Q}$
  NRQCD (without light quarks)

  $\mathcal{H}_I$ $Q\bar{Q} \rightarrow Q\bar{q}+q\bar{Q}$
  light quark pair creation

  $\mathcal{H}_2$ $Q\bar{q}+q\bar{Q}$
  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 $\Omega(z)$

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

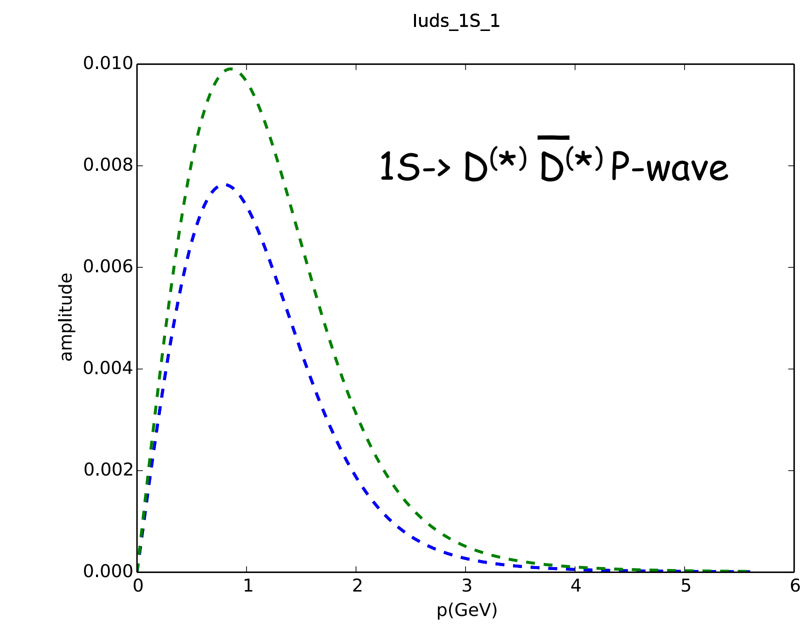
- Decay amplitude $\langle DD|H_I|\psi\rangle$
- Simplifying assumptions
  - H_2 - free meson pairs no final state interactions
  - H_0 - charmonium states are a complete basis - no hybrids

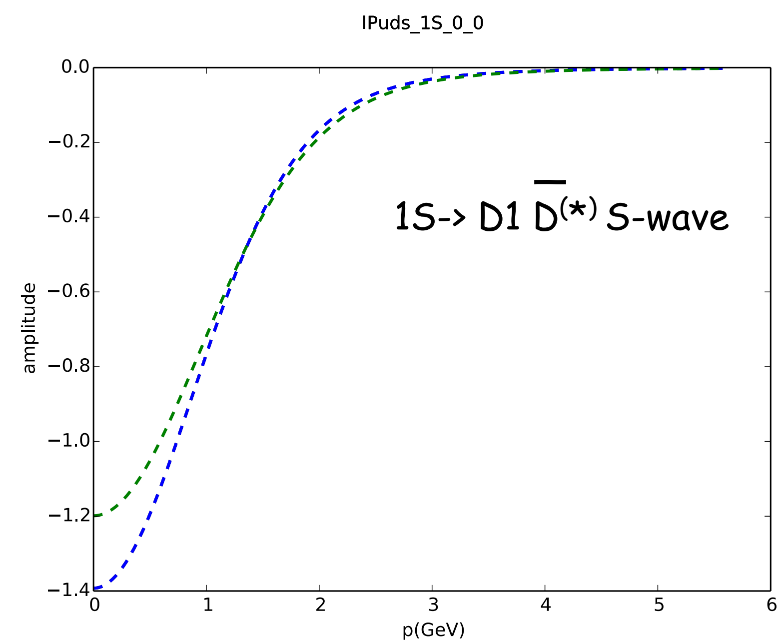
$$< n|\mathcal{G}(z)|m >=< n|\frac{1}{z - \mathcal{H}_0 - \Omega(z)}|m >$$

- Assuming vector meson dominance. Can compute R_c

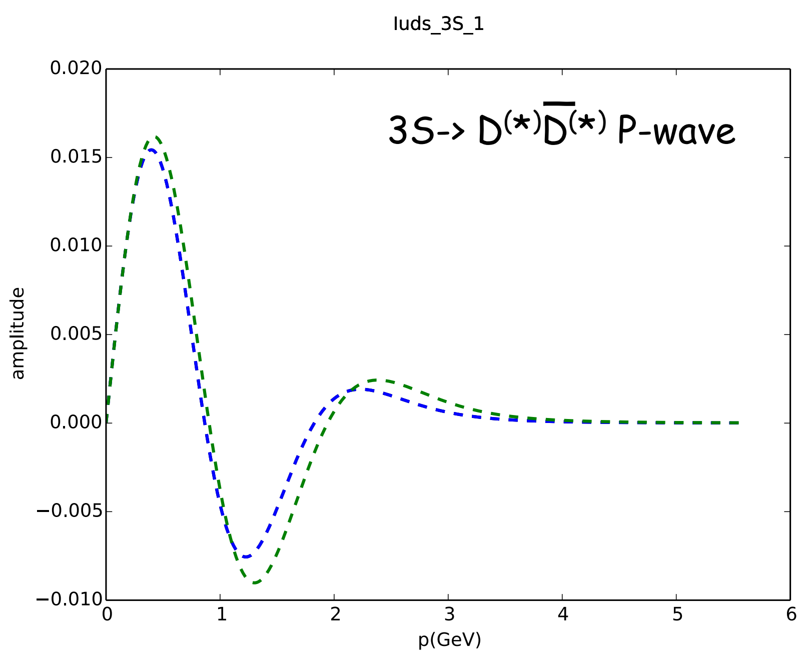
$$R_Q \sim \frac{1}{s} \sum_{nm} \lim_{r\to 0} \psi_n^*(r) \mathrm{Im}\mathcal{G}_{nm}(W + i\epsilon)\psi_m(r)$$

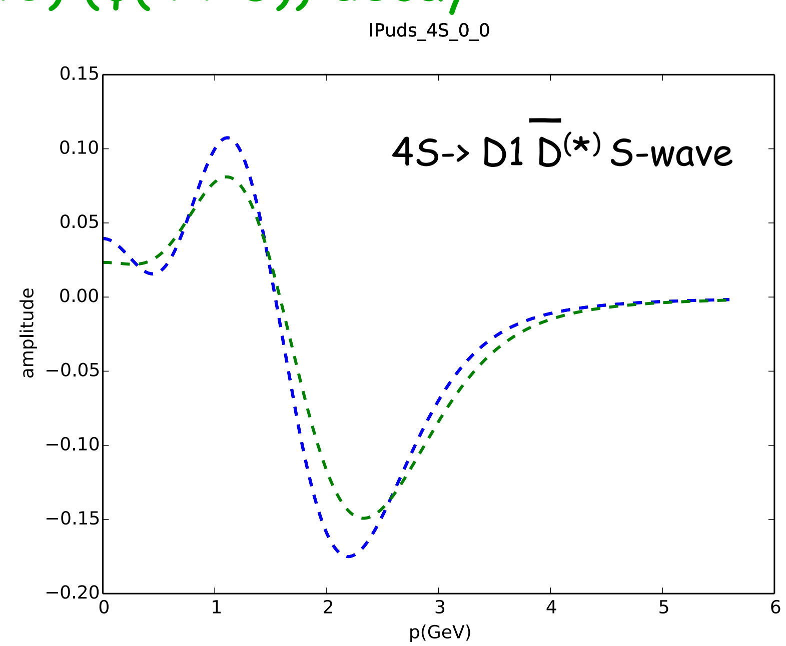
- General features of decays to low-lying heavy-light mesons:
  - Unlike light meson systems, these decays are from highly excited QQ states:
    - Ground state decay amplitudes :





    - Second (third) radial excited state: ψ(4040) (ψ(4415)) decay





  - Have complicated energy dependence.

PHYSICAL REVIEW D VOLUME 17, NUMBER 11 1 JUNE 1978

Charmonium: The model

E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 9 February 1978)

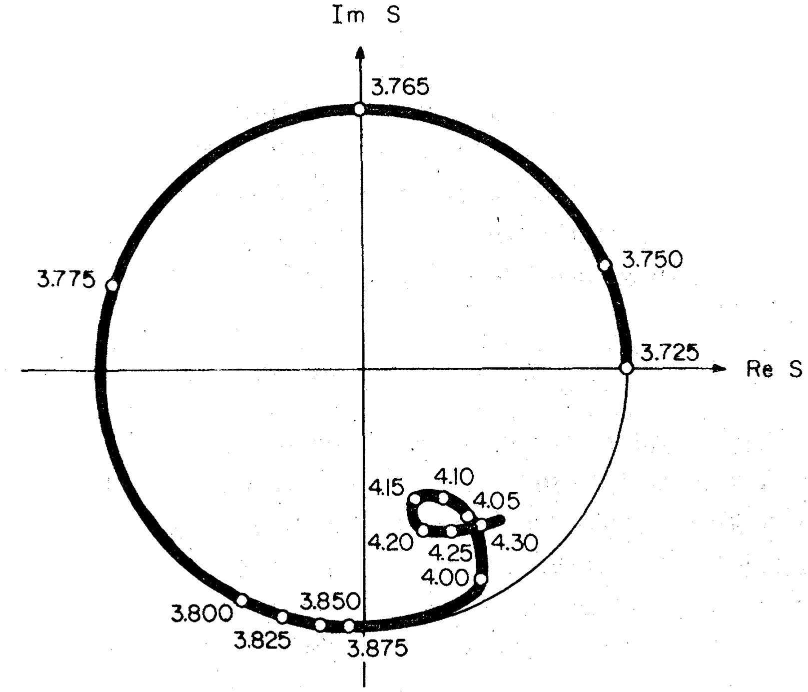


FIG. 9. Argand plot of the $D\bar{D}$ S matrix in the 1^{--} state. The rather narrow elastic ${}^3D_1$ resonance ψ (3772) is clearly in evidence, as is an inelastic resonance at ~4.15 GeV due to the $3\,{}^3S$ $c\bar{c}$ state. The parameters are the same as in Figs. 7 and 8.

is found by substituting (3.58) into (3.23):

$$\Gamma_{nn'} = 8\pi^2(p/W)D_n(W)D_{n'}(W)\,.$$

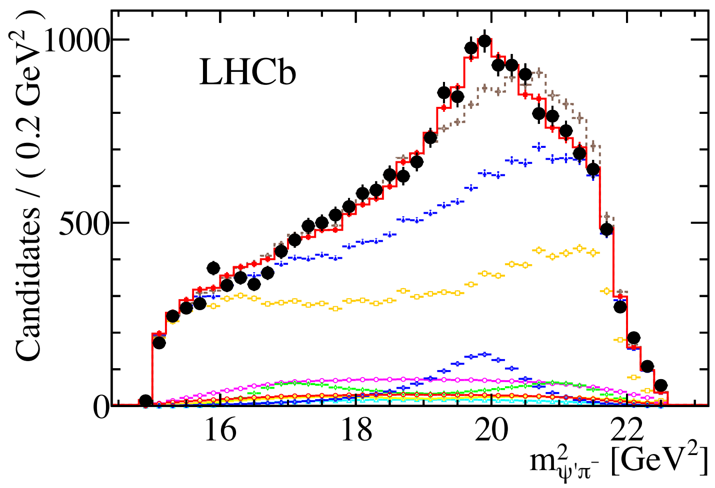
It now only remains to extract the partial-wave amplitude from (3.58). The final result for the phase shift is

$$e^{2i\delta} = 1 - \mathrm{Tr}\,\Gamma\mathcal{G}\,. \qquad (3.59)$$

This expression also applies to other partial waves. Figure 9 shows $e^{2i\delta}$ for $D\bar{D}$ scattering in the 1^{--} partial wave from threshold to 4.3 GeV; the ${}^3D_1$ [ψ(3772)] and $3\,{}^3S$ resonances are clearly visible.

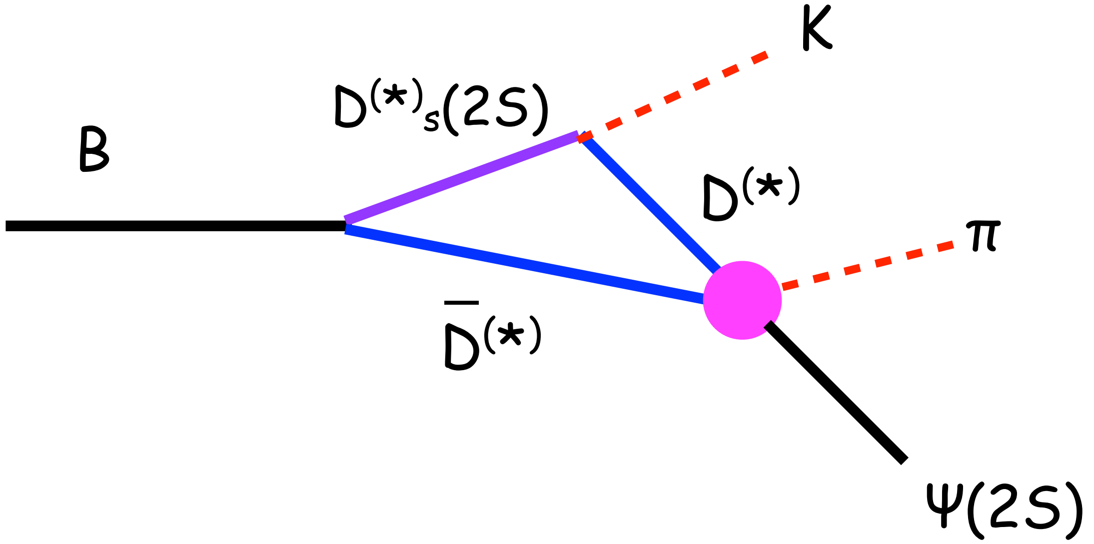
Systematics: Other States

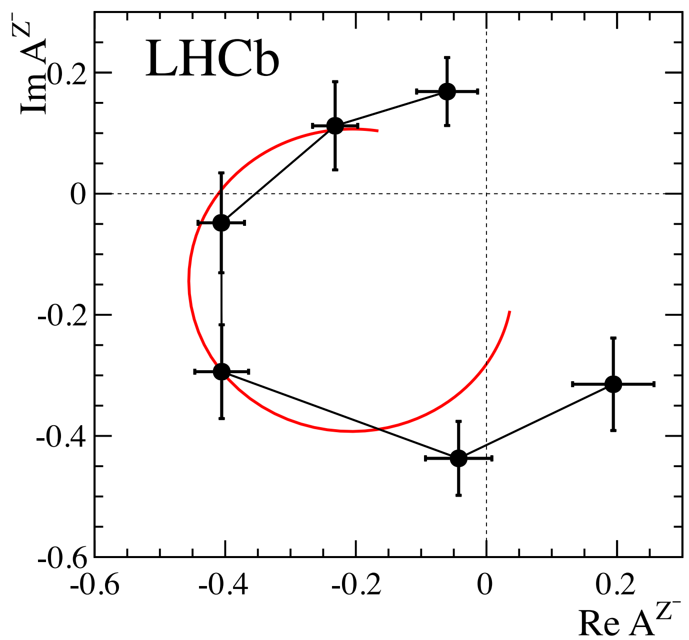
- $Z^-(4430)$: seen in $B^0 \to K^+ \pi^- \psi'$
  - $J^P = 1^+$; $M = (4{,}475 \pm 7 \pm [15/25])$ MeV; $\Gamma = (172 \pm 13 \pm [37/34])$ MeV
  - Resonance behavior observed.
  - Same mechanism in B-decays with $D_s(2S)$ states?
    - $D_s^*(2S)$ M = 2,709 ± 4 MeV Γ = 117 ± 13 MeV
    - $B \to D_s(2^3S_1)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



LHCb [arXiv:1404.1903]

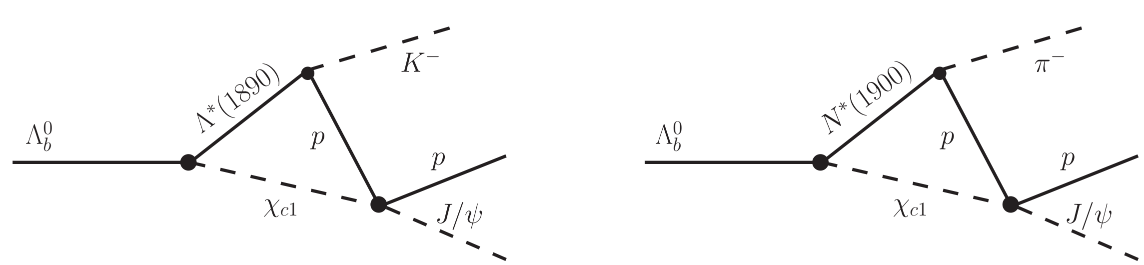
P. Pakhlov and T. Uglov [arXiv:1408.5295]



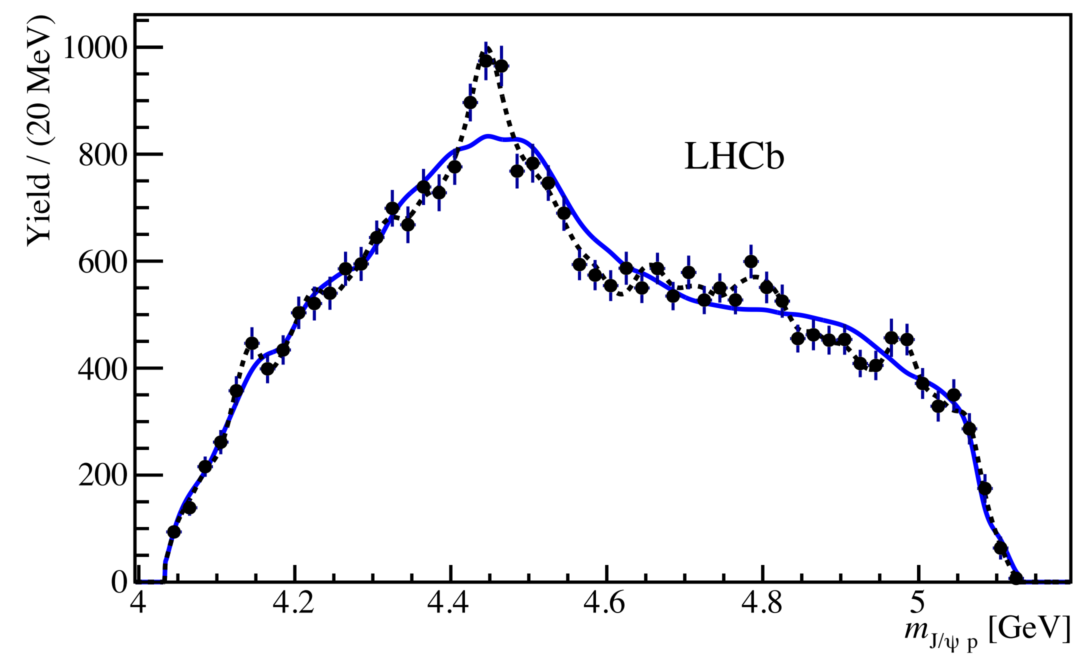


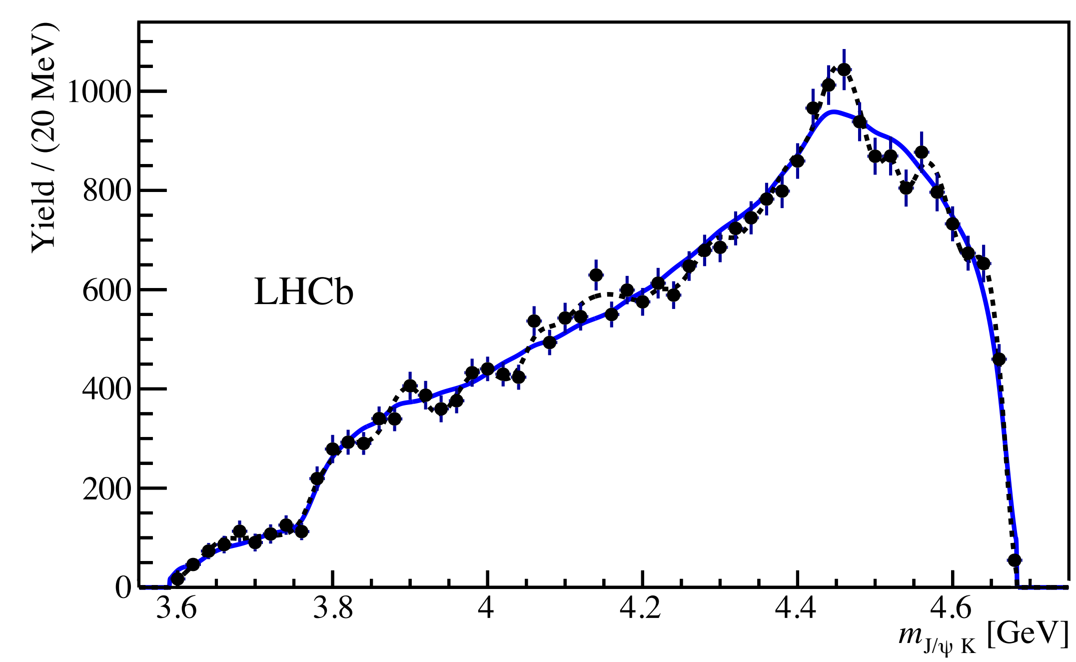
- X(5568): decaying into $B_s \pi^+$
  - by observed by Dzero but not confirmed by LHCb

- Pentaquarks: [Λ_b -> p J/ψ K weak decay] LHCb: [arXiv:507.03414, 1604.05708]
  - $P_c(4450)$ - $J^P = 5/2^+$; M=(4,449.8±1.7±2.5) MeV; Γ= (39±5±19) MeV
  - $P_c(4380)$ - $J^P = 3/2^-$; M=(4,380±8±29) MeV; Γ= (205±18±86) MeV
  - complicated analysis required.
  - possible J/ψ 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]
F.-K. Guo, U.-G. Meißner, J.Nieves and Z. Yang [arXiv:1605.05113]





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

localaized diquark antidiquark

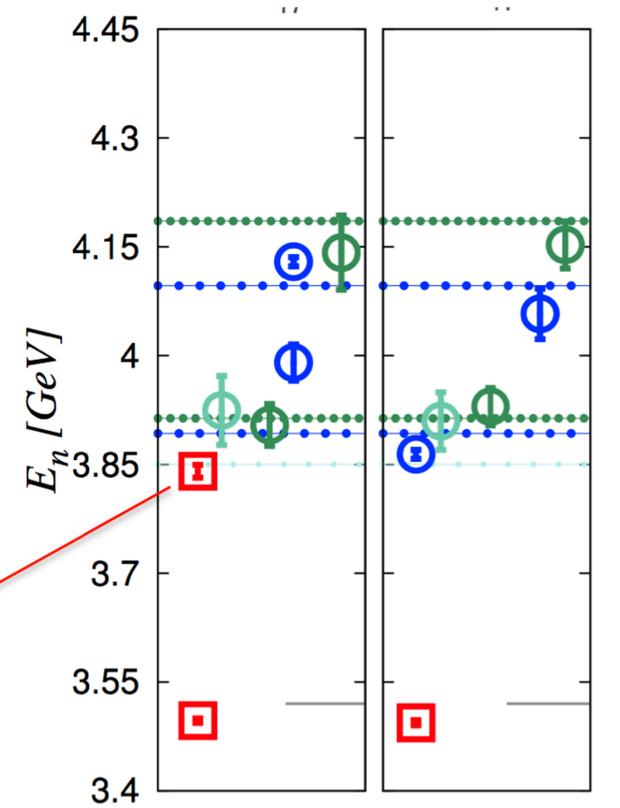
$$\mathcal{O}:\ \bar{c}\,c,\ \ D\bar{D}^*,\ J/\psi\omega,\ \chi_{c1}\sigma,\ \eta_c\sigma,\ \ [\overline{cu}]_{3c}[cu]_{3c},\ [\overline{cu}]_{6c}[cu]_{6c}$$

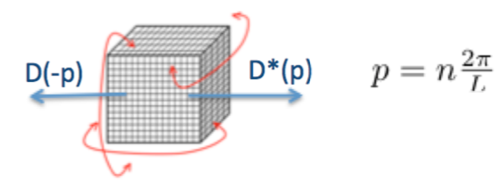
essential

do no seem not essential

interpolating fields

O: all O: all without cc





$m_\pi \approx 266$ MeV

upper red square is candidate for X(3872): it is found only if cc in the basis

X(3872) not found if cc not in the basis, although [cu][cu] in the basis

[M. Padmanath, C.B. Lang, S.P., 1503.03257, PRD 2015]

energies of eigenstates on lattice E(L) (these are not m^{phy})

S. Prelovsek, QWG 2016 13