Decays of Quarkonium States Near Threshold

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Fermilab

- Strong Decays
- $Z^{+}_{(b,c)}$, etc.
- X(3872)
- Summary
- Wish List

Quarkonium 2016
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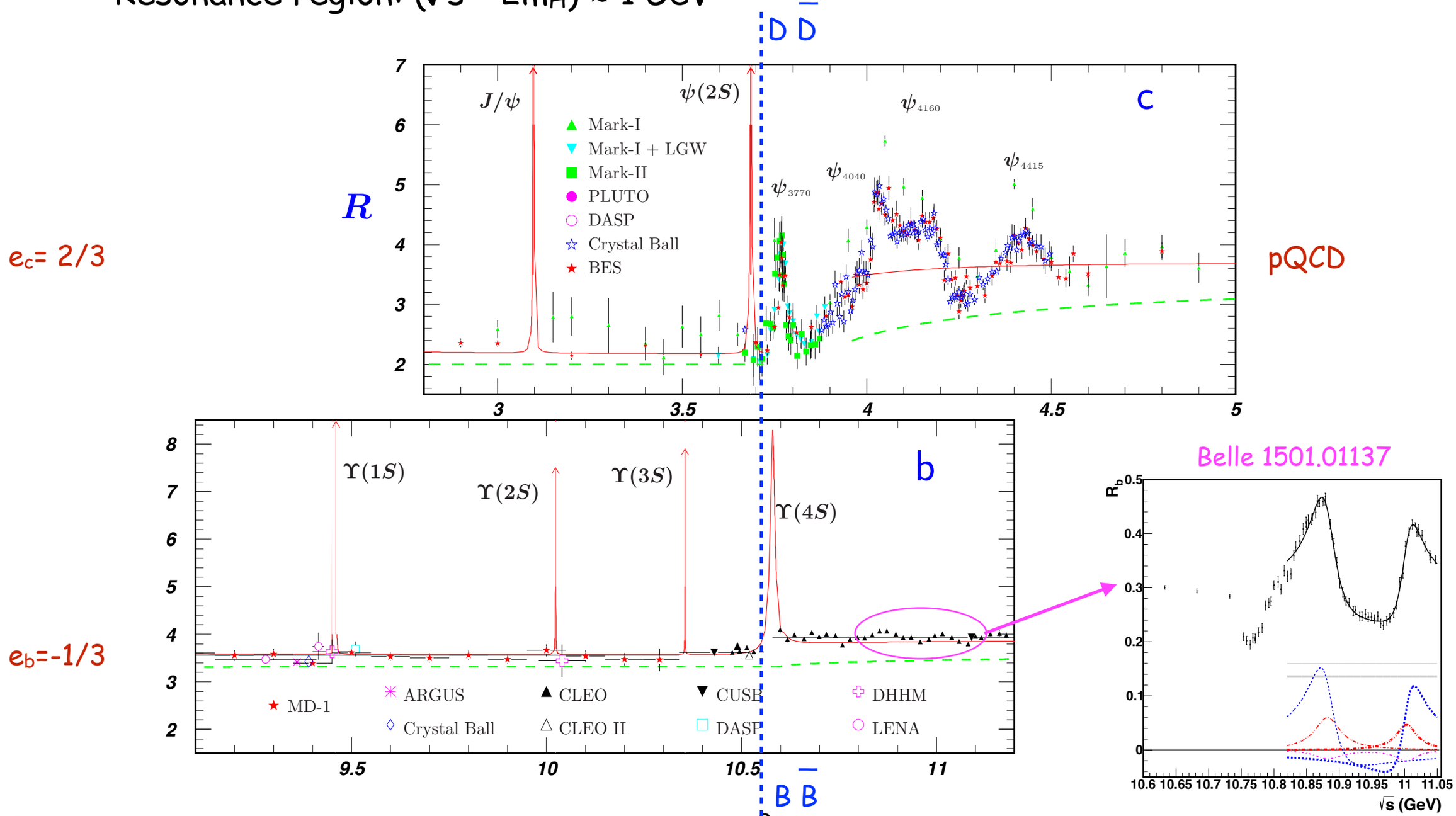
Crossing the Threshold

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

- R = σ(e+e- -> γ* -> hadrons)/σ(e+e- -> γ*-> μ+μ-) $J^{PC} = 1^{--}$
  - Resonance region: $(\sqrt{s} - 2m_H) \lesssim 1$ GeV

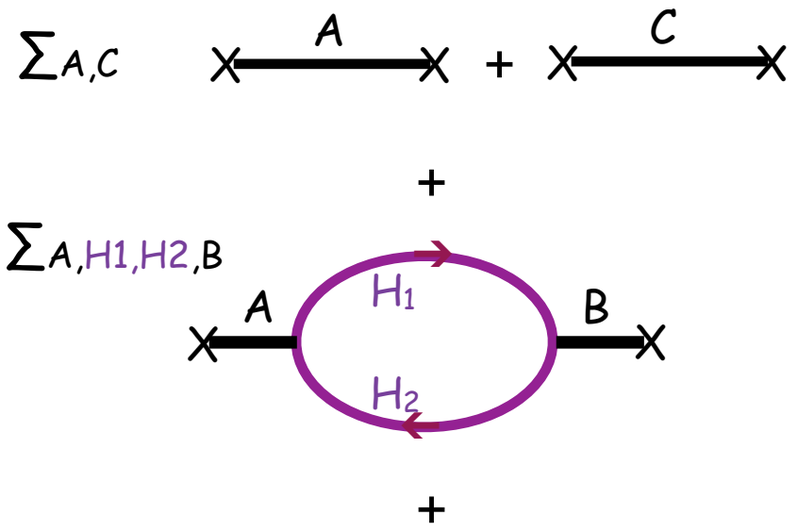


- Two pictures of R: Quark-Hadron Duality

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

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

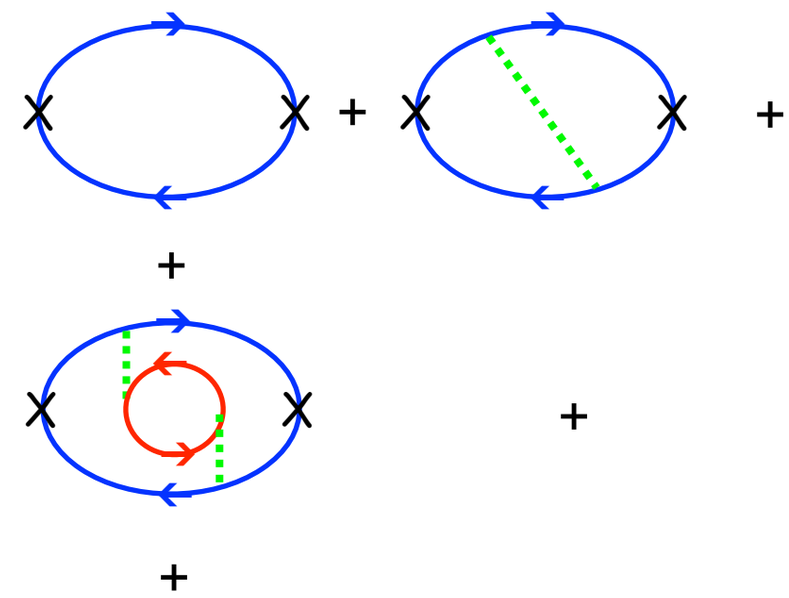
QCD - hadronic
A,B (QQ) , C (QQg)
H_1,H_2(Qq)



Simple expansion near threshold.

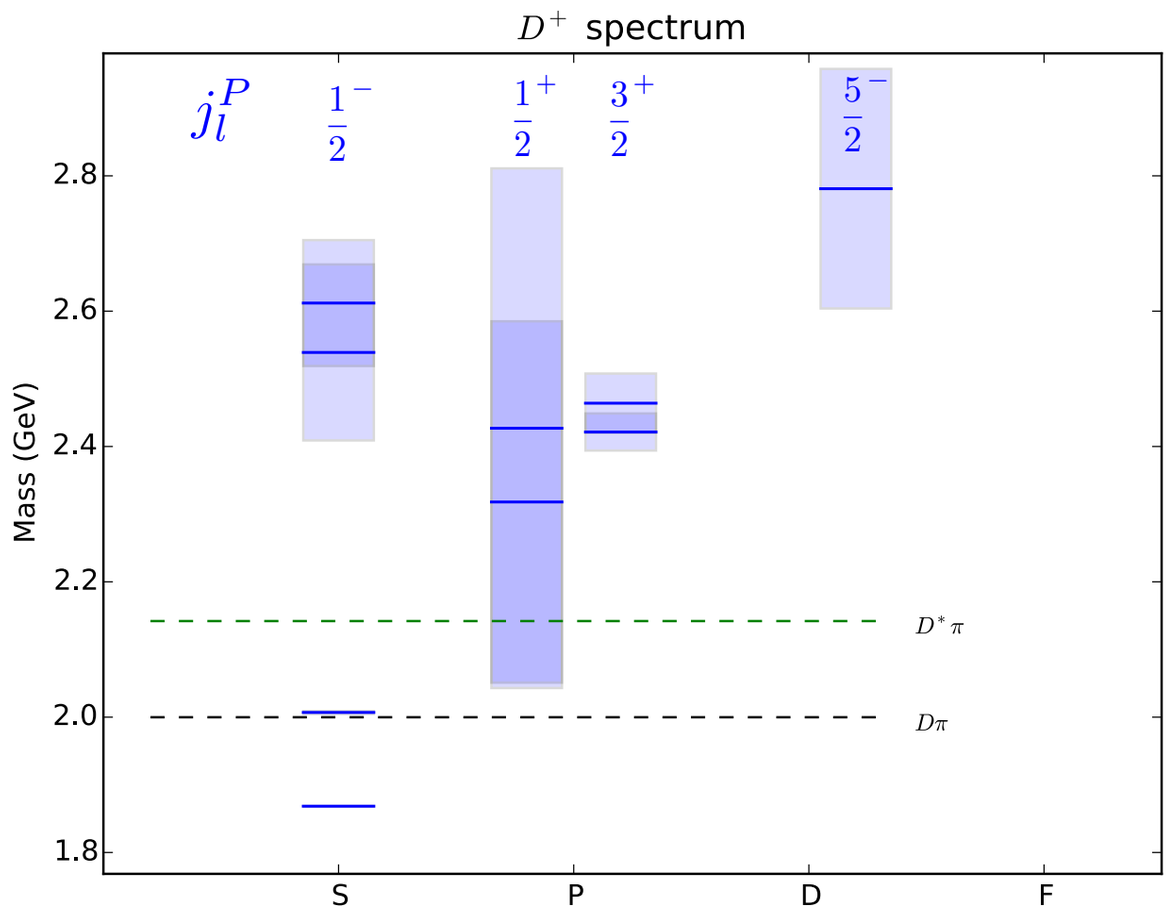
≡

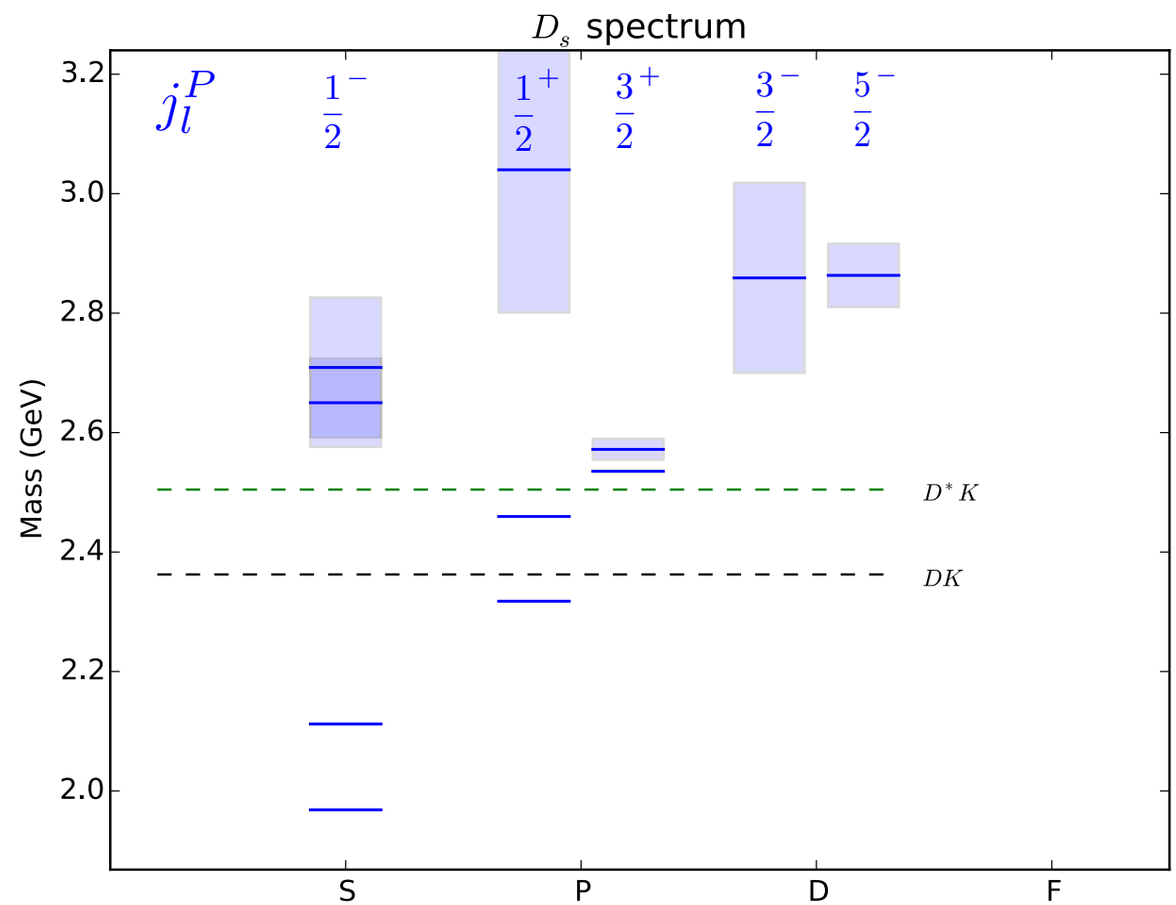
QCD - perturbative
Q, g



Simple expansion far above threshold.

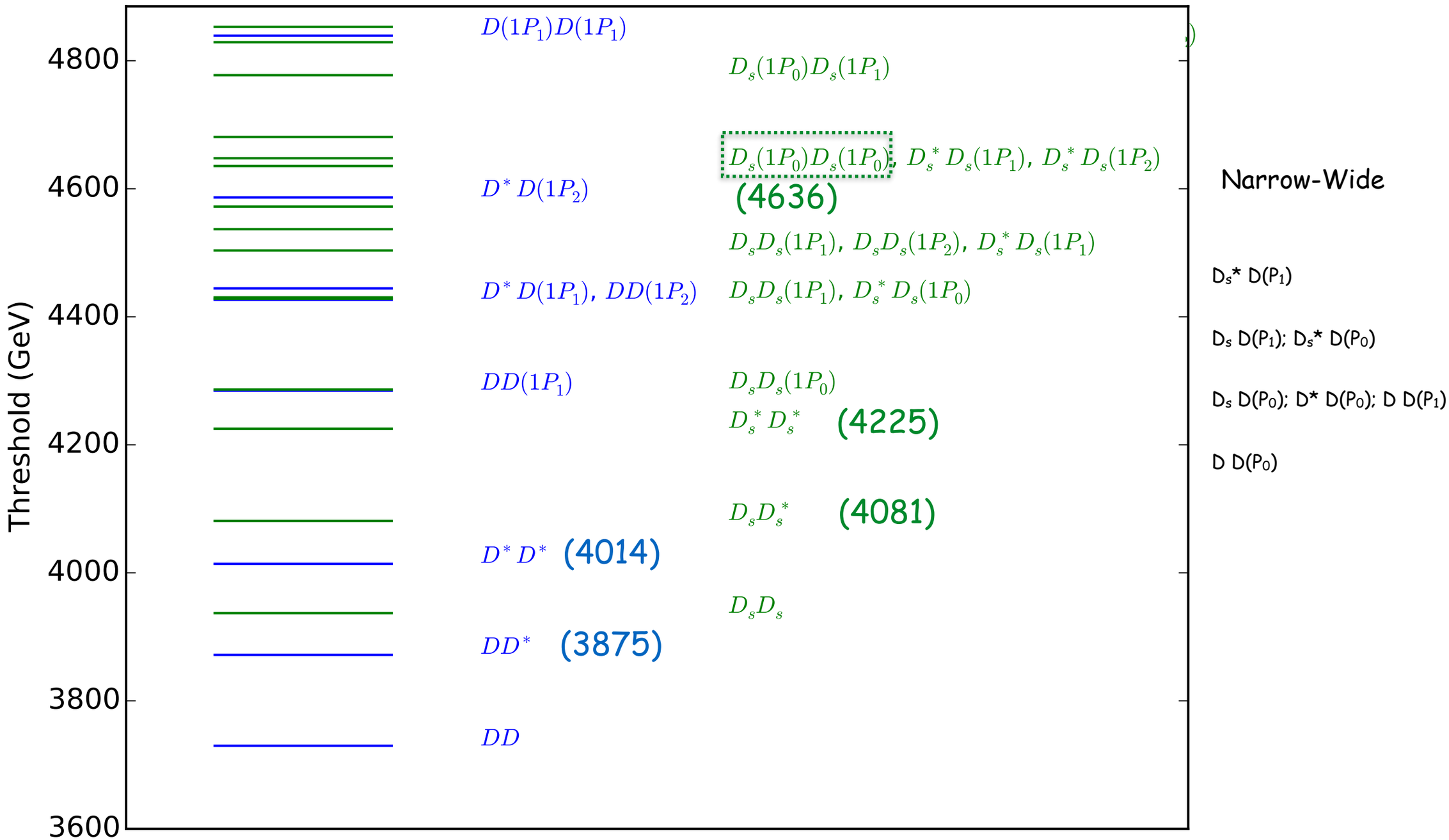
- Observed states in D meson systems:



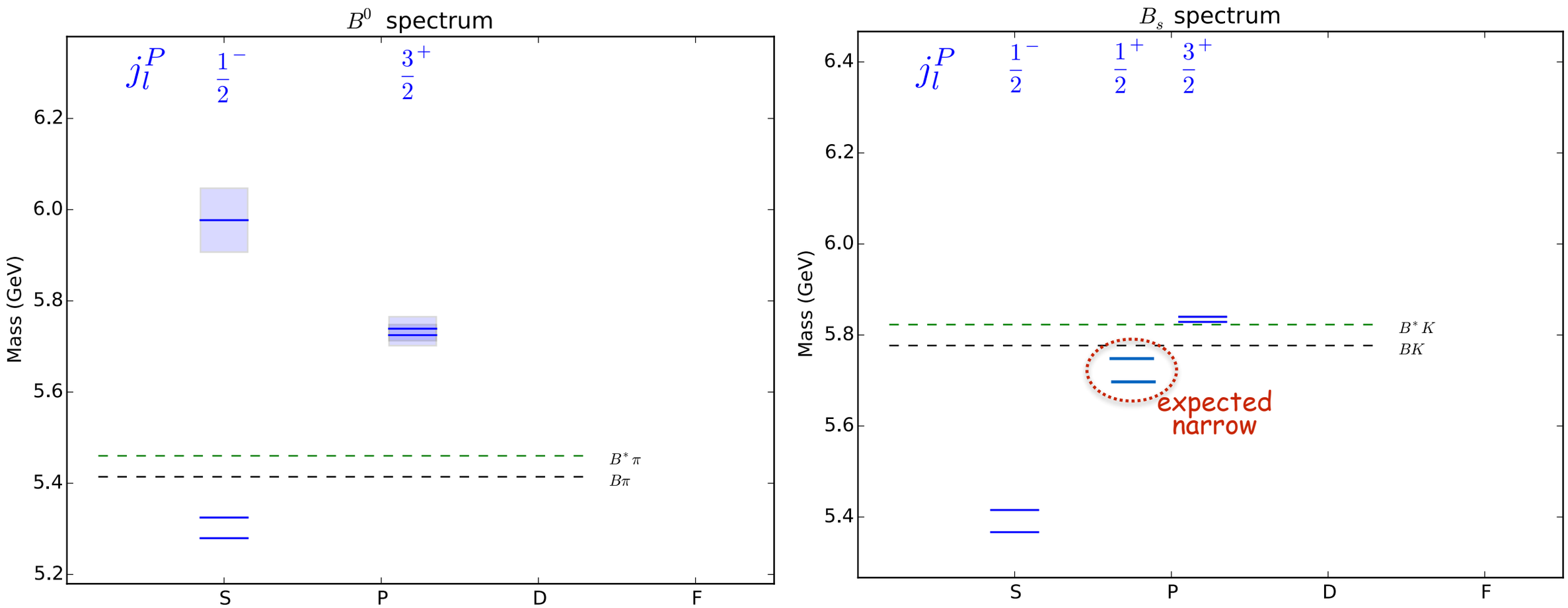


- HQS determines the ratios of hadronic transitions - very useful in distinguishing excited states
- Various proposals for the shifts of the $D_s^*(2317)$ and $D_s(2460)$:
  - Influence of the nearby decay channels.
  - Chiral multiplets (0^-,0^+).
  - Threshold bound states of DK and D*K respectively.

- strangeness zero states:
  - first double wide states: $D(1^3P_0)D(1^3P_0) \sim 4.6$; $D_s(2^1S_0)D_s(2^1S_0) \sim 5.42$



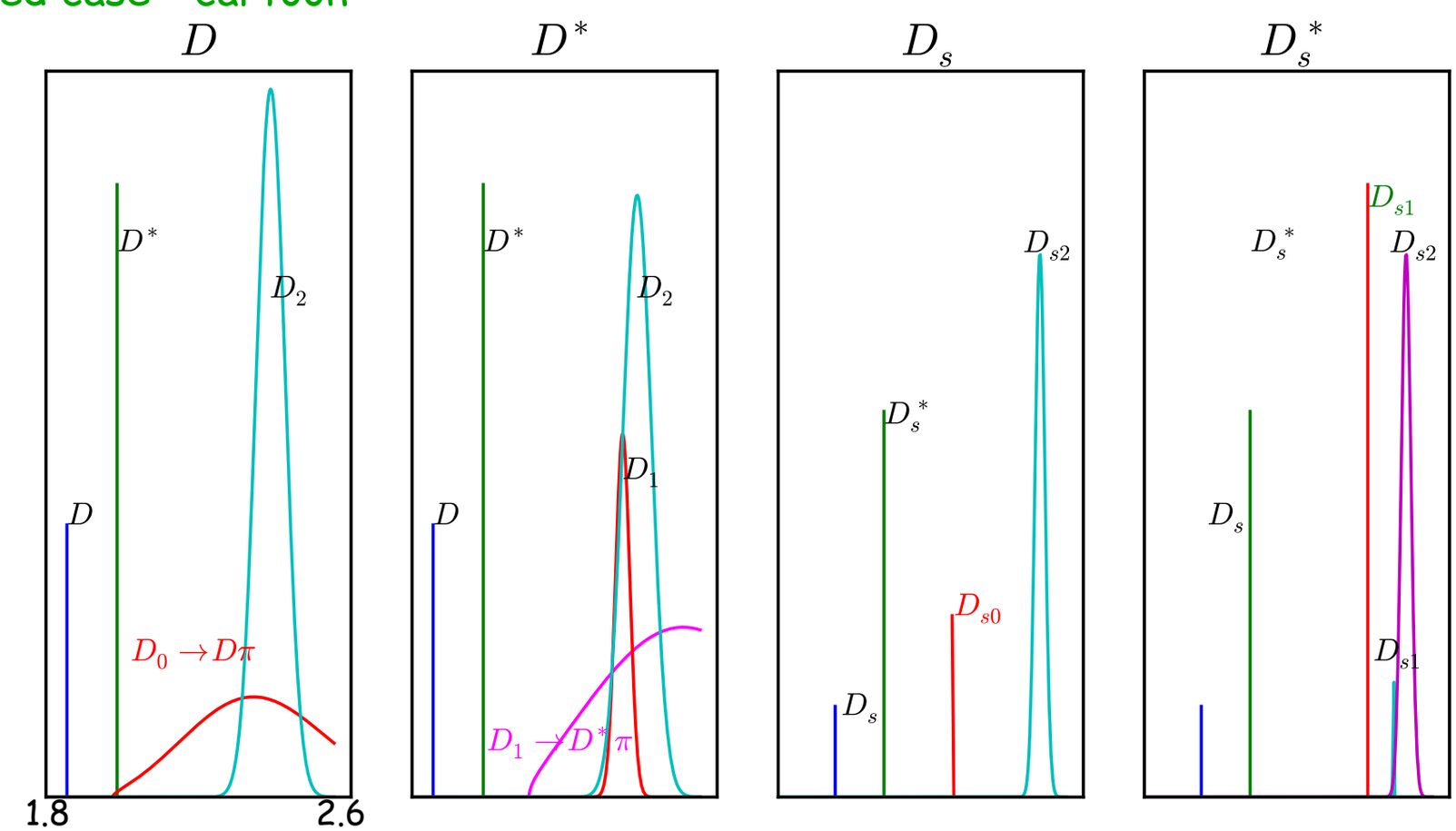
- Observed states in the B meson systems



- 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

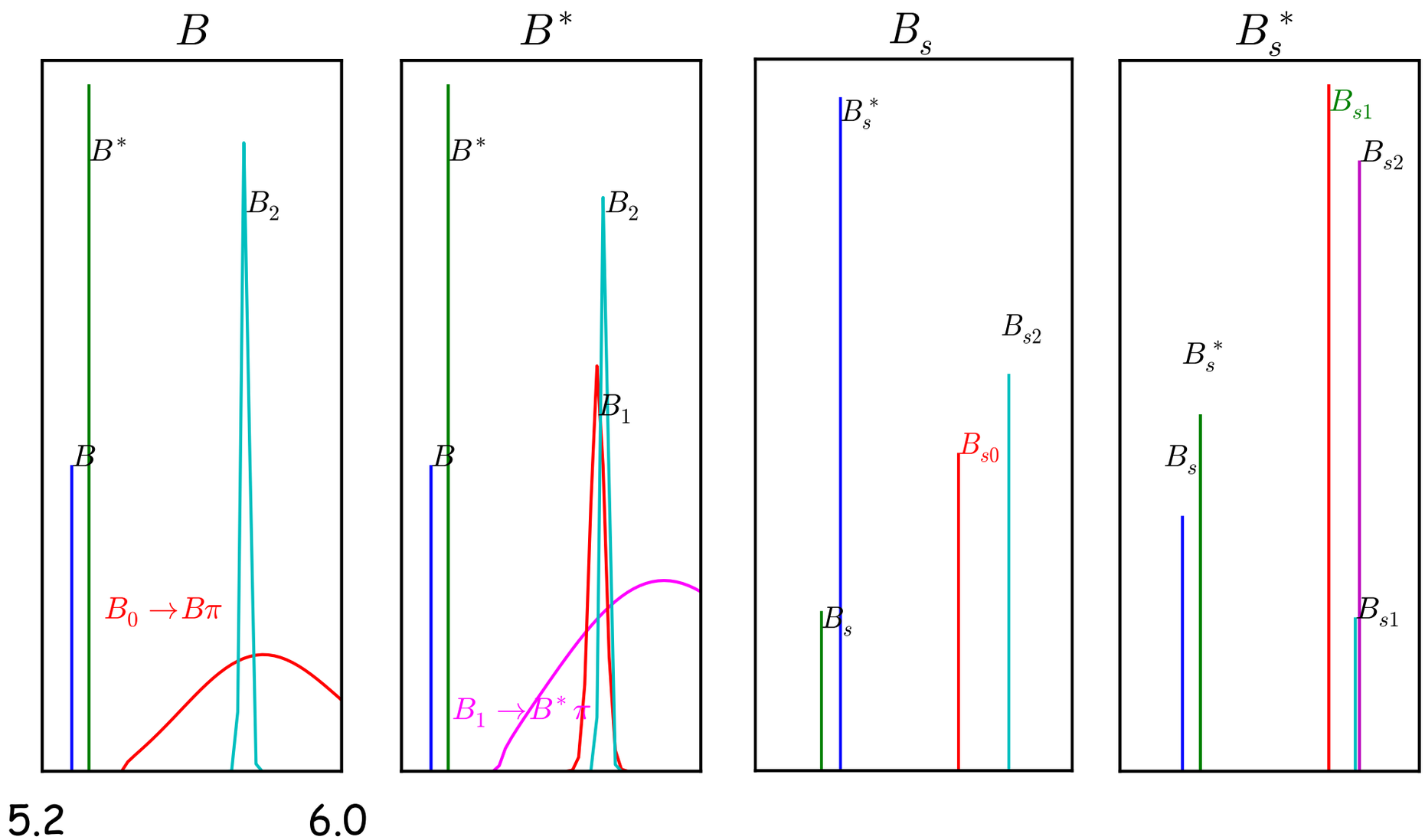
- If we take this picture seriously then:
  - near threshold the meson picture is dominant.
  - decays are expected to be "quasi" two body.
    - continuum production small - set to zero?
    - large hadronic transitions - ignore for now
- This picture suggests that it is very useful to consider the massing mass approach.
  - e^+e^- -> (D, D*, D_s, or D^*_s) + X plot $M_X(s)$. (Similar for B thresholds)
    - Idealized case - cartoon



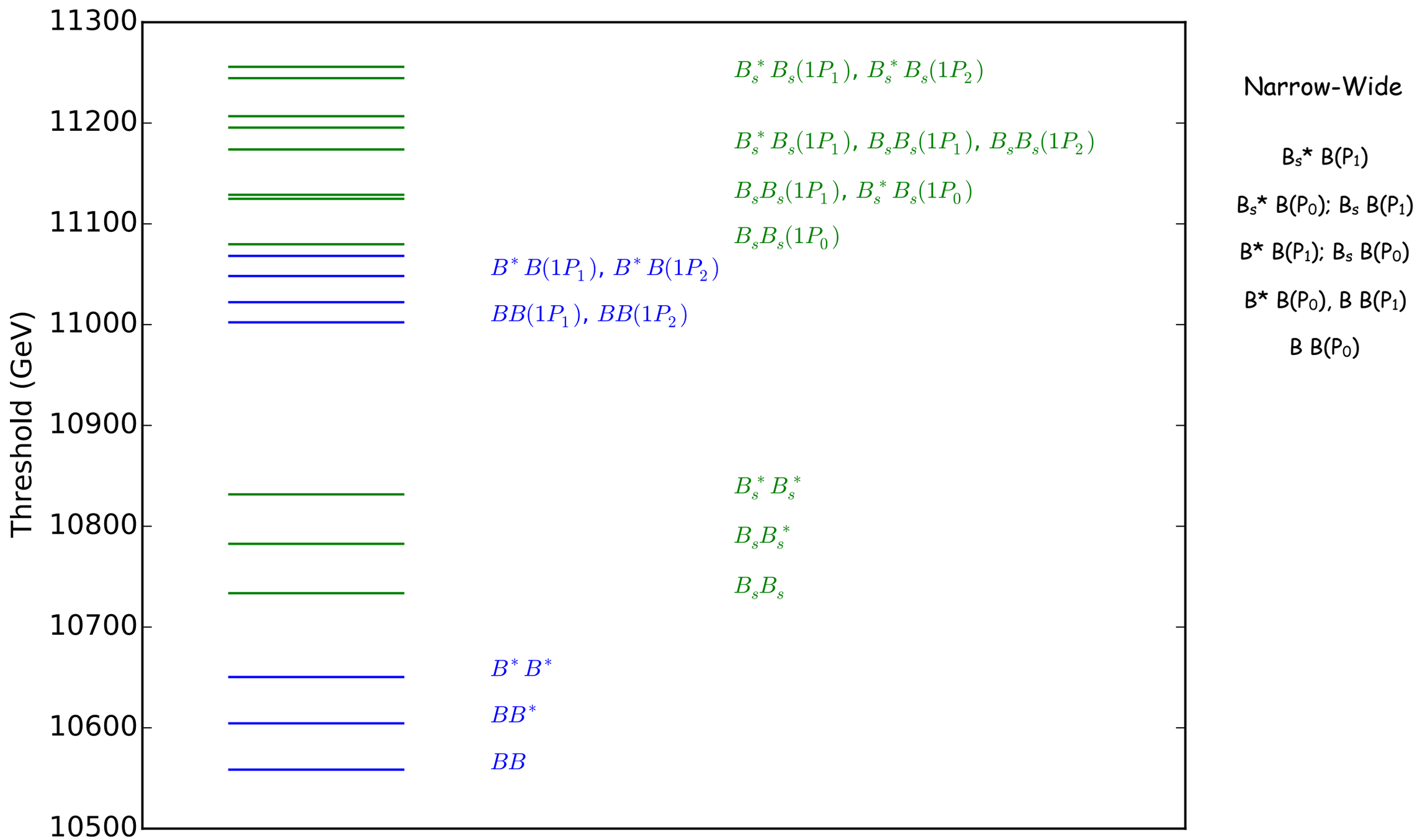
- Comments
  - A detailed calculation is in progress.
  - The non-resonance production of additional pions with heavy-light meson pairs will be small
  - With increased statistics M_X can be measured as a function of $\sqrt{s}$.
  - This inclusive measurement is dual to perturbative QCD with quark fragmentation.
  - More information can be obtained by separation into partial waves.
  - The disentangling the D and D* and the D_s and D_s* is challenging.
  - The tagging of the primary $j^p = 1/2^-$ is possible as long there is only one excited resonance that is decaying. So this breakdown when we reach threshold for two excited heavy-light mesons that are wide.

- The same approach applies to the bottonnmium threshold region

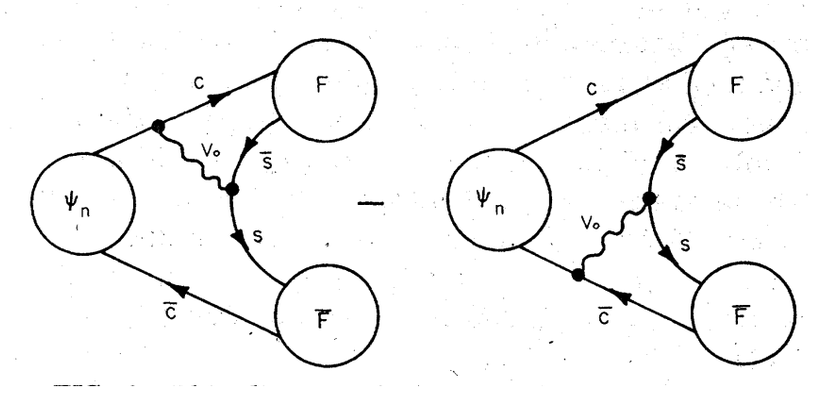
- HQS implies a similar picture in the B system:



- strangeness zero states:
  - first double wide states: $B(1^3P_0)B(1^3P_0) \sim 11.43$; $B_s(B2^1S_0)B_s(2^1S_0) \sim 12.0$



- Decays - 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 $$\Omega_{nL,mL'}(W) = \sum_i \int_0^\infty P^2\,dP\,\frac{H^i_{nL,mL'}(P)}{W-E_1(P)-E_2(P)+i0}$$ Meson loops

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

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

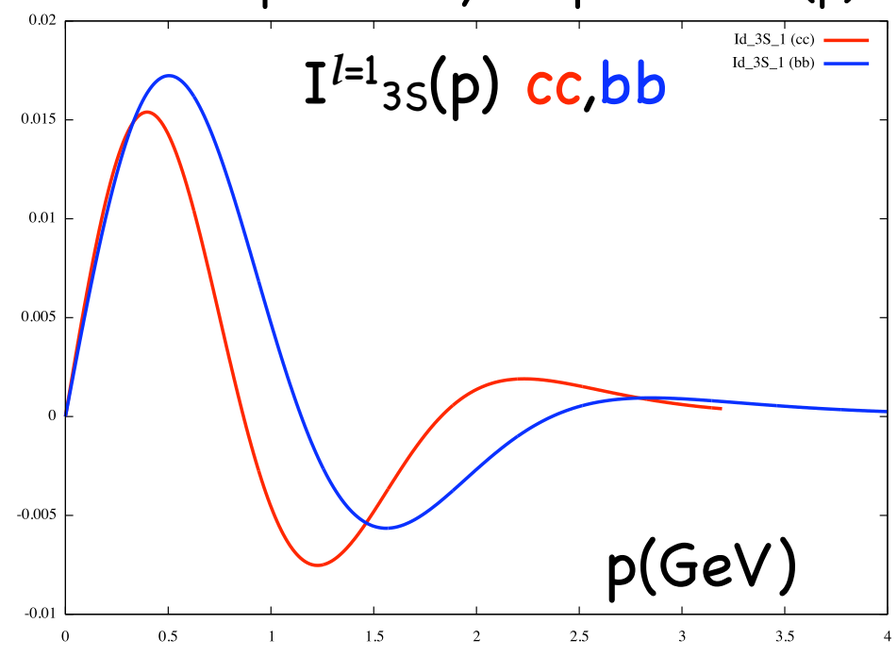
$$\Phi(t) = t e^{-t^2} + (\pi/2)^{1/2}(t^2 - 1) e^{-t^2/2} \operatorname{erf}(t/\sqrt{2})$$

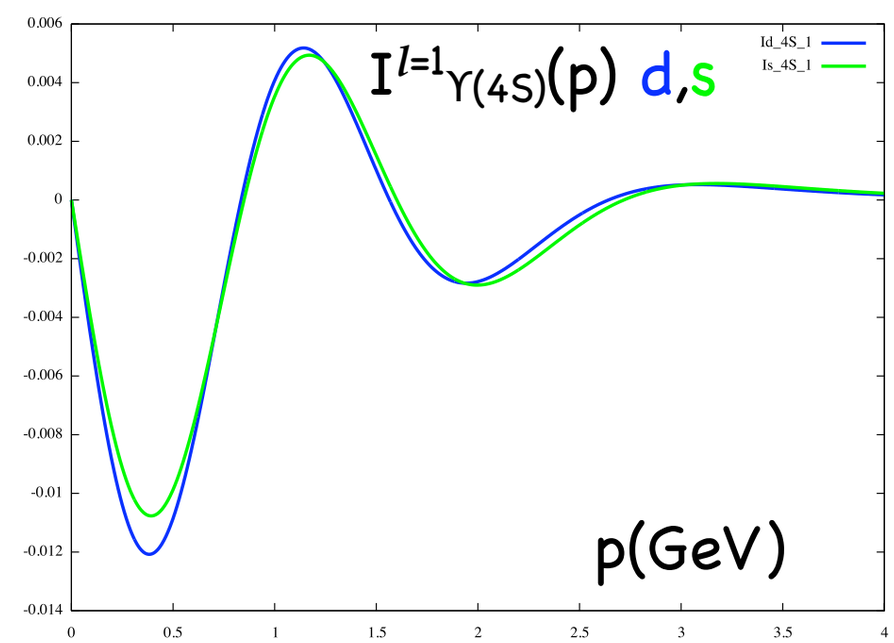
Using HQET this function Φ(t) is the same for all final states in a j_l^P multiplet.

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

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

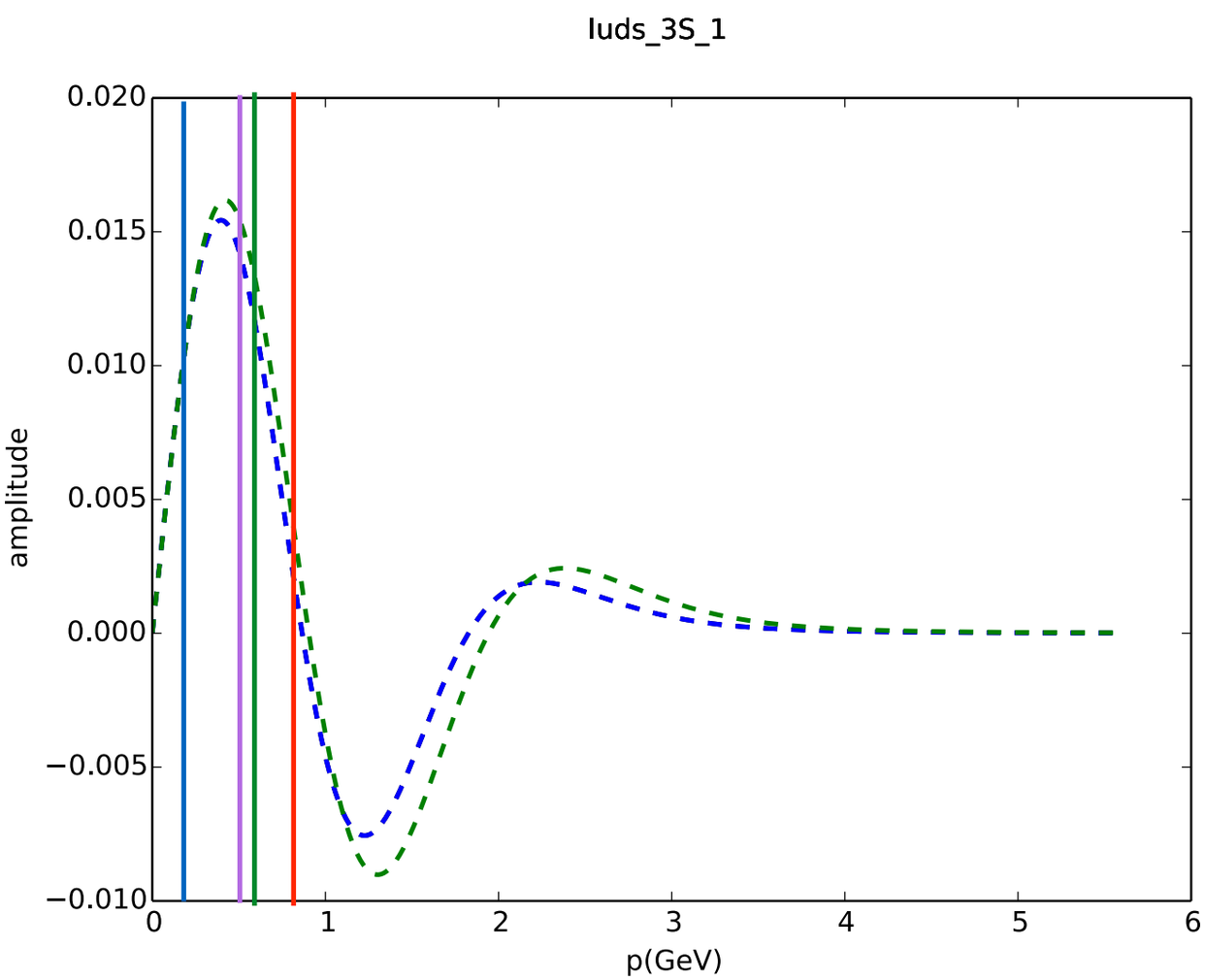
Sample decay amplitudes I(p)





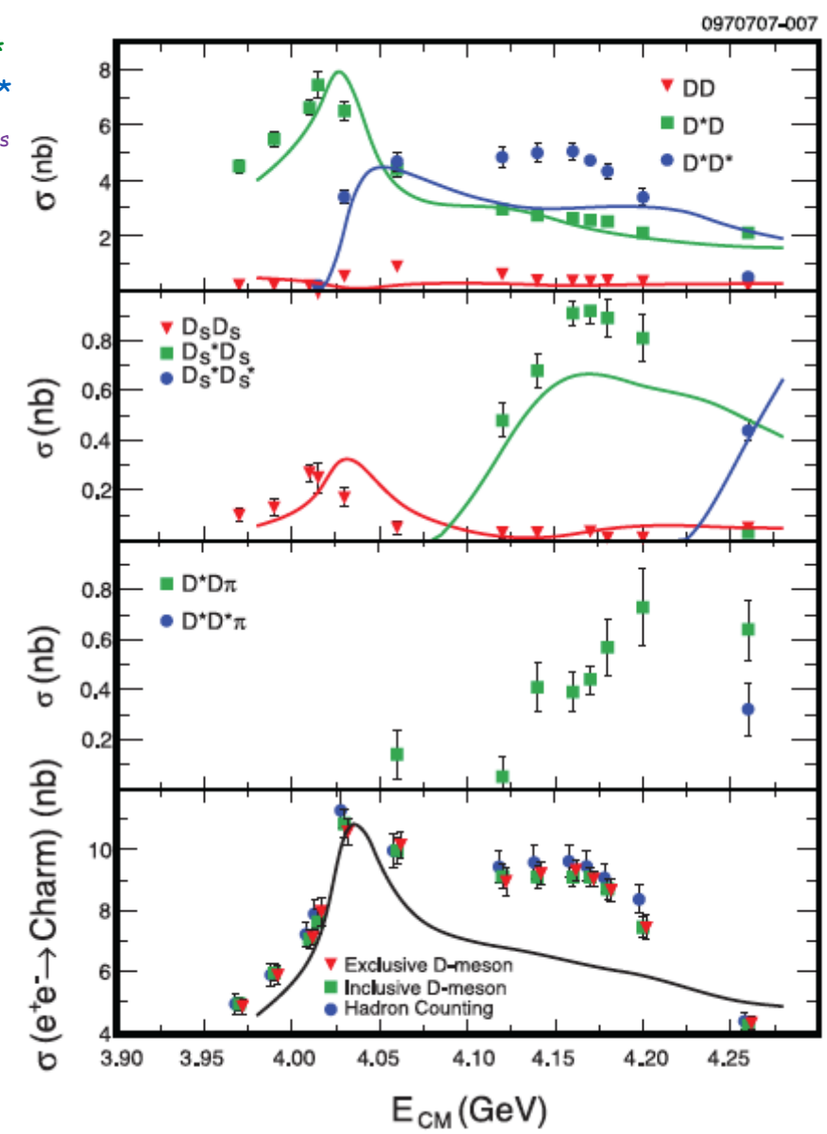
- The mass differences of heavy-light mesons produces large effects in the decay amplitudes to exclusive channels.

- E = 4.04 GeV



- p(DD) = 766 MeV; p(DD*) = 567 MeV; p(D*D*) = 218 MeV; p(D_sD_s) = 453 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, Υ(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 $B\bar{B}$	$> 96\%$
$\Upsilon(1S)\ \pi^+\pi^-$	$(8.1 \pm 0.6) \times 10^{-5}$
$\Upsilon(2S)\ \pi^+\pi^-$	$(8.6 \pm 1.3) \times 10^{-5}$
$h_b(1P)\ \pi^+\pi^-$	(not seen)
$\Upsilon(1S)\ \ \eta$	$(1.96 \pm 0.28) \times 10^{-4}$
$h_b(1P)\ \ \eta$	$(1.83 \pm 0.23) \times 10^{-3}$

—> partial rate = 1.66 ± 0.23 keV — expected rates

—> partial rate = 4.02 ± 0.89 keV — SU(3) violating

—> 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 Υ(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 $\eta + (Q\overline{Q})$.
  - 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. The large size of the hadronic transitions for the Υ(5S).

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 $B\bar{B}X$	$(76.2\ ^{+2.7}_{-4.0})\%$		

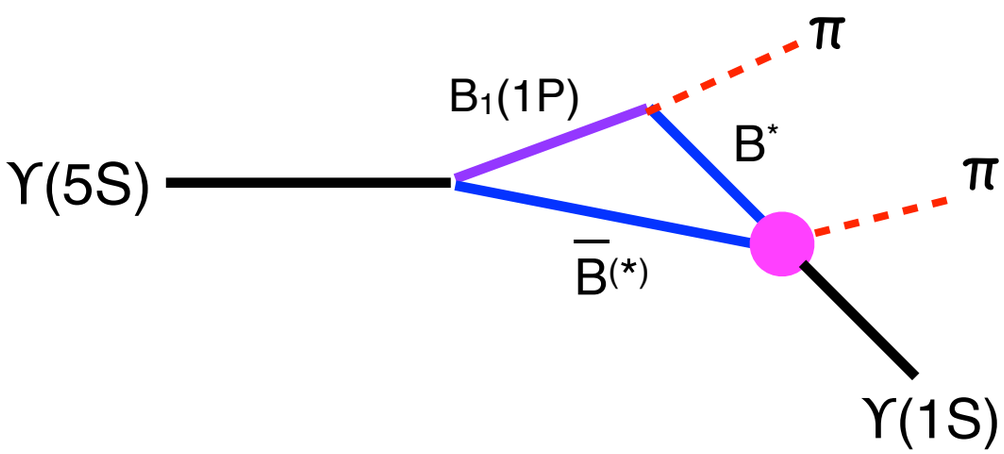
—> partial rate = 0.29 ± 0.13 MeV

—> 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 Υ(5S)
  - Decays involving P-state heavy-light mesons:
    - $n^3S_1(Q\bar{Q}) \to 1^{\frac{1}{2}+}P_J(Q\bar{q}) + 1^{\frac{1}{2}-}S_{J'}(q\bar{Q})$ then
    - $1^{\frac{1}{2}+}P_J(Q\bar{q}) \to 1^{\frac{1}{2}-}S_{J'}(Q\bar{q}') + {}^1S_0\,(q\bar{q}')$ 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) Υ(5S) strong decay is S-wave

(2) The large width of the $B_1(1P)$ implies that the first π is likely emitted while the $B_1(1P)$ and $B^{(*)}$ are still nearby.

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

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

(5) No similar BB system is possible.

- These hadronic transitions seen at both the Υ(5S) and Υ(6S)
- HHChPT

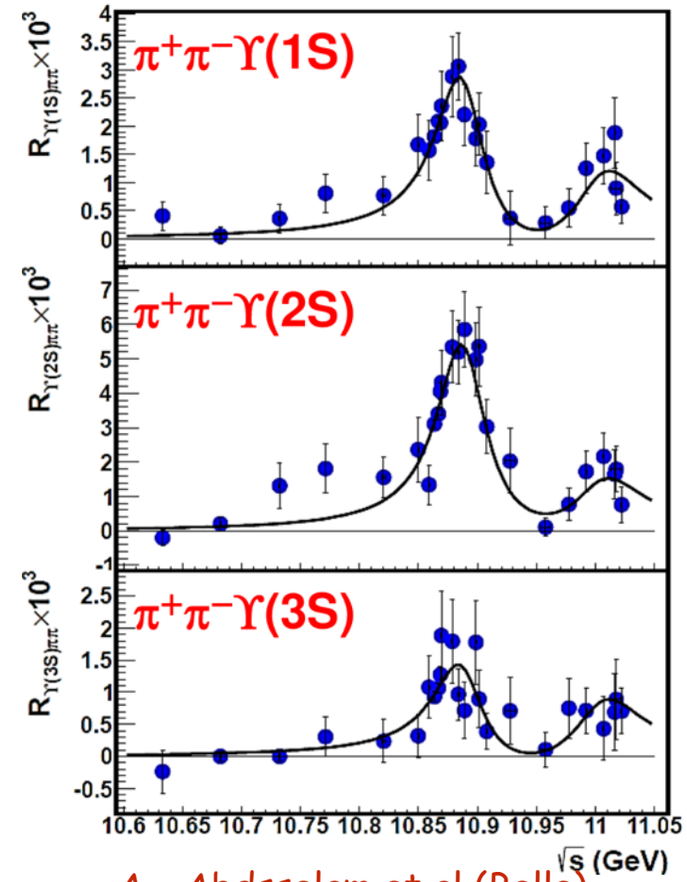
$$H_a = \frac{1+\not{v}}{2}[\mathcal{D}^*_{a\mu}\gamma^\mu - \mathcal{D}_a\gamma_5]\,,$$

$$S_a = \frac{1+\not{v}}{2}\left[\mathcal{D}'^{\mu}_{1a}\gamma_\mu\gamma_5 - \mathcal{D}^*_{0a}\right]\,,$$

$$\mathcal{L}_S = ih\,Tr[\bar{H}_a S_b \gamma_\mu\gamma_5 \mathcal{A}^\mu_{ba}] + h.c.$$

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

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



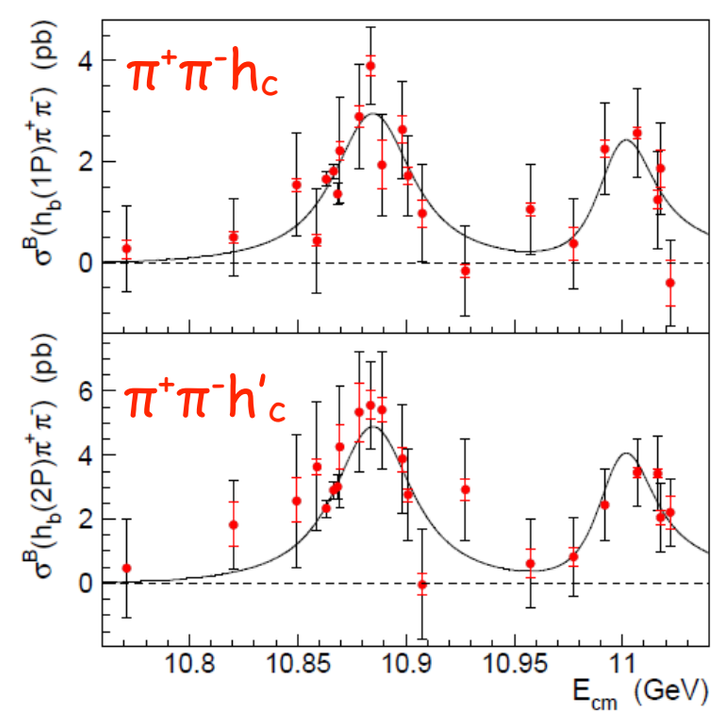
A. Abdsselam et al (Belle) arXiv:1508.06562

- 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.

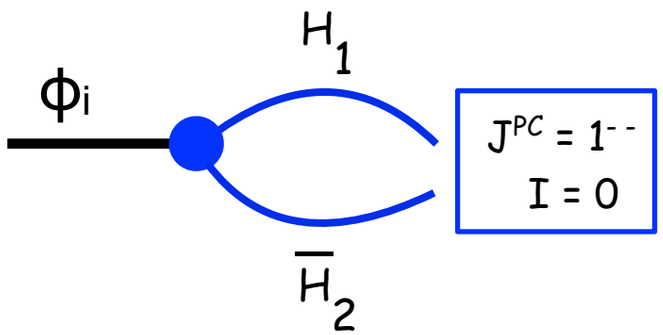
Parameter	$BB\pi$	$BB^*\pi$	$B^*B^*\pi$
Yield, Events	13 ± 25	357 ± 30	161 ± 21
$\mathcal{B}_f$, 10^{-6}	293 ± 22	276 ± 21	223 ± 17
η	1.0	1.066	1.182
$\sigma_{\rm vis}$, pb	< 2.1	$11.2 \pm 1.0 \pm 1.2$	$5.61 \pm 0.73 \pm 0.66$

A. Garmash et al (Belle) arXiv:1512.07419

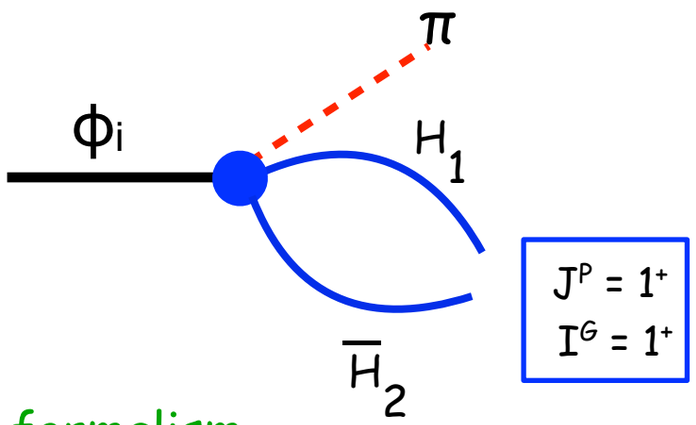


Good Agreement

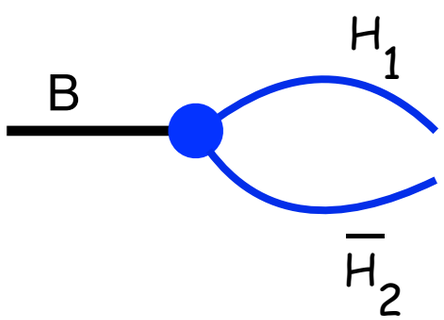
- Production modes: (Where to look for new surprises)
  - e+e- processes
    - direct

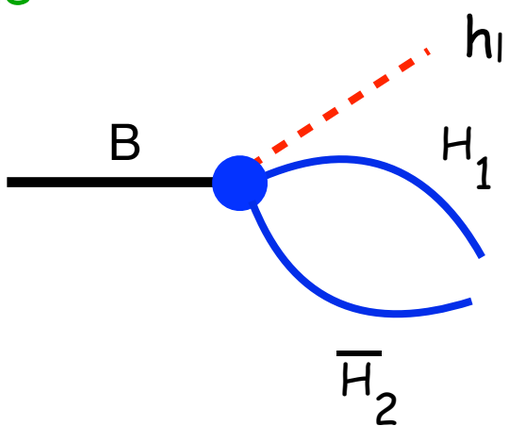


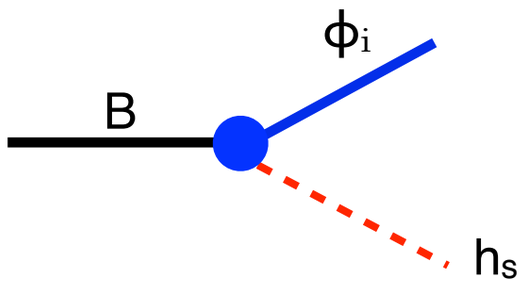
sequential (dominant terms)



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



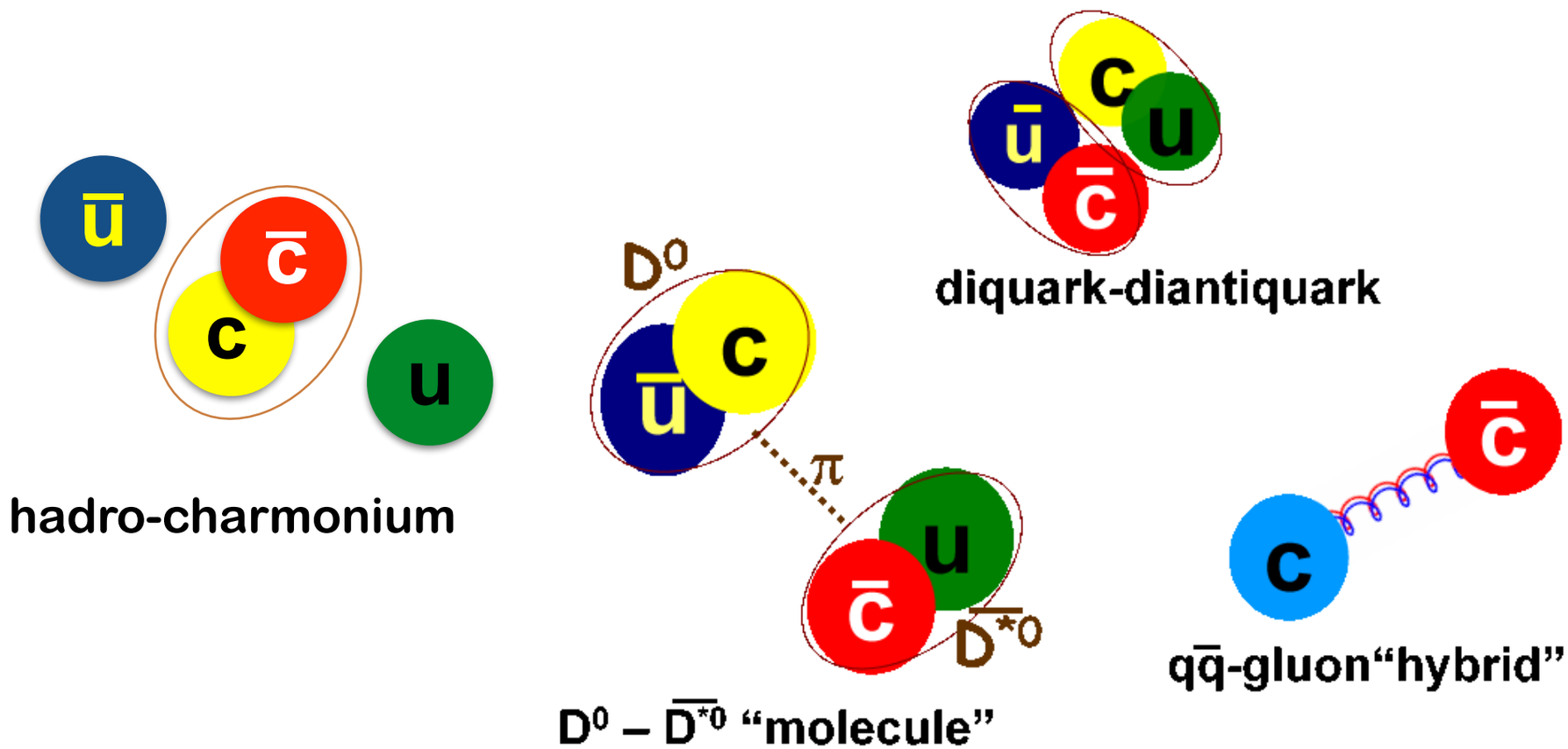




  - Four quark states can easily be produced from two-heavy-light meson at S-wave thresholds

XYZ States Observed

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

- $\Upsilon(5S) \to Z_b^+ + \pi^-$ and $Z_b^+ \to h_b(nP) + \pi^+$.
  - The $Z_b^{\pm}$: M = 10607 MeV, Γ= 15.6 ± 2.5 MeV [BB* threshold (10605)]
  - The $Z_b^{\pm}$: M = 10653 MeV, Γ= 14.4 ± 3.2 [B*B* threshold (10650)].
- Strong threshold dynamics
  - Strong peaking at threshold BB* and B*B*
  - Z+(10610) and Z+(10650) states

$Z^+(10610)$

$B(Z_b(10610) \to BB^* + c.c.)/B(Z_b(10610) \to \text{bottomonium})$
$= 4.76 \pm 0.64 \pm 0.75$

$Z^+(10650)$

$B(Z_b(10650) \to B^*B^*)/B(Z_b(10650) \to \text{bottomonium})$
$= 2.40 \pm 0.44 \pm 0.50.$

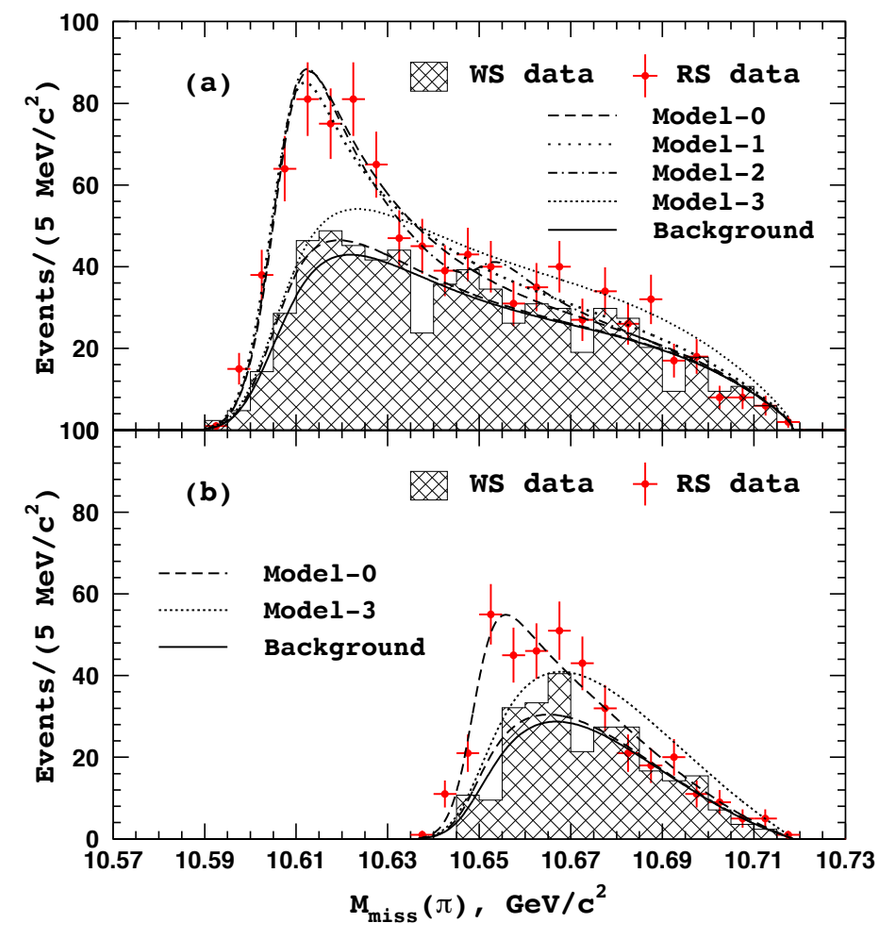
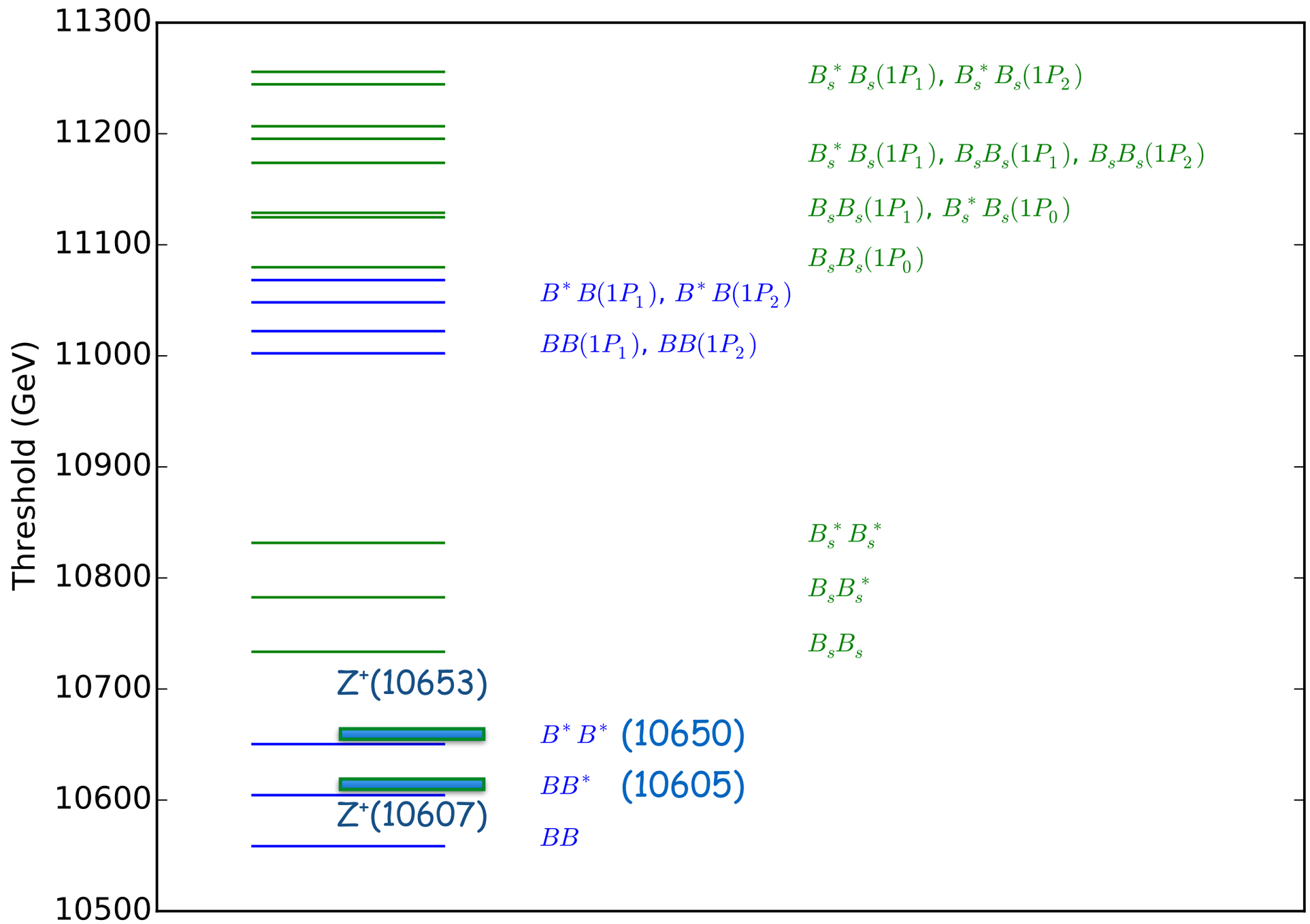


FIG. 2. The $M_{\text{miss}}(\pi)$ distribution for the (a) $BB^*\pi$ and (b) $B^*B^*\pi$ candidate events.

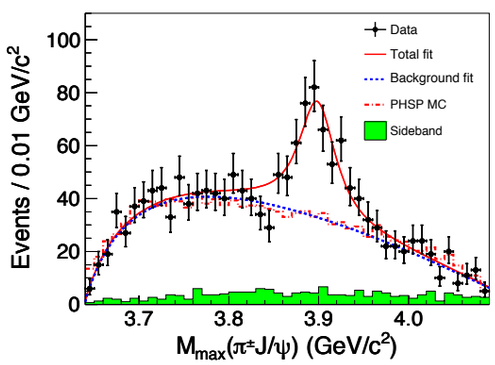
- HQS implies that the same mechanism applies for charmonium-like states

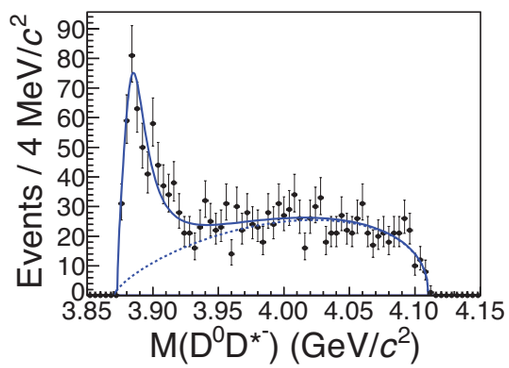
- Strangeness zero states - bottomonium

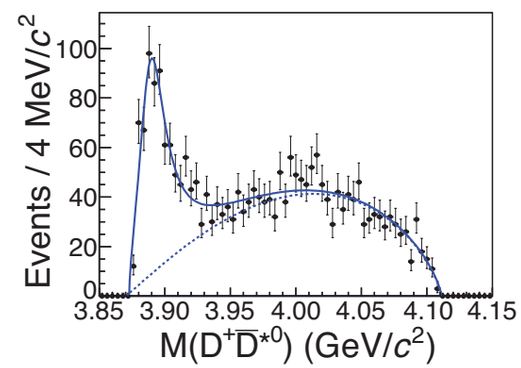


$Z_c^+(3885)$ and $Z_c^+(4020)$

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







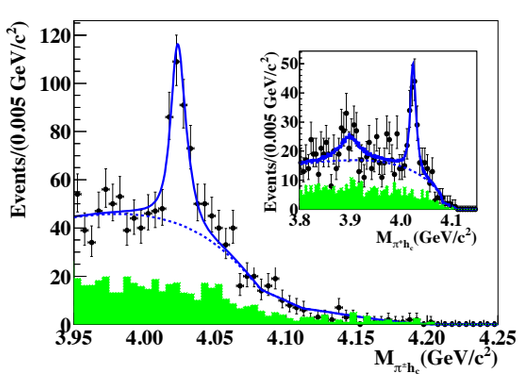
$$\frac{\Gamma[Z_c(3900)\to DD^*]}{\Gamma[Z_c(3900)\to\pi J/\psi]} = 6.2 \pm 1.1_{\rm stat} \pm 2.7_{\rm sys}.$$

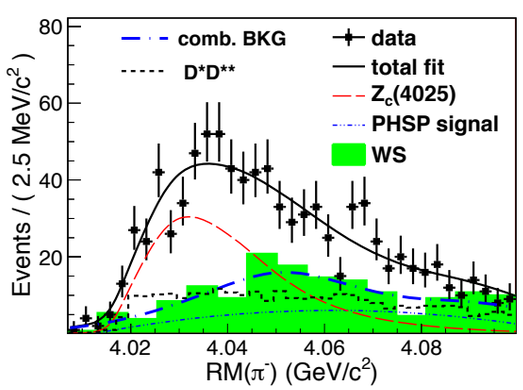
$M(D^0+D^{*-})$ = 3.8752

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

BESIII Z. Lin

[arXiv:1504.06102]





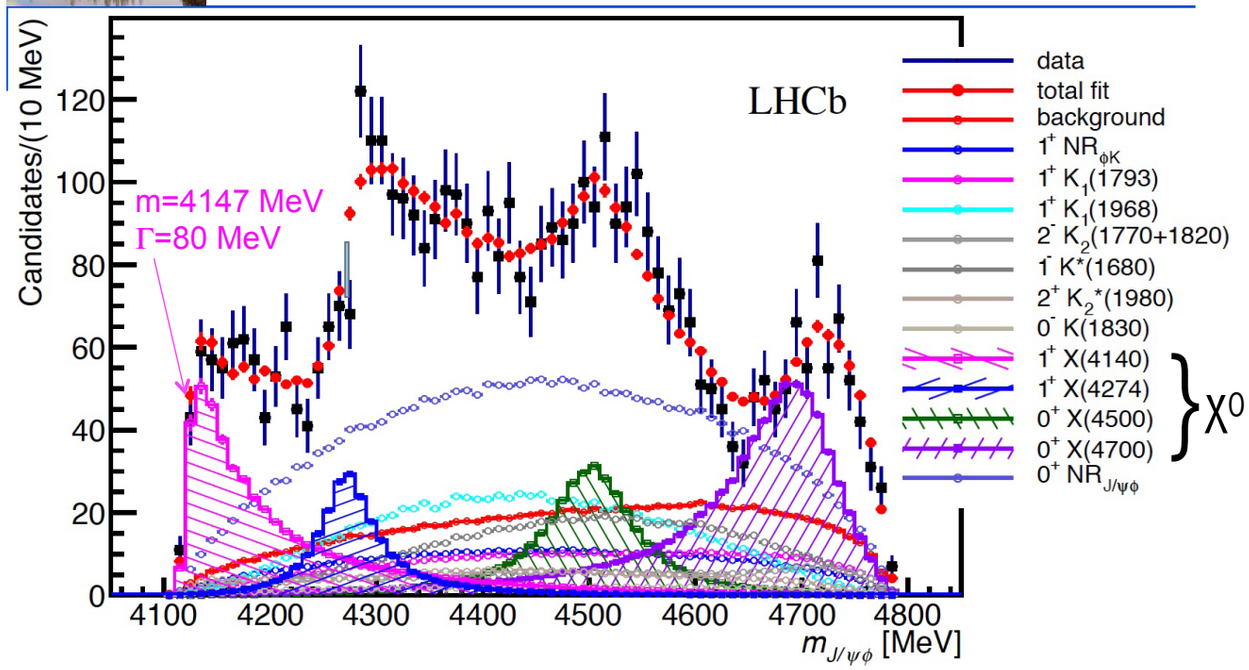
$$\frac{\Gamma[Z_c(4025)\to D^*D^*]}{\Gamma[Z_c(4020)\to\pi h_c]} \sim 9.$$

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

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

- LHCb - T. Skwarnicki talk Meson 2016 - light quarks -> strange quarks

Results of fit: m(J/ψϕ)



- 4 visible structures fit with BW amplitudes

28 Recontres de Blois, June 2, 2016

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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			$46 \pm 11^{+11}_{-21}$

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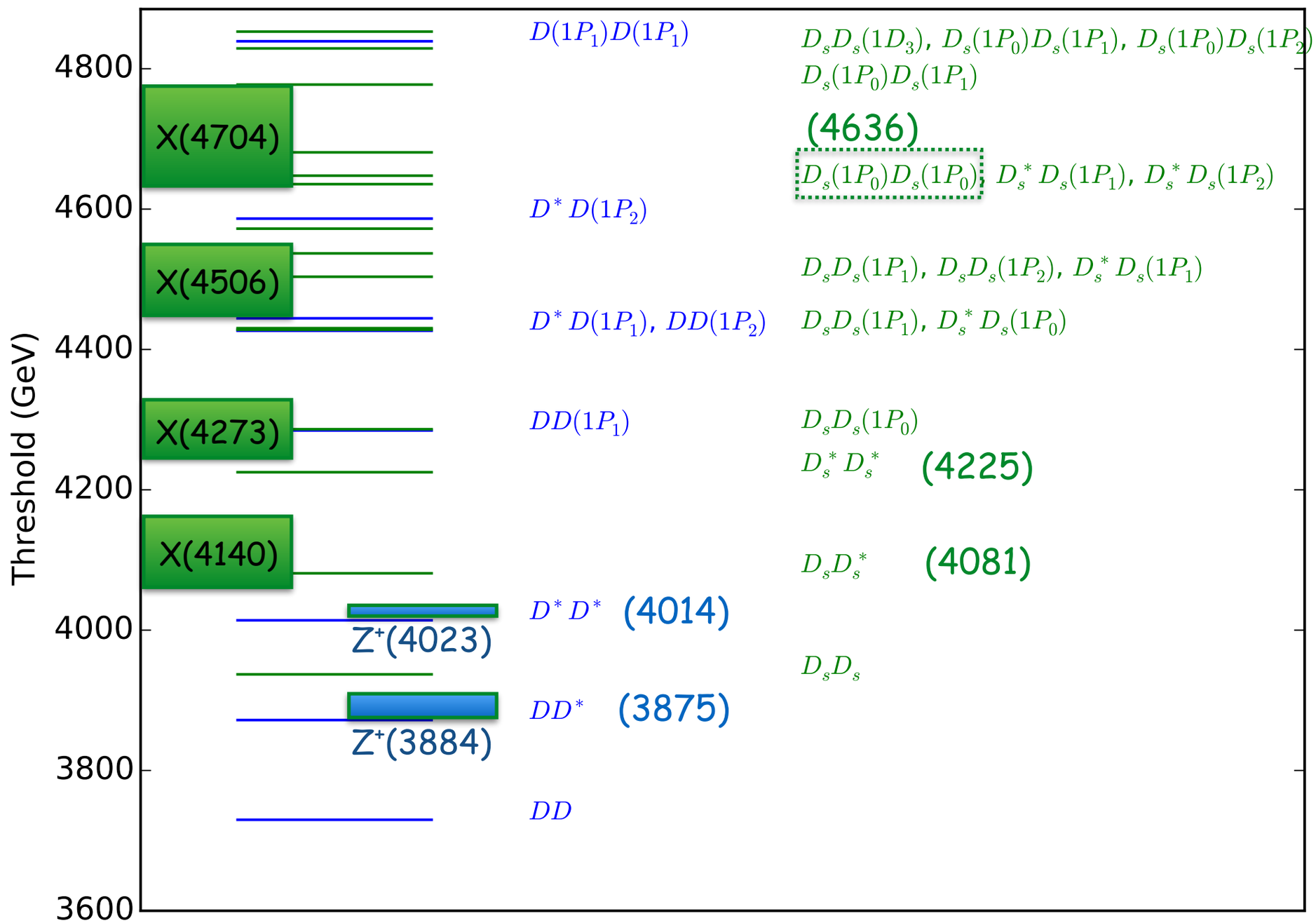
- strangeness zero states - charmonium

B -> X K: M_X < 4785 MeV



- 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?

X(3872)

- X(3872) - $J^{PC} = 1^{++}$ M= 3871.69 ± 0.16 ± 0.19 Γ< 1.2 MeV from J/ψ ππ mode

  - Decays observed:

$\pi^+\pi^- J/\psi(1S)$	$>$ 2.6 %
$\rho^0 J/\psi(1S)$	
$\omega J/\psi(1S)$	$>$ 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] $\frac{\mathcal{B}(\mathrm{X}(3872) \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$ suggests 2P state

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

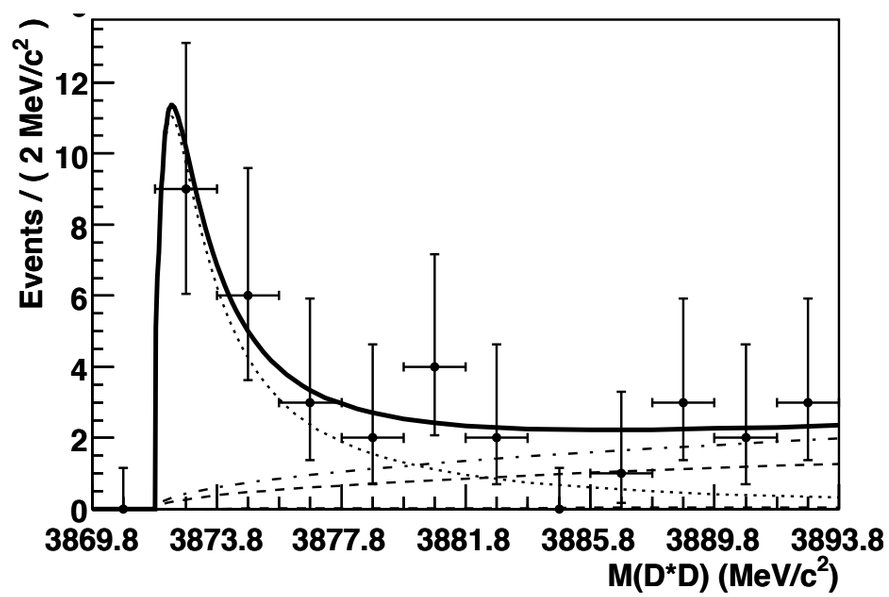
  - Two primary models:
    1. $\chi_{c1}'(2^3P_1)$ state → M. Suzuki, hep-ph/0307118.
    2. $D^0\,\overline{D}^{0*}$ molecule → DeRujula, Georgi, Glashow, PRL 38(1997)317; F. Close and P. Page, Phys. Lett. B578 (2004) 119; M. Voloshin, Phys. Letts. B579 (2004) 316. … E. Braaten [arXiv1503.04791]

  - Mixed state with sizable quarkonium component likely.

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

- B -> X(3872) K -> $(D^0\bar{D}^{0*})$ K
- Strong peaking at threshold for S-wave observed experimentally.

Belle Phys.Rev. D81 (2010) 031103



- Lattice calculations:
  - `A pole appears just below threshold in the J^{PC} =1^{++} I = 0 channel.
  - But requires both the $(c\bar{c})$ 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.

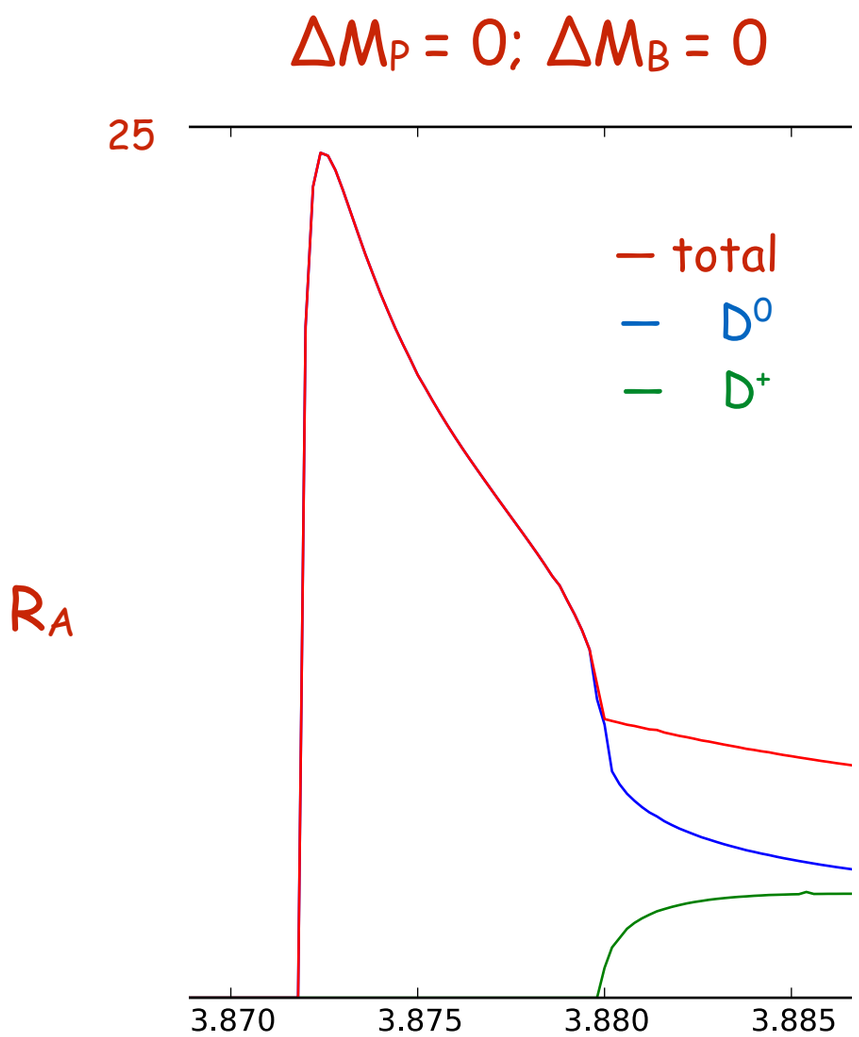
B. A. Galloway, P. Knecht, J. Koponen, C. T. H. Davies, and G. P. Lepage, PoS **LATTICE2014**, 092 (2014), 1411.1318.

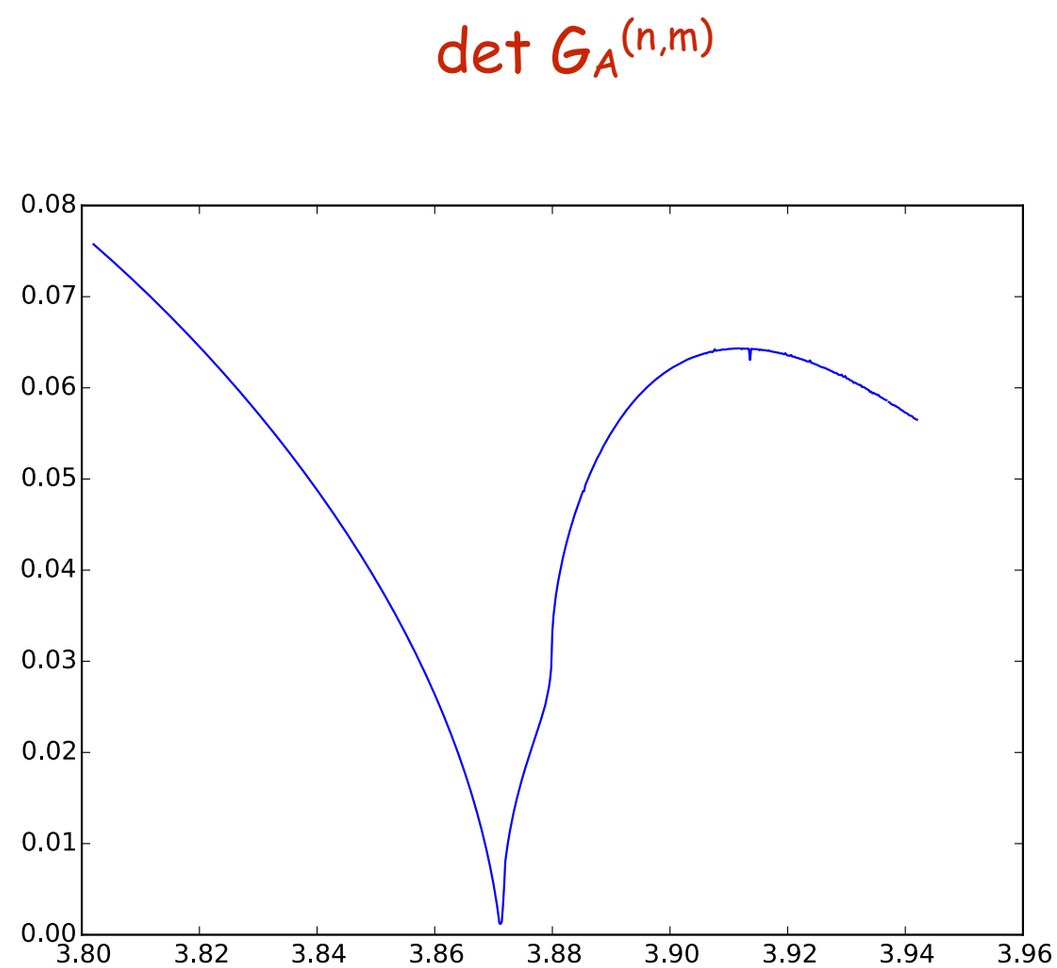
S. Prelovsek and L. Leskovec, Phys.Rev.Lett. **111**, 192001 (2013), 1307.5172.

Fermilab Lattice, MILC, S.-h. Lee, C. DeTar, H. Na, and D. Mohler, (2014), 1411.1389.

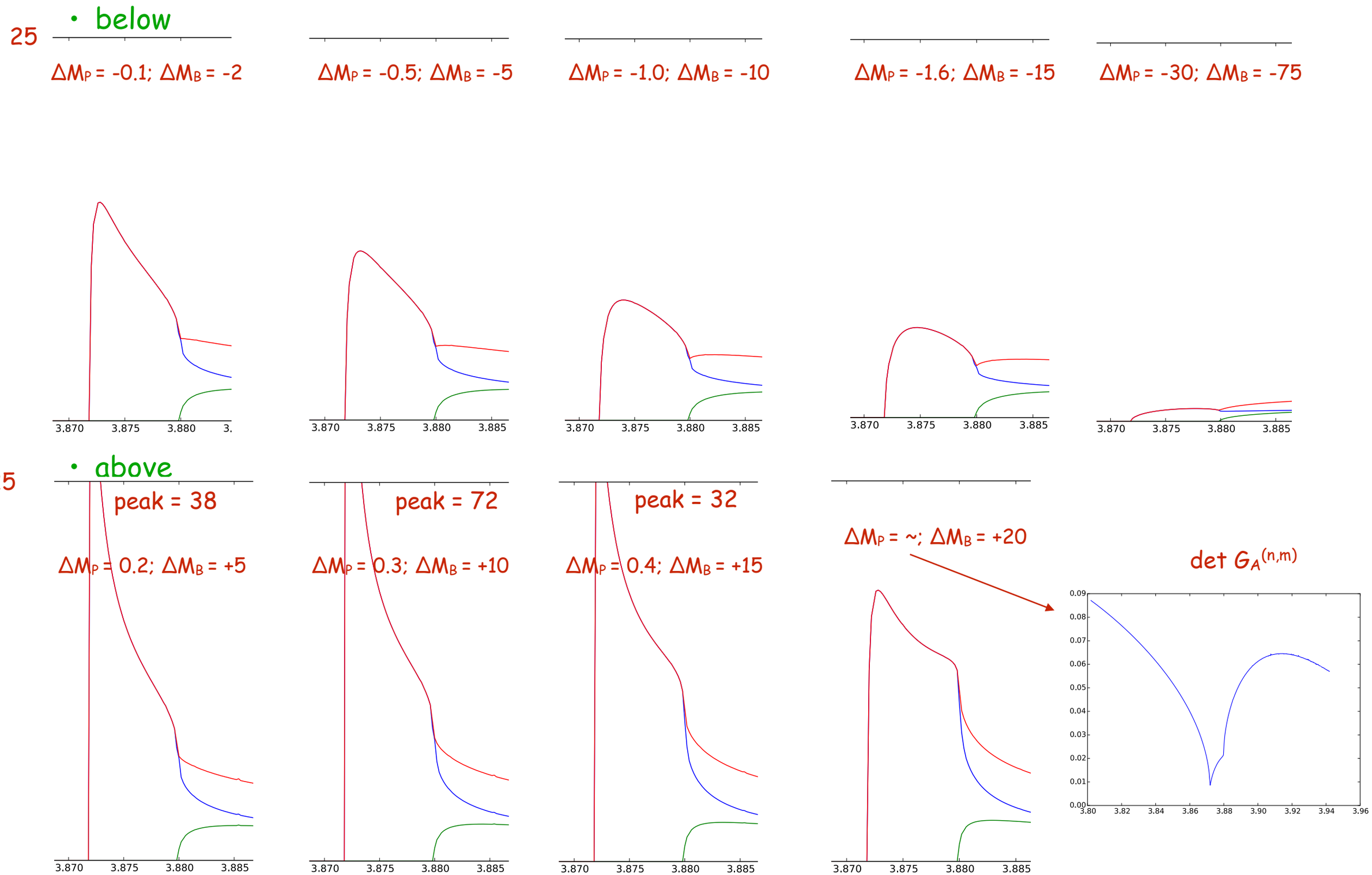
M. Padmanath, C. B. Lang, and S. Prelovsek, Phys. Rev. **D92**, 034501 (2015), 1503.03257.

- R_A - R with axial vector currents - for b meson decays
  - CCCM: only shift the bare mass of the 2^3P_1 state (χ'_{c1})
  - bare mass, m_B, adjusted to physical χ'_{c1} to D^0D^{*0} threshold (3.872):
    $\Delta M_P = m(\chi'_{c1}) - M(D^0) - DMD^{*0})$; $\Delta M_B = m_B(2^3P_1) - m_B(2^3P_{1\,[ref]}) = 0$





- The $\Delta M_B = m_B(2^3P_1) - m_B(2^3P_{1\,[ref]})$ behavior:



- My preliminary conclusions about the X(3872)
  - No need for addition attractive interactions or pion exchange.
  - Detailed measurements can extract the physical mass to high accuracy.
  - For the real shifts of states above threshold:
    - Coupled channel models need to include the contribution of more higher states, or
    - Use subtracted dispersion relations, or
    - Model the high states using perturbative QCD

Summary

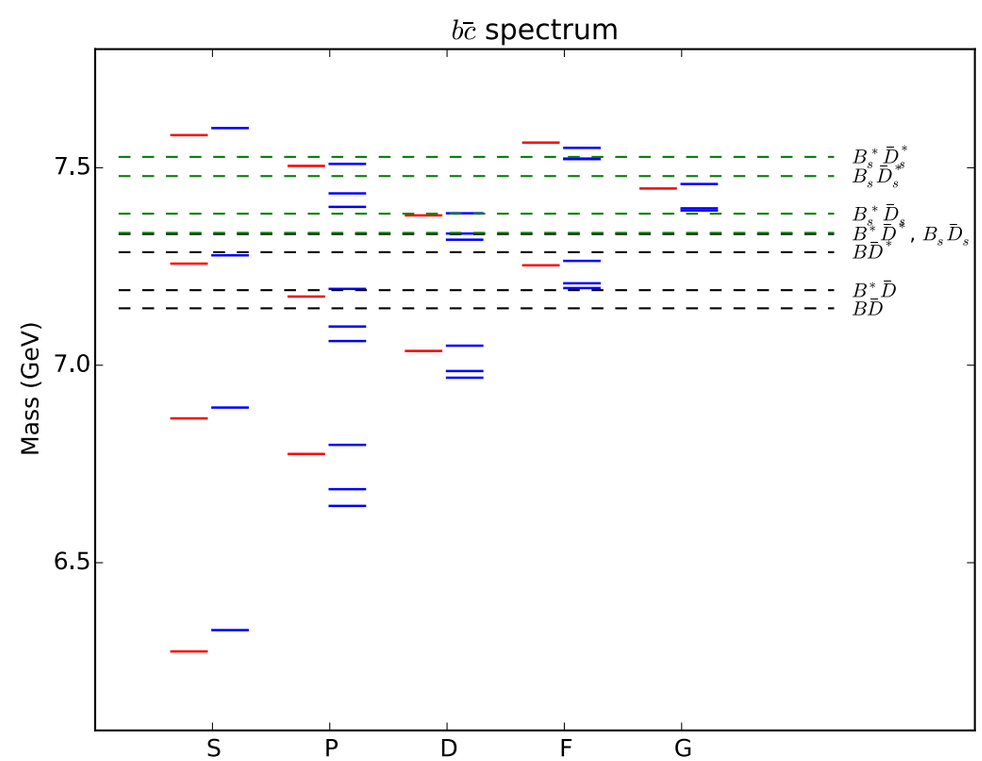
- Heavy quark states are ideal systems to study QCD strong dynamics.
- In the threshold region for decays to open heavy flavor states QCD dynamics is more complicated than below. There have been many surprises and a still incomplete picture of the dynamics:
  - Large violations of heavy quark spin symmetry 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. Points to dynamics of S-wave two heavy-light mesons at threshold.
  - 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.

Wish List-1

- 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) -> (bb) within a given model. Provides a test for various models.
  - e+e- -> $(j_l^P = \frac{1}{2}^-)_{HL}$ + X: Measure $M_X(s)$ for s < [4.6 (D); 5.42(D_s); 11.43 (B); 12.0 (B_s)]
- 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 -> no sequential transitions (as in the Υ(5S) system).
    - $M(D_s^+ D_s^{-*}) = 4{,}081$; $M(D_s^{+*} D_s^{-*}) = 4{,}225$; $M(2^3P_1) = 4{,}310$ MeV -> 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.D D_s*

Wish List-2

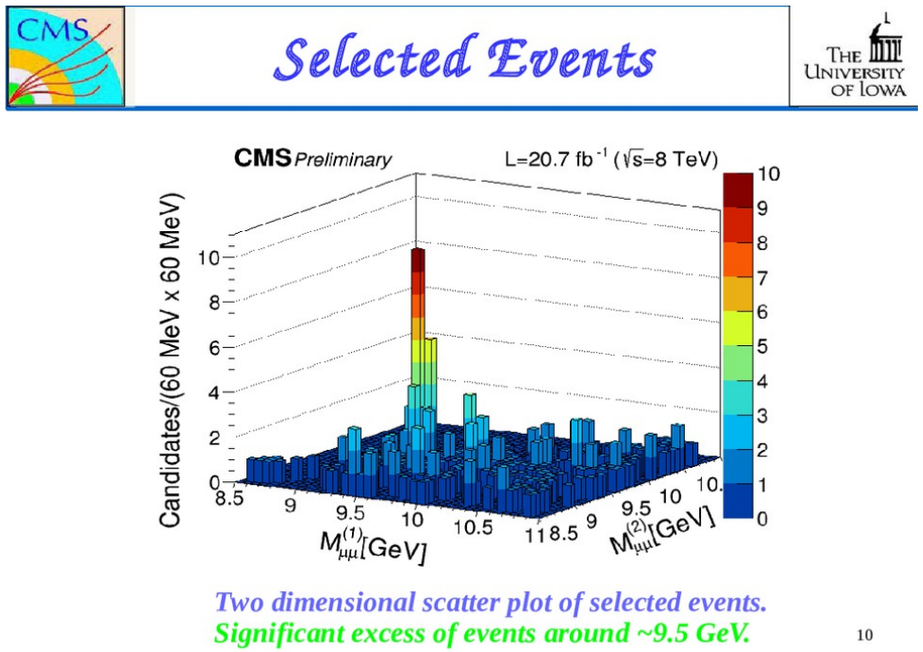
- Double heavy baryons - (ccq), (cbq), (bbq). Both HQET and NRQCD play a role in the excitation spectra.
  - double expansion
  - NRQCD for the two heavy quarks and HQET expansion for the heavy core (QQ) - light quark system.
  - In leading order in $1/m_Q$: Excitation spectrum for the light quark is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



Wish List-3

- CMS at $\sqrt{s}$ = 8 TeV observes double Υ production in the μ+ μ- μ+ μ- final state:
  - $\sigma(p\bar{p} \to \Upsilon\Upsilon) = 68.8 \pm 12.7\ (stat) \pm 7.4\ (syst)$ 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?

Maksat Haymyradov: APS April meeting

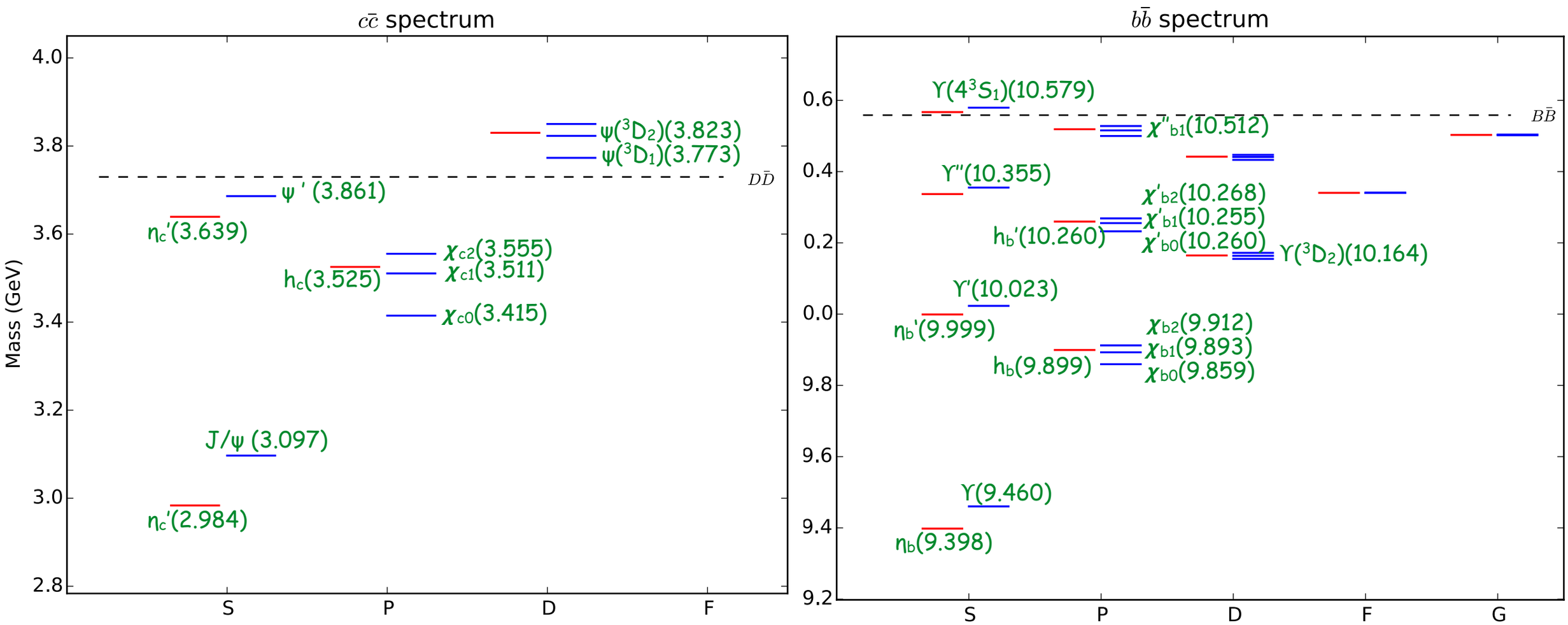


Are there any narrow deeply bound tetraquark states?

BACKUP SLIDES

Narrow States Below Threshold

- expected spectrum below threshold:
  - Observed states (labeled)



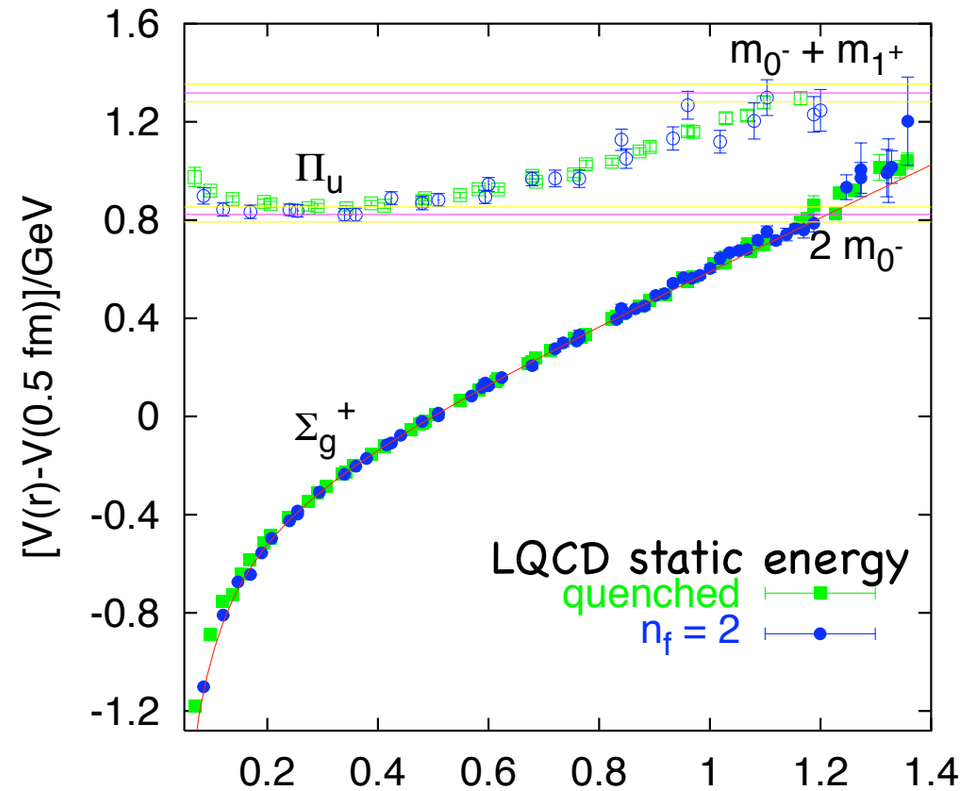
- 2 narrow states still unobserved

18 narrow states still unobserved

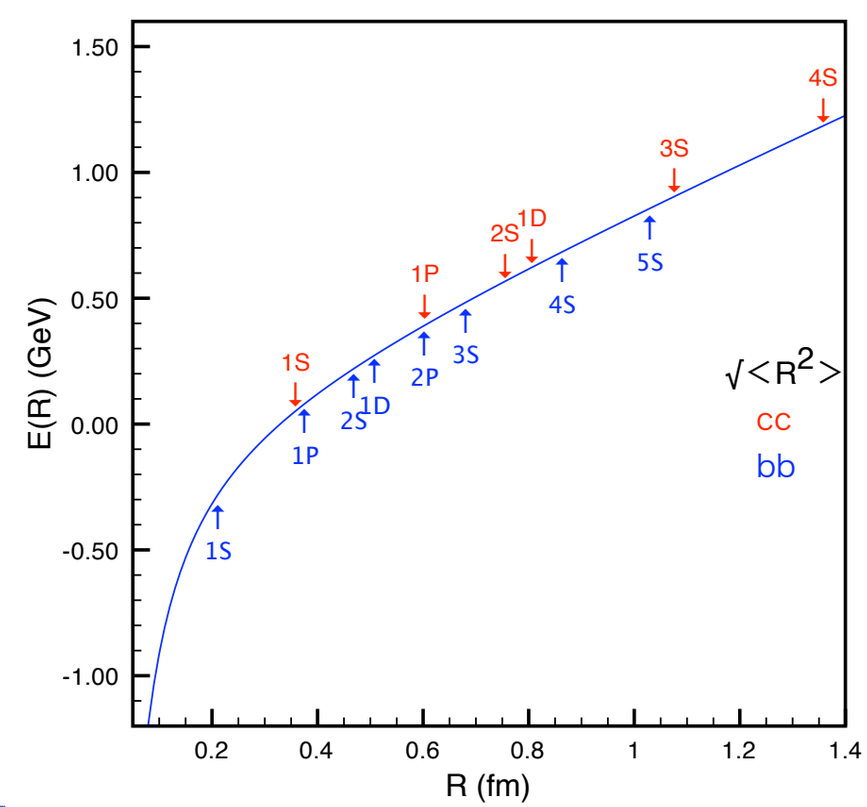
Why it works so well

- Lattice calculation V(r), then SE

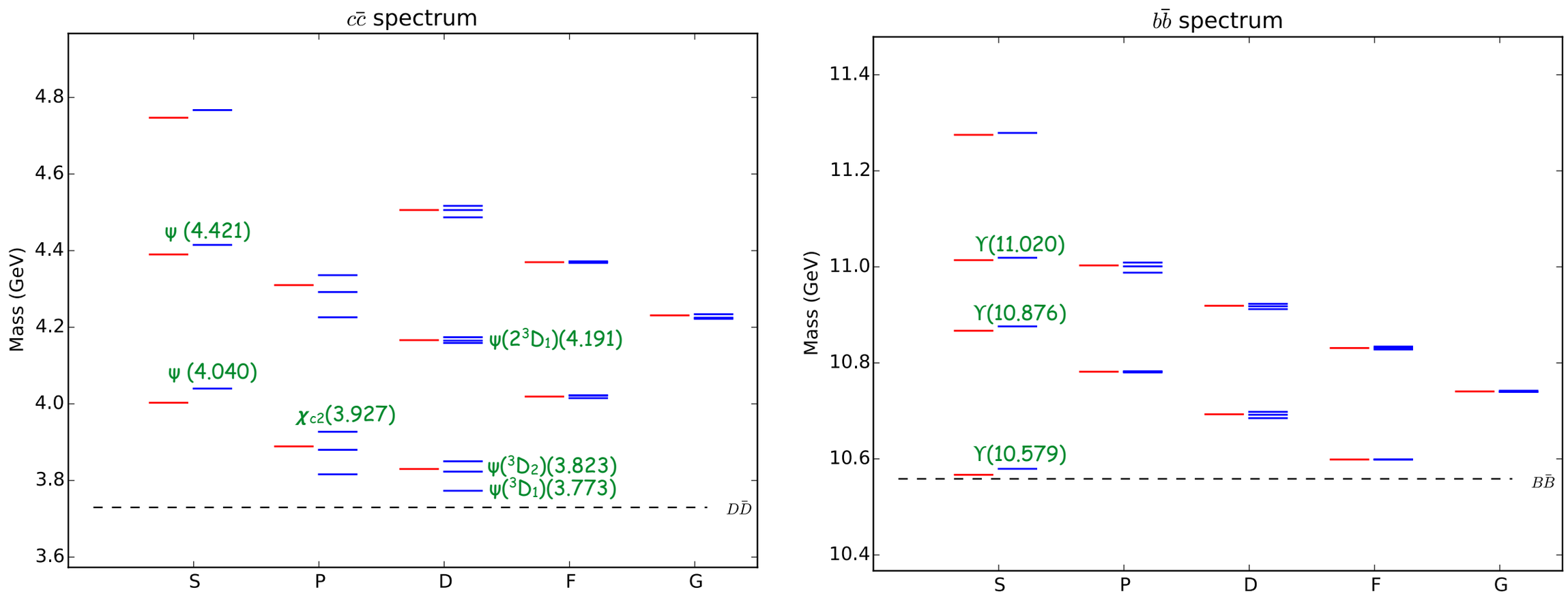
$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\ u(r)$$



- What about the gluon and light quark degrees of freedom 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



- 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 $\Omega(z)$

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

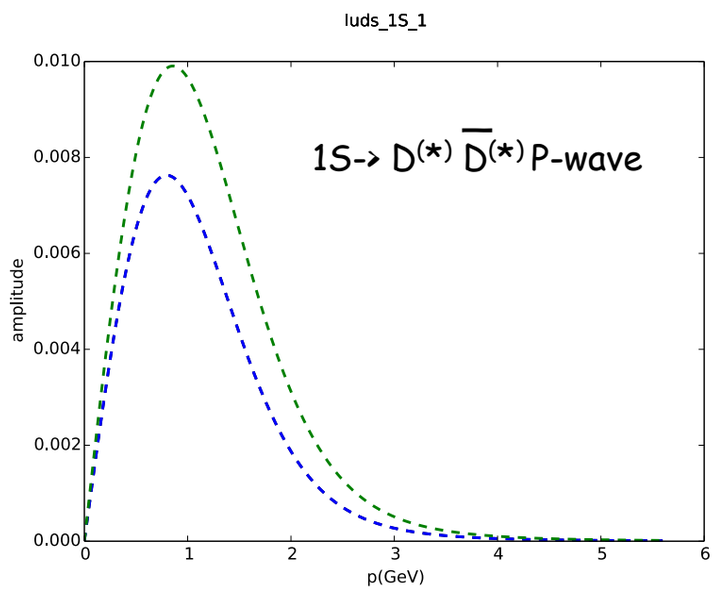
- Decay amplitude $\langle DD|H_I|\psi\rangle$
- Simplifying assumptions
  - H_2 - free meson pairs no final state interactions
  - H_0 - charmonium states are a complete basis - no hybrids

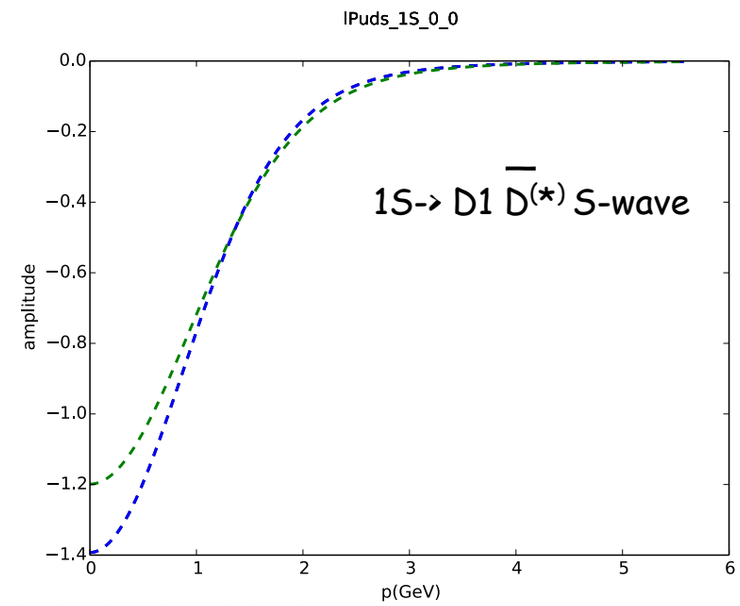
$$< n|\mathcal{G}(z)|m >=< n|\frac{1}{z-\mathcal{H}_0-\Omega(z)}|m >$$

- Assuming vector meson dominance. Can compute R_c

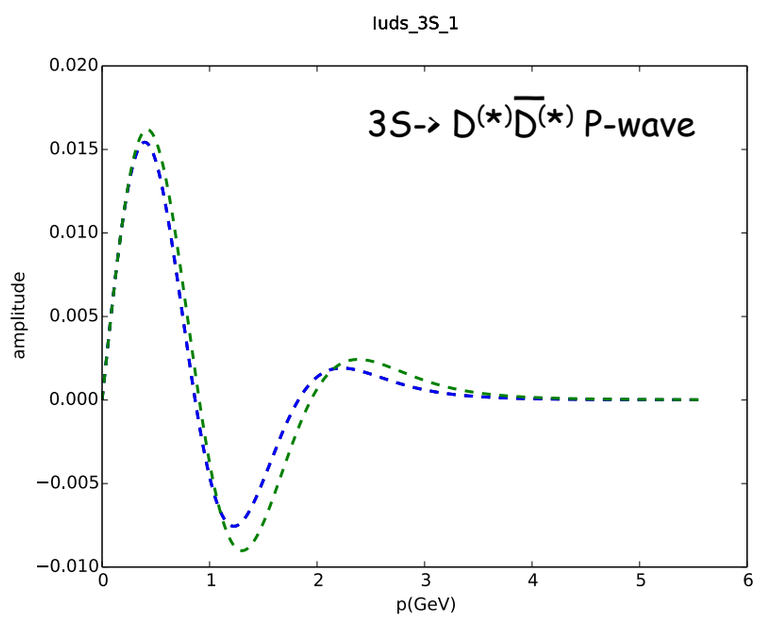
$$R_Q \sim \frac{1}{s}\sum_{nm}\lim_{r\to 0}\psi_n^*(r)\mathrm{Im}\mathcal{G}_{nm}(W+i\epsilon)\psi_m(r)$$

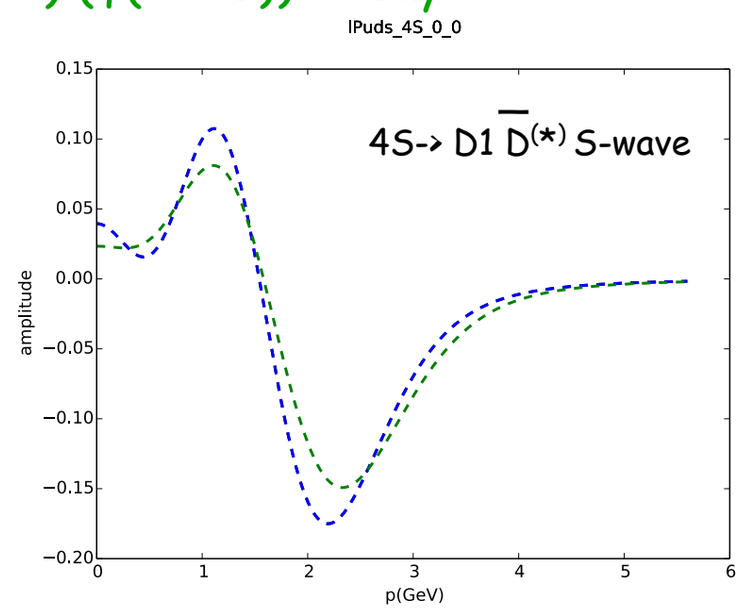
- General features of decays to low-lying heavy-light mesons:
  - Unlike light meson systems, these decays are from highly excited QQ states:
    - Ground state decay amplitudes :





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





  - Have complicated energy dependence.

Heavy Quark Spin Symmetry

- 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
  - $J^{PC} = 1^{--}$ in terms of B(*), B(*) mass eigenstates:

Voloshin [arXiv:1201.1222]

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

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

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

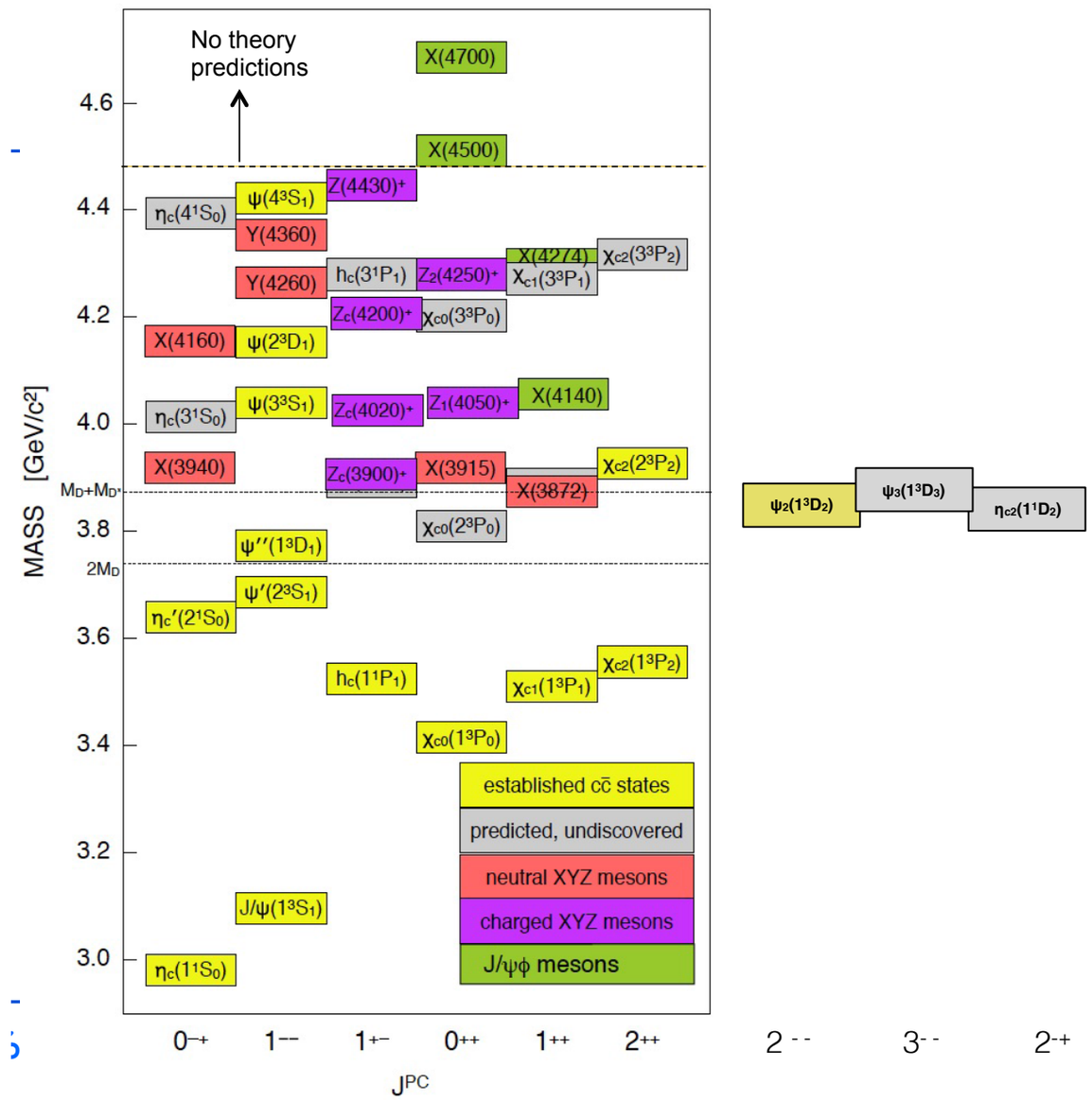
  - $I^G\,(J^P) = 1^-\,(1^+)$
    - S-wave (L=0)

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

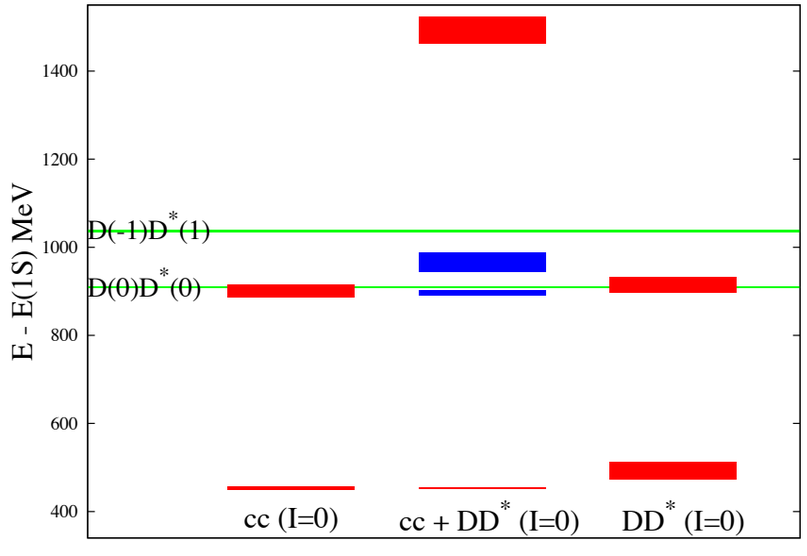
- Notation
  - Y denotes states observed directly in the charm contribution to e^+e^- -> hadrons:
    $\Rightarrow$ $J^{PC} = 1^{--}$ and I = 0
    - $Y_c(4260)$, $Y_c(4360)$, $Y_c(4650)$
  - Z denotes states with I = 1
    - $Z^+_c(3885)$, $Z^+_c(4025)$
    - $Z^+_b(10610)$, $Z^+_b(10650)$
    - $Z^+_c(4430)$, …

HQS

  - X denotes anything else
    - $X_c(3872)$, … $\Rightarrow$ see PDG table
    - Pentaquarks: X(4450) ($J^P = 5/2^+$), …



arXiv:1411.1389



arXiv:1503.03257

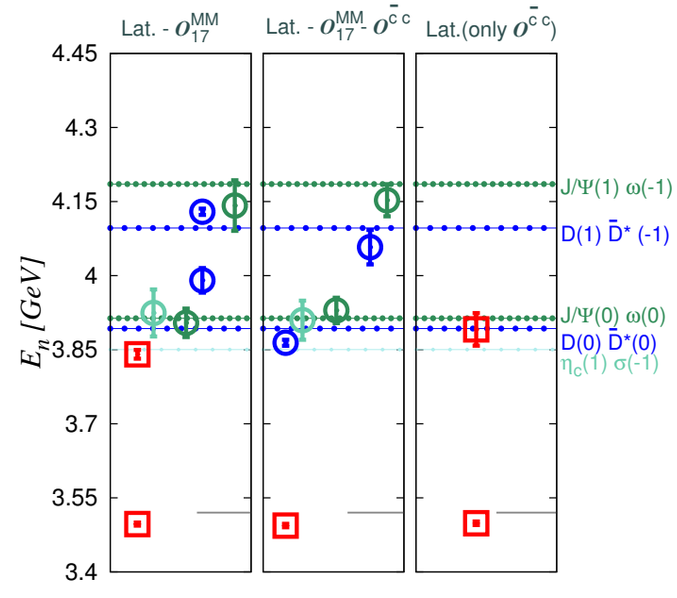
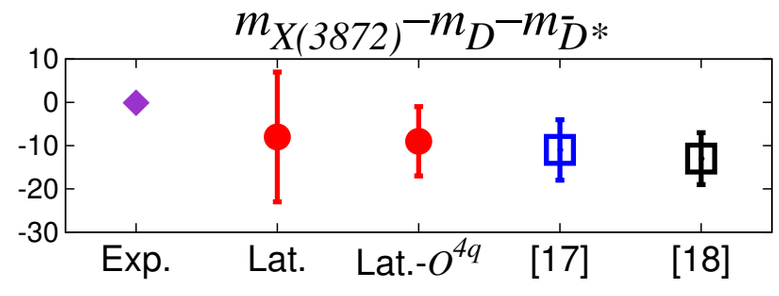


FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note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

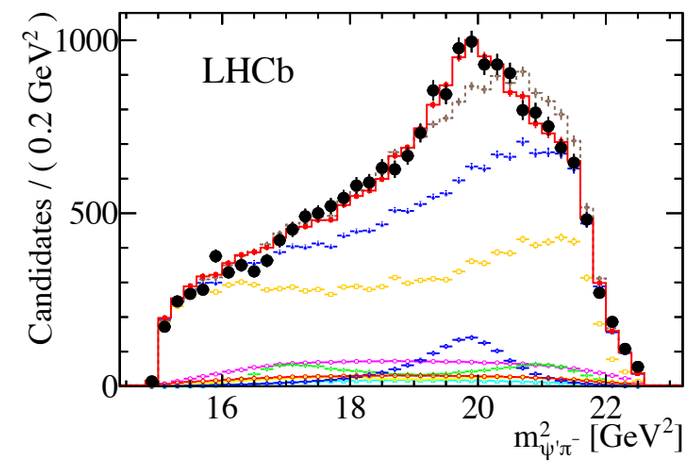


- $X_b(10604)$??
  - No isospin breaking: X is I=0 => G-parity forbids the decay X -> ππΥ(1S).
  - Dominate decay X -> ωΥ(1S) ?
  - $M(\chi_{b1}(3P)) - M(B) - M(B^*) \approx -75$ MeV
  - So the (bb) state is decoupled.

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

Systematics: Other States

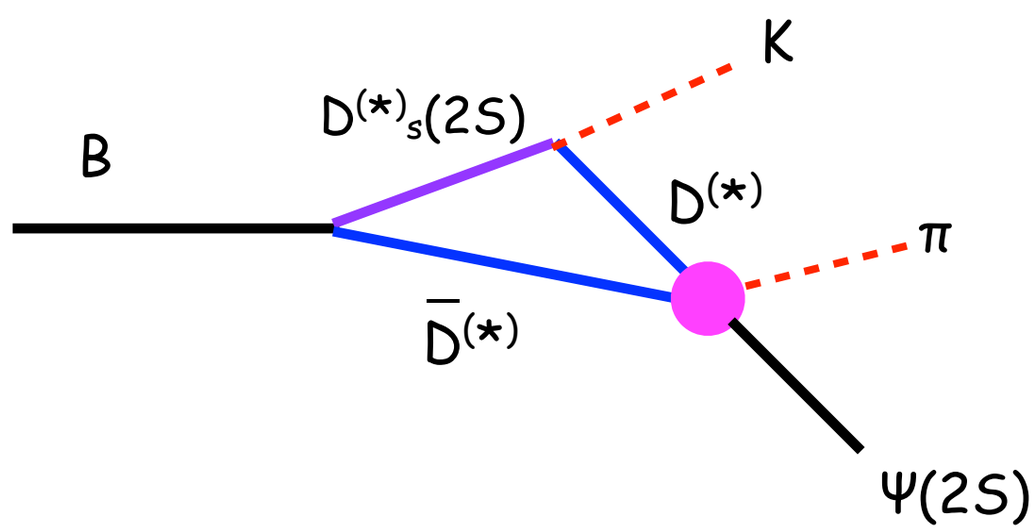
- $Z^-(4430)$: seen in $B^0 \to K^+ \pi^- \psi'$
  - $J^P = 1^+$; $M = (4{,}475 \pm 7 \pm [15/25])$ MeV; $\Gamma = (172 \pm 13 \pm [37/34])$ MeV
  - Resonance behavior observed.
  - Same mechanism in B-decays with $D_s(2S)$ states?
    - $D_s^*(2S)$ $M = 2{,}709 \pm 4$ MeV $\Gamma = 117 \pm 13$ MeV
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

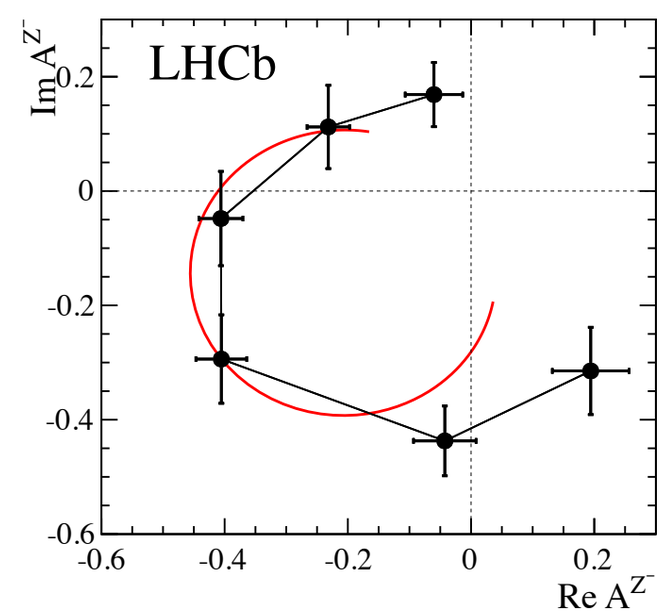


LHCb [arXiv:1404.1903]

P. Pakhlov and T. Uglov

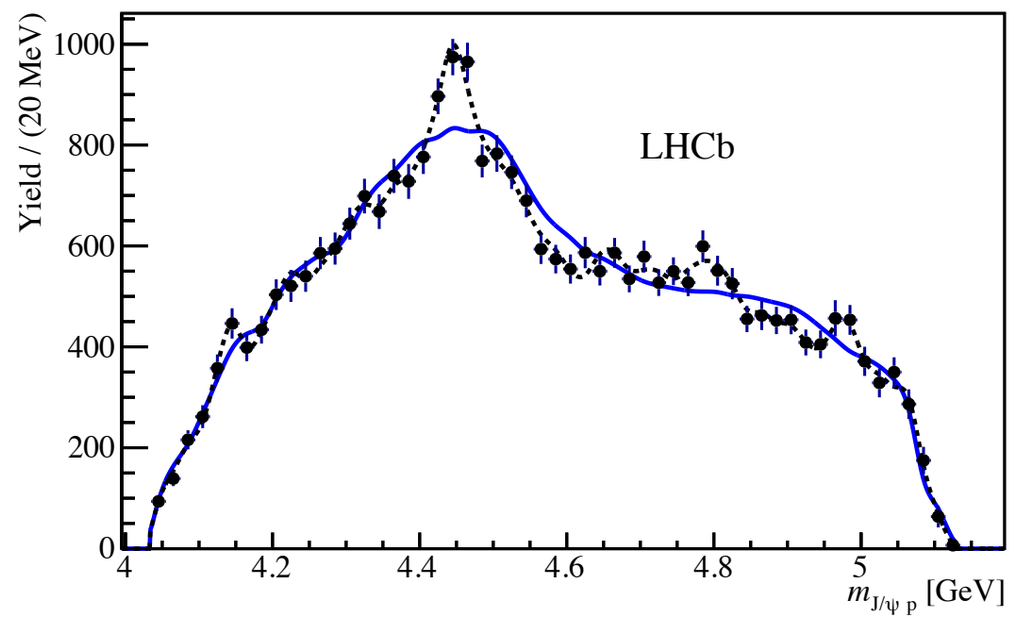
[arXiv:1408.5295]

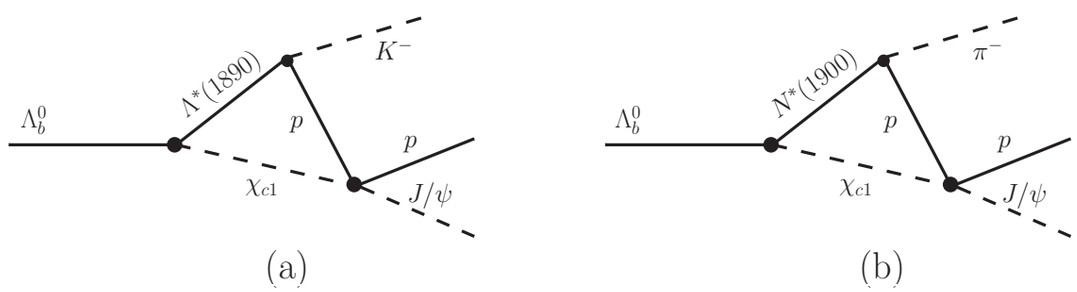


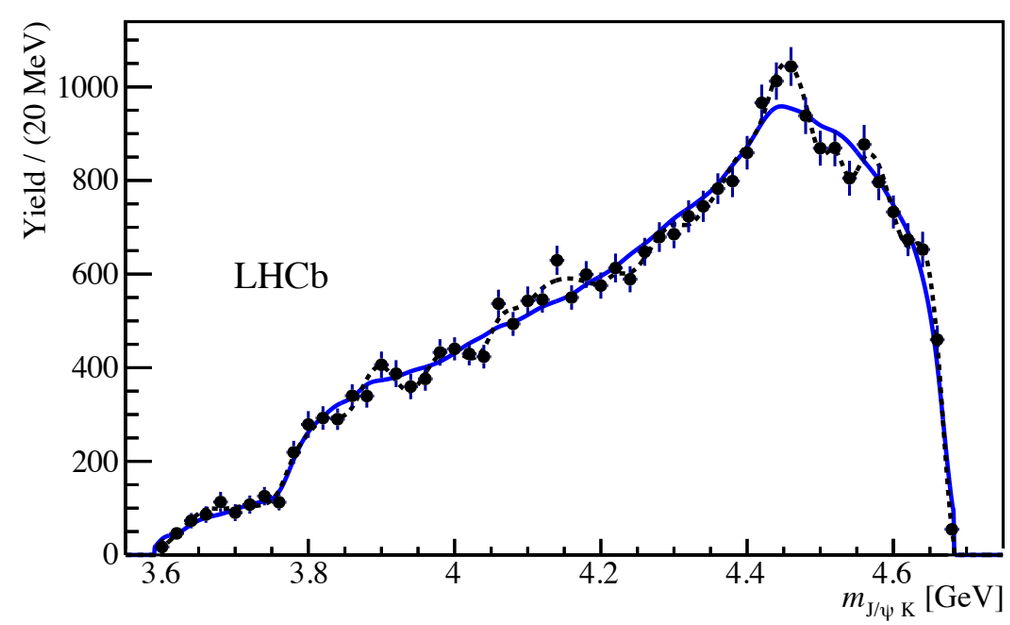


- $X(5568)$: decaying into $B_s\, \pi^+$
  - by observed by Dzero but not confirmed by LHCb

- 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]

I. Adachi et al (Belle) arXiv:1508.06562

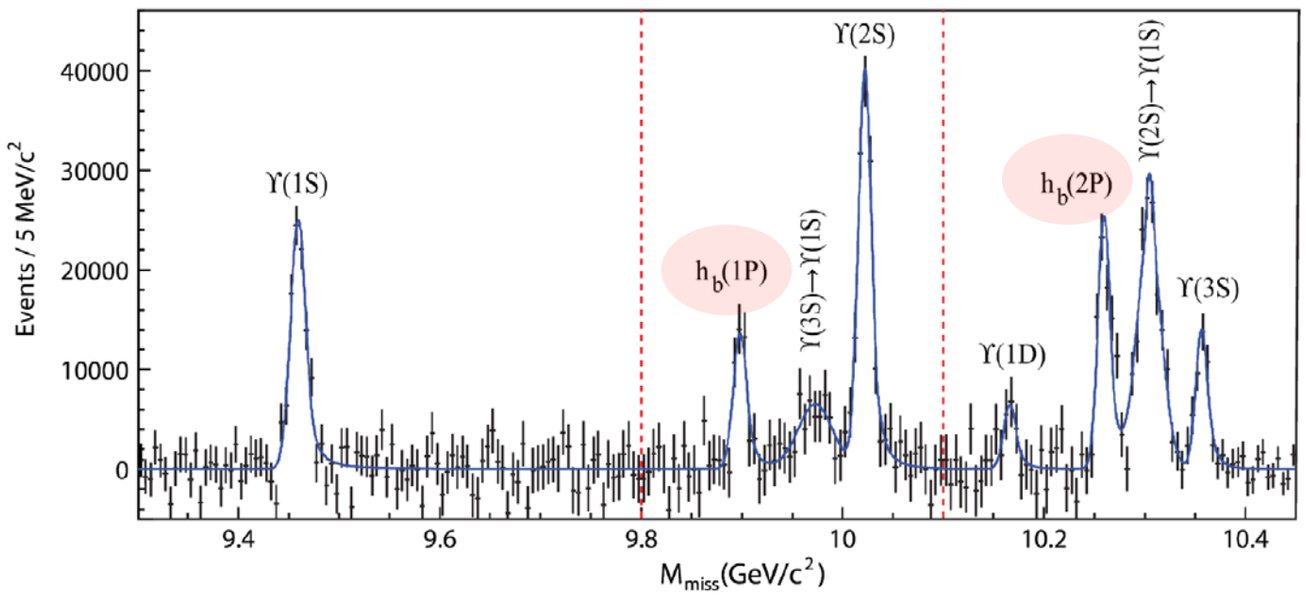
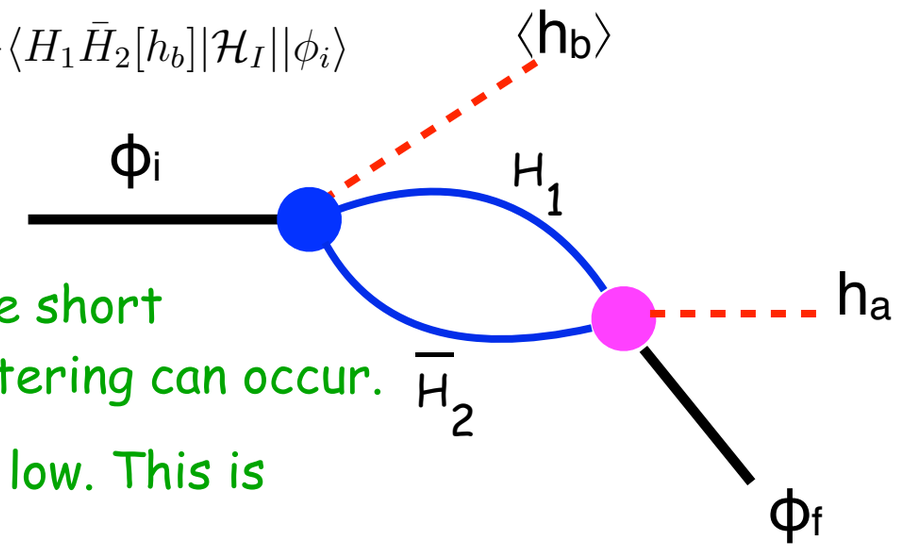


TABLE III. B branching fractions for the $Z_b^+(10610)$ and $Z_b^+(10650)$ decays. The first quoted uncertainty is statistical; the second is systematic.

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	–
$B^{*+}\bar{B}^{*0}$	–	$70.6 \pm 4.9 \pm 4.4$

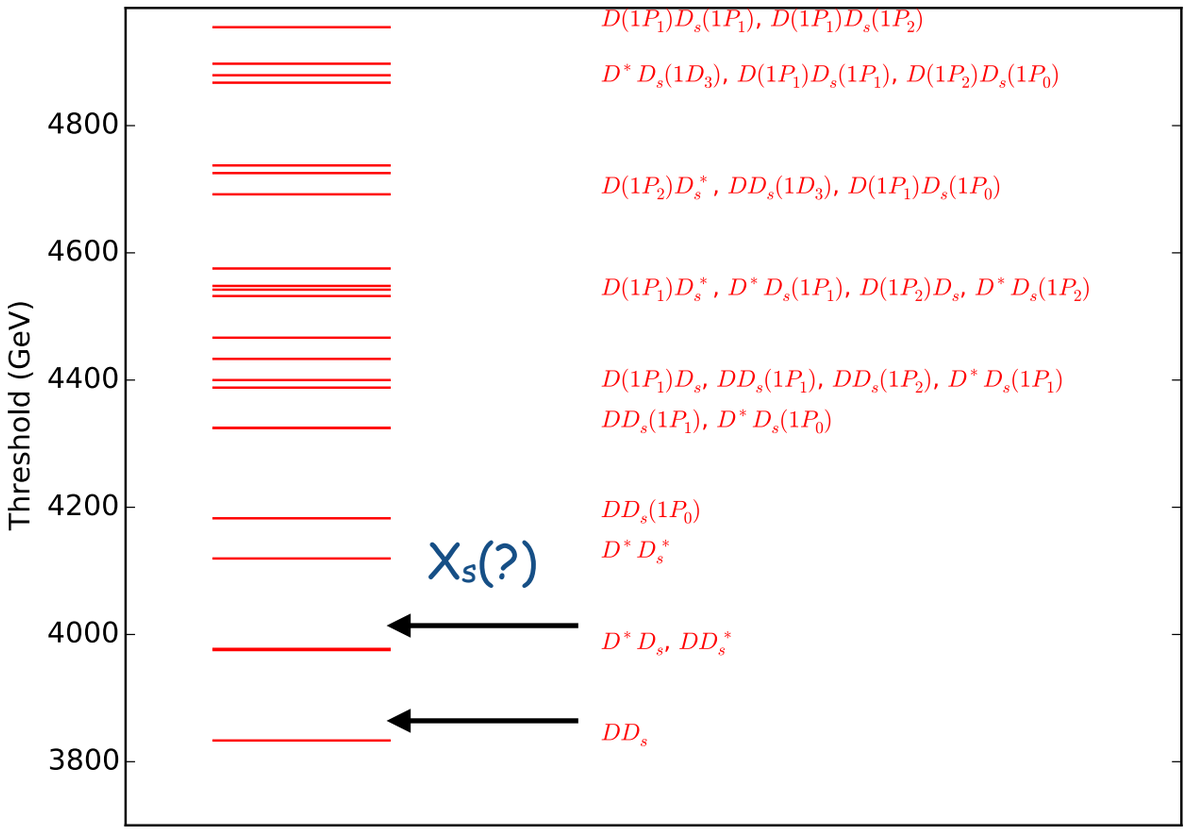
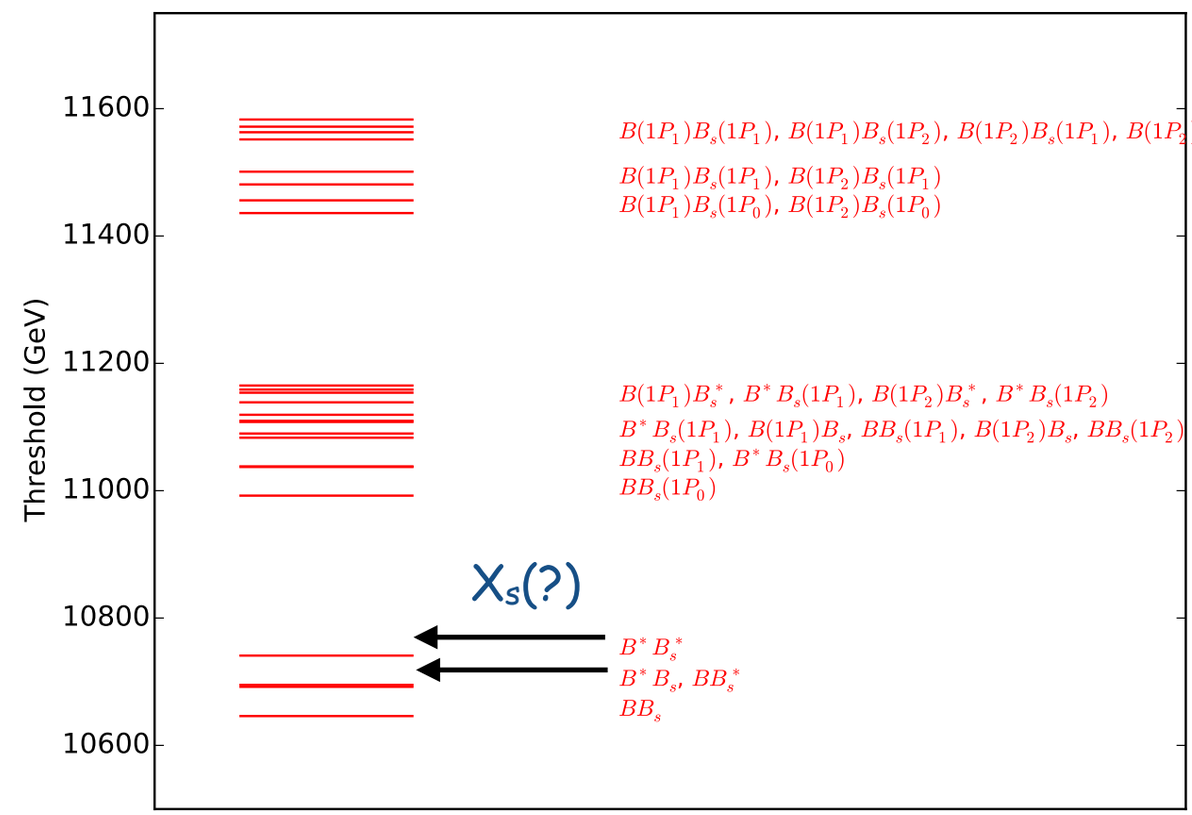
- A new factorization for hadronic transitions above threshold.
  - Production of a pair of heavy-light mesons (H'_1 H_2) near threshold. Where $H'_1 = H_1$ or H'_1 decays rapidly to H_1 + light hadrons (h_b), yielding H_1 H_2 <h_b>
  - Followed by recombination of this (H_1 H_2) state into a narrow quarkonium state (ϕ_f) and light hadrons (h_a).

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



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

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

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

- Strangeness 1 states: expect additional "threshold" states