Heavy Quark Spectroscopy:
Surprises and Opportunities

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Outline

- HQET and NRQCD
  - heavy-light states
- Quarkonium and Threshold States
  - $(c\bar{c})$ and $(b\bar{b})$ states
  - Crossing the Threshold
  - New states, XYZ, …
- 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 nonrelativistic $(Q\bar{Q})$: bound states form with masses M near $2m_Q$:
  - NRQCD: systematic expansion in powers of v/c
  - Quarkonium systems: $(c\bar{c})$, $(b\bar{b})$, $(b\bar{c})$
  - heavy quark velocity: $p_Q/m_Q \approx v/c \ll 1$
  - binding energy: $2m_Q - M \approx m_Q v^2/c^2$
  - QED analogs - positronium (e^+e^-), (true) muonium ($\mu^-\mu^+$), muonium ($e^-\mu^+$)

- Full QCD Hamiltonian (Coulomb gauge)

gluons — heavy quarks — light quarks

$$\mathcal{H}_{\rm QCD} = \frac{1}{g^2}\int d^3x\,[{\rm Tr}(\mathbf{E}^2)+{\rm Tr}(\mathbf{B}^2)] + \sum_{Q=c,b,t}[\mathcal{H}_Q+\mathcal{H}_{Q_c}] + \sum_{f=u,d,s}\int d^3x\,\psi_f^\dagger\,[-i\alpha\cdot\mathbf{D}+\beta m_f]\,\psi_f$$

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

"QCD potential"

heavy quarks:
($1/m_Q$) expansion
HQET
Leading behavior
Static limit.

$$\mathcal{H}_Q = \int d^3x\,Q^\dagger\left((m_Q+\delta m_Q) - \frac{\mathbf{D}^2}{2m_Q}\right)Q$$

$$-\int d^3x\,Q^\dagger\left[c_4\frac{1}{8m_Q^3}(\mathbf{D}^2)^2 + c_d\frac{1}{8m_Q^2}(\mathbf{D}\cdot\mathbf{E}-\mathbf{E}\cdot\mathbf{D})\right]Q$$

$$-\int d^3x\,Q^\dagger\left[c_f\frac{1}{2m_Q}\sigma\cdot\mathbf{B} + c_s\frac{i}{8m_Q^2}\sigma\cdot(\mathbf{D}\ \mathbf{x}\ \mathbf{E}+\mathbf{E}\ \mathbf{x}\ \mathbf{D})\right]Q + \ldots$$

Kinetic; Darwin; Magnetic; Spin- Orbit

relativistic corrections
spin independent
spin dependent

non-local color current interaction

$$G_{ab}(\mathbf{x},\mathbf{y}) = 4\pi < \mathbf{x},a|\frac{1}{\nabla\cdot\mathbf{D}}\nabla^2\frac{1}{\nabla\cdot\mathbf{D}}|\mathbf{y},b> \to \frac{\delta_{ab}}{|\mathbf{x}-\mathbf{y}|}\ \ \text{as}\ g\to 0$$

color charge density

$$J_a^0(\mathbf{x}) = \sum_{Q=c,b,t}[Q^\dagger(\mathbf{x})t_aQ(\mathbf{x}) - Q_c^\dagger(\mathbf{x})t_a^*Q_c(\mathbf{x})] + g f_{abc}\sum_i E_b^i(\mathbf{x})A_c^i(\mathbf{x}) + \sum_{f=u,d,s}\psi_f^\dagger(\mathbf{x})t_a\psi_f(\mathbf{x})$$

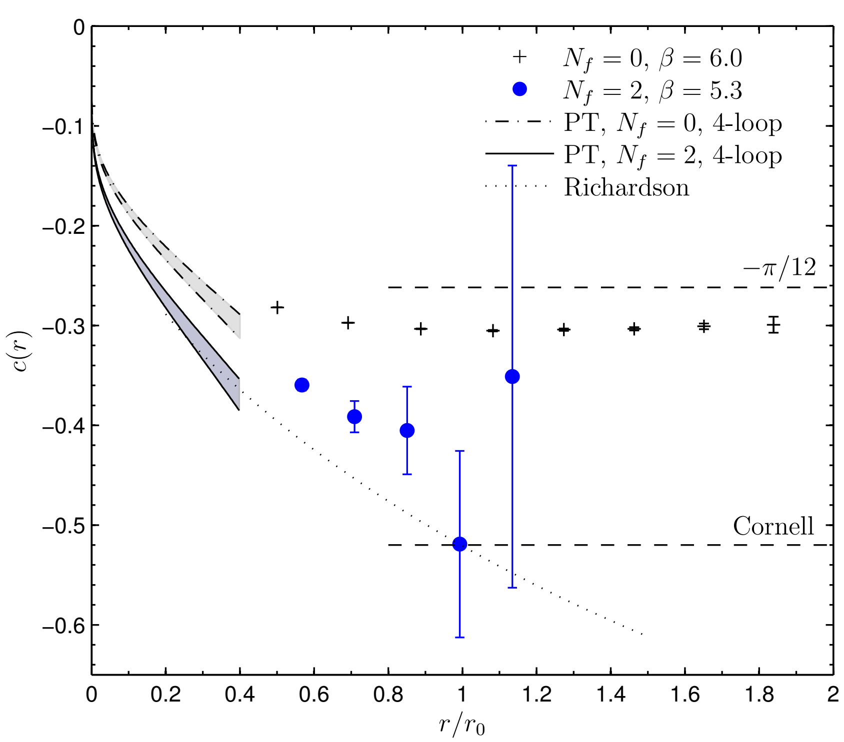
- Lattice QCD calculations include all these terms: light quark loops in 2+1 (+1) simulations

Static Limit

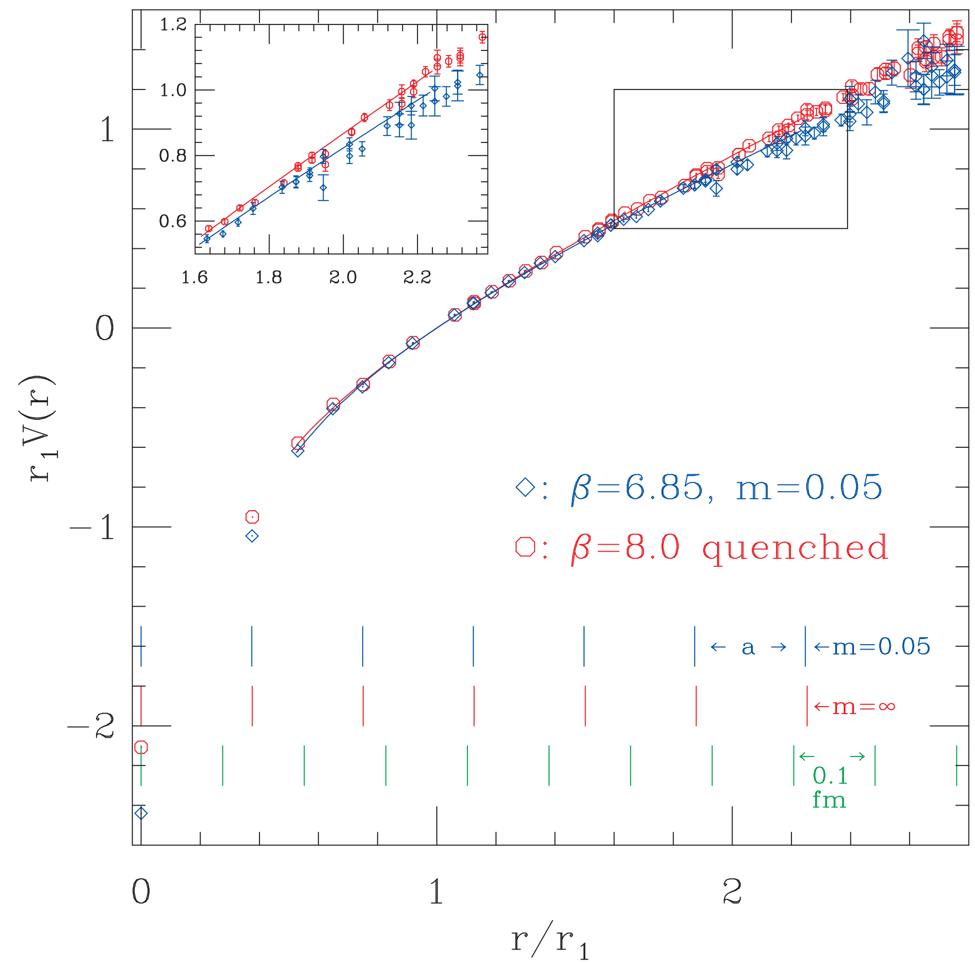
- LQCD calculations with and without 3 light quark loops

- More details of light quark effects on short distance piece of static energy.

$$c(r) = \frac{1}{2} r^3 \frac{dV(r)}{dr} \xrightarrow{r \to 0} \frac{4}{3} \alpha(r)$$

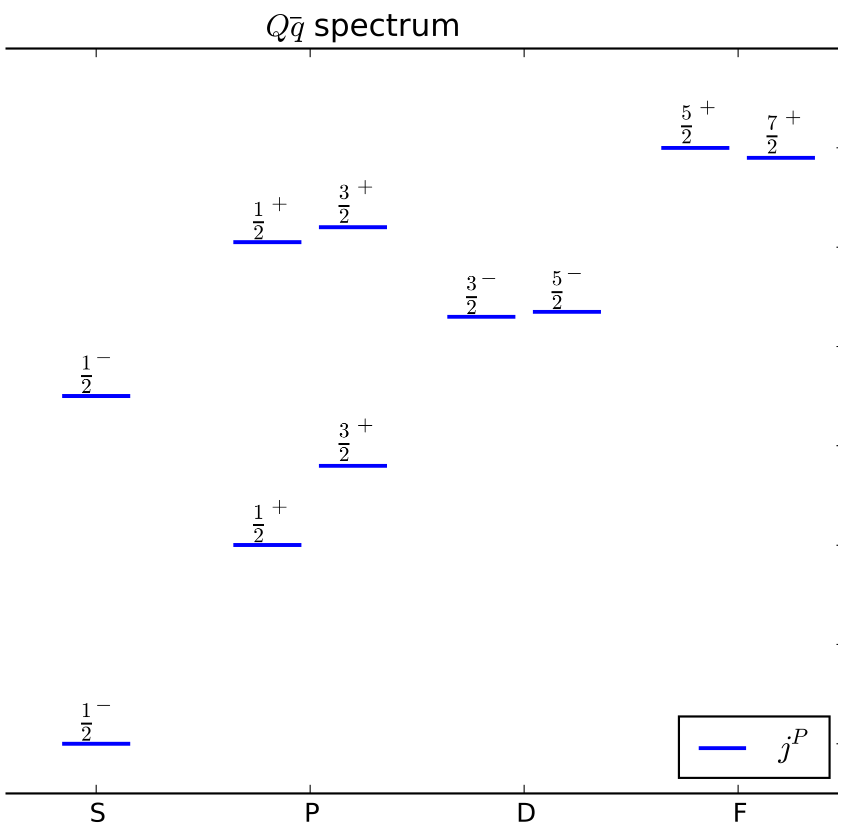


M. Donnellan, F. Knechtli, B. Leder, R. Sommer
NP B 849 (2011) 45 [arXiv:hep-lat/1012.3037]

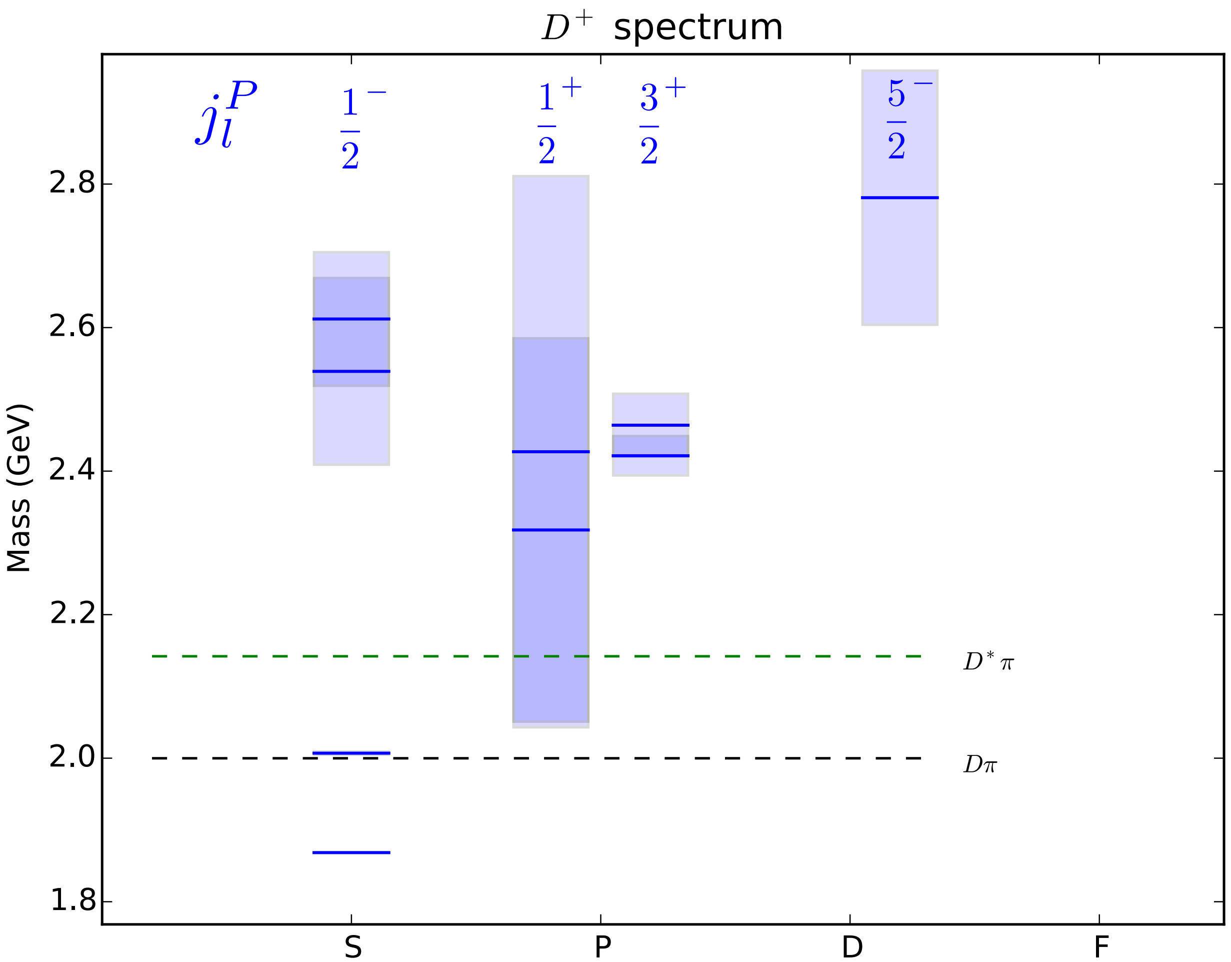


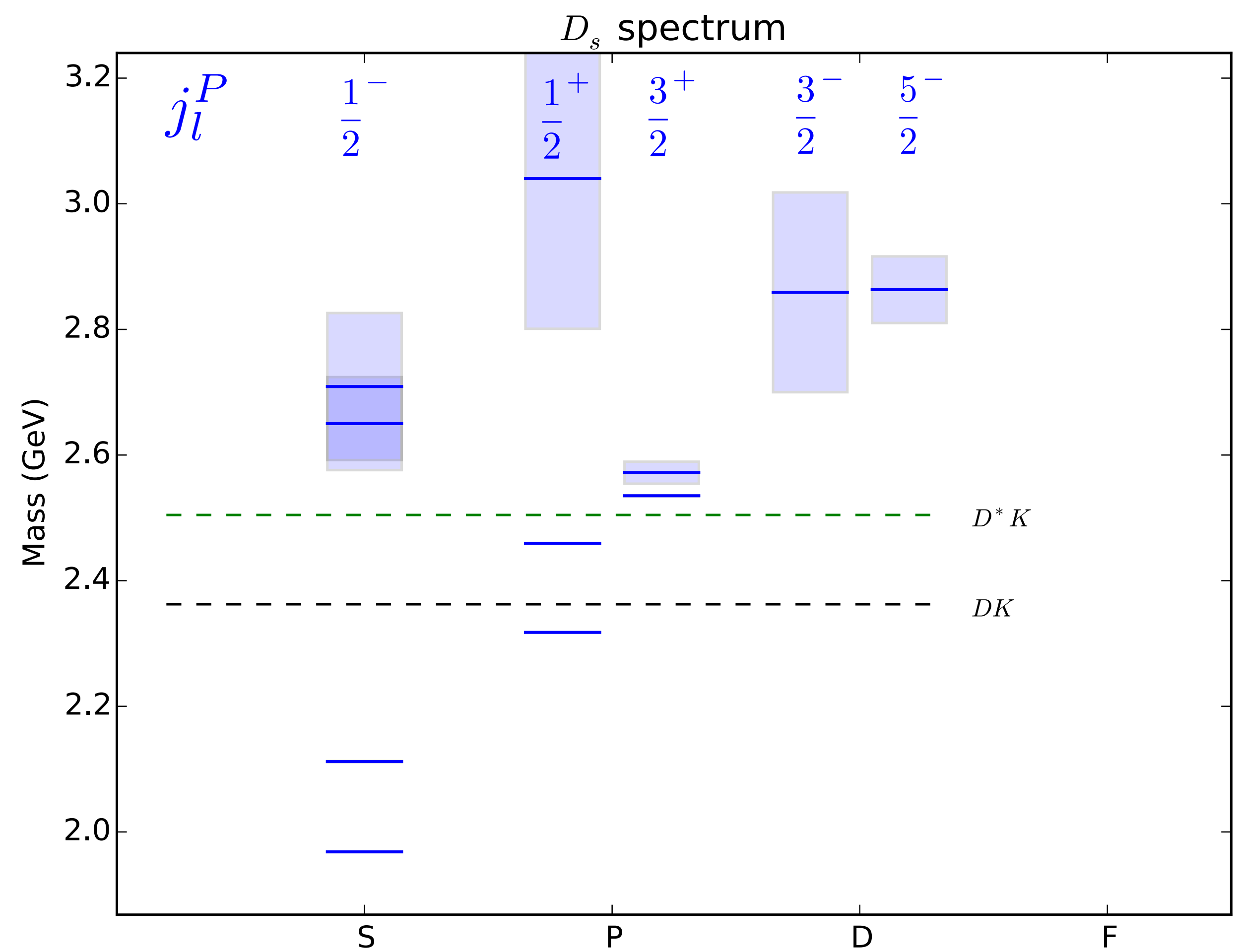
C. W. Bernard *et al.*, Phys. Rev. D **62**, 034503 (2000) [arXiv:hep-lat/0002028]

- Heavy-light states: $(c\bar{u})$, $(c\bar{d})$, $(c\bar{s})$, $(b\bar{u})$, $(b\bar{d})$, $(b\bar{s})$, ...
  - The excitation spectrum is independent of m_Q in leading order.
  - States are classified by the total angular momentum of the light quark system (j_l) and the parity (P).
  - $J = j_l \pm \frac{1}{2}$ doublets
  - The (Λ_{QCD}/m_Q) corrections include the kinetic energy of the heavy quark and spin dependent terms.
- Potential models for light quarks are not reliable:
  - Relativistic Quark Model (S. Godfrey and N. Isgur). Decay widths in recent work (S. Godfrey and K. Moats [arXiv:1510.08305])
  - Dirac Potential for light quarks (M. Di Pierro+EE)
  - Potential models failed to predict the $\frac{1}{2}^+$ P-wave states of the D_s system. $D_s^*(2317)$ and $D_s(2460)$ narrow states.



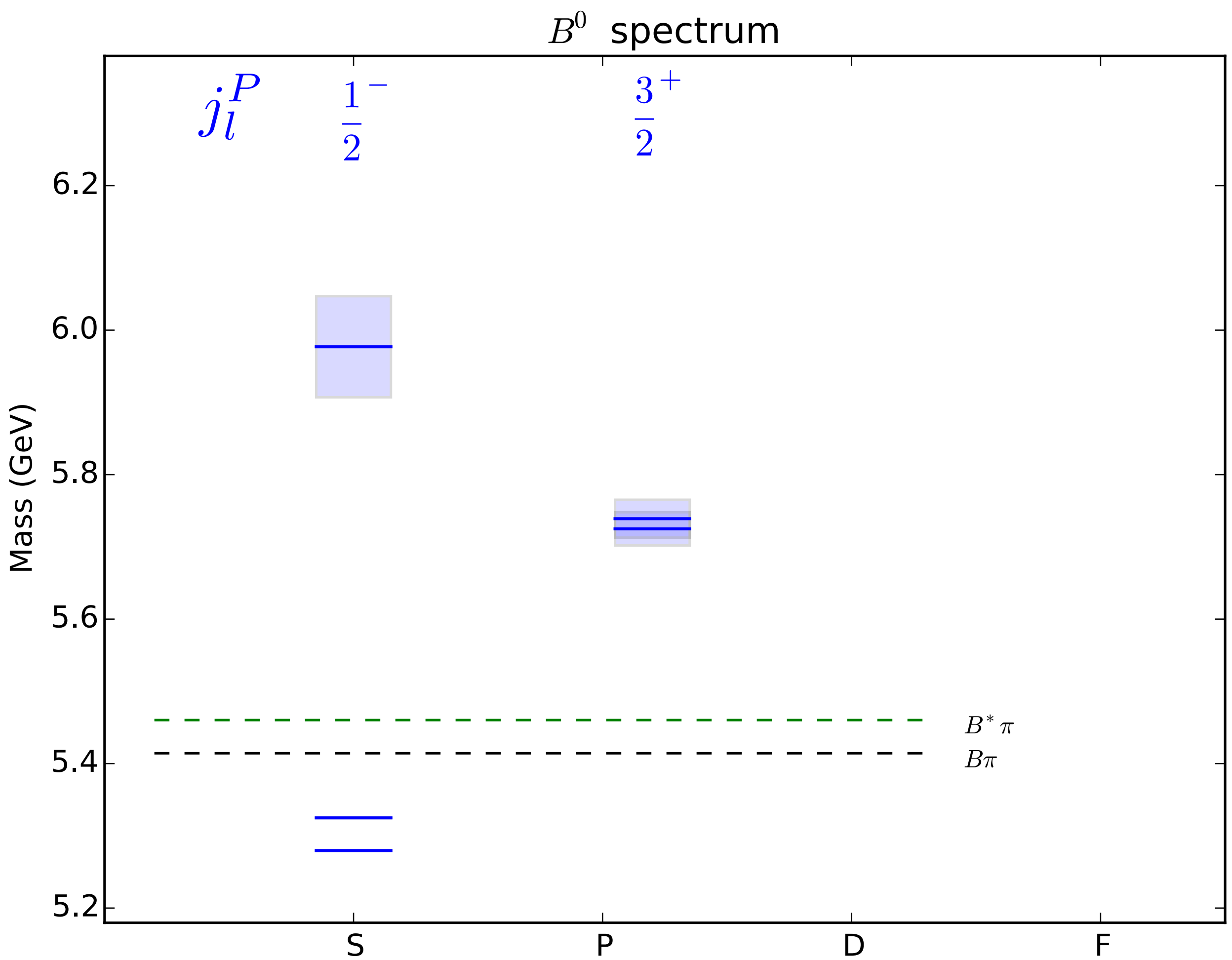
- Observed states in D meson systems:

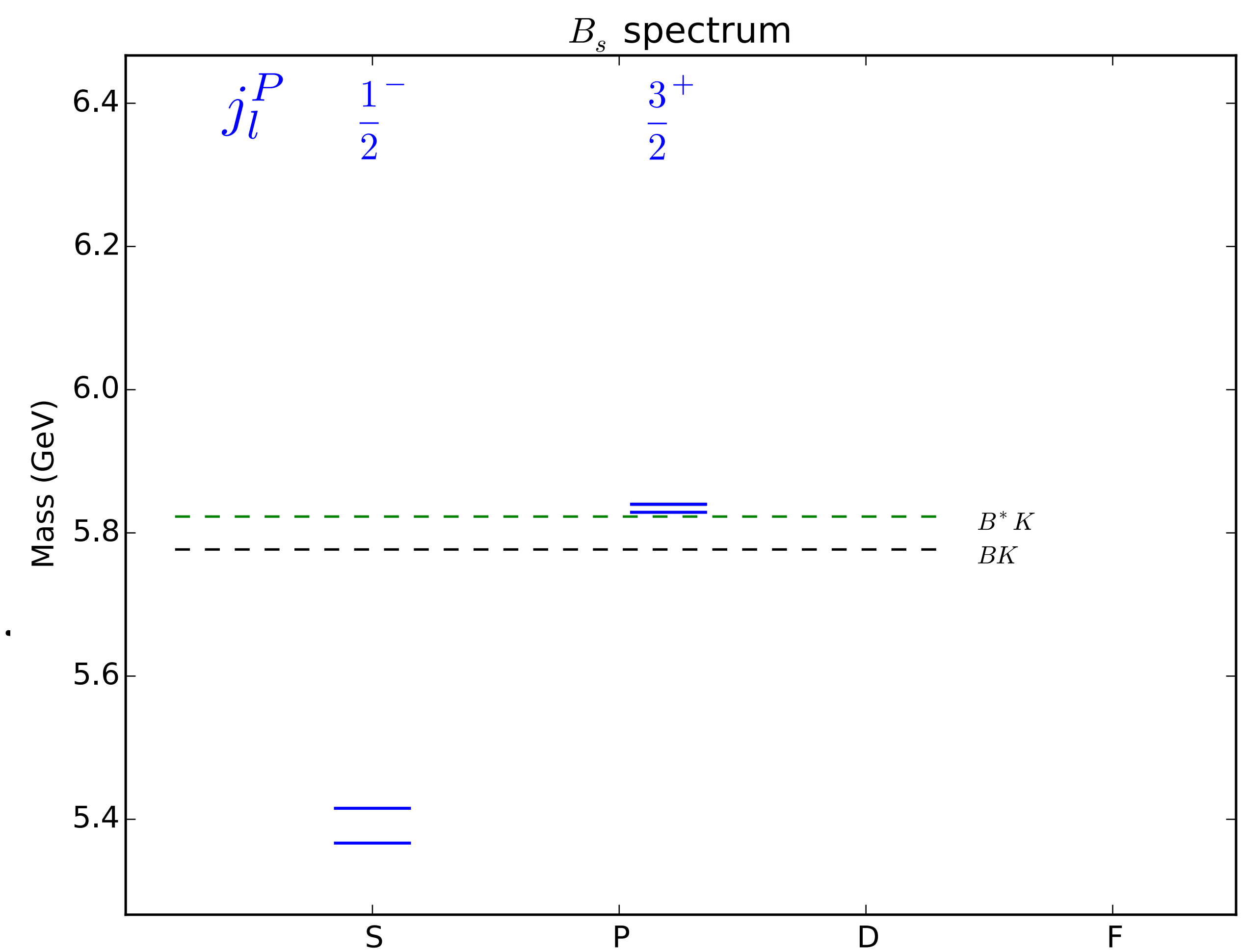




- HQS determines the ratios of hadronic transitions - very useful in distinguishing excited states
- Various proposals for the shifts of the $D_s^*(2317)$ and $D_s(2460)$:
  - Influence of the nearby decay channels.
  - Chiral multiplets (0^-,0^+).
  - Threshold bound states of DK and D*K respectively.

- 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.

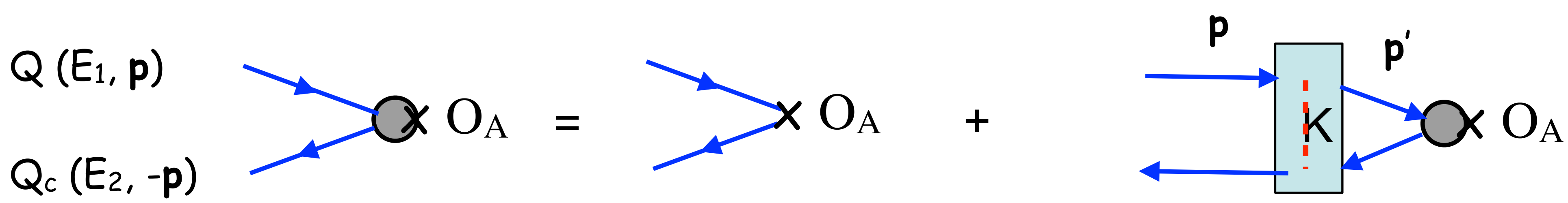
- Branching fractions:

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

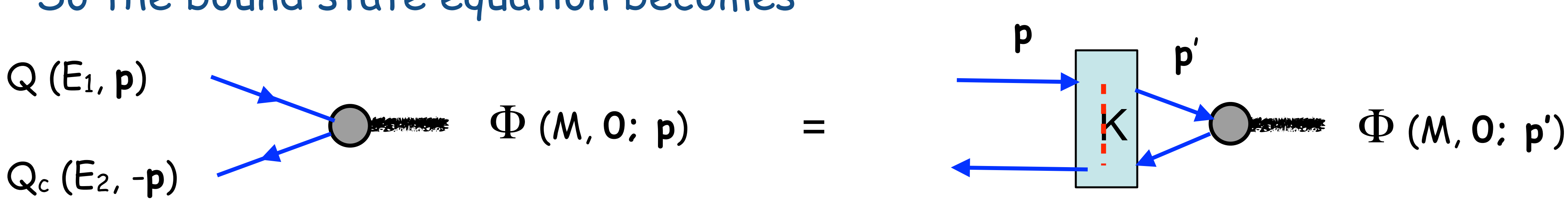
W.Bardeen, E.E., C. Hill PR D68 054024 (2003) [hep-ph/0305049]

Quarkonium States

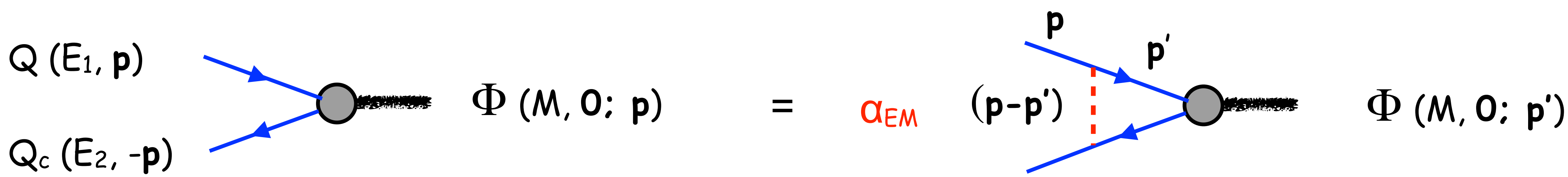
- Threshold bound states
  - let O_A be a local operator coupling to QQ_c with bare vertex Γ the full vertex function satisfies the equation:



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



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



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

- But α_{EM} << 1 -> no solutions unless:

$$\begin{aligned}\sqrt{m_1^2+\mathbf{p}'^2}+\sqrt{m_2^2+\mathbf{p}'^2}-M &= (m_1+m_2-M)+\frac{\mathbf{p^2}}{\mu_R}+\ldots << m_1+m_2\\ E(\text{binding}) &\sim \frac{v_{\rm rel}^2}{2\mu_R}\\ \mathbf{p},\mathbf{p}' &\sim v_{\rm rel}\mu_R\end{aligned}$$

- Non relativistic states with natural expansion in v/c ≈α_{EM}
- Schrödinger Equation:

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

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

with

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

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

Gauge

$$\mathcal{H}^{\rm eff}_{\rm QCD} = \frac{1}{g^2}\int d^3x\,\left[{\rm Tr}(\mathbf{E}^2) + {\rm Tr}(\mathbf{B}^2)\right] + \sum_{Q=c,b,t}\left[\mathcal{H}_Q + \mathcal{H}_{Q_c}\right]$$
$$+ \frac{g^2}{4\pi}\int d^3x \int d^3y\,\{J^0_a(x)\mathcal{G}(\mathbf{x},\mathbf{y})_{ab}J^0_b(y)\}$$

Potential

$$\mathcal{H}_Q = \int d^3x\; Q^\dagger\left((m_Q + \delta m_Q) - \frac{\mathbf{D}^2}{2m_Q}\right)Q$$
$$- \int d^3x\; Q^\dagger\left[c_4\frac{1}{8m_Q^3}(\mathbf{D}^2)^2 + c_d\frac{1}{8m_Q^2}(\mathbf{D}\cdot\mathbf{E} - \mathbf{E}\cdot\mathbf{D})\right]Q$$
$$- \int d^3x\; Q^\dagger\left[c_f\frac{1}{2m_Q}\sigma\cdot\mathbf{B} + c_s\frac{i}{8m_Q^2}\sigma\cdot(\mathbf{D}\;\mathbf{x}\;\mathbf{E} + \mathbf{E}\;\mathbf{x}\;\mathbf{D})\right]Q + \ldots$$

Darwin

Kinetic

Spin Independent

Relativistic corrections

Spin Dependent

Magnetic

Spin- Orbit

Practical realities

- The scales that enter NR calculations are :
  - for heavy quarks: m_Q^2 - p^2 ~ $m_Q v^2$ ~ (binding energy), **p ~ m_Qv**
  - for gauge fields: k ~ m_Qv ("soft" or "potential" gluons) ; k ~ $m_Q v^2$ ("ultrasoft")
- In QED $v \sim \alpha_{em} \ll 1$ so bound states are always nonrelativistic: $mv^2 \ll mv \ll 1$. Corrections to the NR limit Coulomb interaction can be calculated in perturbation theory.
- In QCD there is a strong interaction scale Λ_{QCD} .
  - $\Lambda_{QCD} \ll m_Q v^2 \ll m^Q v \ll 1$ only for the $(t\bar{t})$ system, but the top quark decays before toponium states form.
  - For the $(c\bar{c})$, $(b\bar{b})$ and $(b\bar{c})$ systems: $\Lambda_{QCD} \sim m_Q v^2 < m_Q v < m_Q$ at best.
  - Integrate out perturbative scales: m_Q (NRQCD) and m_Q v (pNRQCD). Still left with non perturbative theory that must be modeled or computed in LQCD.

- Effects of light quarks
  - Color current includes light quarks

$$J_a^0(\mathbf{x}) \to [J_a^0(\mathbf{x})]_{\text{gauge}} + \sum_{Q=c,b,t} [J_a^0(\mathbf{x})]_Q + \sum_{f=u,d,s} [J_a^0(\mathbf{x})]_f \quad \text{with} \quad [J_a^0(\mathbf{x})]_f = \psi_f^\dagger(\mathbf{x}) t_a \psi_f(\mathbf{x})$$

  - Relativistic form for H_f appropriate for (u,d,s) quarks

$$\mathcal{H}_{\text{QCD}} = \mathcal{H}_{\text{QCD}}^{\text{eff}} + \sum_{f=u,d,s} \mathcal{H}_f \quad \text{where} \quad \mathcal{H}_f = \int d^3x \; \psi_f^\dagger \left[-i\alpha \cdot \mathbf{D} + \beta m_f\right] \psi_f$$

    - Light quarks have both important effects on quarkonium physics
    - modify properties of narrow states
    - above threshold allow strong decays to heavy-light meson pairs
    - more details later

- QCD with sufficiently heavy quarks: $\langle v^2/c^2 \rangle$ will be small
    - charmonium ~ $\langle v^2/c^2 \rangle \approx 0.24$ bottomonium ~ $\langle v^2/c^2 \rangle \approx 0.08$

Narrow States Below Threshold

- Basic to this NR picture is the adiabatic assumption
  - Heavy quarks react slowly relative to the interactions of the gauge degrees of freedom
  - This allows the velocity expansion in NRQCD and the $1/m_Q$ expansion in HQET

– So for the ($Q\ Q_c$) system at rest:

$$\Psi(\mathbf{R}) = \frac{u_{nl}(r)}{r} Y_{lm}(\theta, \phi) \qquad \mu = \frac{m_1 m_2}{m_1 + m_2}$$

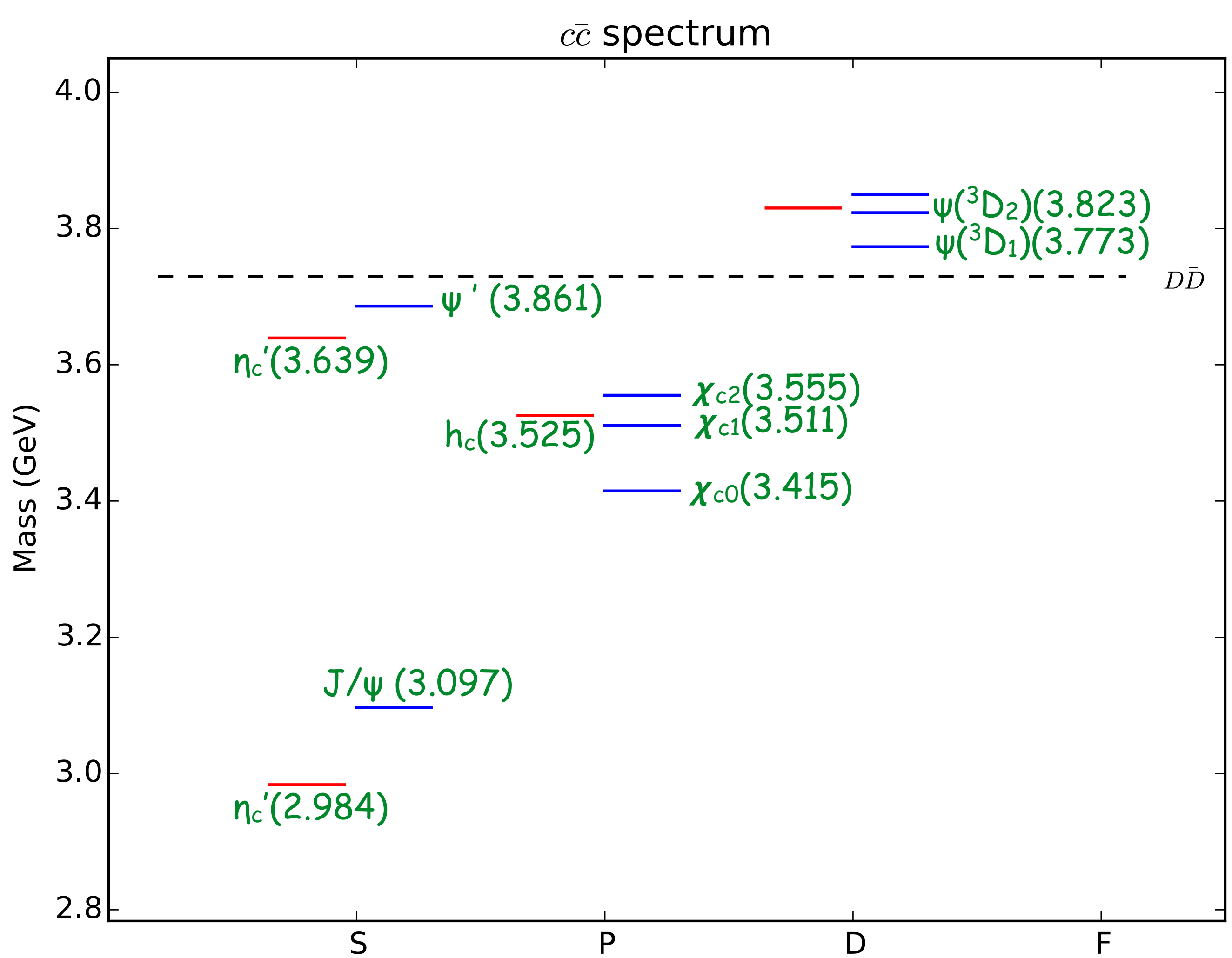
$$-\frac{1}{2\mu}\frac{d^2 u_{nl}(r)}{dr^2} + \left\{\frac{\mathbf{L}^2}{2\mu r^2} + V_{Q\bar{Q}}(r)\right\} u_{nl}(r) = E_{nl} u_{nl}(r) \qquad M = E_o + E_{nl}$$

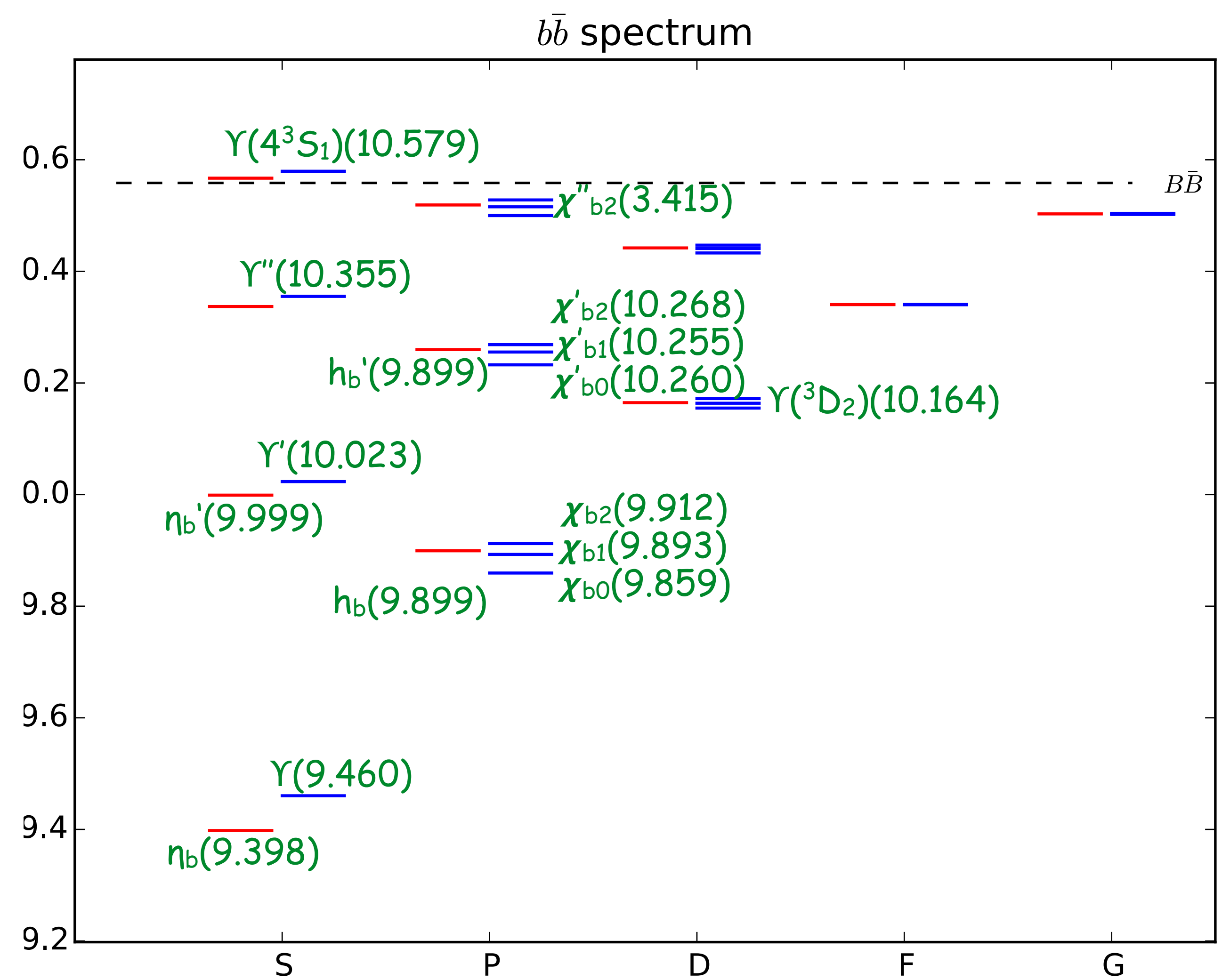
– Phenomenological potential models:

- V(r) [Cornell, Richardson, Buchmueller-Tye, Godfrey-Isgur, ...]
- Many successful predictions

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

S=0
S=1



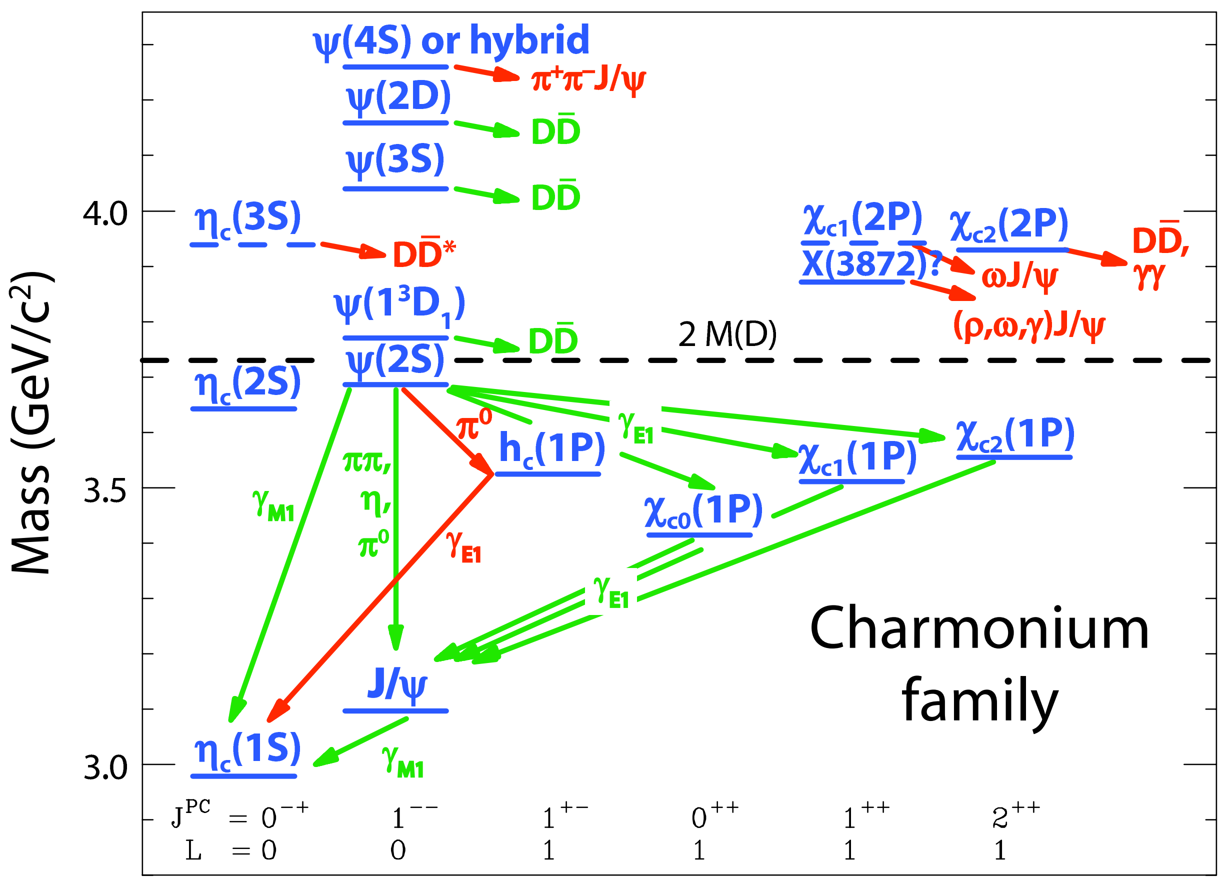


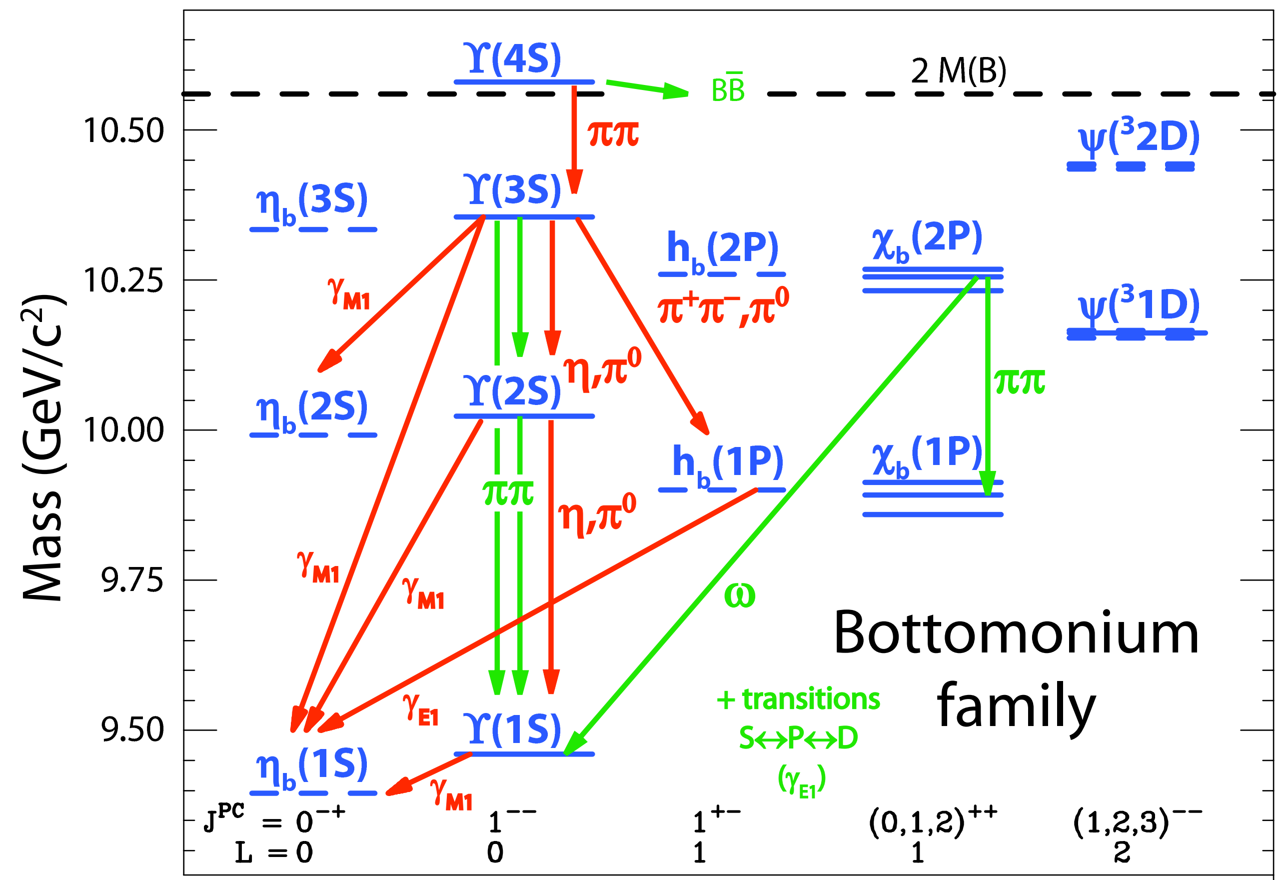
- 2 narrow states still unobserved

18 narrow states still unobserved

- 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



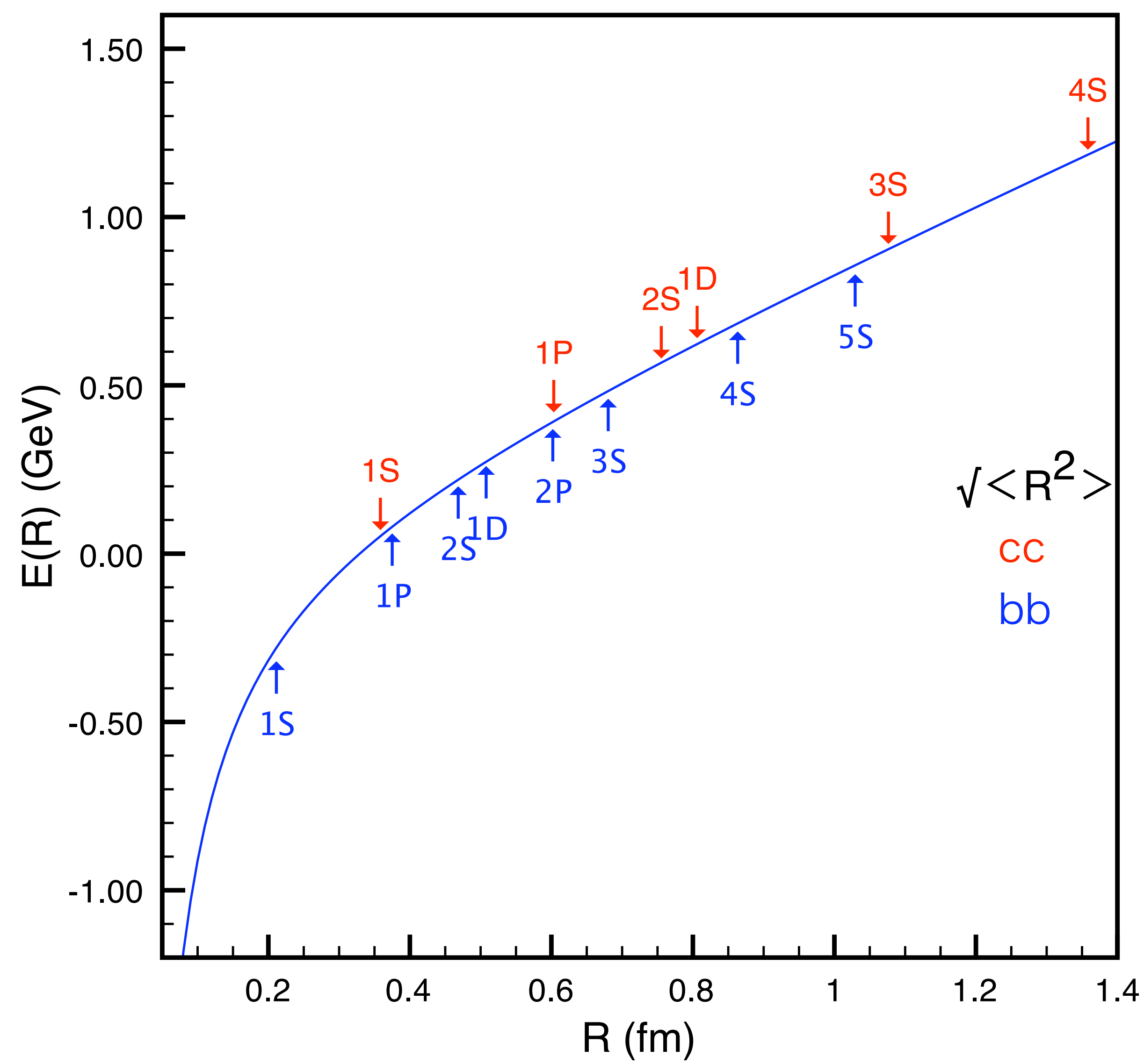


Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E. [Rev. Mod. Phys. 80, 1161 (2008)]

- Narrow states allow precise experimental probes of the subtle nature of QCD.

- Consistency between ($c\bar{c}$) and ($b\bar{b}$) systems validates the NRQCD approach:
    - masses (models, pNRQCD, LQCD)
    - spin splittings (models, pNRQCD, LQCD)
    - EM transitions (ME, LQCD)
    - hadronic transitions(QCDME, LQCD)
    - direct decays (pQCD)

- Simple potential models reproduced the spectrum and EM transitions well



Cornell Potential Model

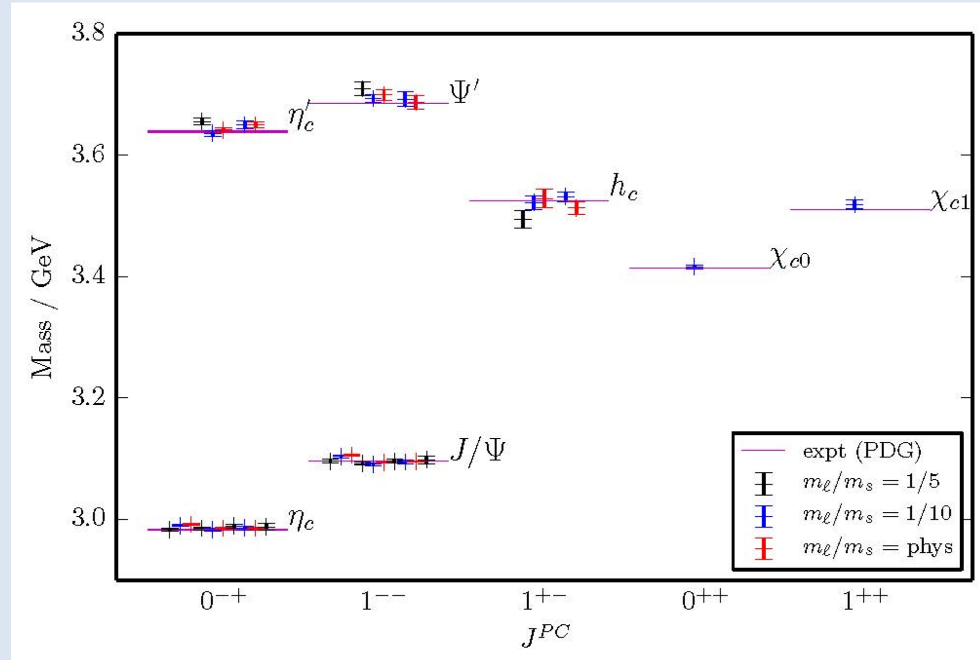
$V(R) = -\kappa/R + R/a^2$

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

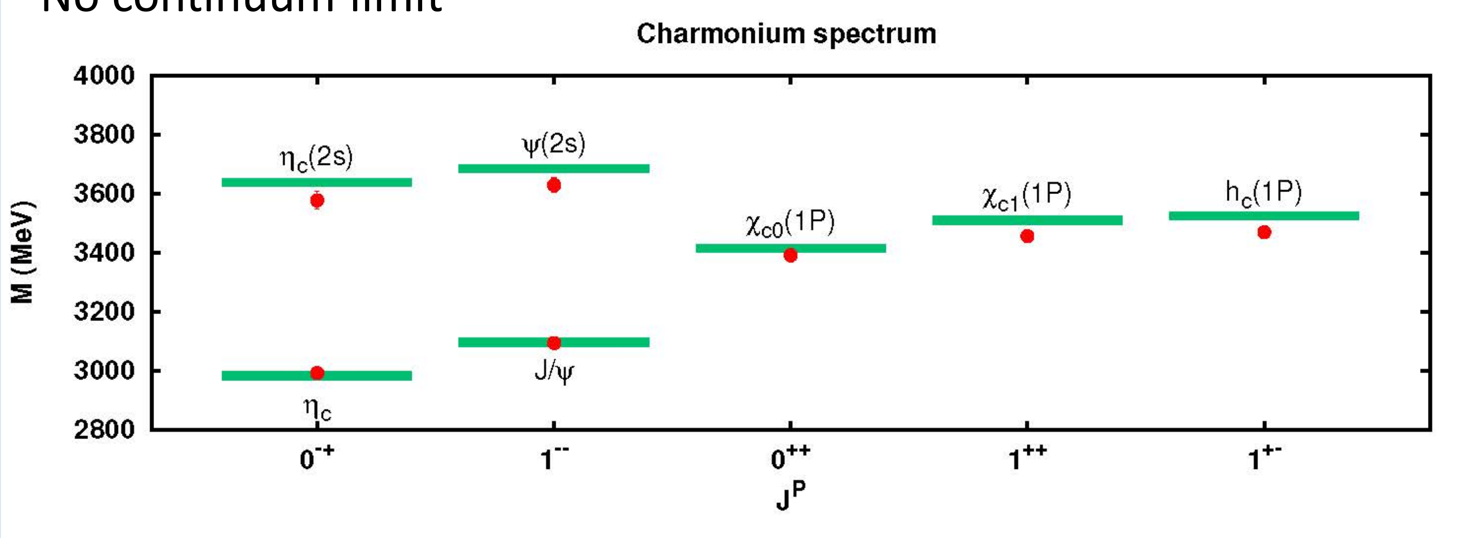
Low lying charmonium levels

Reasonably well understood

Glasgow 1411.1318
Continuum limit,
Physical quark masses



Regensburg 1503.08440
No continuum limit



C. DeTar, Lepton-Photon 2015

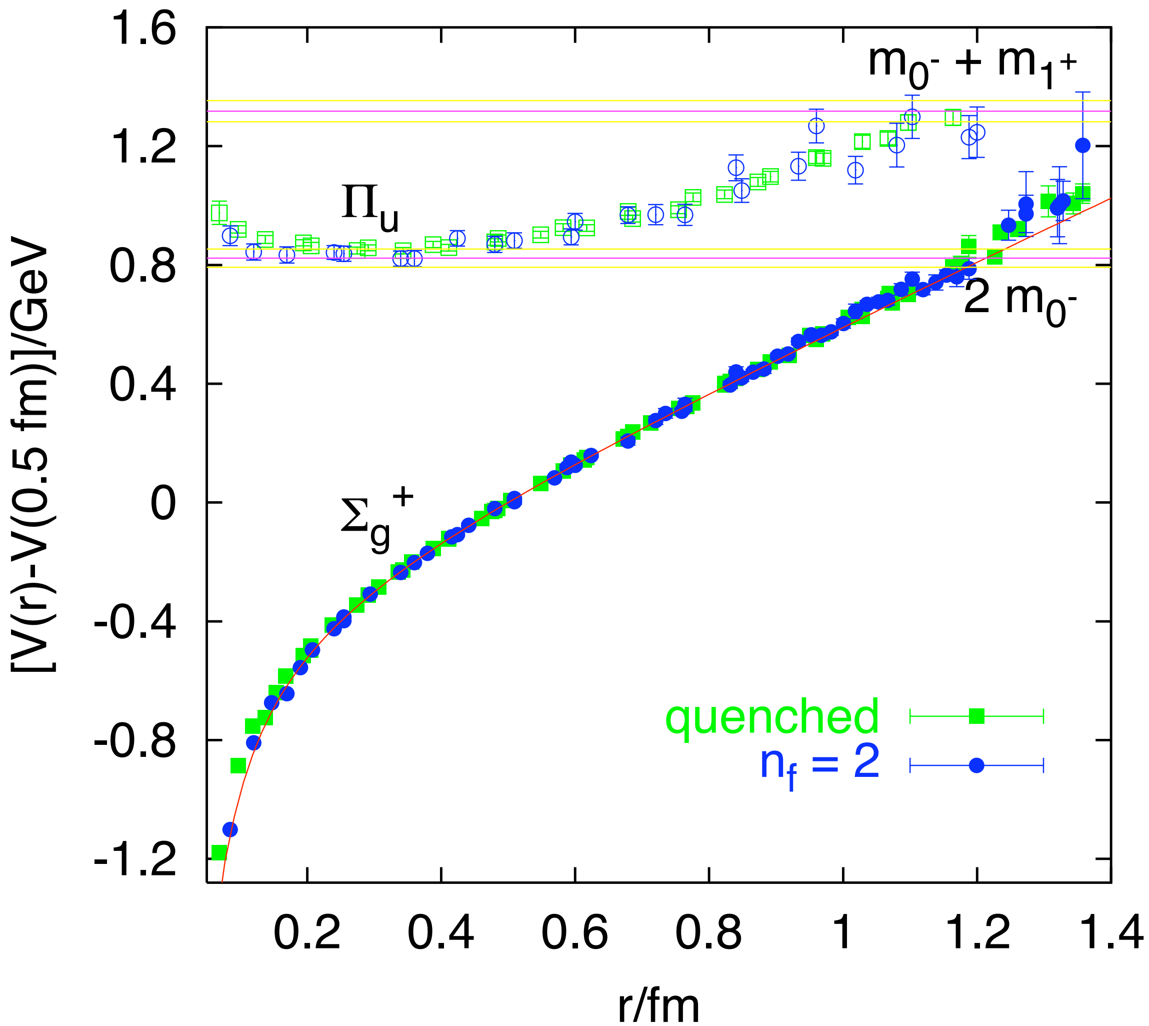
Why it works so well

- 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 $(b\bar{b})$.

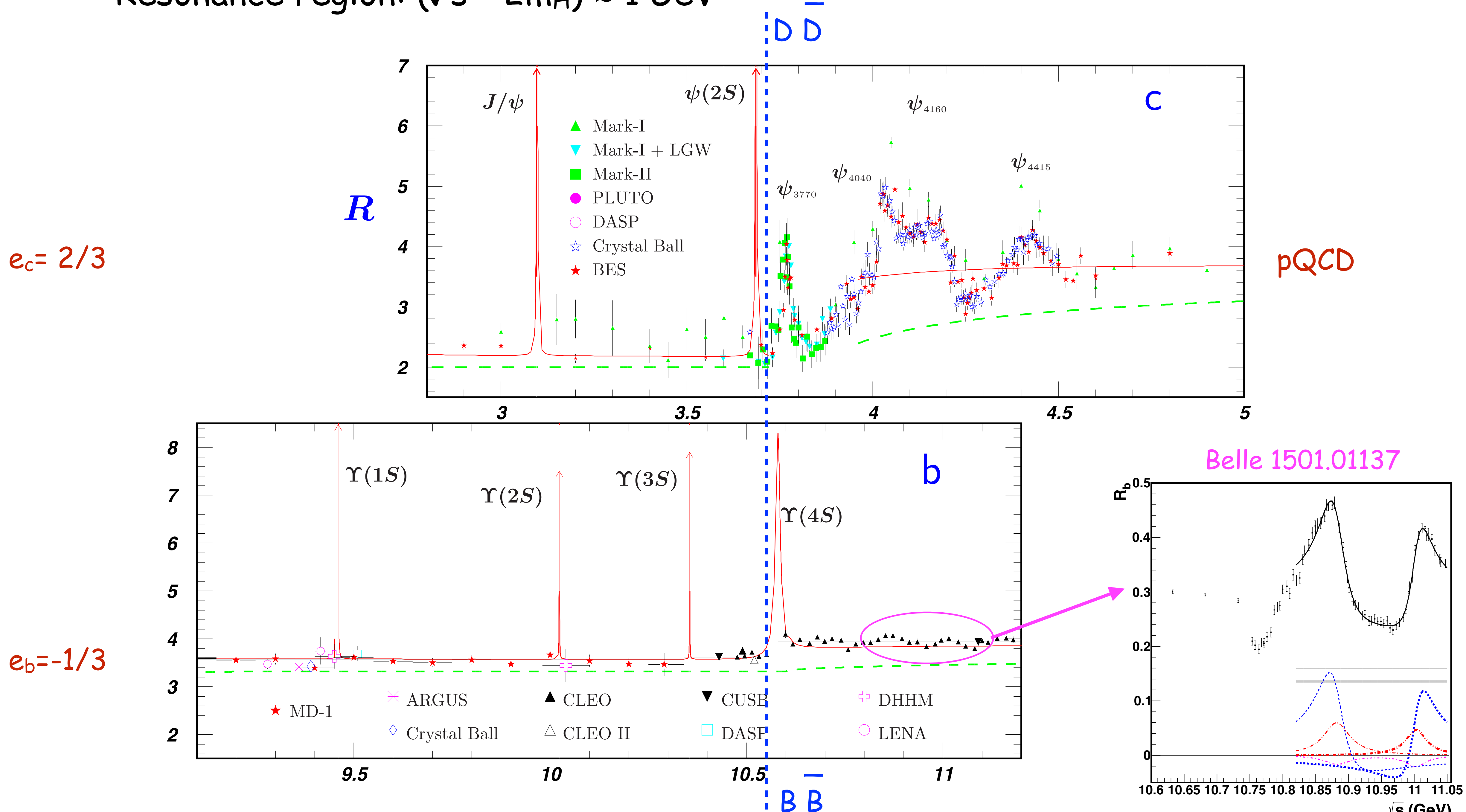
LQCD calculation of static energy



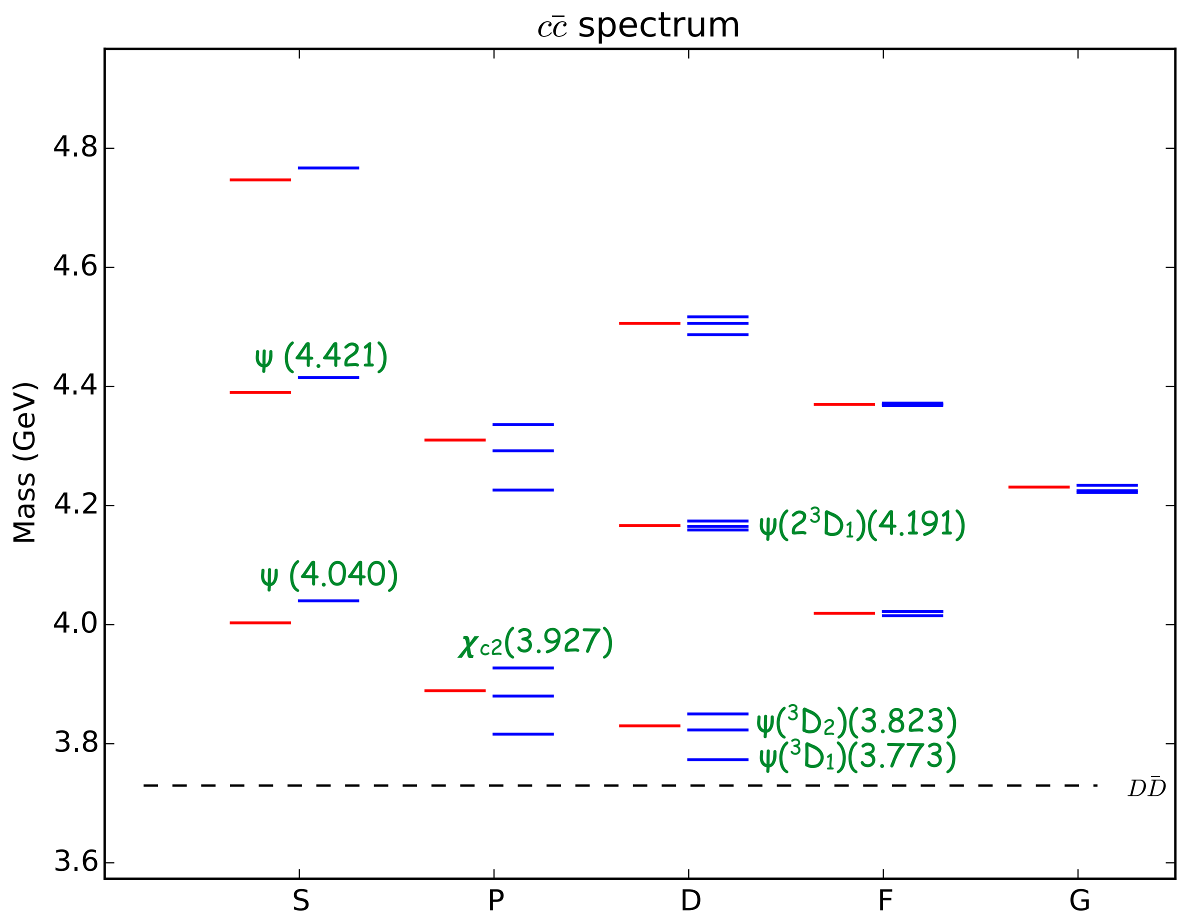
Crossing the Threshold

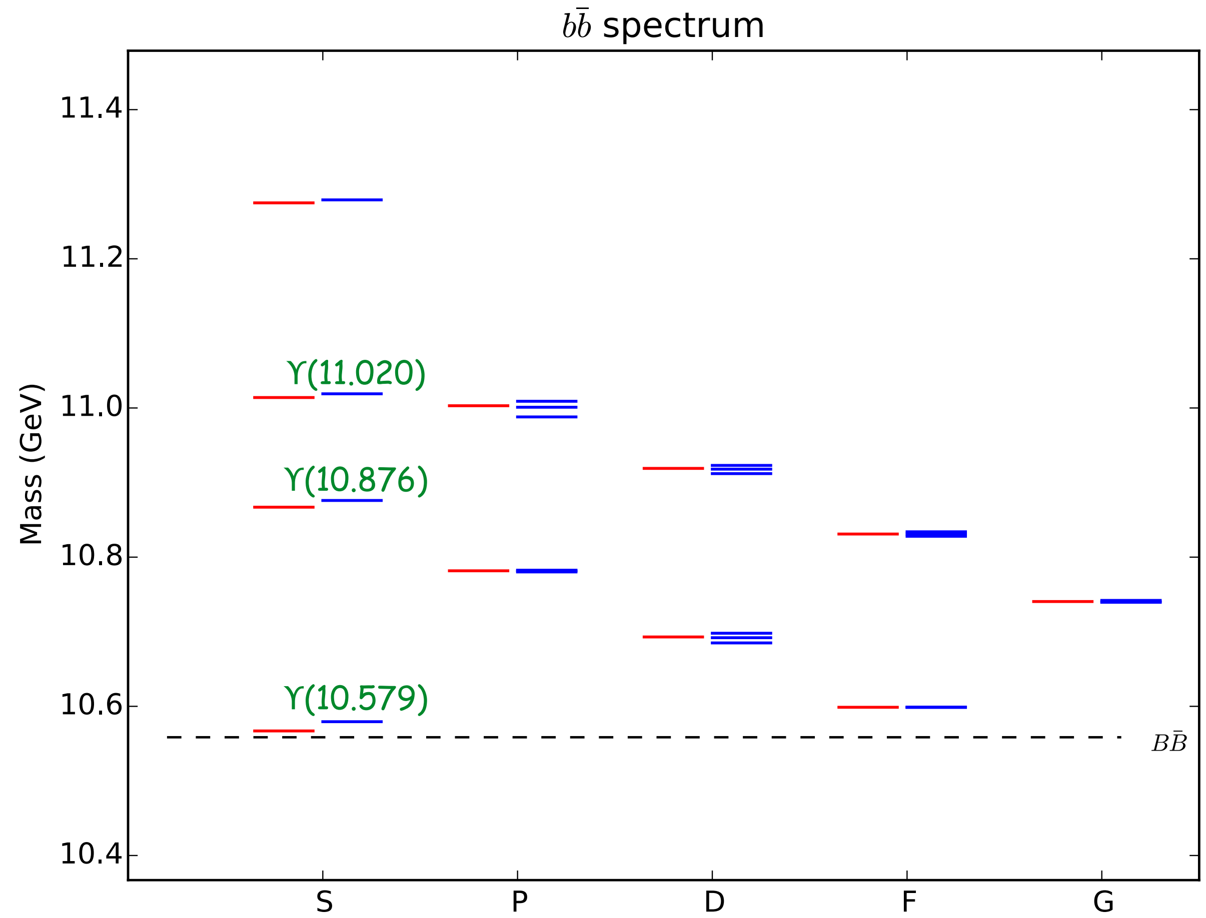
1. Strong decays - resonances become wide and eventually hard to extract.

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



- Observed quarkonium states above threshold



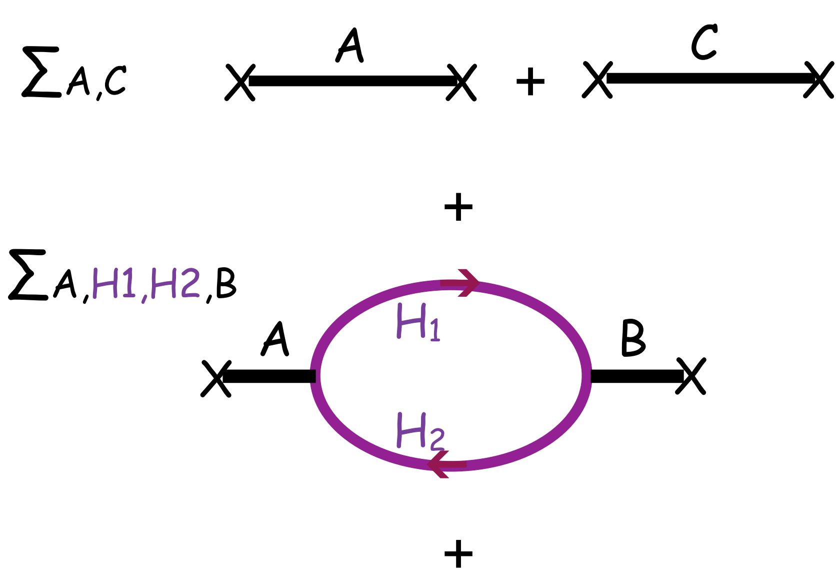


- Two pictures of R: Quark-Hadron Duality

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

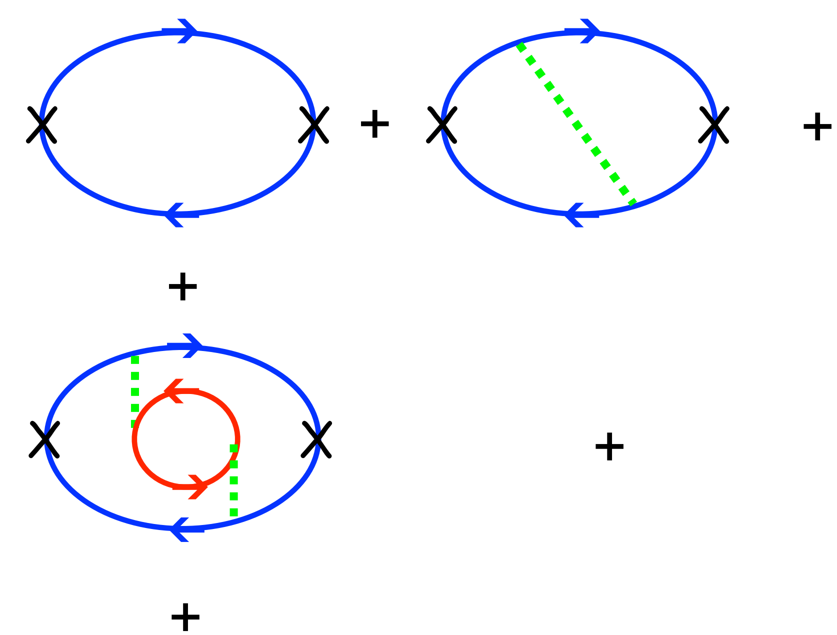
$$= \int d^4x\, e^{iqx}\langle 0|j_\mu(x)j_\nu(0)|0\rangle\Big|_{\mathrm{charm}}.$$

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.

- 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 $\Omega(z)$

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

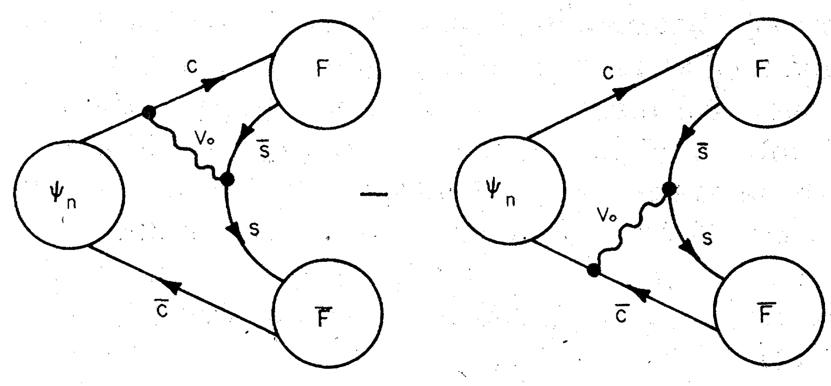
- Decay amplitude $\langle DD|H_I|\psi\rangle$
- Simplifying assumptions
  - H_2 - free meson pairs no final state interactions
  - H_0 - charmonium states are a complete basis - no hybrids

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

- Assuming vector meson dominance. Can compute R_c

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

- 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 ($^3P_0$)

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

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

Statistical factor

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

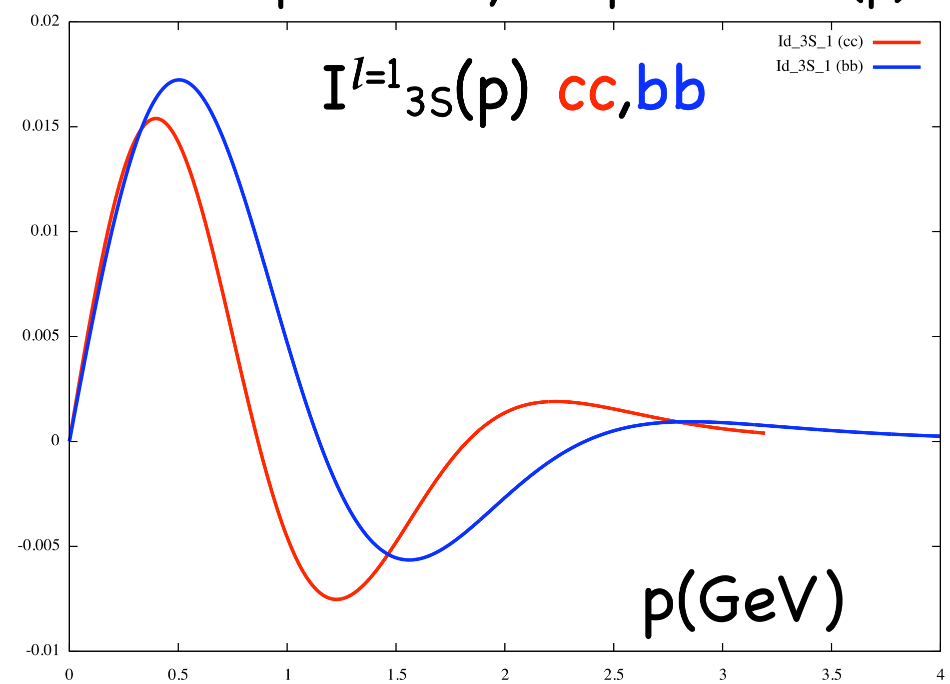
$$\Phi(t) = t e^{-t^2} + (\pi/2)^{1/2}(t^2-1)e^{-t^2/2}\,\mathrm{erf}(t/\sqrt{2})$$

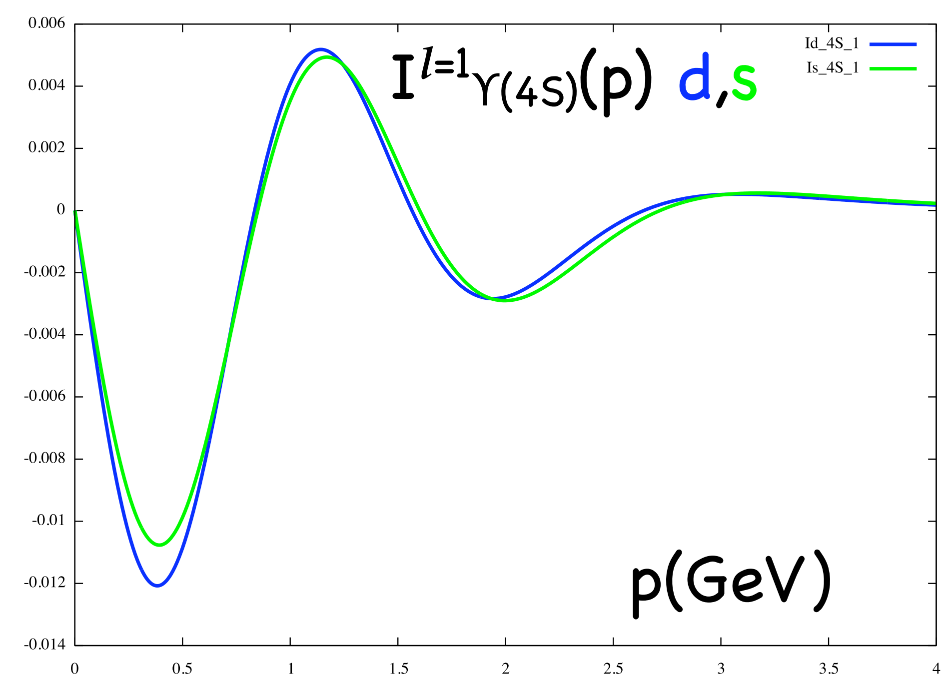
Using HQET this function Φ(t) is the same for all final states in a j_l^P multiplet.

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

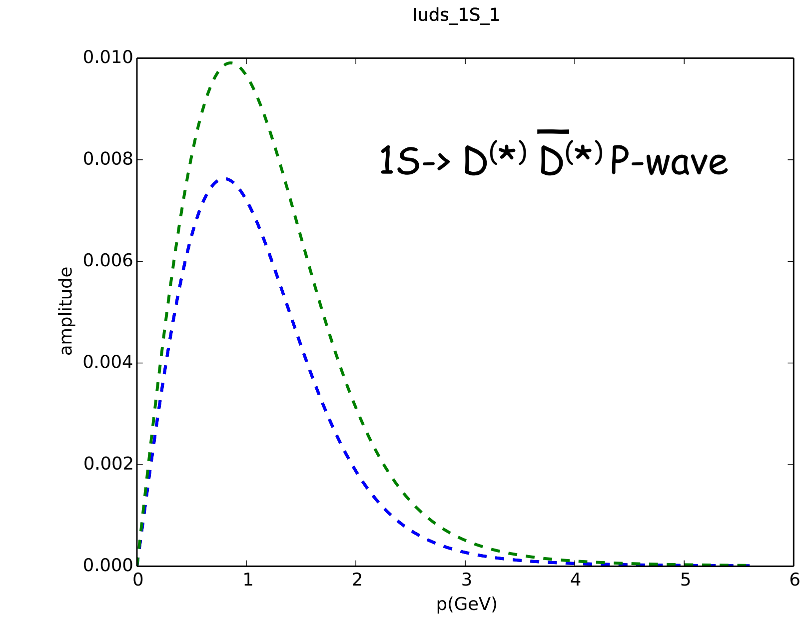
One universal function, Φ(t), determines R_Q in the threshold region.

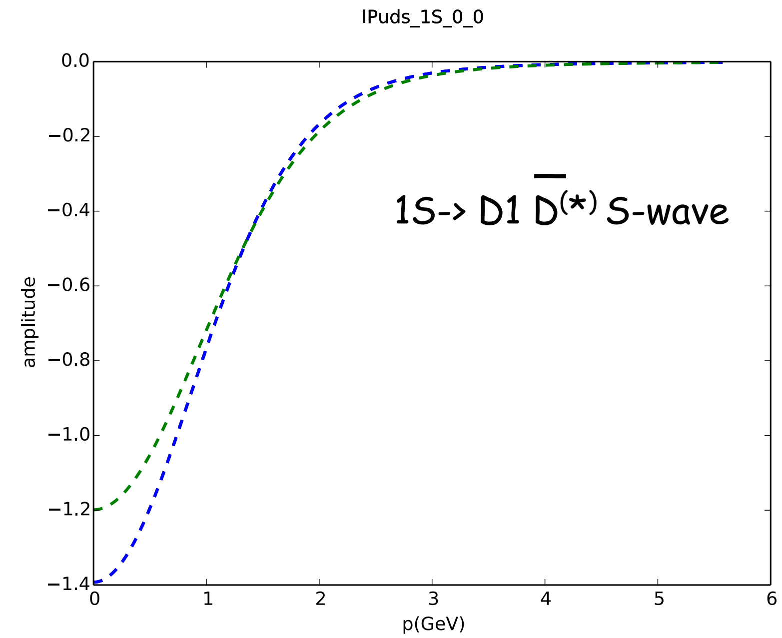
Sample decay amplitudes I(p)



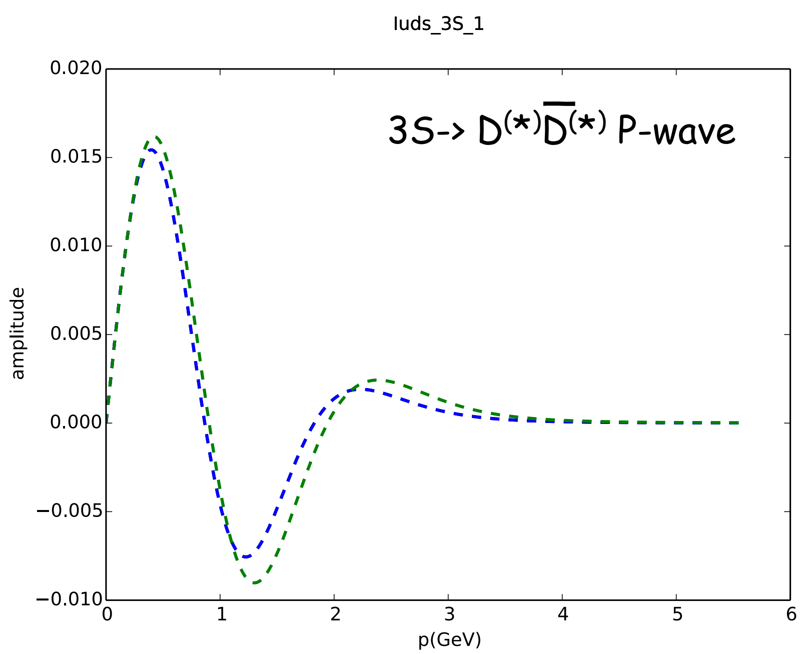


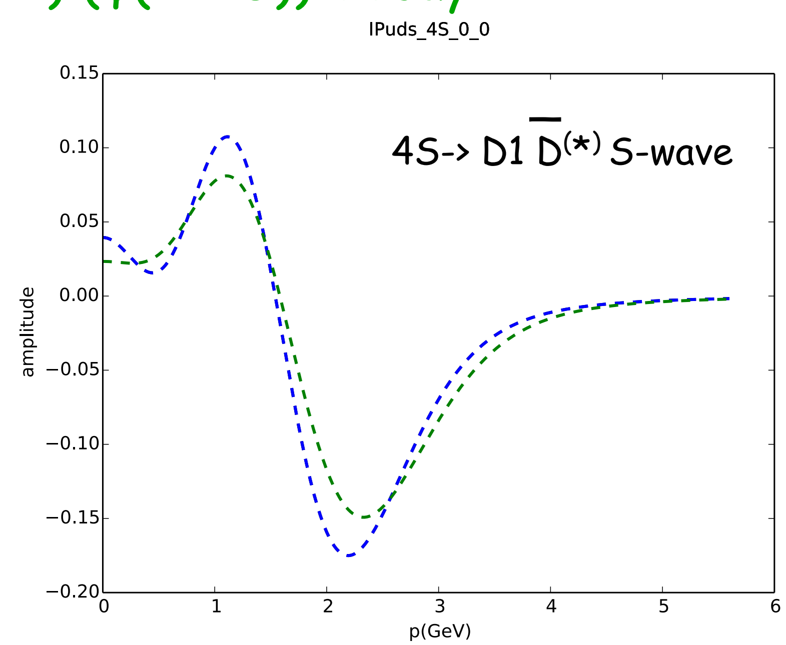
- General features of decays to low-lying heavy-light mesons:
  - Unlike light meson systems, these decays are from highly excited QQ states:
    - Ground state decay amplitudes :





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

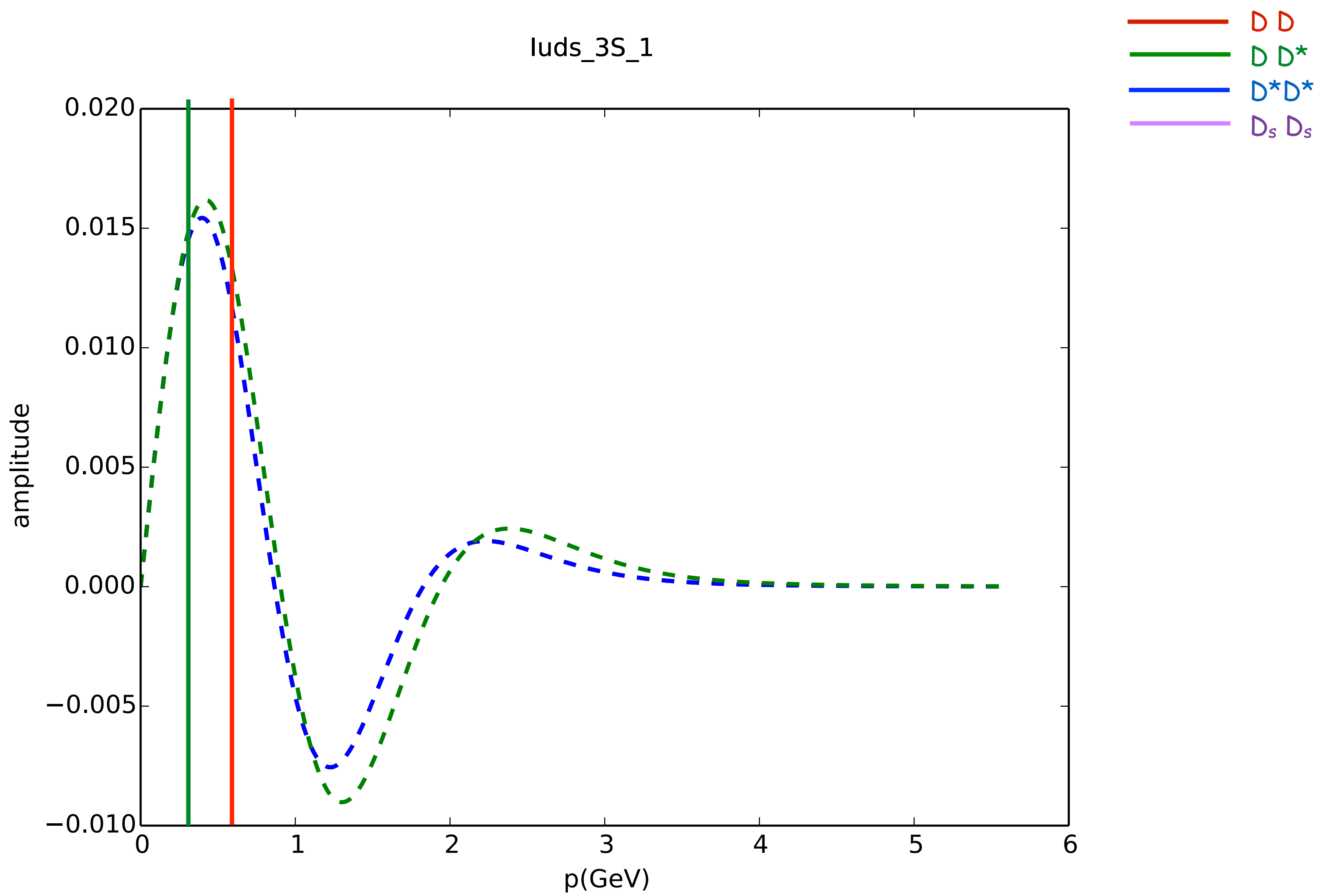




  - Have complicated energy dependence.

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

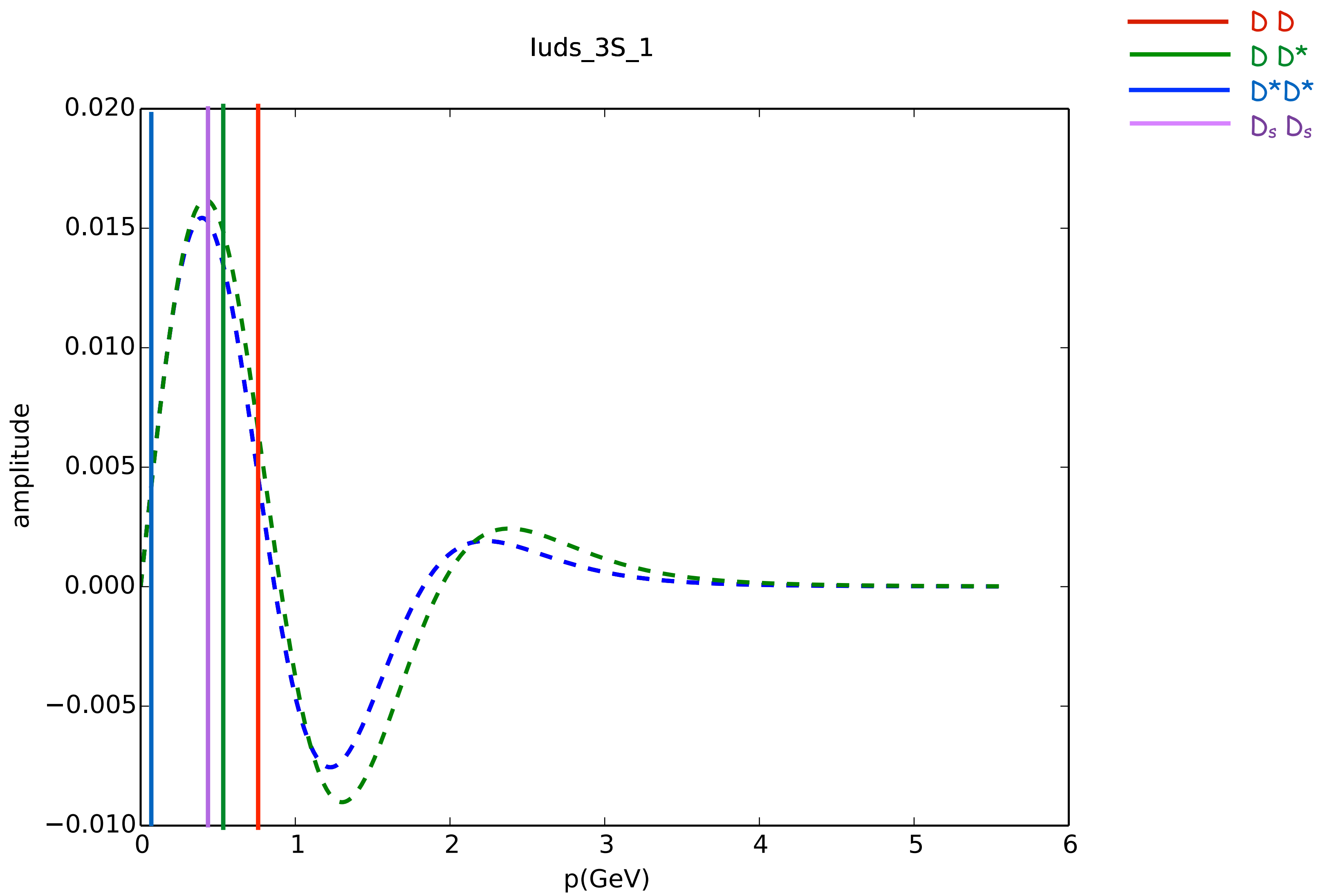
  - E = 4.00 GeV



  - p(DD) = 590 MeV; p(DD*) = 288 MeV

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

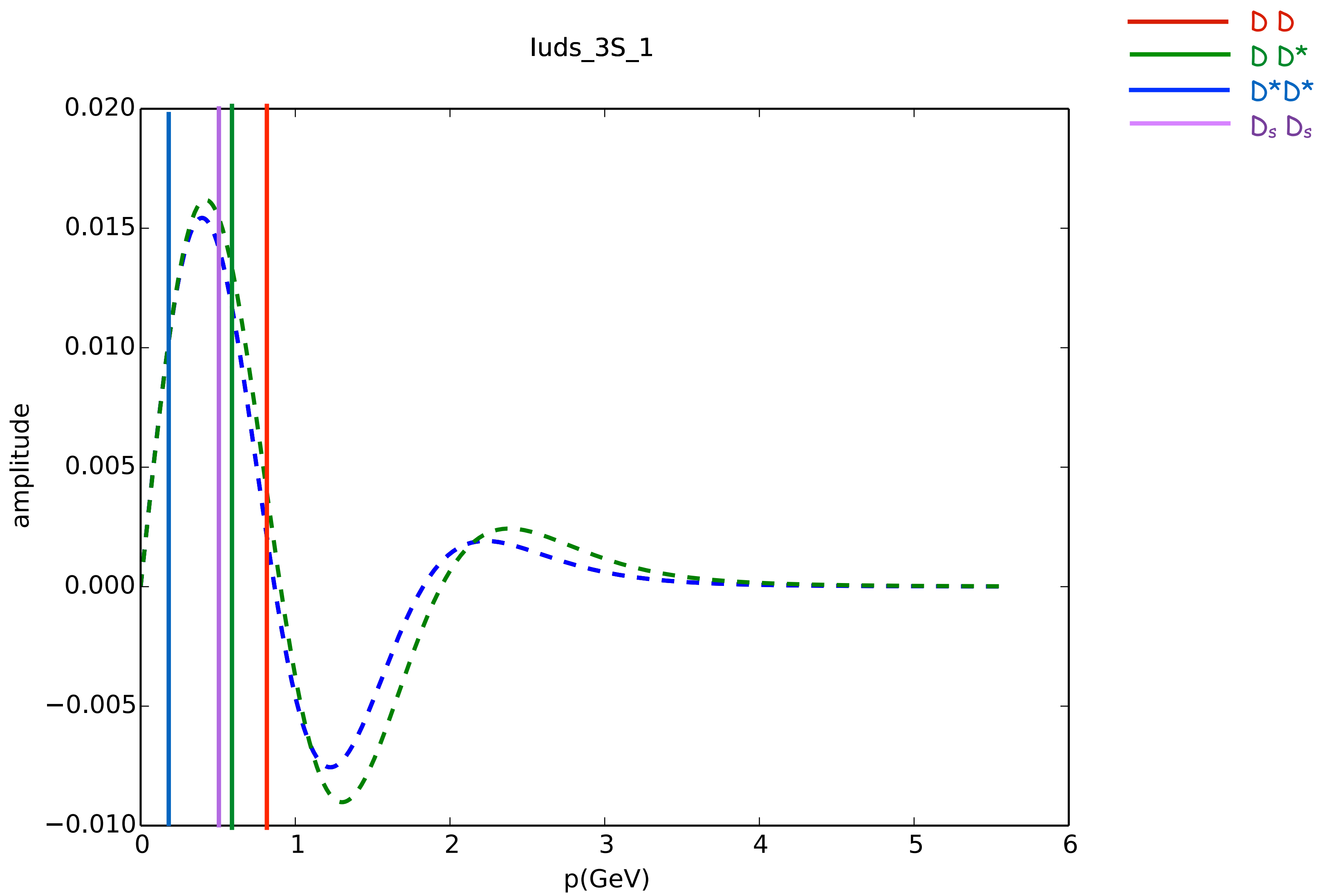
  - E = 4.02 GeV



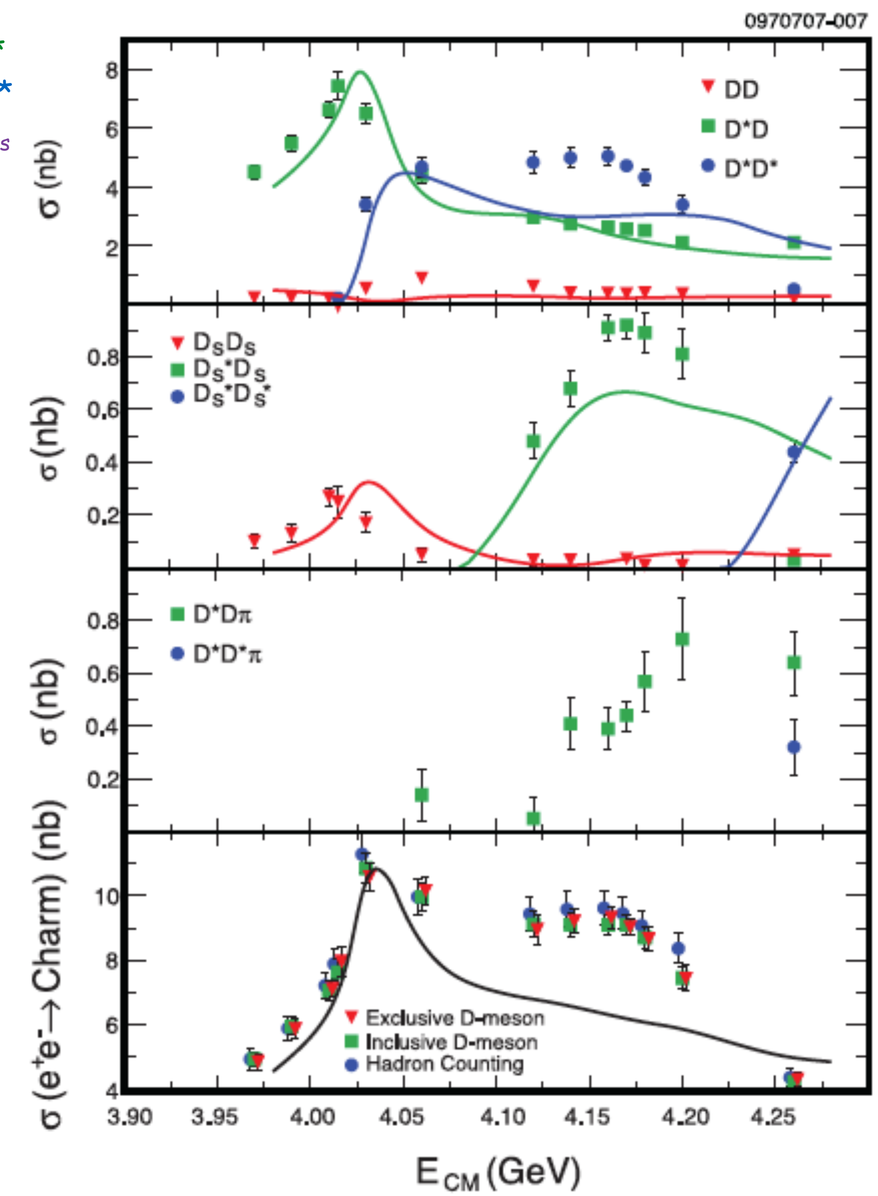
  - p(DD) = 740 MeV; p(DD*) = 530 MeV; p(D*D*) = 085 MeV; p(D_sD_s) = 406 MeV

– 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

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.

- Υ(4S)
  - M = 10,579.4 ± 1.2 MeV Γ = 20.5 ± 2.5 MeV;
  - Open decay channels:
    - $M(B^+B^-)$ = 10,578.52 MeV, $M(B^0B^0)$ = 10,579.16 MeV
    - Essentially no isospin breaking in the masses.

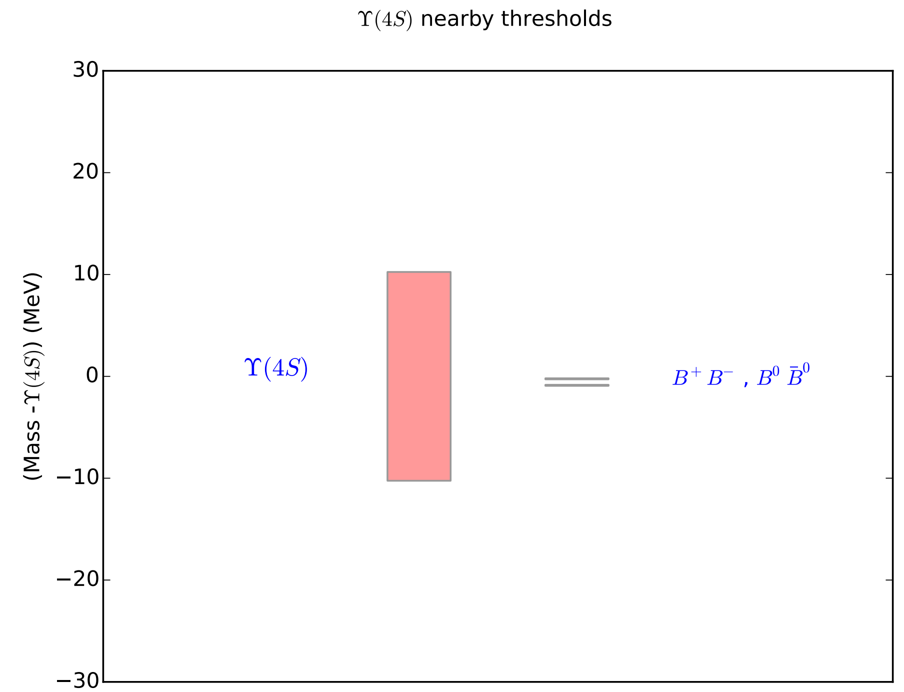


Table 1: Selected Υ(4S) decays.

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 = 3.75 ± 0.73 keV — HQS violating

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 ϒ(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]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

- $\Upsilon(10860)$

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

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

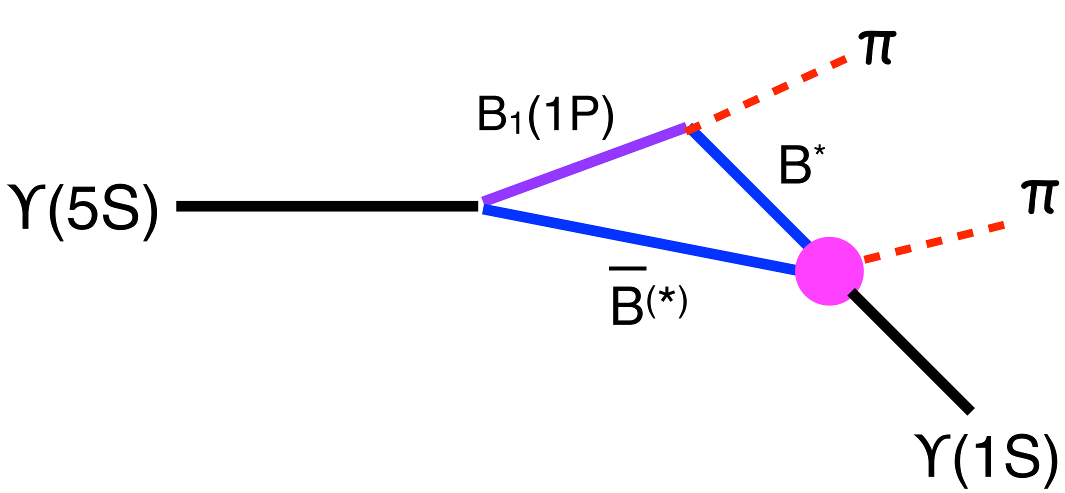
→ partial rate = 0.15 ± 0.08 MeV

- Very large 2π hadronic transitions [> 100 times $\Upsilon(4S)$ 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:
    - $n^3S_1(Q\bar{Q})$ -> $1^{\frac{1}{2}+}P_J(Q\bar{q})$ + $1^{\frac{1}{2}-}S_{J'}(q\bar{Q})$ 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) 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.

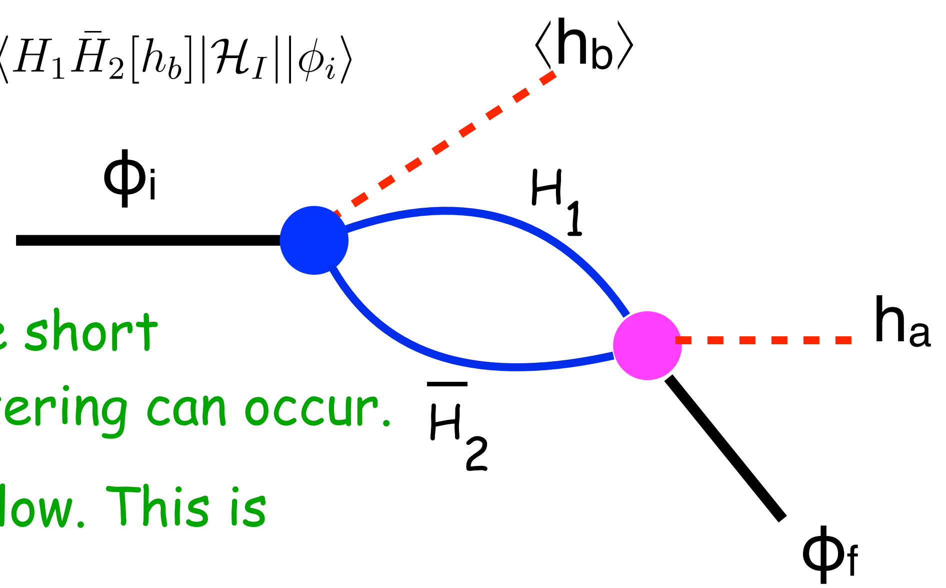
(3) The $B_1(1P)$ decay is S-wave

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

(5) No similar BB system is possible.

- 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).

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



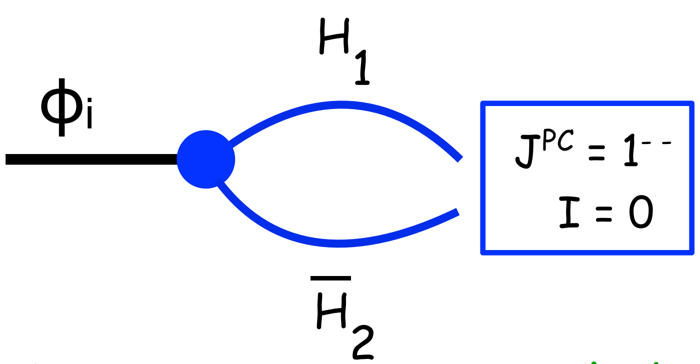
- The time scale of the production process has to be short relative to the time scale over which H_1 H_2 rescattering can occur.
- The relative velocity in the H_1 H_2 system must be low. This is only possible near threshold.

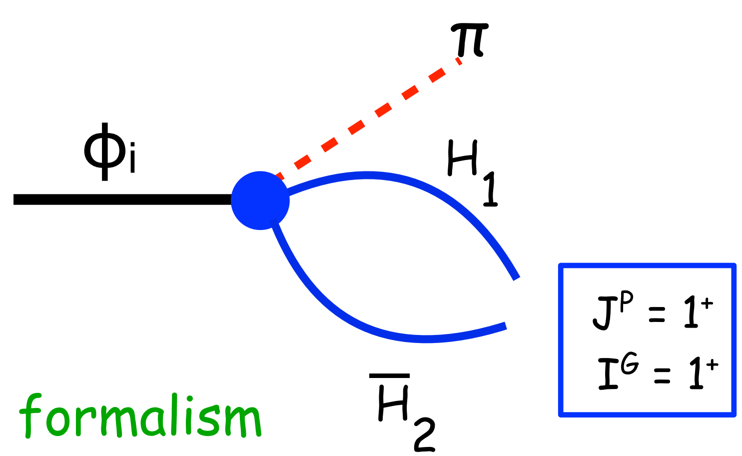
  - Here we need not speculate on whether the observed rescattering is caused by a threshold bound state, cusp, or other dynamical effect.

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

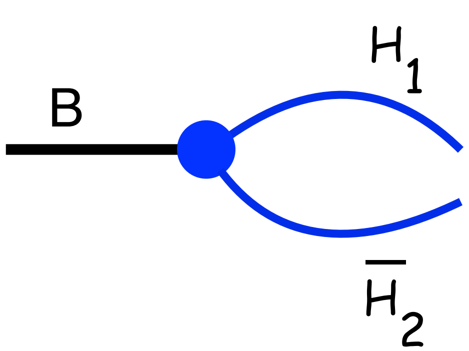
Four Quark States May Be Easily Produced at Two Heavy-Light Mesons S-wave Thresholds

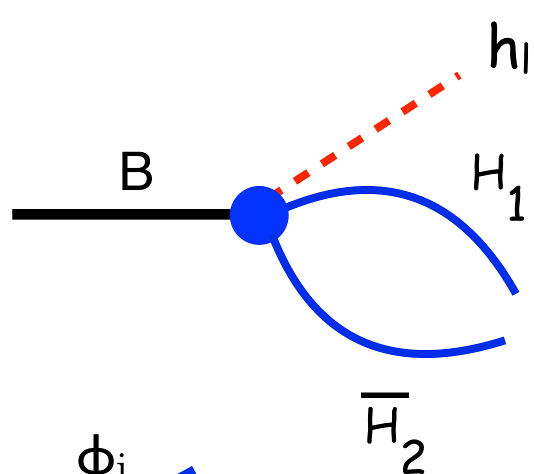
- Production modes: (Where to look for new surprises)
  - e+e- processes
    - direct sequential (dominant terms)

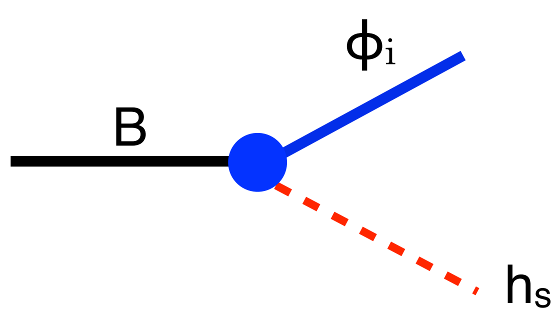




    - Can compute using coupled channel formalism
  - B weak decays
    - More quantum numbers accessible







Biggest Surprise:

Resonances are seen at these thresholds

XYZ States

- X(3872) - the first surprising new state

S.-K. Choi et al. [Belle] (1200 cites)
PRL 91 (2003)262001 [hep-ph/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? $\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$

- Y(4260)- another surprise

B. Aubert et al. [BaBar] (626 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: γ X(3872)

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

A. Bondar et al. [Belle] (271 cites)
PRL 108 (2012) 122001 [arXiv:1110.2251]

M. Ablikim et al. [BESIII] (175 cites)
PRL 111 (2013) 242001 [arXiv:1309.1896]

  - I = 1 isospin triplets -> 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

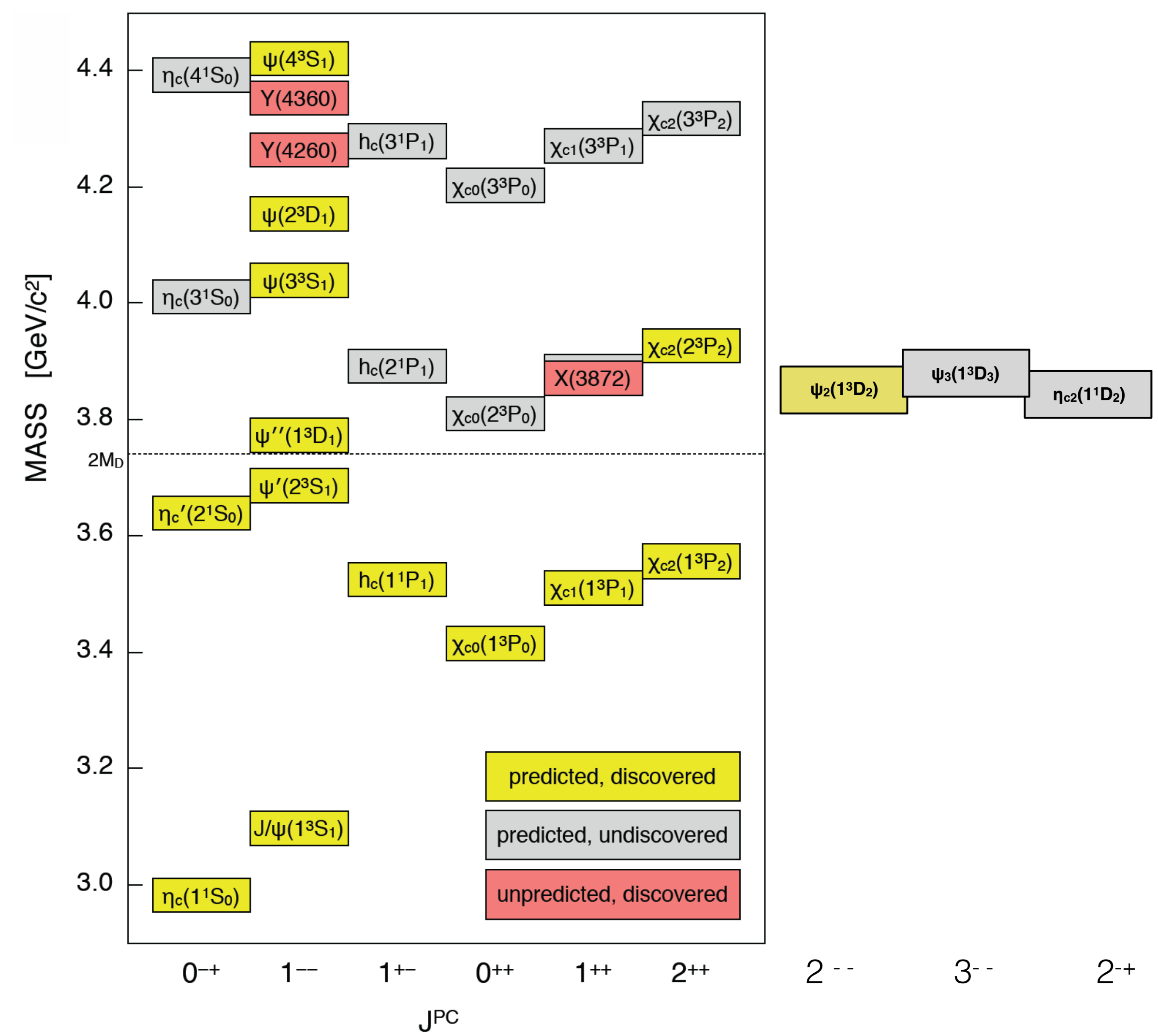
- Notation
  - Y denotes states observed directly in the charm contribution to e^+e^- -> hadrons:

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

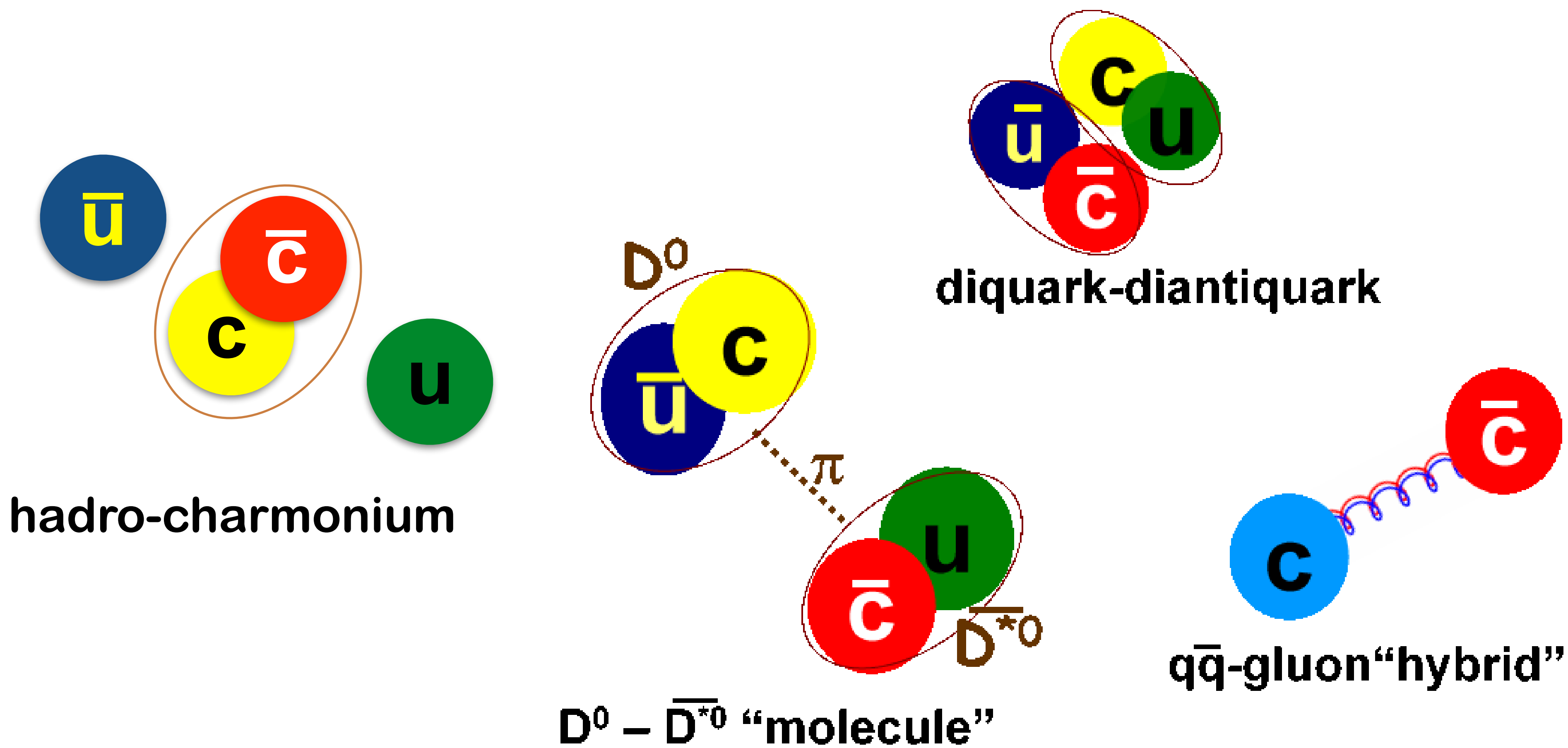


- Updated from PDG - other X states need more information

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}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle(6.0)	2007
				$e^+e^- \to J/\psi(...)$	Belle (5.0)	
				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

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

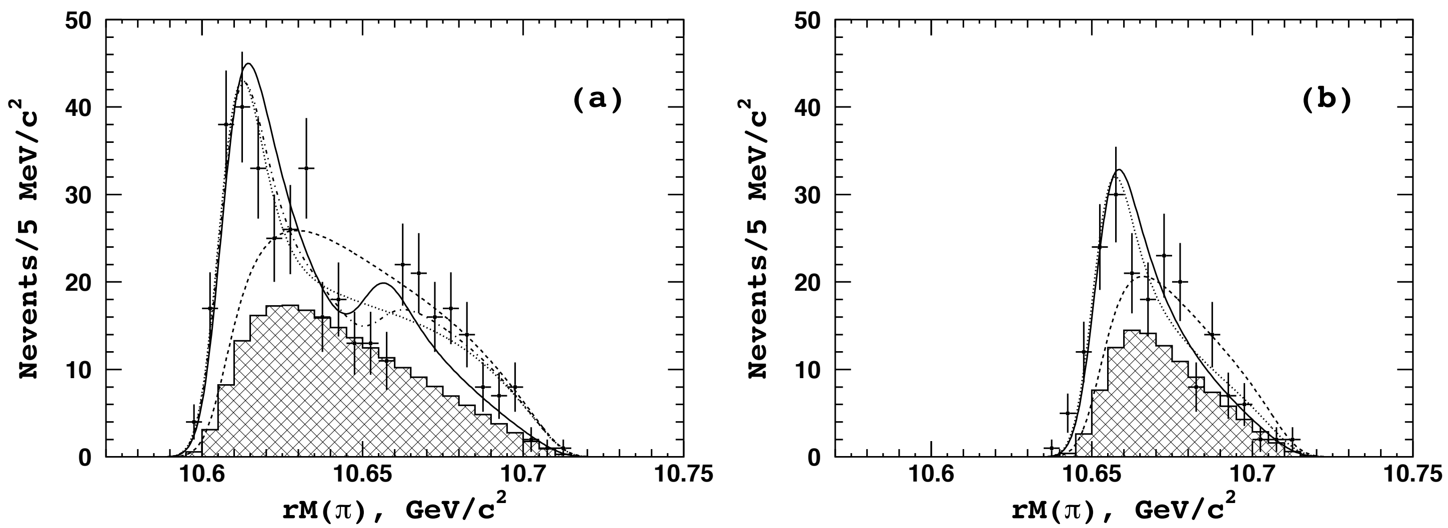
TABLE 1. Masses, widths, and relative phases of peaks observed in $h_b\pi$ and $\Upsilon\pi$ channels, from fits described in text.

	$h_b(1P)\pi^{\pm}\pi^{\mp}$	$h_b(2P)\pi^{\pm}\pi^{\mp}$	$\Upsilon(1S)\pi^{\pm}\pi^{\mp}$	$\Upsilon(2S)\pi^{\pm}\pi^{\mp}$	$\Upsilon(3S)\pi^{\pm}\pi^{\mp}$	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

$Z^{+}(10610)$ $Z^{+}(10650)$



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

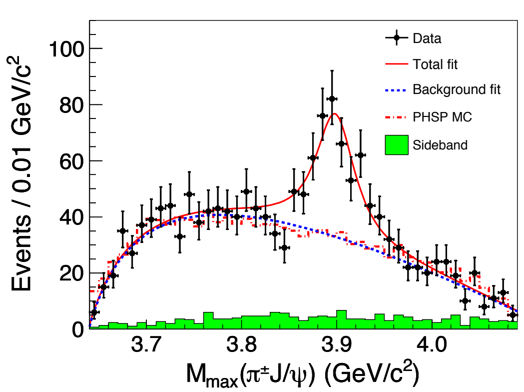
and

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

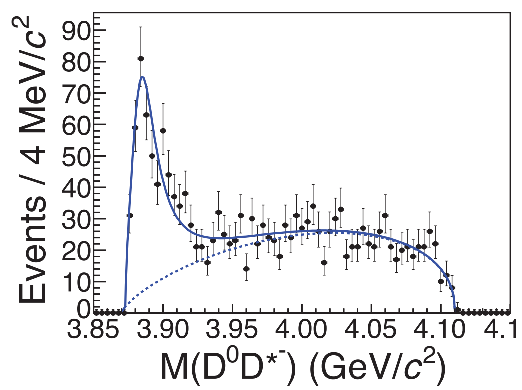
  - HQS implies that the same mechanism applies for charmonium-like states

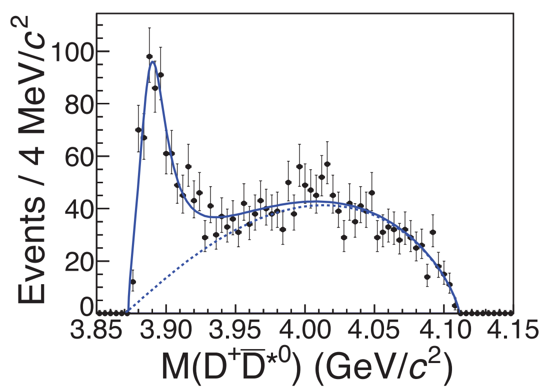
$Z_c^+(3885)$ and $Z_c^+(4020)$

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



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





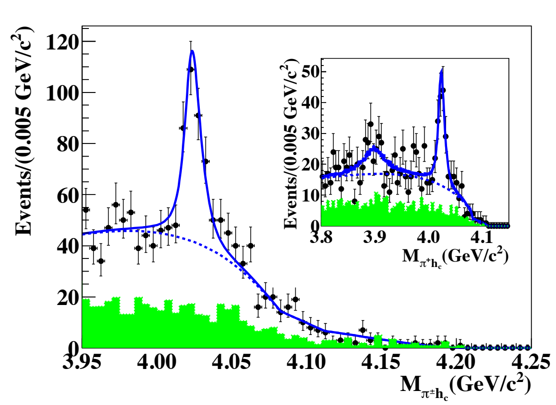
$M_{\rm pole} = 3883.9 \pm 1.5 \pm 4.2$ MeV

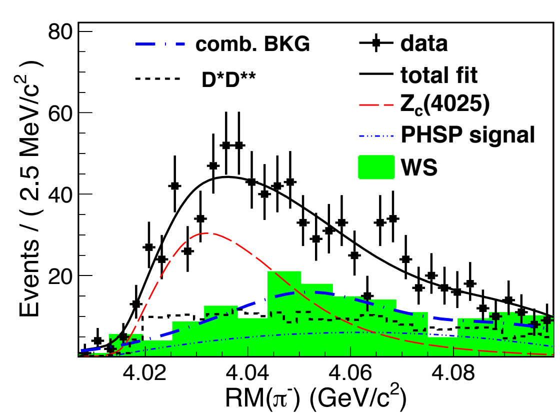
$\Gamma_{\rm pole} = 24.8 \pm 3.3 \pm 11.0$ MeV

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

BESIII Z. Lin

[arXiv:1504.06102]





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

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV

$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

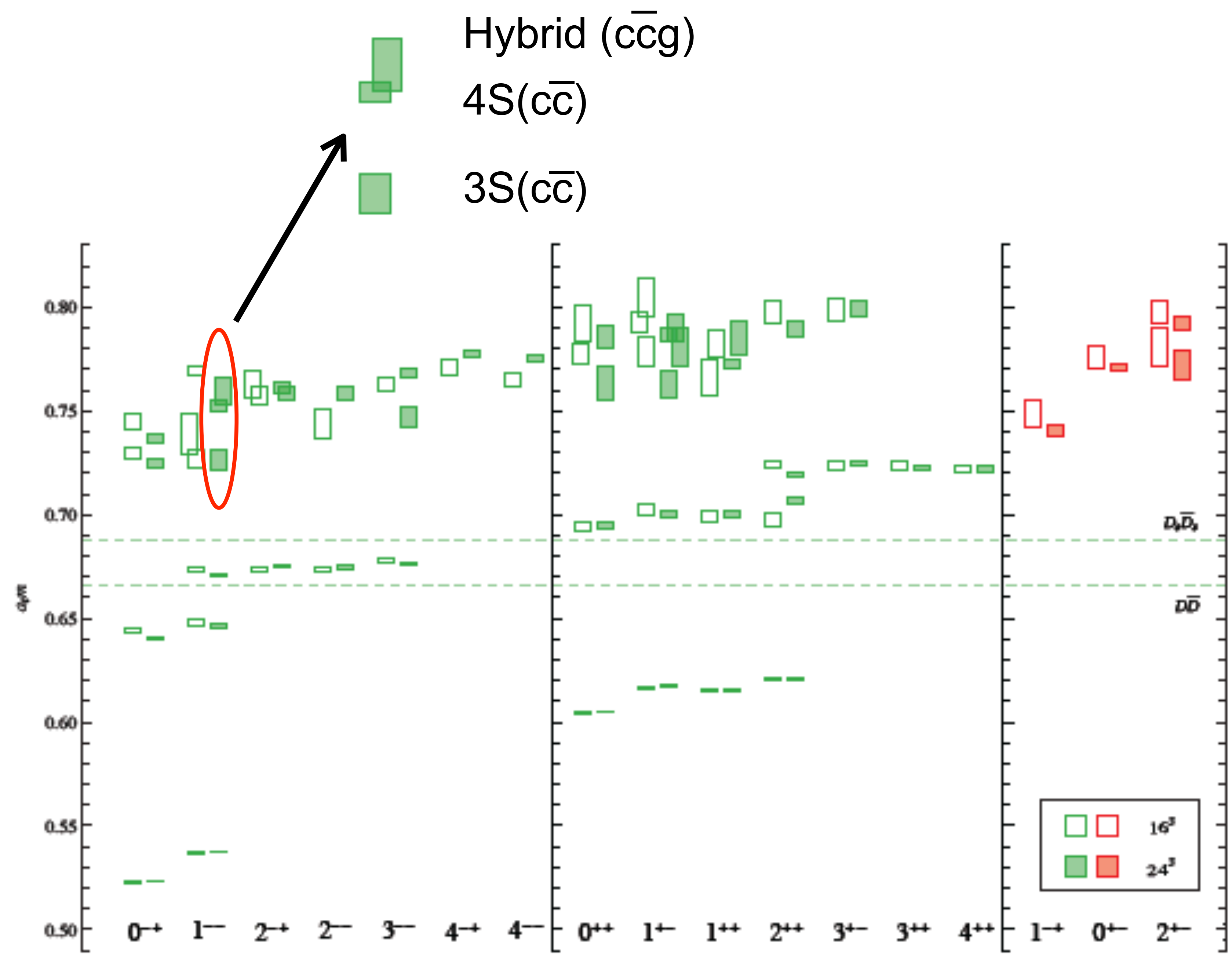
M(D^{*0}+D^{*-}) = 4.0178

Y(4260)

- Y(4260) - not standard charmonium state. JPC = 1- - M= 4259 ± 9 Γ= 120 ± 12 MeV
  - Decays observed:
    - $J/\psi\pi^+\pi^-$
      - $J/\psi f_0(980)$, $f_0(980) \to \pi^+\pi^-$
      - $X(3900)^\pm\pi^\mp$, $X^\pm \to J/\psi\pi^\pm$
    - $J/\psi\pi^0\pi^0$
    - $J/\psi K^+K^-$
    - $X(3872)\gamma$
  - Many models:
    1. Charmonium hybrid → ZHU S L. Phys. Lett. B, 2005, **625**: 212; Kou E and Pene O. Phys. Lett. B, 2005, **631**: 164; Close F E and Page P R. Phys. Lett. B, 2005, **628**: 215
    2. D_1 D molecule → DING G J, Zhu J J and YAN M L. Phys. Rev. D, 2008, **77**: 014033; Ding G J. Phys. Rev. D, 2009, **79**: 014001; WANG Q, Hanhart C and ZHAO Q. Phys. Rev. Lett., 2013, **111**: 132003
    3. Hadrocharmonium → Voloshin M B. Prog. Part. Nucl. Phys., 2008, **61**: 455; S. Dubynskiy and Voloshin M B. Phys. Lett. B, 2008, **666**: 344; LI X and Voloshin M B. Phys. Rev. D, 2013, **588**: 034012
    4. Tetraquark (ccss) → Maiani L, Riquer V, Piccinini F and Polosa A D. Phys. Rev. D, 2005, **72**: 031502
    5. Cusp/nonresonance → Beveren E van and Rupp G. arXiv:0904.4351 [hep-ph]; Beveren E van and Rupp G. Phys. Rev. D, 2009, **79**: 111501; Beveren E van, Rupp G and Segovia J. Phys. Rev. Lett., 2010, **105** 102001; CHEN D Y, HE J and LIU X. Phys. Rev. D, 2011, **83** 054021

    ...
  - Lattice results from the hadron spectroscopy collaboration suggest the possibility of a hybrid
  - HQS expectations require to see an analog state in the bottomonium system
    - 1. Using the static potential of the excited string Π_u : Hybrid state should be ~ 10,870 MeV
    - 2. At threshold of B_1 B : 11,000 MeV

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



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

X(3872)

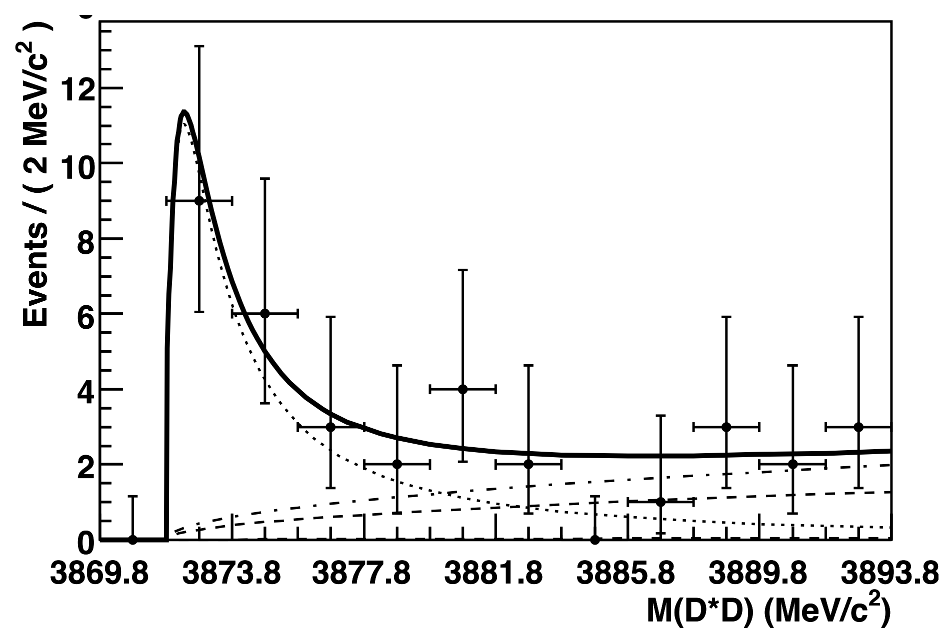
- X(3872) - $J^{PC} = 1^{++}$ M= 3871.69 ± 0.16 ± 0.19 Γ< 1.2 MeV from $J/\psi\ \pi\pi$ mode
  - Decays observed:

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

  - 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.

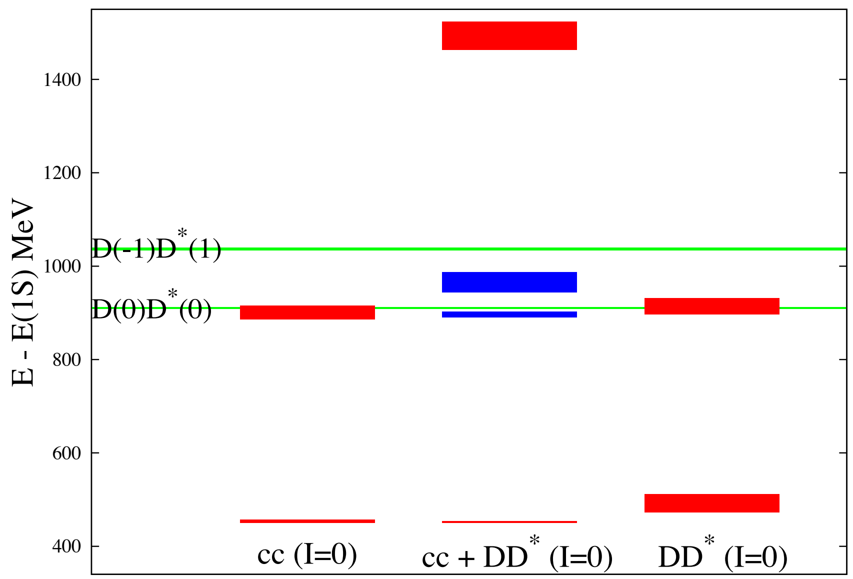
B. A. Galloway, P. Knecht, J. Koponen, C. T. H. Davies, and G. P. Lepage, PoS **LATTICE2014**, 092 (2014), 1411.1318.

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

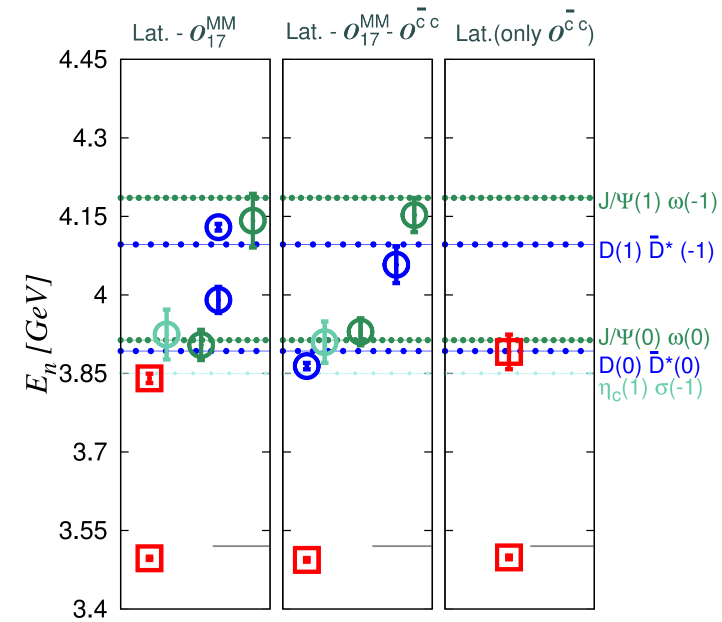
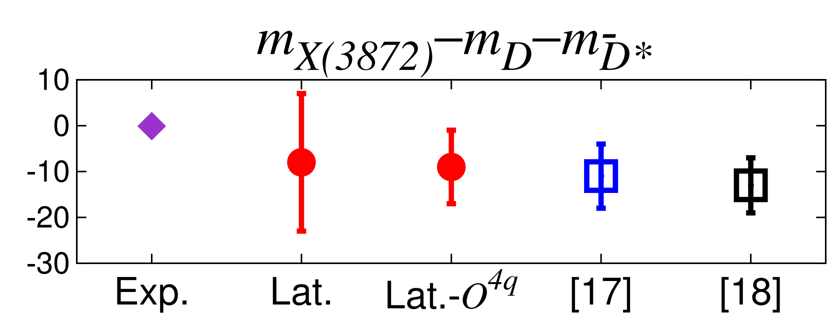


FIG. 5. The spectrum of states (Eq. (11)) with $J^{PC} = 1^{++}$ and quark content $\bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$. (i) Optimized basis (without O_{17}^{MM}), (ii) optimized basis without $\bar{c}c$ operators (and without O_{17}^{MM}) and (iii) basis with only $\bar{c}c$ operators. Note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

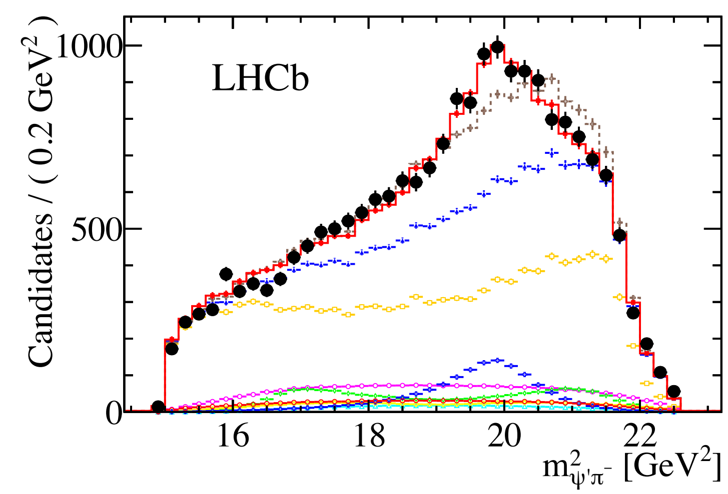
- $X_b(10604)$??
  - No isospin breaking: X is I=0 => G-parity forbids the decay X -> ππϒ(1S).
  - Dominate decay X -> ωϒ(1S) ?
  - M(χ_{b1}(3P)) - M(B) - M(B*) ≈ - 75 MeV
  - So the (bb) state is decoupled.



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

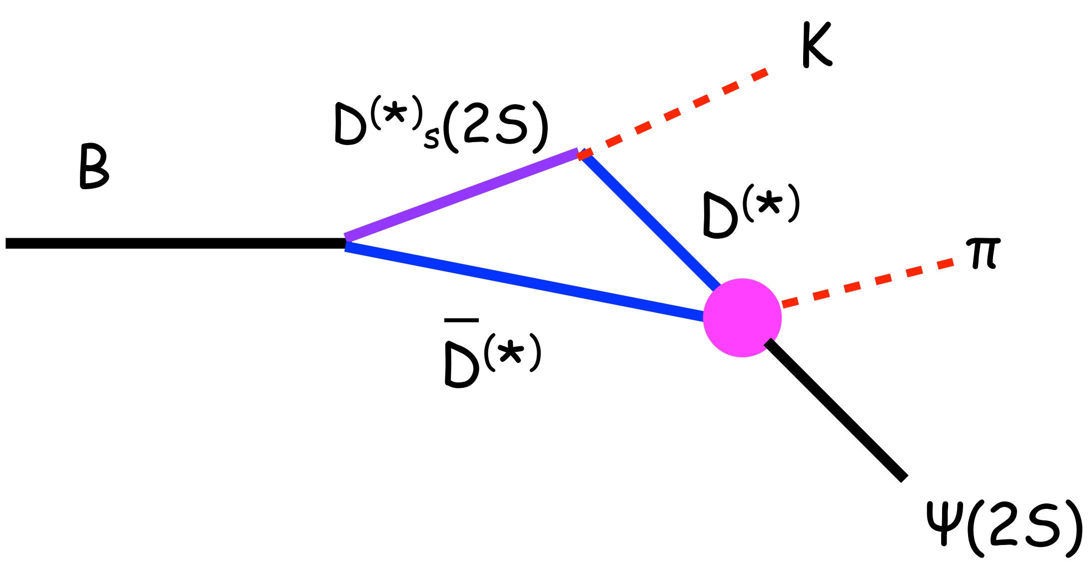
Systematics: Other States

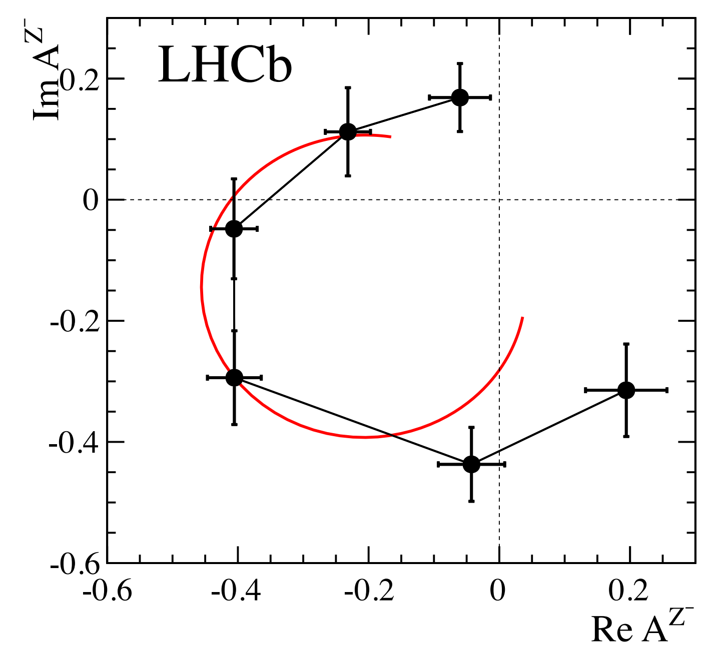
- $Z^{-}(4430)$: seen in $B^0 \to K^+ \pi^- \psi'$
  - $J^P = 1^+$; $M = (4{,}475 \pm 7 \pm [15/25])$ MeV; $\Gamma = (172 \pm 13 \pm [37/34])$ MeV
  - Resonance behavior observed.
  - Same mechanism in B-decays with $D_s(2S)$ states?
    - $D_s^*(2S)$ $M = 2{,}709 \pm 4$ MeV $\Gamma = 117 \pm 13$ MeV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



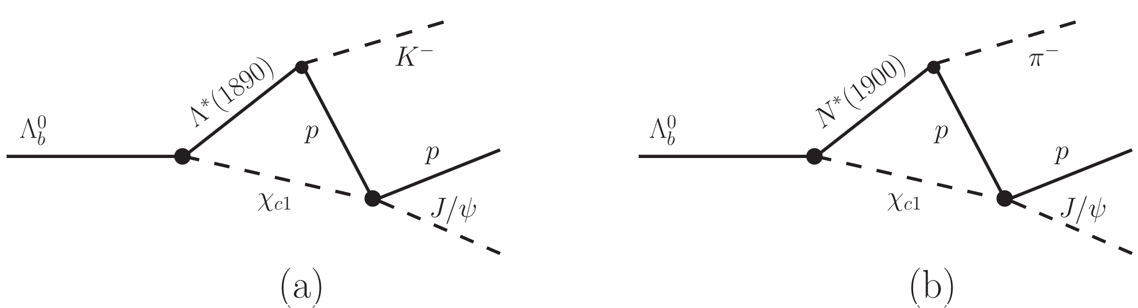


- X(5568): decaying into $B_s \pi^+$
  - by observed by Dzero but not confirmed by LHCb

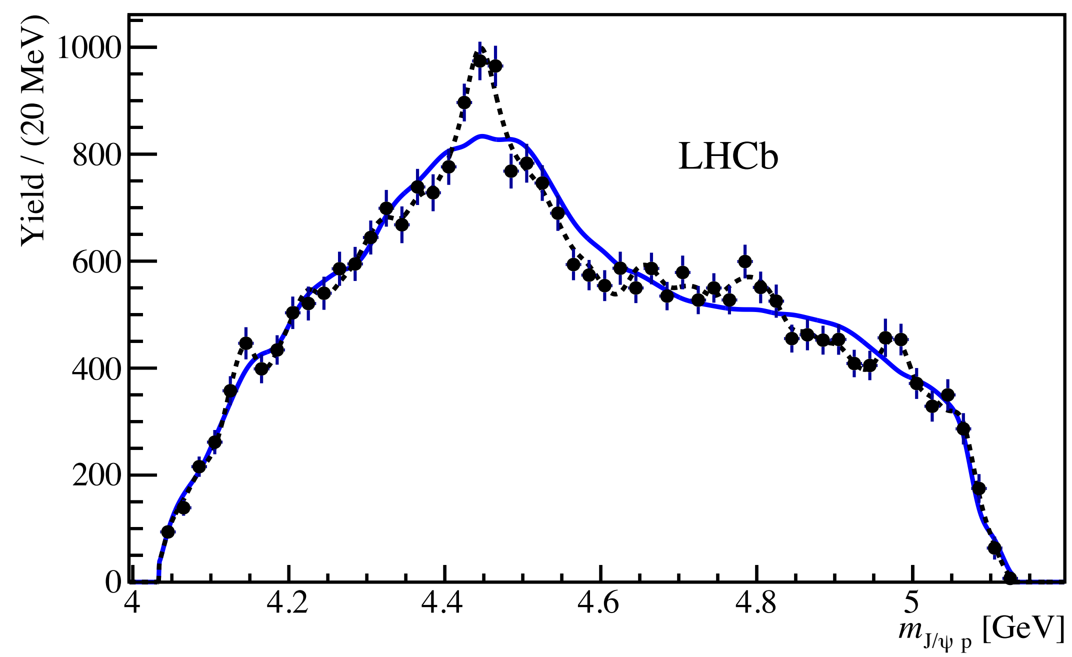
- Pentaquarks: [Λ_b -> p J/ψ K weak decay]

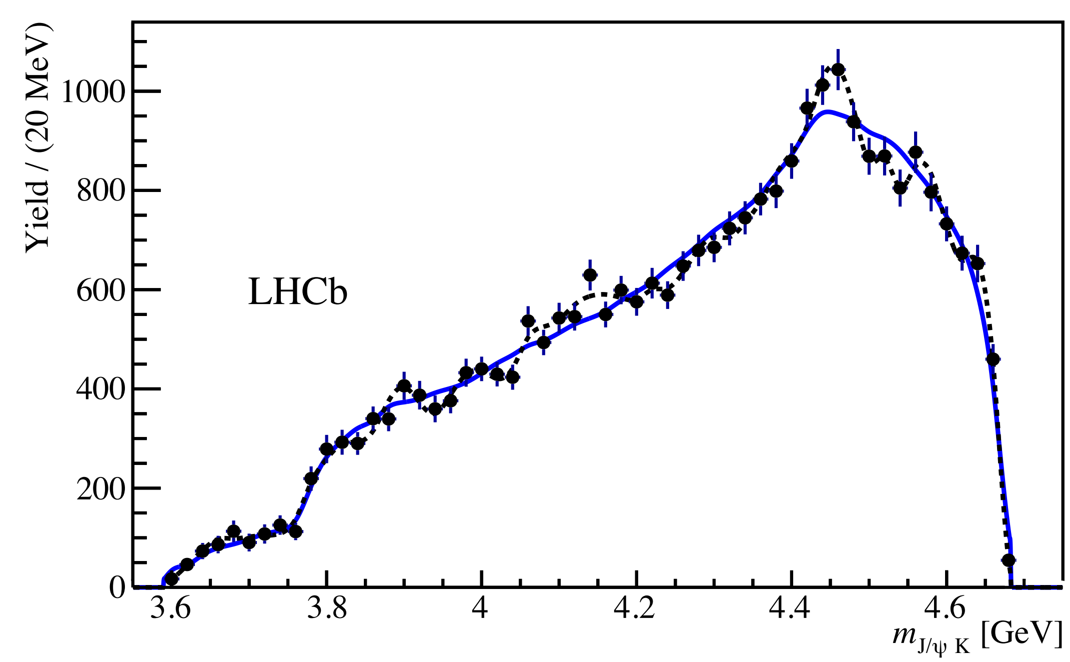
LHCb: [arXiv:507.03414, 1604.05708]

  - $P_c(4450)$ - $J^P = 5/2^+$; 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]





Unexplored Territory

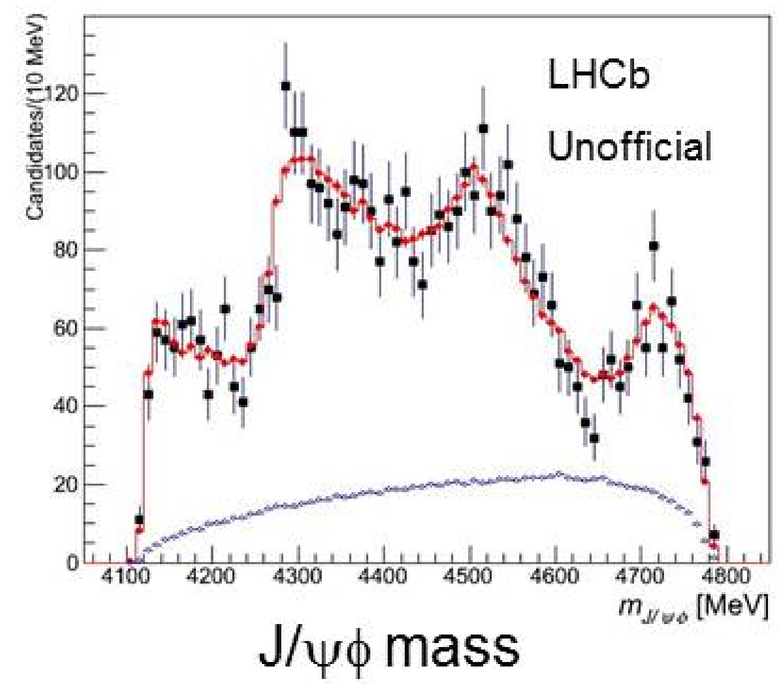
Many surprises still ahead?

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

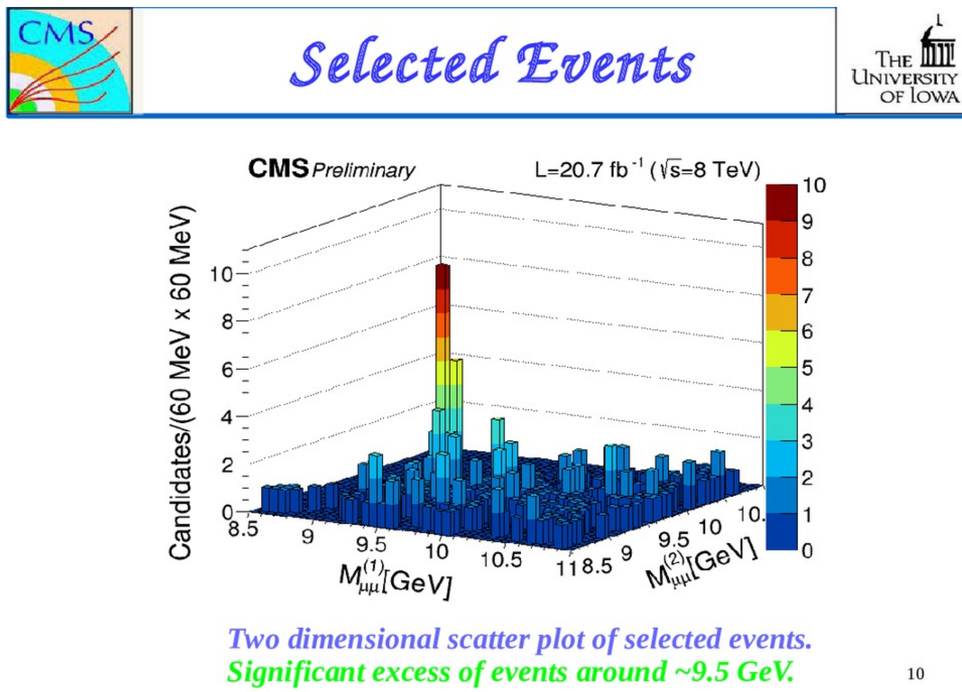
- Have four quark states with heavier light quarks been observed?
  - $(c\bar{s}s\bar{c})$ X(4140) and others?
- CMS at $\sqrt{s}$ = 8 TeV observes double ϒ production in the μ+ μ- μ+ μ- final state:
  - $\sigma(pp \to \Upsilon\,\Upsilon) = 68.8 \pm 12.7\,(stat) \pm 7.4\,(syst)$ pb for $|y| < 2.0$ and $p_T^{\Upsilon} < 50$ 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?

Are there any narrow bound tetraquark states?

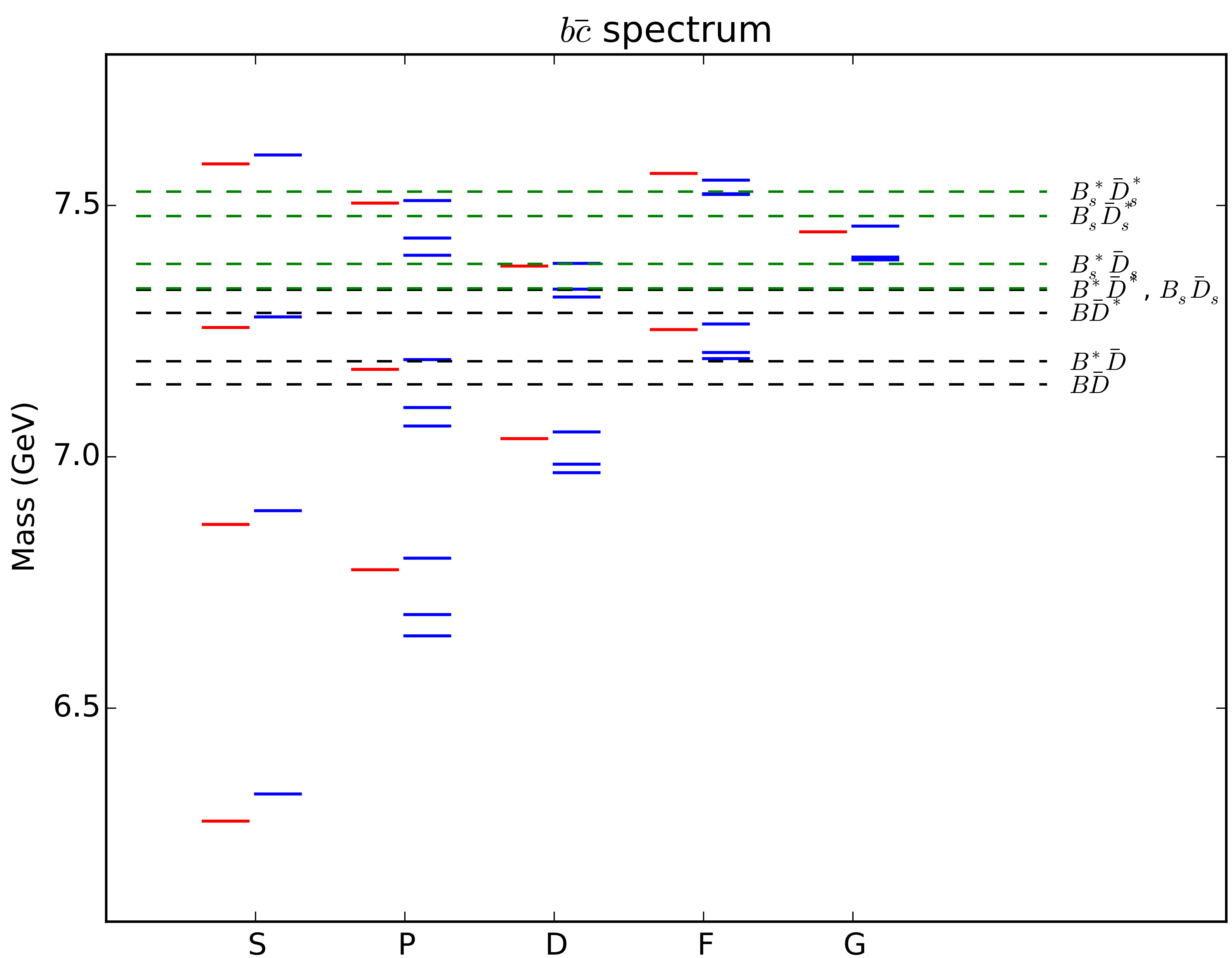
Thomas Britton: APS April meeting



Maksat Haymyradov: APS April meeting



- 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 only heavy-heavy meson that only has weak decays.
- Many opportunities to study CKM and BSM physics.

TABLE XI: Branching ratios of exclusive B_c^+ decays at the fixed choice of factors: $a_1^c = 1.20$ and $a_2^c = -0.317$ in the non-leptonic decays of c quark, and $a_1^b = 1.14$ and $a_2^b = -0.20$ in the non-leptonic decays of $\bar{b}$ quark. The lifetime of B_c is appropriately normalized by $\tau[B_c] \approx 0.45$ ps.

Mode	BR, %	Mode	BR, %	Mode	BR, %
$B_c^+ \to \eta_c e^+ \nu$	0.75	$B_c^+ \to J/\psi K^+$	0.011	$B_c^+ \to B_s^0 K^+$	1.06
$B_c^+ \to \eta_c \tau^+ \nu$	0.23	$B_c \to J/\psi K^{*+}$	0.022	$B_c^+ \to B_s^{*0} K^+$	0.37
$B_c^+ \to \eta_c' e^+ \nu$	0.020	$B_c^+ \to D^+ \overline{D}^0$	0.0053	$B_c^+ \to B_s^0 K^{*+}$	–
$B_c^+ \to \eta_c' \tau^+ \nu$	0.0016	$B_c^+ \to D^+ \overline{D}^{*0}$	0.0075	$B_c^+ \to B_s^{*0} K^{*+}$	–
$B_c^+ \to J/\psi e^+ \nu$	1.9	$B_c^+ \to D^{*+} \overline{D}^0$	0.0049	$B_c^+ \to B^0 \pi^+$	1.06
$B_c^+ \to J/\psi \tau^+ \nu$	0.48	$B_c^+ \to D^{*+} \overline{D}^{*0}$	0.033	$B_c^+ \to B^0 \rho^+$	0.96
$B_c^+ \to \psi' e^+ \nu$	0.094	$B_c^+ \to D_s^+ \overline{D}^0$	0.00048	$B_c^+ \to B^{*0} \pi^+$	0.95
$B_c^+ \to \psi' \tau^+ \nu$	0.008	$B_c^+ \to D_s^+ \overline{D}^{*0}$	0.00071	$B_c^+ \to B^{*0} \rho^+$	2.57
$B_c^+ \to D^0 e^+ \nu$	0.004	$B_c^+ \to D_s^{*+} \overline{D}^0$	0.00045	$B_c^+ \to B^0 K^+$	0.07
$B_c^+ \to D^0 \tau^+ \nu$	0.002	$B_c^+ \to D_s^{*+} \overline{D}^{*0}$	0.0026	$B_c^+ \to B^0 K^{*+}$	0.015
$B_c^+ \to D^{*0} e^+ \nu$	0.018	$B_c^+ \to \eta_c D_s^+$	0.28	$B_c^+ \to B^{*0} K^+$	0.055
$B_c^+ \to D^{*0} \tau^+ \nu$	0.008	$B_c^+ \to \eta_c D_s^{*+}$	0.27	$B_c^+ \to B^{*0} K^{*+}$	0.058
$B_c^+ \to B_s^0 e^+ \nu$	4.03	$B_c^+ \to J/\psi D_s^+$	0.17	$B_c^+ \to B^+ \overline{K^0}$	1.98
$B_c^+ \to B_s^{*0} e^+ \nu$	5.06	$B_c^+ \to J/\psi D_s^{*+}$	0.67	$B_c^+ \to B^+ \overline{K^{*0}}$	0.43
$B_c^+ \to B^0 e^+ \nu$	0.34	$B_c^+ \to \eta_c D^+$	0.015	$B_c^+ \to B^{*+} \overline{K^0}$	1.60
$B_c^+ \to B^{*0} e^+ \nu$	0.58	$B_c^+ \to \eta_c D^{*+}$	0.010	$B_c^+ \to B^{*+} \overline{K^{*0}}$	1.67
$B_c^+ \to \eta_c \pi^+$	0.20	$B_c^+ \to J/\psi D^+$	0.009	$B_c^+ \to B^+ \pi^0$	0.037
$B_c^+ \to \eta_c \rho^+$	0.42	$B_c^+ \to J/\psi D^{*+}$	0.028	$B_c^+ \to B^+ \rho^0$	0.034
$B_c^+ \to J/\psi \pi^+$	0.13	$B_c^+ \to B_s^0 \pi^+$	16.4	$B_c^+ \to B^{*+} \pi^0$	0.033
$B_c^+ \to J/\psi \rho^+$	0.40	$B_c^+ \to B_s^0 \rho^+$	7.2	$B_c^+ \to B^{*+} \rho^0$	0.09
$B_c^+ \to \eta_c K^+$	0.013	$B_c^+ \to B_s^{*0} \pi^+$	6.5	$B_c^+ \to \tau^+ \nu_\tau$	1.6
$B_c^+ \to \eta_c K^{*+}$	0.020	$B_c^+ \to B_s^{*0} \rho^+$	20.2	$B_c^+ \to c\bar{s}$	4.9

First lattice calculations
Bc -> η_c and Bc -> J/ψ
weak form factors.

A. Lytle, B. Colquhoun, C. Davies, J. Koponen [arXiv:1605.05645]

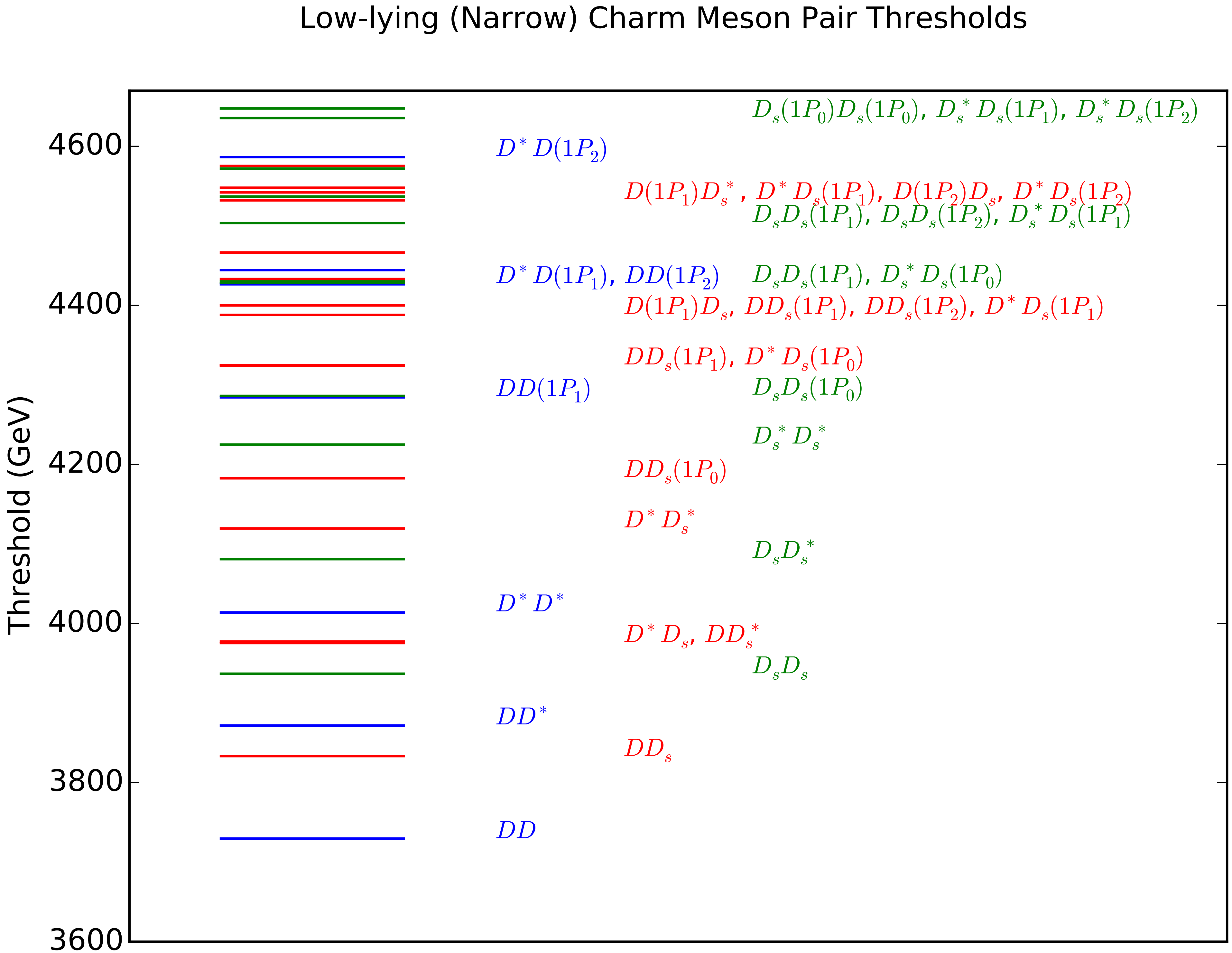
- Double heavy baryons - (ccq), (cbq), (bbq). Both HQET and NRQCD play a role in the excitation spectra of these states.
  - double expansion
  - NRQCD for the two heavy quarks and HQET expansion for the heavy core (QQ) - light quark system.
  - In leading order in $1/m_Q$: Excitation spectrum for the light quark is same as for heavy-light mesons (HQET)

Conclusions

- Heavy quark states are ideal systems to study QCD strong dynamics.
- Observation of $j_l^P=\frac{1}{2}^+$ $B_s(1P)$ states and their decays will help distinguish models of heavy-light dynamics.
- Narrow quarkonium states below threshold allow precision studies of the non-relativistic limit of QCD. Lattice QCD and the non-relativistic expansion provides a detailed picture of these states.
- In the threshold region for decays to open heavy flavor states QCD dynamics is more complicated. There have been many surprises and a still incomplete picture of the dynamics:
  - Large hadronic transition rates. New transition contributions with two open flavor intermediate states.
  - Large violations of heavy quark spin symmetry and SU(3) expectations. Likely induced by the symmetry breaking of the heavy-light mesons masses coupled to the rapid energy variation of the decay amplitudes.
  - New states with additional degrees of freedom: Threshold effects, hybrid states, tetraquarks, pentaquark provide a multitude of possibilities. More clues from BESIII, Belle2, LHCb, PANDA,… coupled with Lattice QCD calculations are needed.
- Many heavy quark systems remain essentially unexplored; more surprises may await.

BACKUP SLIDES

Low-lying thresholds



Narrow-Wide Thresholds

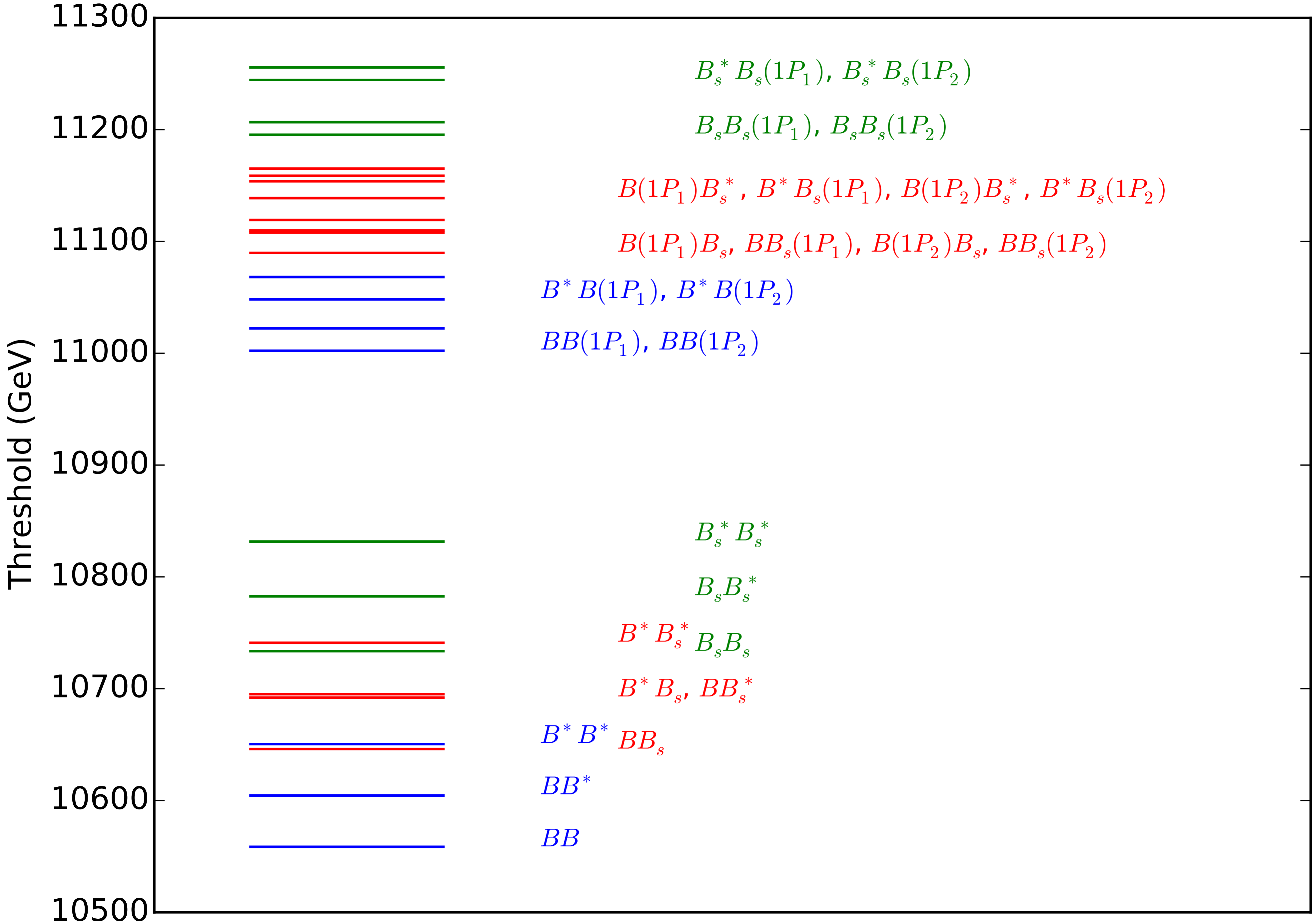
D_s^* $D(P_1)$

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

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

D $D(P_0)$

Low-lying (Narrow) Bottom Meson Pair Thresholds



Narrow-Wide Thresholds

B_s* $B(P_1)$

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

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

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

B $B(P_0)$

- All the X states above threshold