Теория Тяжелого Кваркония

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ITEP

Сессия-конференция секции ядерной физики ОФН РАН
5-8 ноября 2013 г.

Theory $\equiv$ QCD

$$\mathcal{L}_{QCD} = \sum_q \bar{q}(i\gamma_\mu D^\mu - m_q)q - \frac{1}{4}G^{\mu\nu}G_{\mu\nu}$$

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Heavy Quarks

$$m_Q \gg \Lambda_{QCD}$$

Quark Model

$$H = 2m_Q + \frac{p^2}{m_Q} + V$$

$$V = -\frac{4\alpha_s}{3r} + \sigma r + V_{SS} + V_{LS} + V_T$$

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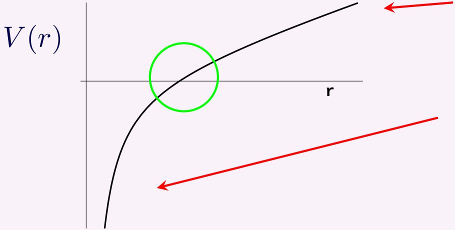

linear confinement $\sigma \approx 0.18$ GeV^2

OGE $\alpha_s \approx 0.35$

What is missed:

Degrees of freedom which are frozen in quark models

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Degrees of freedom which are frozen in quark models

- Constituent glue
- Light quarks: loops and thresholds
- Light quarks: pions

Lattice

Charmonium on the Lattice

Liu *et al*

- Extensive set of excited states, including exotics
- Dynamical unquenched u-, d- and s-quarks
- Anisotropic: $a_s/a_t \approx 3.5$
- Two volumes: 16^3, 24^3
- $M_\pi \approx 400$ MeV
- Large number of different structures, including gluonic excitatons

Non-exotic quantum numbers

J^{PC}	M (MeV)					
0^{-+}		3647	4127	4195		
exp		3639				
1^{--}	3064	3682	3824	4138	4285	4323
exp	3097	3636	3773	4153	4260	4361
2^{-+}	3844	4318	4334			
0^{++}	3446	3956	4345	4472		
exp	3415	3918				
1^{+-}	3518	3990	4344	4446	4477	4497
exp	3525					
1^{++}	3506	3986	4399	4468		
exp	3511					
2^{++}	3538	4025	4096	4492		
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In red: non-exotic hybrids

Hybrids

J^{PC}	M (MeV	
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Lightest hybrid multiplet

$J^{PC} = (0,1,2)^{-+}$, $J^{PC} = 1^{--}$
$M \approx 4.2 - 4.3$ GeV
$M(0^{-+}) < M(1^{-+}) < M(1^{--}) < M(2^{-+})$

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Constituent gluon model: YuSK, Nefediev

$c\bar{c}$ pair with $L_{c\bar{c}} = 0$ spin-triplet/spin-singlet coupled to 1^{+-} (magnetic) gluon

Mixing with open charm states

Question: Is lattice suitable for open charm studies?
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With reservations: Open charm thresholds are higher in this simulation than in the real world

Loops

New Quarkonia and Relevant Thresholds

- $X(3872)$ — D^0D^{*0} 3872 MeV
- $Y(4260)$ — DD_1 4285 MeV
- $Y(4325)$ — D^*D_0 4360 MeV
- $\psi(4430)$ — D^*D_1 4430 MeV charged
- $Z_c(3900)$ — D^+D^- 3880 charged

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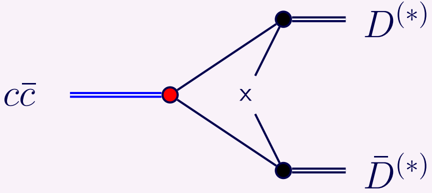
Threshold affinity could mean that the wave function contains large admixture of $D\bar{D}/B\bar{B}$ pairs

Coupled channels: $c\bar{c} \leftrightarrow D^{(*)}\bar{D}^{(*)}$



$\sim \langle c\bar{c}|\mathcal{O}|D^{(*)}\bar{D}^{(*)}\rangle$

$\mathcal{O} \Rightarrow$ operator of light quark pair creation

Coupled Channels

$$|\Psi\rangle = \begin{pmatrix} |Q\bar{Q}\rangle \\ |M_1 M_2\rangle \end{pmatrix}$$

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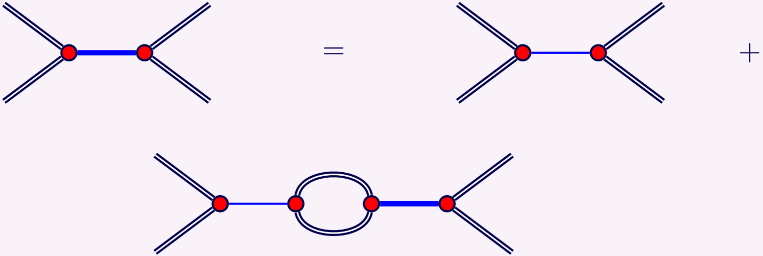

Loop Theorems

Barnes, Swanson

Loop effects are large, however, in the Heavy Quark limit:

- No splitting within N, L, S multiplets due to the loops
- No $J, L, S \leftrightarrow J, L', S'$ mixing due to the loops

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Violations arise from $(1/m_Q)^2$ effects: splittings within $c\bar{c}$ and open-charm meson multiplets

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$\Rightarrow$ Expect strong loop effects near thresholds

Baru *et al*

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"CC pole" (Coupled Channel pole Simonov)

Example: $X(3872)$

$$M_X = (3871.85 \pm 0.27 \pm 0.19)\ \text{MeV},$$

$$M_{D^0\bar{D}^{*0}} = 3871.81 \pm 0.36\ \text{MeV}.$$

$$Br(B^+ \to K^+X)Br(X \to J/\psi\pi^+\pi^-) = (8.63{\pm}0.82{\pm}0.52){\times}10^{-6}$$

$$Br(X \to J/\psi\pi^+\pi^-\pi^0)/Br(X \to J/\psi\pi^+\pi^-) = 0.8 \pm 0.3$$

no charged partners seen

$$Br(B^+ \to K^+X)Br(X \to D^{*0}\bar{D}^0) = (0.73 \pm 0.17 \pm 0.13) \times 10^{-4}.$$

$$J^{PC} = 1^{++}$$

$X(3872)$ as CC pole

Both 2^3P_1 and 2^1P_1 $c\bar{c}$ are near $D\bar{D}^*$ threshold

$$1^{++} \rightarrow \frac{1}{\sqrt{2}}(D\bar{D}^* + \bar{D}D^*)_{S-wave}$$

$$1^{+-} \rightarrow -\frac{1}{2}(D\bar{D}^* - \bar{D}D^*)_{S-wave} + \frac{1}{\sqrt{2}}(D^*\bar{D}^*)_{S-wave}$$

All the S-wave strength of the ${}^3P_1$ decay is concentrated in the $D\bar{D}^*$ channel, while in the ${}^1P_1$ decay it is shared equally between $D\bar{D}^*$ and $D^*\bar{D}^*$

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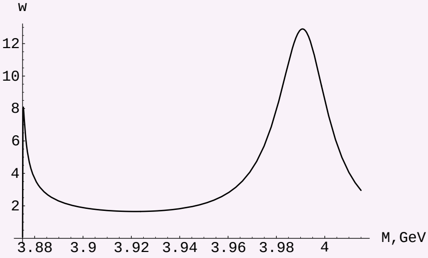
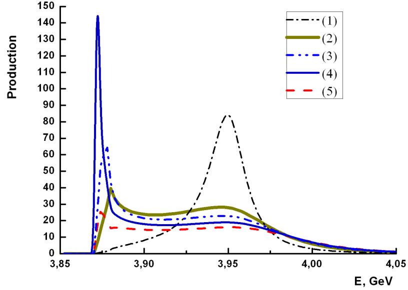
Expect large CC effects in the 1^{++} $c\bar{c} \leftrightarrow D\bar{D}^*$ channel

Results: Production Rate





$\mathcal{O} \Rightarrow {}^3P_0$ pair creation model

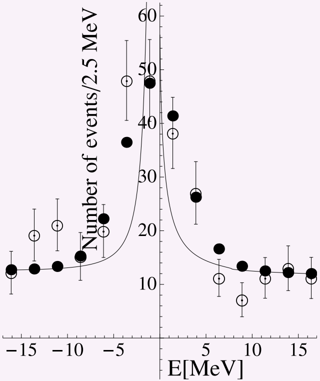
$\mathcal{O} \Rightarrow$ QCD calculations for string breaking

YuSK

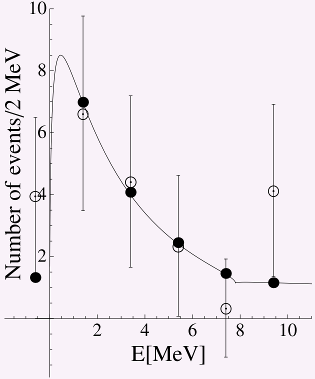
Danilkin Simonov

$X(3872)$ as coupled channel pole in $2^3P_1(c\bar{c}) \leftrightarrow D\bar{D}^*$ system

Coupled Channel fit to Belle data



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



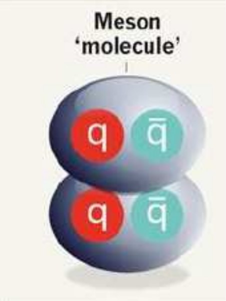
$D^0\bar{D}^0\pi^0$

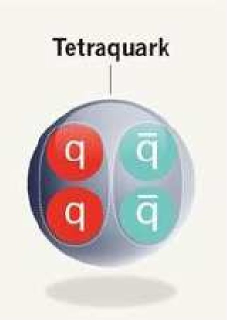
Probability to find 2^3P_1 $c\bar{c}$ in the X wave function: $\mathcal{Z} = 0.37$

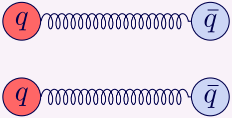
YuSK Nefediev

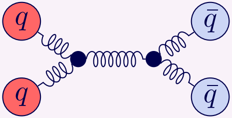
Models

Dynamically generated object *vs* compact tetraquark

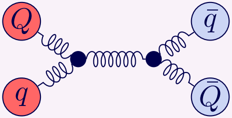








Tetraquarks



Tetraquark is not related to $B\bar{B}/D\bar{D}$ threshold

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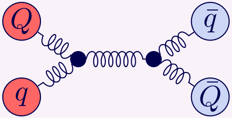

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Small coupling: narrow resonance,

$$\Gamma(B\bar{B}/D\bar{D}) \approx \Gamma(\Upsilon/\Psi \quad \pi)$$

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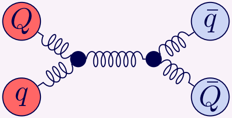

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Small coupling: narrow resonance,

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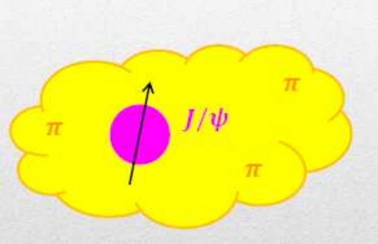
Large coupling: the state either disappears in mesonic continuum, or a CC pole is attracted by threshold, with large admixture of mesonic molecule in the state w.f.

Mesonic Molecules

- Genuine molecule is predominantly an S-wave $D\bar{D}/B\bar{B}$ state, bound or virtual
  It can be formed either by t-channel (e.g. OPE) exchange or s-channel exchange (CC pole)
- An S-wave molecule is not a resonance: there is no reasonable explanation for a potential barrier which form a resonance well above threshold (at least one unit of angular momentum is needed to provide a centrifugal barrier)
- As a bound/virtual state molecule does not decay into constituents
  What is called BF is production rate into mesonic final state
- Decay into $Q\bar{Q}$ + light mesons is suppresed as short-range one

Hadroquarkonium



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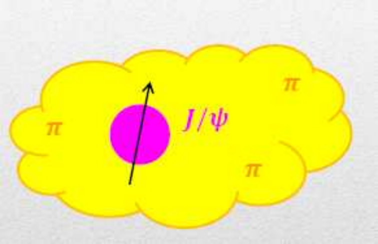

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Hadroquarkonium decays into $Q\bar{Q}$ + light mesons

- $\psi(4430) \to \pi^+\psi(2S)$
- $Z(4050) \to \pi^+\chi_{c1}(1P)$
- $Z(4250) \to \pi^+\chi_{c1}(1P)$

Voloshin

Charged States

Charged States

- $Z_b(10610), Z_b(10650) \to \Upsilon(nS)/h_b(mP)\pi$, $B\bar{B}^*$, $B^*\bar{B}^*$

- $Z_c(3900) \to J/\psi\pi$, $D^0 D^{*-}$, $h_c\pi$
- $Z_c(4020) \to h_c\pi$
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These are open flavour exotics

Summary on Z_b Belle

$Z_b(10610)$ $M_{Zb} - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV $\Gamma_{Zb} = 18.4 \pm 2.4$ MeV

$Z_b(10650)$ $M_{Zb'} - 2M_{B^*} = +1.8 \pm 1.7$ MeV $\Gamma_{Zb'} = 11.5 \pm 2.2$ MeV

Channel	BF[$Z_b(10610)$], %	BF[$Z_b(10650)$], %
$\Upsilon(1S)\pi^+$	0.3 ± 0.1	0.18 ± 0.05
$\Upsilon(2S)\pi^+$	4.4 ± 1.2	1.80 ± 0.47
$\Upsilon(3S)\pi^+$	2.2 ± 0.6	1.23 ± 0.30
$h_b(1P)\pi^+$	2.8 ± 1.1	5.6 ± 2.0
$h_b(2P)\pi^+$	4.3 ± 2.1	11.1 ± 4.7
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	25 ± 10
$B^{*+}\bar{B}^{*0}$	–	55.1 ± 5.3

arxiv:1209.6450

dominant

suppressed

despite much larger PHSP

6D amplitude analysis : $J^P = 1^+$

Krokovny Moriond QCD 2013

Molecular structure

⇐ masses at thresholds

⇐ $B\bar{B}^*$ and $B^*\bar{B}^*$ are in S-wave

⇐ decay pattern: $B^{(*)}\bar{B}^*$ dominate, h_b not suppressed

Z_bs and heavy quark limit

Belle has observed $Z_b(10605)$ and $Z_b(10650)$ both in

$$\Upsilon(5S) \to Z_b\pi \to \Upsilon(nS)\pi\pi, \quad n = 1, 2, 3$$

and

$$\Upsilon(5S) \to Z_b\pi \to h_b(nP)\pi\pi, \quad m = 1, 2$$

with approximately the same rate

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But

$$\Upsilon = 1^{--}, \quad S_{b\bar{b}} = 1$$

$$h_b = 1^{+-}, \quad S_{b\bar{b}} = 0$$

Spin-flip of heavy quark!

B-meson scenario

Bondar *et al*

Heavy quark spin content for $J^P = 1^+$:

$$B\bar{B}^* + c.c. \sim |S_{b\bar{b}} = 0\rangle + |S_{b\bar{b}} = 1\rangle$$

$$B^*\bar{B}^* \sim |S_{b\bar{b}} = 0\rangle - |S_{b\bar{b}} = 1\rangle$$

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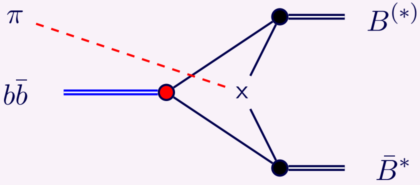
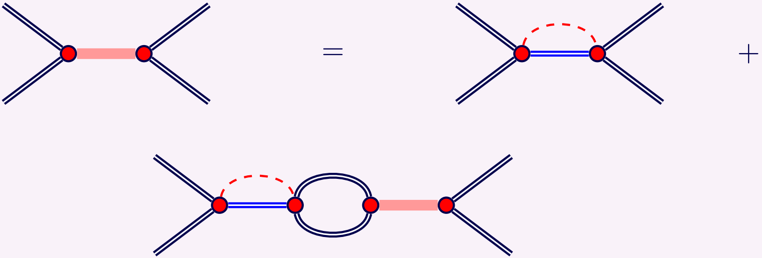
- Heavy quark limit is violated by hyperfine splitting between M_B and M_{B^*}
- $M(Z_b') - M(Z_b) \approx M(B^*) - M(B)$
- Z_b and Z_b' are made of BB^* and B^*B^* in S-wave

Z_bs as CC effect: string breaking with pion emission

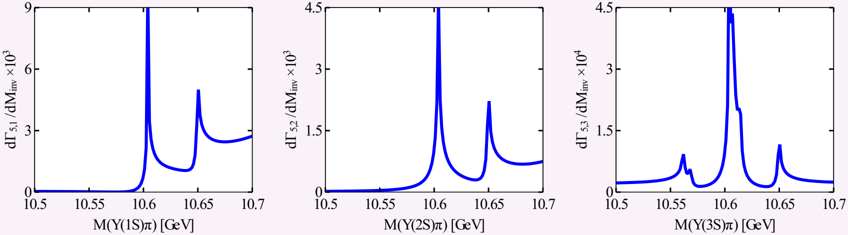


Simonov



$$\Upsilon(5S) \to Z_b\pi \to \Upsilon(nS)\pi\pi$$

Coupled Channels $B\bar{B}^* \leftrightarrow \Upsilon(nS)\pi \leftrightarrow B^*\bar{B}^*$



Danilkin Orlovsky Simonov

Z_c story

Charged molecules in $b\bar{b}$:

$Z_b(10610)$ @ $B\bar{B}^*$, $Z_b(10650)$ @ $B^*\bar{B}^*$

Z_c story

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Z_cs: charged molecules in $c\bar{c}$?

$Y(4260) \to \pi Z_c(3900)$

Belle, BESIII, Cleo-c:

$Z_c \to \pi J/\psi$

$$M = 3891.5 \pm 3.5 \quad MeV$$

$$M - M(DD^*) = 16 \quad MeV$$

BESIII:

$Z_c \to D^{*-}\bar{D}^0$, $Z_c \to h_c\pi$, $J^P = 1^+$

$$M = 3883.9 \pm 1.5 \pm 4.2 \quad MeV$$

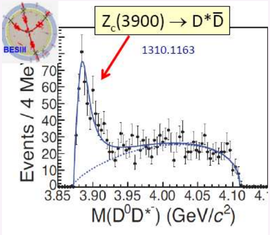
$$M - M(DD^*) = 9 \quad MeV$$

$Z_c(3900)$ is charmonium partner of $Z_b(10610)$?

If $Z_c \to DD^*$ is the same as $Z_c \to \pi J/\psi \quad \Rightarrow$

$$\frac{BF(DD^*)}{BF(\pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

Looks like DD^* molecule:

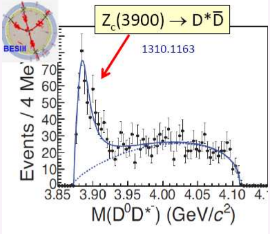


$Z_c(3900)$ is charmonium partner of $Z_b(10610)$?

If $Z_c \to DD^*$ is the same as $Z_c \to \pi J/\psi \quad \Rightarrow$

$$\frac{BF(DD^*)}{BF(\pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

Looks like DD^* molecule:



- **Peak lies too high above threshold**
- **Peak in the inelastic $\pi J/\psi$ channel is higher than in DD^***
- $Z_c(3900) \to \pi h_c$ **is small**
- **Where is Z_c'?**

$Z_c(4020)/Z_c(4025)$ @ $D^*\bar{D}^*$ threshold

BESIII:

$Z_c(4025) \to (D^*\bar{D}^*)^+$

$M = 4026.3 \pm 4.5$ MeV
$\Gamma = 24.8 \pm 9.5$ MeV
$\sigma \times BF = 89 \pm 19$ pb

$Z_c(4020) \to \pi h_c$

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Problems with $h_c\pi\pi$ Dalitz plot $\to$ $J^P \neq 1^+$?
Is there a resonance in $D^*\bar{D}^*$?
Not a Z_b' partner...

$Y(4260) \to Z_c\pi$

- $Z_c(3900)$ is seen in $Y(4260) \to \pi\pi J/\psi$
- $Y(4260)$ is unusual $c\bar{c}$ vector (large $\pi^+\pi^-\psi(nS)$)
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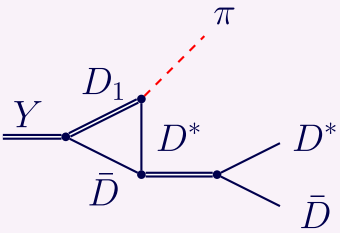
- $Y(4260)$ is a $D_1\bar{D}$ molecule

$Y(4260) \to \pi D^*\bar{D}$



No $D^*\bar{D}^*$ pairs

$\Rightarrow$ no Z_c'

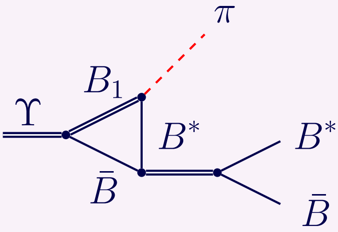
Wang, Hanhart, Zhao

$\Upsilon(5S) \to Z_b\pi$

$\Upsilon(5S)$ is a $B_1\bar{B}$ molecule?

Too deeply bound: $\epsilon_B = 120$ MeV?

$\Upsilon(5S) \to \pi B^*\bar{B}$



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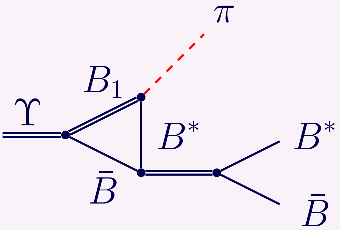

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Summary

Quarkonia above open-flavour threshold: more questions than answers

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Each exotic state seems to be unique

Heavy Quark symmetry could be misleading, and (at least some) dynamical input is needed to resolve the case

In particular, the role of open charm/beauty thresholds is to be understood