XYZ twenty years later:
the known and the unknown

Chair: N. Brambilla

Panel Members: E. Eichten, T. Mehen, R. Mussa, M. Oka, C. Thomas, B. Yabsley

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Q9: How could the synergy between experiments, lattice QCD, EFTs and models be improved in the quest for a general understanding of the XYZ states?

Q1: After 20 years is there a minimal agreement about the nature of the X(3872)?

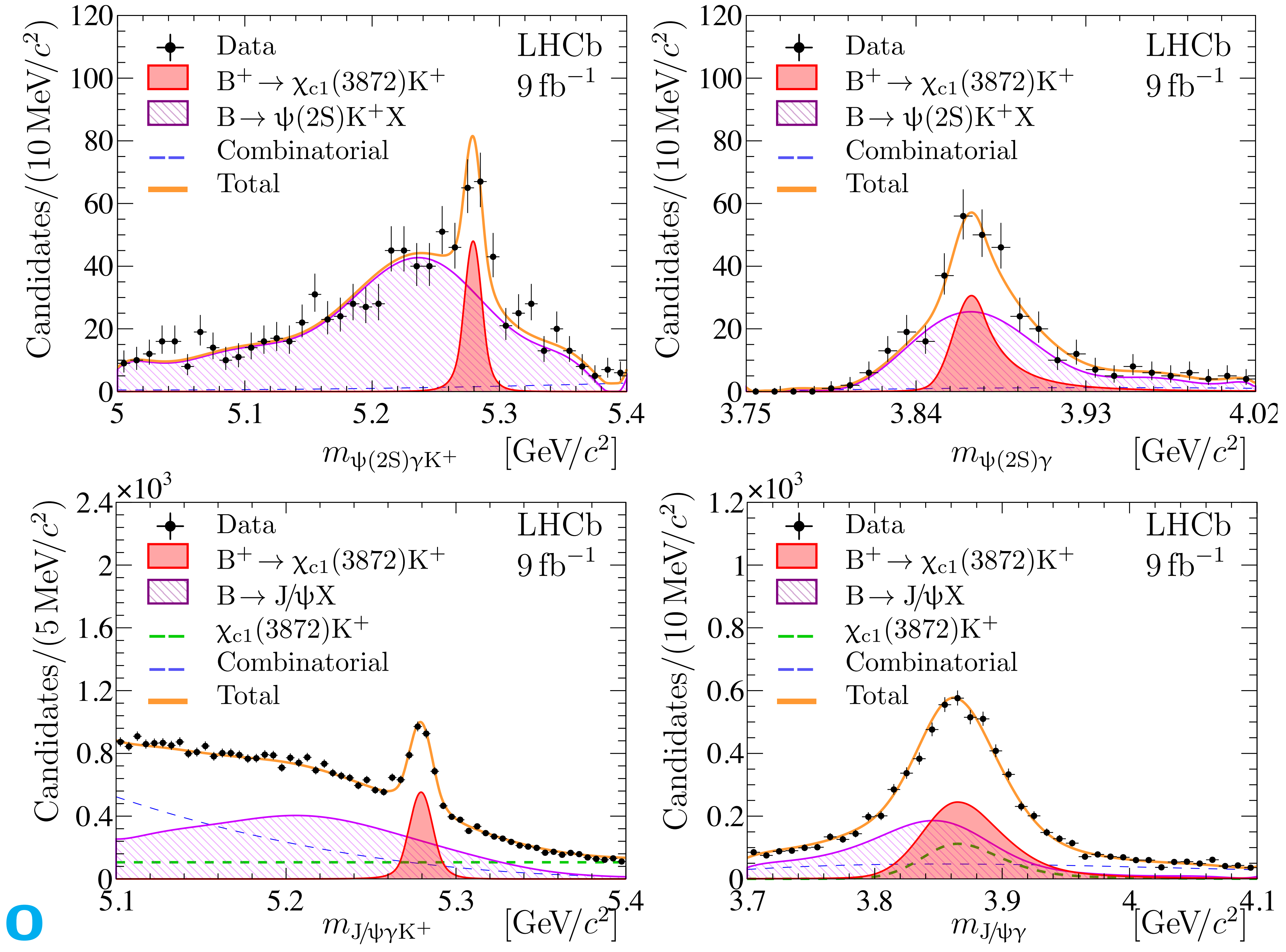
Is there minimal agreement about the nature of the $X(3872)$?

LHCb (2406.17006) has resolved any remaining question about the $\gamma\psi(2S)$ decay:

- $\Gamma_{\gamma\psi'}/\Gamma_{\gamma\psi} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$
- inconsistent with naïve/vanilla $D^*\overline{D} + D\overline{D}^*$ molecular state

But this fits into a longstanding story:

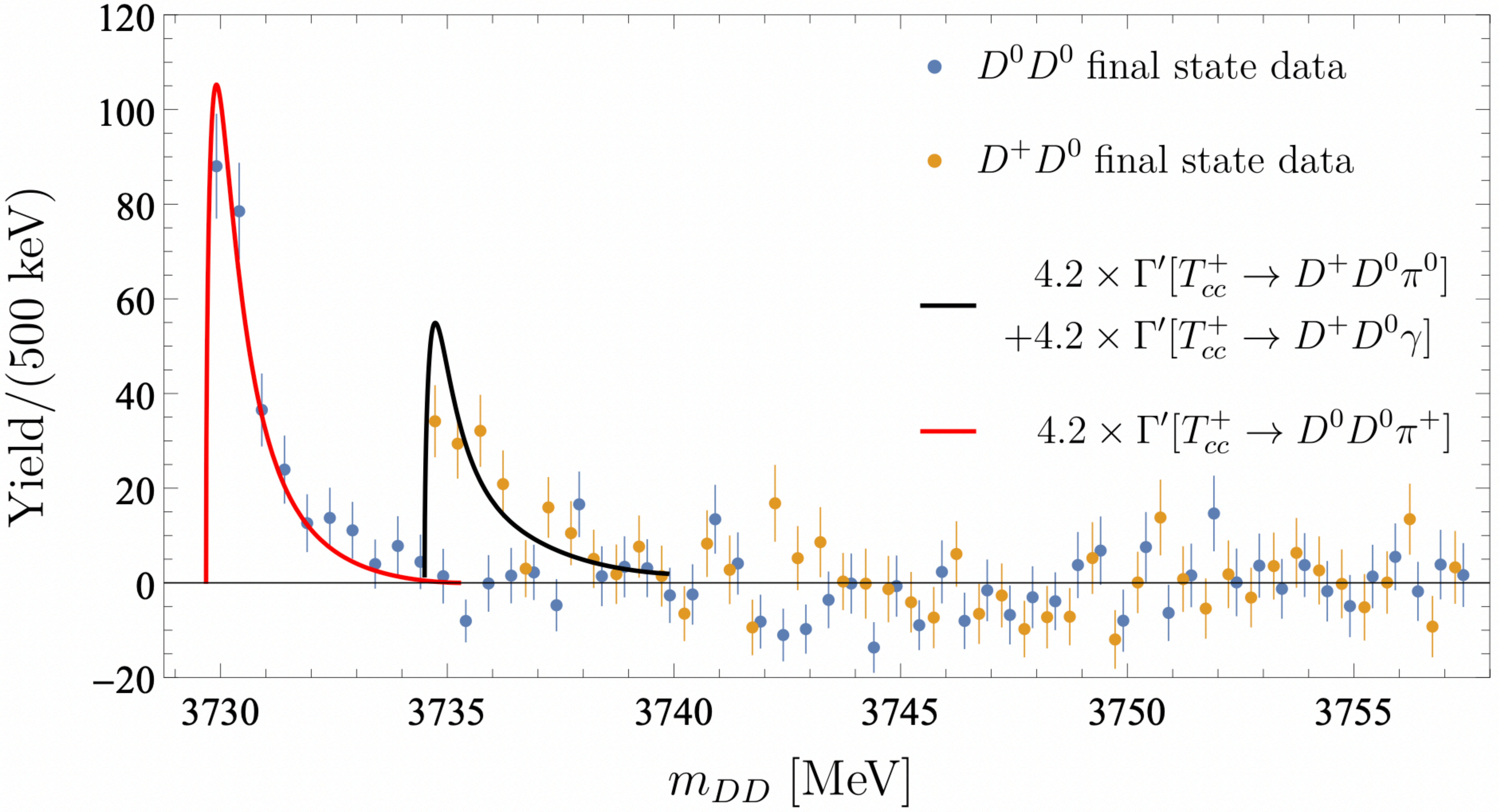
- **pro: $D^*\overline{D}$ threshold, 1^{++}, I violation, $D\overline{D}\pi^0$ coupling . . .**
- **con: $\gamma\psi^{(\prime)}$, hadronic prod^n, . . .**
- $|\text{mol}\rangle \cos\theta + |c\bar{c}\rangle \sin\theta$ is naïve too



- since Kalashnikova (*PRD* **72** (2005) 034010), we have u'stood that the 3872 might *start out* as $c\bar{c}$, but manifest at threshold; some lattice support . . .
- $\exists$ schemes (*e.g.* B-O) that unify different structures as limiting cases
- but what do we *call* the 3872 in a textbook? after all these measurements? what should experiments look for next *to add value*?

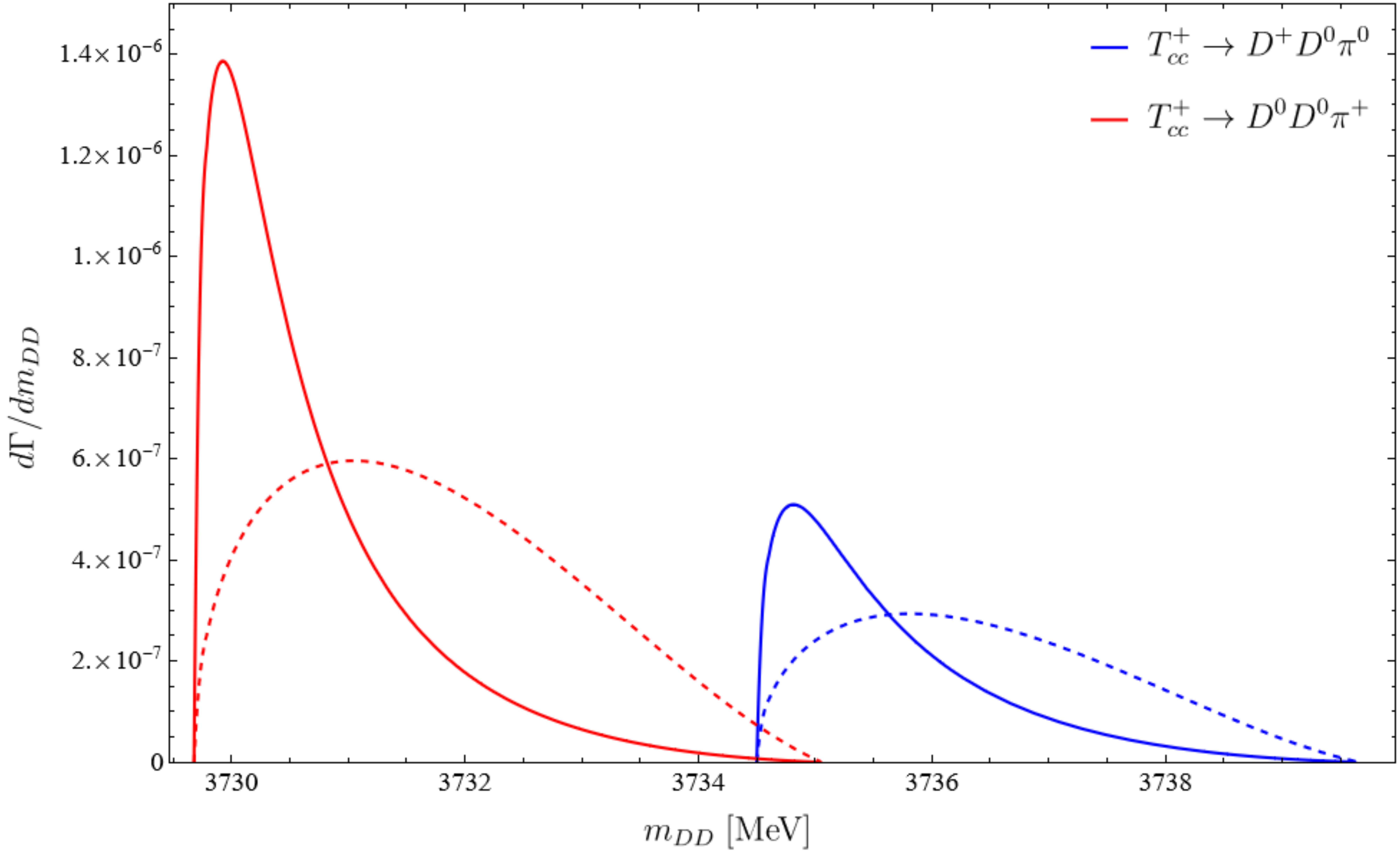
Tom

$d\Gamma/dm_{DD}$ vs. data



correctly predict total width: $\Gamma[T_{cc}^+] = 47\,\text{keV}$ vs. $\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\,\text{keV}$

Tom

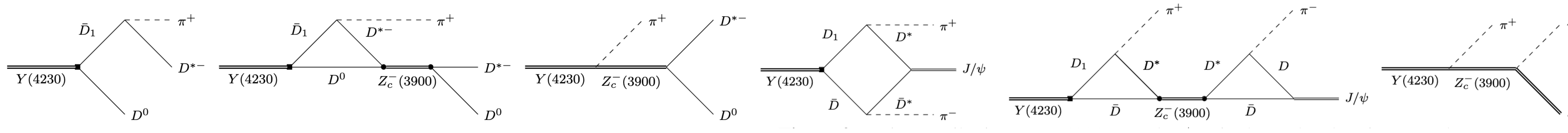


comparison with p_{π}^{2} $\times$ phase space (dashed)

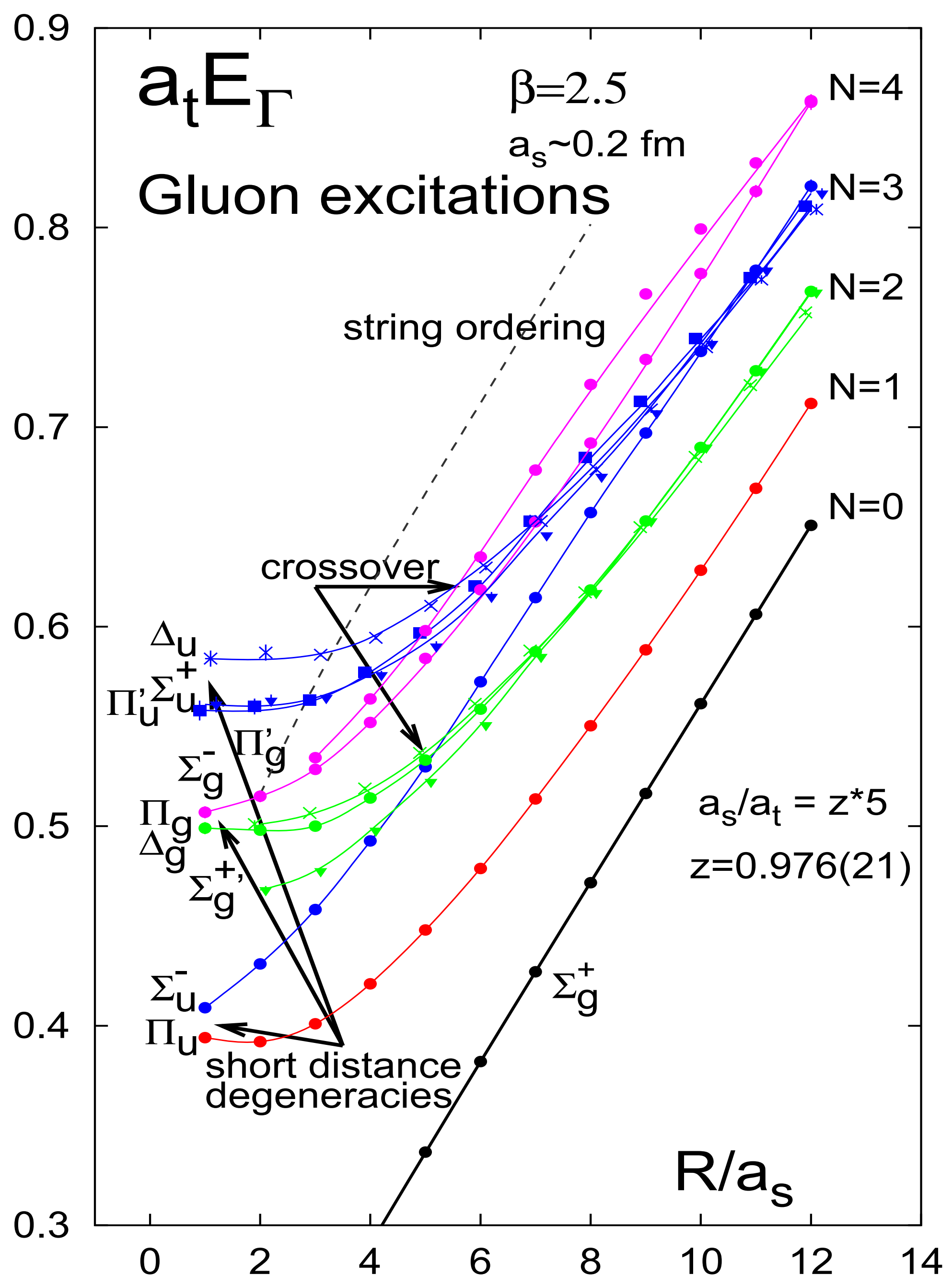
Q2: Is there a favourite molecular/hybrids/compact tetraquark candidate? What are the most unambiguous experimental signatures in the three cases

Estia

- For me the Y(4230) state is the most interesting. It is a natural candidate for a quarkonium hybrid.
- Consider QCD without light quarks. We know from lattice QCD that there must states with excitations of the gluo degrees of freedom. Will be smaller contributions to R because not allowed in lowest order in $\alpha_s(Q^2)$
- The 1^{--} state (Π_u/Σ_u^-) with a mass in the 4.2-4.3 GeV region. Associated with I=1 triplet: $(0,1,2)^{-+}$
- Decay -> $\bar{D}D_1(2420)$. Same as molecular state, but provides the binding core like the X(3872) case.
- Recent analysis of final states from $\bar{D}D_1(2420)$: Detten, Hanhart, Baru : ArXiv: 2309.11970



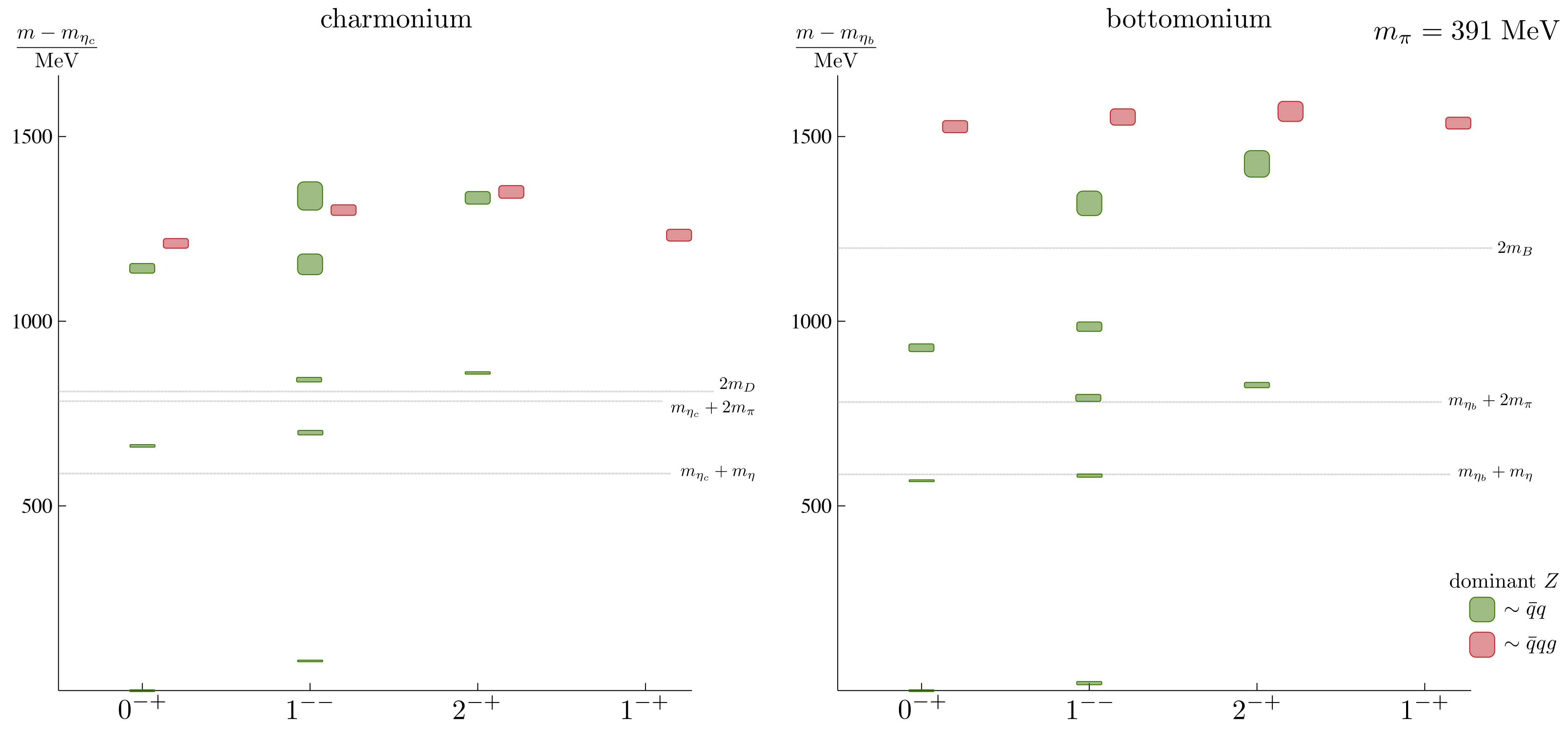
- Also a near point like contribution from $\bar{D}D_1(2430)$



Final State	Width D_P (MeV)	Partial Wave	Threshold (GeV)
$\bar{D}(1865)D_{P_1}(2430)(j=1/2)$	314	S-wave	4.295 ←
$\bar{D}^*(2007)D_{P_0}(2300)(j=1/2)$	229	S-wave	4.307
$\bar{D}^*(2007)D_{P_1}(2430)(j=1/2)$	314	S-wave	4.437
$\bar{D}(1865)D_{P_2}(2461)(j=3/2)$	47.3	D-wave	4.326
$\bar{D}(1865)D_{P_1}(2422)(j=3/2)$	31.3	D-wave	4.287 ←
$\bar{D}^*(2007)D_{P_1}(2422)(j=3/2)$	31.3	D-wave	4.429
$\bar{D}^*(2007)D_{P_2}(2461)(j=3/2)$	47.3	D-wave	4.468

	$c\bar{c}$	$b\bar{b}$
$H_{1/2}$	4.246	10.864
H_3	4.566	11.097
$H_{4/5}$	4.428	10.964
$H'_{1/2}$	4.596	11.071

BOEFT
Braaten, Langmack, Smith PRL 112, 222001,(2014)



Ryan and Wilson JHEP 02 (2021) 214

- In the BbarB system, very likely the hybrid state will be below the B B_P thresholds.

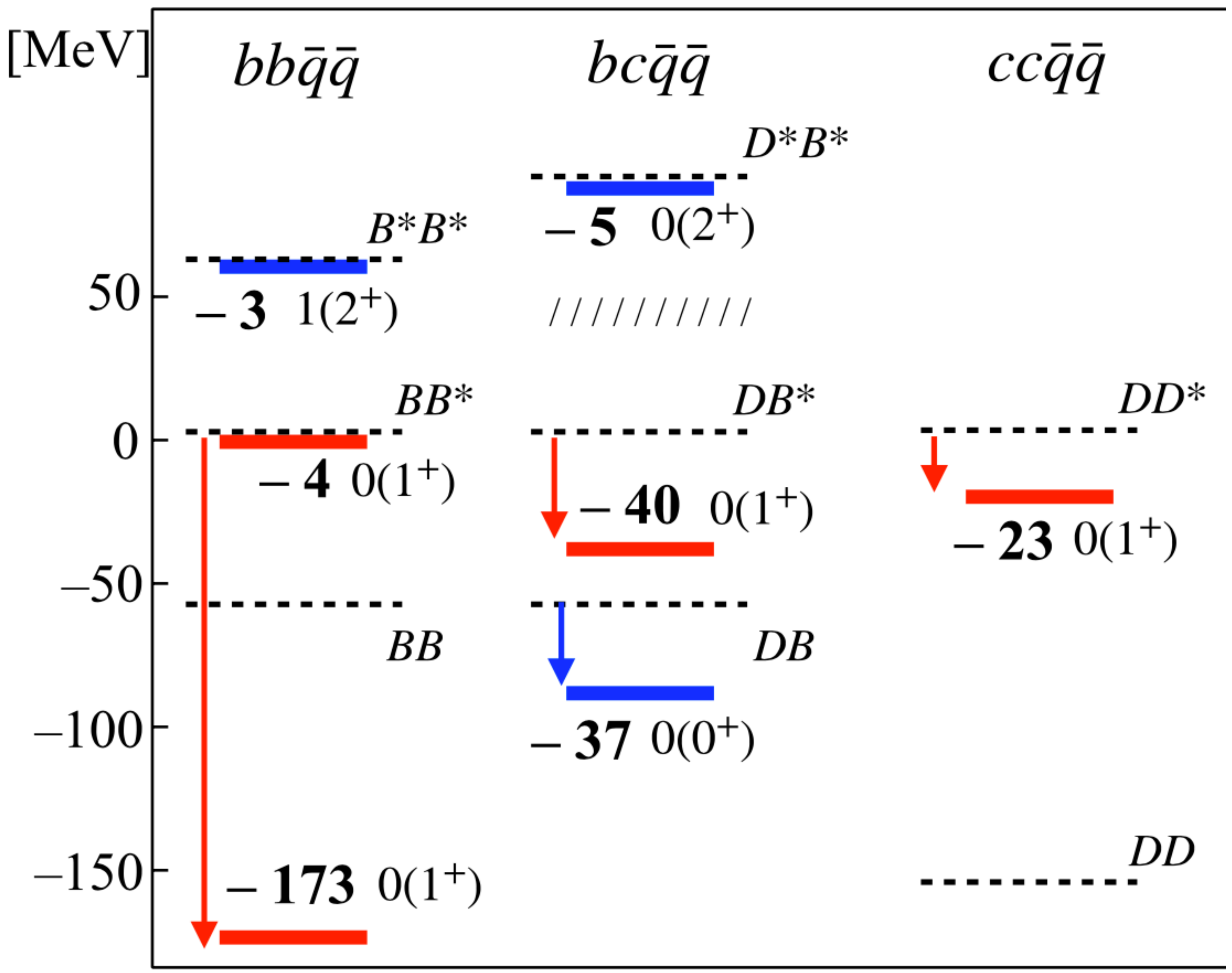
Belle: Y(10.75) GeV in $e^+e^- \to Y(nS)\pi^+\pi^-(n=1,2,3)$ Hybrid

Makoto

$T_{\bar{b}\bar{b}}(J^P = 1^+, I = 0) = (bb\bar{u}\bar{d})$ **will be most significant, as it is predicted to be deeply bound below the lowest threshold, $\bar{B}\bar{B}$, decaying only by the weak interaction. The binding energy predicted is around 150-200 MeV below the $\bar{B}\bar{B}^*$ threshold.**

4-body quark model calculation

Q. Meng et al., Phys.Lett. B 814 (2021) 136095



	$I(J^P)$	This work	[22]	[23]	[24]	[25]
$bb\bar{q}\bar{q}$	$0(1^+)$	-173	-189 ± 13	-143 ± 34	–	-186 ± 15
$bc\bar{q}\bar{q}$	$0(1^+)$	-40	–	–	13 ± 3	–
$cc\bar{q}\bar{q}$	$0(1^+)$	-23	–	-23 ± 11	–	–
$bs\bar{q}\bar{q}$	$0(1^+)$	-5	–	–	16 ± 2	–
$bb\bar{s}\bar{q}$	$\frac{1}{2}(1^+)$	-59	-98 ± 10	-87 ± 32	–	–
$bb\bar{q}\bar{q}$	$1(0^+)$	N	–	-5 ± 18	–	–
$bc\bar{q}\bar{q}$	$0(0^+)$	-37	–	–	17 ± 3	–
$cc\bar{q}\bar{q}$	$1(0^+)$	N	–	26 ± 11	–	–
$bs\bar{q}\bar{q}$	$0(0^+)$	-7	–	–	18 ± 2	–

Lattice QCD predictions

[22] A. Francis, R. J. Hudspith, R. Lewis and K. Maltman, Phys. Rev. Lett. **118**, no.14, 142001 (2017) doi:10.1103/PhysRevLett.118.142001 [arXiv:1607.05214 [hep-lat]].

[23] P. Junnarkar, N. Mathur and M. Padmanath, Phys. Rev. D **99**, no.3, 034507 (2019) doi:10.1103/PhysRevD.99.034507 [arXiv:1810.12285 [hep-lat]].

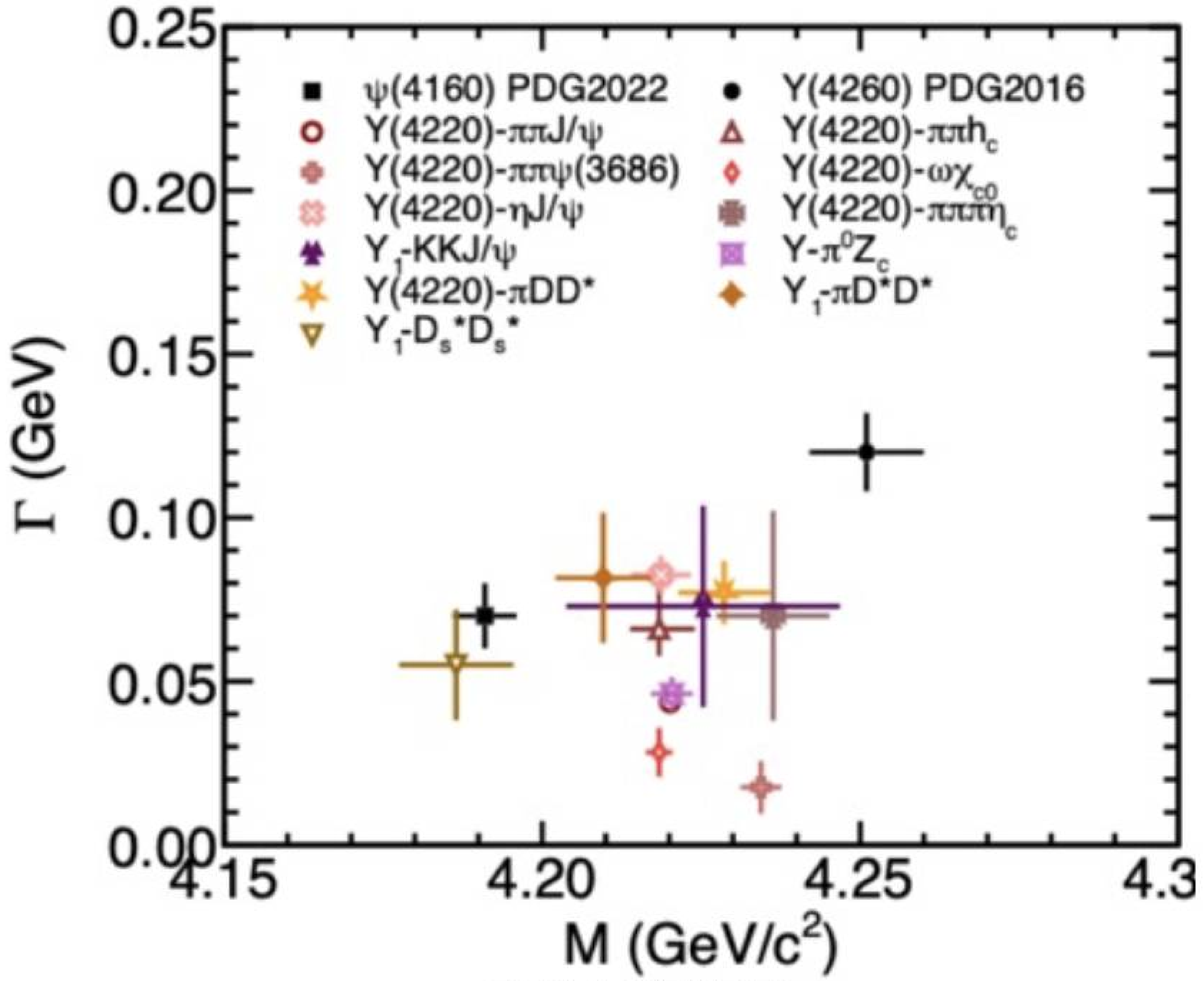
[24] R. J. Hudspith, B. Colquhoun, A. Francis, R. Lewis and K. Maltman, [arXiv:2006.14294 [hep-lat]].

[25] P. Mohanta and S. Basak, [arXiv:2008.11146 [hep-lat]].

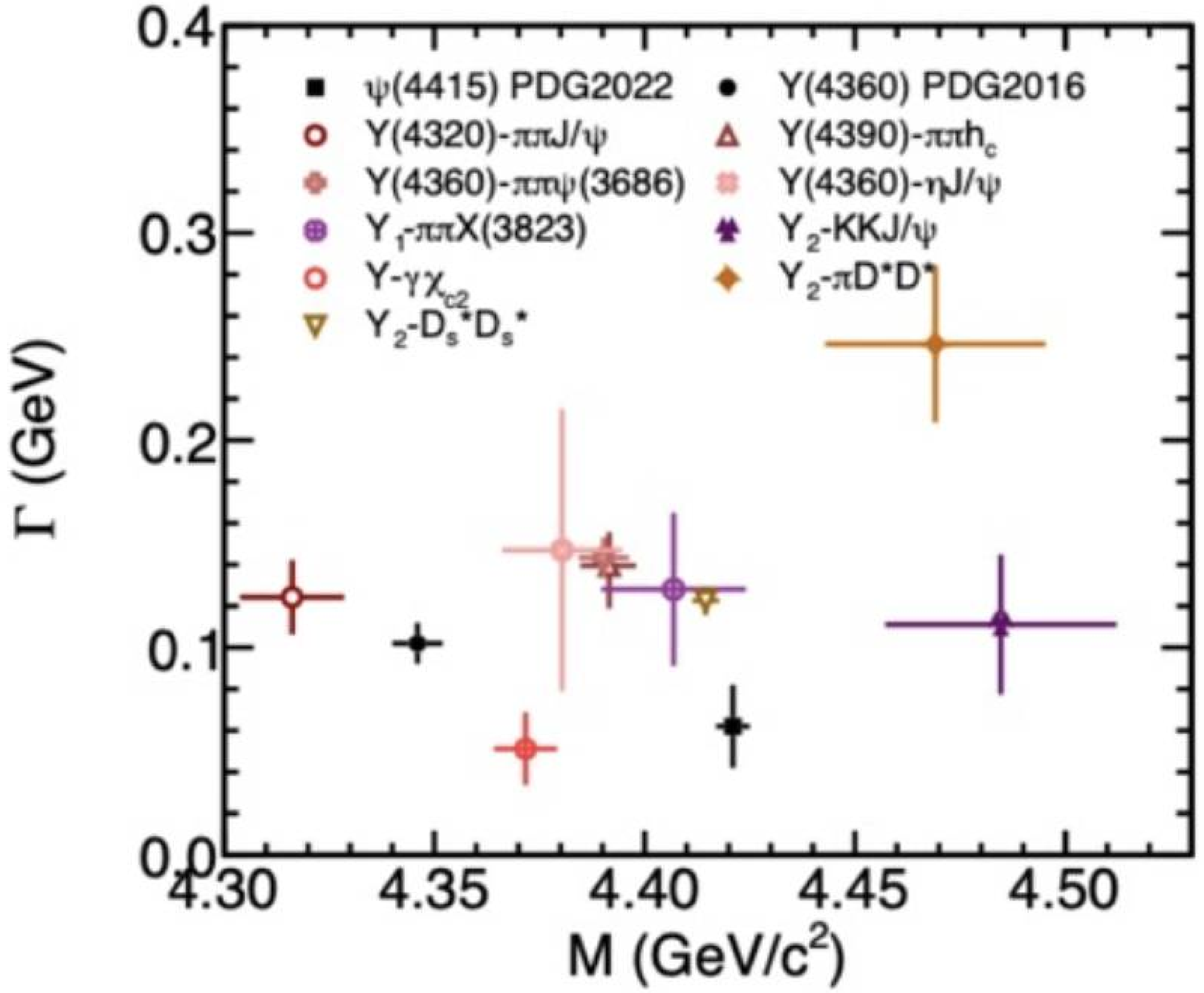
Q3: What old/new experimental signatures could give more insight in the nature of the exotics?

Roberto

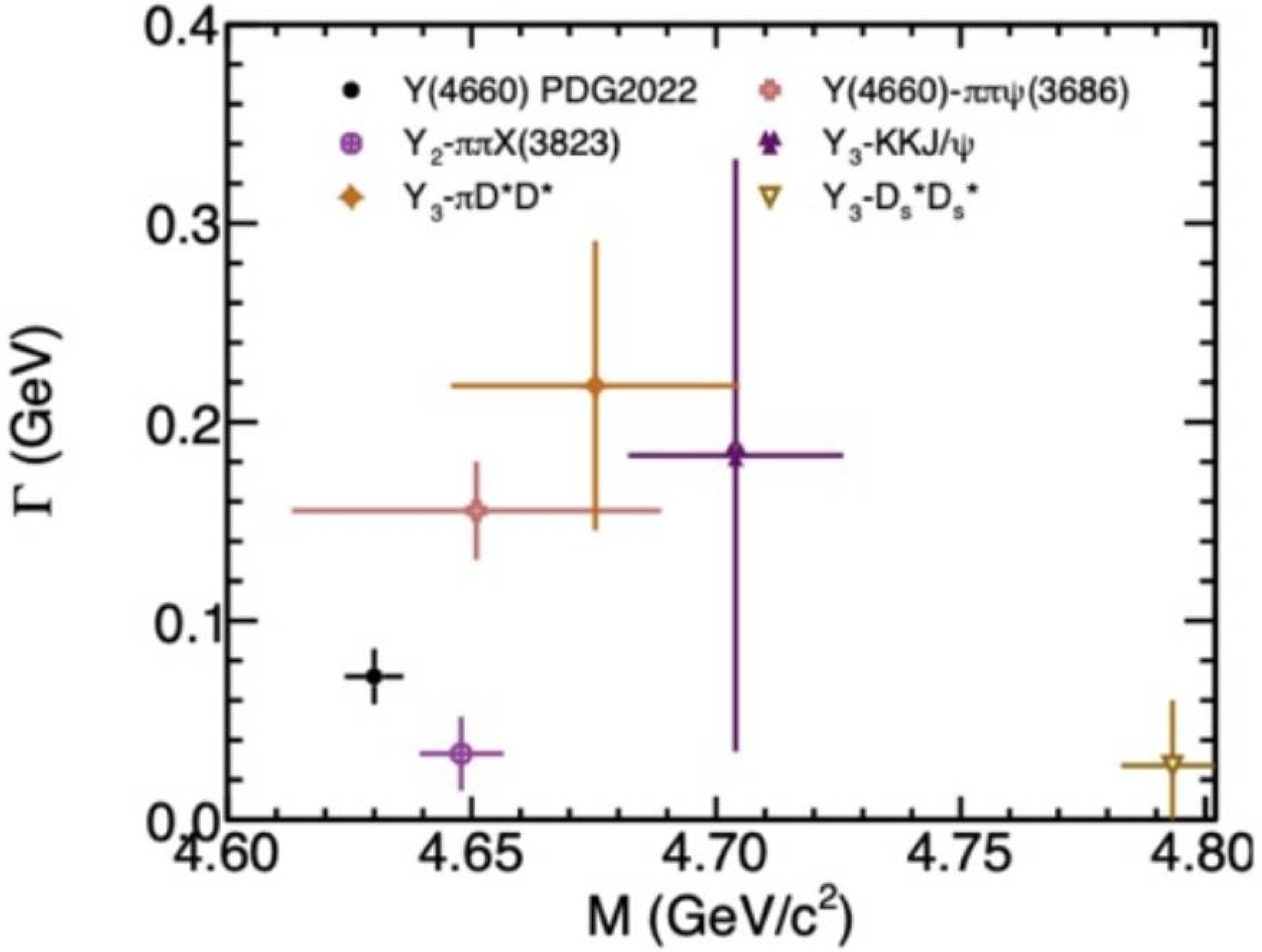
The vector $c\bar{c}$ exotica: it all started with Y(4260) …. after 20 years we have this:



Y(42XX)



Y(43XX), ψ(4415), Y(4500)



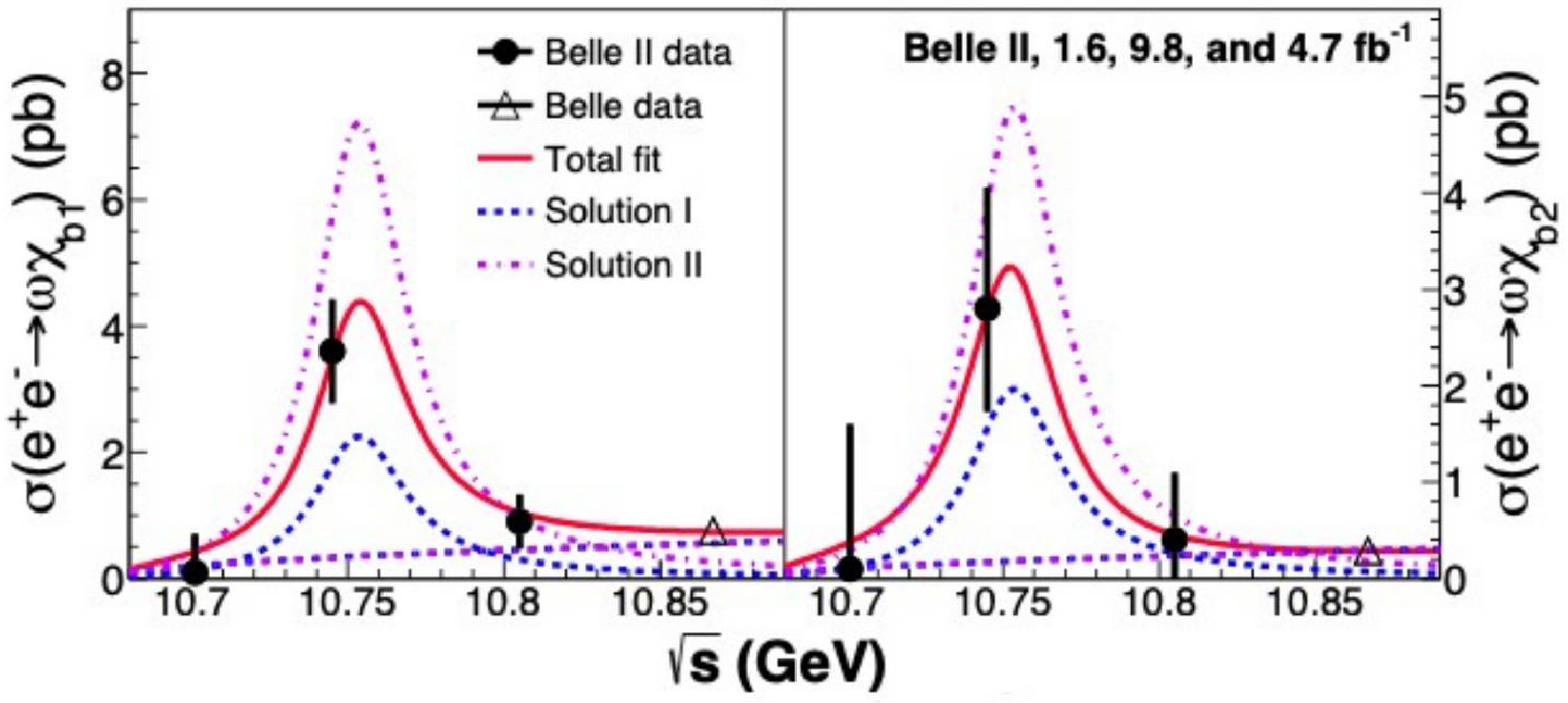
Y(46XX), Y(47XX)

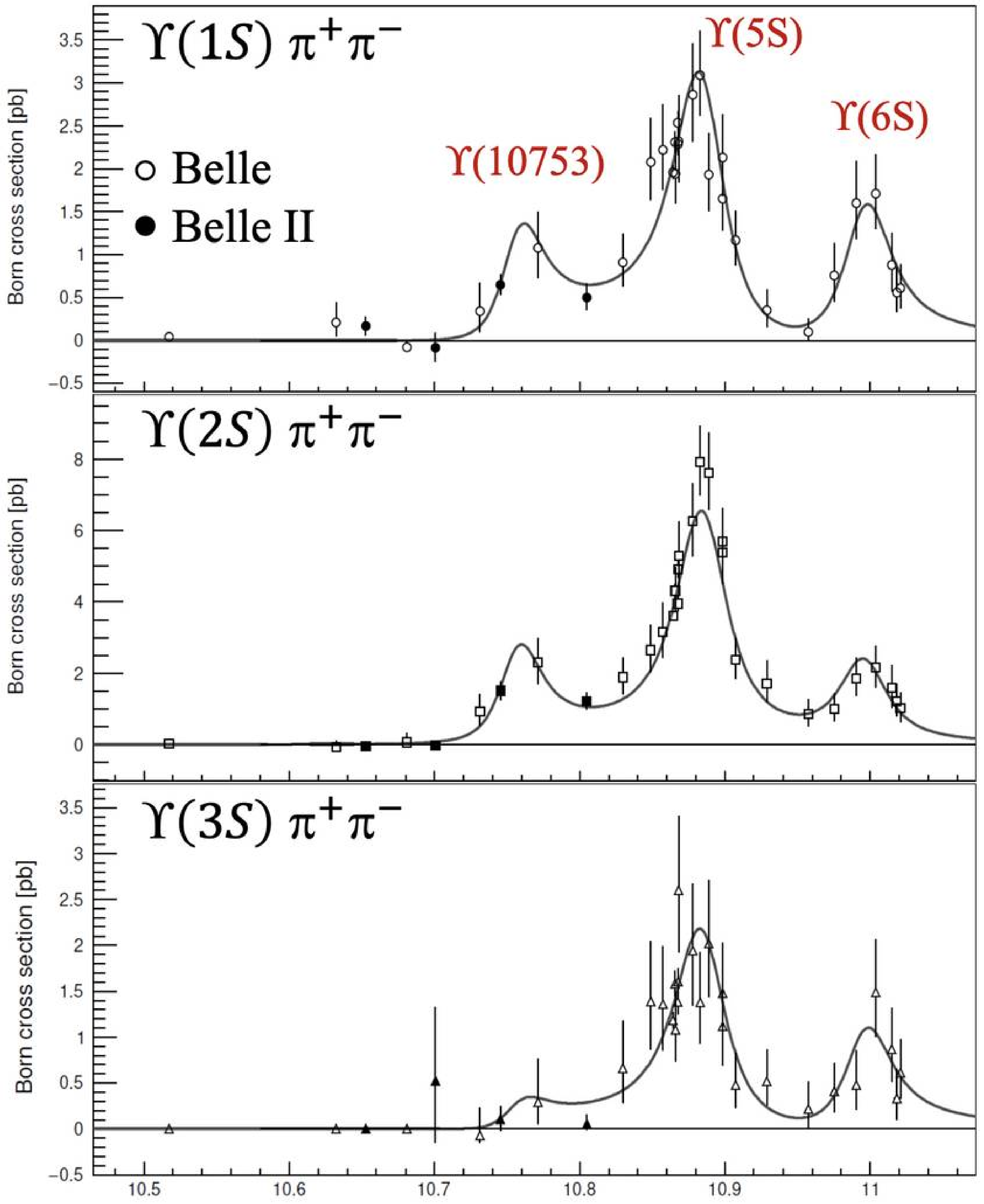
We have one production mechanism, J^{PC} fixed, and compare many decay modes.

- clear tension between the results: too simple parametrizations? Interference not properly accounted for?
- can a coupled channel analysis with global fit help understanding this landscape?

Roberto

In $b\bar{b}$ the ϒ(5S) showed its exotic nature in Belle, where we learned about the Y(10750) ….





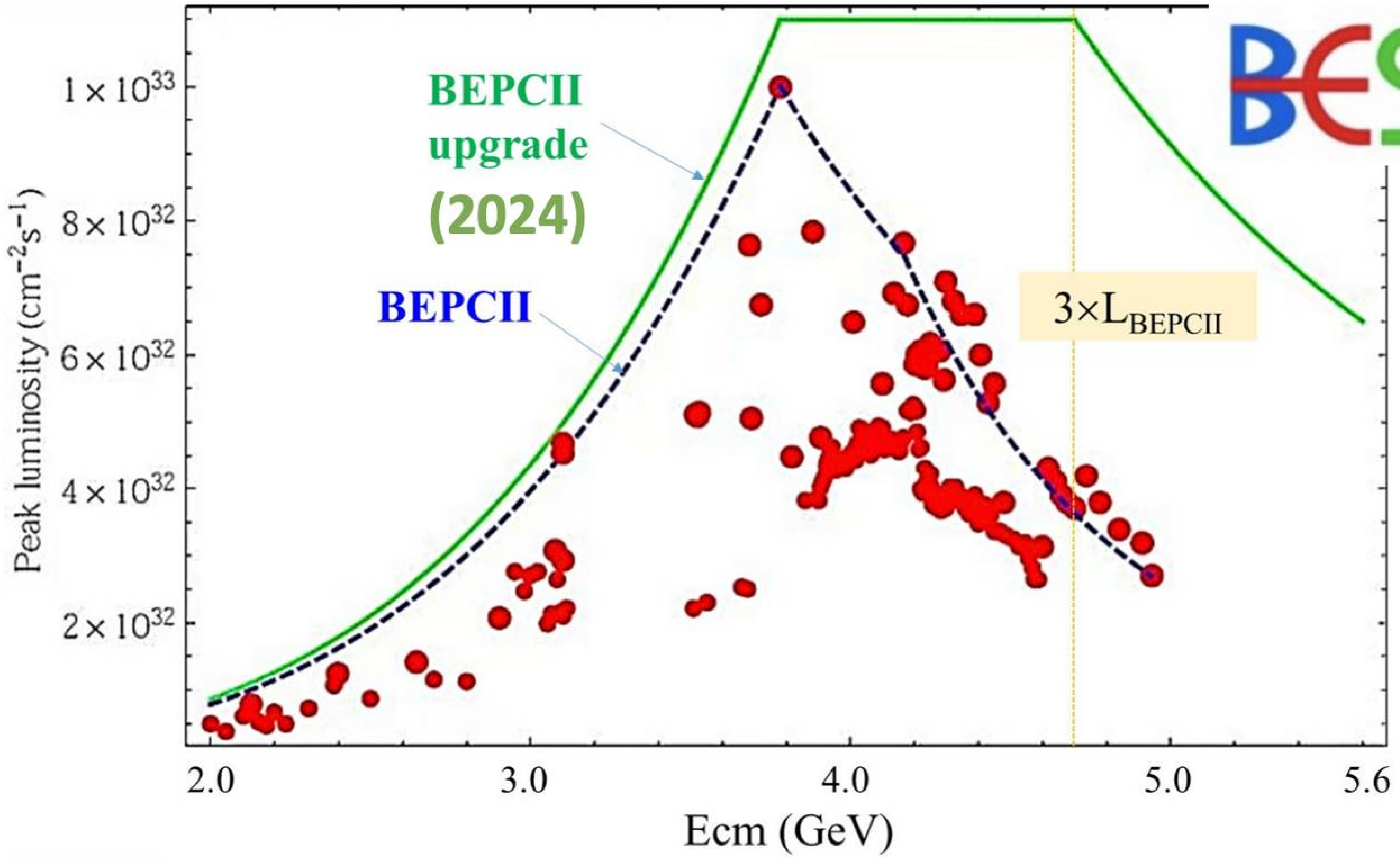
Not yet clear indications on the nature of the Y(10750)

→ S-D mixed state model compatible with $\omega\eta_b$(1S), but not with $\omega\chi_{bj}$(1P)
→ No enhancement of $\omega\eta_b$(1S) predicted by tetraquark model.
→ No indication of f_0 in M(ππ) in Y(10750) → ππ ϒ(nS)

What's next: ππ h_b(1P), ηh_b(1P), ηϒ(1D), η$^{(\prime)}$ϒ(nS), ϒ(1S) inclusive, radiative transitions … stay tuned !

Q4: What new detection possibilities/new analysis could be expected from experiments in near future?

Roberto



- High energy scans up to 5 GeV

- Rescan the X(3872) peak?

- Search for pentaquarks at $p\bar{p}c\bar{c}$ thresholds:
  - $p\bar{p}\eta_c$:4.86 GeV , $p\bar{p}J/\psi$: 4.97 GeV

Energy range	Physics target	Data already taken	Future plans	time allocation
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Roberto

Outside Υ(4S):

- O(10 fb^{-1}) : Υ(6S) peak running
  - new pathways to conventional and exotic states
- O(100 fb^{-1}) : larger scan in the 10.75 GeV region

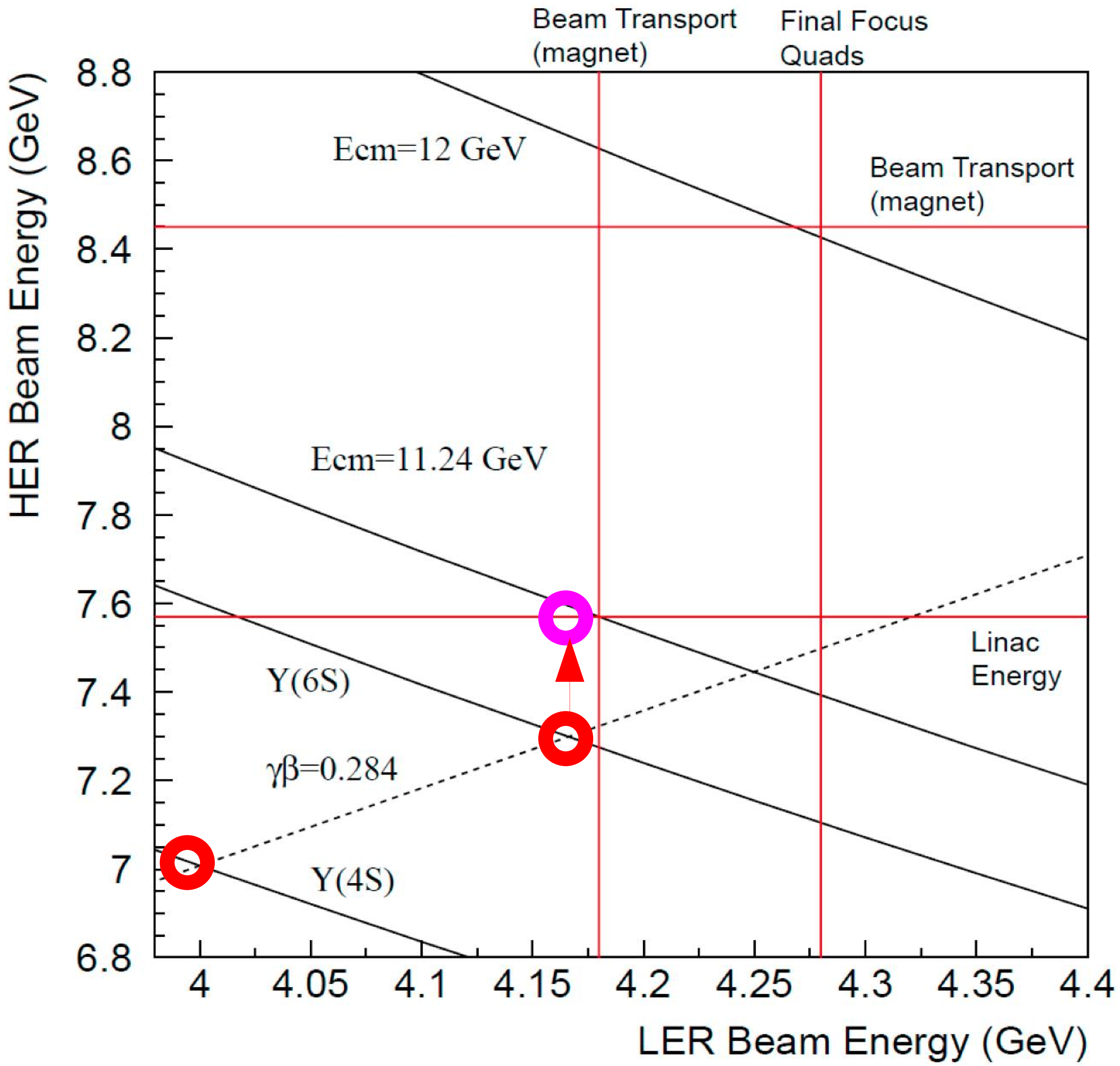
- … but even on Υ(4S):
  - are we sure about conventional $b\bar{b}$ nature ?
  - can we explain the large HQSS violation in $h_b\eta$?

- from all energies :
  - using ISR, explore $\eta_c J/\psi$ bound states
  - using η_c,χ_c recoil, explore C=-1 exotica
  - T_{cc} searches (in double $c\bar{c}$)

- O(300 fb^{-1}) :Υ(3S) peak running
inclusive production of charmonium-like tetraquarks and pentaquarks

- O(400 fb^{-1}): 10 fb^{-1} /pt in 10 MeV steps

Mod.Phys.Lett.A 32 (2017) 04, 1750025



Q5: What is the contribution of lattice to the identification process? Is that direct or mediated by some mode?l

Christopher

To identify without a model, must define rigorously in QFT what is meant by 'molecule', 'tetraquark', 'hybrid', …

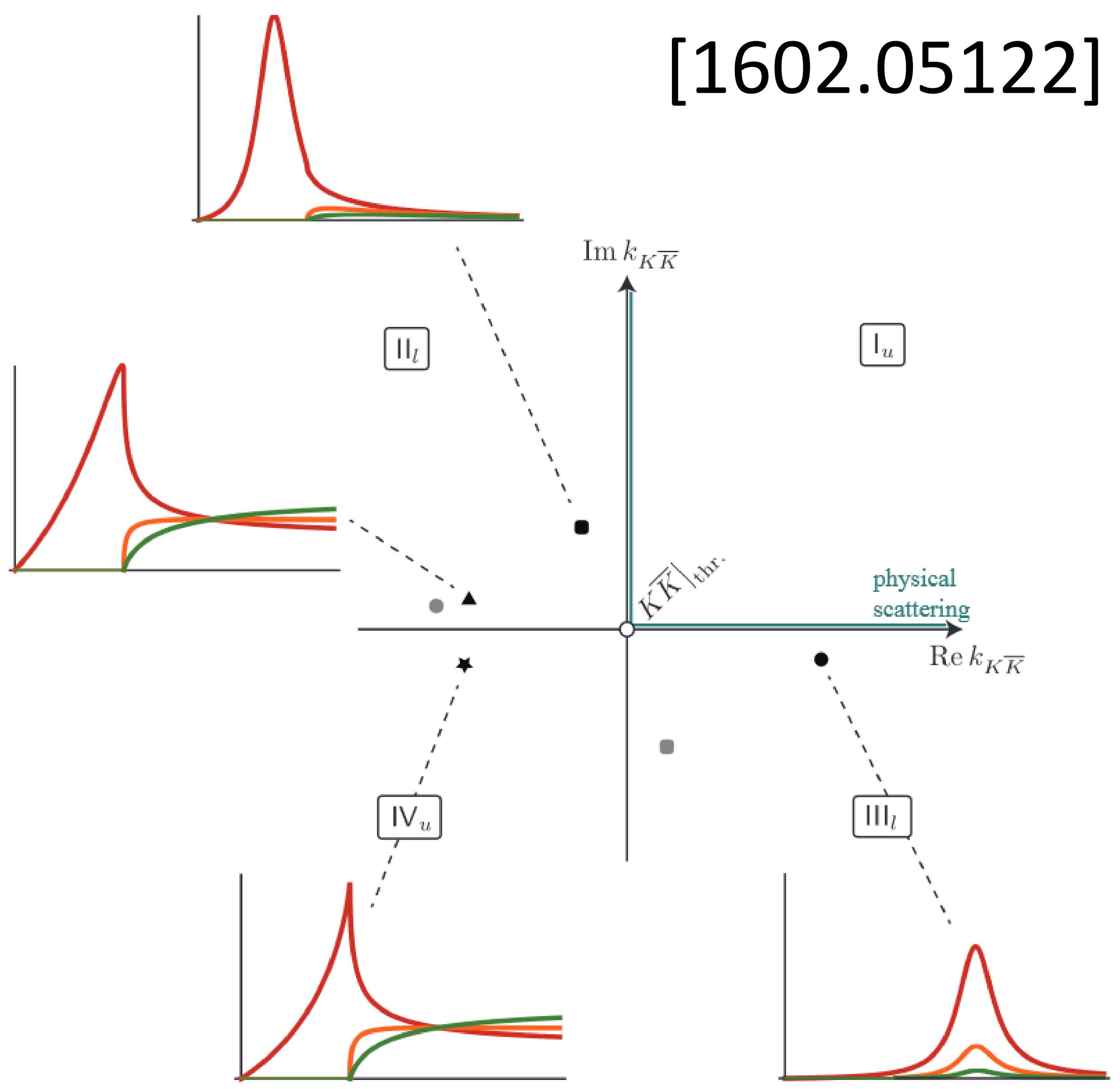
Weinberg compositeness condition for weakly-bound states.

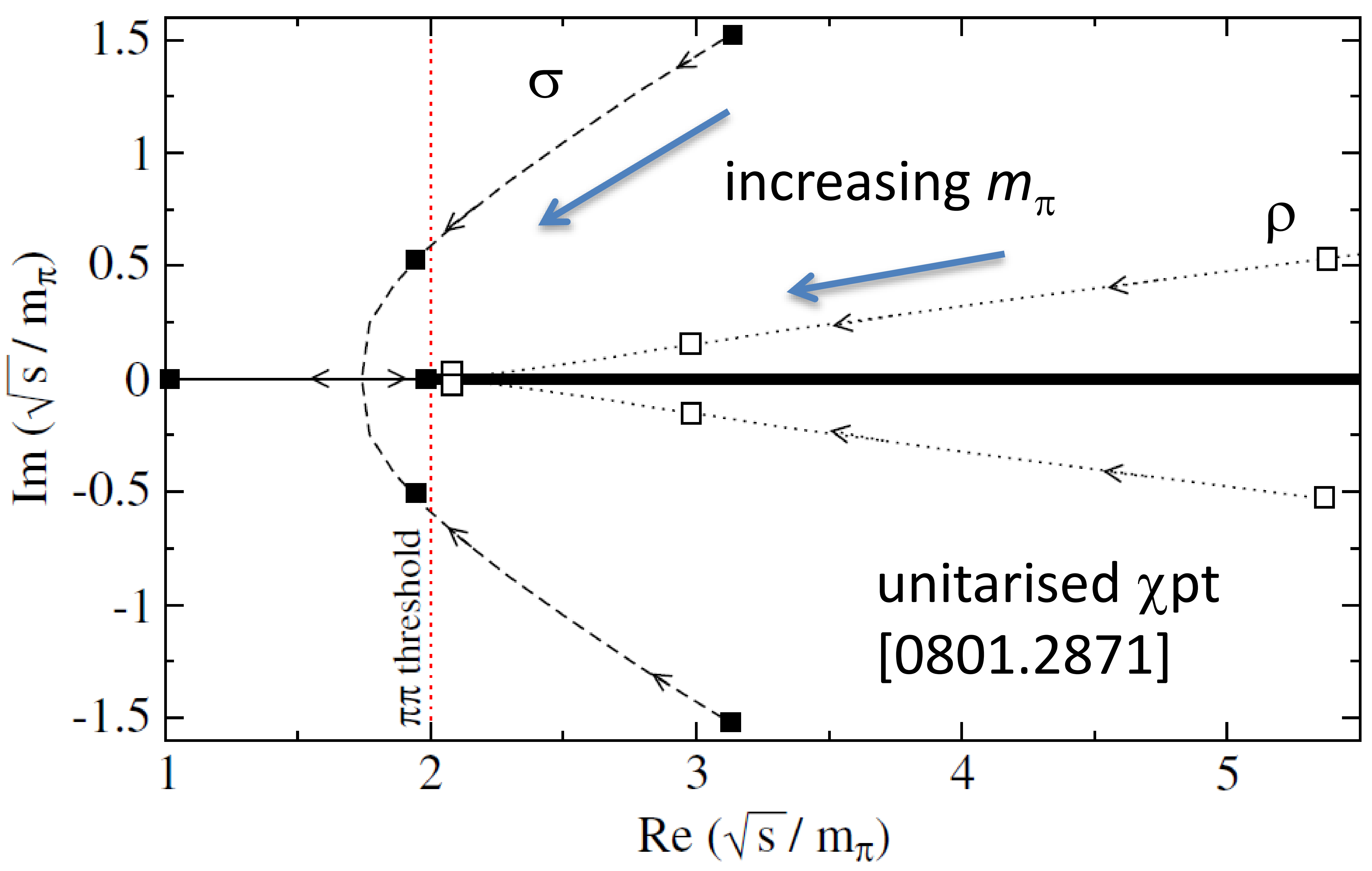
Scattering amplitude pole positions and sheets
[Nucl. Phys. A543, 632 (1992); PR D48, 1185 (1993); nucl-th/0410099]

In conjunction with model or other approach:

- Number of and patterns of states (e.g. with different quantum numbers).
- Couplings to different decay channels.
- Evolution as vary quark masses (e.g. evolution of pole positions).
- Couplings to a current, e.g. $\langle M|J|0\rangle$, $\langle M|J|M'\rangle$
  → info decay constants, form factors, etc.

[1602.05122]





unitarised χpt
[0801.2871]

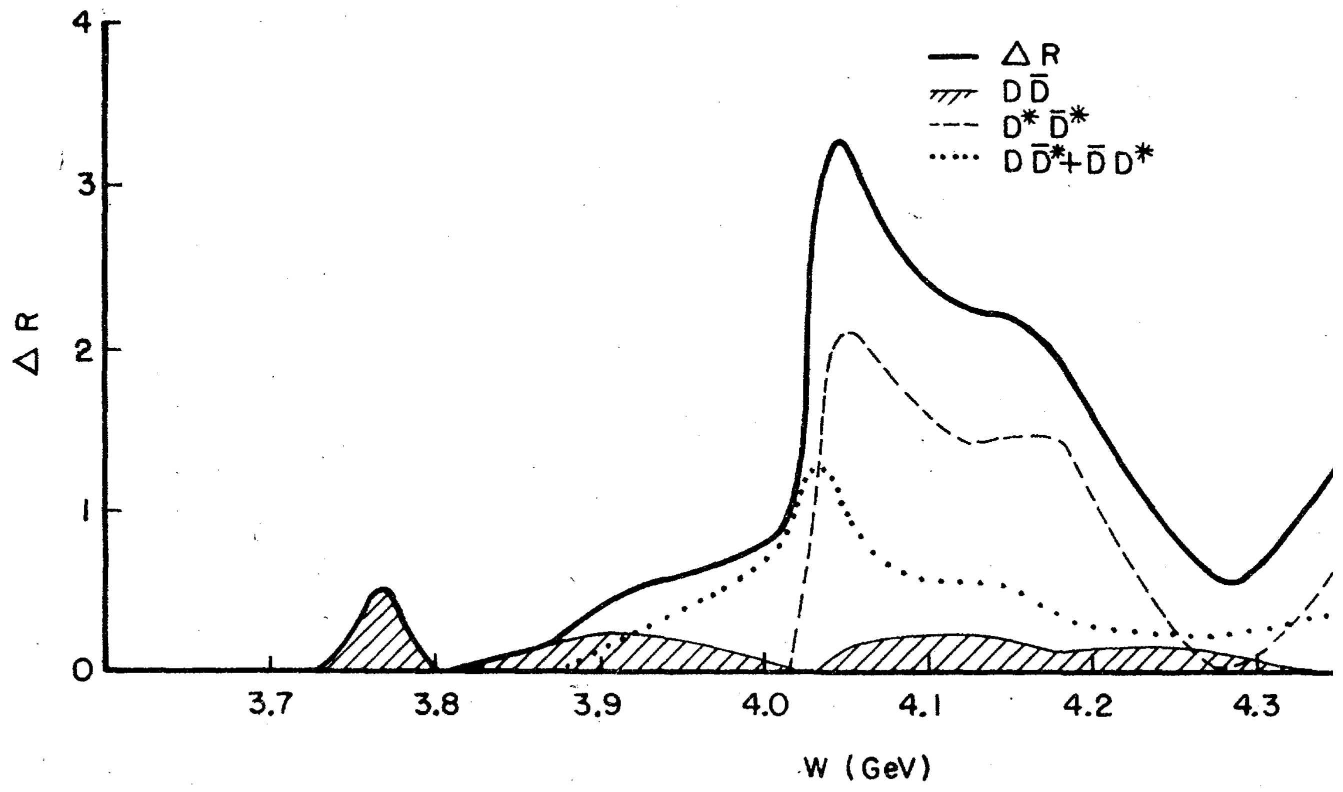
Q6: After almost 50 years from the Cornell model, how good is our understanding of ordinary quarkonium states above thresholds? How is lattice QCD changing our theoretical understanding of these states?

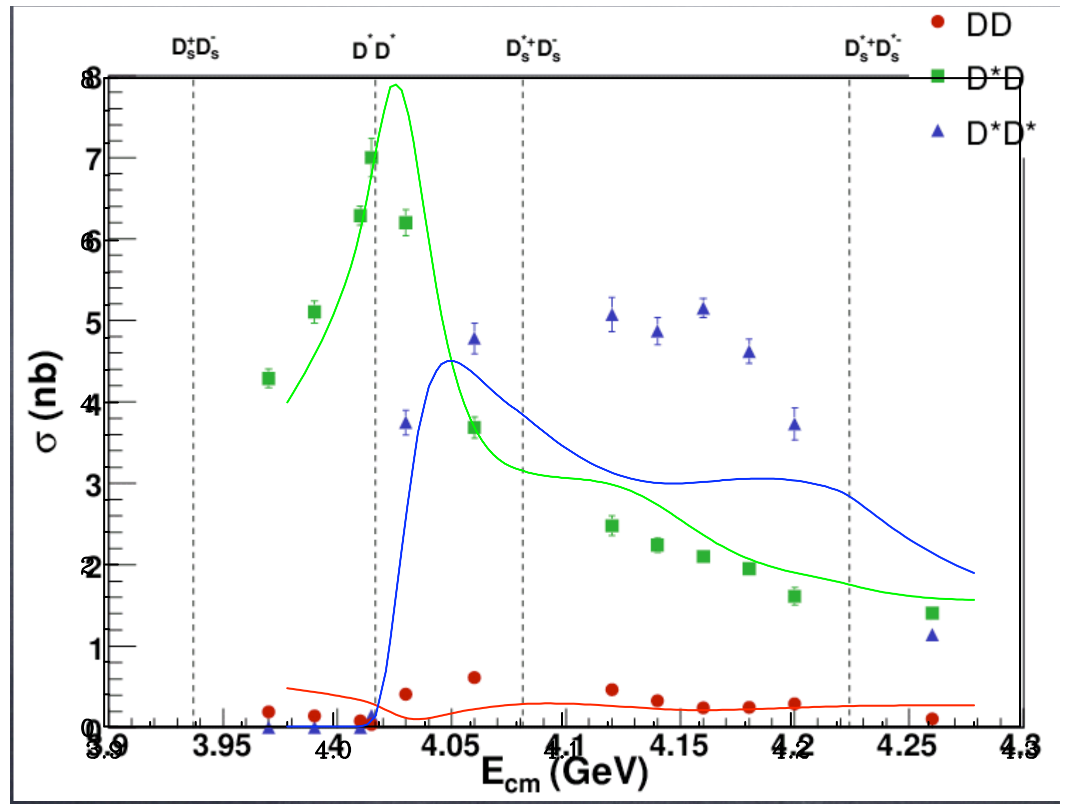
Estia

- Below Threshold - Lattice QCD put the model of the force between heavy quark-antiquark systems on a sound footing. Both the leading behavior of the potential between heavy quarks and the relativistic corrections ($\Lambda_Q/m_Q, ..$) have been measured using lattice methods and generally agree with the simple models. The effects of light quark loops are mainly limited to give the running coupling constant $\alpha_s(Q^2)$ and renormalizing the coefficients of the terms. Not too significant but must be included. The situation above threshold is much more dramatic.

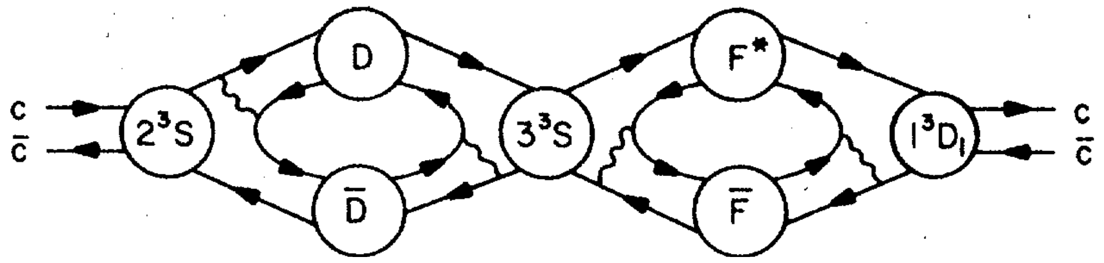
- Above Threshold - The $\bar{Q}Q$ states can decay by strong interactions. Cornell model PR D **21**, 203 (1980). No free parameters.

For the 3S - 2D region the total and individual channels are roughly in agreement with the observed individual channels.

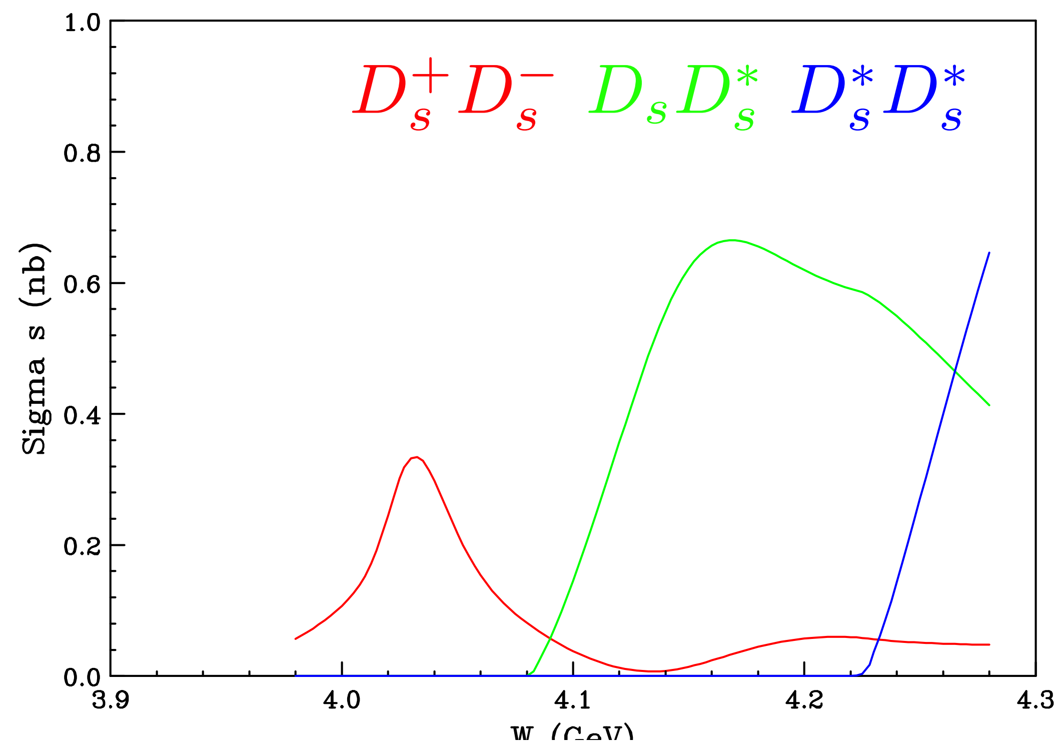




- $$|\psi'\rangle = \sum_n a_n |n^3S(c\bar{c})\rangle + \sum_n b_n |n^3D_1(c\bar{c})\rangle$$
$$+ \alpha|D\bar{D}; p\text{-wave}\rangle + \beta|D^*\bar{D}^*; f\text{-wave}\rangle + \cdots ,$$



- The coupling to the charmed strange mesons are smaller in this region. The Cornell model gives ->



- As we go to higher energies must include more decay channels. Also the resonances will become wider and overlap.

- In addition there are new states even without light quarks. The hybrid spectrum (required by lattice QCD) The lowest 1^{--} state should appear in the region of 4.2-4.3 Gev (see Question 2)

- Understanding the underlying physics is difficult without an accurate model.

Estia

The $2^3P_0(c\bar{c})$ State?

$\chi_{c0}(3860)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

The assignment $J^P = 0^+$ is preferred over 2^+ by 2.5 sigma.

Observed by CHILIKIN 17 using full amplitude analysis of the process $e^+e^- \to J/\psi D\bar{D}$, where $D = D^0$, D^+. Not seen by AAIJ 20AI in the decay $B^+ \to D^+D^-K^+$.

$\chi_{c0}(3860)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$3862^{+26}_{-32}{}^{+40}_{-13}$	CHILIKIN	17	BELL	$e^+e^- \to J/\psi D\bar{D}$

$\chi_{c0}(3860)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$201^{+154}_{-67}{}^{+88}_{-82}$	CHILIKIN	17	BELL	$e^+e^- \to J/\psi D\bar{D}$

$\chi_{c0}(3915)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

was $X(3915)$

The $\chi_{c0}(3915)$ was originally seen by BELLE in its $\omega J/\psi$ decay mode and was produced in both B decays in CHOI 05 and $\gamma\gamma$ collisions in UEHARA 10. The J^{PC} was determined to be 0^{++} by BABAR in LEES 12AD but this assignment was questioned by ZHOU 15C. In AAIJ 20AI LHCb found the D^+D^- decay mode of the $\chi_{c0}(3915)$ using B decays and determined its J^{PC} to be 0^{++}. Based on their compatible mass, width, and J^{PC}, we assume the state decaying to $\omega J/\psi$ and the state decaying to D^+D^- are both the $\chi_{c0}(3915)$. See also the $\chi_{c2}(3930)$.

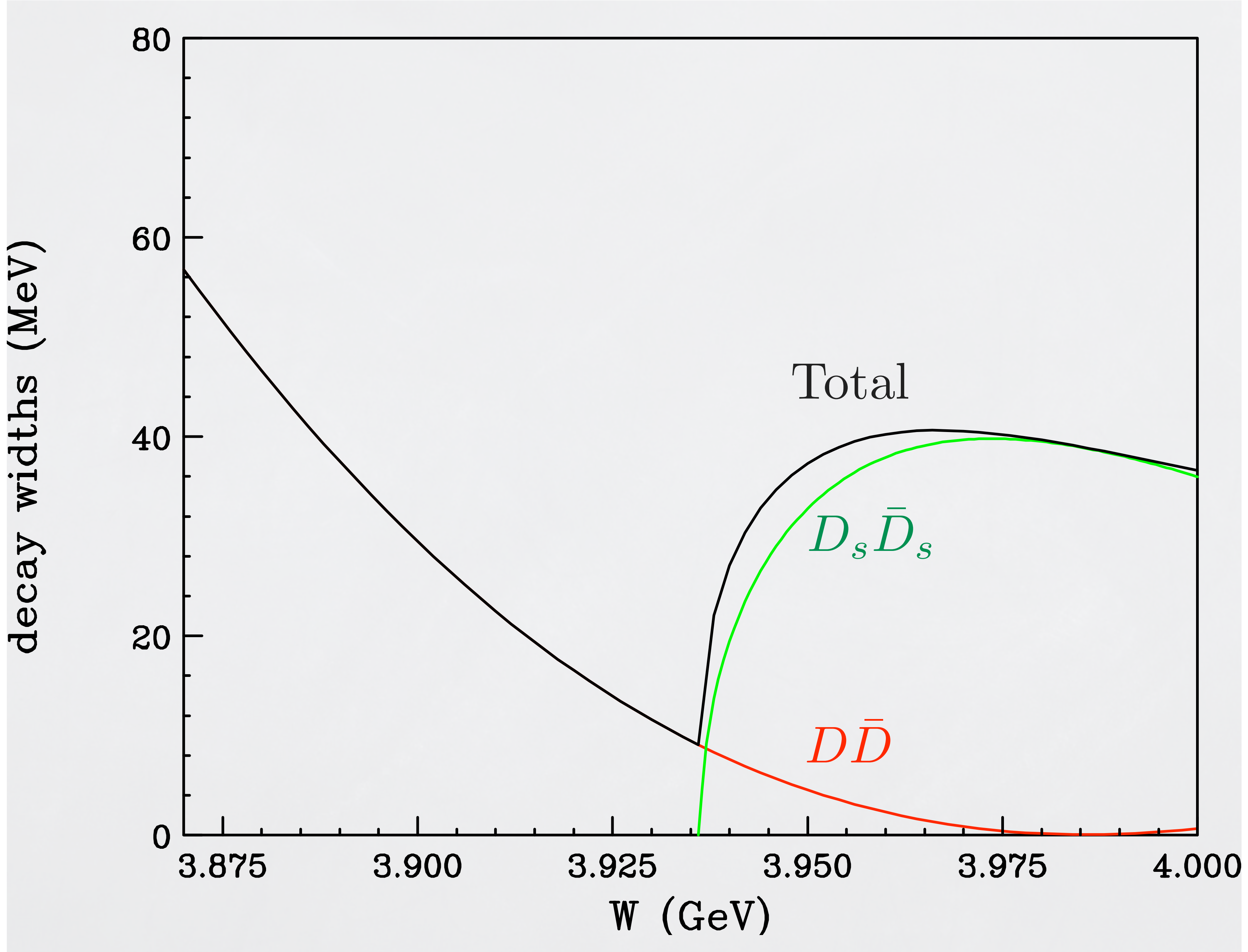
$\chi_{c0}(3915)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3922.1 ± 1.8 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.			
3956 ± 5 ± 10	360	[1] AAIJ	23AA	LHCB	$B^+ \to D_s^+ D_s^- K^+$

$\chi_{c0}(3915)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
20 ± 4 OUR AVERAGE		Error includes scale factor of 1.1.			
43 ± 13 ± 8	360	[1] AAIJ	23AA	LHCB	$B^+ \to D_s^+ D_s^- K^+$
17.4 ± 5.1 ± 0.8	1.2k	[2] AAIJ	20AI	LHCB	$B^+ \to D^+ D^- K^+$

With coupled decay channels



All from single 2^3P_0 state with mass about 3860 Mev

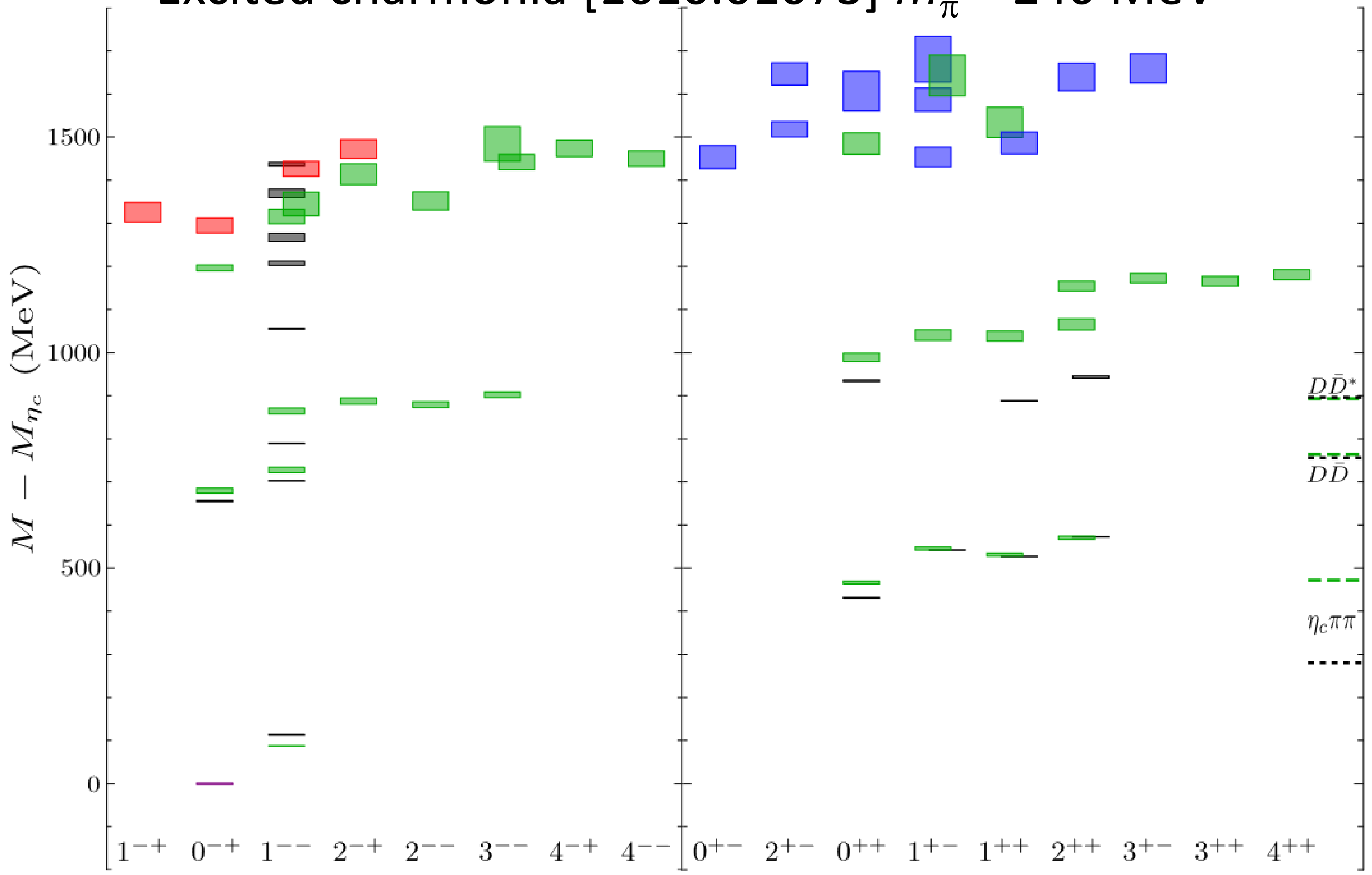
Christopher

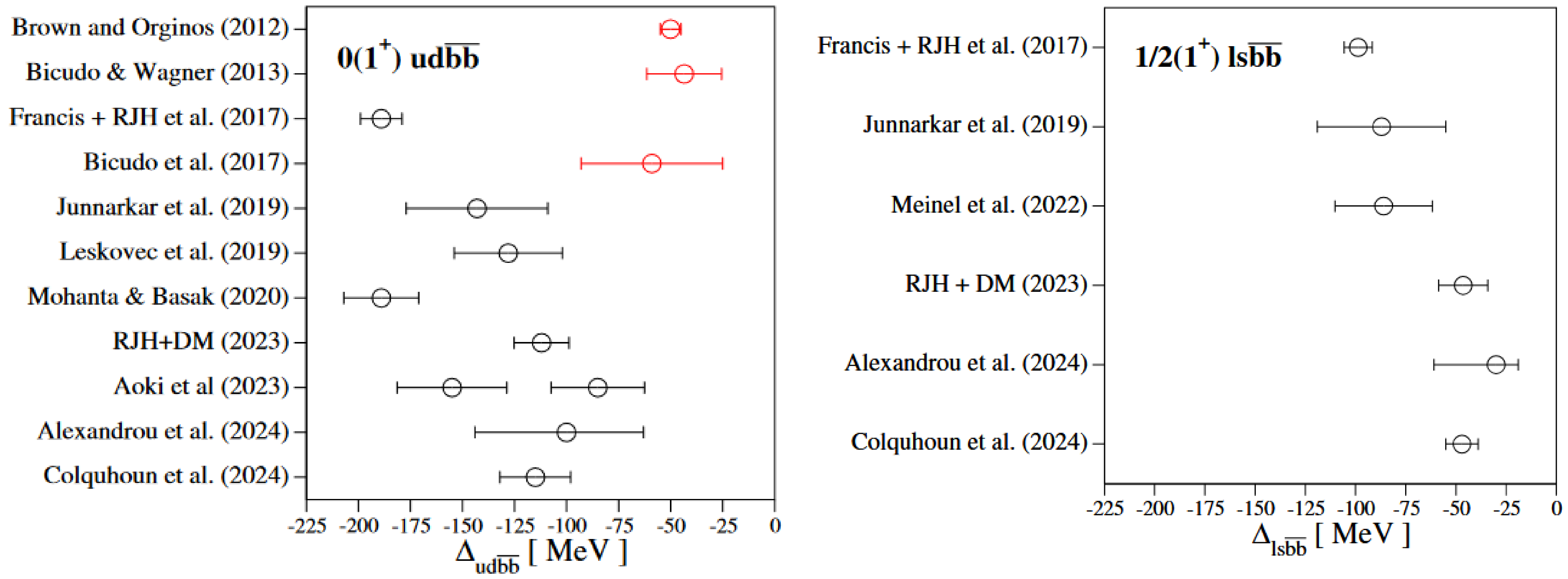
If *neglect unstable nature* of heavy quarkonia above threshold, lattice QCD suggests get pattern of quark model states + extras that could be identified as hybrid mesons (including exotic $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \ldots$).

Huge progress in last 10 or so years in lattice QCD calculations of hadron-hadron scattering and resonances.

Don’t yet have clear picture of most charmonium and bottomonium resonances.

Excited charmonia [1610.01073] $m_\pi \approx 240$ MeV





[Daniel Mohler at Lattice 2024]

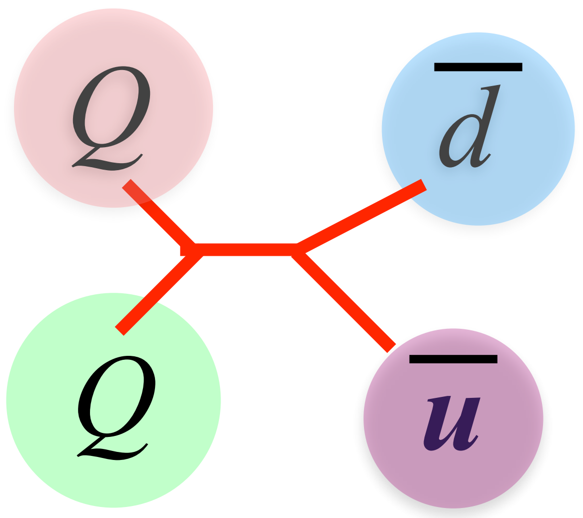
Lattice QCD also finds exotic-flavour states:

- $bb\bar{l}\bar{l}$ and $bb\bar{l}\bar{s}$ bound states with $J^P=1^+$
- Possibly bound states/virtual bound states/resonances in $T_{cc}(cc\bar{l}\bar{l})$ and other channels.

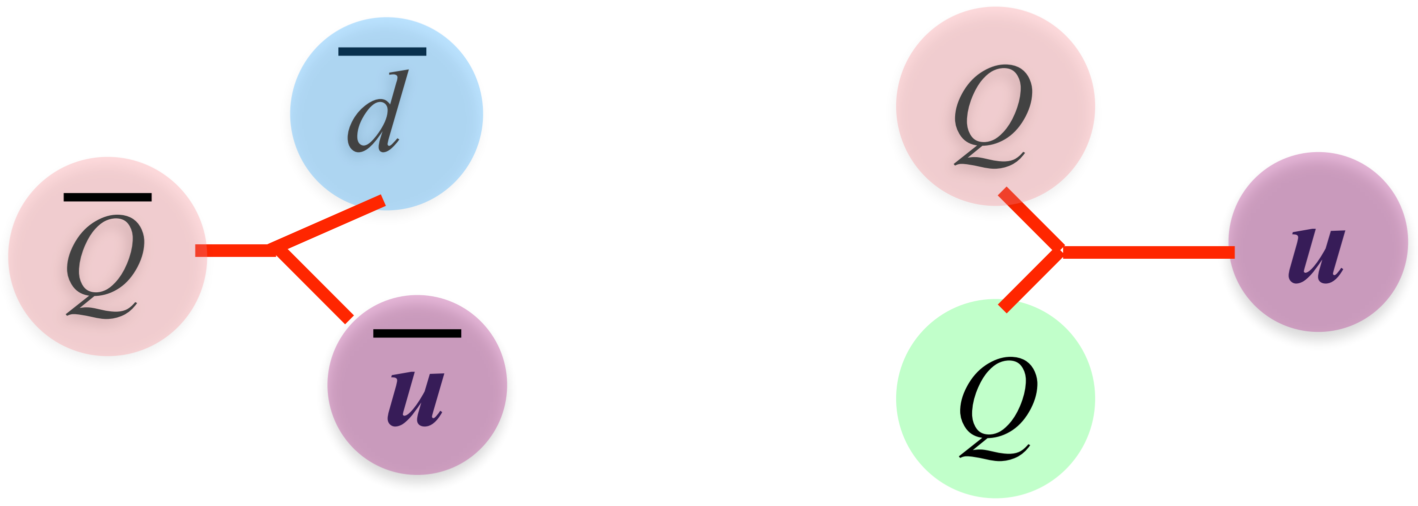
Q7: What is the link of the different phenomenological approaches (quark models, molecule models, compact tetraquark models, chiral unitary approaches, ...) with QCD? How well we understand the confinement of quarks in multi-quark states?

Makoto

- Is T_{QQ} ($QQ\bar{u}\bar{d}$) analogous to Λ_Q (Qud)? Or to Ξ_{QQ}(QQu/QQd)?

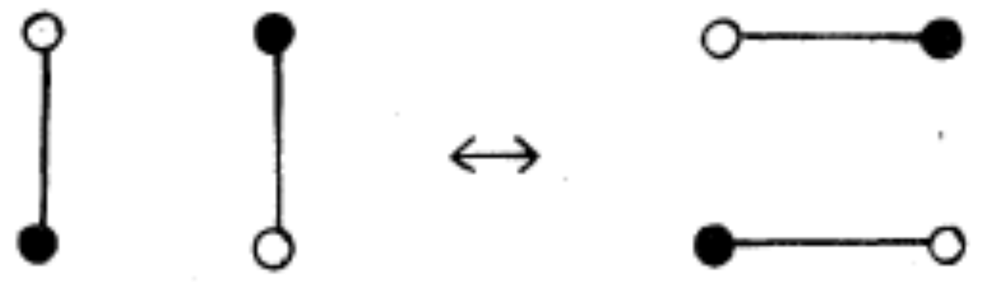


four-body confinement

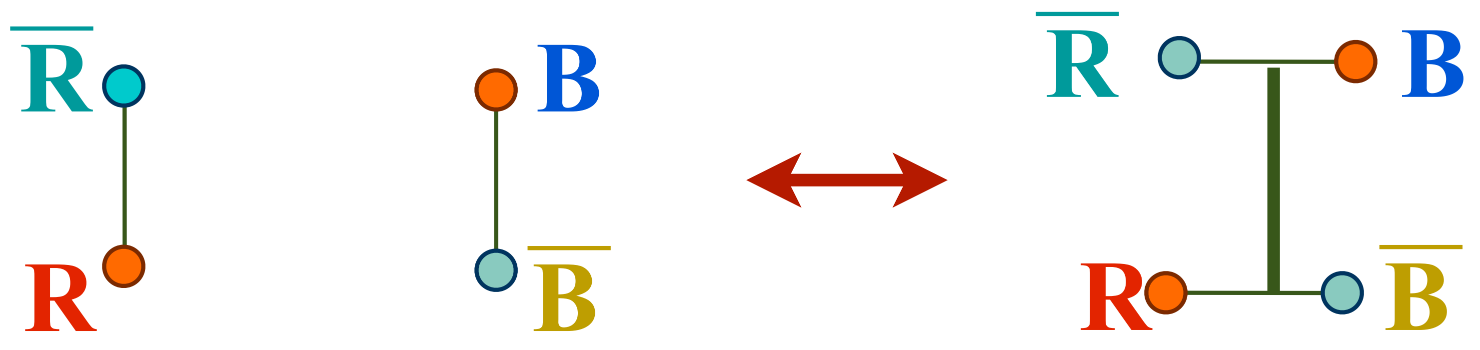


three-body confinement

- Confinement of multi-quark systems (which does not appear in ordinary hadrons) is not trivial or not well understood.
- String-flip-flop type model may require new color configurations for color SU(3).



color U(1)



color SU(3)

hidden color

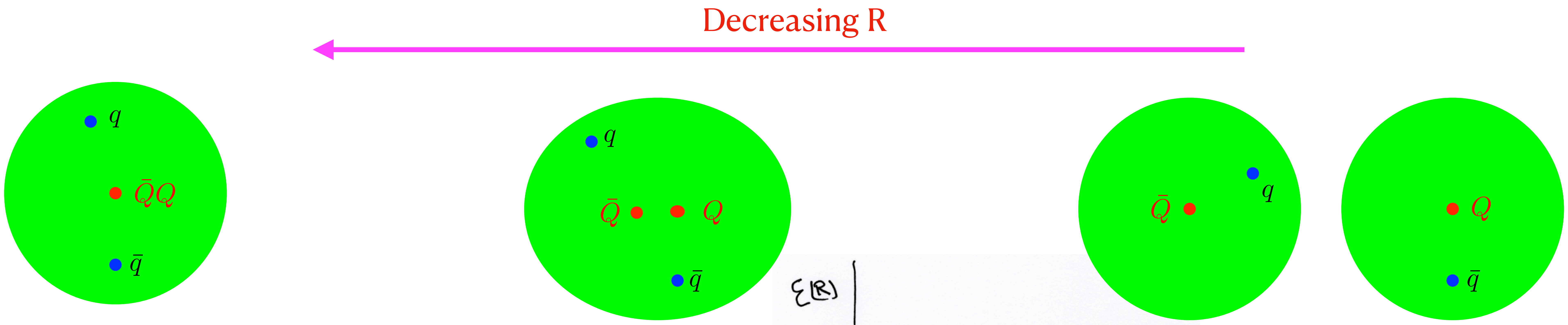
Q7B. What is our understanding of the couplings between different Fock states, such as Q Qbar and Qq Qbar qbar states?

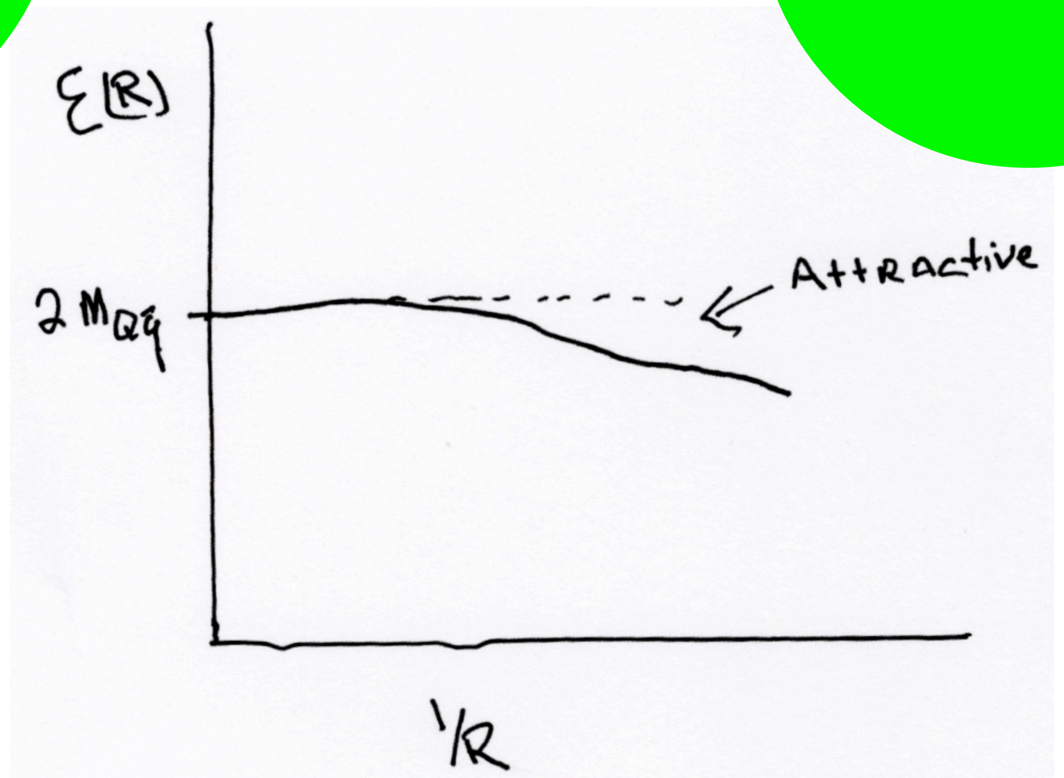
- T_{QQ} ($QQ\bar{u}\bar{d}$) decays into $Q\bar{u} + Q\bar{d}$ by fall-apart, while the decays of 3q baryons are associated with $q\bar{q}$ creation.
- Molecular states may be distinguished from compact states by the production/decay processes. (ex. X(3872))

Q8: Is the molecular picture (and to what extent) included in the BOEFT approach? Are compact tetraquark and molecular descriptions really exclusive?

Estia

- Usually lattice calculations with static quarks become very difficult as the distance between heavy quarks increases much beyond one Fermi. In fact, string breaking on the lattice has not been directly observed. Instead we measure the mixing between quarkonium states and two heavy-light meson states.
- When we add two dynamical light quarks the static energy doesn't continue to grow with distance, so extracting the behavior at large distance is possible (although noisy). At large distance the system well approximates two heavy-light mesons. This works best for two ground state heavy-light mesons. In fact, the Born Oppenheimer approximation is ideal for molecular atomic physics.
- The behavior as a function of heavy quark separation gives insight into the nature of the force between the two mesons.
- It is limited because it only easily finds the ground state for any set of quantum numbers for the light quarks. Extracting the excited spectrum is more difficult. Also final states of the form $[\bar{Q}(R/2)Q(-R/2)] + (\bar{q}q)$ can appear.

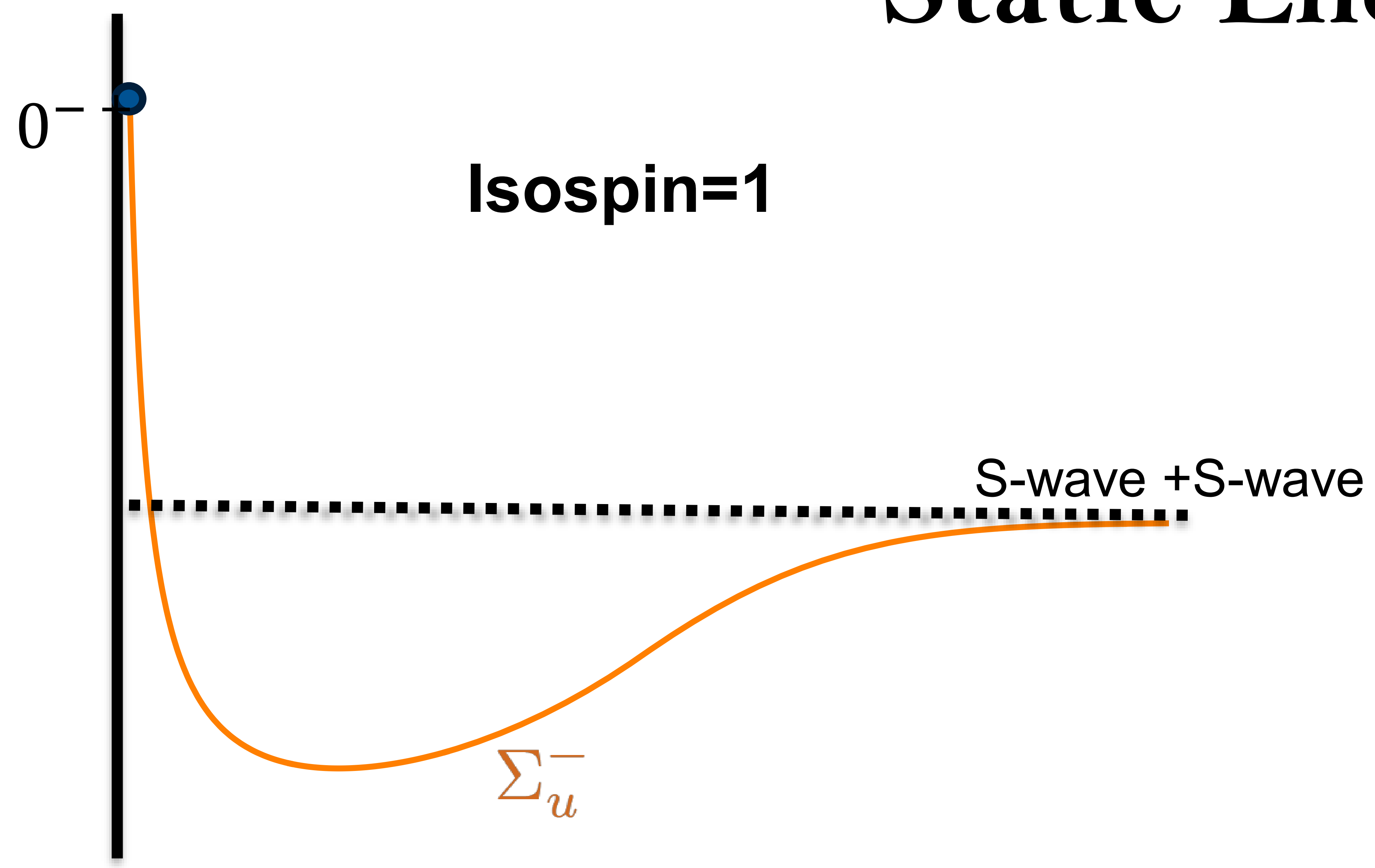


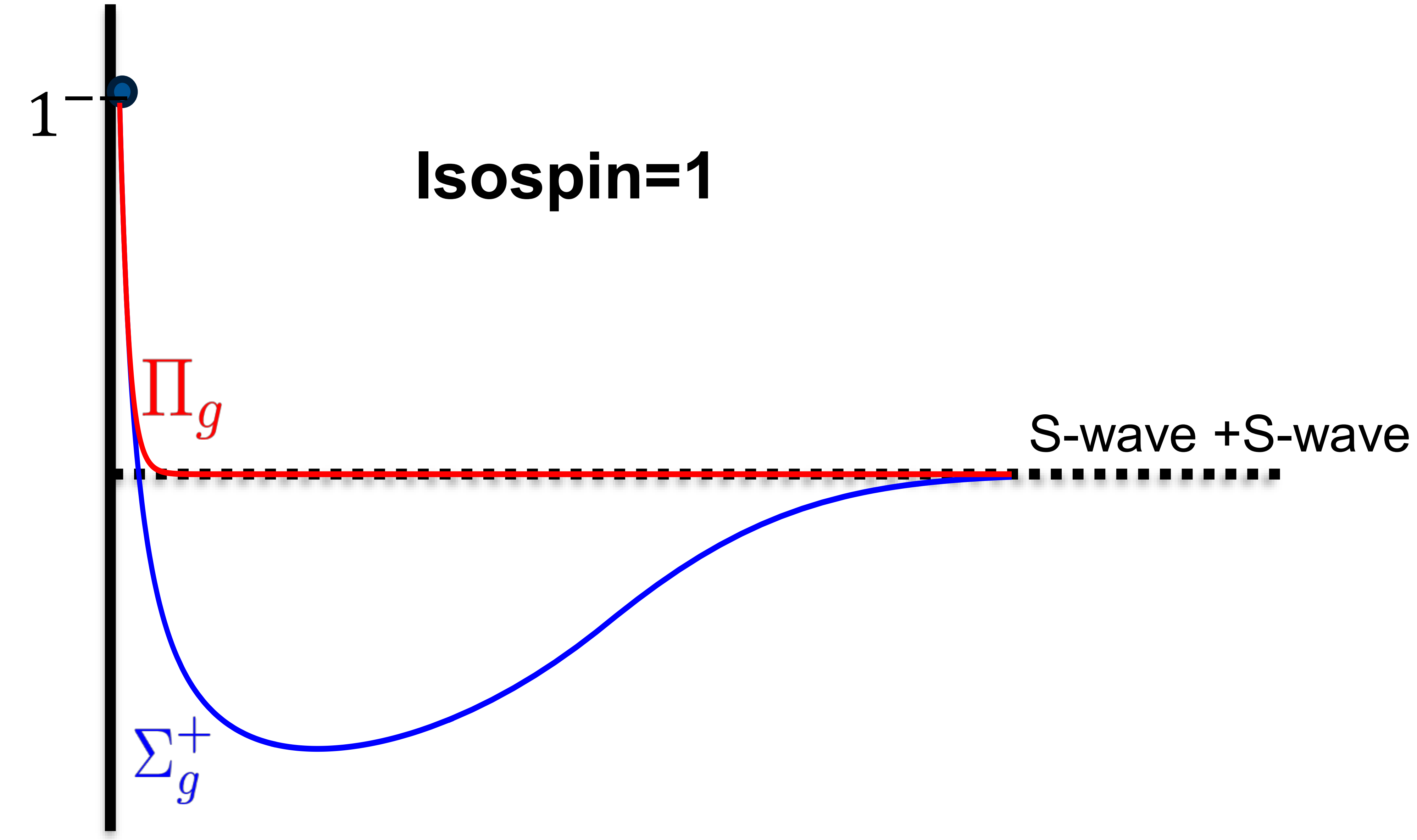


Can learn: Attractive /Repulsive
Exchange Potentials
Spin Dependency

Static Energies: Tetraquark

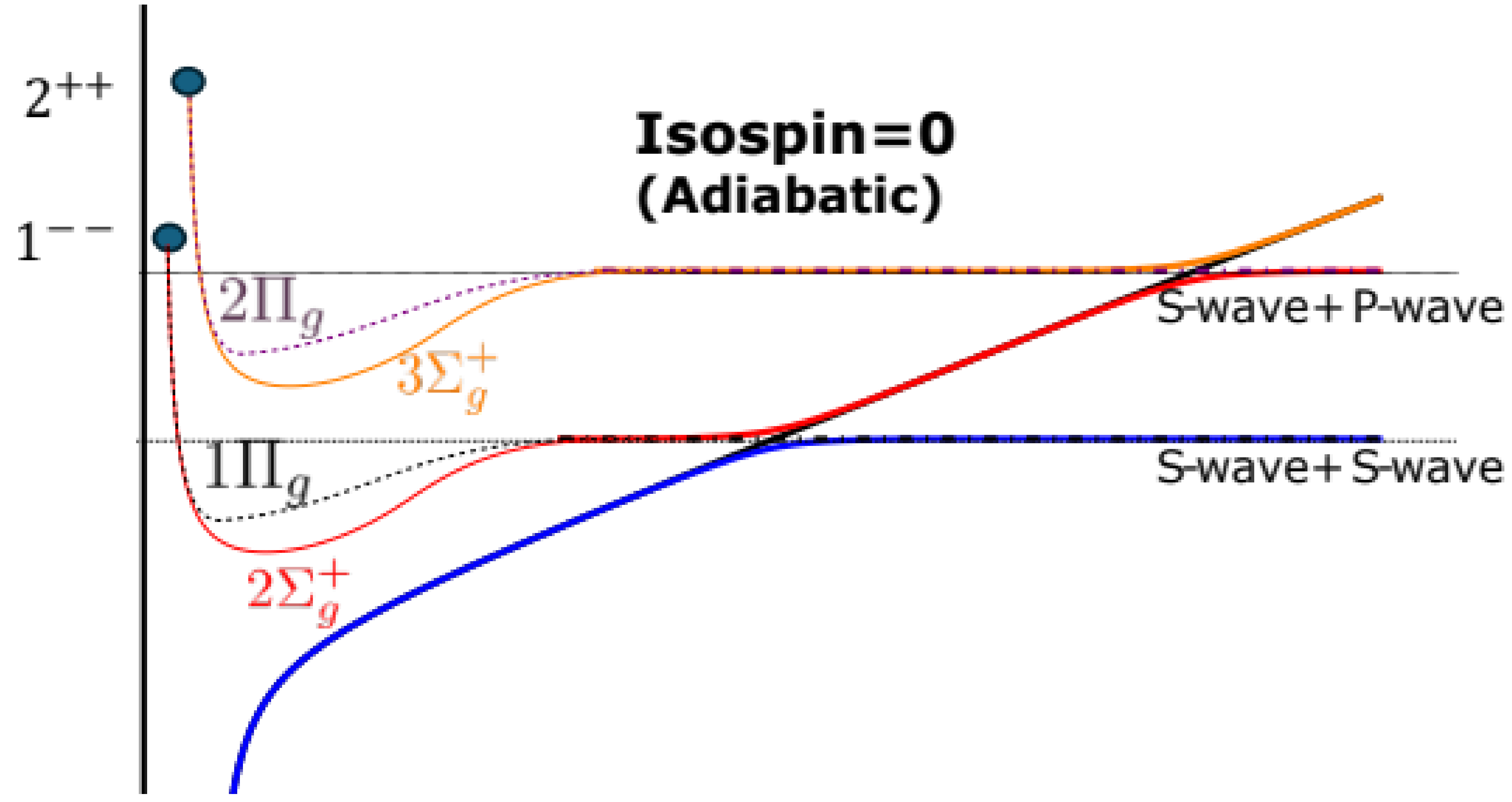
Berwein, Brambilla, AM, Vairo,
arXiv 2408.04719





Behavior of tetraquark static energy:

- Adjoint meson behavior at small r $(r \to 0)$
- Heavy meson pair threshold at large r $(r \to \infty)$
- Avoided crossing with quarkonium static energy (Isopsin=0)



Q9: How could the synergy between experiments, lattice QCD, EFTs and models be improved in the quest for a general understanding of the XYZ states?

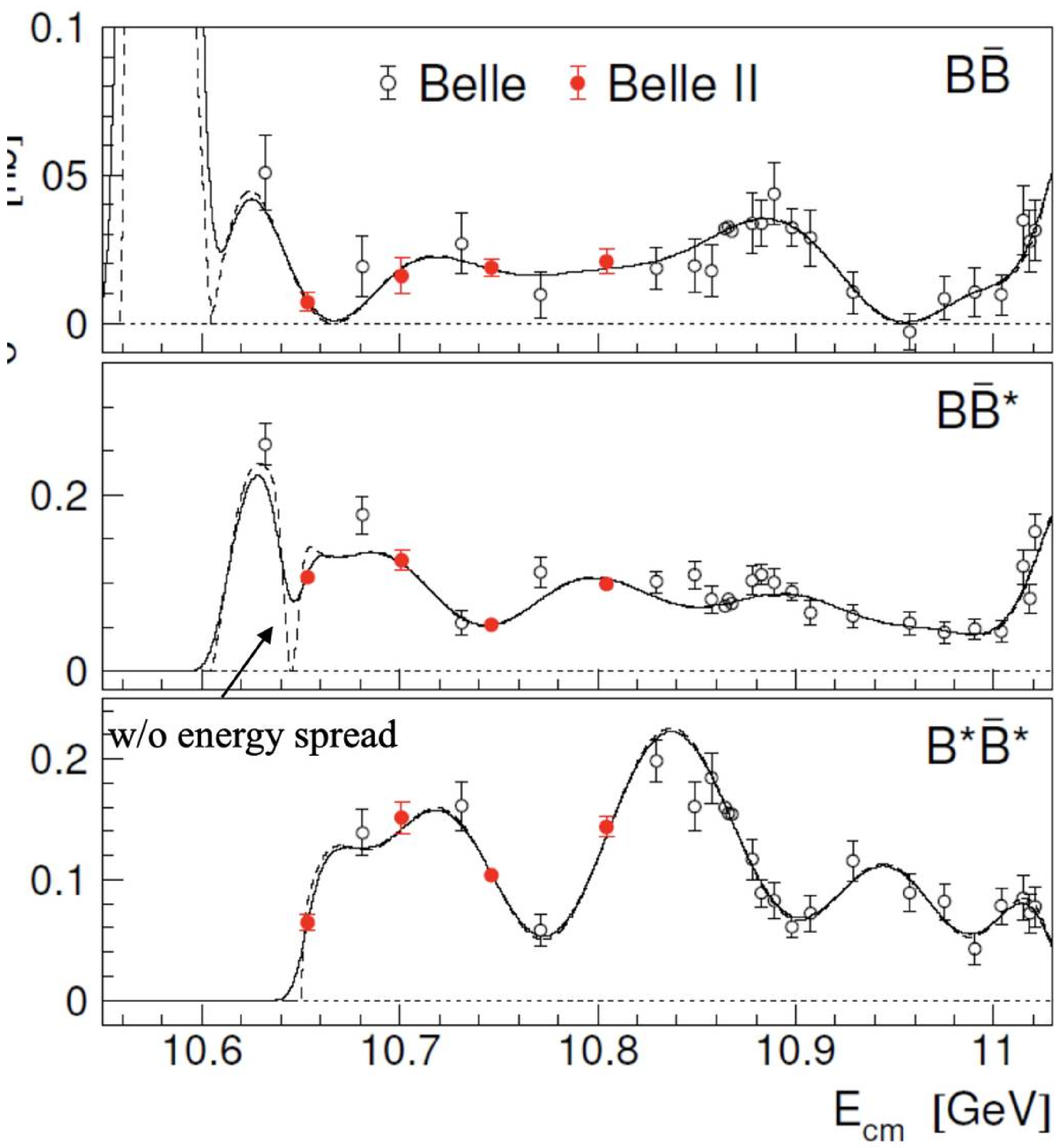
Roberto

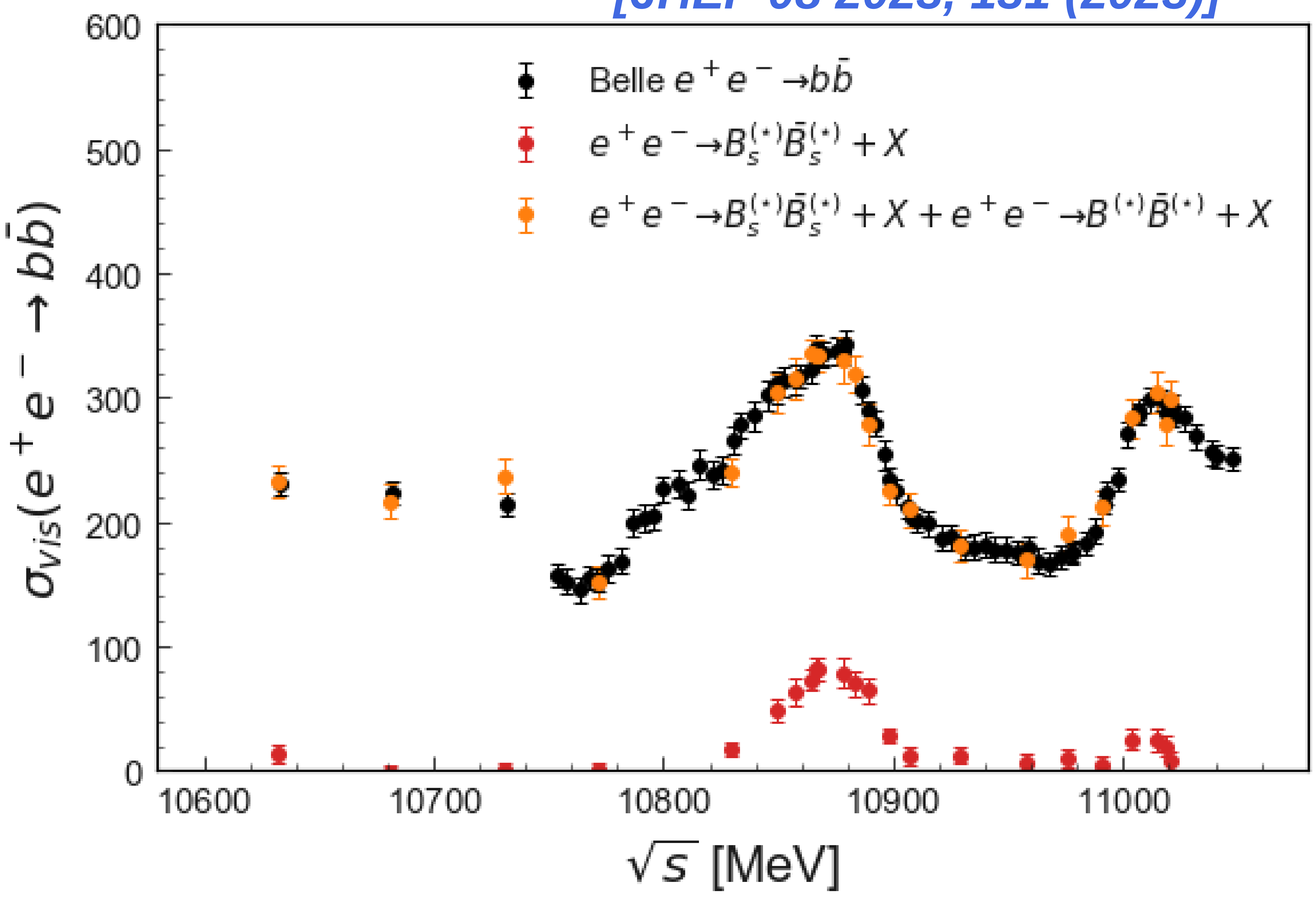
.Synergy between experiments and theory: open flavor cross sections

Semi-inclusive reconstruction:
→ Reconstruct one $B^{(*)}$ in 16 modes with $D_{(s)}^{(*)}$ or J/ψ
→ Ignore γ from B^* to B
→ Separate processes by momentum (M_{bc})

Measure the fully-inclusive $e^+e^- \to B_{(s)}^{(*)}B_{(s)}^{(*)}+X$
→ Use D^0 as proxy for a B^0
→ Use D_s^- as proxy for B_s^0

[JHEP 08 2023, 131 (2023)]





Roberto

Q9. Synergy between experiments and theory: coupled channel analyses

Global fit of both open and hidden flavor channels *[Hüsken et al. PRD 106 094013 (2022)]*