On vector-quarkonia

and poltergeists

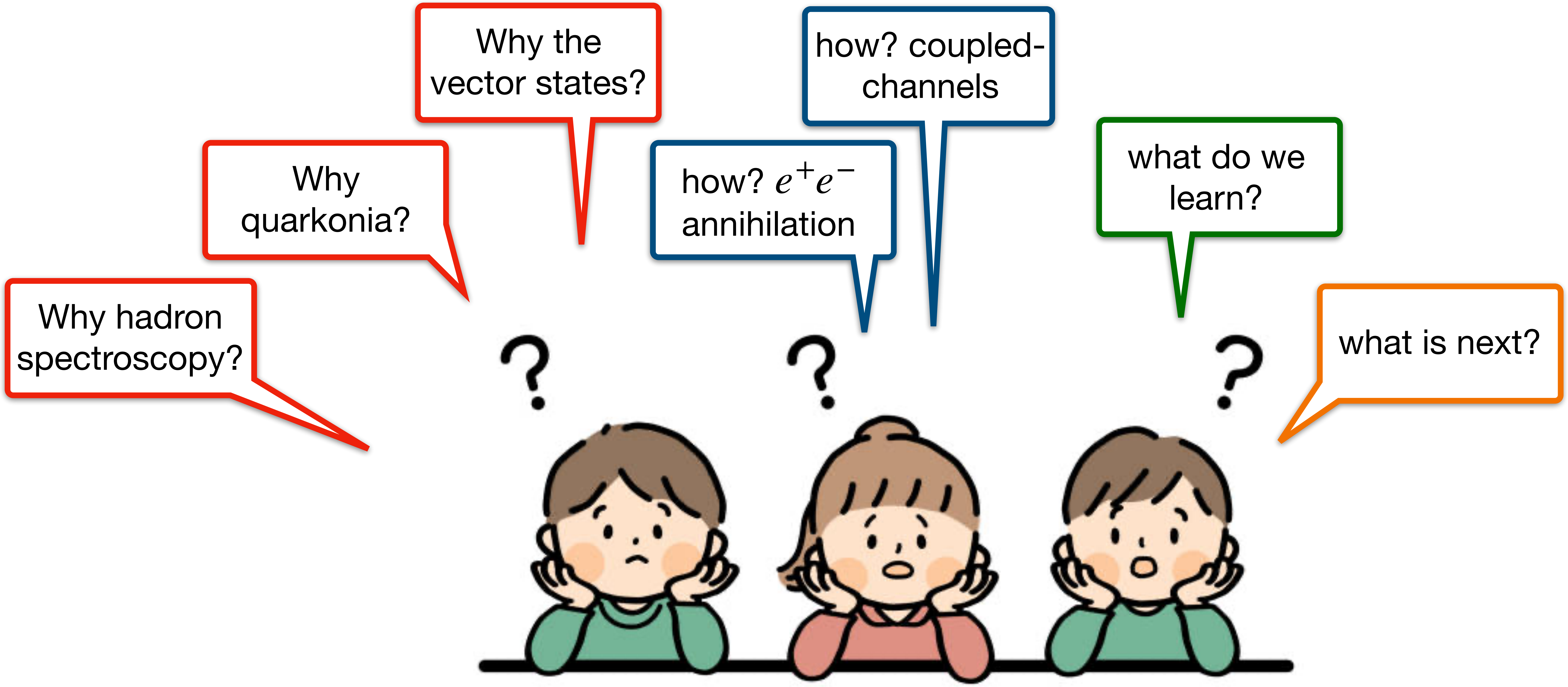
Nils Hüsken
JGU Mainz
Seminar at the University of Manchester, February 20th, 2026

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

work done with the BESIII collaboration,
R. Mitchell, E. Swanson, R. Lebed, A. Szczepaniak, Y.Q. Wang, C.Z. Yuan

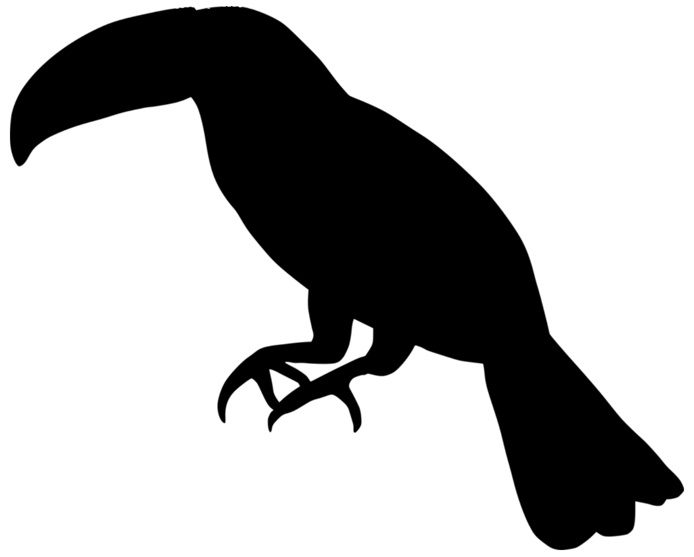
Table of contents

or: A story of 3 why's, 2 how's and 2 what's



Why hadron spectroscopy?

Spectroscopy is collecting



Silhouettes from https://www.phylopic.org/

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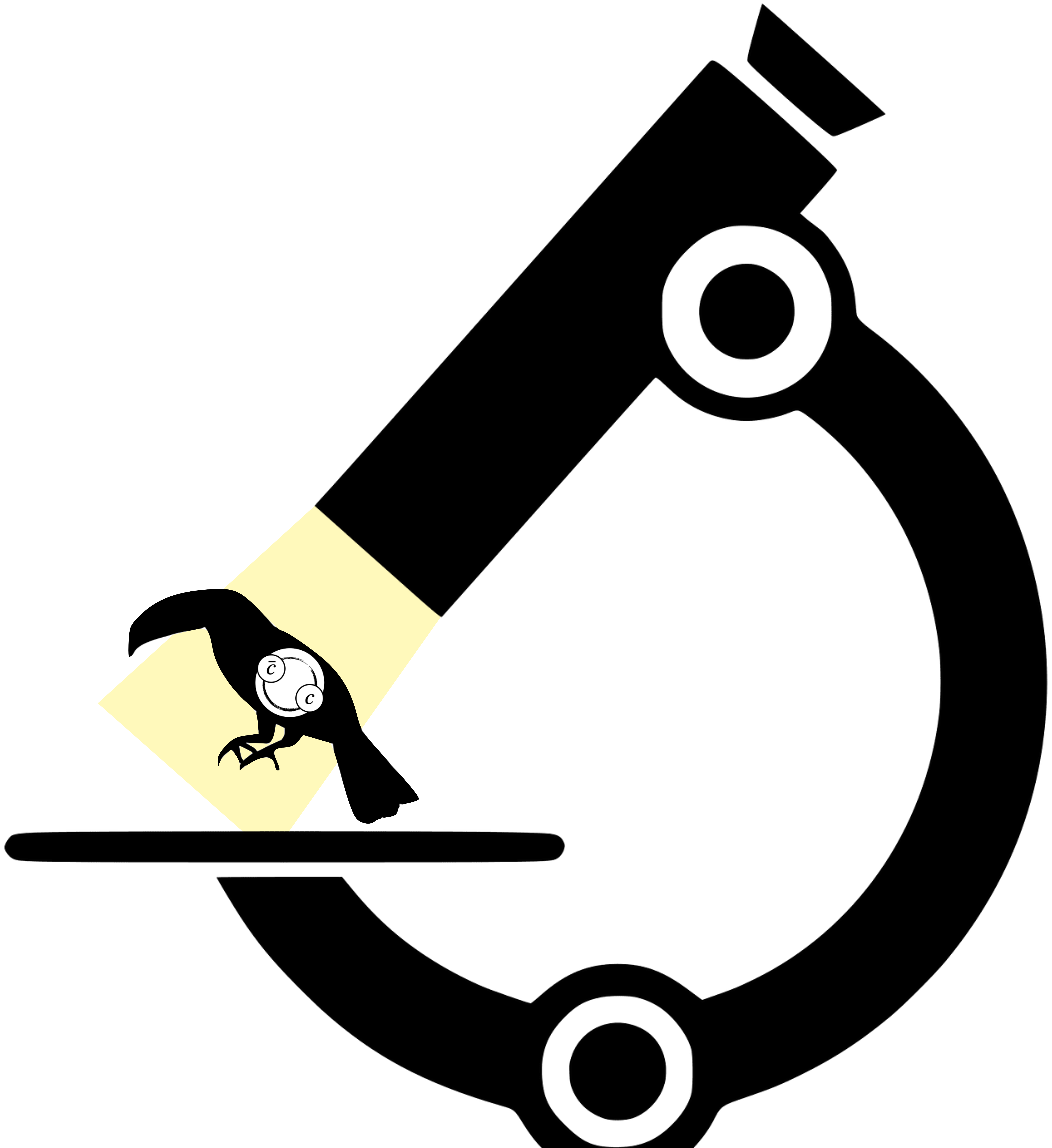
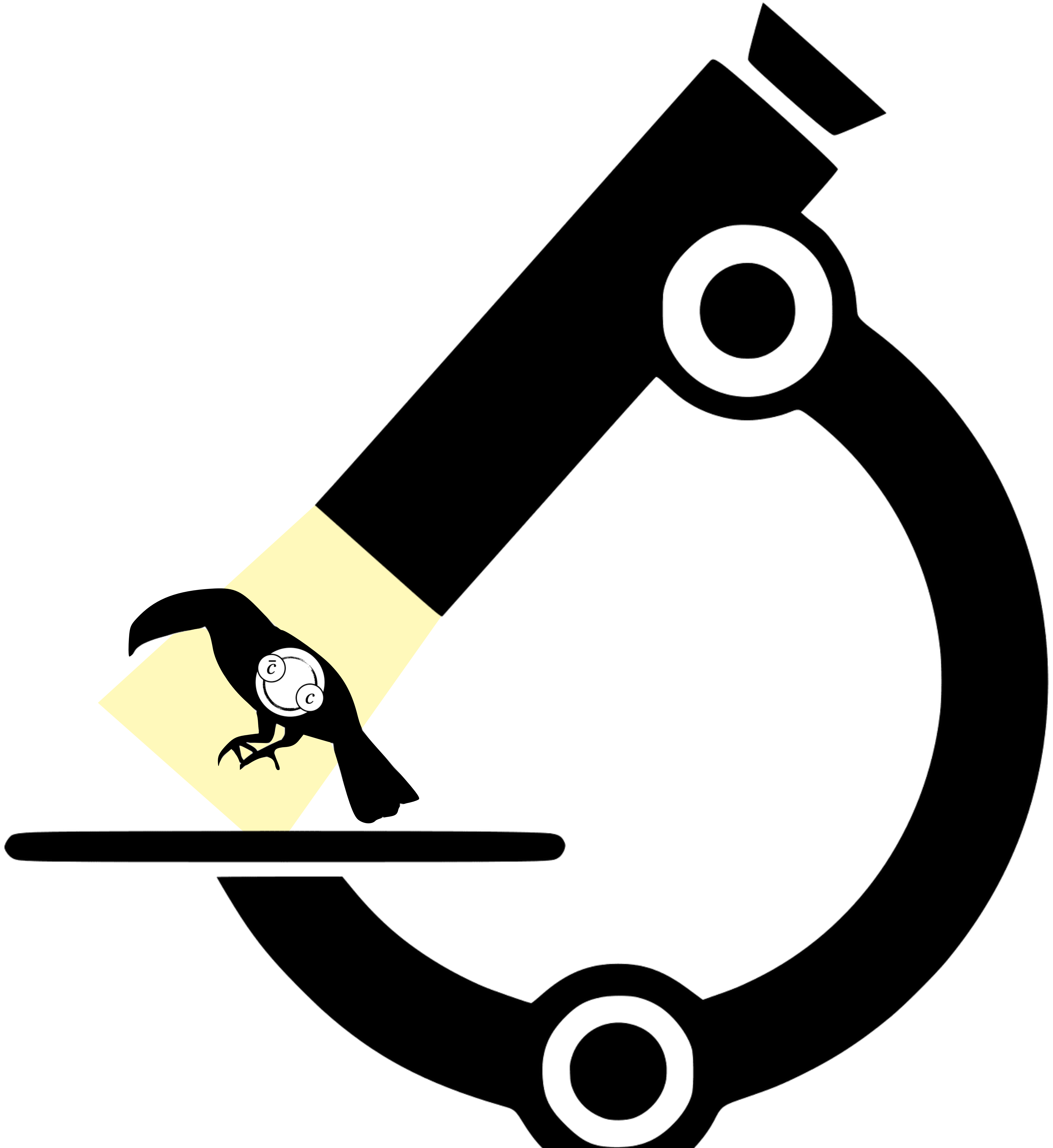
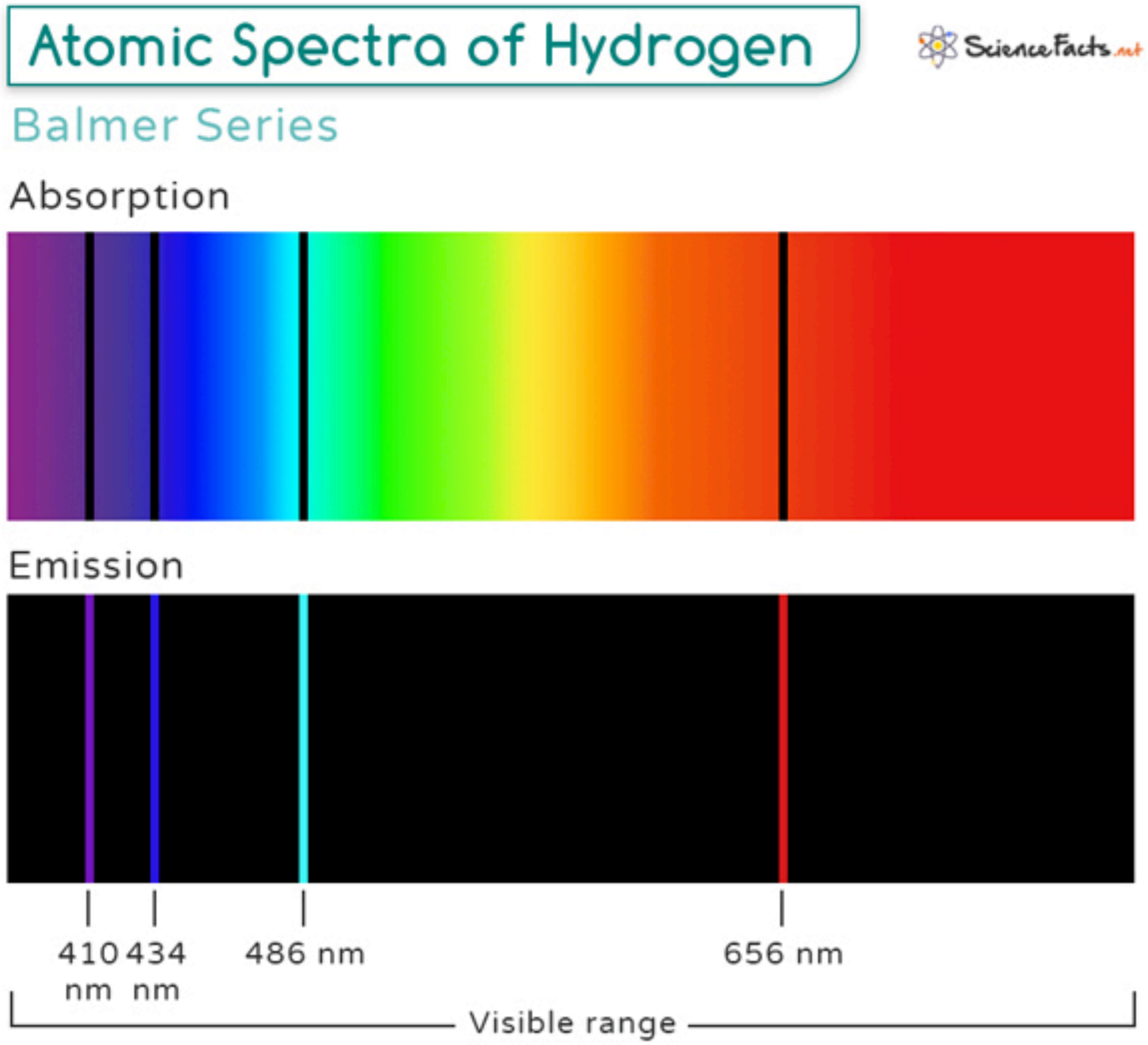


Spectroscopy is collecting

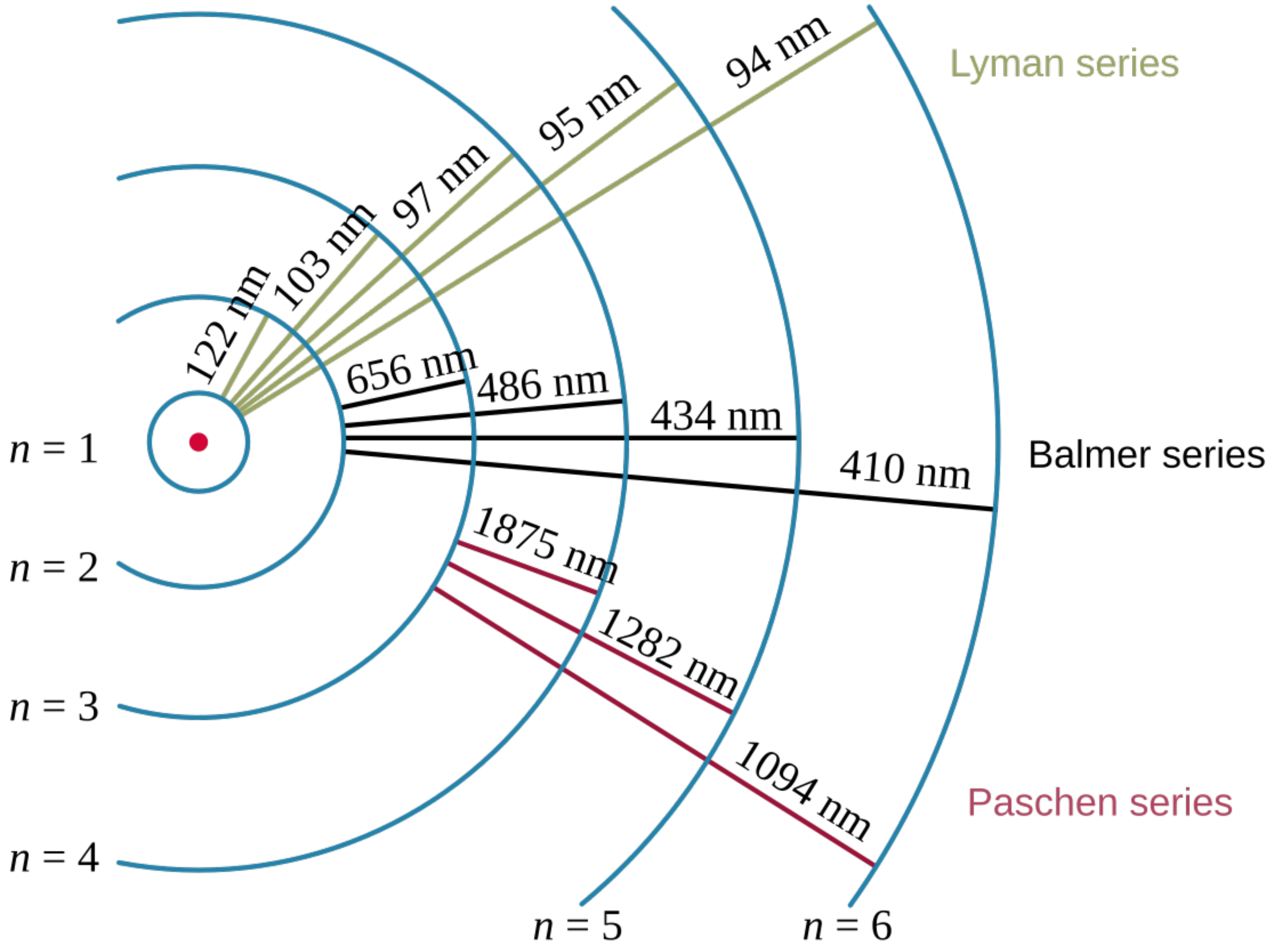
for the sake of understanding the underlying interaction



Spectroscopy

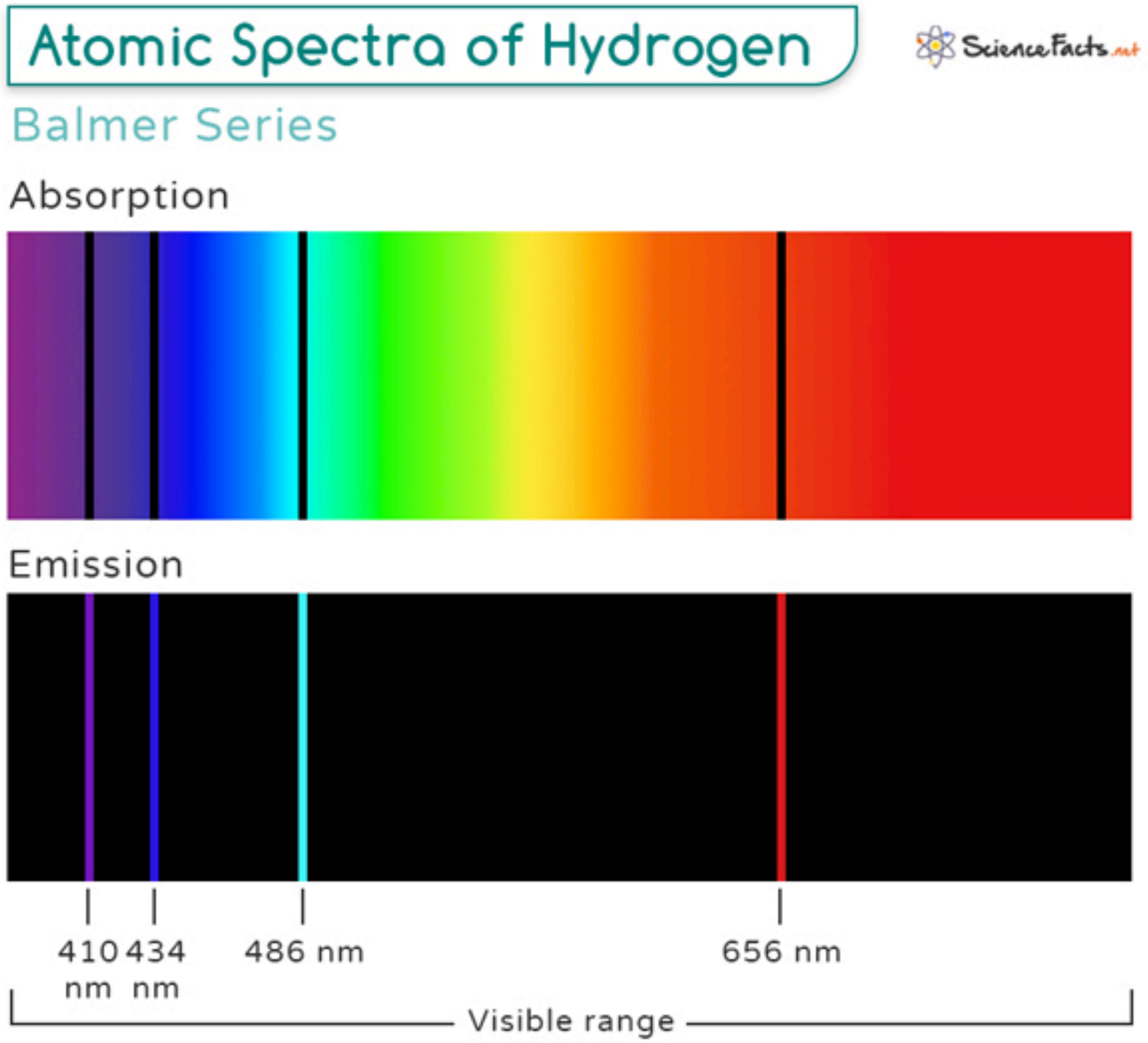


$$E_n = -\frac{m_e e^4}{2(4\pi\epsilon_0)^2\hbar^2}\frac{1}{n^2}$$

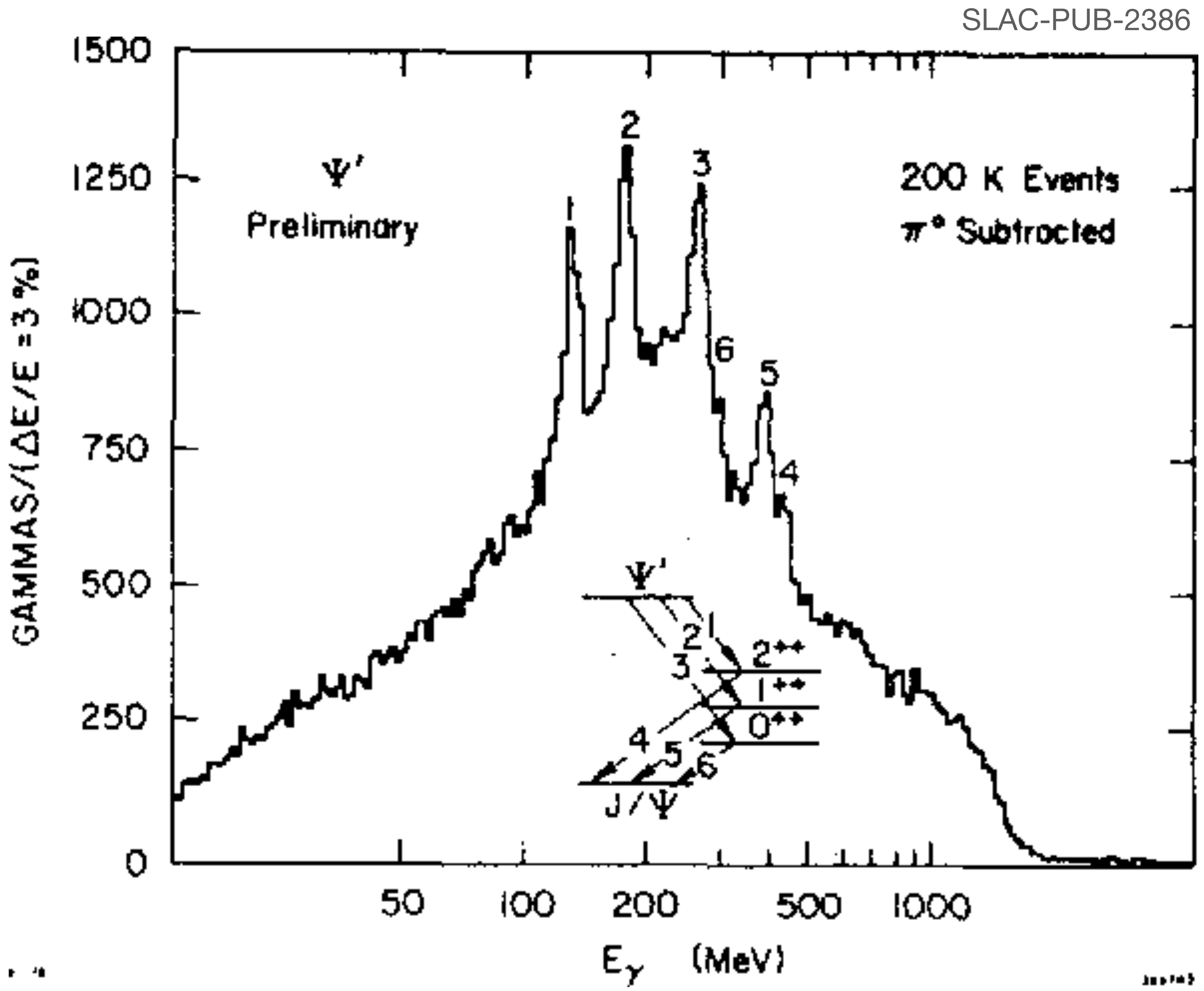


Why quarkonia?

Quarkonium spectroscopy



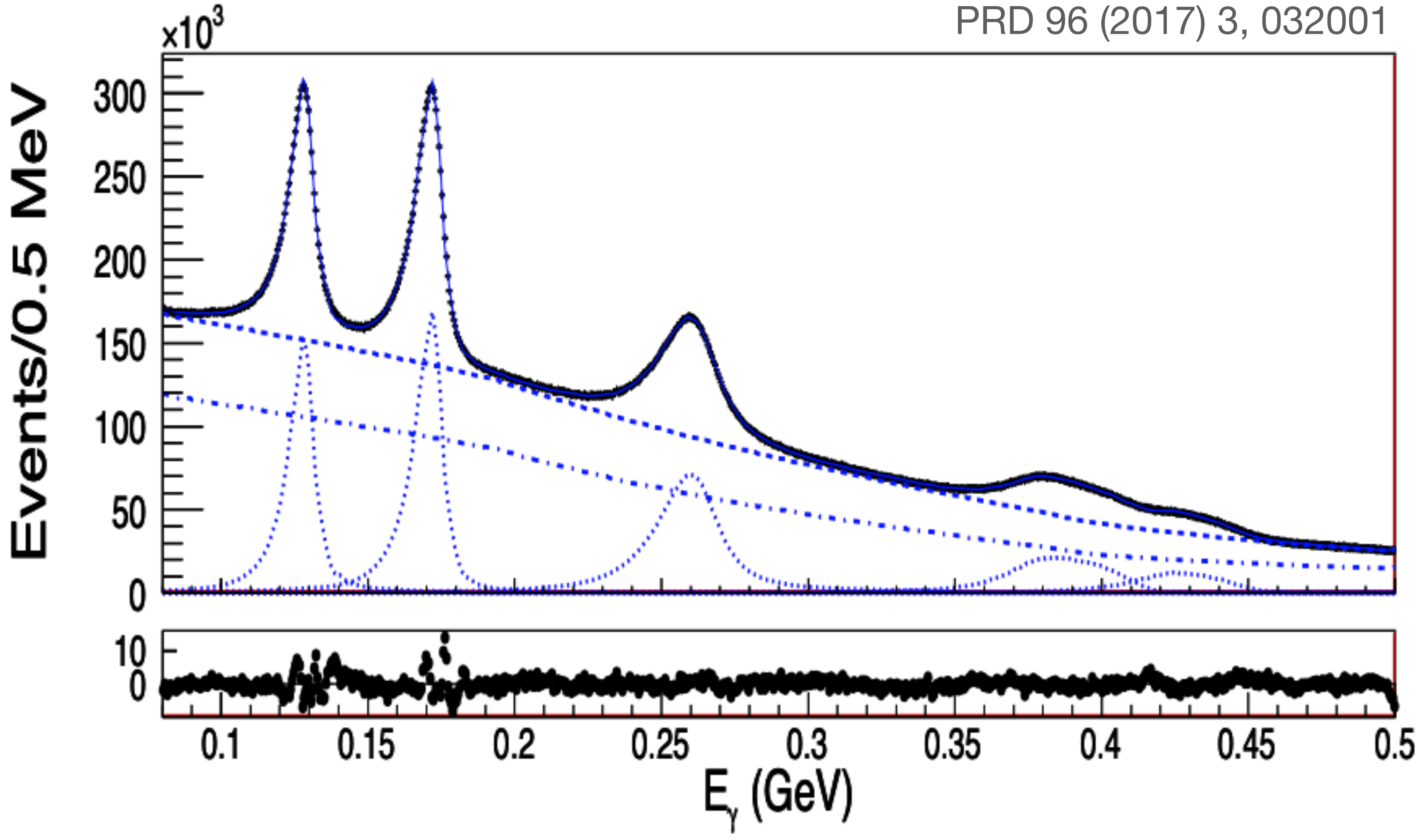
Charmonium



Quarkonium spectroscopy

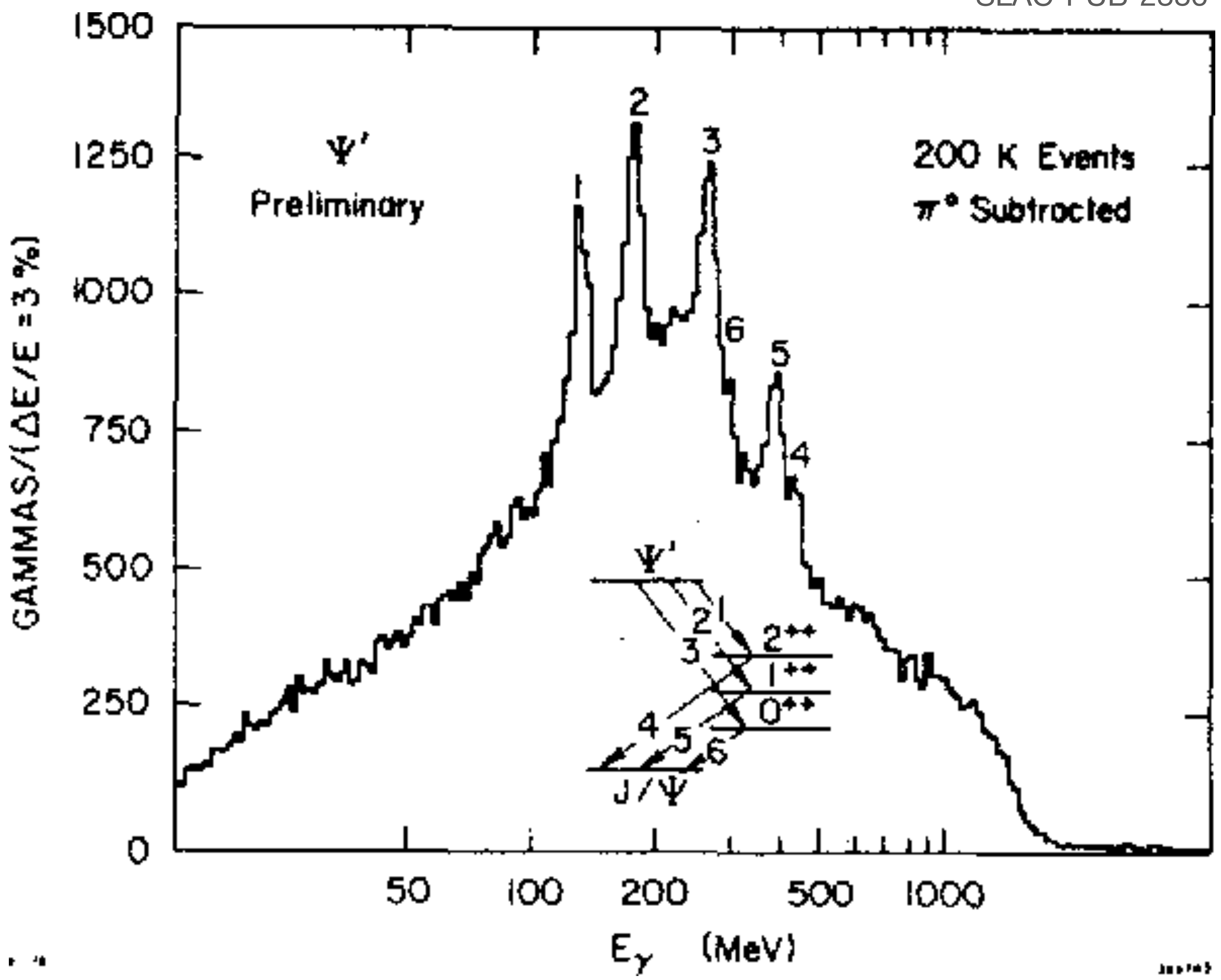
Charmonium

PRD 96 (2017) 3, 032001



Charmonium

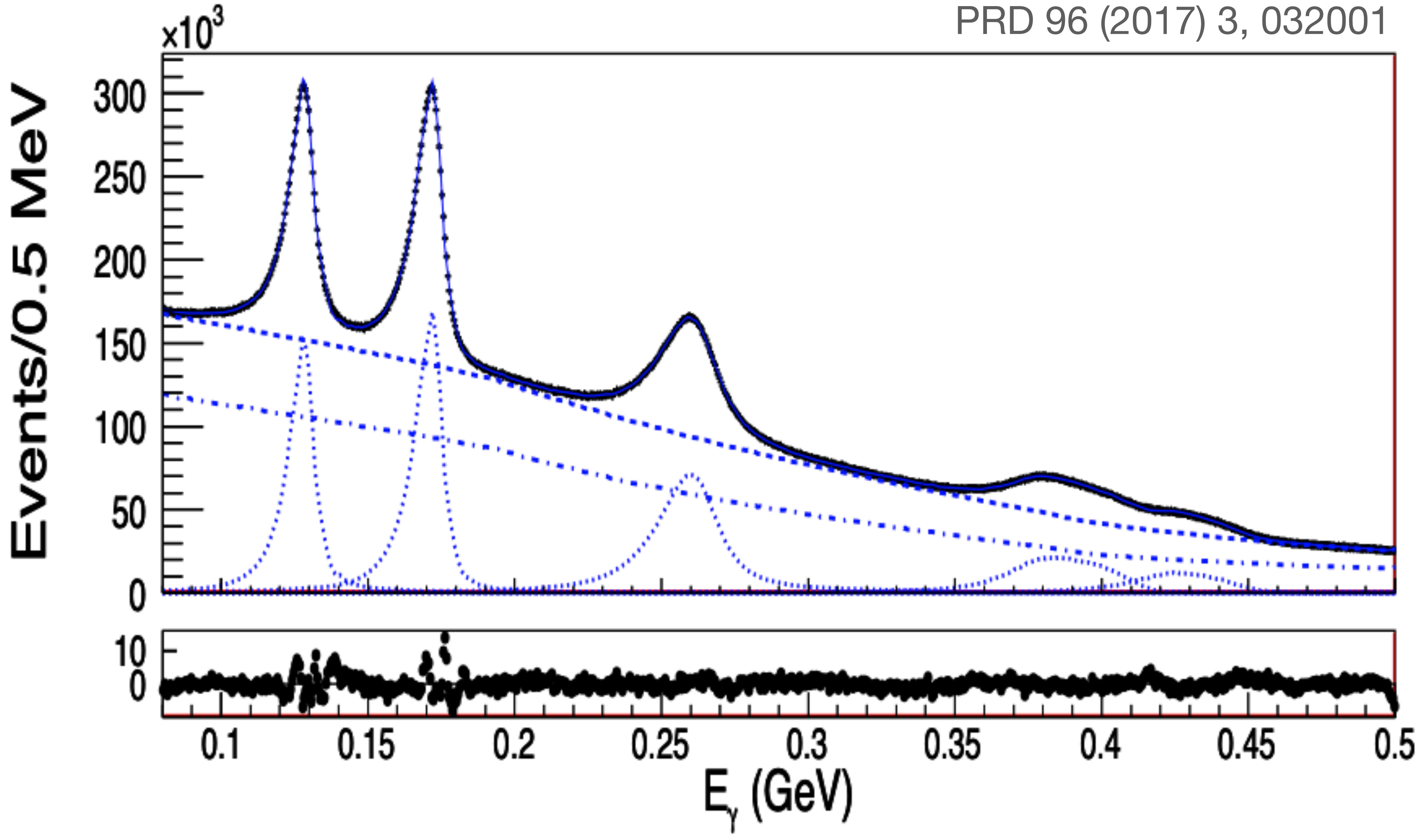
SLAC-PUB-2386



Quarkonium spectroscopy

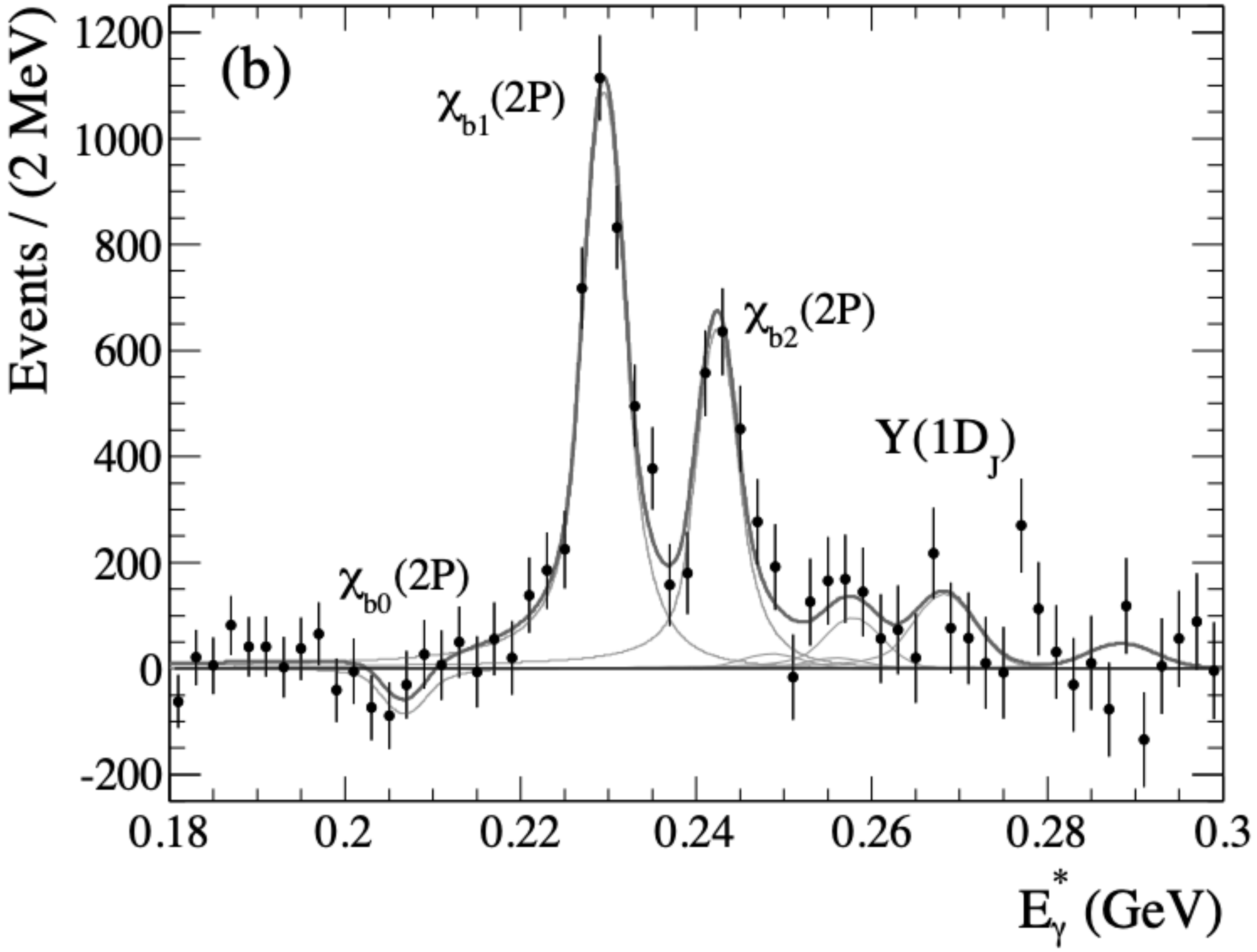
Charmonium

PRD 96 (2017) 3, 032001

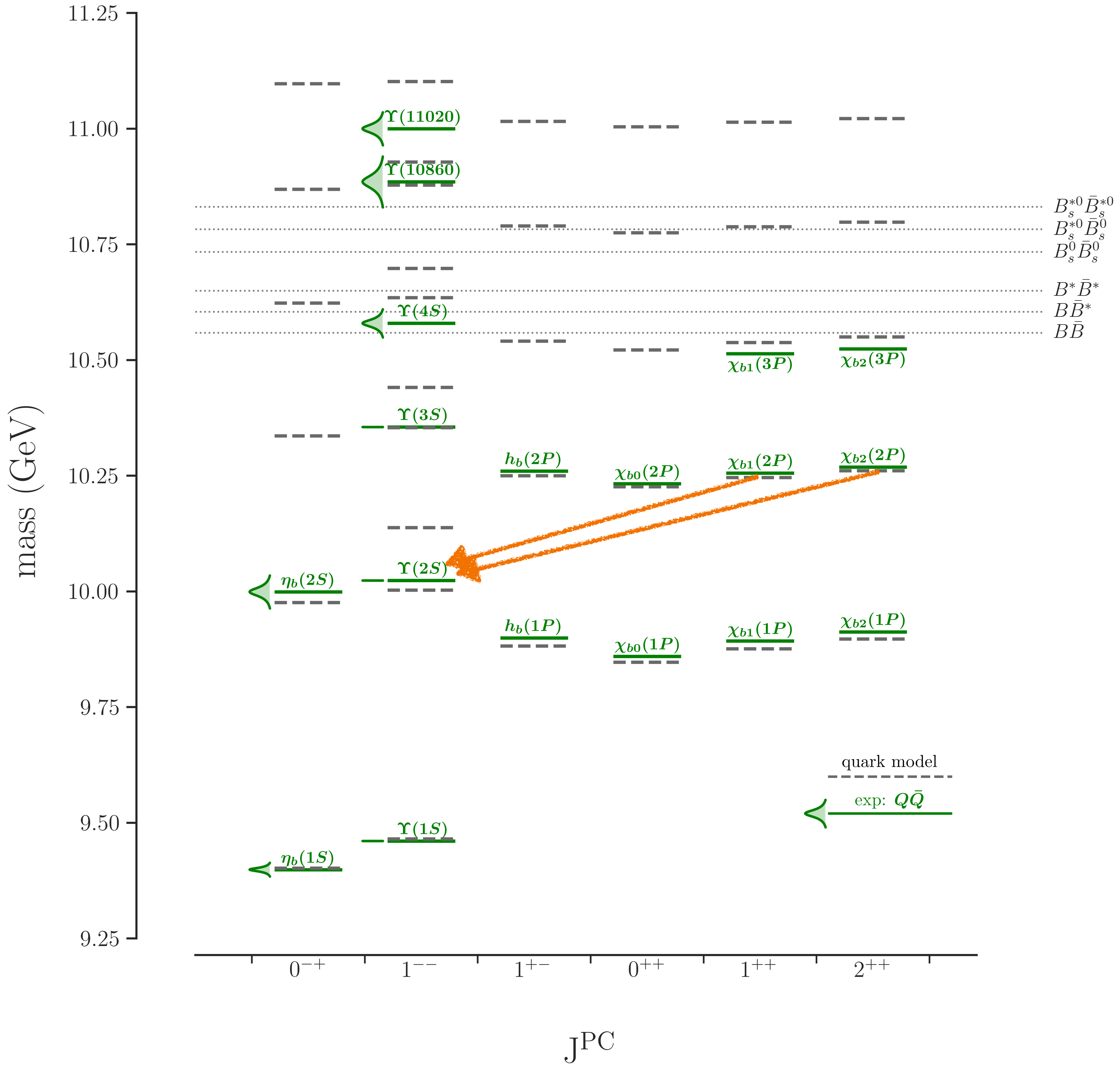


Bottomonium

BABAR, PRD 84 (2011) 072002



Quarkonium spectroscopy



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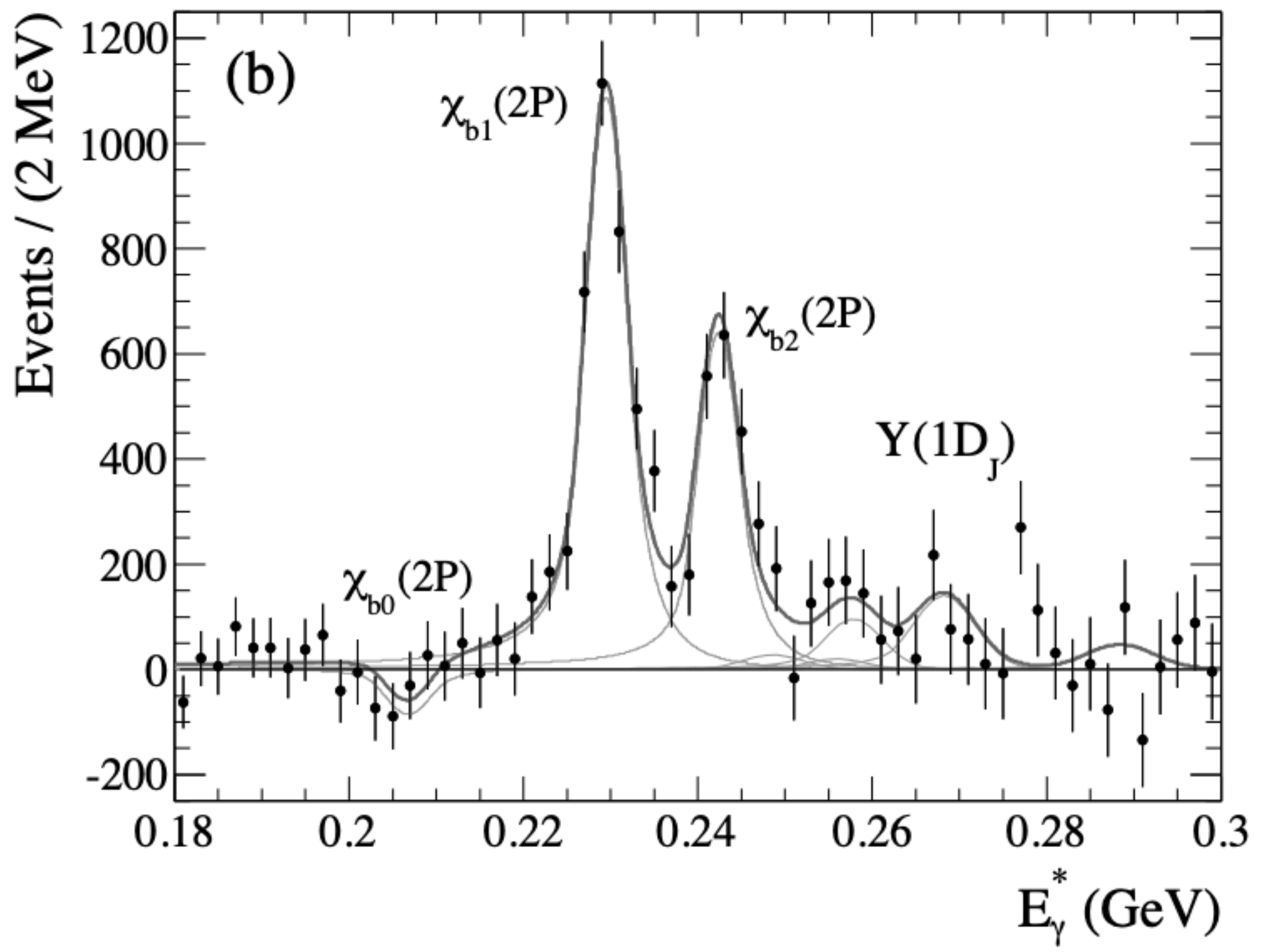

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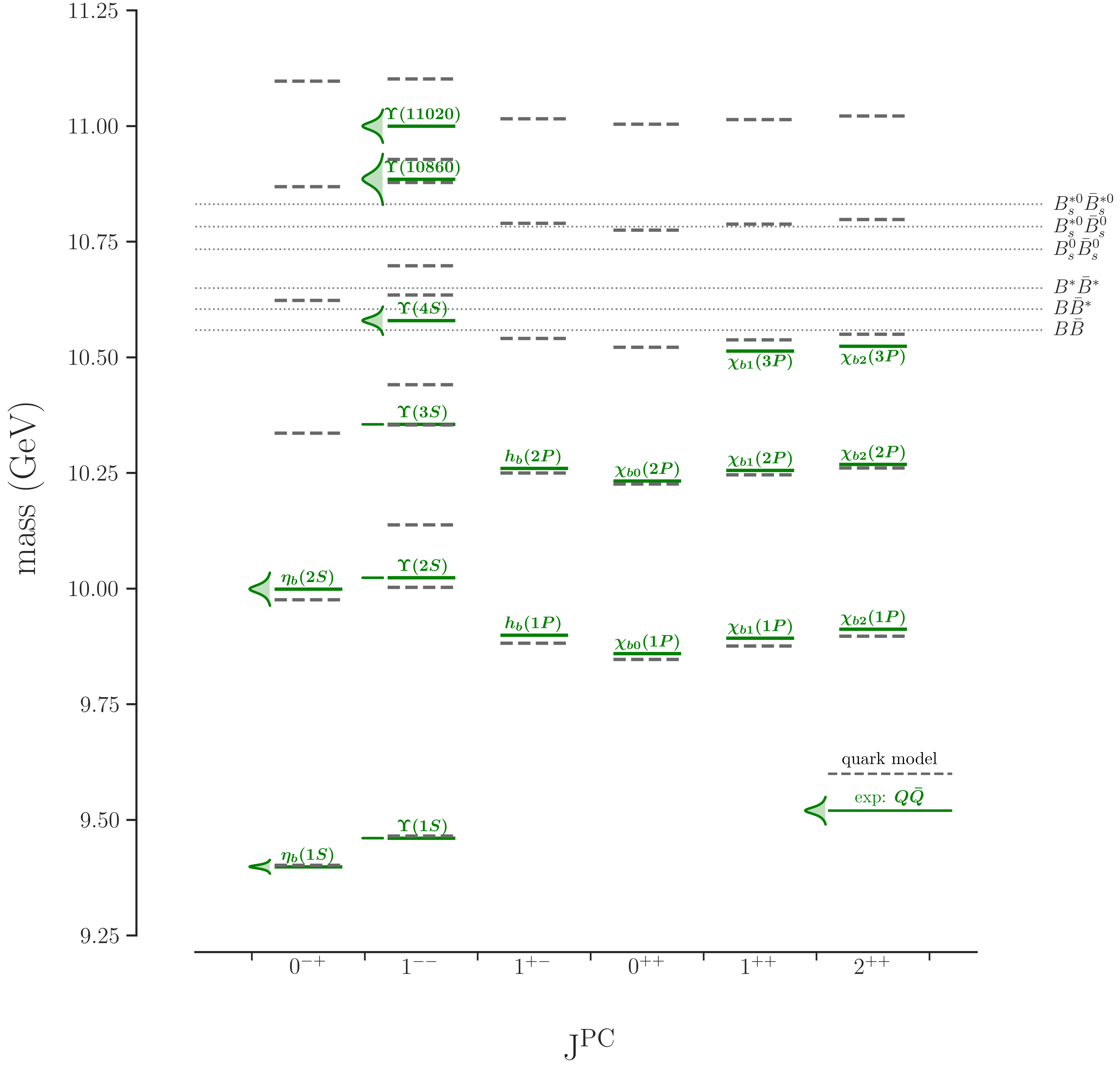
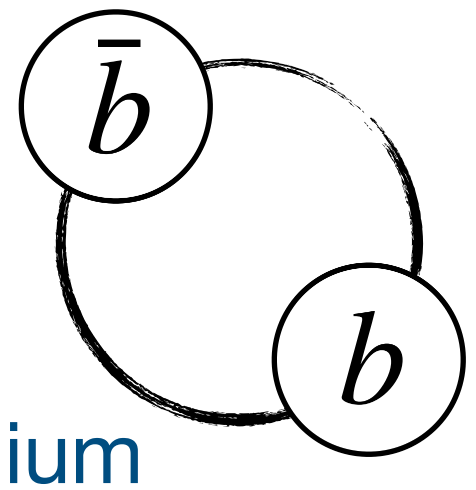
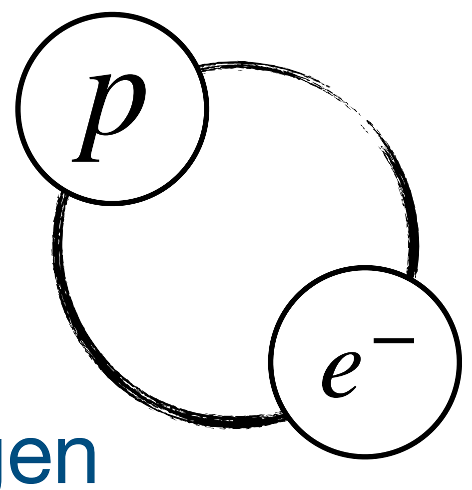


quarkonium: $Q\bar{Q}$-meson

strong interaction version of the hydrogen atom



bottomonium



hydrogen

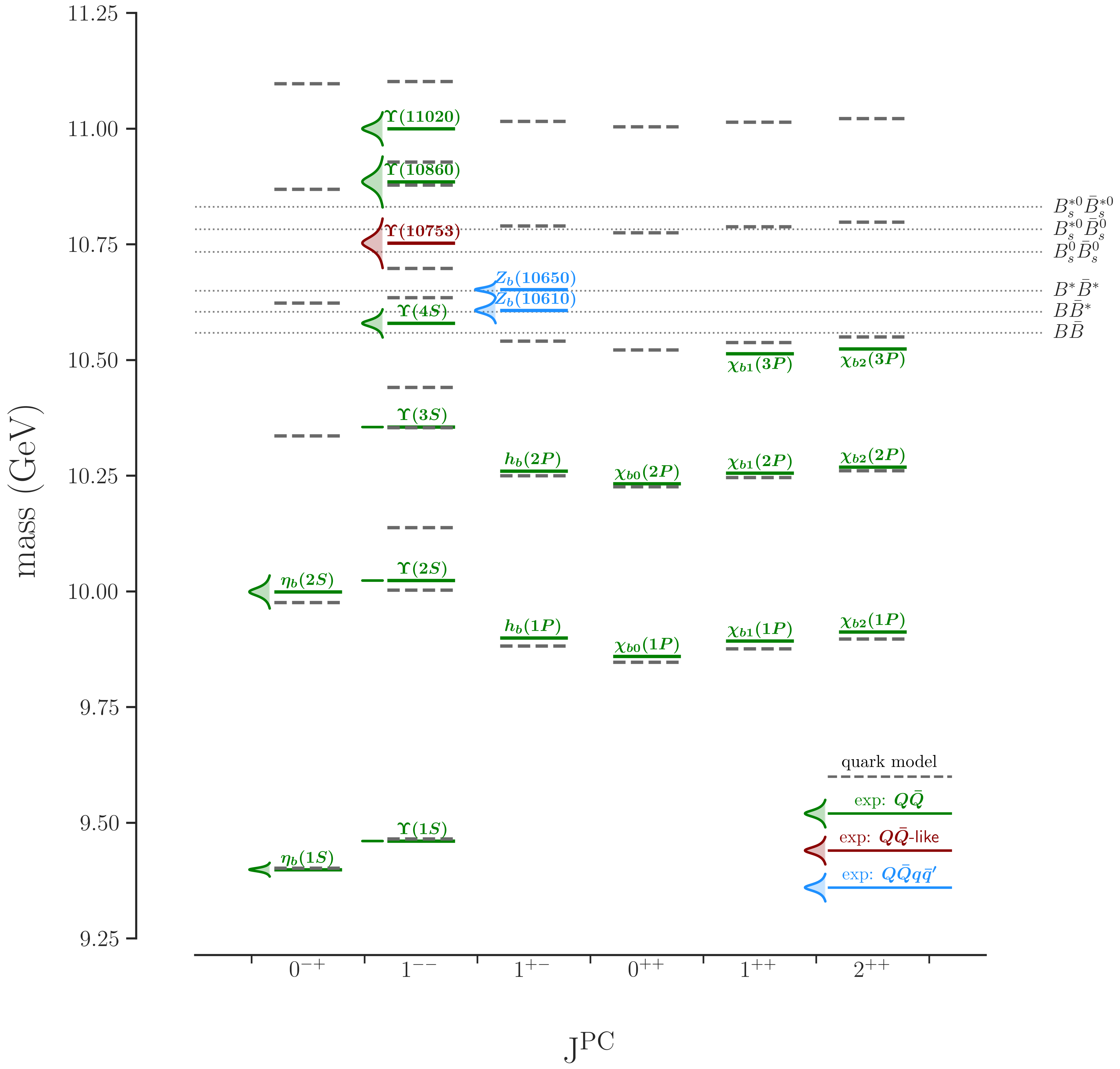
we can calculate the spectrum using similar methods

potential: $$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + kr$$

+ spin-dependent terms

see e.g.: Godfrey & Isgur, PRD 32 (1985) 189-231
Barnes, Godfrey, Swanson, PRD 72 (2005) 054026
Godfrey & Moates, PRD 92 (2015) 054034

Quarkonium spectroscopy



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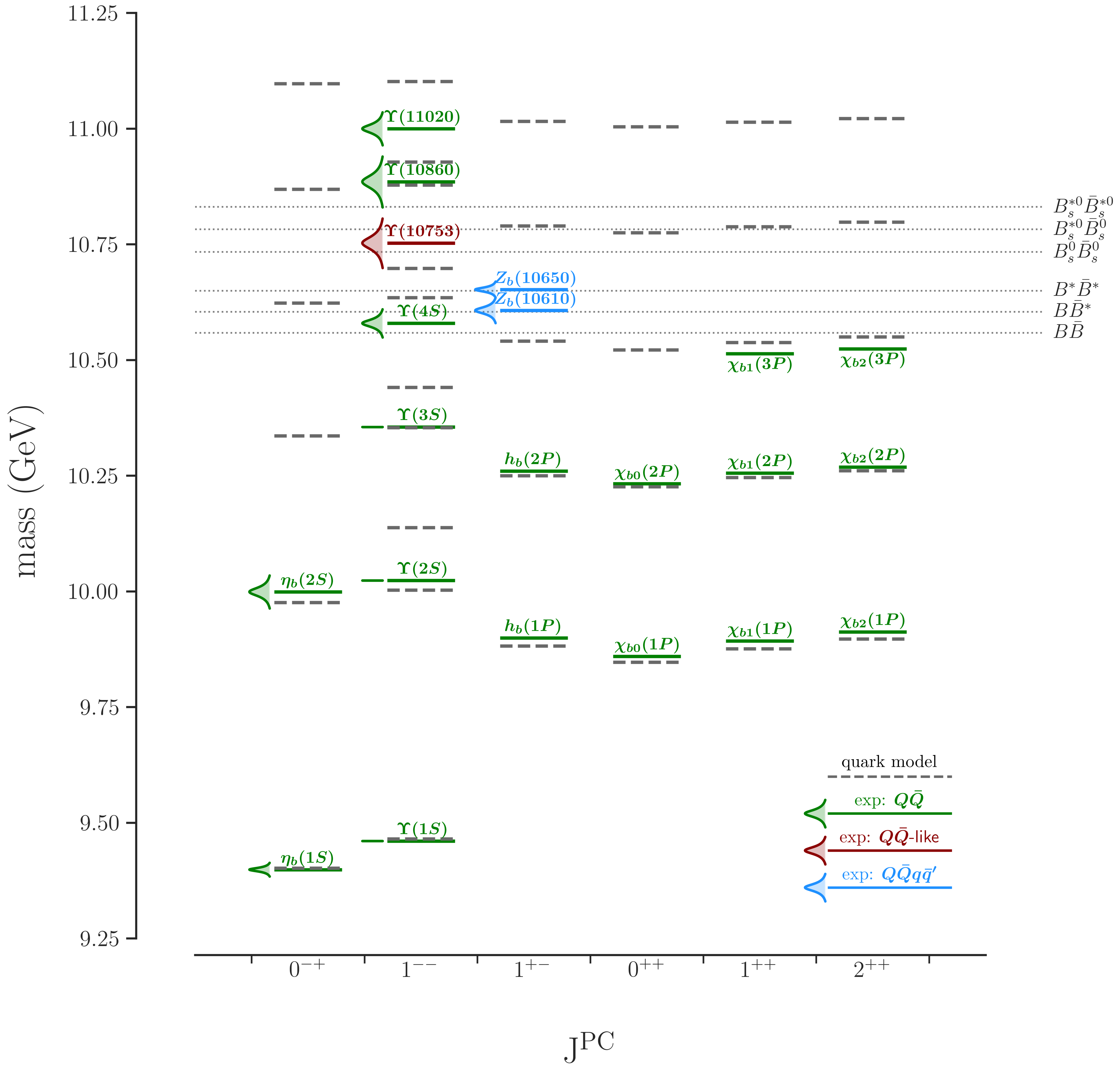
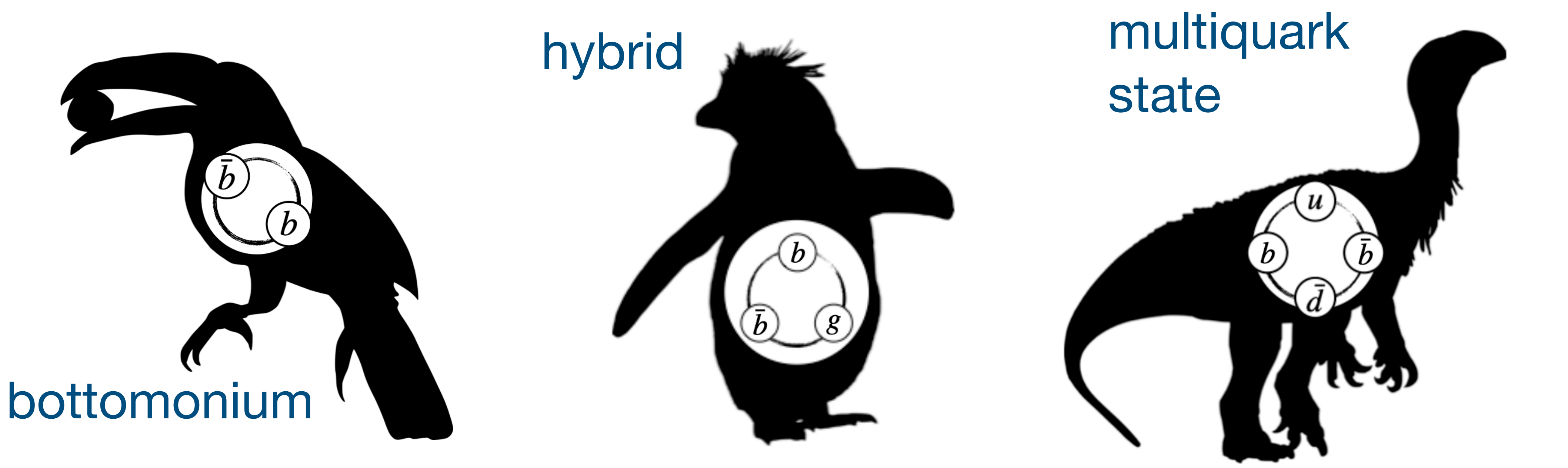


Idea: exotic / supernumerary states will stand out in well-understood quarkonium

but what are they? which kind of bound-states does the strong interaction form?



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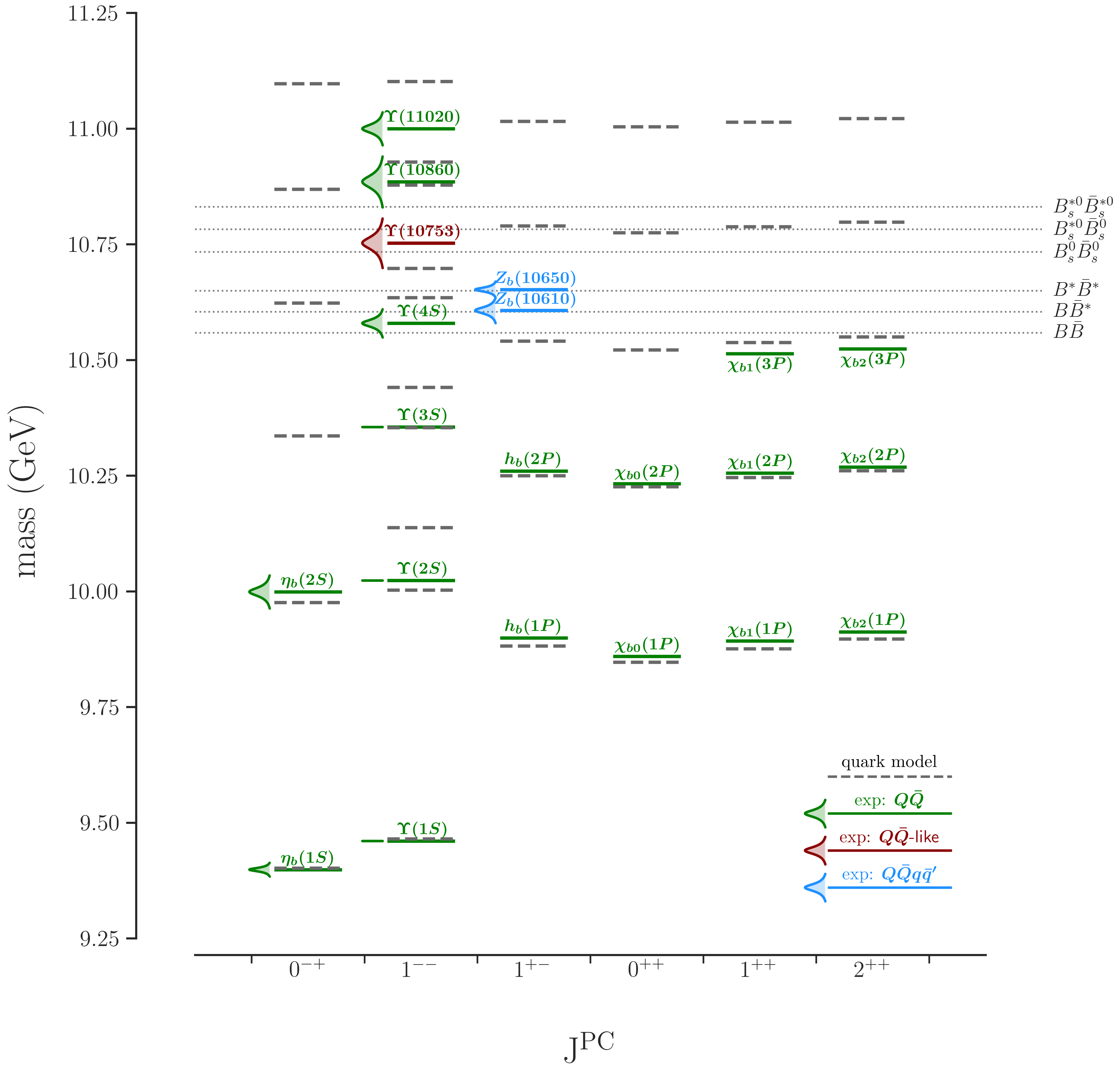

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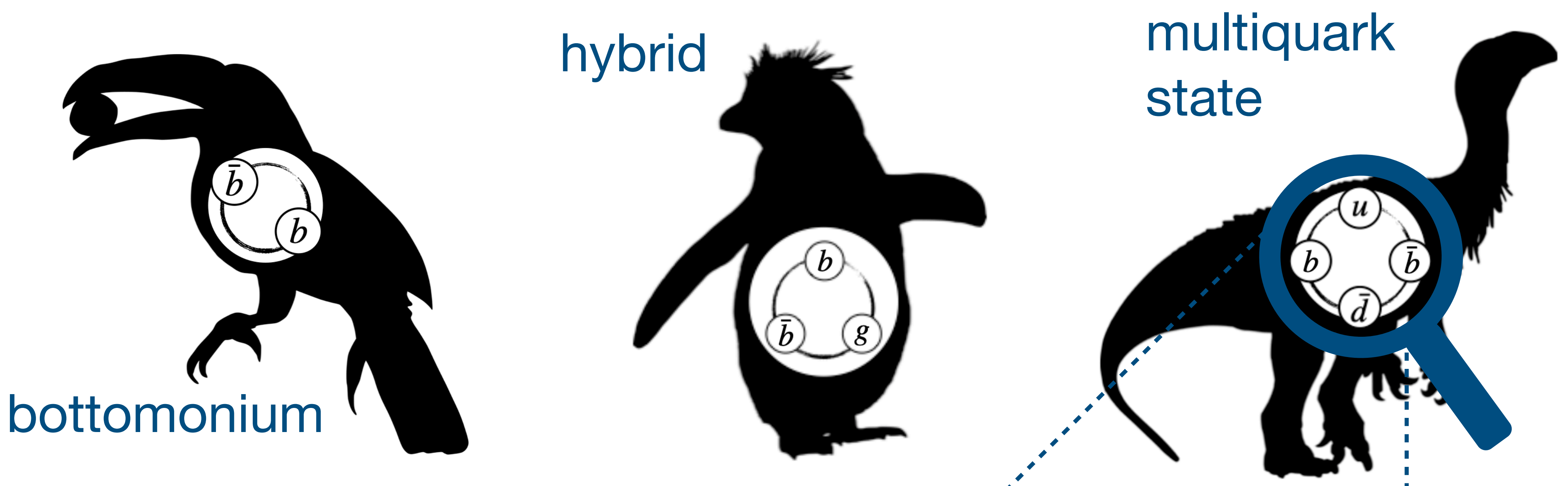
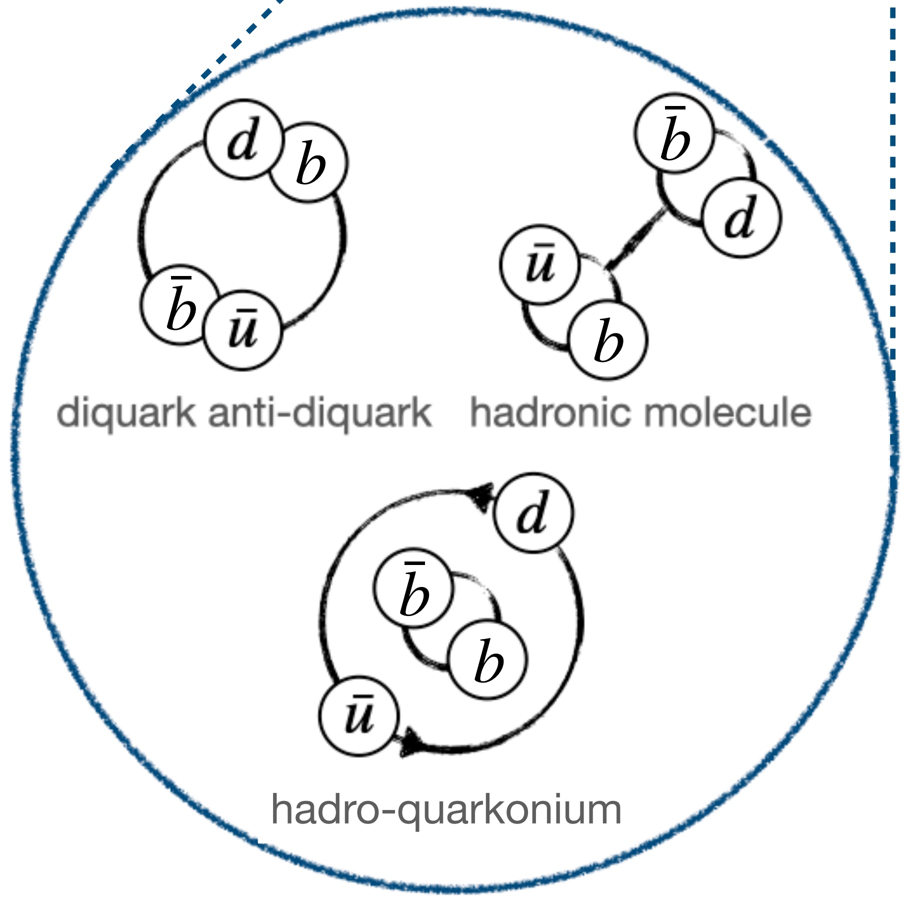
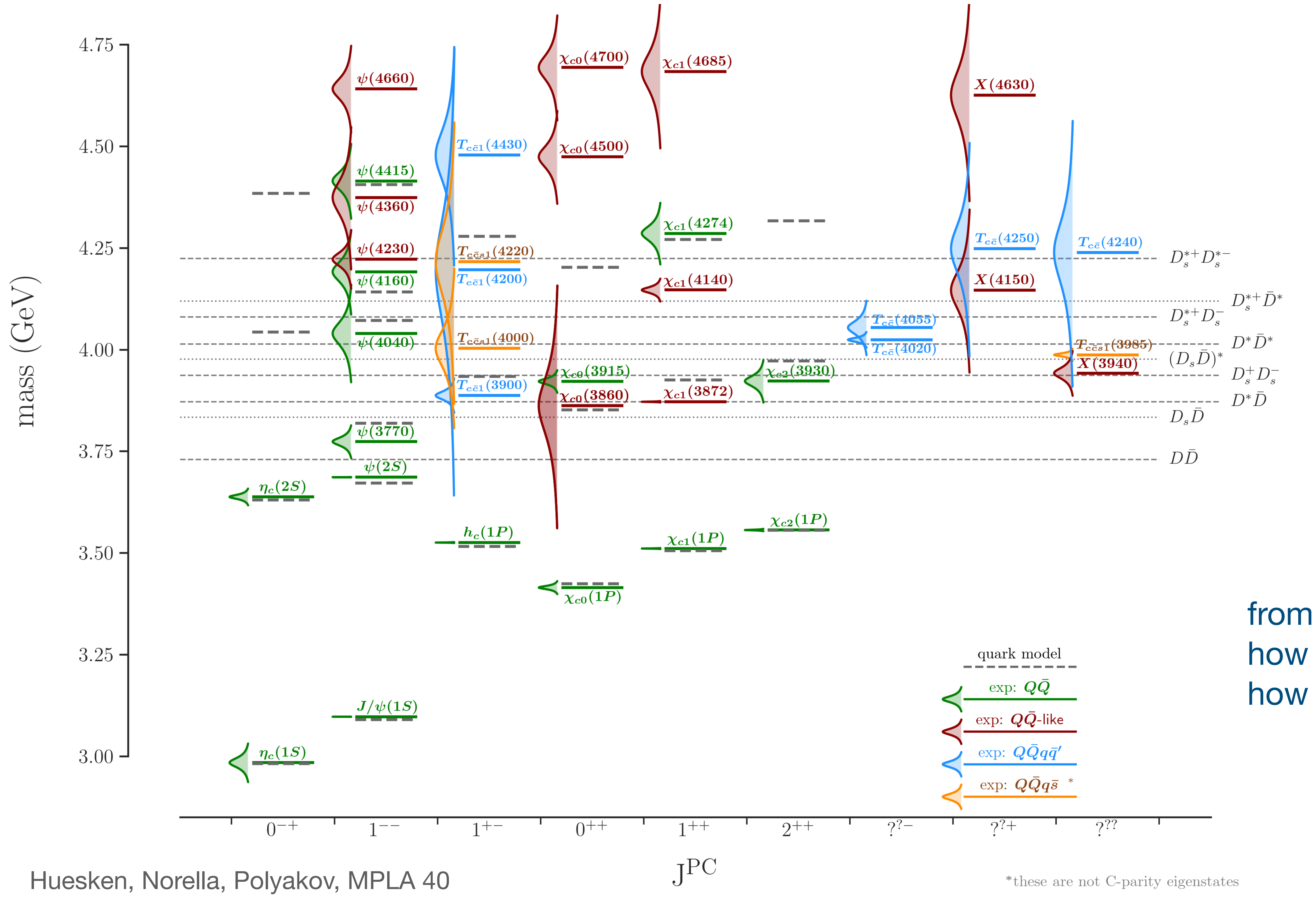


from experiment: provide information
how is a state produced?
how does it decay?



Quarkonium spectroscopy



Huesken, Norella, Polyakov, MPLA 40 (2025) 17n18, 2530002

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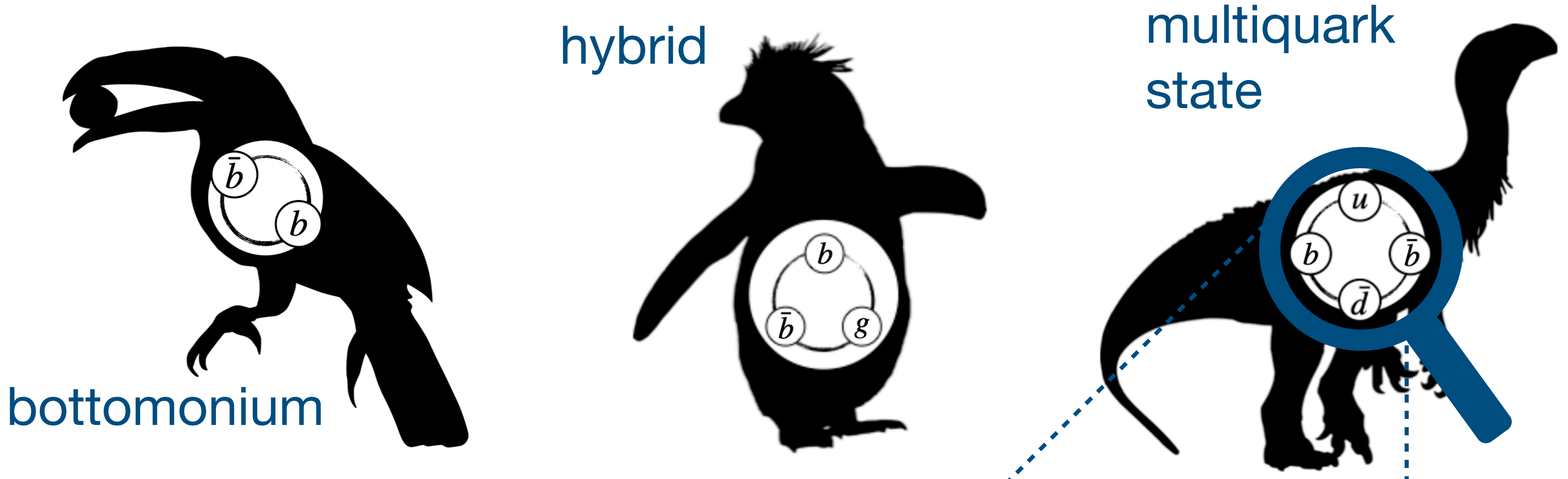

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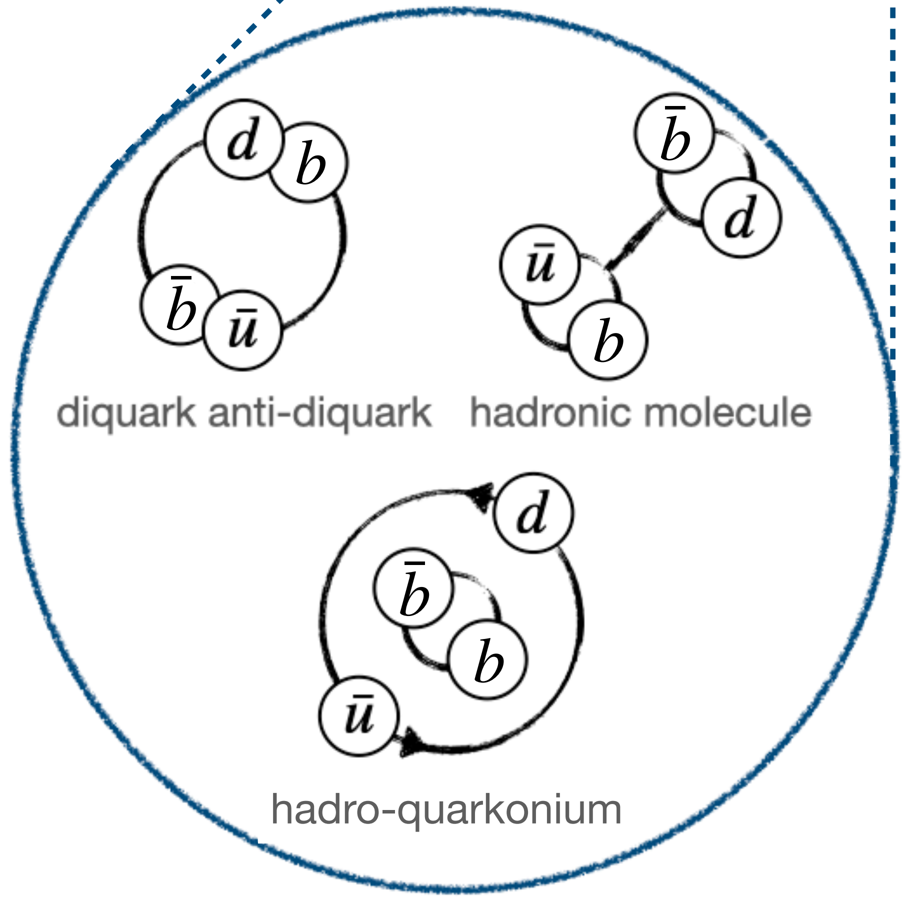
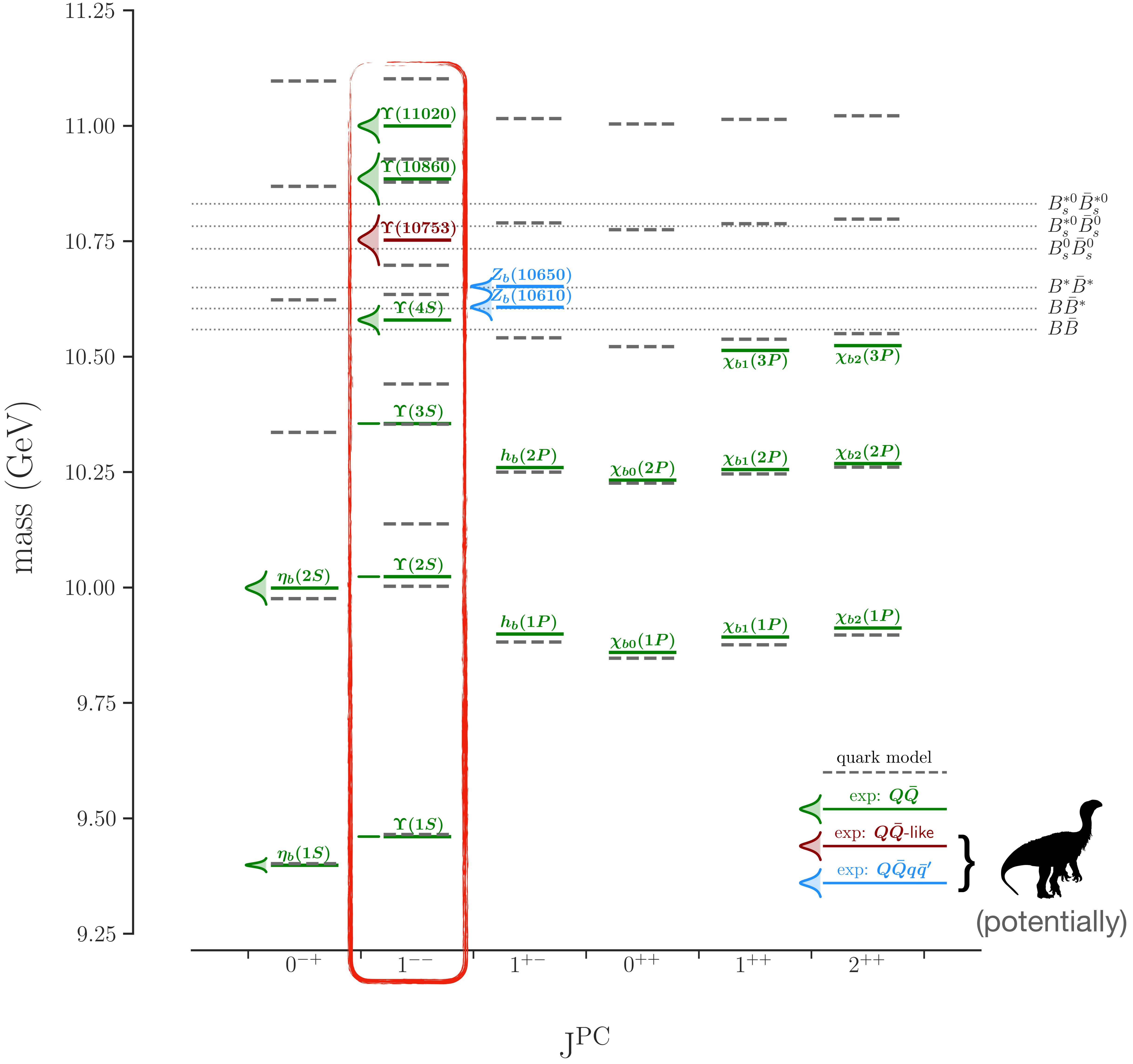
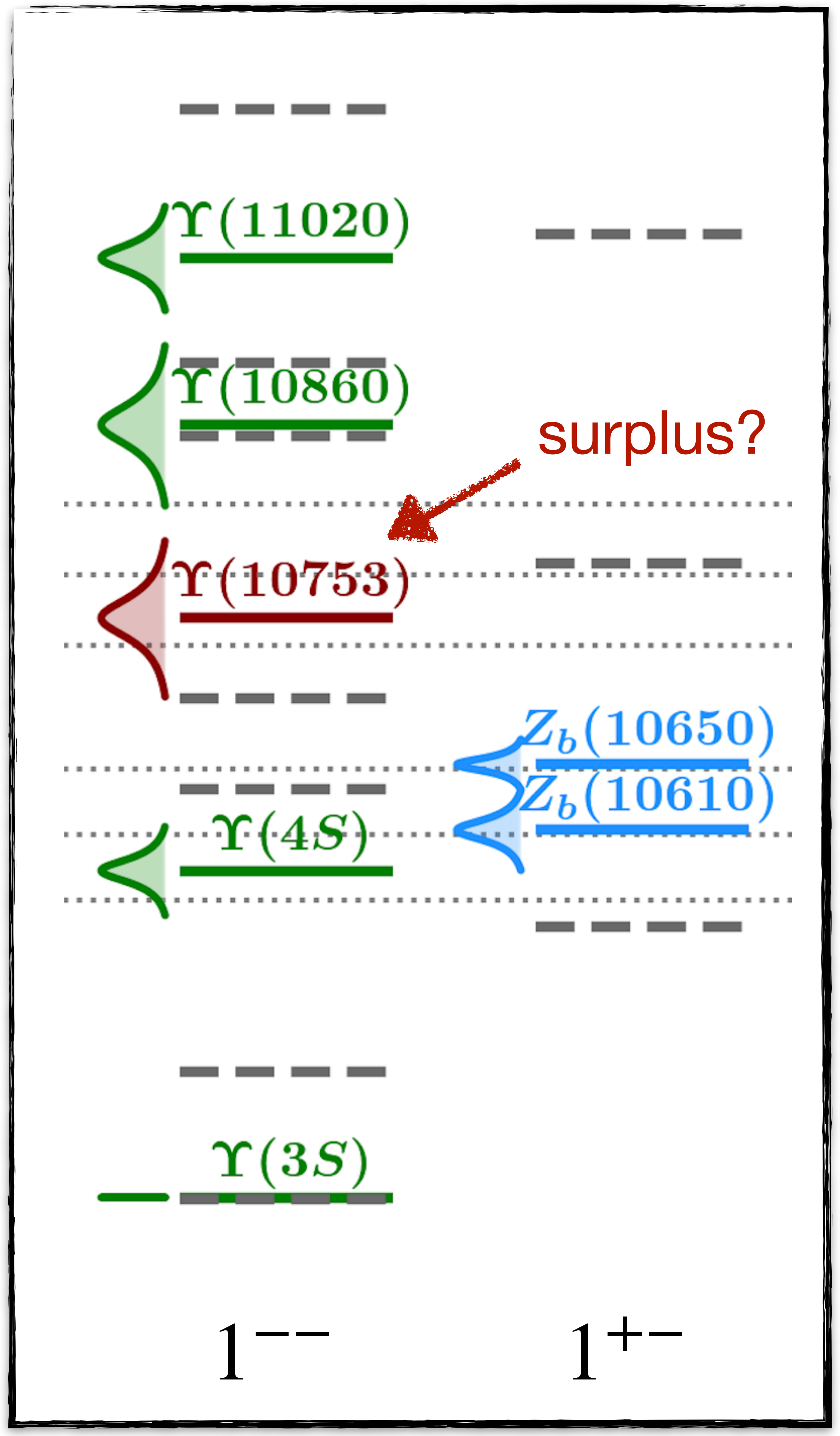


Why the vector states?

Vector bottomonia

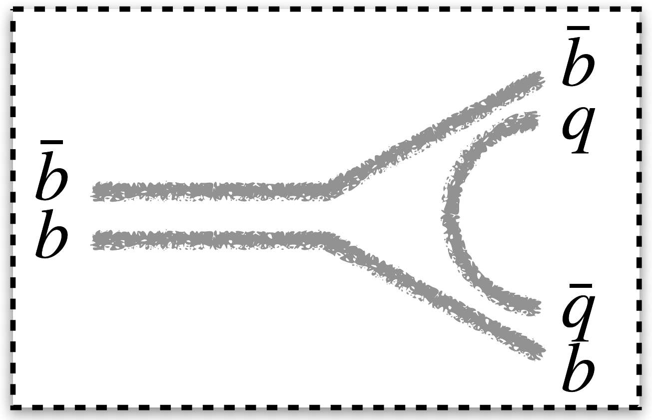


Vector bottomonia



$B\bar{B}$

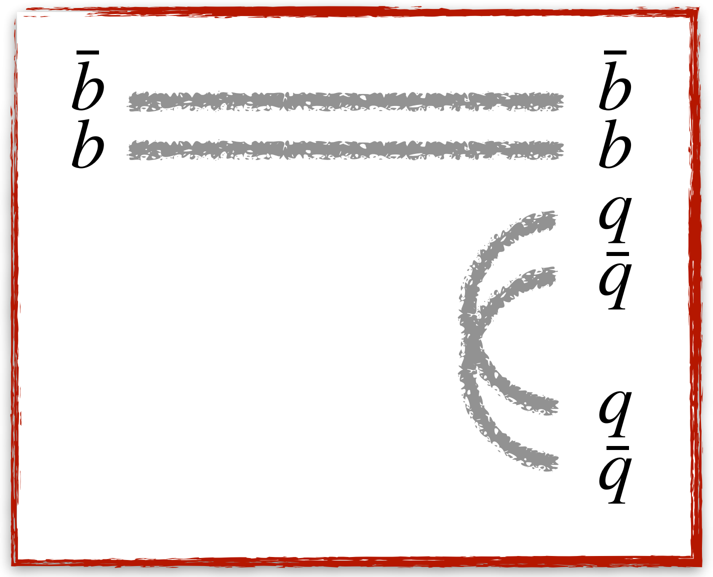
this decay
should dominate



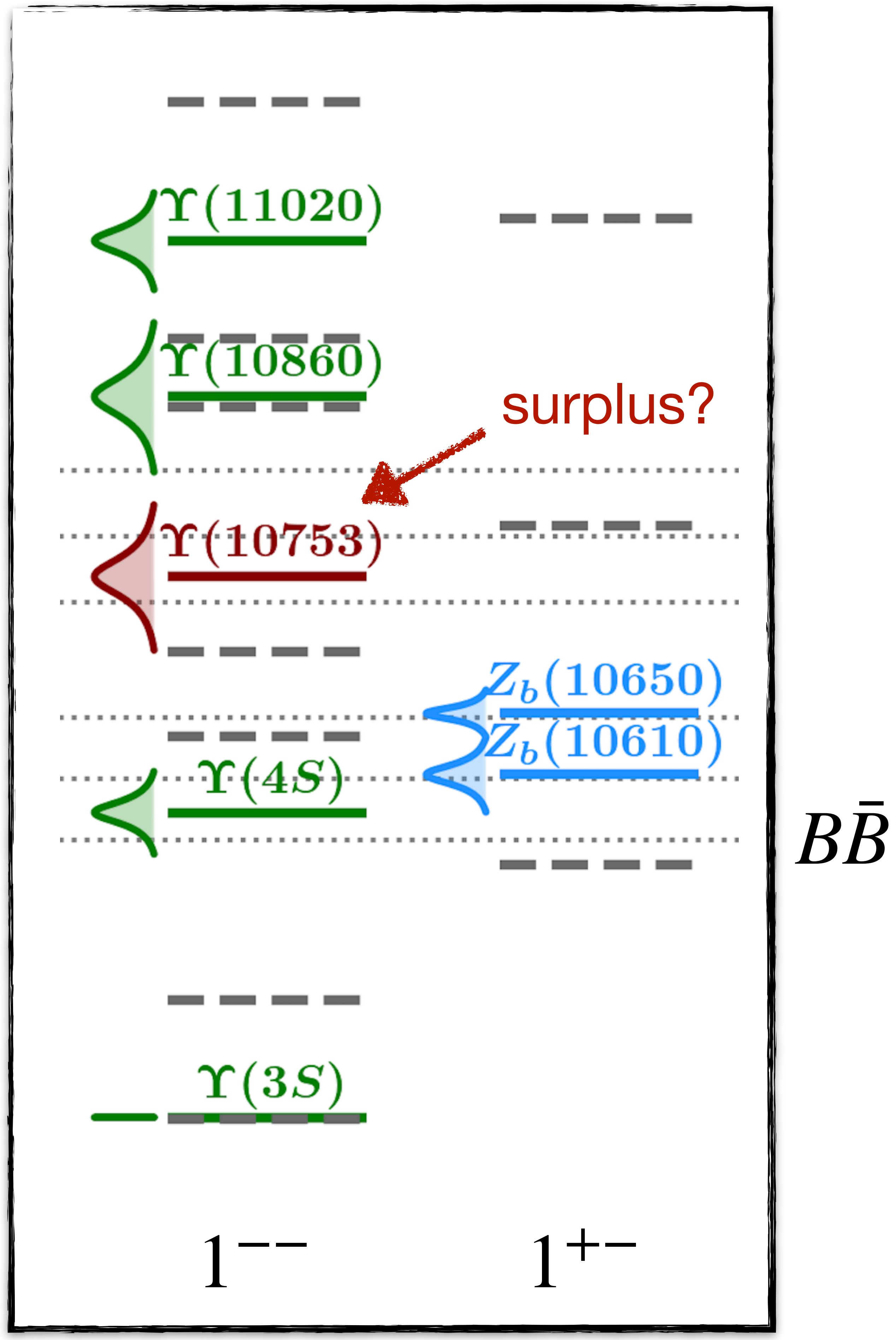
(Zweig-rule)

Vector bottomonia

$$e^+e^- \to \Upsilon(2S)\pi^+\pi^-$$



this sets the expectation!



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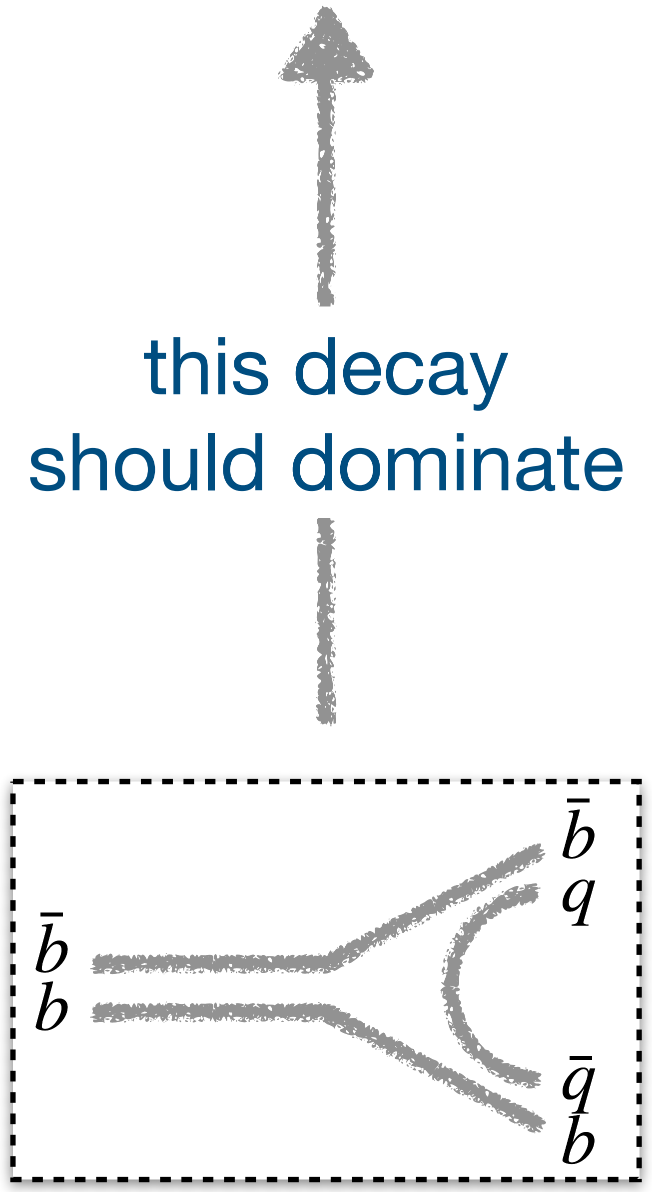

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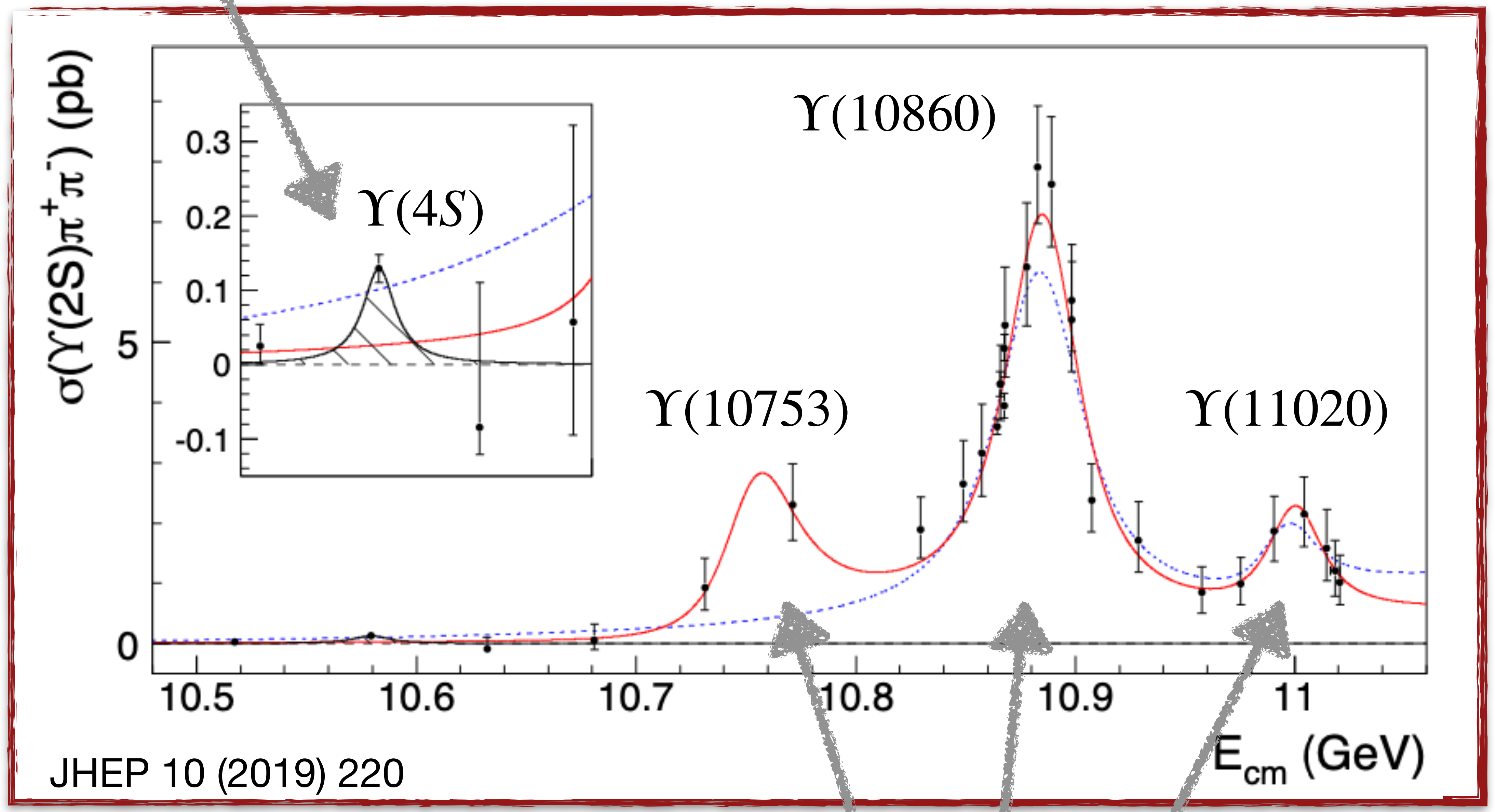
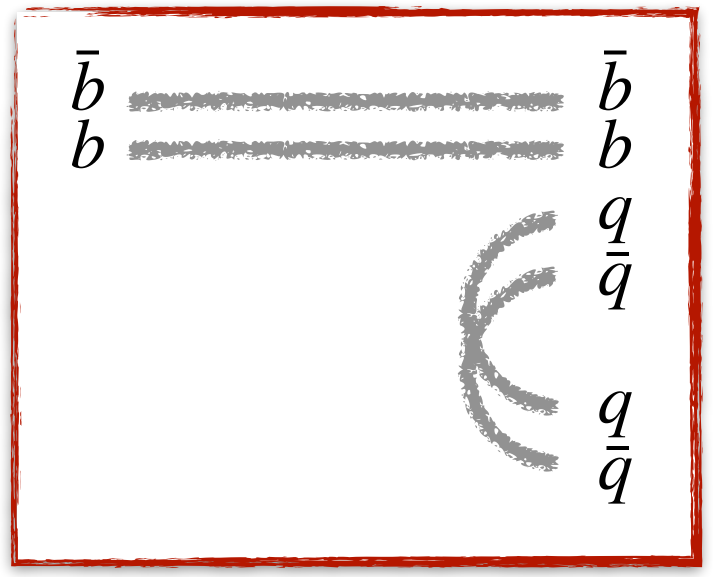


so then what is going on here?

Vector bottomonia

$e^+e^- \to \Upsilon(2S)\pi^+\pi^-$



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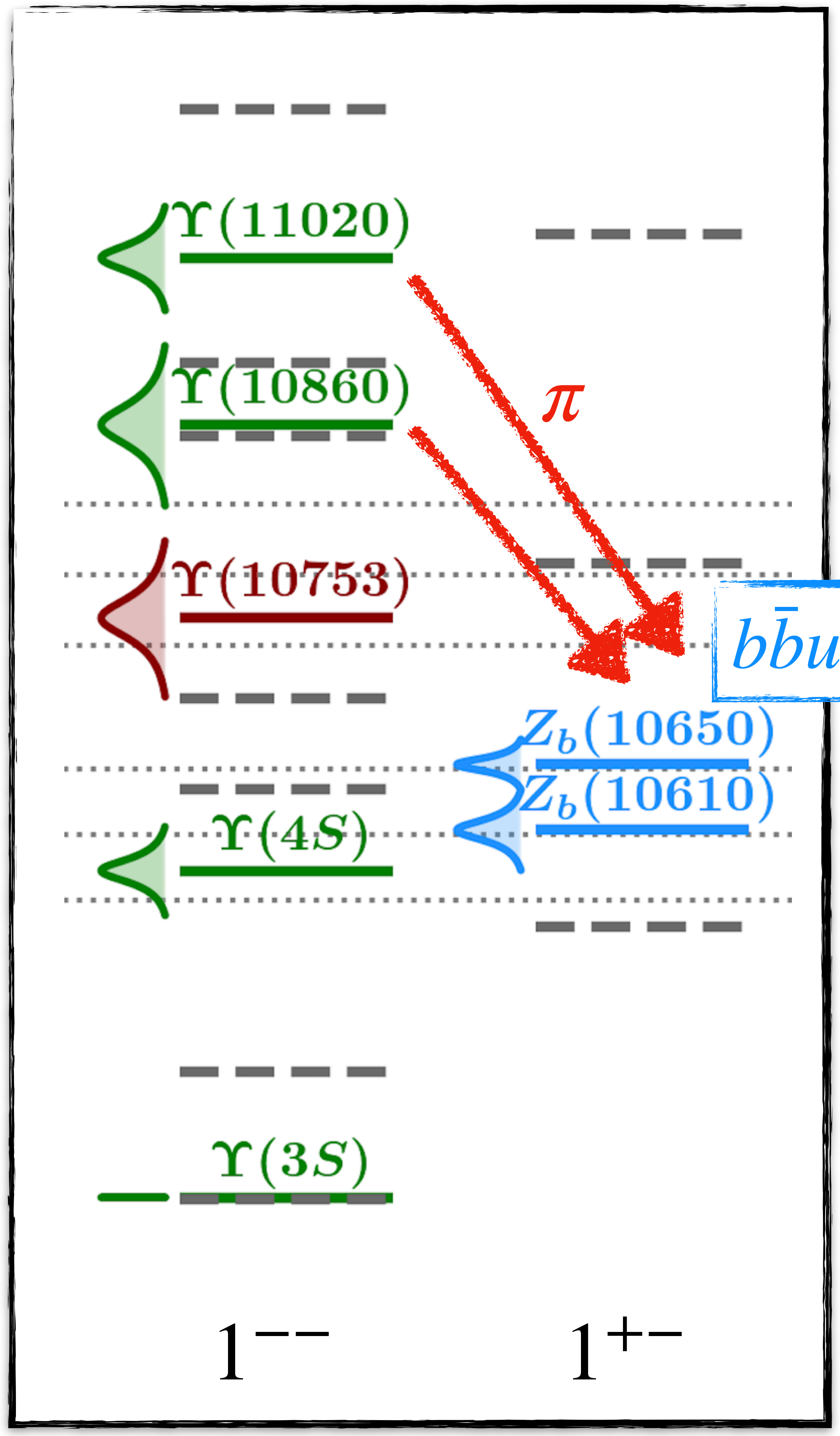
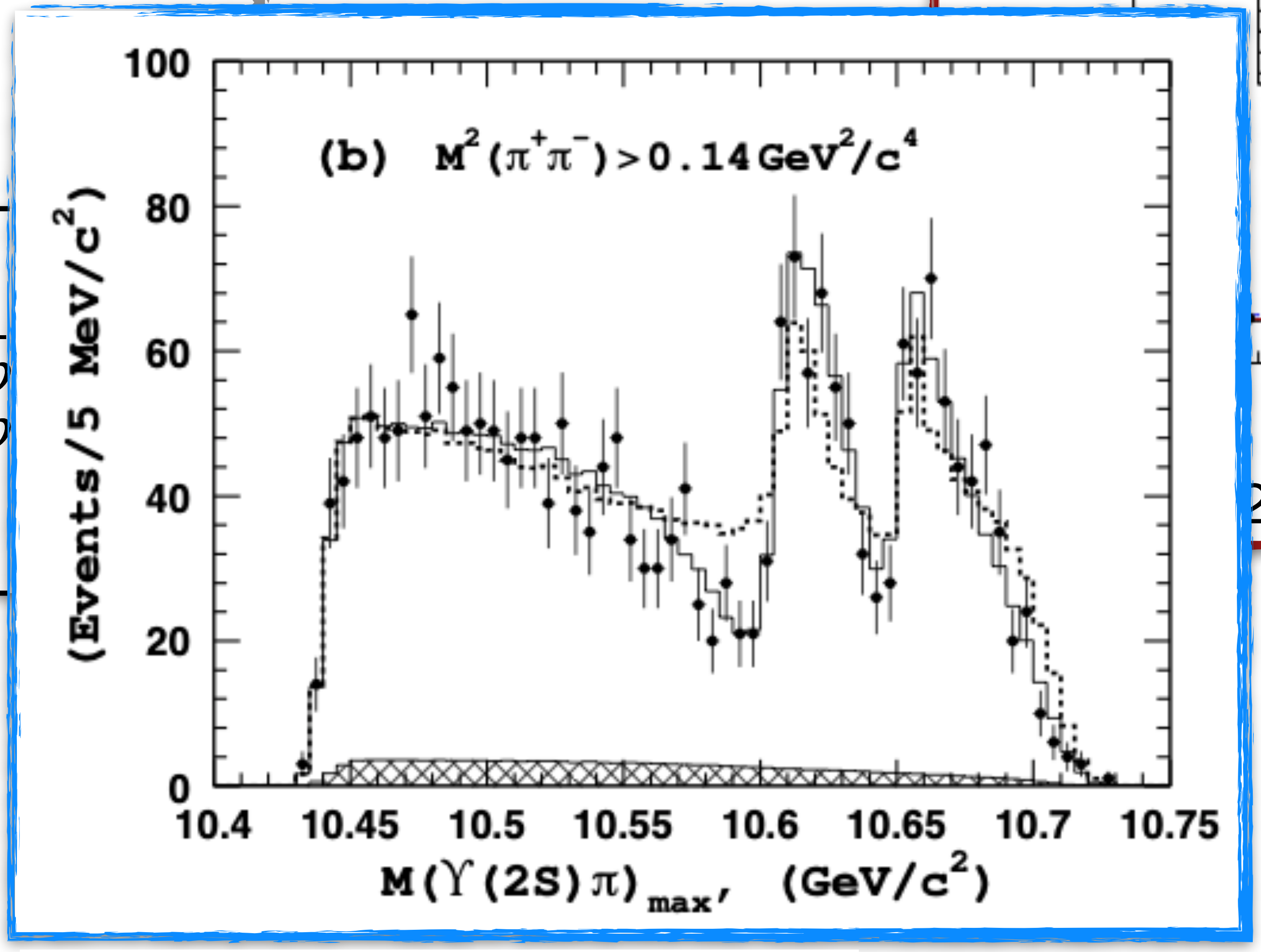


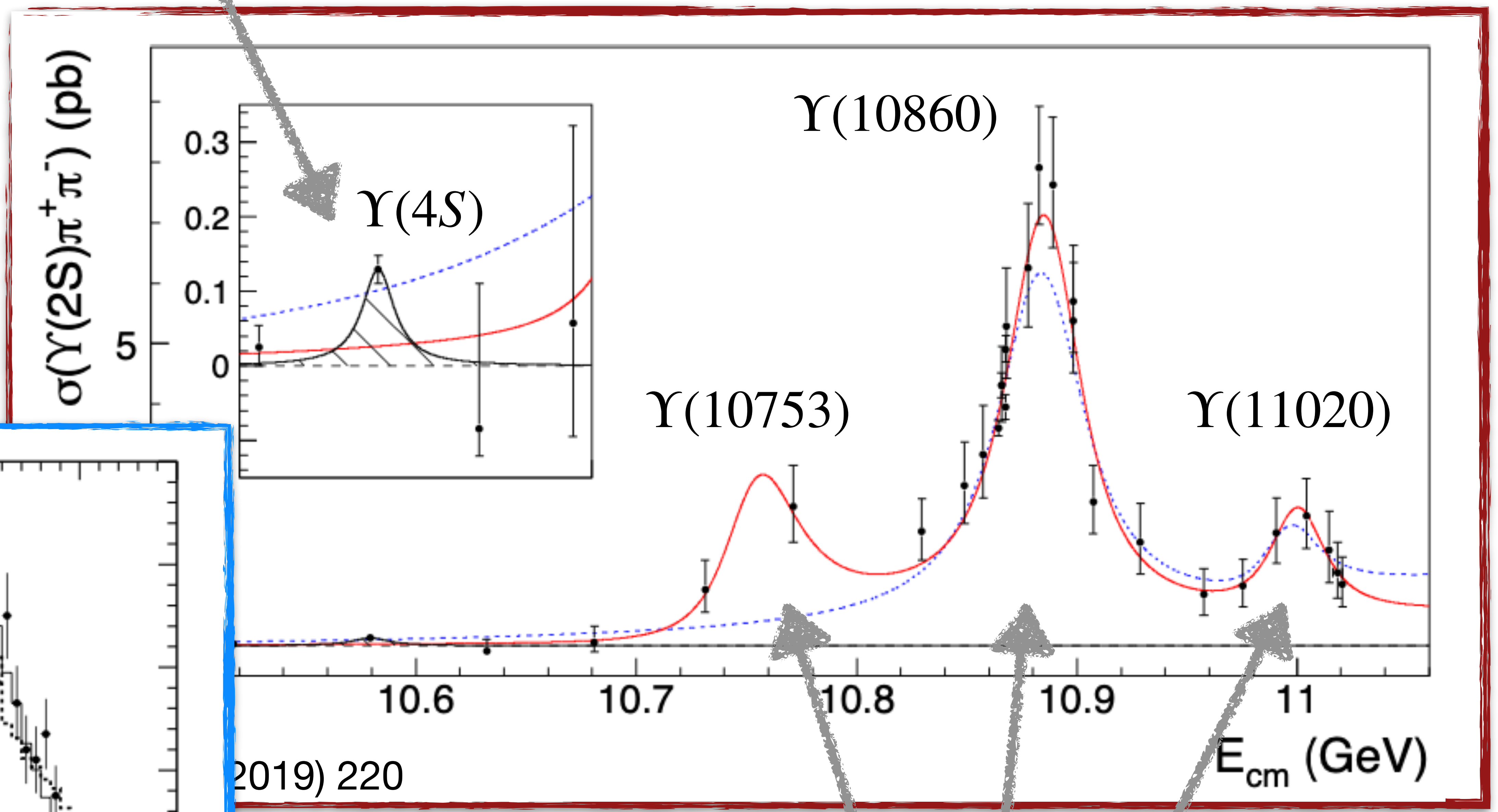
$b\bar{b}u\bar{d}$ states!

$B\bar{B}$

this decay should dominate



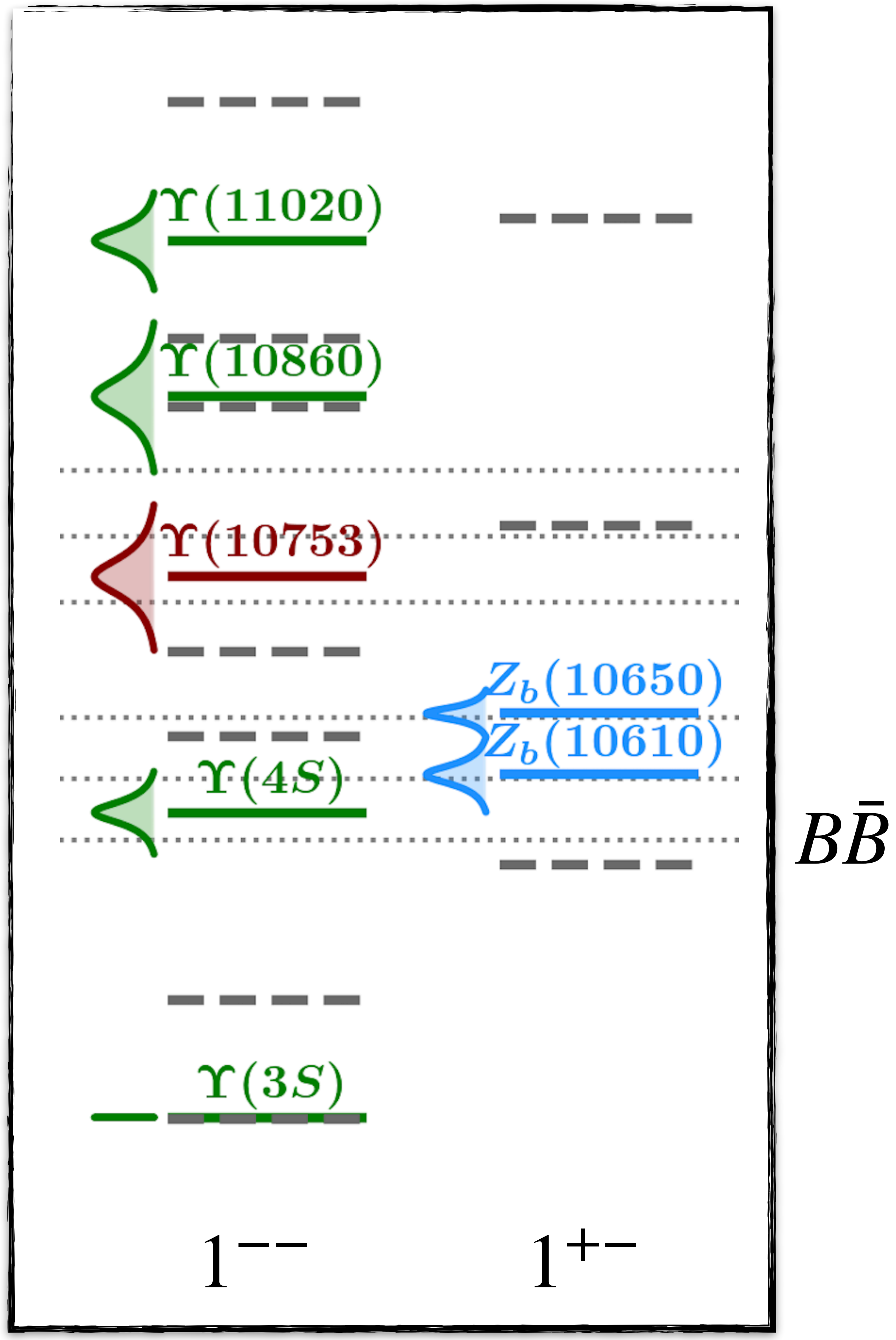
Phys. Rev. D 91 (2015) 7, 072003

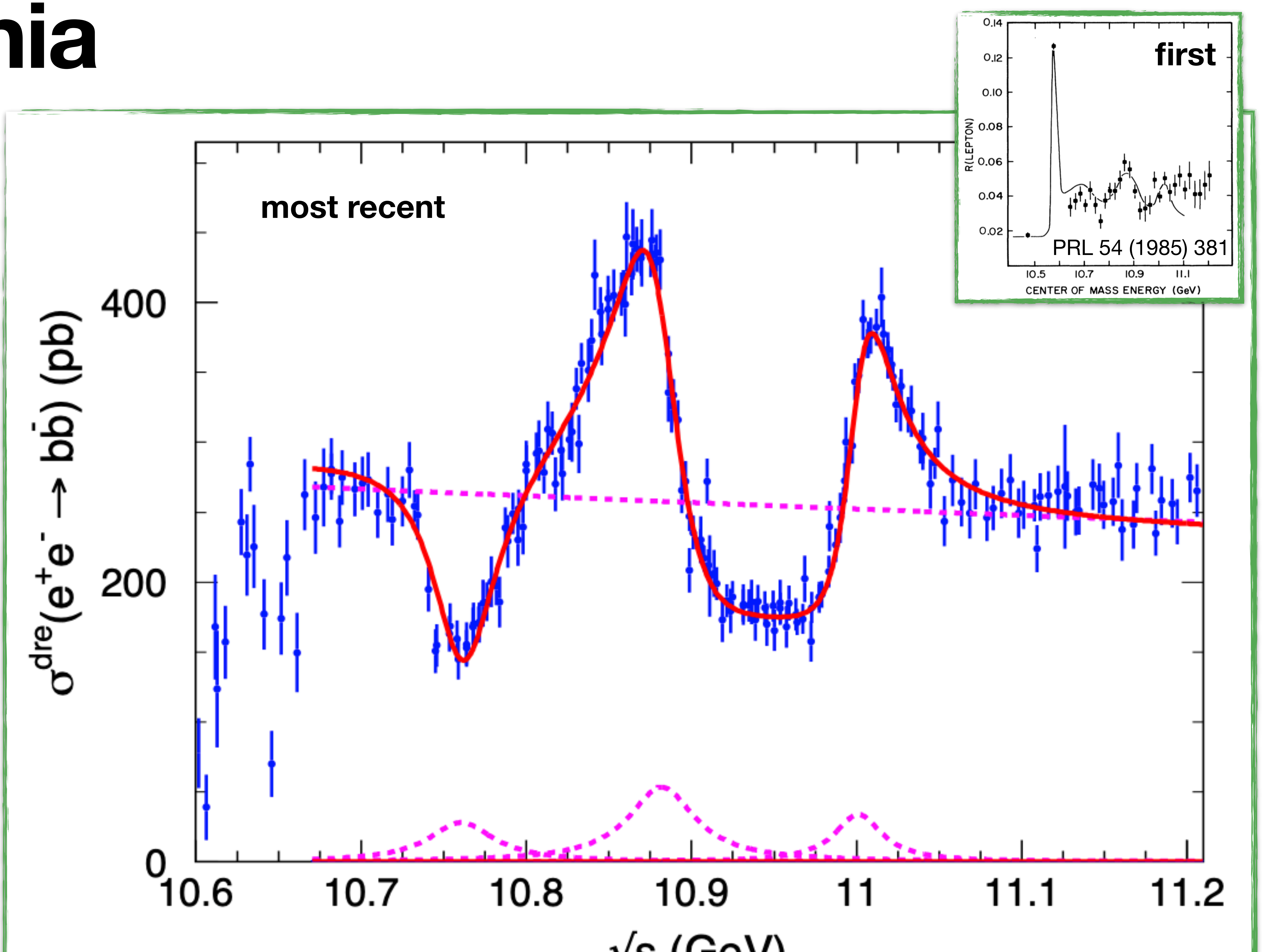


so then what is going on here?

Vector bottomonia

what else do we know?

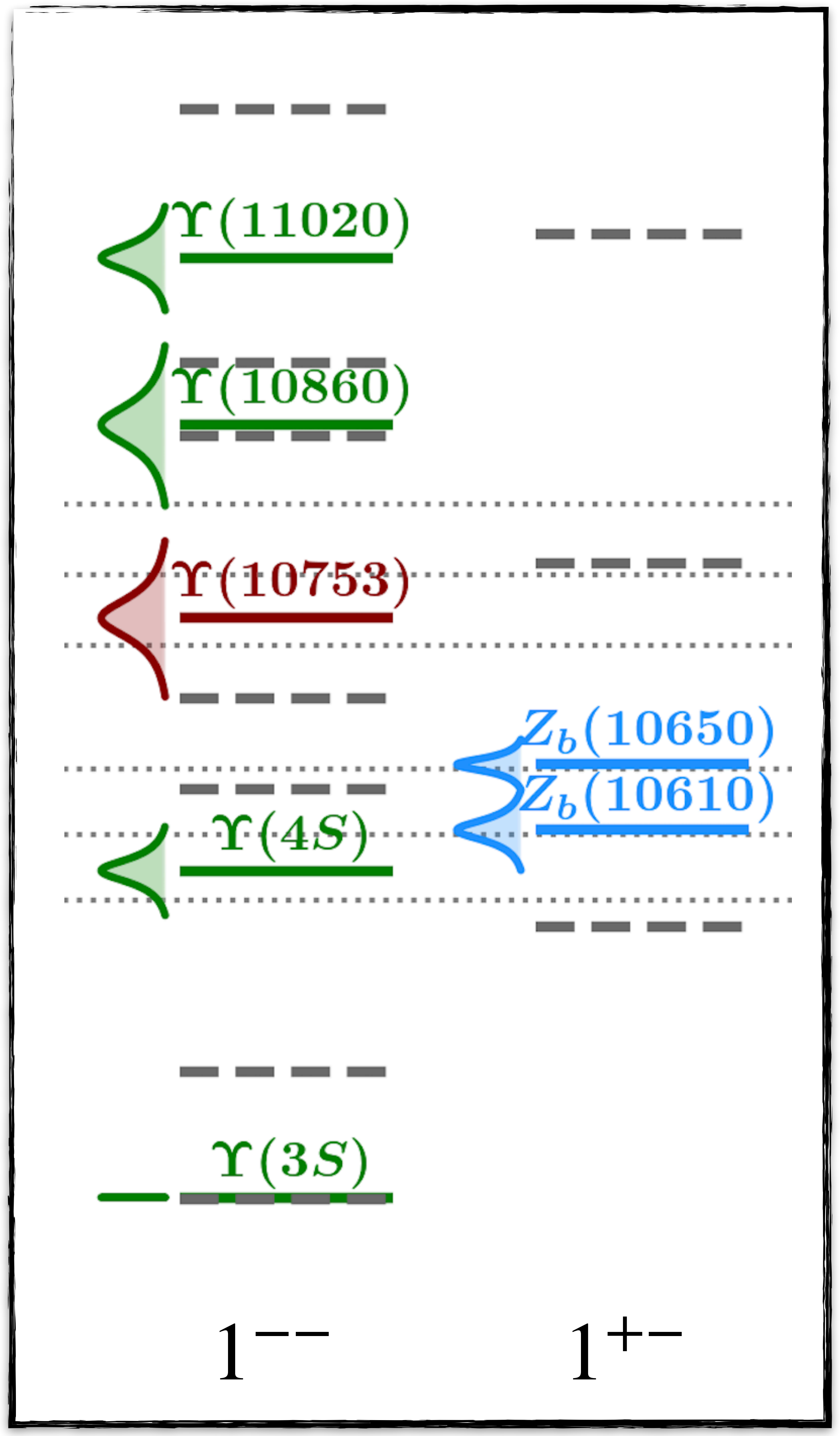




CPC 44 (2020) no.8 083001

Vector bottomonia

what else do we know?



$B\bar{B}$

PRL54 (1985) 381

[9]The choice of Gaussian peak shape is arbitrary and is made only for convenience in fitting. Theory predicts not Breit-Wigner peaks but rather irregular shapes, sensitive to assumptions about decay channels and thresholds; see, for example, E. Eichten *et al.*, Phys. Rev. D **21**, 203 (1980).

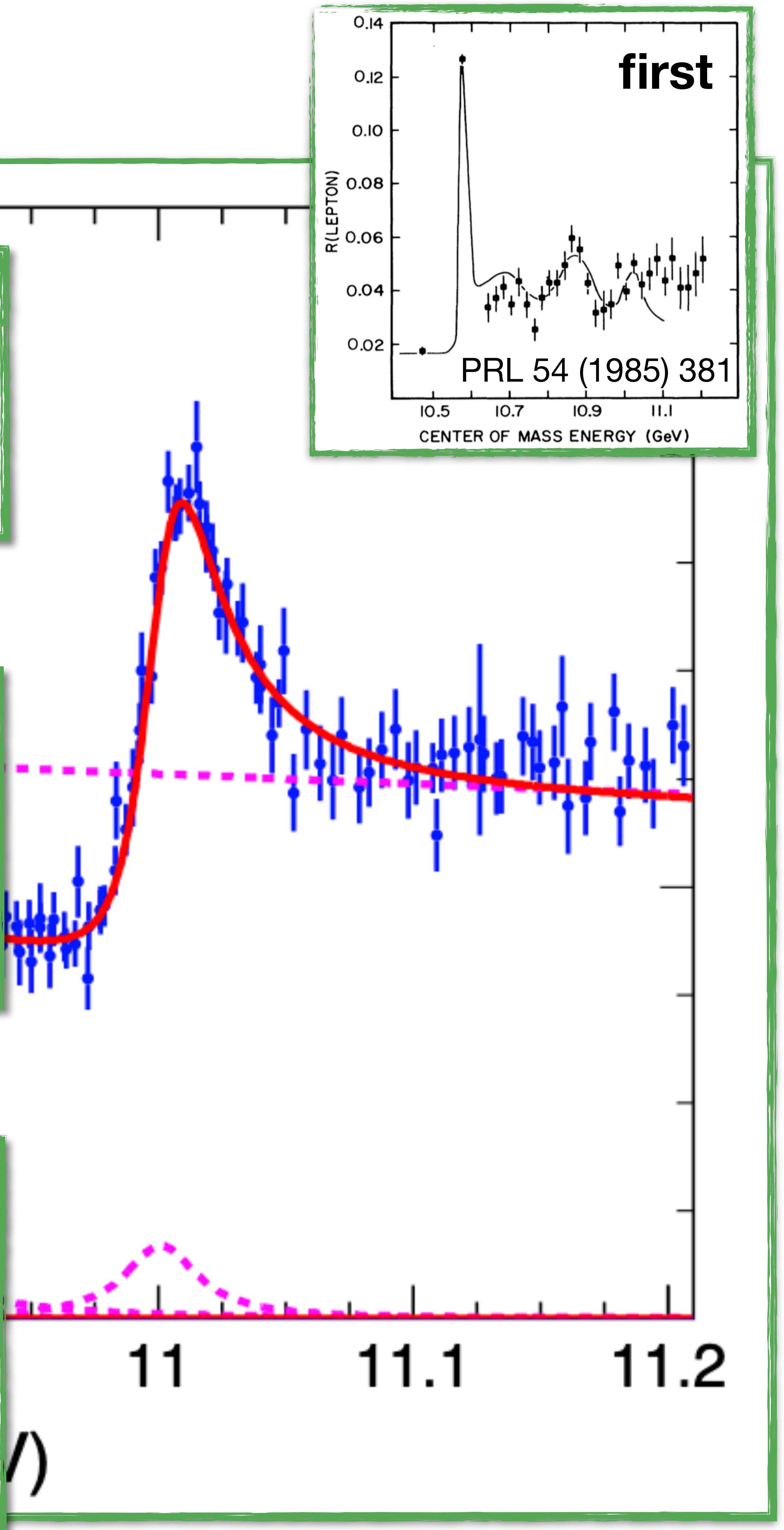
PRL102 (2009) 012001

The number of states is, *a priori*, unknown as are their energy dependencies. Therefore, a proper coupled channel approach [16,17] including the effects of the various thresholds outlined earlier would be likely to modify the results obtained from our simple fit. As an illustration of

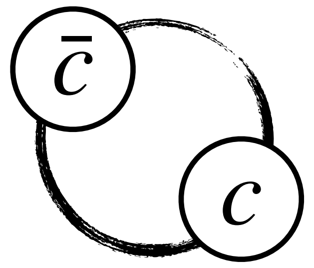
CPC 44 (2020) no.8 083001

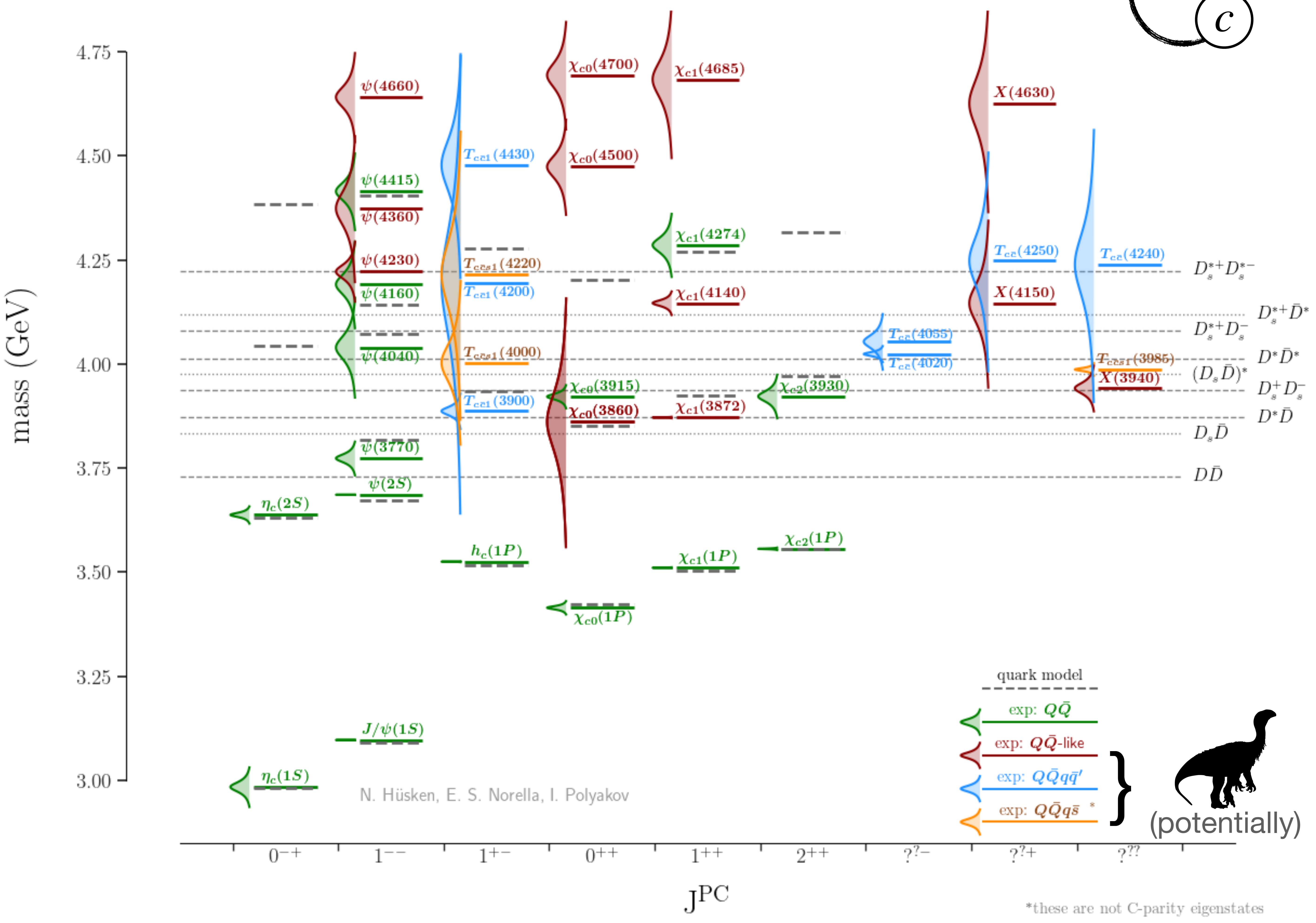
also complicated. The results from these fits may change dramatically by including more information on each exclusive mode.

The data obtained in this analysis can be used to extract resonant parameters of these states if a better parametrization of the cross sections is developed.



Vector charmonia





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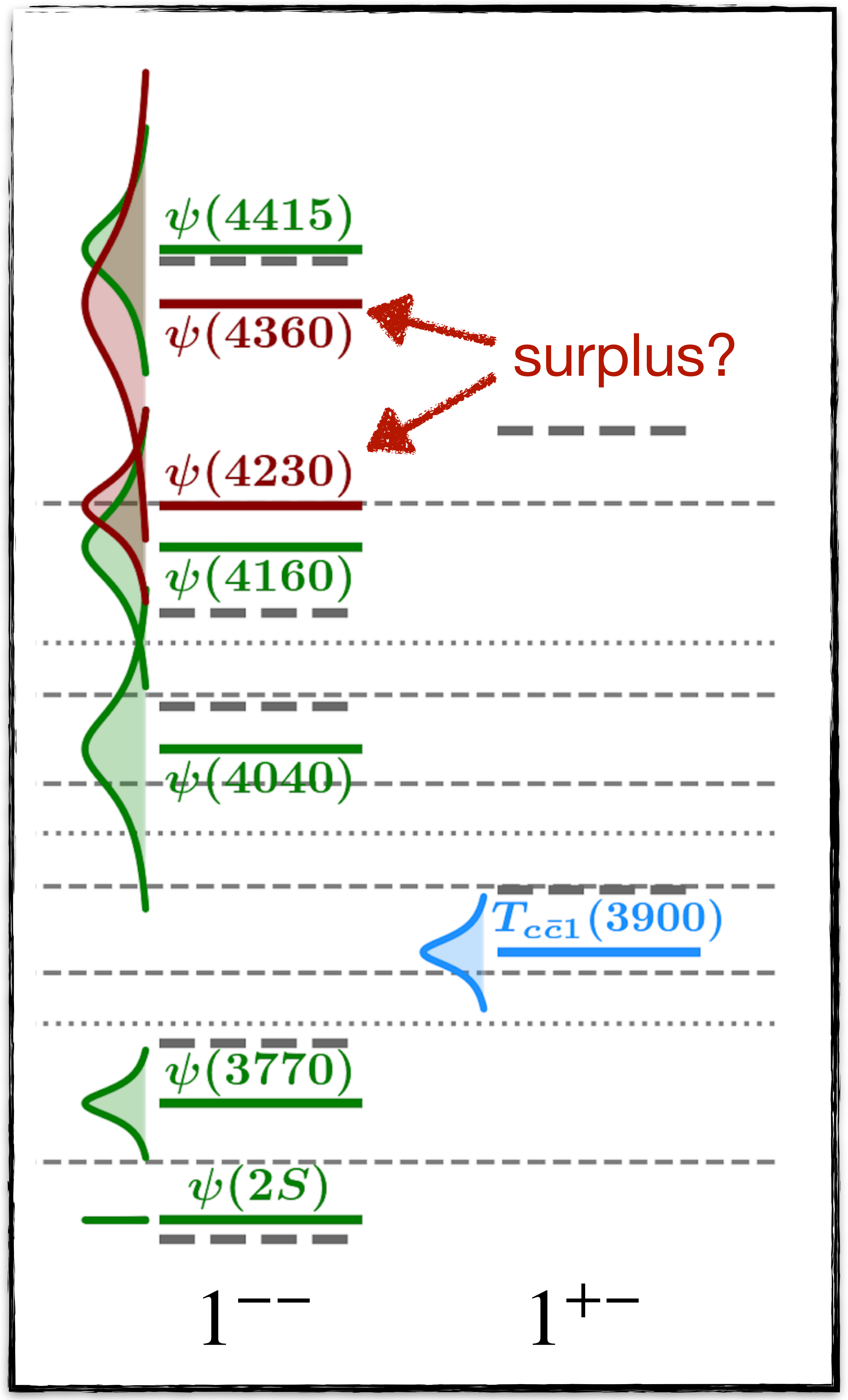

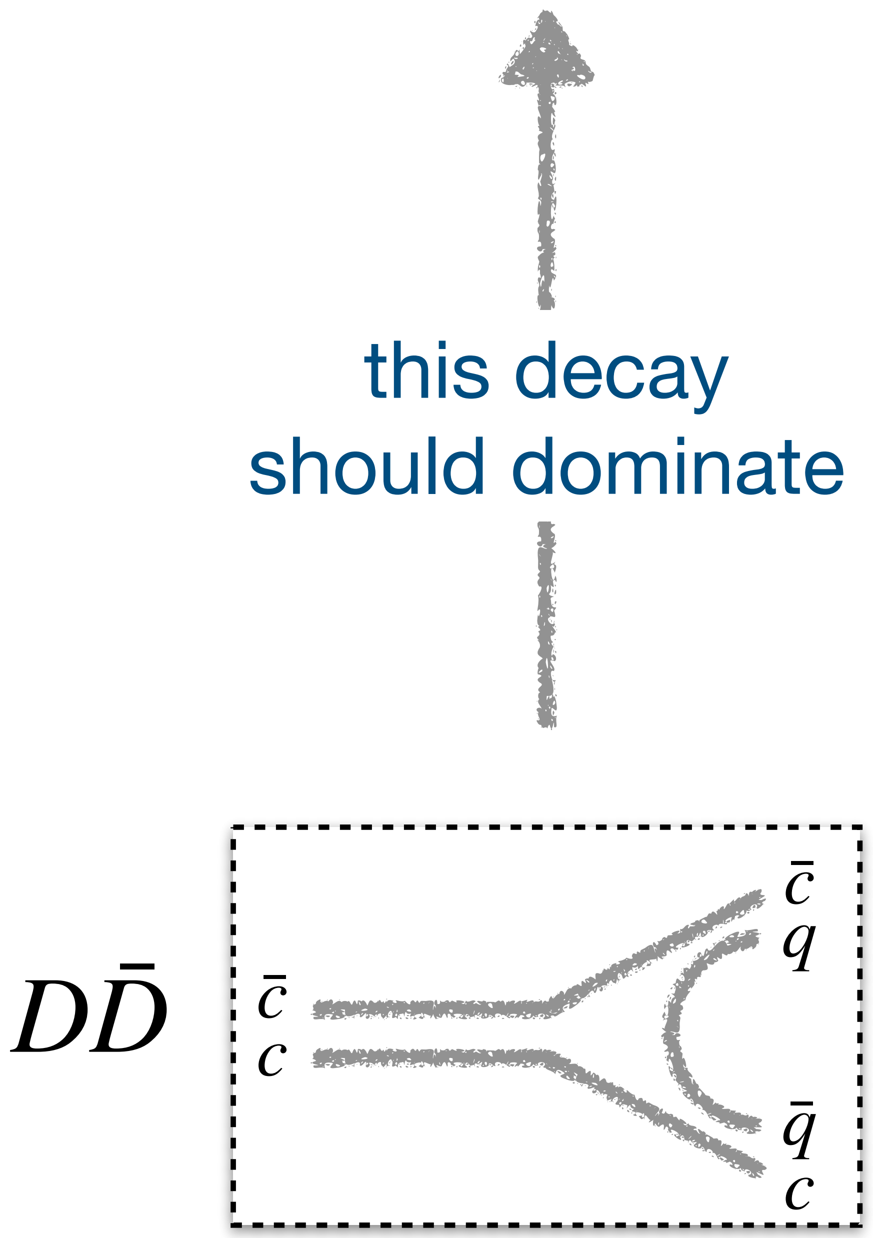

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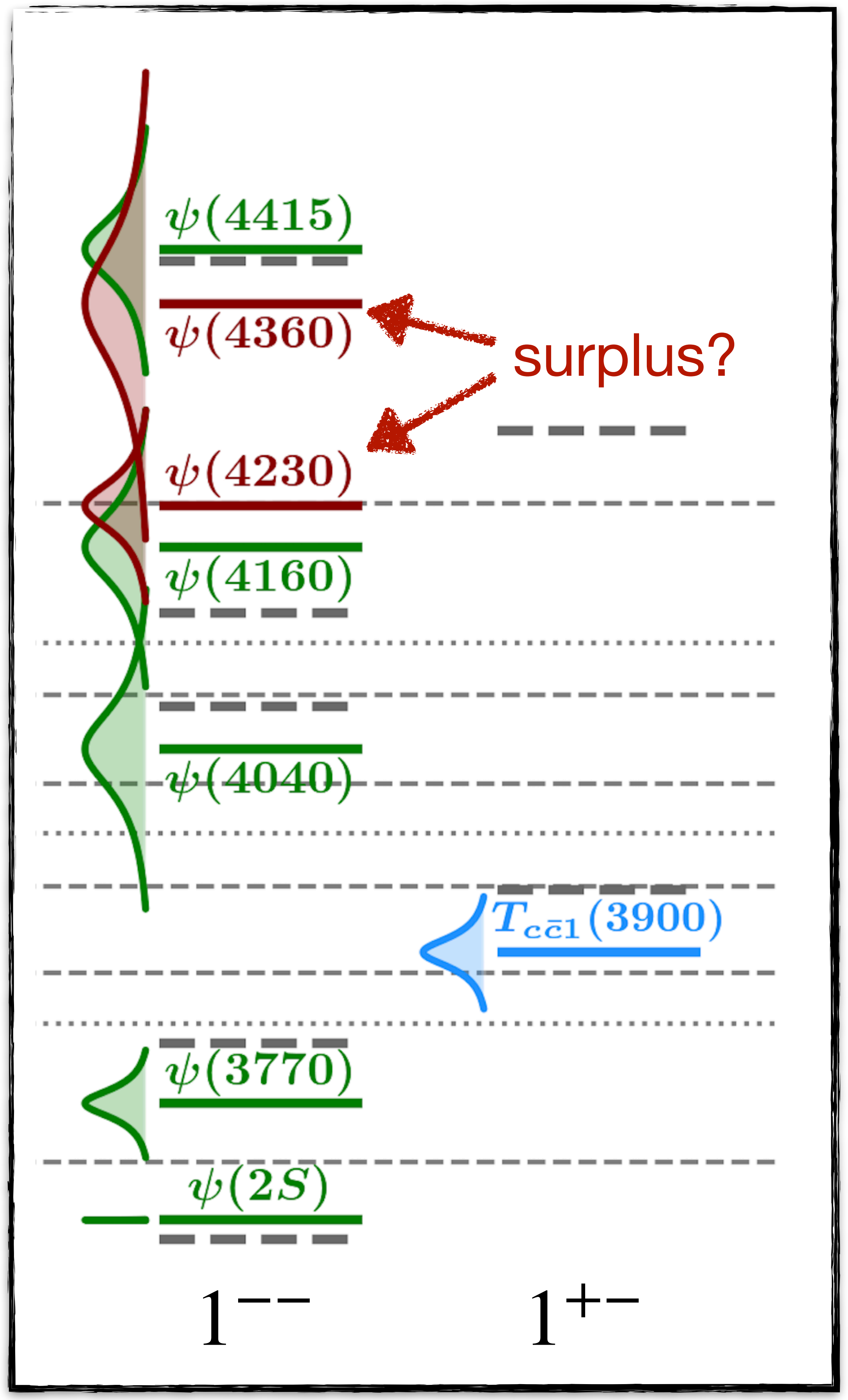
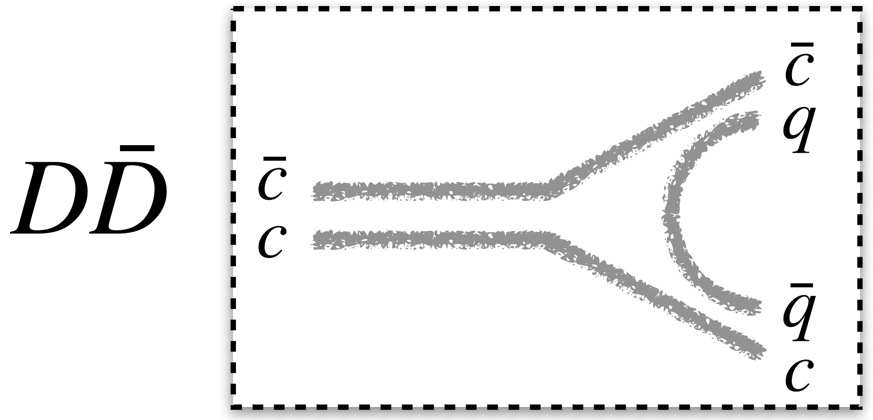
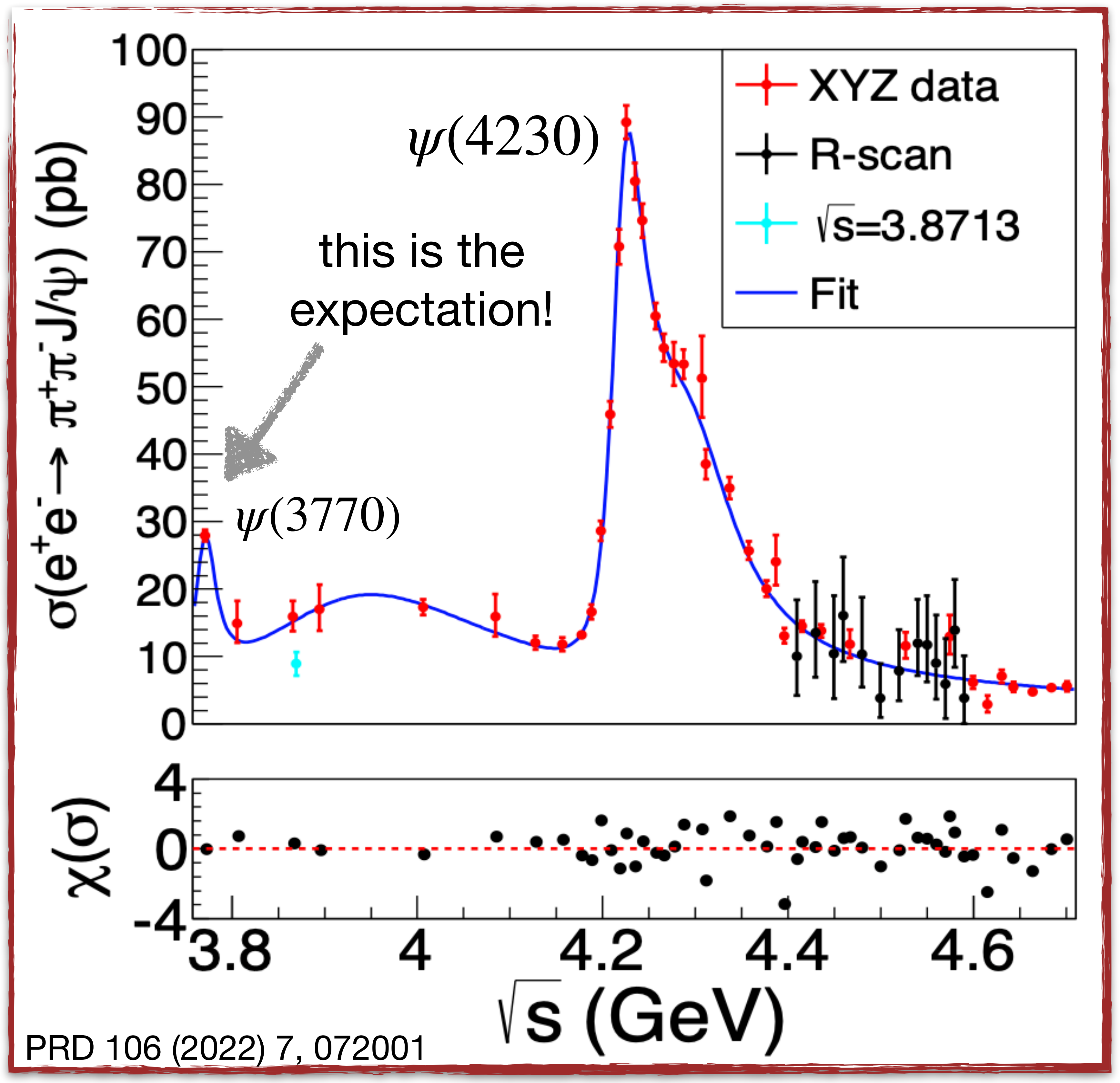
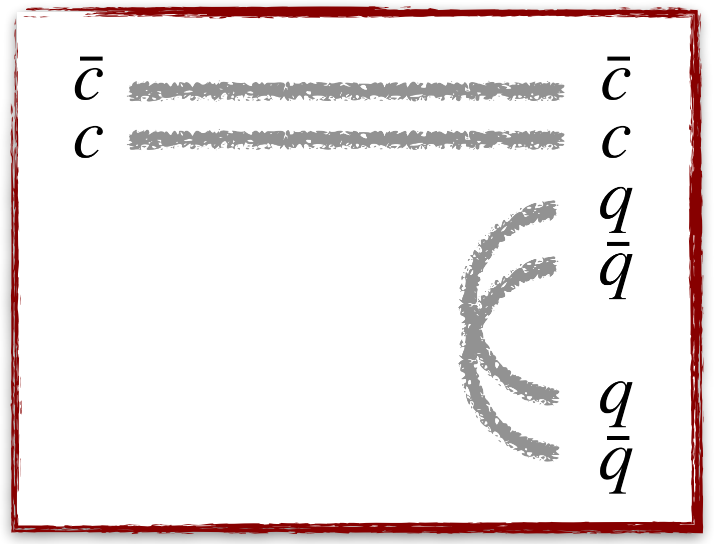


this decay
should dominate







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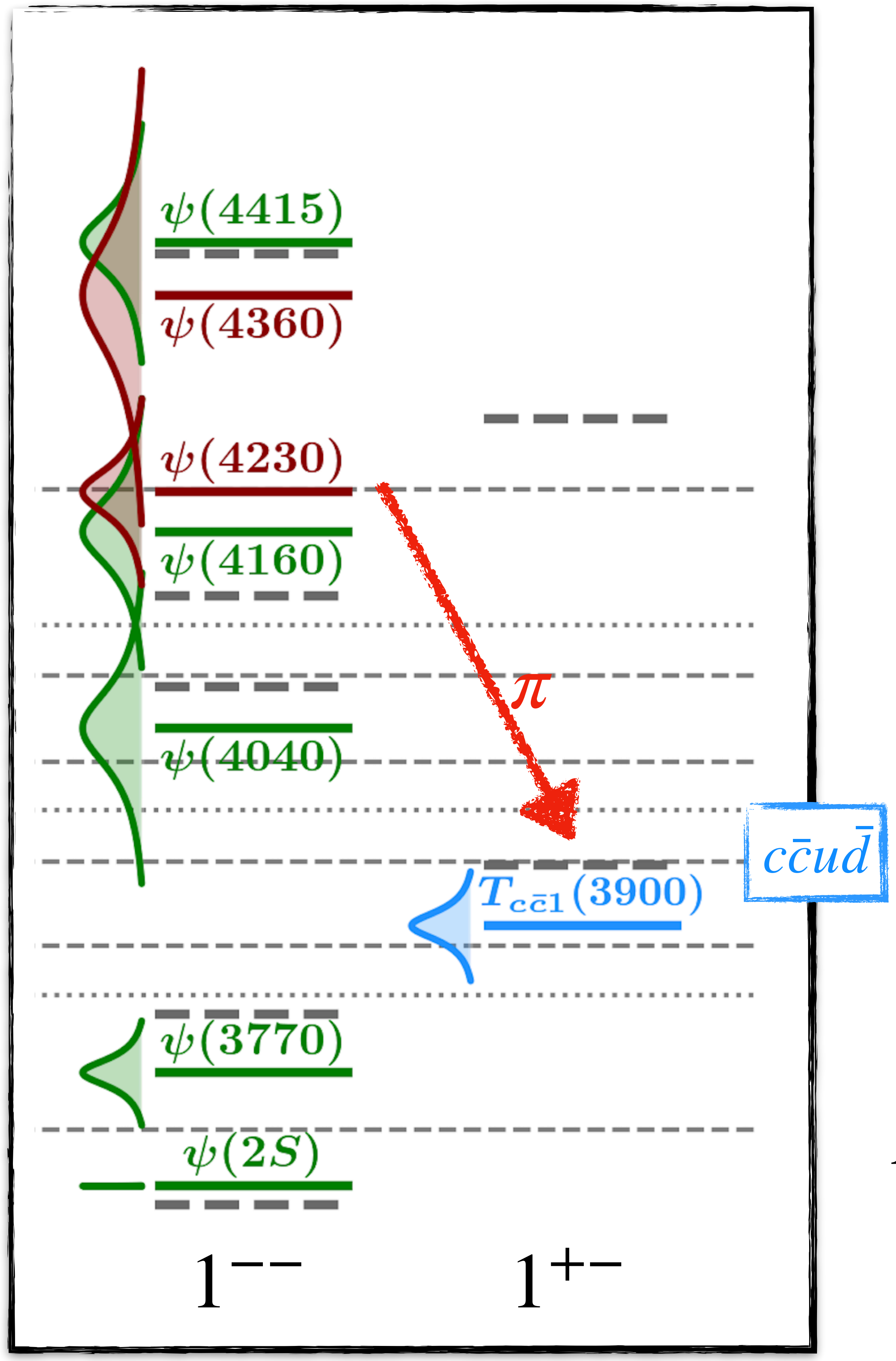

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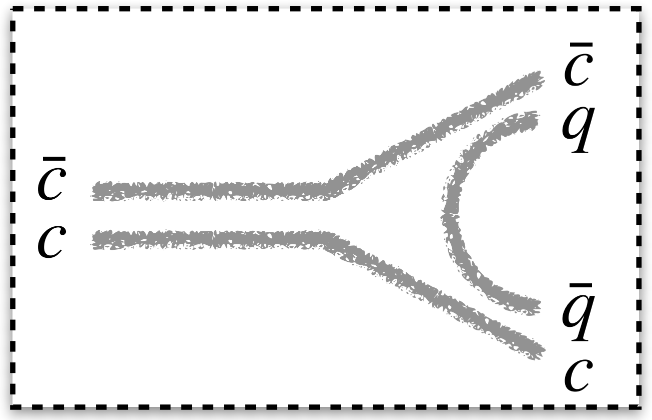
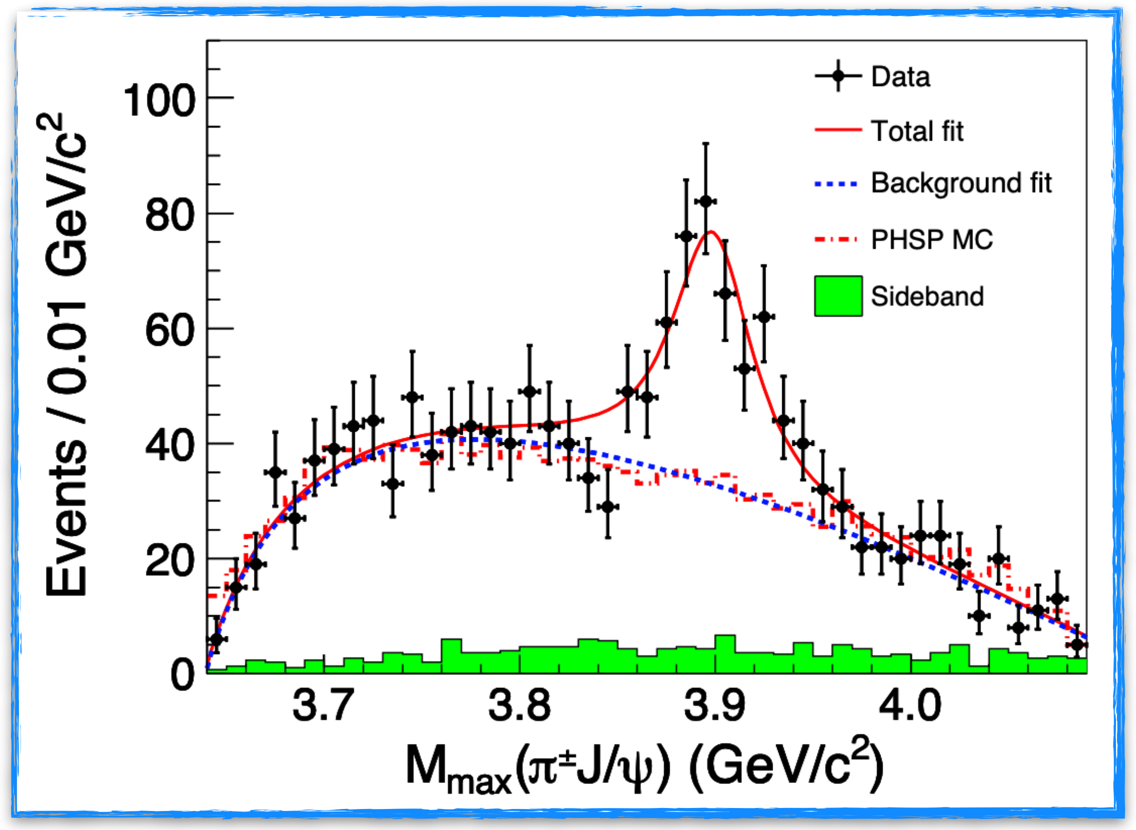
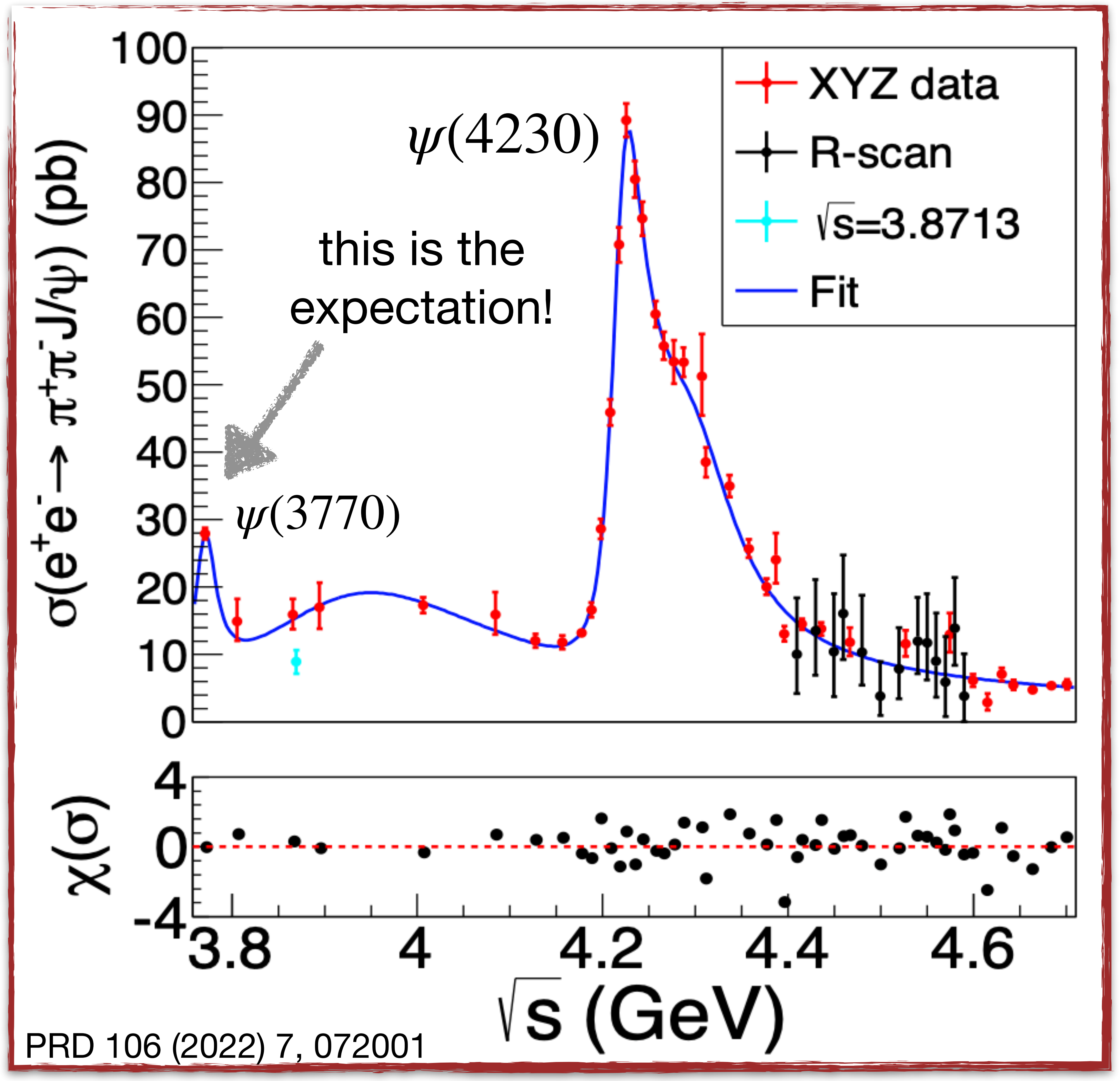
$D\bar{D}$

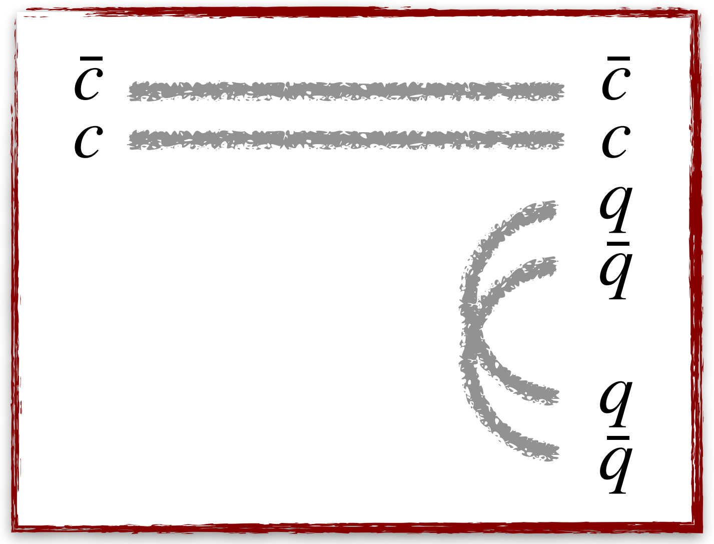




PRL 110 (2013) 252001



PRD 106 (2022) 7, 072001



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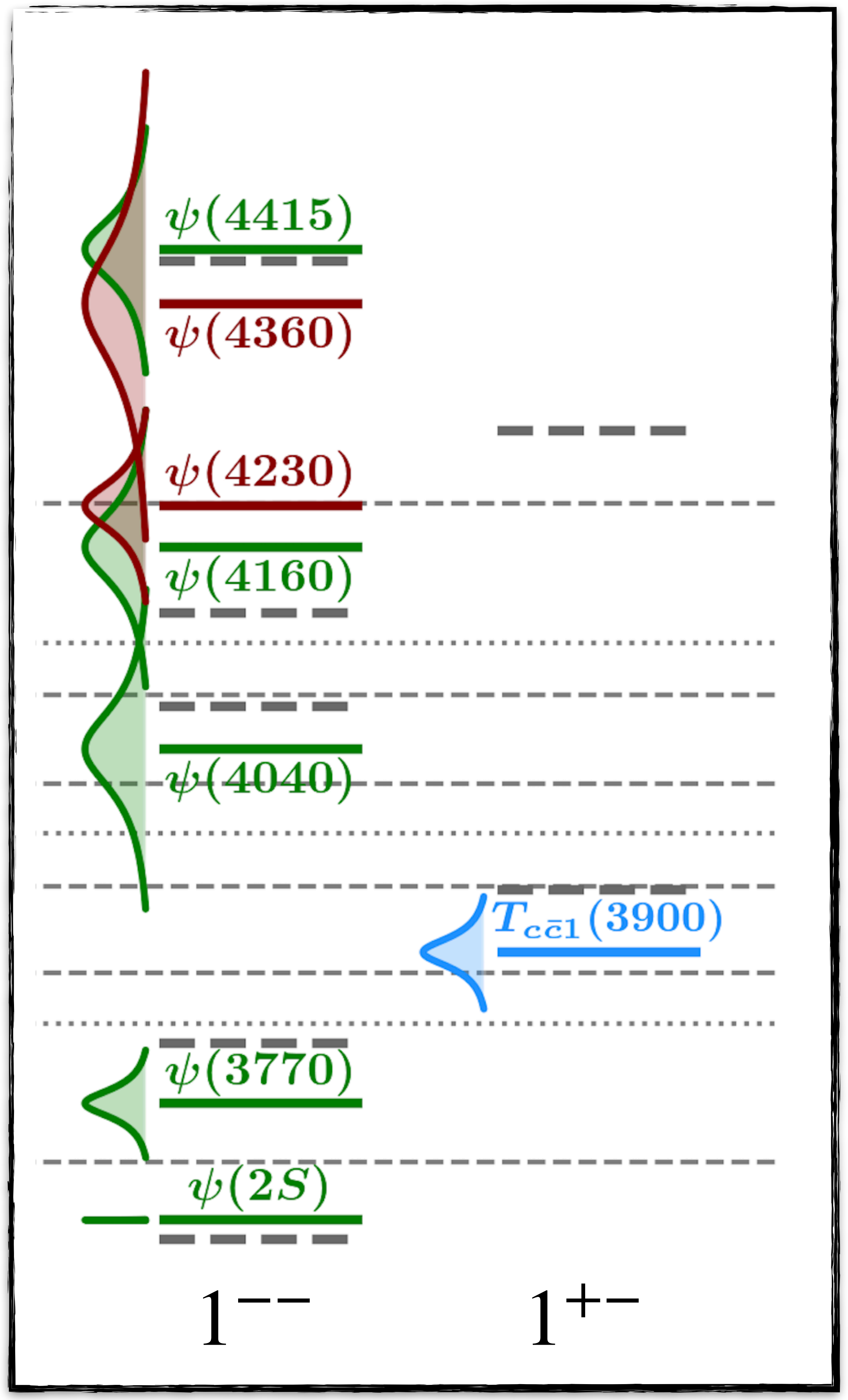
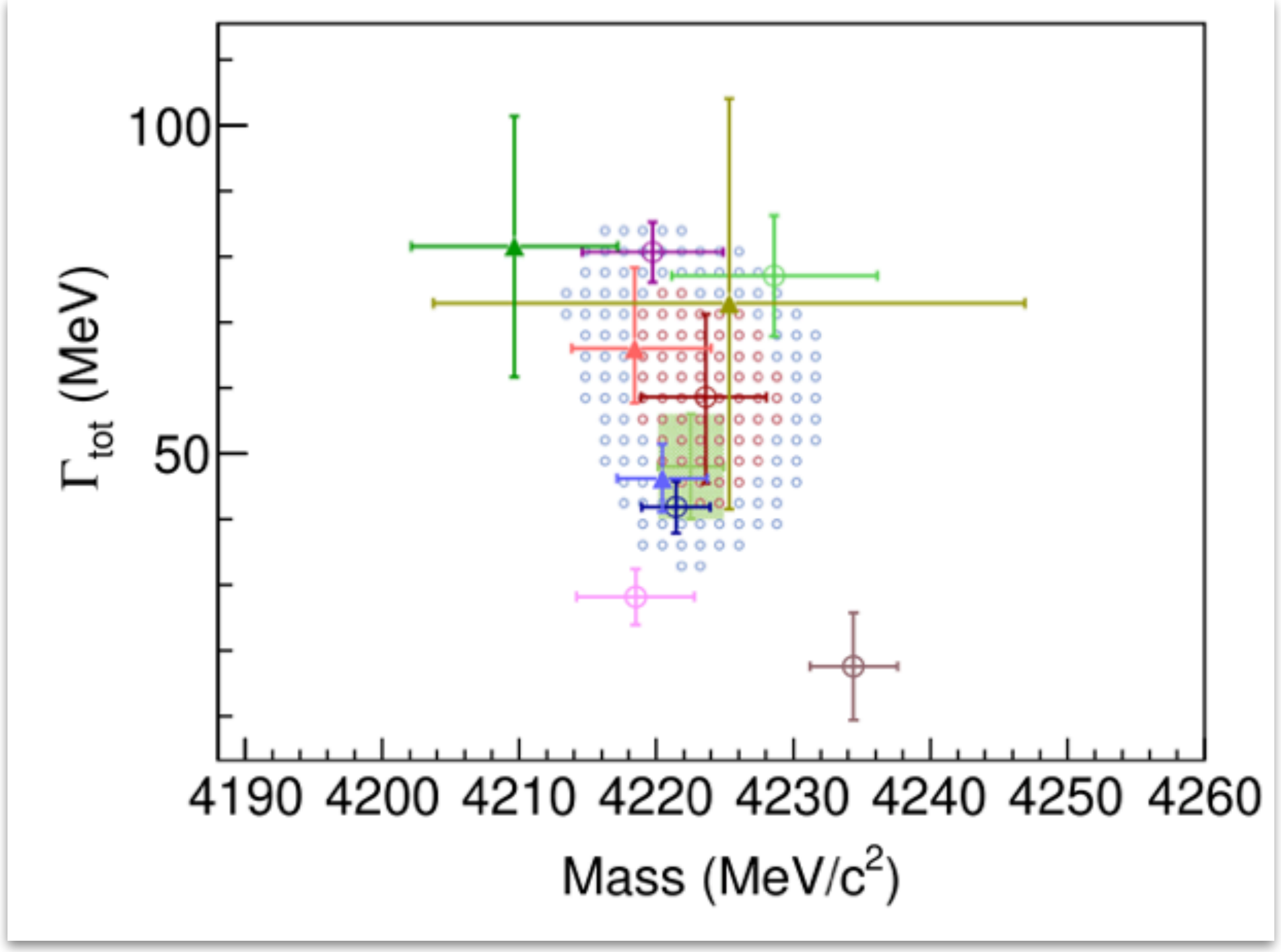
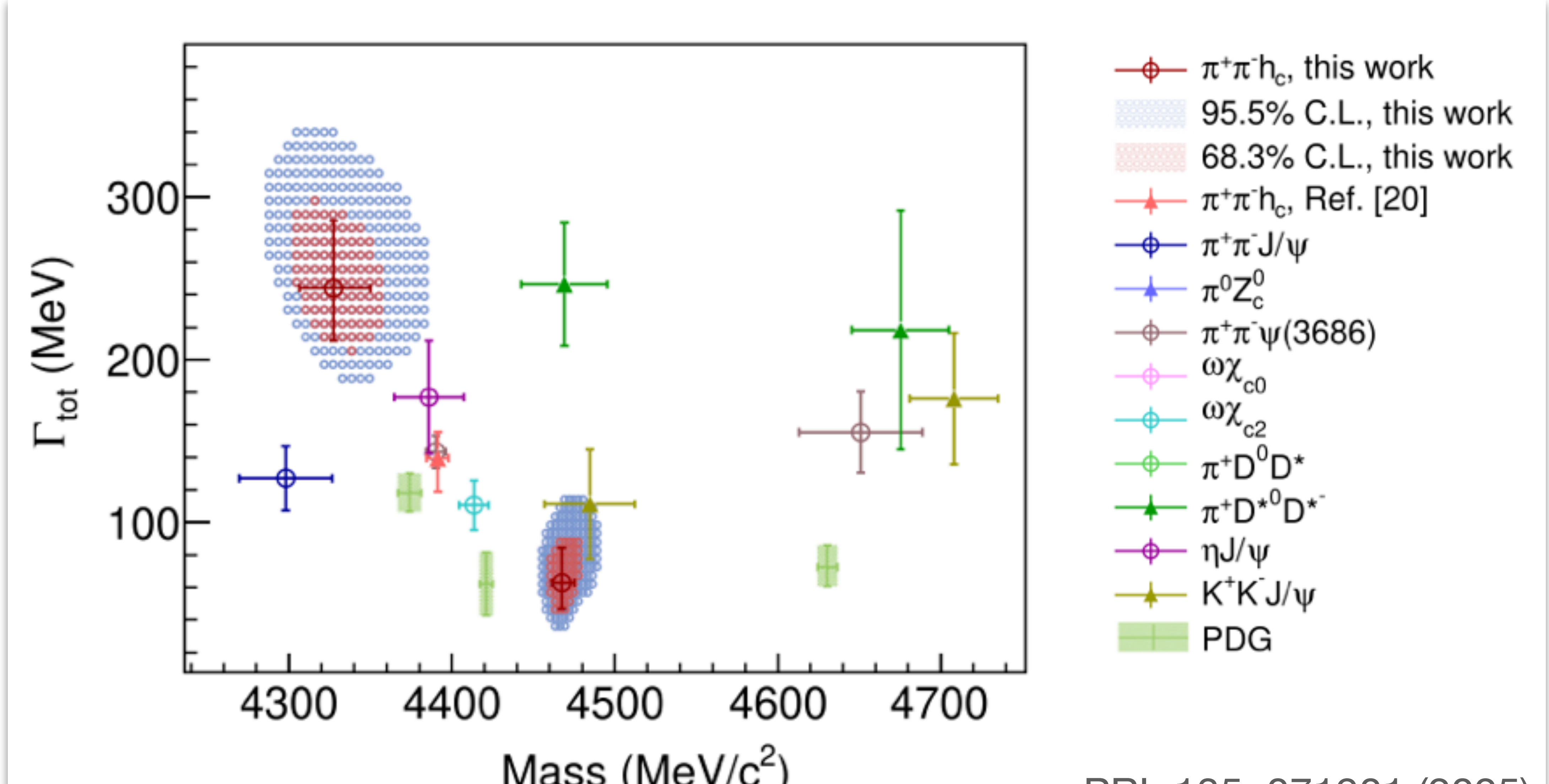


- at least two (?) states in hidden-charm + light hadron(s)
- mass of $\psi(4230)$ fairly consistent between exclusive channels, but the width is not
- very little consistency for higher mass state

→ need a more reliable way to extract information than just looking at each exclusive channel individually

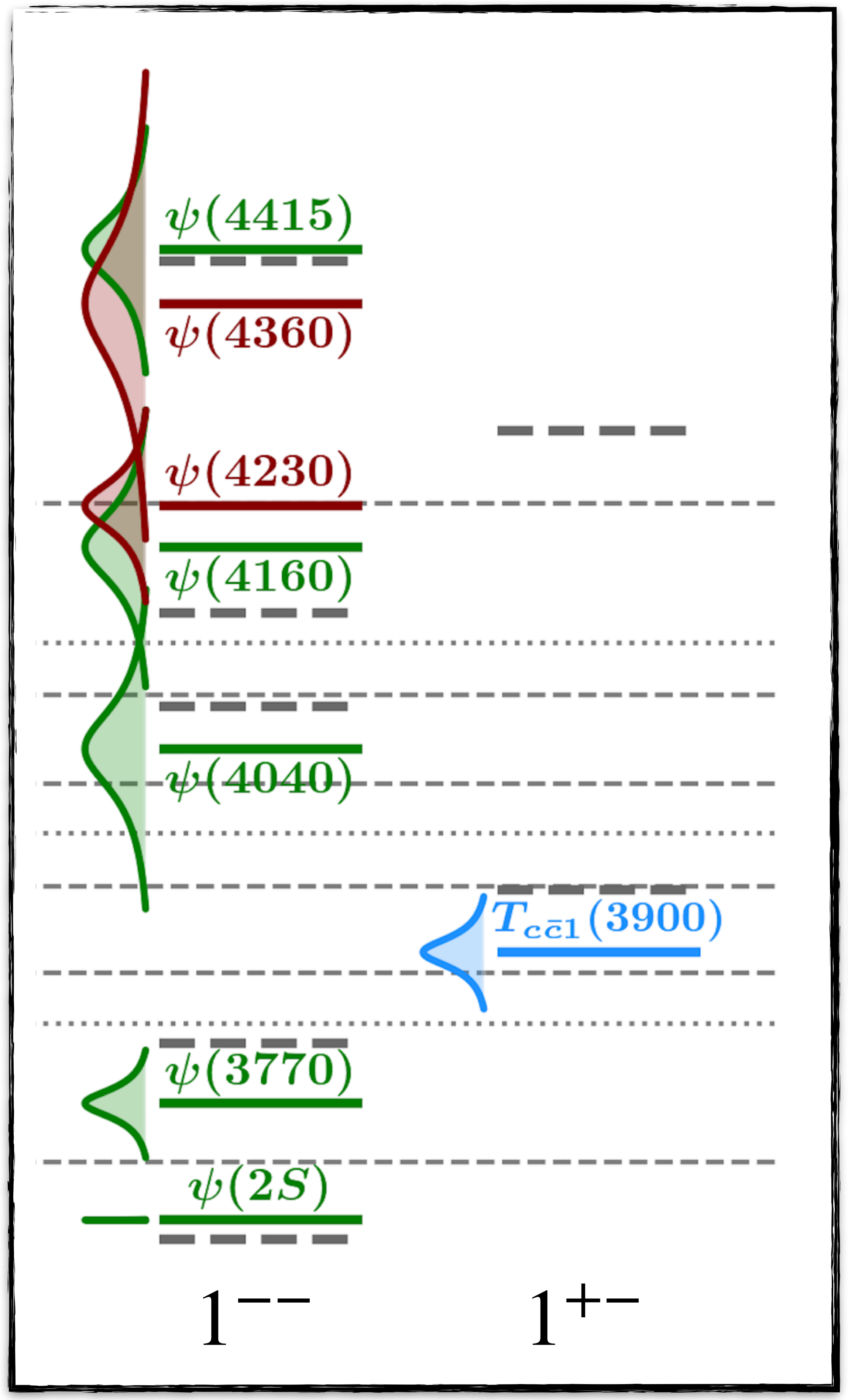


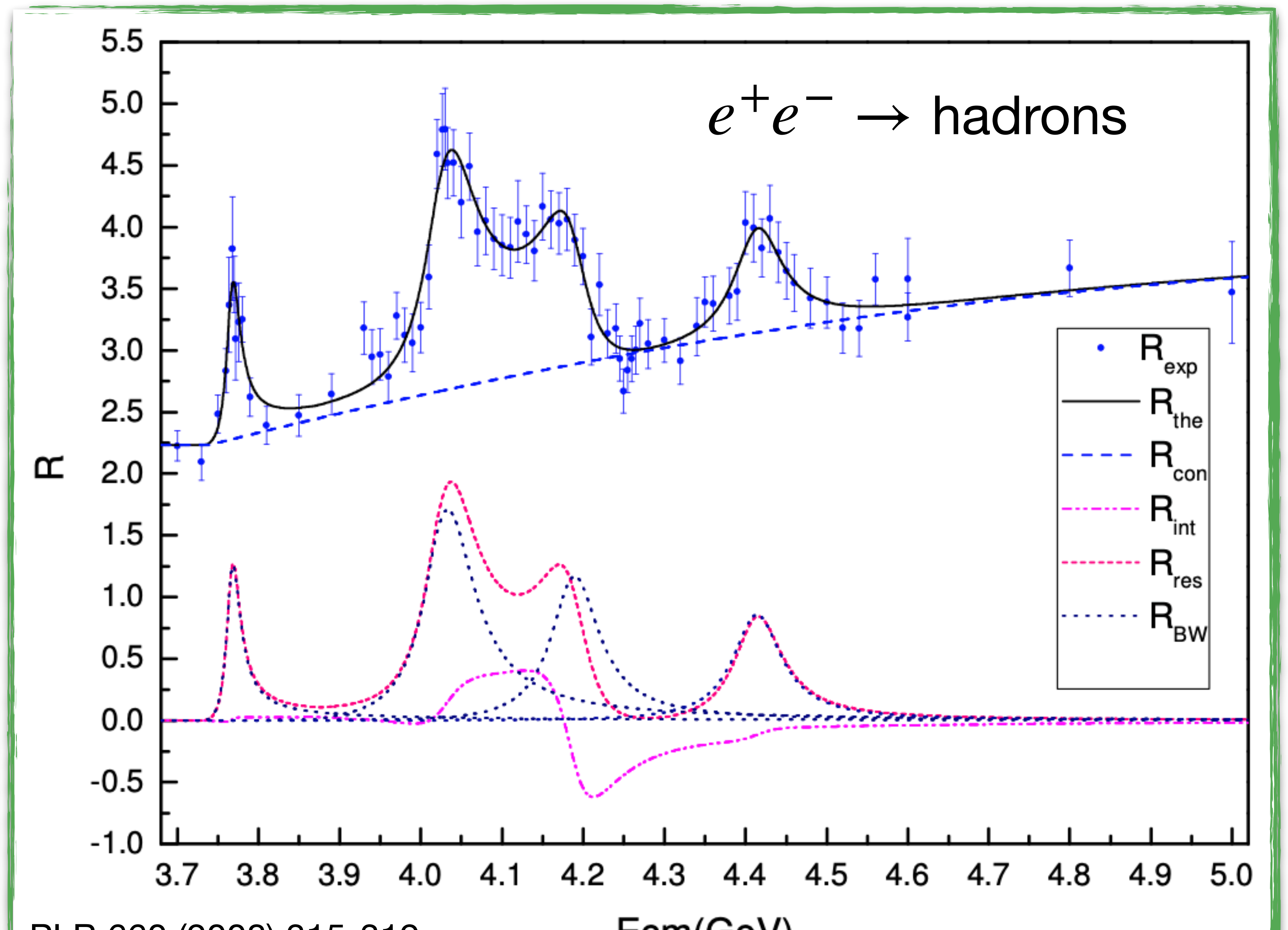


PRL 135, 071901 (2025)

Vector charmonia

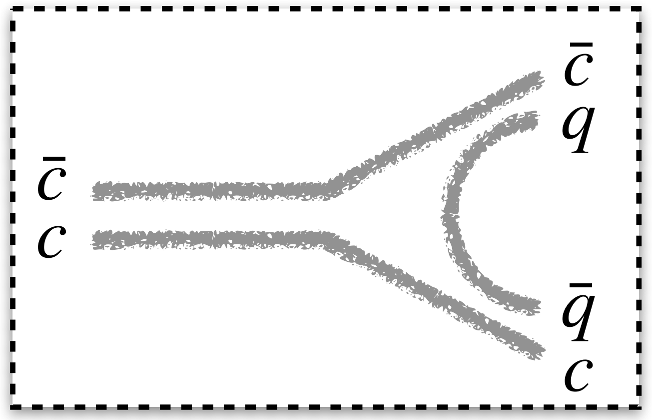
what else do we know?





PLB 660 (2008) 315-319

$D\bar{D}$



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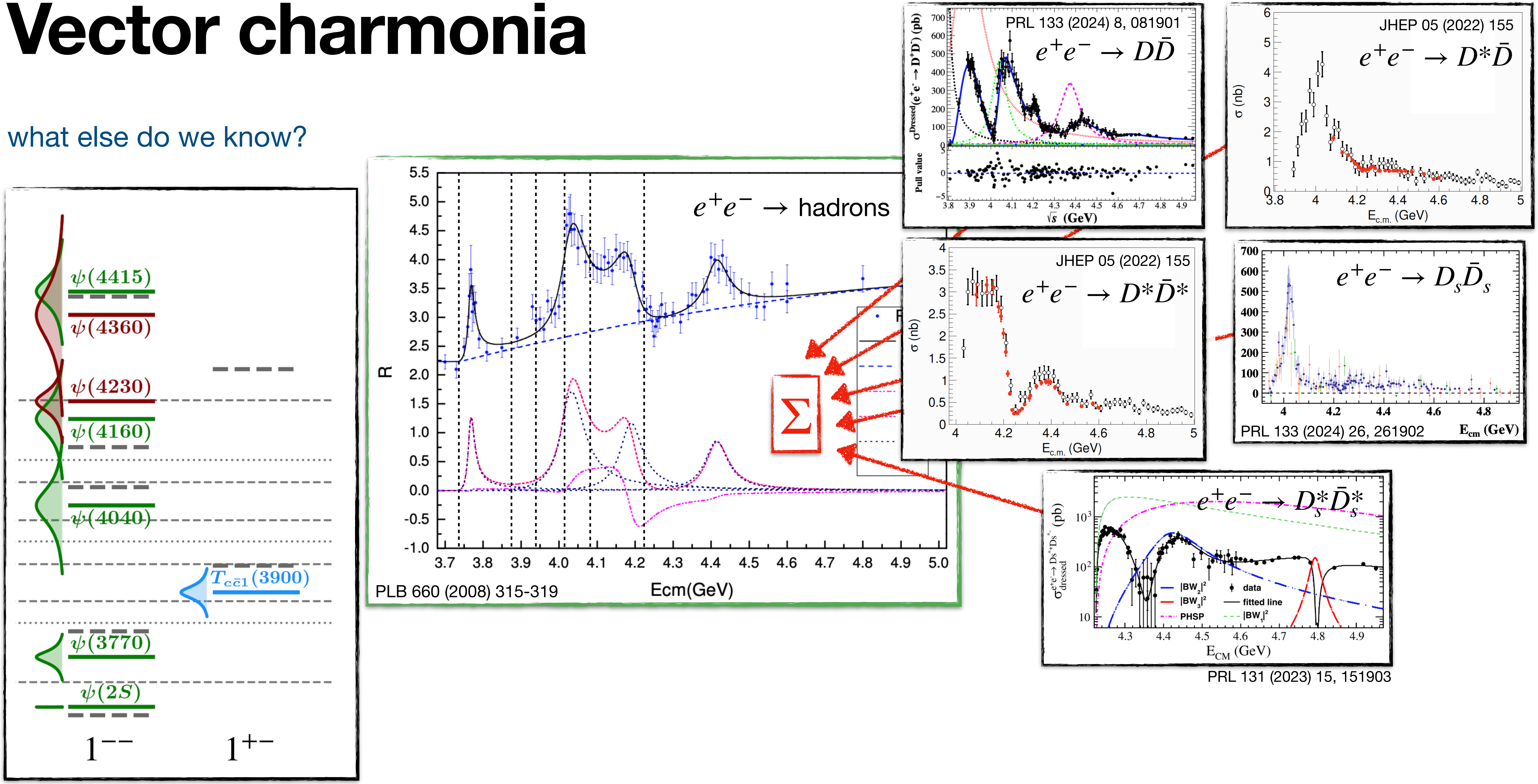

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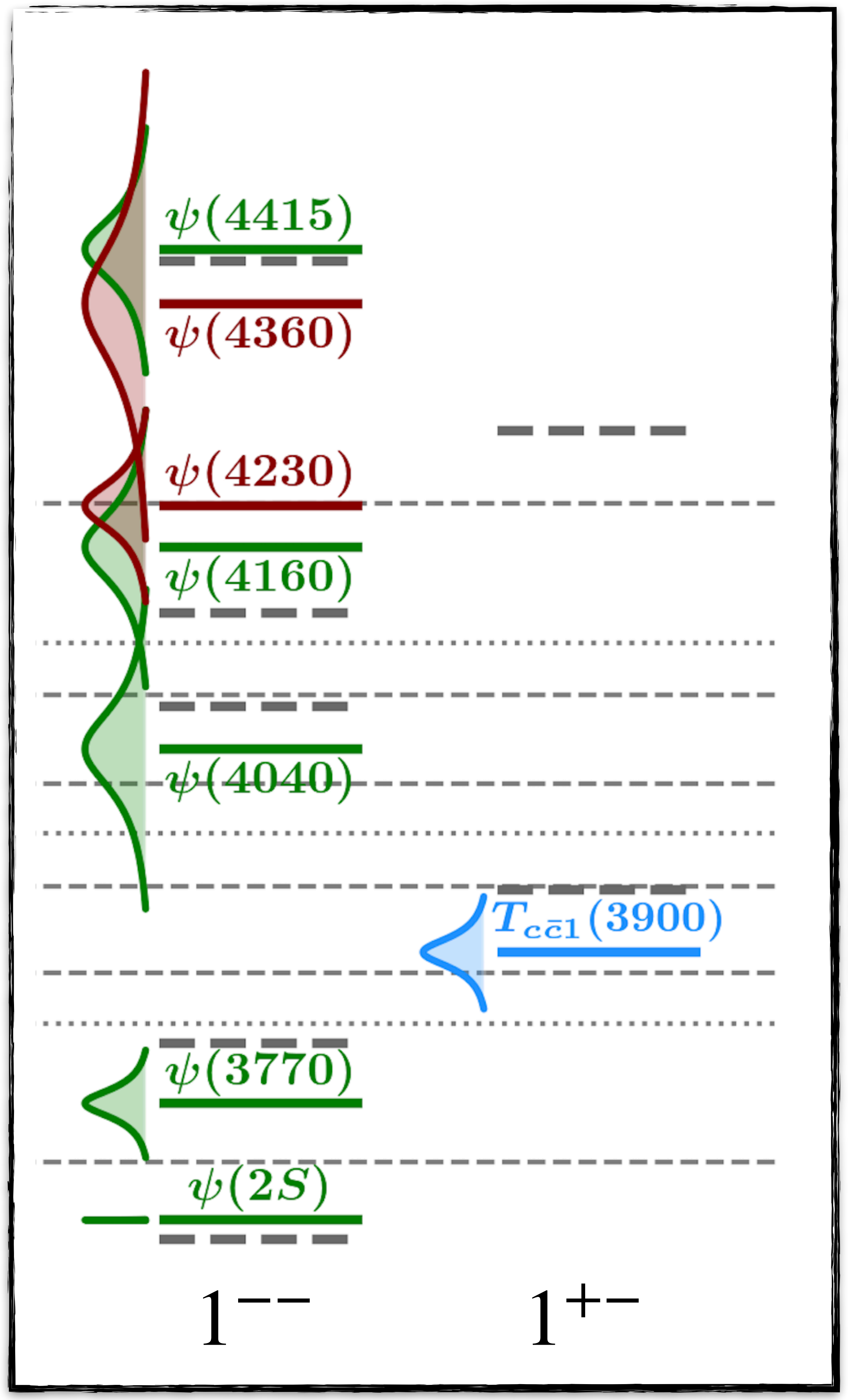
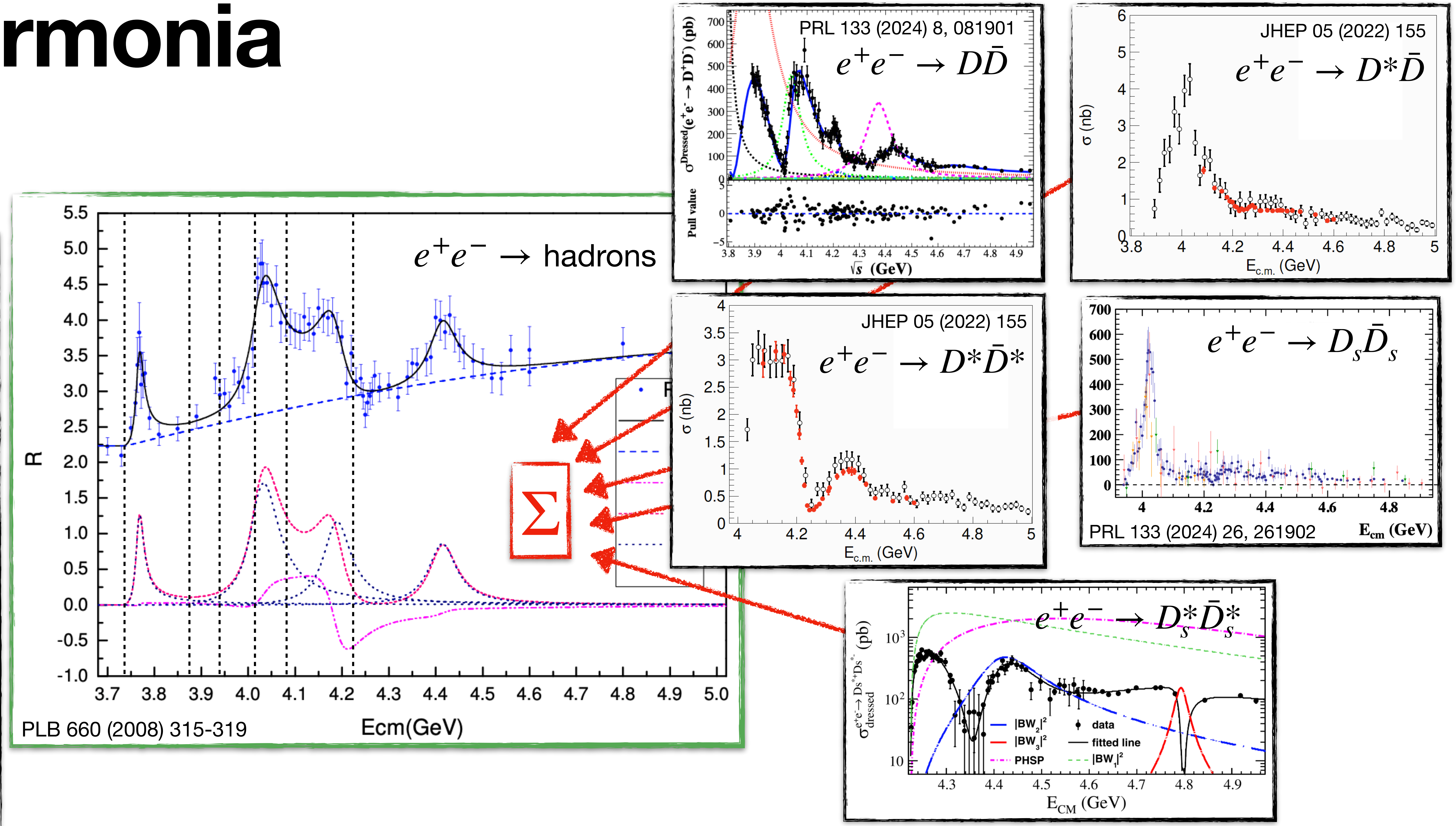




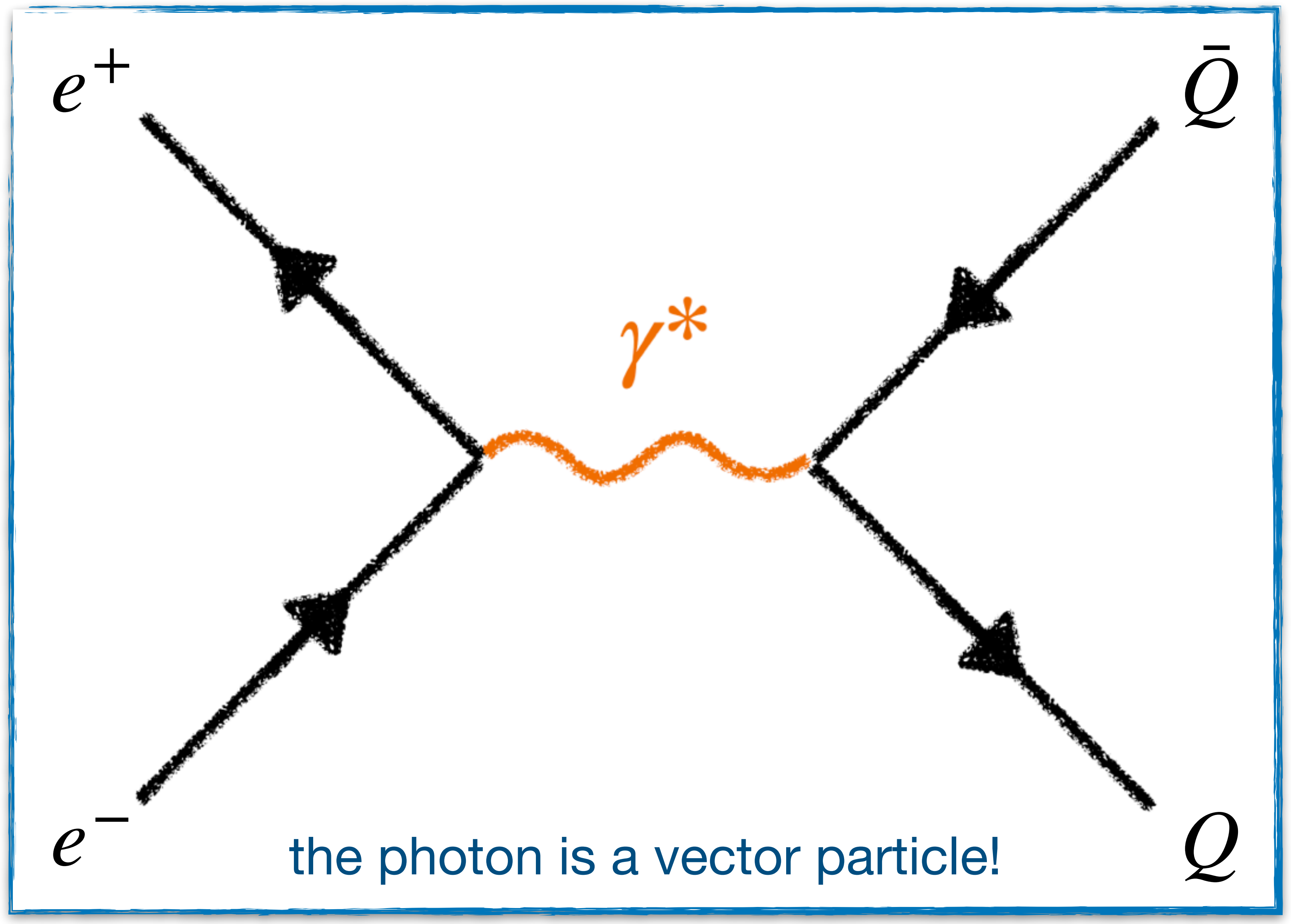
- so, how well established is the existence of $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ really?
- are there supernumerary vector charmonia?

So, why vector quarkonia?

- we have surprisingly little solid information on them
- how many exist?
- what are their properties?
- are some exotic hadrons?

How to produce them?

e^+e^- annihilation

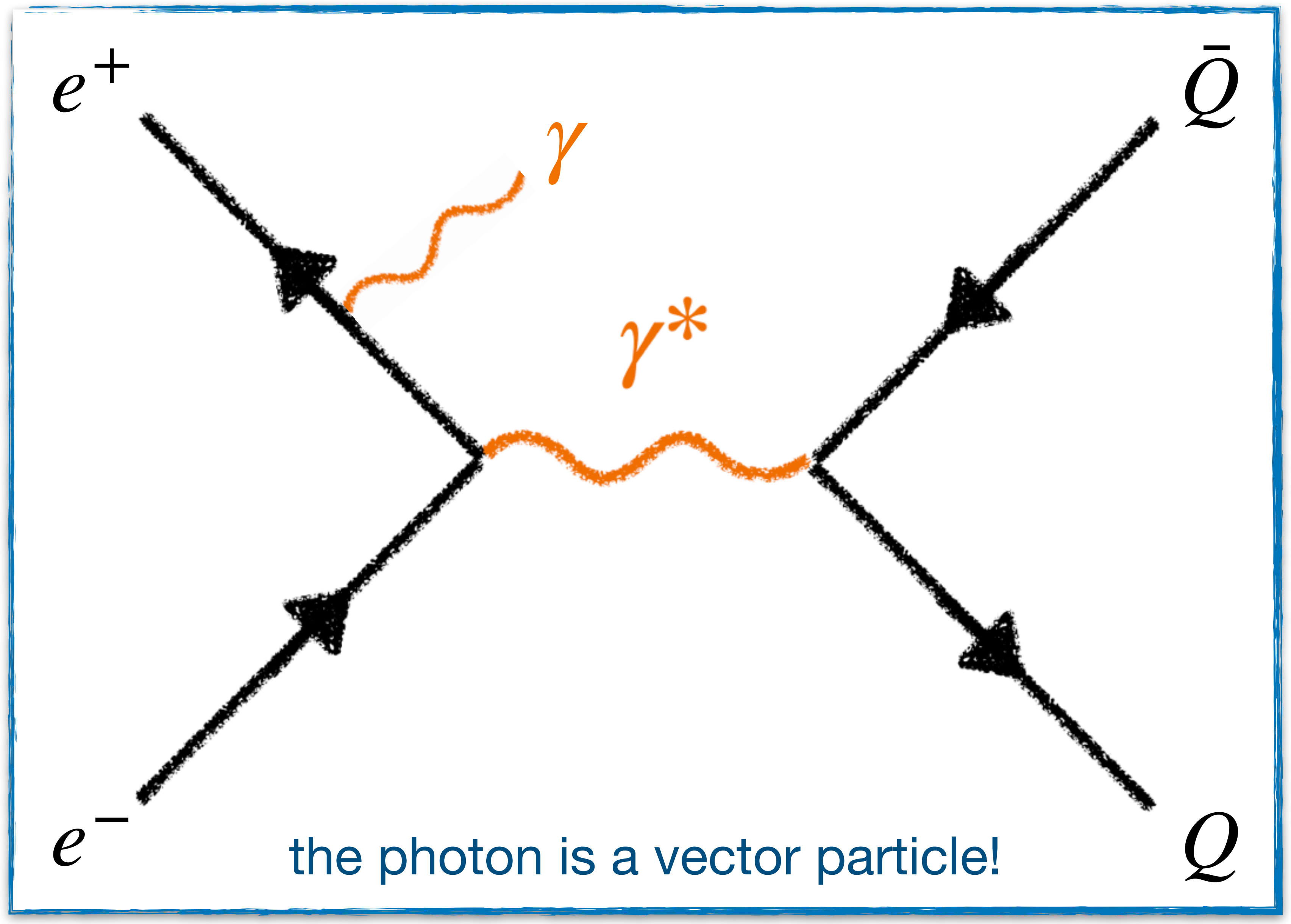


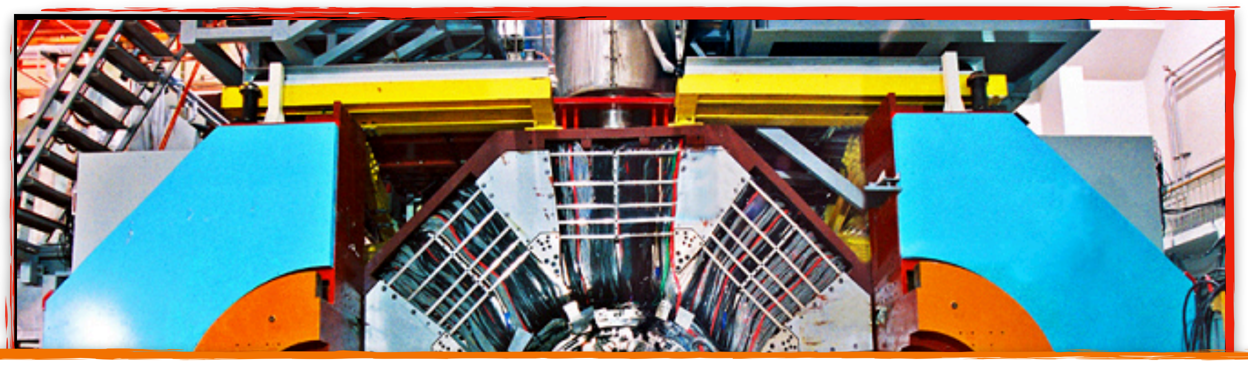
$c\bar{c}$

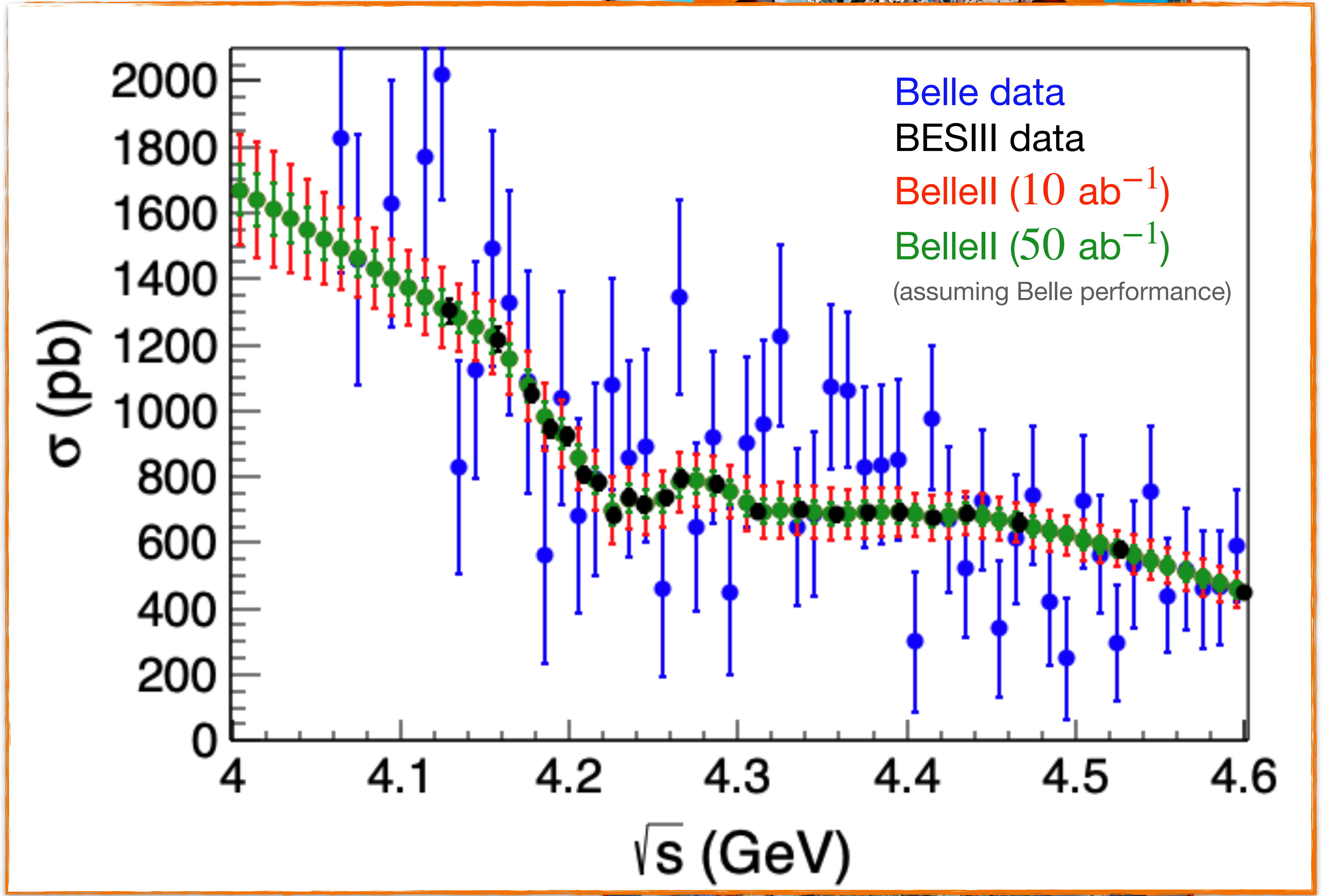
$c\bar{c}$ and $b\bar{b}$

$c\bar{c}$ and $b\bar{b}$

e^+e^- annihilation



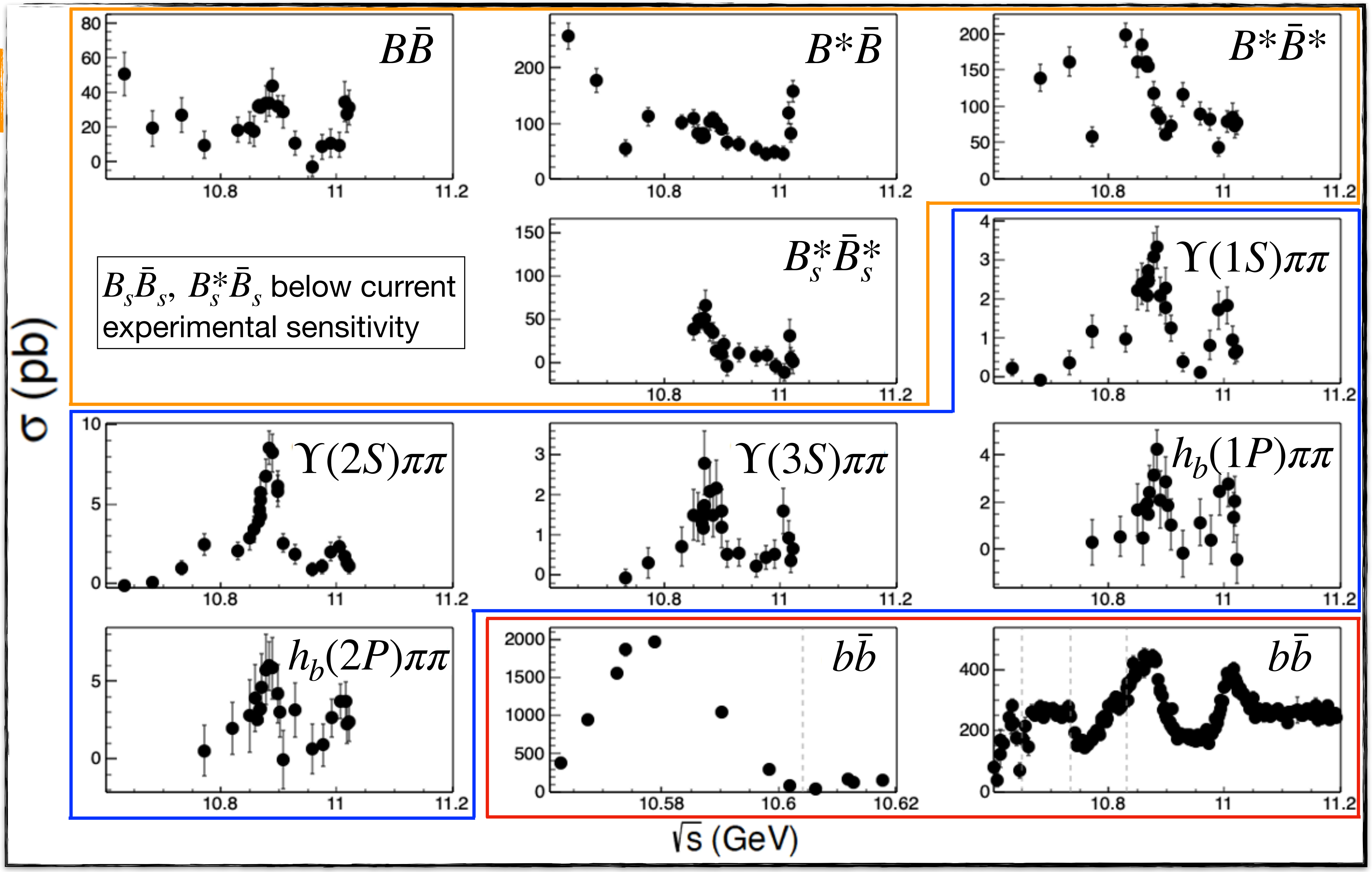




$e^+e^- \to b\bar{b}$ data

all exclusive data is from **Belle**
inclusive data from Belle & BaBar

$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$ open-flavour



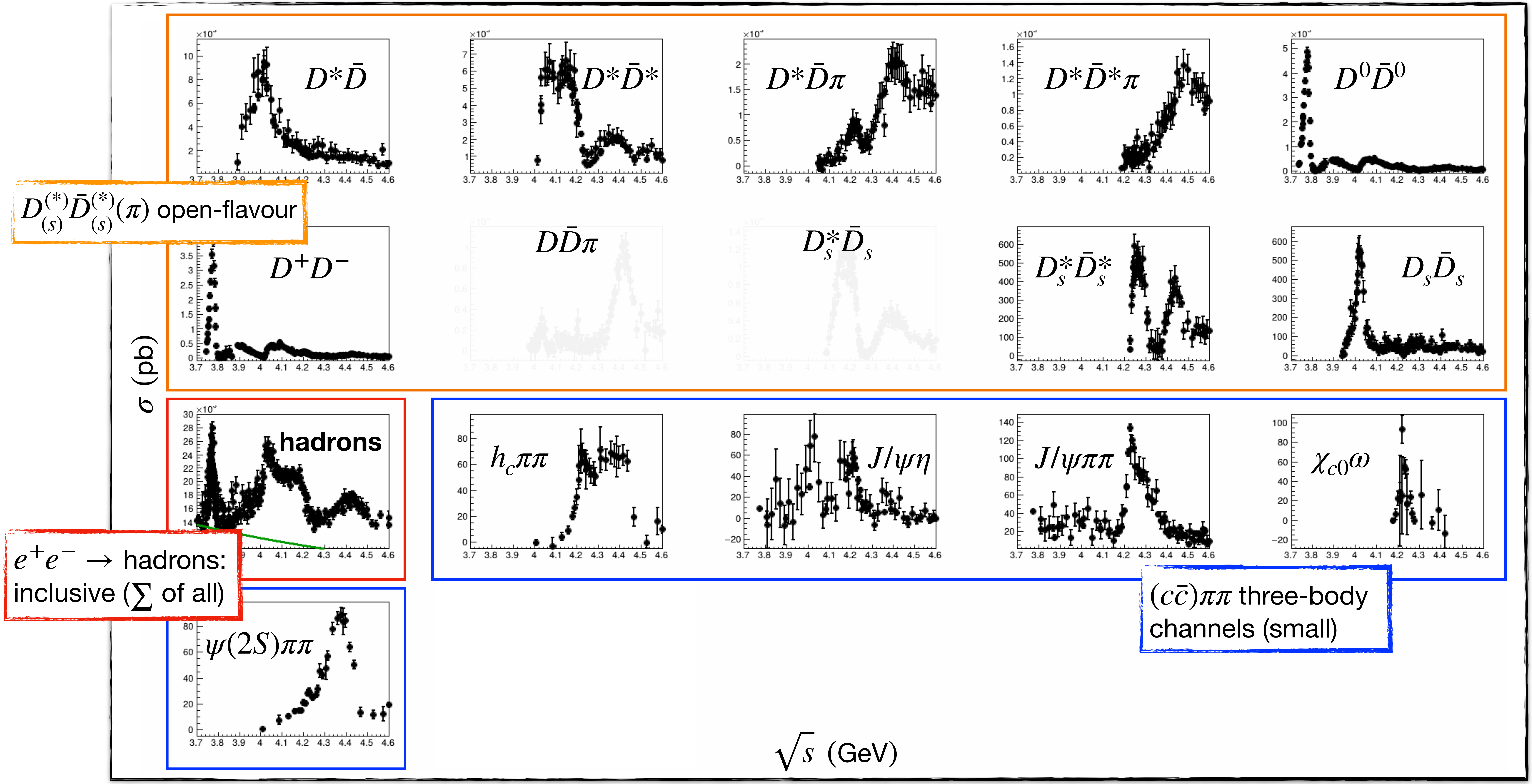
$(b\bar{b})\pi\pi$ three-body channels (small)

$B^{(*)}\bar{B}^{(*)}\pi$ multi-body not measured

$e^+e^- \to b\bar{b}$: inclusive ($\sum$ of all)

$e^+e^- \to c\bar{c}$ data

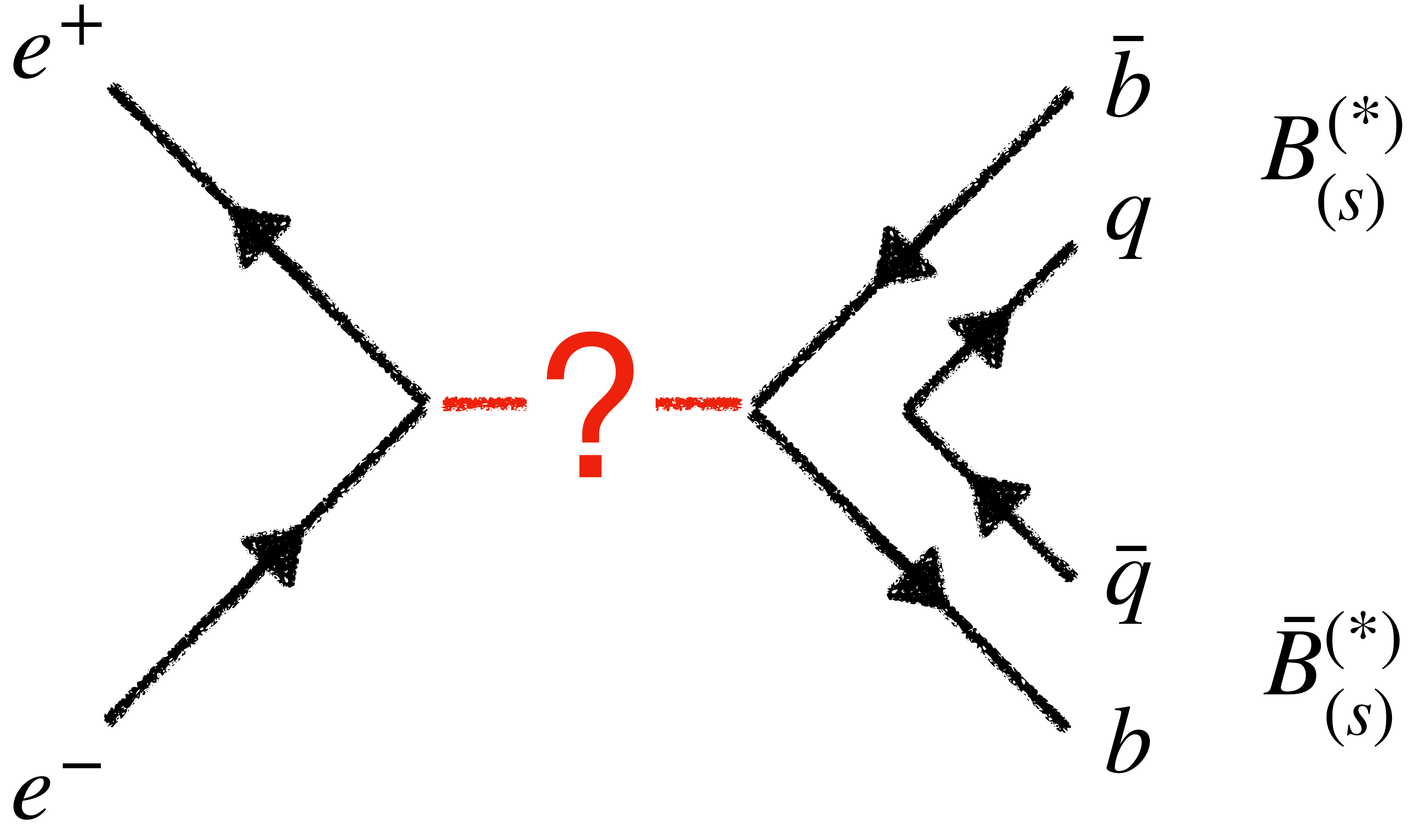
data from BESIII, Belle, BaBar, CLEO, …



How to make the most out of the data?

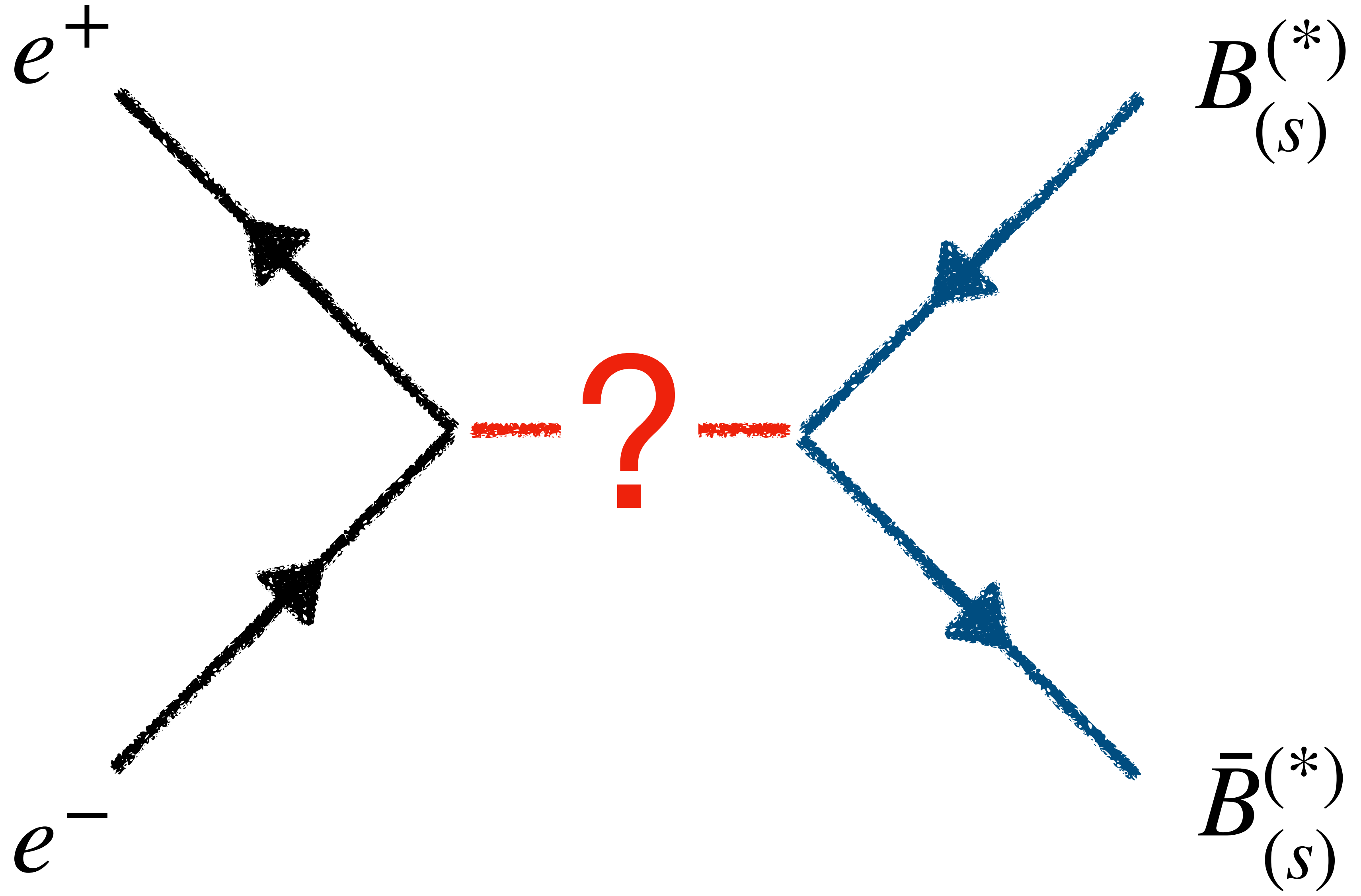
Coupled channel analysis

from the experiment, we have an almost complete picture of heavy-flavour hadron production in e^+e^- annihilation



idea: use all the data at the same time to learn more about the intermediate vector resonances

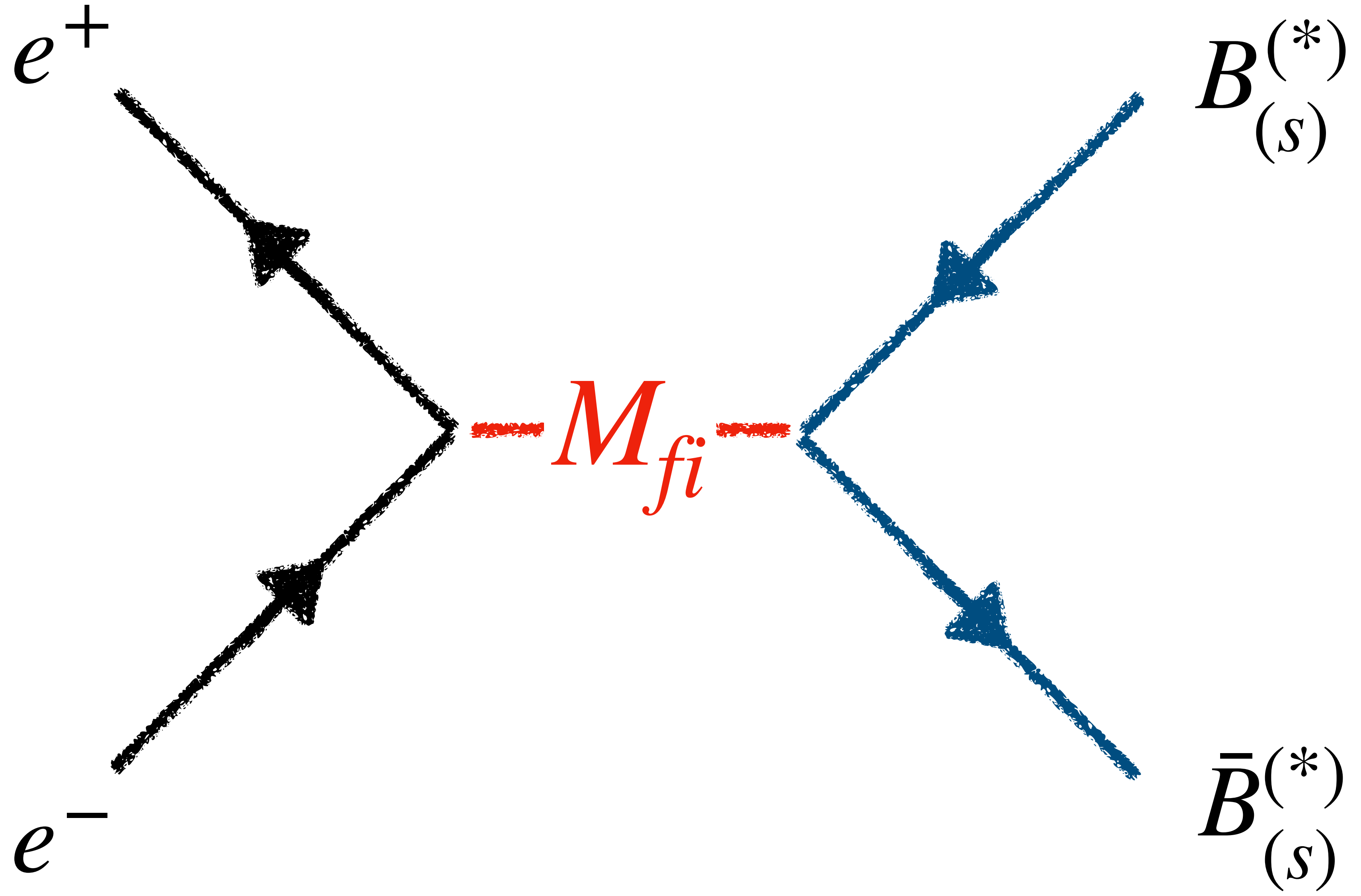
Coupled channel analysis



not QED/QCD, but scattering theory
we care about the outgoing hadrons

Coupled channel analysis

M_{fi} for $i = e^+e^-$ and any final state f



not QED/QCD, but scattering theory
we care about the outgoing hadrons

Coupled channel analysis

M_{fi} for $i = e^+e^-$ and any final state f

one way to model the matrix element: K-matrix formalism

$$M_{fi} = \sum_j [1 + KC]^{-1}_{fj} \cdot K_{ji}$$

where

$$K_{ij} = \sum_R \frac{g_{R,i} g_{R,j}}{m_R^2 - s} + b_{ij}$$

Coupled channel analysis

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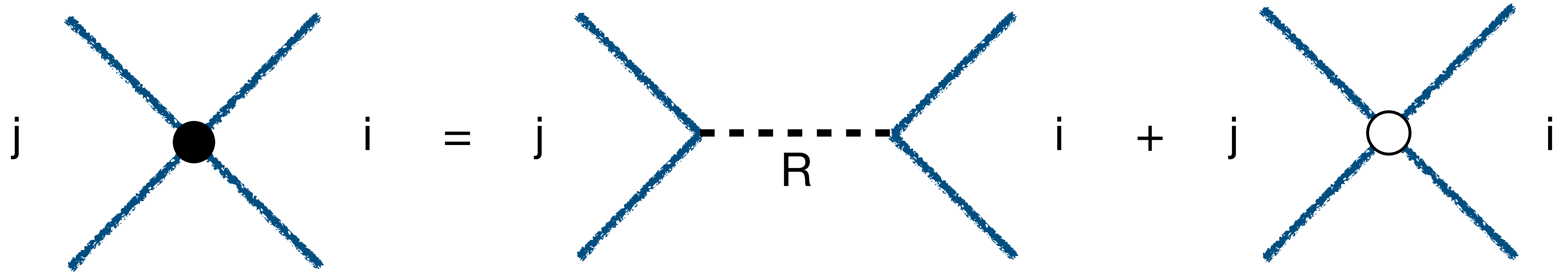


the bare interactions

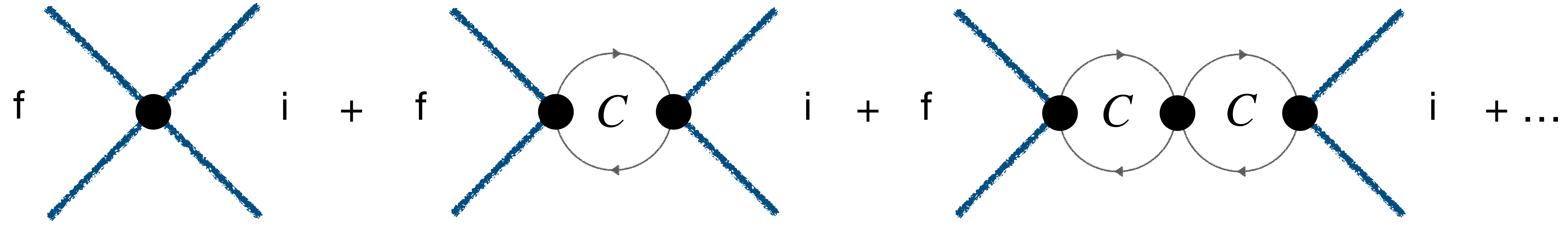
Coupled channel analysis

M_{fi} for $i = e^+e^-$ and any final state f

one way to model the matrix element: K-matrix formalism

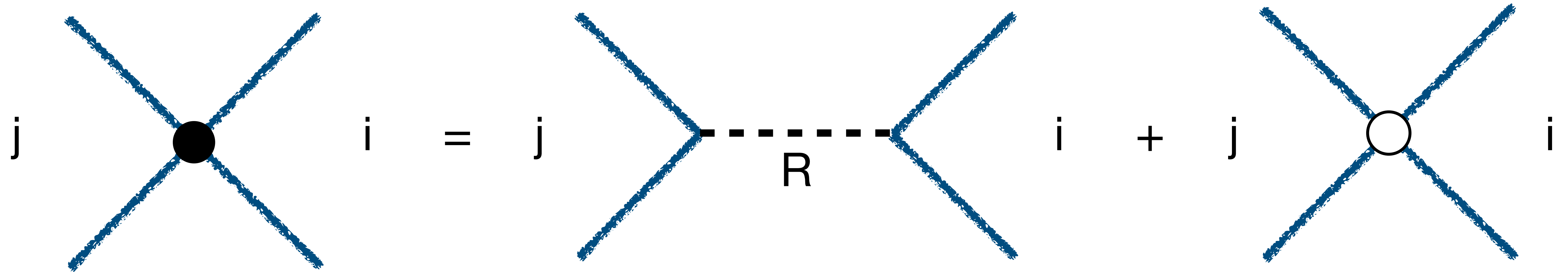
note: these loops couple $i \to f$ scattering to $i \to j$ and $j \to f$ scattering

$$M_{fi} = \sum_j [1 + KC]^{-1}_{fj} \cdot K_{ji}$$



where

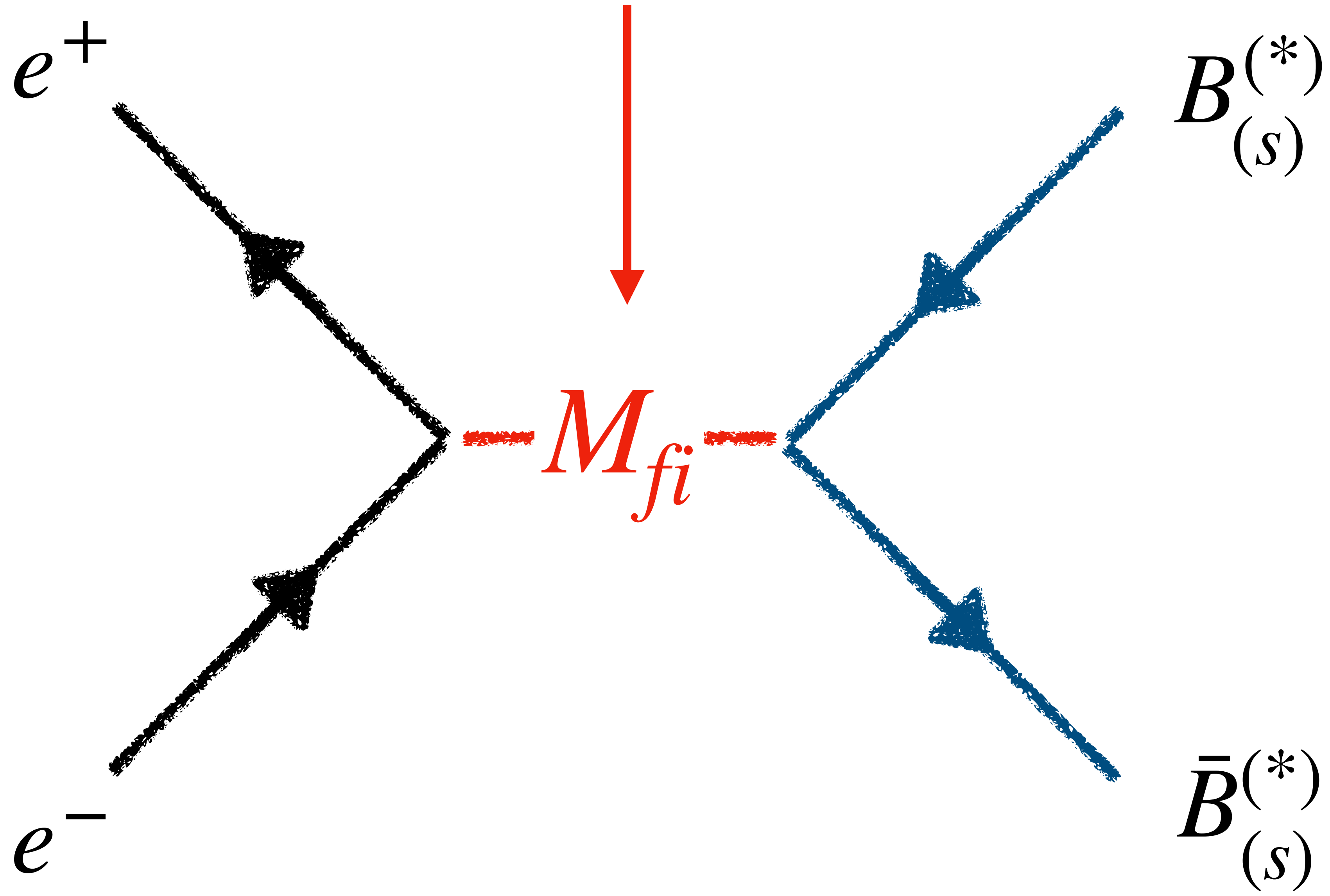
$$K_{ij} = \sum_R \frac{g_{R,i} g_{R,j}}{m_R^2 - s} + b_{ij}$$



the bare interactions

Coupled channel analysis

perform simultaneous fit to all $e^+e^- \to b\bar{b}$ data to
obtain bare couplings $g_{R,i}$, b_{ij} and bare masses m_R



Coupled channel analysis

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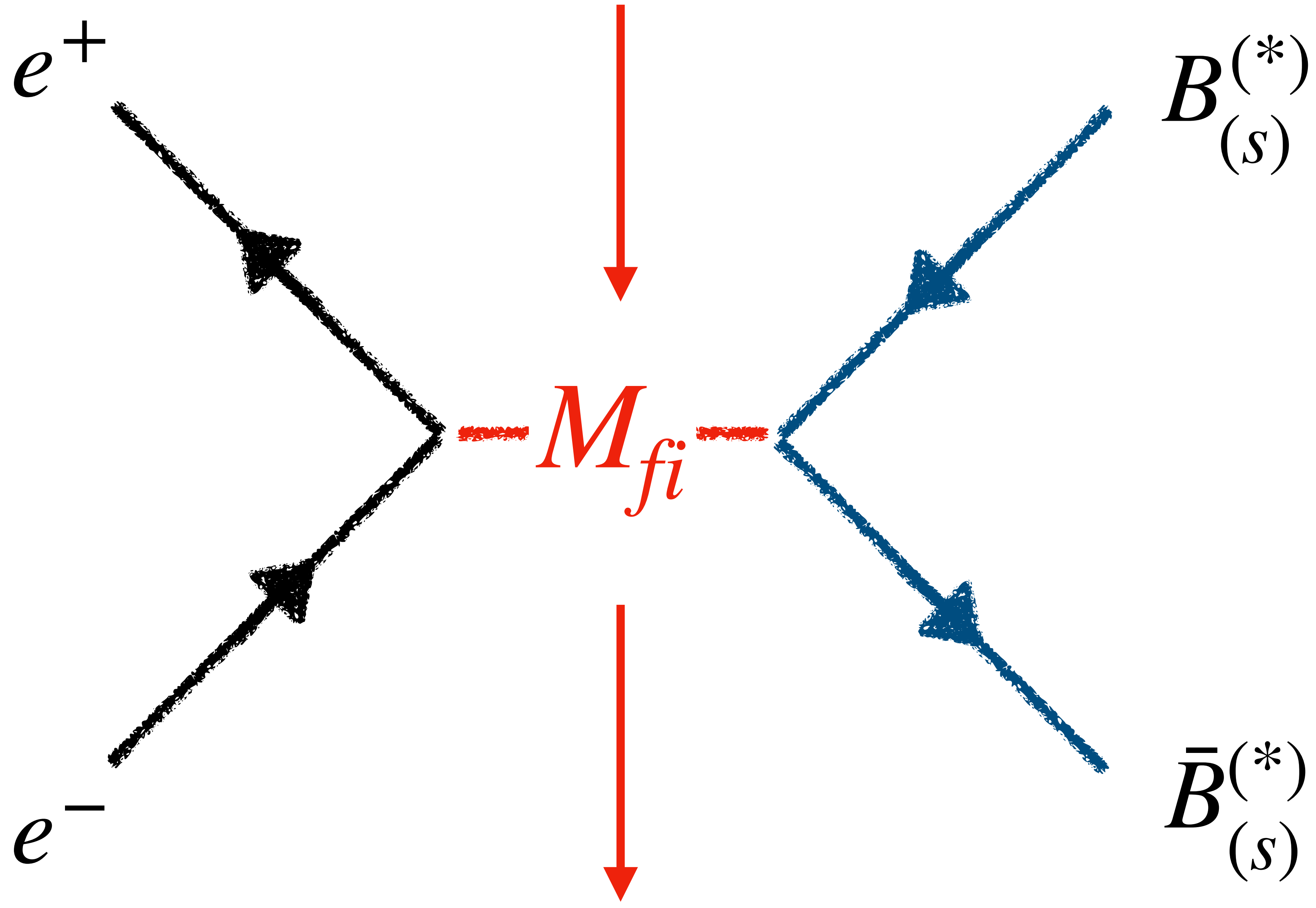
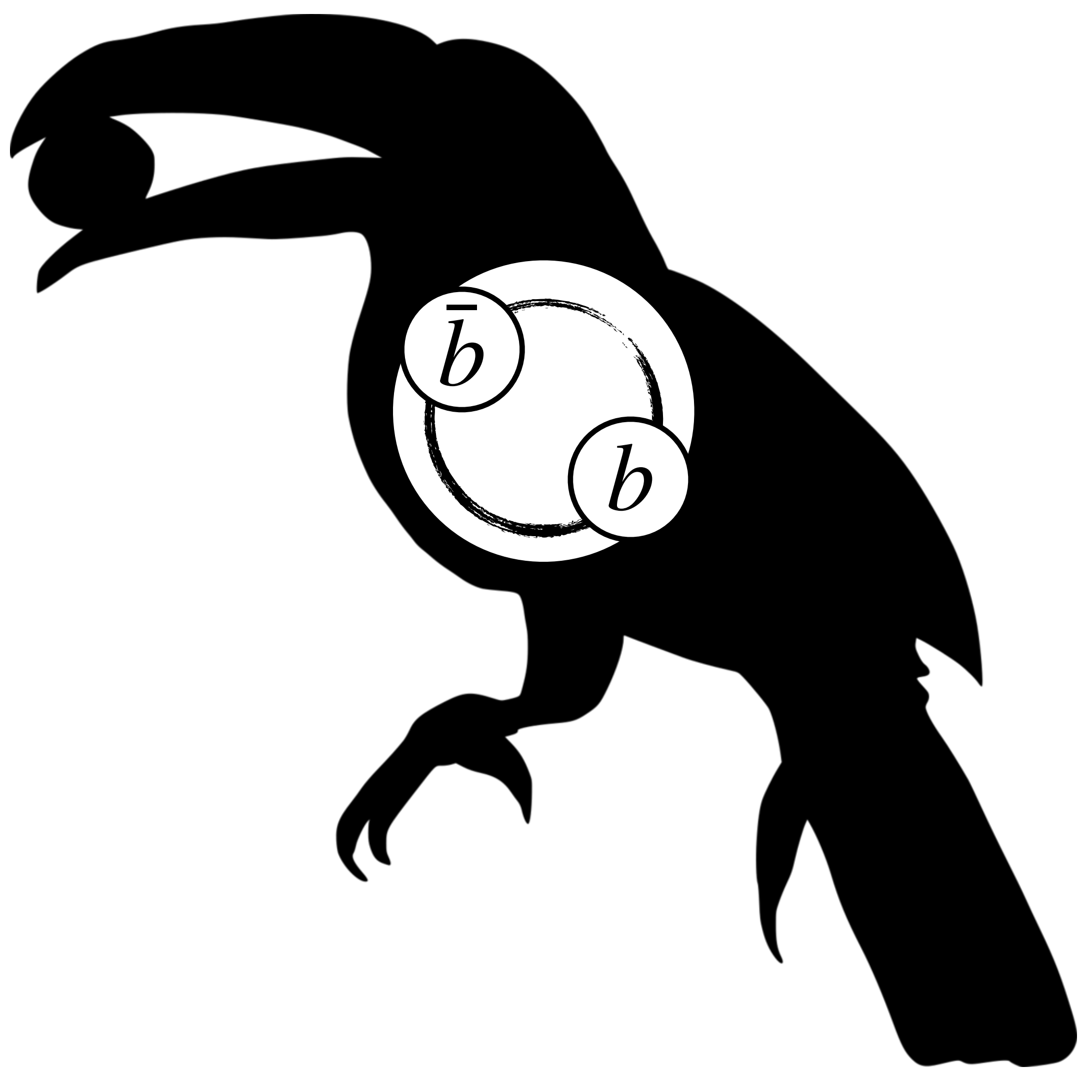


extract the physical information from poles in M

What do we learn?

(a) bottomonia

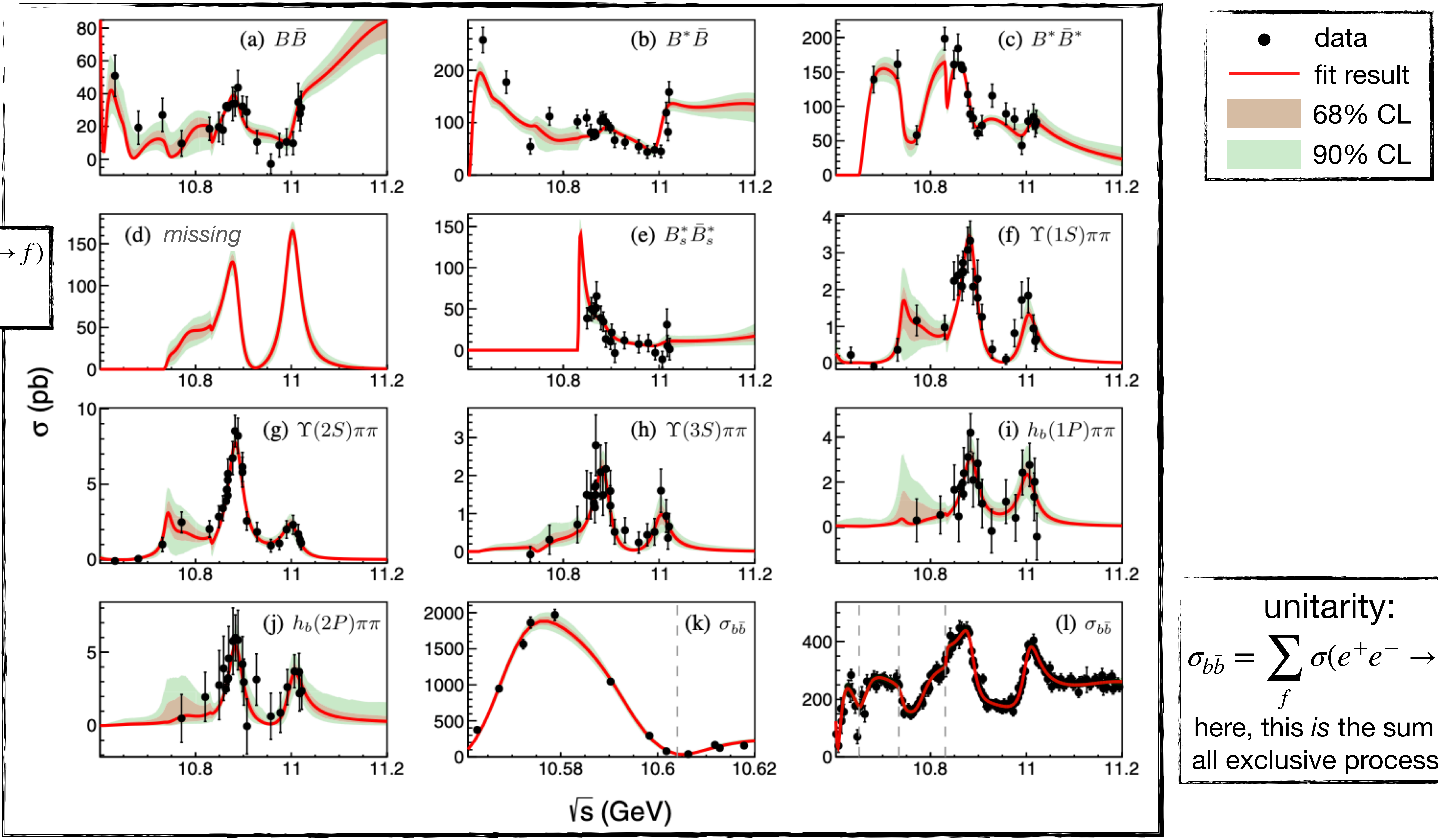


NH, R. Mitchell, E. Swanson
PRD 106 (2022) 9, 094013

Results: bottomonium

$$\sigma(e^+e^- \to b\bar{b}) \; - \; \sum_f \sigma(e^+e^- \to f)$$

unmeasured processes



unitarity:

$$\sigma_{b\bar{b}} = \sum_f \sigma(e^+e^- \to f)$$

here, this *is* the sum of all exclusive processes

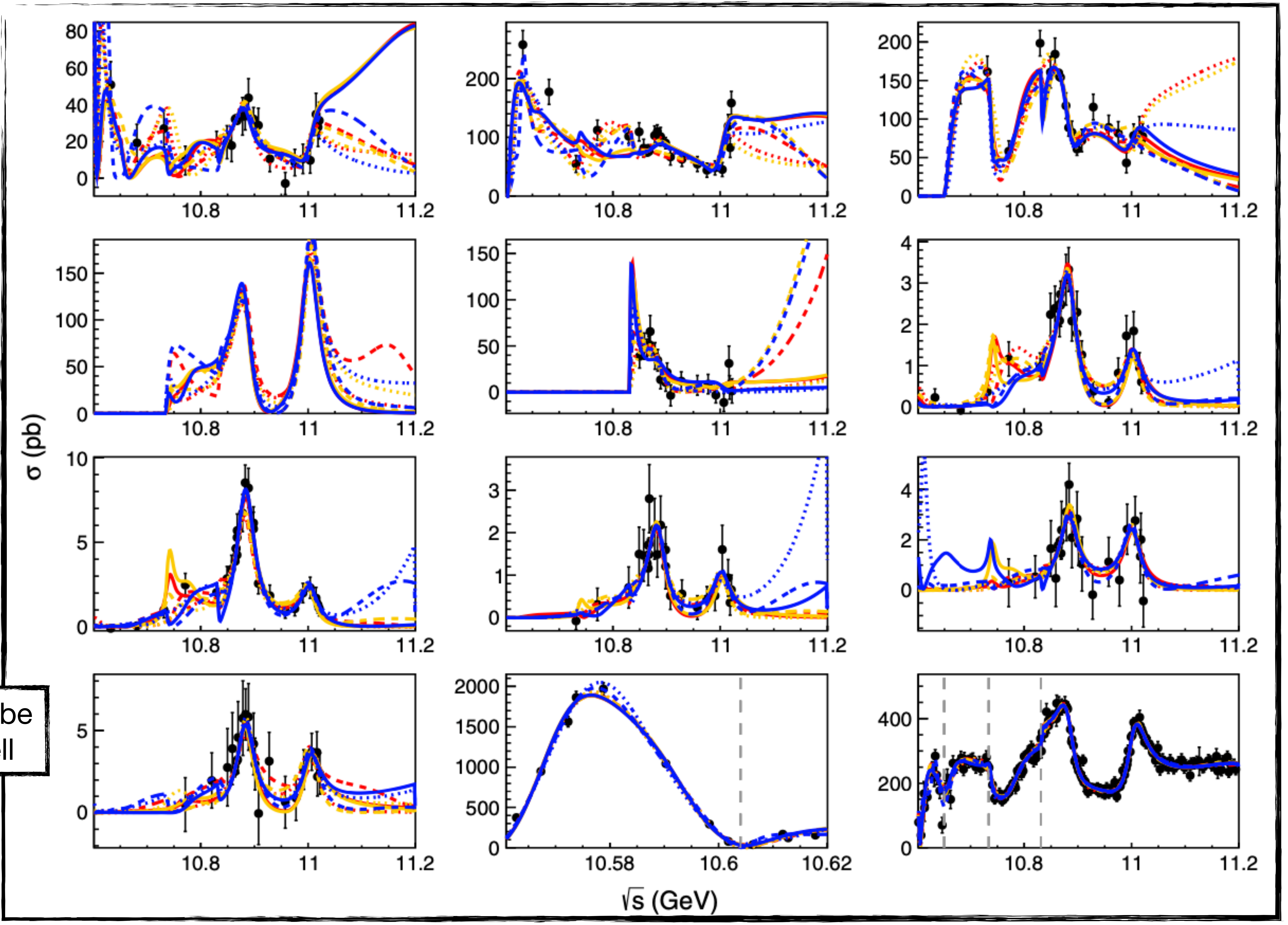
Results: bottomonium

different line-style = variation of $B(s)$
different colour = variation in three-body treatment

there is some model freedom:

- $g_{R,i}(s) = g_{R,i} \cdot k^L \cdot B(s)$
- three-body channels

→ test robustness of results for different assumptions

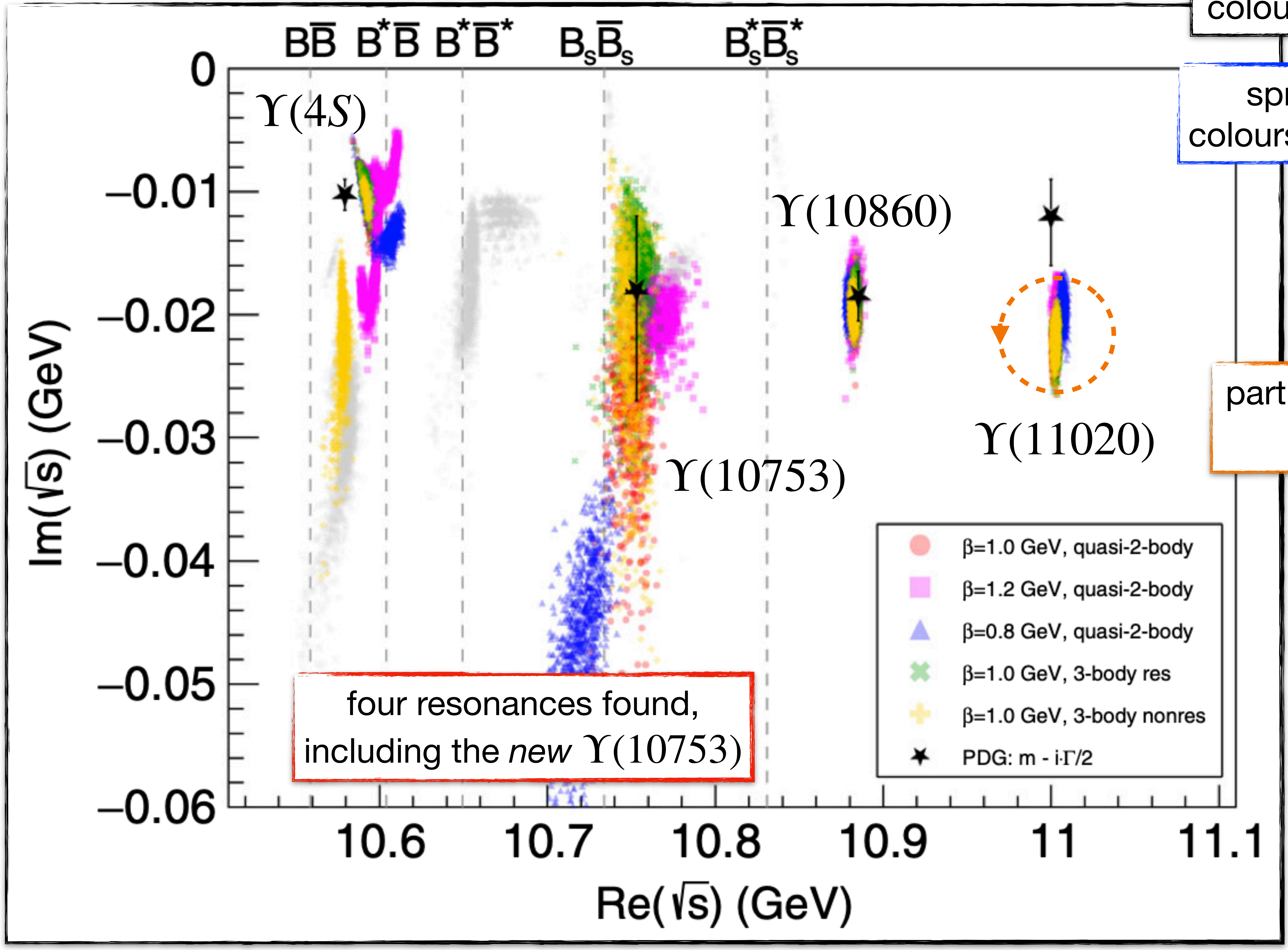


all models describe data equally well

The resonances

resonance:

pole of matrix element $M(s)$ at $\sqrt{s} = m - i\frac{\Gamma}{2}$



spread of points with same colour = statistical uncertainty

spread between different colours = systematic uncertainty

partial widths from residues $\Gamma_{R:i} \propto |\text{Res}_{R:i}|$

What do we learn?

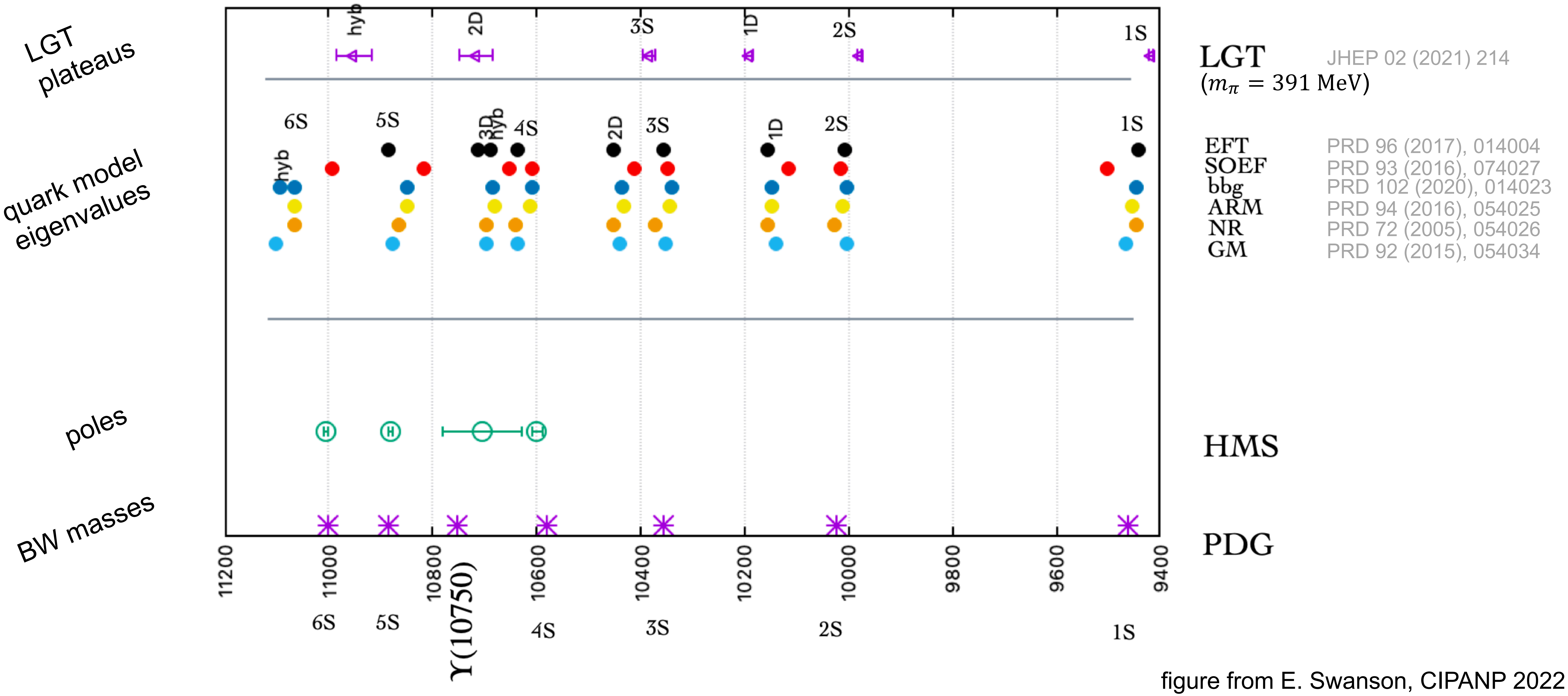
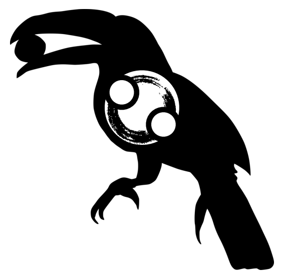


figure from E. Swanson, CIPANP 2022

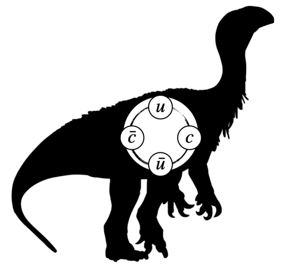
What do we learn?

- for the first time, decay branching fractions are determined

  → sensitive input for interpretation

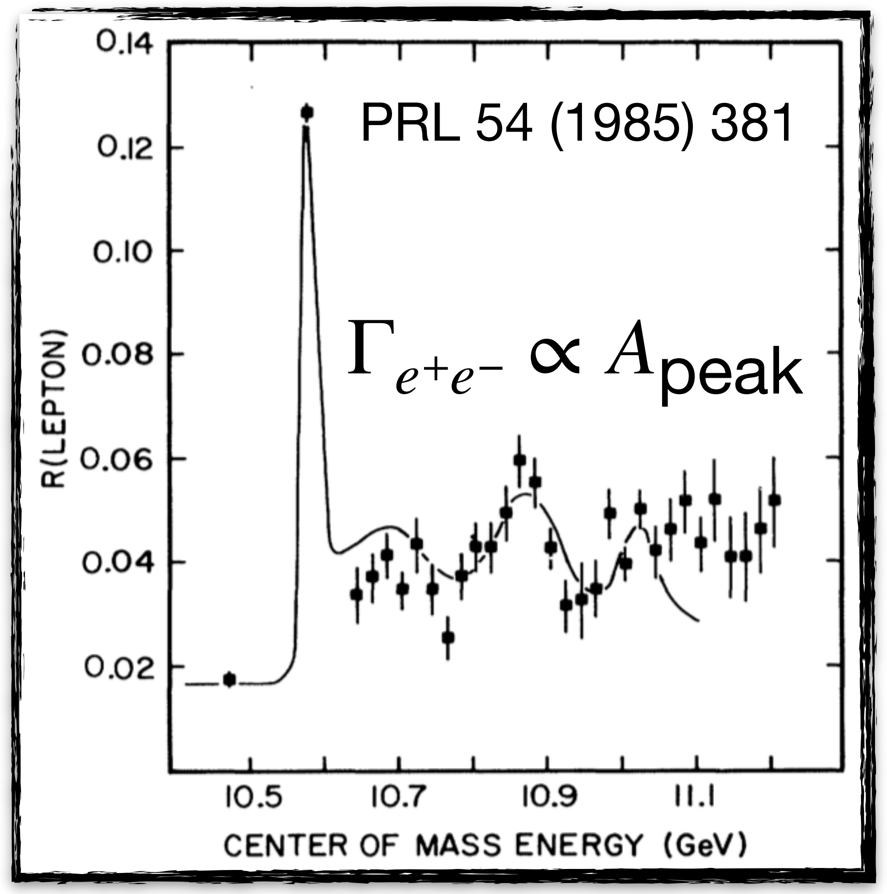


versus



- we can improve upon old measurements

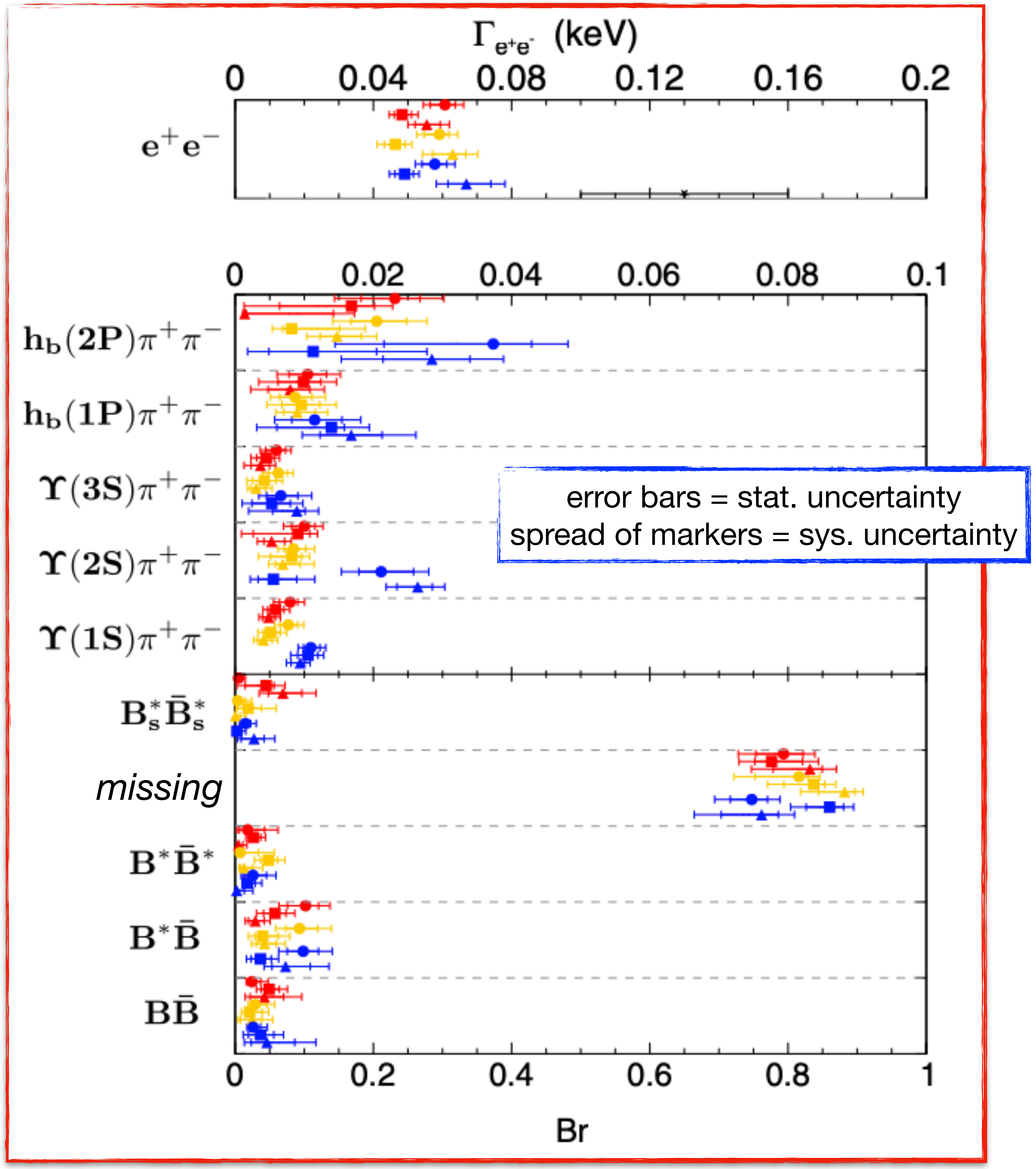
  → accounting for non-resonant processes is important!



- we can provide some guidance for future measurements

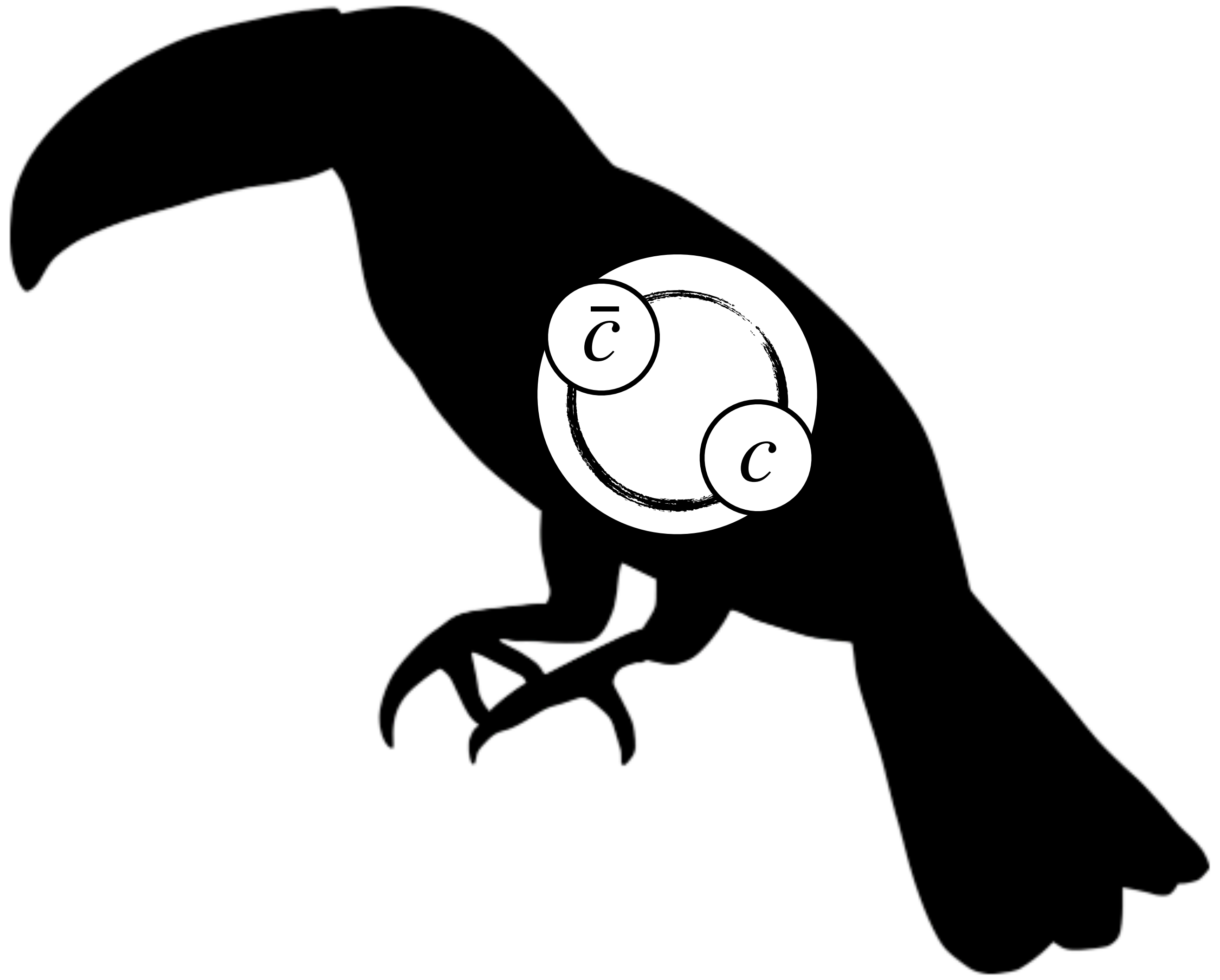
  → 80% of $\Upsilon(11020)$ peak intensity has not been measured yet!

example: decays of the $\Upsilon(11020)$



What do we learn?

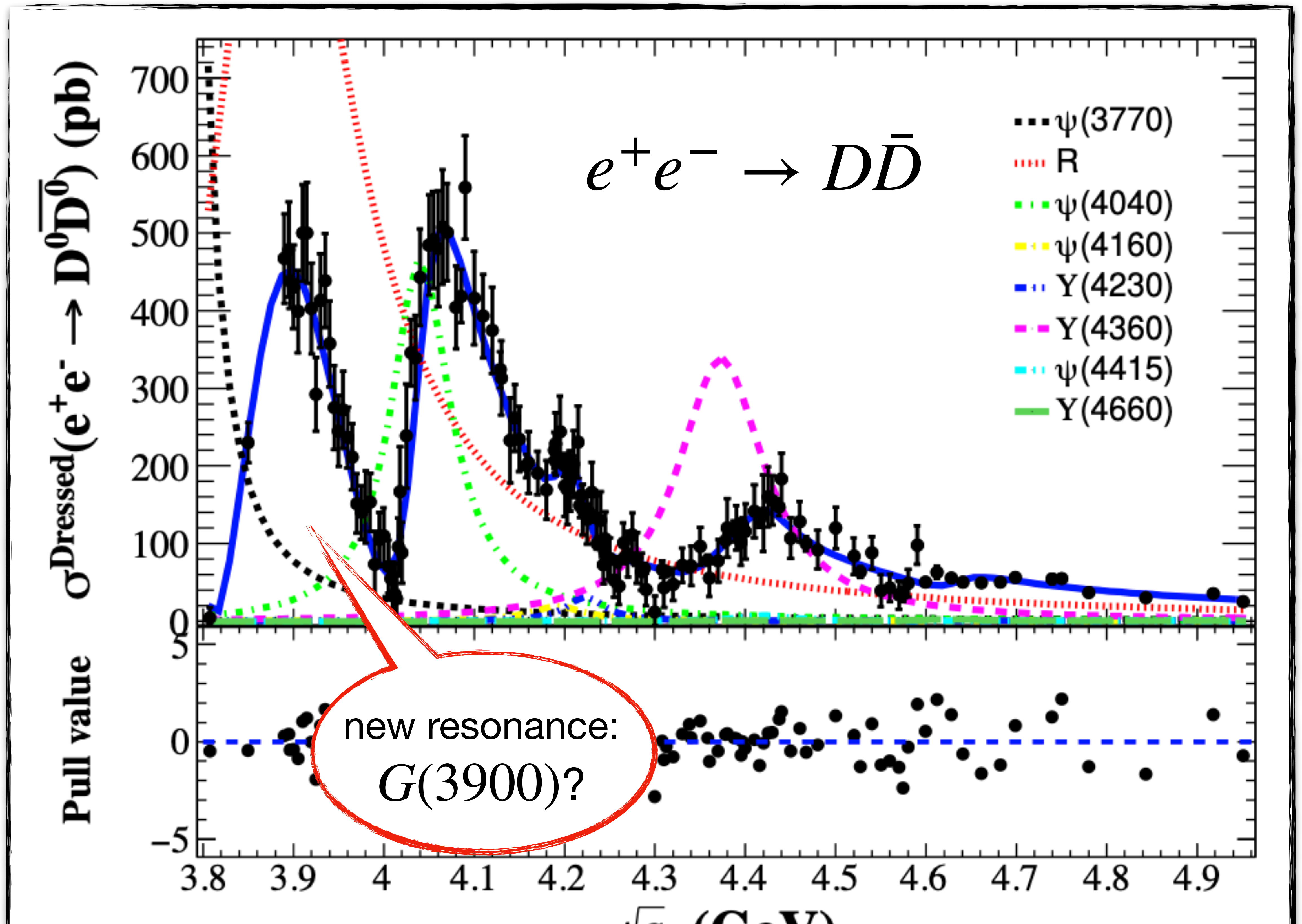
(b) charmonia



NH, R. Lebed, R. Mitchell, E. Swanson, Y. Wang, C. Yuan
PRD 109 (2024) 11, 114010

A piece of the puzzle

the $G(3900)$ problem



PRL 133 (2024) 8, 081901

A piece of the puzzle

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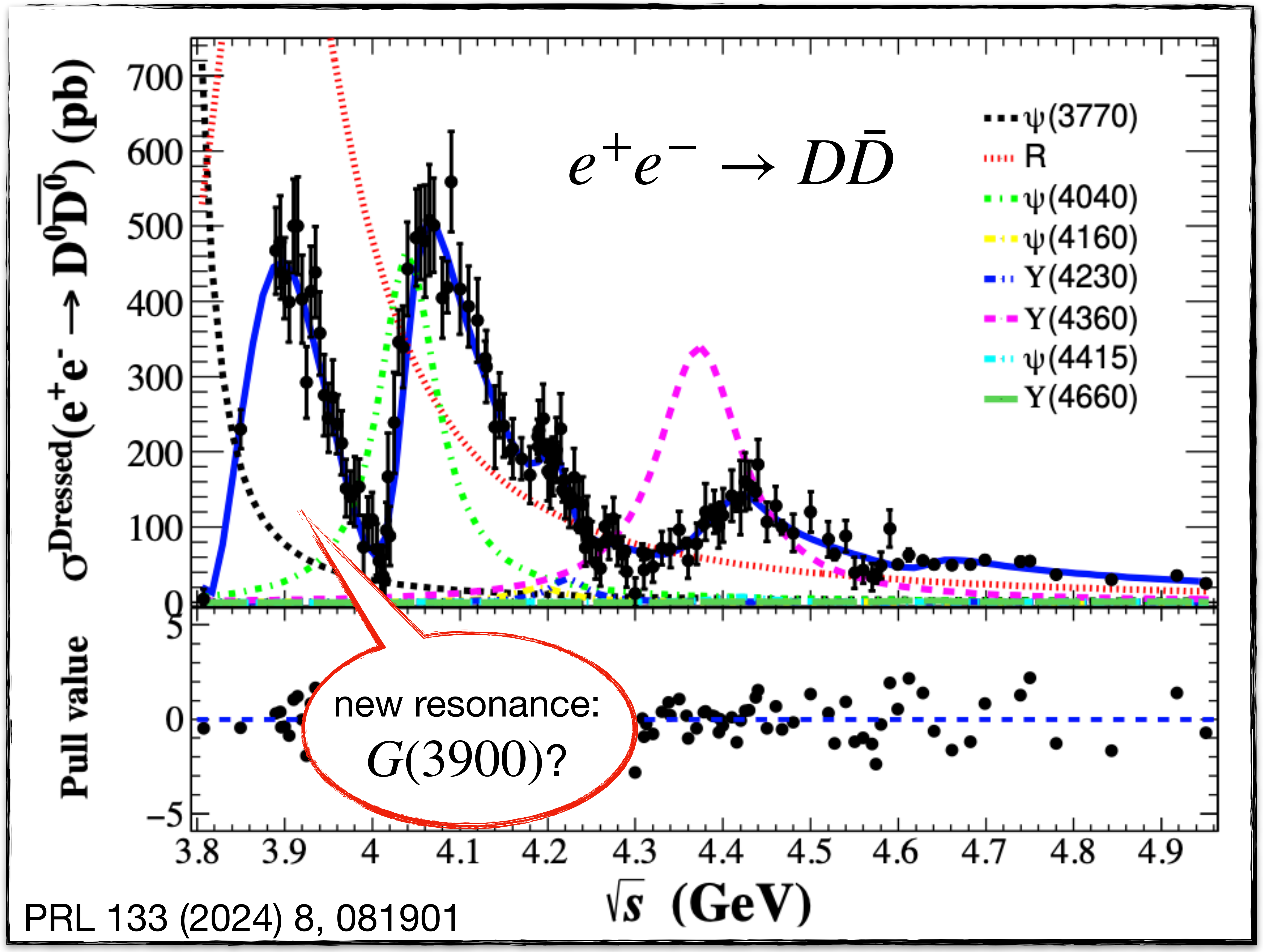
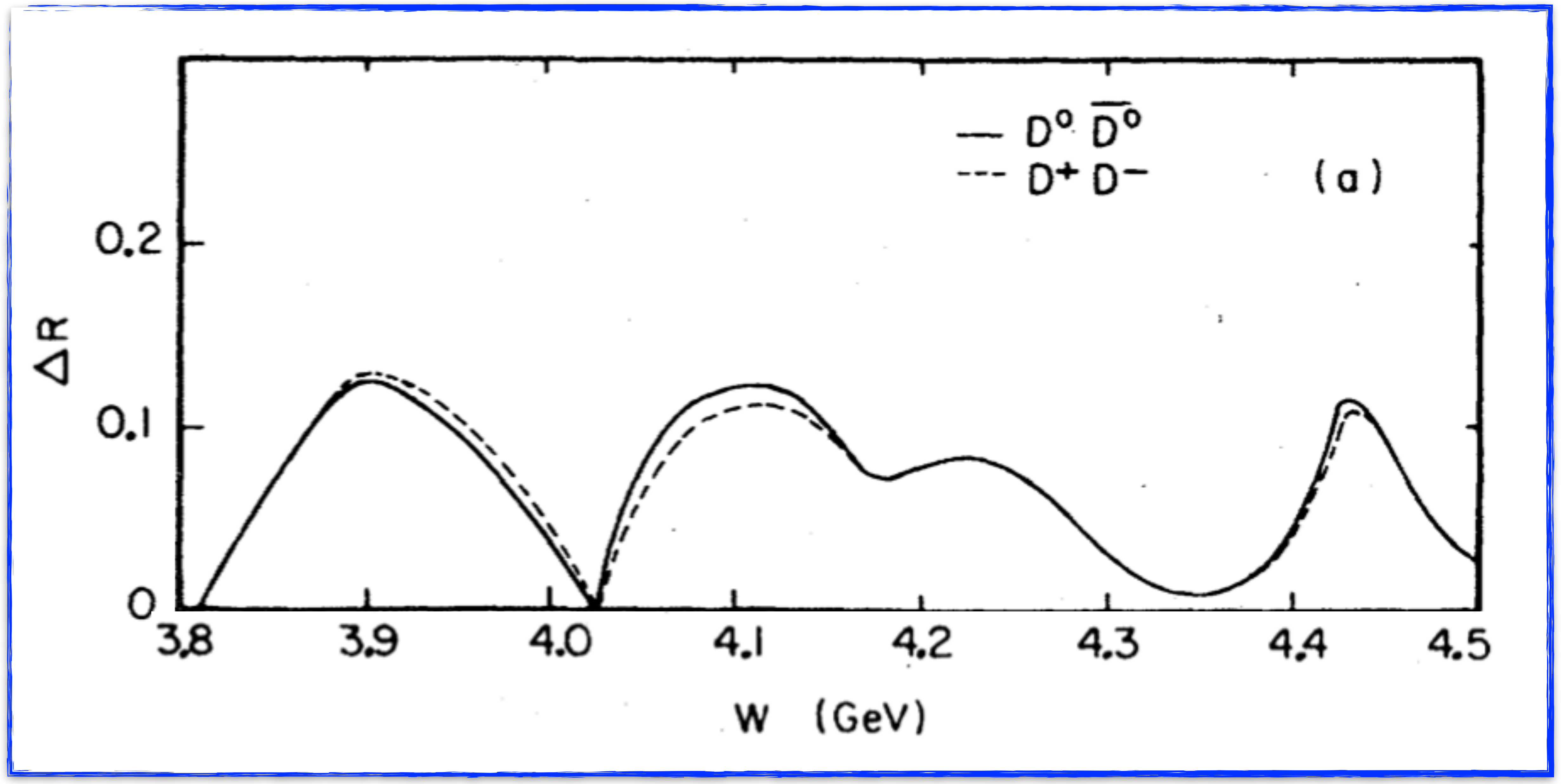
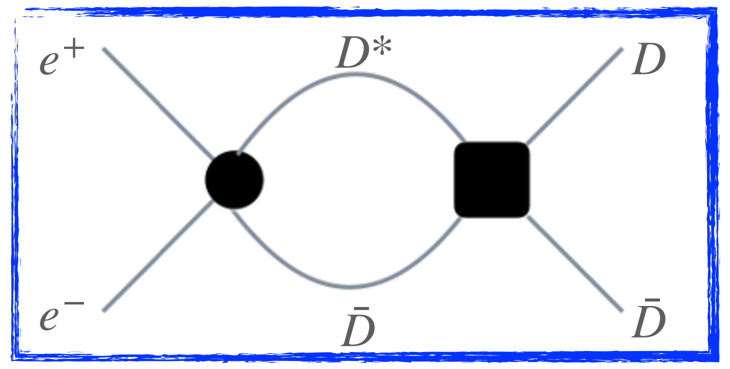


PRL 133 (2024) 8, 081901

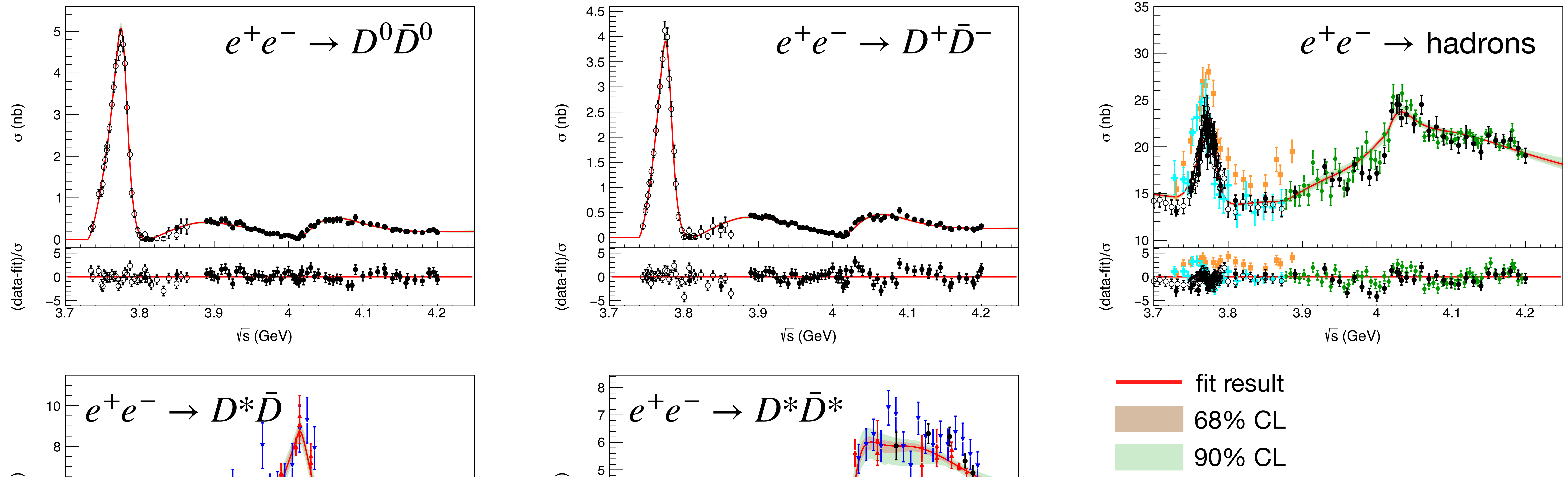
Eichten et al., Phys. Rev. D 21 (1980) 203

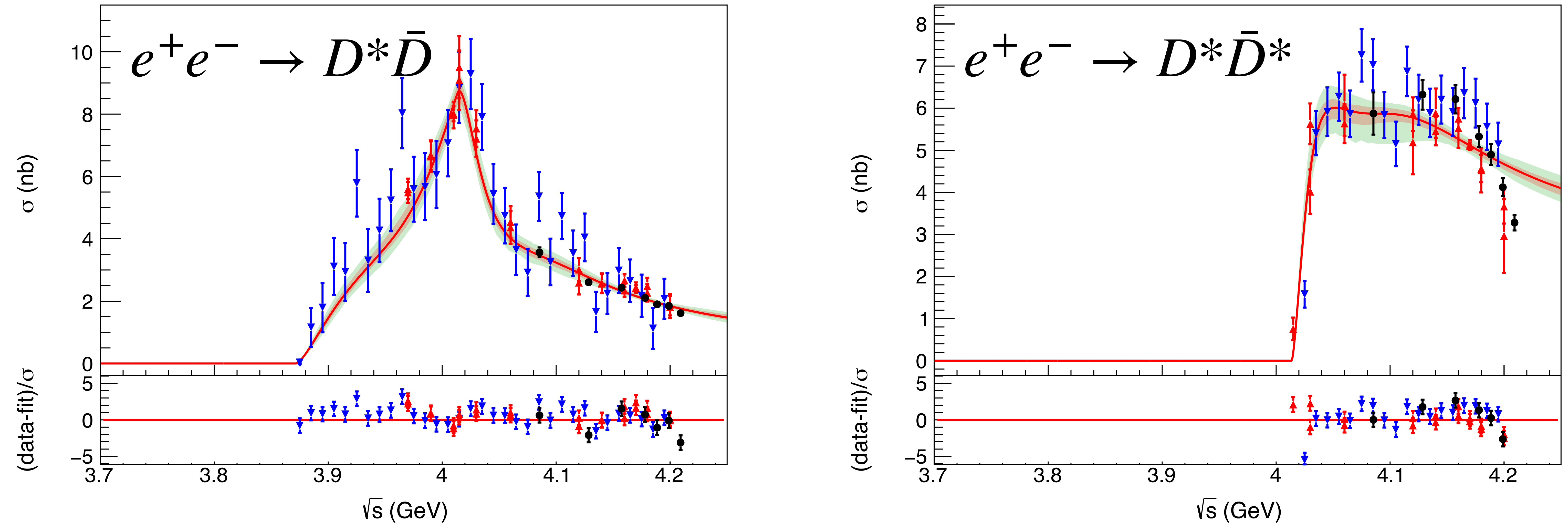


In our calculation there is some weak structure in the 3.9–4.0 GeV region. It does not arise from a $c\bar{c}$ resonance, but from the opening of the $D\bar{D}^* + D^*\bar{D}$ channel and a decrease in the $D\bar{D}$ channel due to a nearby zero in the 3S decay amplitude.



A piece of the puzzle

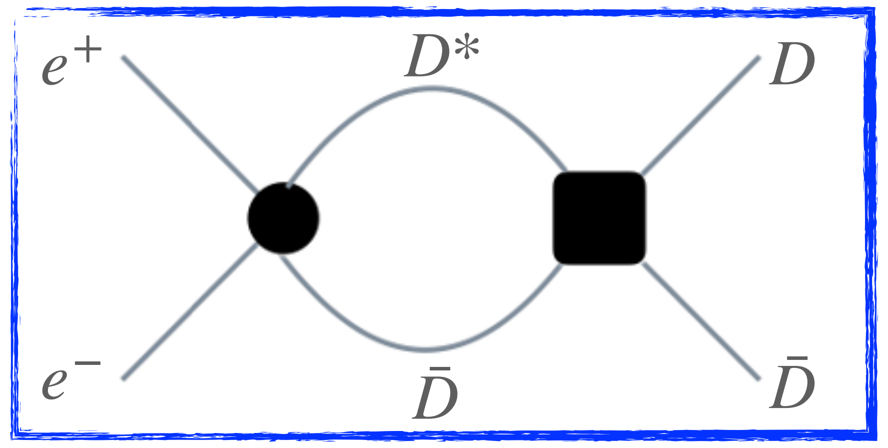


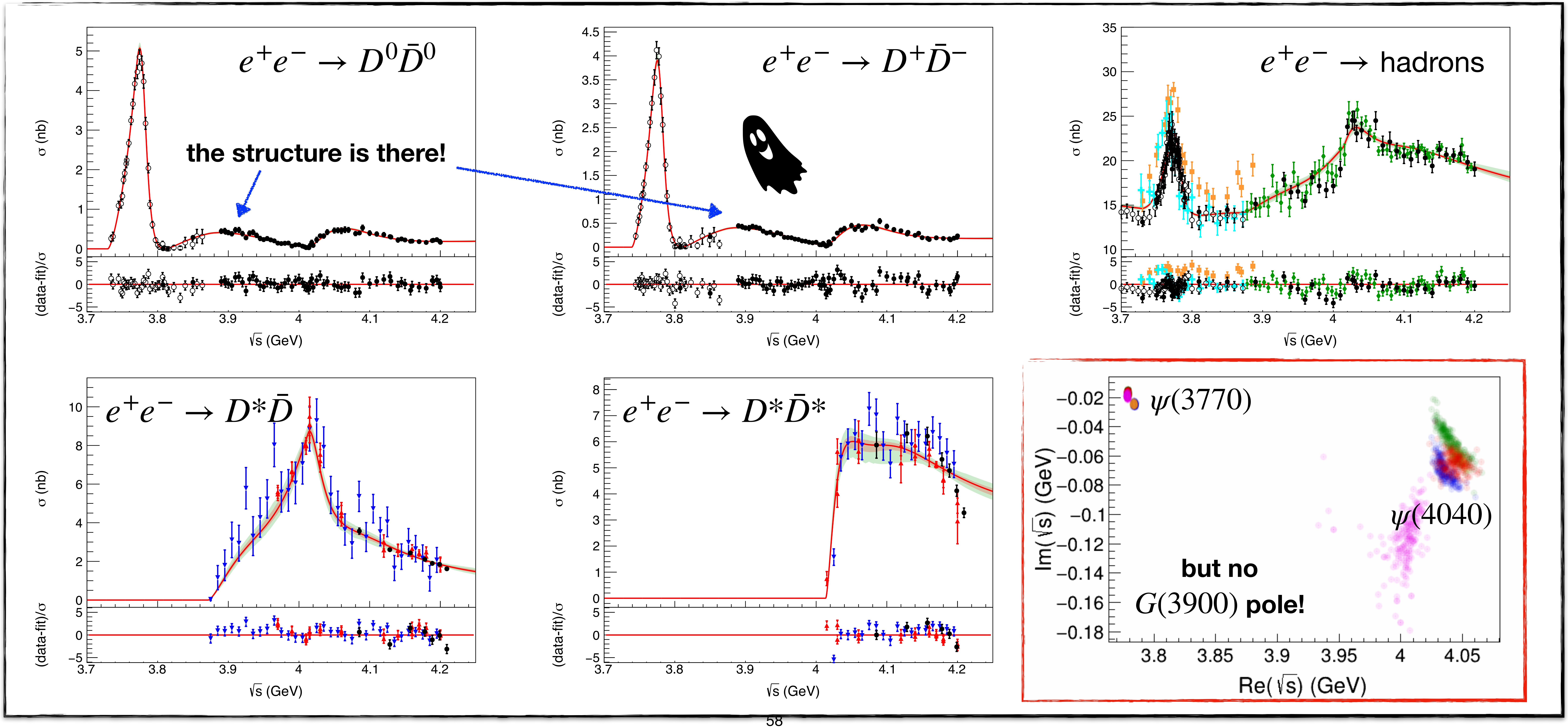


Data from:

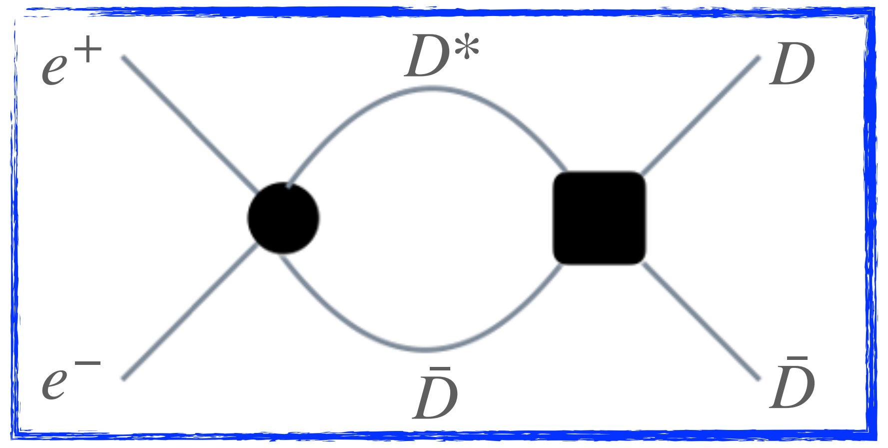
BESIII (unoff.) Andy Julin, University of Minnesota
BESIII: PRL 133 (2024) 8, 081901
BESIII: JHEP 05 (2022) 155
Belle: Phys.Rev.D 97 (2018) 1, 012002
CLEO: Phys.Rev.D 80 (2009) 072001
BES: PRL 88, 101802 (2002)
BESII: PRL 97, 262001 (2006)
SPEAR: PRL 39, 526 (1977);
A. Osterheld et al. 86; Schindler 79

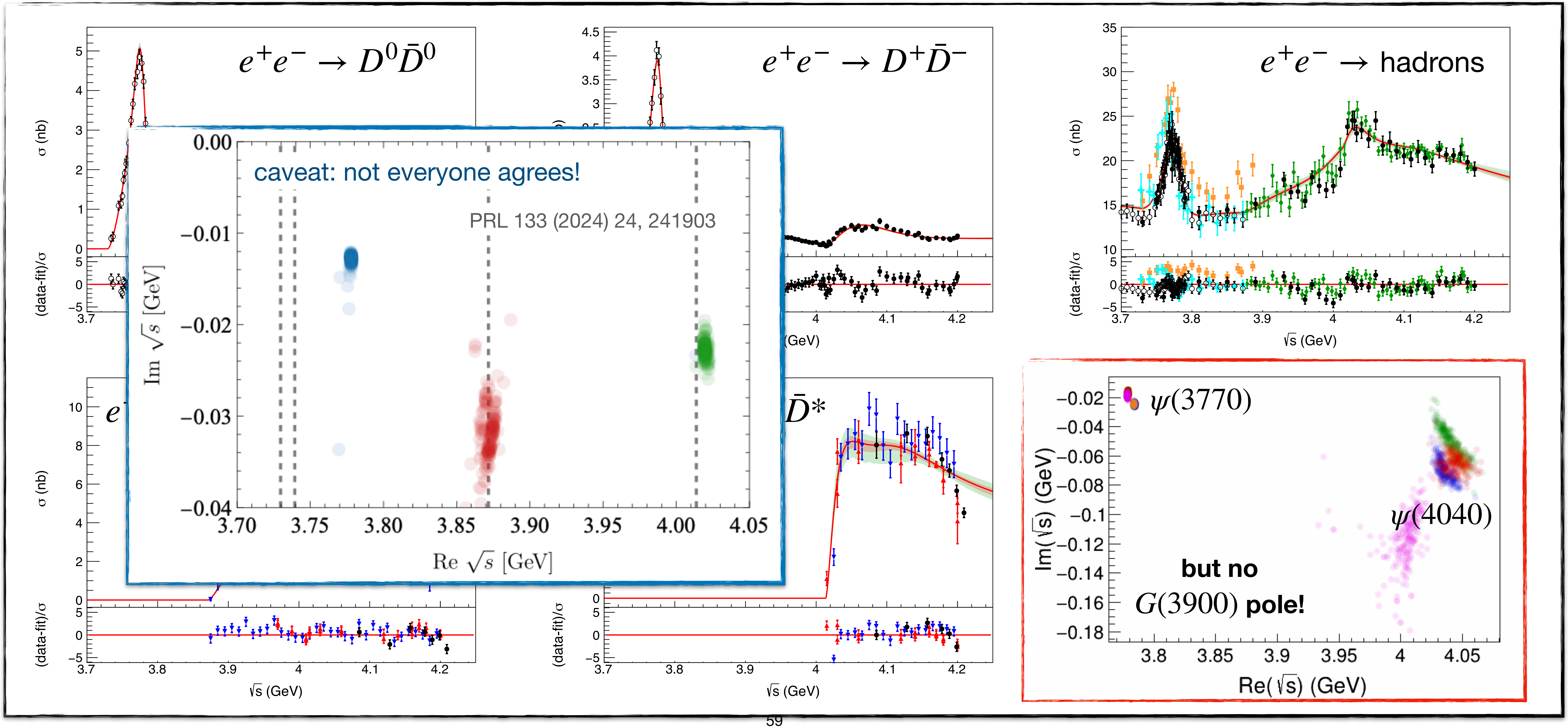
A piece of the puzzle



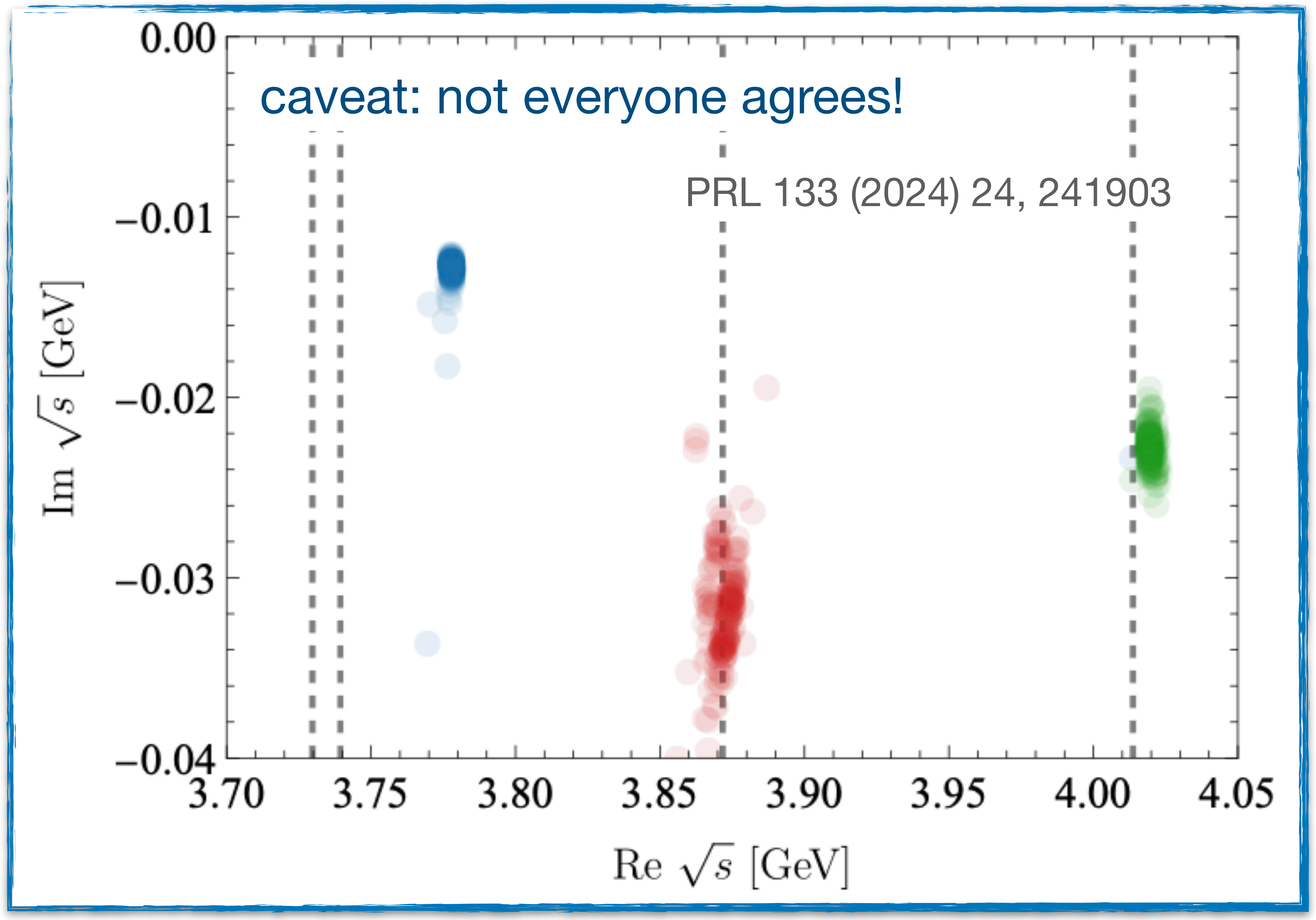


A piece of the puzzle



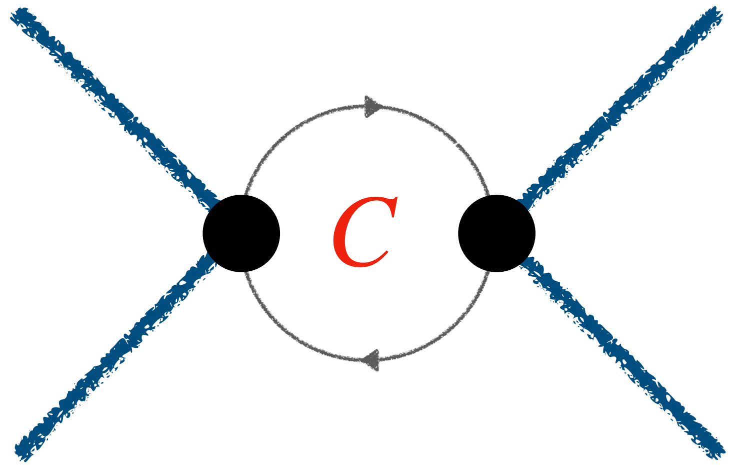


What is the lesson here?



it is (very) valuable to compare (many) different models!

the devil is in the details:



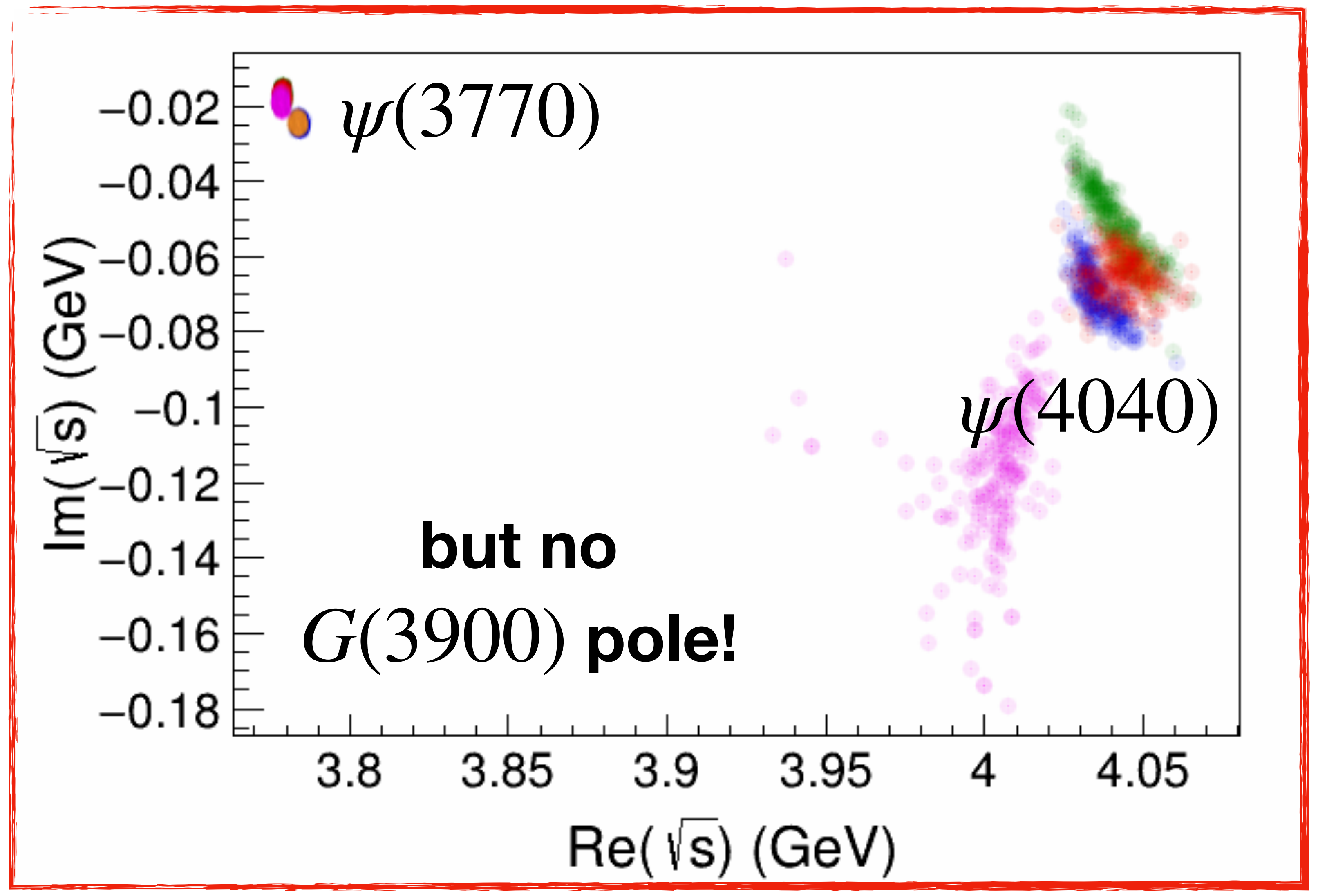
$$M_{fi} = \sum_j [1 + KC]^{-1}_{fj} \cdot K_{ji}$$

here: different treatment of angular momentum between particles in the bubble

→ using a well-defined (toy-)problem, we studied stability of poles under hundreds of different parameterisations

→ we find: truth is in the data, not the parameterisation - real poles remain consistent irrespective of choice of K_{ij}, C

arXiv:2601.09844 [hep-ph]

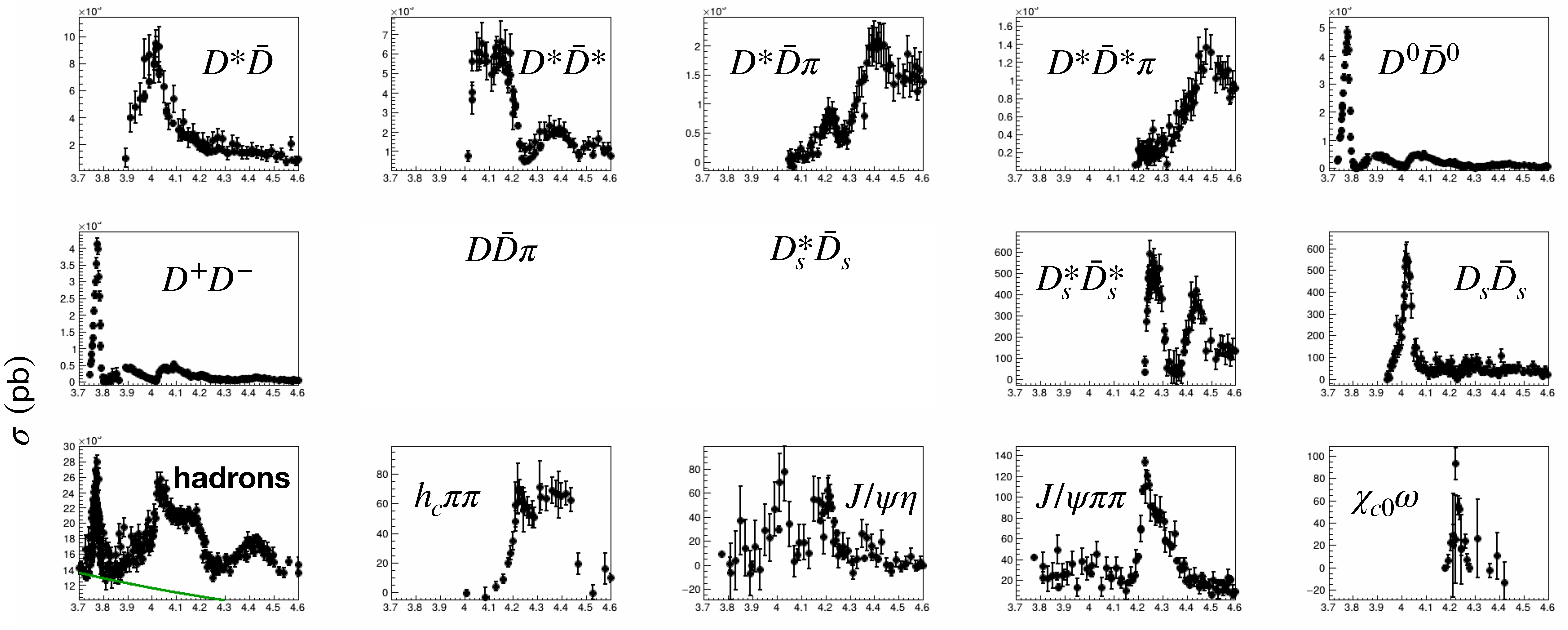


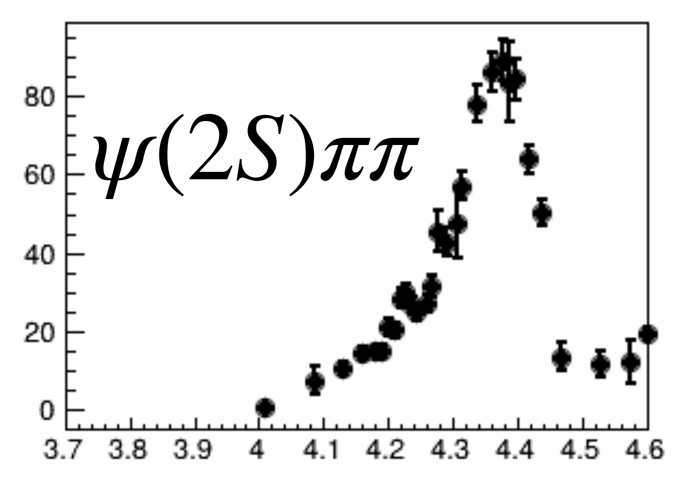
also: Salnikov, Milstein, PRD 109 (2024) 11, 114015

What is next?

The full charmonium case

data from BESIII, Belle, BaBar, CLEO, …



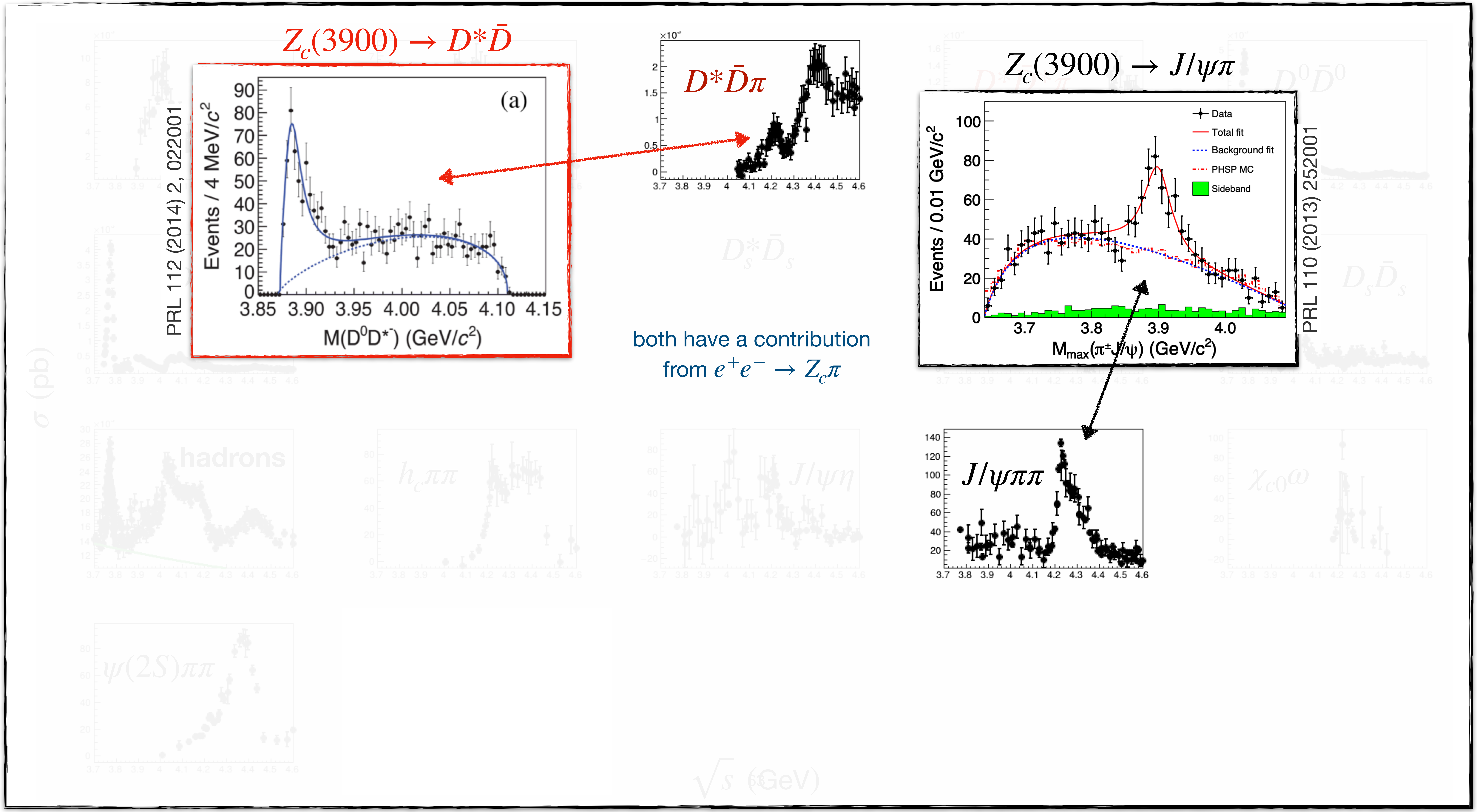


apply the same idea to the full $e^+e^- \to c\bar{c}$ dataset?

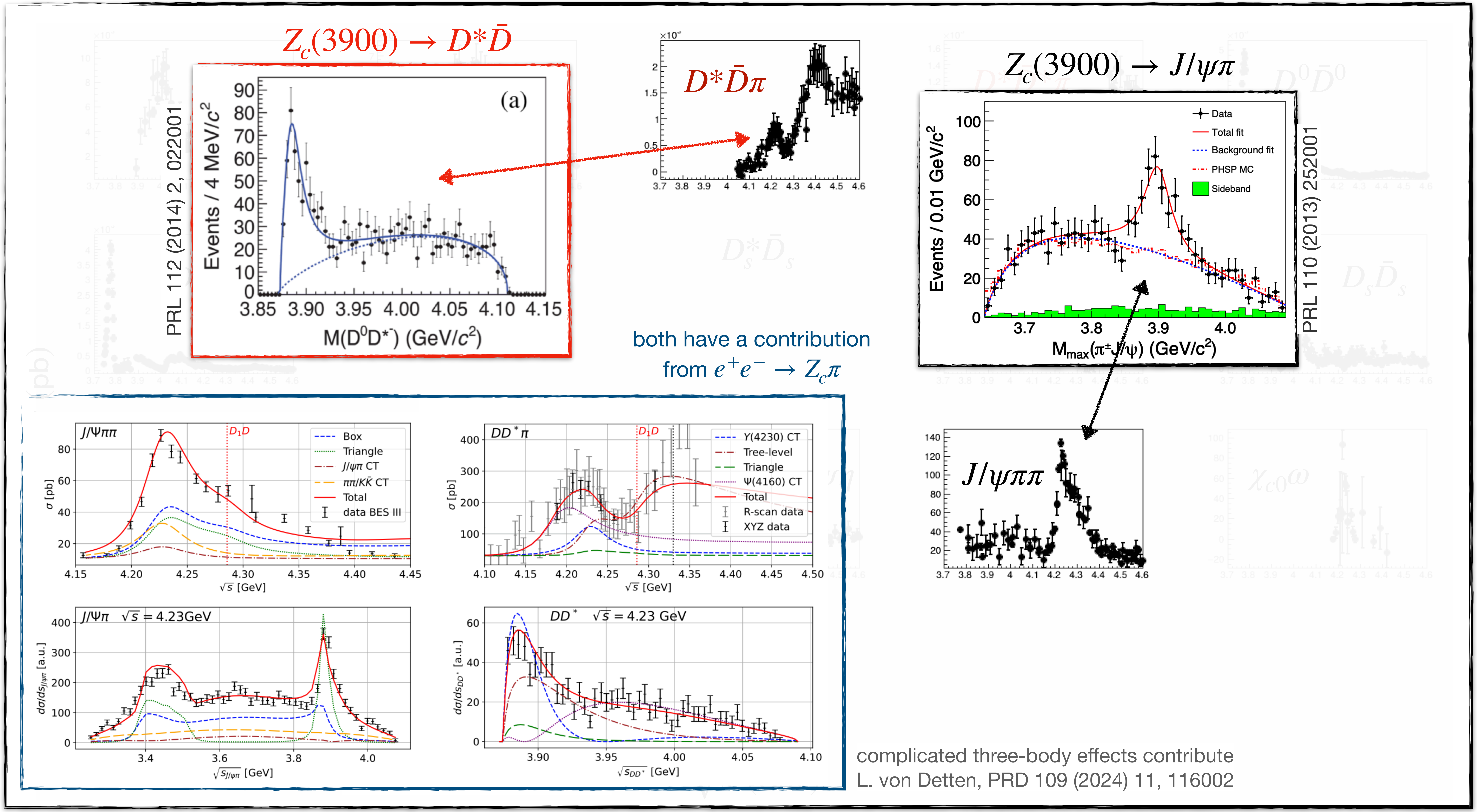
but: sizable three-body processes → no (easy) solution to handle three-body (re-)scattering

$\sqrt{s}$ (GeV)

The full charmonium case

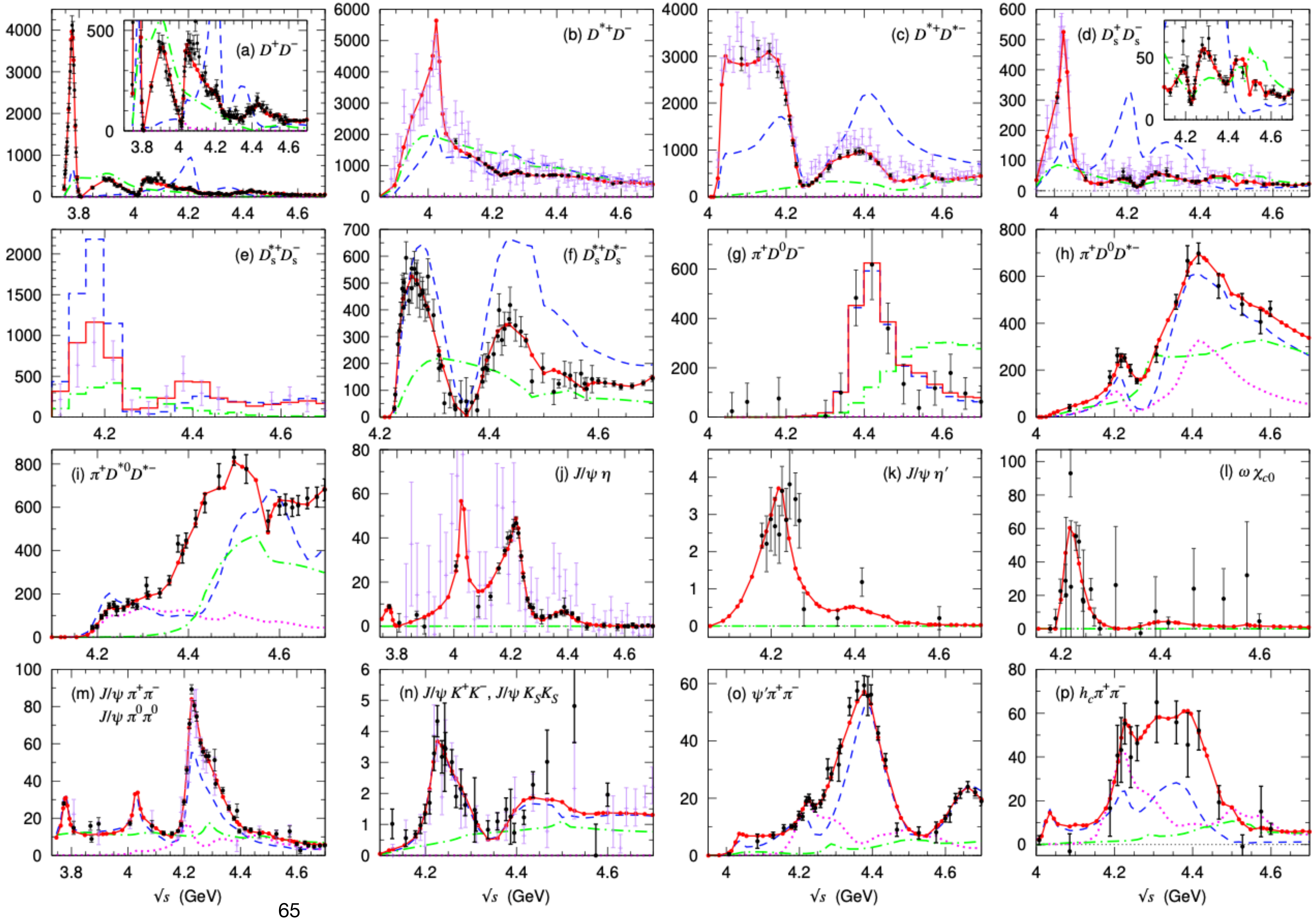


The full charmonium case



The full charmonium case

Nakamura et al., PRD 112 (2025) 5, 054027



- our approach: bottom-up
  - as simple as possible, only increase complexity if that's needed
  - study robustness of results for different model assumptions

- the other approach: top-down
  - built in everything you believe contributes
  - high complexity, high detail → fit to Dalitz plots at various $\sqrt{s}$
  - model dependence?

The full charmonium case

- our approach: bottom-up
  - as simple as possible, only increase complexity if that’s needed
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- the other approach: top-down
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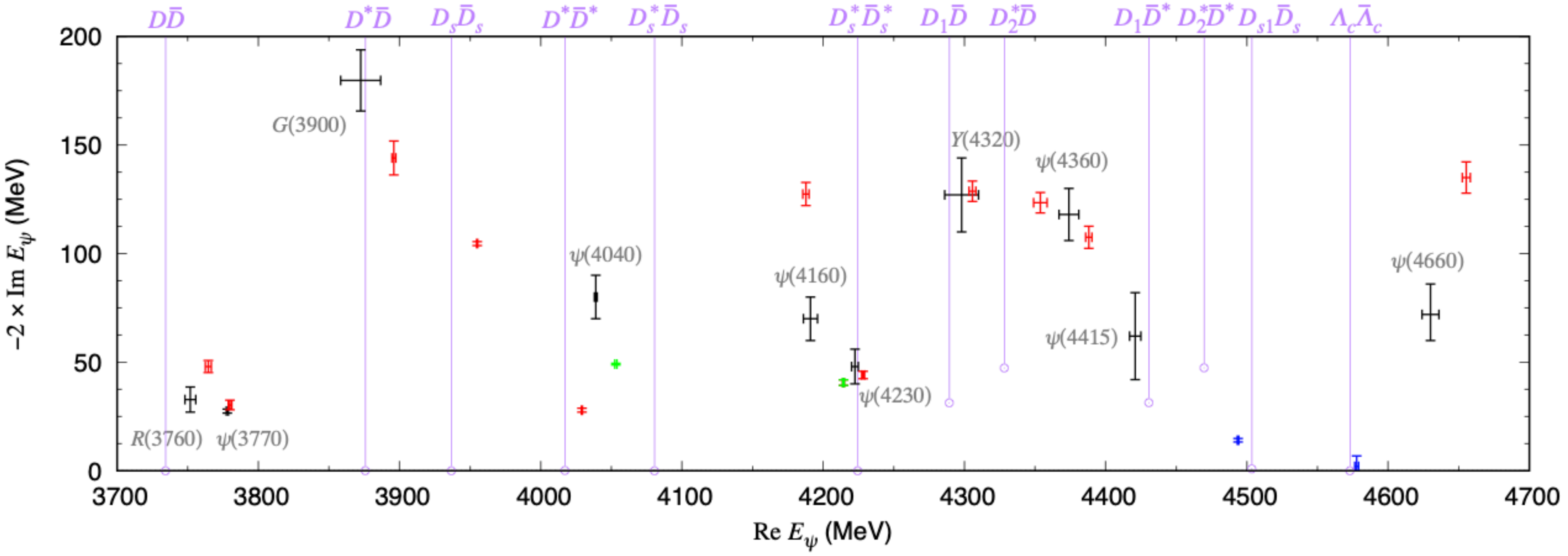
  - model dependence?

stay tuned!

Nakamura et al., PRD 112 (2025) 5, 054027

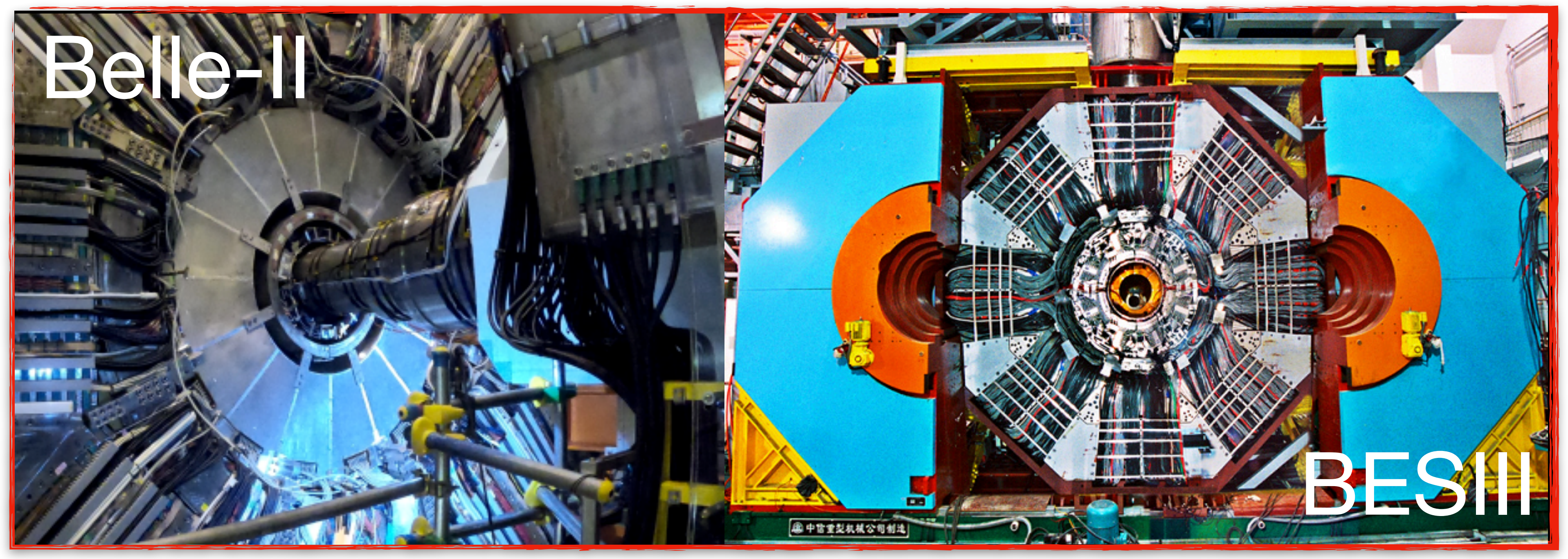


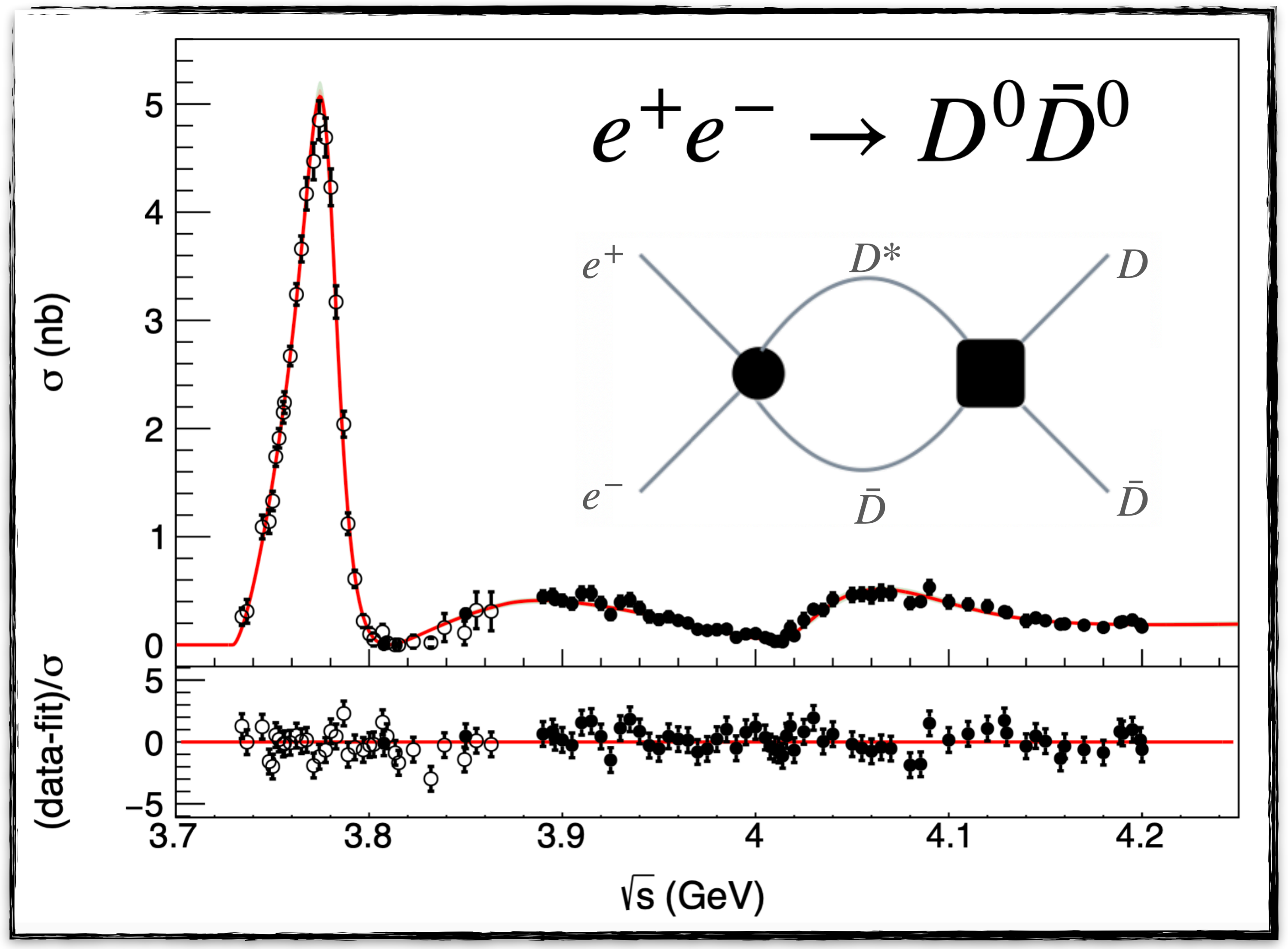
finds a total of 15 poles above the open-charm threshold

Summary

How well do we know vector quarkonia?

- a lot of effort has gone into finding new exotic hadrons - but surprisingly little is known about regular vector quarkonia
- we have the necessary data, but there is no free lunch:
  → this is no bump-hunt, simple interpretations tend to fail
  → coupled channel effects matter & global analyses are key - but hard!
- the future is bright: BESIII and Belle-II keep producing high quality data





- very active field with many different approaches - some examples:
- many things still to be learned!

Lin et al., PRL 133, 241903
Nakamura et al., PRD 112 (2025) 5, 054027
Cleven et al., PRD 90 (2014) 7, 074039
L. von Detten, PRD 109 (2024) 11, 116002

Thank you for your attention!