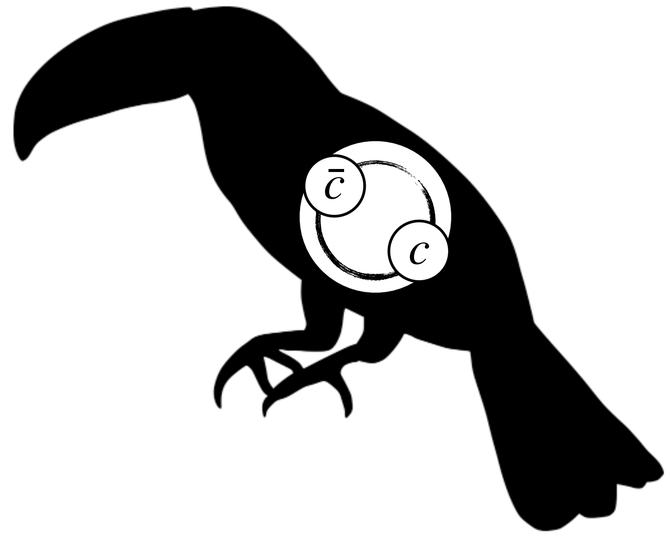
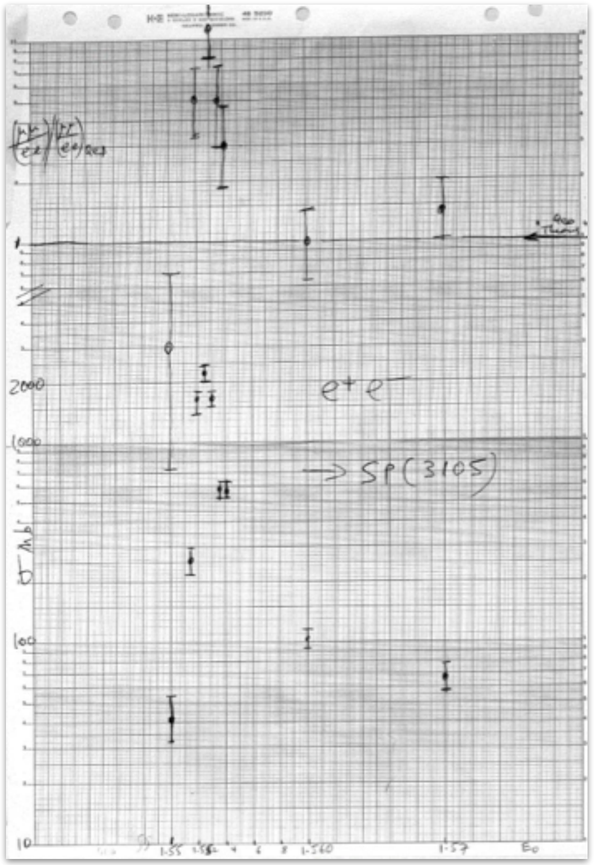
How well do we know the vector quarkonia?

Nils Hüsken
Johannes Gutenberg-Universität Mainz
DPG Spring Meeting Cologne, March 12th 2025

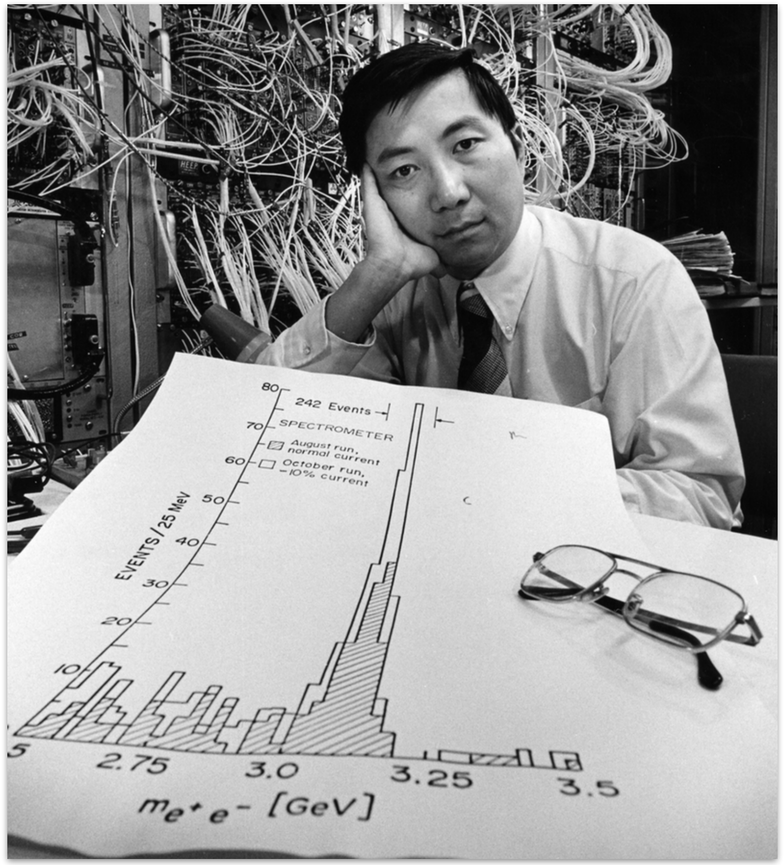


work done with/by the BESIII collaboration,
R. Mitchell, E. Swanson, R. Lebed, Y.Q. Wang, C.Z. Yuan

50 years of charmonium (just last year)



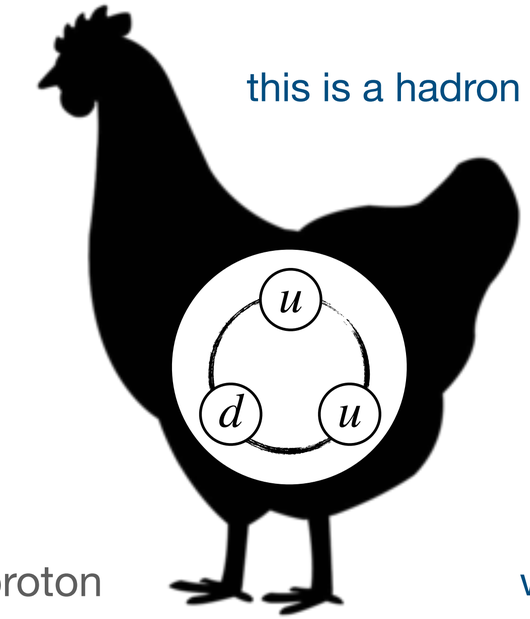
the ψ as seen at SLAC



S. Ting with the J particle

https://indico.slac.stanford.edu/event/9040/
https://indico.ihep.ac.cn/event/23322/

Understanding hadrons



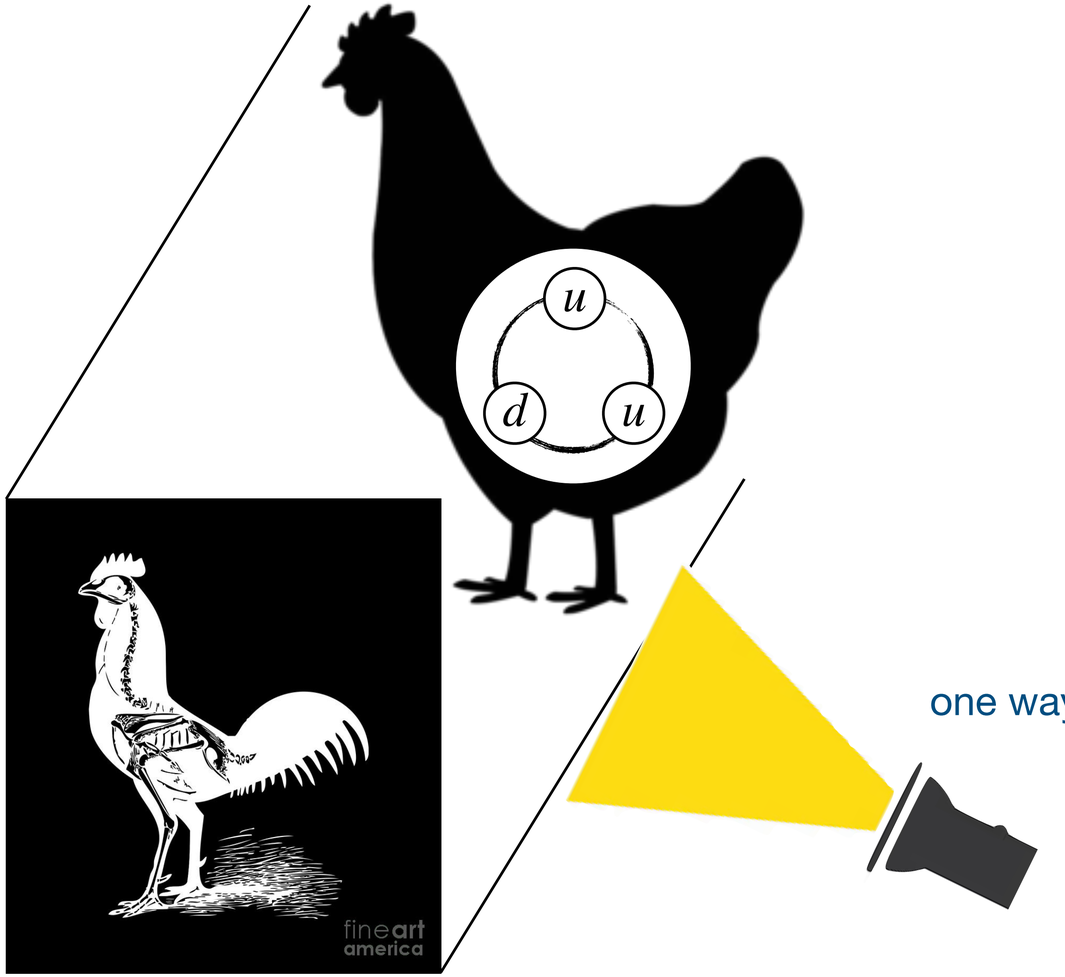
this is a hadron (obviously)

proton

we can use it to study the strong interaction

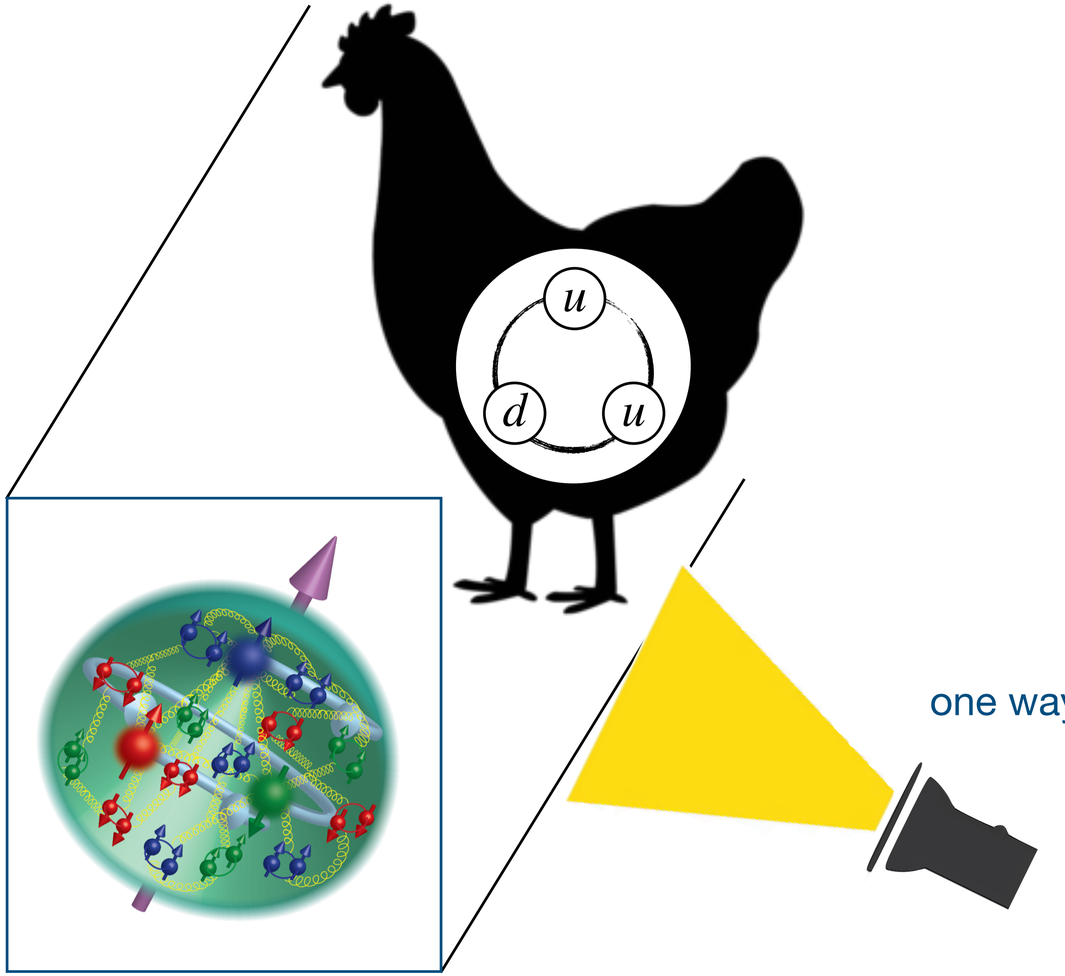
Silhouettes from https://www.phylopic.org/

Understanding hadrons



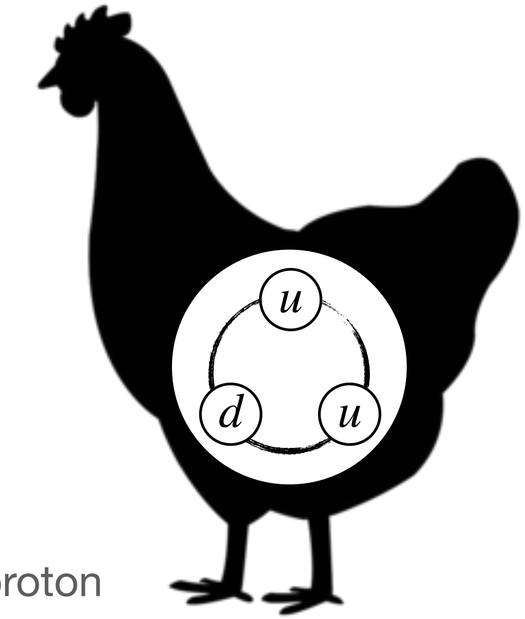
one way is to study hadron structure

Understanding hadrons

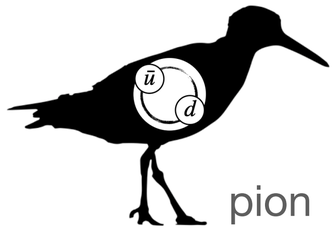


one way is to study hadron structure

Understanding hadrons



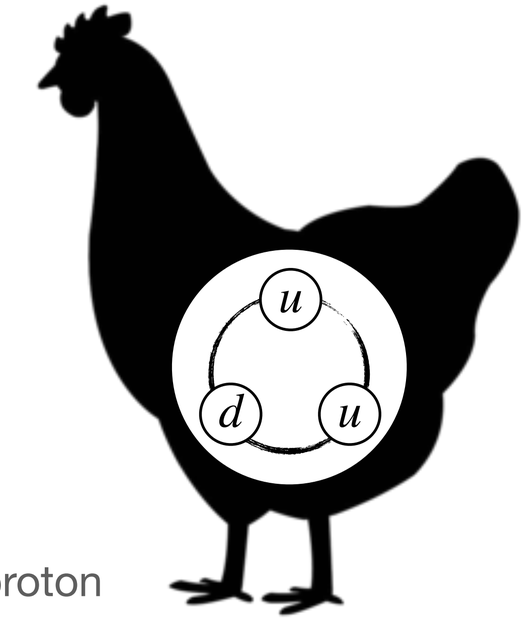
proton



pion

there are many different hadrons

Understanding hadrons



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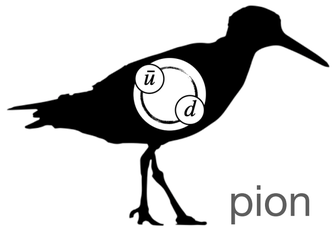
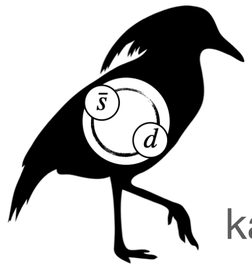


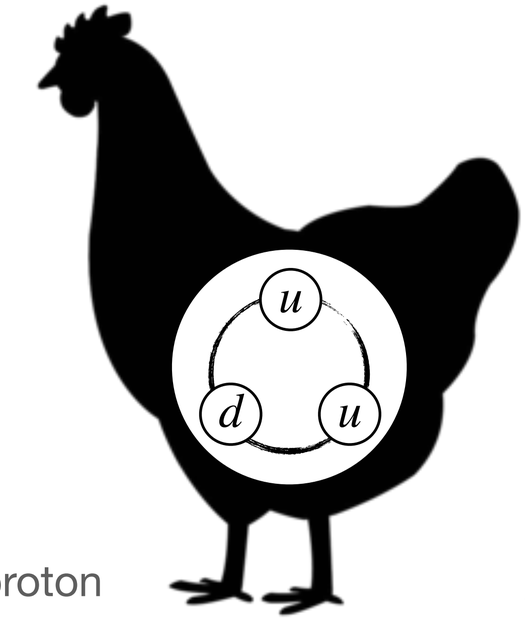
pion



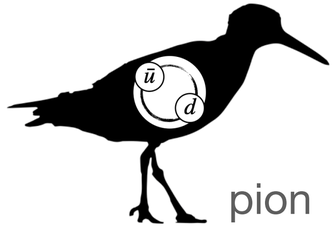
kaon

there are many different hadrons

Understanding hadrons

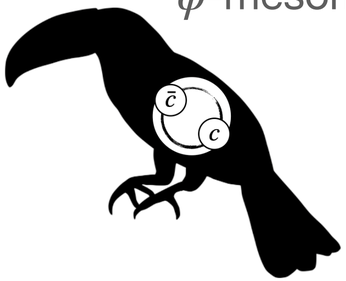


proton

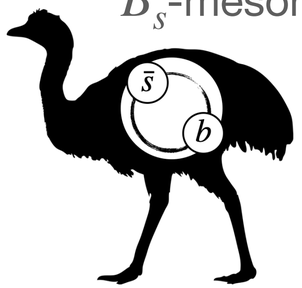


pion

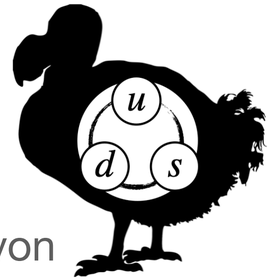
kaon



ψ-meson



$\bar{B}_s$-meson



Λ-baryon

Ω_{bb}-baryon

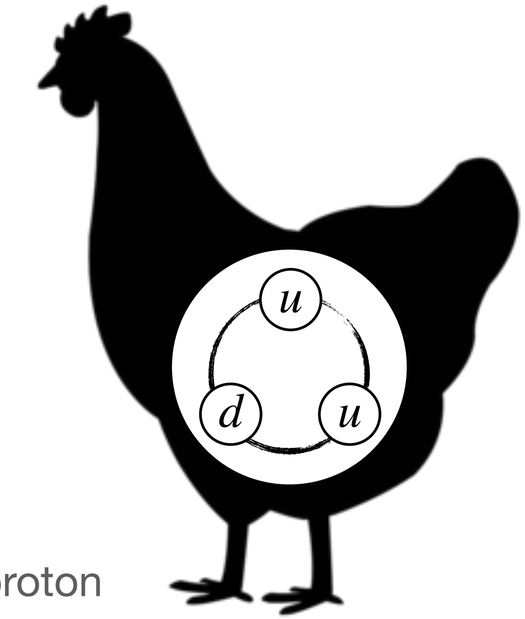
...

there are many, many (…) different hadrons

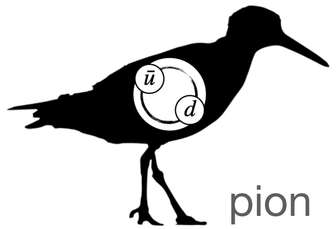
→ hadron spectroscopy

variety & patterns also teach us about the strong interaction

Understanding hadrons

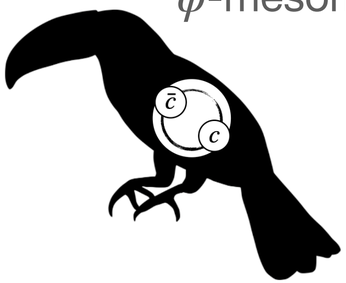


proton

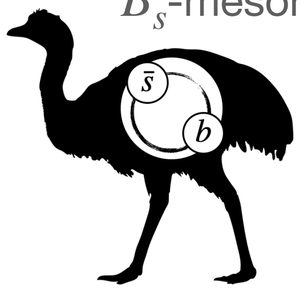


pion

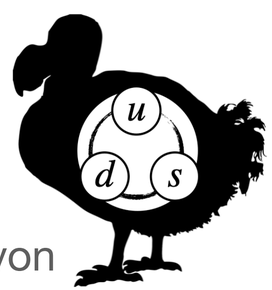
kaon



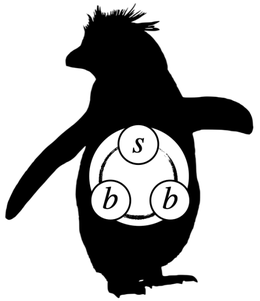
ψ-meson



$\bar{B}_s$-meson

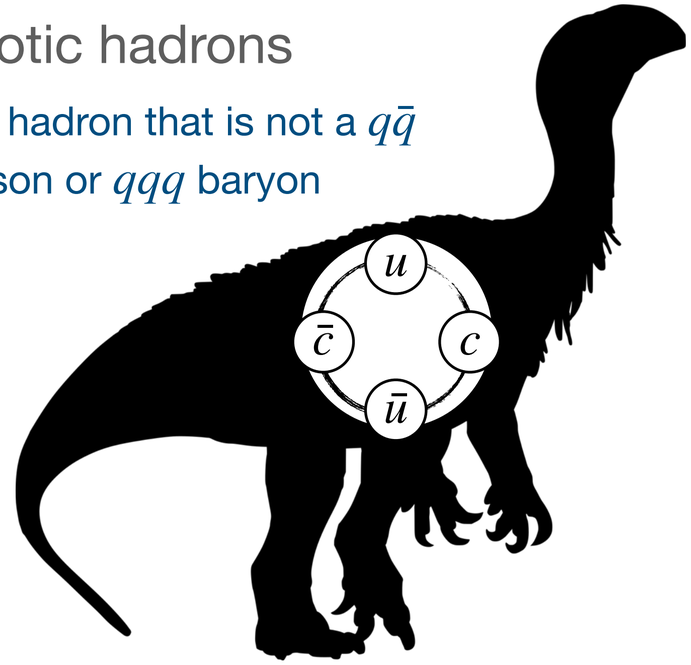


Λ-baryon



Exotic hadrons

any hadron that is not a $q\bar{q}$ meson or qqq baryon

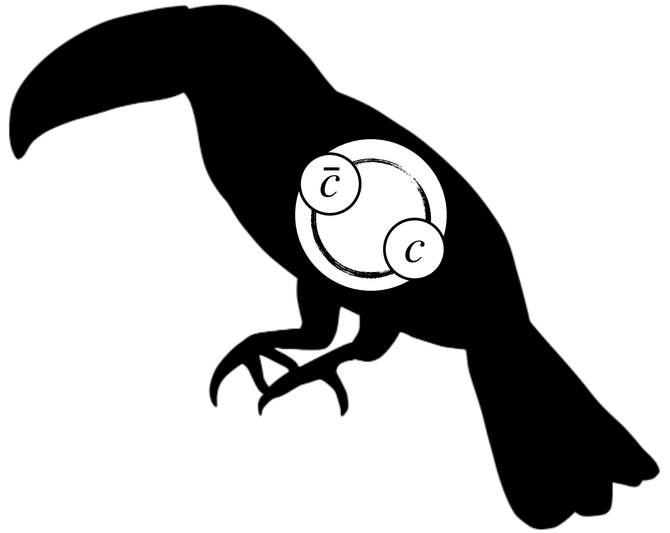


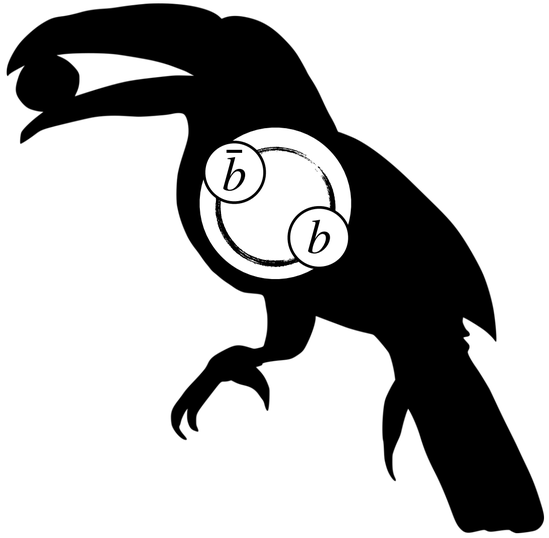
experimentally & theoretically challenging

matching expectation & reality will tell us a lot about how well we understand hadrons!

A brief guide to exotic hadrons
arXiv:2410.06923 [hep-ph]

Why quarkonium?

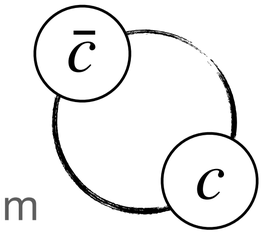


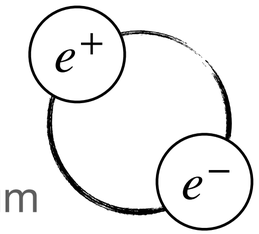


Quarkonium

quarkonium: $Q\bar{Q}$-meson (where $Q = c, b$)

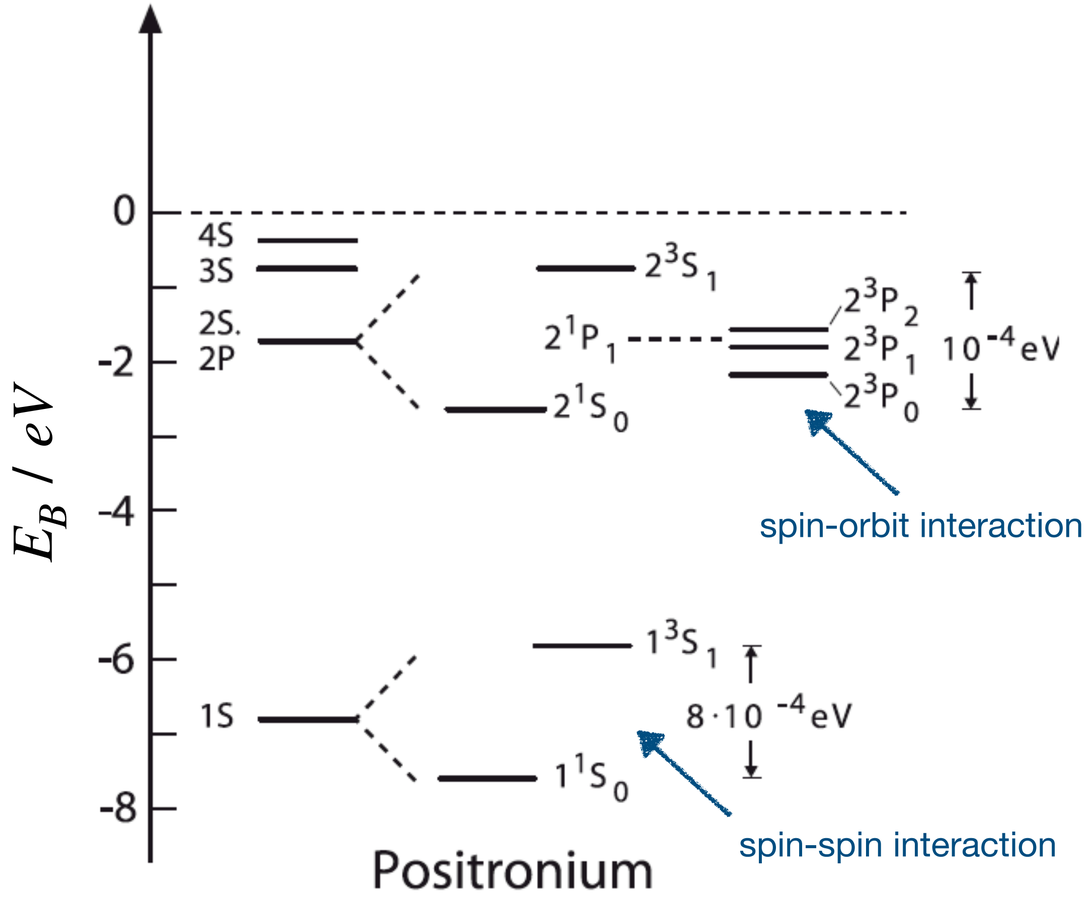
strong interaction version of positronium (or the hydrogen atom)

charmonium 

positronium 

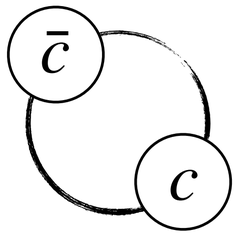
we can calculate the spectrum using similar methods

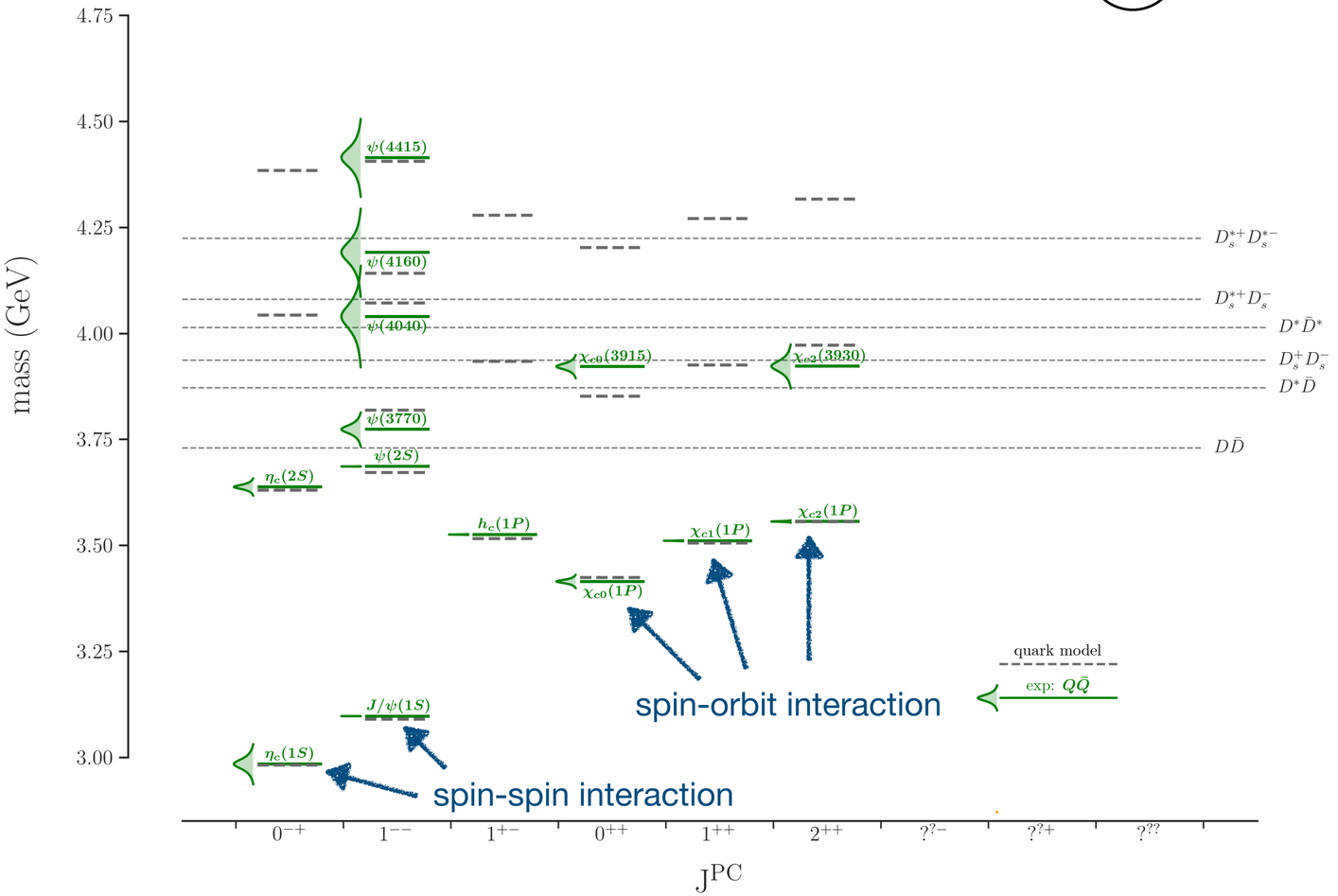
Godfrey & Isgur, PRD 32 (1985) 189-231
Barnes, Godfrey, Swanson, PRD 72 (2005) 054026
Godfrey & Moates, PRD 92 (2015) 054034

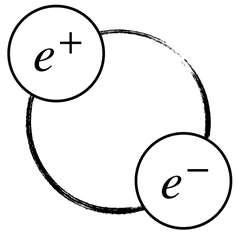


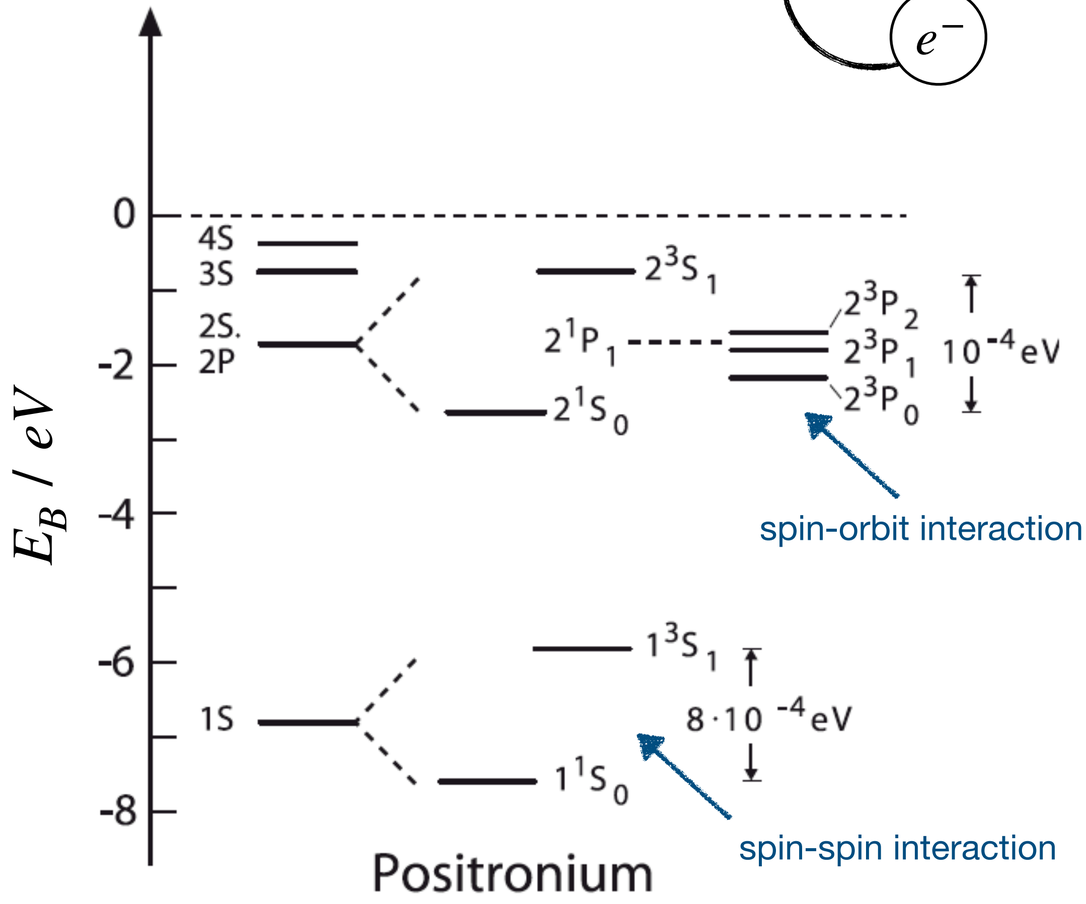
from Povh, Rith, Scholz, Zetsche, Rodejohann, Teilchen und Kerne

Charmonium









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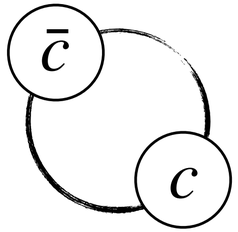
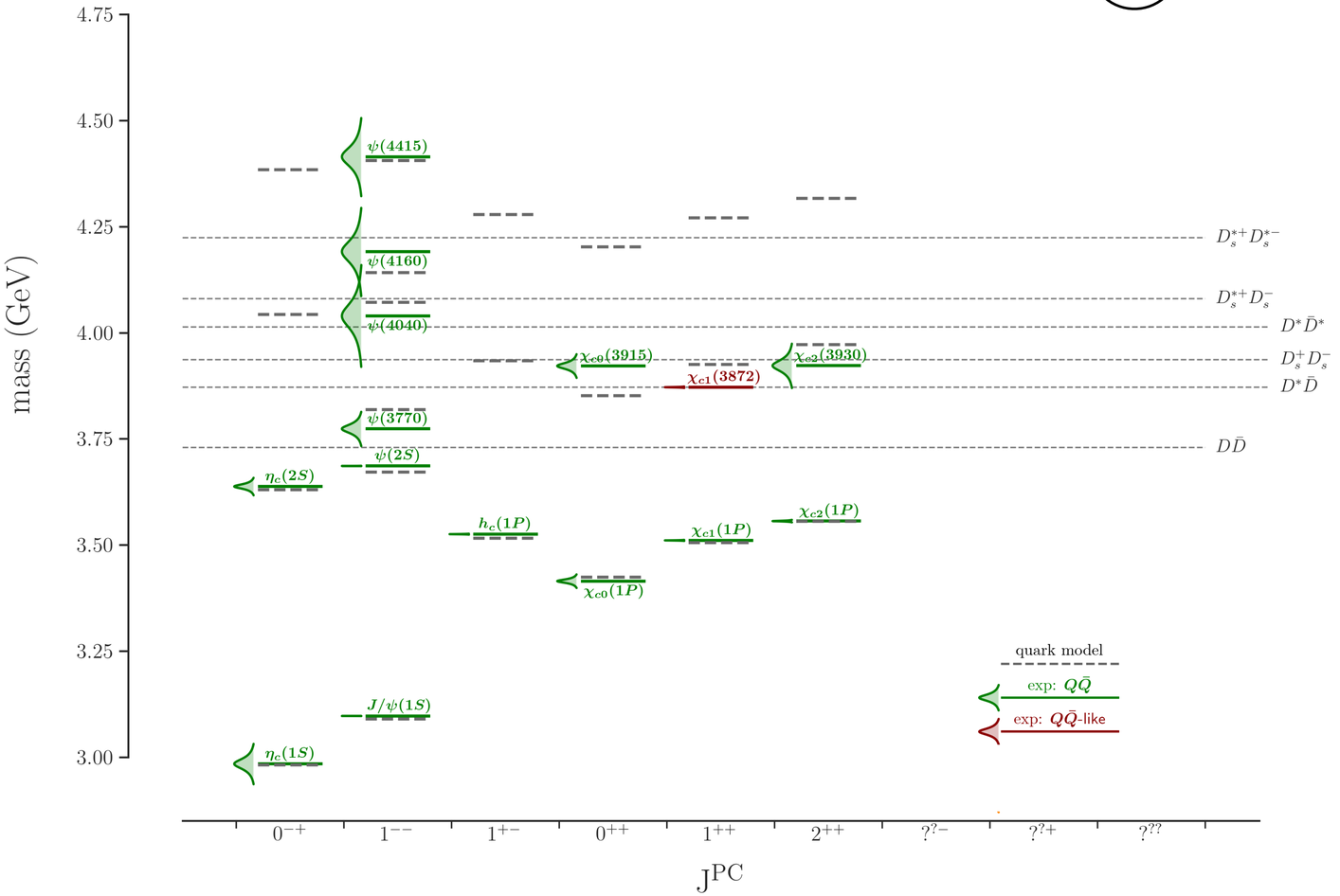
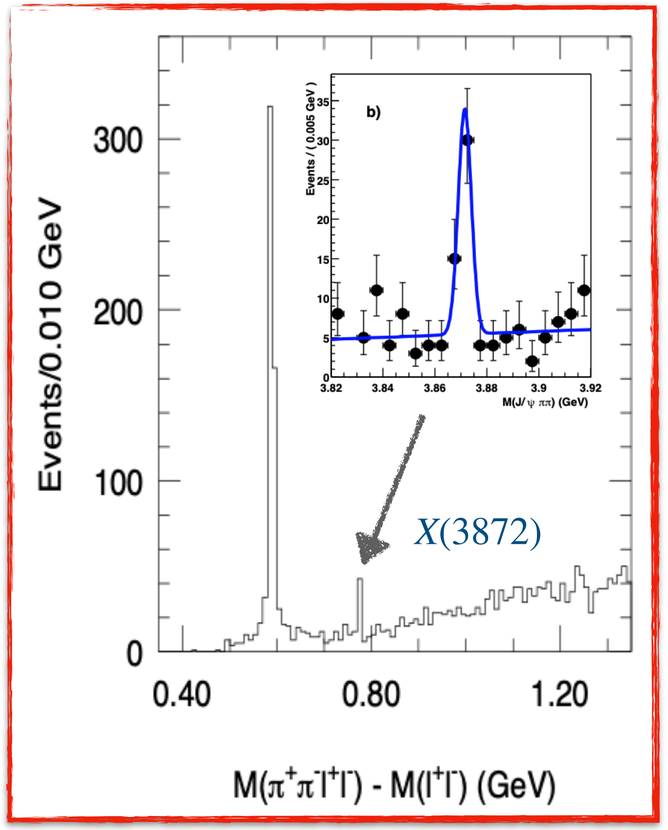
Charmonium

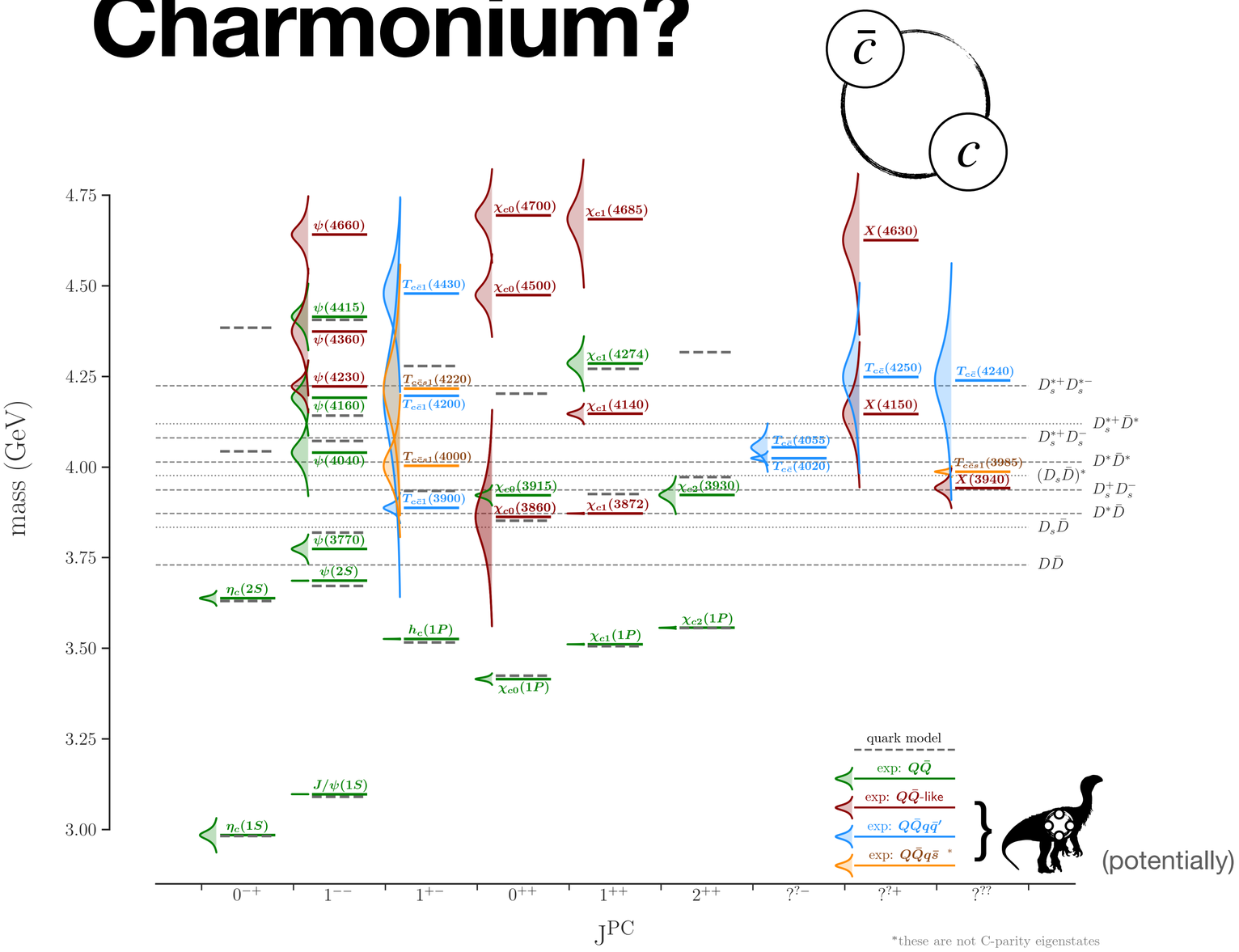






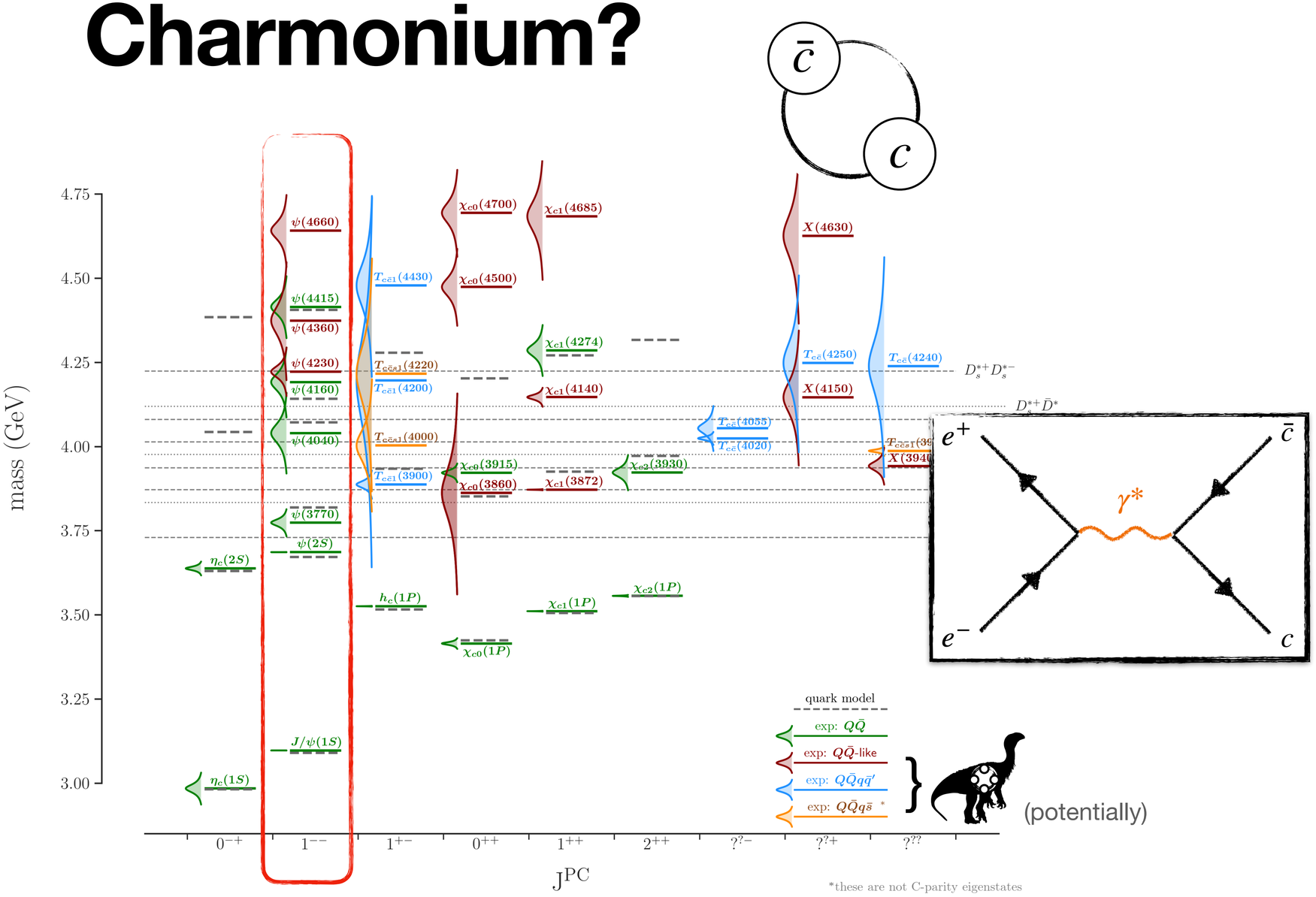
Belle, PRL 91 (2003) 262001

Charmonium?



(potentially)

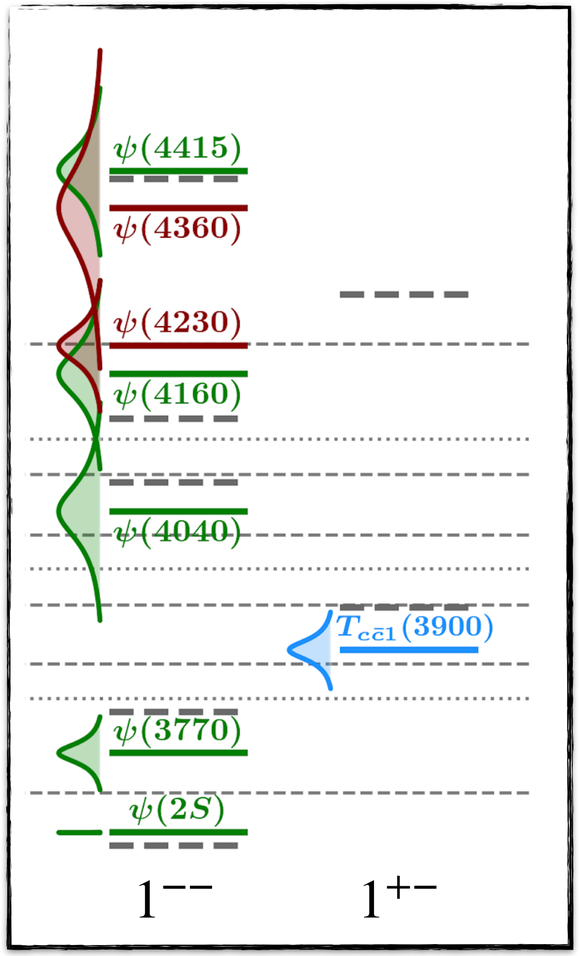
Charmonium?


mass (GeV)
4.75
4.50
4.25
4.00
3.75
3.50
3.25
3.00
$\psi(4660)$
$\psi(4415)$
$\psi(4360)$
$\psi(4230)$
$\psi(4160)$
$\psi(4040)$
$\psi(3770)$
$\psi(2S)$
$\eta_c(2S)$
$J/\psi(1S)$
$\eta_c(1S)$
$T_{c\bar{c}1}(4430)$
$T_{c\bar{c}\bar{s}1}(4220)$
$T_{c\bar{c}1}(4200)$
$T_{c\bar{c}\bar{s}1}(4000)$
$T_{c\bar{c}1}(3900)$
$h_c(1P)$
$\chi_{c0}(4700)$
$\chi_{c0}(4500)$
$\chi_{c0}(3915)$
$\chi_{c0}(3860)$
$\chi_{c0}(1P)$
$\chi_{c1}(4685)$
$\chi_{c1}(4274)$
$\chi_{c1}(4140)$
$\chi_{c1}(3872)$
$\chi_{c1}(1P)$
$\chi_{c2}(3930)$
$\chi_{c2}(1P)$
$X(4630)$
$T_{c\bar{c}}(4250)$
$X(4150)$
$T_{c\bar{c}}(4240)$
$T_{c\bar{c}}(4055)$
$T_{c\bar{c}}(4020)$
$D_s^{*+}D_s^{*-}$
$D^{*+}\bar{D}^{*}$
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
$?^{?-}$
$?^{?+}$
$?^{??}$
J^PC
quark model
exp: $Q\bar{Q}$
exp: $Q\bar{Q}$-like
exp: $Q\bar{Q}q\bar{q}'$
exp: $Q\bar{Q}q\bar{s}$ *
(potentially)
*these are not C-parity eigenstates

e^+
e^-
$\bar{c}$
c
γ^*

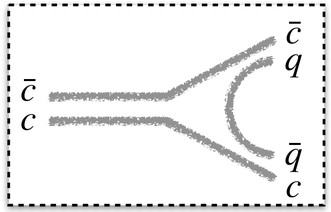

BESIII
Belle(-II)
BABAR

Vector charmonium



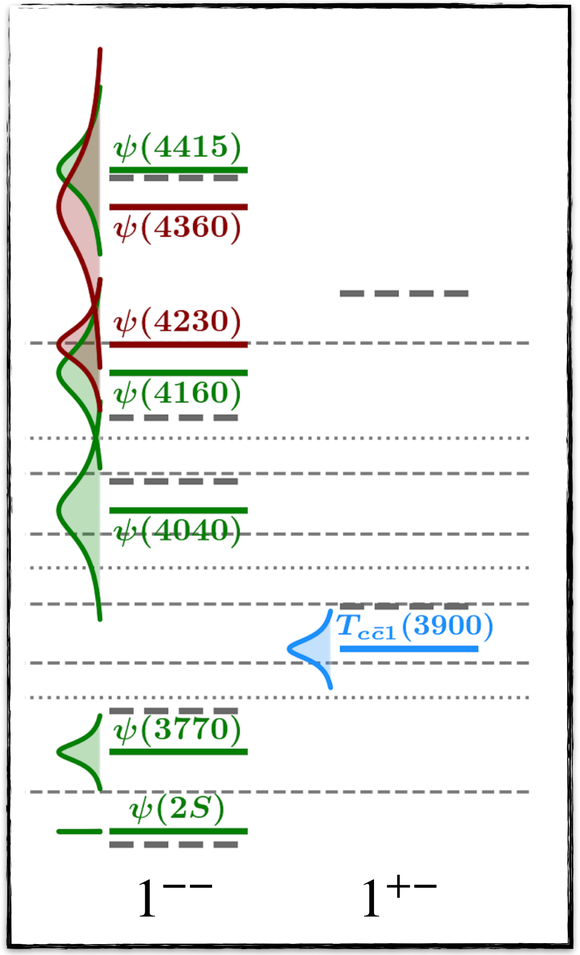
this decay
should dominate

$D\bar{D}$



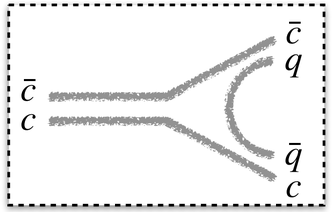
(Zweig rule)

Vector charmonium

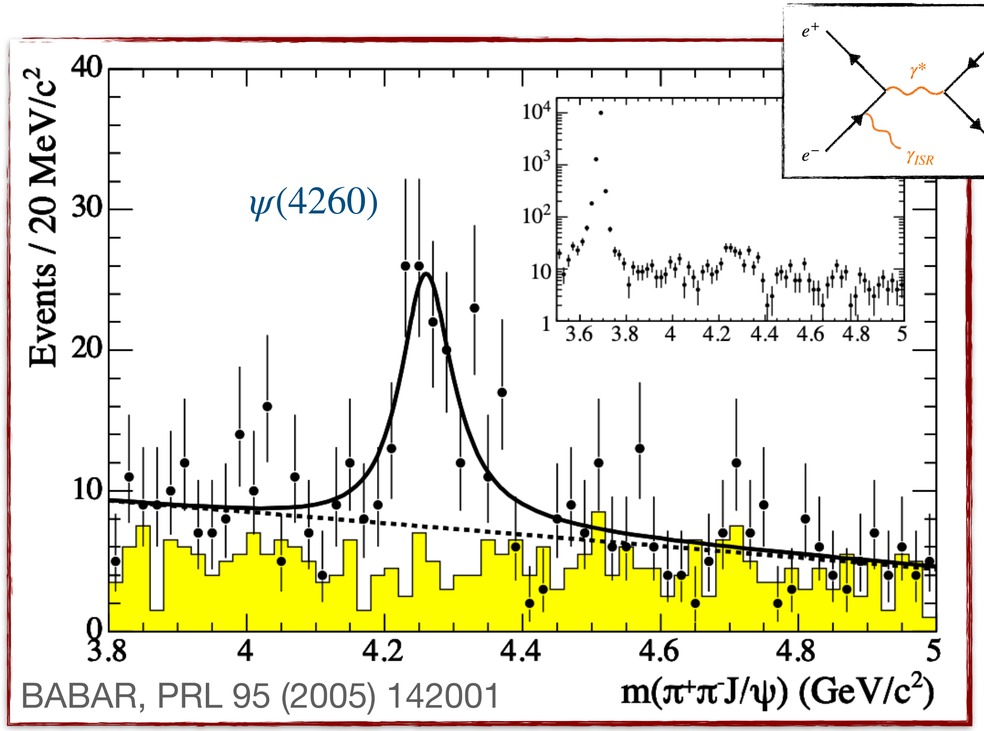


this decay should dominate

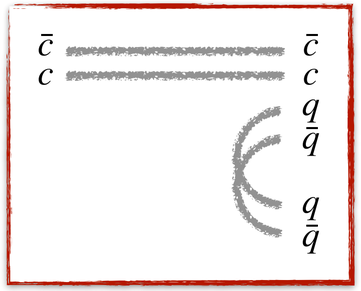
$D\bar{D}$



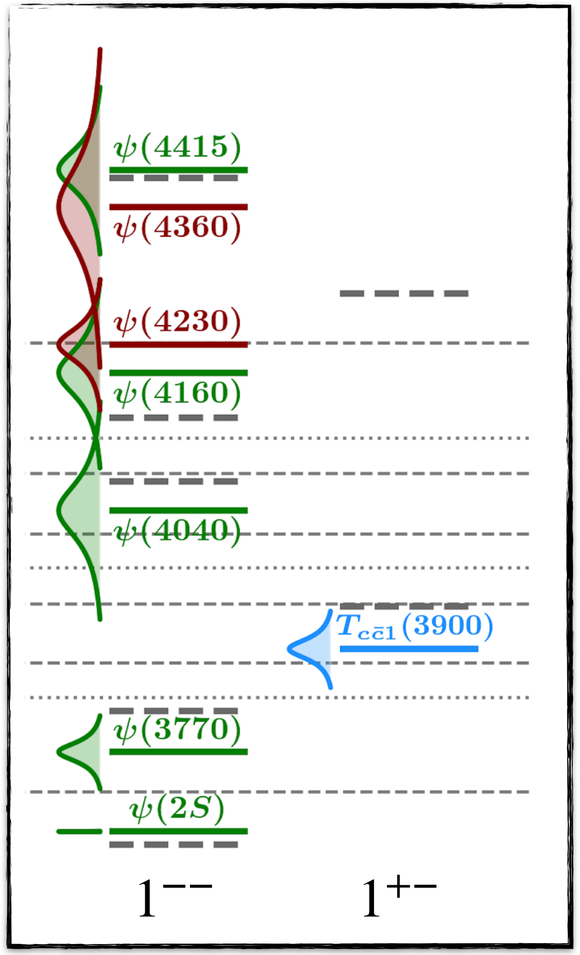
(Zweig rule)



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

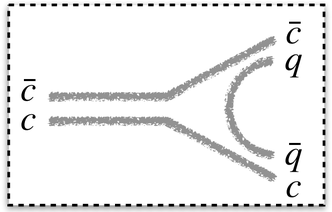


Vector charmonium

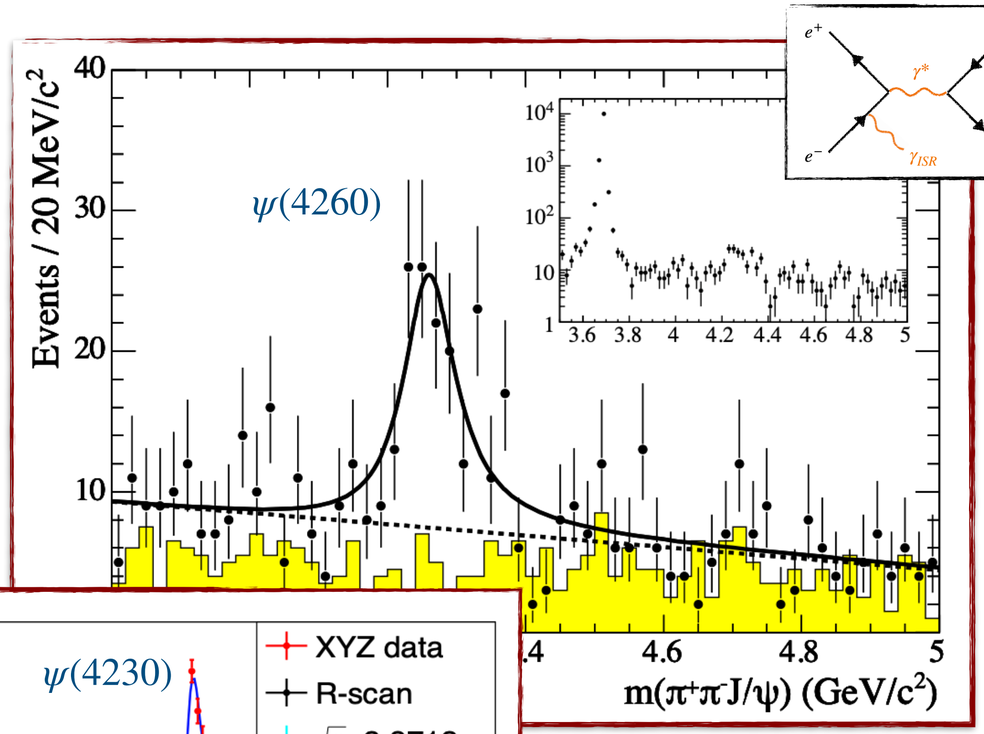


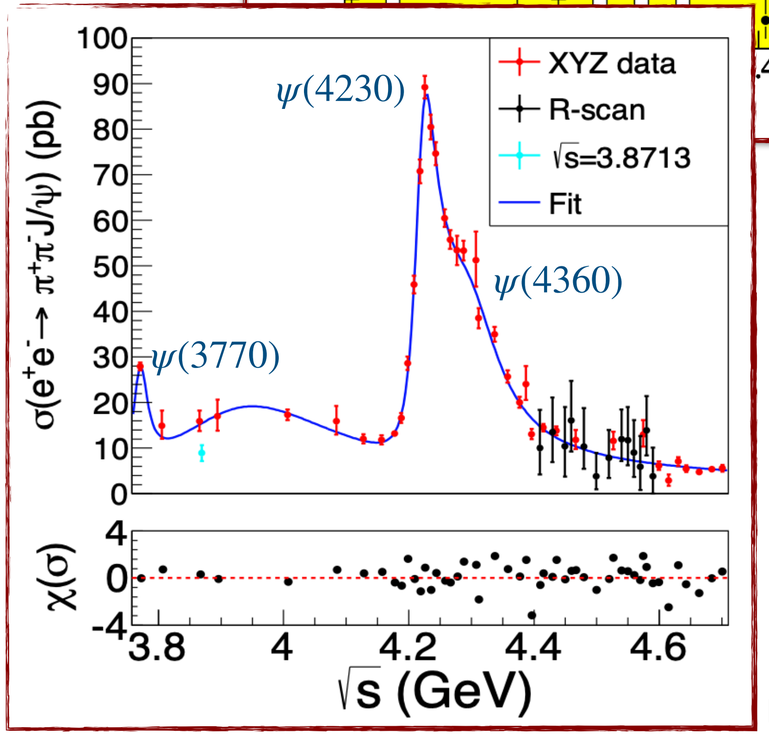
this decay should dominate

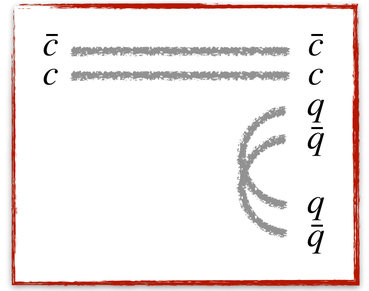
$D\bar{D}$



(Zweig rule)

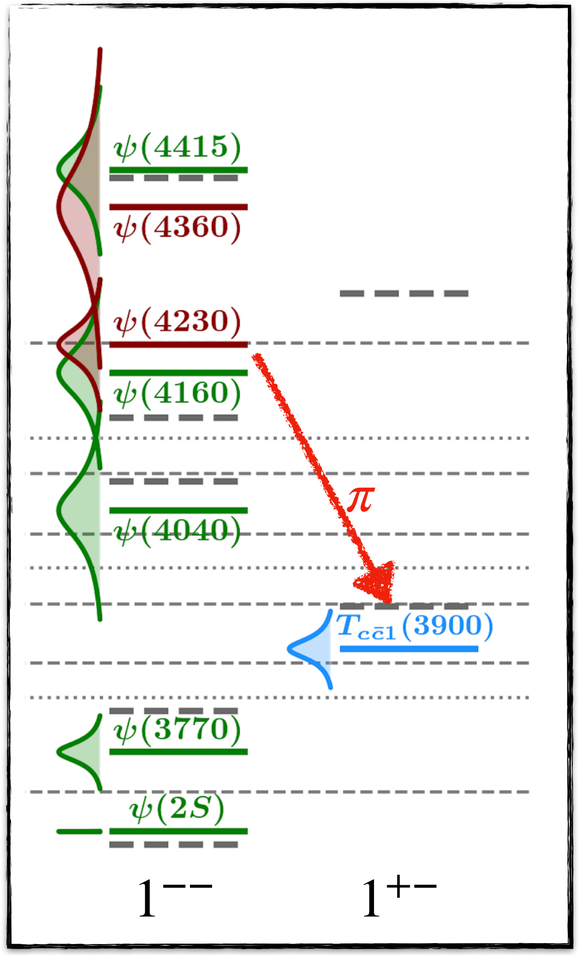






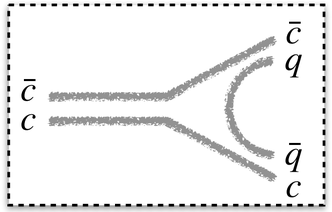
BESIII, PRD 106 (2022) 7, 072001

Vector charmonium



this decay should dominate

$D\bar{D}$



(Zweig rule)

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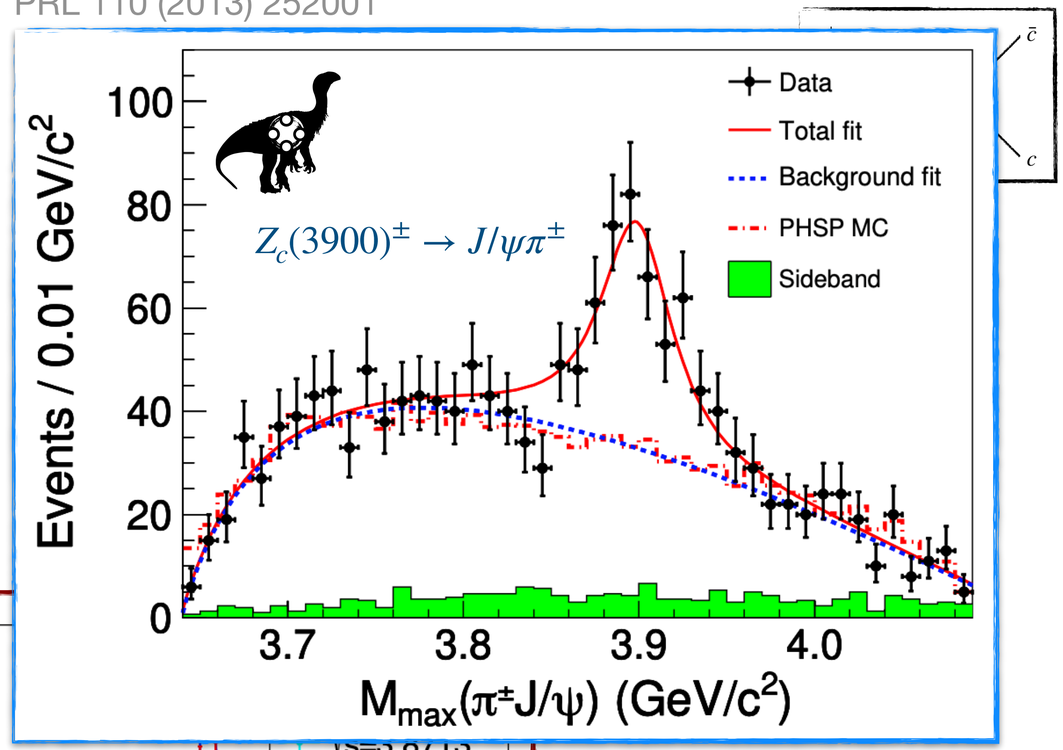
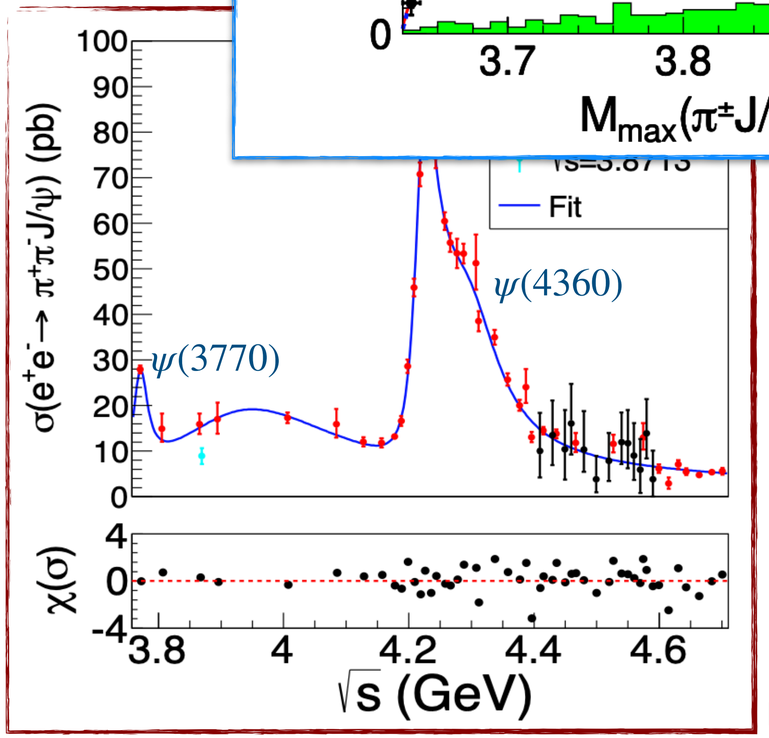
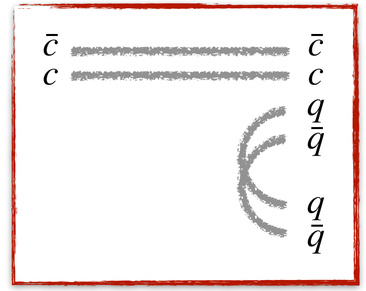
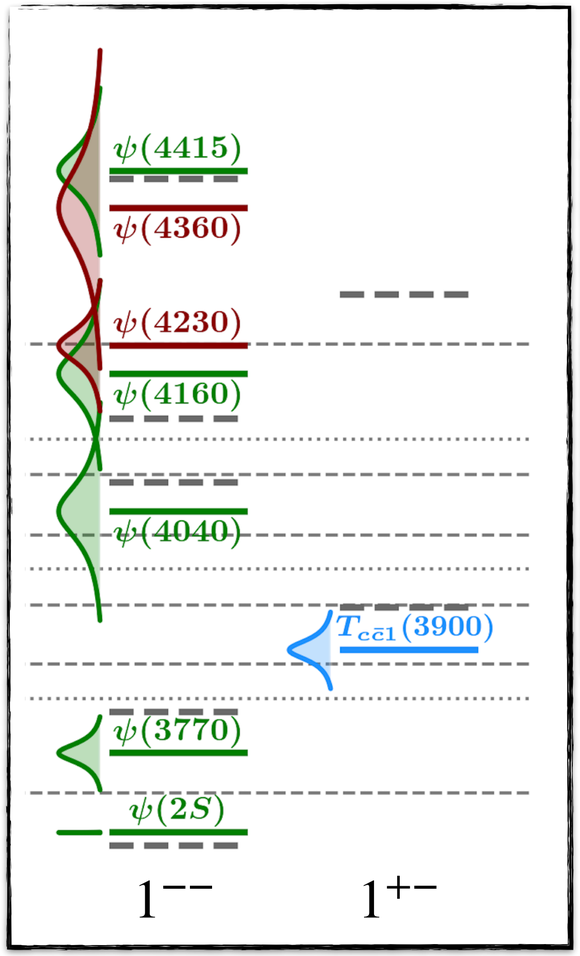




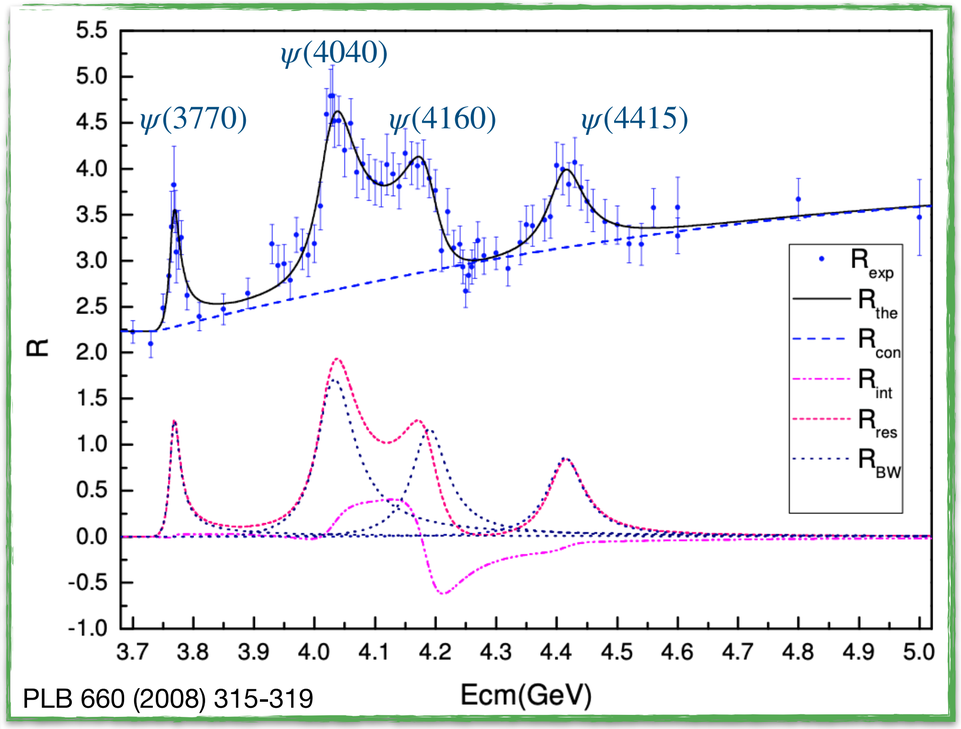


BESIII, PRD 106 (2022) 7, 072001

Vector charmonium

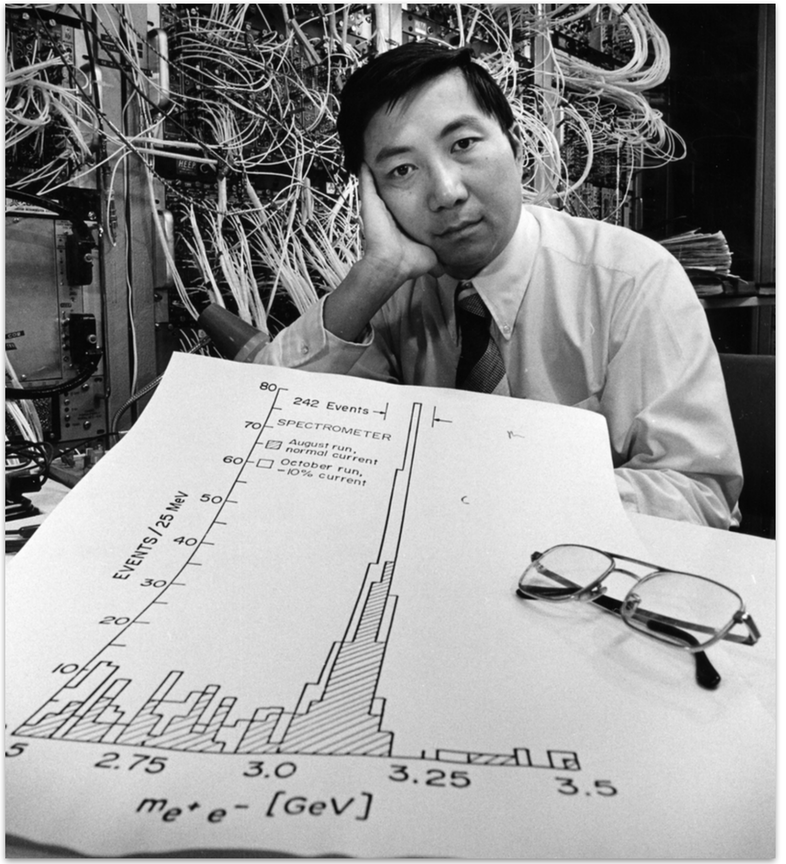


$e^+e^- \to$ hadrons



us with the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$

S. Ting with the J particle



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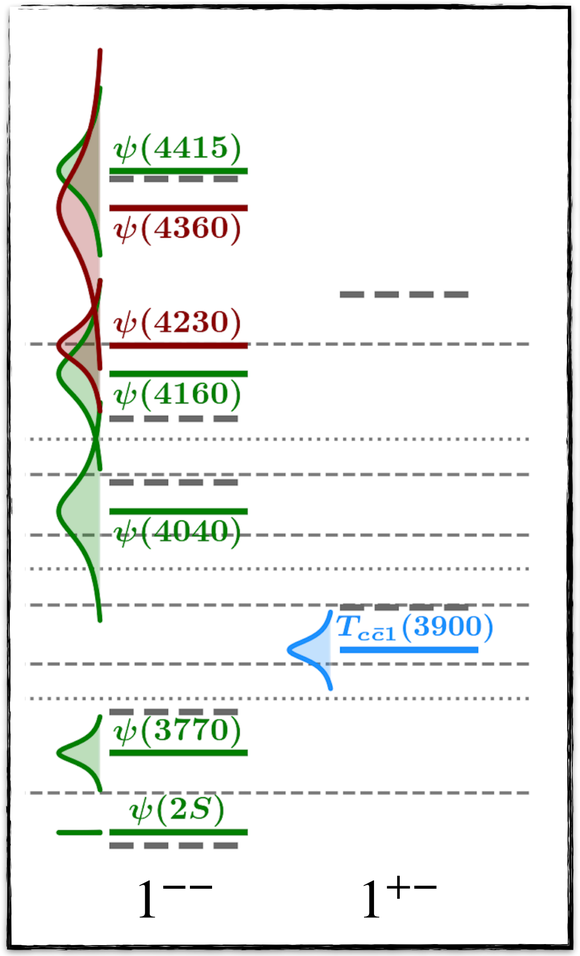
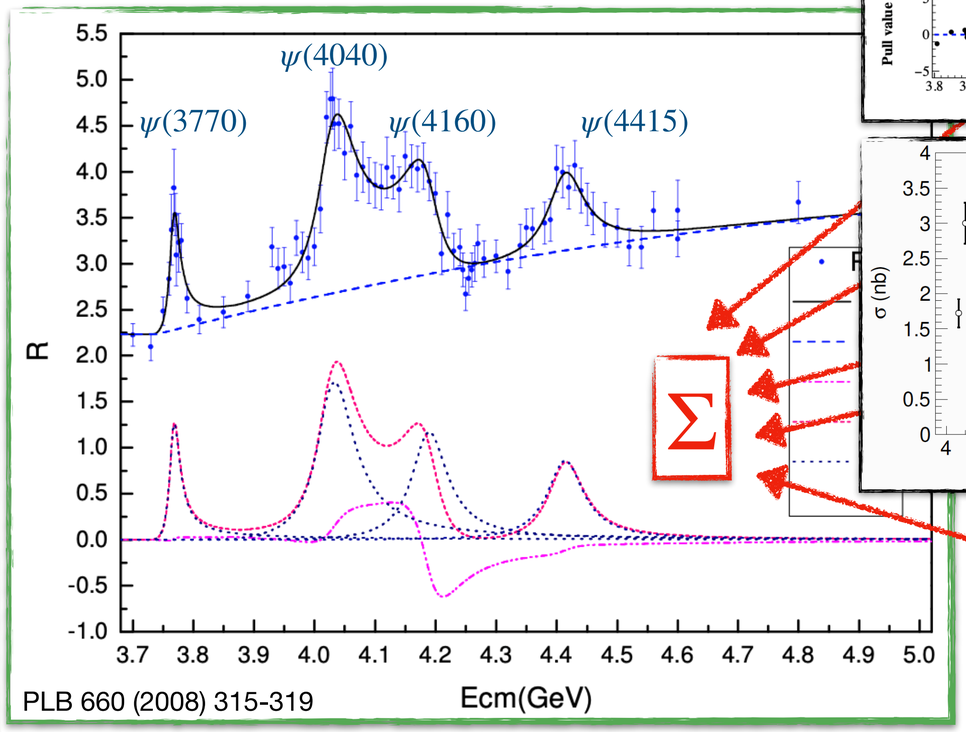
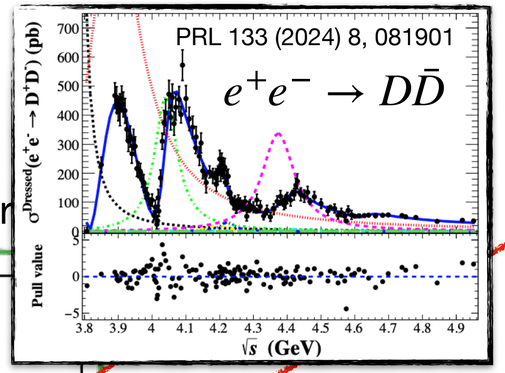
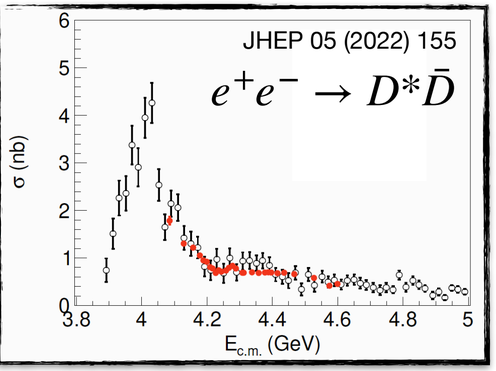
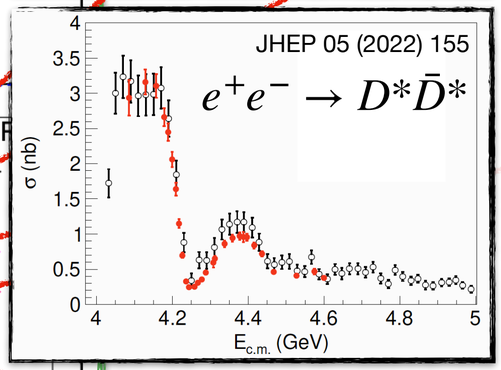


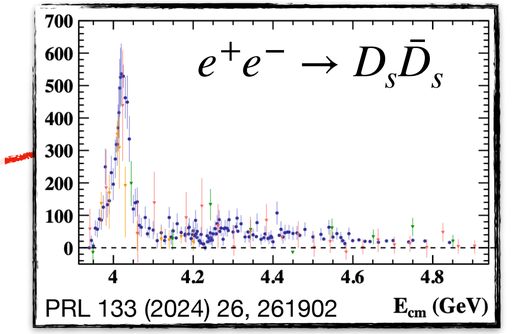
$e^+e^- \to$ hadr

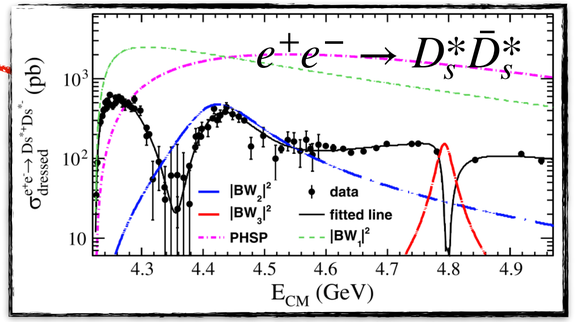












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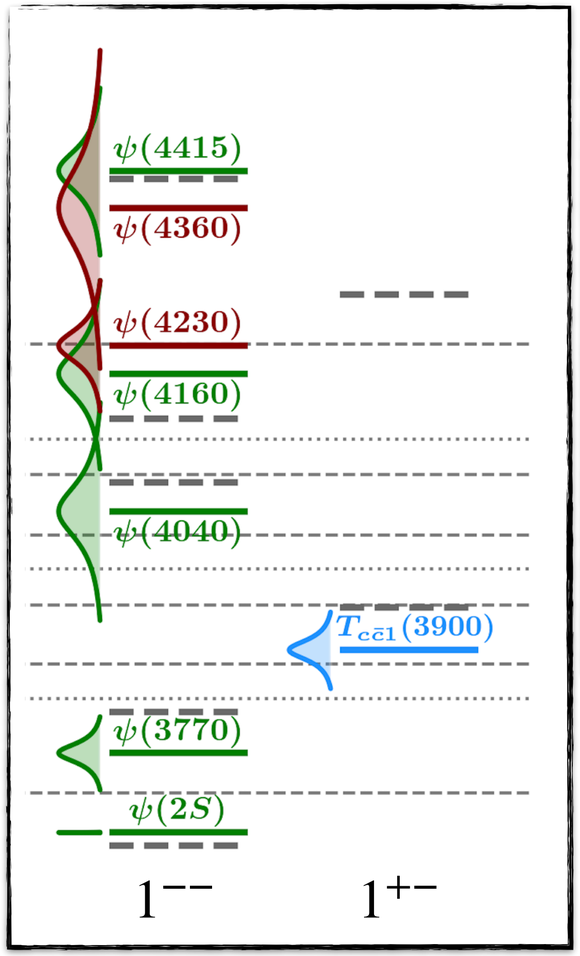
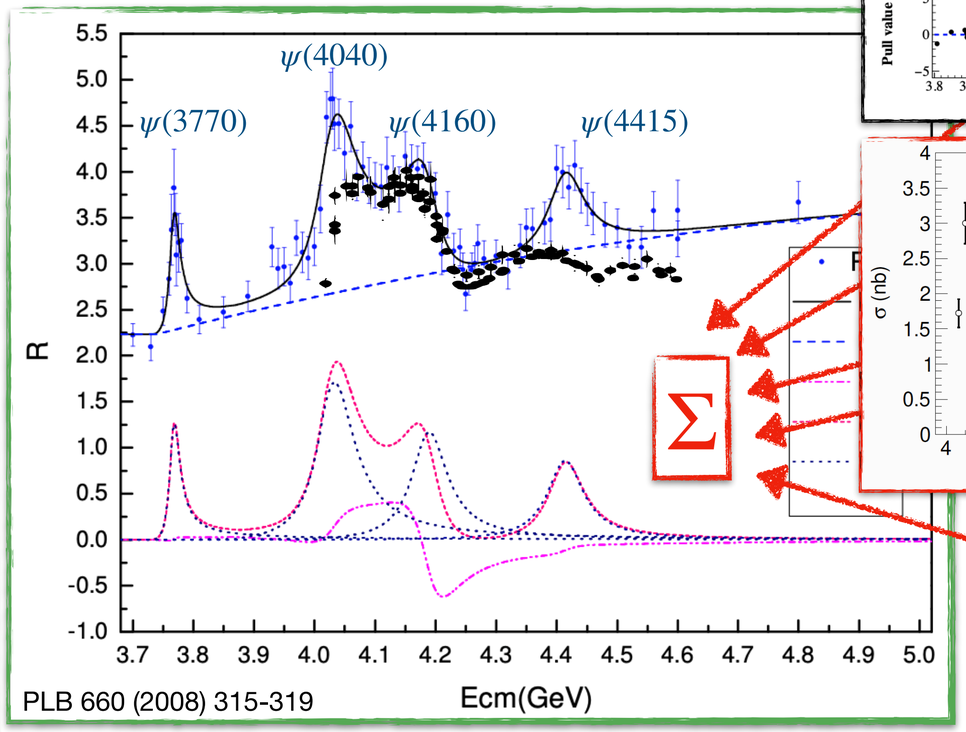
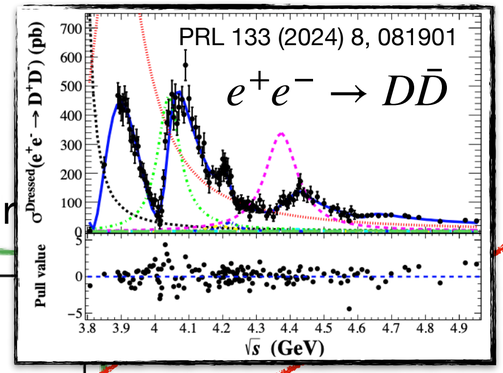
us with the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$

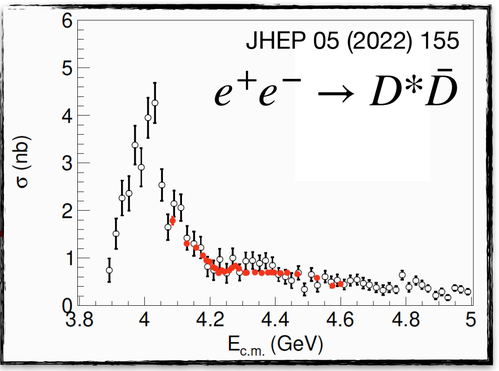
Vector charmonium

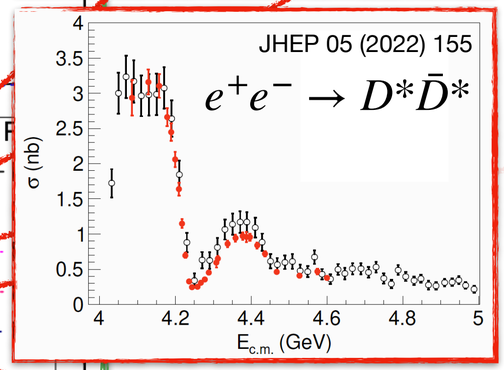


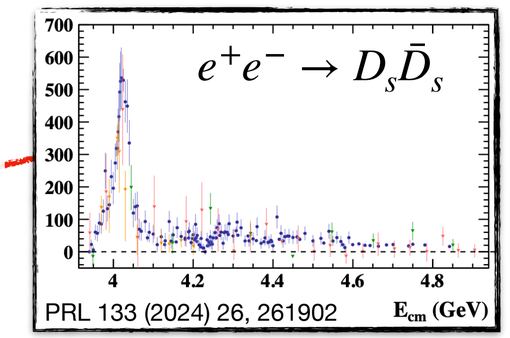
$e^+e^- \to$ hadr

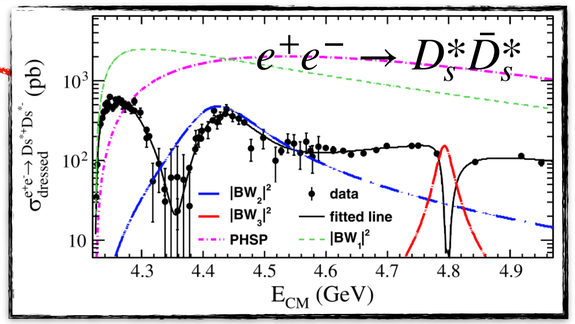












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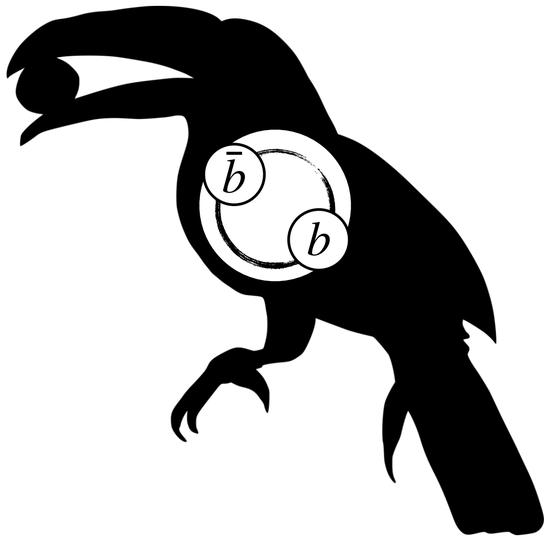
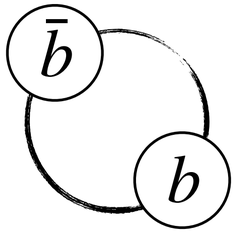
us with the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$

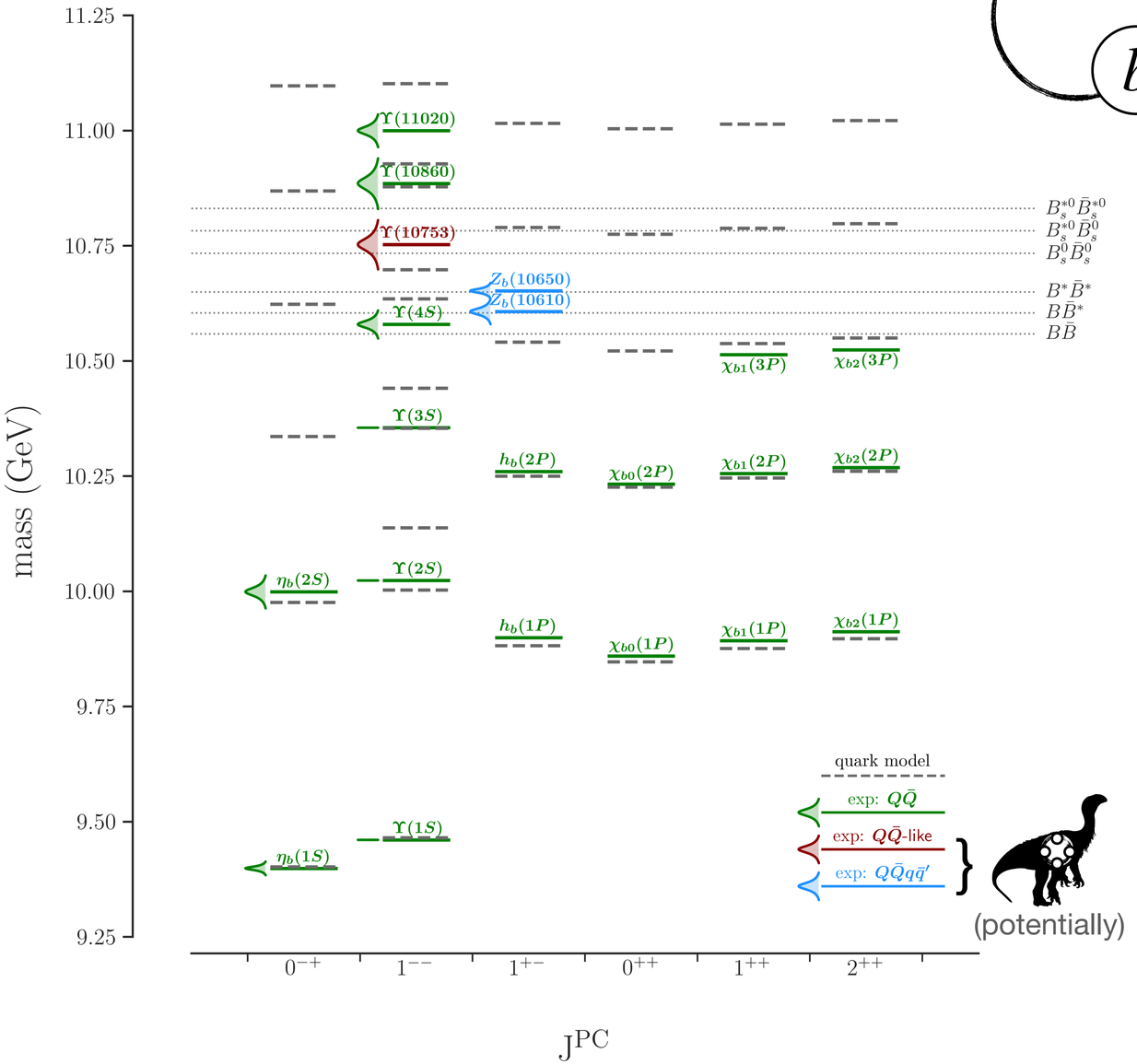
can we reliably extract information on vector charmonia in this way?

How about vector bottomonium?

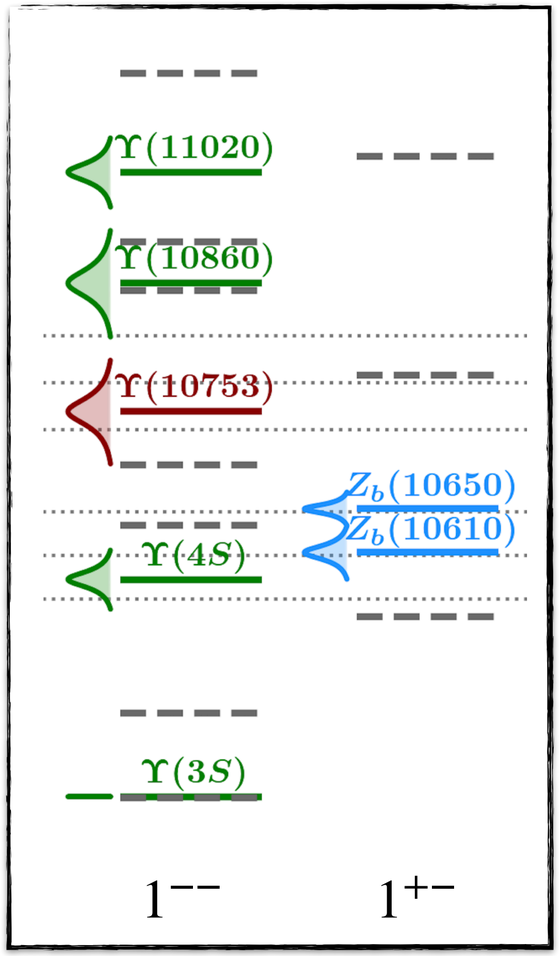


Bottomonium



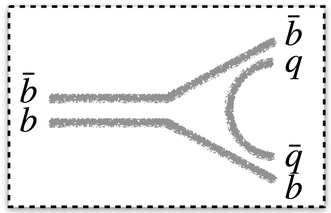


Vector bottomonium

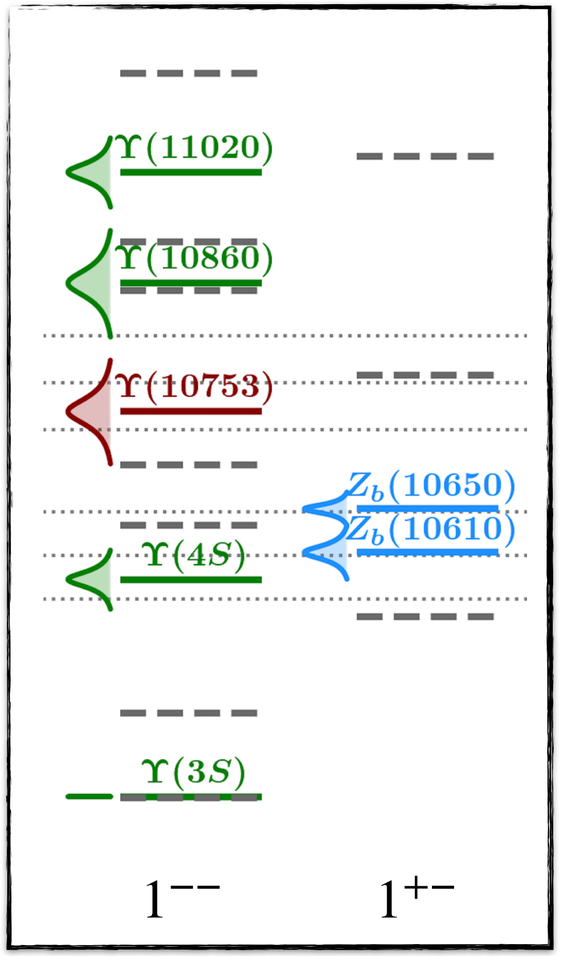


$B\bar{B}$

this decay
should dominate

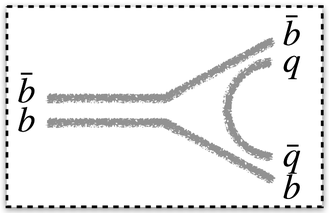


Vector bottomonium

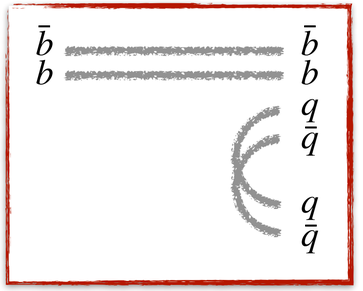


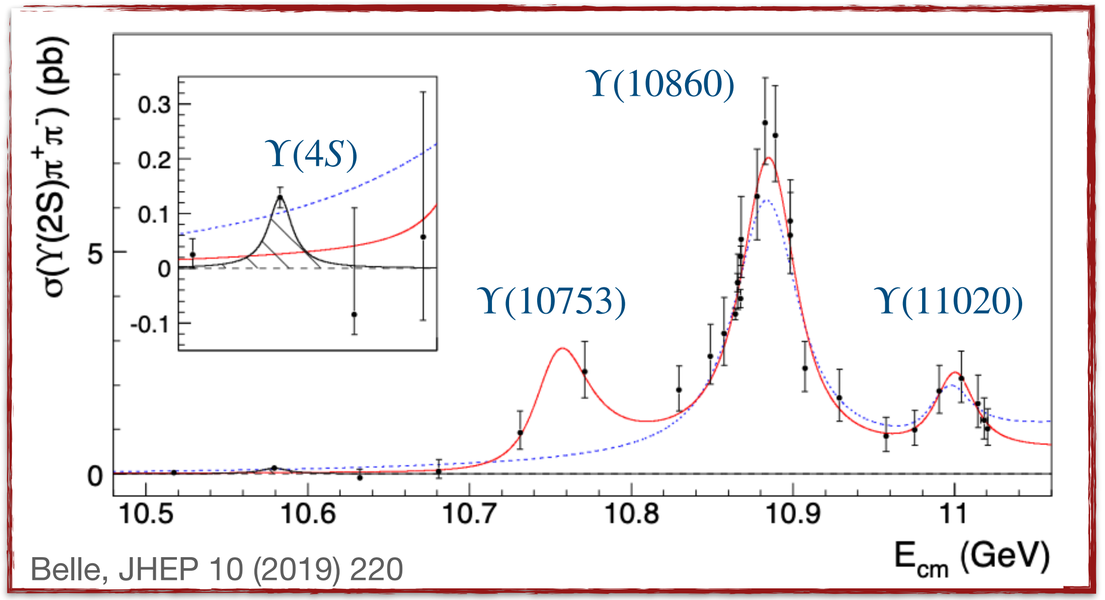
$B\bar{B}$

this decay should dominate

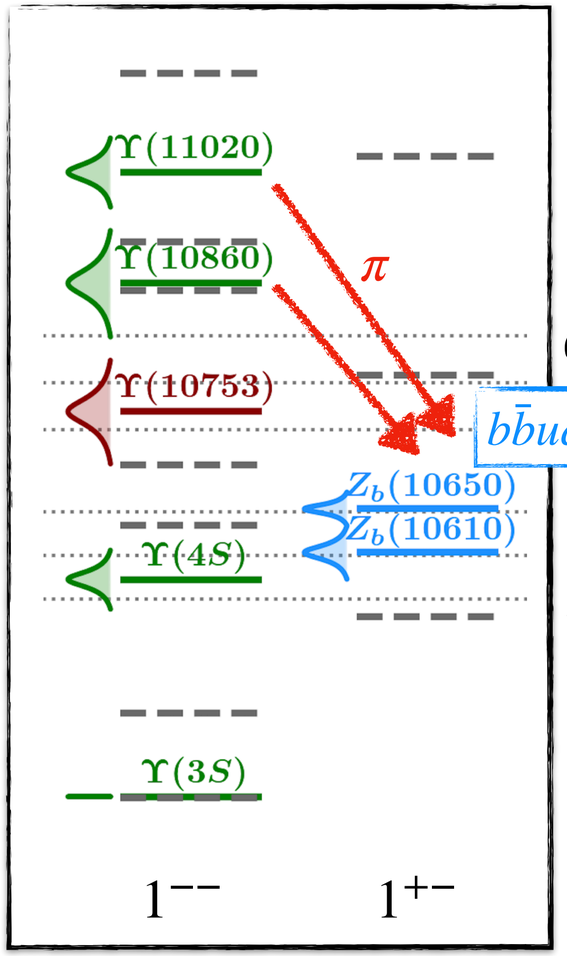


$e^+e^- \to \Upsilon(2S)\pi^+\pi^-$





Vector bottomonium

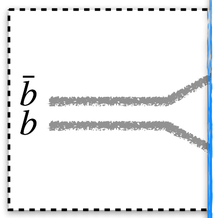


π

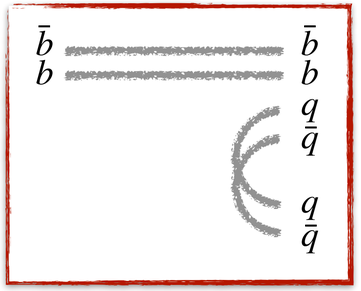
$b\bar{b}ud\bar{}$ states!

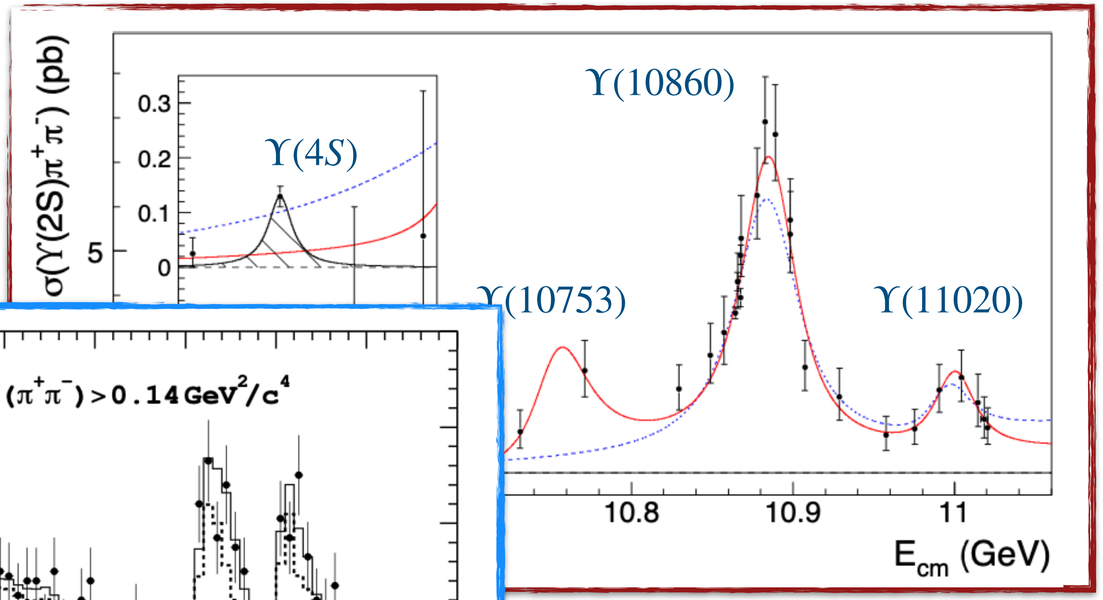
$B\bar{B}$

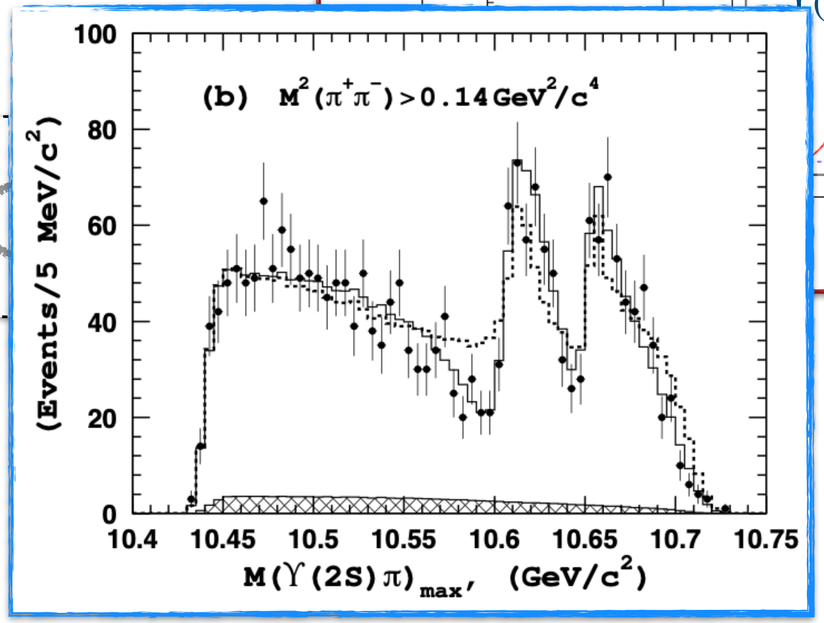
this decay should dominate



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







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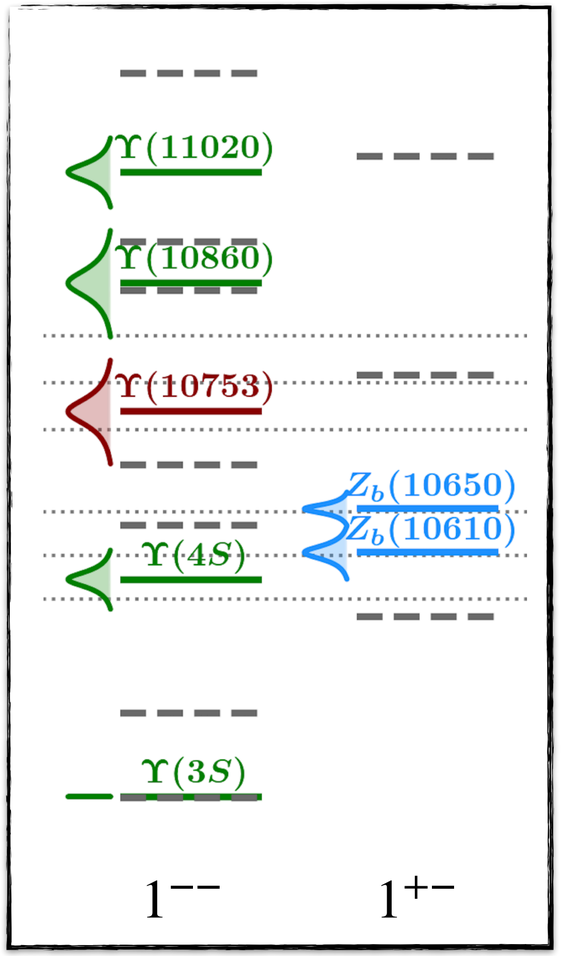
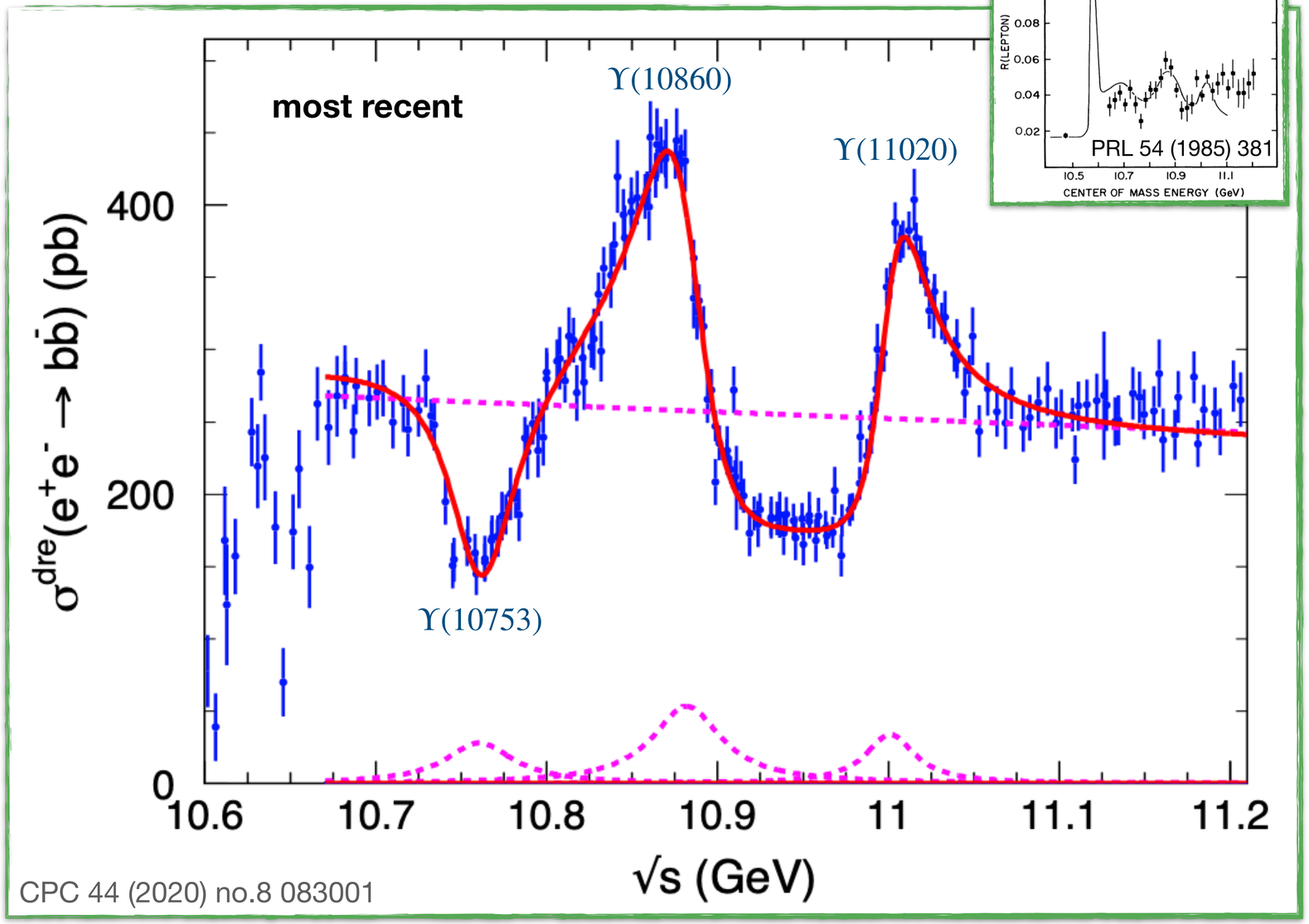
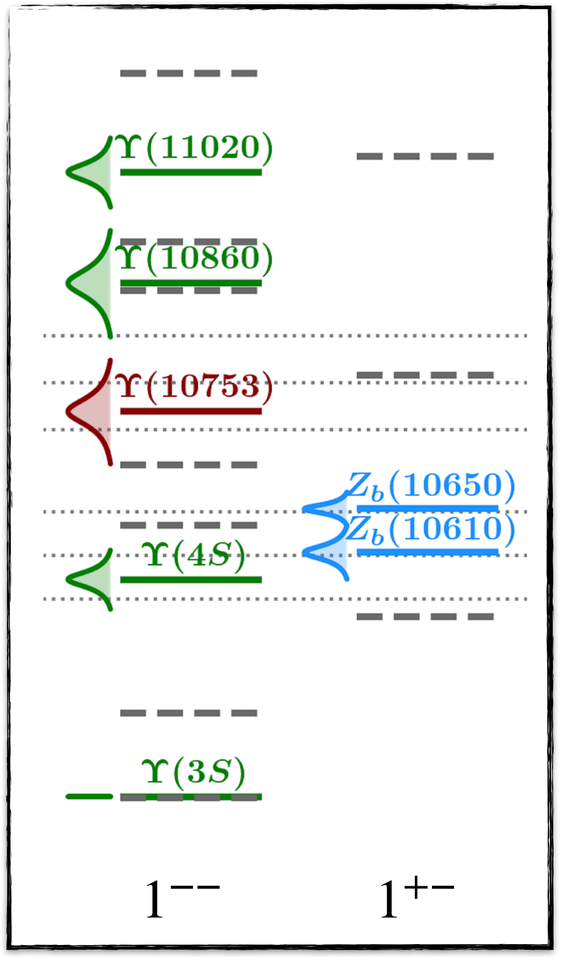
Vector bottomonium



$B\bar{B}$



Vector bottomonium



$B\bar{B}$

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[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).

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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

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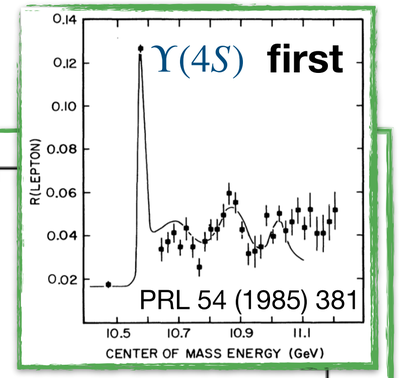
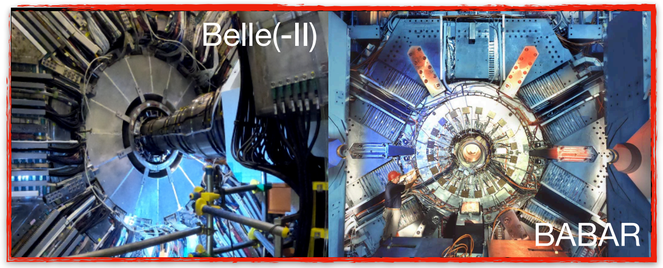
also complicated. The results from these fits may change dramatically by including more information on each exclusive mode.

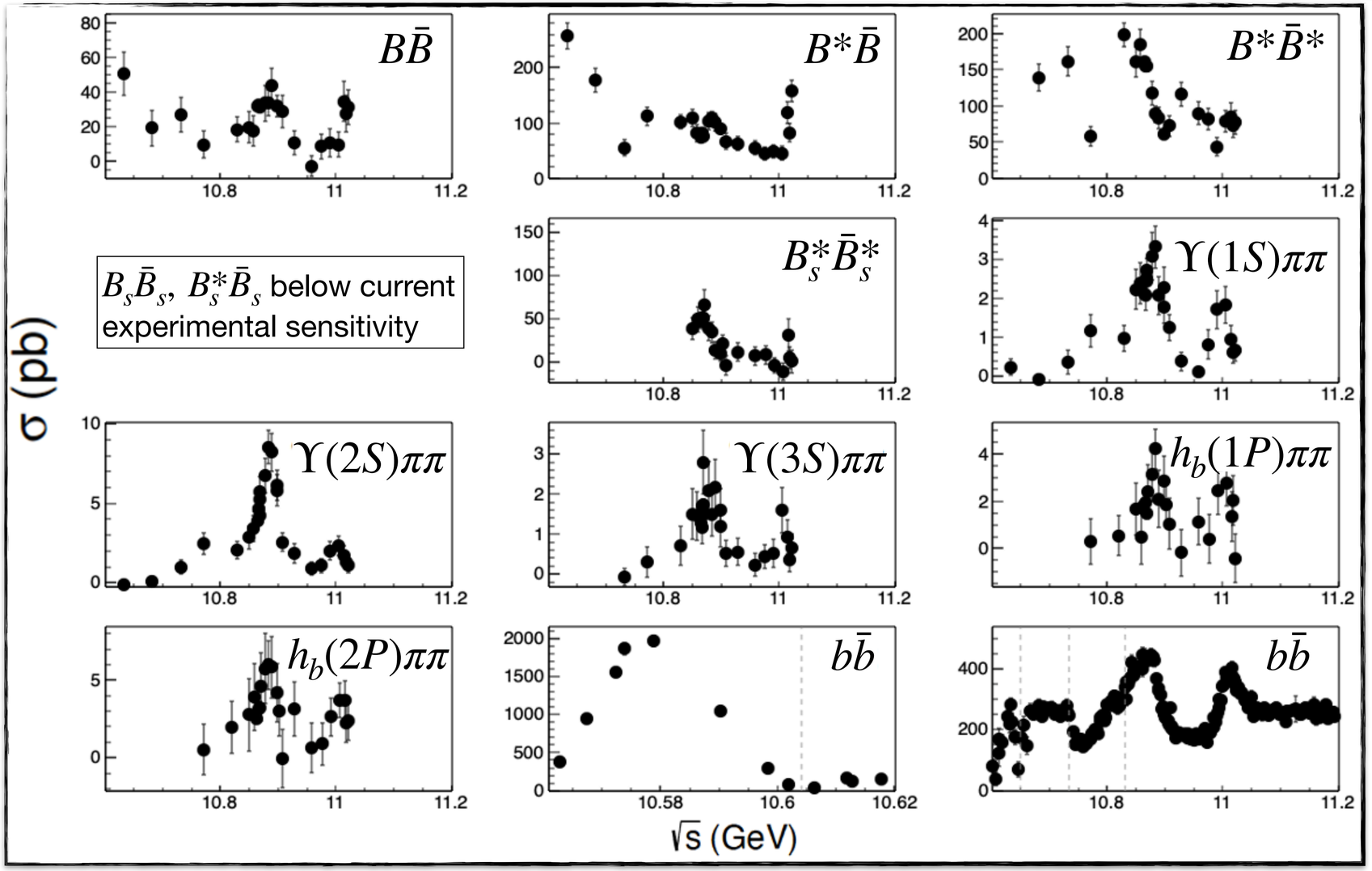
The data obtained in this analysis can be used to extract resonant parameters of these states if a better parametrization of the cross sections is developed.



The database: $e^+e^- \to b\bar{b}$

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





The database: $e^+e^- \to b\bar{b}$

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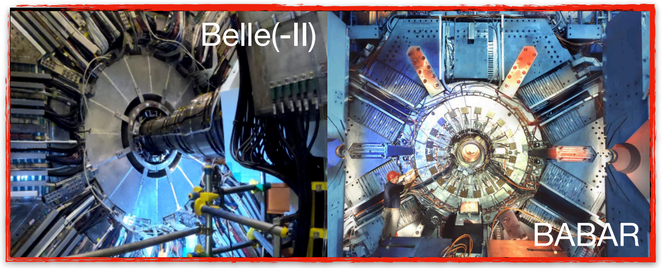
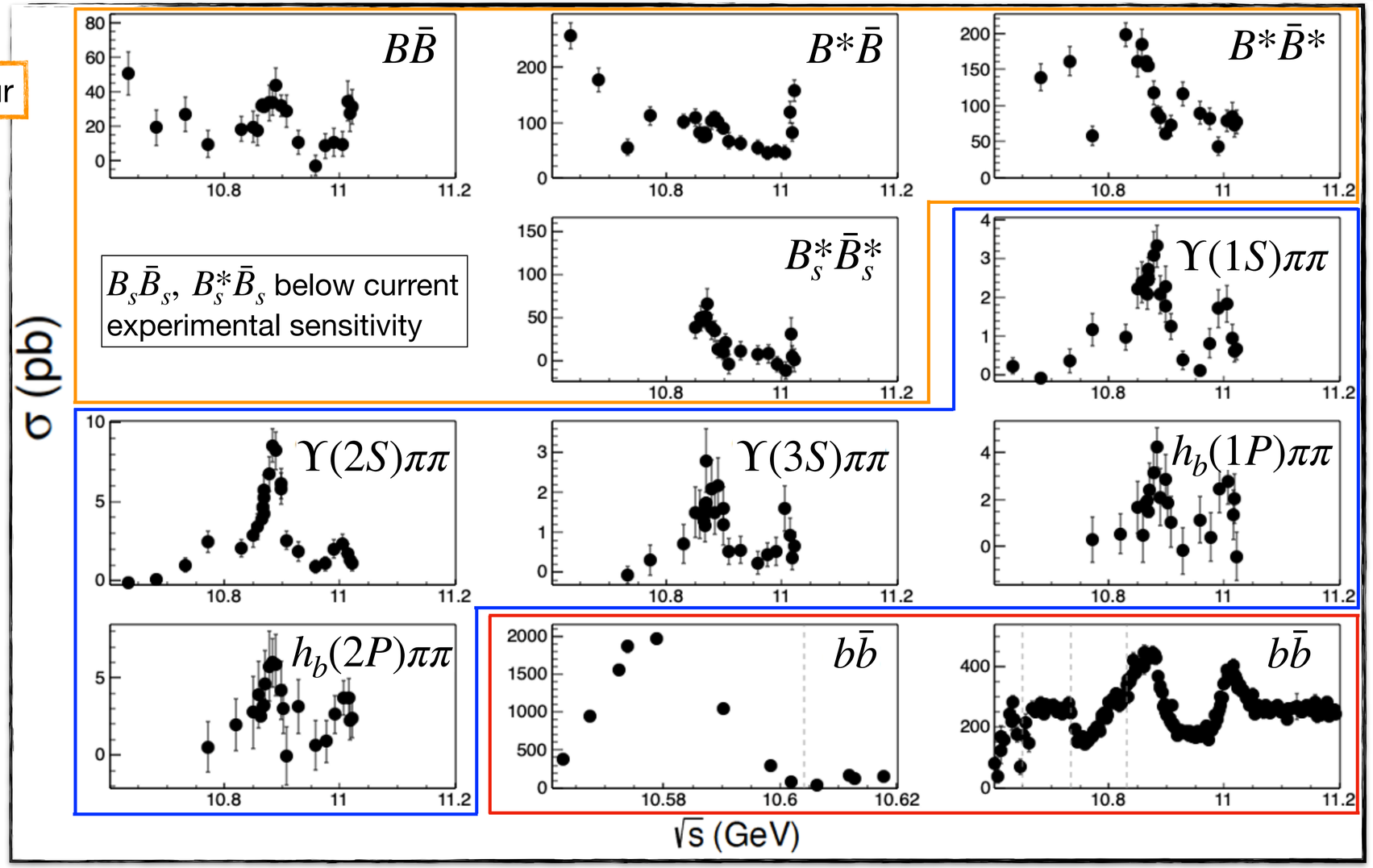


two-body open-flavour



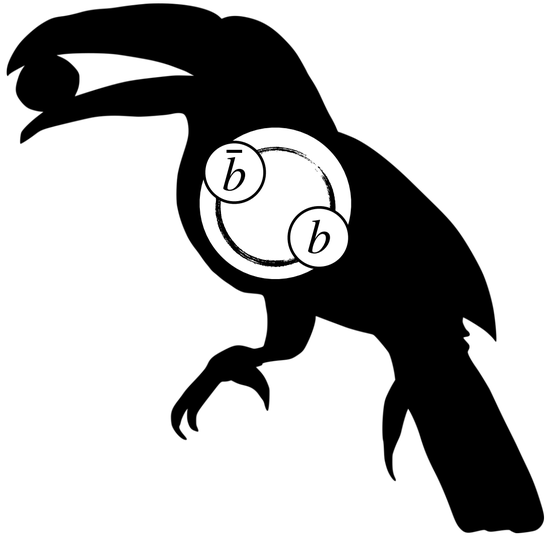
$B_s\bar{B}_s$, $B_s^*\bar{B}_s$ below current experimental sensitivity

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

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

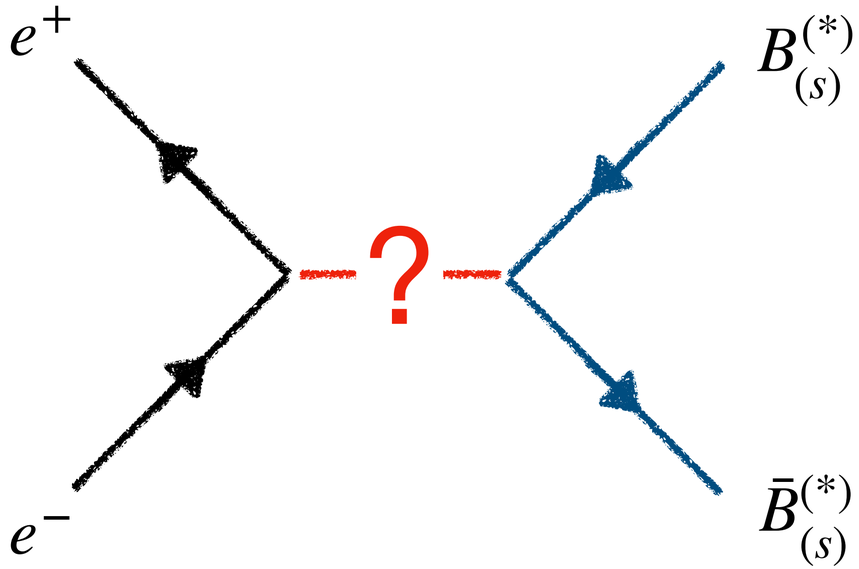
$e^+e^- \to b\bar{b}$: inclusive ($\sum$ of all)

How to improve: coupled channel analysis



Coupled channel analysis

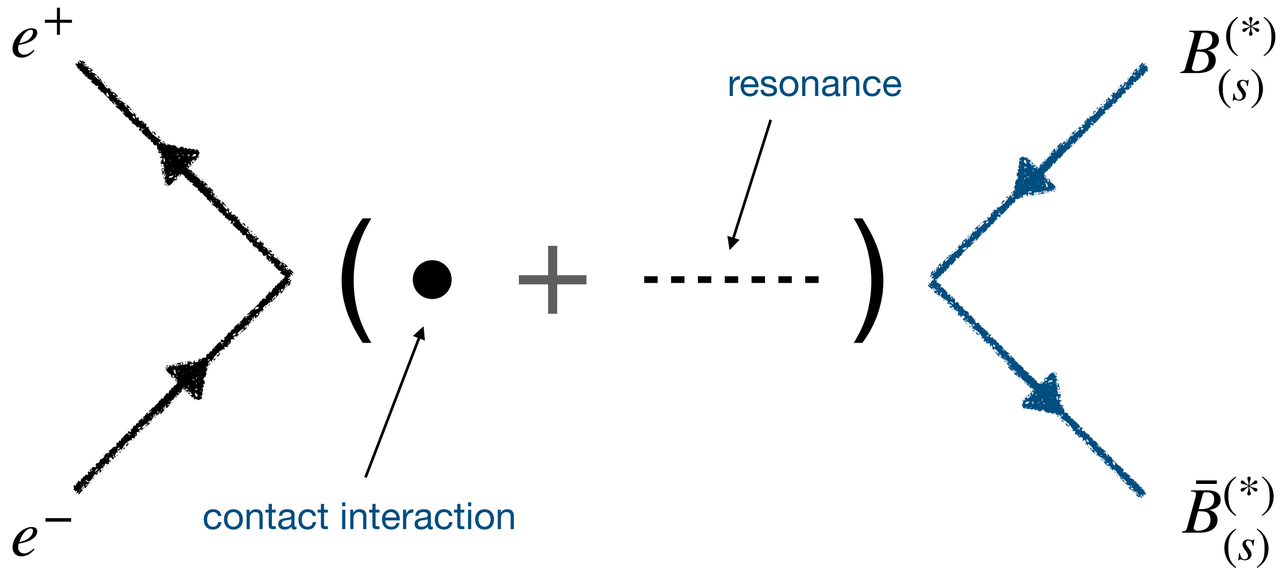
from the experiment, we have an almost complete picture of bottom hadron production in e^+e^- annihilation



idea: use all the data to learn more about the intermediate vector bottomonium resonances

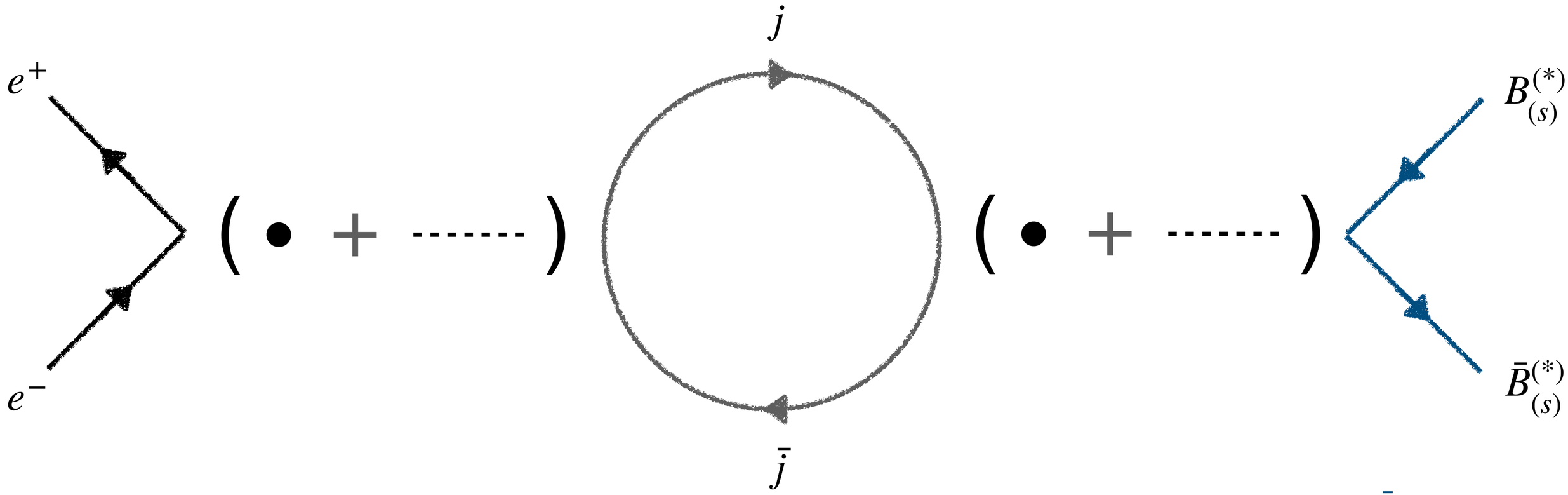
Coupled channel analysis

the most simple model we could think of: $M = b + BW(s)$



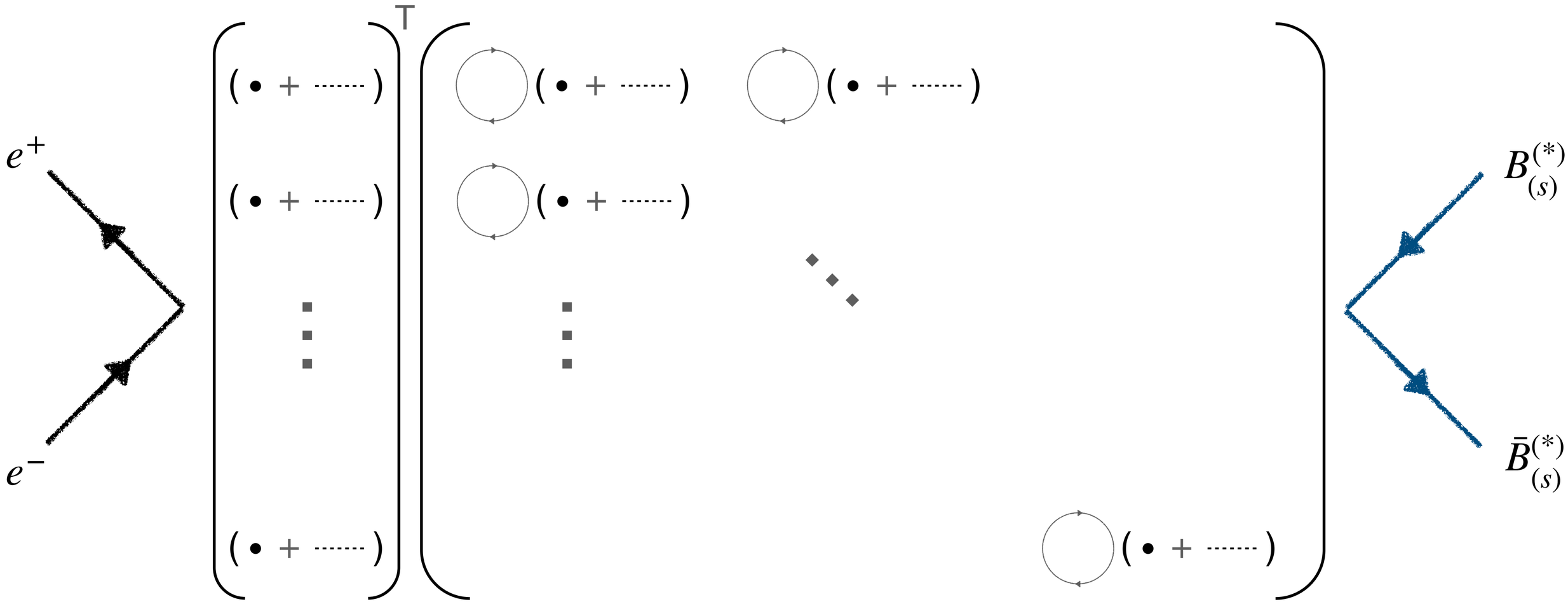
Coupled channel analysis

unfortunately, that is insufficient:



we could have an intermediate pair of hadrons $j\bar{j}$

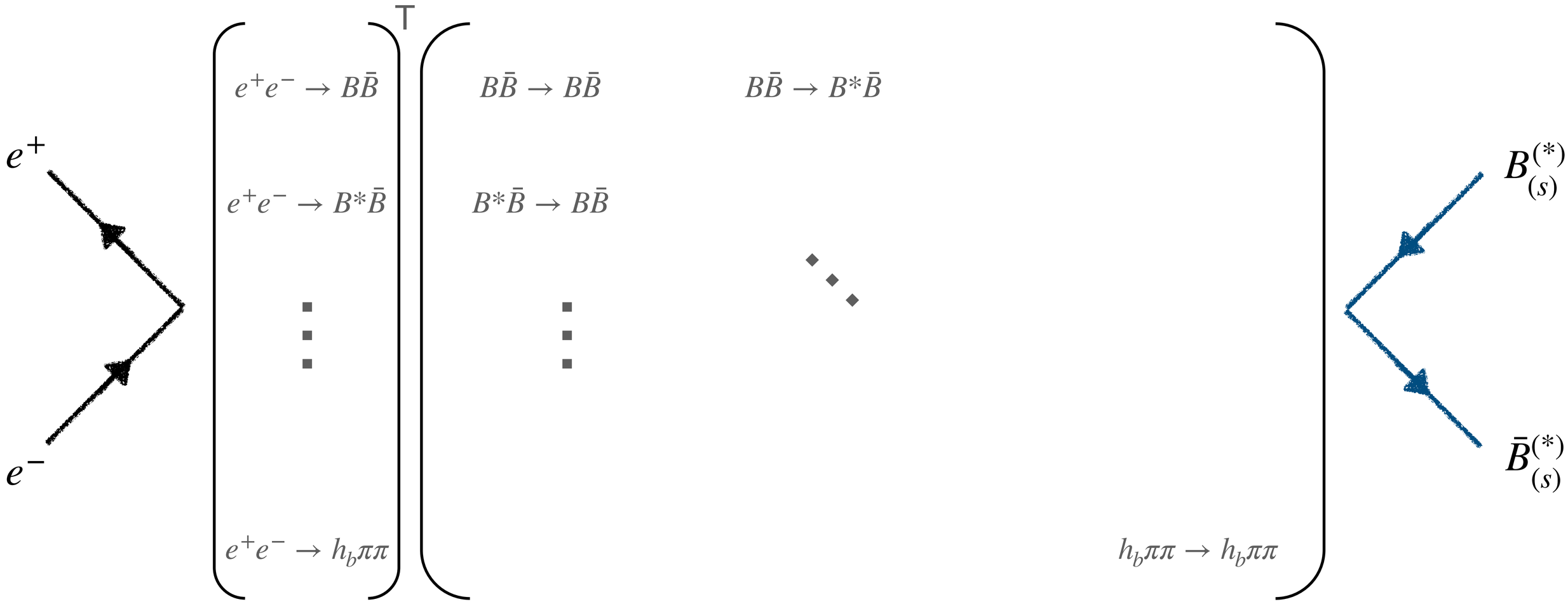
Coupled channel analysis



produce intermediate pair $j\bar{j}$

rescattering to the final state $j\bar{j} \to f\bar{f}$

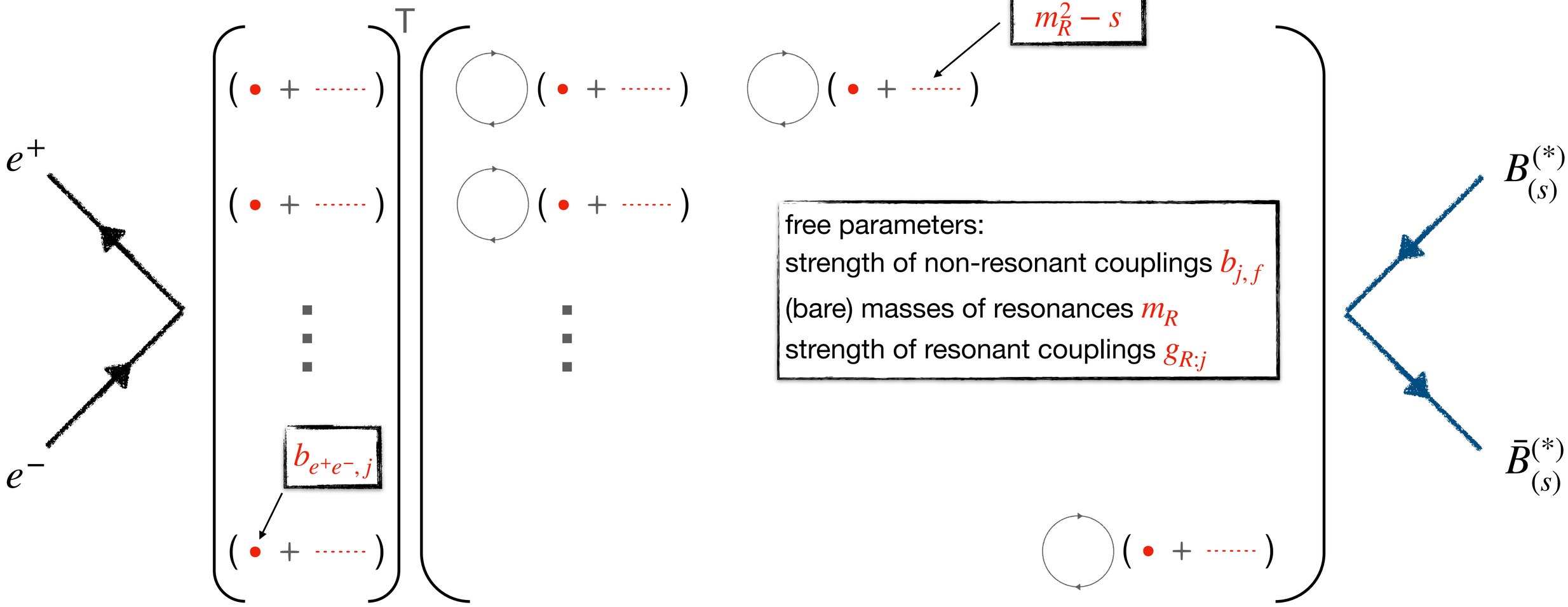
Coupled channel analysis



produce intermediate pair $j\bar{j}$

rescattering to the final state $j\bar{j} \to f\bar{f}$

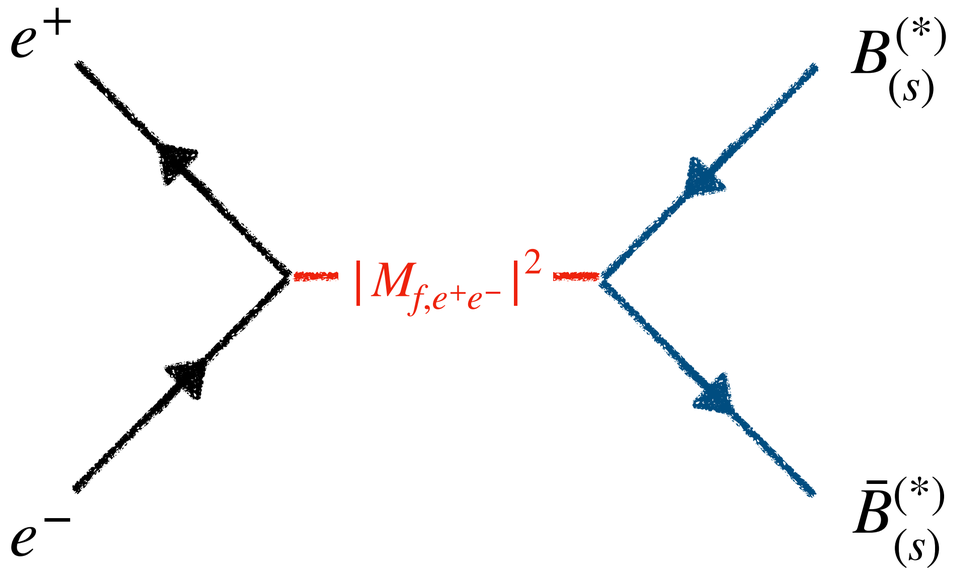
Coupled channel analysis



produce intermediate pair $j\bar{j}$

rescattering to the final state $j\bar{j} \to f\bar{f}$

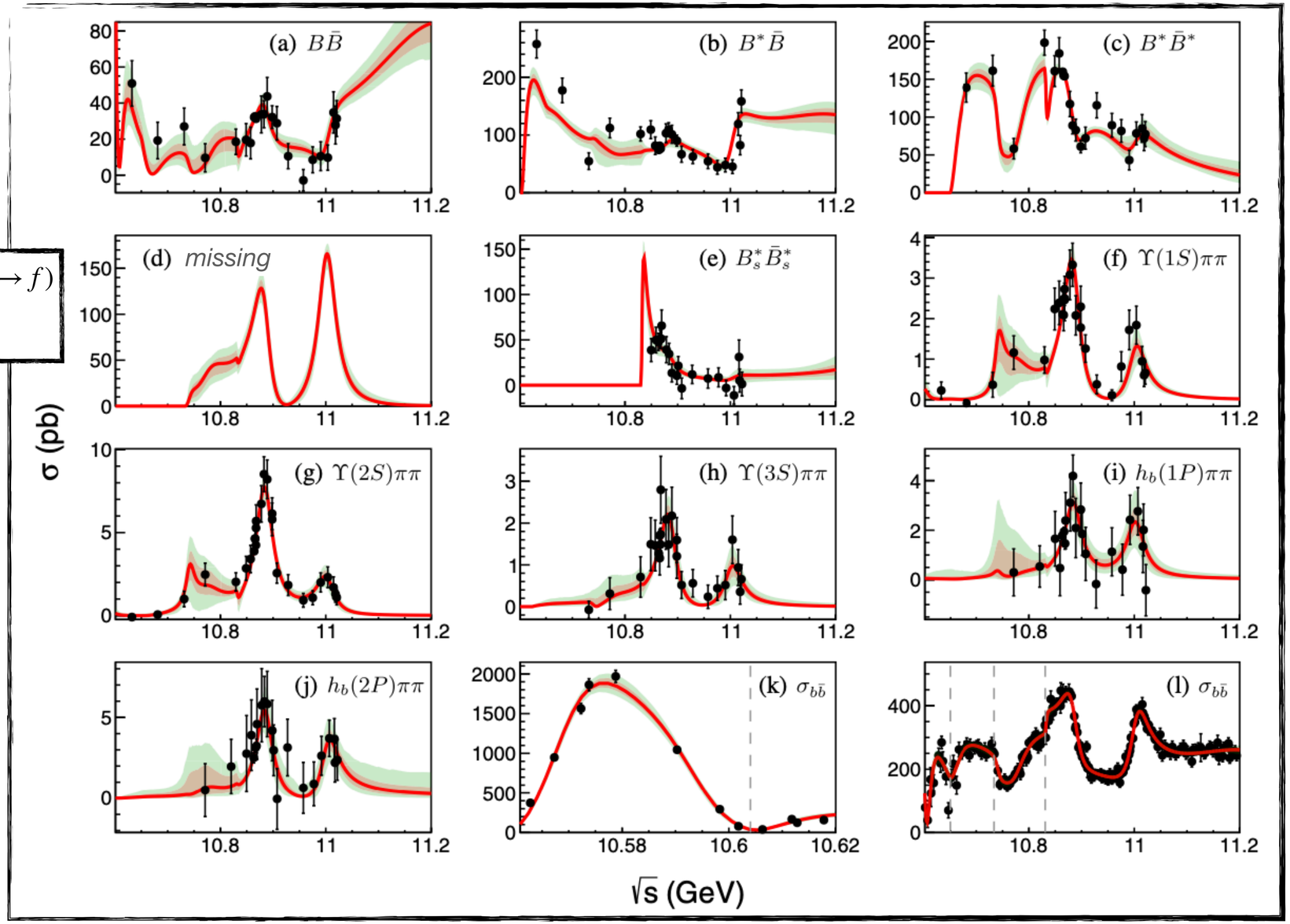
Coupled channel analysis



Coupled channel analysis

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

unmeasured processes



data
fit result
68% CL
90% CL

unitarity:

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

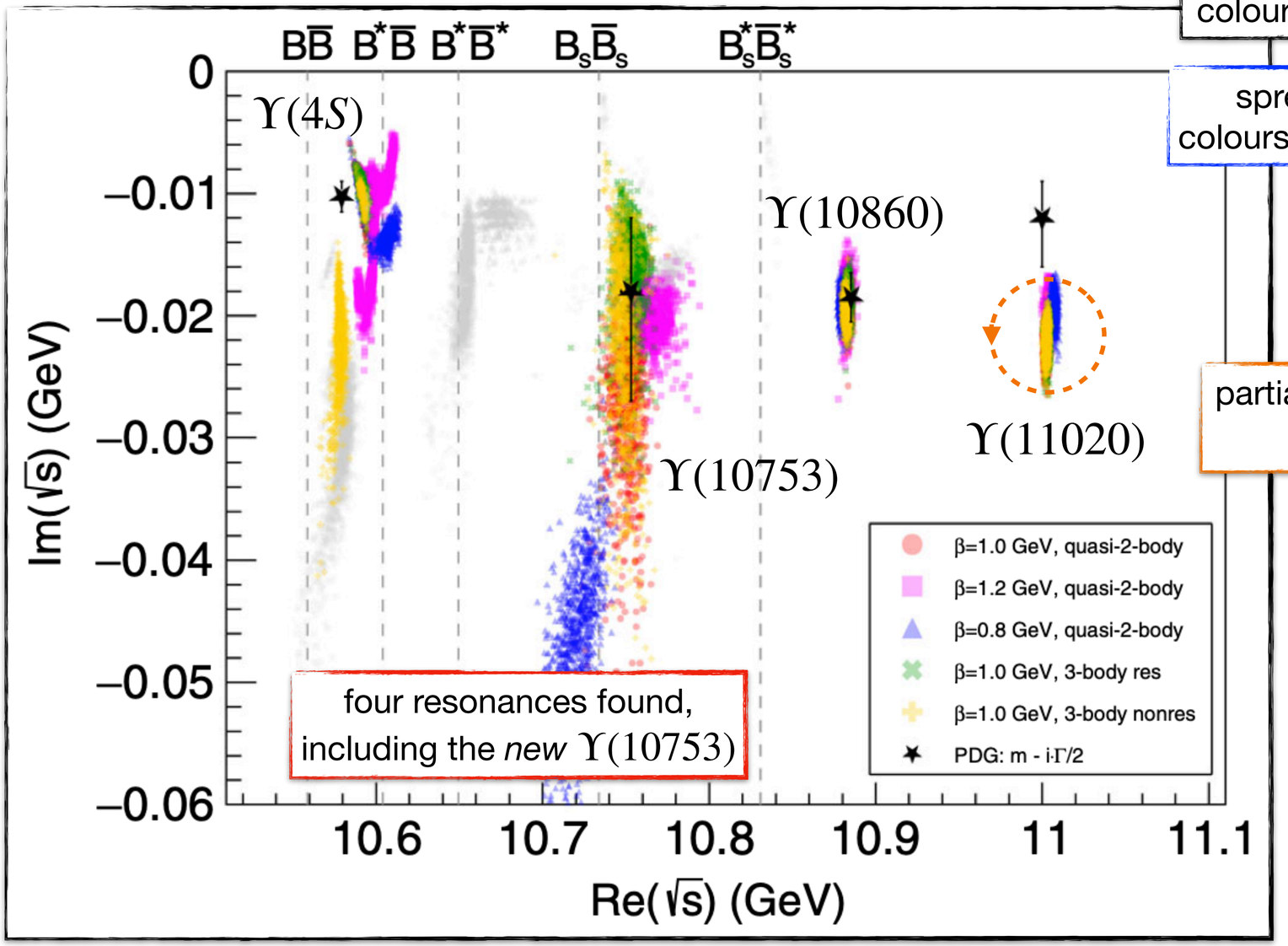
here, this *is* the sum of all exclusive processes

PRD 106 (2022) 9, 094013

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 $\Gamma_{R:i} \propto |\mathrm{Res}_{R:i}|$

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What do we learn?

- for the first time, decay branching fractions are determined

  → sensitive input for interpretation

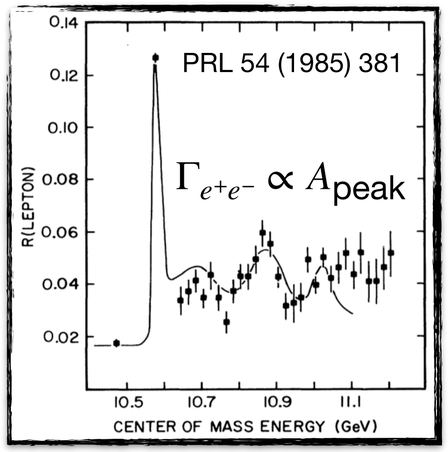
versus

- we can improve upon old measurements

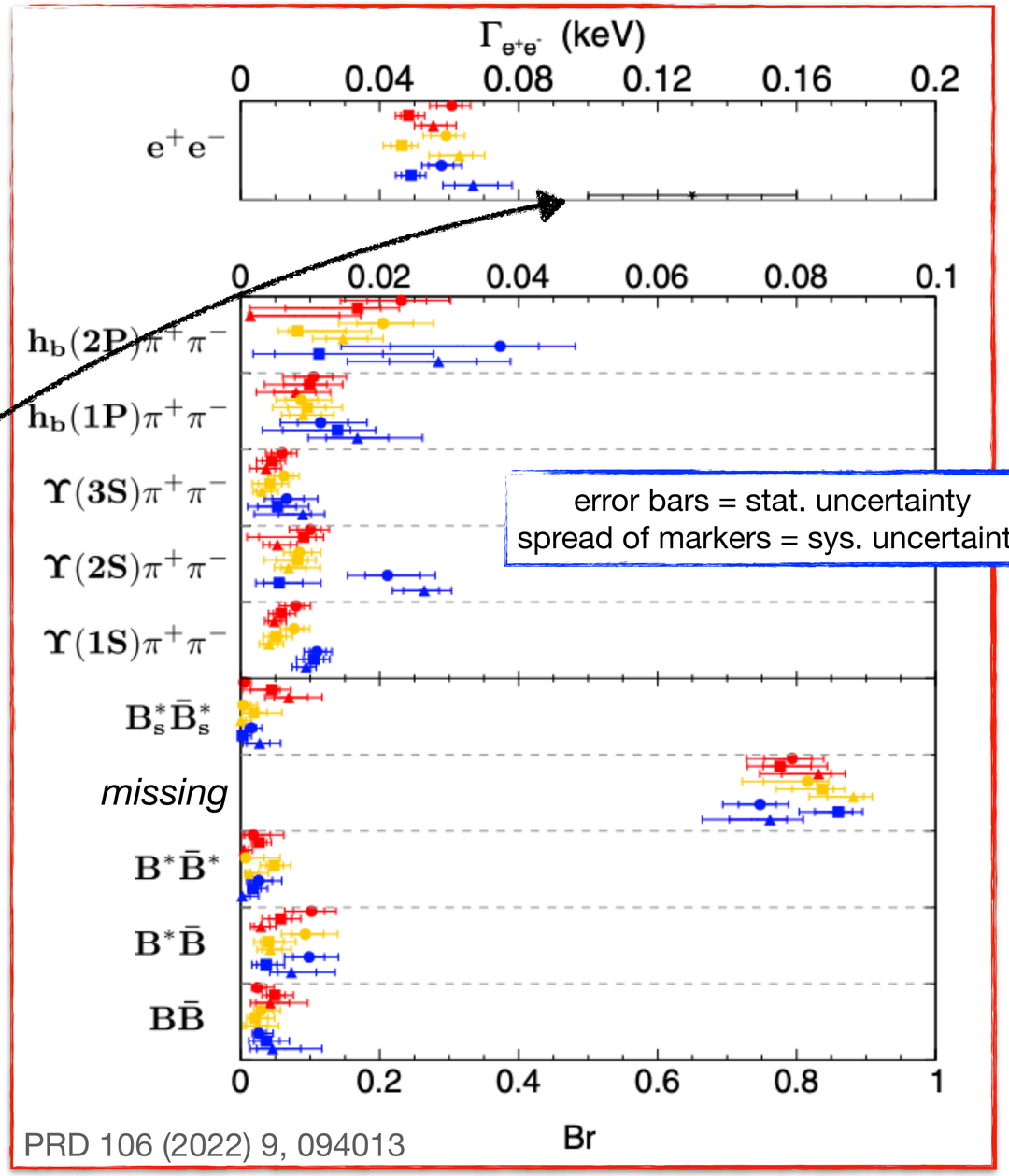
  → accounting for non-resonant processes is important!

- we can provide some guidance for future measurements

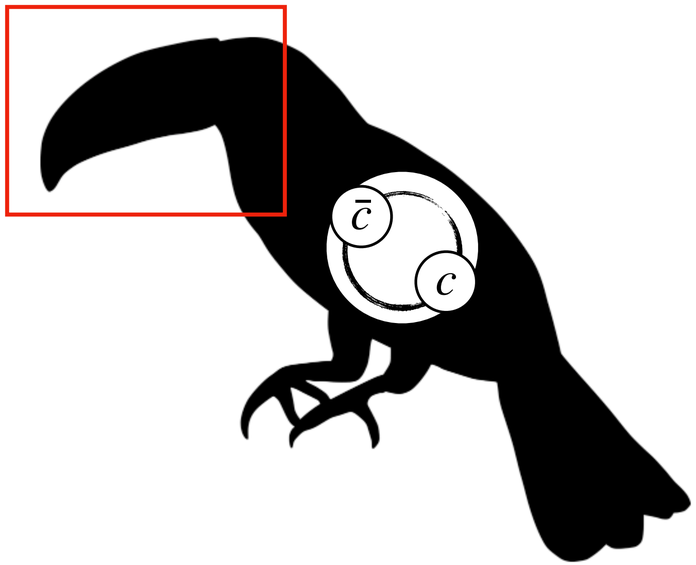
  → 80% of $\Upsilon(11020)$ peak intensity has not been measured yet!



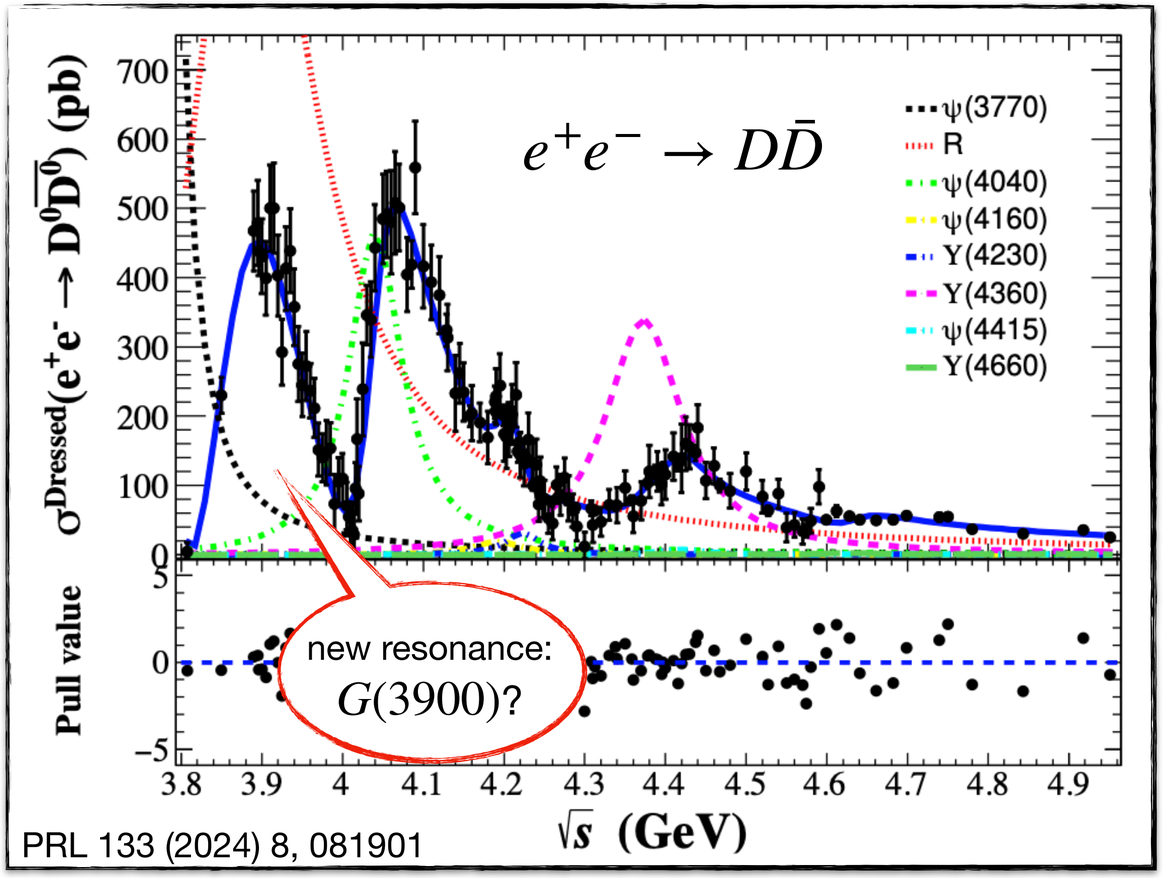
example: decays of the $\Upsilon(11020)$



Charmonium:
A piece of the puzzle

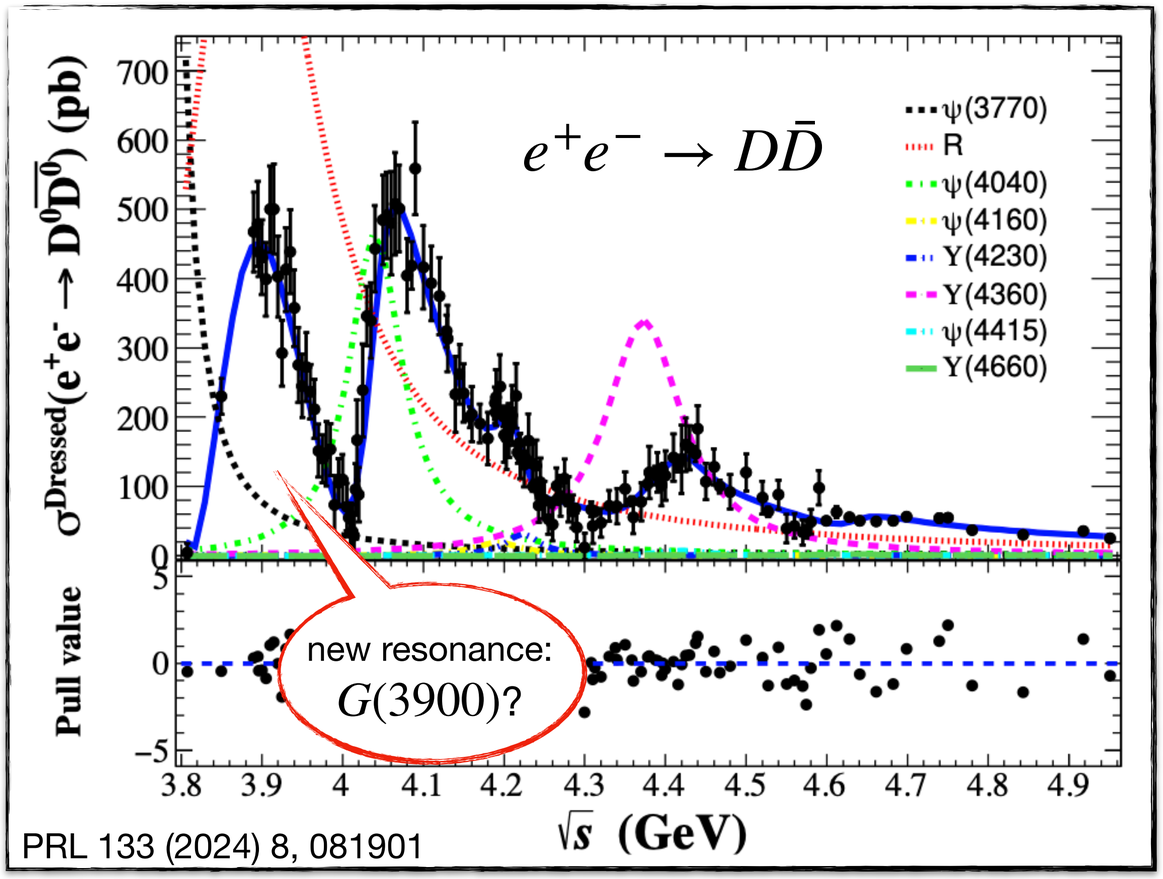


The case of $G(3900)$



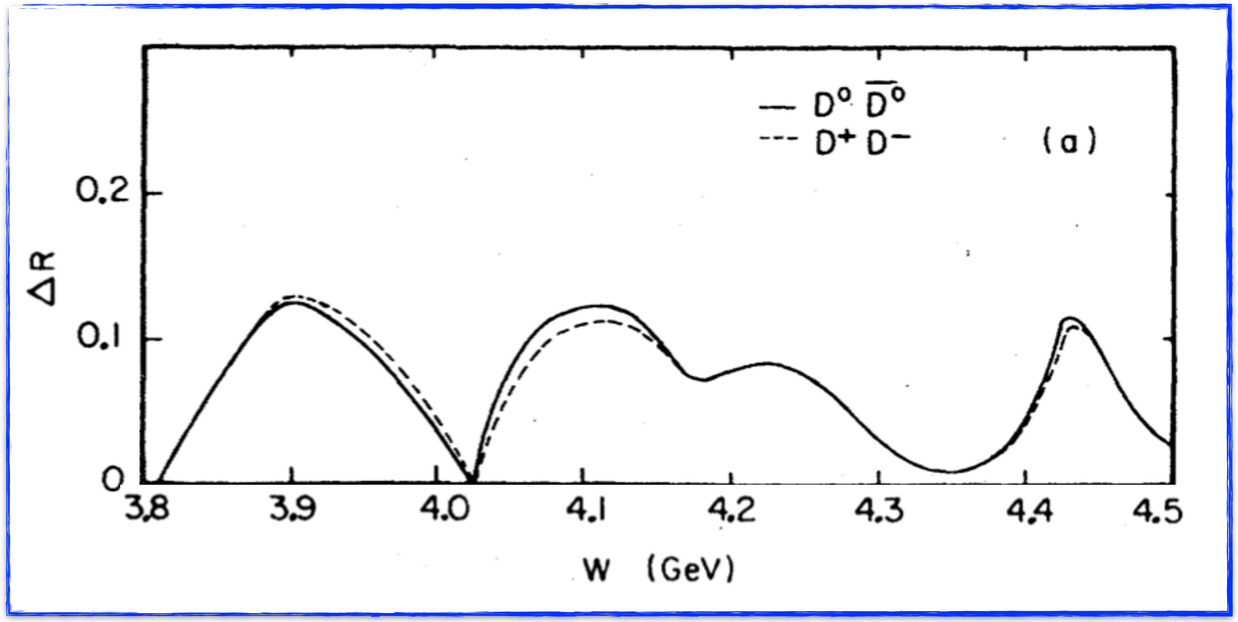
PRL 133 (2024) 8, 081901

The case of $G(3900)$

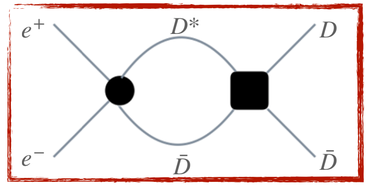


PRL 133 (2024) 8, 081901

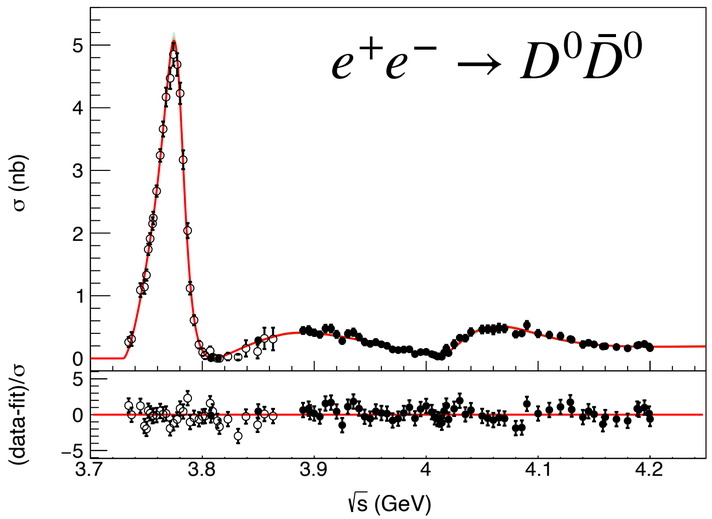
Eichten et al., Phys. Rev. D 21 (1980) 203

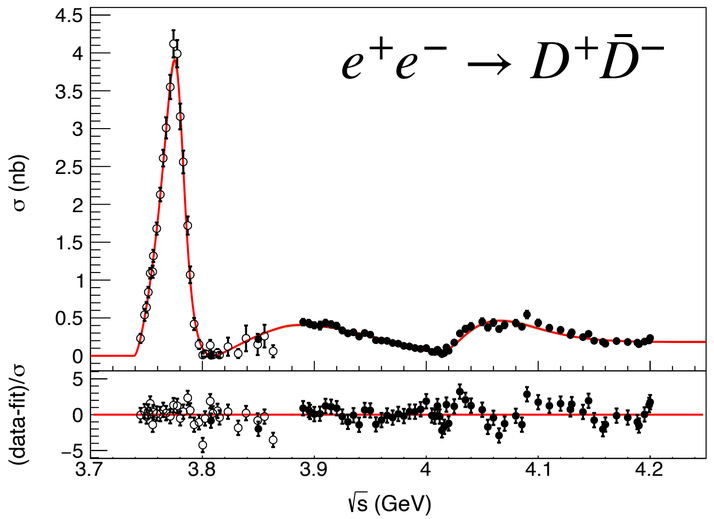


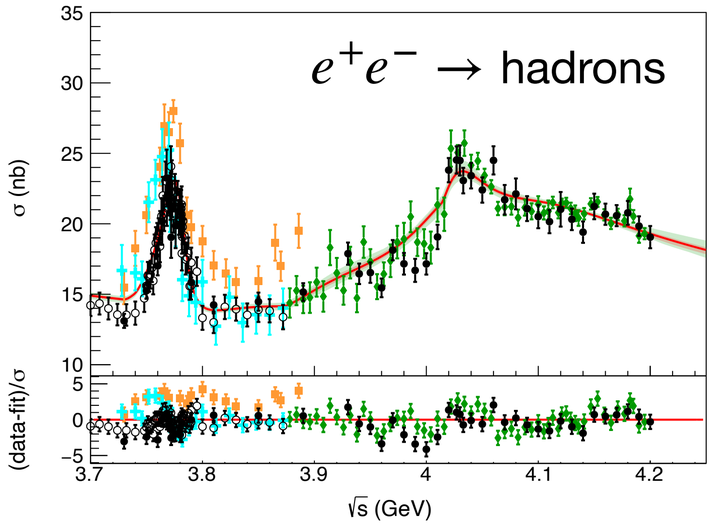
In our calculation there is some weak structure in the 3.9–4.0 GeV region. It does not arise from a $c\bar{c}$ resonance, but from the opening of the $D\bar{D}^* + D^*\bar{D}$ channel and a decrease in the $D\bar{D}$ channel due to a nearby zero in the $3S$ decay amplitude.

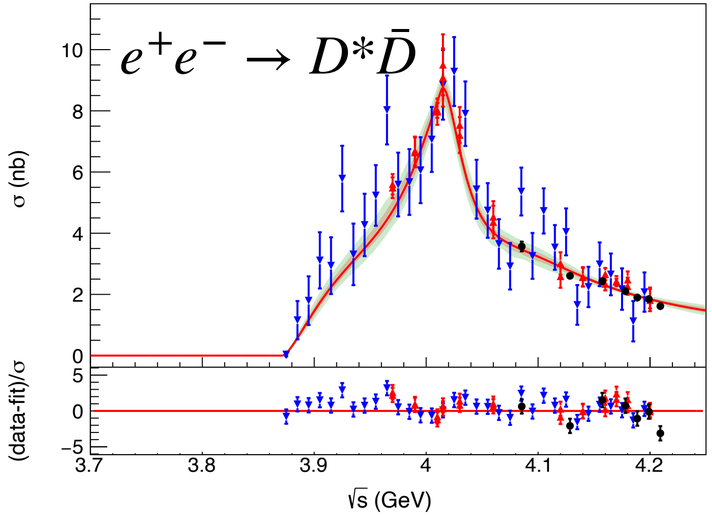


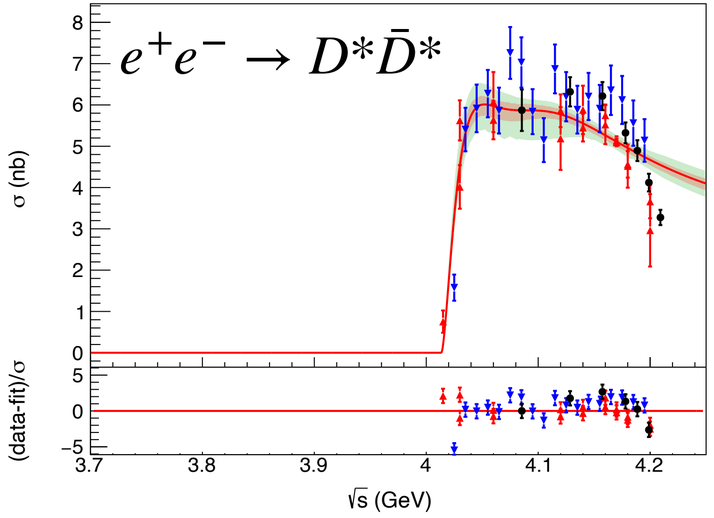
The case of $G(3900)$











fit result

68% CL

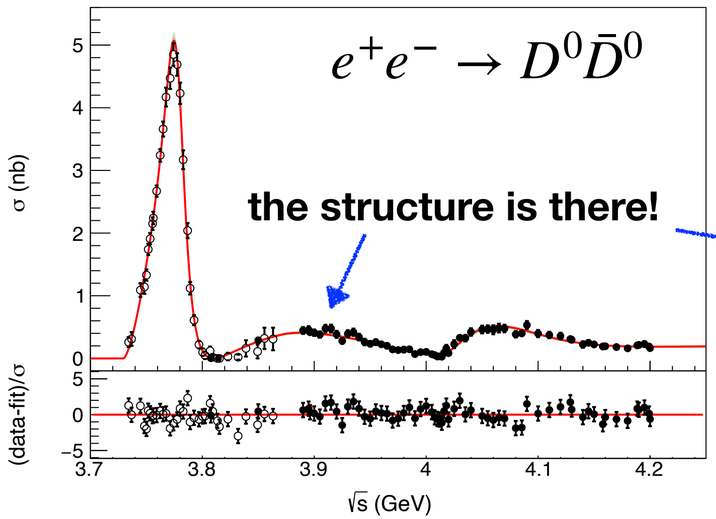
90% CL

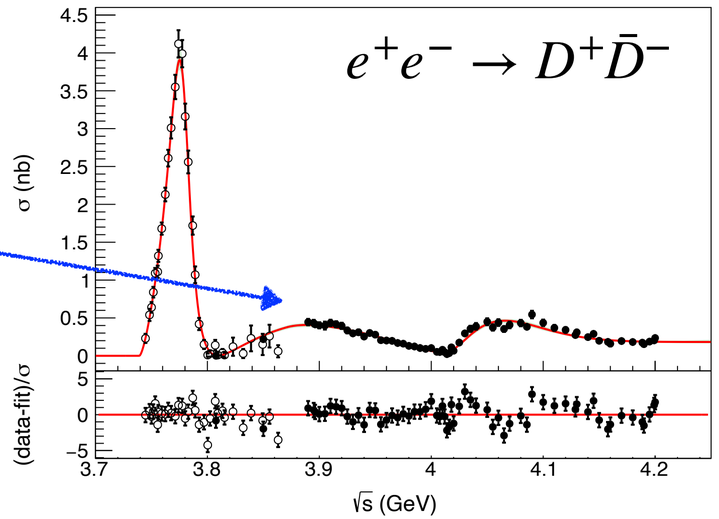
Data from:

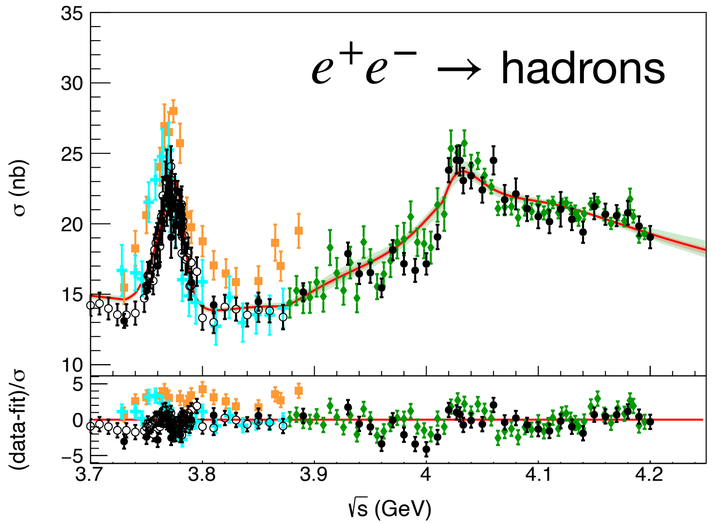
BESIII (unoff.) Andy Julin, University of Minnesota
BESIII: PRL 133 (2024) 8, 081901
BESIII: JHEP 05 (2022) 155
Belle: Phys.Rev.D 97 (2018) 1, 012002
CLEO: Phys.Rev.D 80 (2009) 072001
BES: PRL 88, 101802 (2002)
BESII: PRL 97, 262001 (2006)
SPEAR: PRL 39, 526 (1977);
A. Osterheld et al. 86; Schindler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

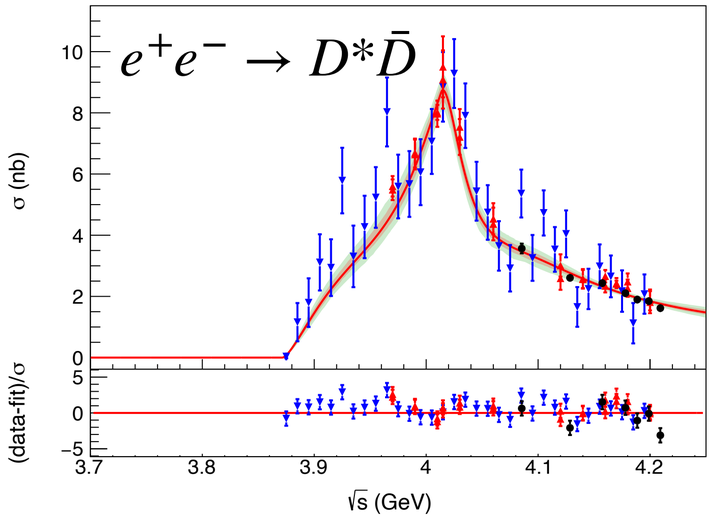
PRD 109 (2024) 11, 114010

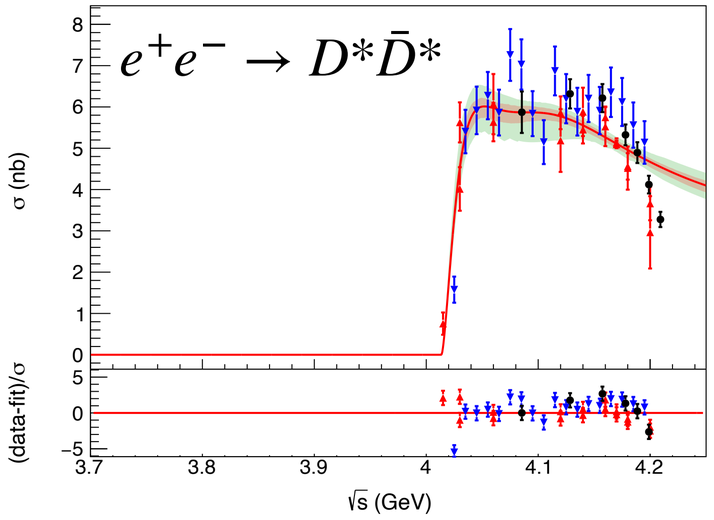
The case of $G(3900)$











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PRD 109 (2024) 11, 114010

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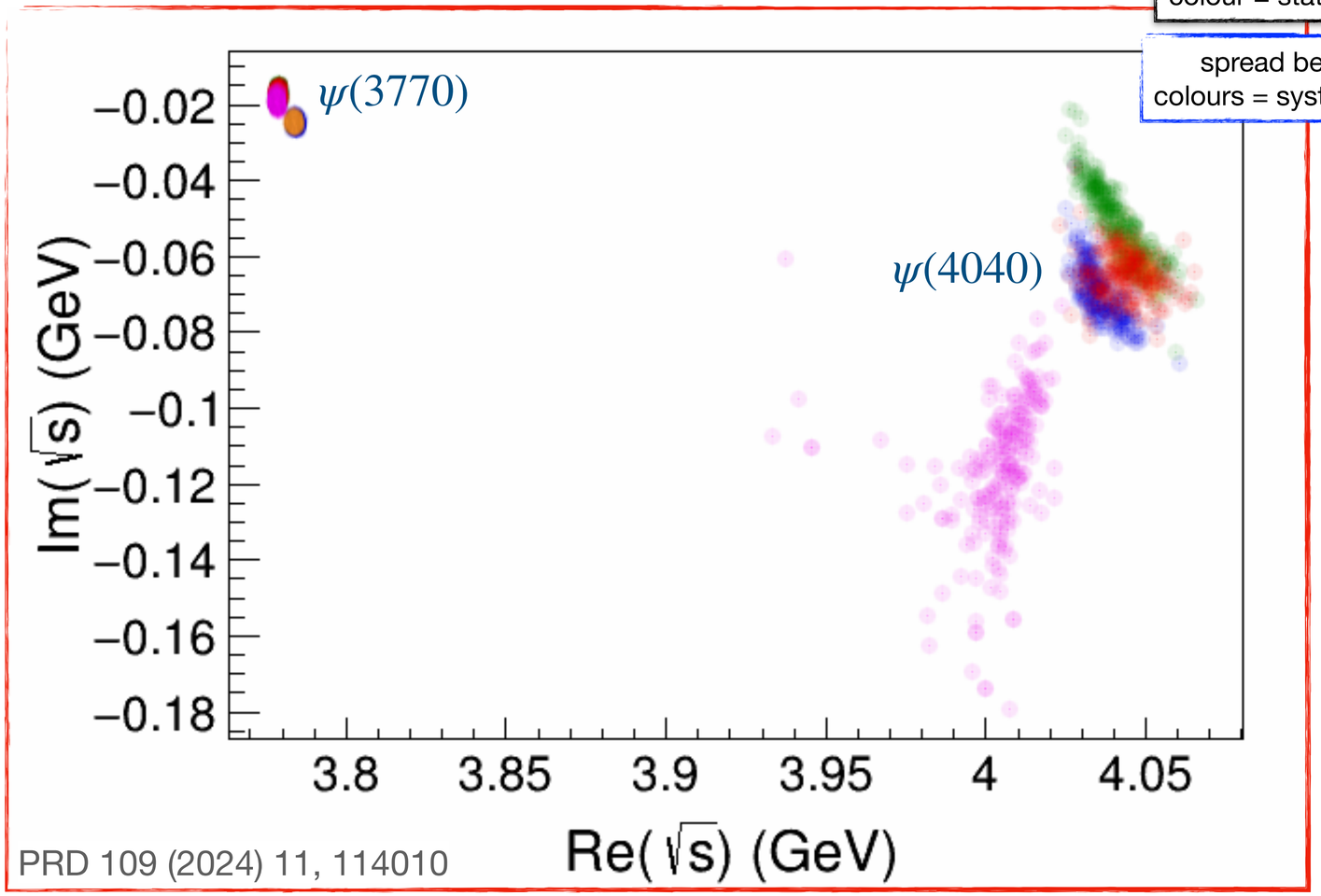
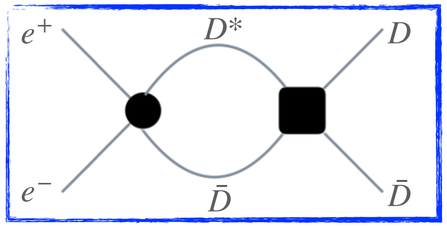


PRD 109 (2024) 11, 114010

- we find no $G(3900)$ pole!
- effects from the opening of other channels matter when interpreting the data!

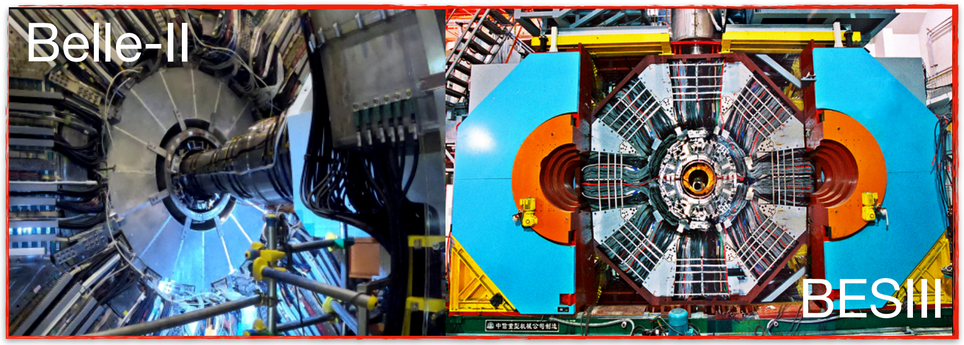


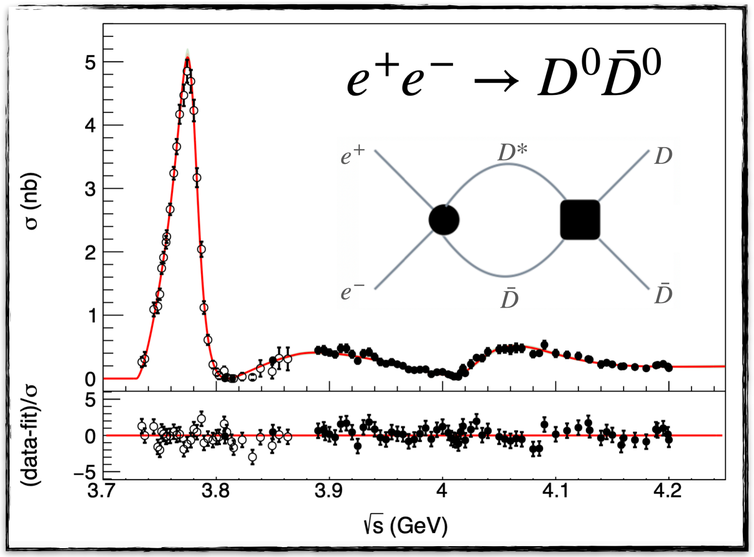
(others disagree: Lin et al., PRL 133, 241903)

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!
  do $\psi(4160)$, $\psi(4230)$, $\psi(4360)$ all exist?

Lin et al., PRL 133, 241903
Nakamura et al., arXiv:2312.17658 [hep-ph]
Cleven et al., PRD 90 (2014) 7, 074039
L. von Detten, PRD 109 (2024) 11, 116002

Thank you for your attention!