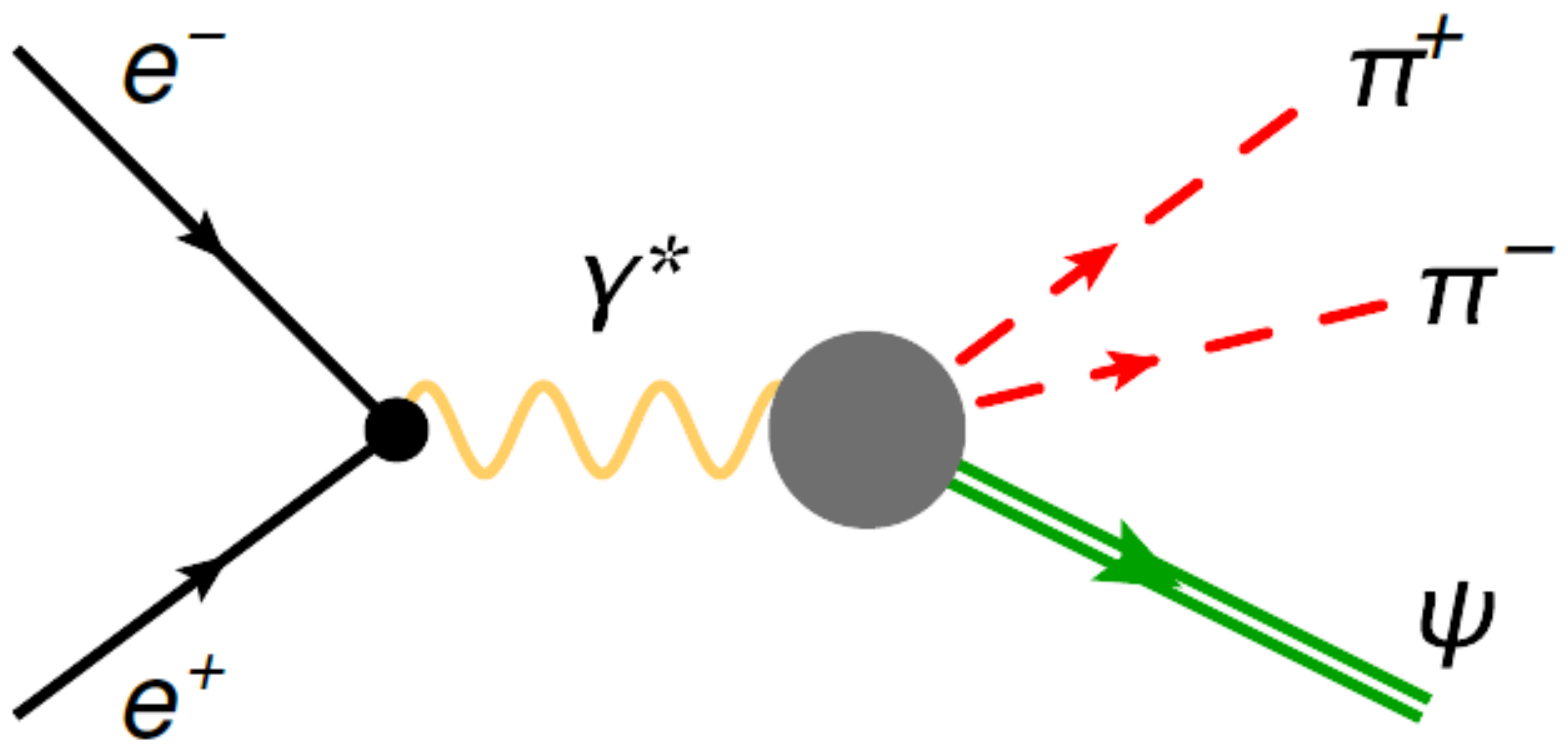
Understanding the Y in XYZ

Vector mesons in e^+e^- annihilation

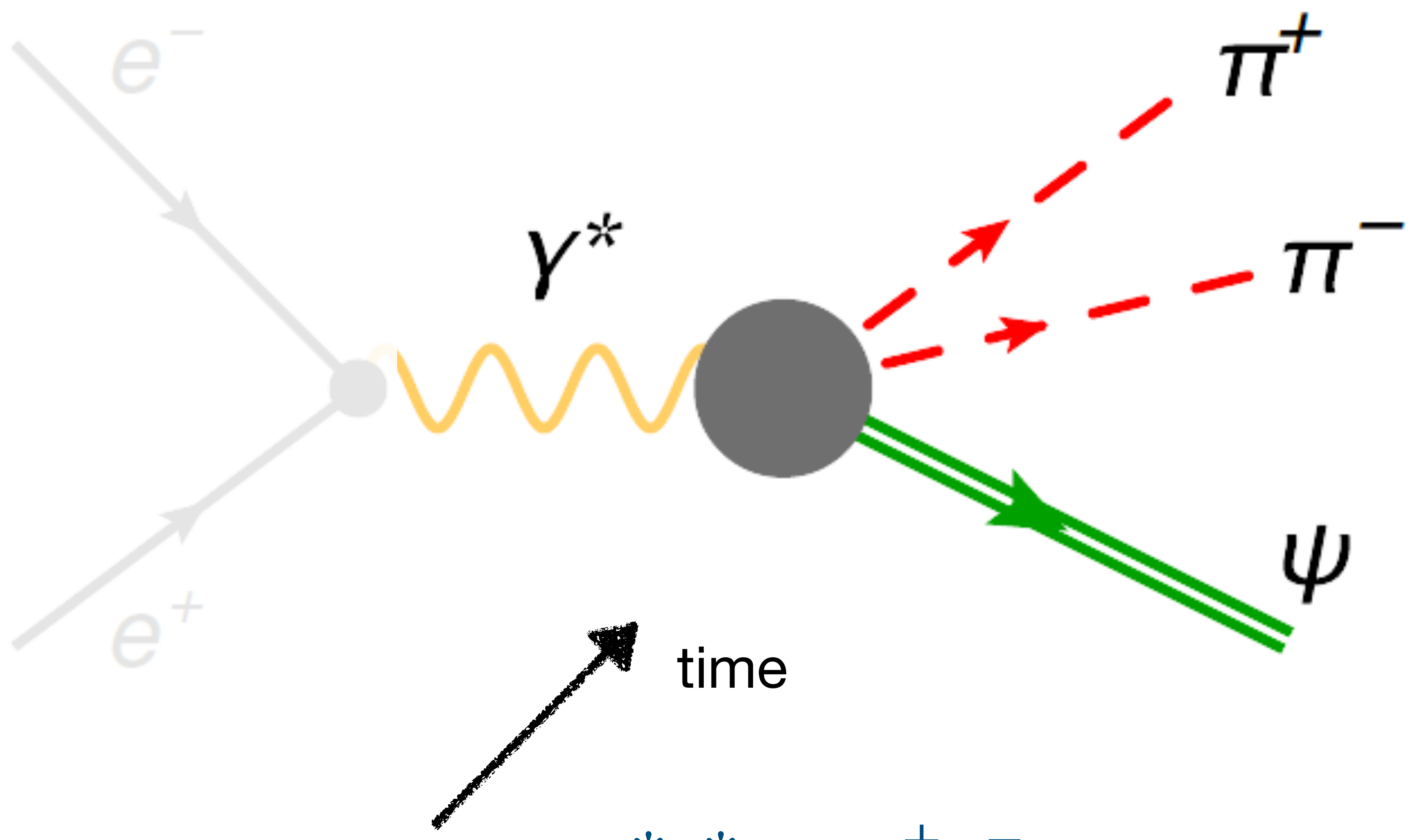
Nils Hüsken
June 12th 2025, St. Goar
Workshop of Research Unit FOR5327

Connecting to FOR5327



see talks by V. Ermolina, Y. Guo

Connecting to FOR5327

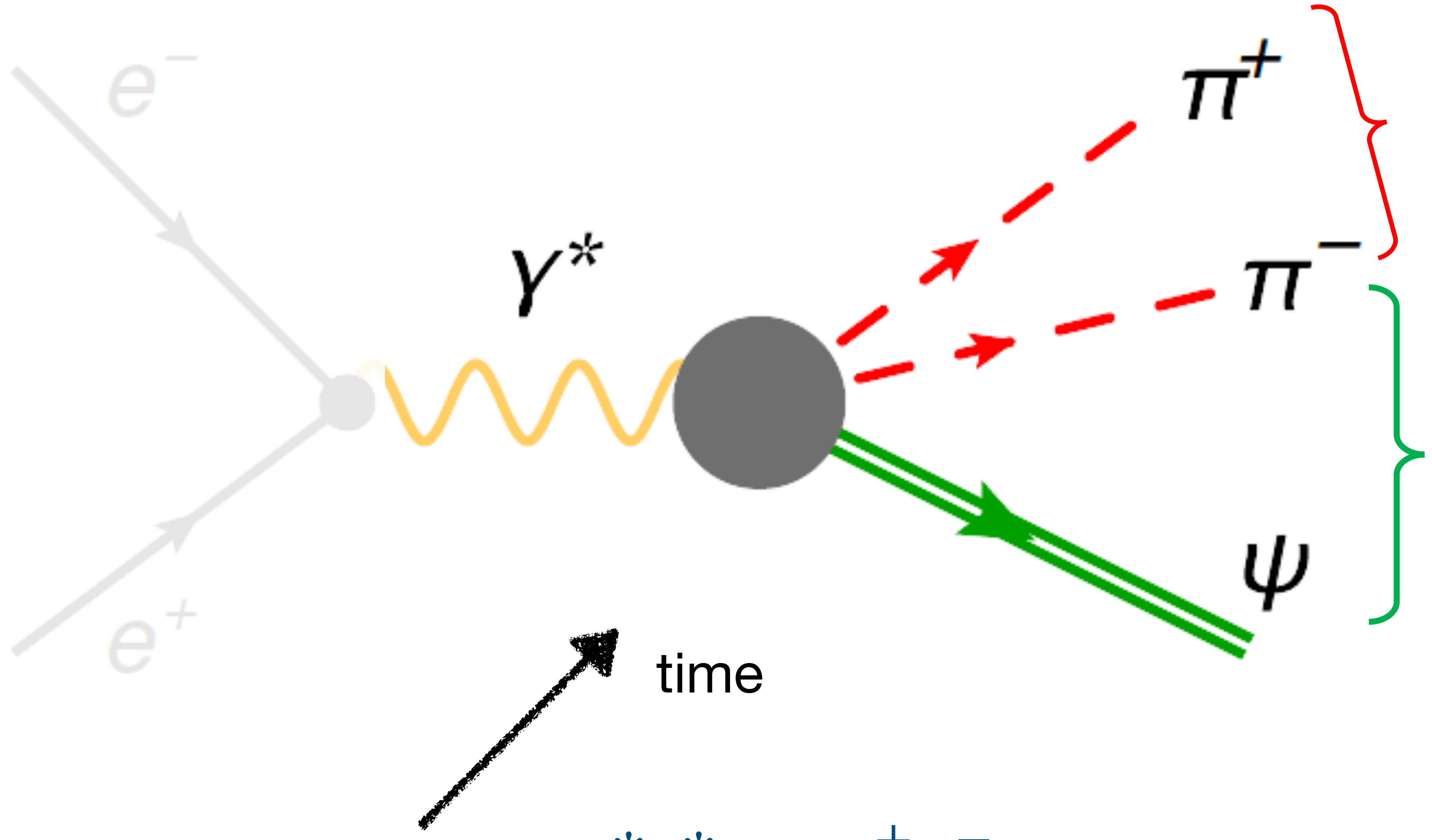


$\gamma^* \gamma^* \to \pi^+ \pi^-$

see talks by V. Ermolina, Y. Guo

Connecting to FOR5327

V. Ermolina, I. Danilkin, M. Vanderhaeghen, PLB 864 (2025) 139450



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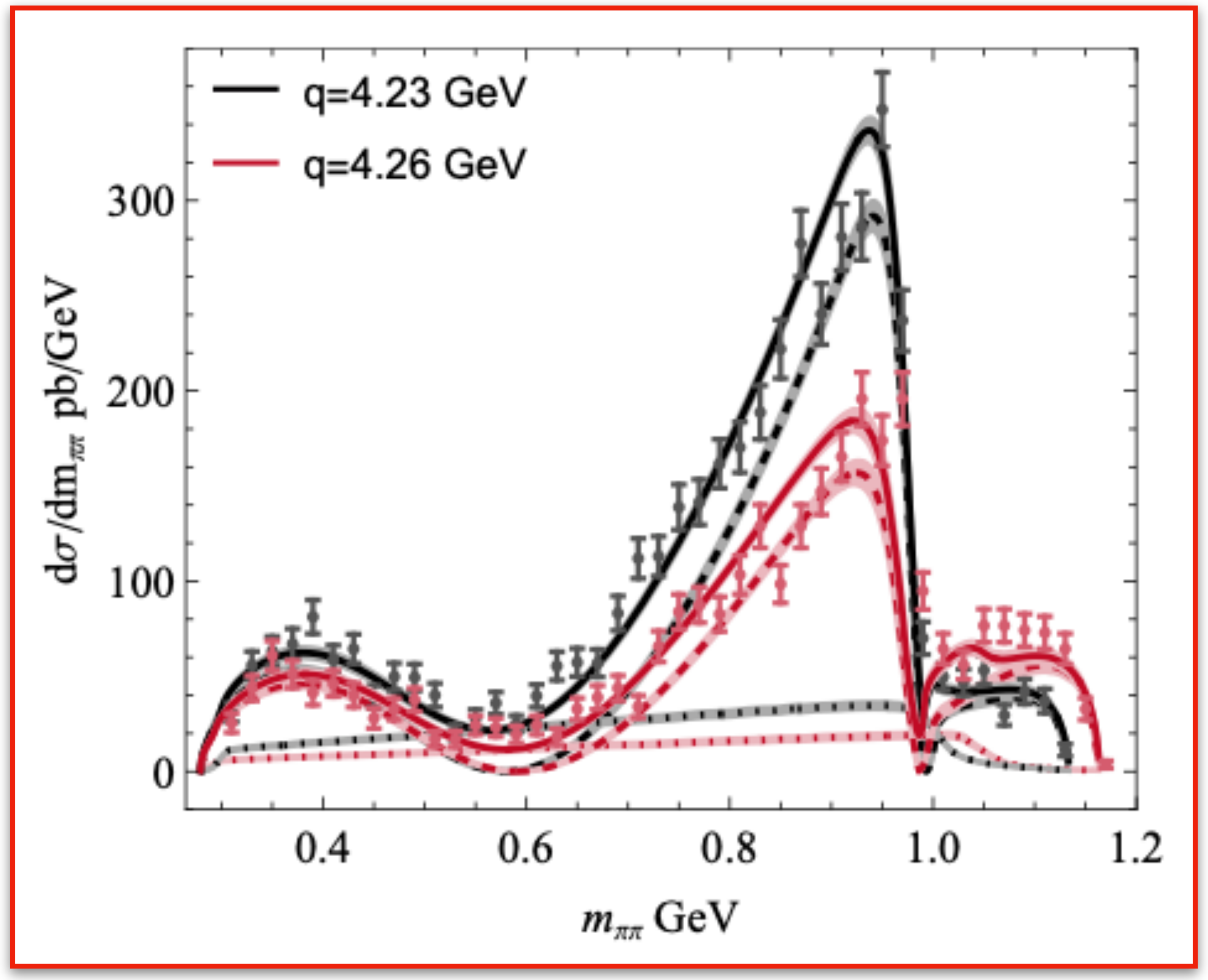

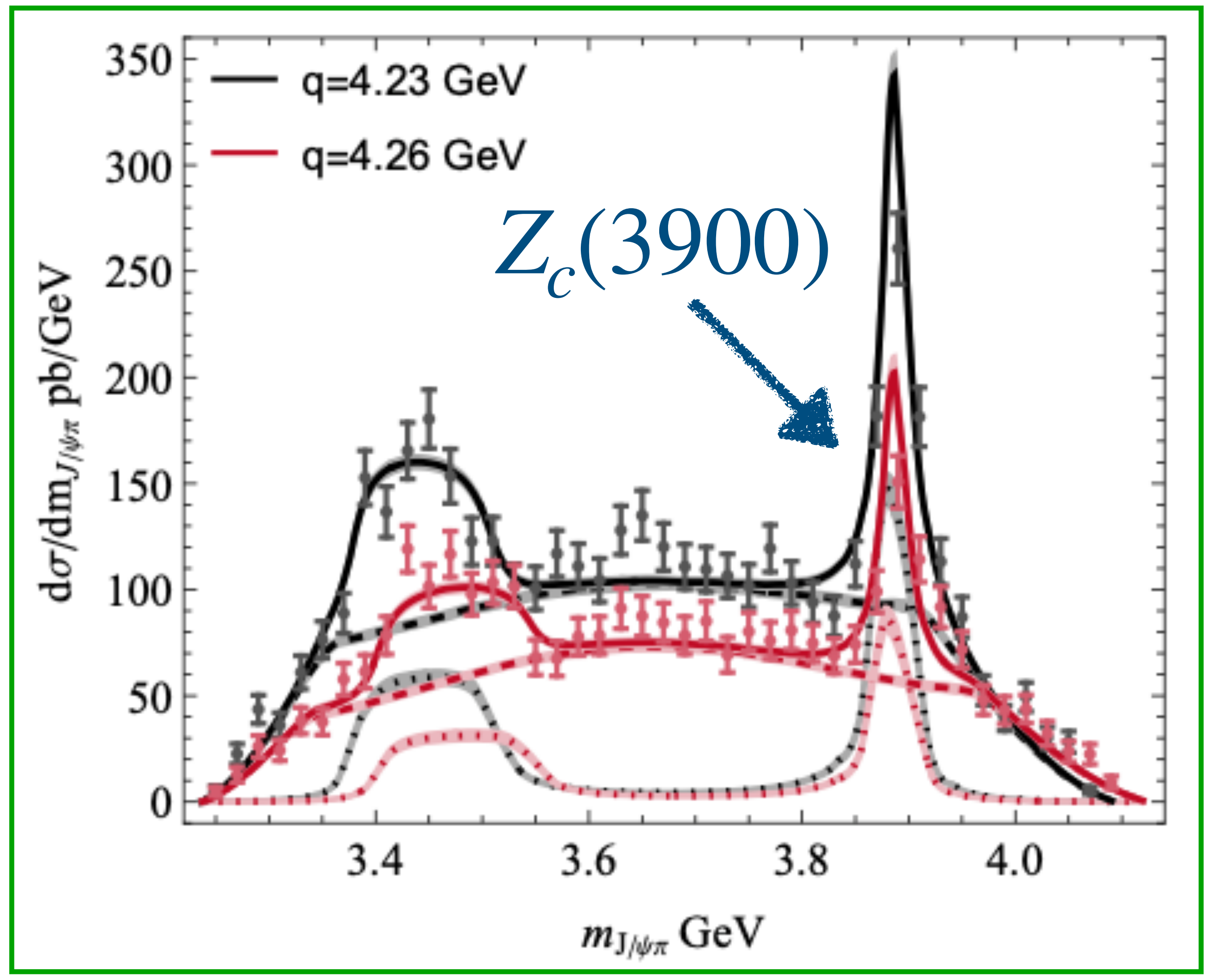

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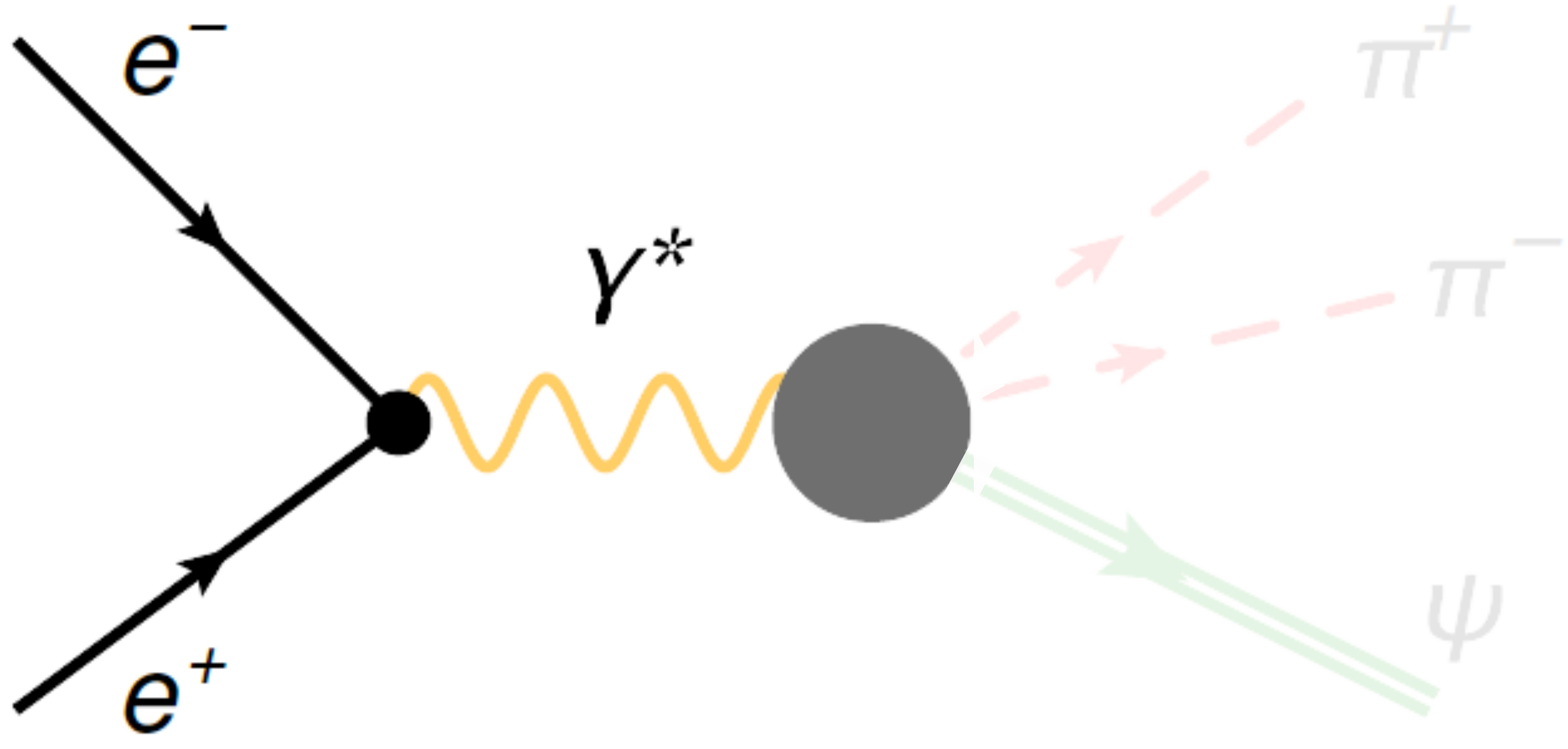

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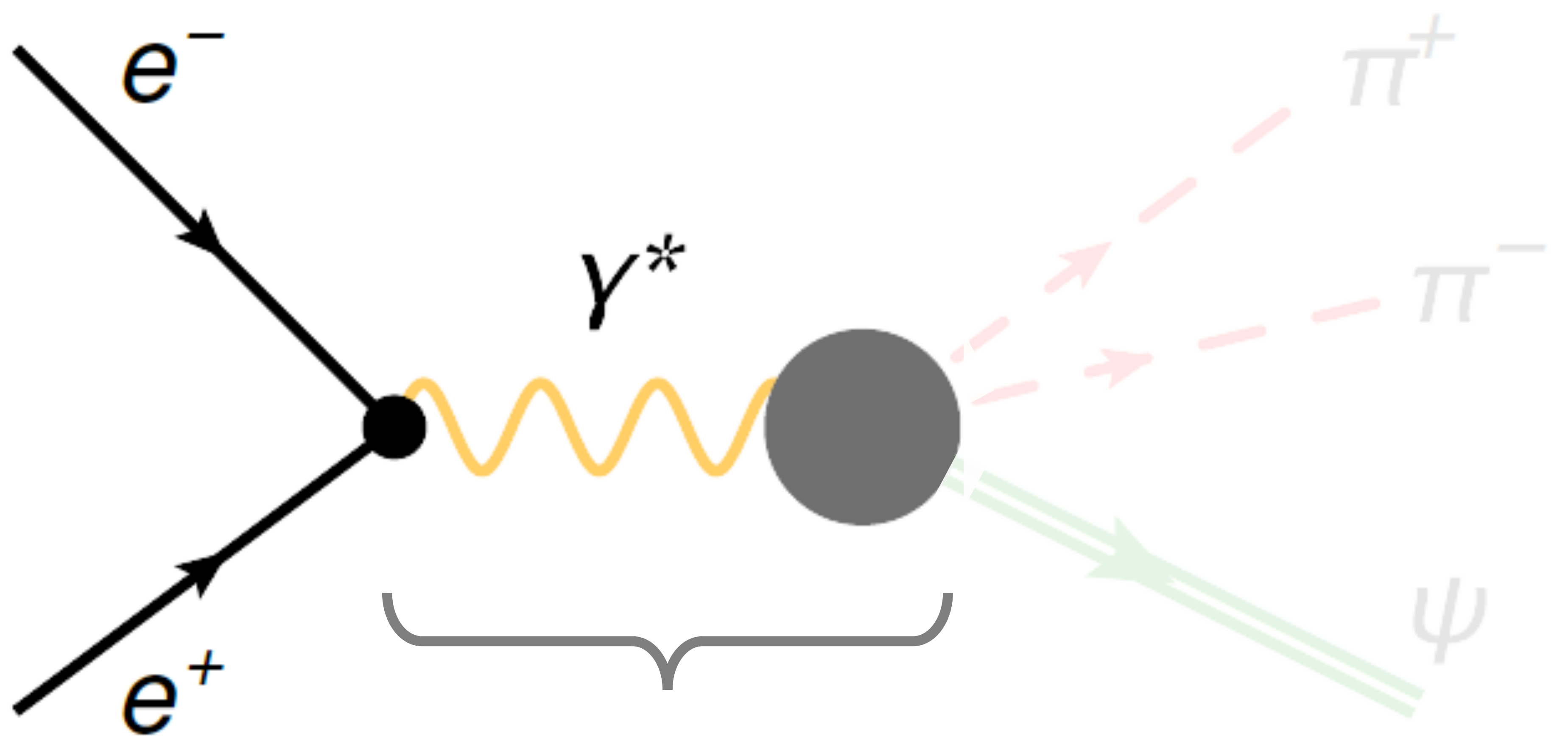
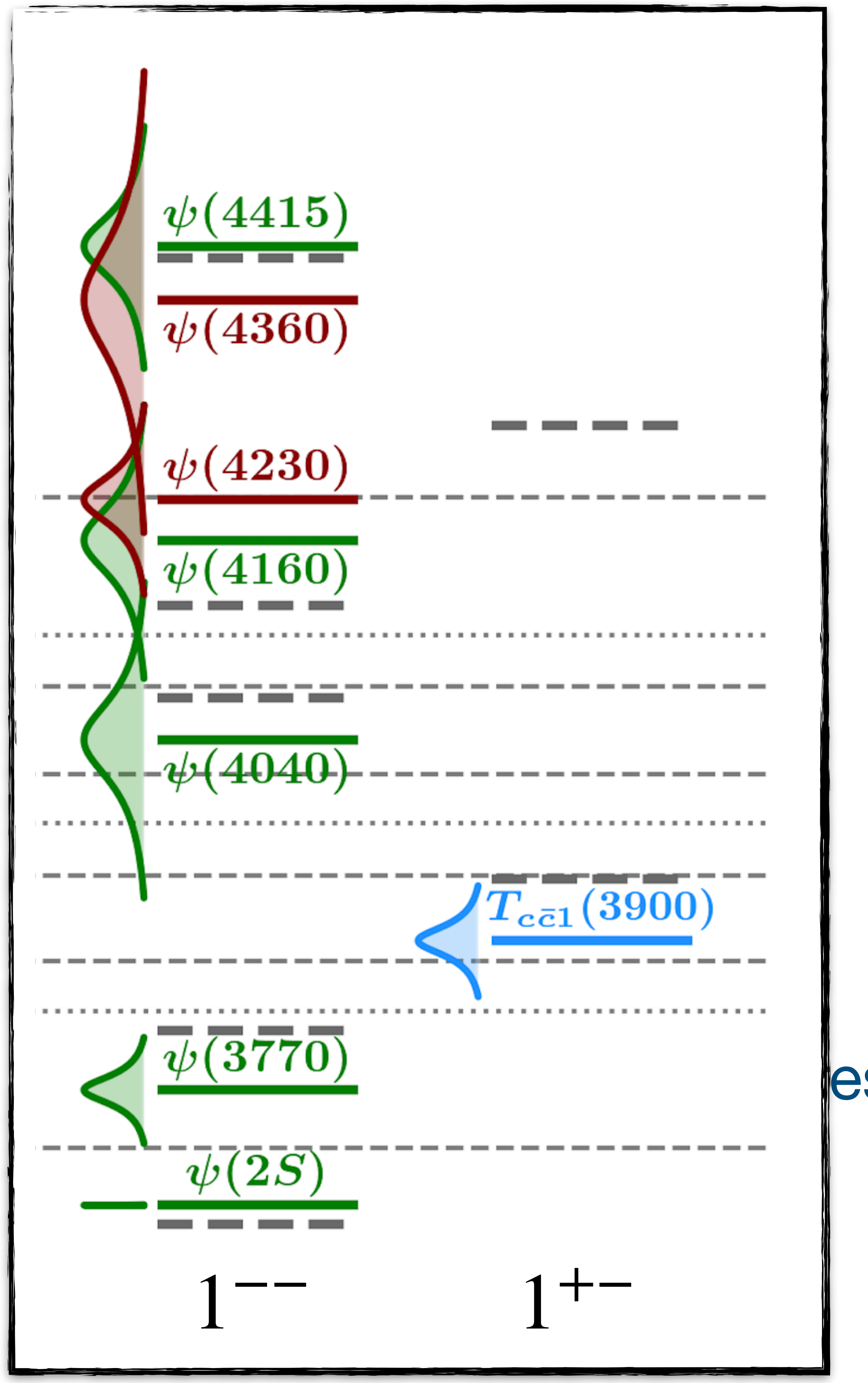
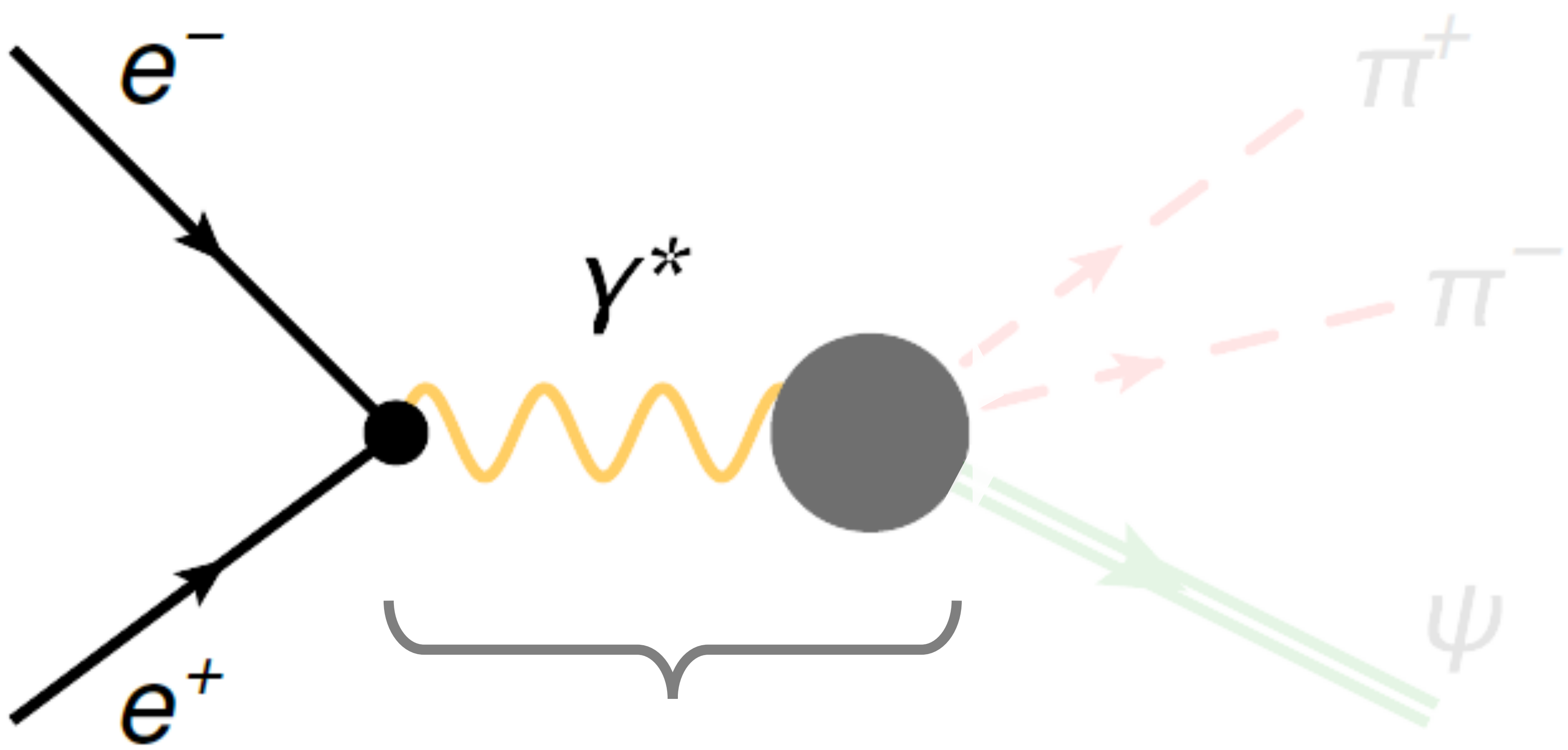


resonances: ψ $(c\bar{c})$, Υ $(b\bar{b})$
exotic: Y

non-resonant, contact

Connecting to FOR5327





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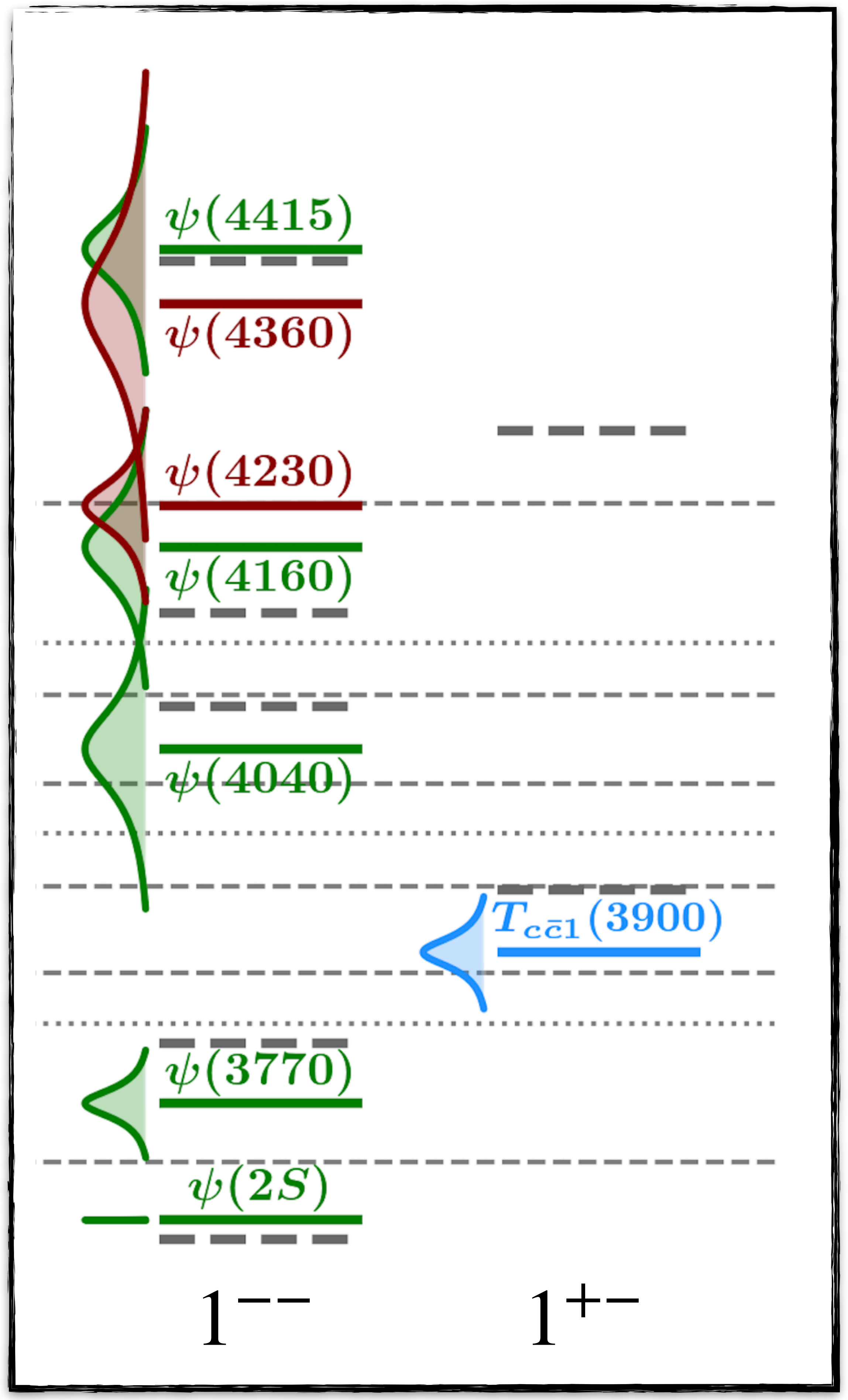
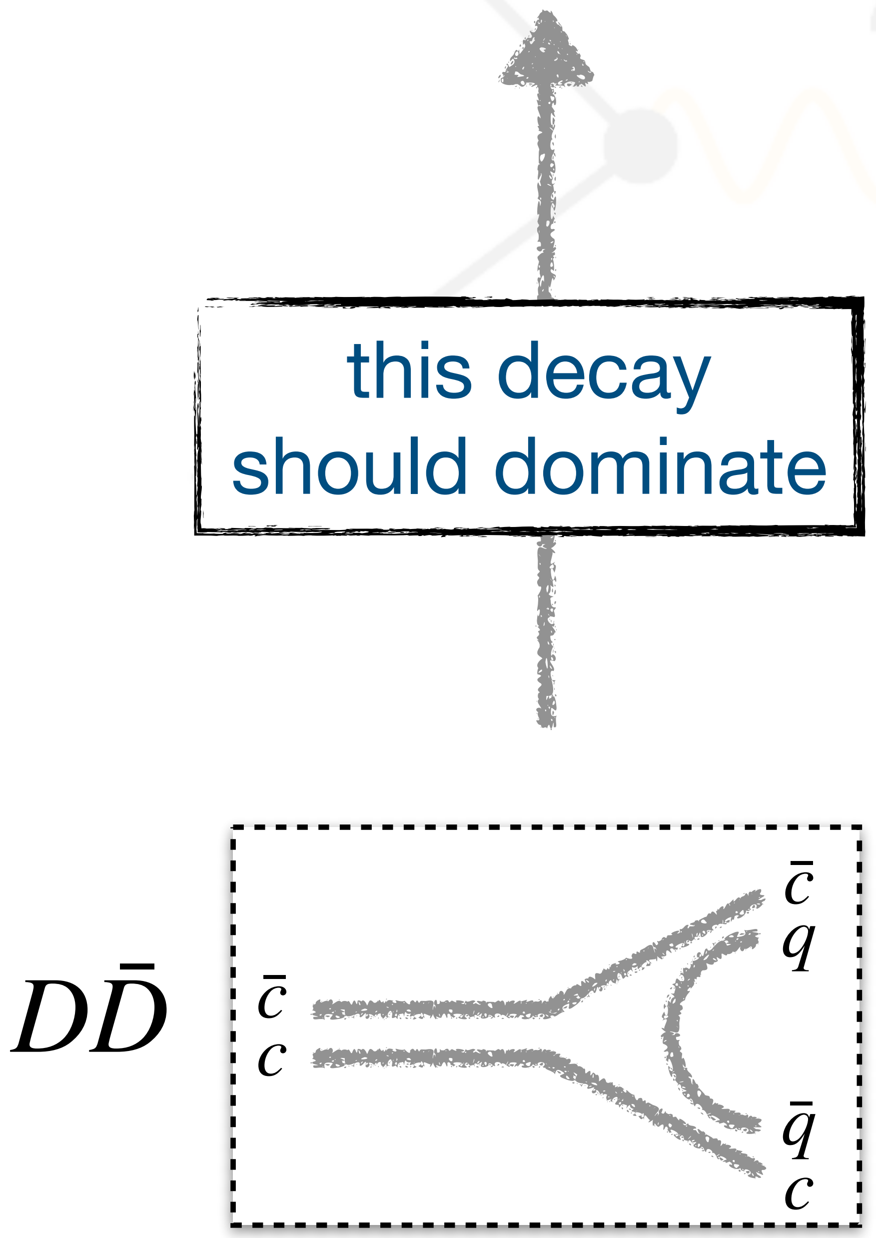
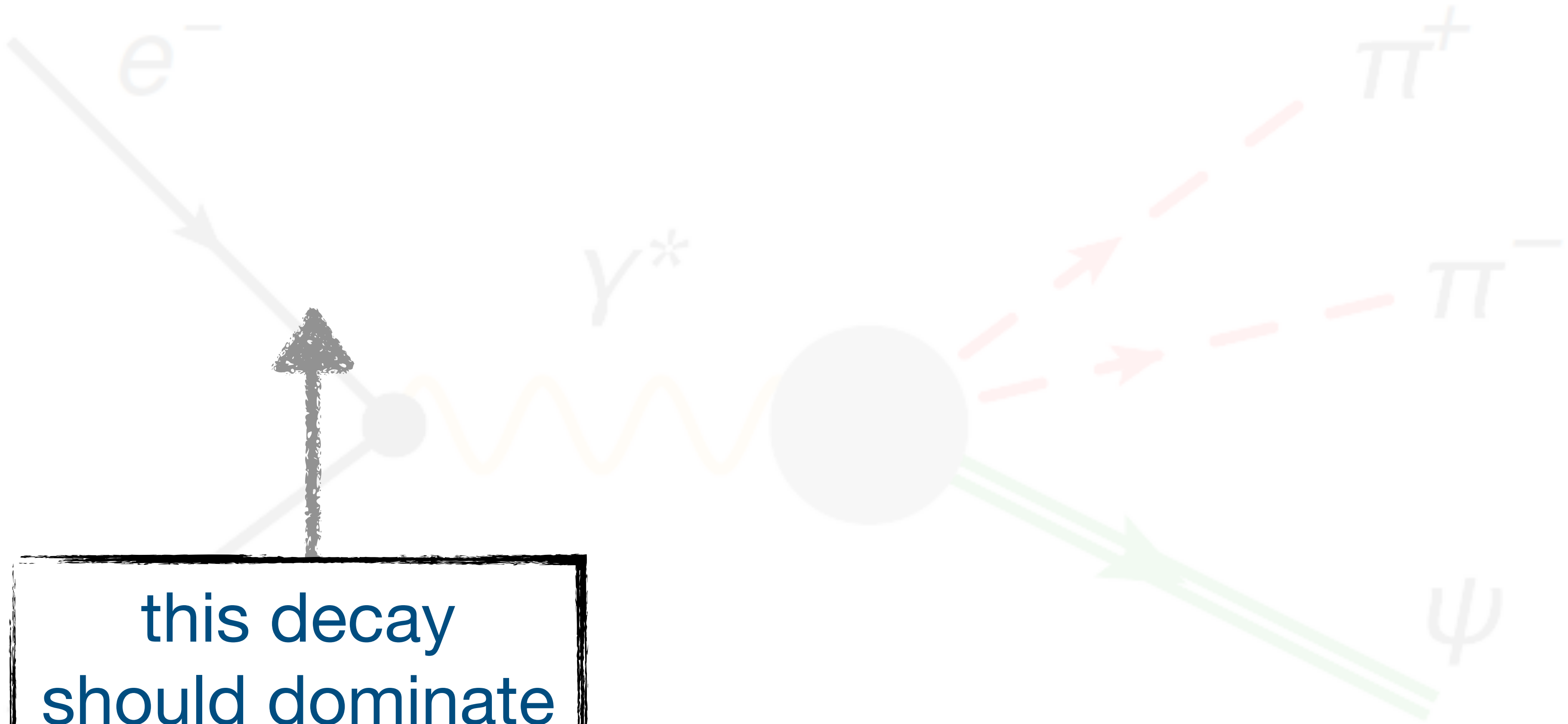
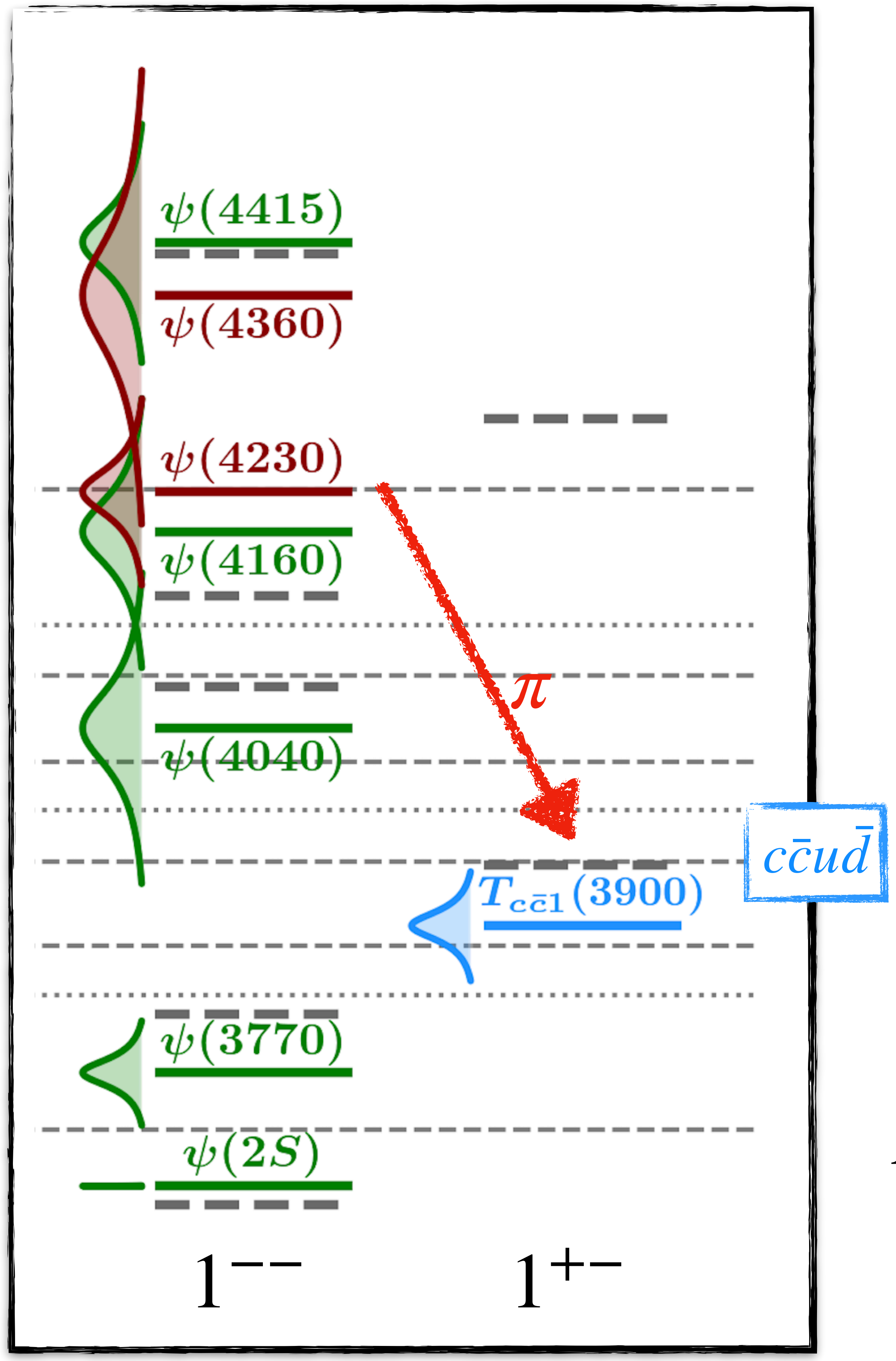
Vector charmonia



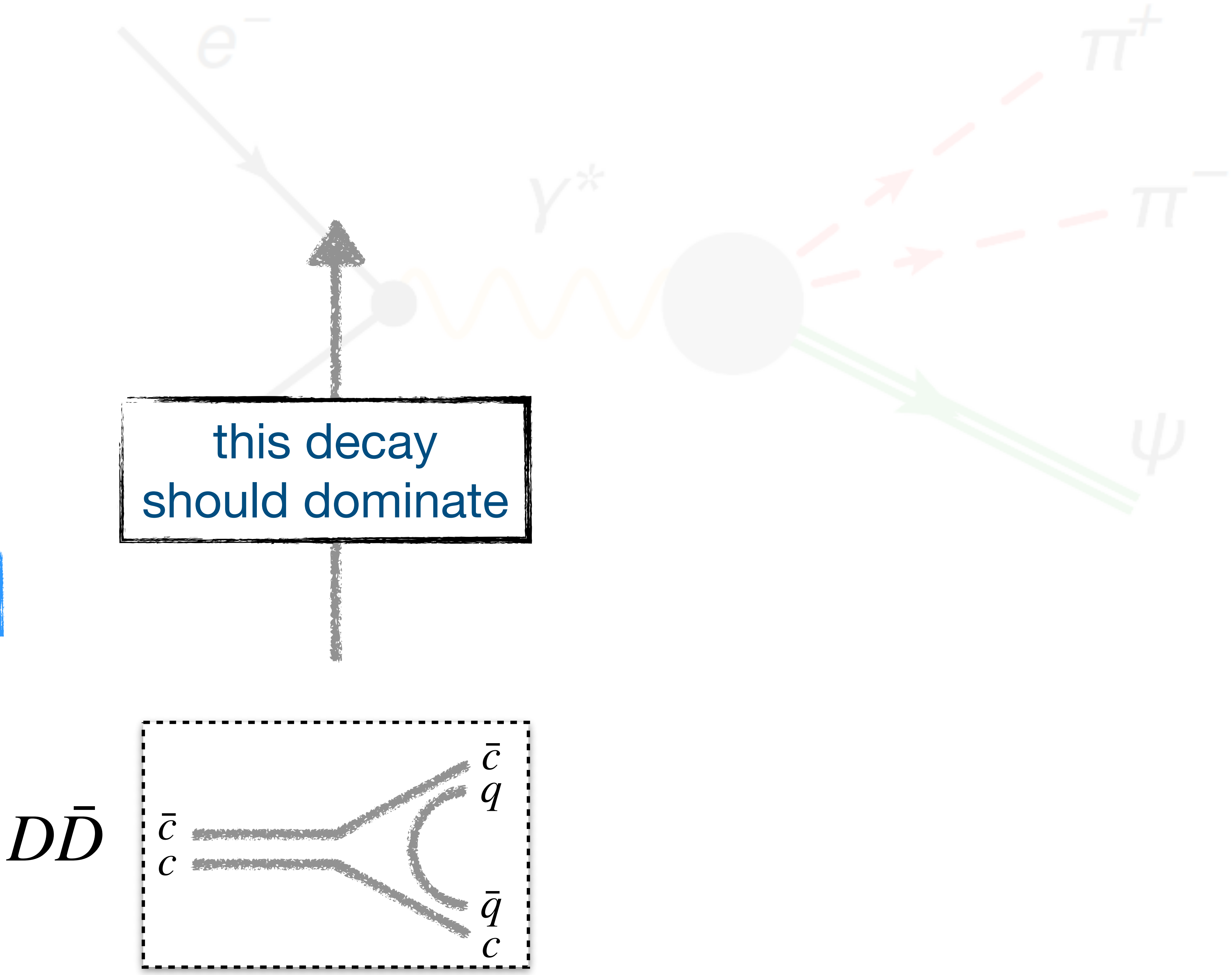


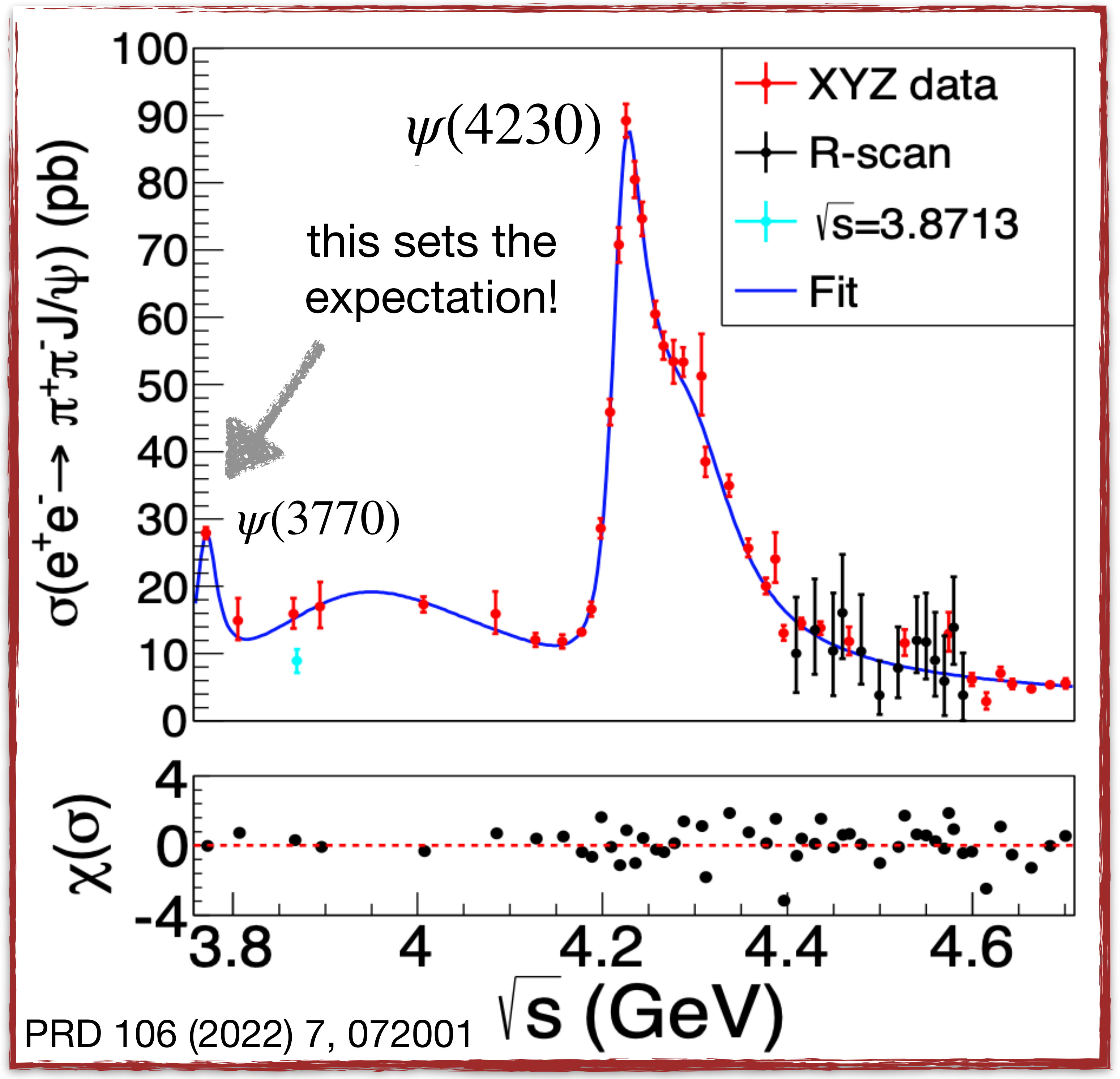


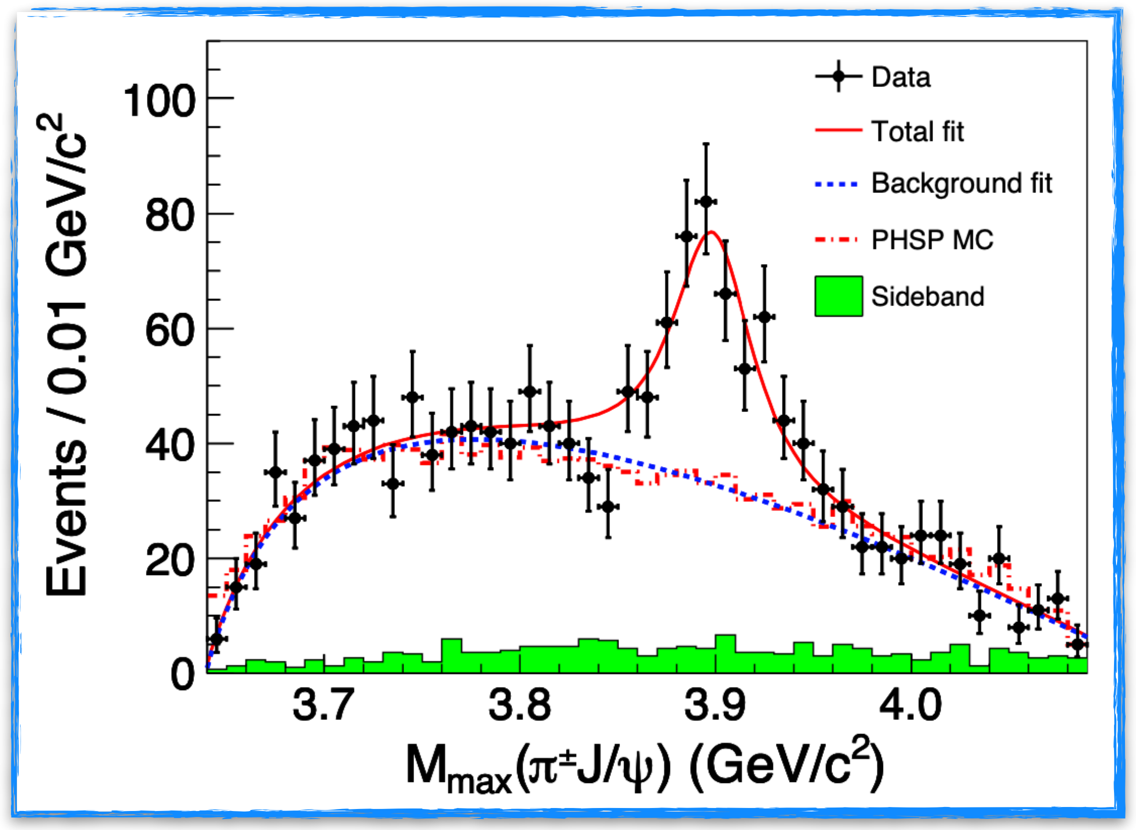
Vector charmonia



exotic candidates appear in
a different kind of process







PRL 110 (2013) 252001

Vector charmonia

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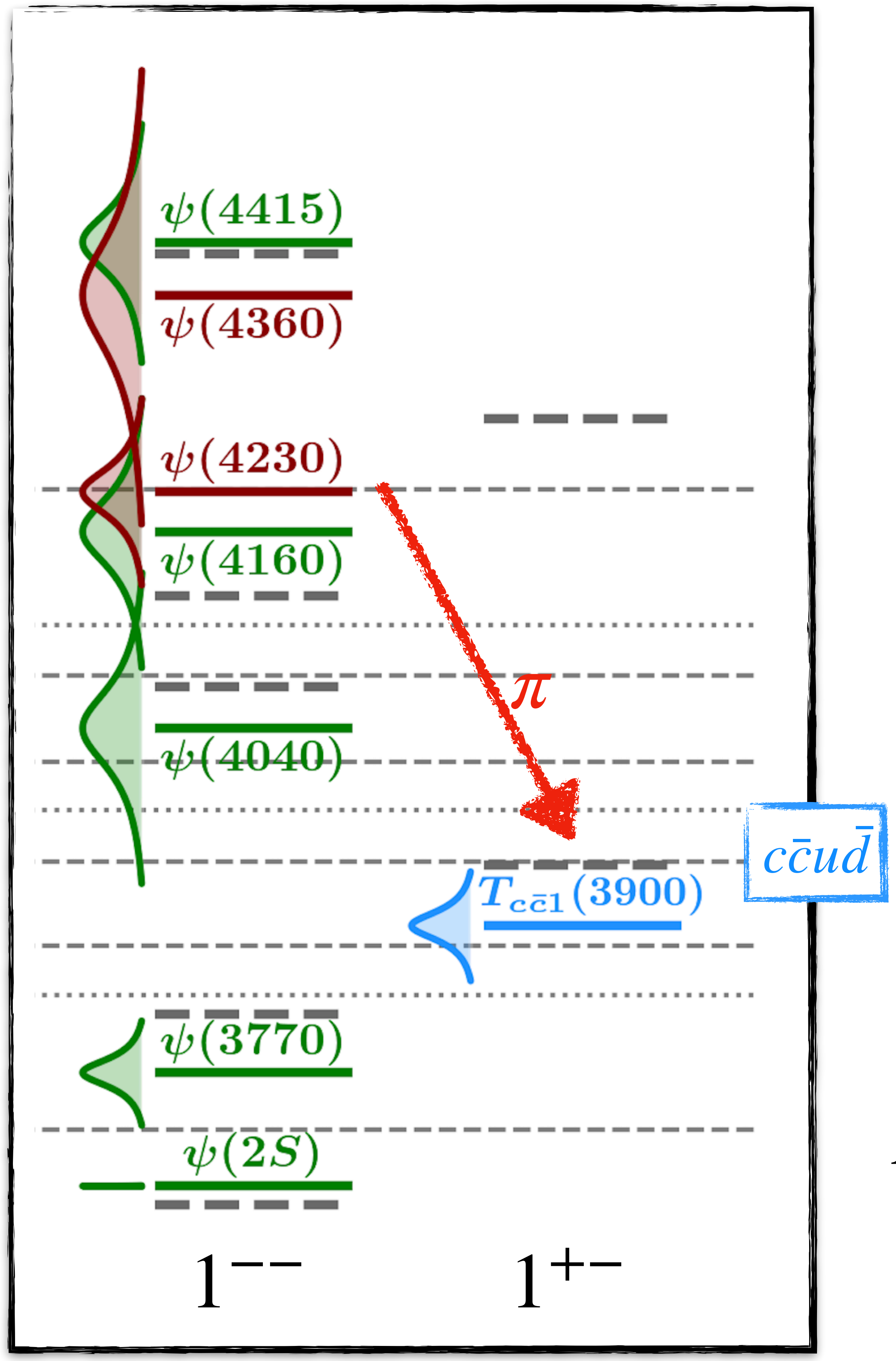
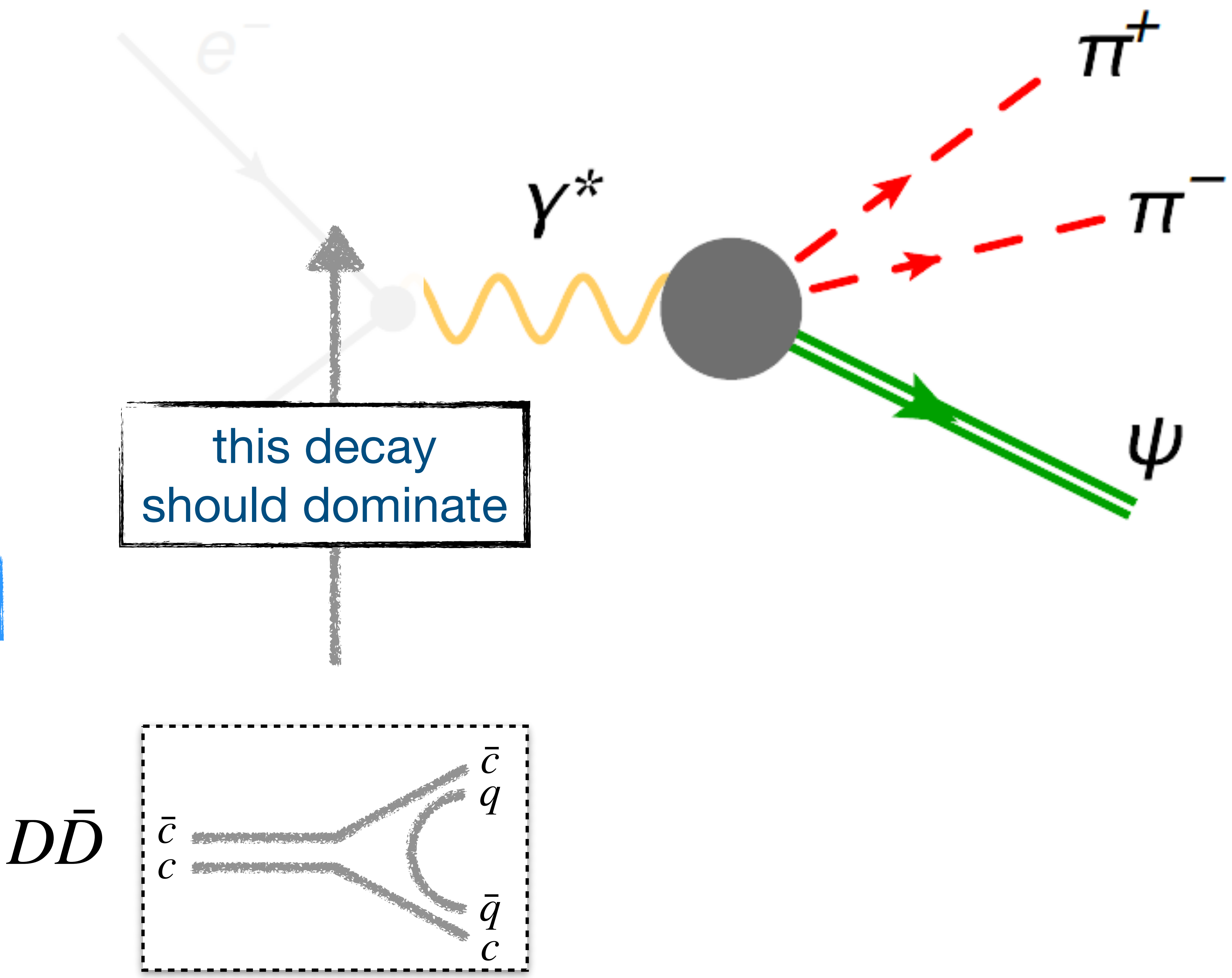
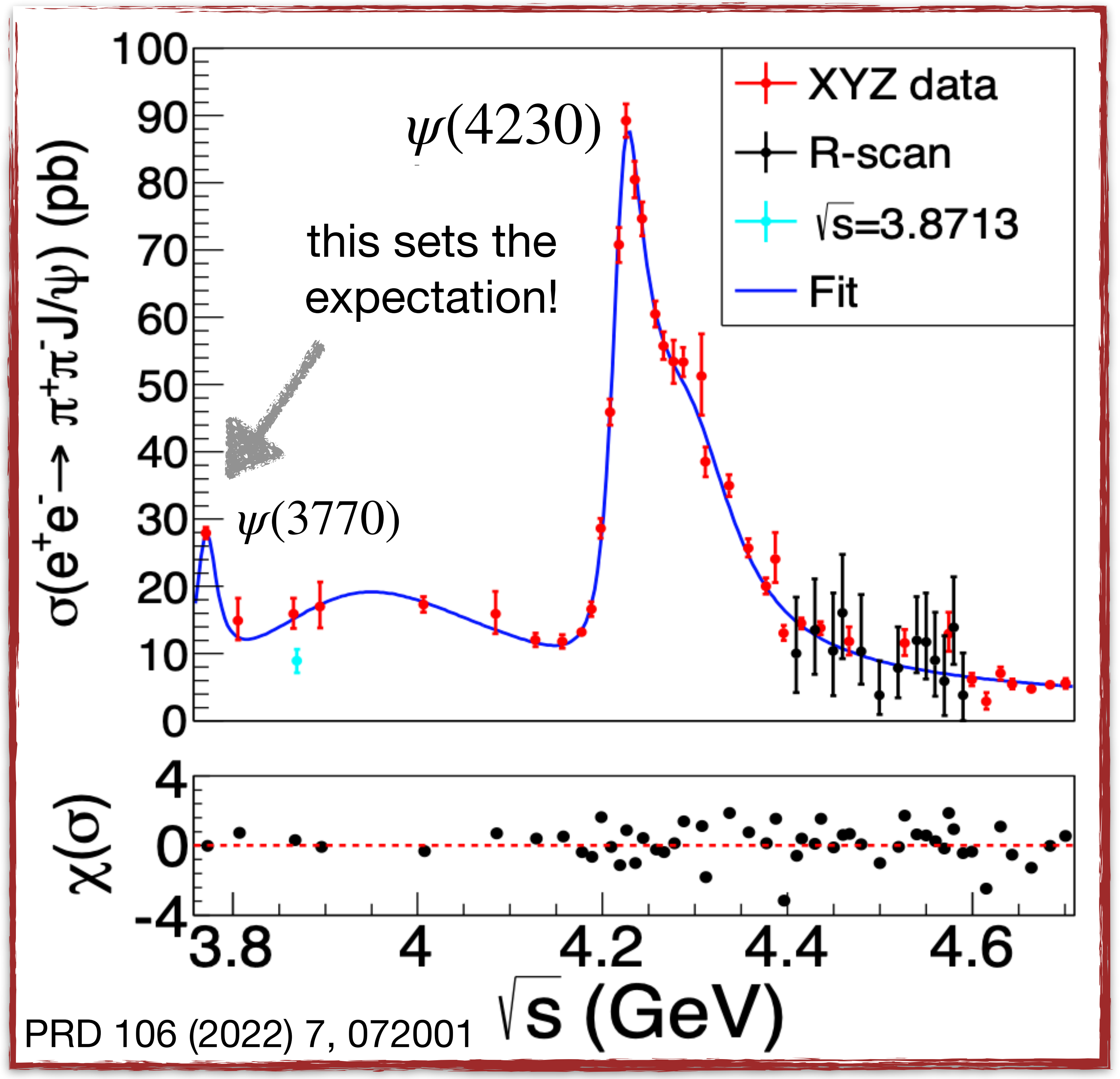
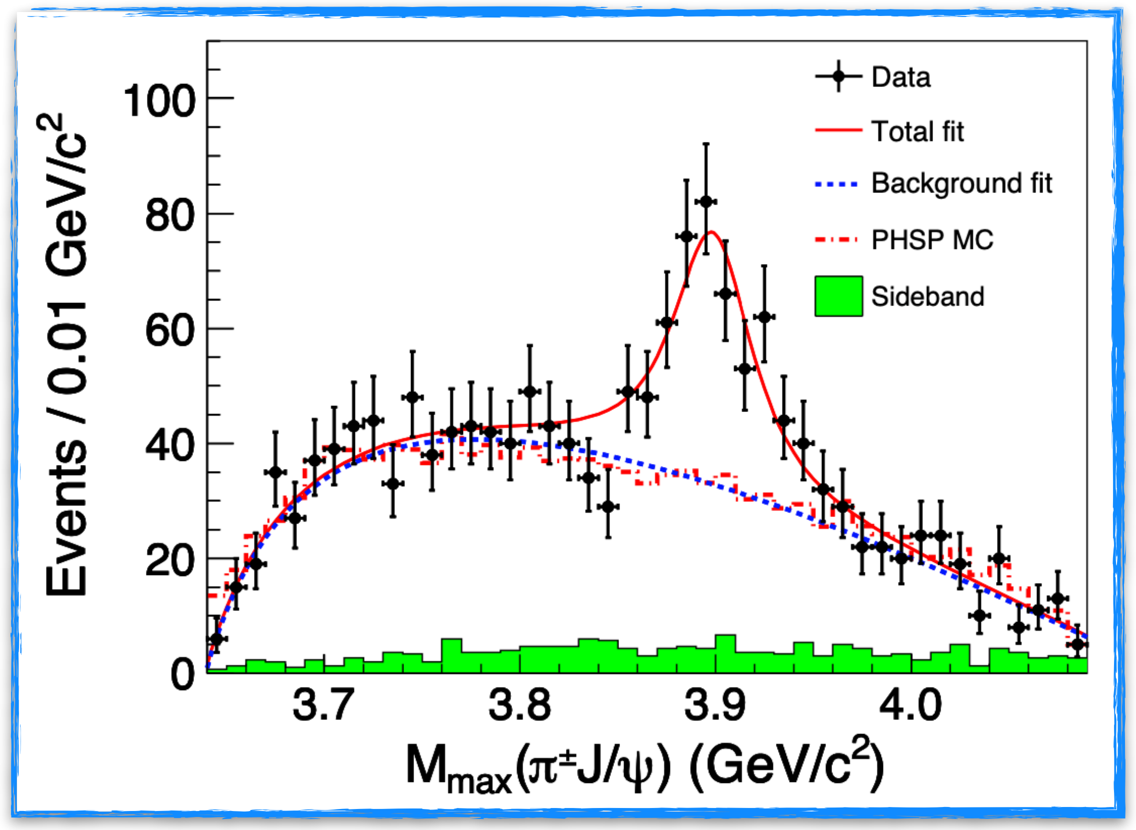




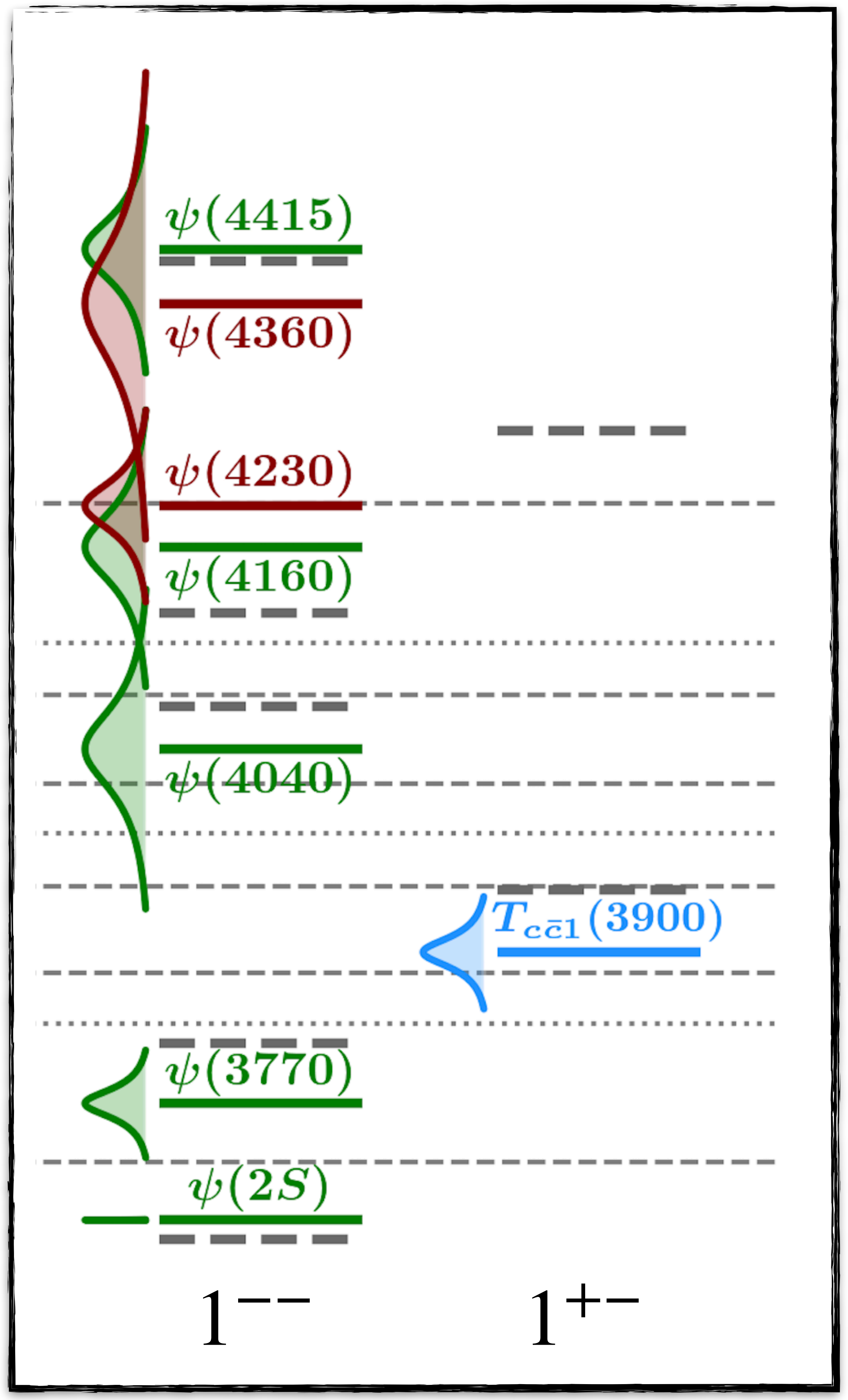


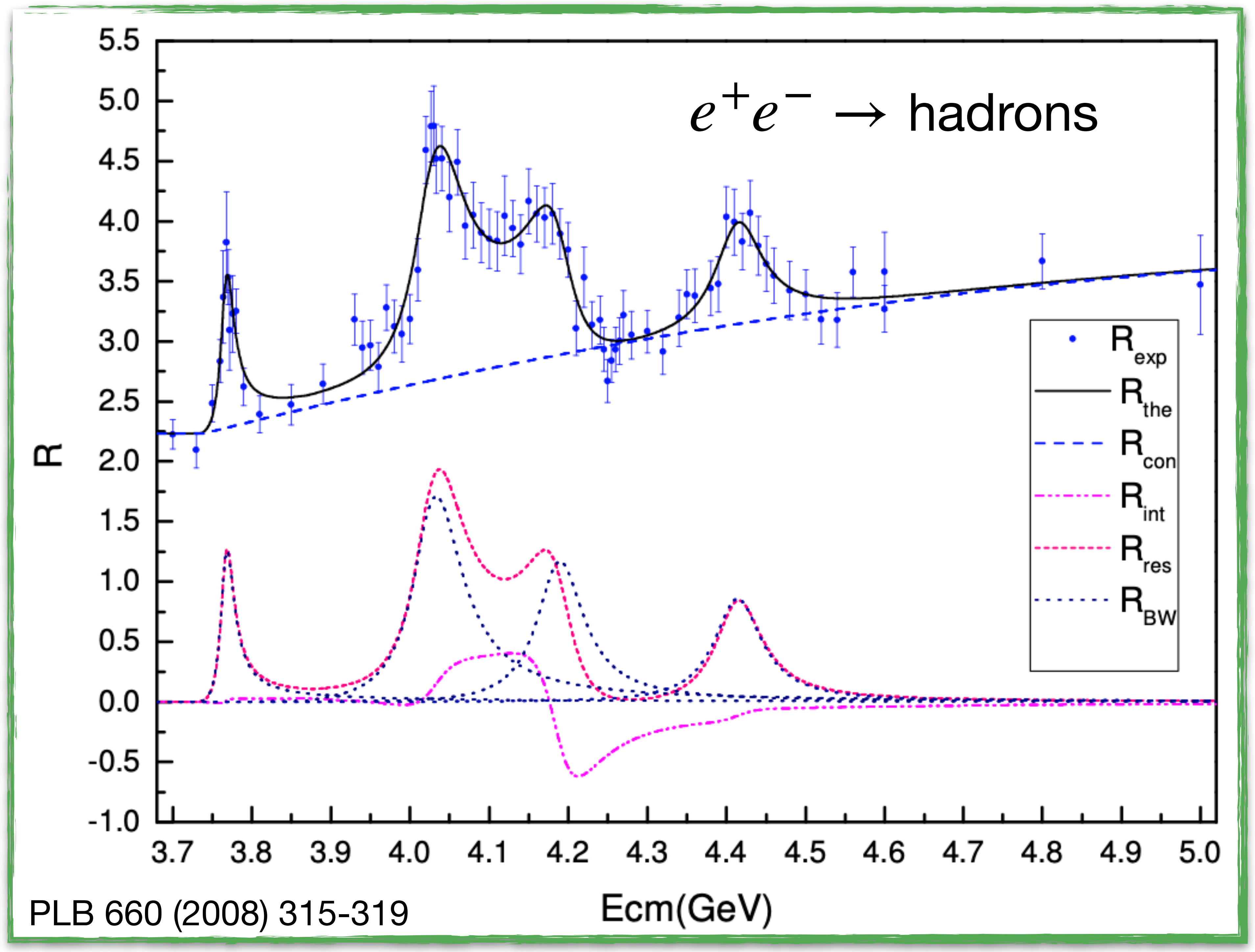


PRL 110 (2013) 252001

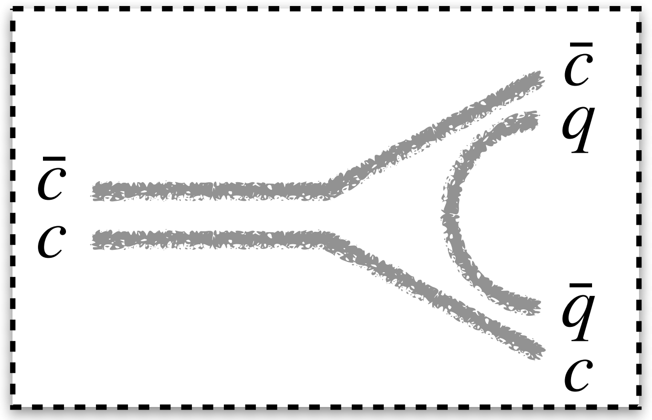
Vector charmonia

what else do we know?





$D\bar{D}$



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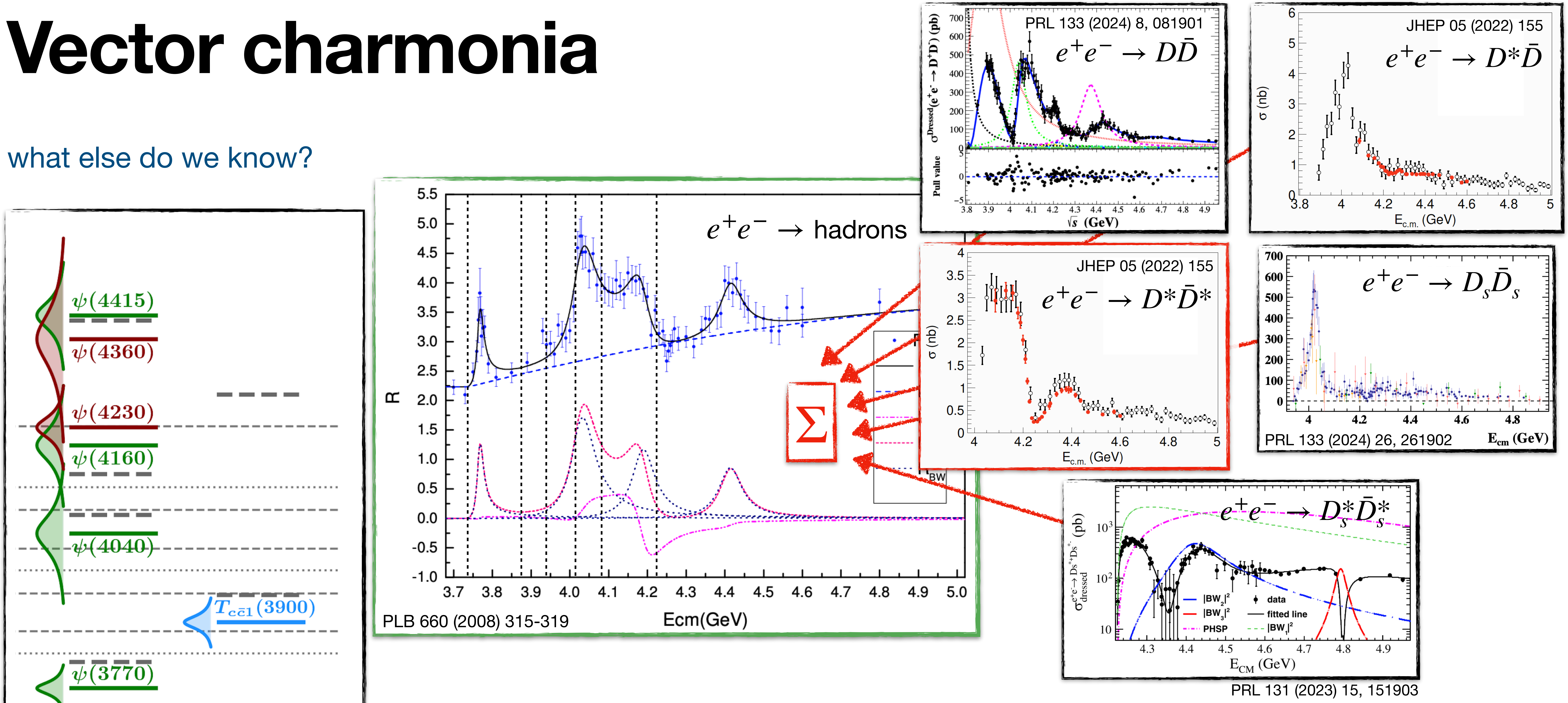

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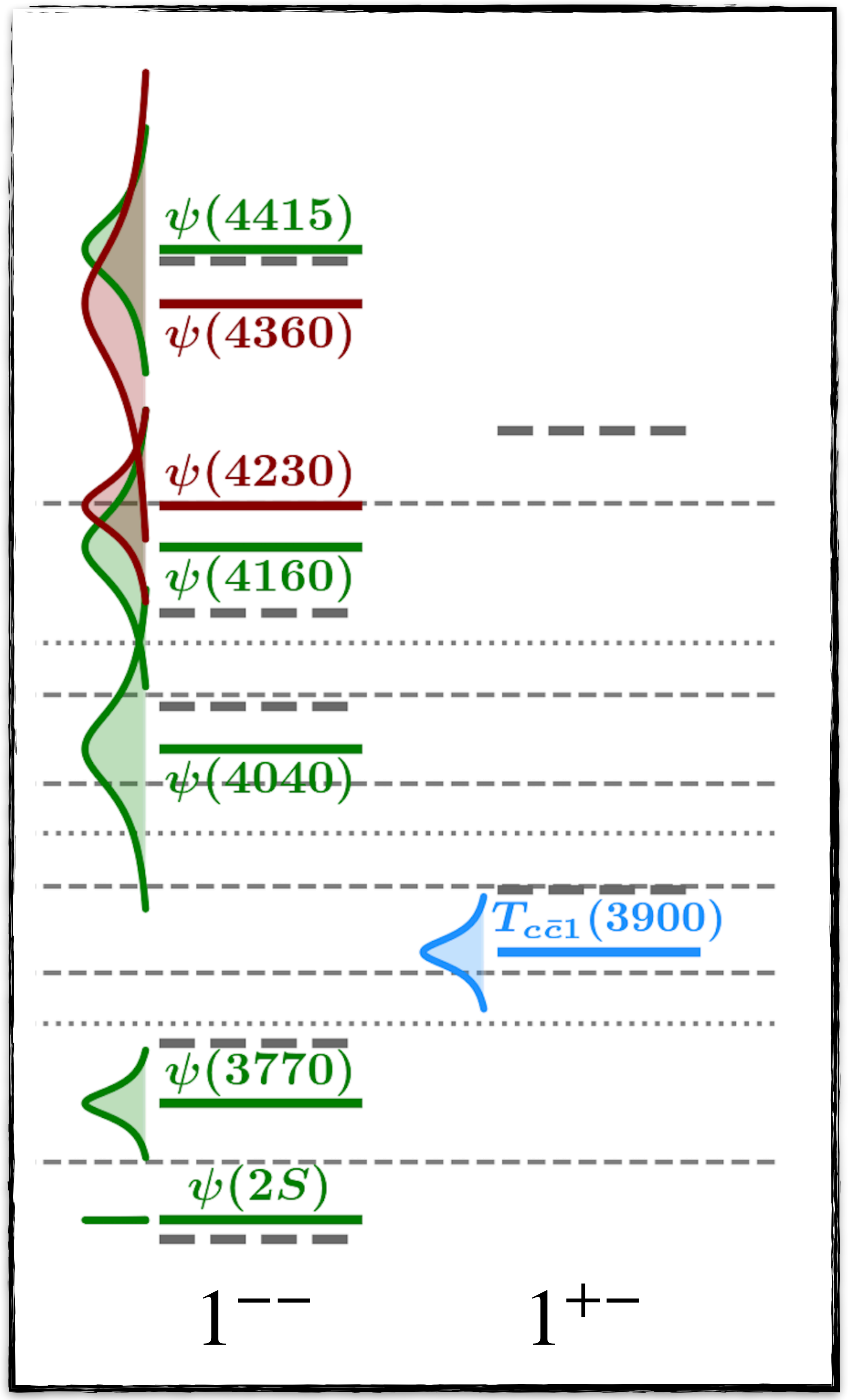
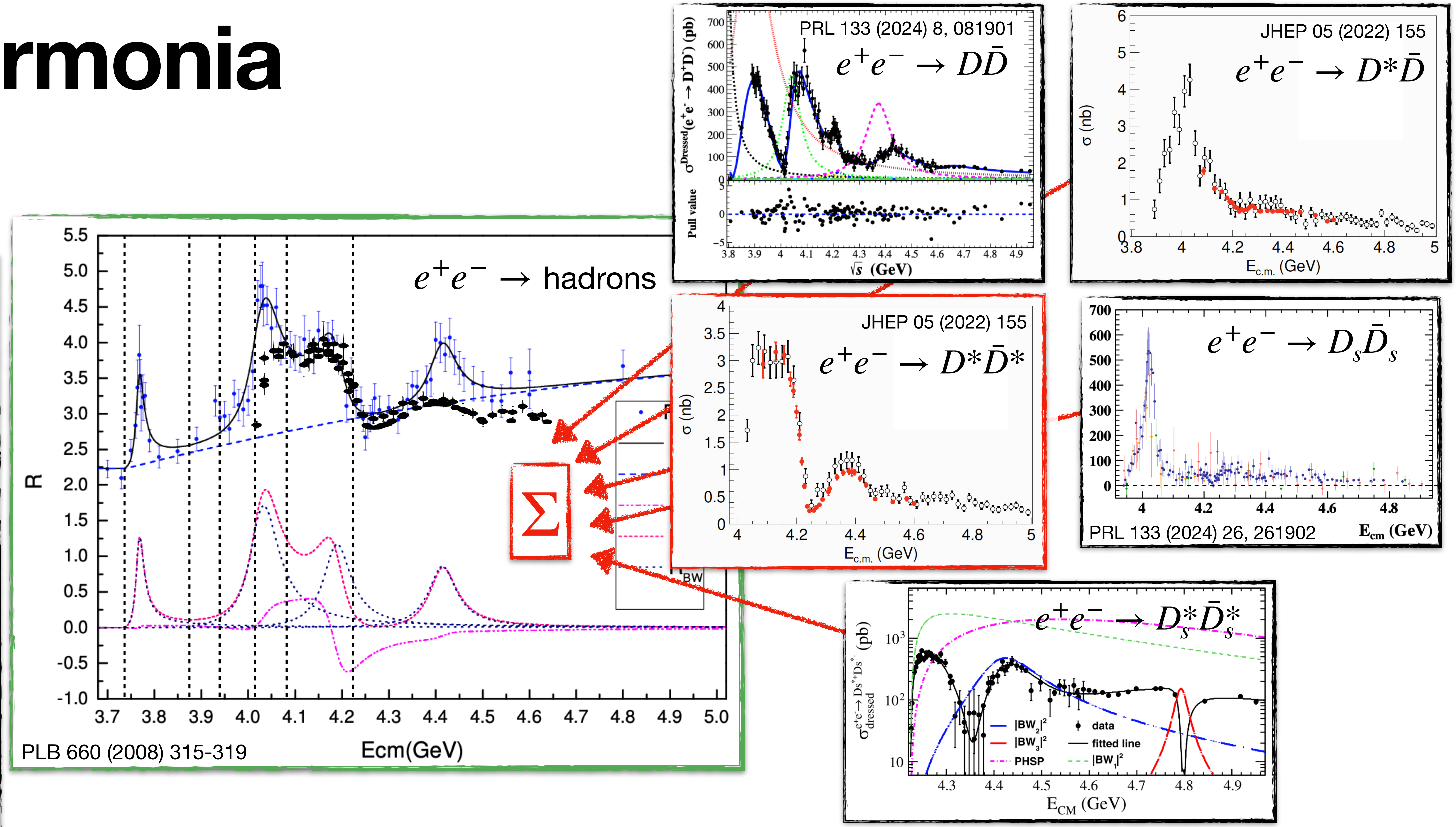




PRL 131 (2023) 15, 151903

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

How to study vector quarkonia

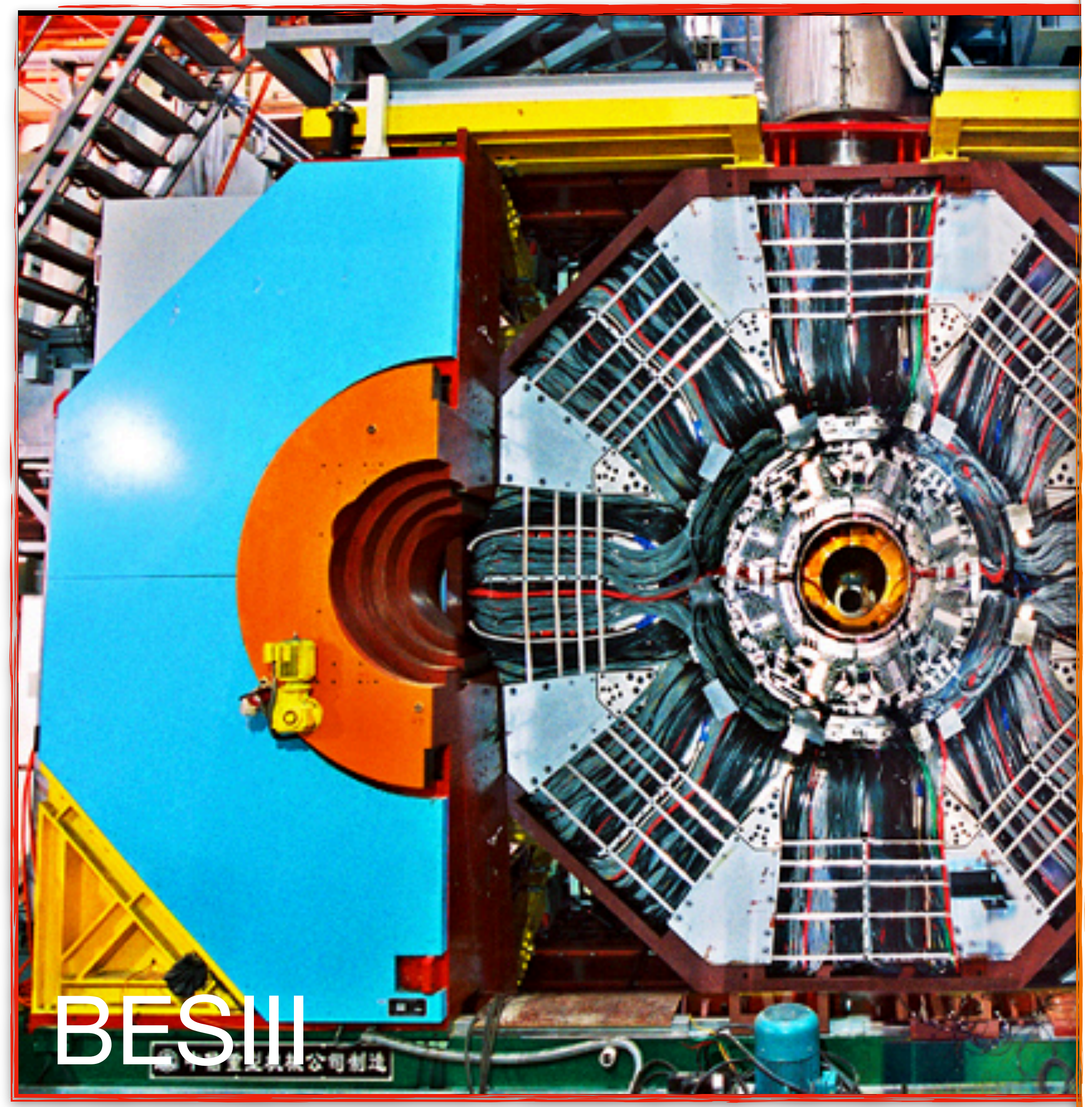
e^+e^- annihilation

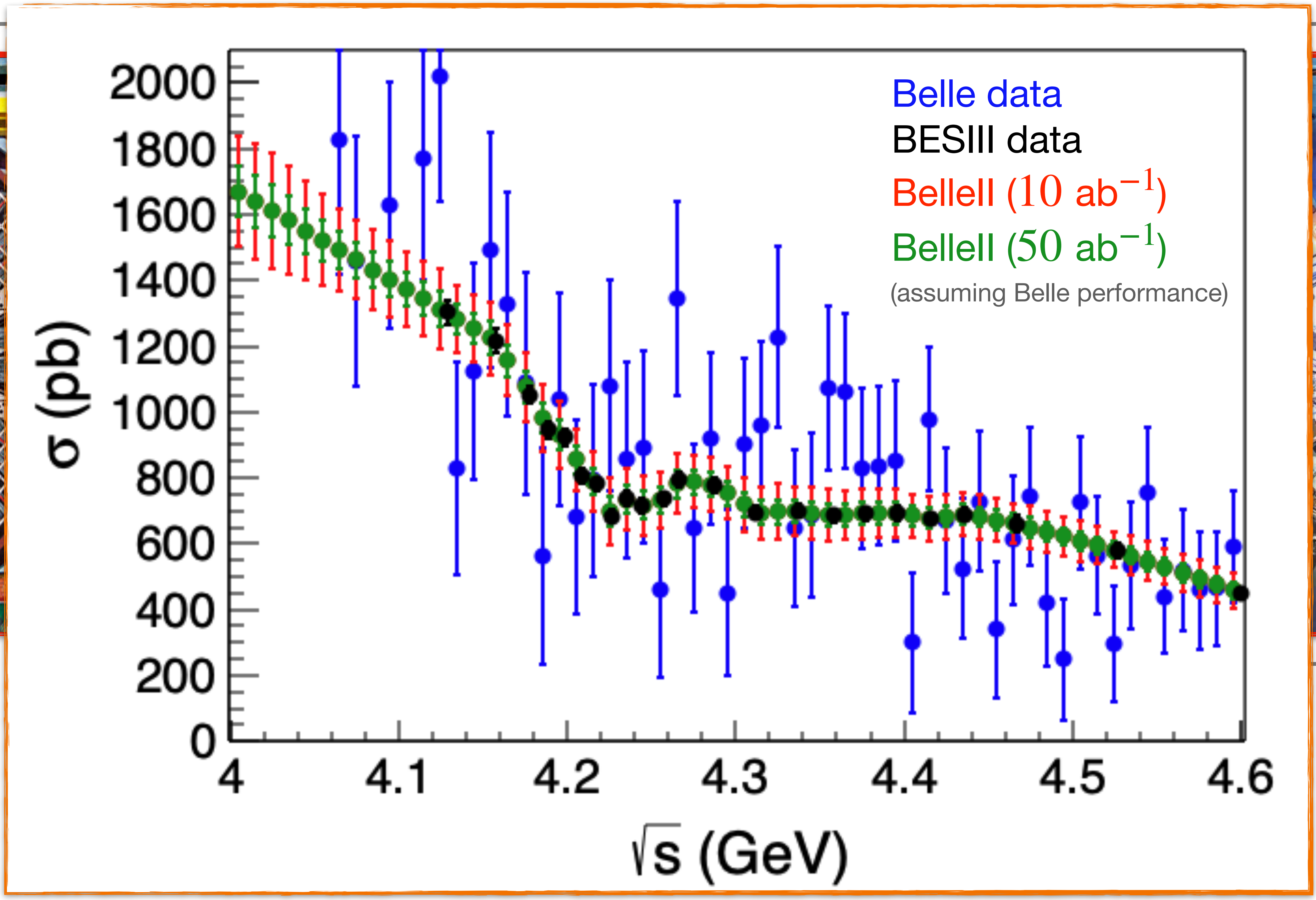
$e^+e^- \to c\bar{c}(\gamma_{ISR})$

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

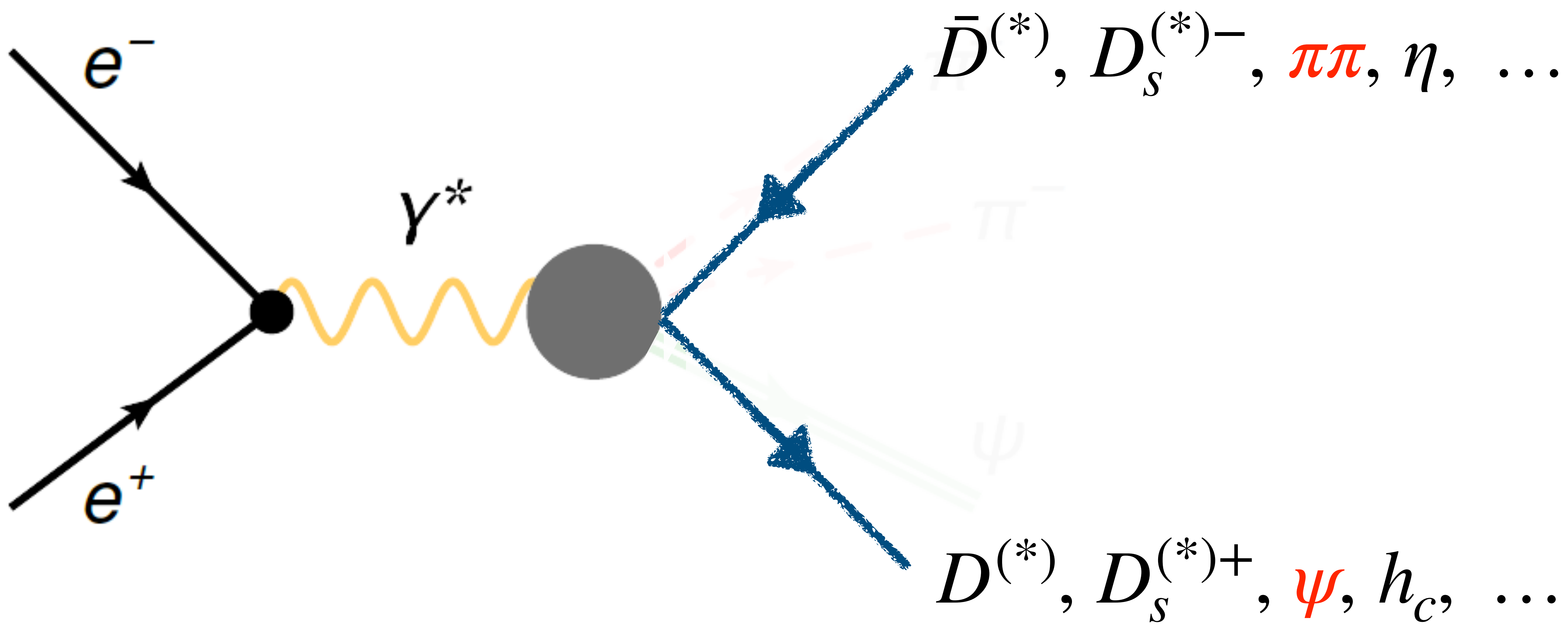
e^+e^- annihilation

$e^+e^- \rightarrow c\bar{c}(\gamma_{ISR})$





What we want to do



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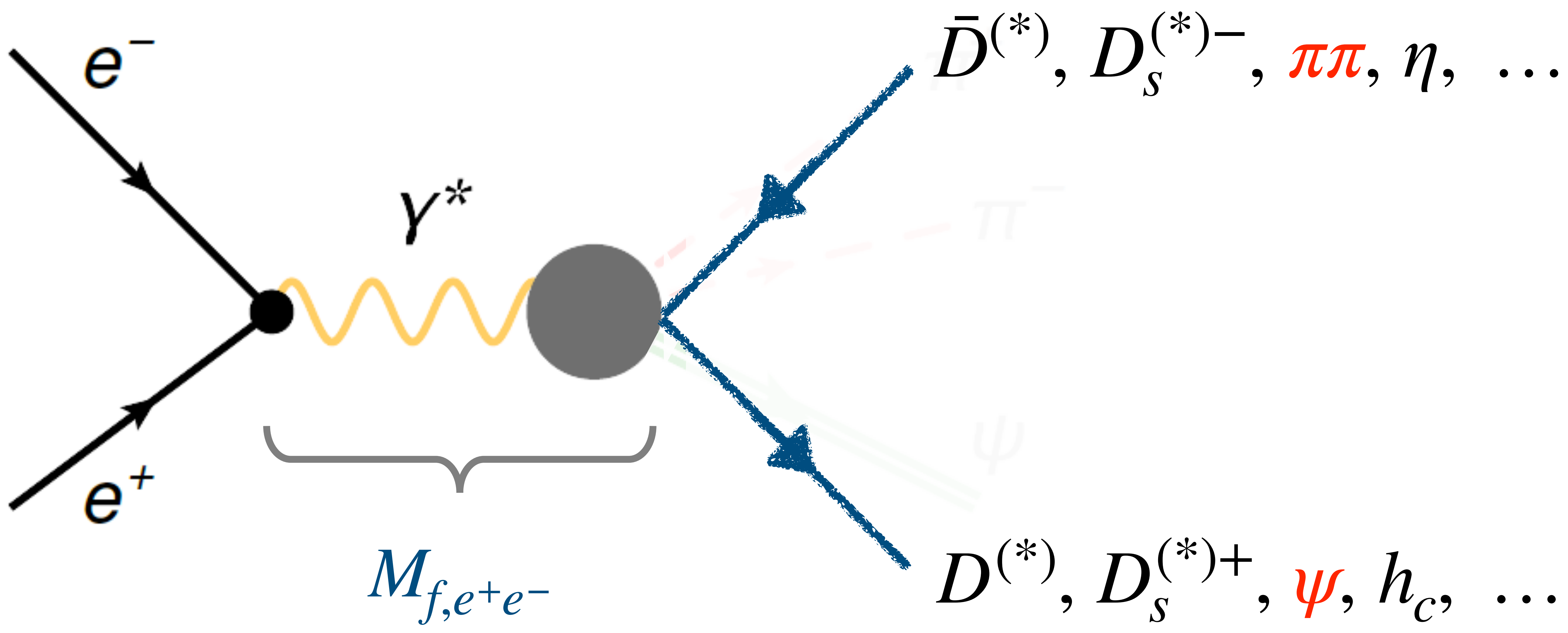

there will be a common scattering matrix connecting $i = e^+e^-$ to any of these final states

The K-matrix approach

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

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

where

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

see also talk by Meike Kuessner,
International K-matrix day: https://indico.global/event/14144/

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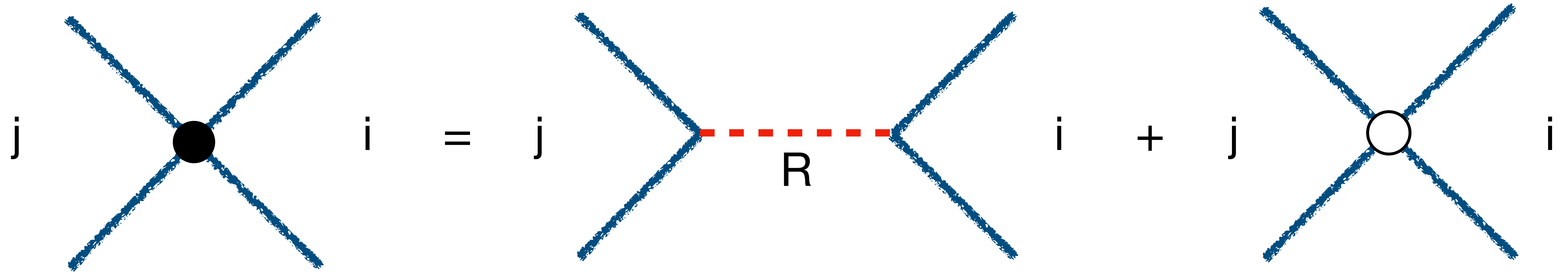

the bare interactions

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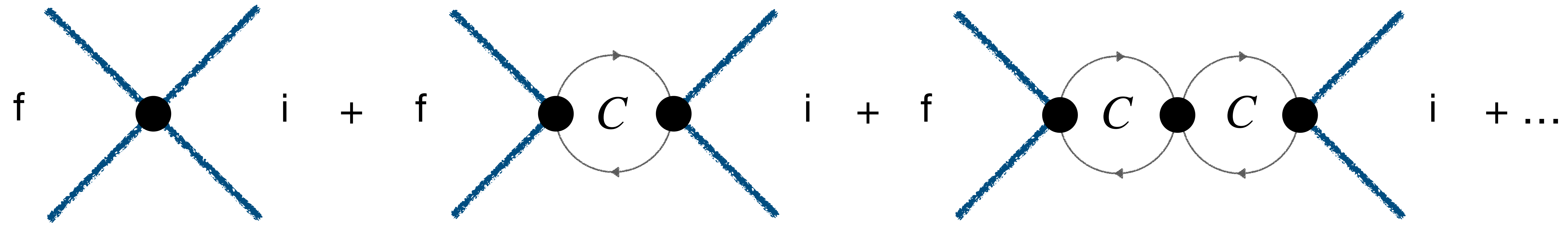

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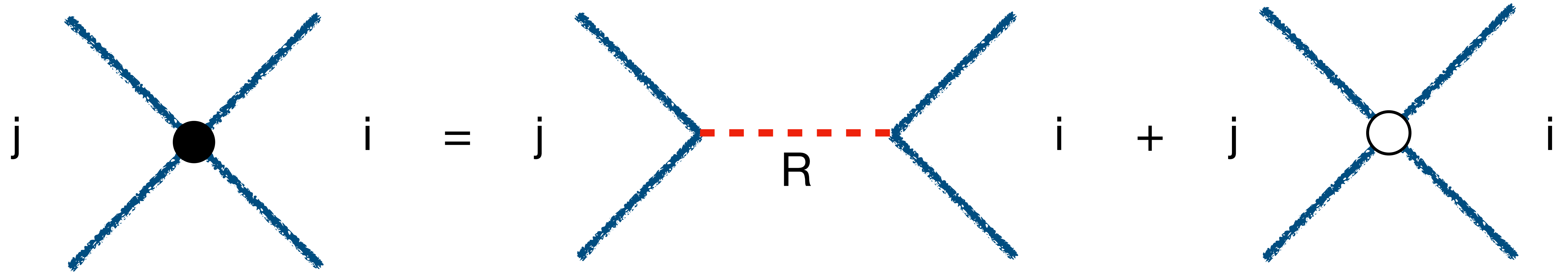

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note: these loops couple $i \to f$ scattering to $i \to j$ and $j \to f$ scattering

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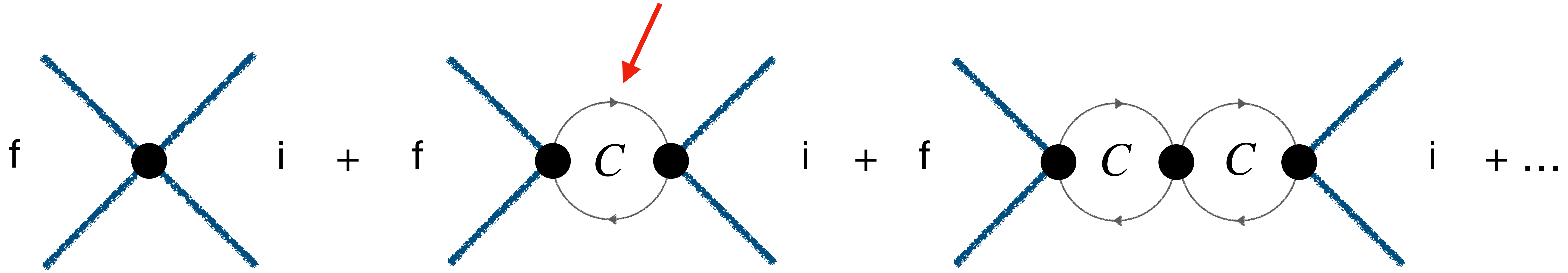

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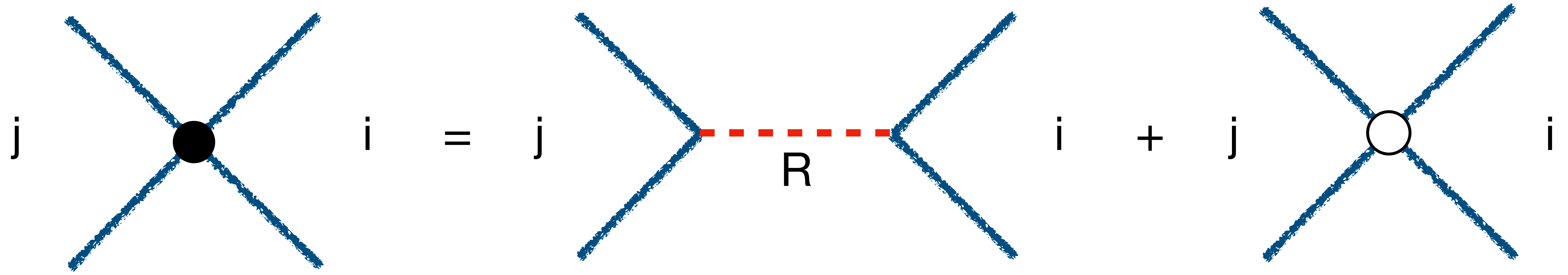

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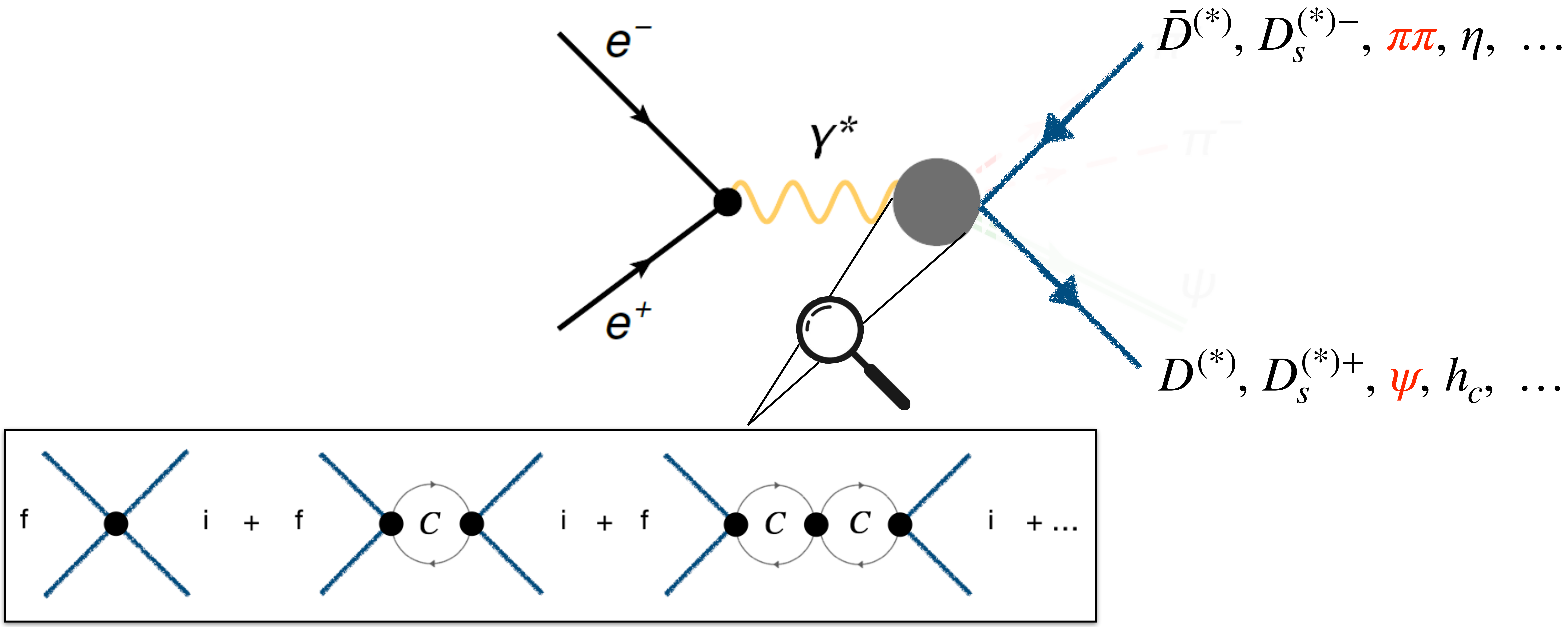
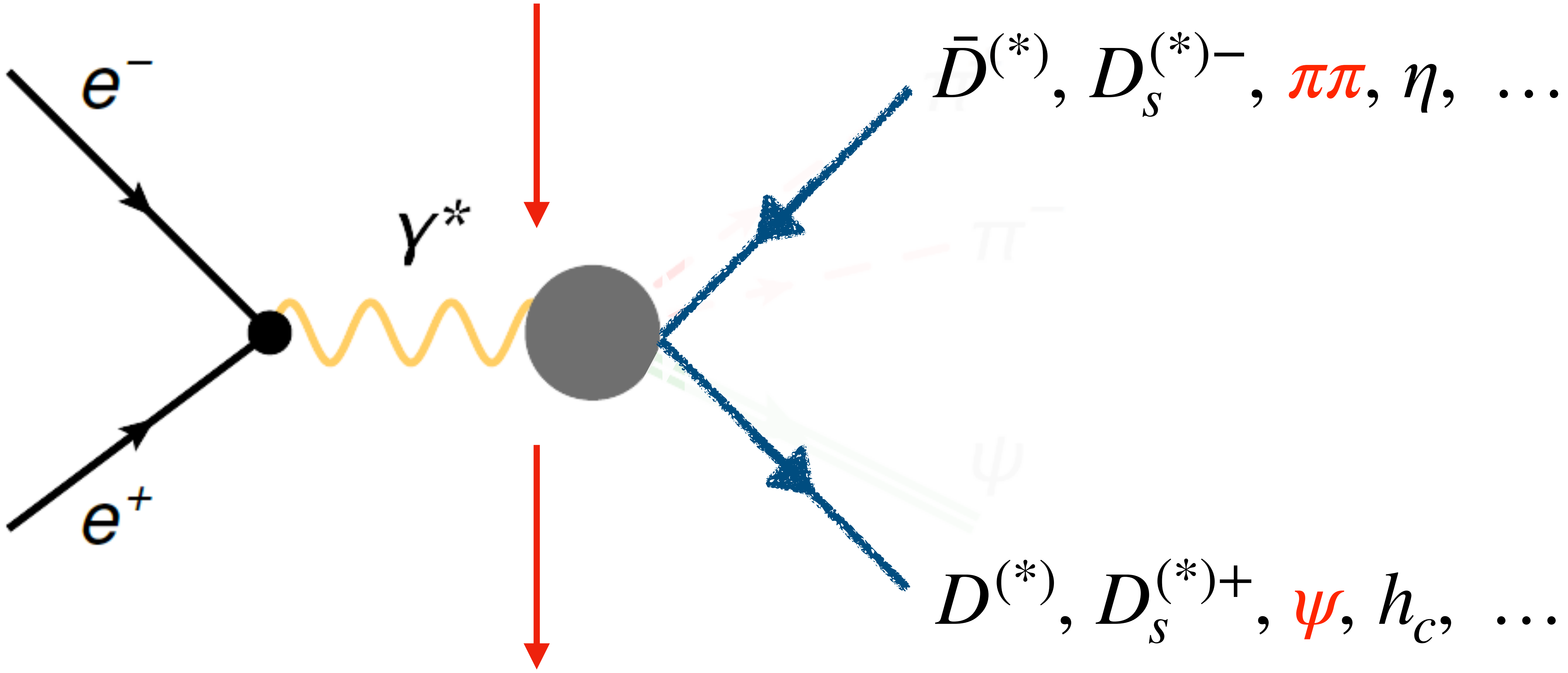


The K-matrix approach

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



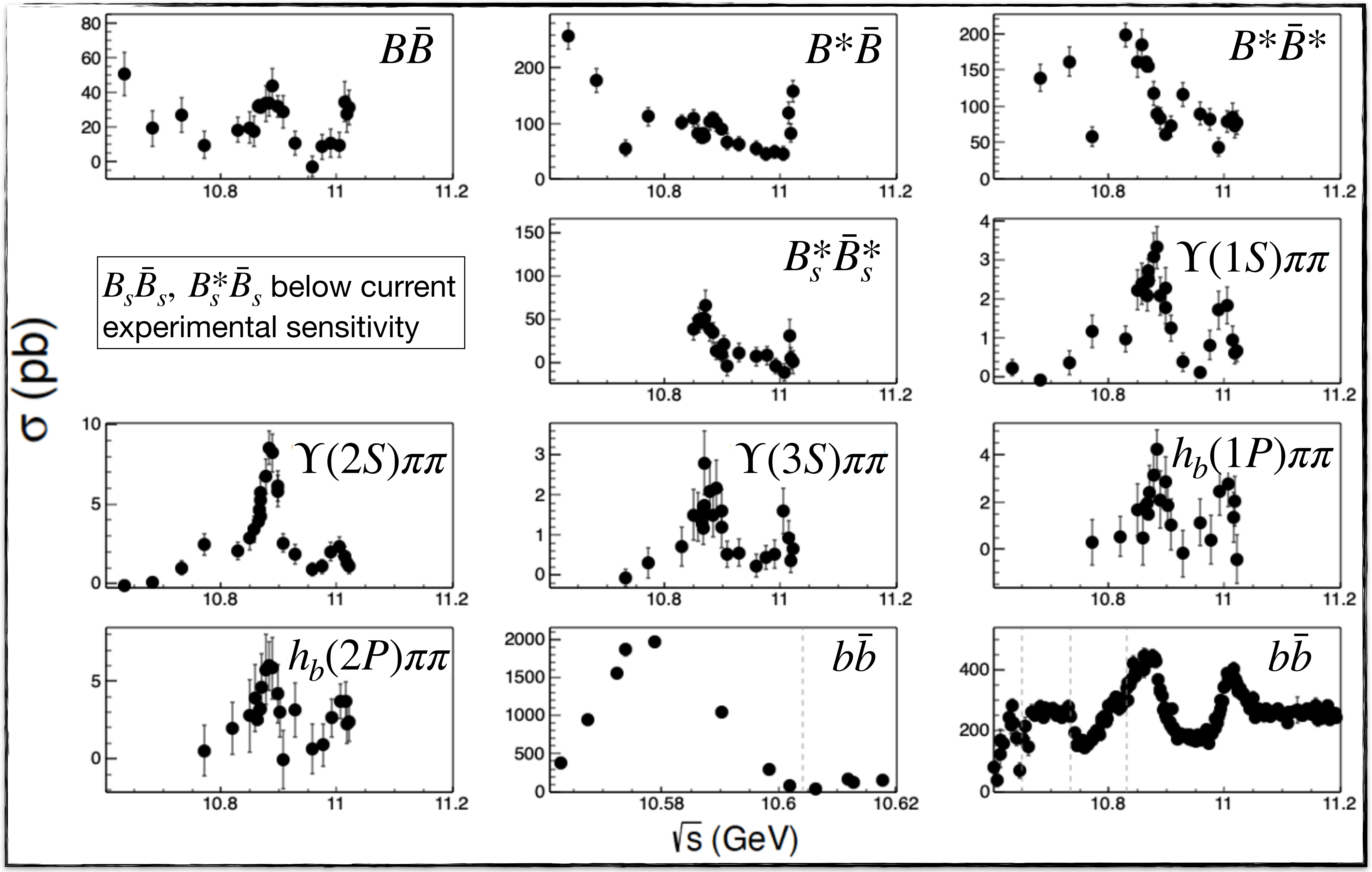
extract the physical information from poles in M

The test case: bottomonium

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

Bottomonium

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



Bottomonium

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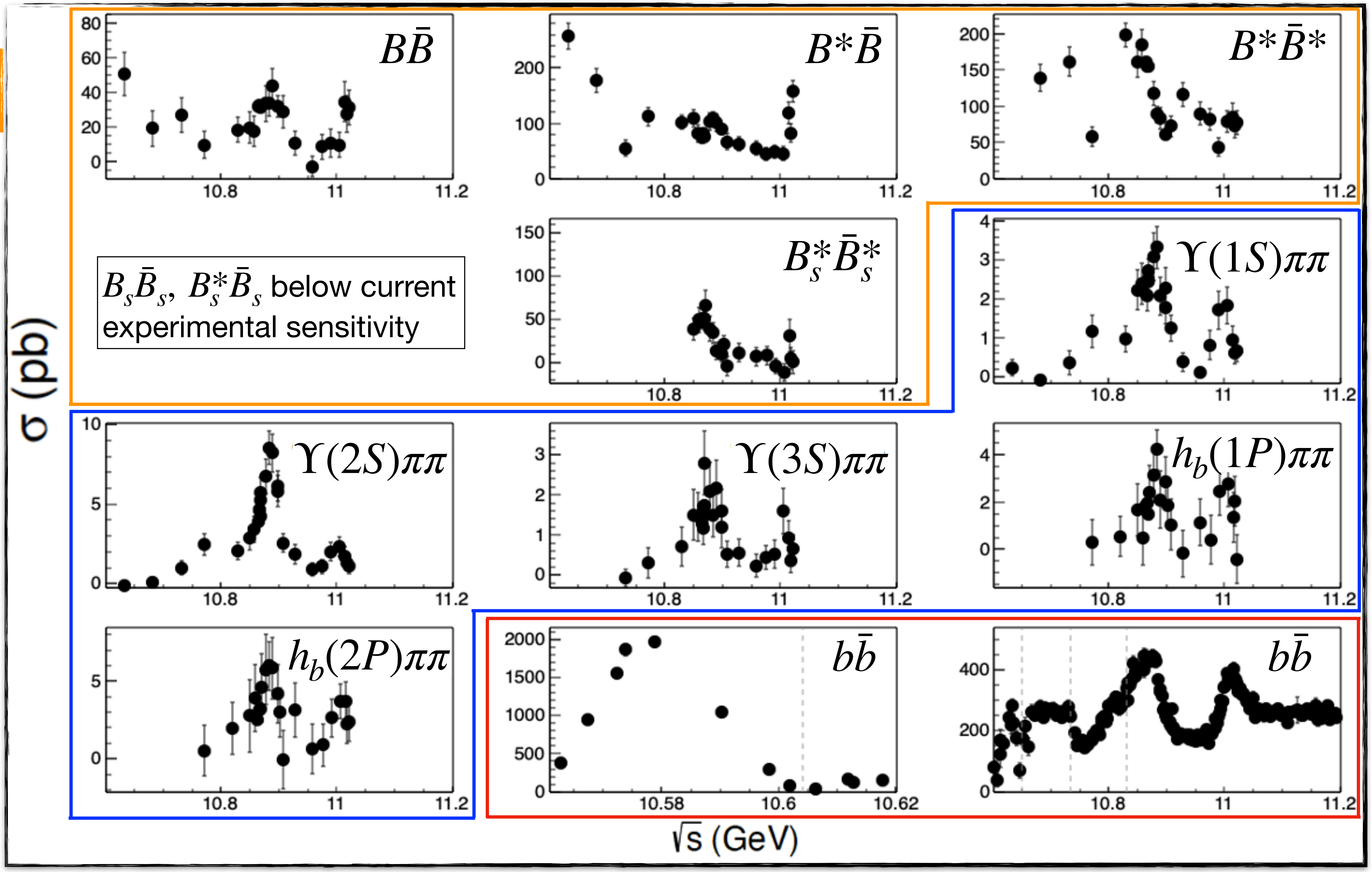
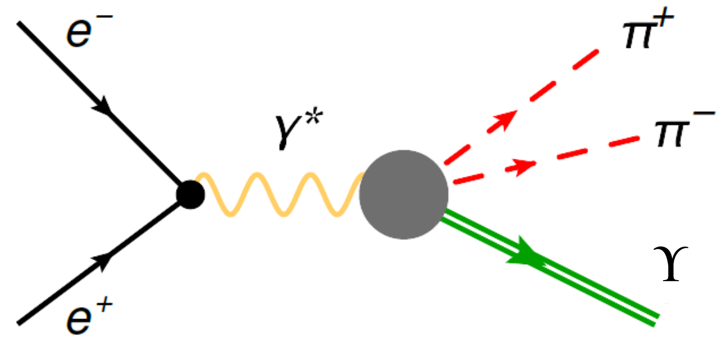
$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$ open-flavour



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



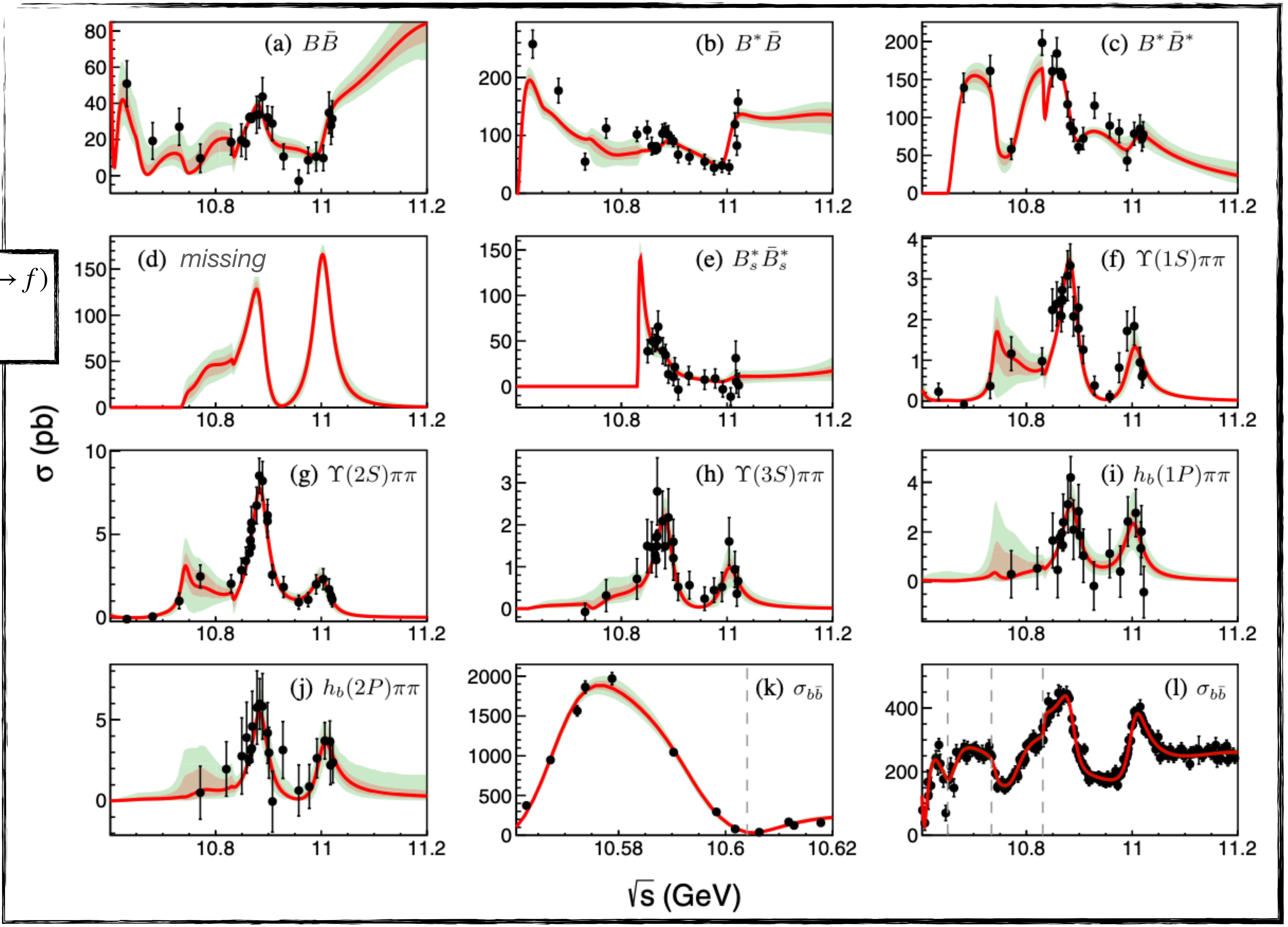
$B^{(*)}\bar{B}^{(*)}\pi$ multi-body not measured

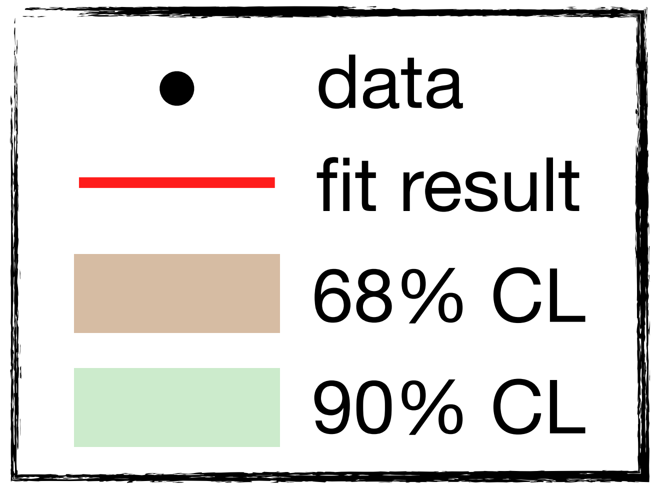
$e^+e^- \rightarrow b\bar{b}$: inclusive ($\sum$ of all)

Bottomonium

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

unmeasured processes





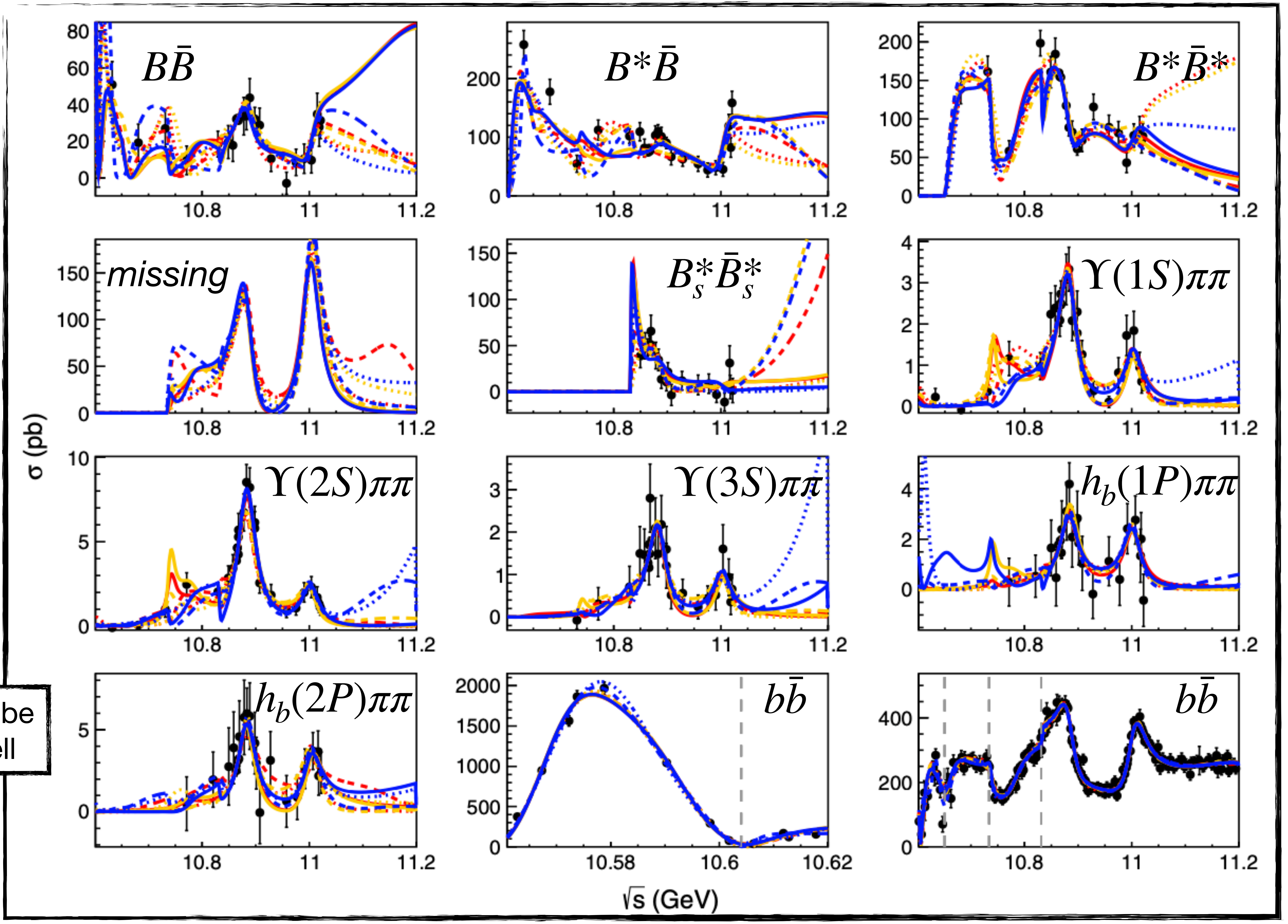
unitarity:

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

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

Bottomonium

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



all models describe data equally well

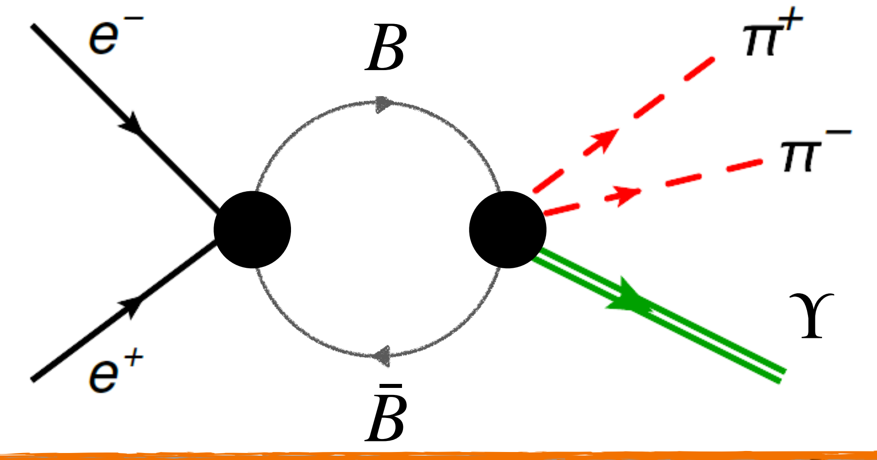
Bottomonium

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

naive expectation:
suppression of $e^+e^- \to \Upsilon\pi\pi$

blue and yellow lines:
disable bare $e^+e^- \to \Upsilon\pi\pi$ coupling

leaves only:



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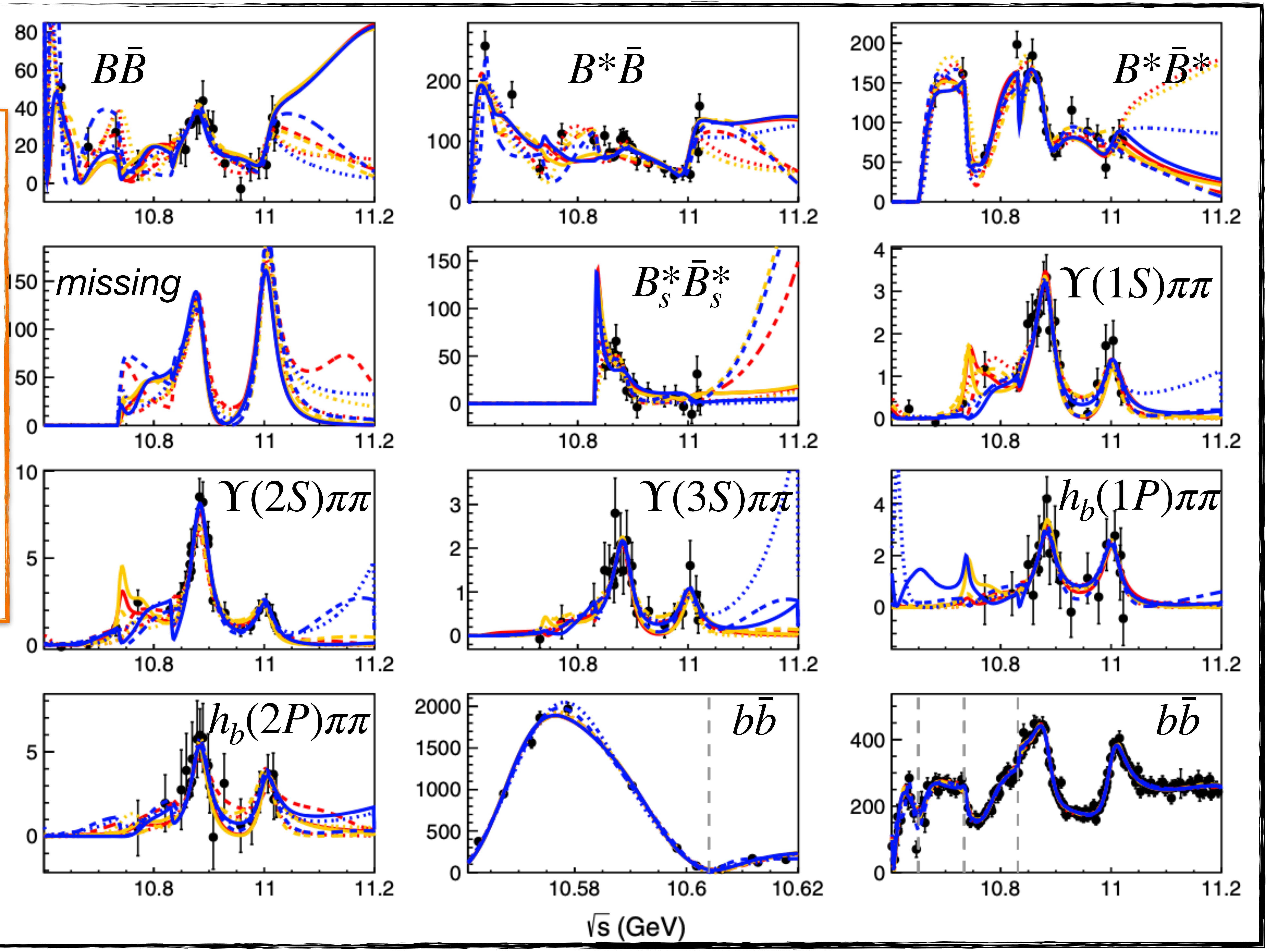
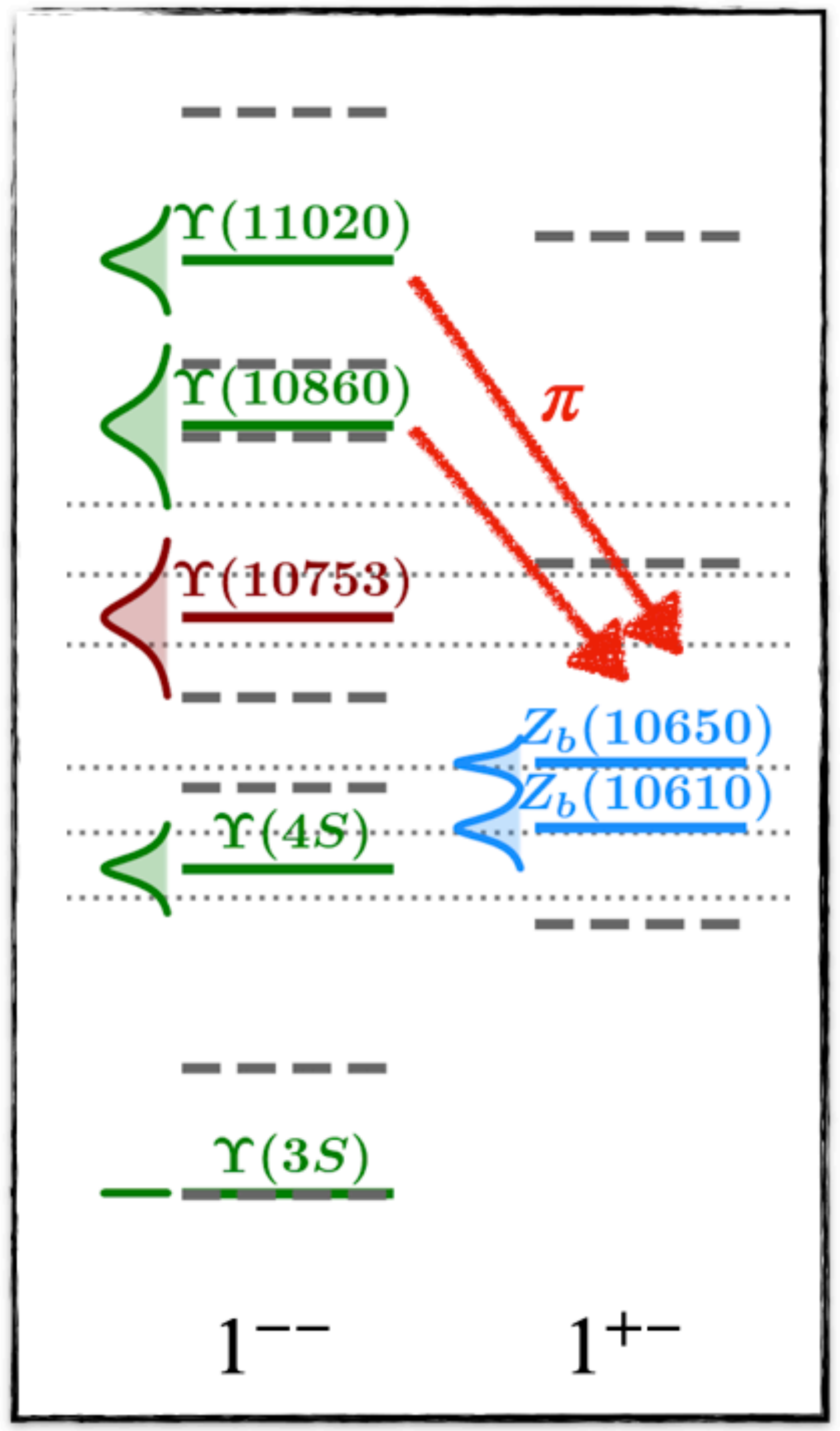
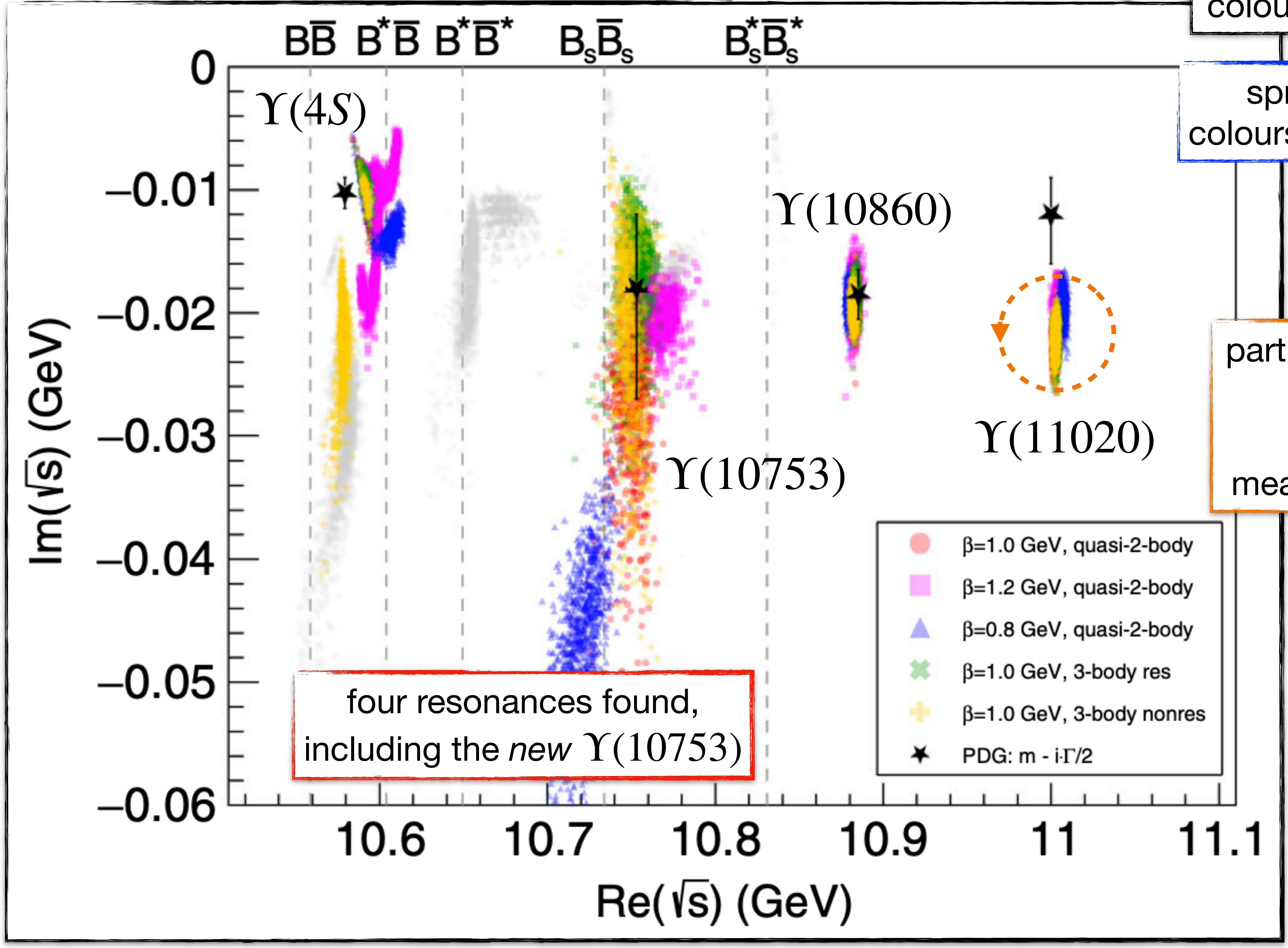


The resonances

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

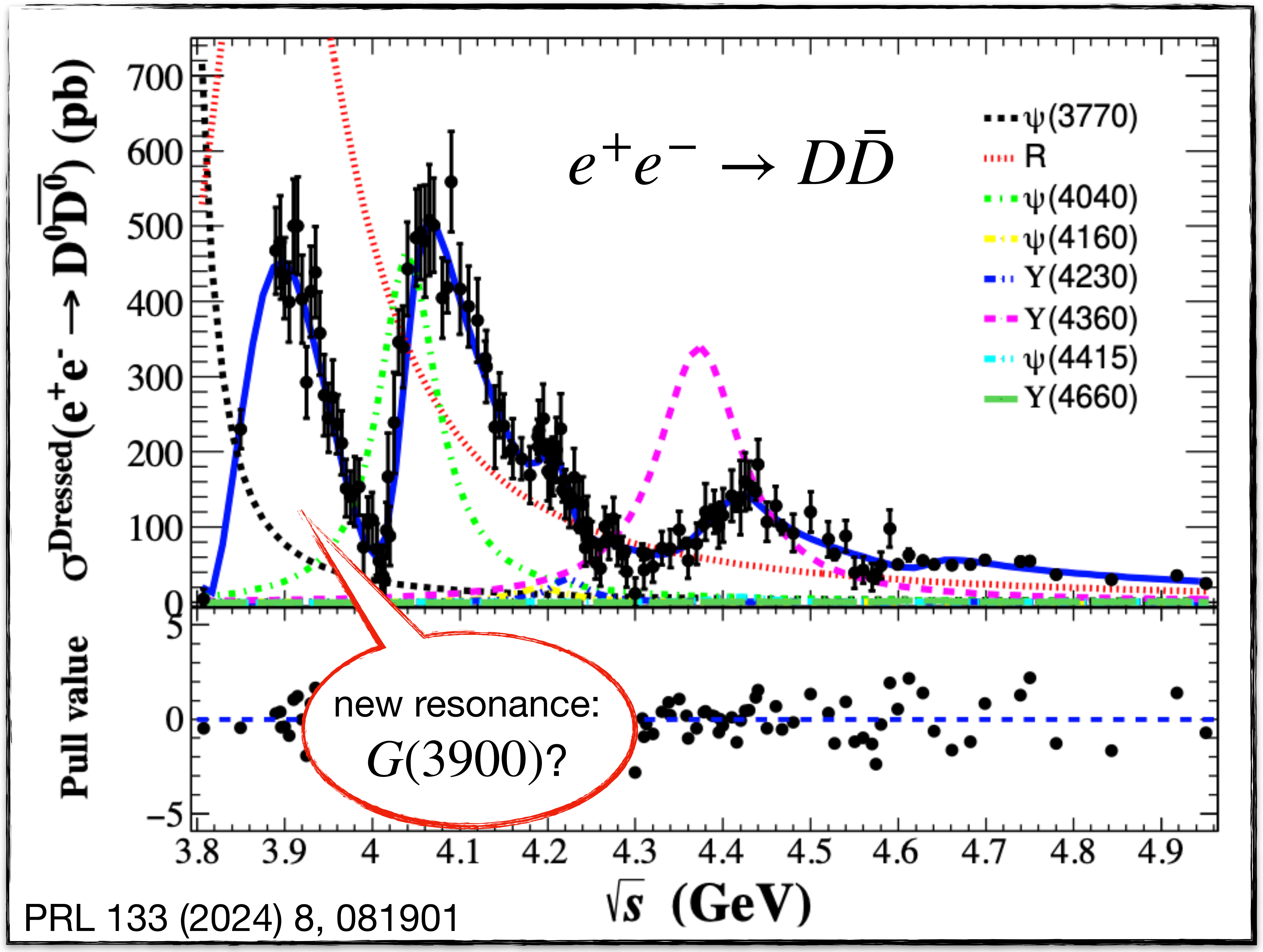
measured for the first time!

Towards charmonium

NH, R. Lebed, R. Mitchell, E. Swanson, Y. Wang, C. Yuan, PRD 109 (2024) 11, 114010
ongoing work with R. Mitchell, E. Swanson, C. Yuan, S. Dawid, A. Szczepaniak and others

A piece of the puzzle

the $G(3900)$ problem



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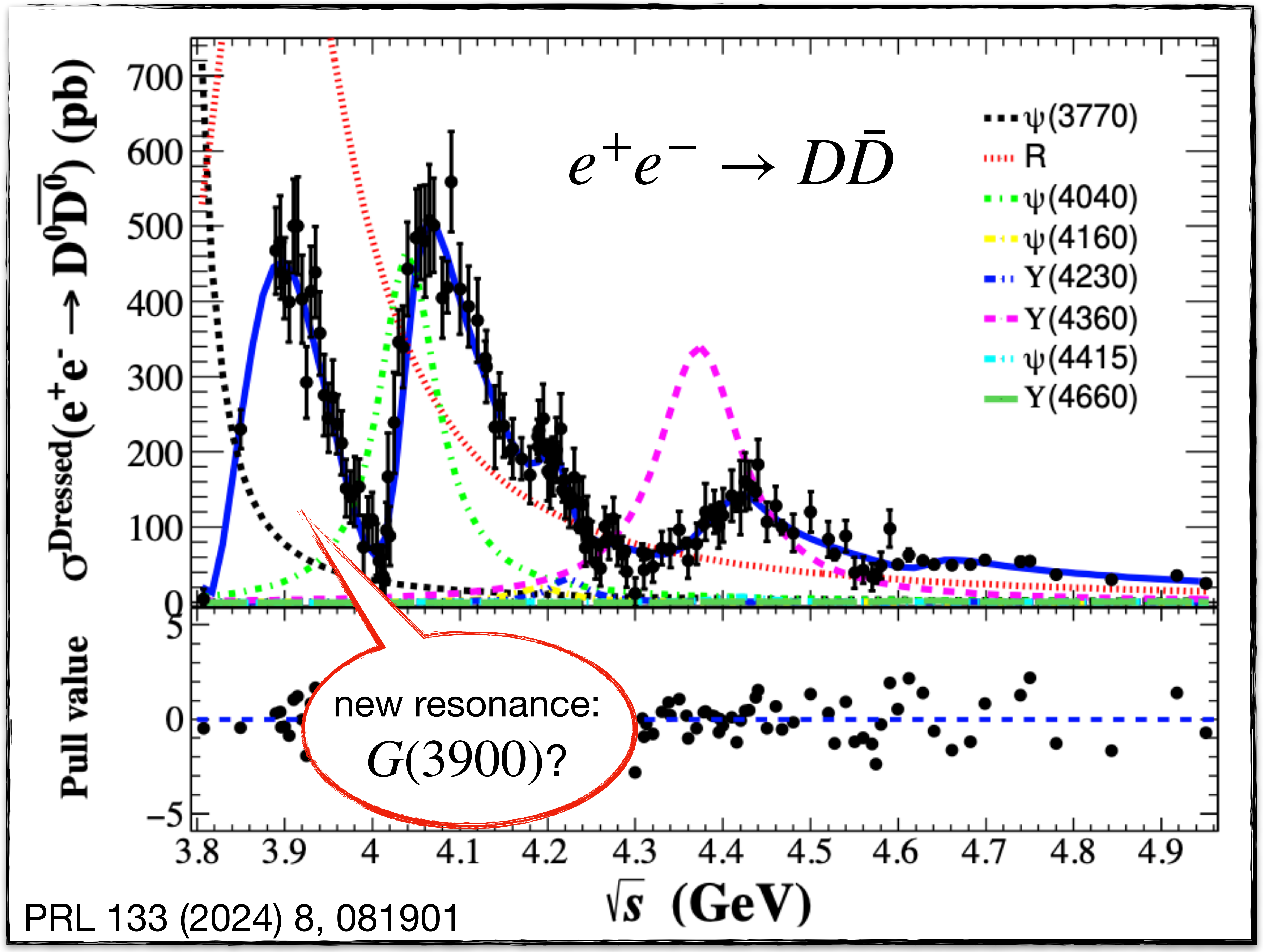
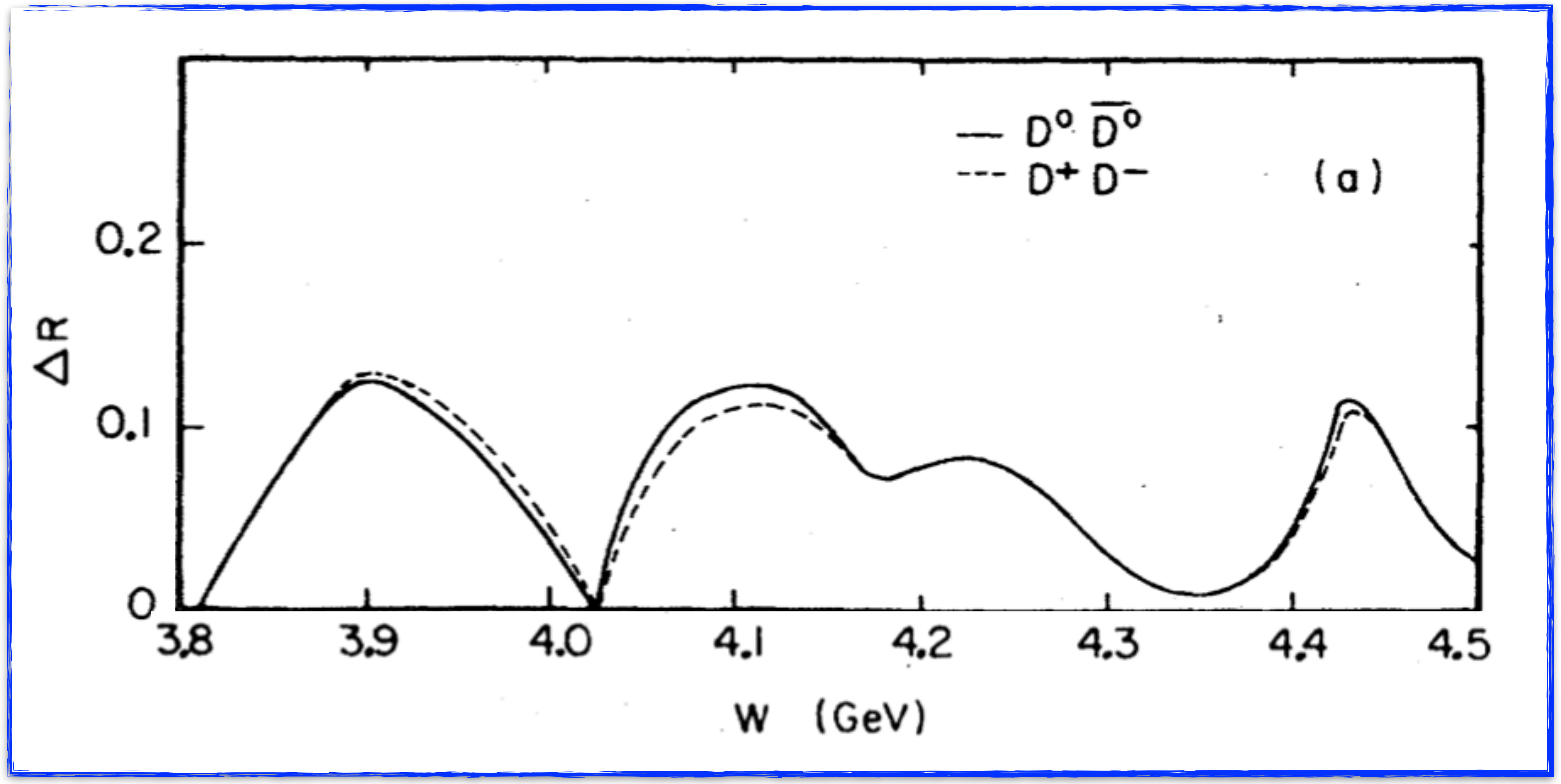
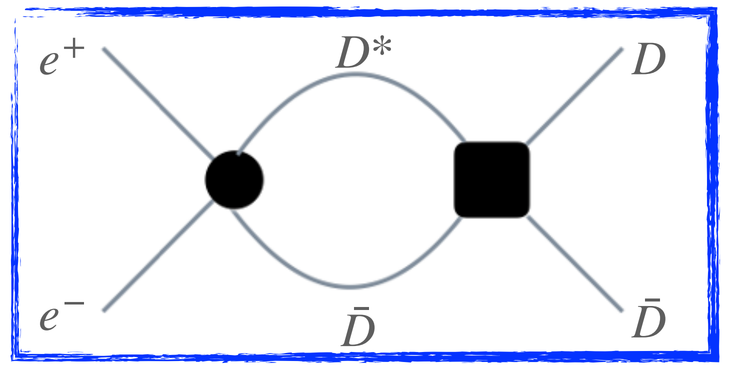


Eichten et al., Phys. Rev. D 21 (1980) 203



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.



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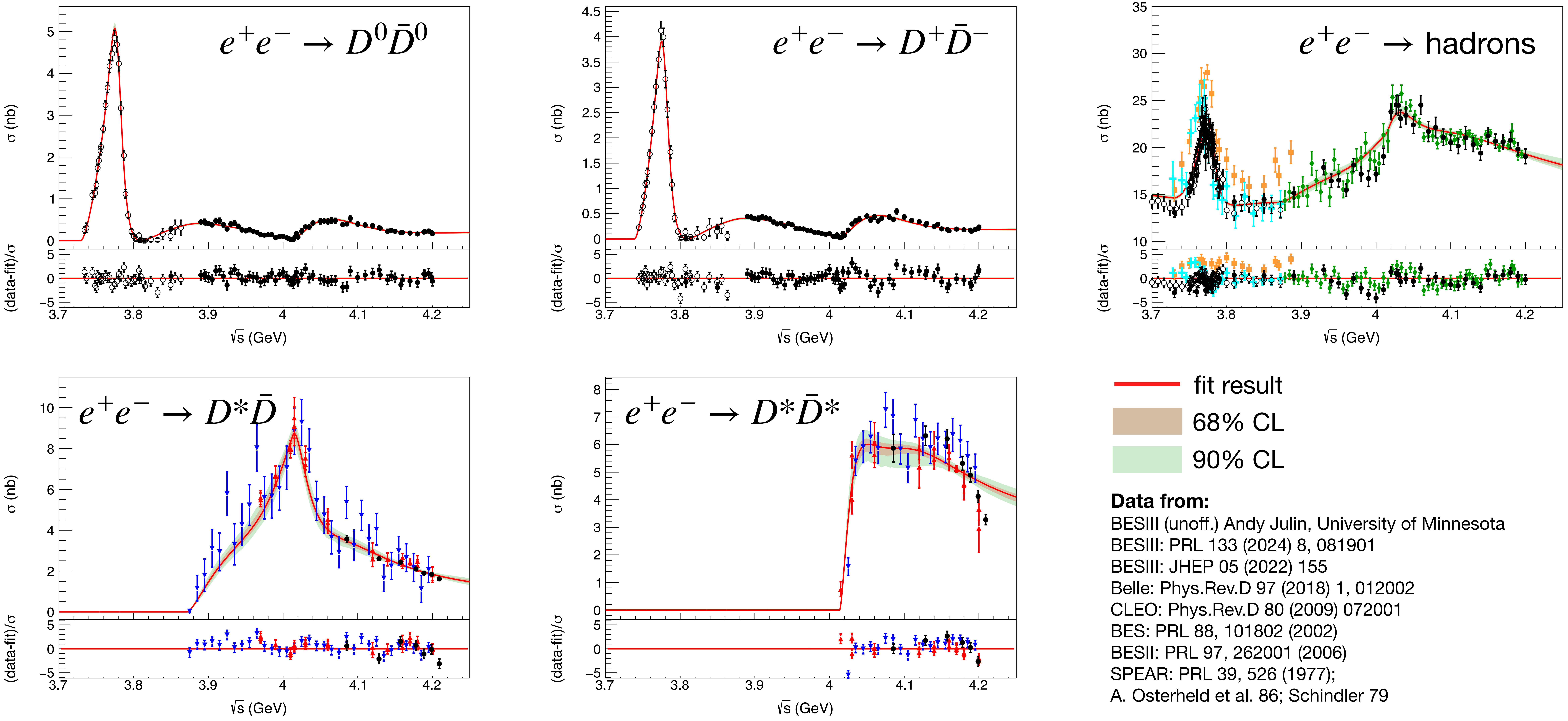
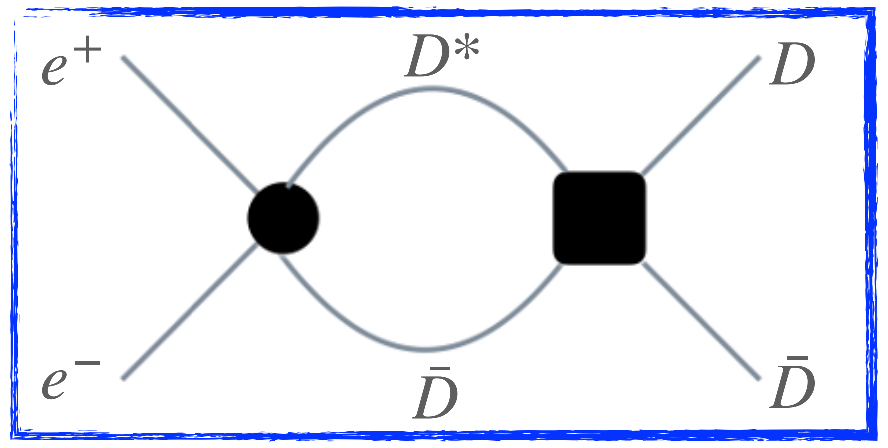
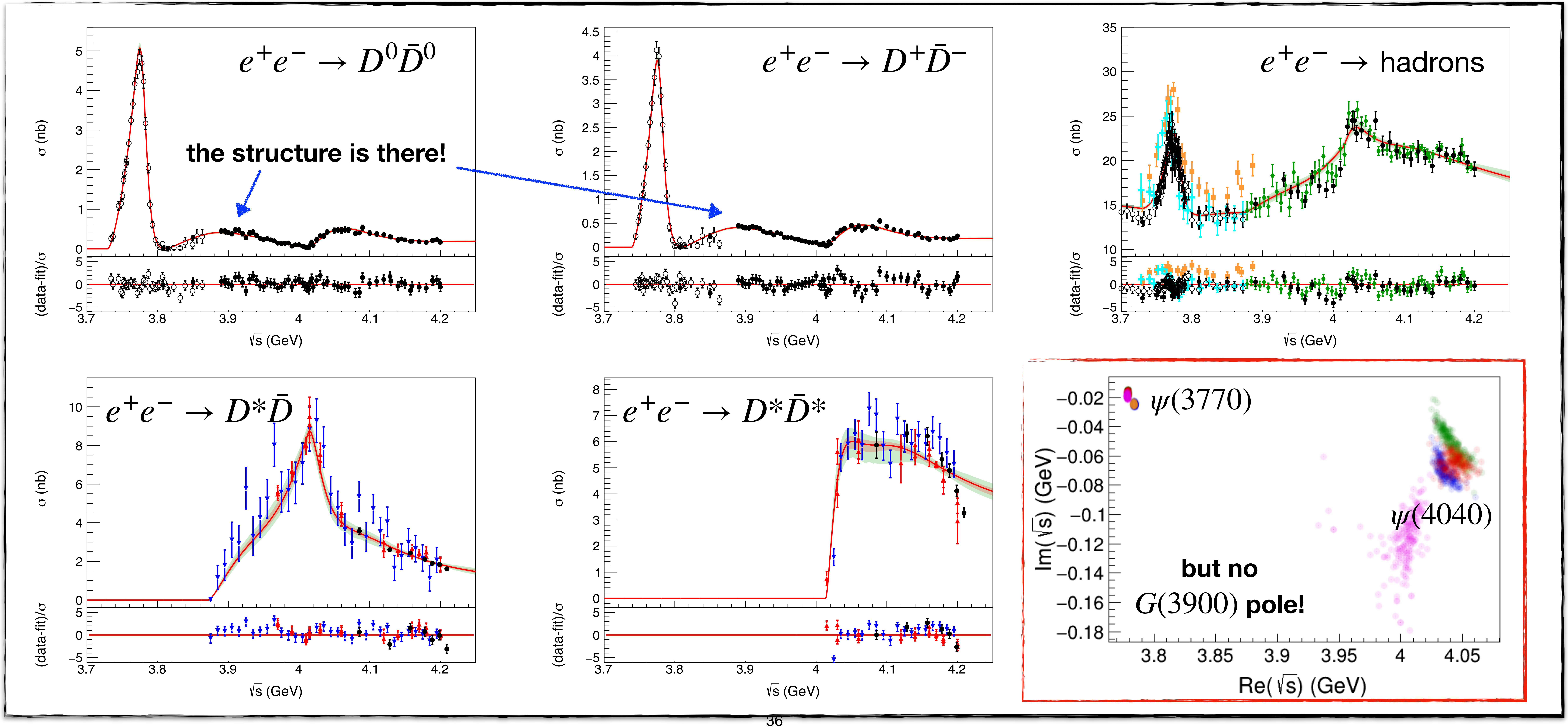


Data from:
BESIII (unoff.) Andy Julin, University of Minnesota
BESIII: PRL 133 (2024) 8, 081901
BESIII: JHEP 05 (2022) 155
Belle: Phys.Rev.D 97 (2018) 1, 012002
CLEO: Phys.Rev.D 80 (2009) 072001
BES: PRL 88, 101802 (2002)
BESII: PRL 97, 262001 (2006)
SPEAR: PRL 39, 526 (1977);
A. Osterheld et al. 86;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

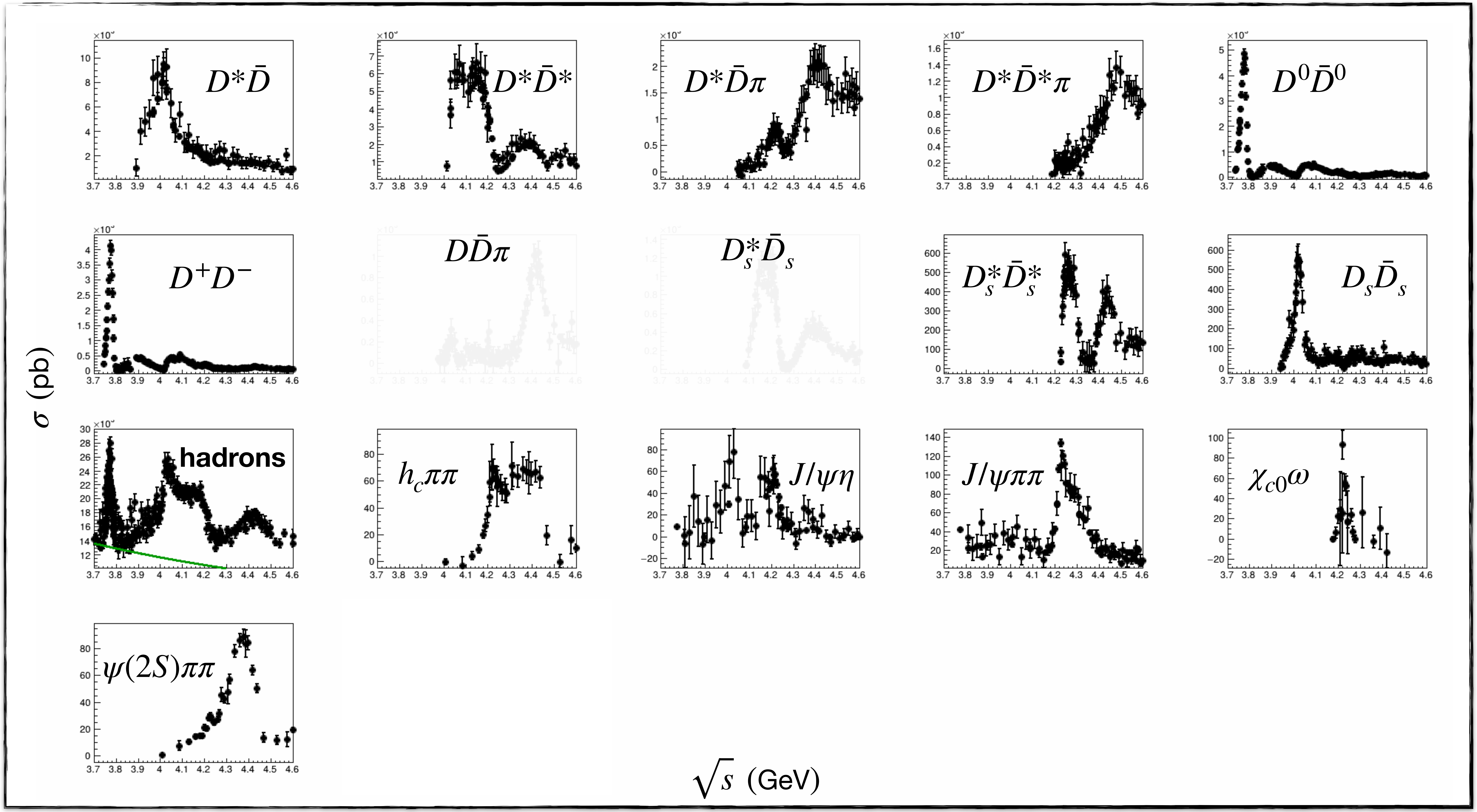
A piece of the puzzle





The full charmonium case

data from BESIII, Belle, BaBar, CLEO, …



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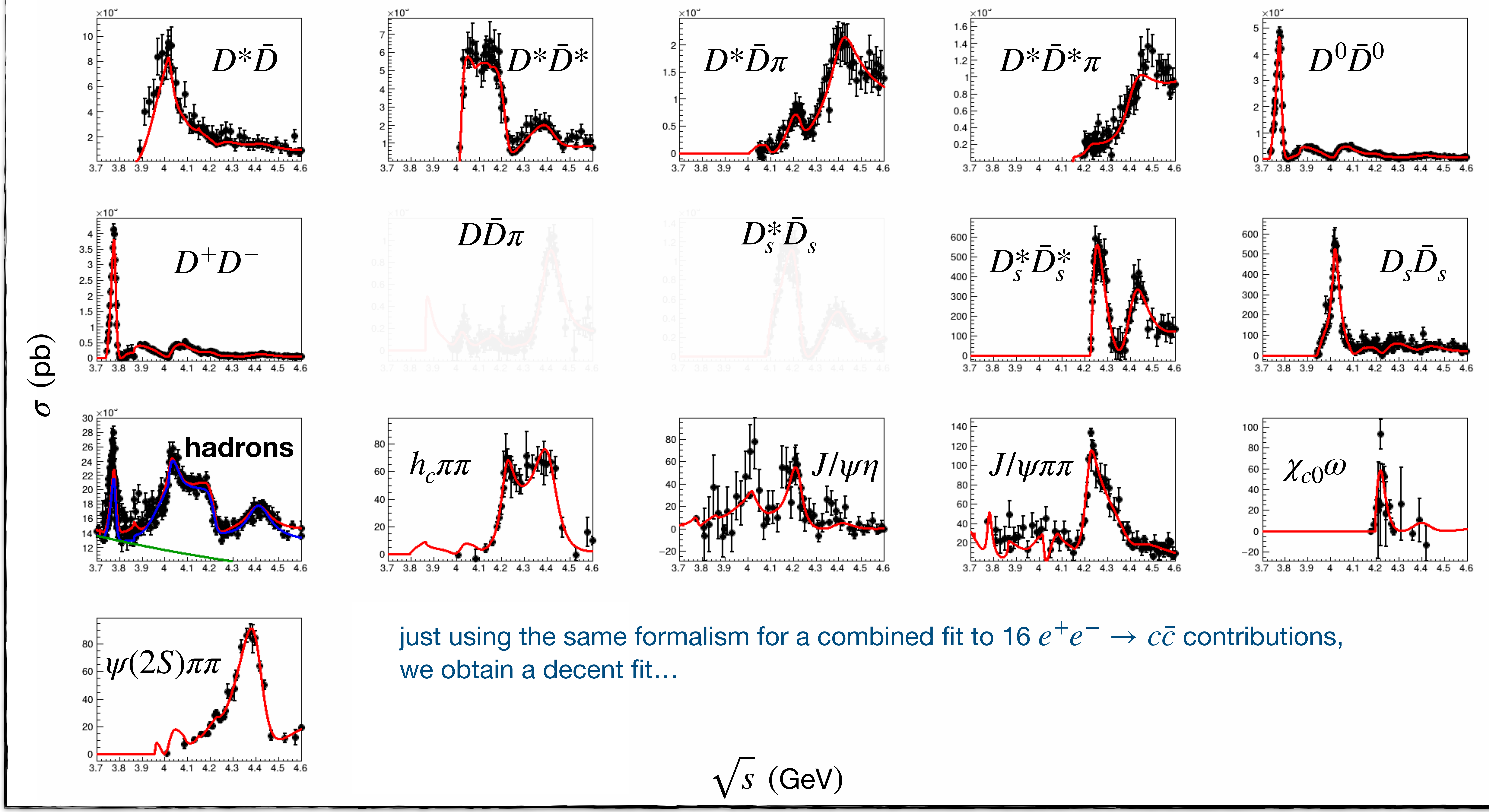

just using the same formalism for a combined fit to 16 $e^+e^- \to c\bar{c}$ contributions, we obtain a decent fit…

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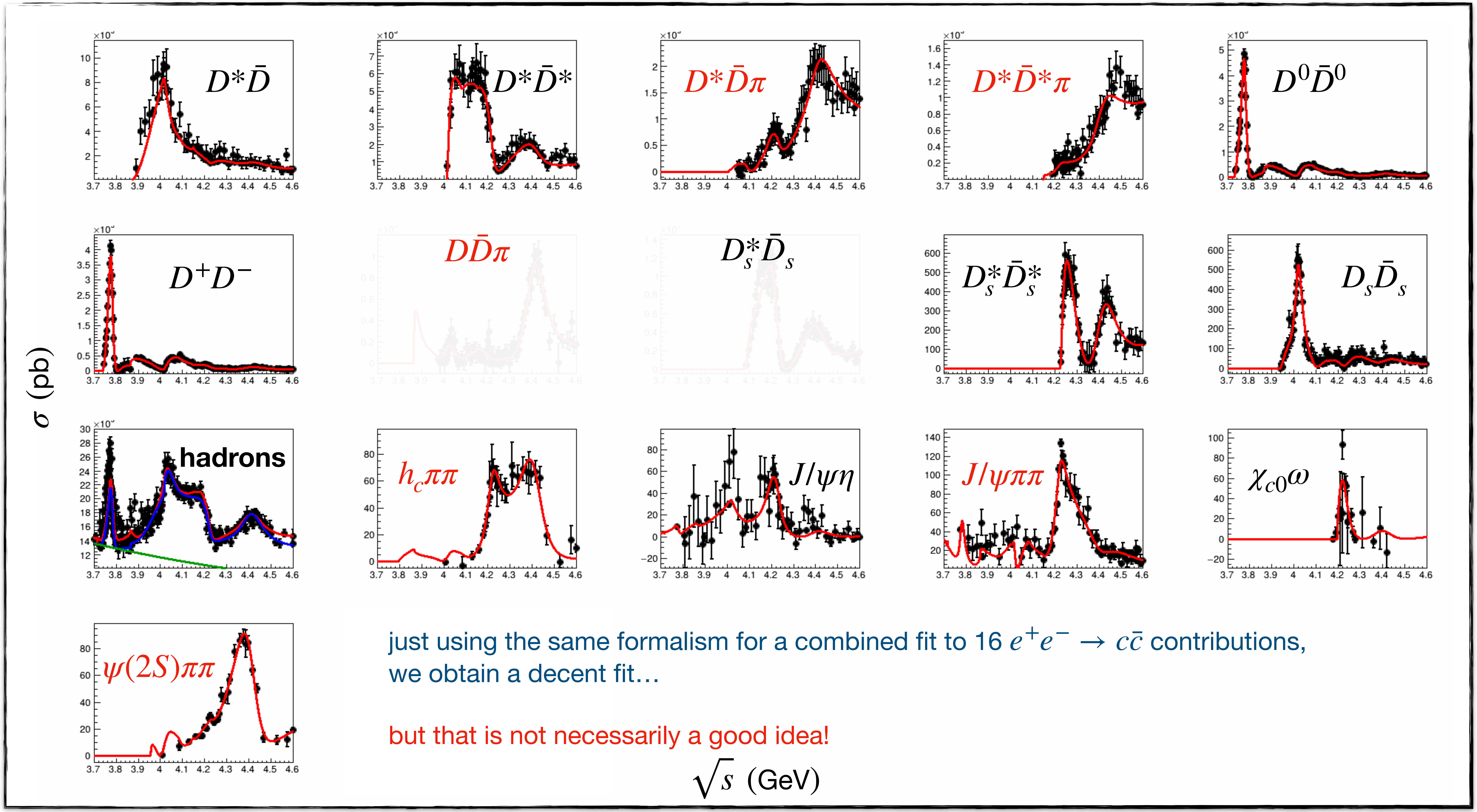
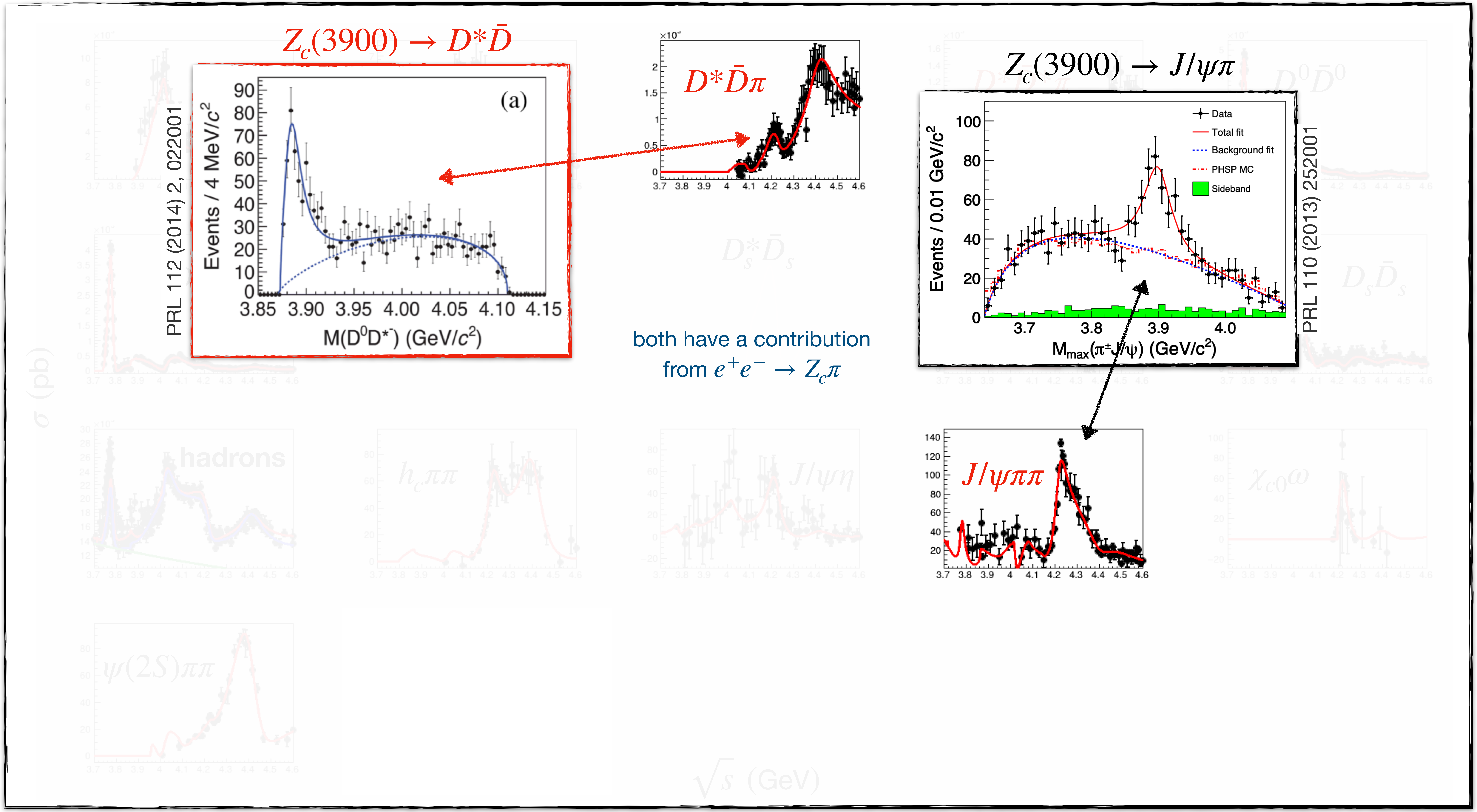


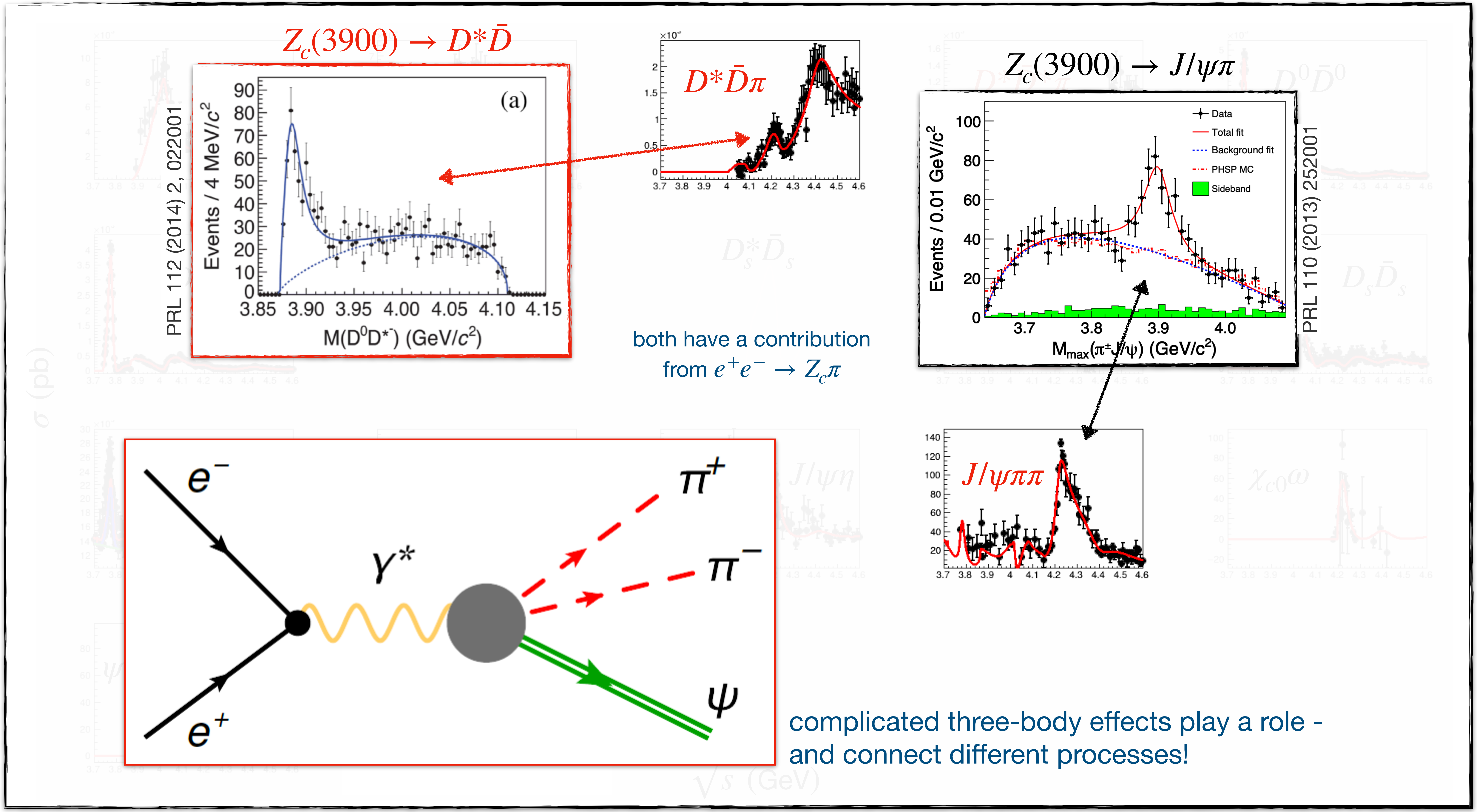
just using the same formalism for a combined fit to 16 $e^+e^- \to c\bar{c}$ contributions, we obtain a decent fit…

but that is not necessarily a good idea!

The full charmonium case



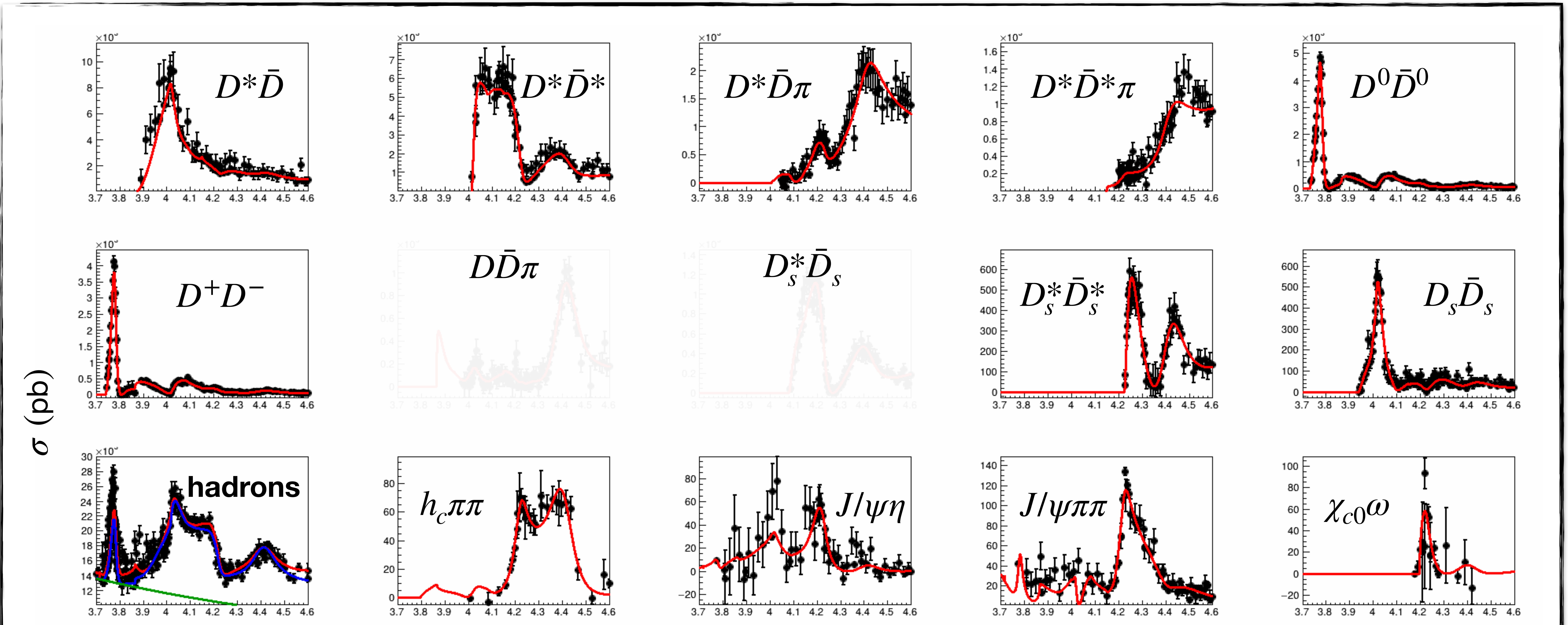
The full charmonium case

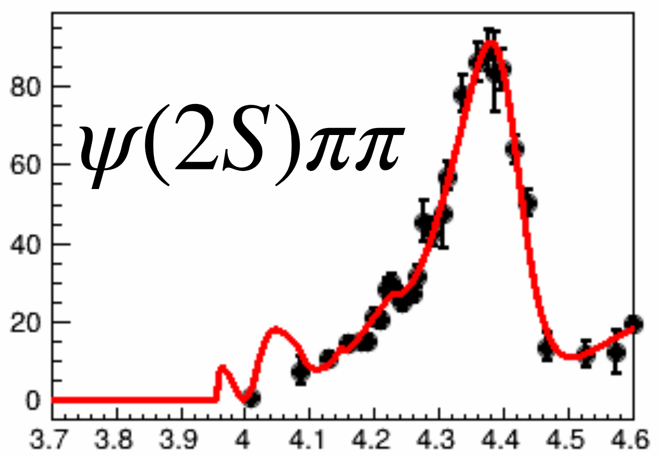


both have a contribution from $e^+e^- \to Z_c\pi$

complicated three-body effects play a role - and connect different processes!

The full charmonium case



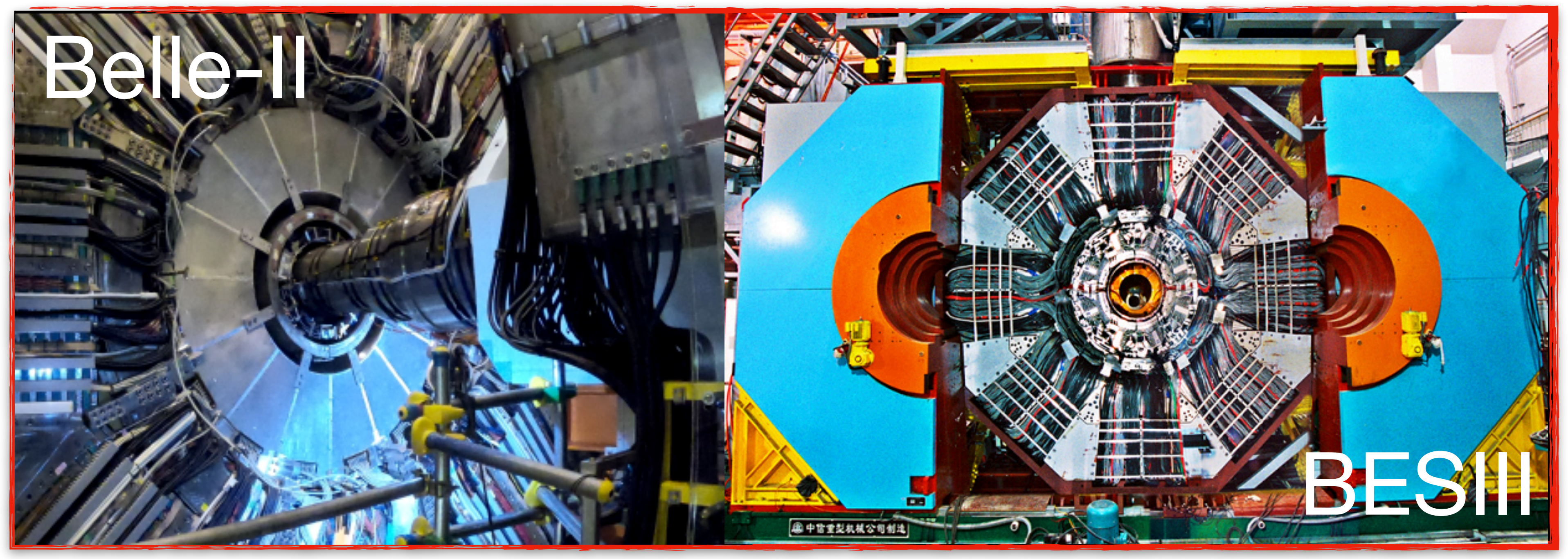


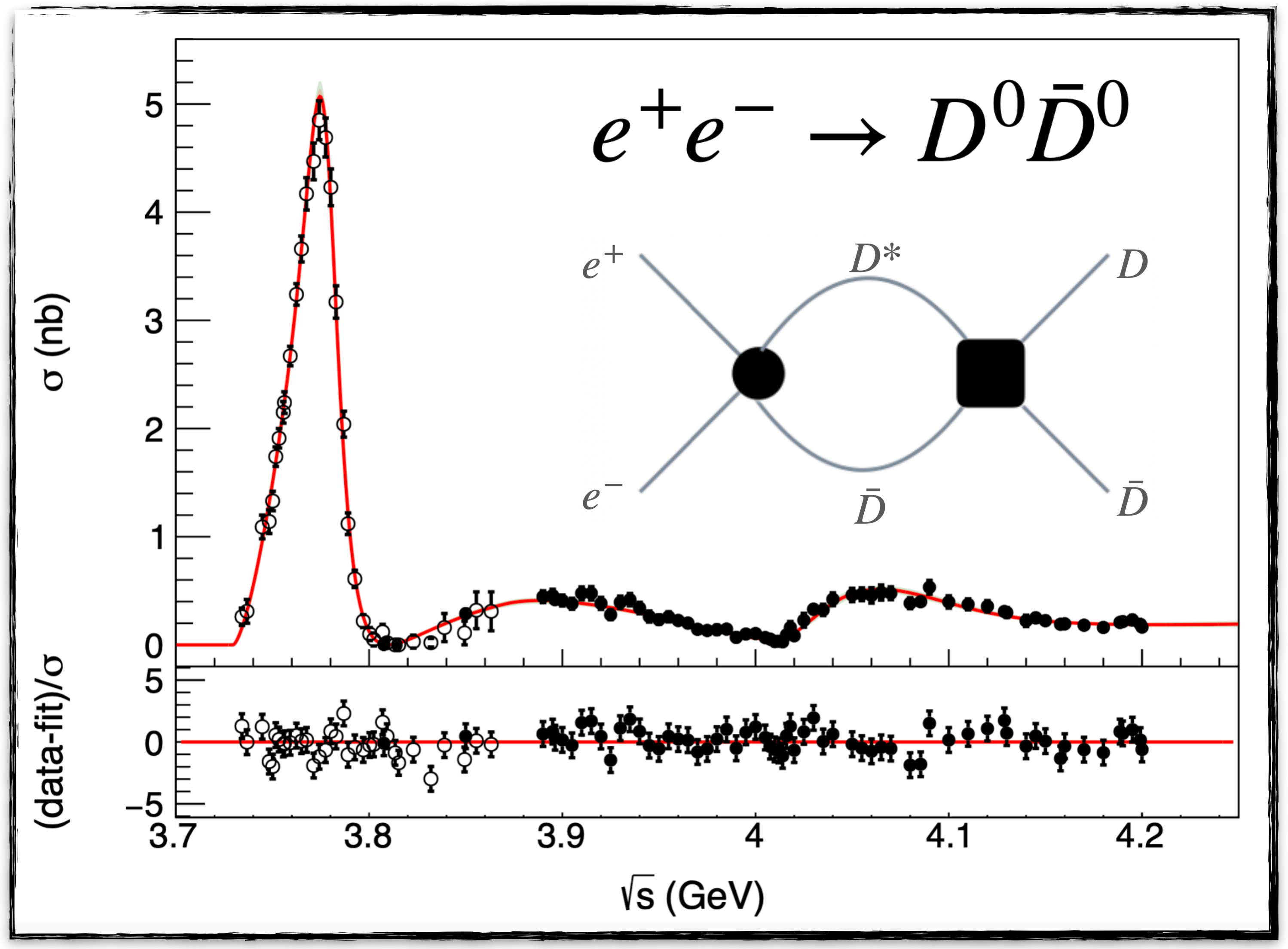
clearly, this can not be the end of the story…

$\sqrt{s}$ (GeV)

Summary

- 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 complementary approaches - collaboration with theory is key!
- many things still to be learned!

Thank you for your attention!