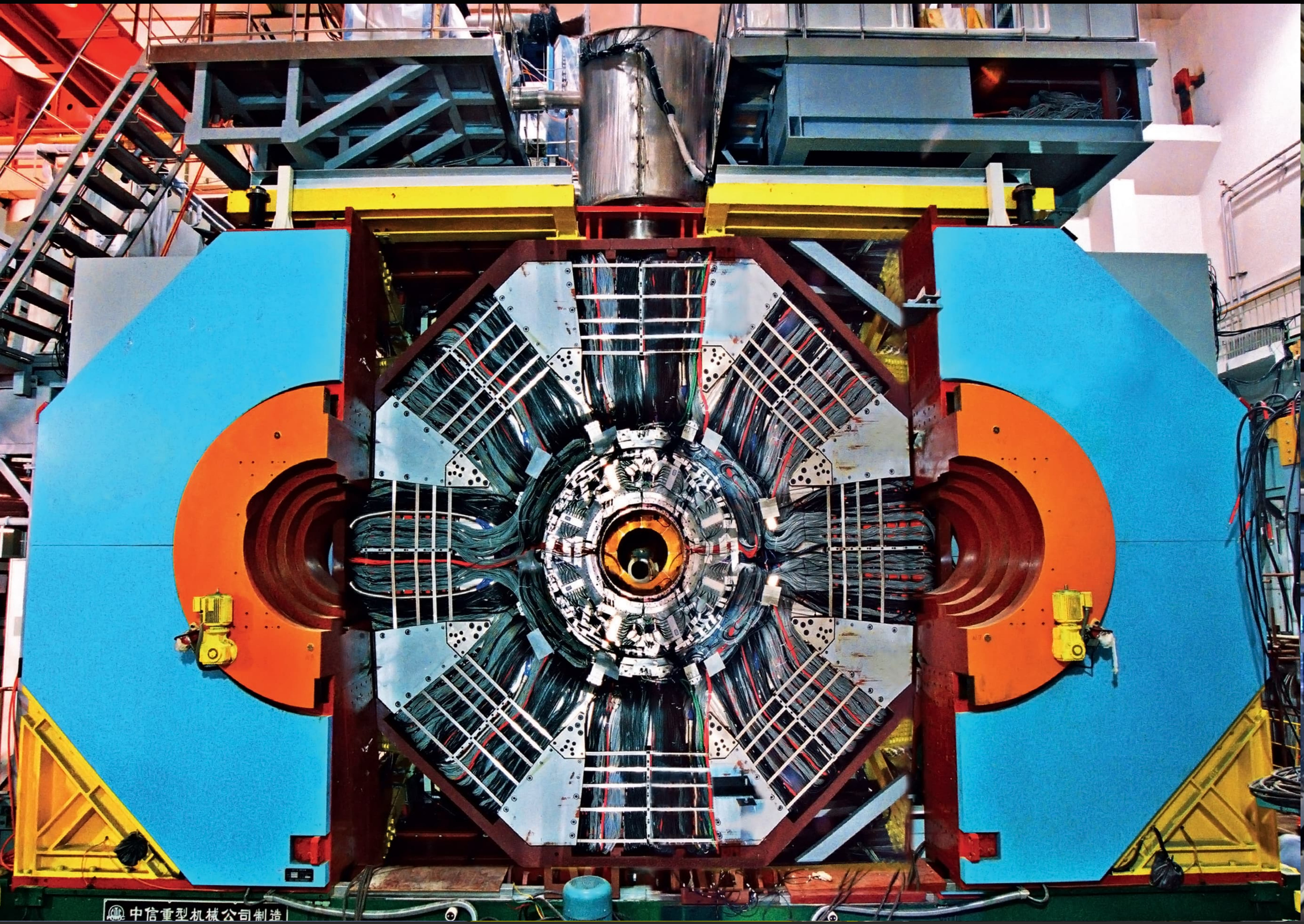
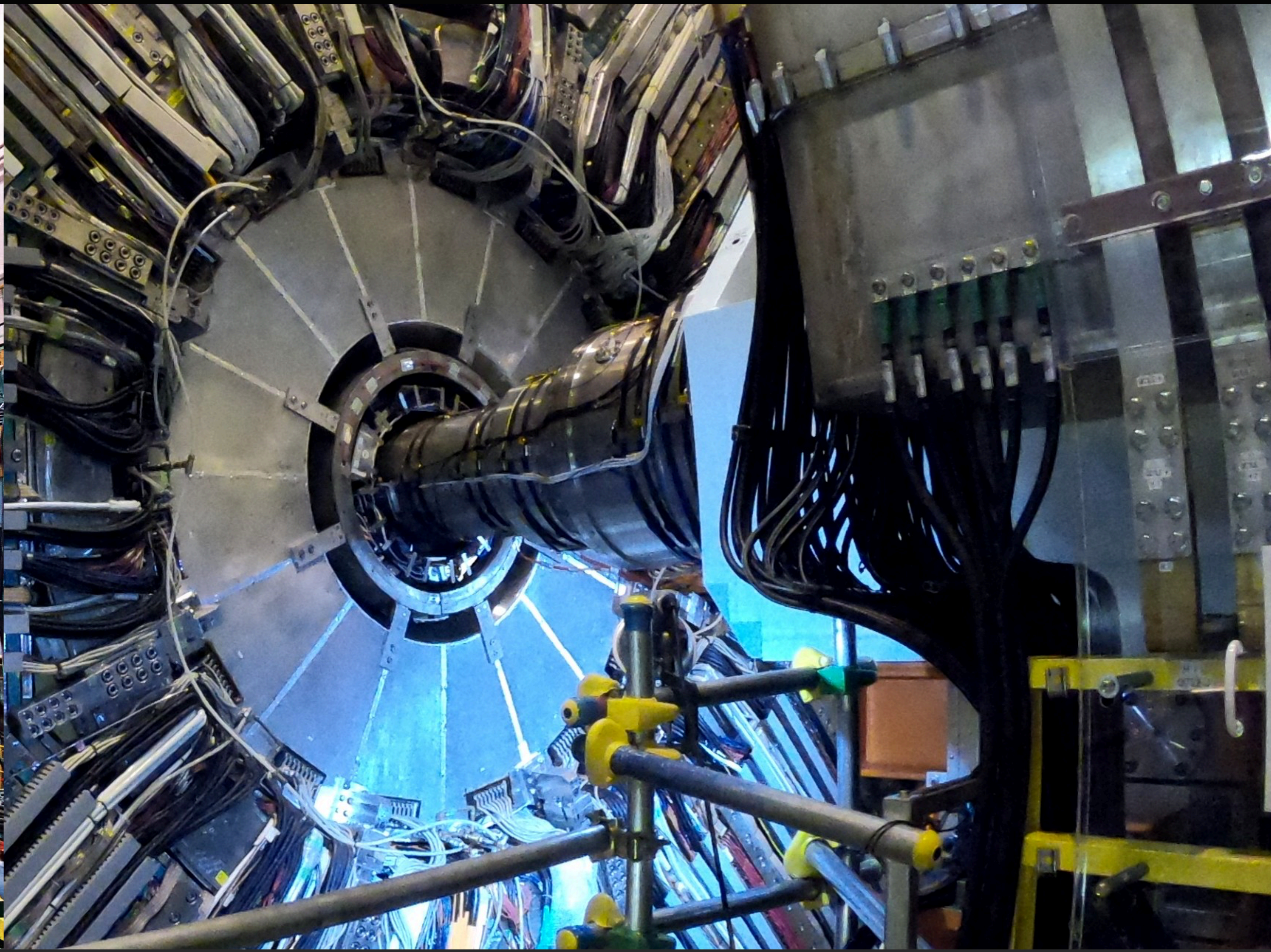




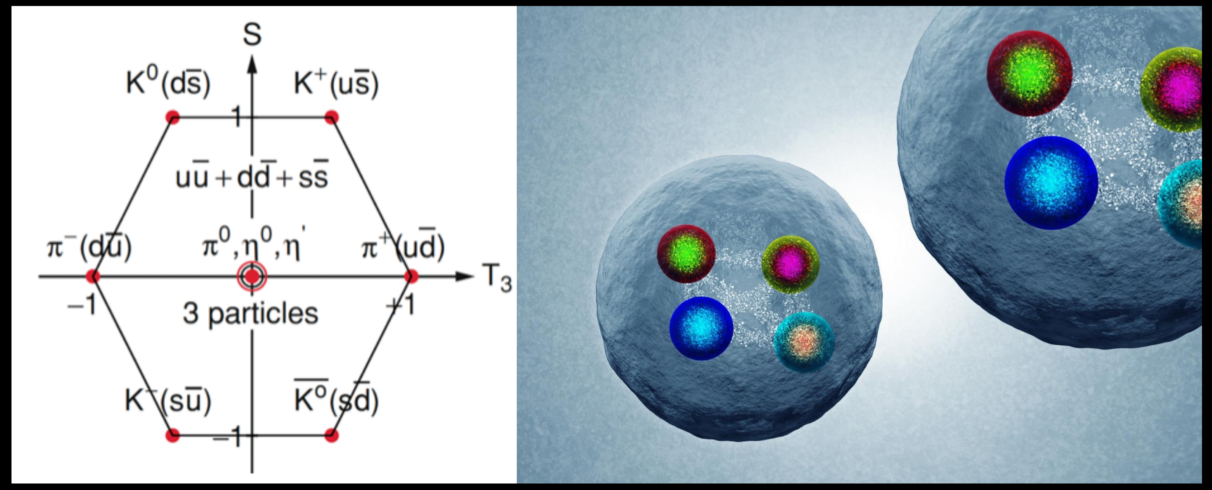
Spectroscopy at e^+e^- machines in the JLAB 22 GeV era

Nils Hüsken
JGU Mainz
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

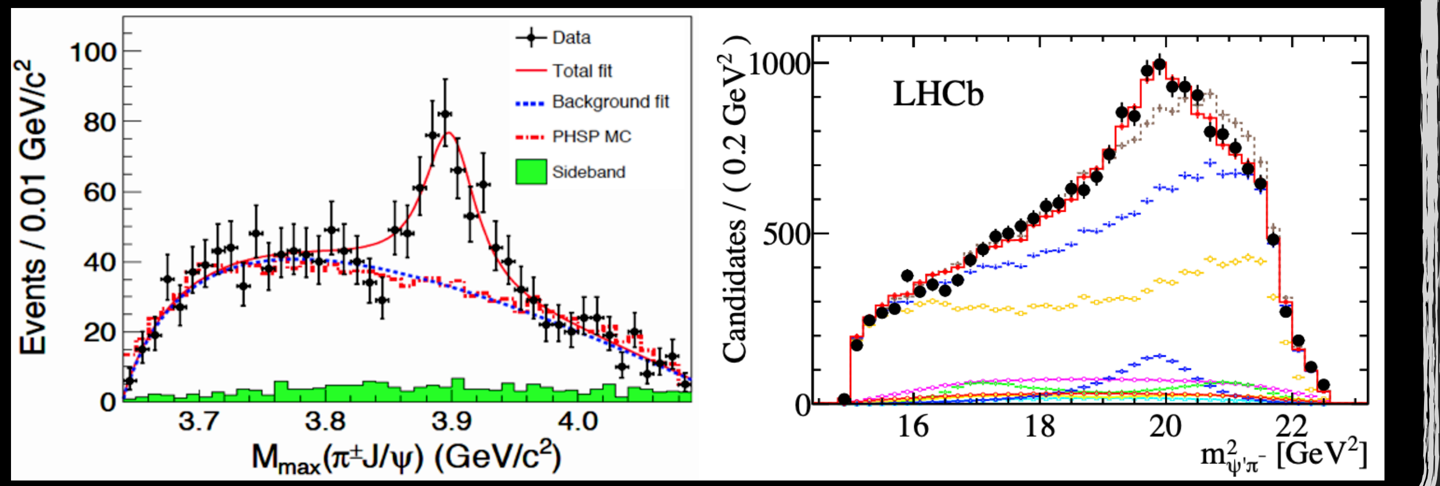
Disclaimer:
I am a member of BESIII, but not Belle II
that may or may not colour the talk!

outlook: a STCF?

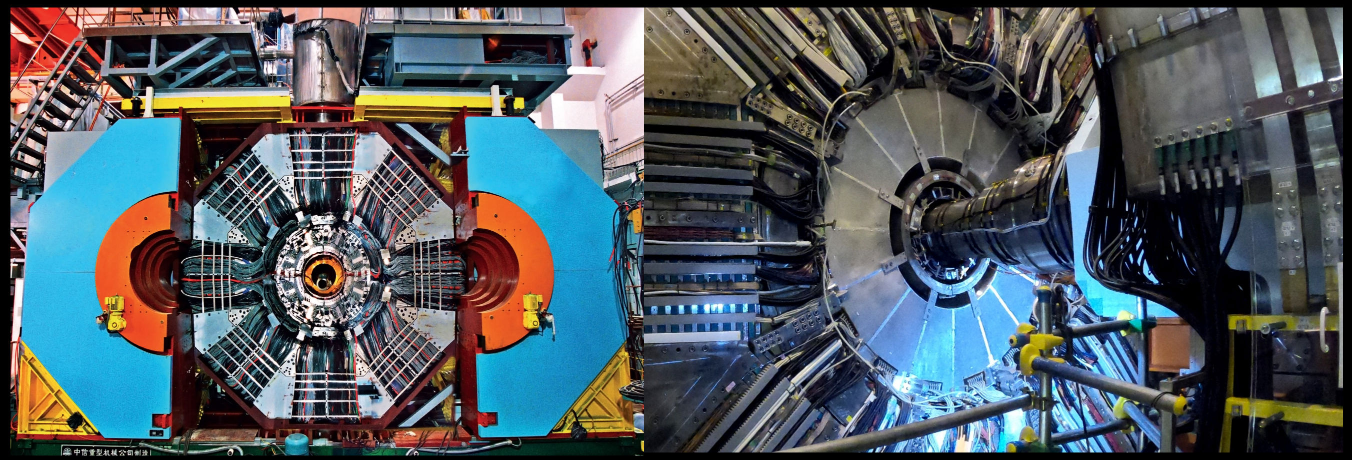
hadron spectroscopy



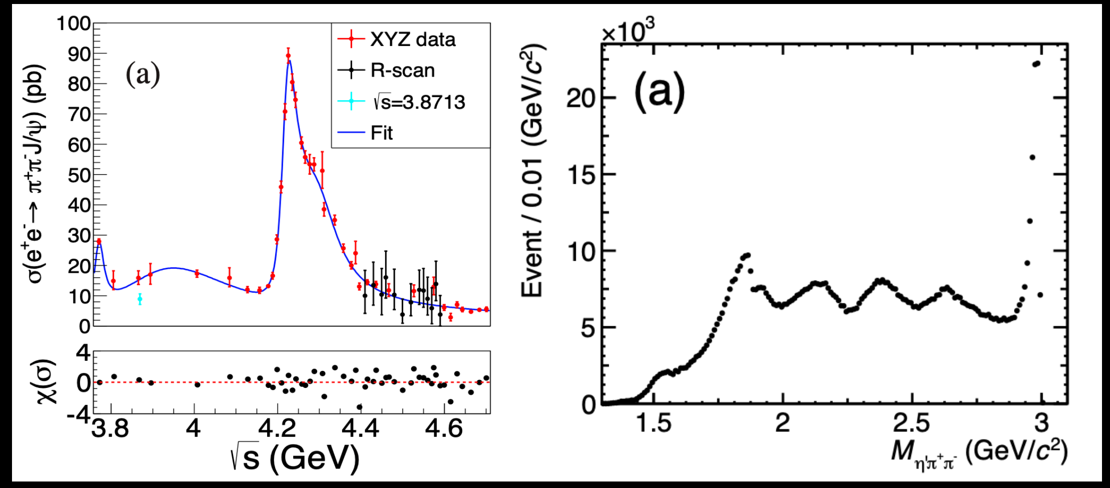
open questions



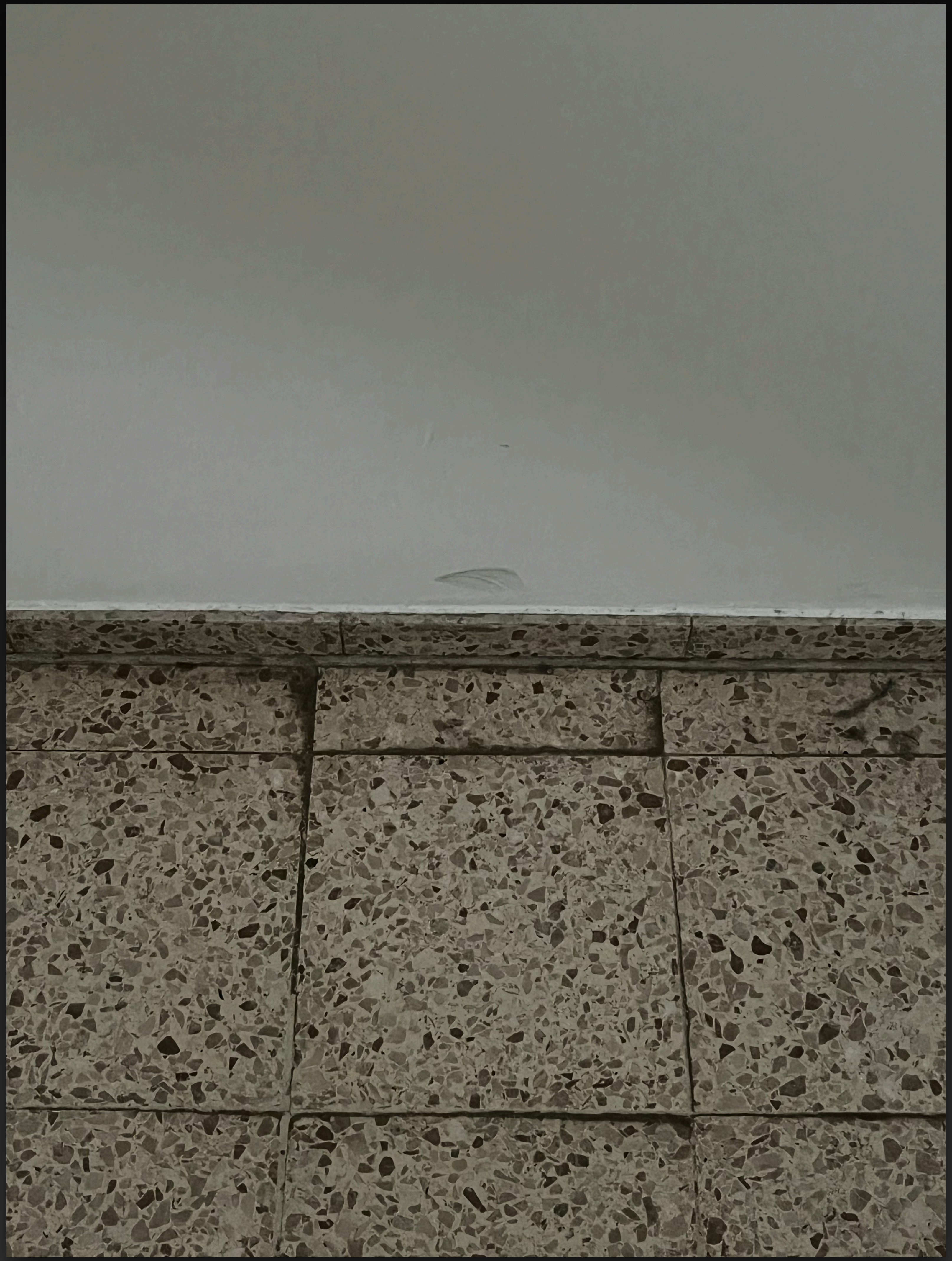
current e^+e^- machines



what we do well

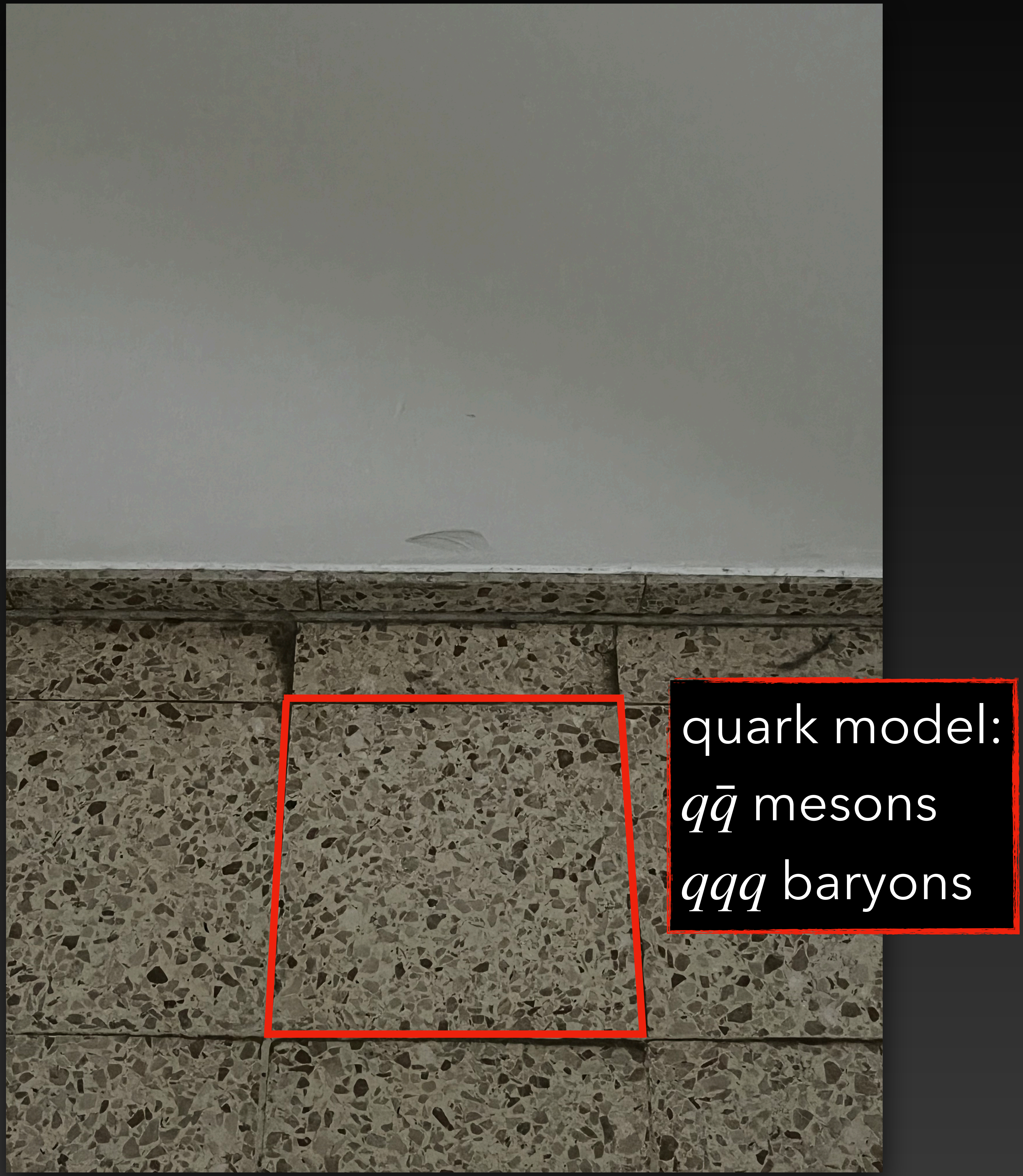


Hadron spectroscopy



workshop on science communication:
explain your field with a photo taken on the way to lunch

Hadron spectroscopy



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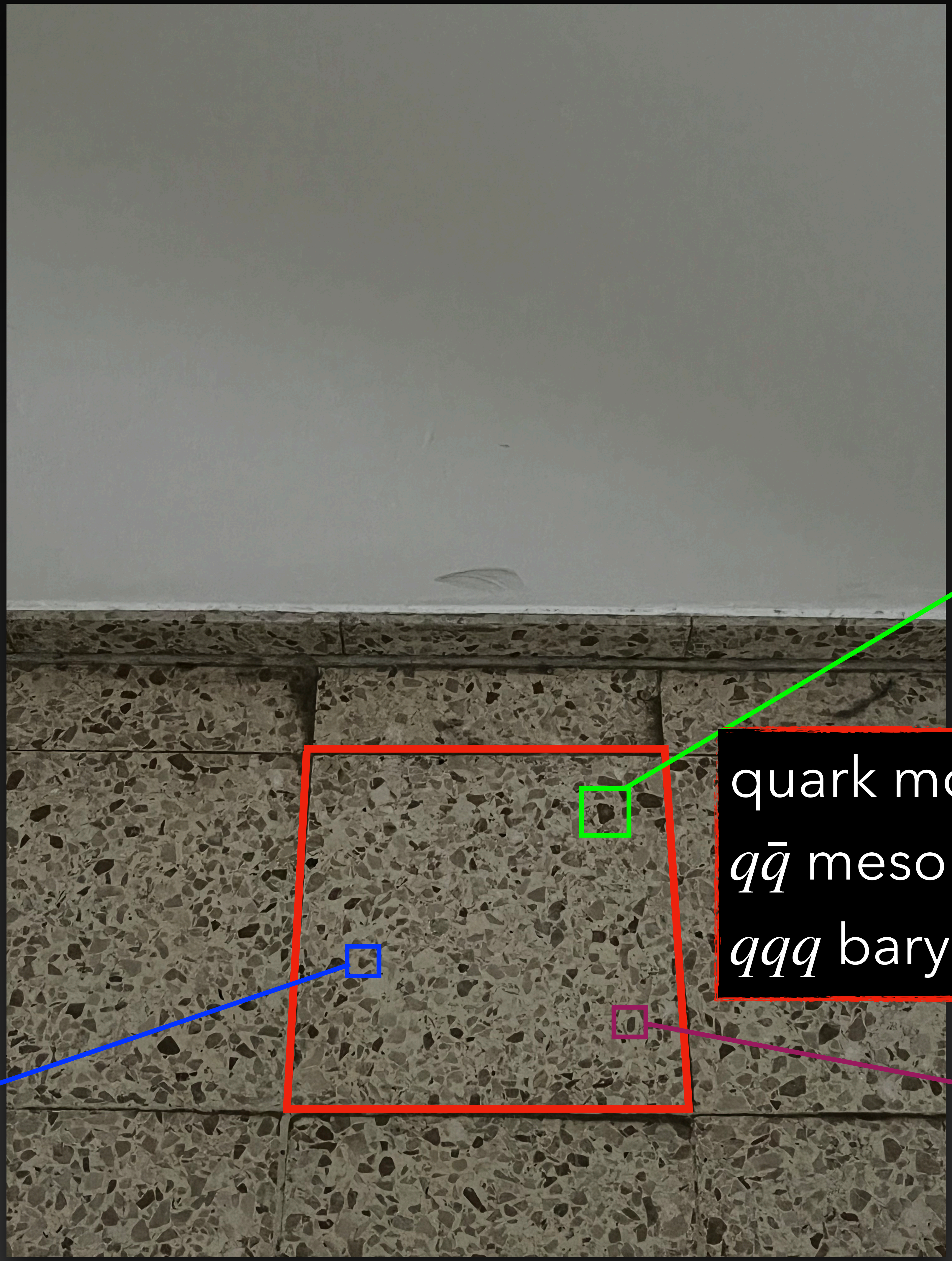
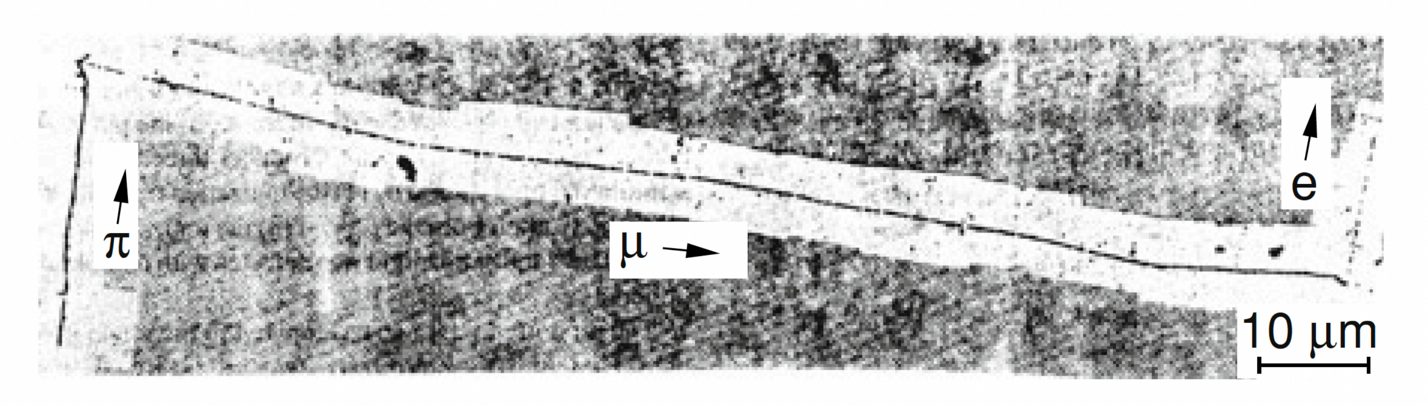


quark model:
$q\bar{q}$ mesons
qqq baryons

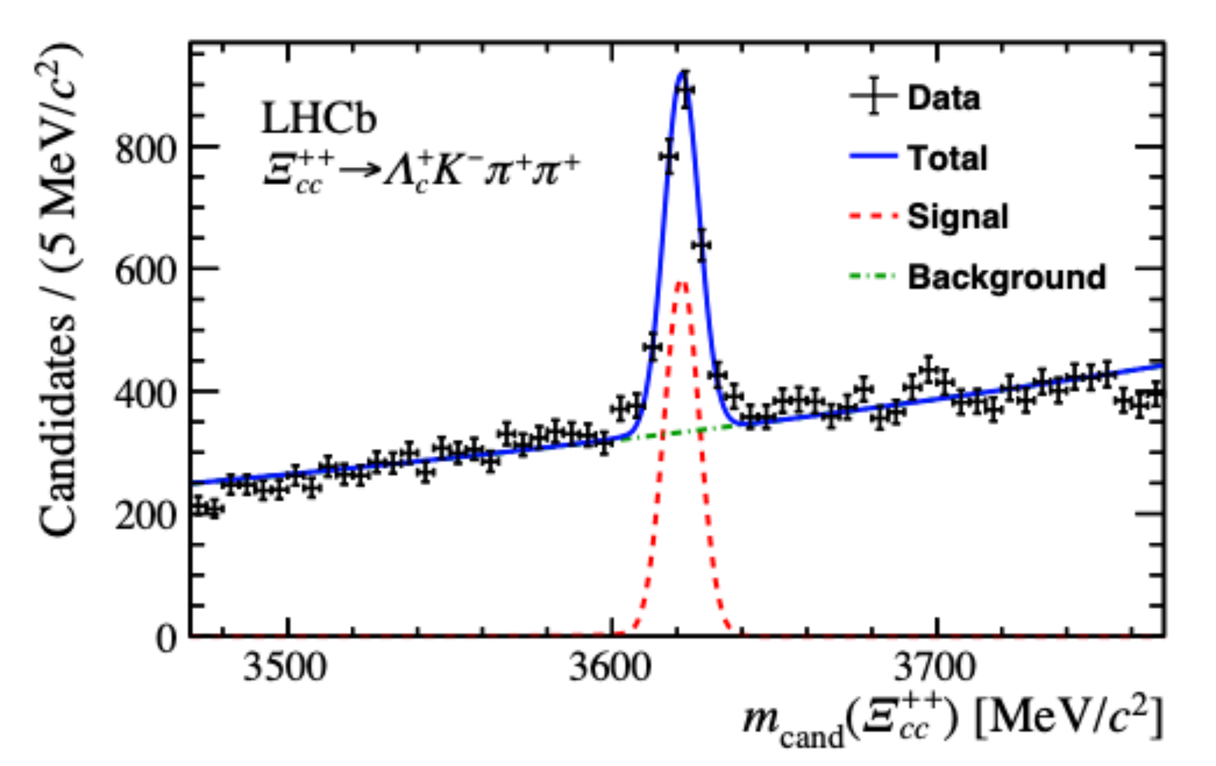
wide variety of hadrons



Nature 160, 453–456 (1947)

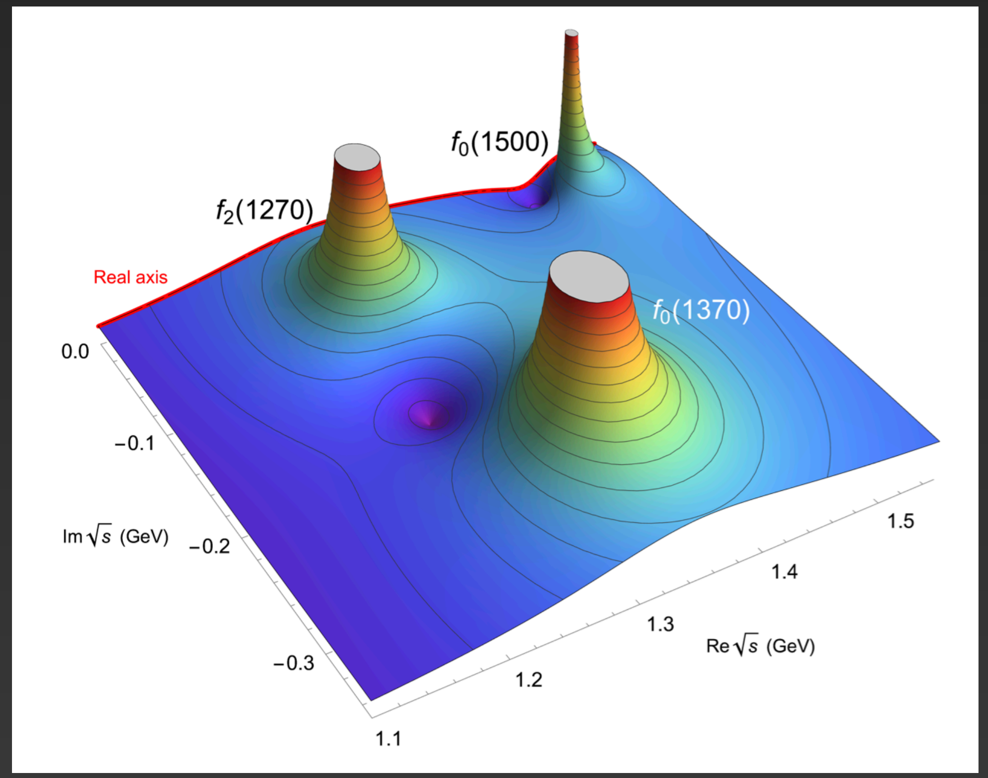
from light and narrow…

… to heavy quarks



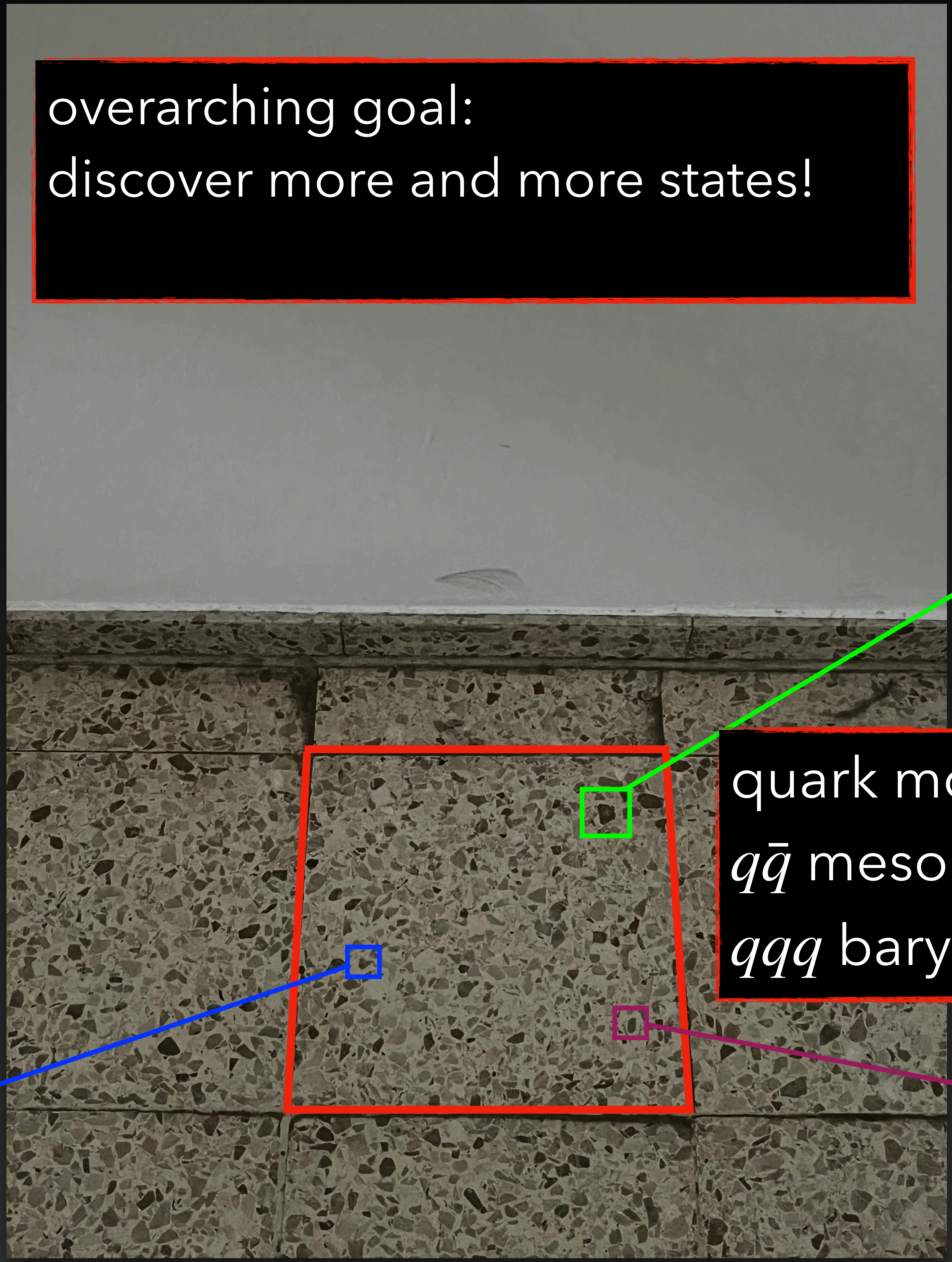
Phys. Rev. Lett. 124, 082002 (2020)

… and broad objects



PRL 130 (2023) 5, 5

Hadron spectroscopy



overarching goal:
discover more and more states!

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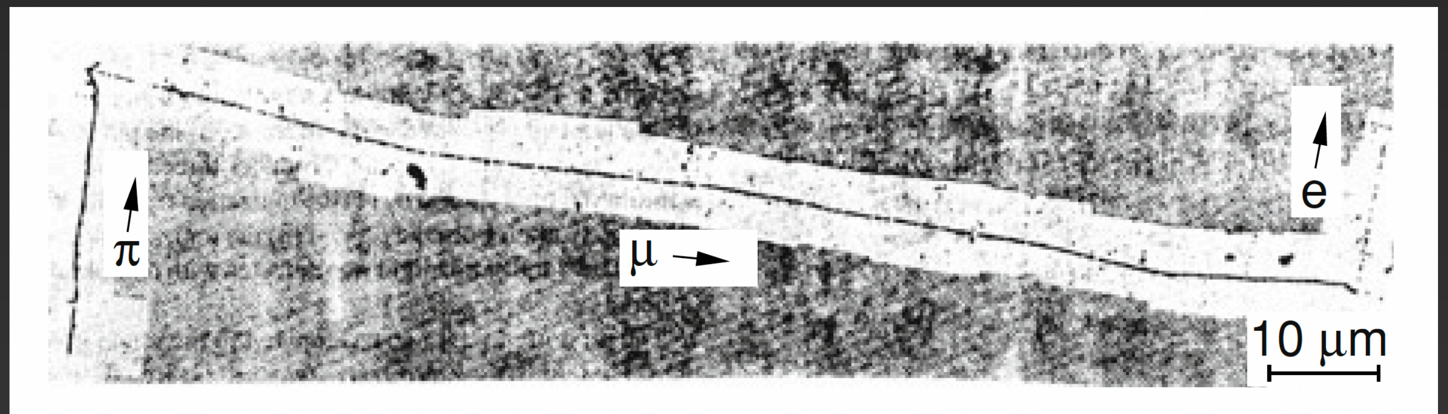

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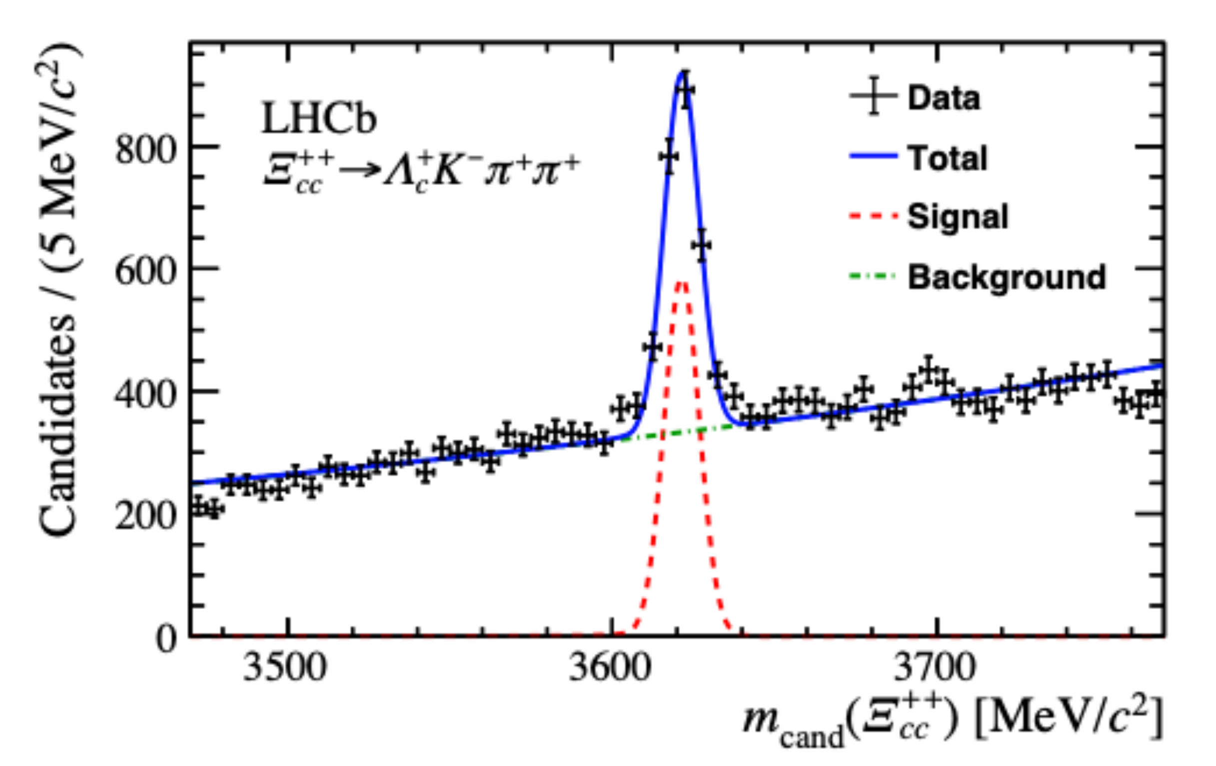

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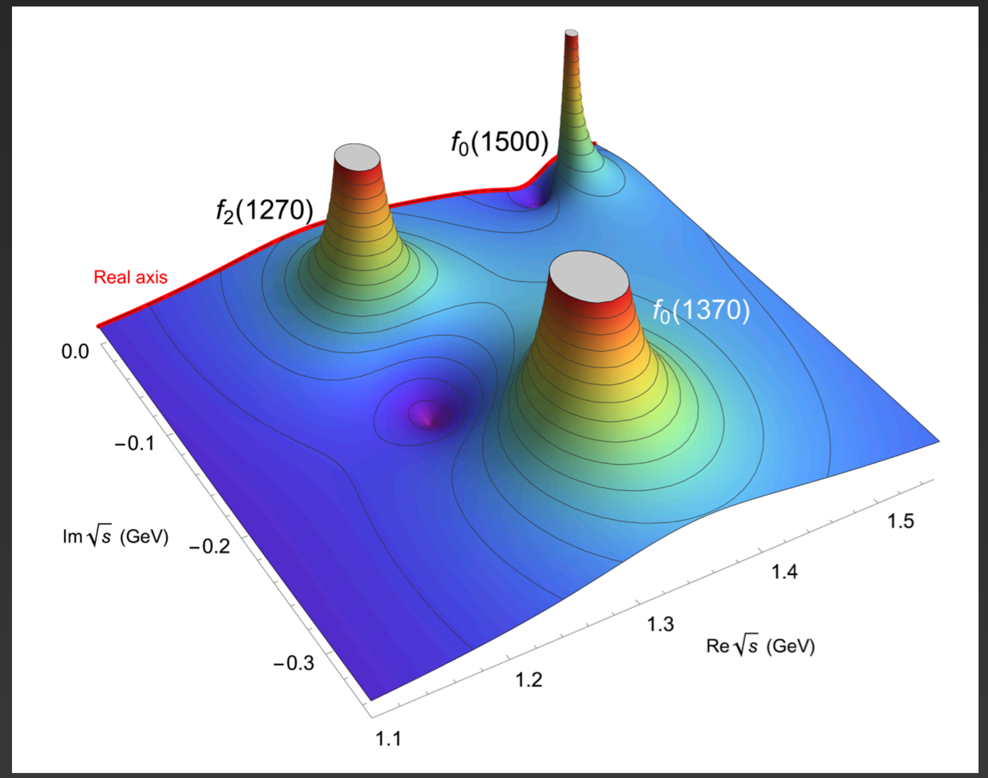
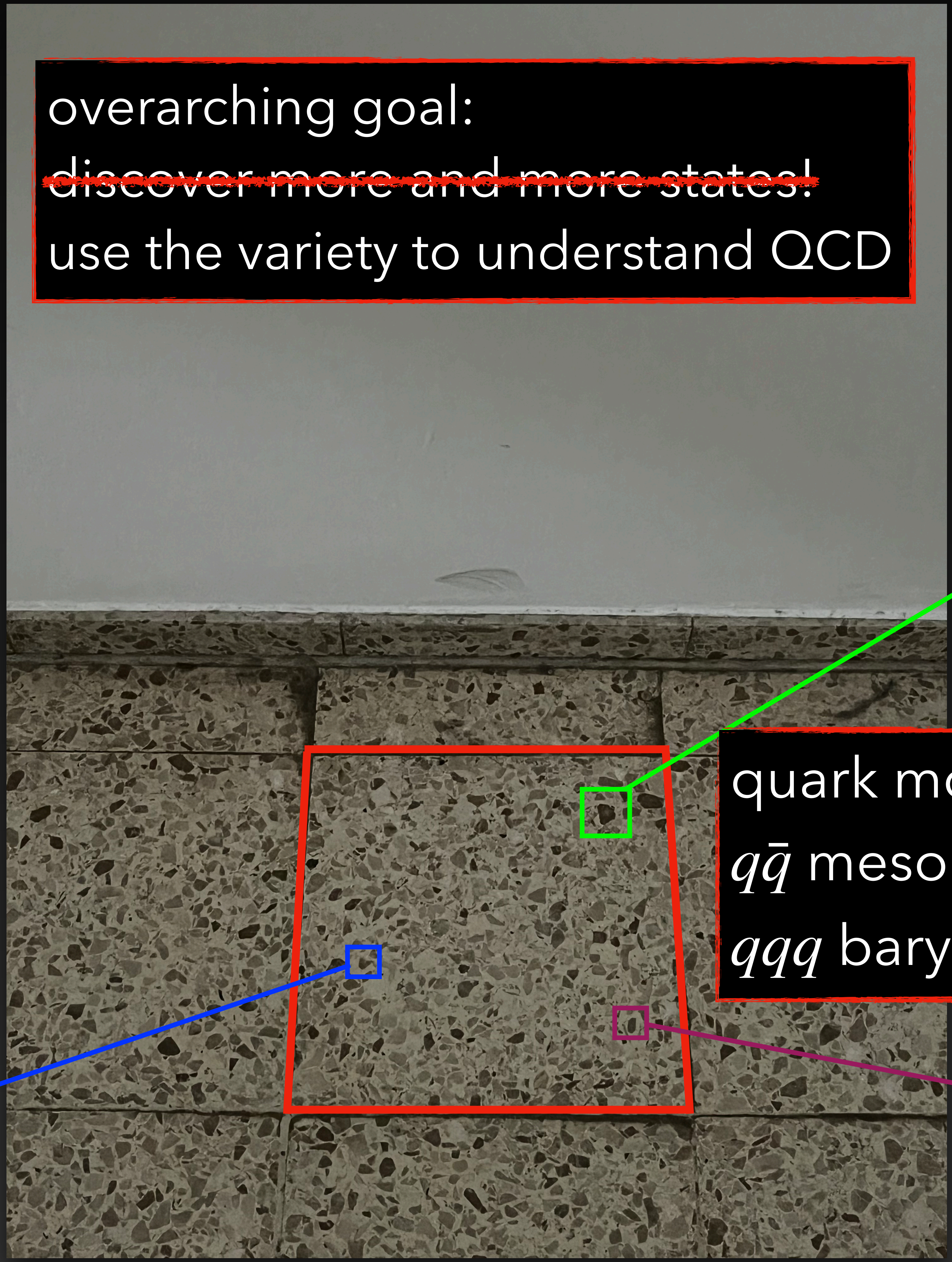


PRL 130 (2023) 5, 5

Hadron spectroscopy



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use the variety to understand QCD

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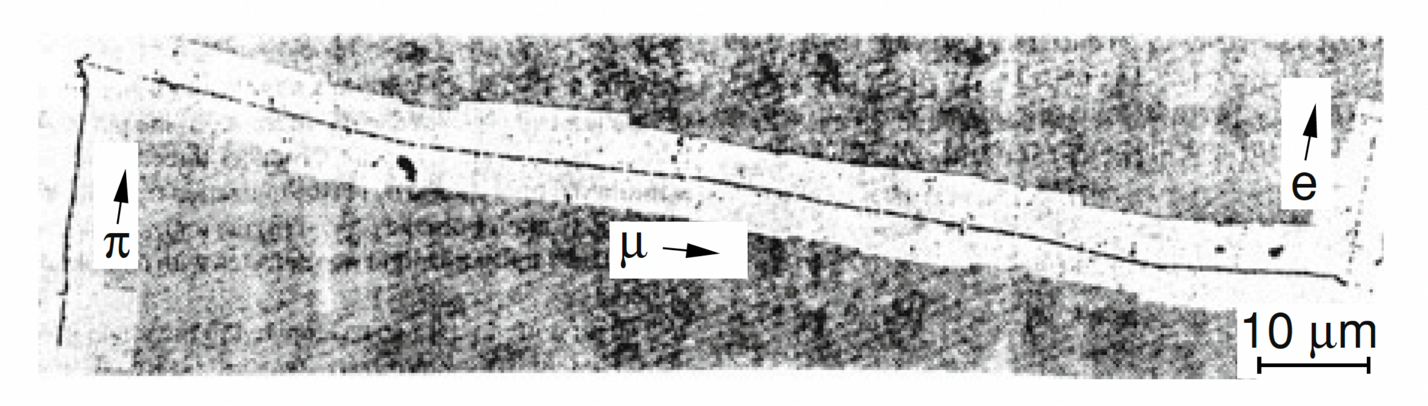

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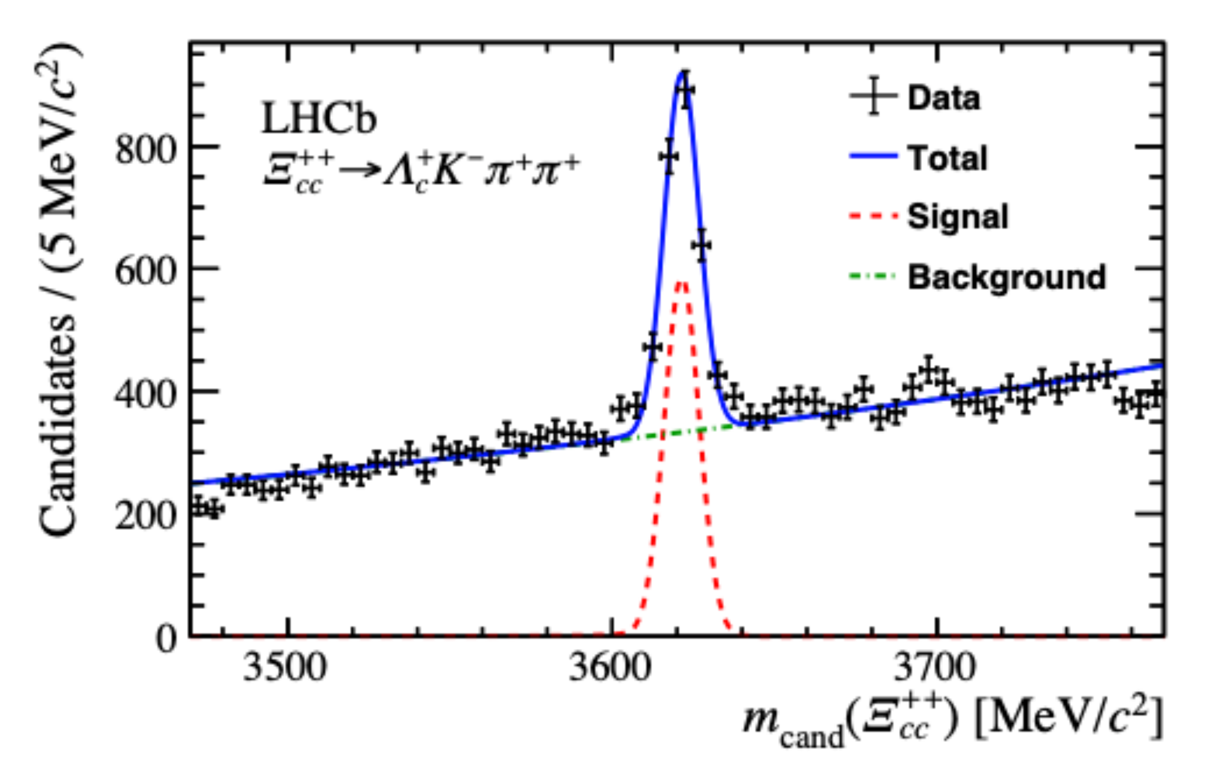

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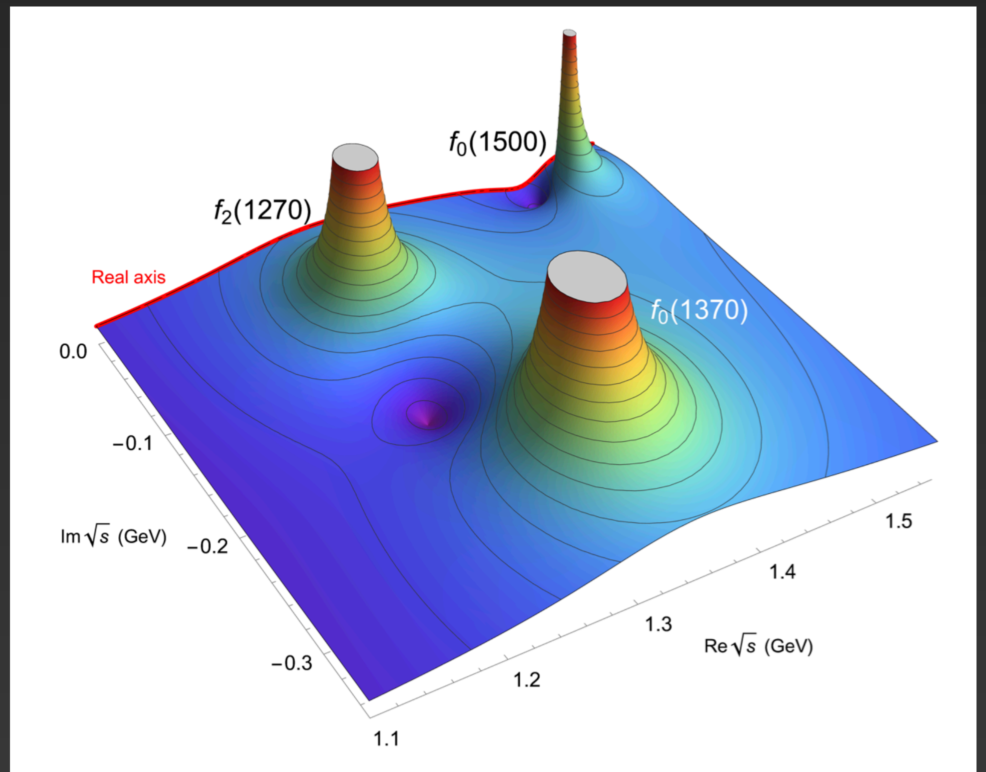
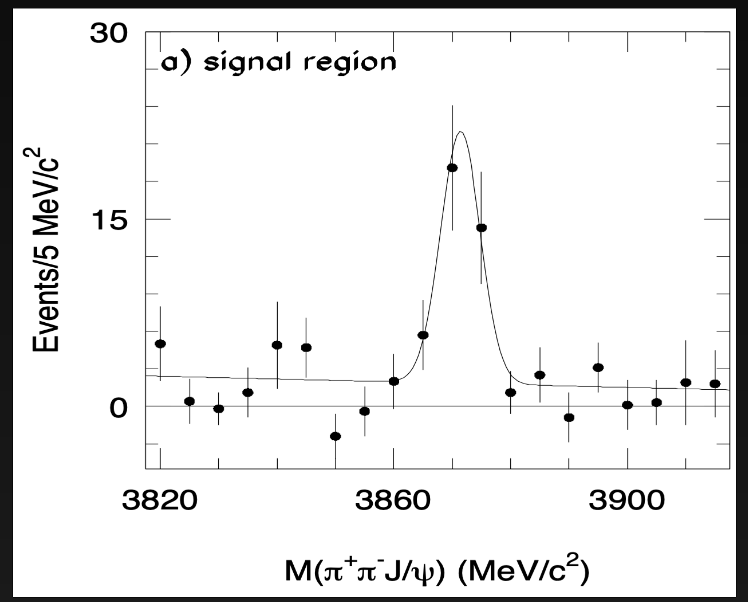


PRL 130 (2023) 5, 5

Hadron spectroscopy

What does not fit: Exotic hadrons



$X(3872)$

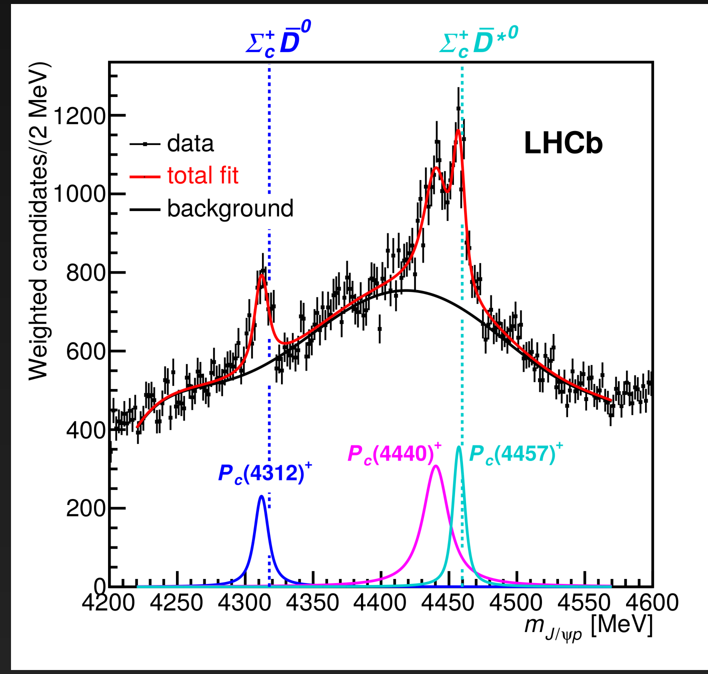
in $B \to KJ/\psi\pi\pi$

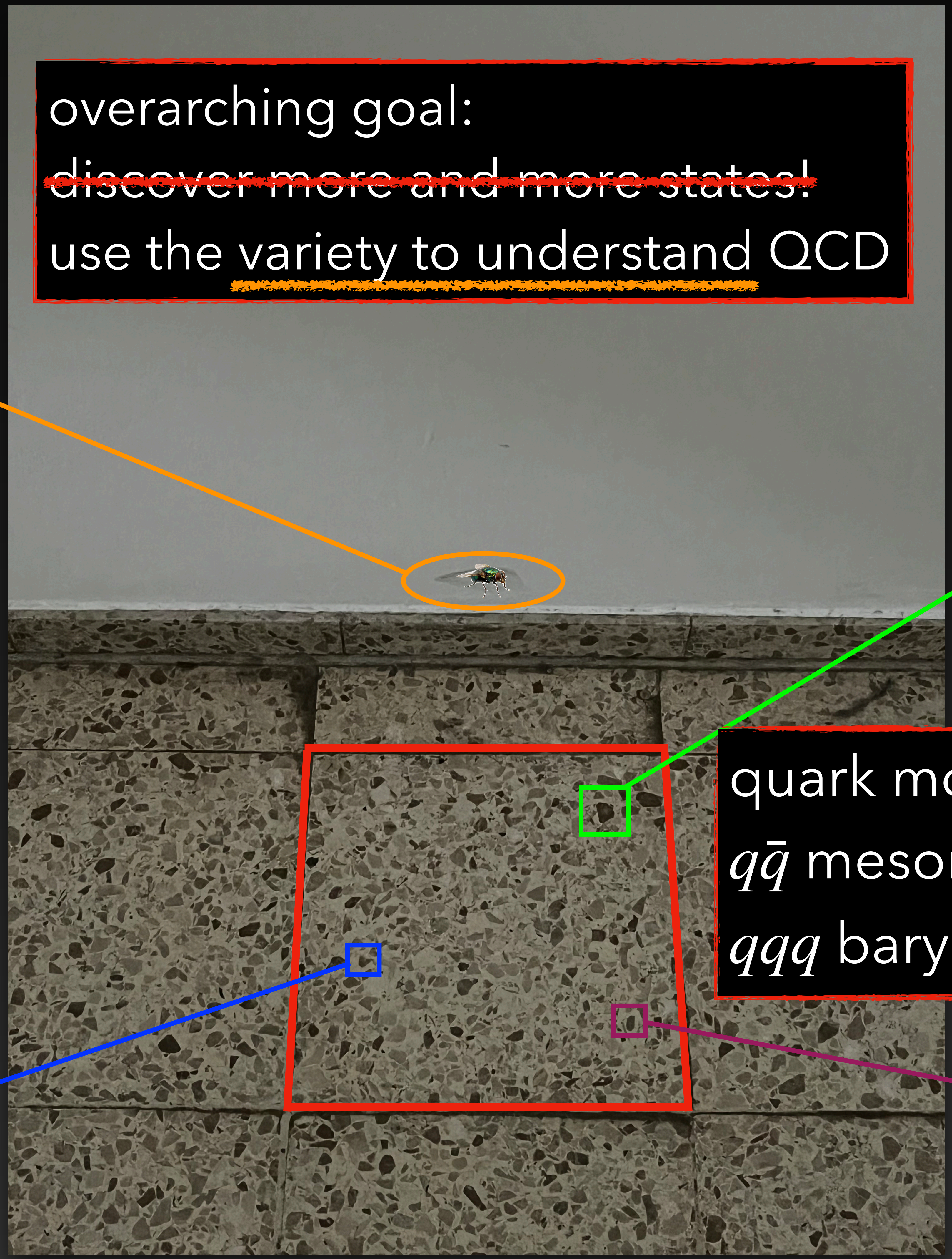
PRL 91, 262001 (2003)

$P_{c\bar{c}}$-states

in $\Lambda_b \to KJ/\psi p$

PRL 122 (2019) 22, 222001





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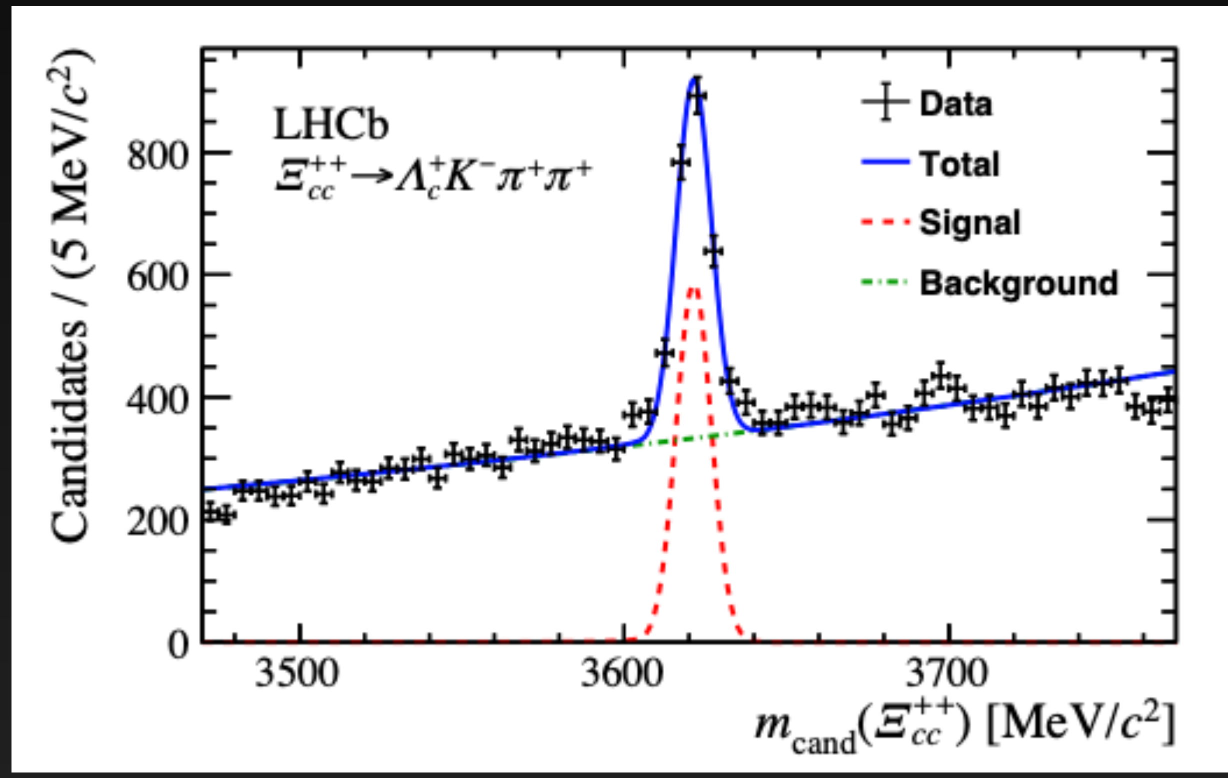

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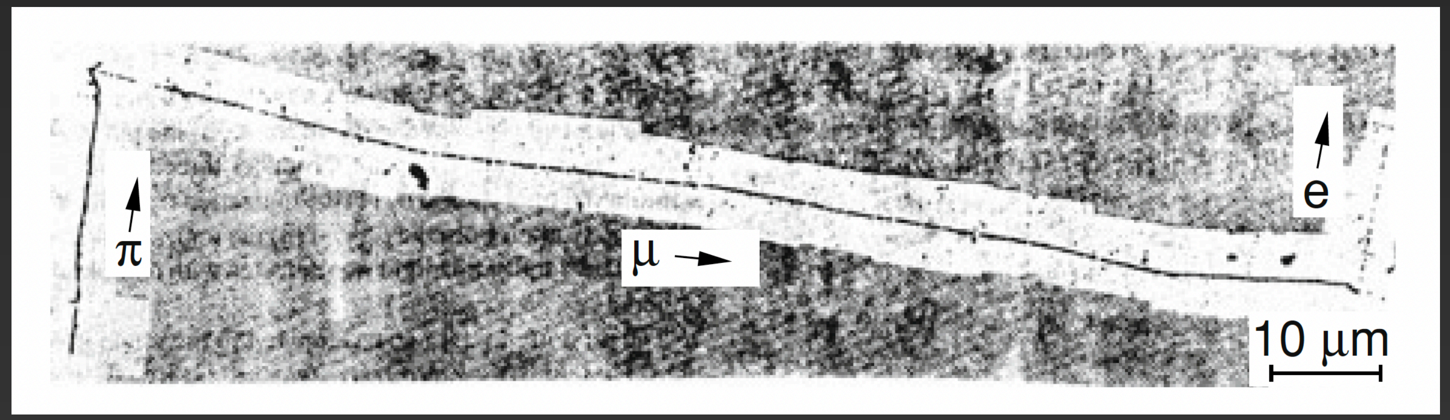

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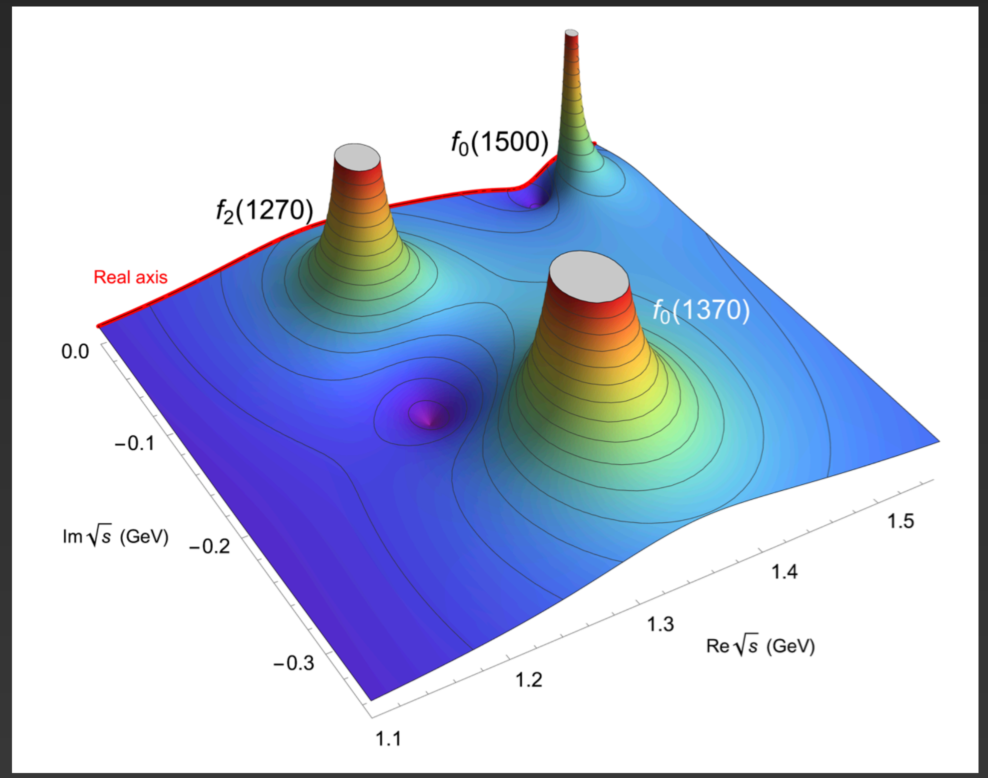
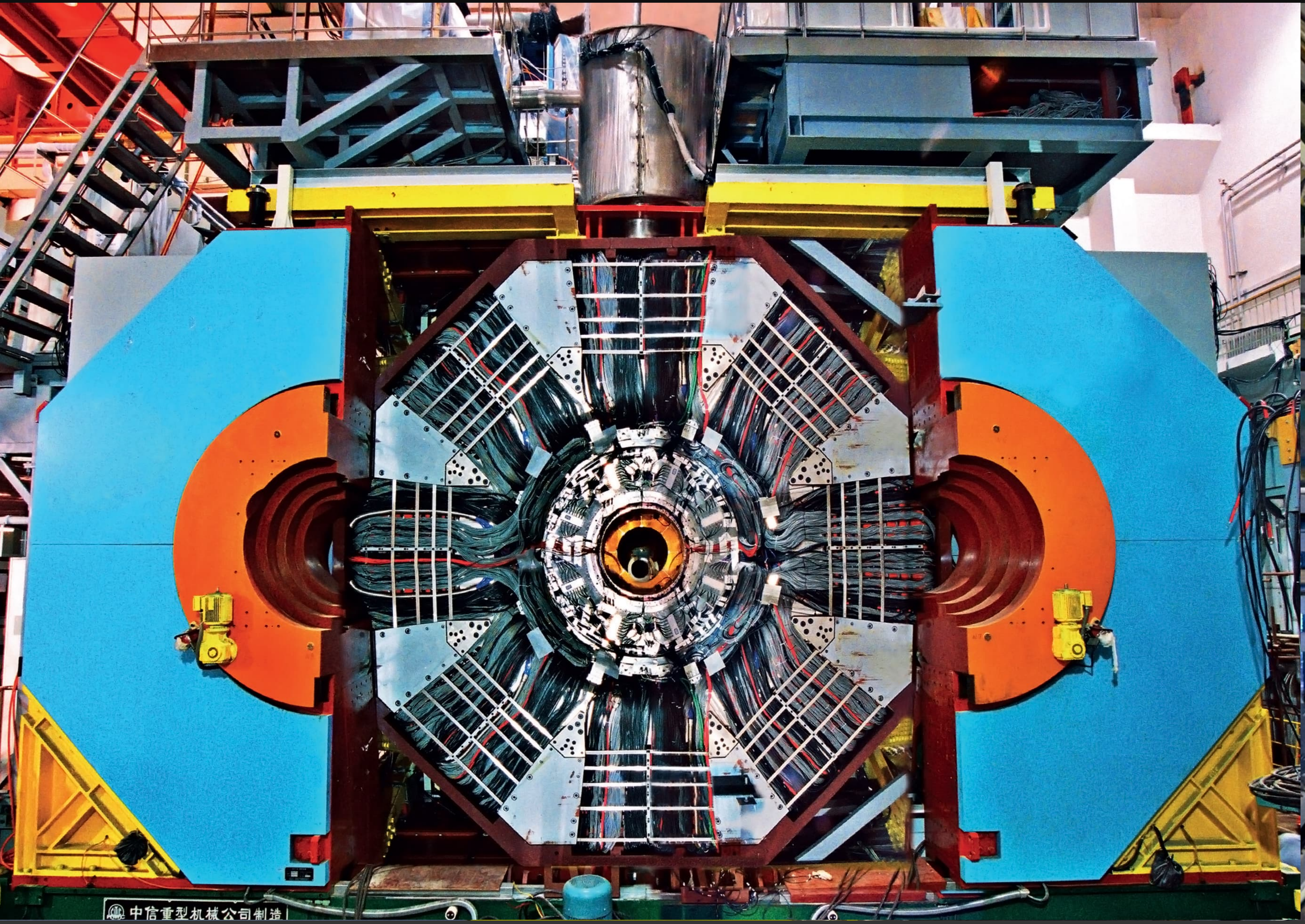
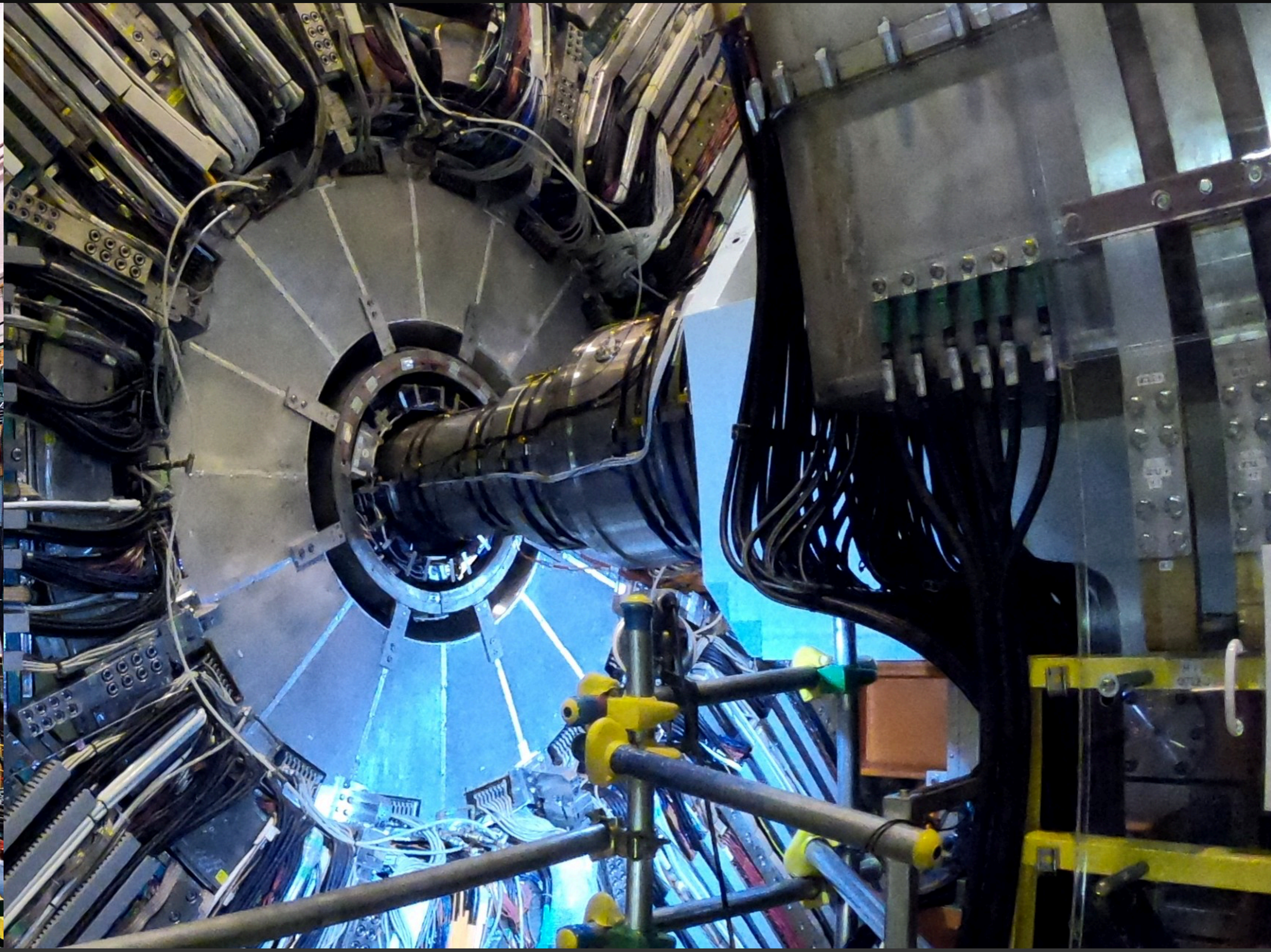


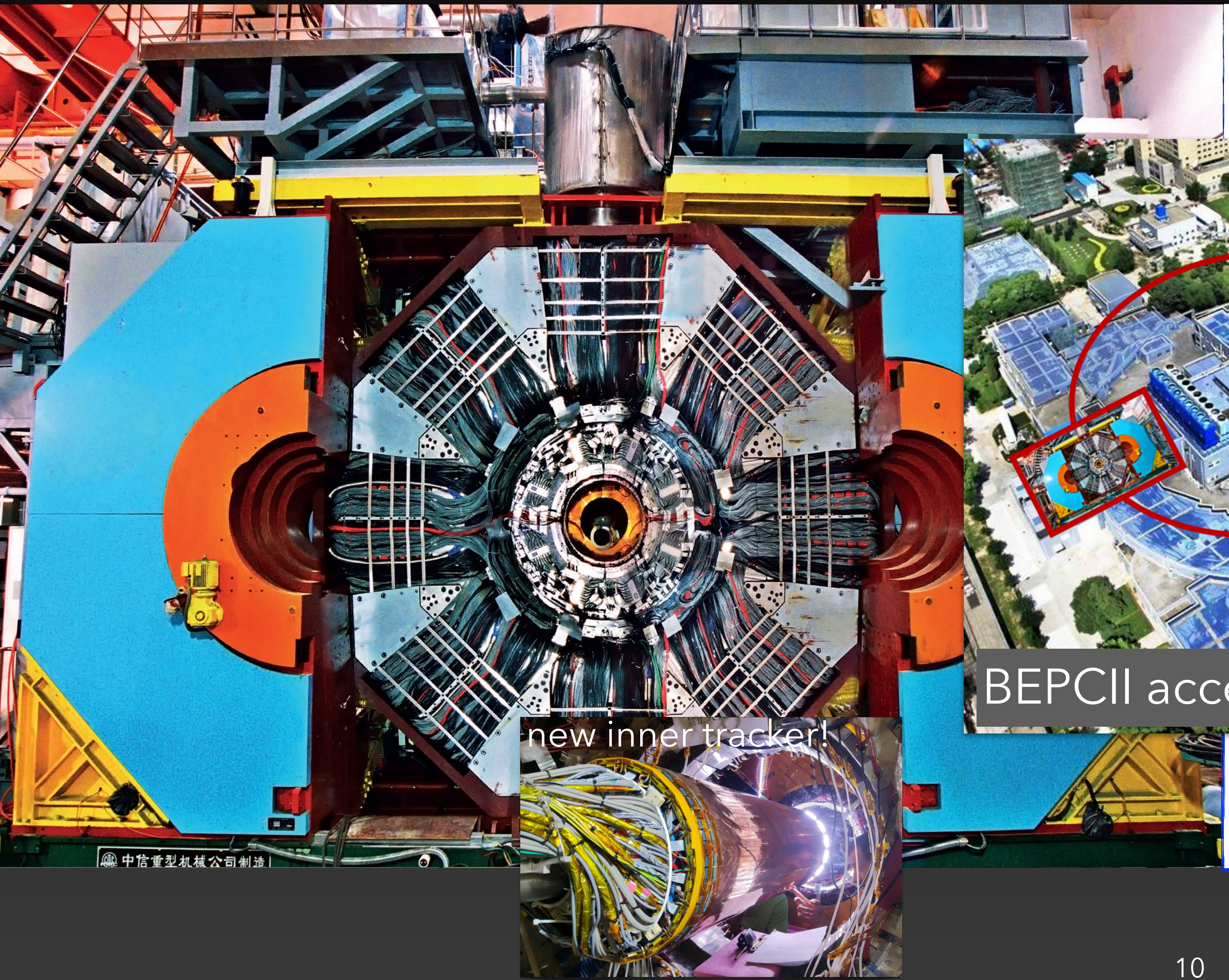
PRL 130 (2023) 5, 5

… at e^+e^- machines

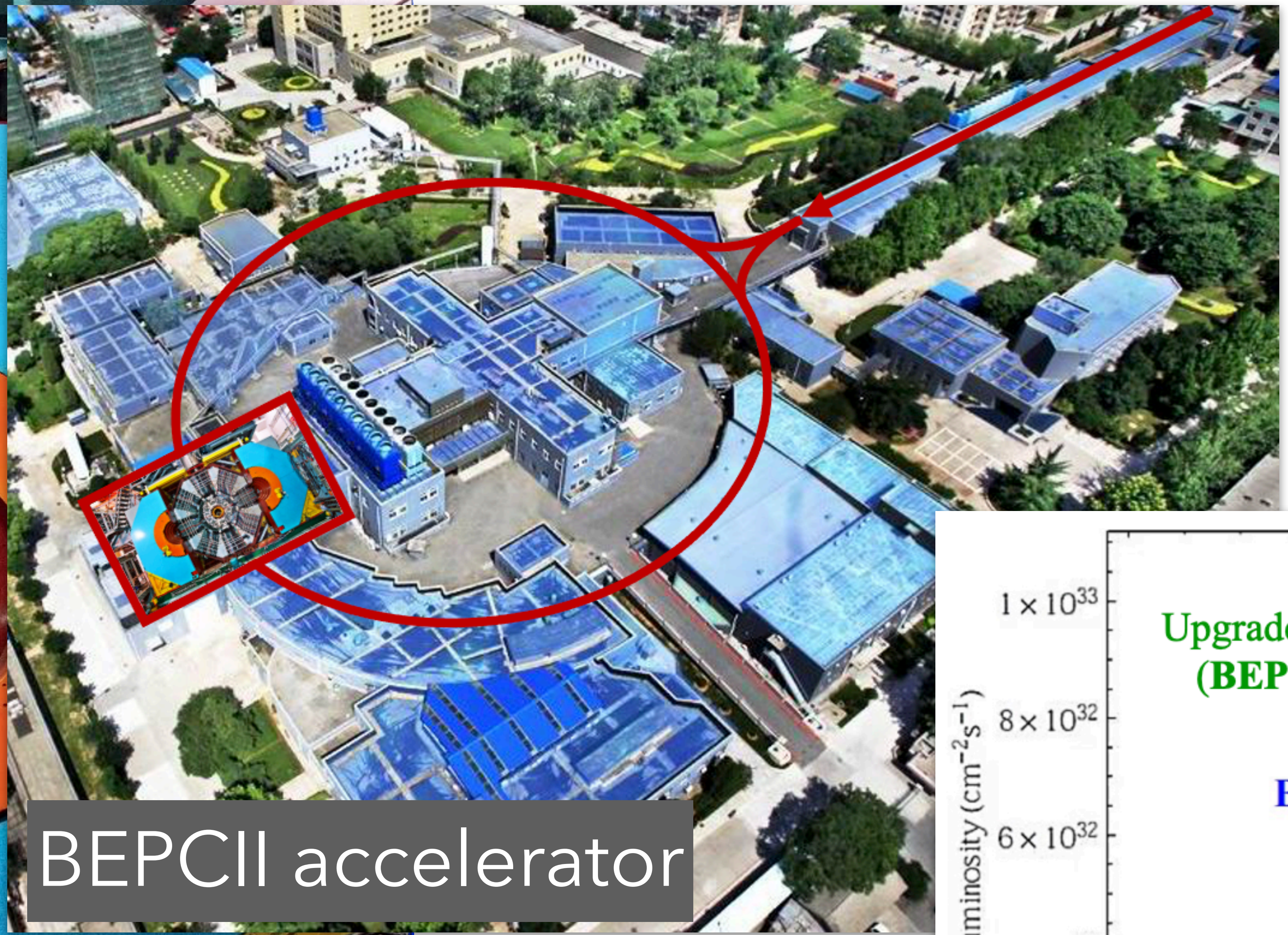




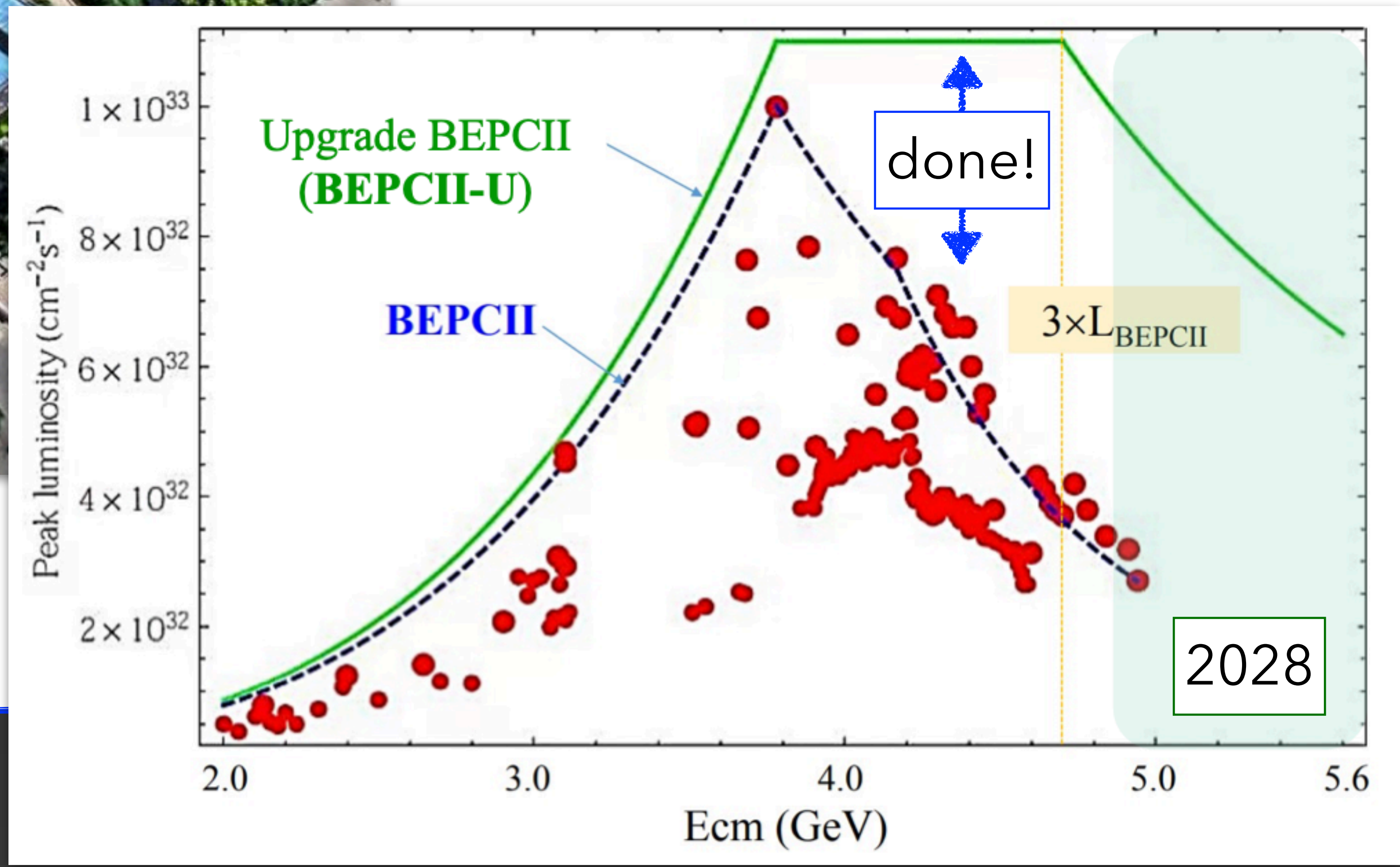
… at e^+e^- machines



The BESIII experiment



- located at IHEP, Beijing
- operating in τ-charm region: 2 GeV – 5 GeV
- undergoing upgrades:



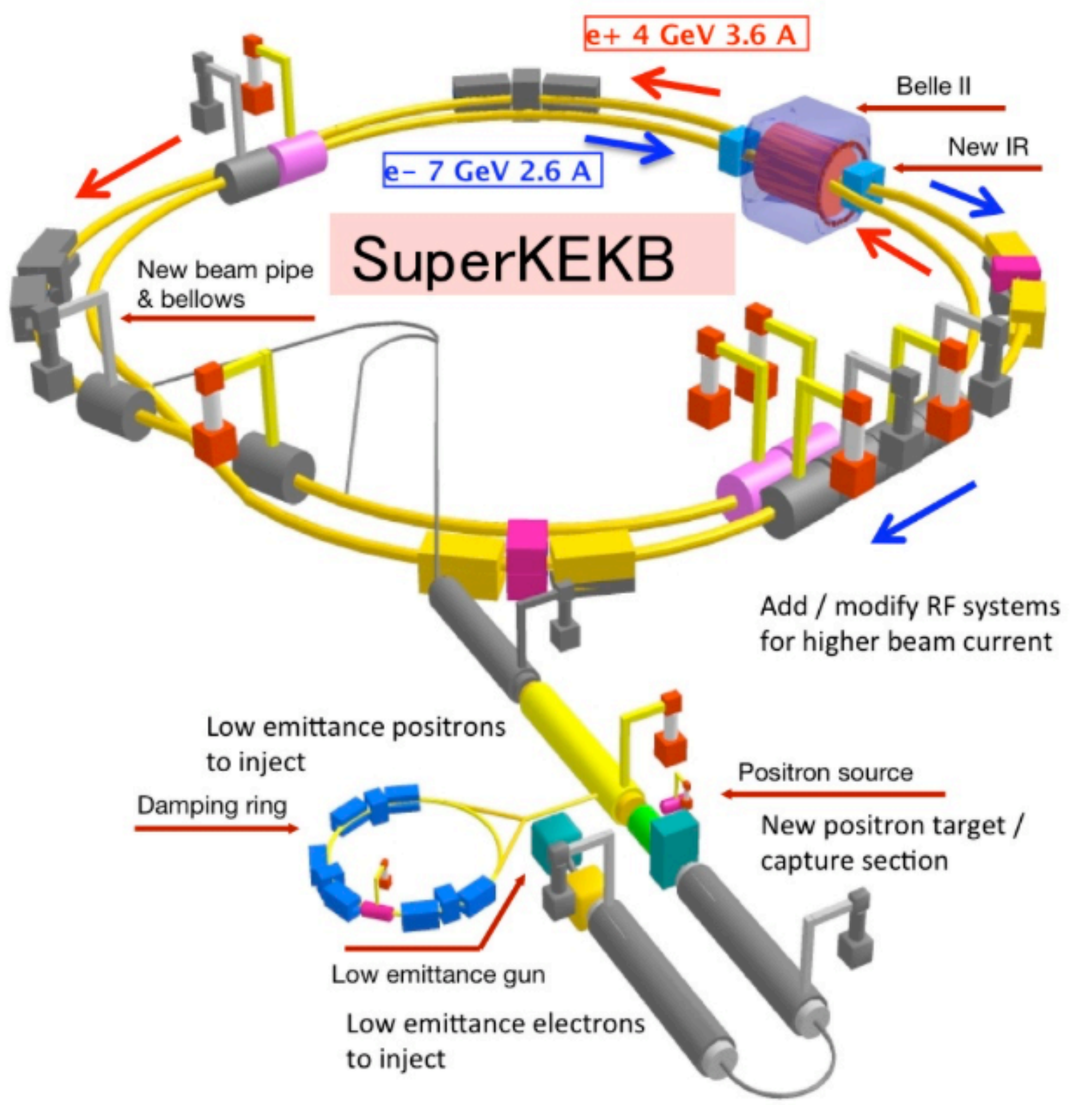
… at e^+e^- machines

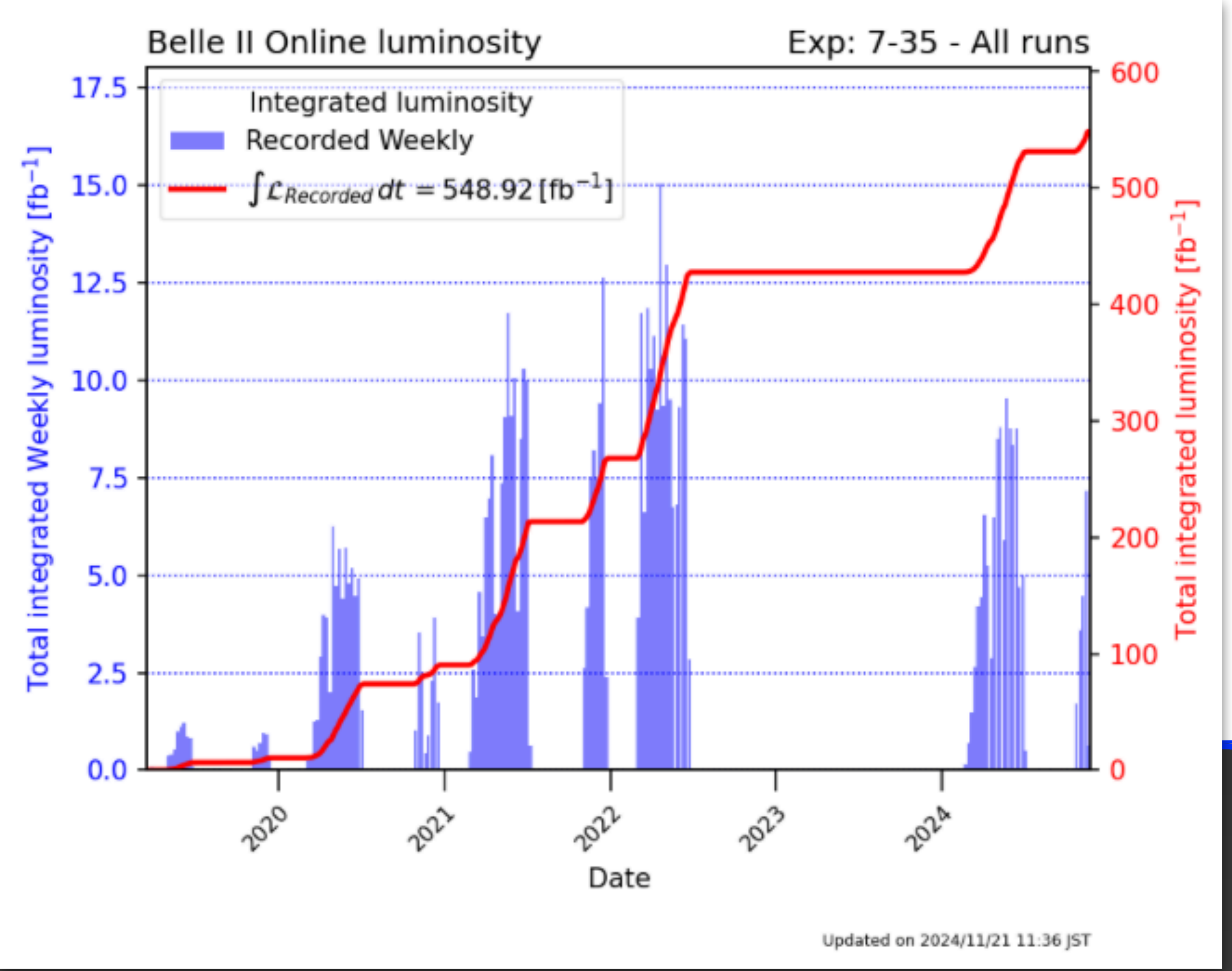
The Belle II experiment

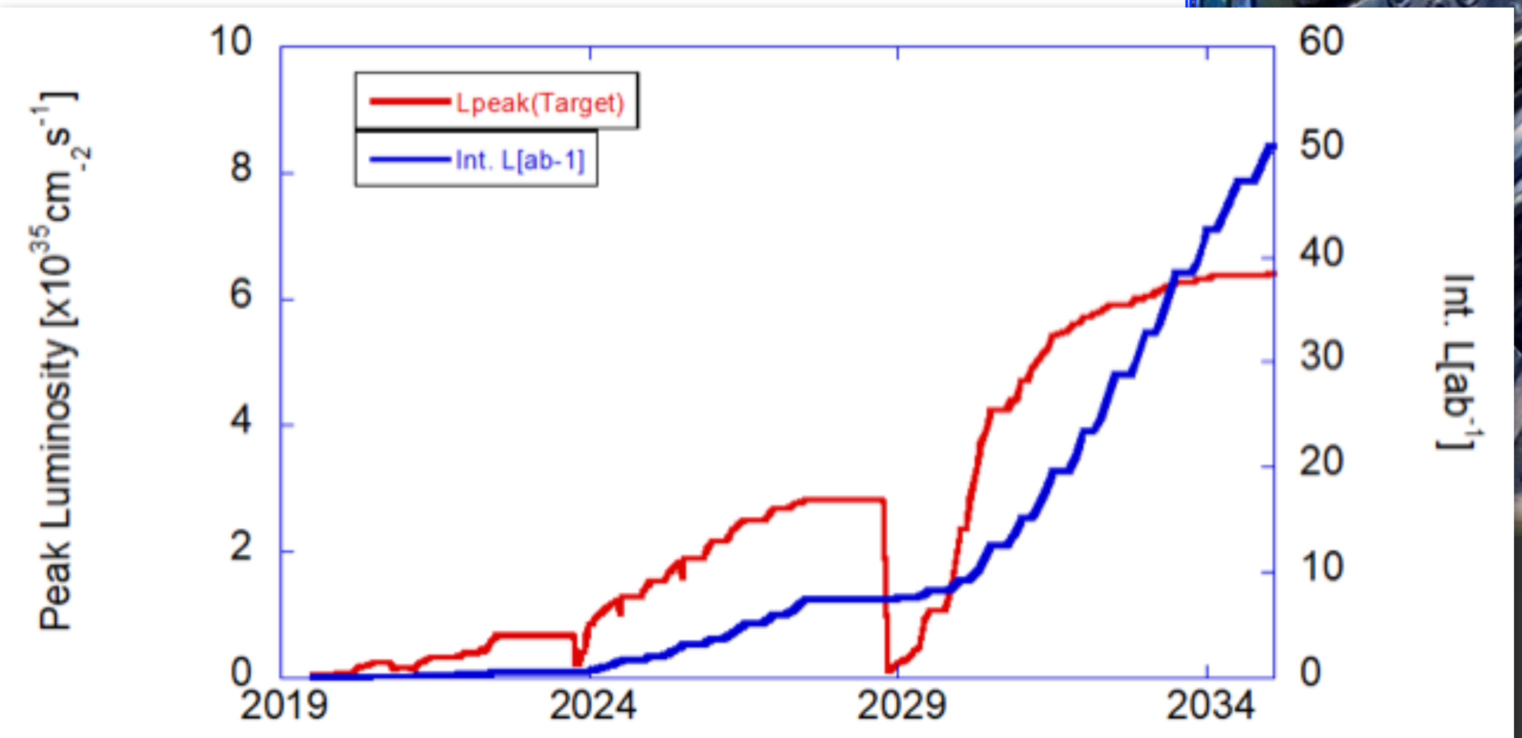
- located at KEK, Tsukuba

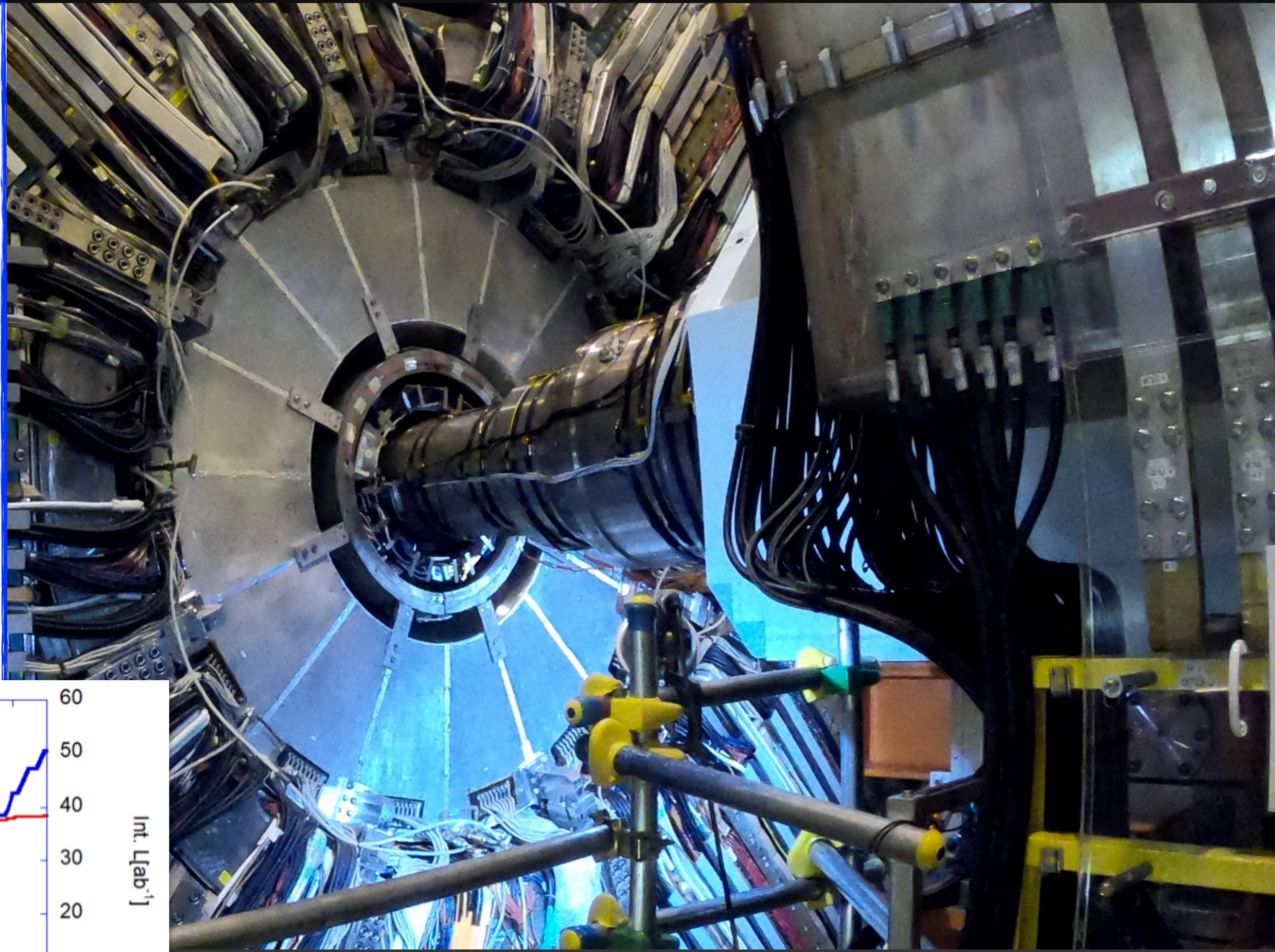
- successor to the B-factories, operating in bottomonium region

- world-record luminosity 4.7×10^{34} cm^{-2} s^{-1}



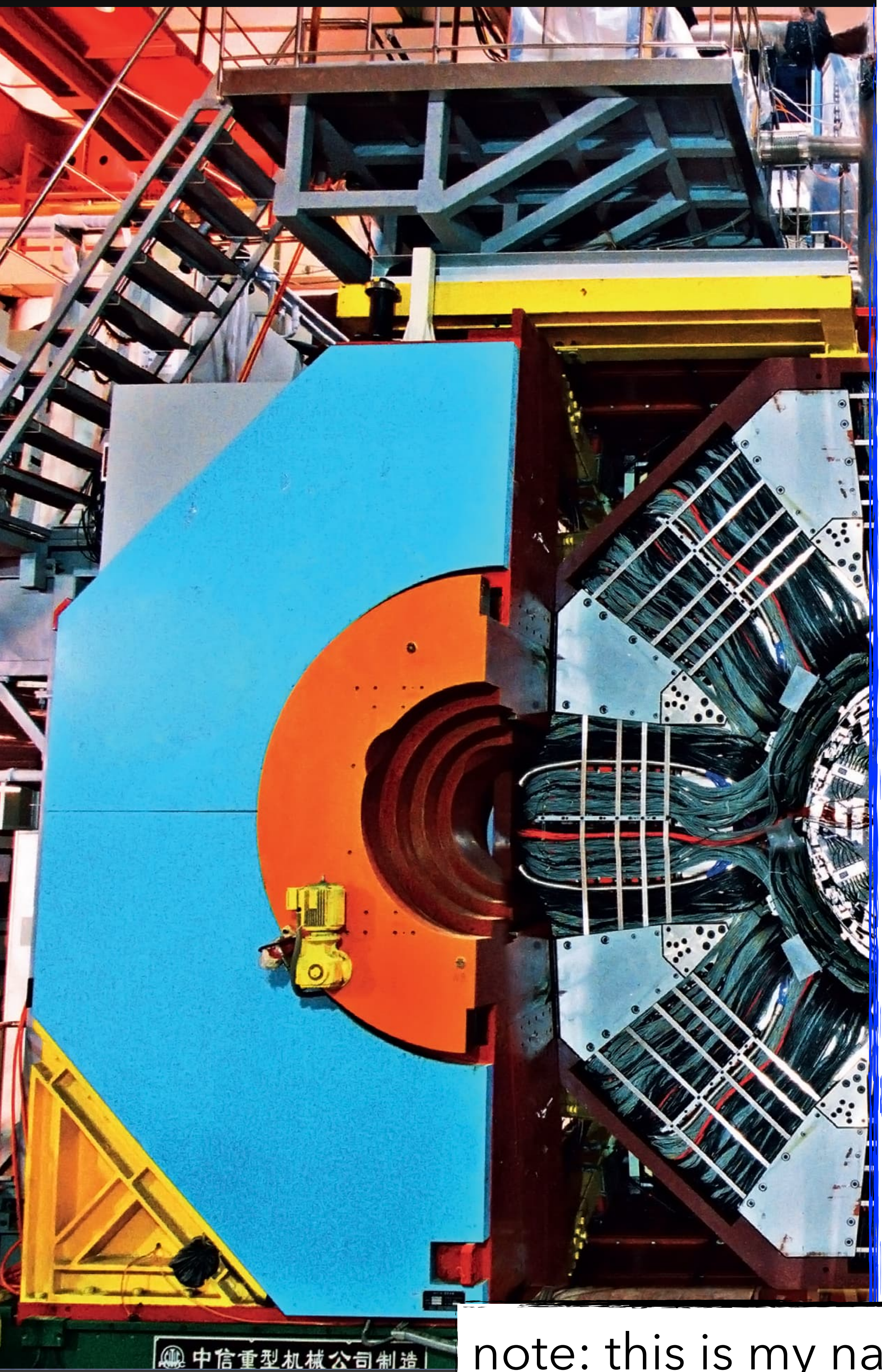






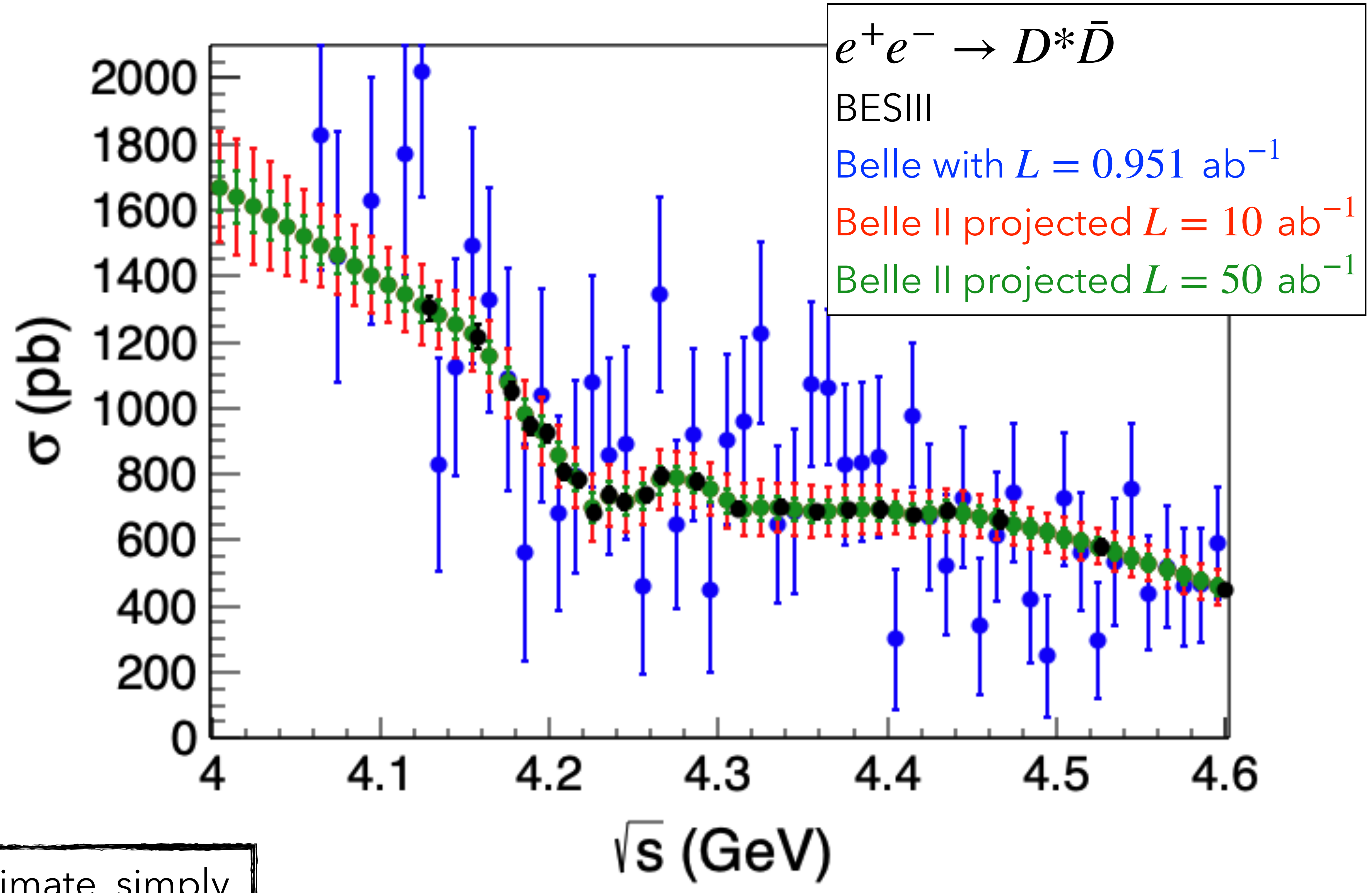
not a Belle II member, apologies if I misrepresent s.th.

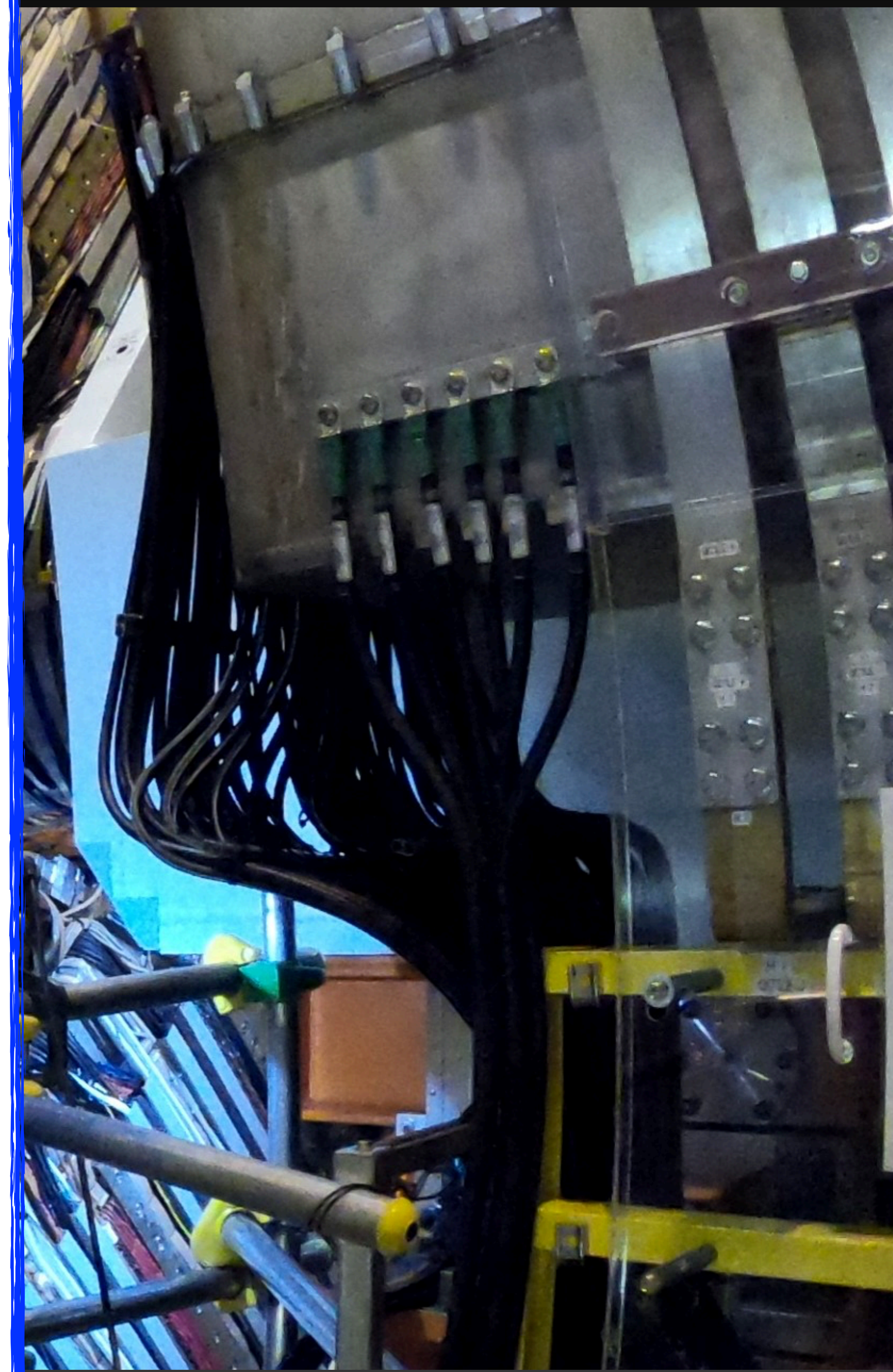
… at e^+e^- machines



A simple comparison: BESIII vs. Belle II ISR

(or: why to discuss Belle II in the context of spectroscopy in JLab 22 GeV era)

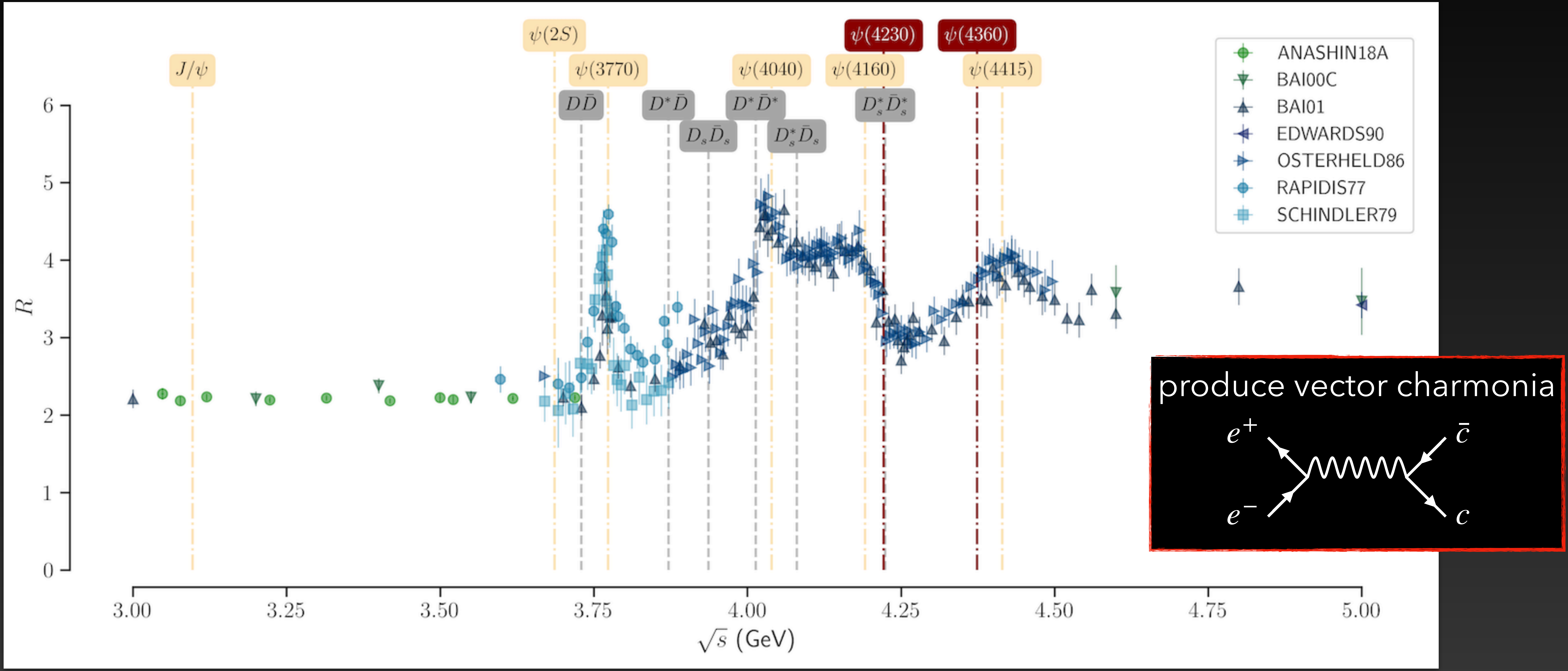




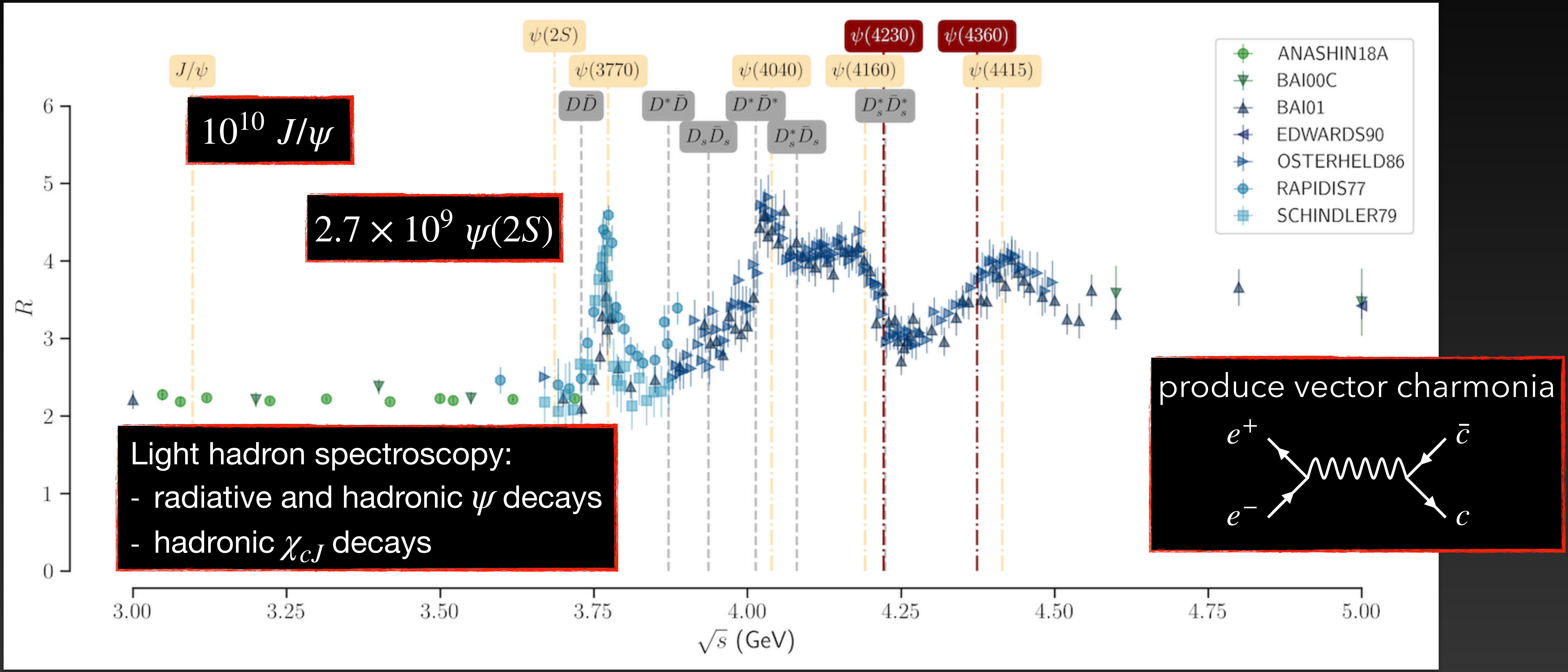
note: this is my naive estimate, simply scaling Belle precision by luminosity

not a Belle II member, apologies if I misrepresent s.th.

What we do well



Light hadrons



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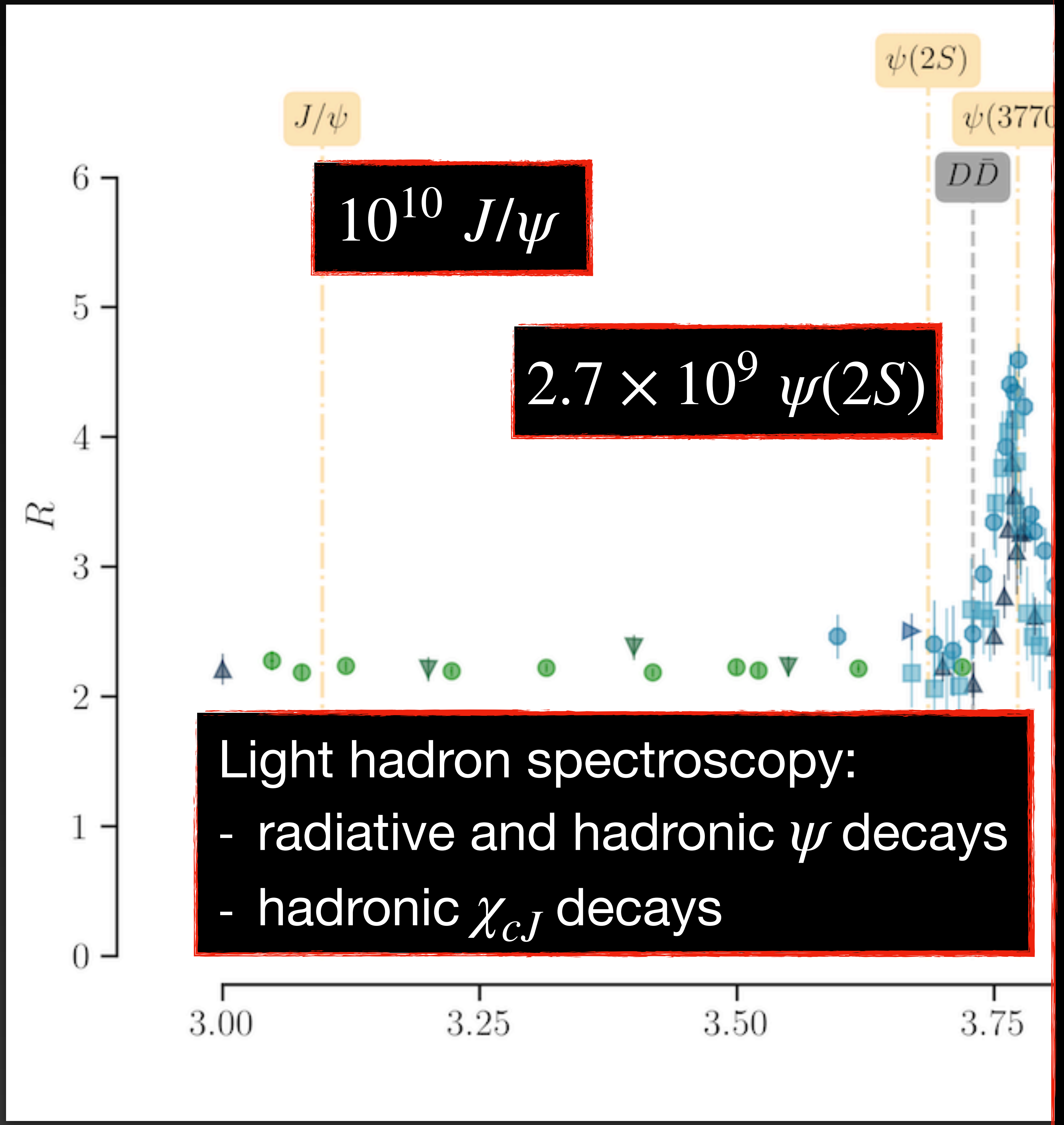


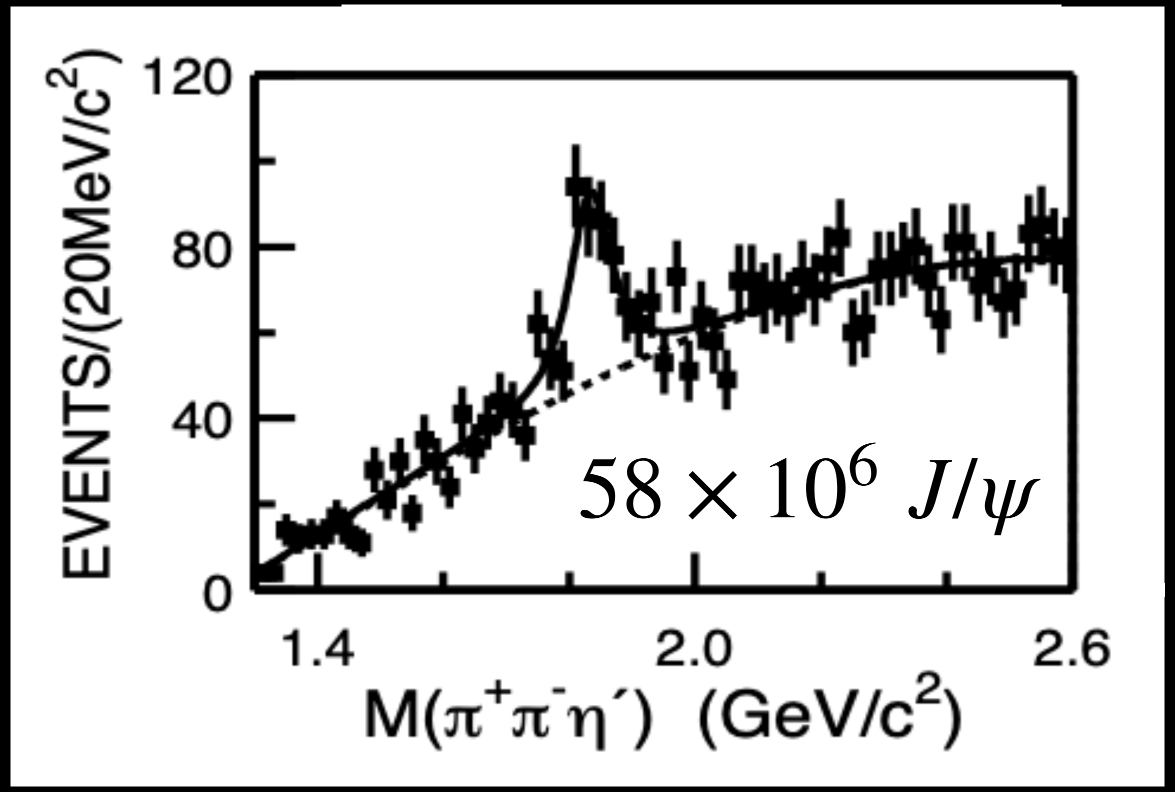
10^{10} J/ψ

2.7×10^{9} $\psi(2S)$

Light hadron spectroscopy:
- radiative and hadronic ψ decays
- hadronic χ_{cJ} decays

$J/\psi \to \gamma\eta'\pi\pi$ - or: no such thing as enough J/ψ

PRL 95 (2005) 262001



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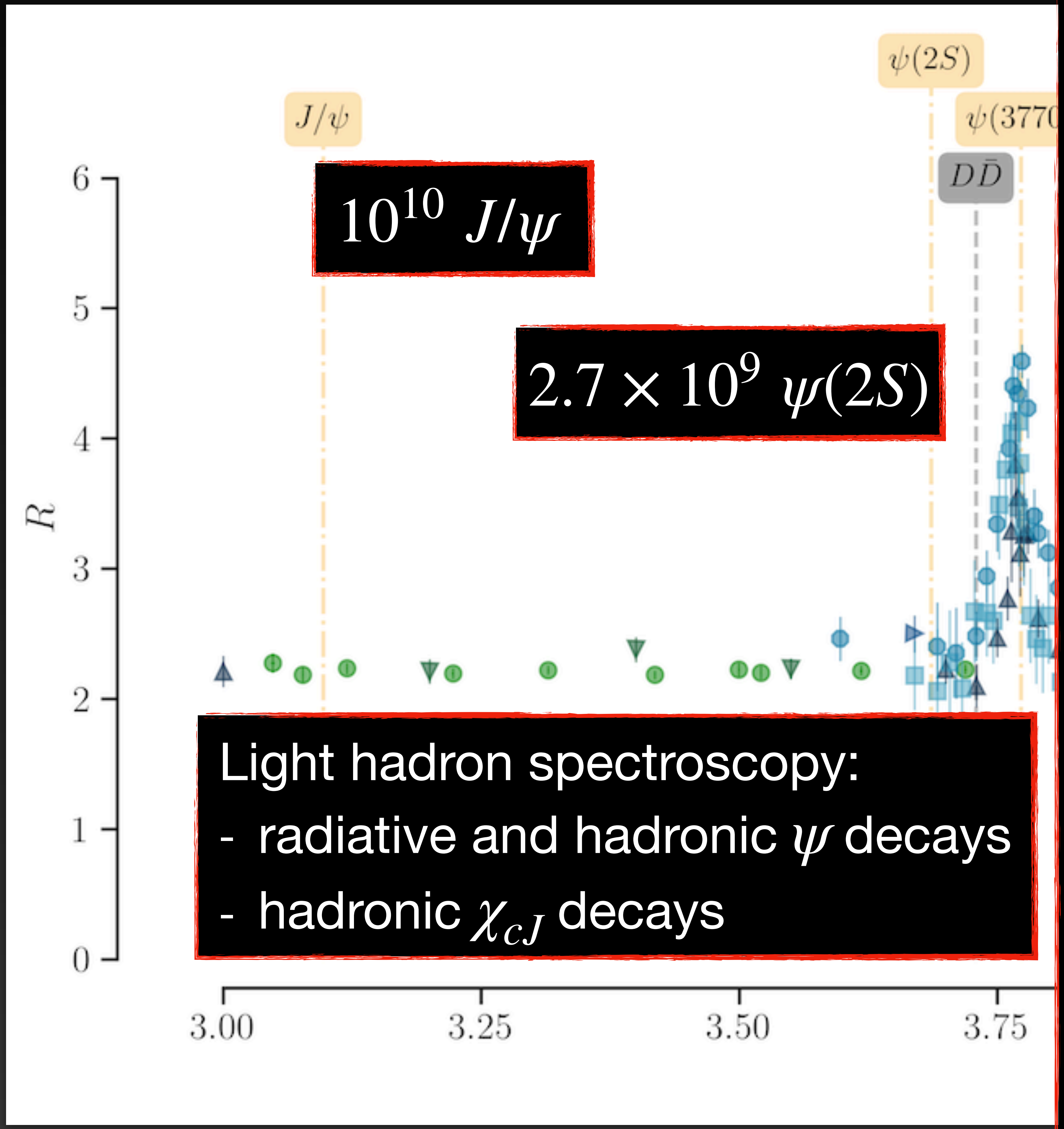

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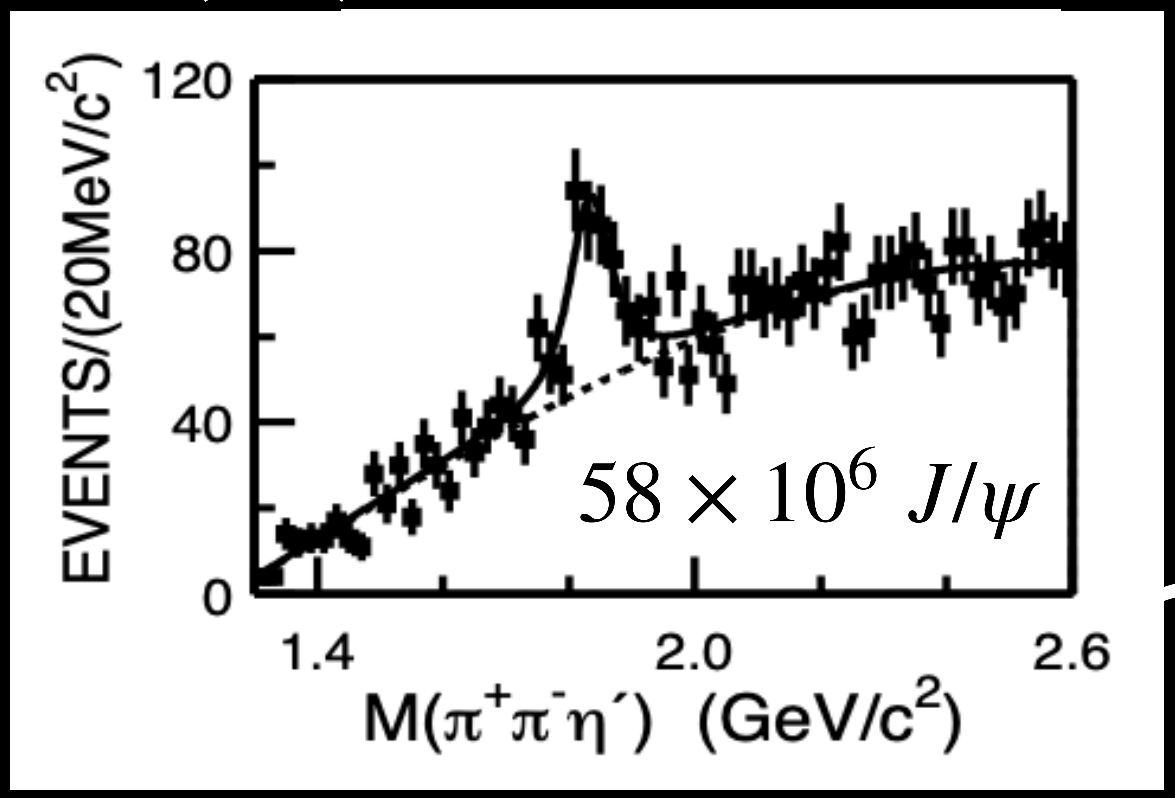
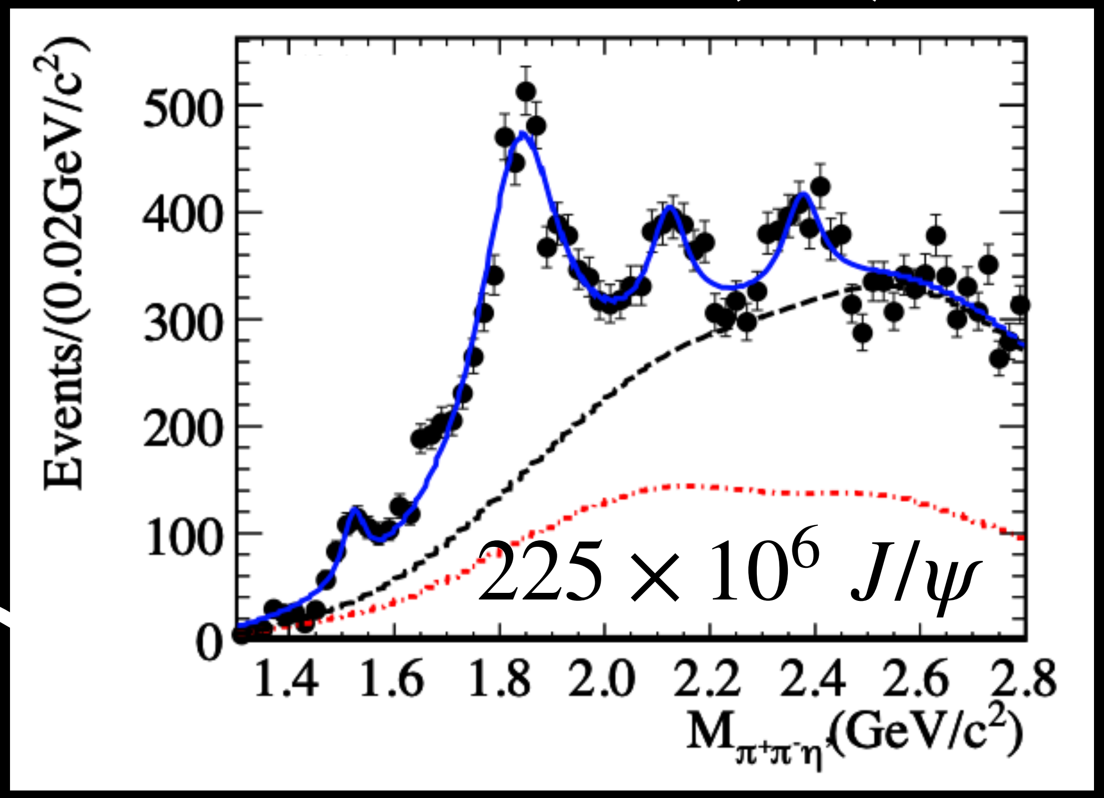


PRL 106 (2011) 072002



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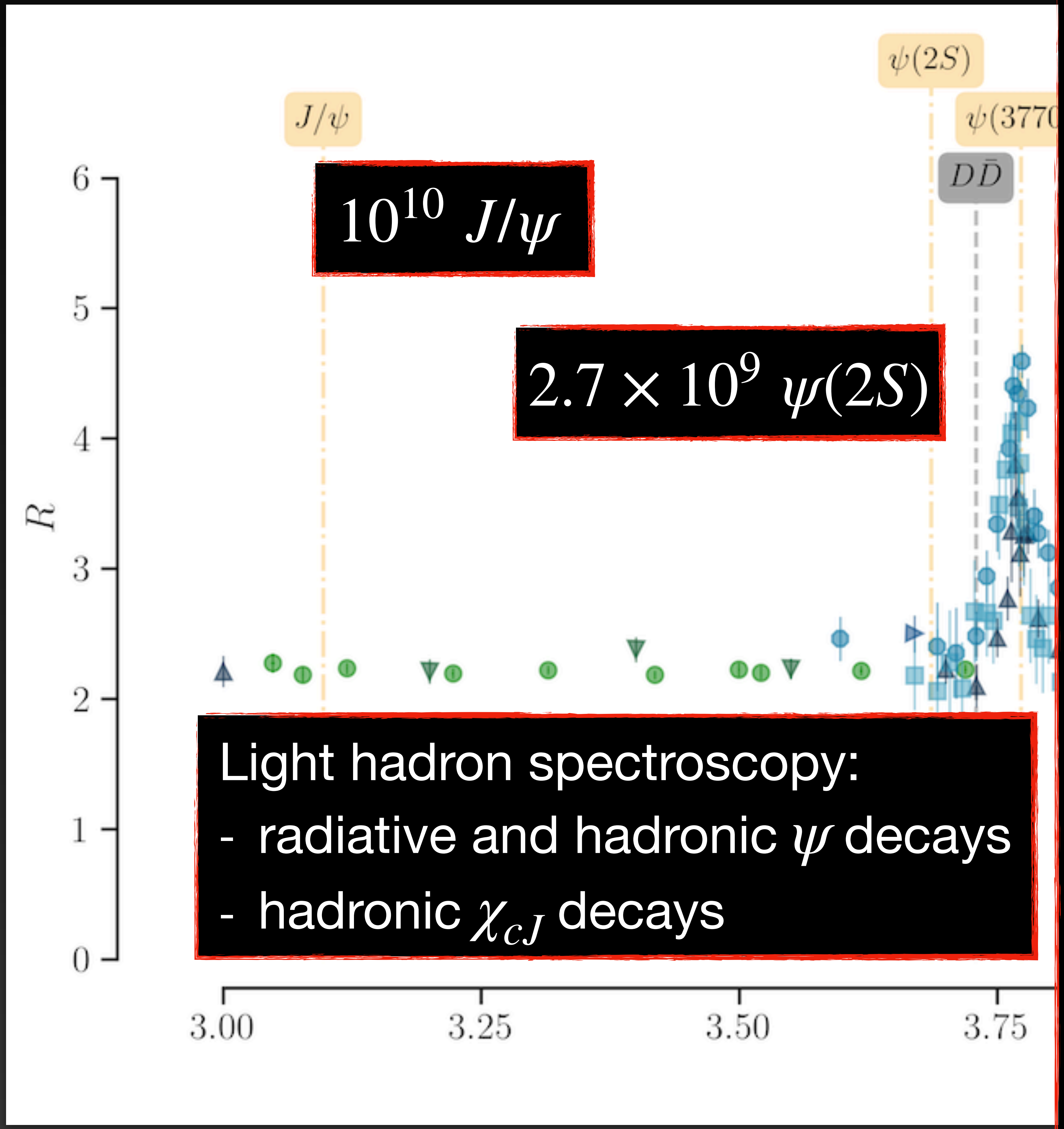

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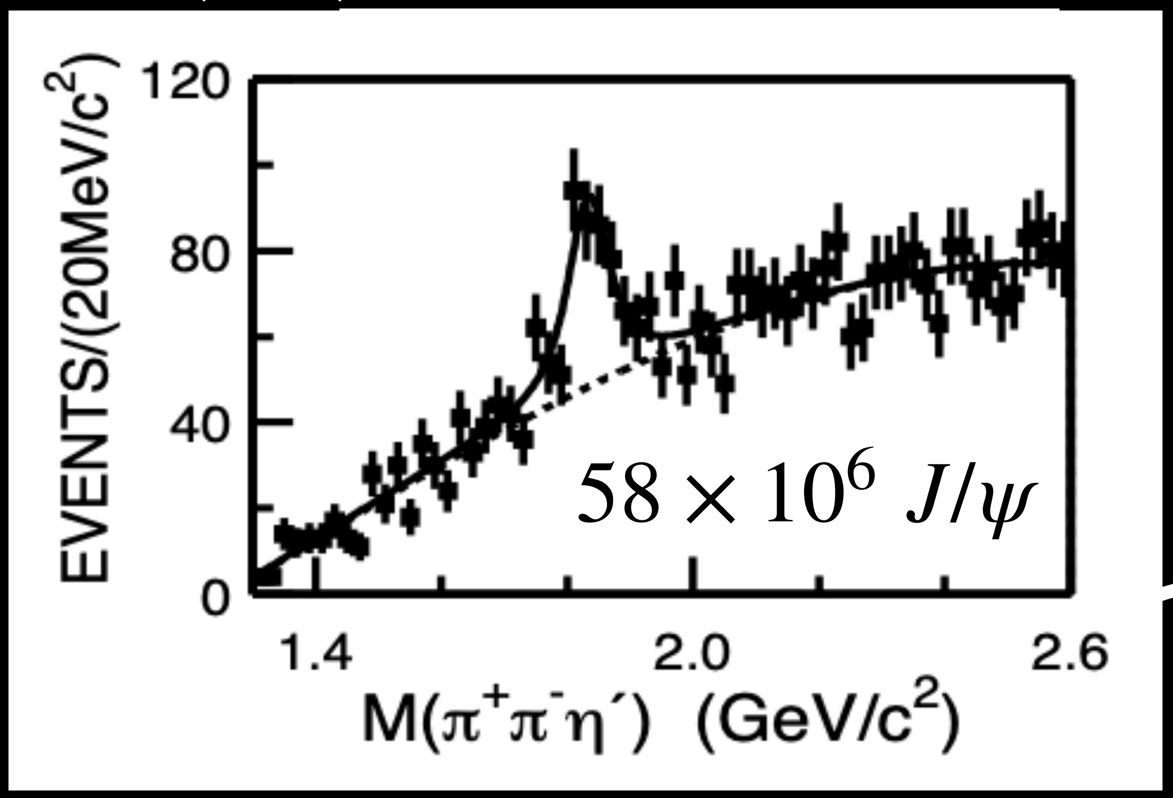
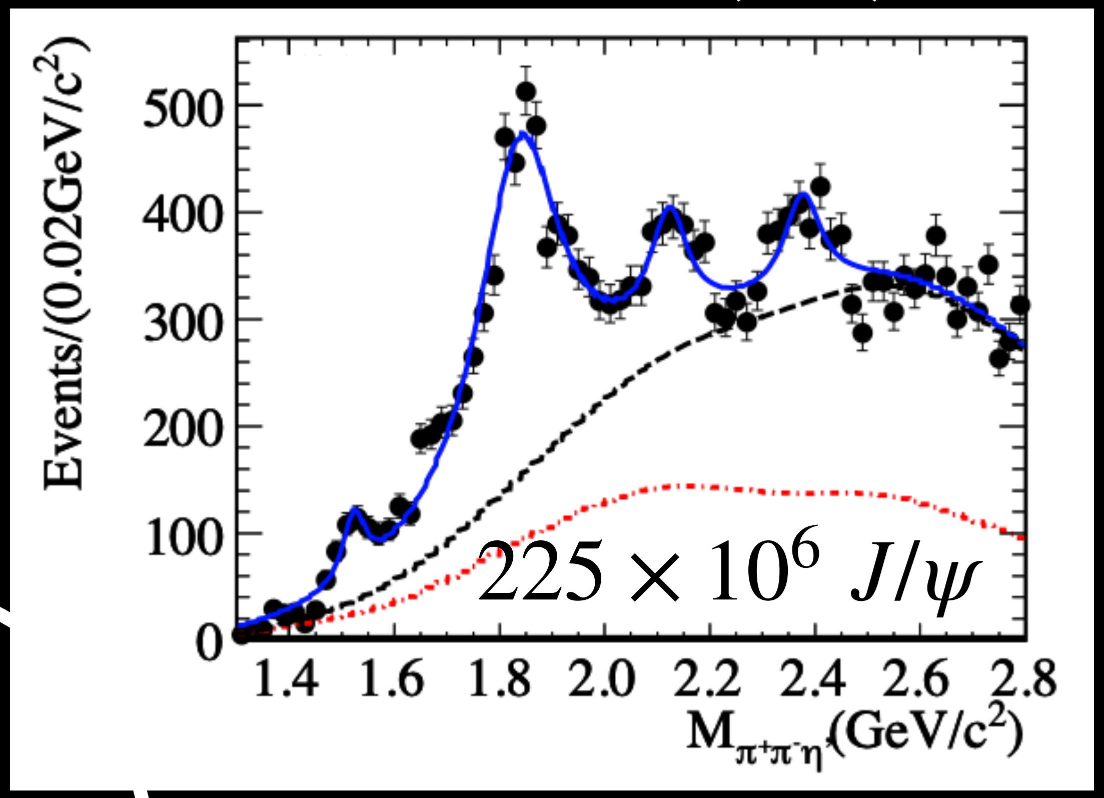
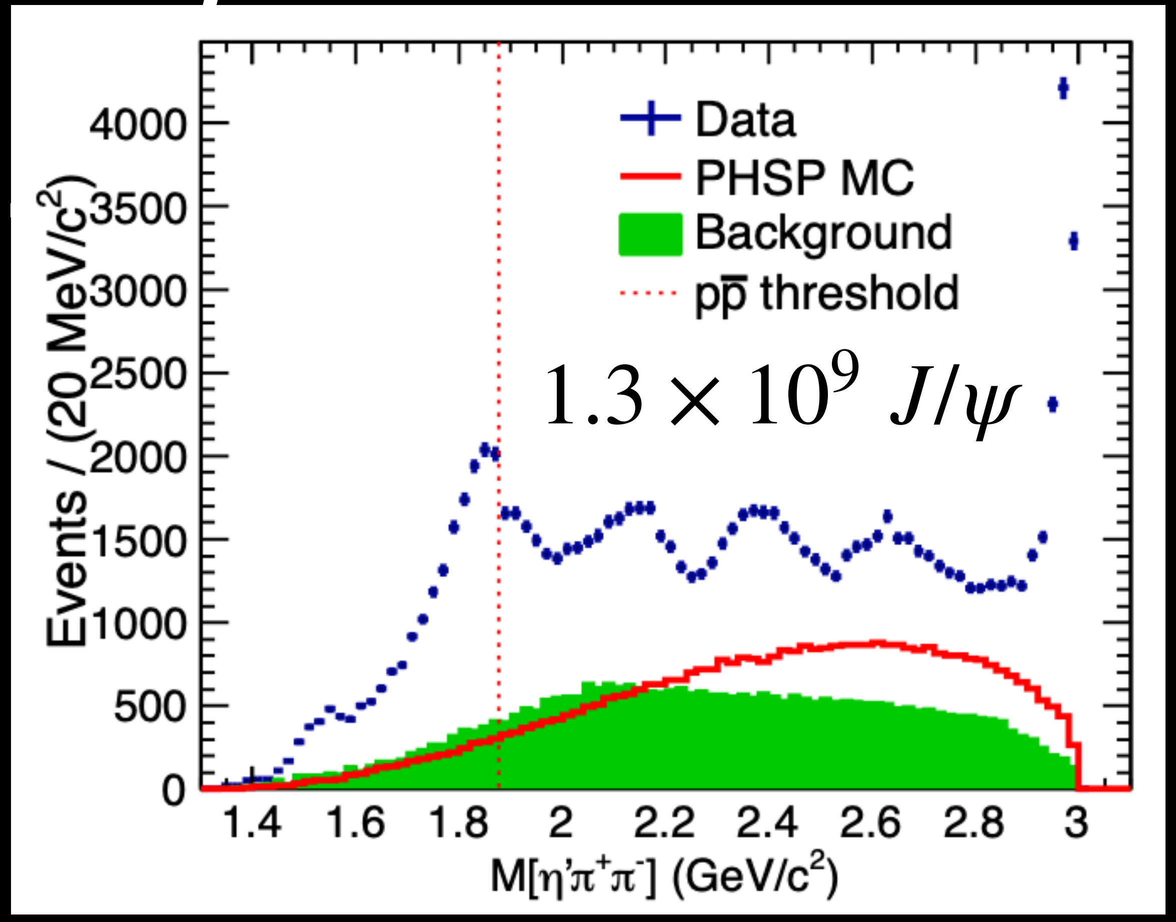


PRL 106 (2011) 072002



PRL 117 (2016) 4, 042002



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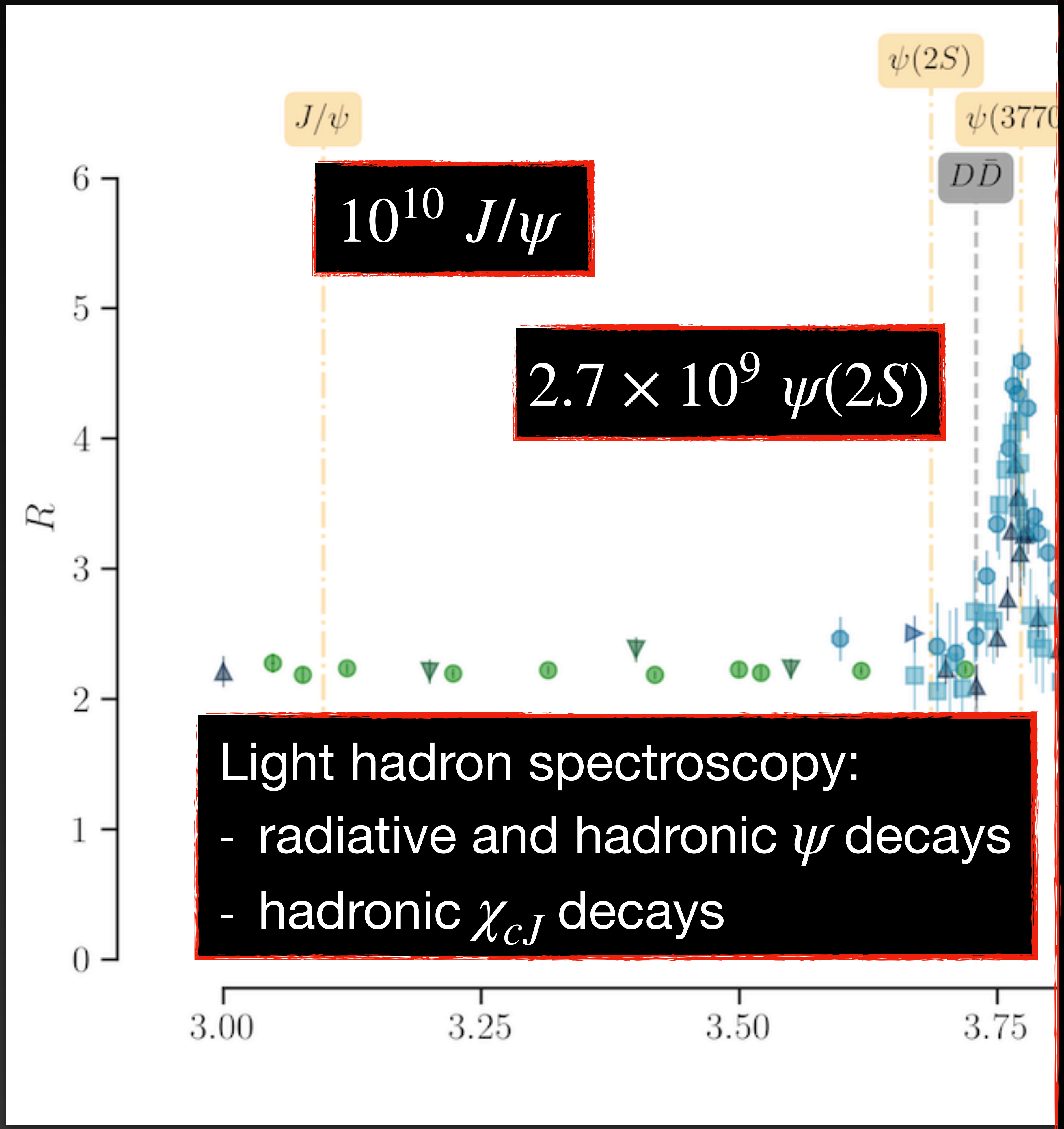

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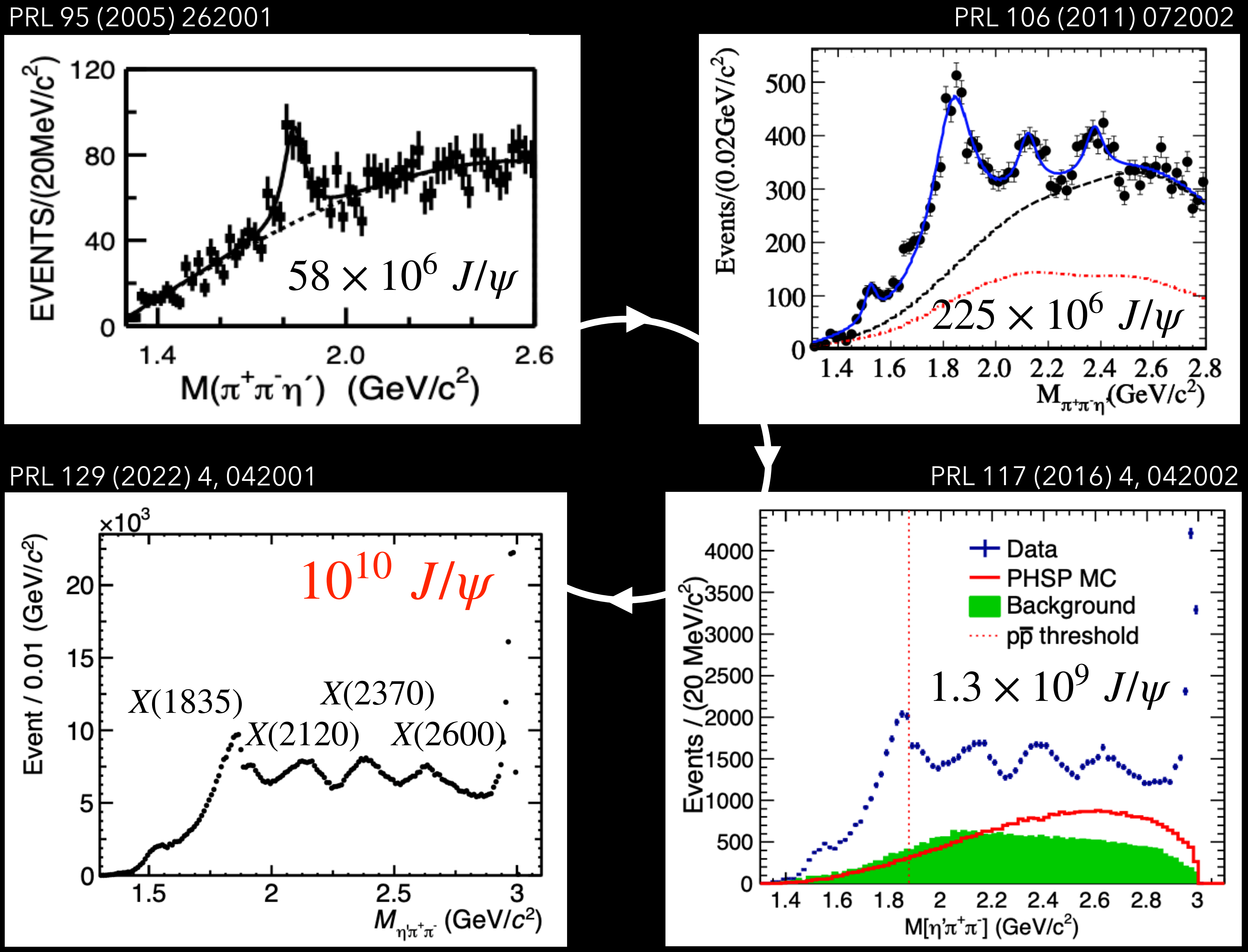

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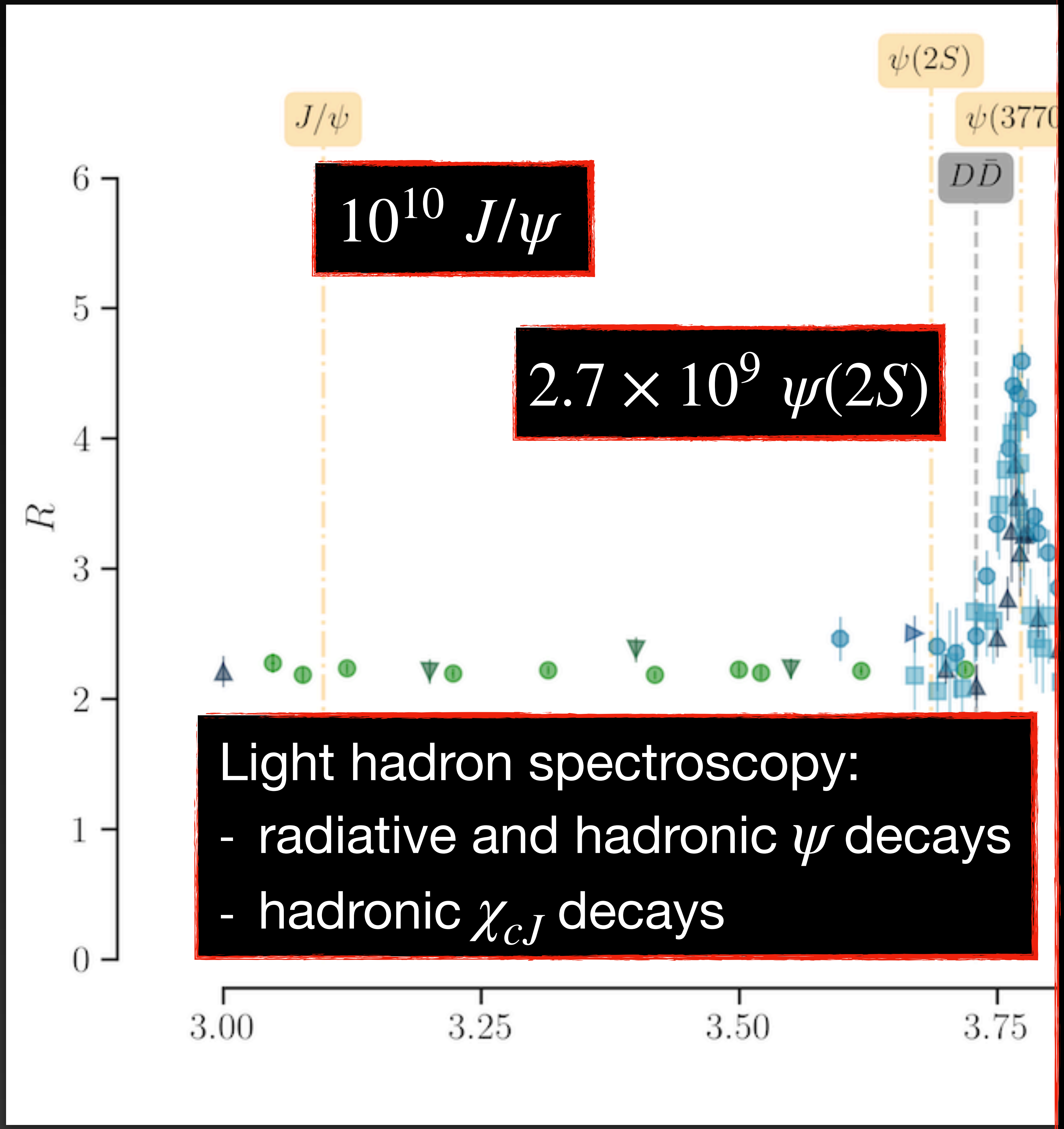

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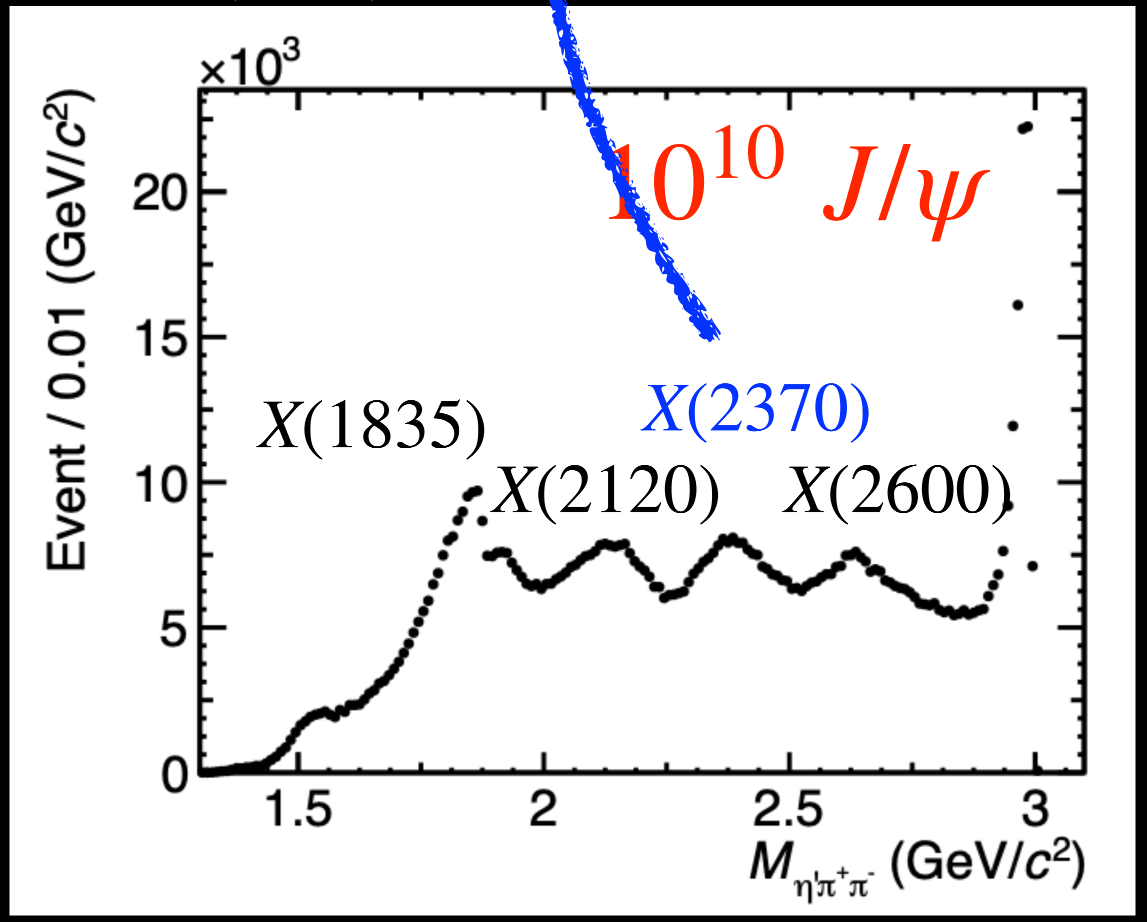
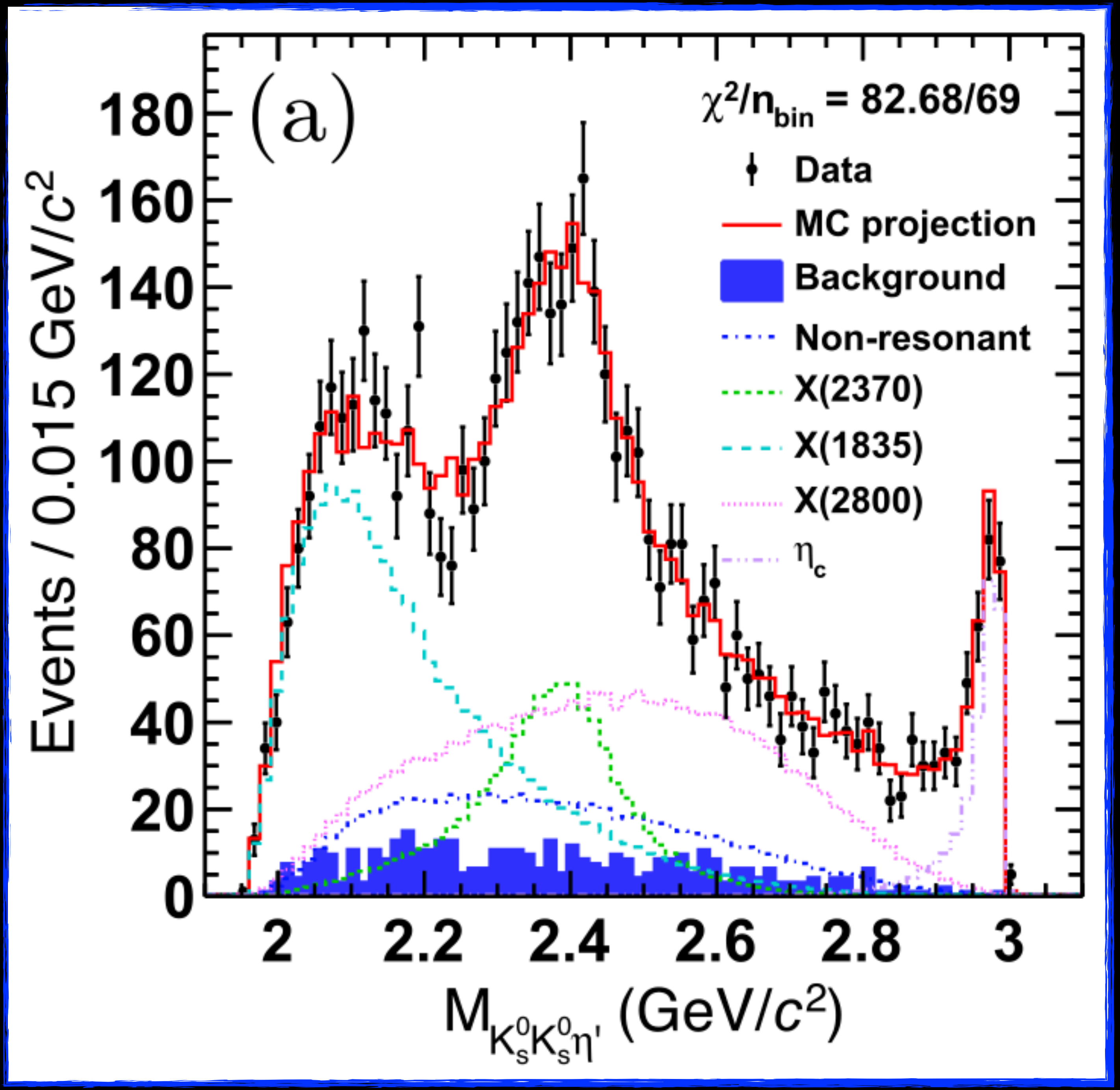
determination of spin and parity in $J/\psi \to \gamma\eta' K_S^0 K_S^0$

PRL 129 (2022) 4, 042001





PRL 132, 181901 (2024)

the $X(2370)$ is a pseudoscalar!

(mass in the ballpark where pseudoscalar glueball is expected)

Light hadrons

(personal opinion: way too early for such a claim)

$J/\psi \to \gamma\eta'\pi\pi$ - or: no such thing as enough J/ψ

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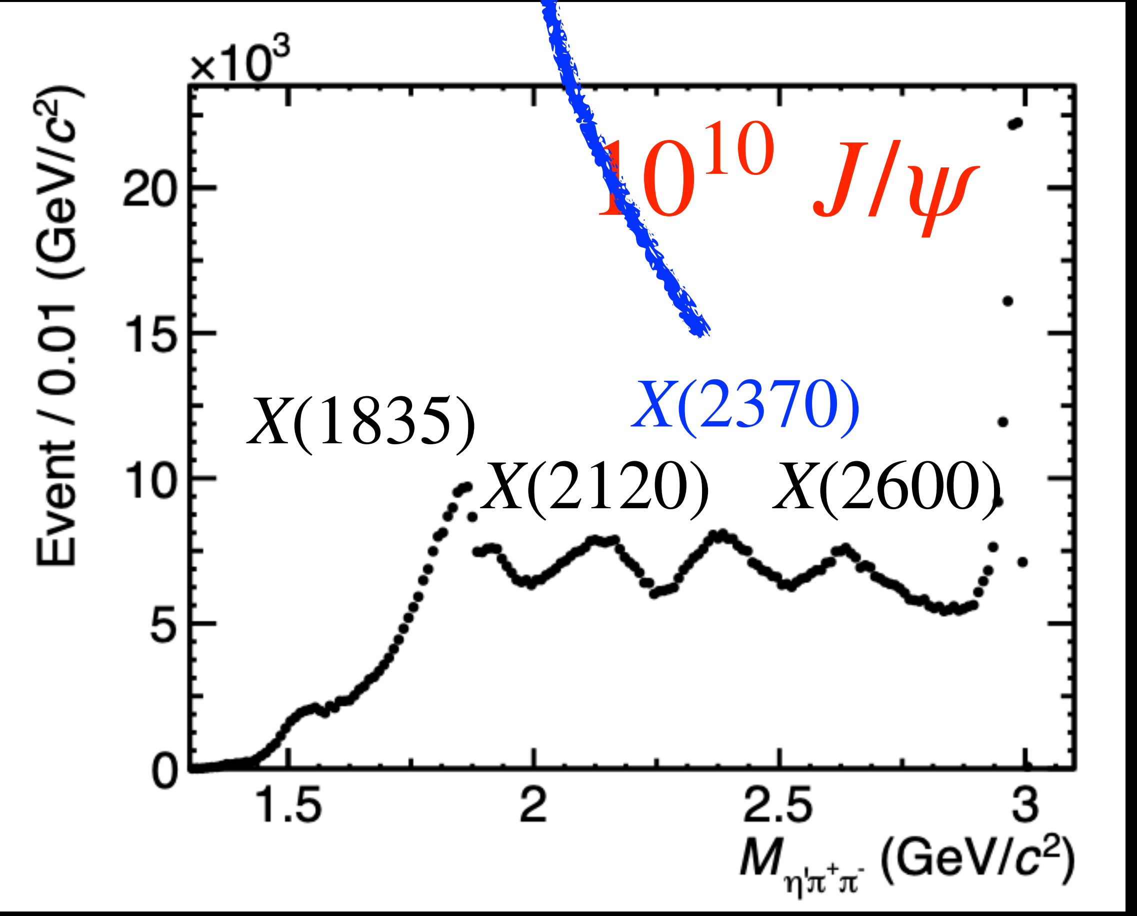
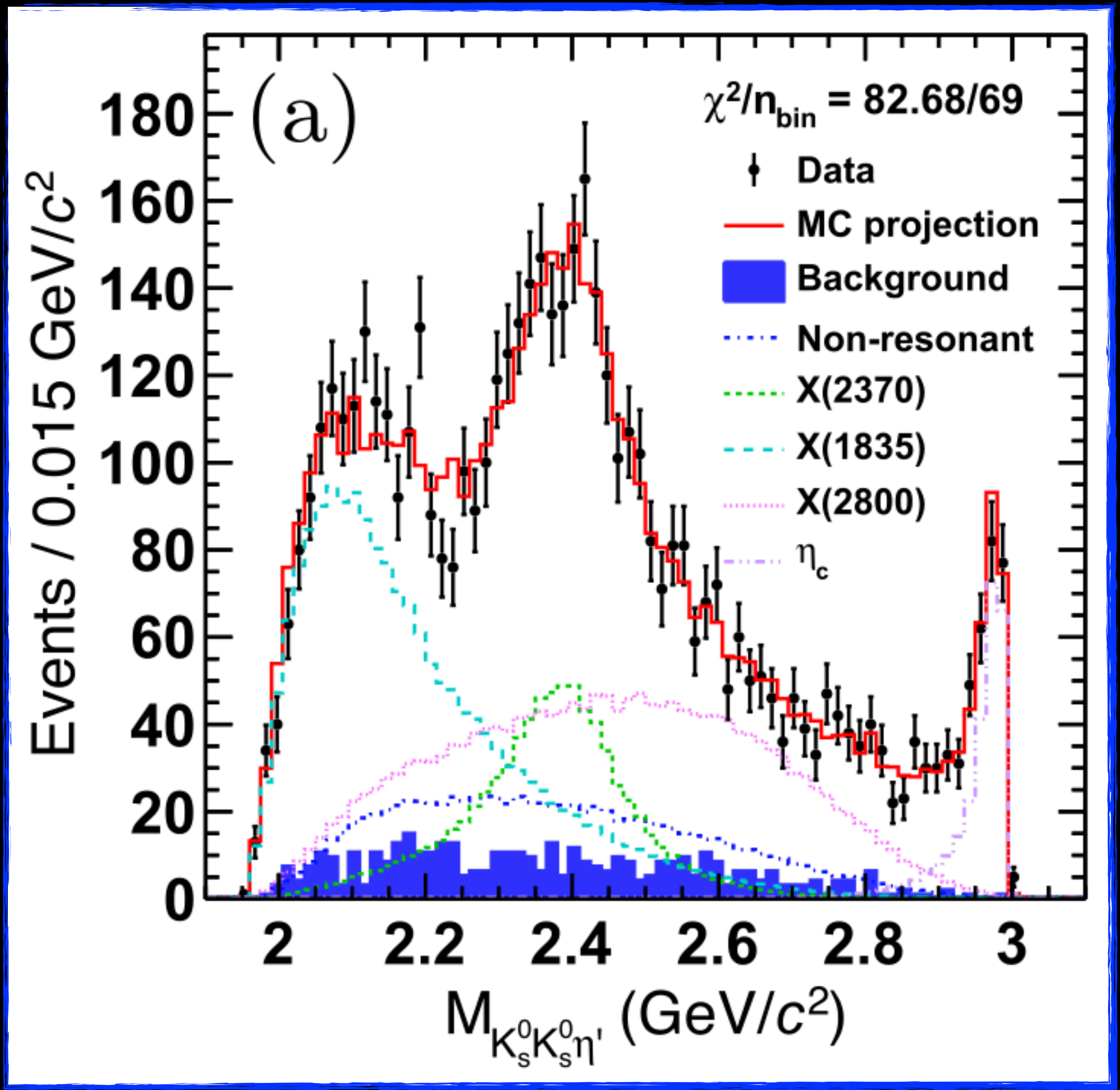
PRL 129 (2022) 4, 042001





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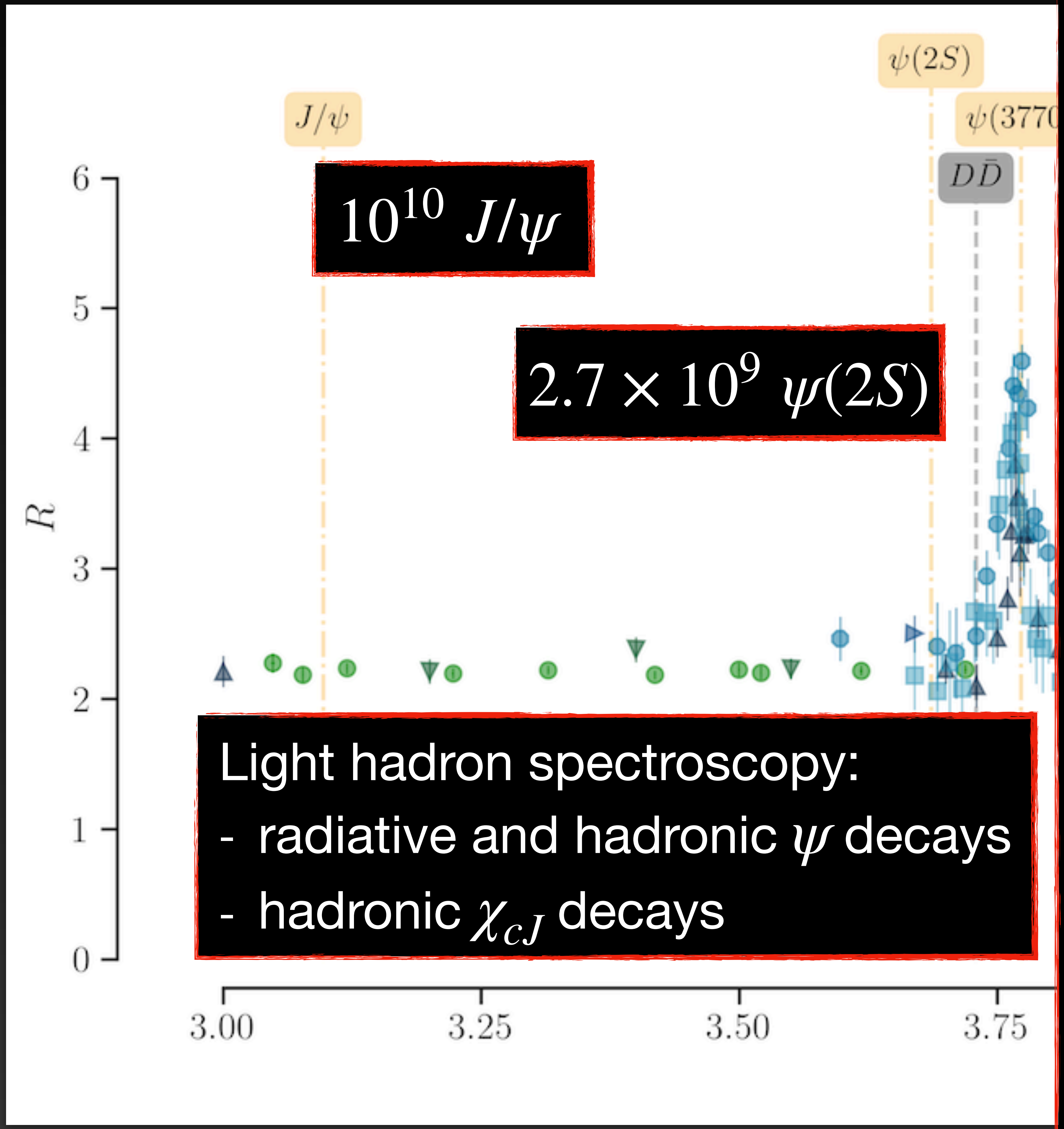
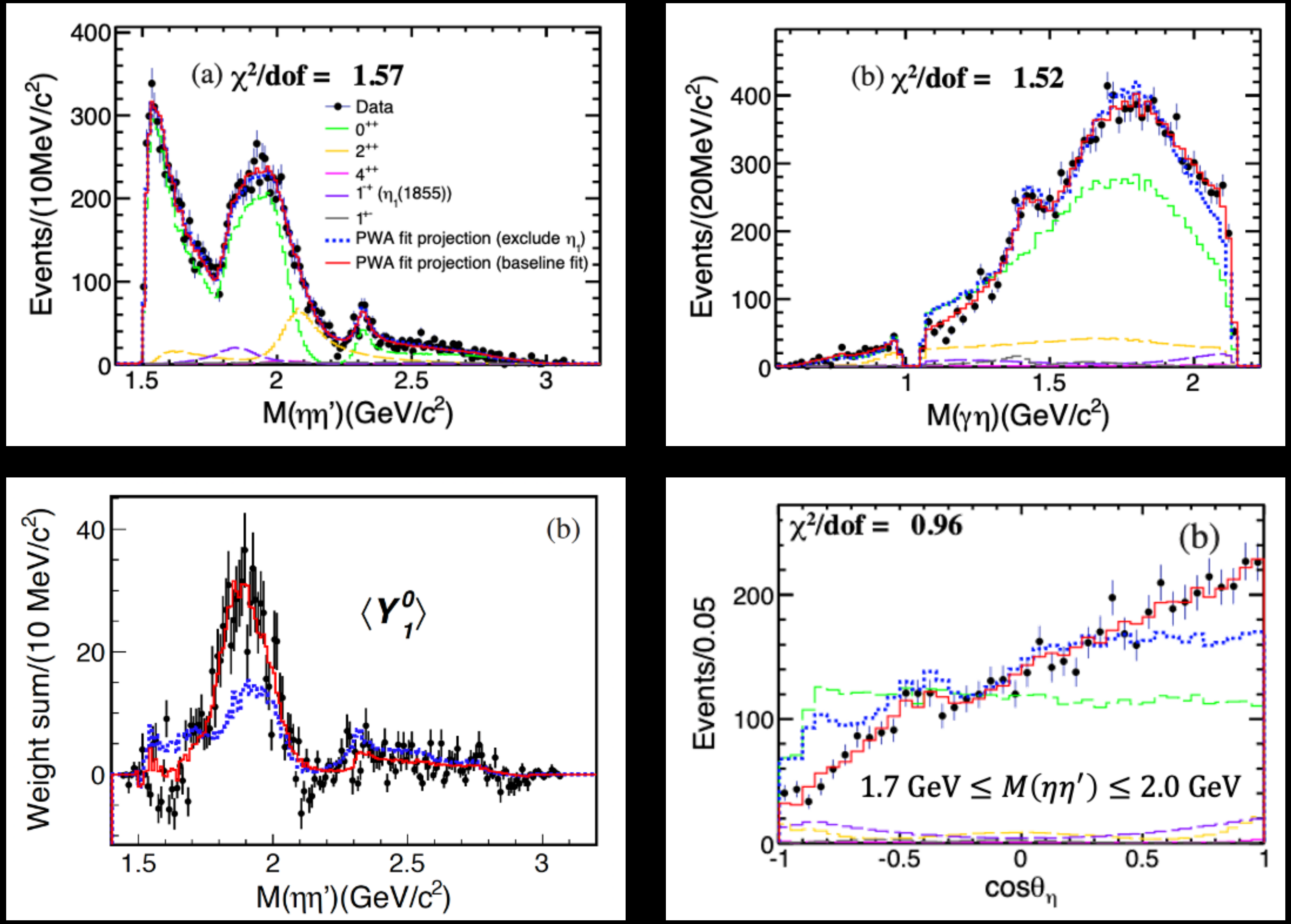


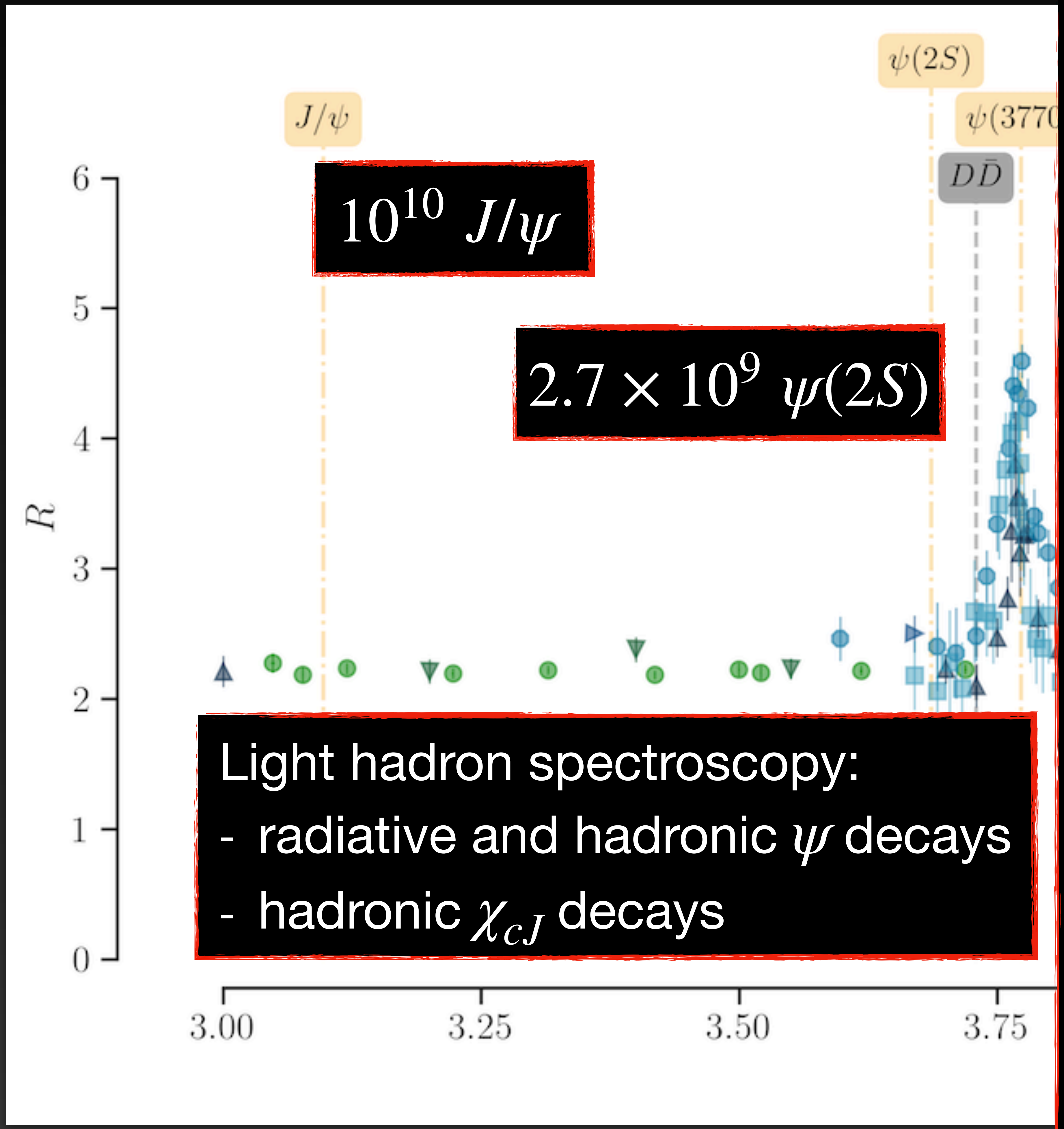
A new hybrid meson candidate in $J/\psi \to \gamma\eta\eta'$



independent confirmation is needed!

PRL 129 (2022) 19, 192002, PRL 130 (2023) 15, 159901 (erratum)
PRD 106 (2022) 7, 072012, PRD 107 (2023) 7, 079901 (erratum)

Light hadrons



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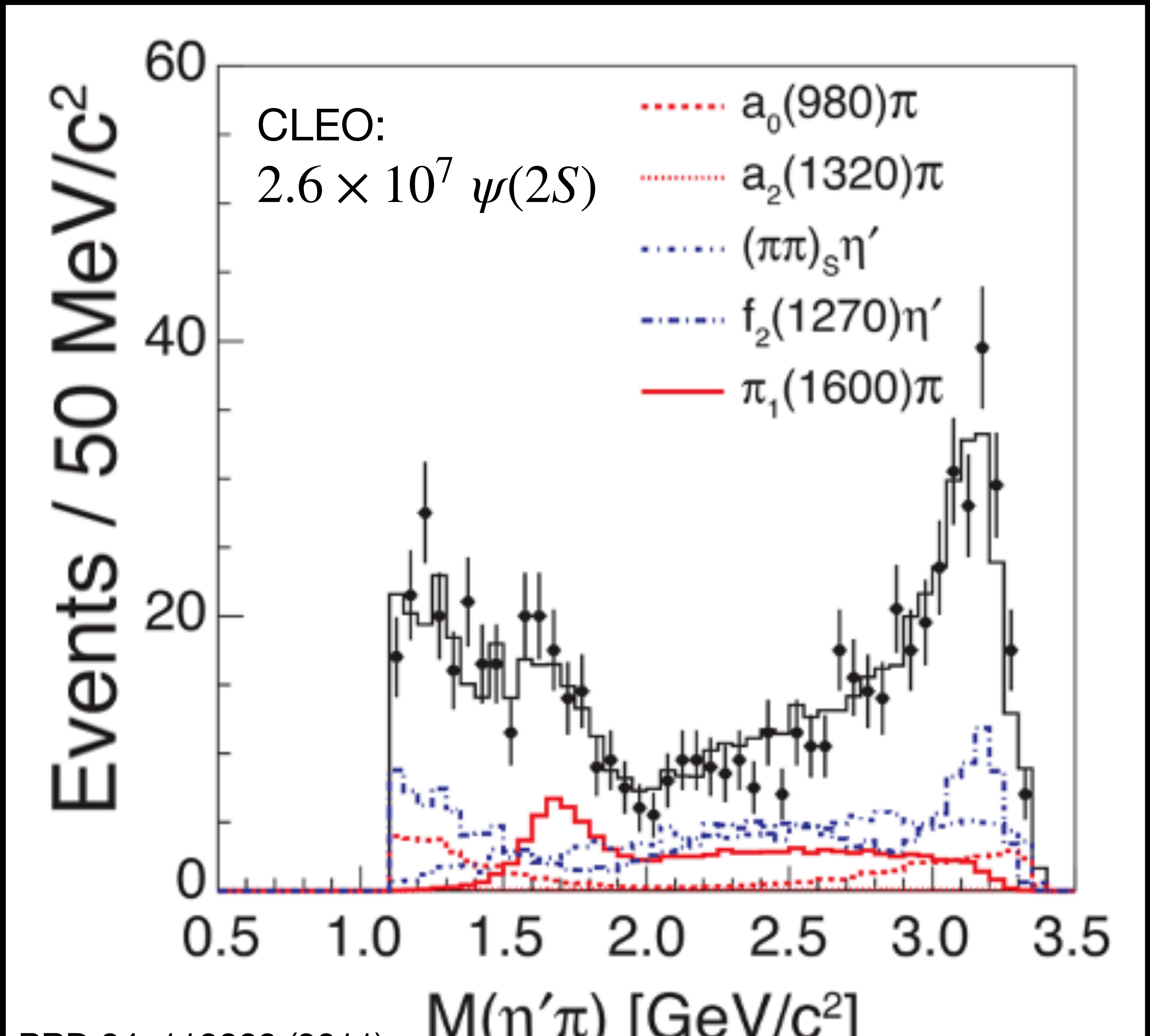
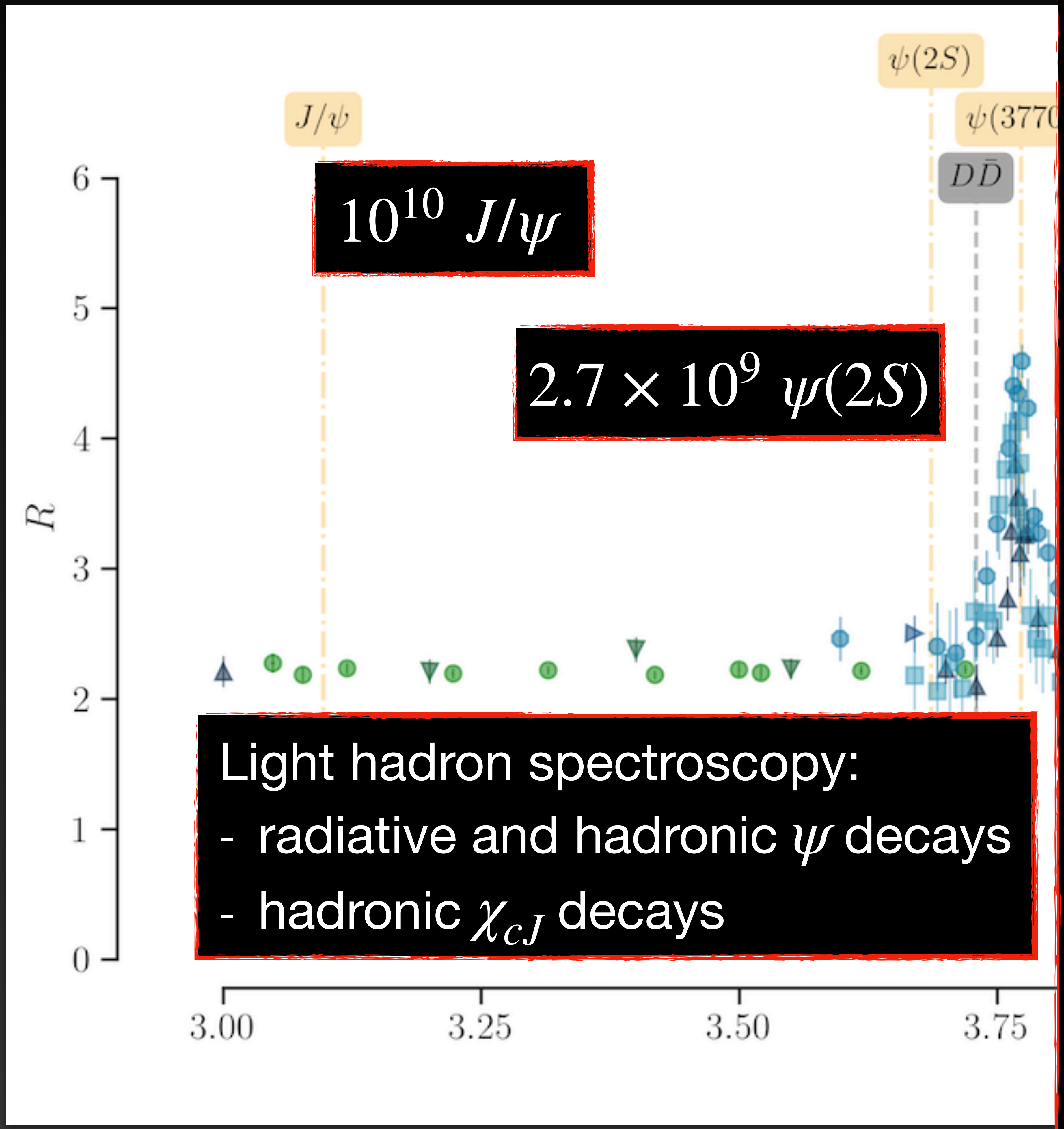
The $\pi_1(1600)$ in $\chi_{c1} \to \eta' \pi\pi$



PRD 84, 112009 (2011)

Light hadrons



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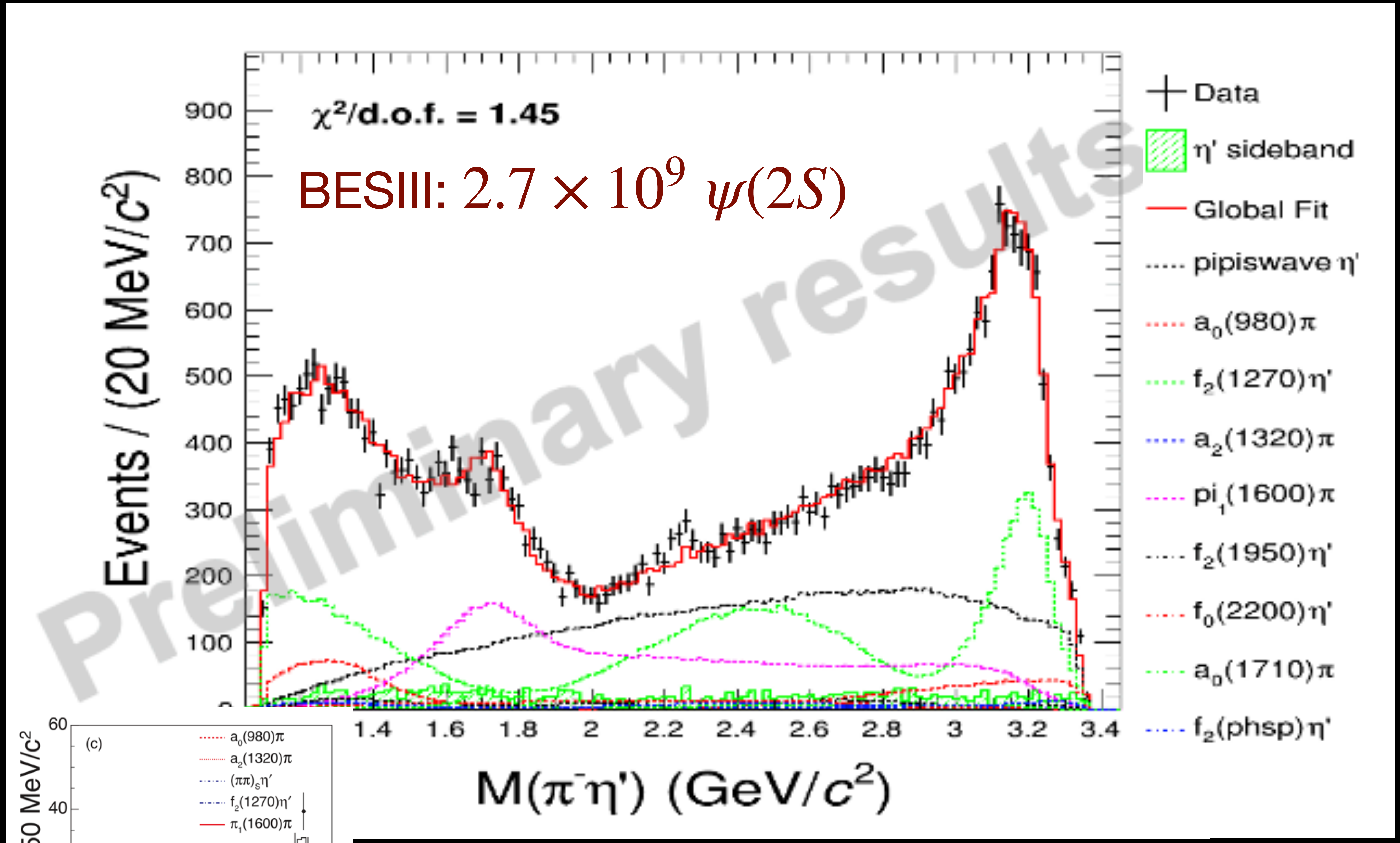
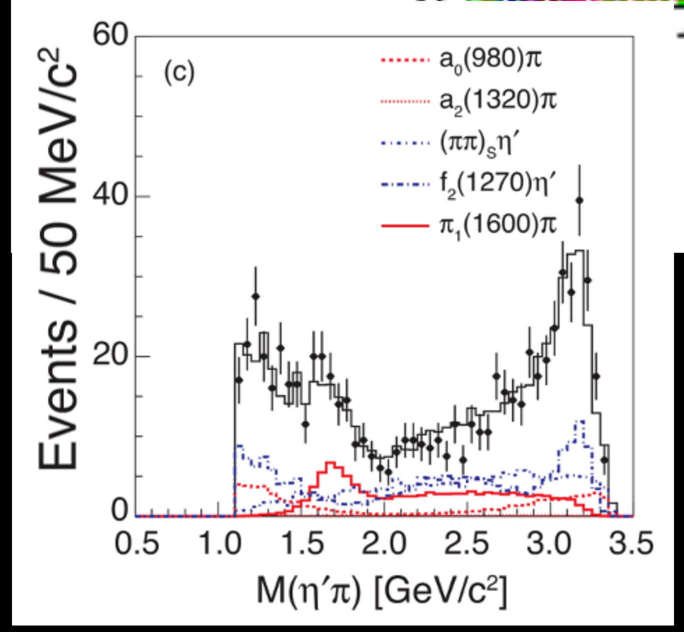
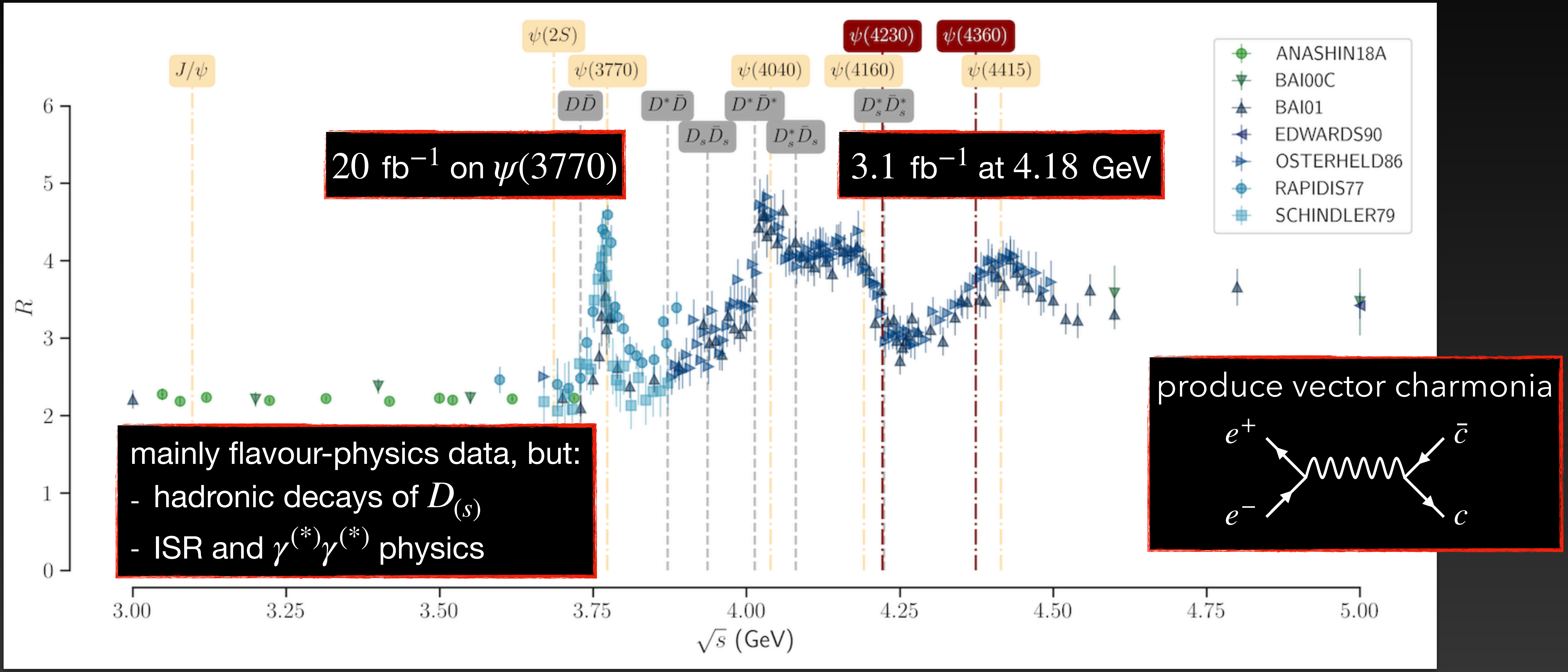
The $\pi_1(1600)$ in $\chi_{c1} \to \eta'\pi\pi$



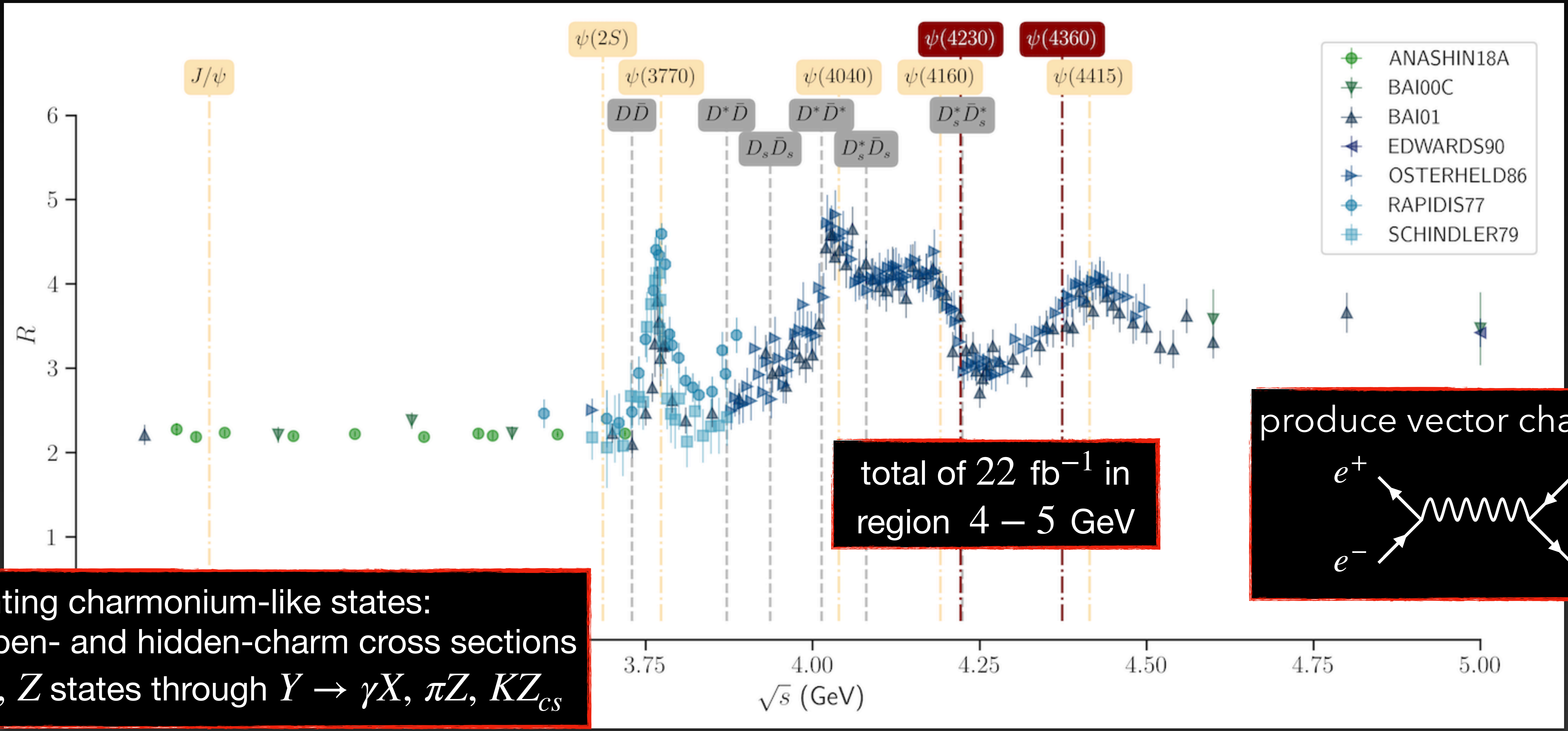


- clear signal of $\chi_{c1} \to \pi_1(1600)\pi$
- now looking for other decay modes

Open charm decays



Charmonium(-like) states



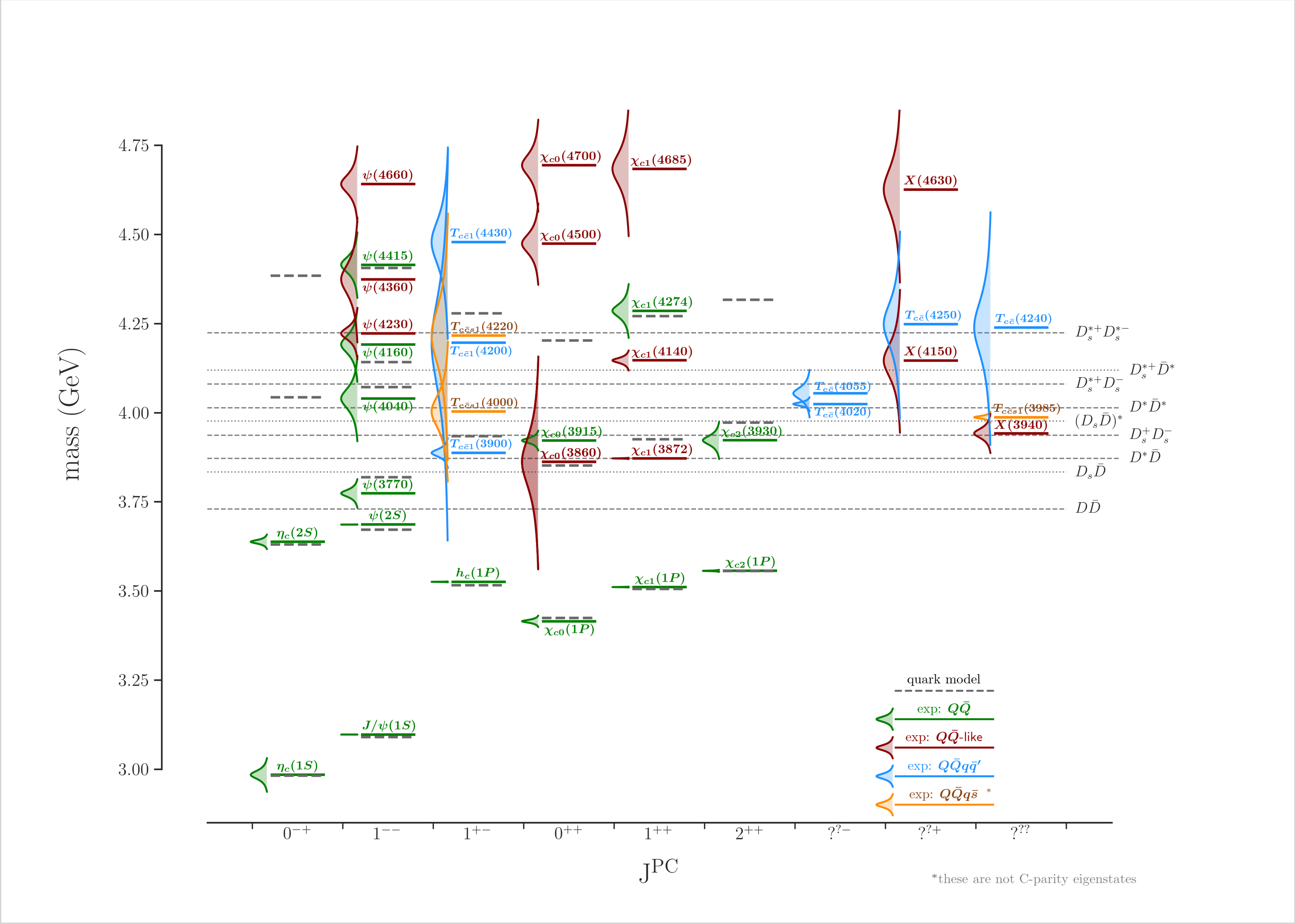
total of 22 fb^{-1} in region $4-5$ GeV

produce vector charmonia

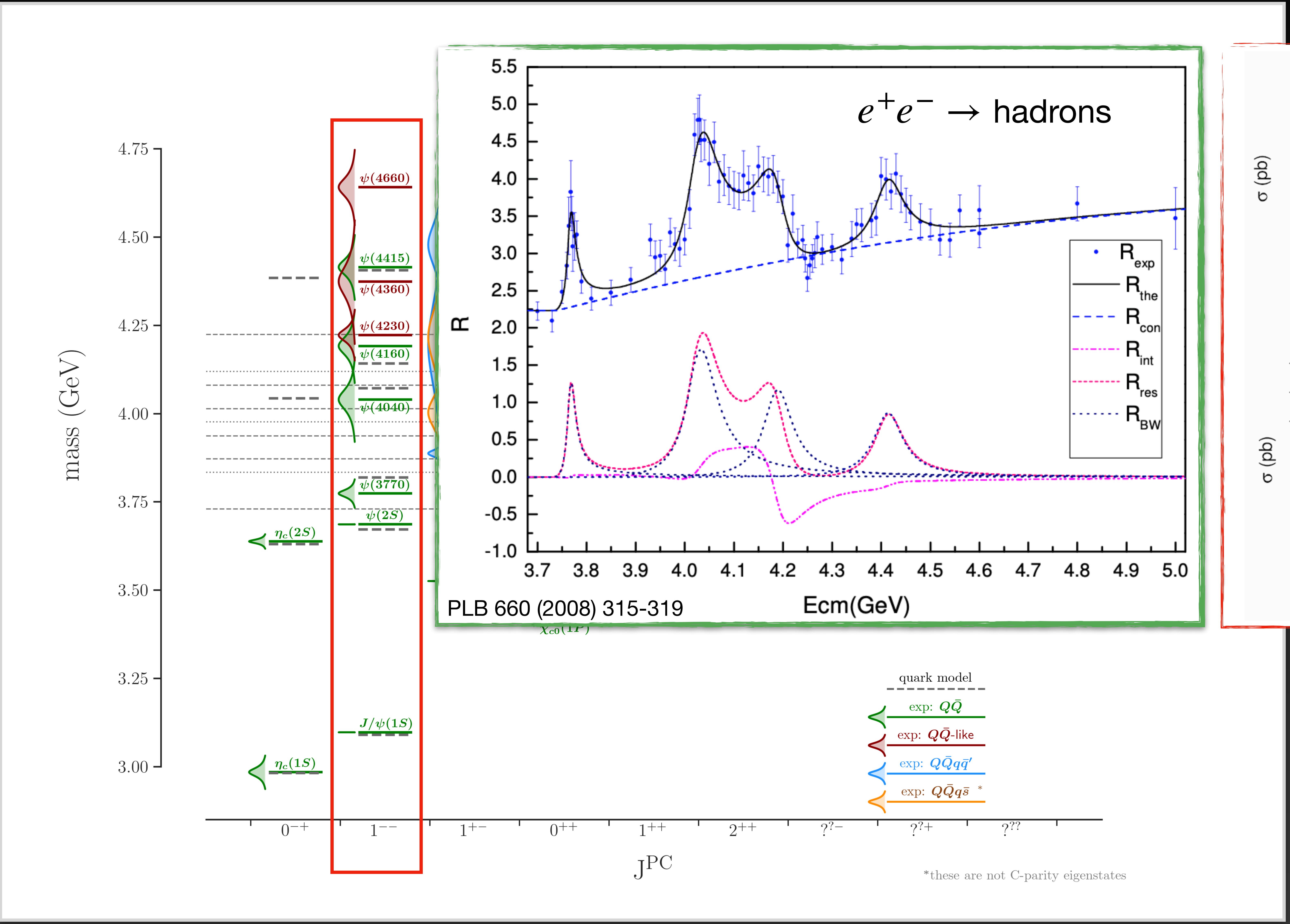
e^+ e^- $\bar{c}$ c

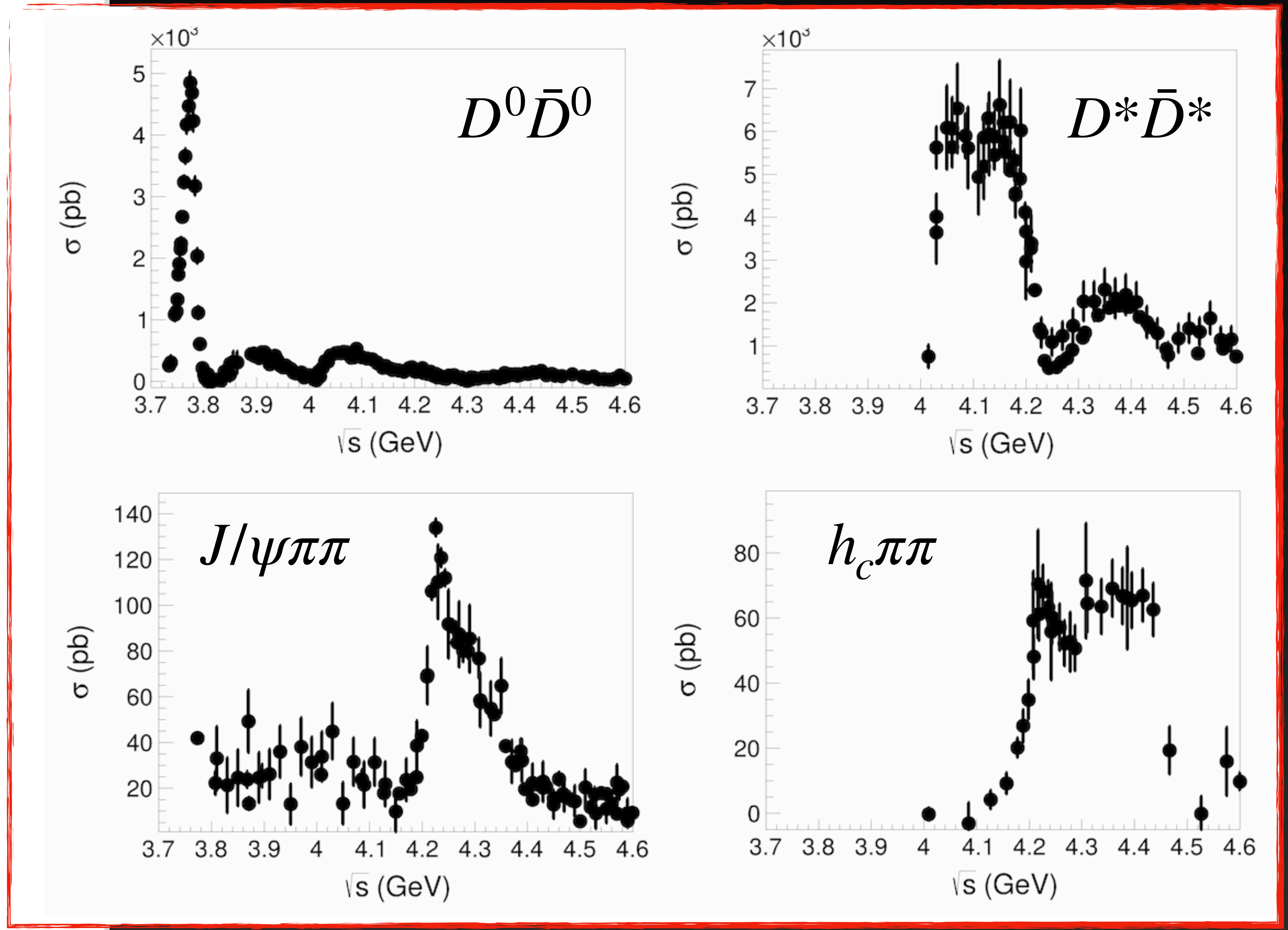
hunting charmonium-like states:
- open- and hidden-charm cross sections
- X, Z states through $Y \to \gamma X$, πZ, KZ_{cs}

Charmonium(-like) states



Charmonium(-like) states

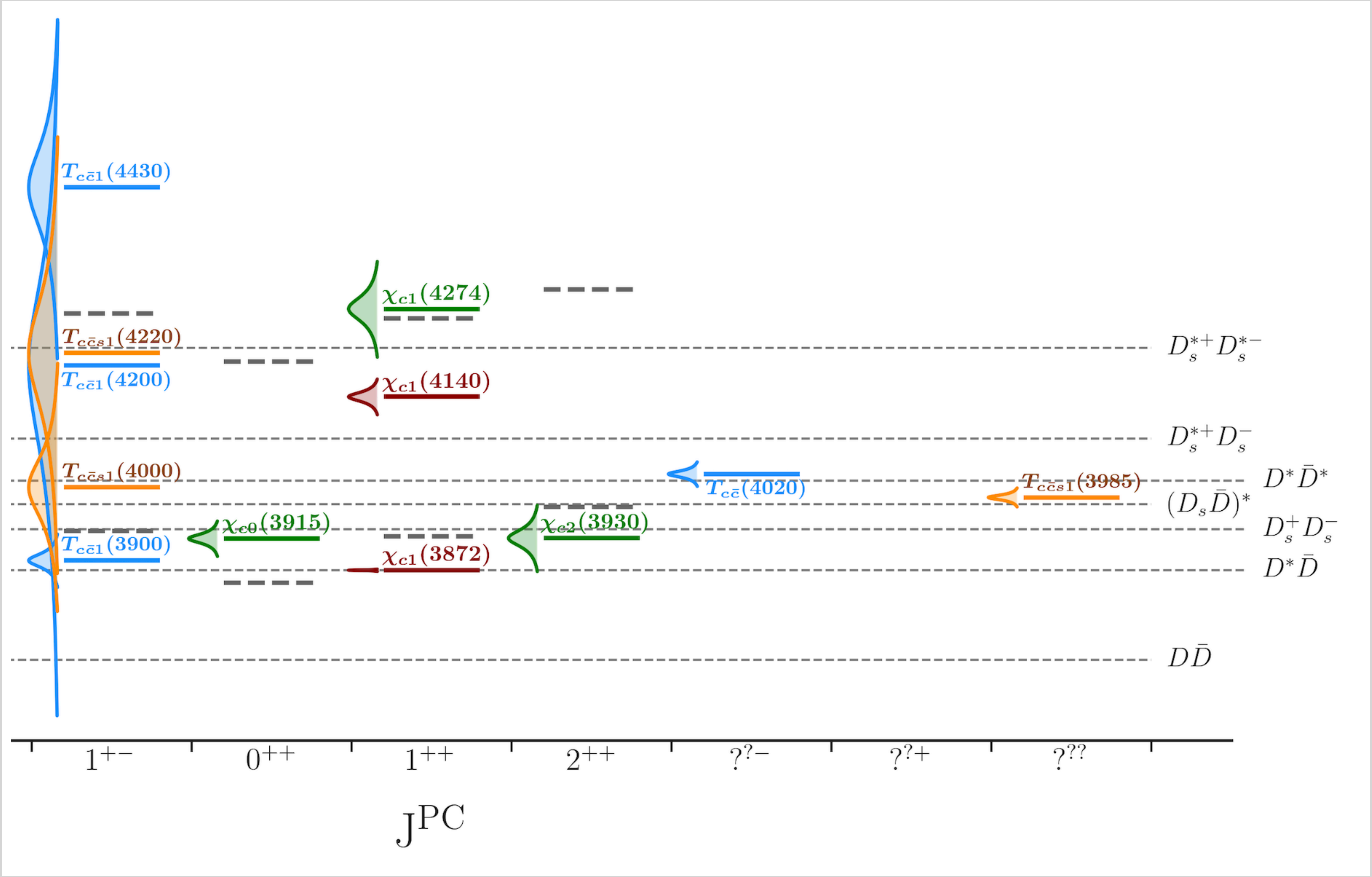




+ many more

puzzling out the vector states (I think) is a task for the e^+e^- experiments!

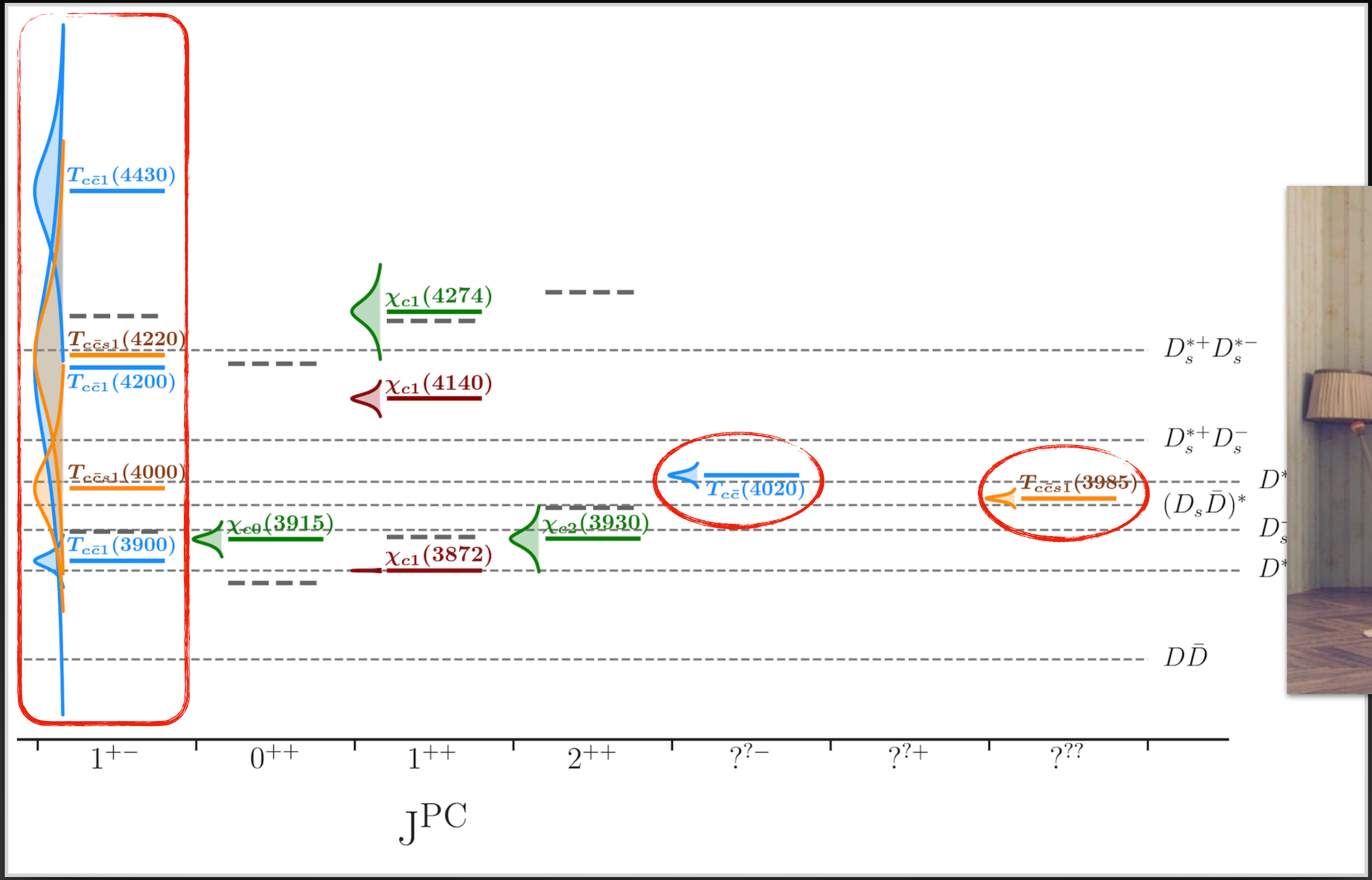
Open questions



(a) inconsistencies

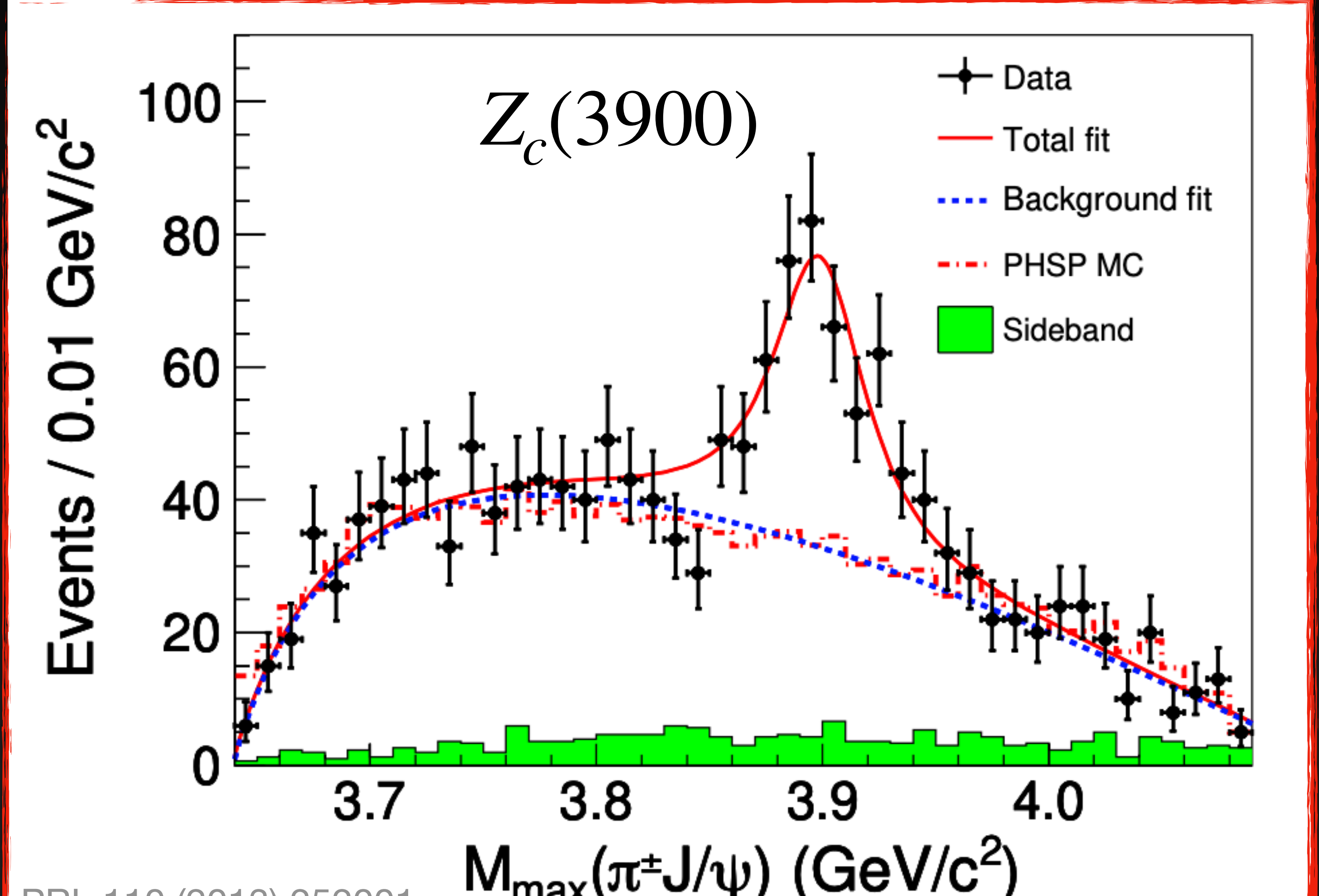
(b) missing states

The elephant in the room…

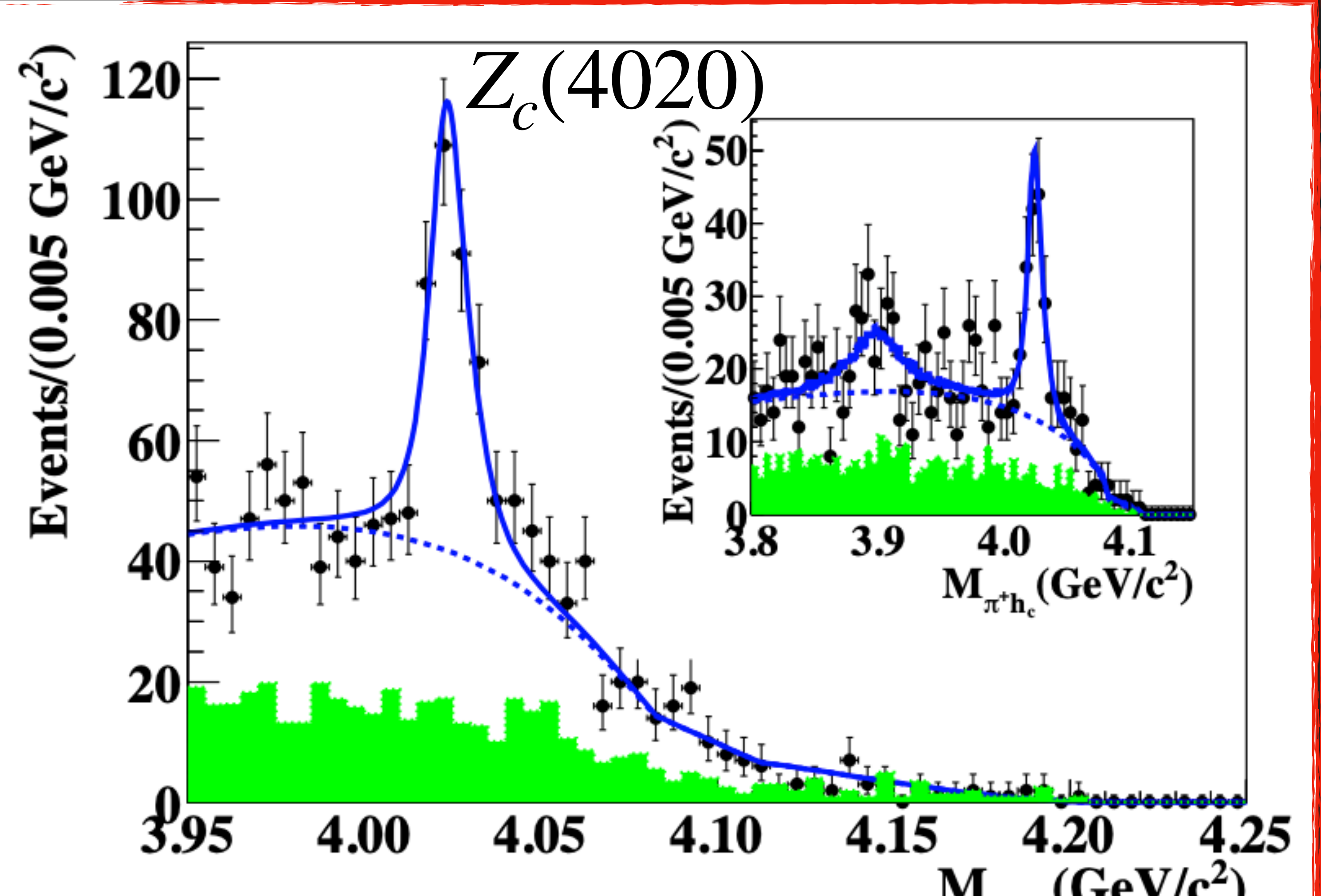


The Z_c states

$e^+e^- \to Z_c\pi$

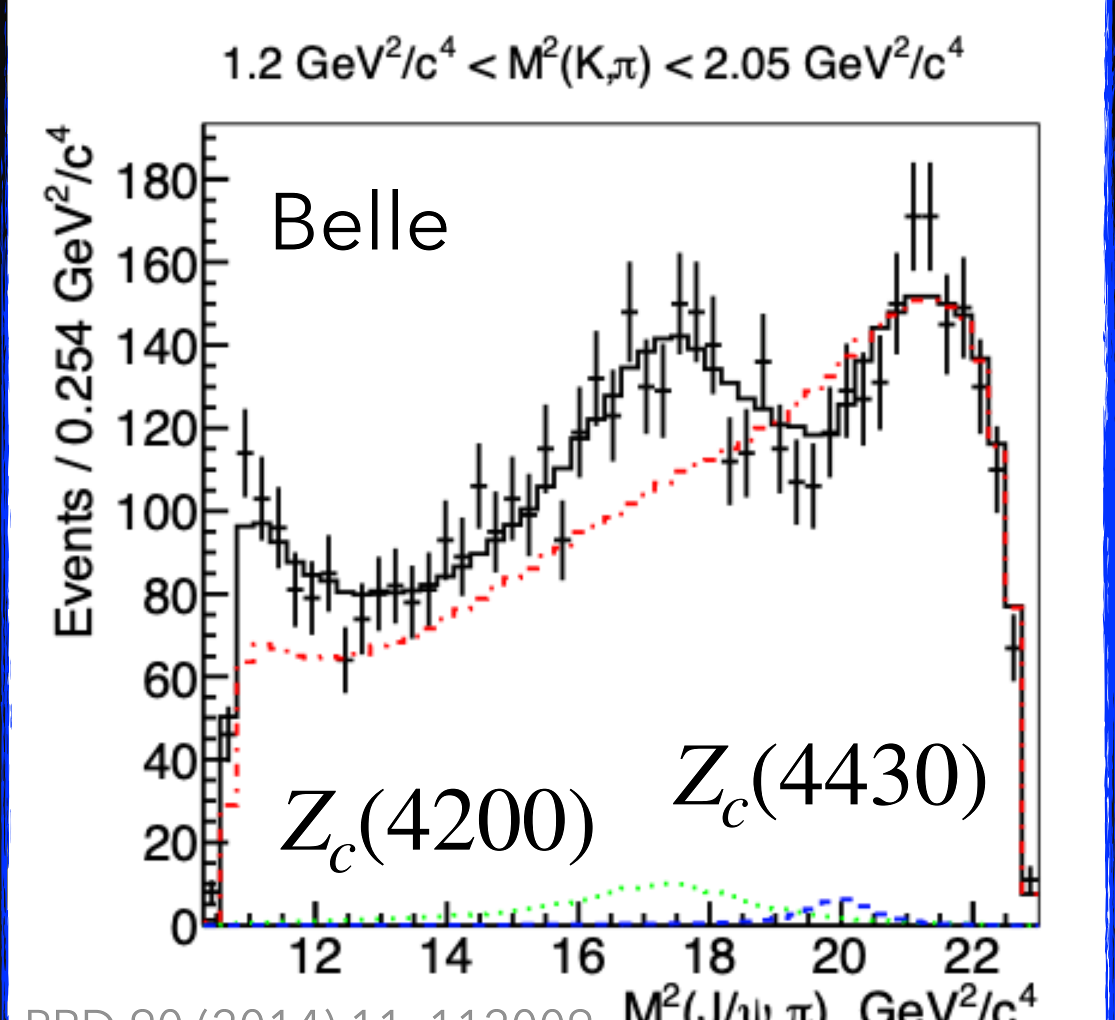


PRL 110 (2013) 252001

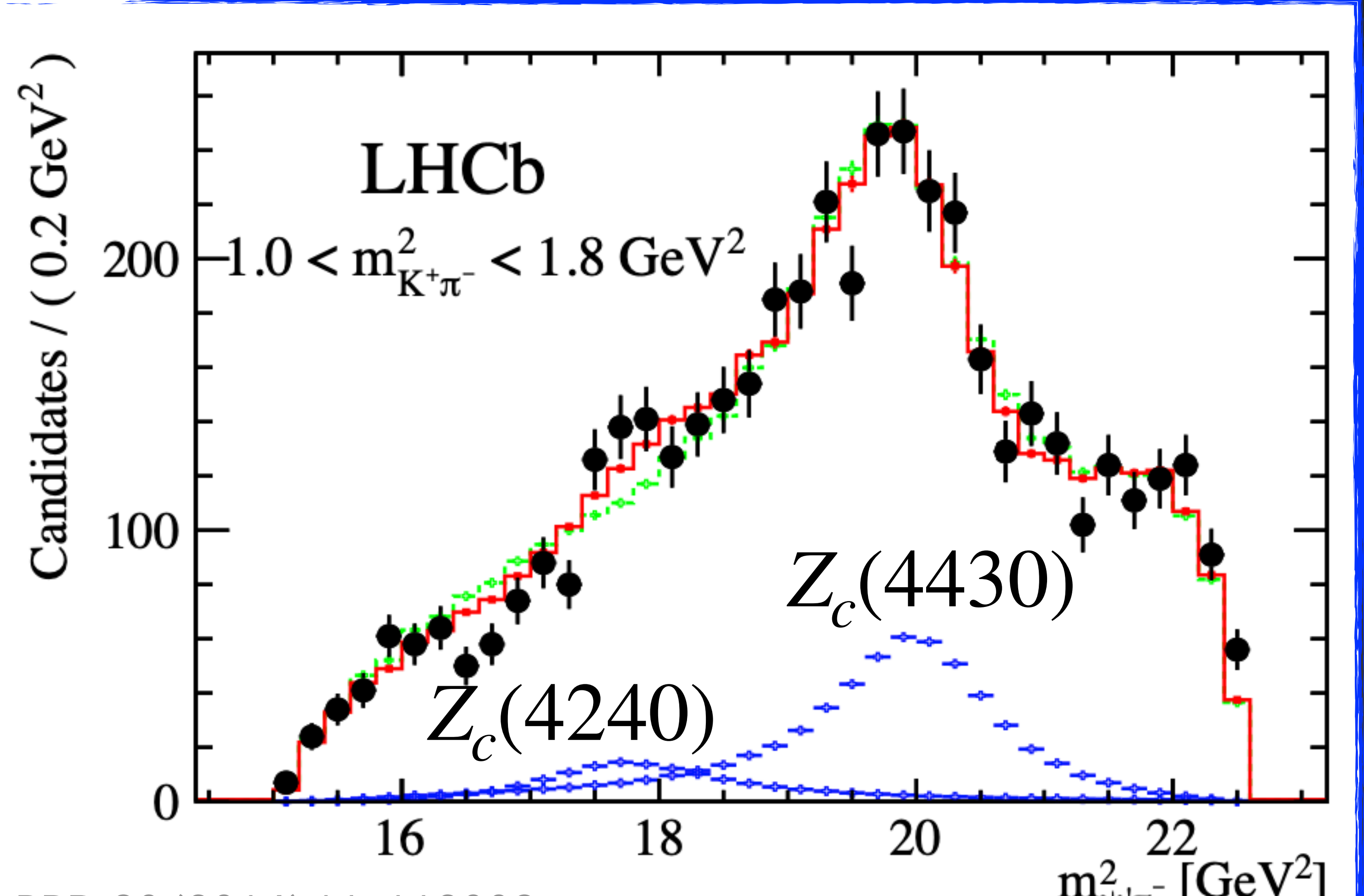


PRL 111 (2013) 24, 242001

$B \to Z_c K$



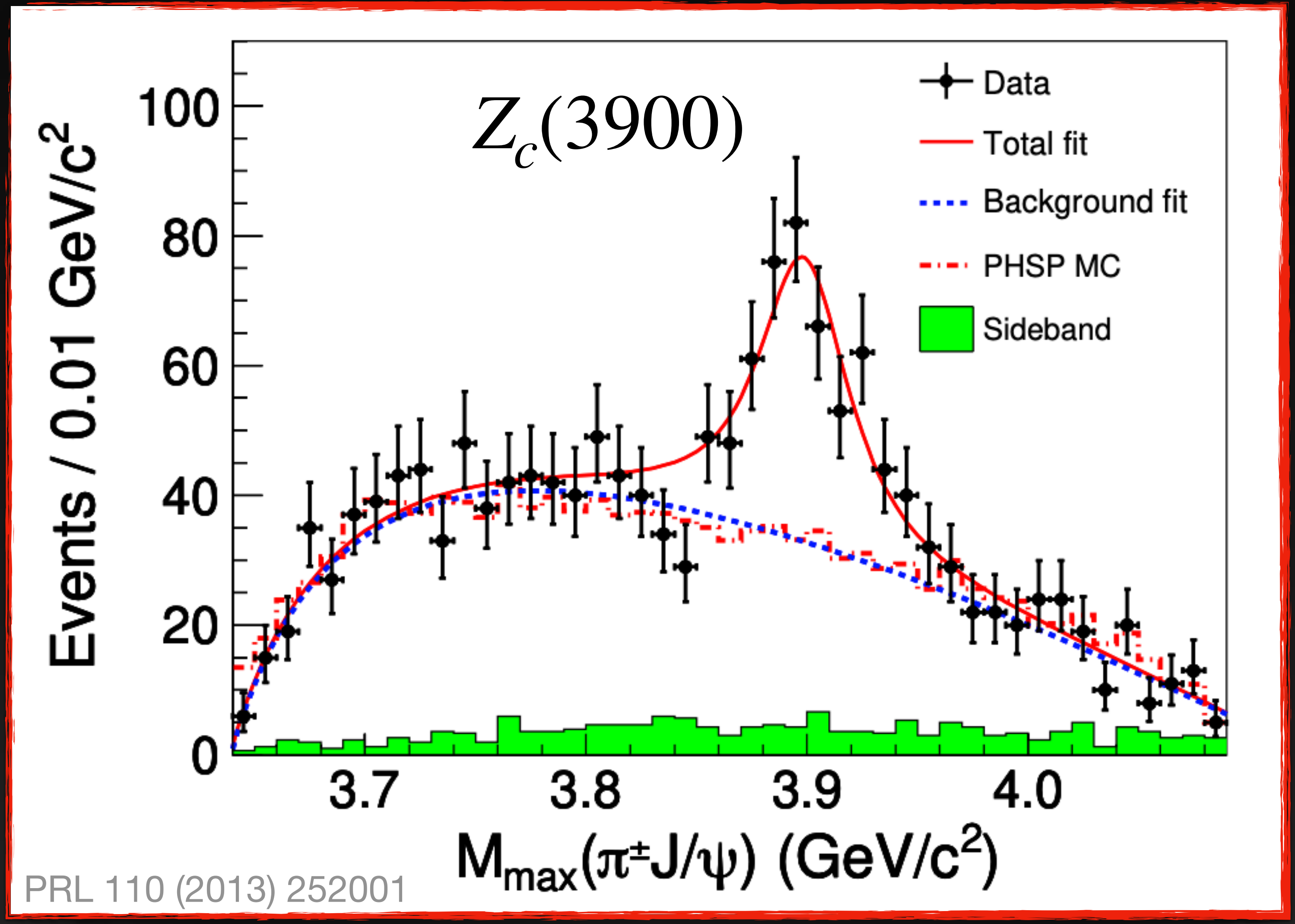
PRD 90 (2014) 11, 112009



PRD 90 (2014) 11, 112009

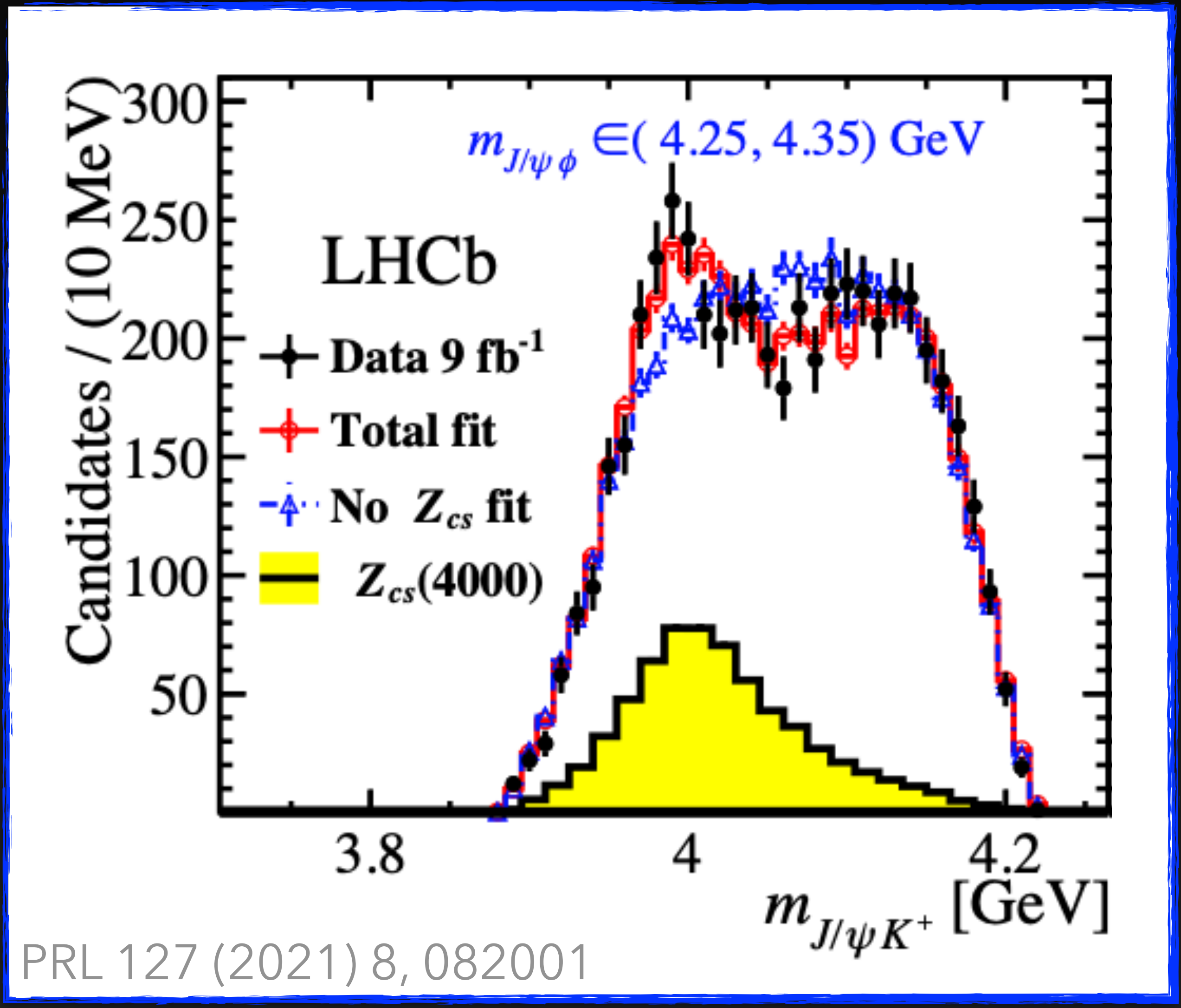
The Z_c states

$e^+e^- \to Z_c\pi$



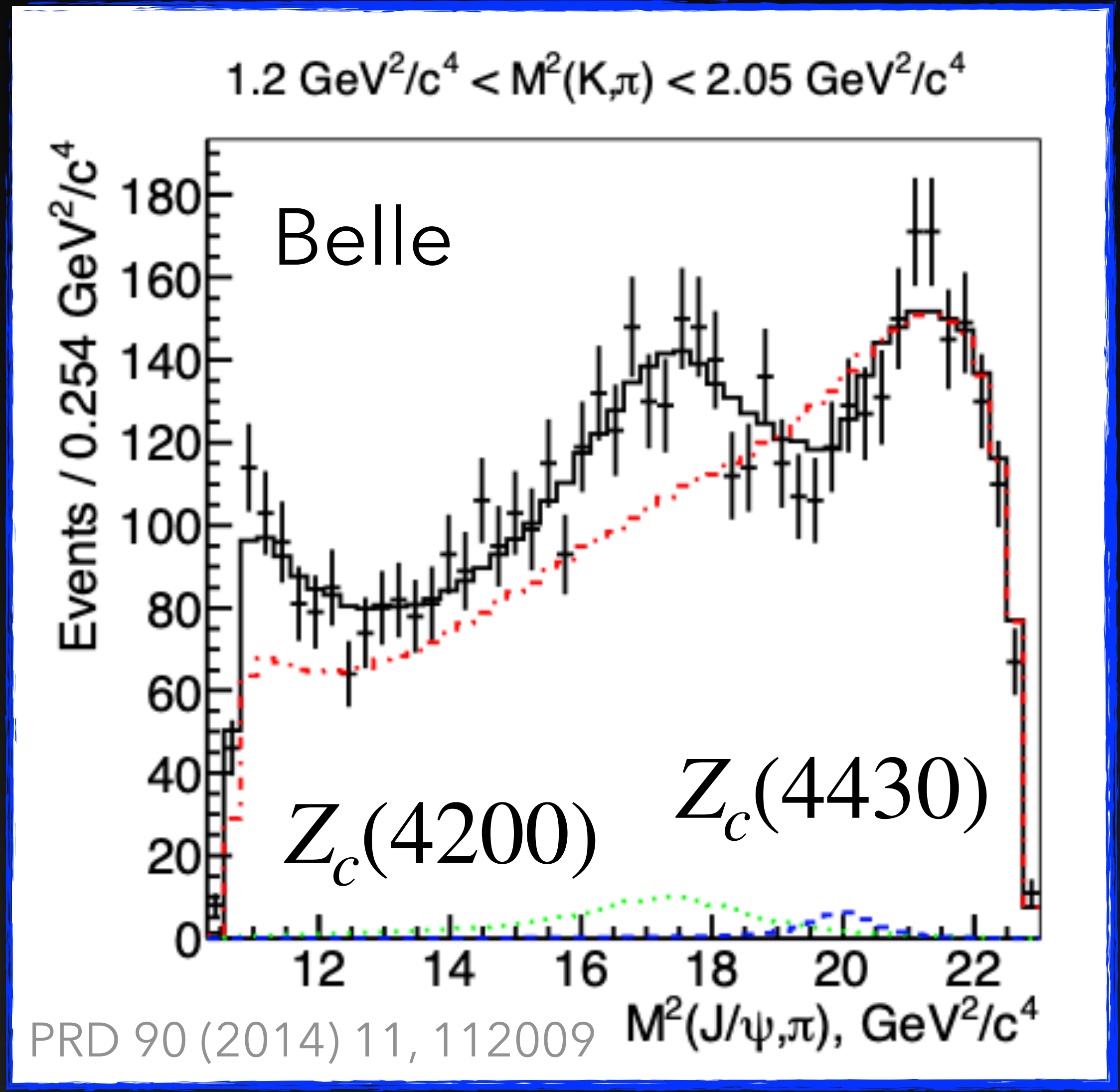
PRL 110 (2013) 252001

$B \to Z_{cs}\phi$

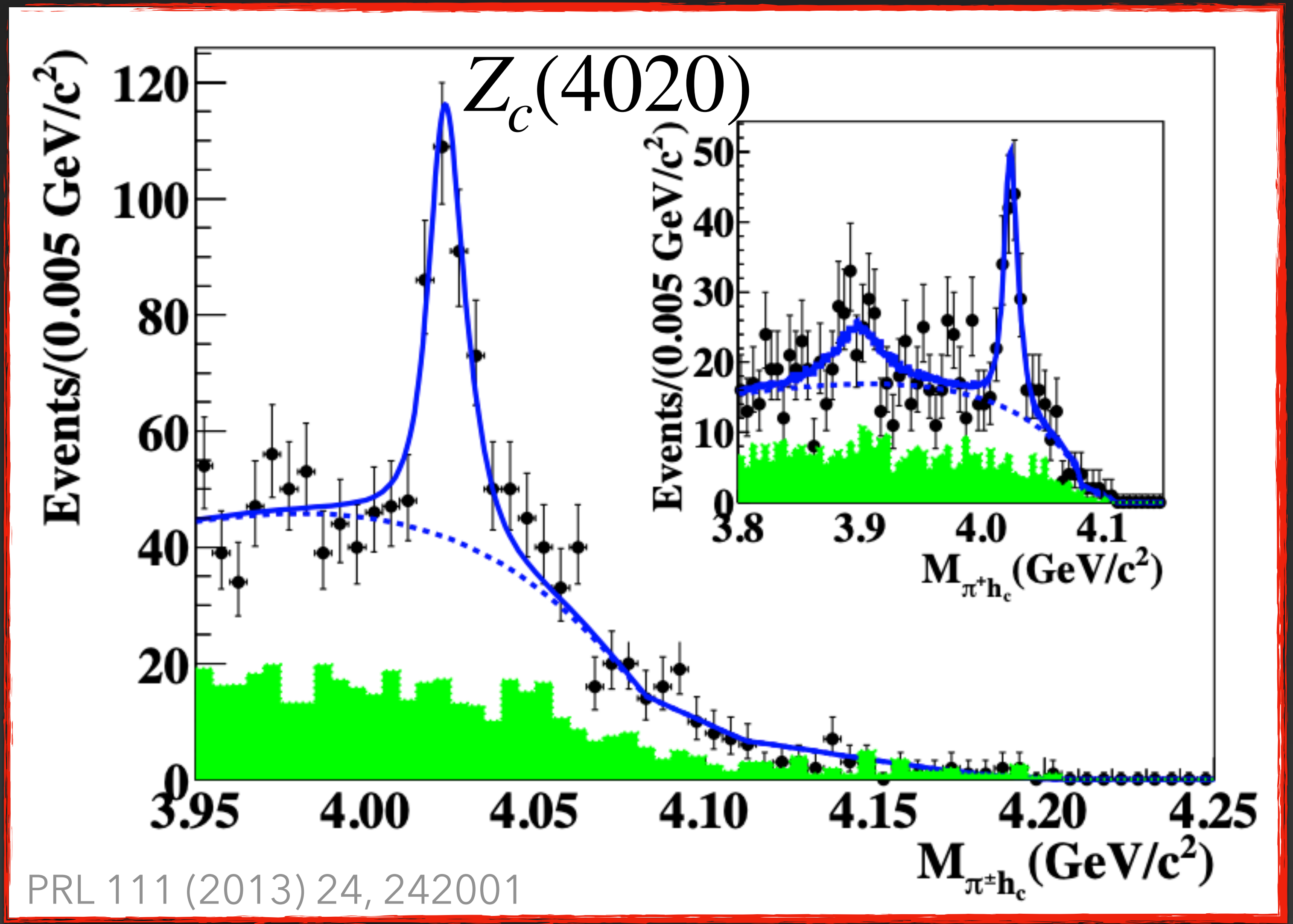


PRL 127 (2021) 8, 082001

$B \to Z_c K$

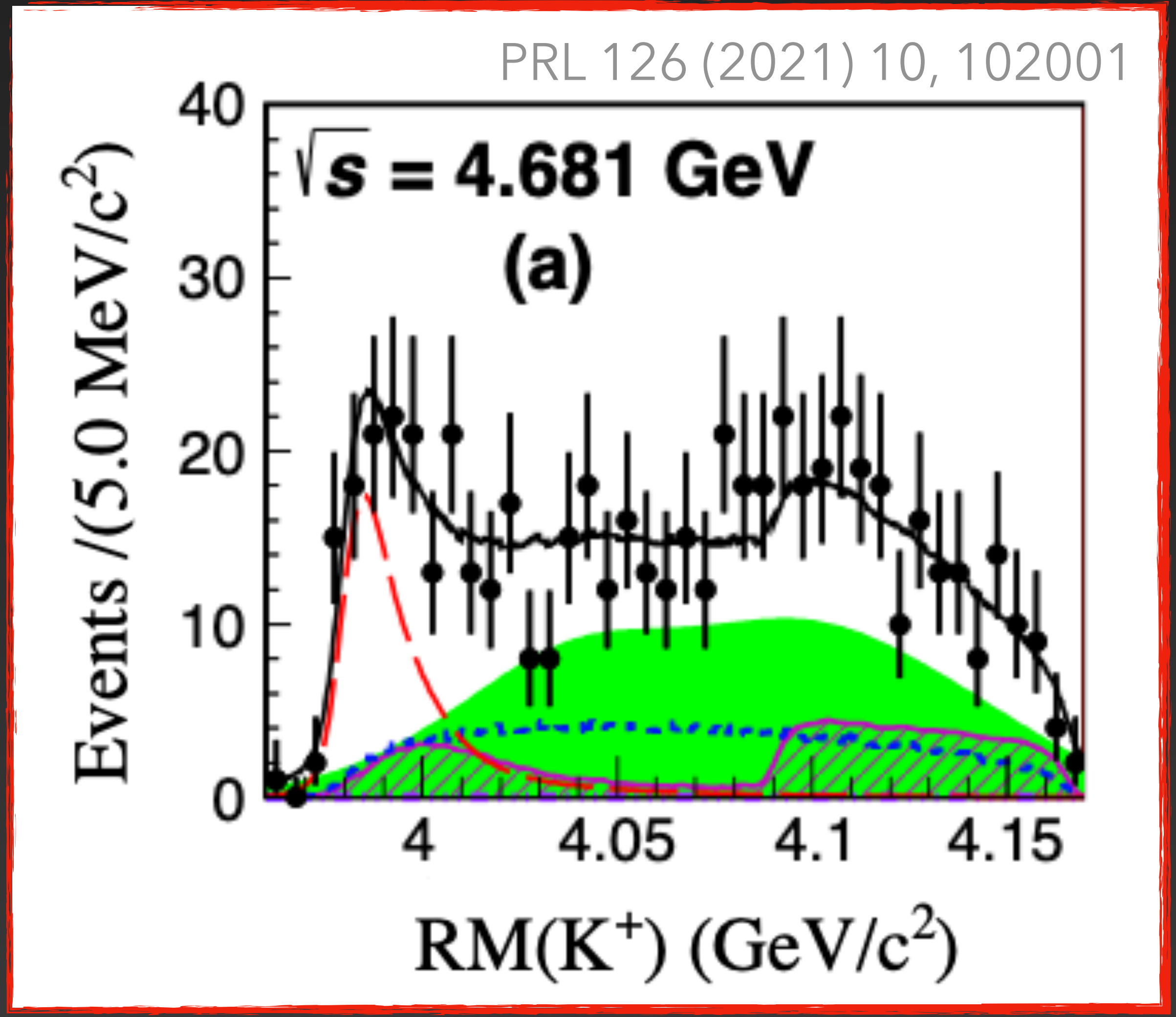


PRD 90 (2014) 11, 112009

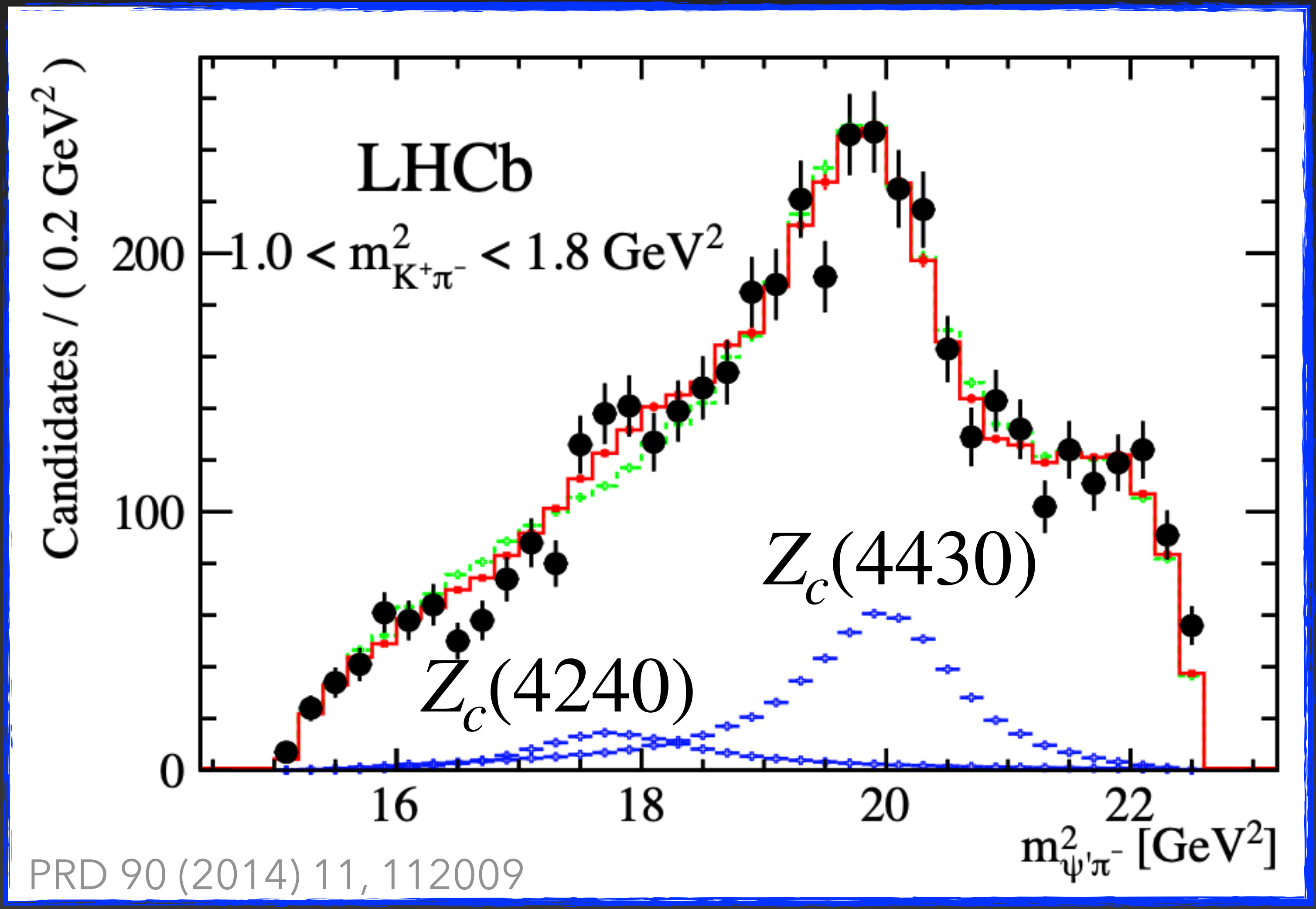


PRL 111 (2013) 24, 242001

$e^+e^- \to Z_{cs}K$



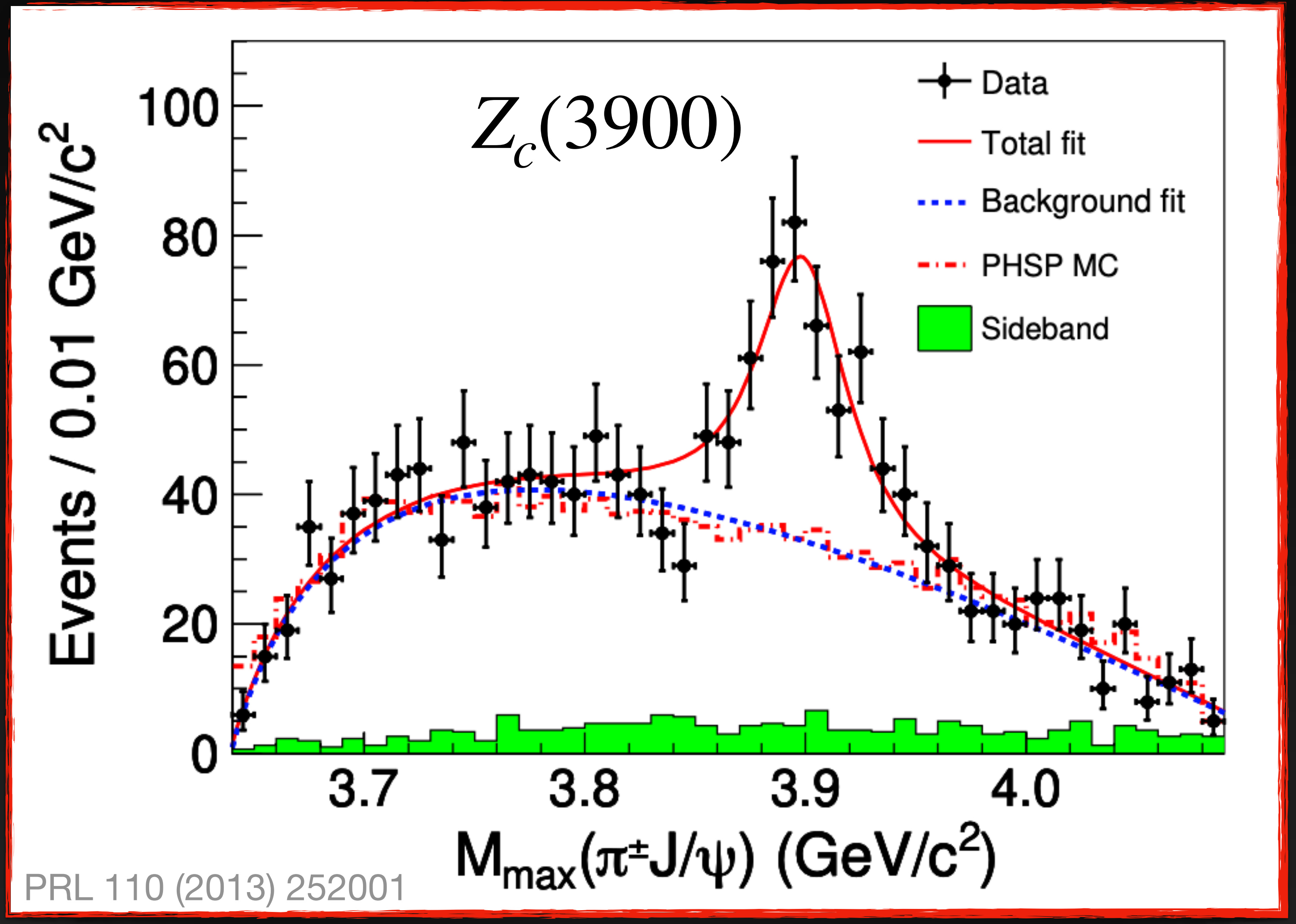
PRL 126 (2021) 10, 102001

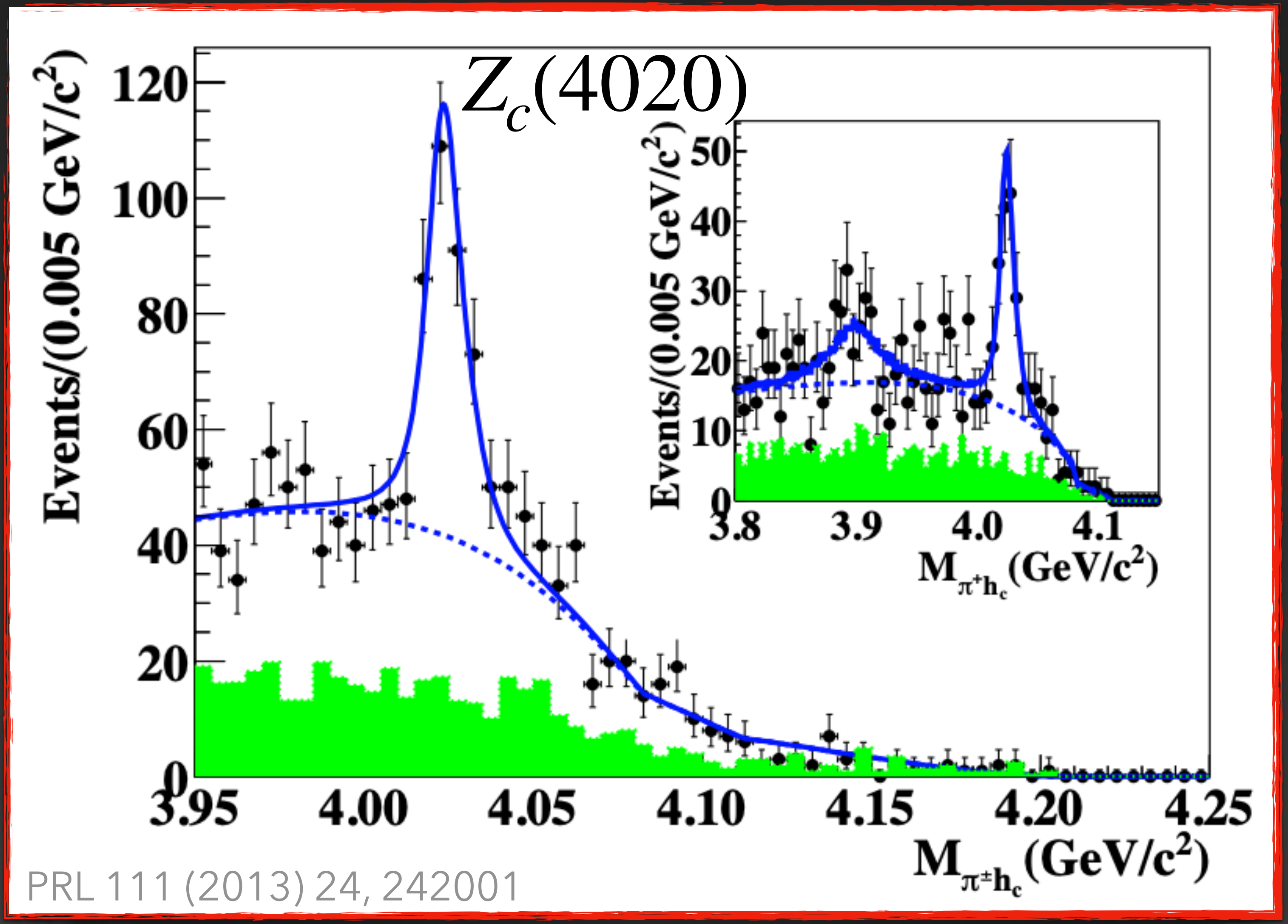


PRD 90 (2014) 11, 112009

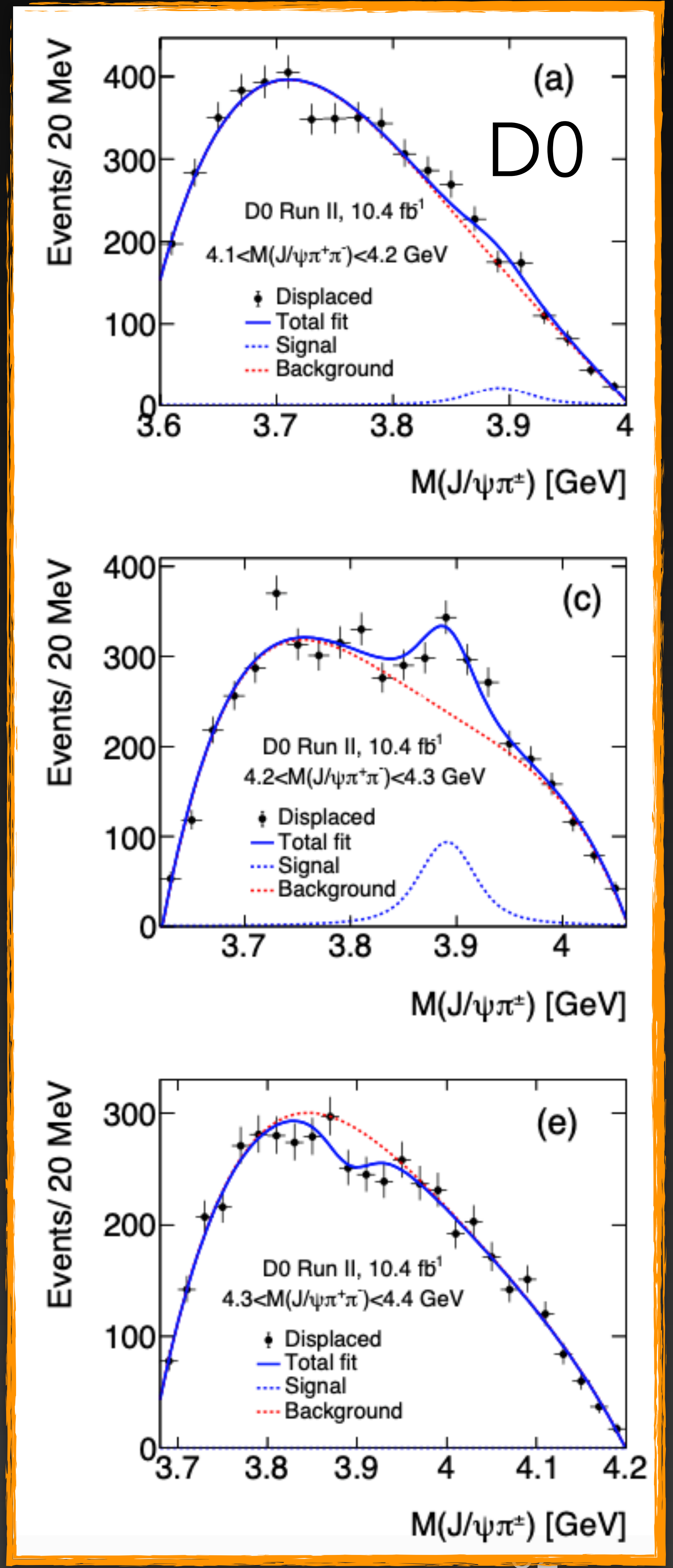
The Z_c states

$e^+e^- \to Z_c\pi$





displaced $J/\psi\pi\pi$



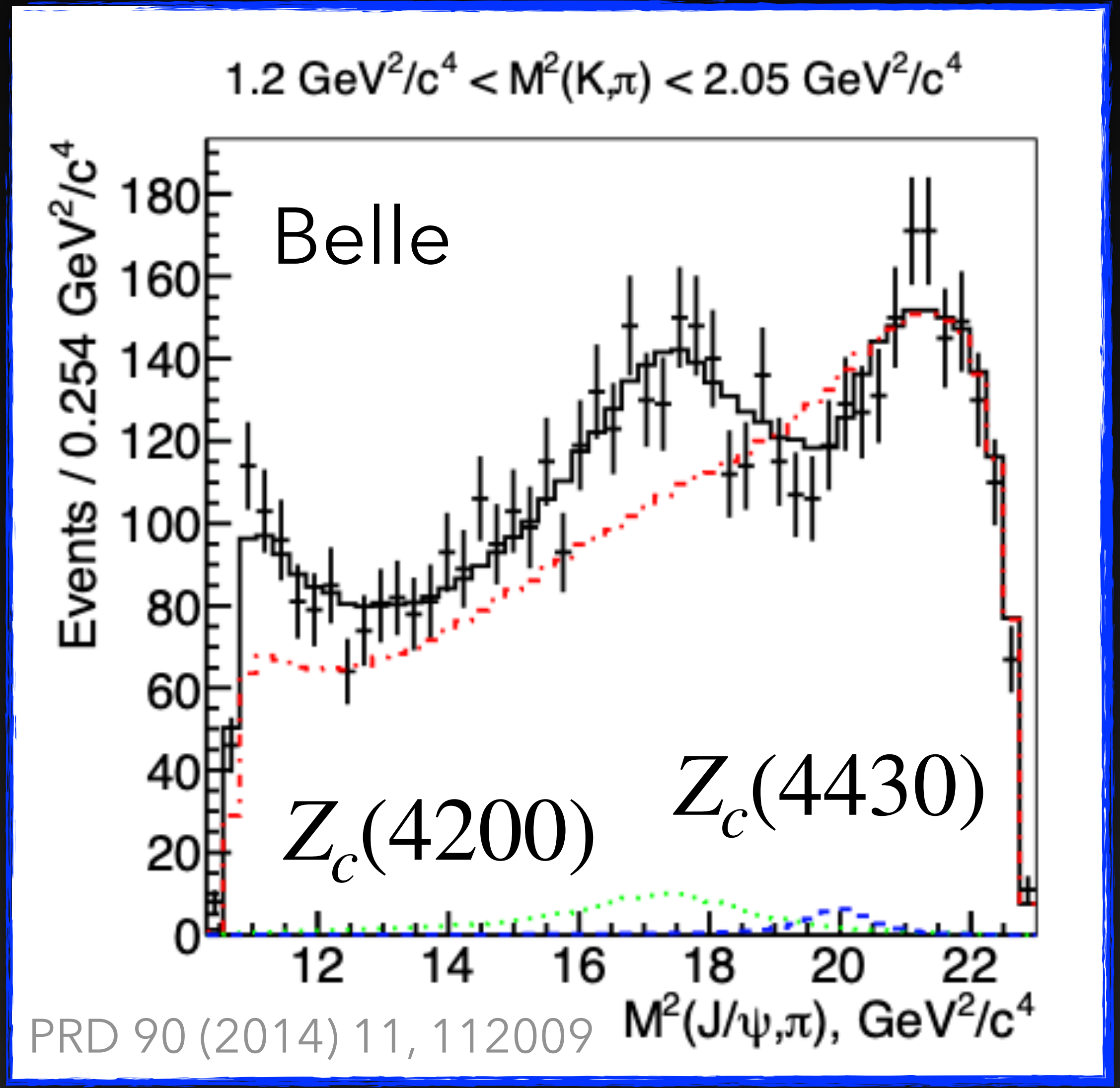
PRD 100 (2019) 012005

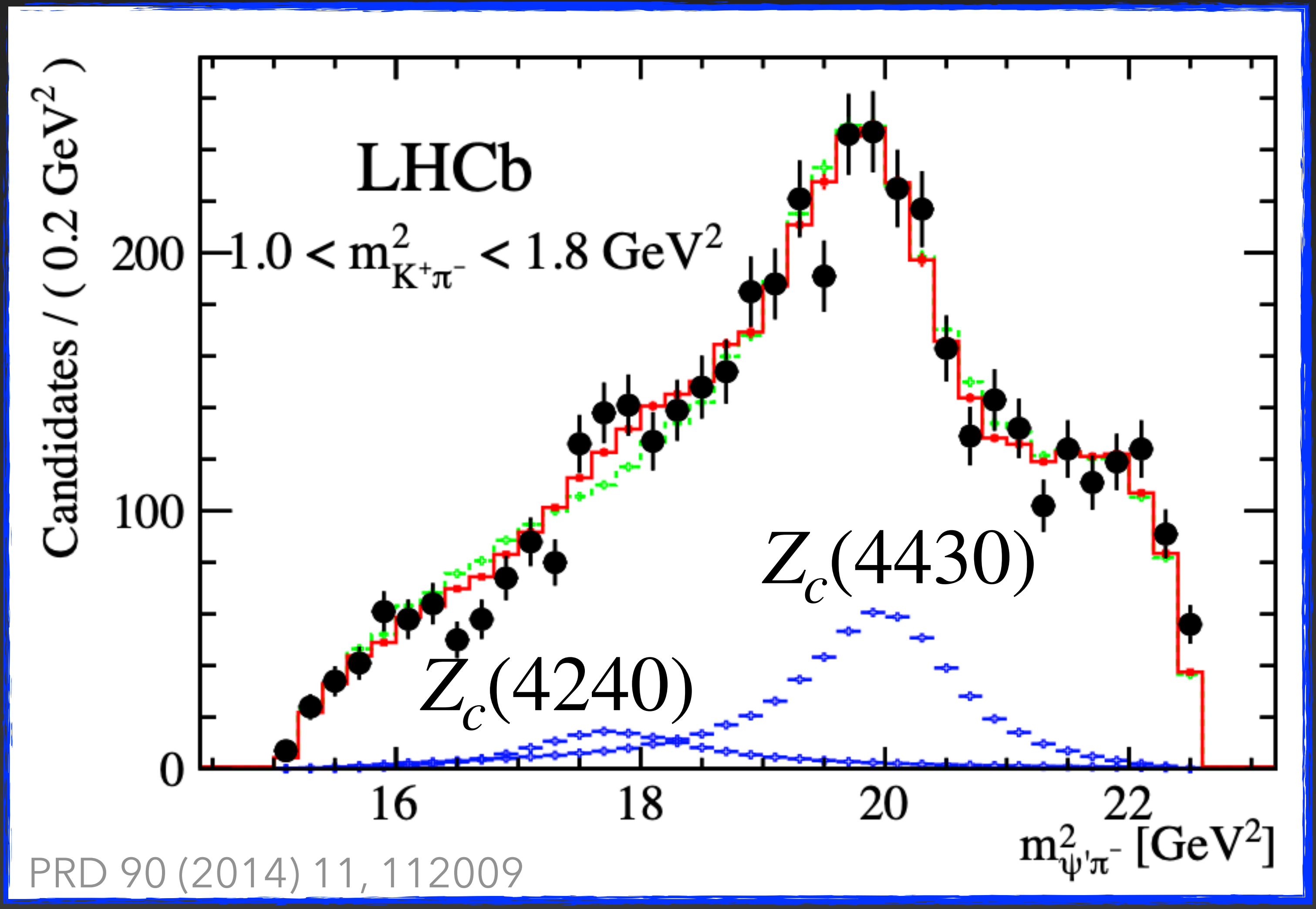
Entirely separate set of Z_c states

… well not entirely

for $m(J/\psi\pi\pi)$ in $\psi(4230)$ region

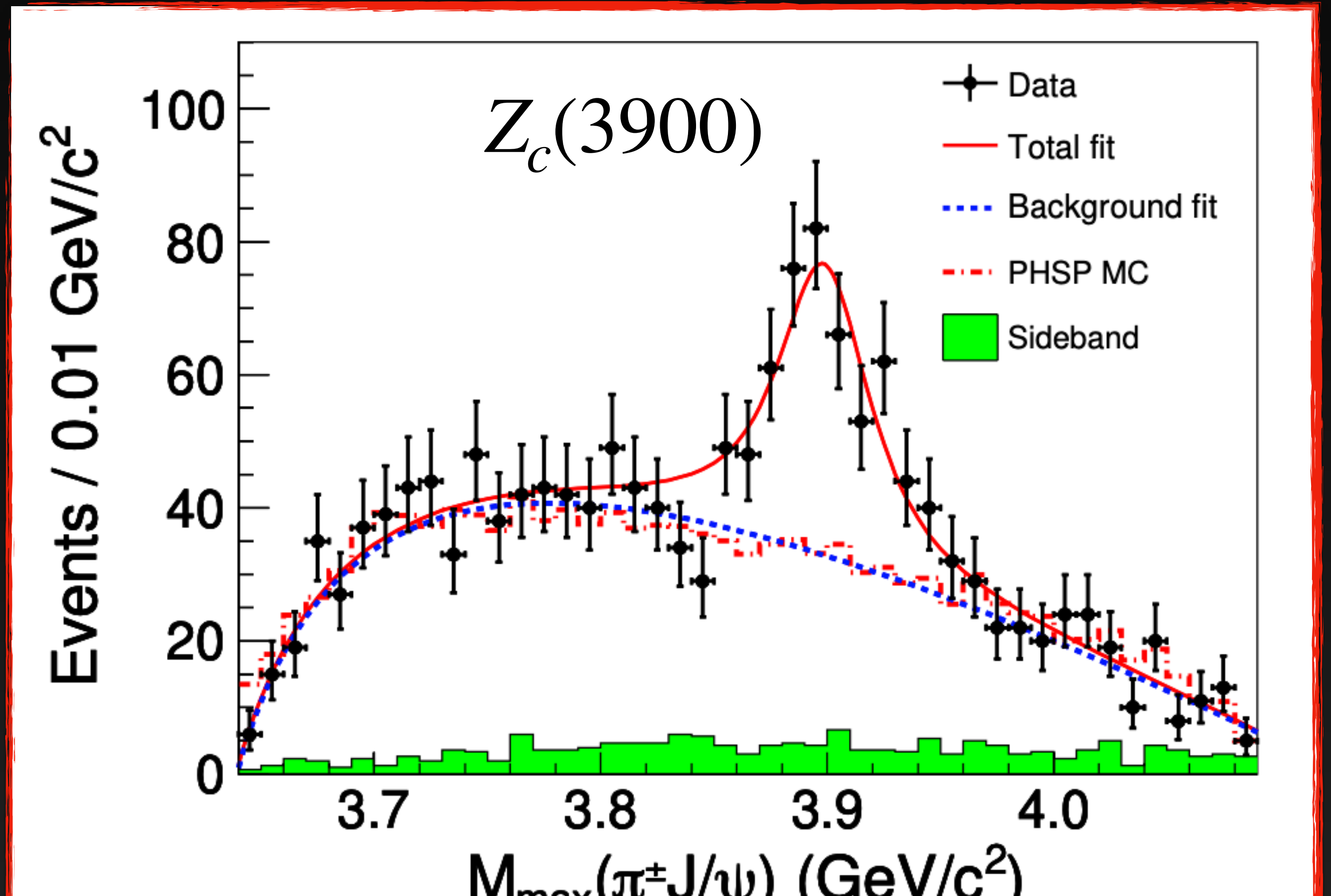
$B \to Z_cK$



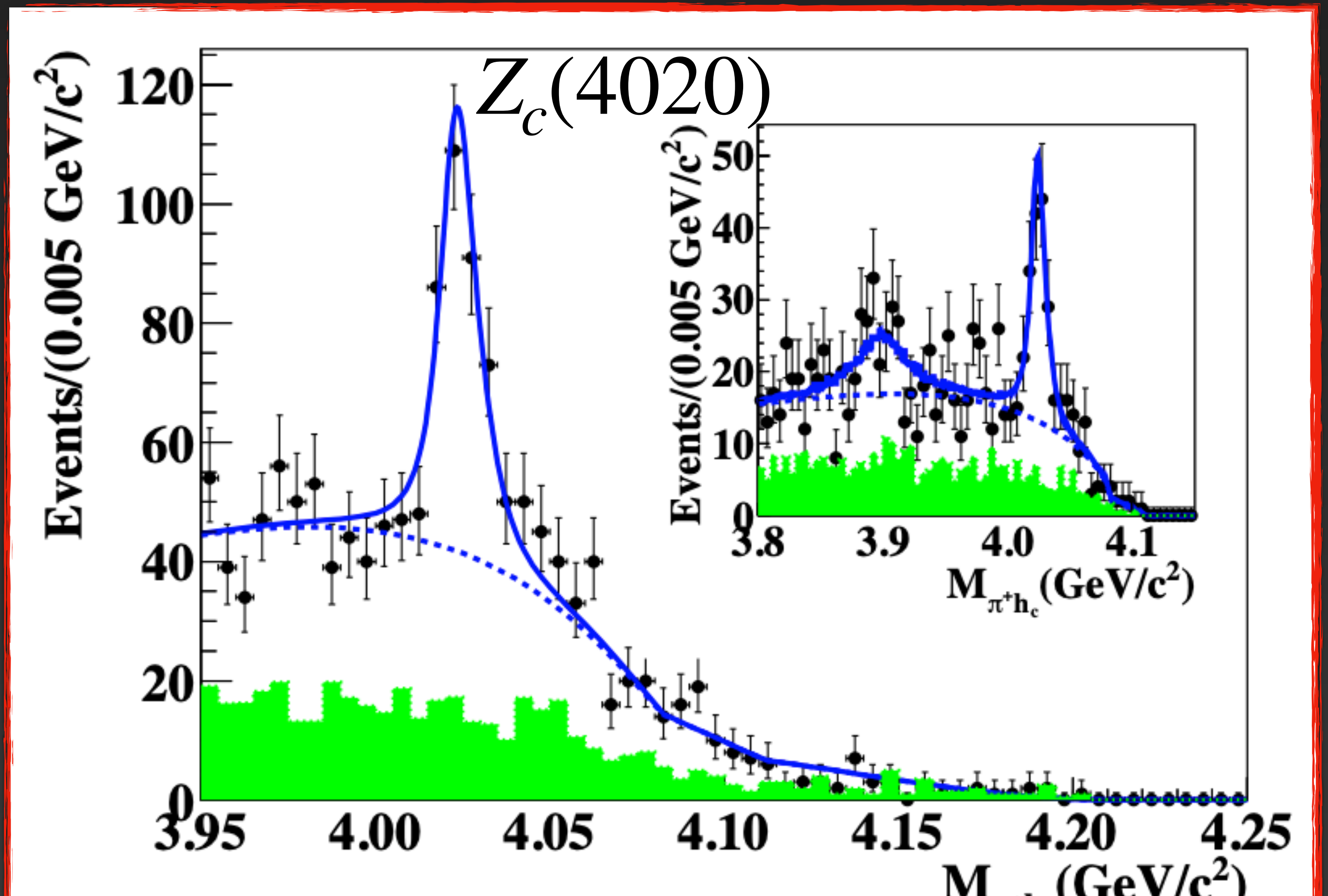


The Z_c states

$e^+e^- \to Z_c\pi$

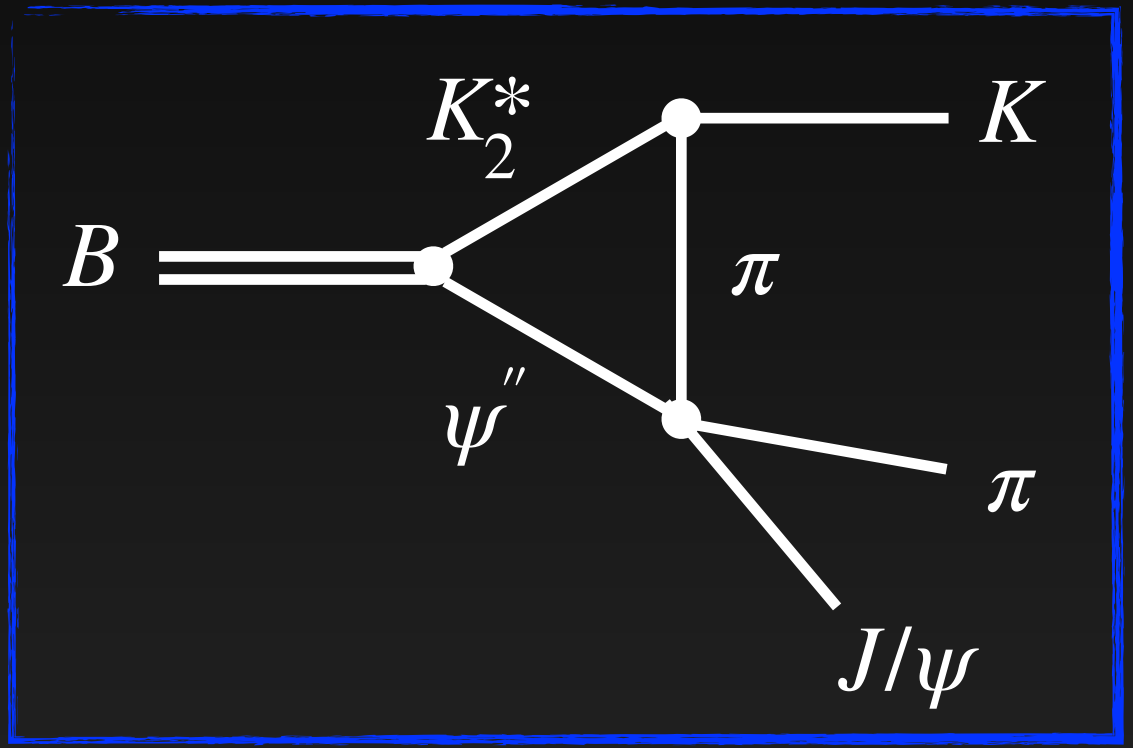


PRL 110 (2013) 252001

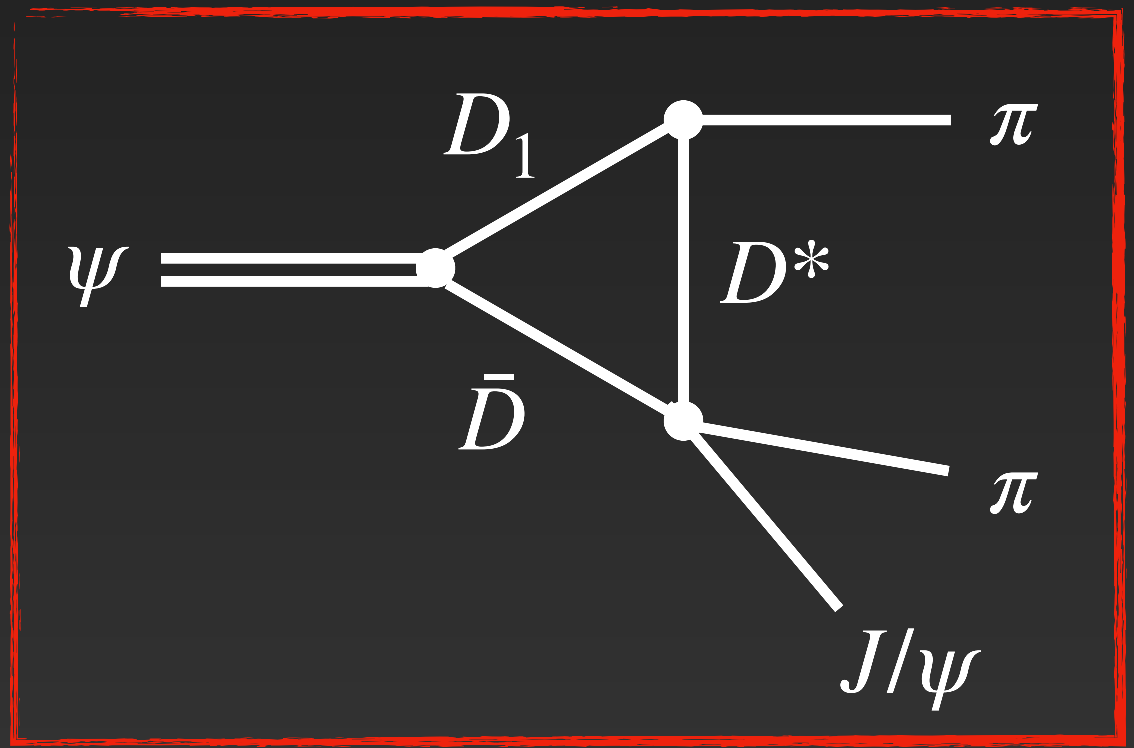


PRL 111 (2013) 24, 242001

are triangle singularities the solution?

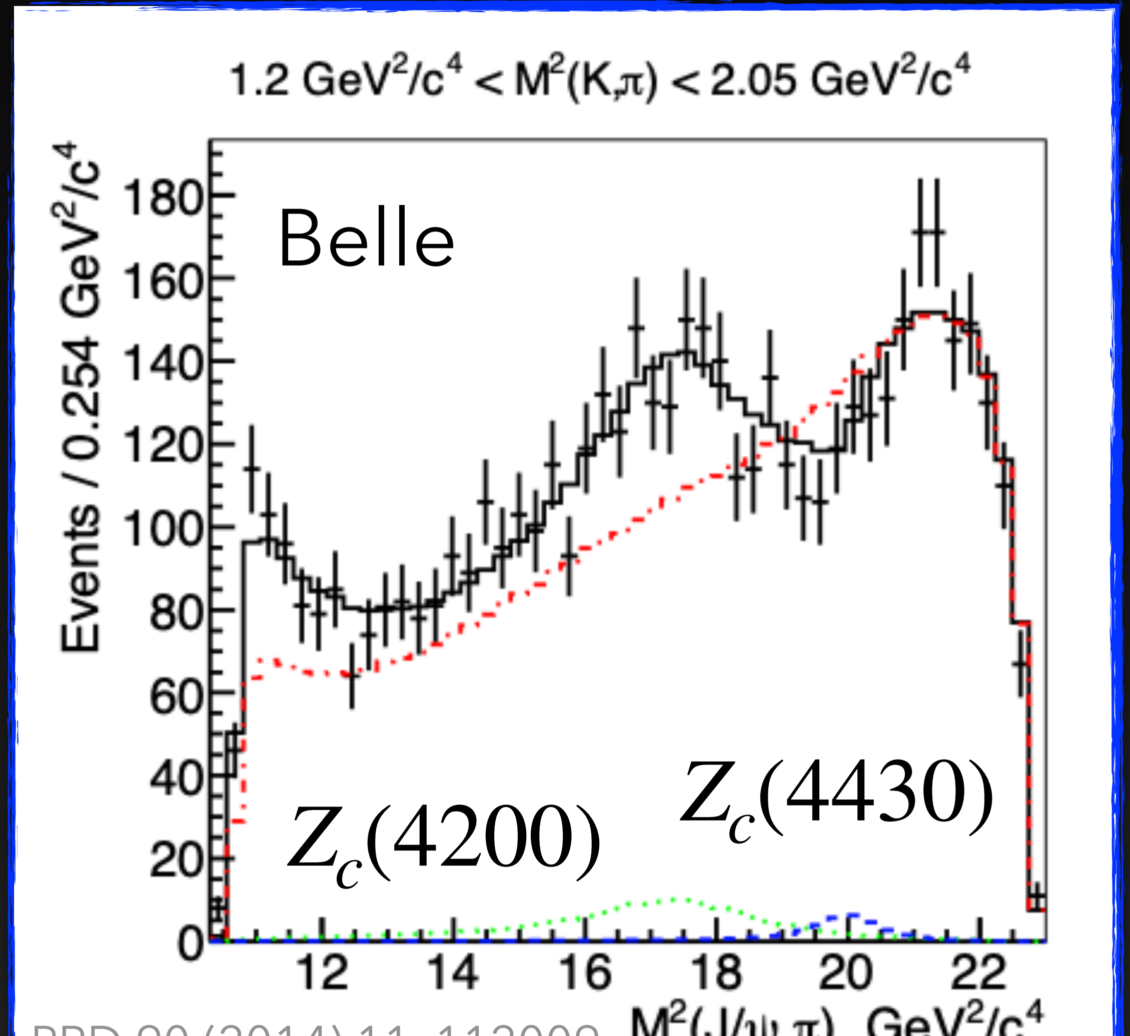


PRD 100 (2019) 1, 011504

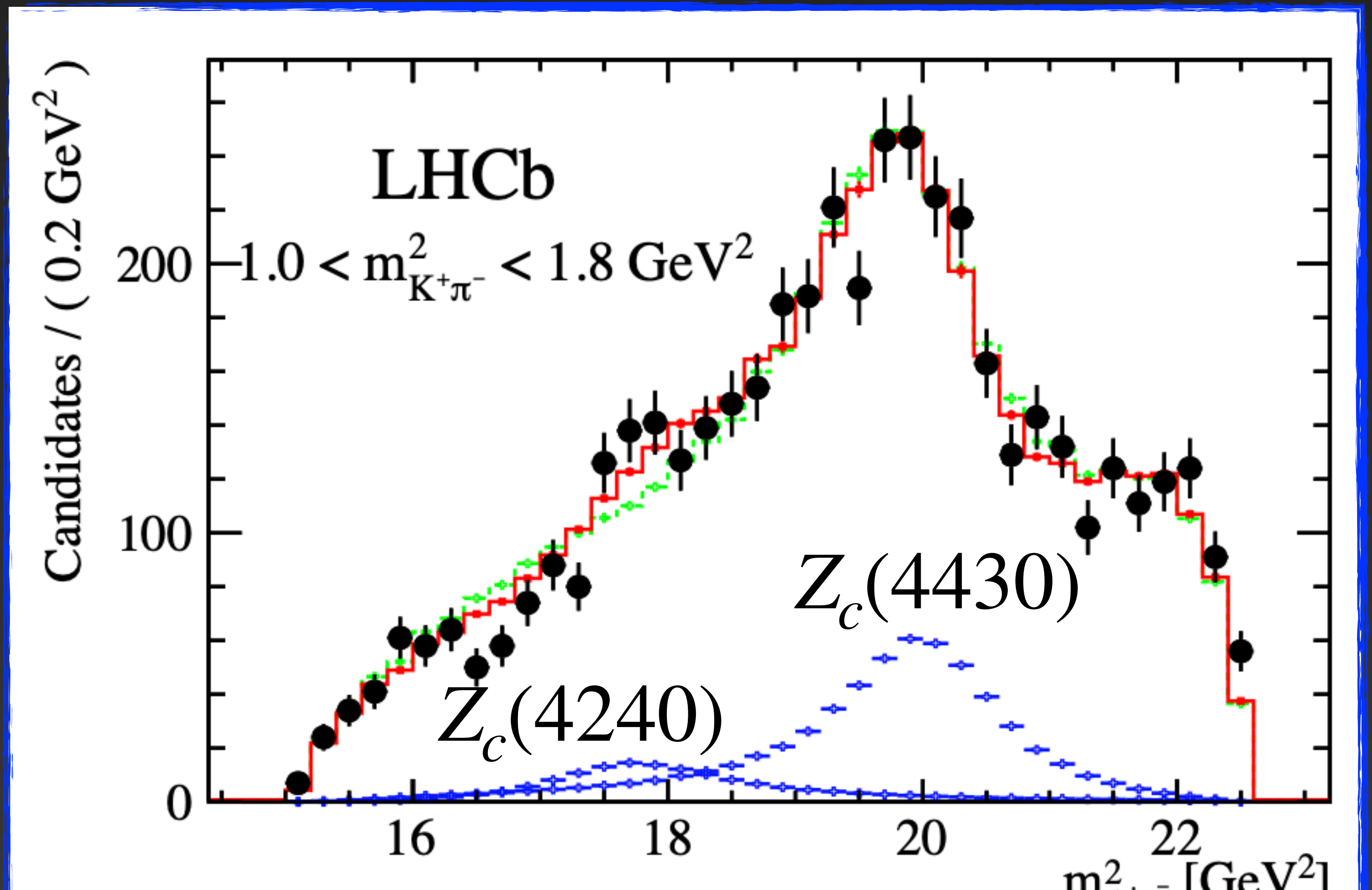


PRL 111 (2013) 13 132003
PLB 747 (2015) 410
PLB 755 (2016) 337
PLB 772 (2017) 200
EPJ C 80 (2020) 12 1179
PRD 109 (2024) 11, 116002

$B \to Z_cK$



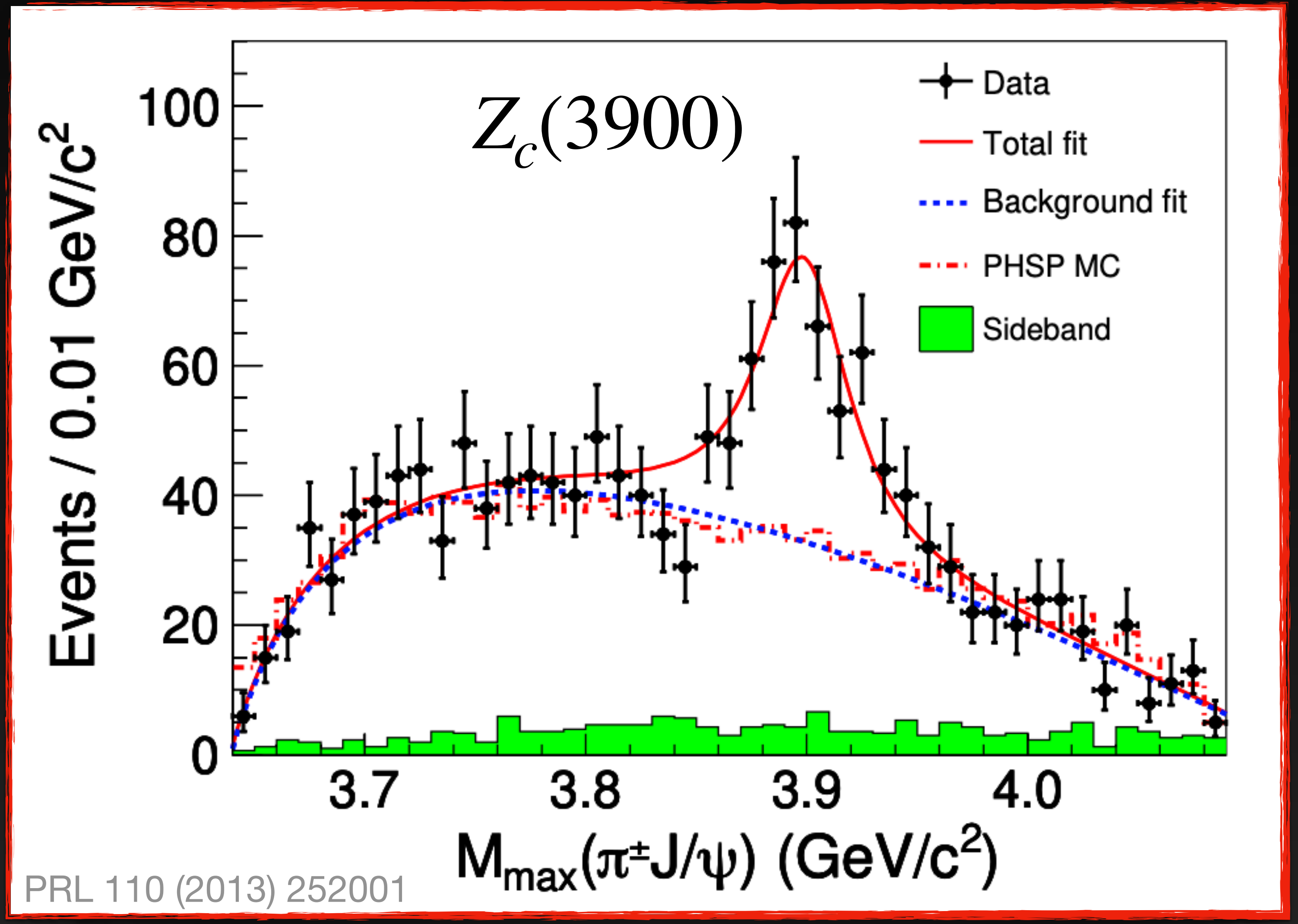
PRD 90 (2014) 11, 112009



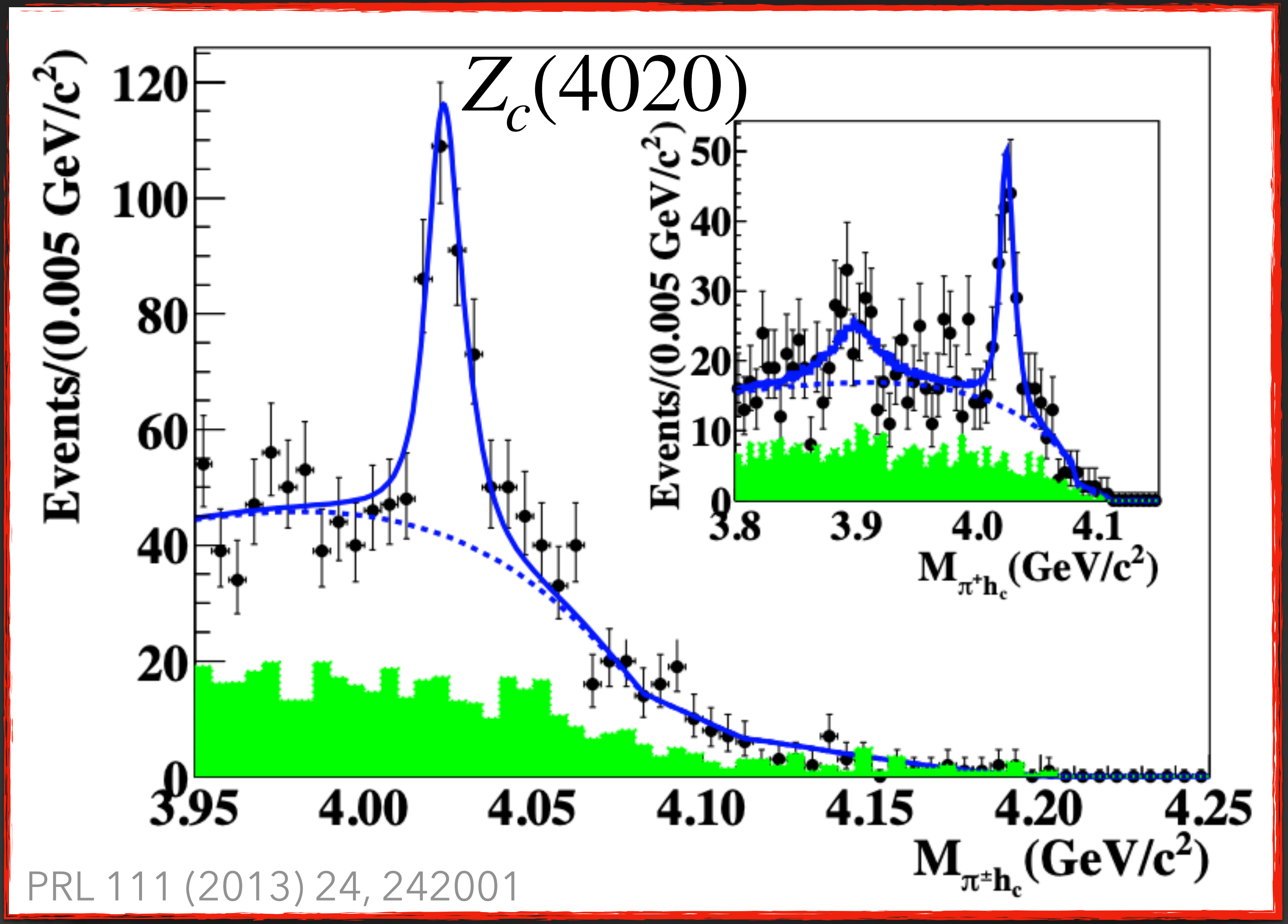
PRD 90 (2014) 11, 112009

The Z_c states

$e^+e^- \to Z_c\pi$



PRL 110 (2013) 252001



PRL 111 (2013) 24, 242001

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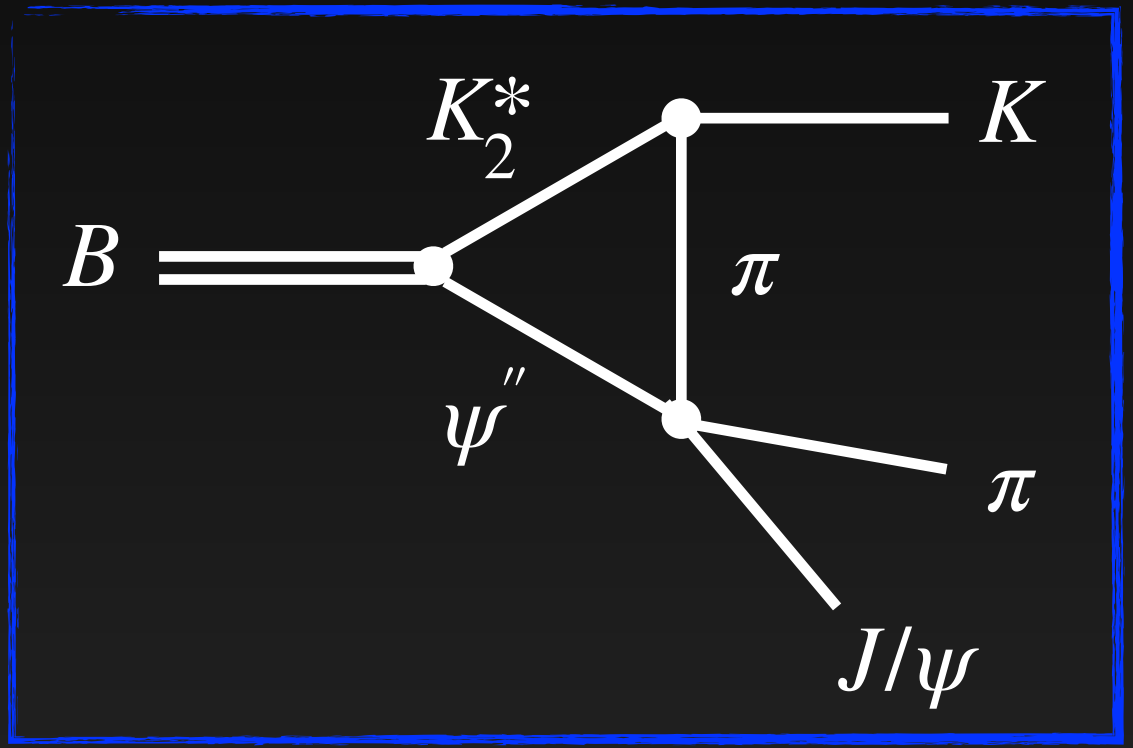
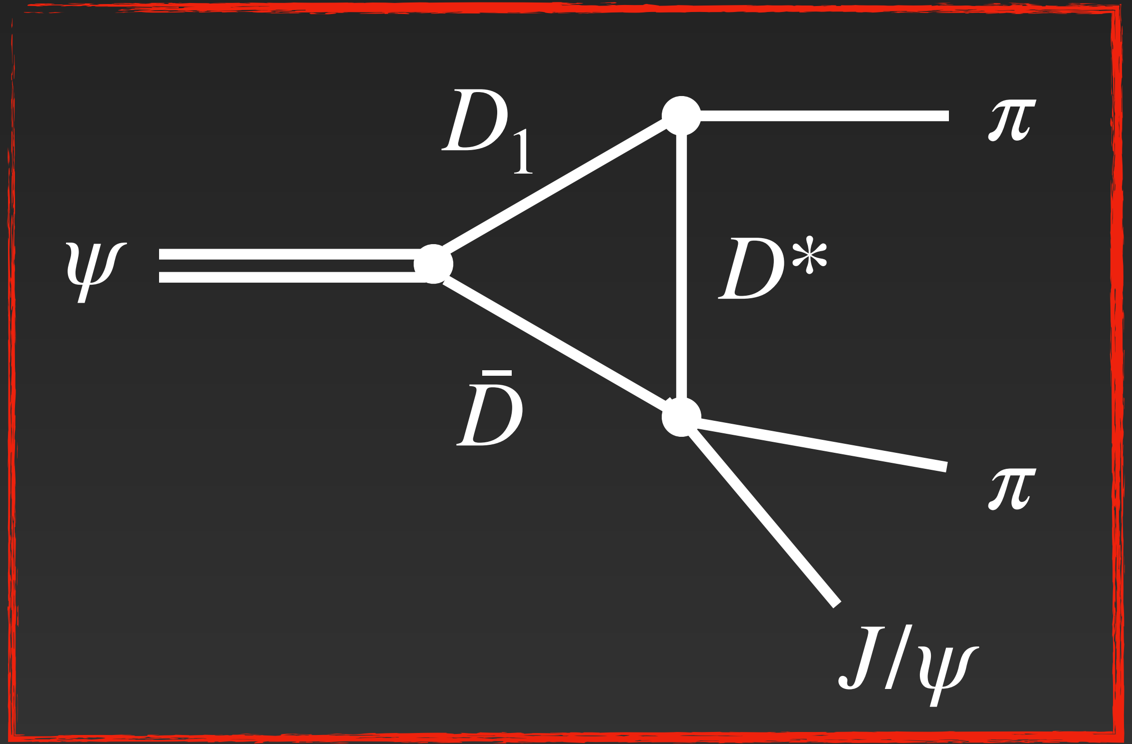
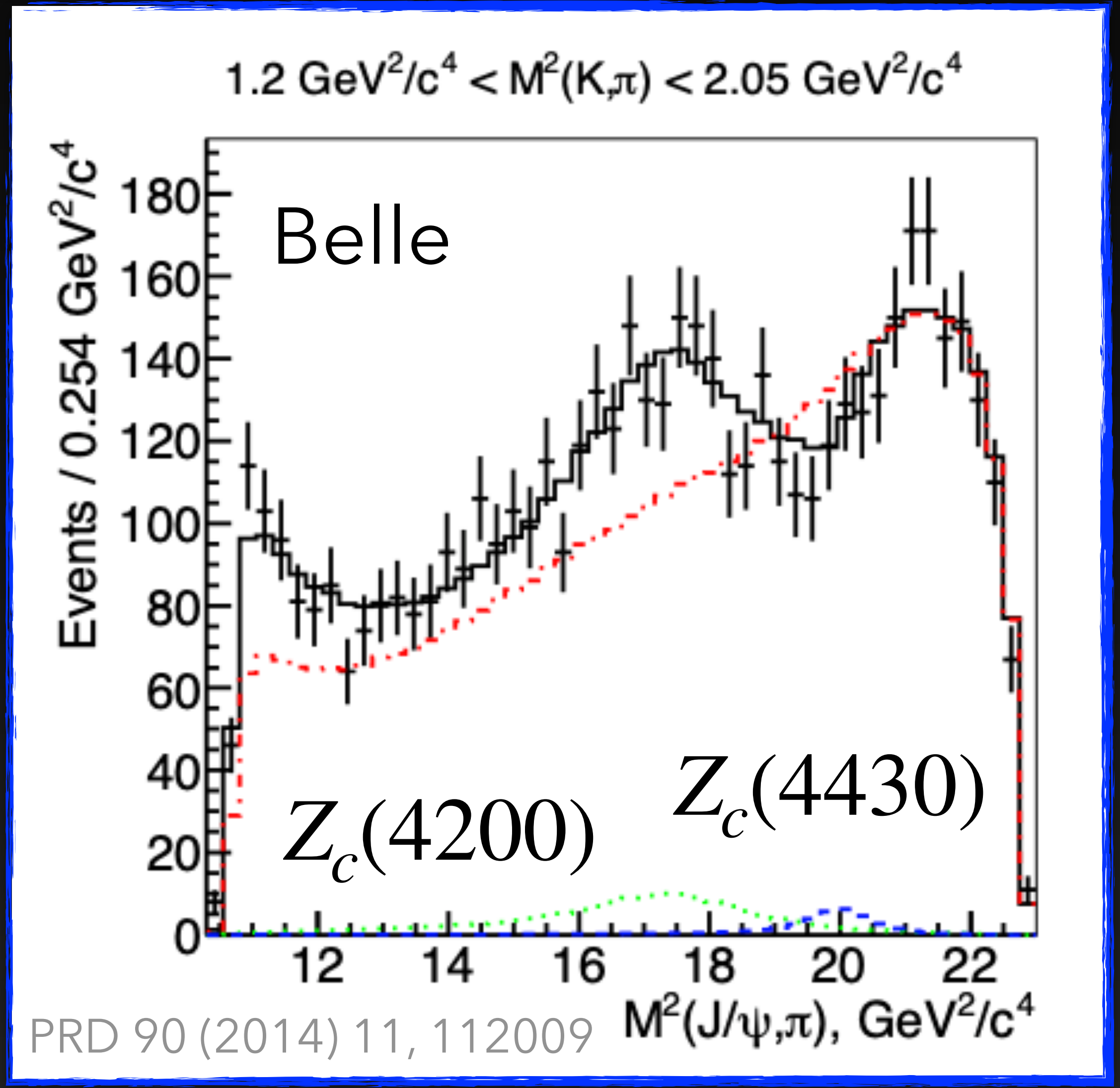


PRD 100 (2019) 1, 011504

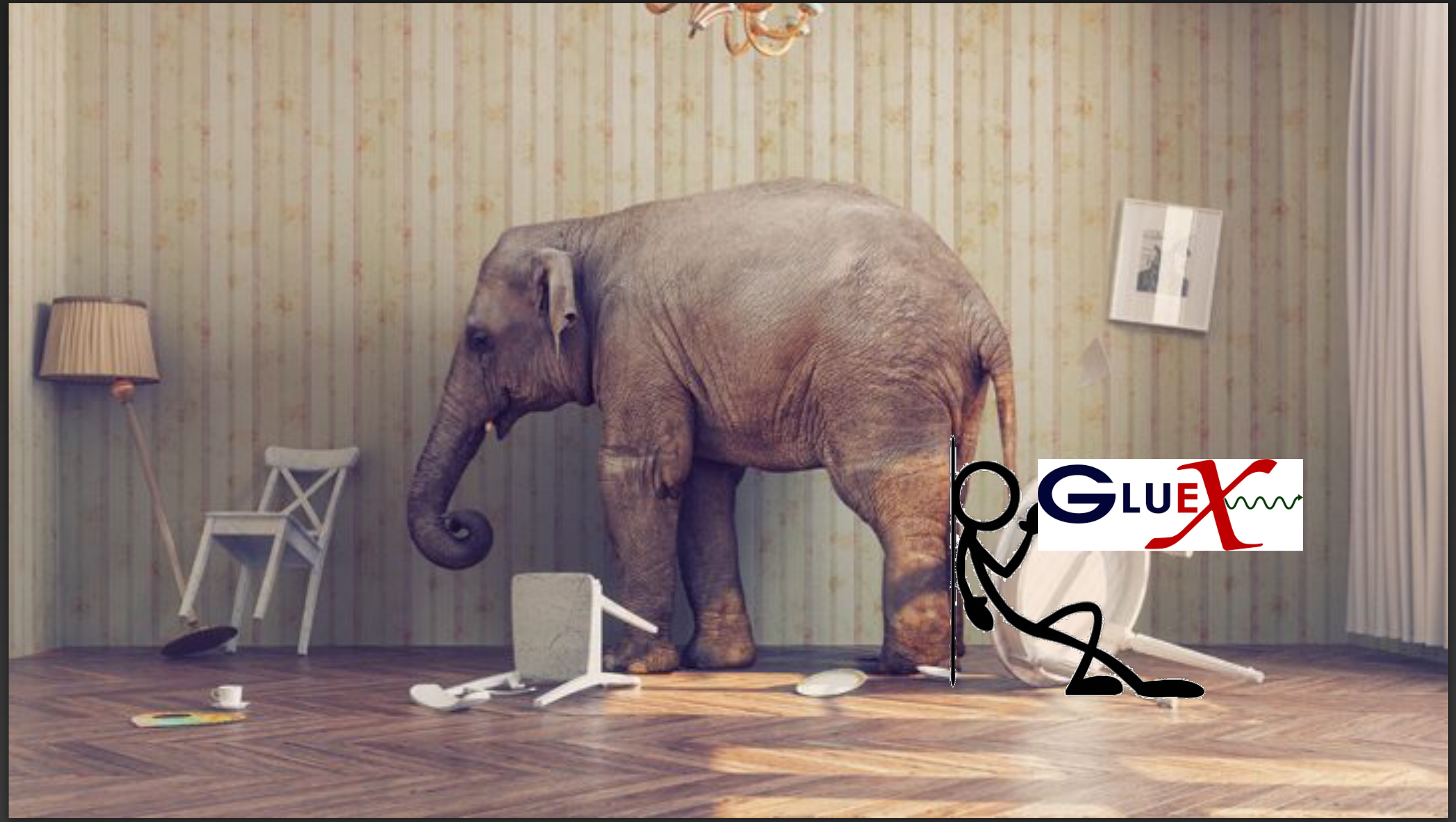


PRL 111 (2013) 13 132003
PLB 747 (2015) 410
PLB 755 (2016) 337
PLB 772 (2017) 200
EPJ C 80 (2020) 12 1179
PRD 109 (2024) 11, 116002

$B \to Z_c K$

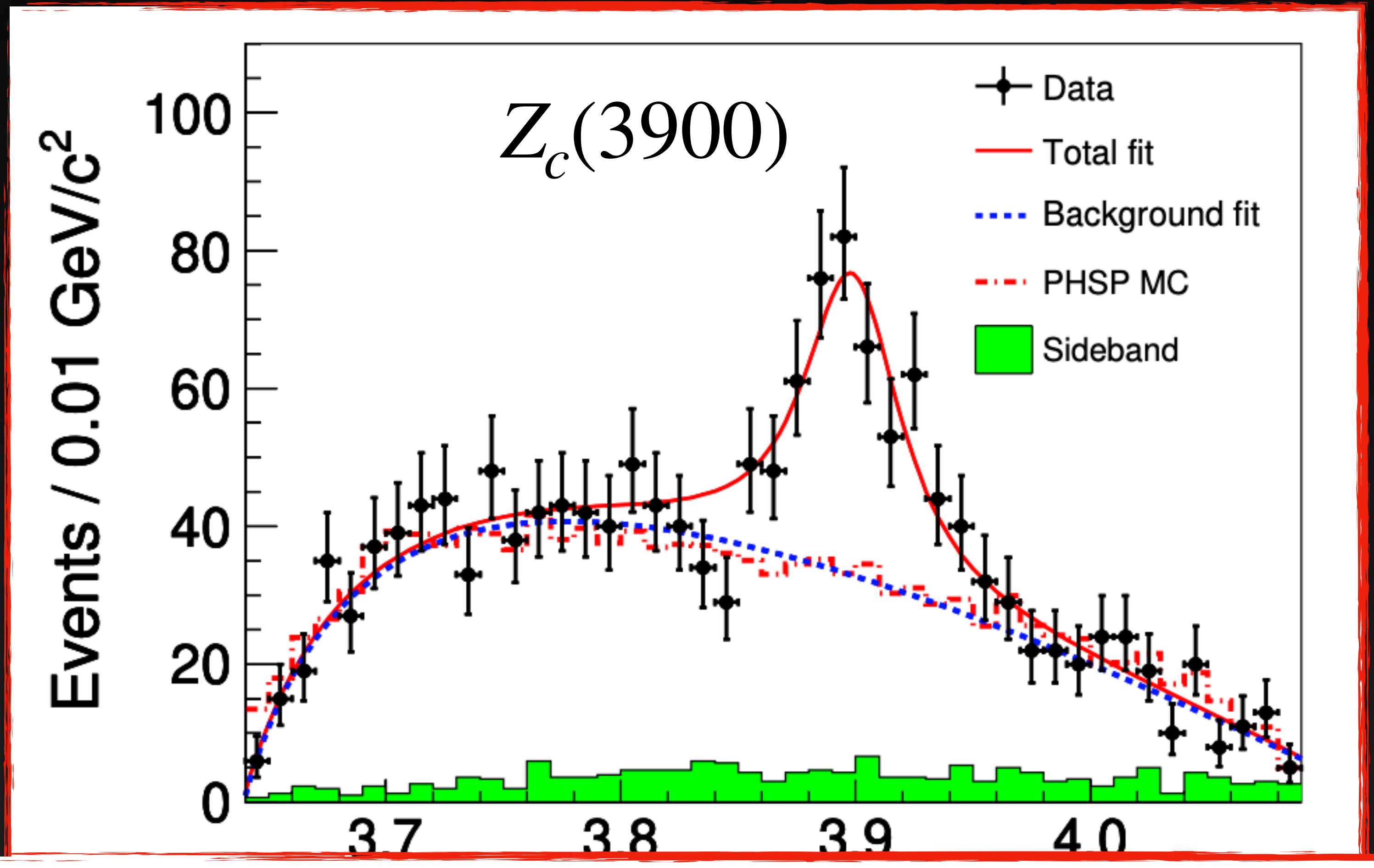


PRD 90 (2014) 11, 112009

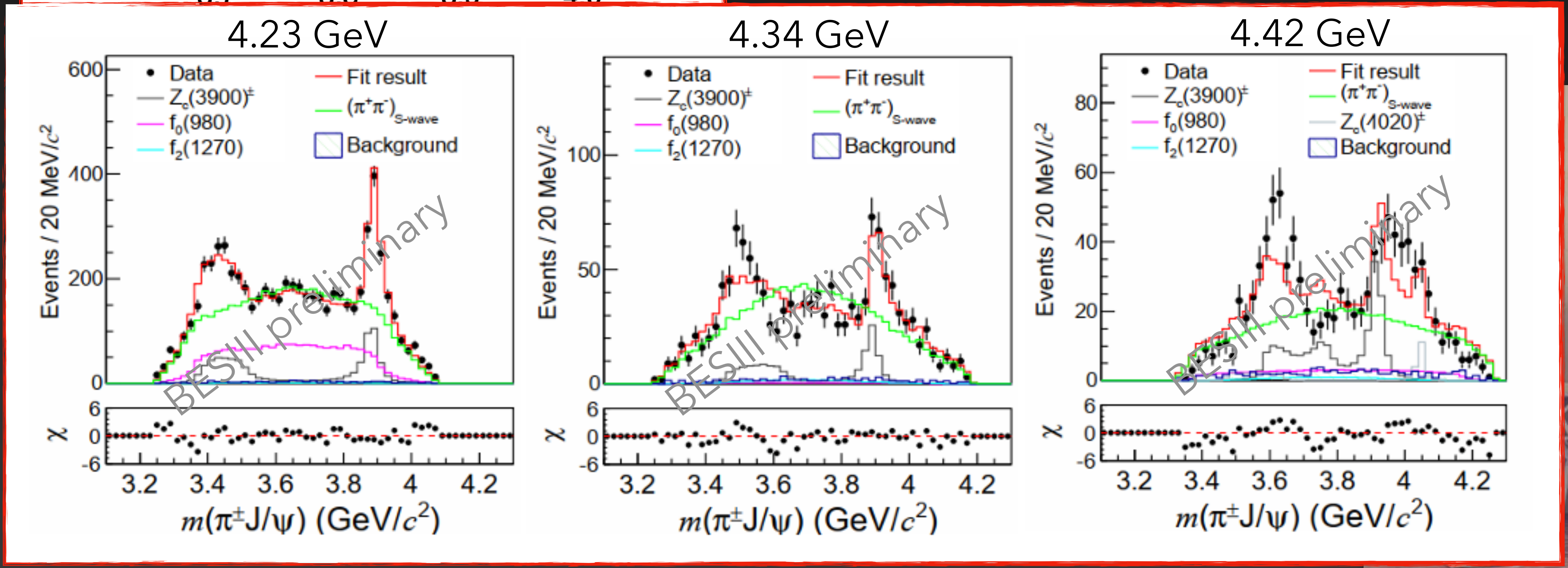


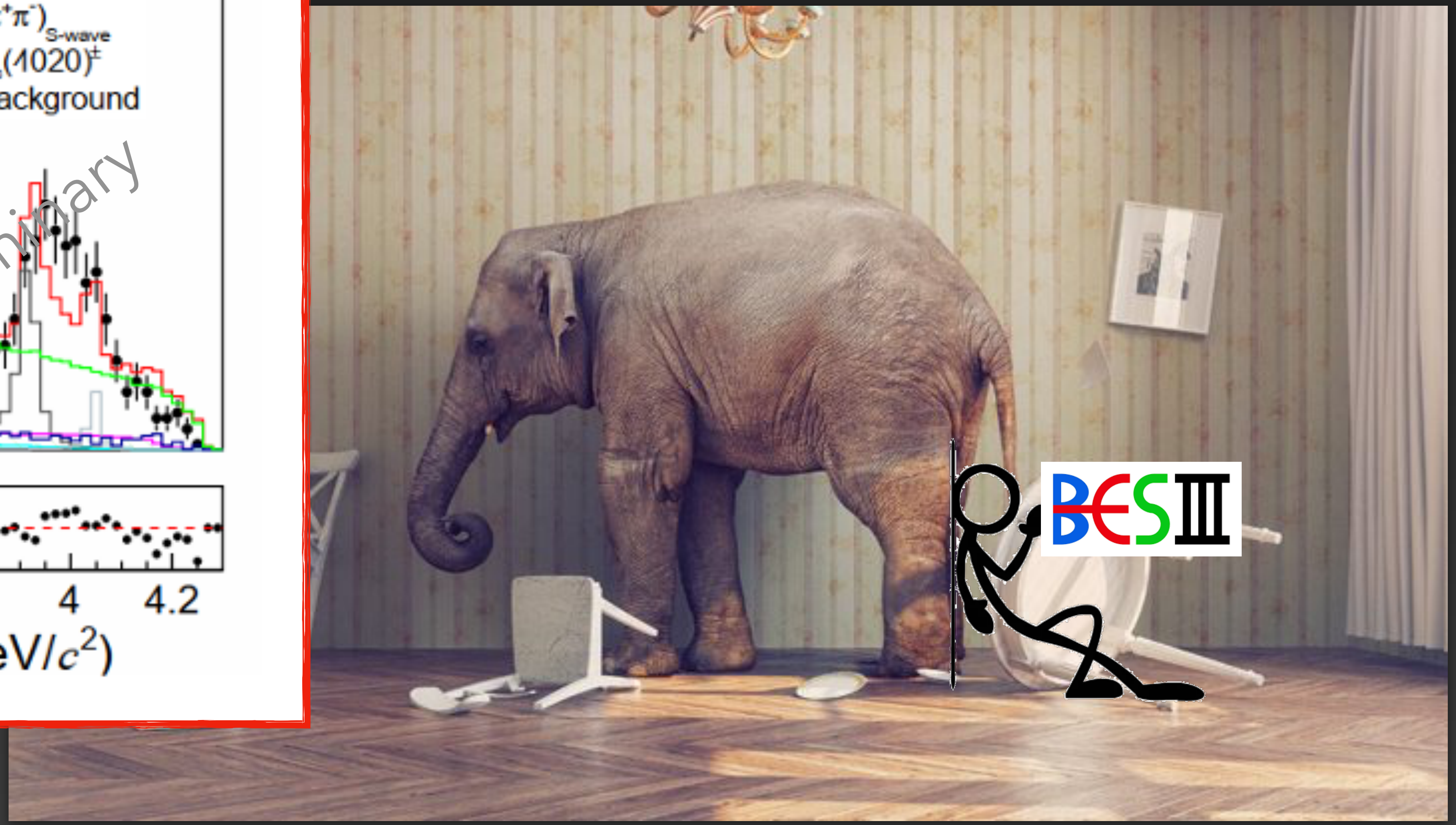
The Z_c states

$e^+e^- \to Z_c\pi$



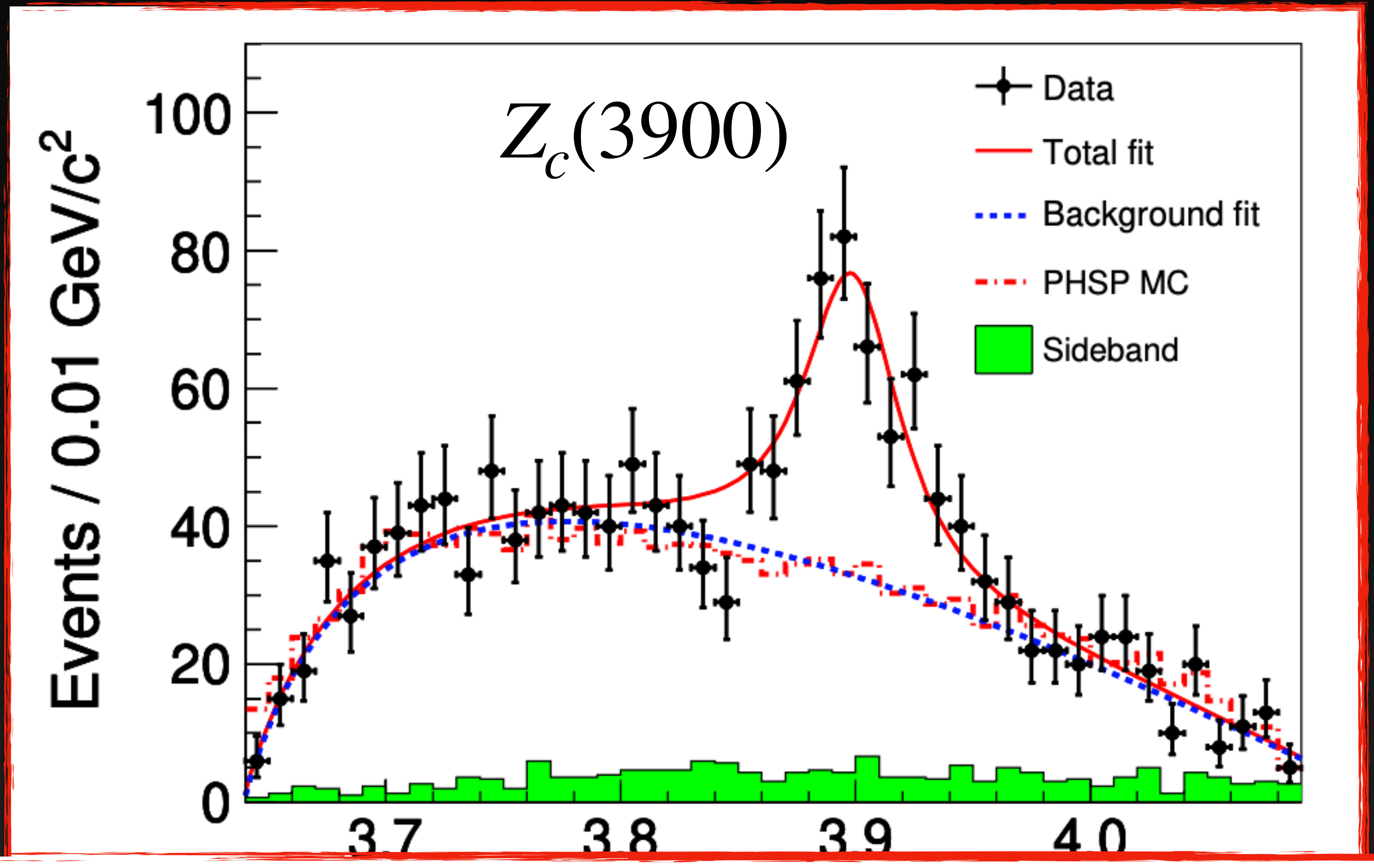
caveat: this problem can also be approached with precise (more) data

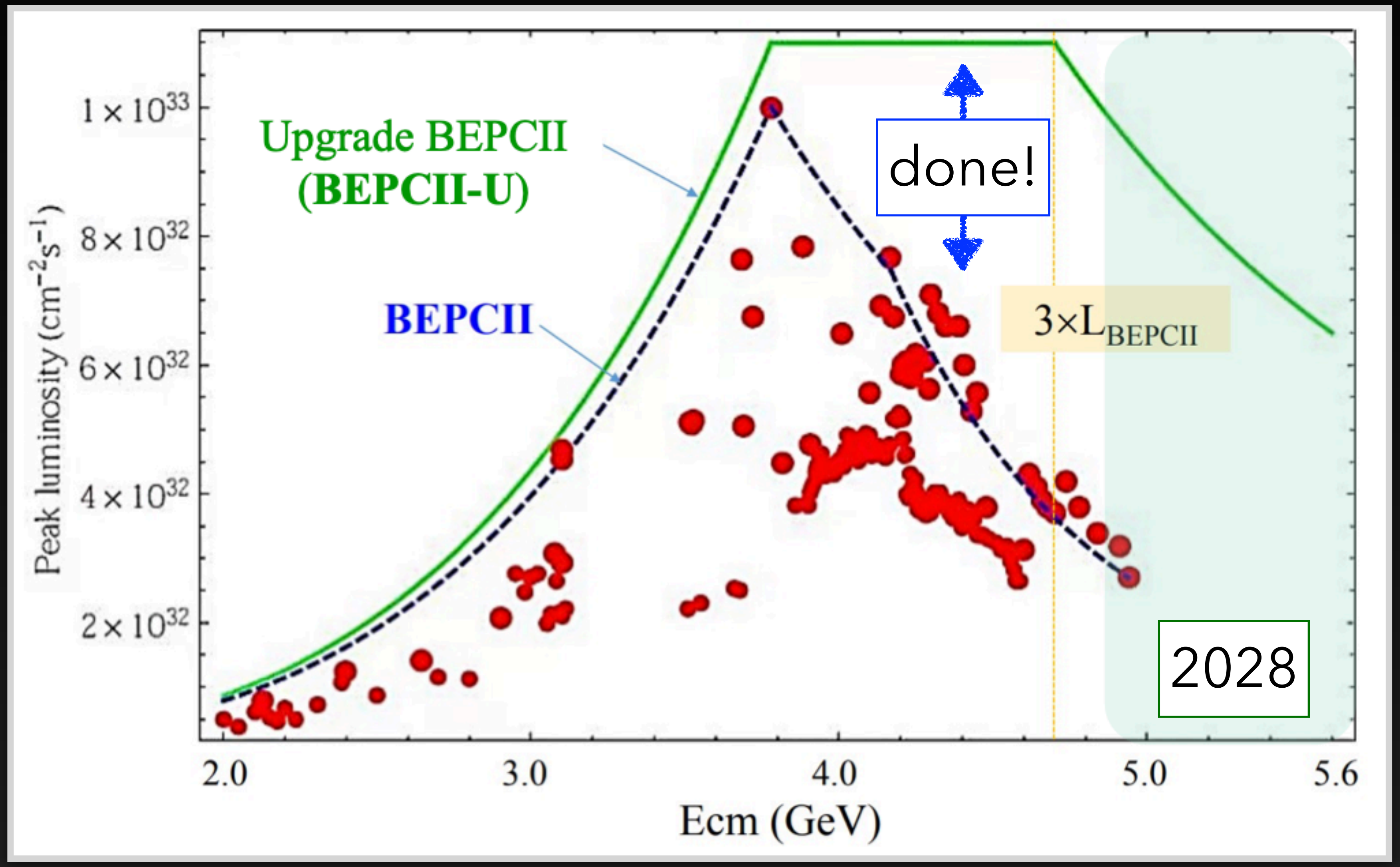




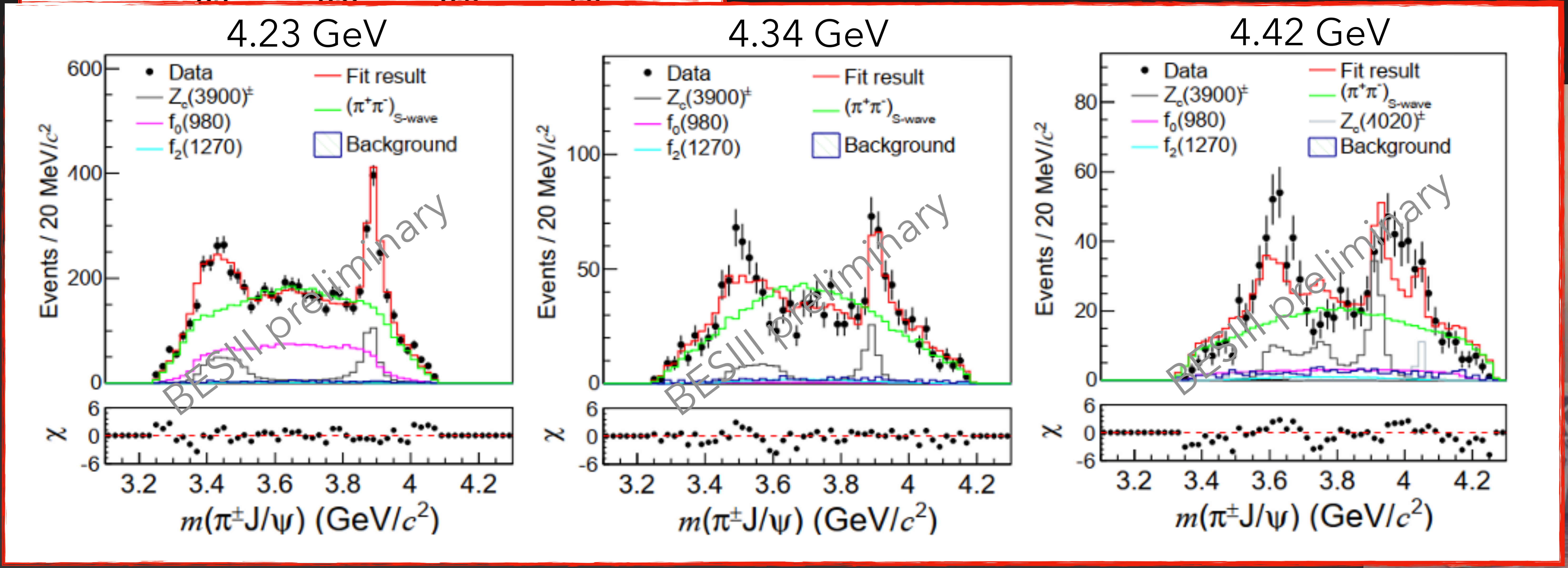
The Z_c states

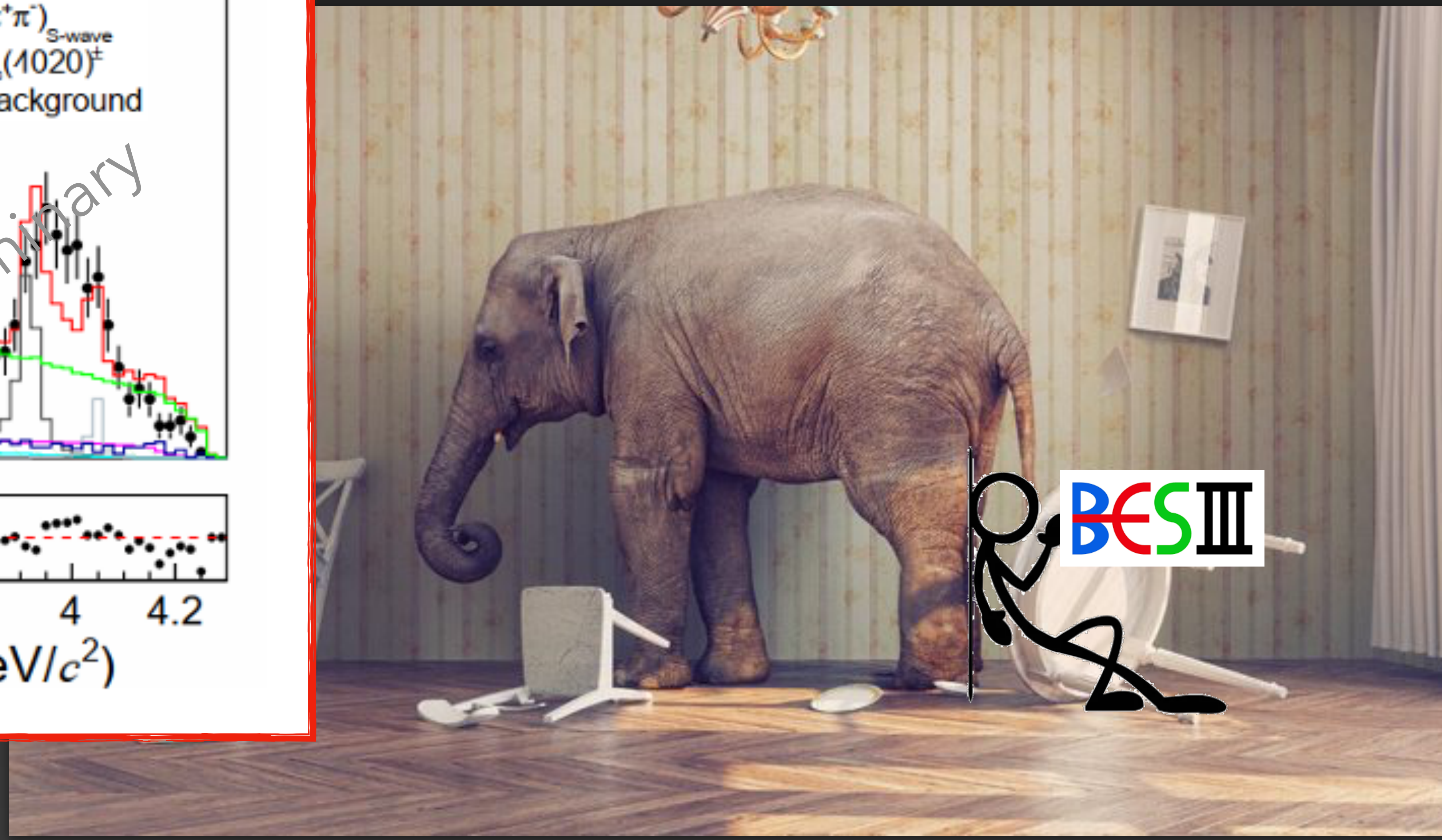
$e^+e^- \to Z_c\pi$





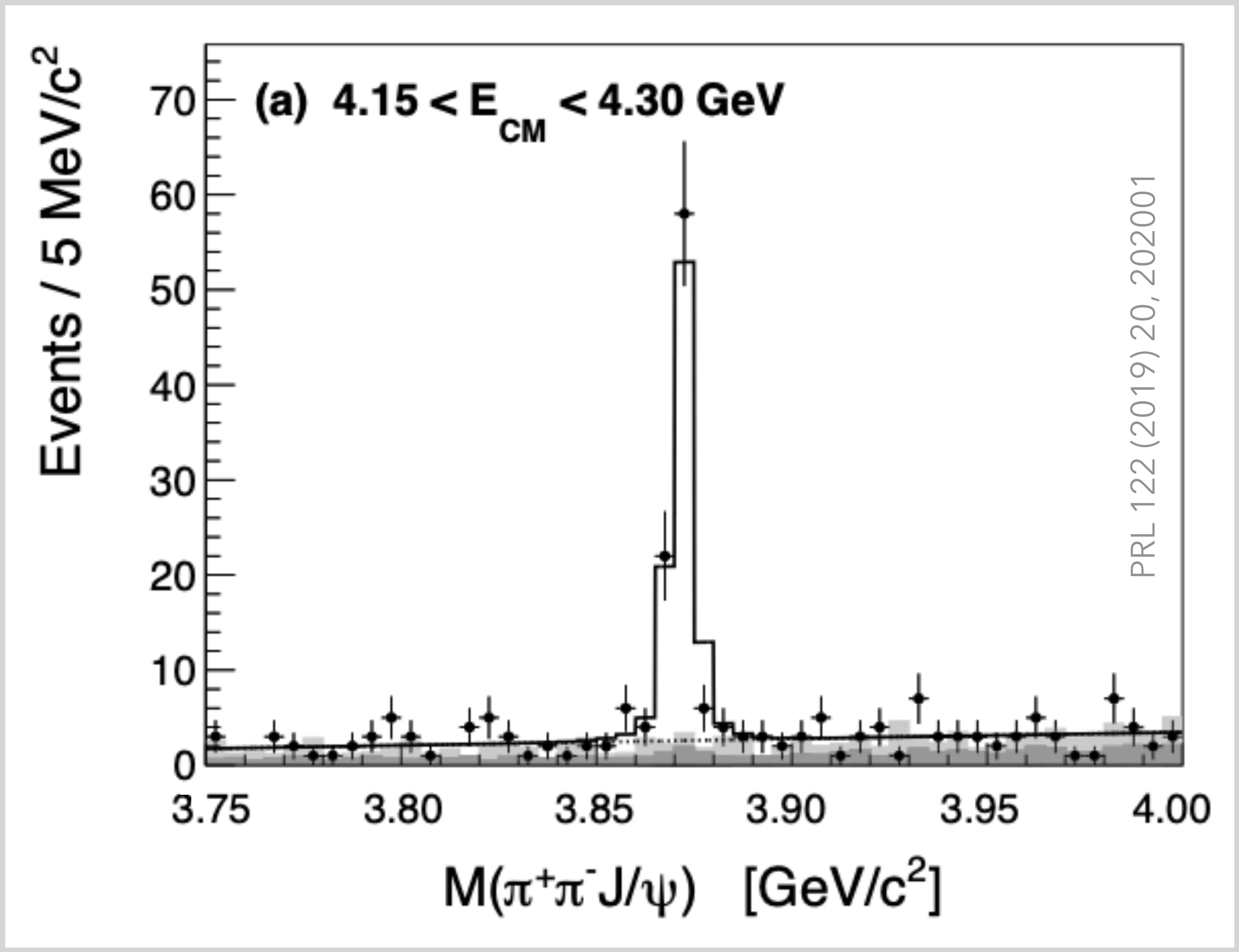
caveat: this problem can also be approached with precise (more) data



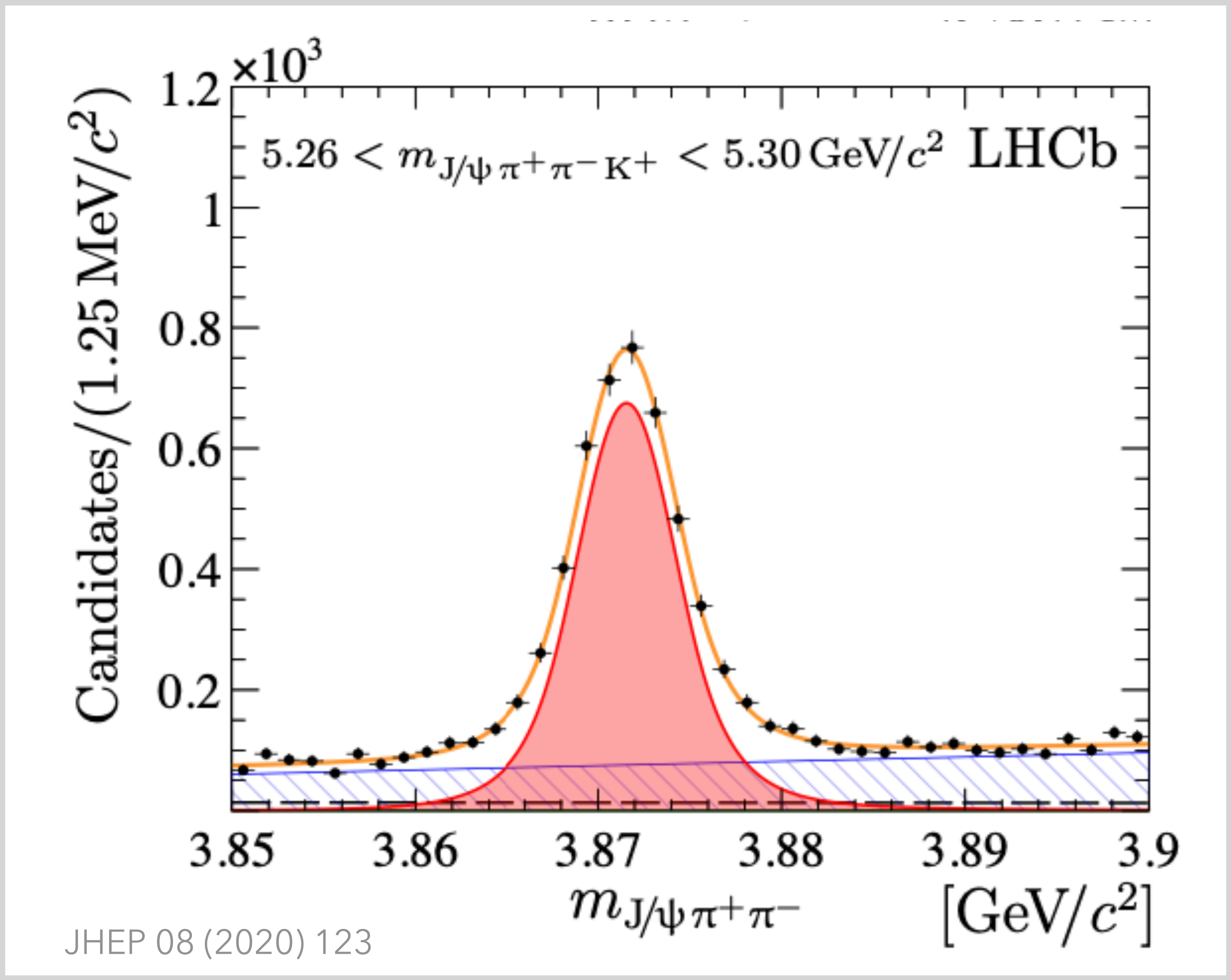


Radiative decays of the $X(3872)$

$e^+e^- \to \gamma X(3872)$



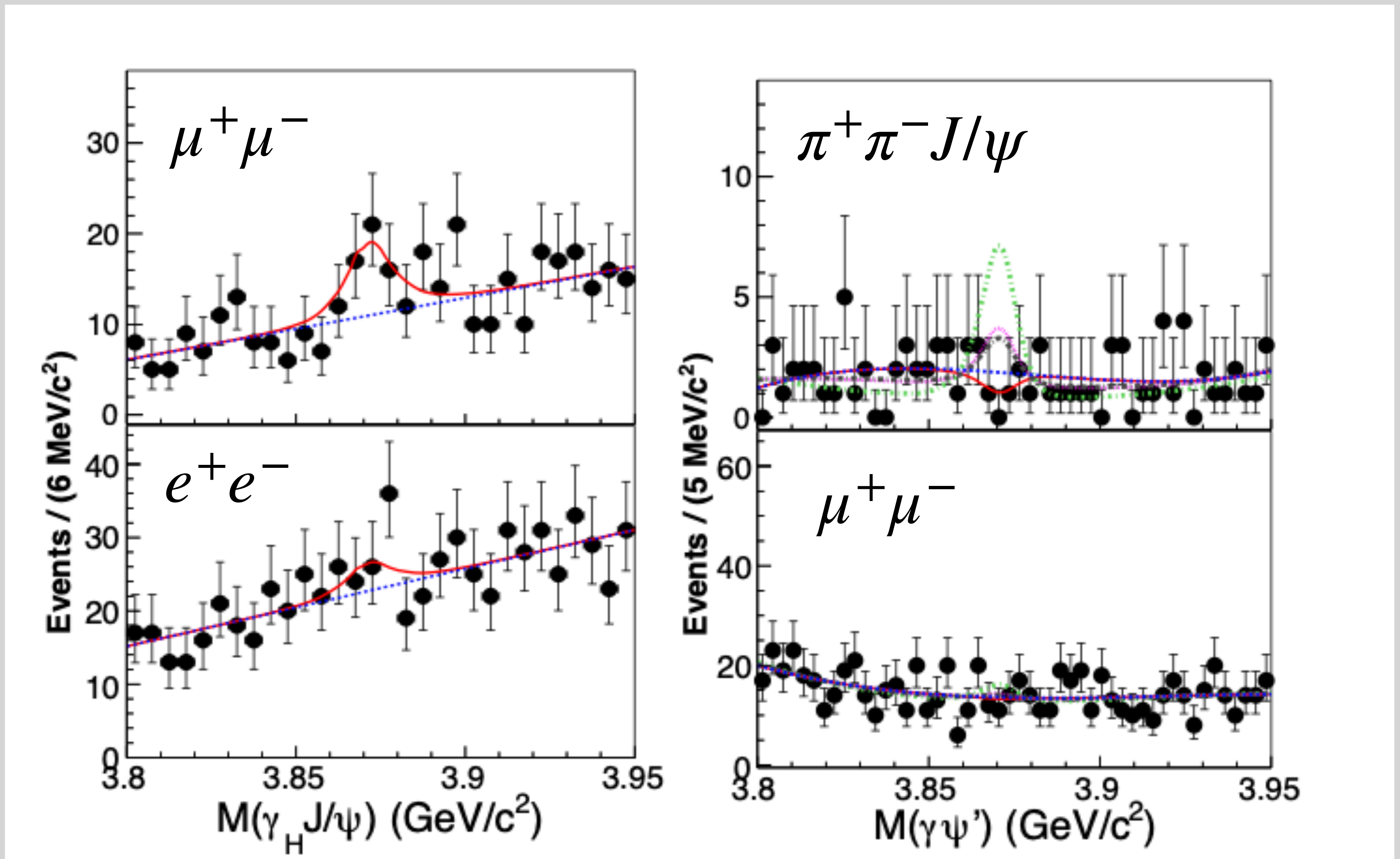
$B \to K\ X(3872)$



Hallelujah, an exotic hadron candidate in multiple production processes!

Radiative decays of the $X(3872)$

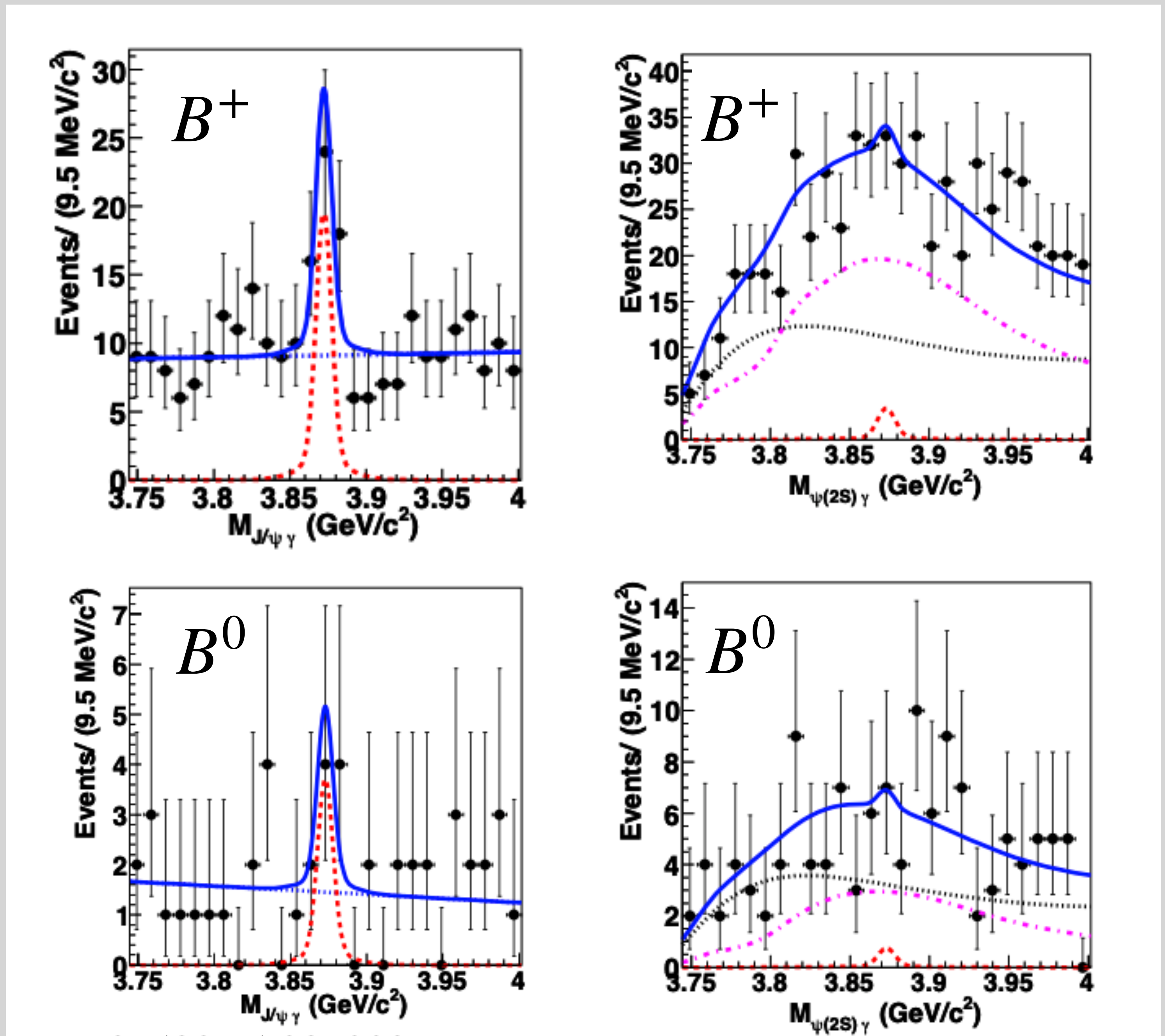
$e^+e^- \to \gamma X(3872)$



PRL 124 (2020) 24, 242001

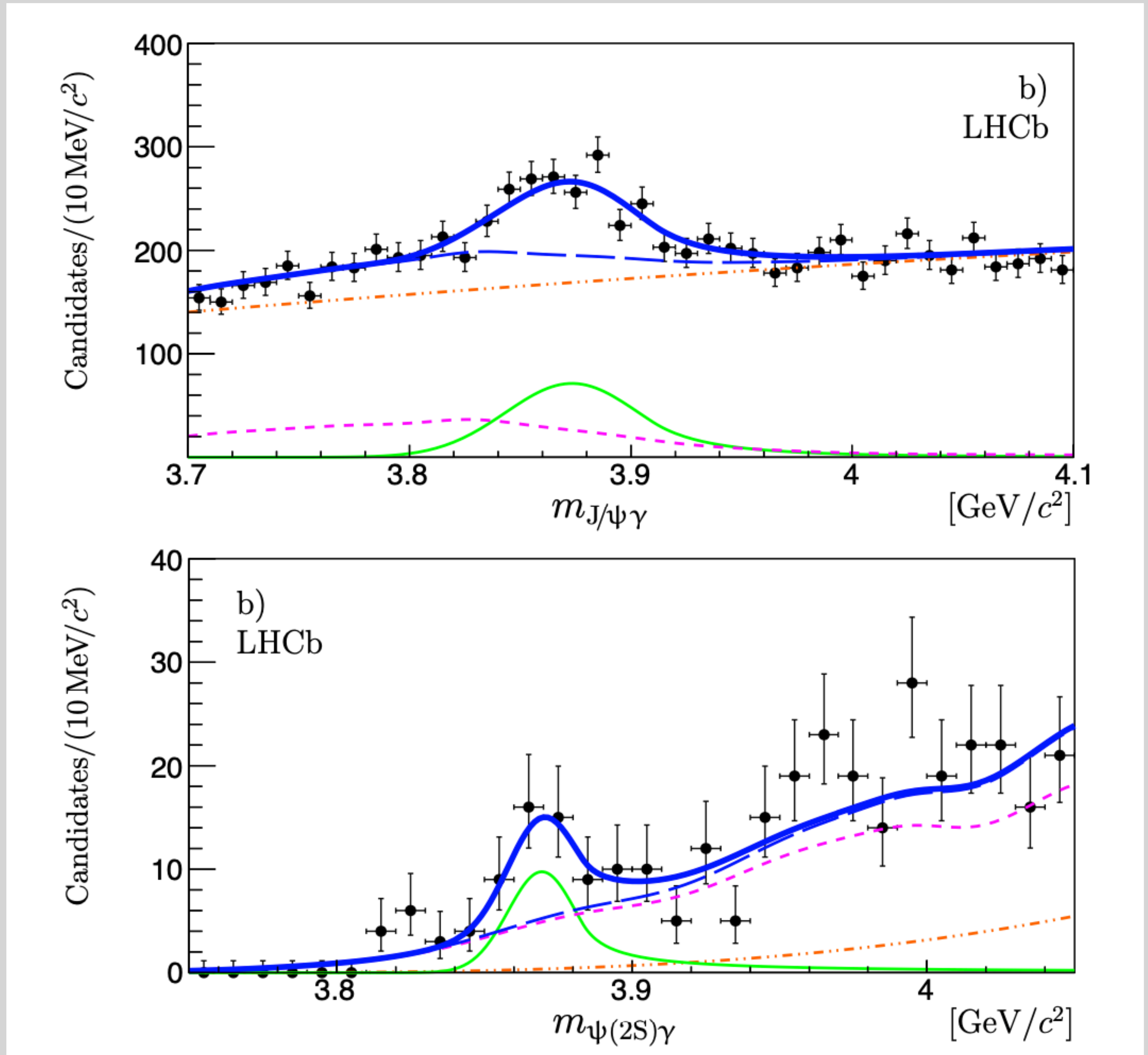
$B \to K\, X(3872)$

Belle



PRL 107 (2011) 091803

LHCb



Nucl. Phys. B 886 (2014) 665-680

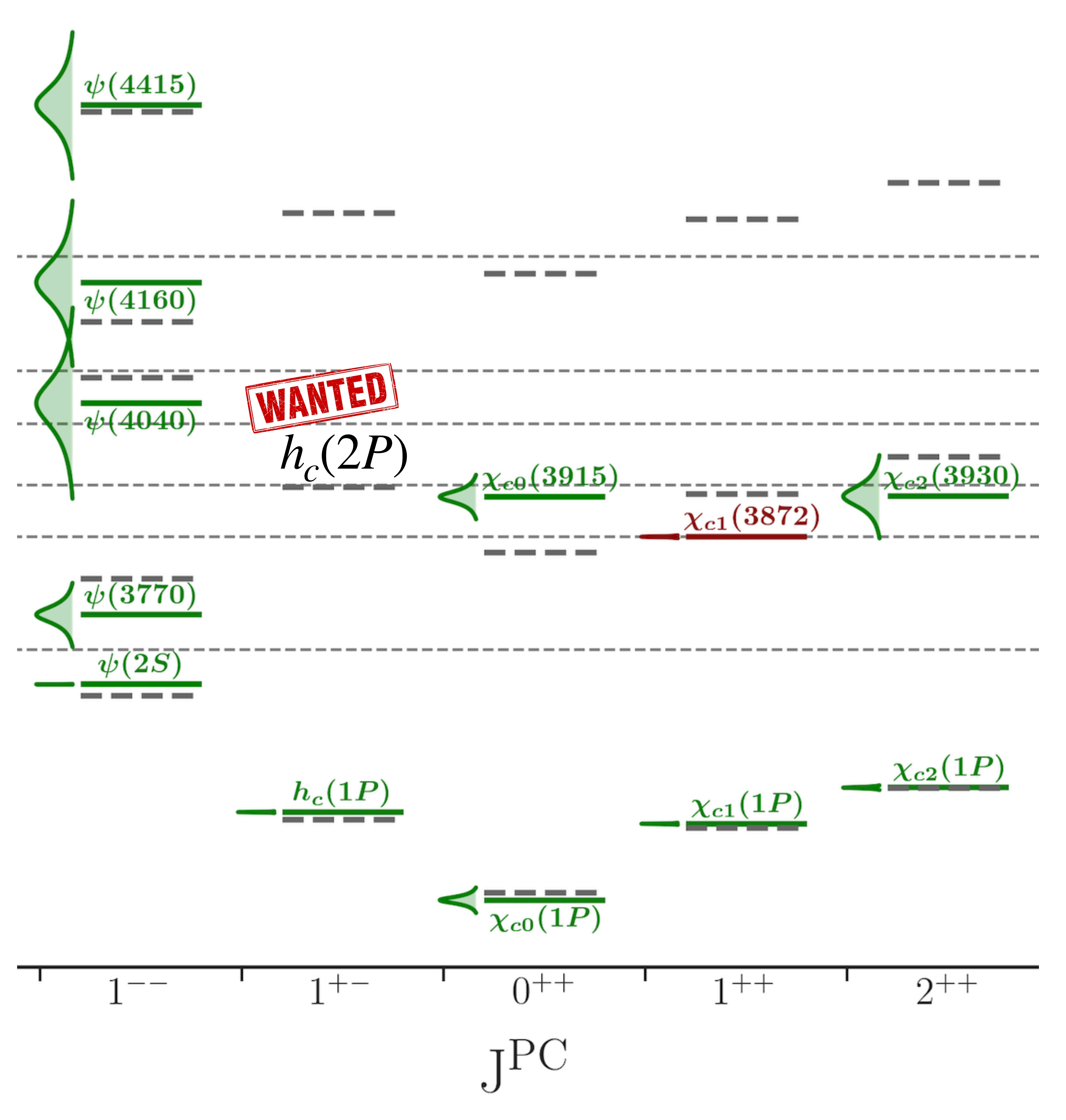
$$\frac{\Gamma_{\gamma\psi(2S)}}{\Gamma_{\gamma J/\psi}} < 0.59$$

$$\frac{\Gamma_{\gamma\psi(2S)}}{\Gamma_{\gamma J/\psi}} < 2.1$$

$$\frac{\Gamma_{\gamma\psi(2S)}}{\Gamma_{\gamma J/\psi}} < 2.46 \pm 0.64 \pm 0.29$$

can this be addressed with 22 GeV photons?

Missing charmonium states



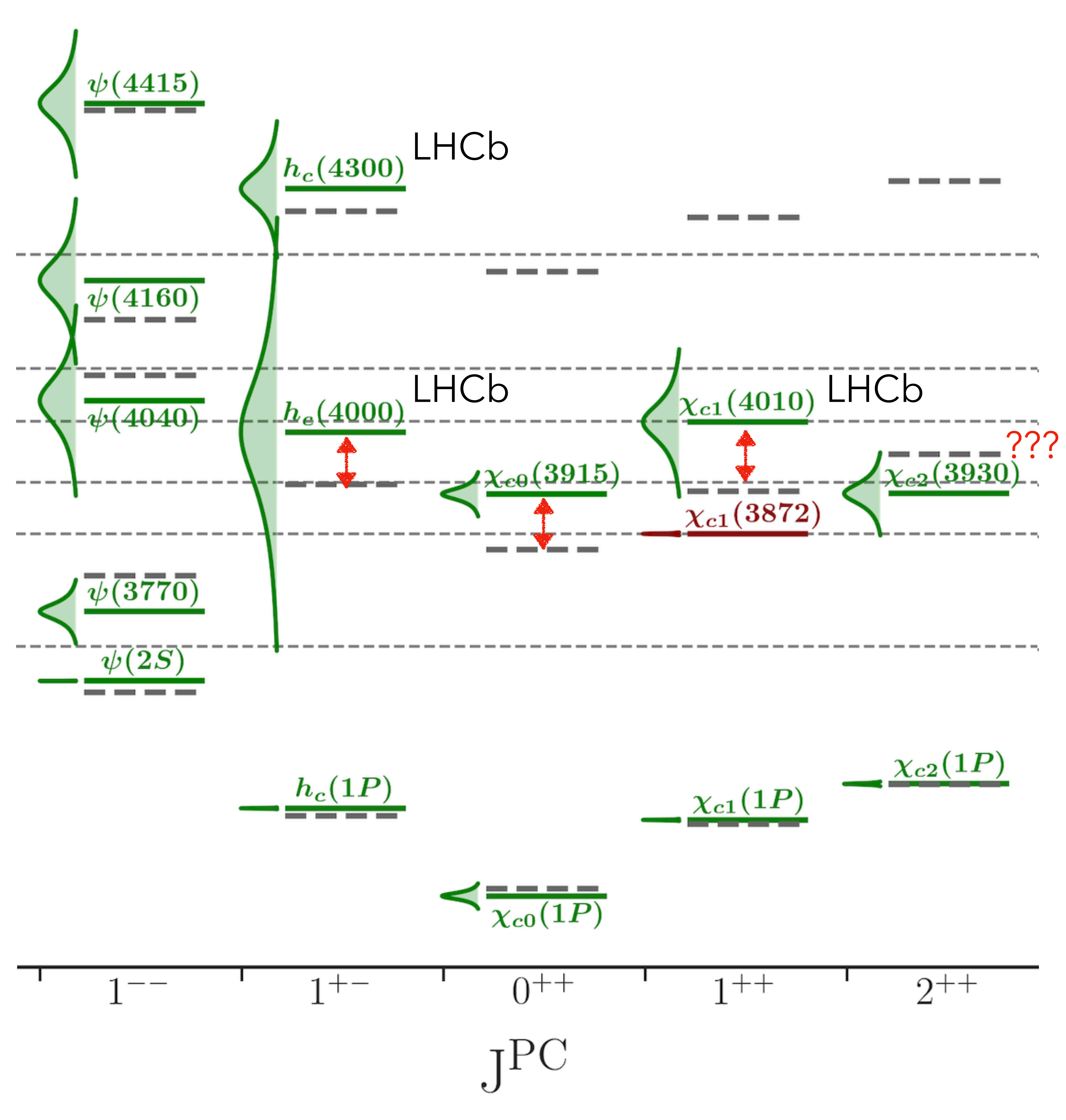
- the nature of the $X(3872)$ is still disputed
- if it's not the $\chi_{c1}(2P)$, then where is that?
- are the $\chi_{c0}(3915)$ and $\chi_{c2}(3930)$ the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$?
- finding the $h_c(2P)$ would be very helpful
- that is very challenging in e^+e^-: $1^{--} \to 1^{+-} \; J^{P+}$

if there is no ψ to populate this, cross section could be very small

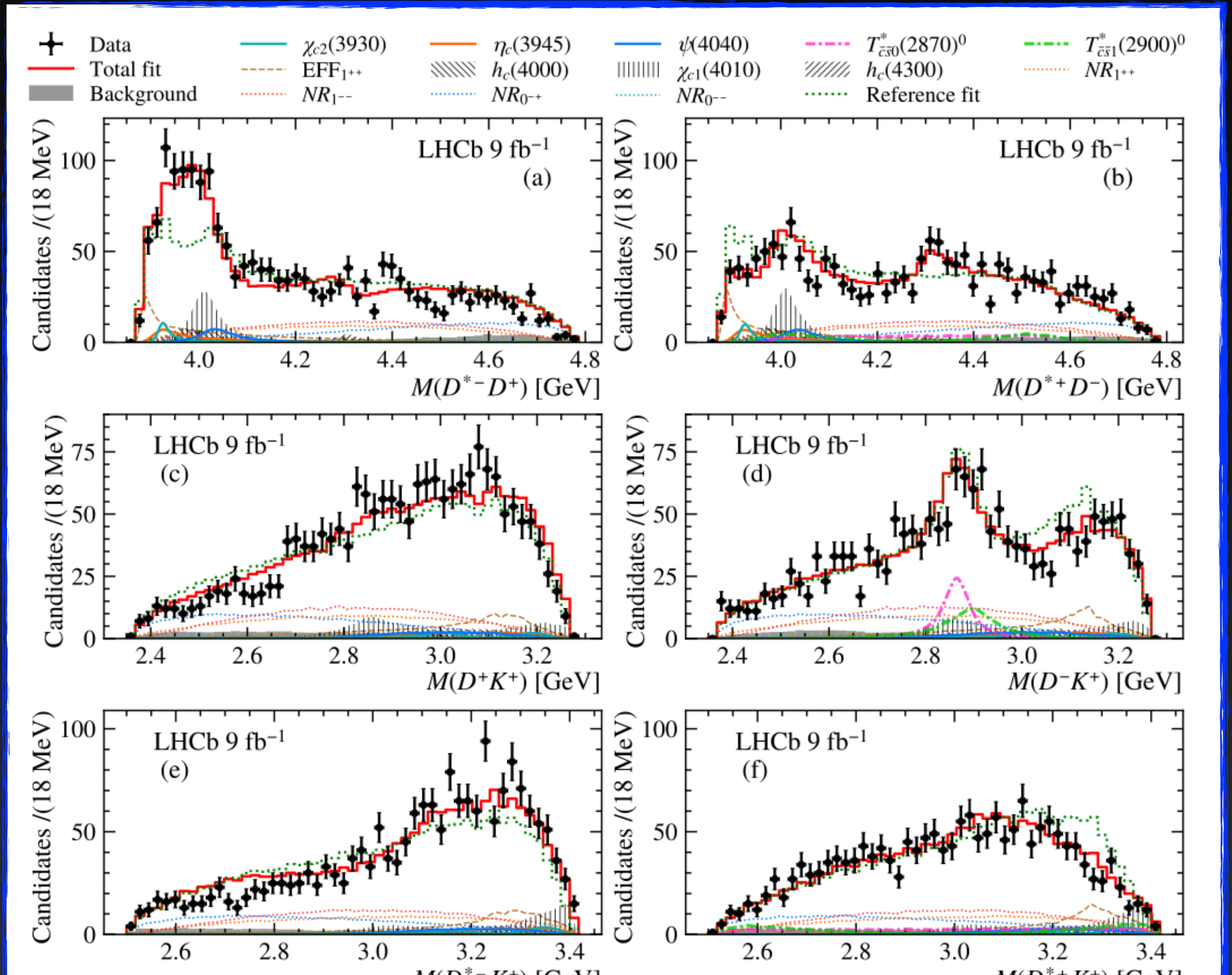
$D^*\bar{D}$ is an open S-wave decay

π^0 violates isospin
η, σ

Missing charmonium states



$B \to K D^* \bar{D}$



PRL 133 (2024) 13, 131902

the expected $h_c(2P)$ mass is in the ballpark of the Z_c, $X(3872)$

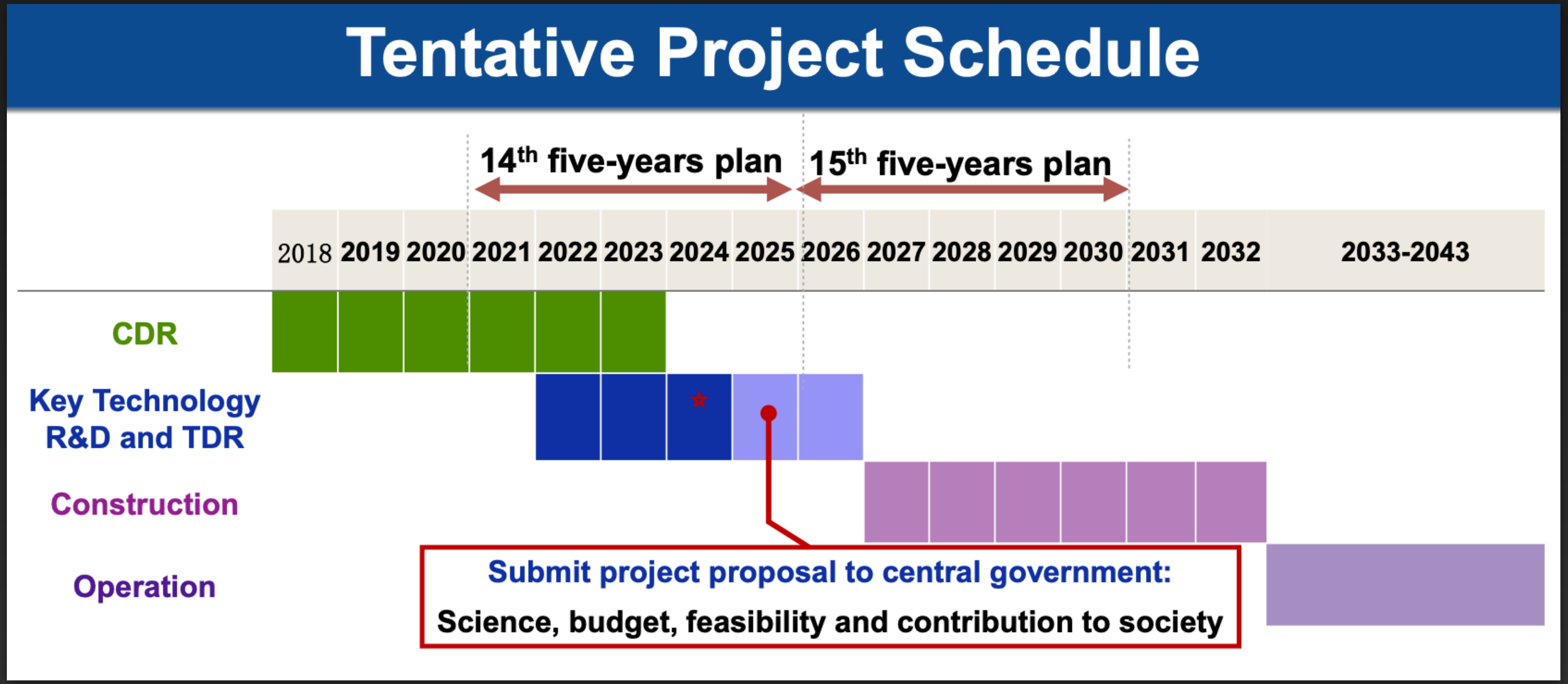
→ could this be addressed with 22 GeV photons?

A Super-Tau-Charm Facility

https://tinyurl.com/4zmajzkd

A Super-Tau-Charm Facility

- energy range: 2 - 7 GeV
- luminosity: $> 0.5 \times 10^{35}$ cm^{-2} s^{-1}
- timeline:



detailed information on technical concepts can be found here:
International Workshop on Future Tau Charm Facilities: https://indico.pnp.ustc.edu.cn/event/1948/overview
CDR: Front. Phys. 19(1), 14701 (2024)

A Super-Tau-Charm Facility

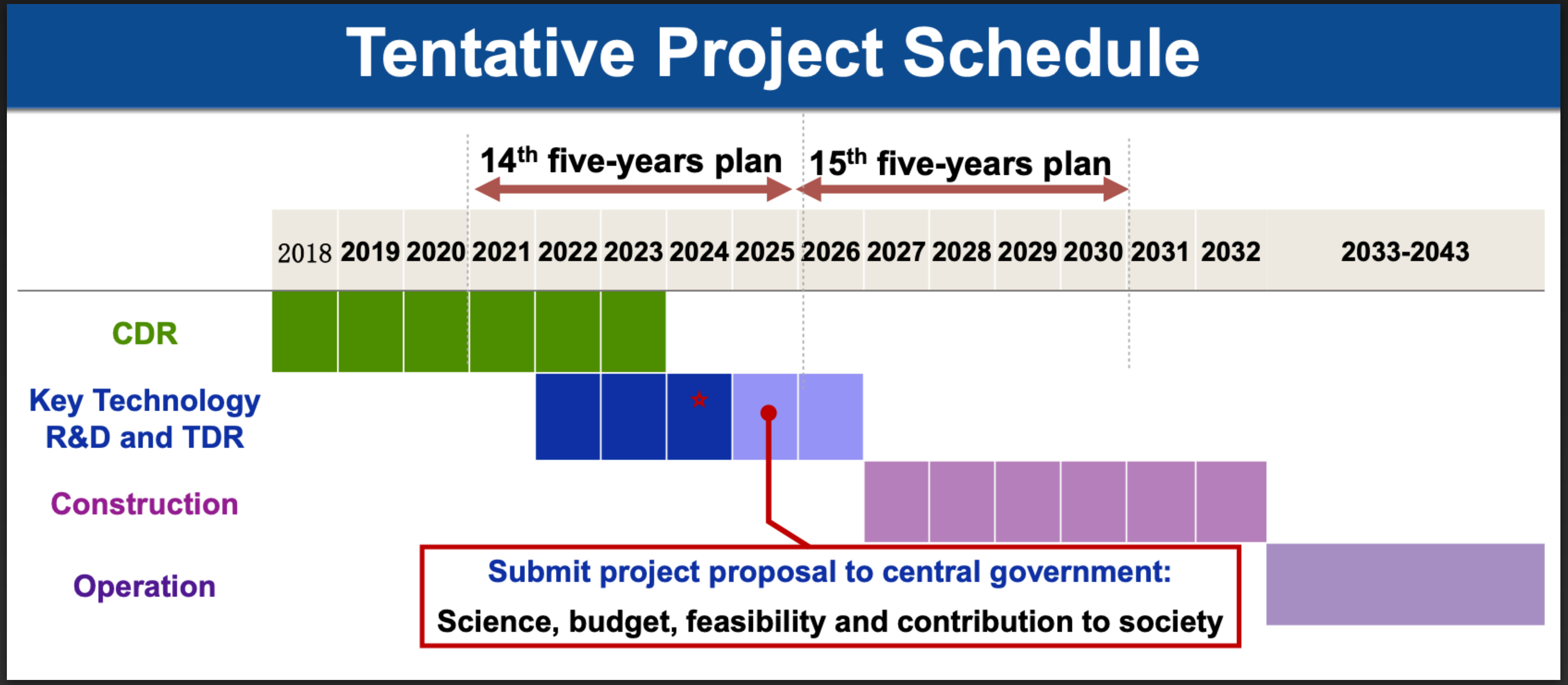
Table 2.1 The expected numbers of events per year at different STCF energy points.

CME (GeV)	Lumi (ab^{-1})	Samples	σ (nb)	No. of events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	3 trillion J/ψ
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
		$\psi(3686)$	640	6.4×10^{11}	600 billion $\psi(2S)$
3.686	1	$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686)\to\tau^+\tau^-$		2.0×10^{9}	
		$D^0\bar{D}^0$	3.6	3.6×10^{9}	a few billion D
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
3.770	1	$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
		$D^{*0}\bar{D}^0+\text{c.c.}$	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0}=+$
		$D^{*0}\bar{D}^0+\text{c.c.}$	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0}=-$
4.009	1	$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
		$D_s^{+*}D_s^-+\text{c.c.}$	0.90	9.0×10^{8}	
4.180	1	$D_s^{+*}D_s^-+\text{c.c.}$		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	85 million $\pi\pi J/\psi$
4.230	1	$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630		$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
	1	$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
>5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

Table 2.2 The expected numbers of produced XYZ-particle events before reconstruction per year at the STCF.

XYZ	$Y(4260)$	$Z_c(3900)$	$Z_c(4020)$	$X(3872)$
No. of events	10^9	10^8	10^8	5×10^6

- energy range: 2 - 7 GeV
- luminosity: $>0.5\times10^{35}$ cm^{-2} s^{-1}
- timeline:



/event/1948/overview

A Super-Tau-Charm Facility

Table 2.1 The expected numbers of events per year at different STCF energy points.

CME (GeV)	Lumi (ab^{-1})	Samples	σ (nb)	No. of events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	3 trillion J/ψ
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	600 billion $\psi(2S)$
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686) \to \tau^+\tau^-$		2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^{9}	a few billion D
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
		$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$D^{*0}\bar{D}^0$ + c.c.	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0} = +$
		$D^{*0}\bar{D}^0$ + c.c.	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0} = -$
		$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^{8}	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	85 million $\pi\pi J/\psi$
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

Table 2.2 The expected numbers of produced XYZ-particle events before reconstruction per year at the STCF.

XYZ	$Y(4260)$	$Z_c(3900)$	$Z_c(4020)$	$X(3872)$
No. of events	10^9	10^8	10^8	5×10^6

- energy range: 2 - 7 GeV
- luminosity: $> 0.5 \times 10^{35}$ cm^{-2} s^{-1}

hadron spectroscopy at a STCF

- high precision data on Z_c, $X(3872)$ decays & lineshapes
- study the exotic J^{++} states in $e^+e^- \to \omega/\phi\ X$
- charmed baryons and their excitations
- hidden-charm pentaquark states in $e^+e^- \to P_{c\bar{c}}\bar{p}$
- double-charmonium production $e^+e^- \to J/\psi\eta_c$ or χ_{cJ}
- search for the charmonium hybrid with $J^{PC} = 1^{-+}$
- fill in the conventional charmonium spectrum
- light hadrons in J/ψ and $\psi(2S)$ decays

Summary

- e^+e^- machines are very powerful at specific tasks in hadron spectroscopy
  → light-quark & gluonic exotics in charmonium decays
  → vector mesons directly in the annihilation

- but: above 4 GeV, (exotic) charmonia with other J^{PC} are a challenge (two-photon production at Belle II?)

- open questions between e^+e^- and b-decays

- a Super-Tau-Charm Facility could be a game-changer for XYZ physics