

Overview of charmonium-like spectroscopy

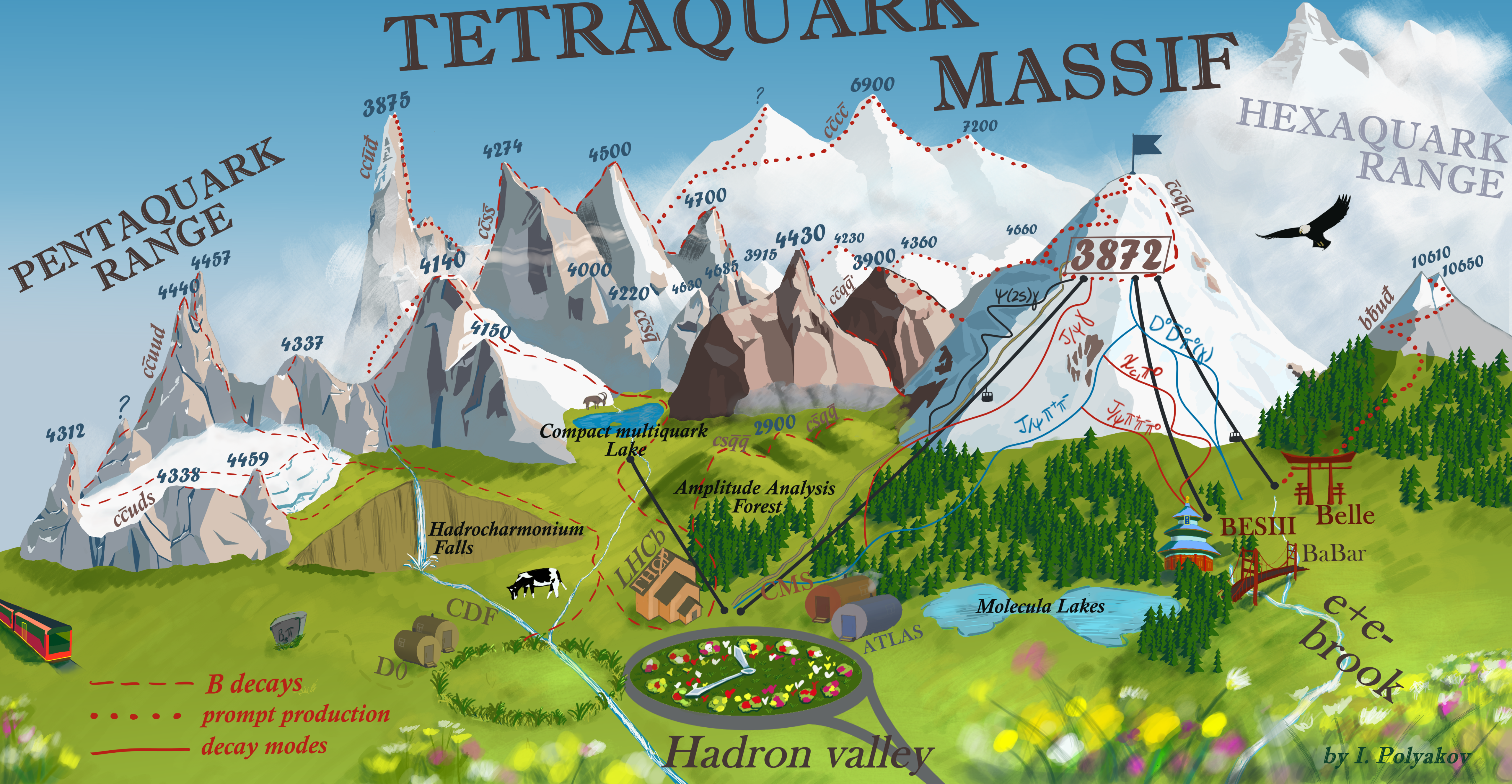
Taking a hike in hadron valley

Nils Huesken, JGU Mainz
EINN 2025, Paphos, October 29th 2025

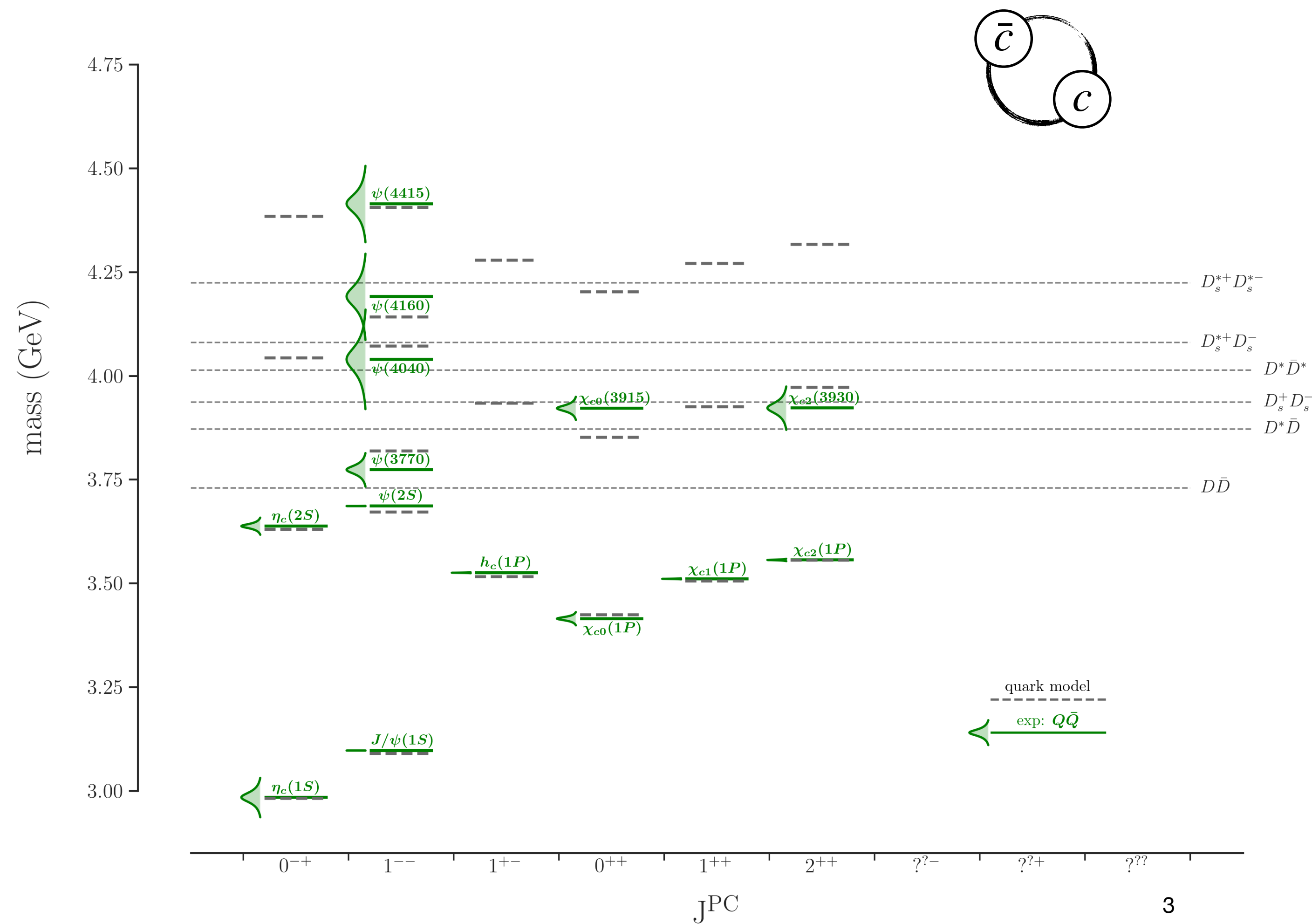


JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

TETRAQUARK MASSIF

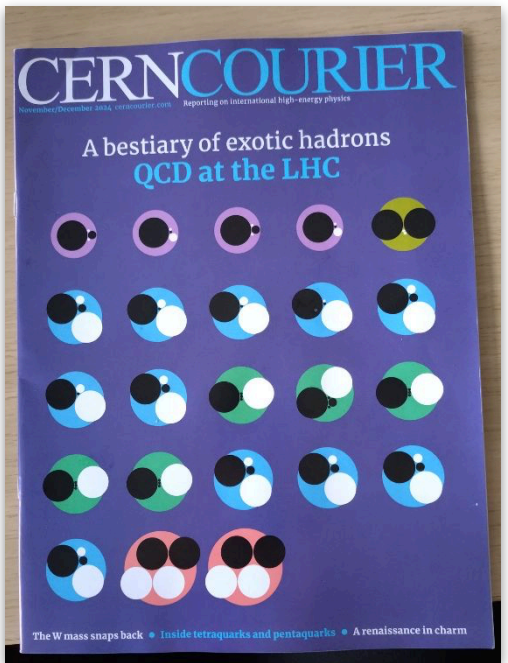


Charmonium

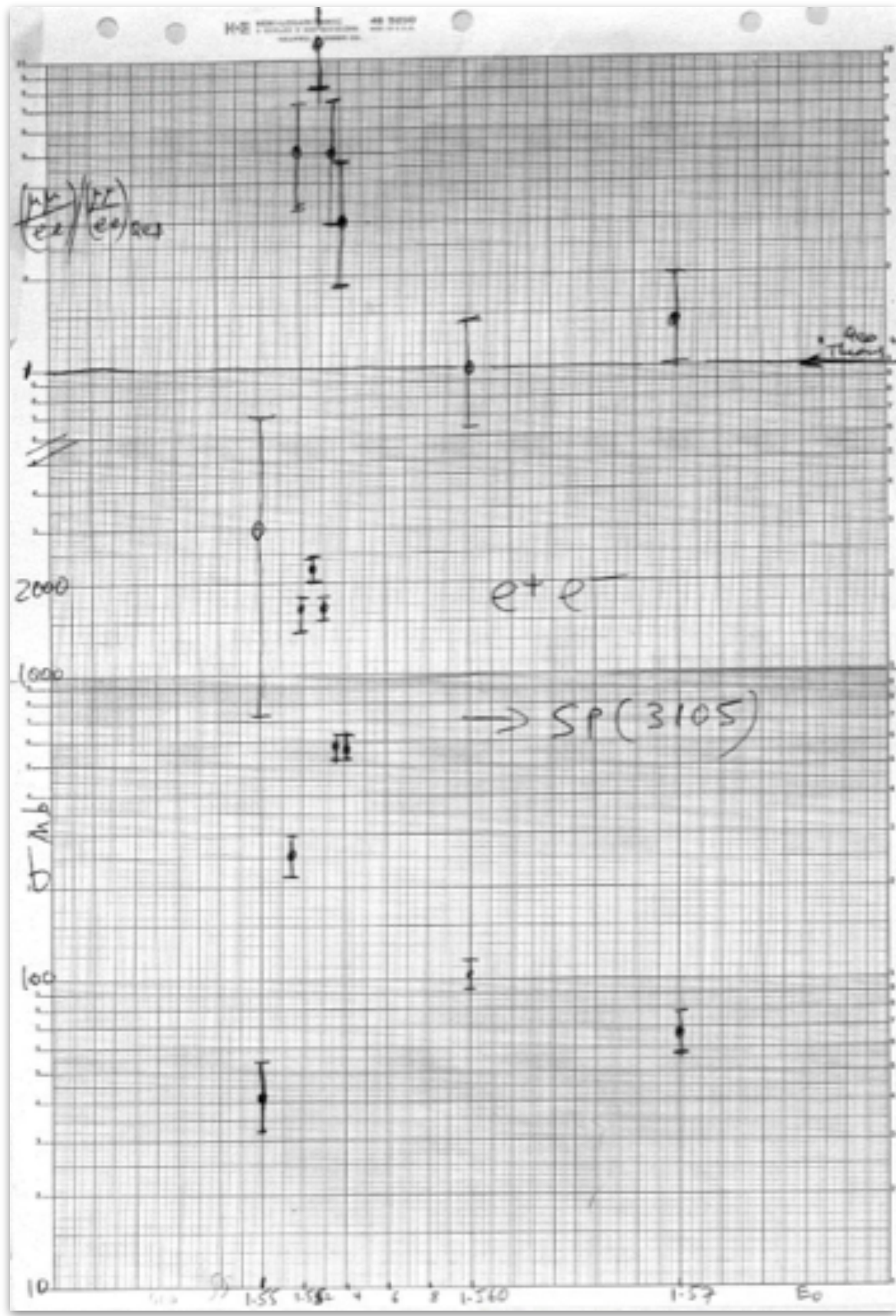


- quarkonium: $Q\bar{Q}$ -meson (where $Q = c, b$)
 - strong interaction version of positronium (or the hydrogen atom)
 - we can calculate the spectrum using similar methods
- Godfrey & Isgur, PRD 32 (1985) 189-231
Barnes, Godfrey, Swanson, PRD 72 (2005) 054026
Godfrey & Moates, PRD 92 (2015) 054034
- good agreement between experiment and theory
 - ideal hunting-ground for exotic hadrons

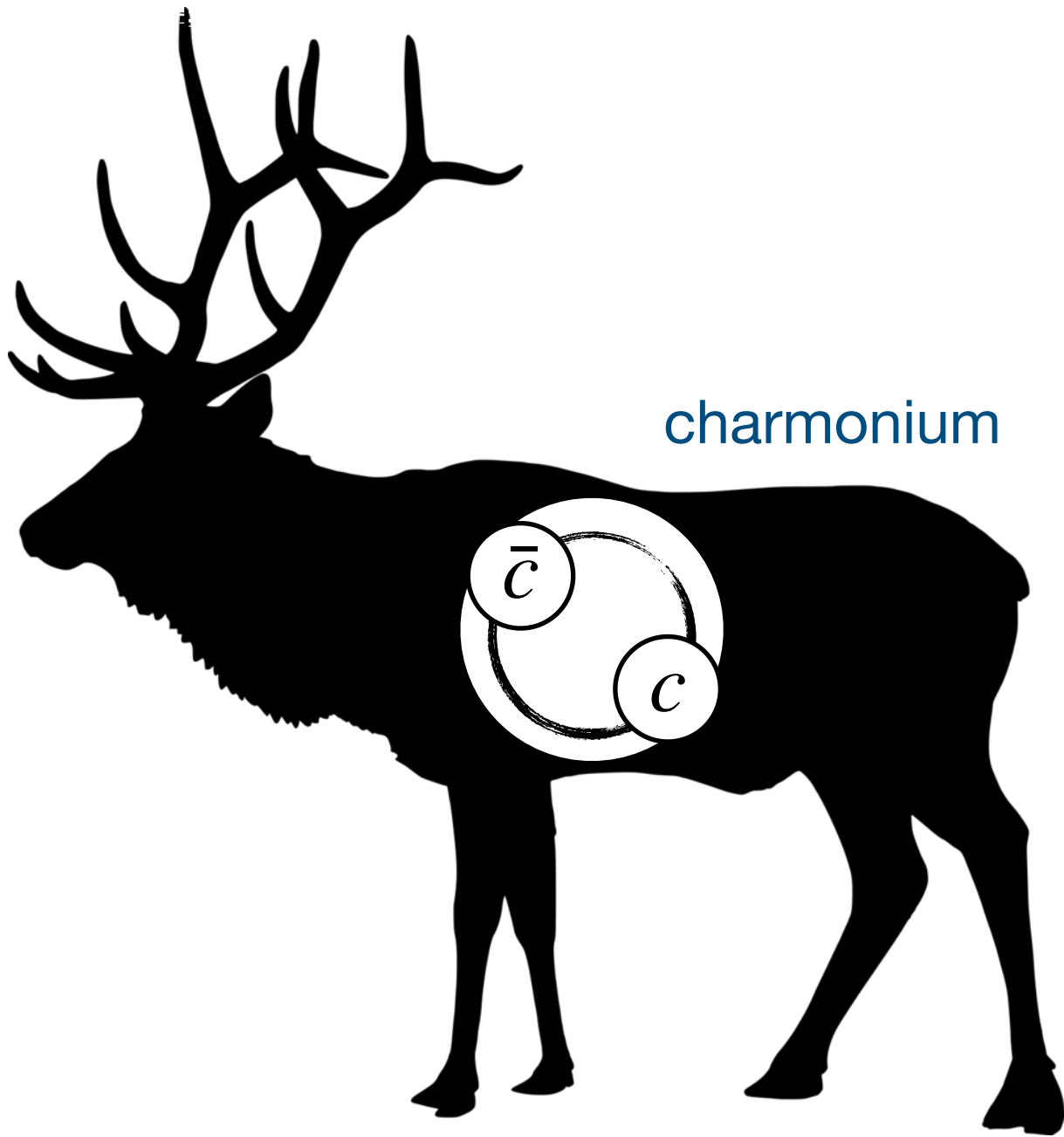
Bestiary: charmonium-like hadrons



@PKoppenburg

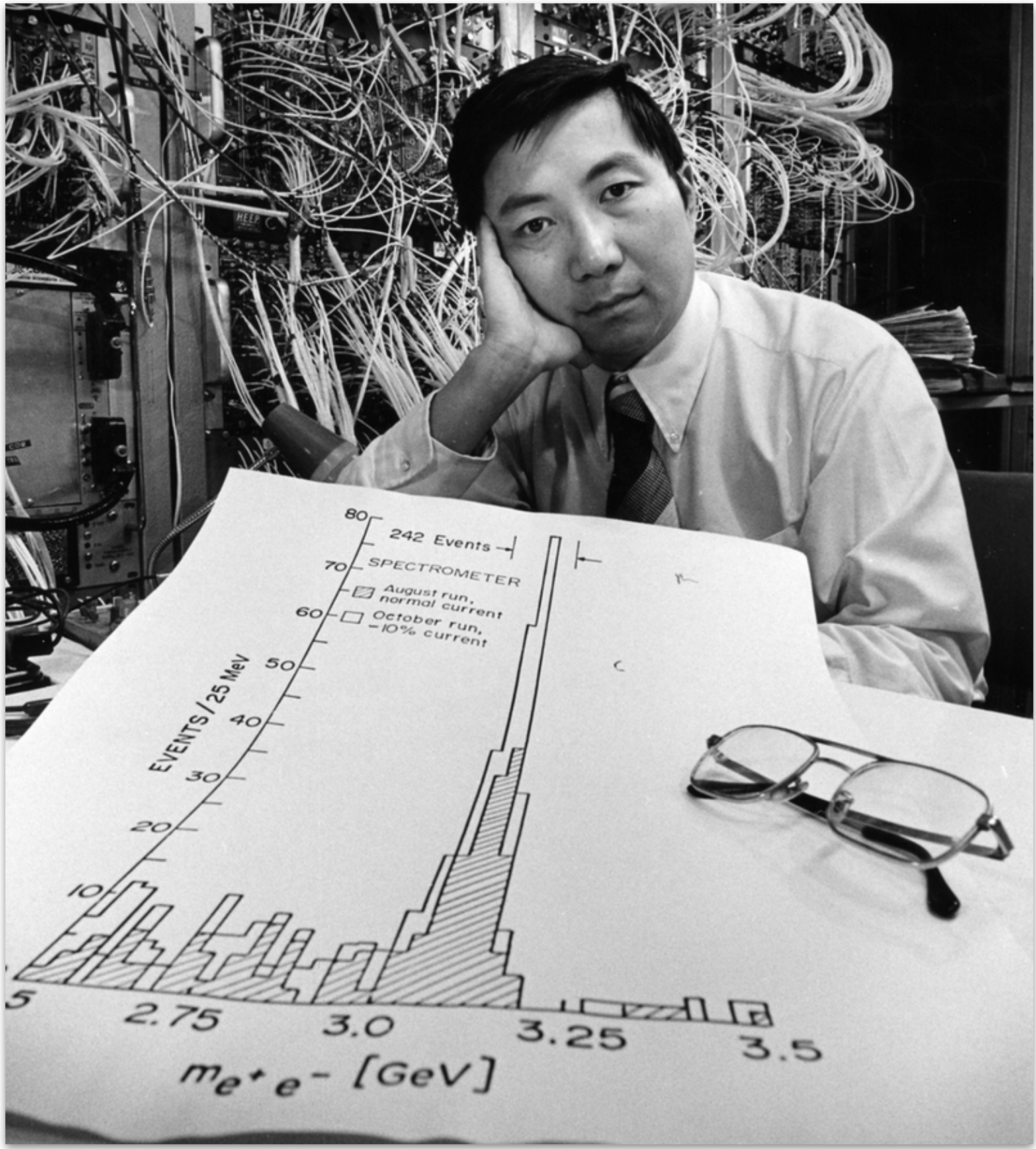


the ψ as seen at SLAC



charmonium

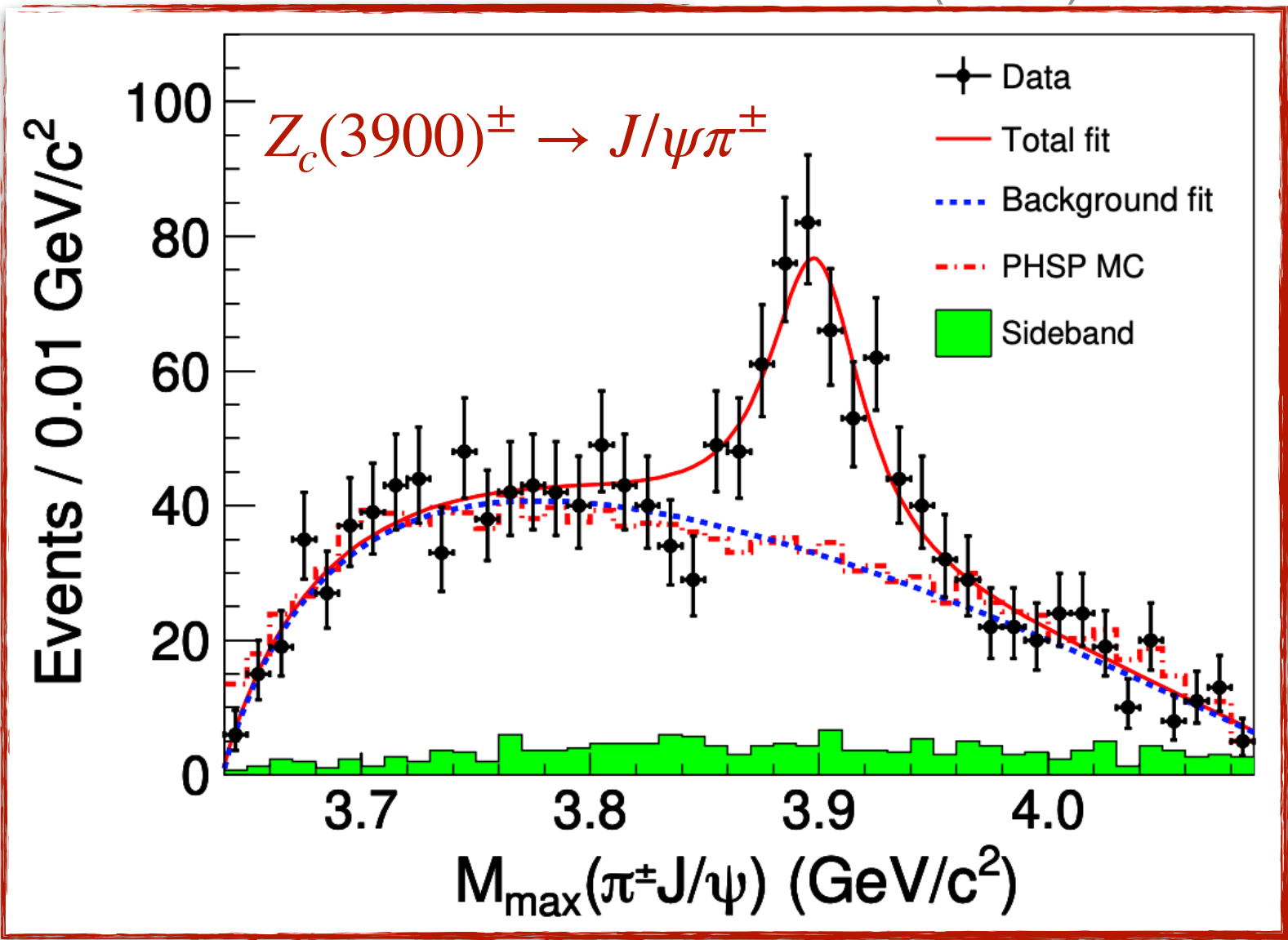
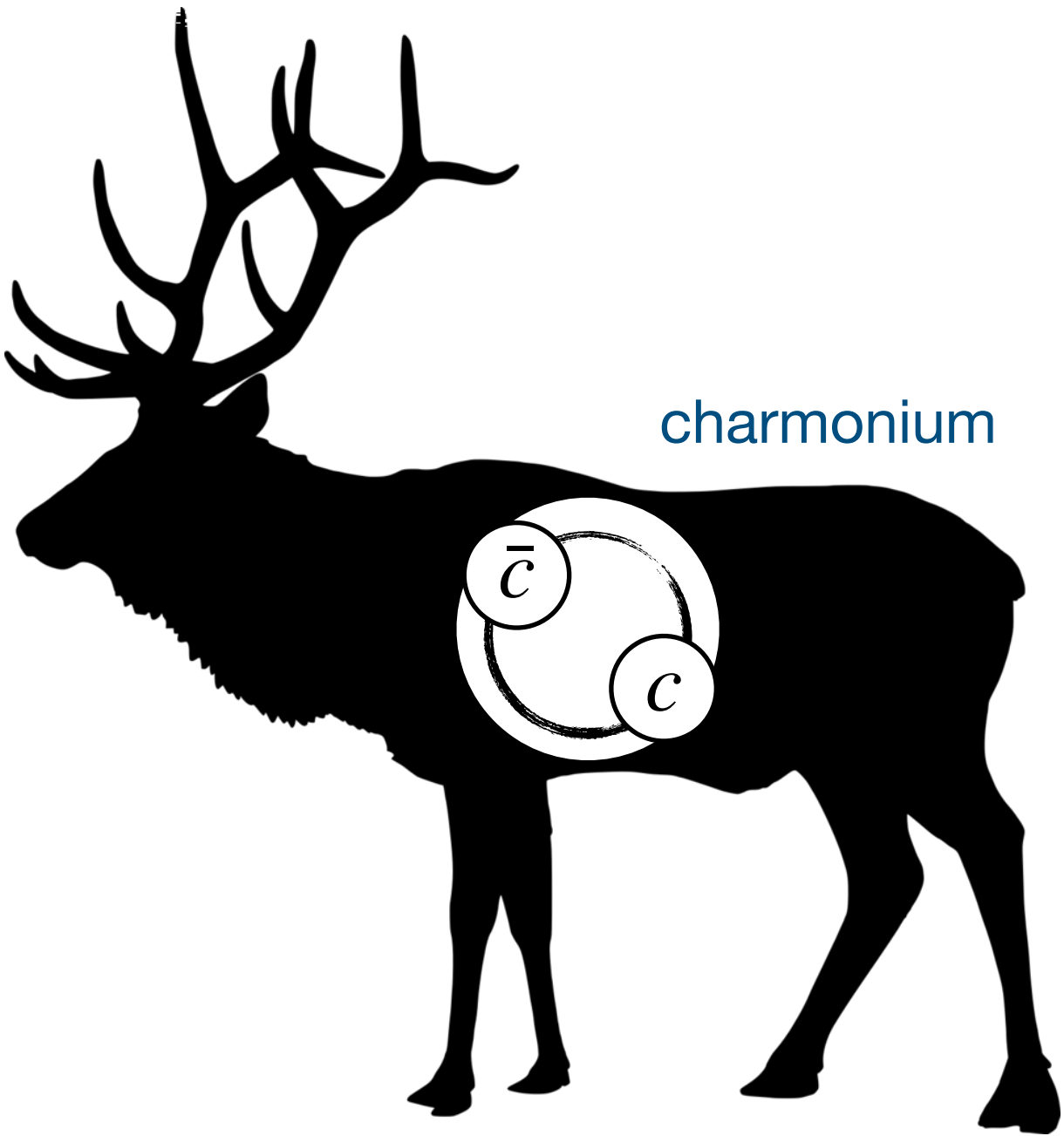
50th birthday last year:
<https://indico.slac.stanford.edu/event/9040/>
<https://indico.ihep.ac.cn/event/23322/>



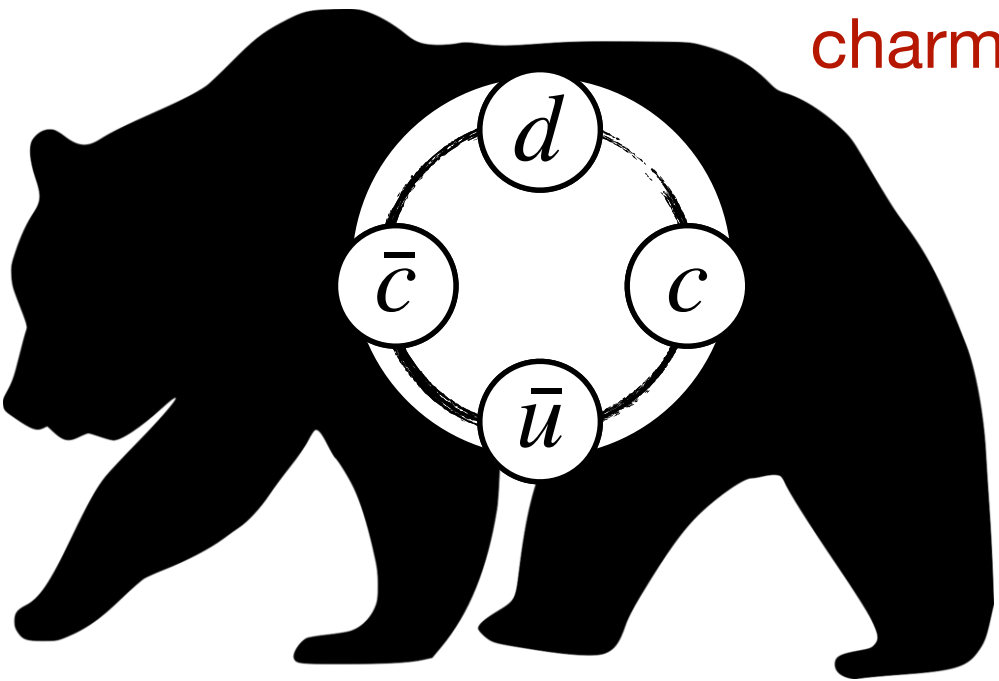
S. Ting with the J particle

Bestiary: charmonium-like hadrons

PRL 110 (2013) 252001



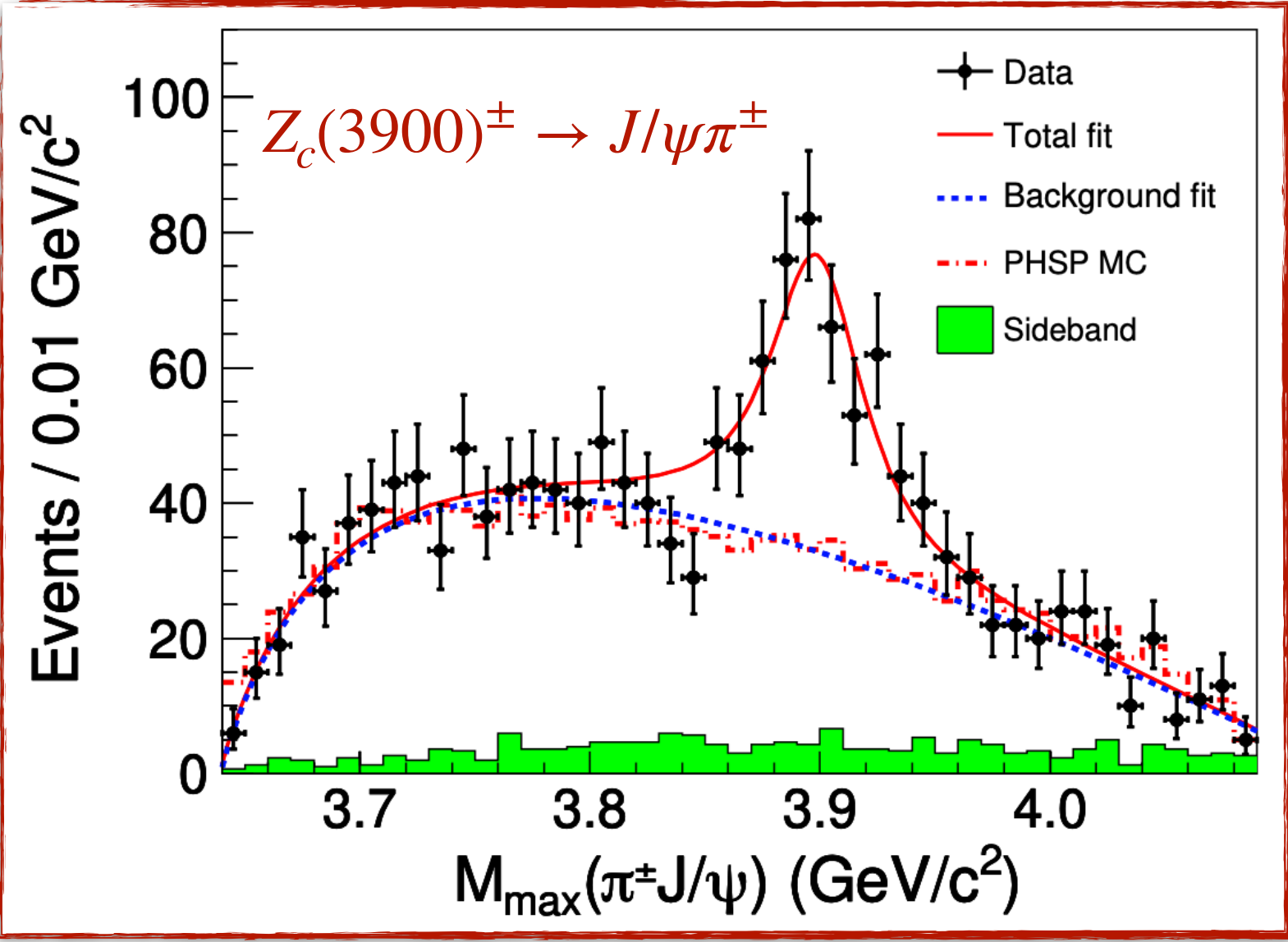
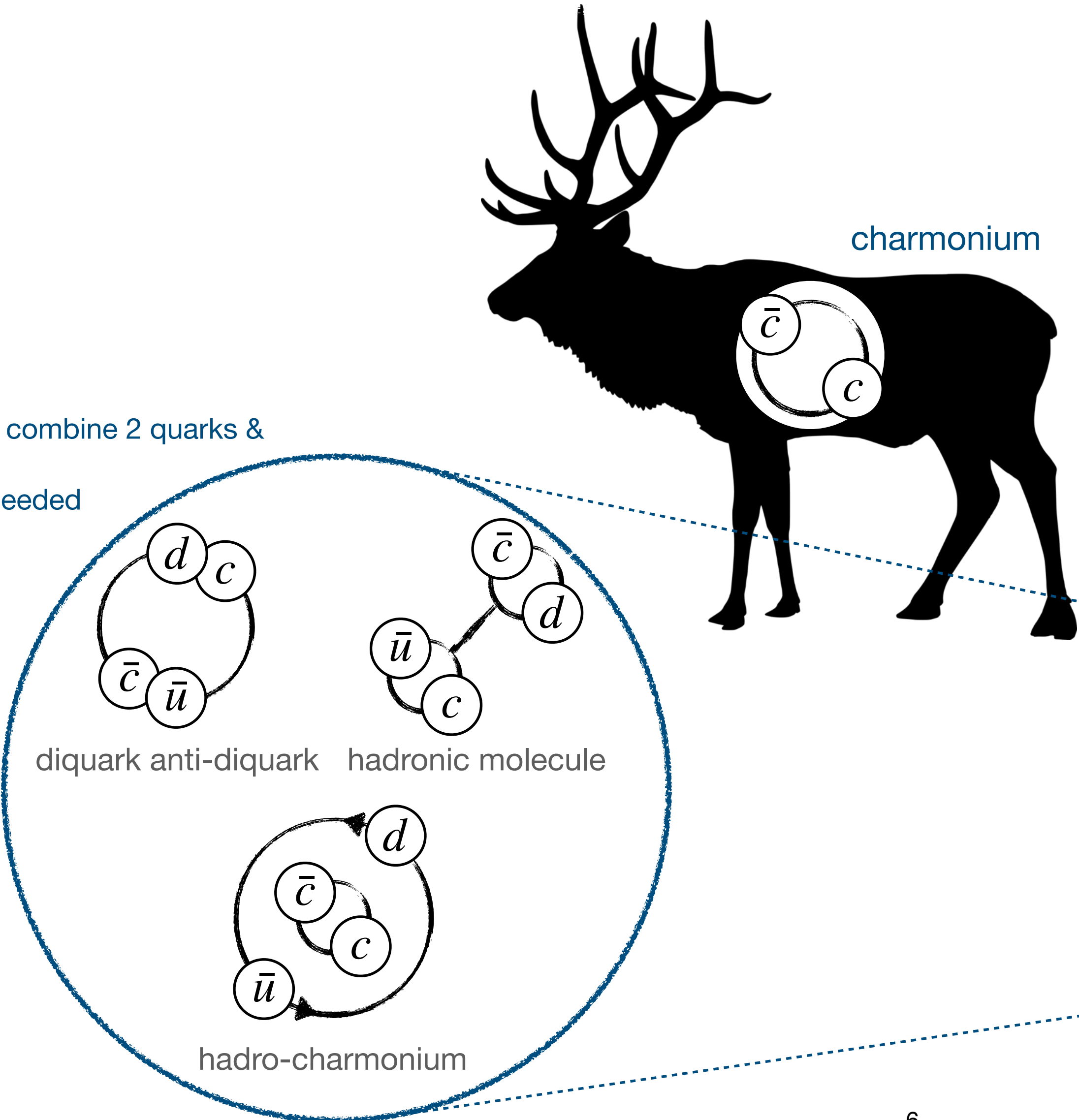
$Z_c(3900)$ (now named $T_{c\bar{c}1}(3900)$) in BESIII data



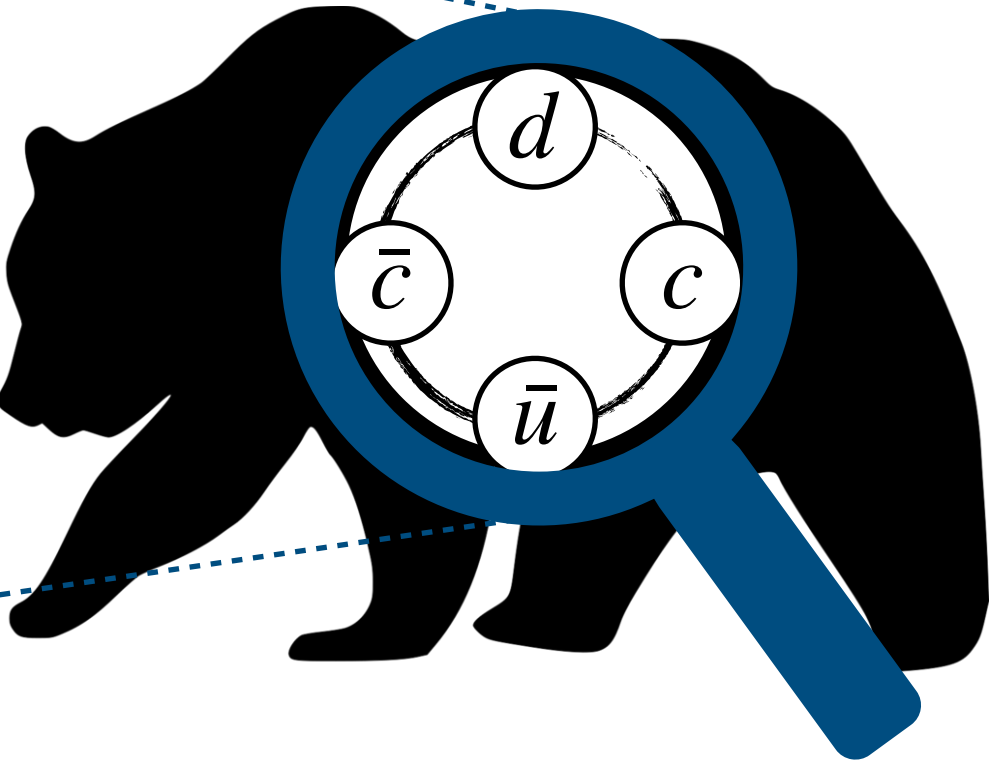
Bestiary: charmonium-like hadrons

PRL 110 (2013) 252001

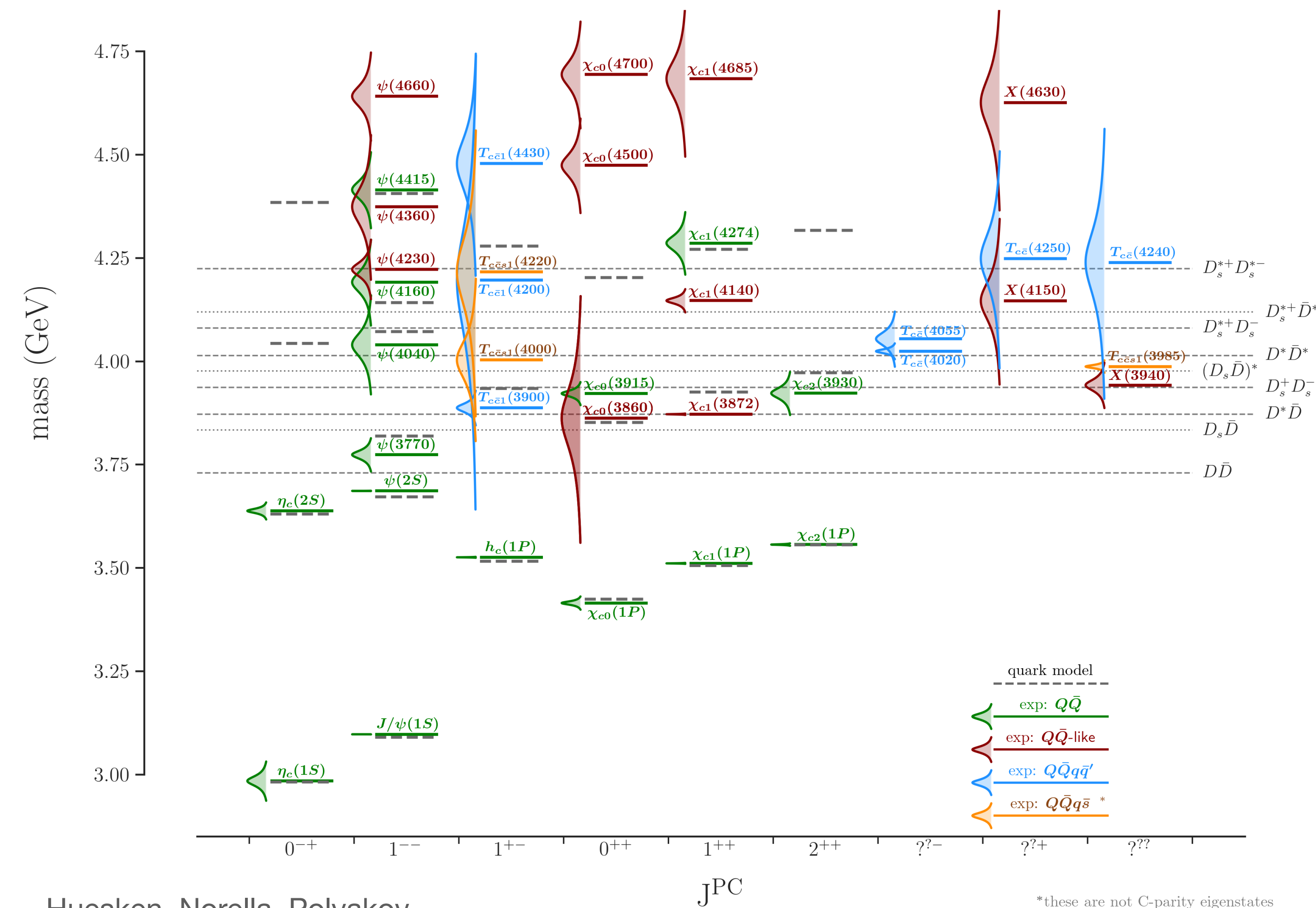
- more than one way to combine 2 quarks & 2 anti-quarks
- experiment + theory needed to disentangle



$Z_c(3900)$ (now named $T_{c\bar{c}1}(3900)$) in BESIII data



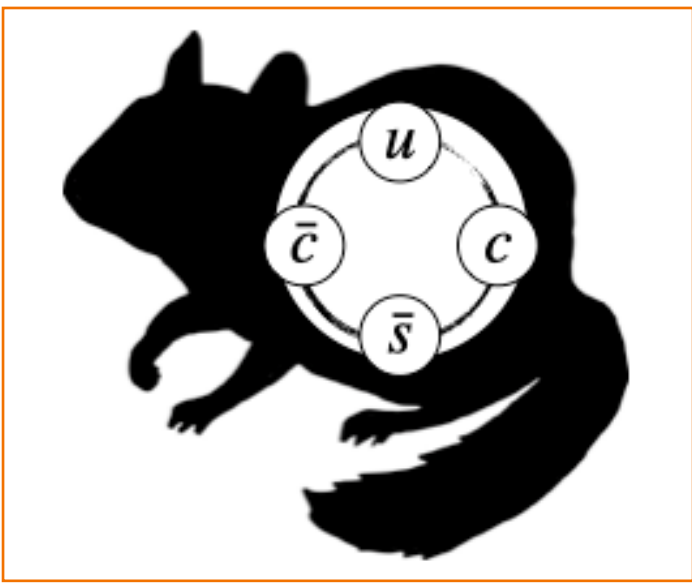
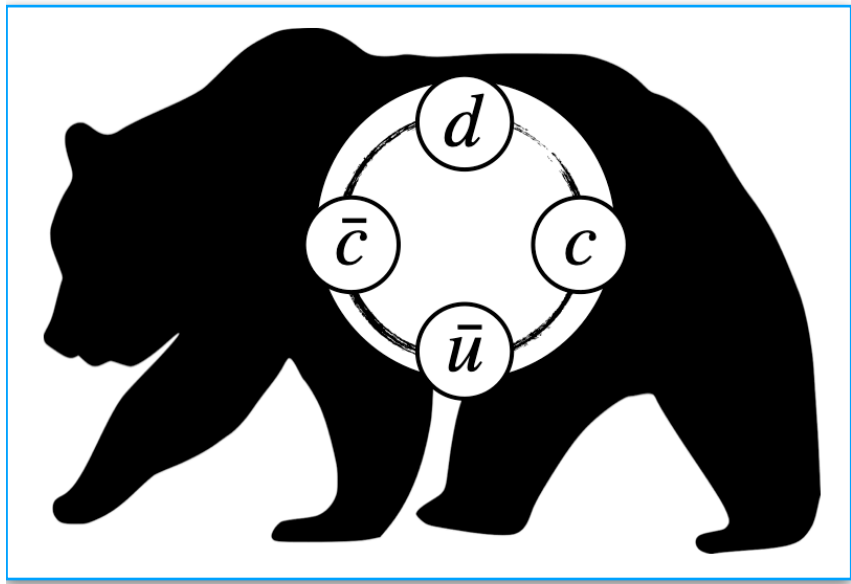
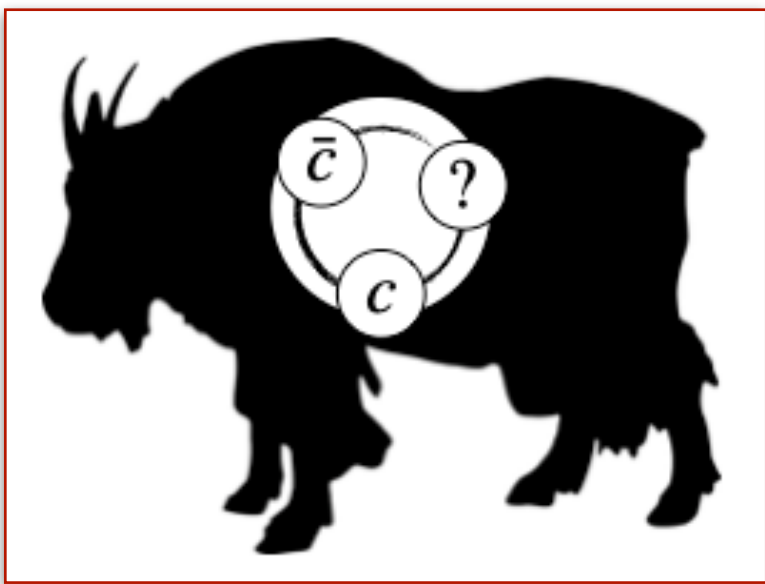
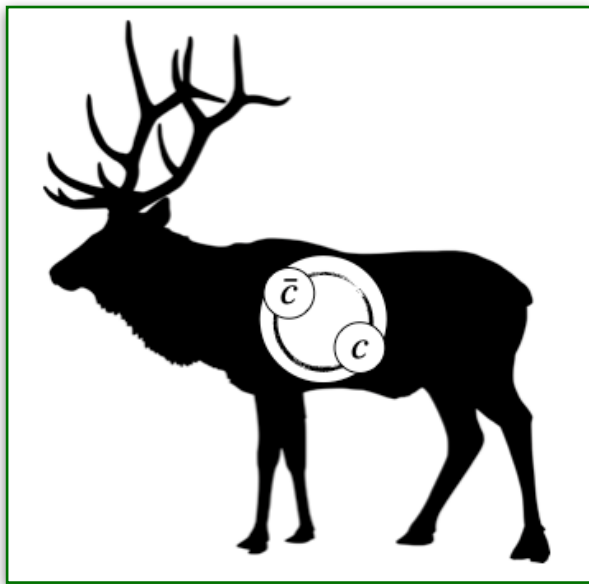
Bestiary: charmonium-like hadrons



- today: plethora of states discovered

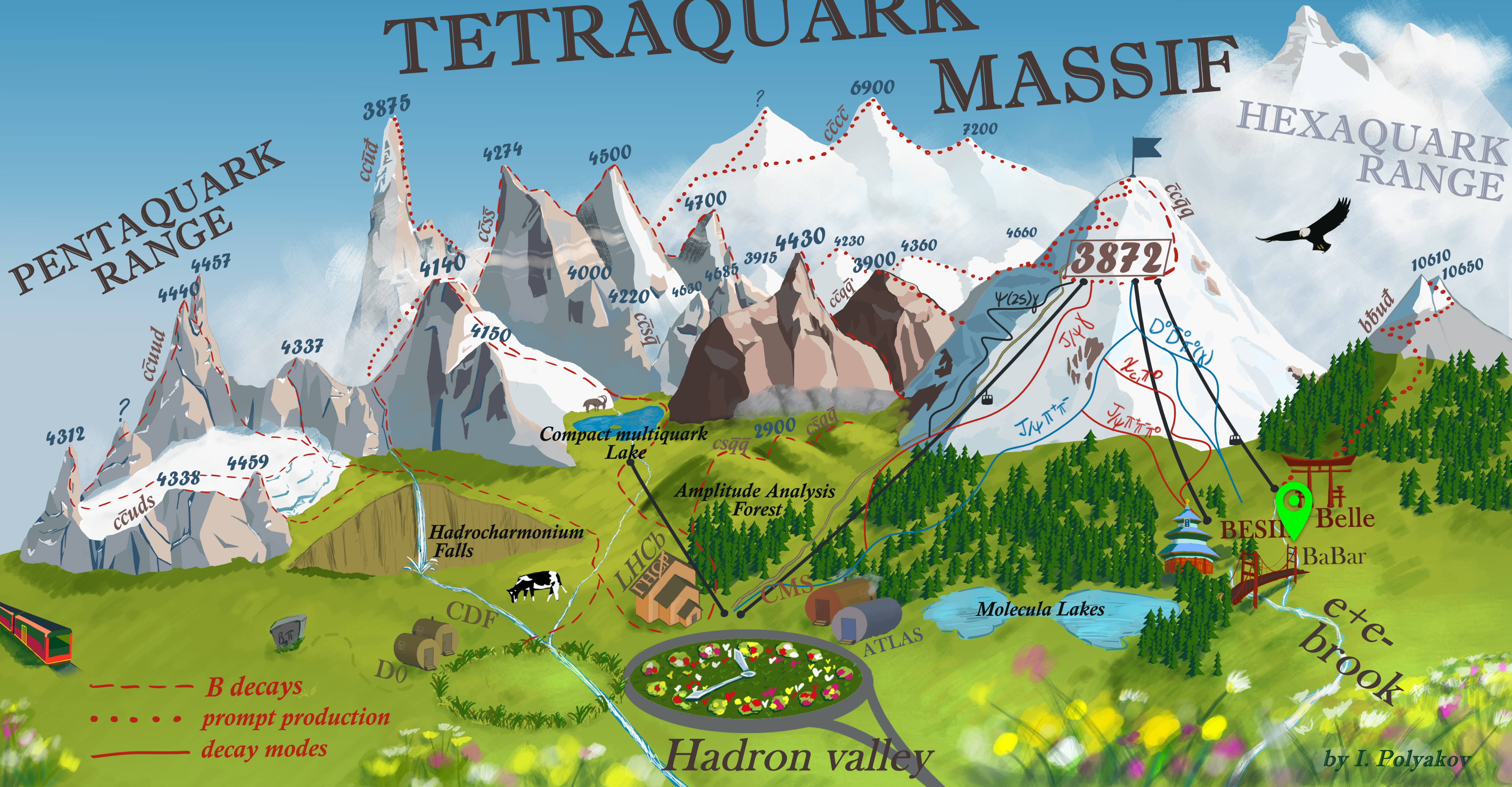
LHCb: <http://www.koppenburg.ch/particles.html>

BESIII: Sci. Bull. 68 (2023) 2148-2150

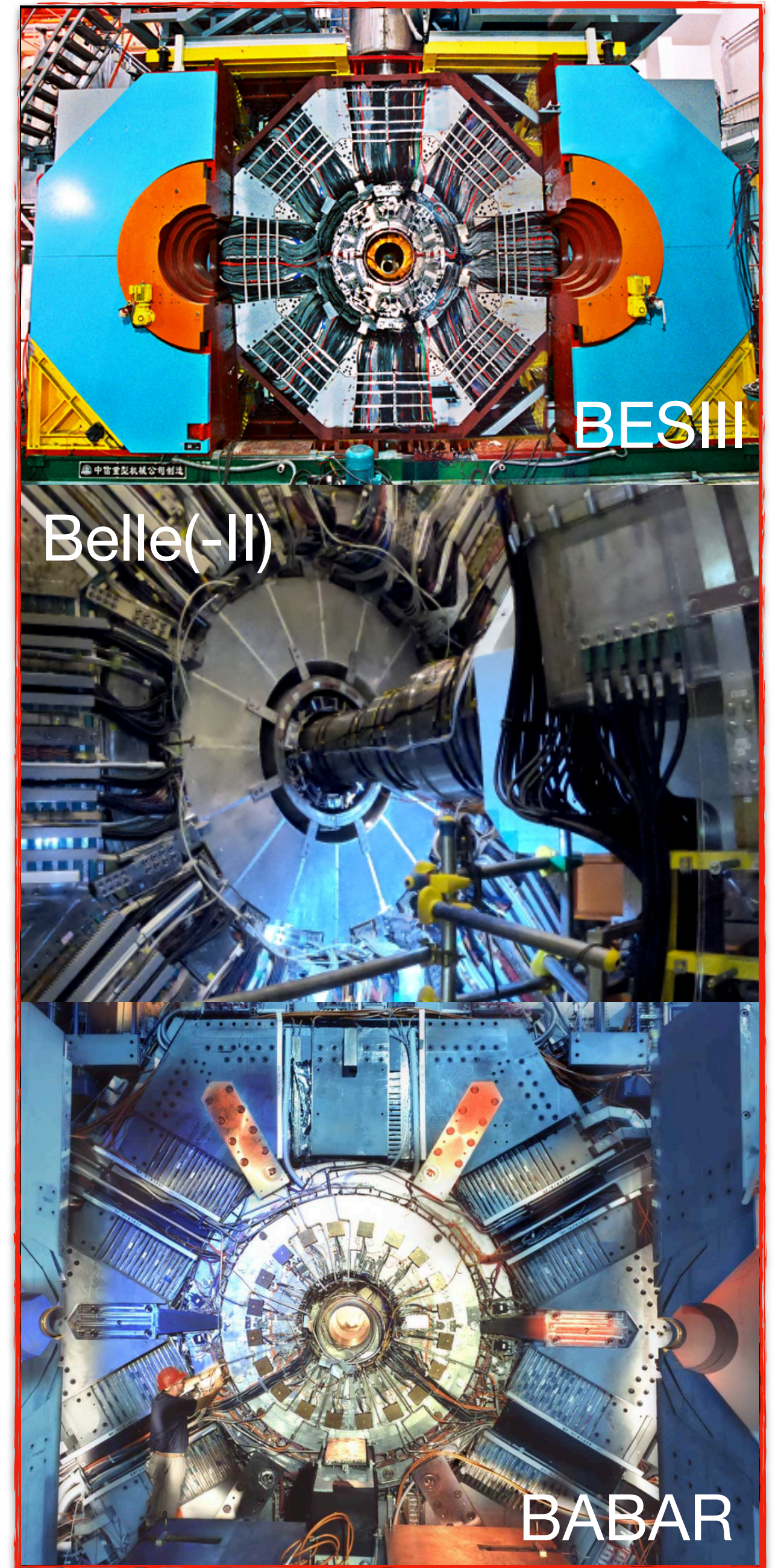


- for many, obvious they are not $c\bar{c}$ hadrons - but internal configuration remains unclear

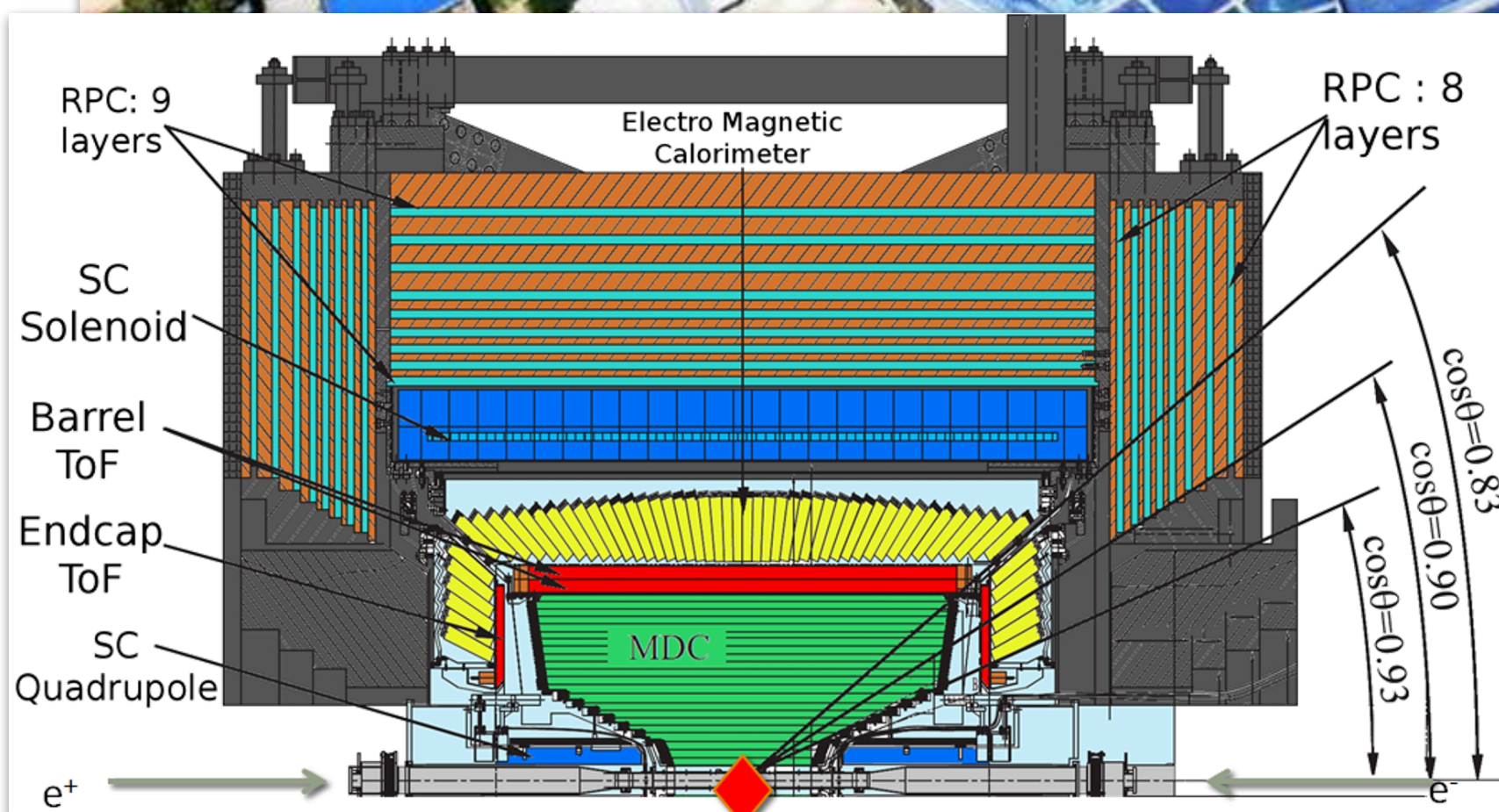
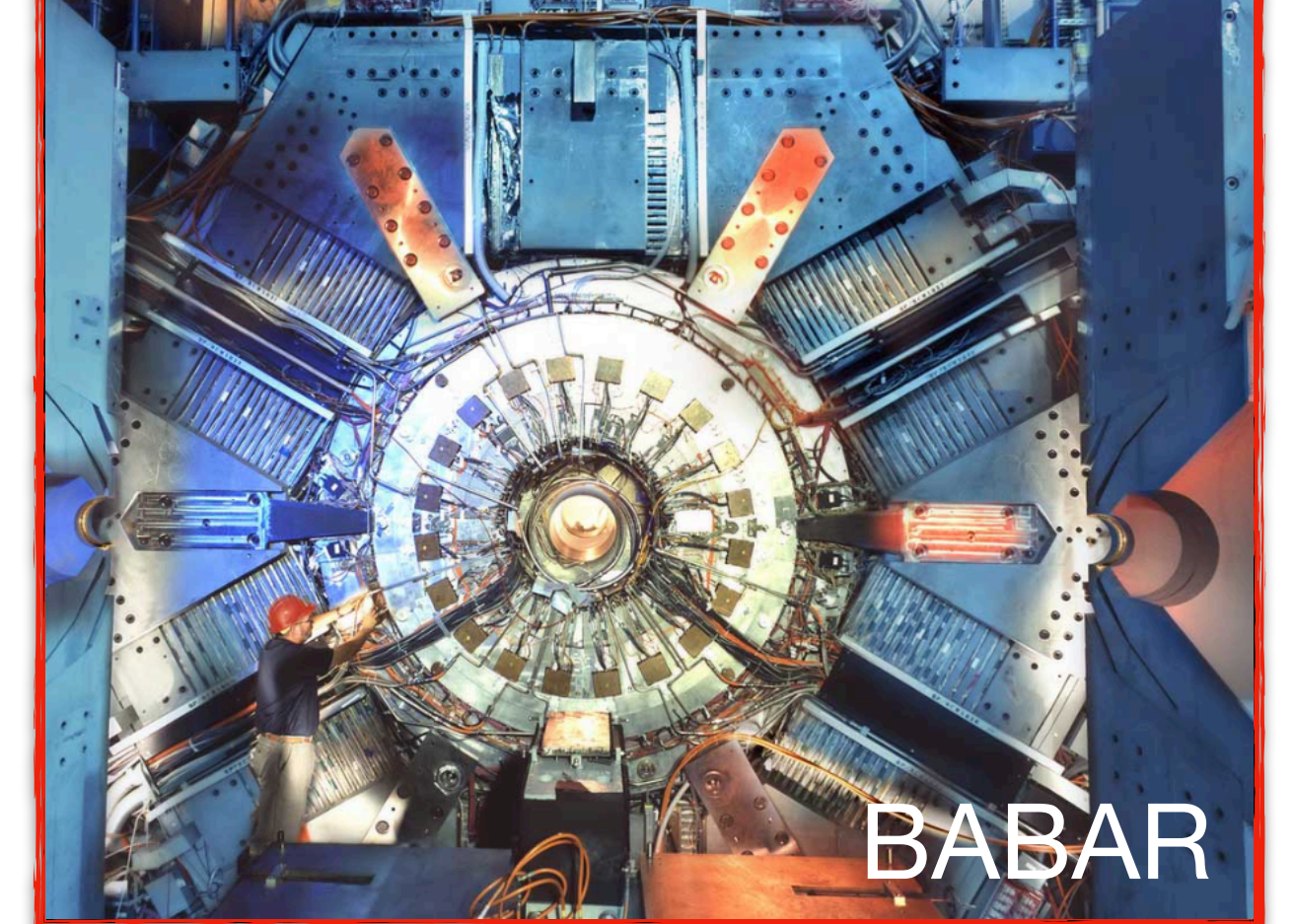
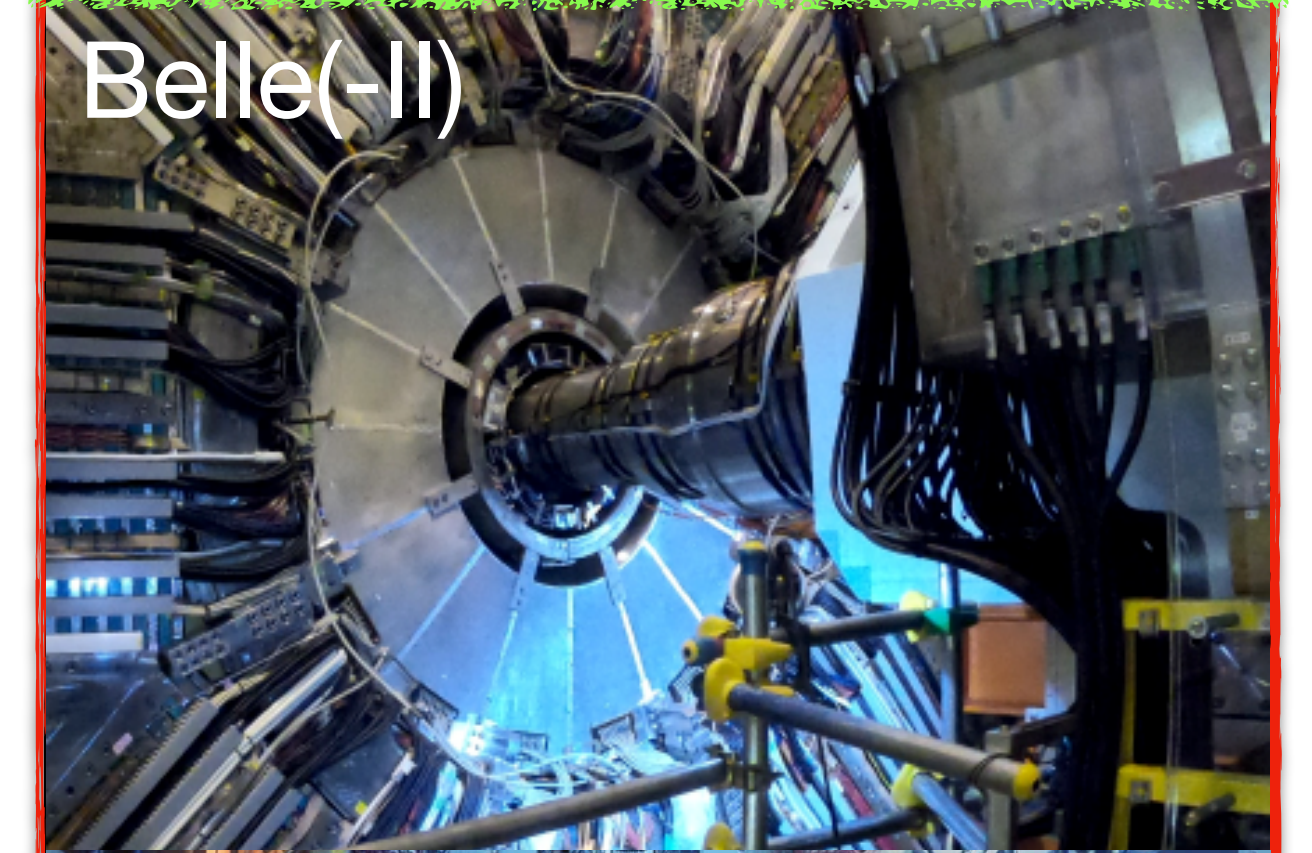
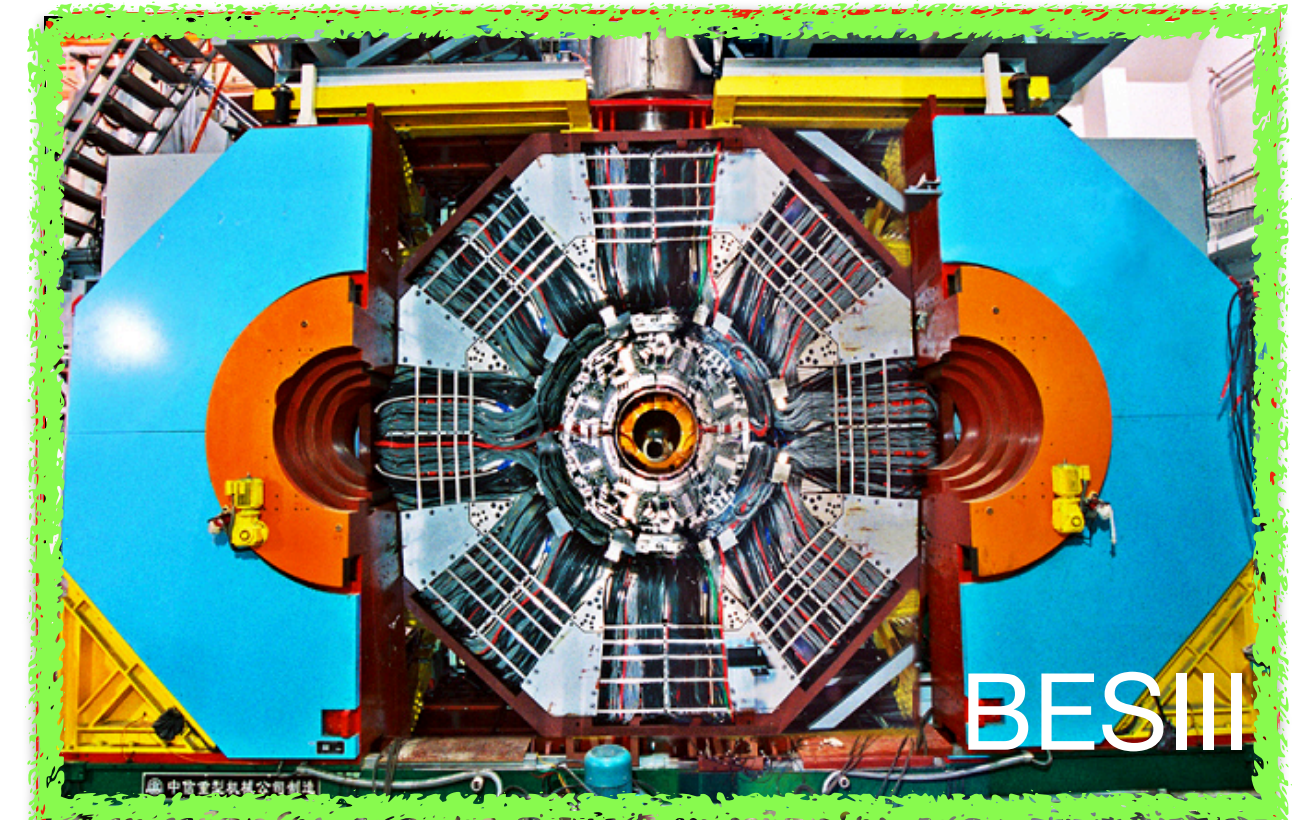
TETRAQUARK MASSIF



e^+e^- facilities



e^+e^- facilities



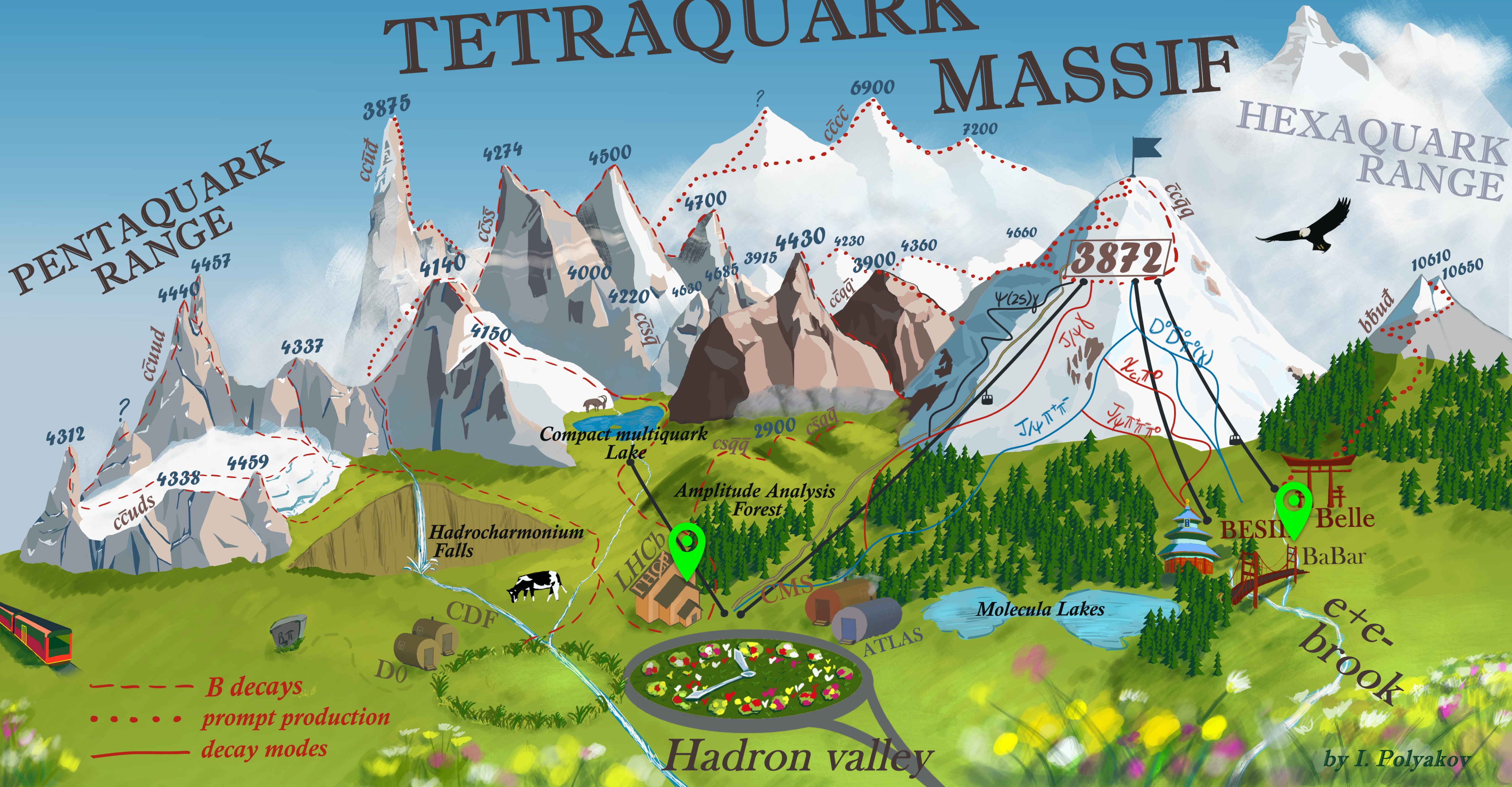
Beijing Spectrometer - BESIII

- drift chamber in 1 T magnetic field
- time of flight detector
- electromagnetic calorimeter
- muon counter

TETRAQUARK MASSIF

PENTAQUARK RANGE

HEXAQUARK RANGE



- *B decays*
- ... *prompt production*
- *decay modes*

Hadron valley

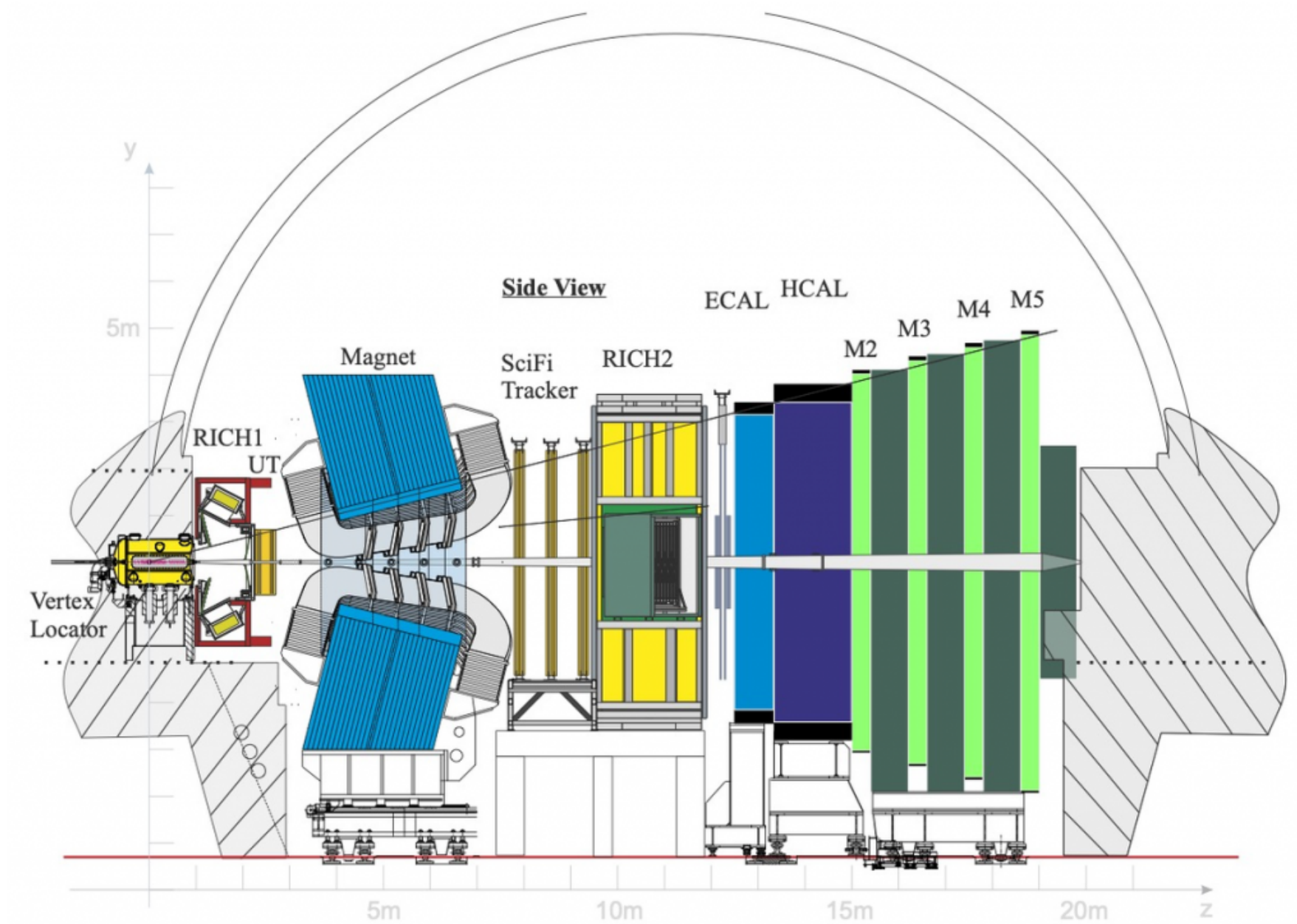
by I. Polyakov

LHCb



photo credit: Maximilien Brice, CERN

- pp collisions at $\sqrt{s} = 7, 8, 13, 13.6$ TeV
- forward spectrometer with high precision tracking
- using forward production of b, c quarks



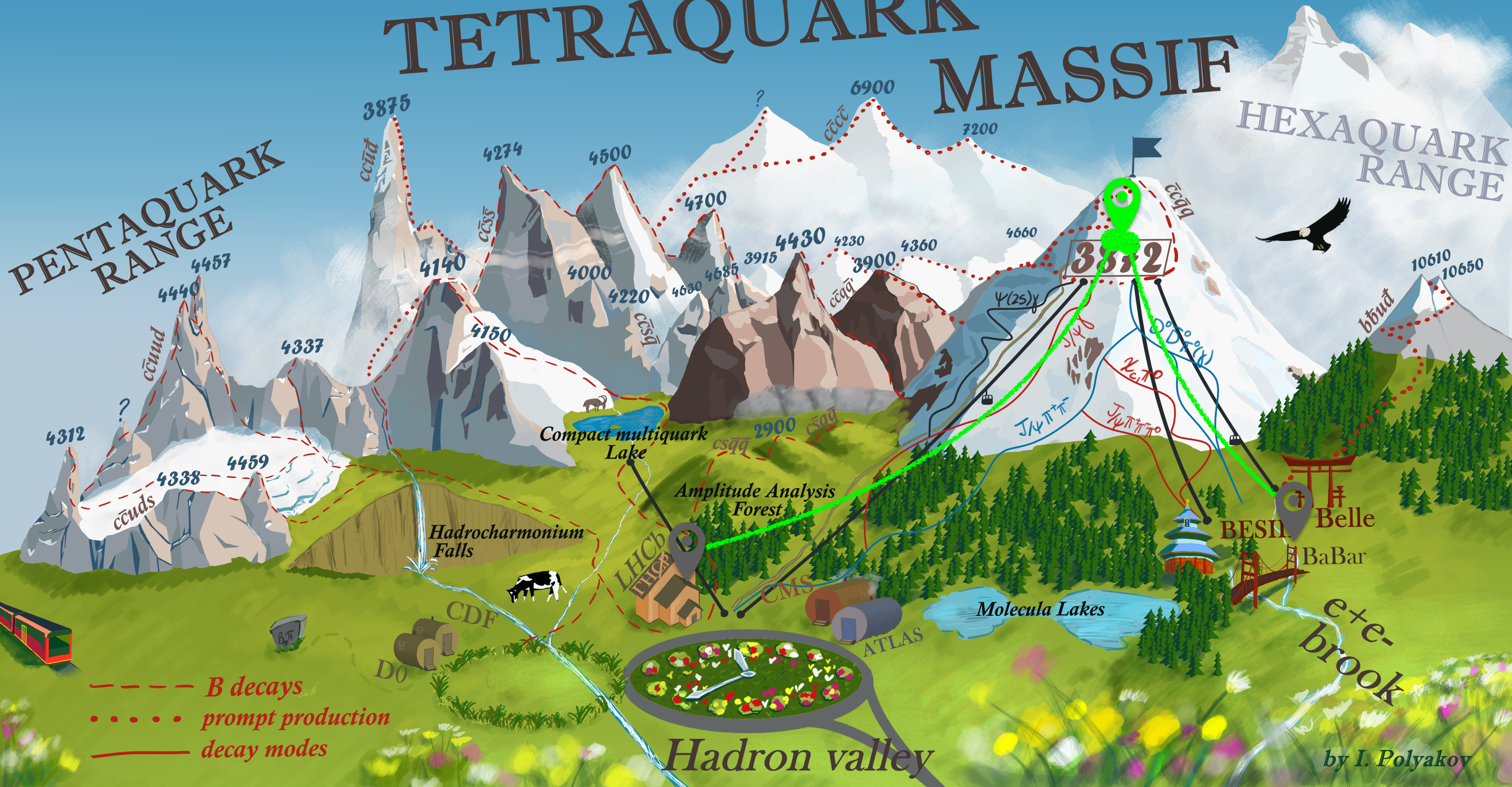
<https://lhcb-outreach.web.cern.ch/detector/>

more infos: [JINST 3 S08005](#)

TETRAQUARK MASSIF

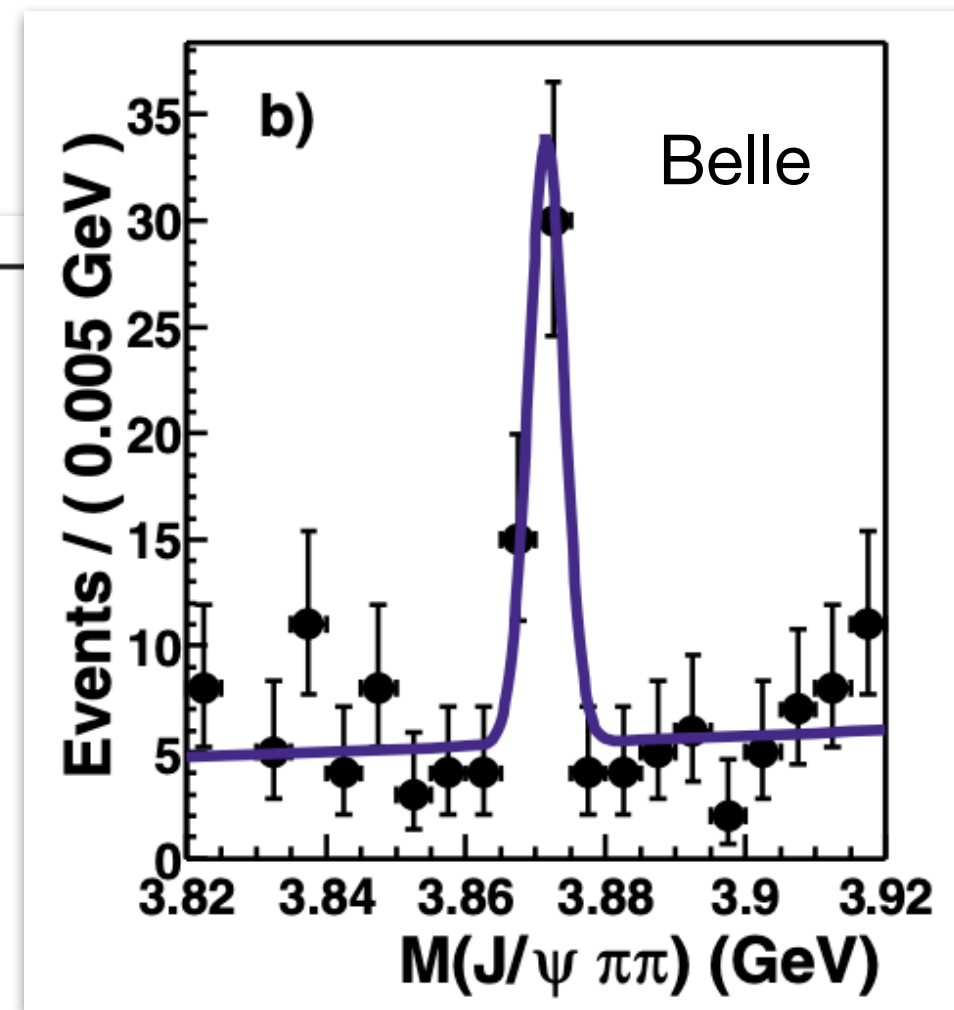
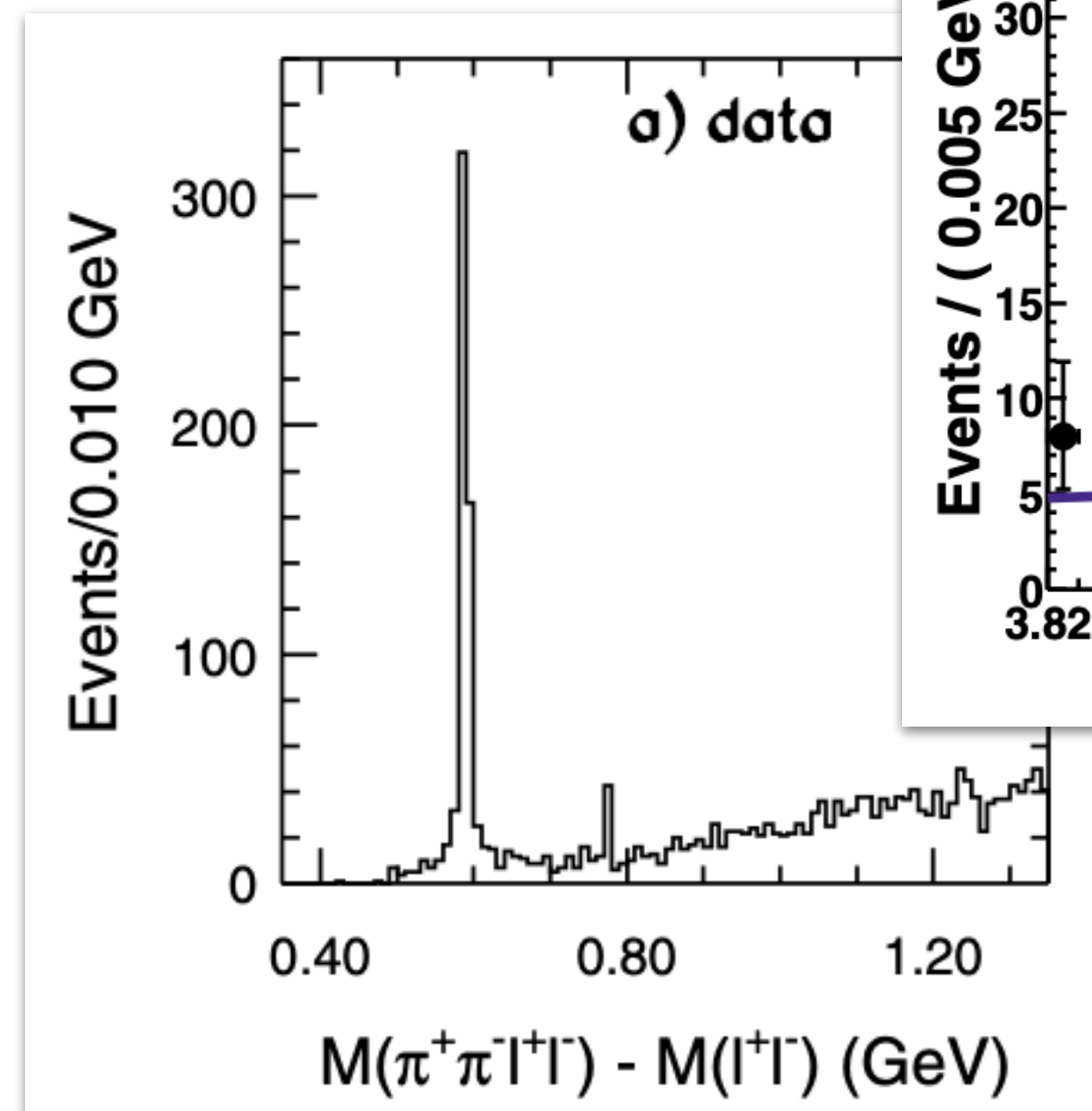
PENTAQUARK RANGE

HEXAQUARK RANGE



Where it all began: the $X(3872)$

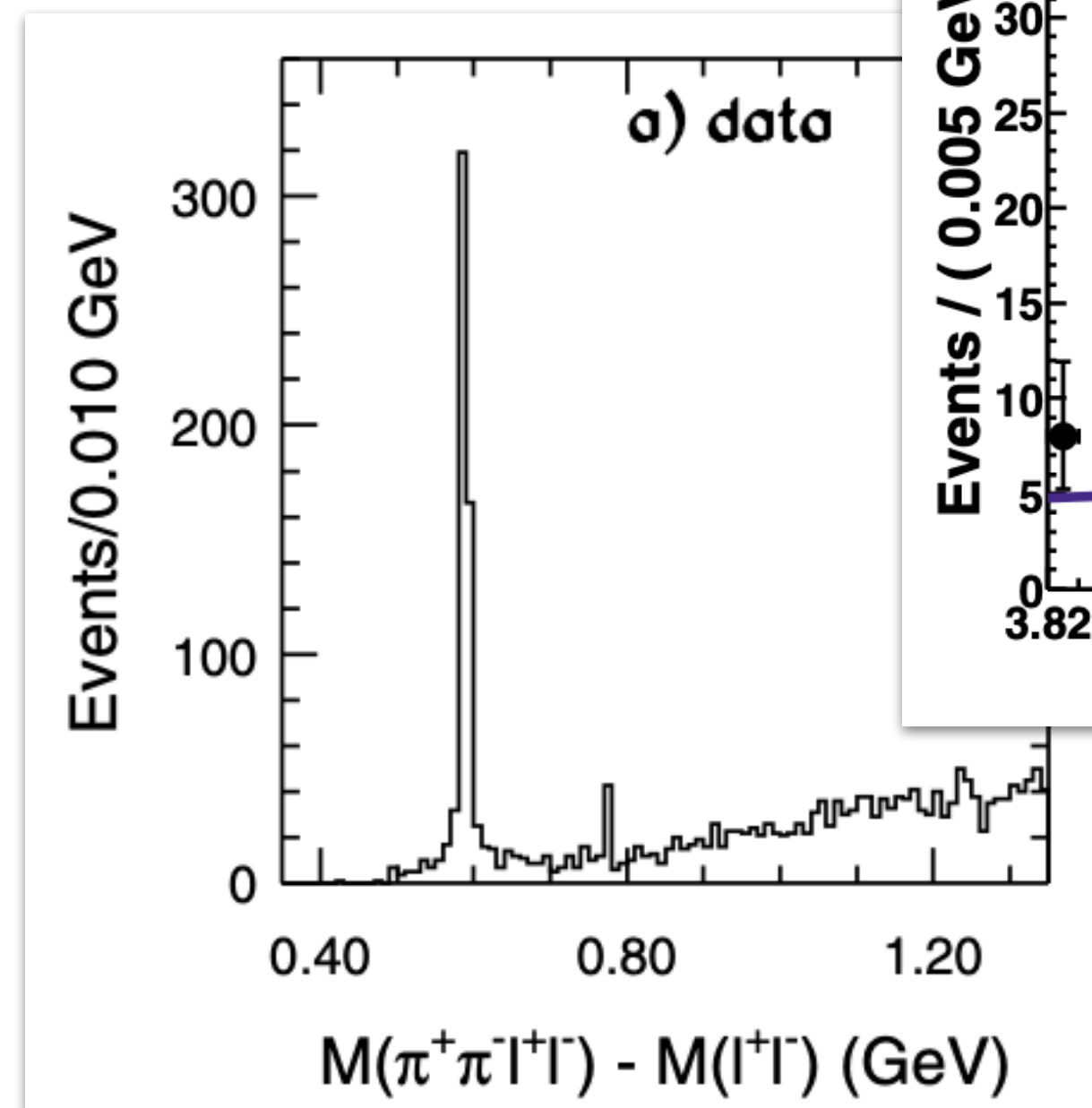
$$B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$$



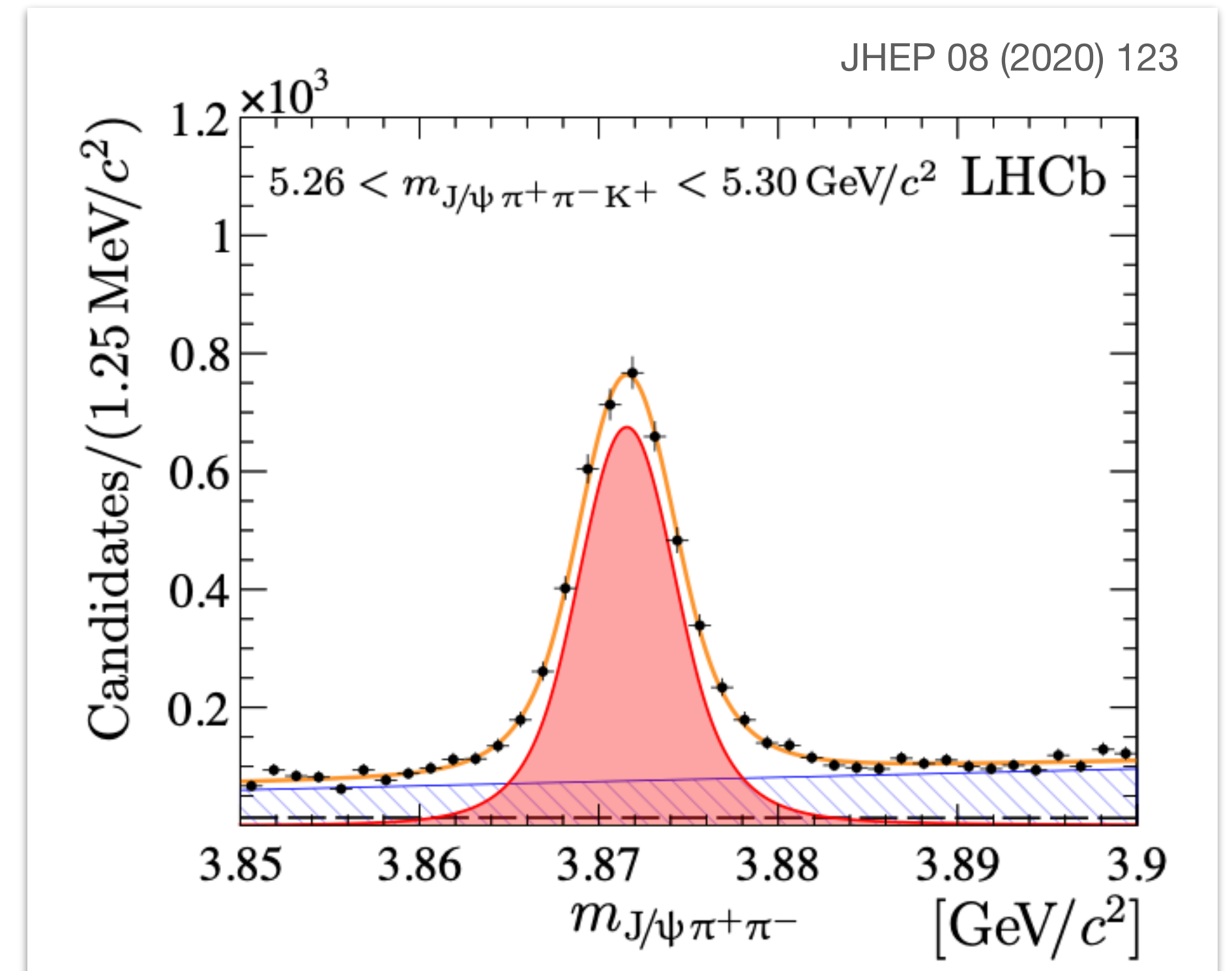
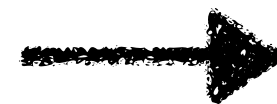
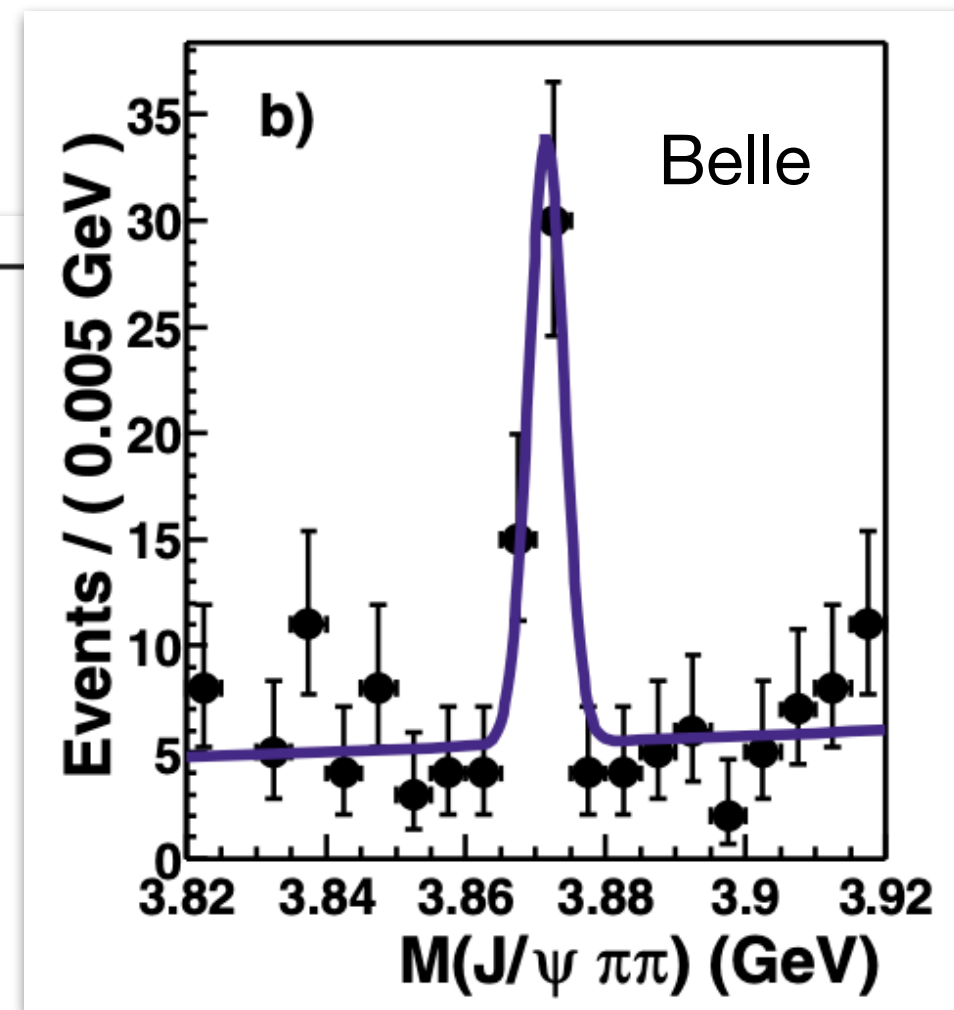
PRL 91, 262001 (2003)

Where it all began: the X(3872)

$$B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$$



PRL 91, 262001 (2003)



- now in an era of precision measurements:

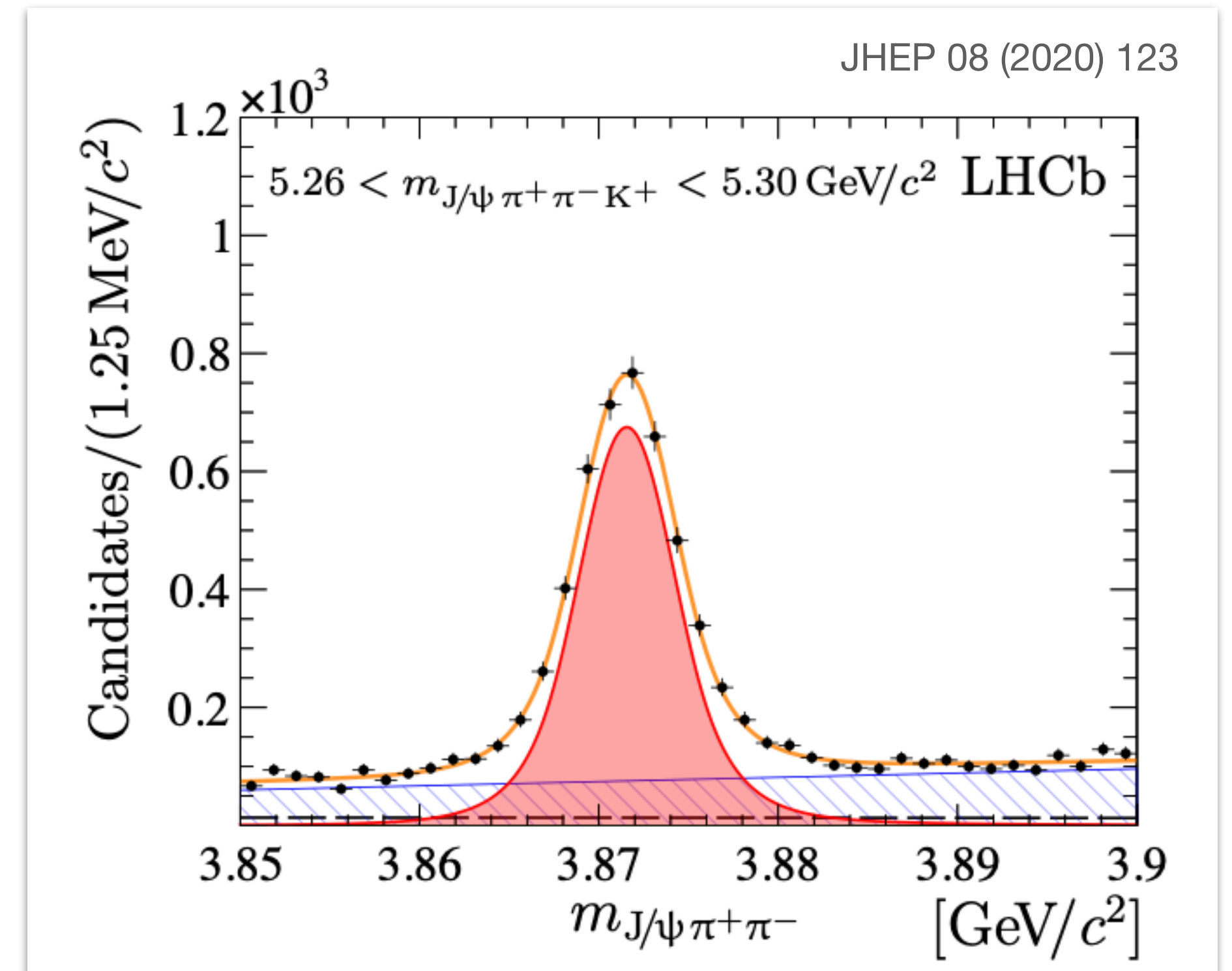
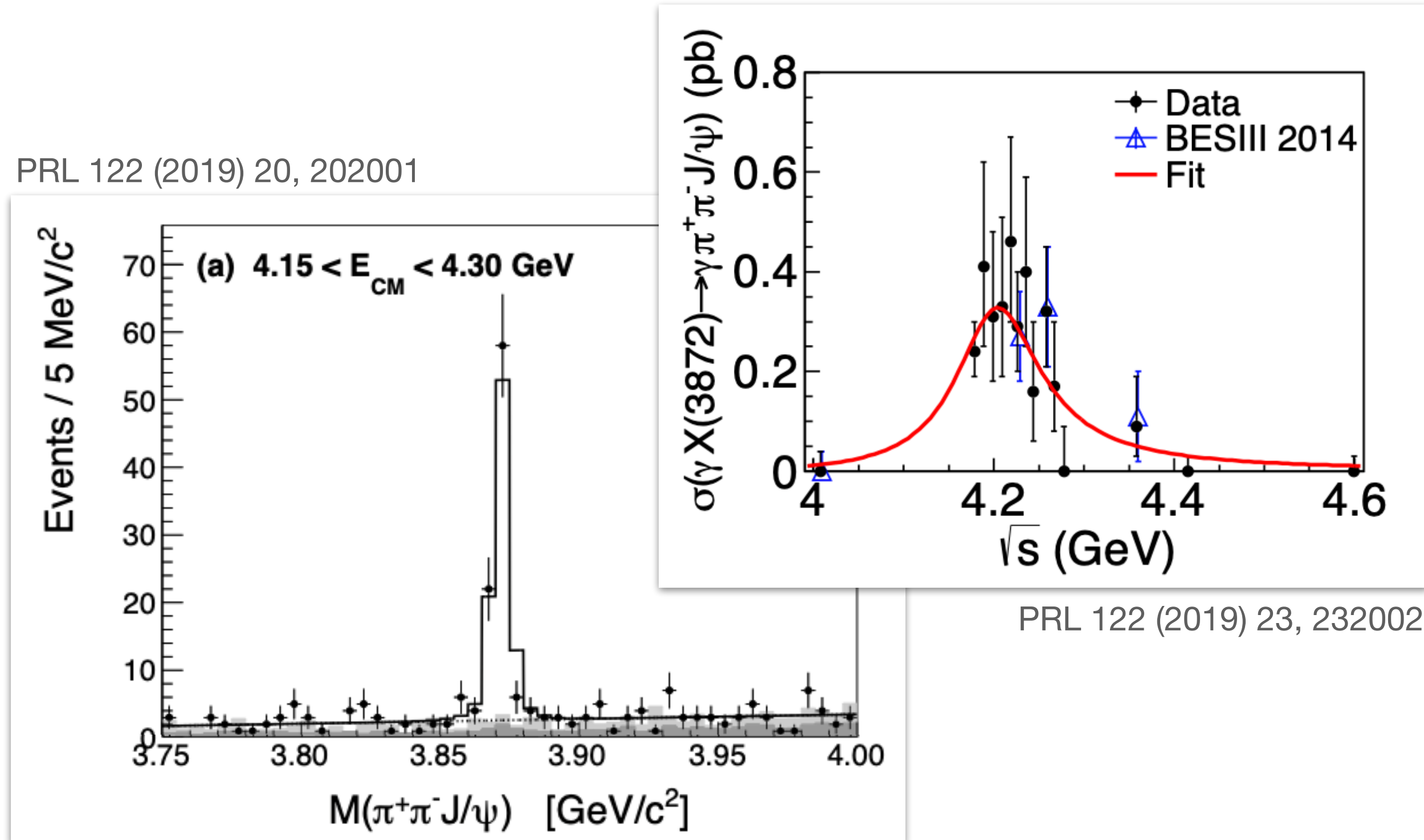
$$m = 3871.64 \pm 0.06 \text{ MeV}, \quad \Gamma = 1.19 \pm 0.21 \text{ MeV}$$

PDG

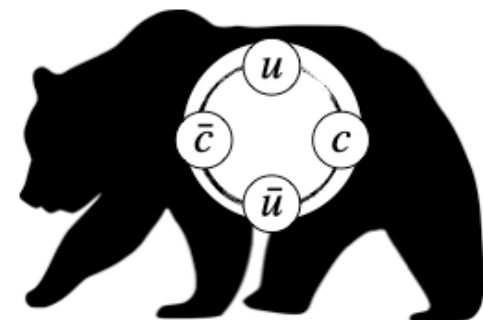
- many decay modes discovered:

$$D^{*0} \bar{D}^0, \rho J/\psi, \omega J/\psi, \pi^0 \chi_{c1}, \gamma J/\psi, \gamma \psi(2S)$$

Where it all began: the X(3872)



- alternative production process: $e^+e^- \rightarrow \gamma X(3872)$ in vicinity of the $\psi(4230)$
- production mechanism was predicted in molecular scenario PLB 725 (2013) 127-133



- now in an era of precision measurements:

$$m = 3871.64 \pm 0.06 \text{ MeV}, \quad \Gamma = 1.19 \pm 0.21 \text{ MeV} \quad \text{PDG}$$

- many decay modes discovered: $D^{*0}\bar{D}^0, \rho J/\psi, \omega J/\psi, \pi^0 \chi_{c1}, \gamma J/\psi, \gamma \psi(2S)$

What is the nature of the $X(3872)$?

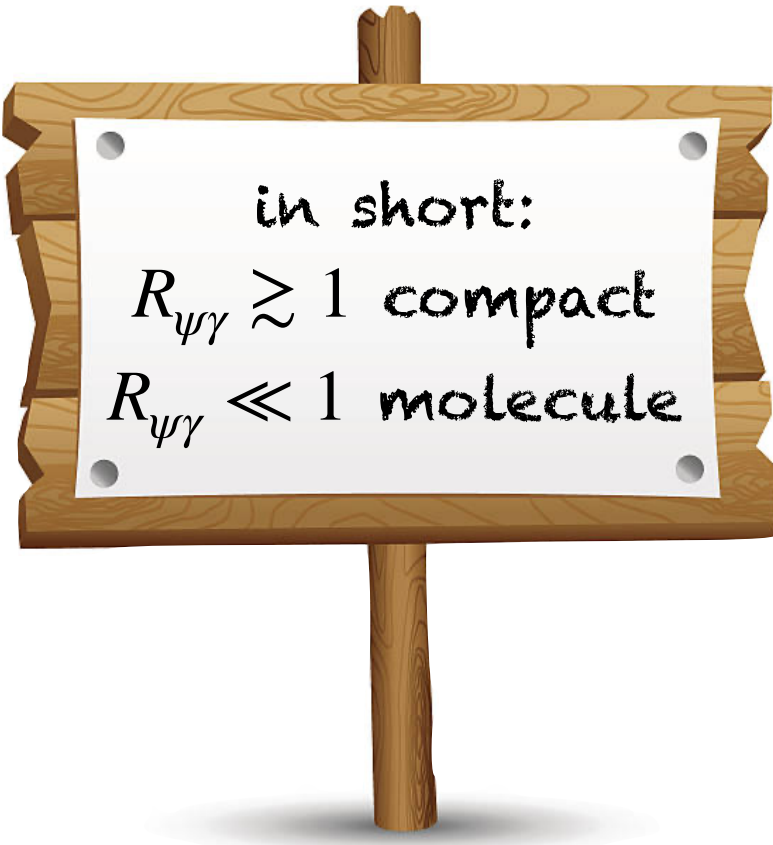
- we still do not know what exactly the $X(3872)$ is
- need observables sensitive on nature of the state:

$$R_{\psi\gamma} = \frac{\Gamma(X(3872) \rightarrow \gamma\psi(2S))}{\Gamma(X(3872) \rightarrow \gamma J/\psi)}$$



- but: longstanding discrepancy between experiments

BaBar: $R_{\psi\gamma} = 3.4 \pm 1.4$
LHCb: $R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29$
Belle: $R_{\psi\gamma} < 2.1$ (90 % CL)
BESIII: $R_{\psi\gamma} < 0.59$ (90 % CL)



Reference		$\mathcal{R}_{\psi\gamma}$	
T. Barnes and S. Godfrey	67	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	69	2.6	$c\bar{c}$
F. De Fazio	84	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	85	1.3	$c\bar{c}$
Y. Dong <i>et al.</i>	86	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian <i>et al.</i>	87	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	88	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	89	2.4	$c\bar{c}$
W. J. Deng <i>et al.</i>	90	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	71	5.4	$c\bar{c}/vc$
E. S. Swanson	81	0.38 %	$D\bar{D}^*$
Y. Dong <i>et al.</i>	86	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	91	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	92	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	93	3.6 %	$D\bar{D}^*$
F.-K. Guo <i>et al.</i>	82	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	83	$2 - 10$	$D\bar{D}^*$
E. Cincioglu <i>et al.</i>	94	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	95	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	93	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

What is the nature of the $X(3872)$?

- we still do not know what exactly the $X(3872)$ is
- need observables sensitive on nature of the state:

$$R_{\psi\gamma} = \frac{\Gamma(X(3872) \rightarrow \gamma\psi(2S))}{\Gamma(X(3872) \rightarrow \gamma J/\psi)}$$

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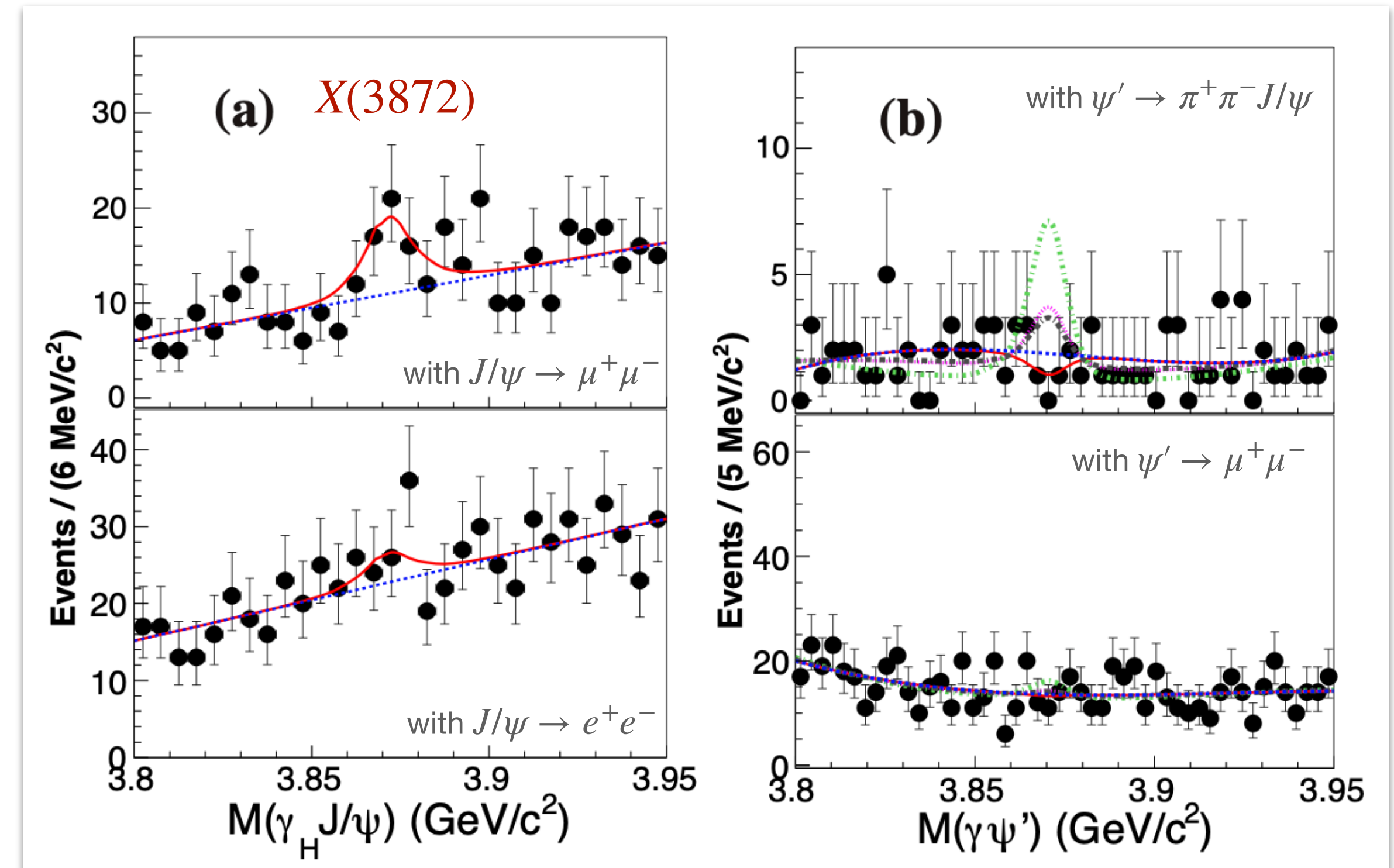
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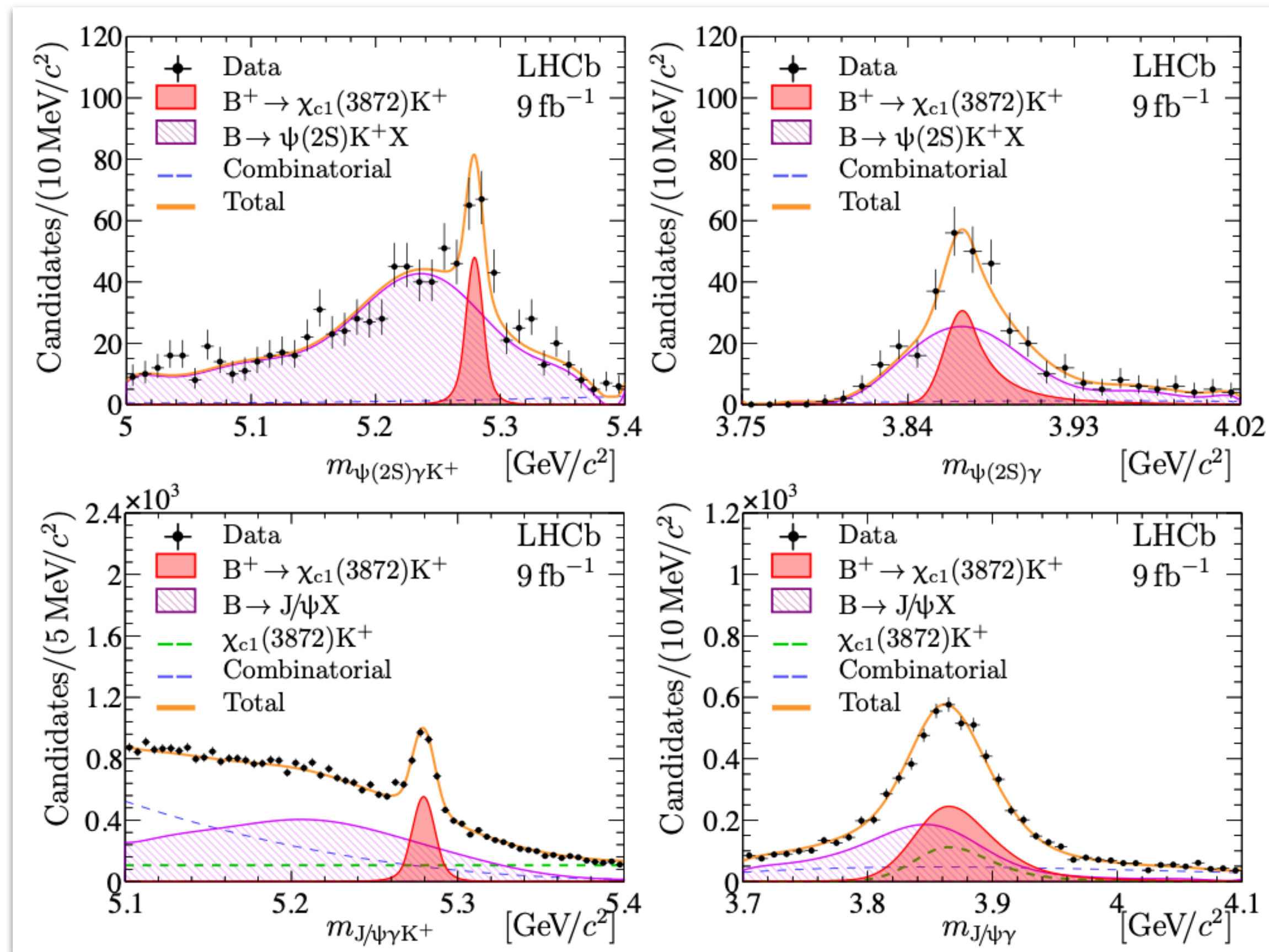
BESIII: $e^+e^- \rightarrow \gamma X(3872)$



PRL 124 (2020) 24, 242001

What is the nature of the $X(3872)$?

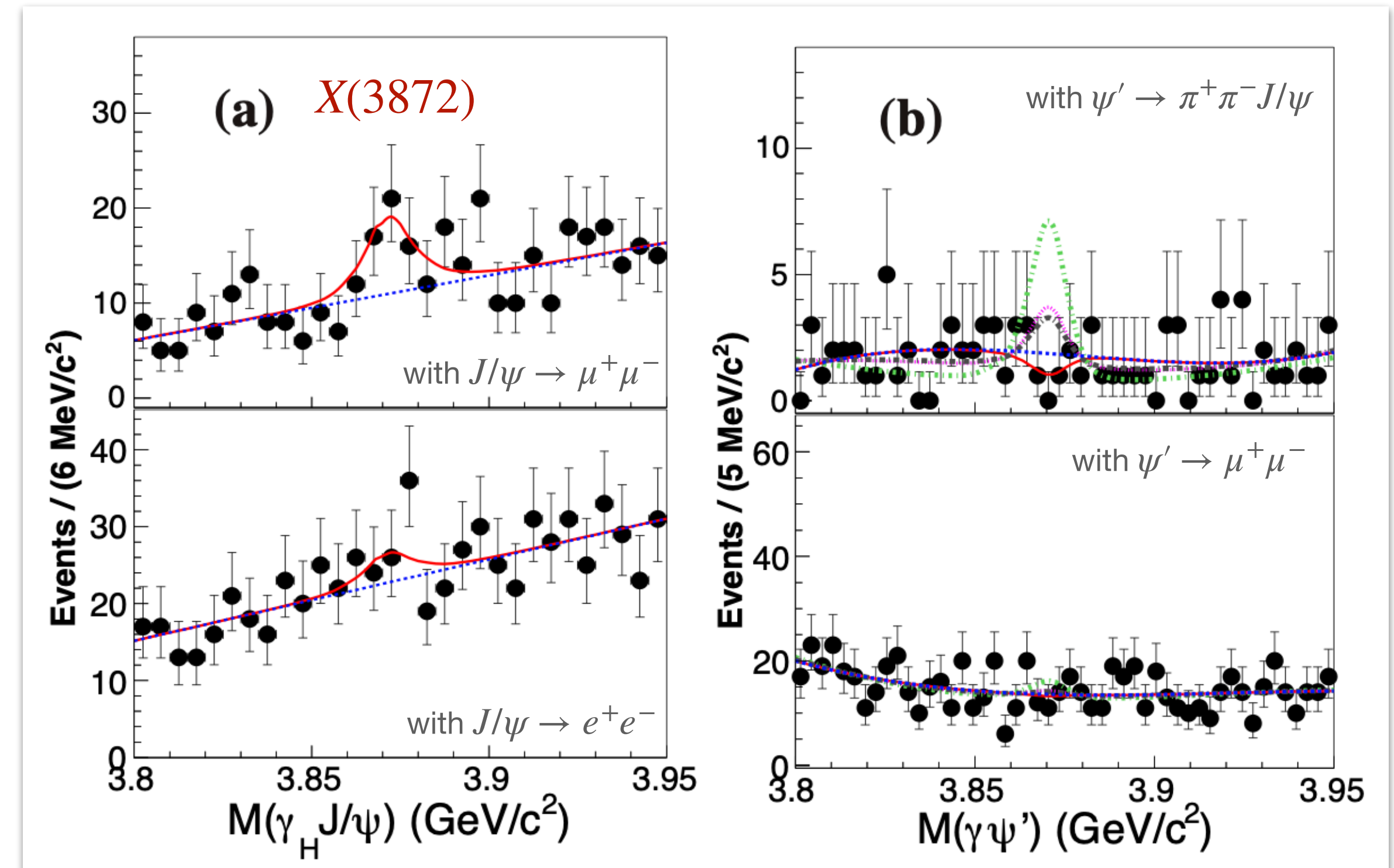
new from LHCb: $B \rightarrow KX(3872)$



JHEP 11 (2024) 121

$$\text{LHCb: } R_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

BESIII: $e^+e^- \rightarrow \gamma X(3872)$

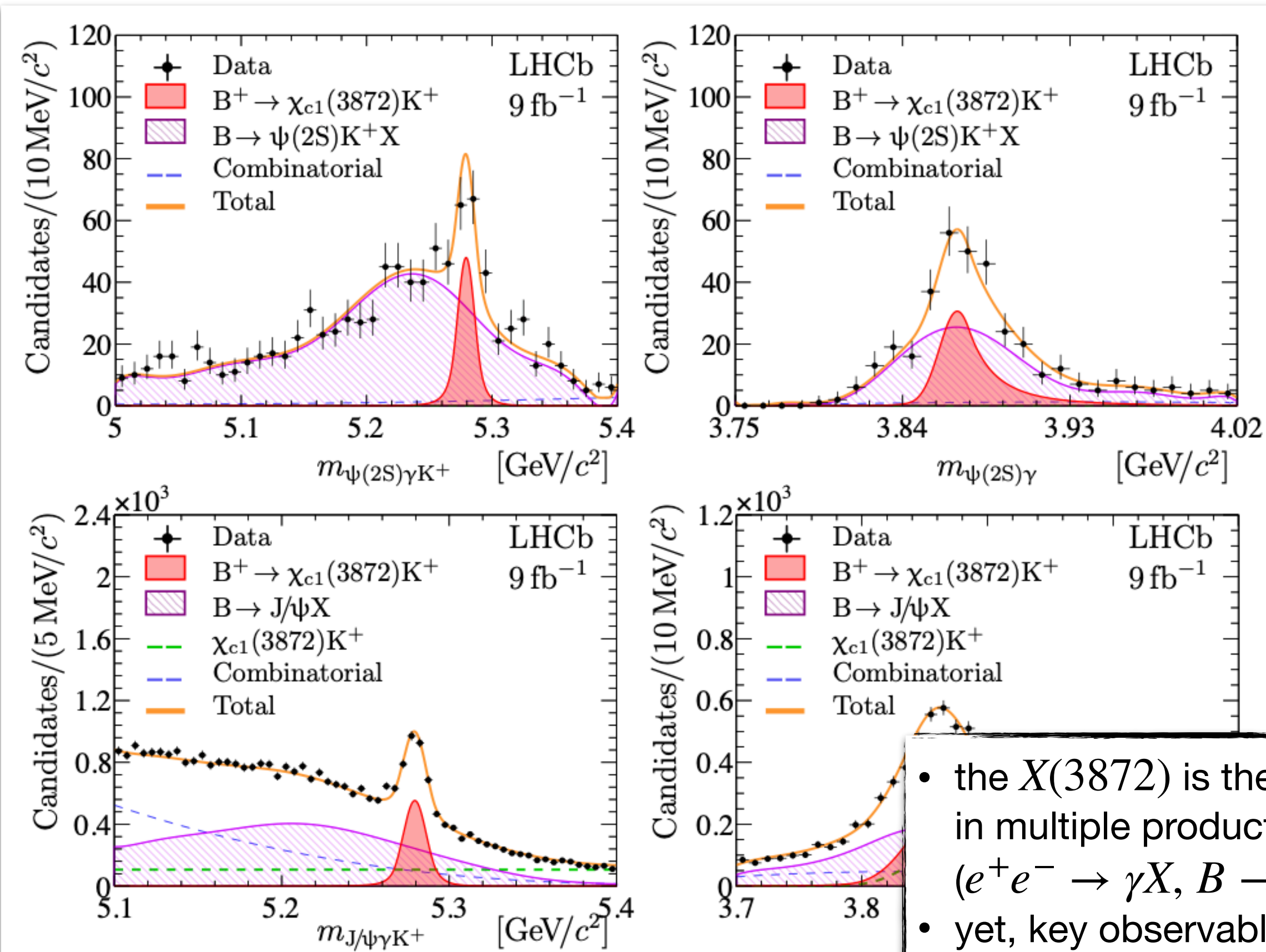


PRL 124 (2020) 24, 242001

$$\text{BESIII: } R_{\psi\gamma} < 0.59 \text{ (90 \% CL)}$$

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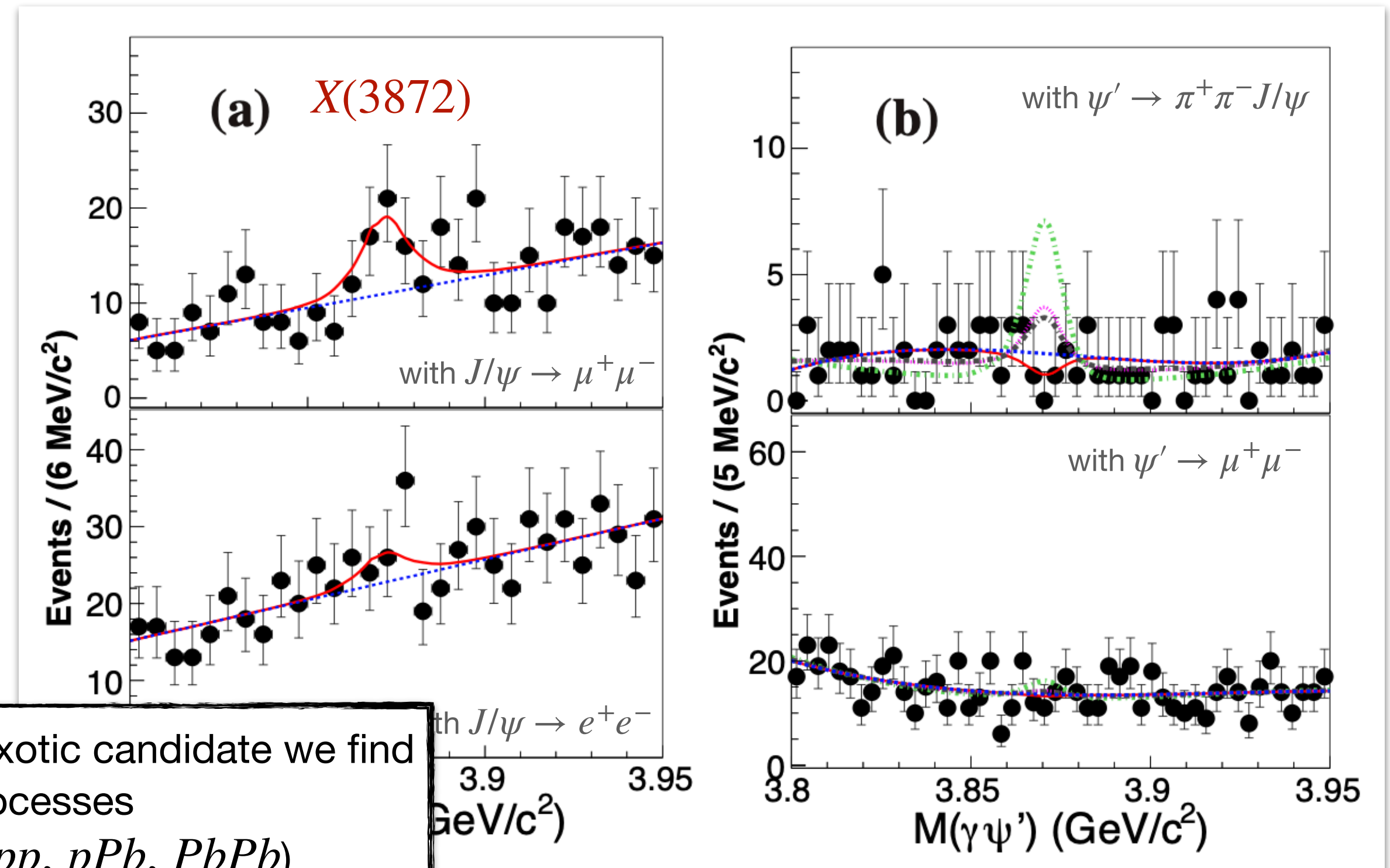
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JHEP 11 (2024) 121

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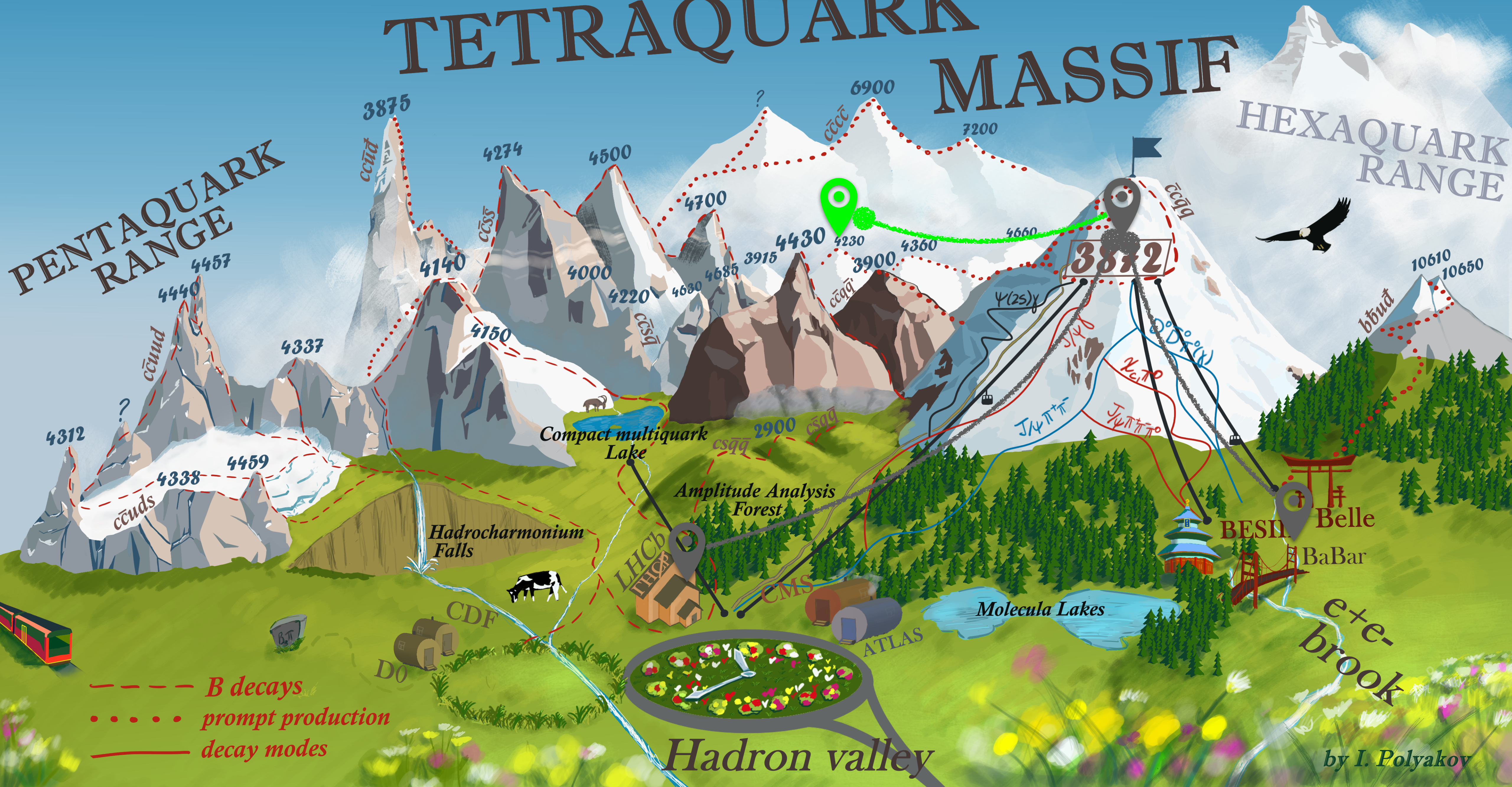
BESIII: $e^+e^- \rightarrow \gamma X(3872)$



- the $X(3872)$ is the one exotic candidate we find in multiple production processes ($e^+e^- \rightarrow \gamma X$, $B \rightarrow KX$, pp , pPb , $PbPb$)
- yet, key observables disagree...
- more BESIII data would be helpful

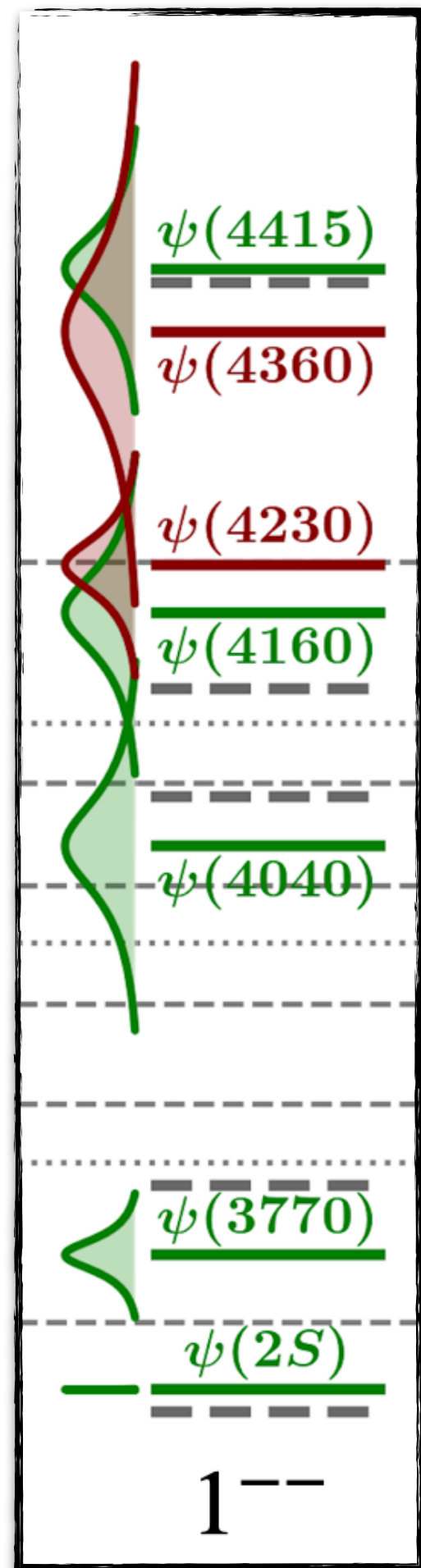
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TETRAQUARK MASSIF

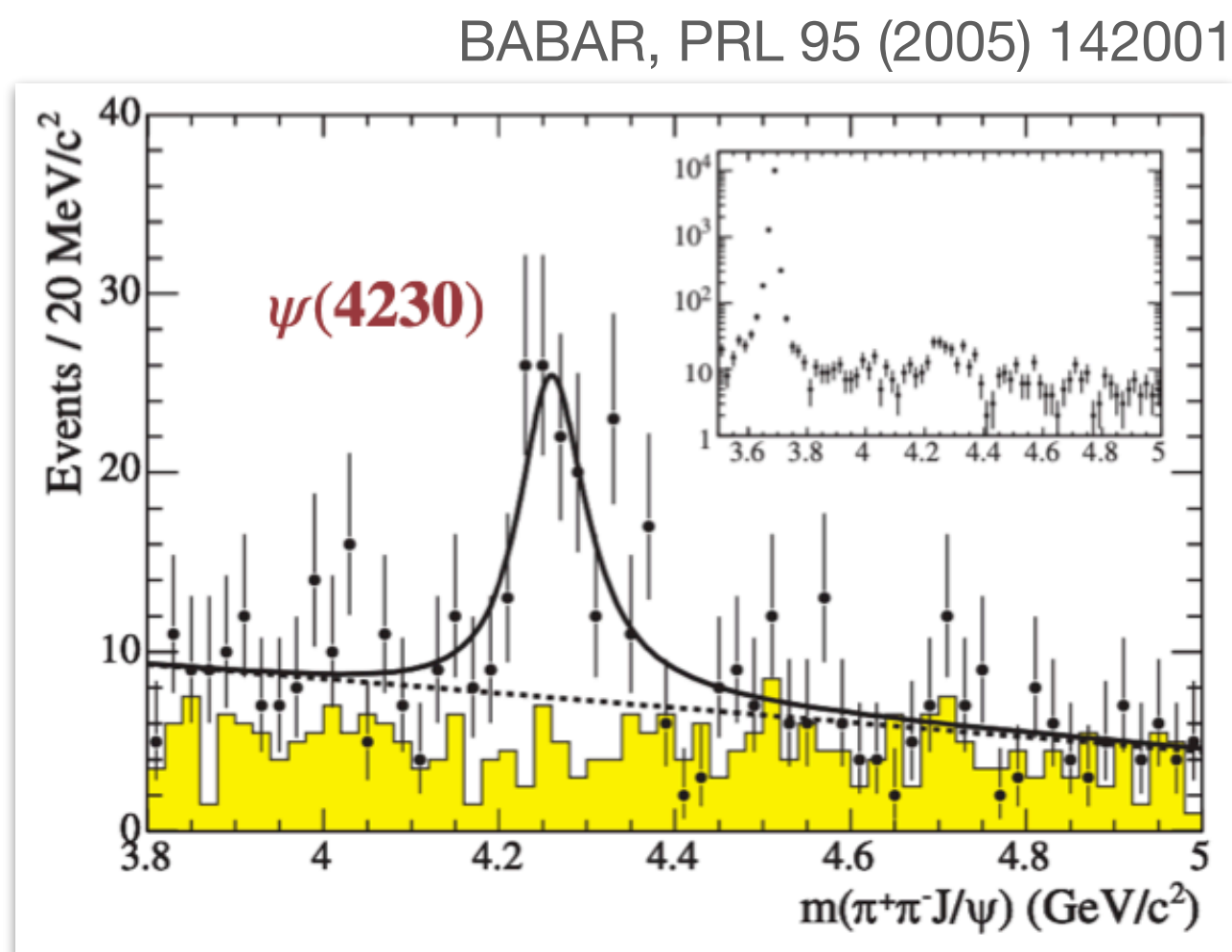


On $\psi(4230)$ and other vectors

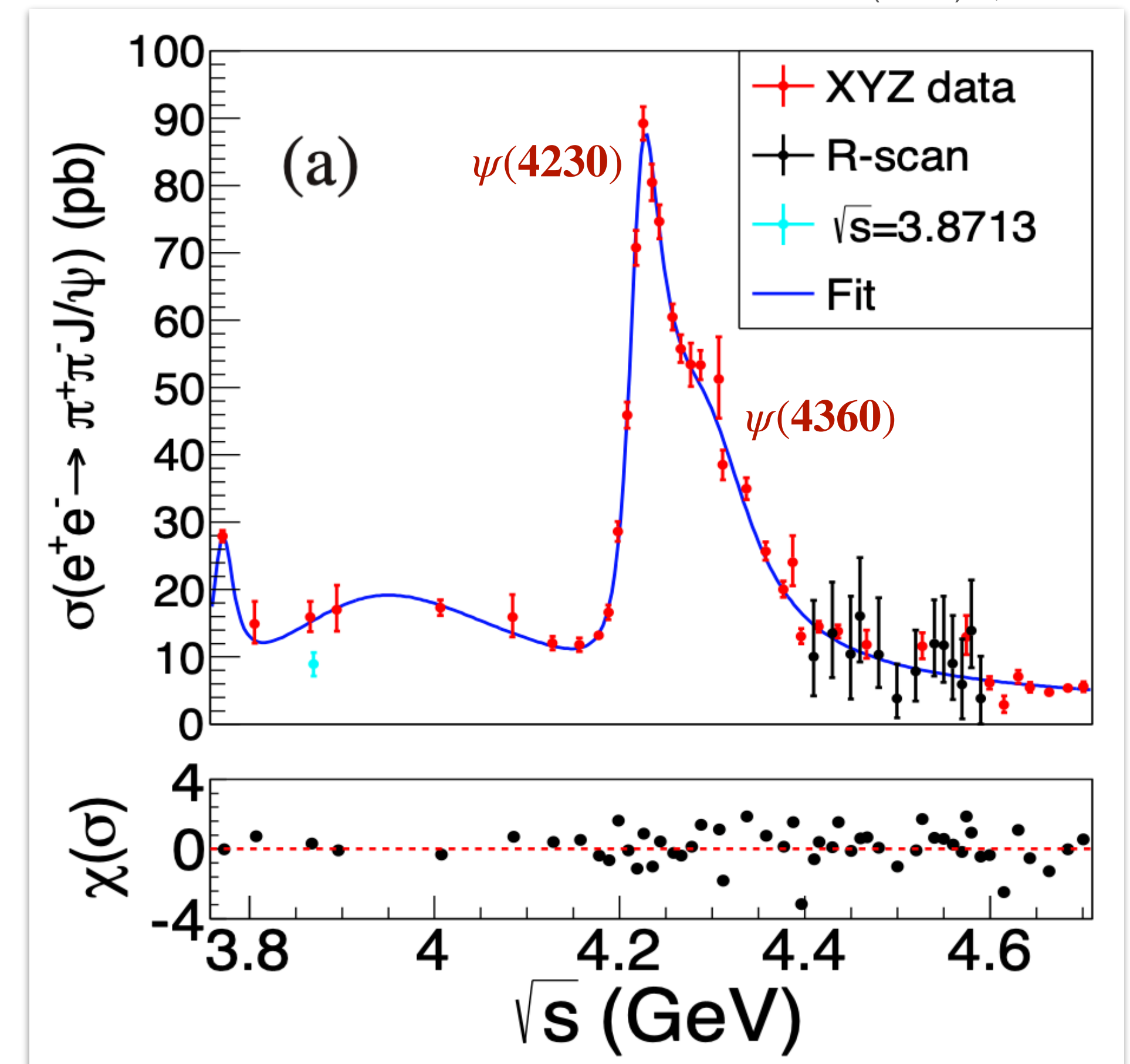
PRD 106 (2022) 7, 072001



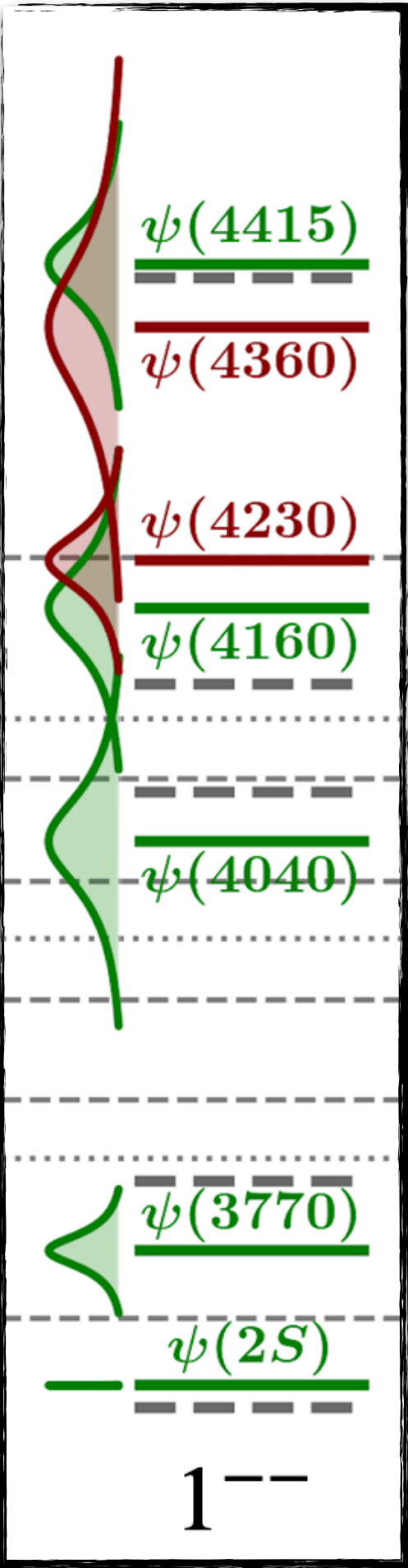
note: this is where
 e^+e^- machine excel



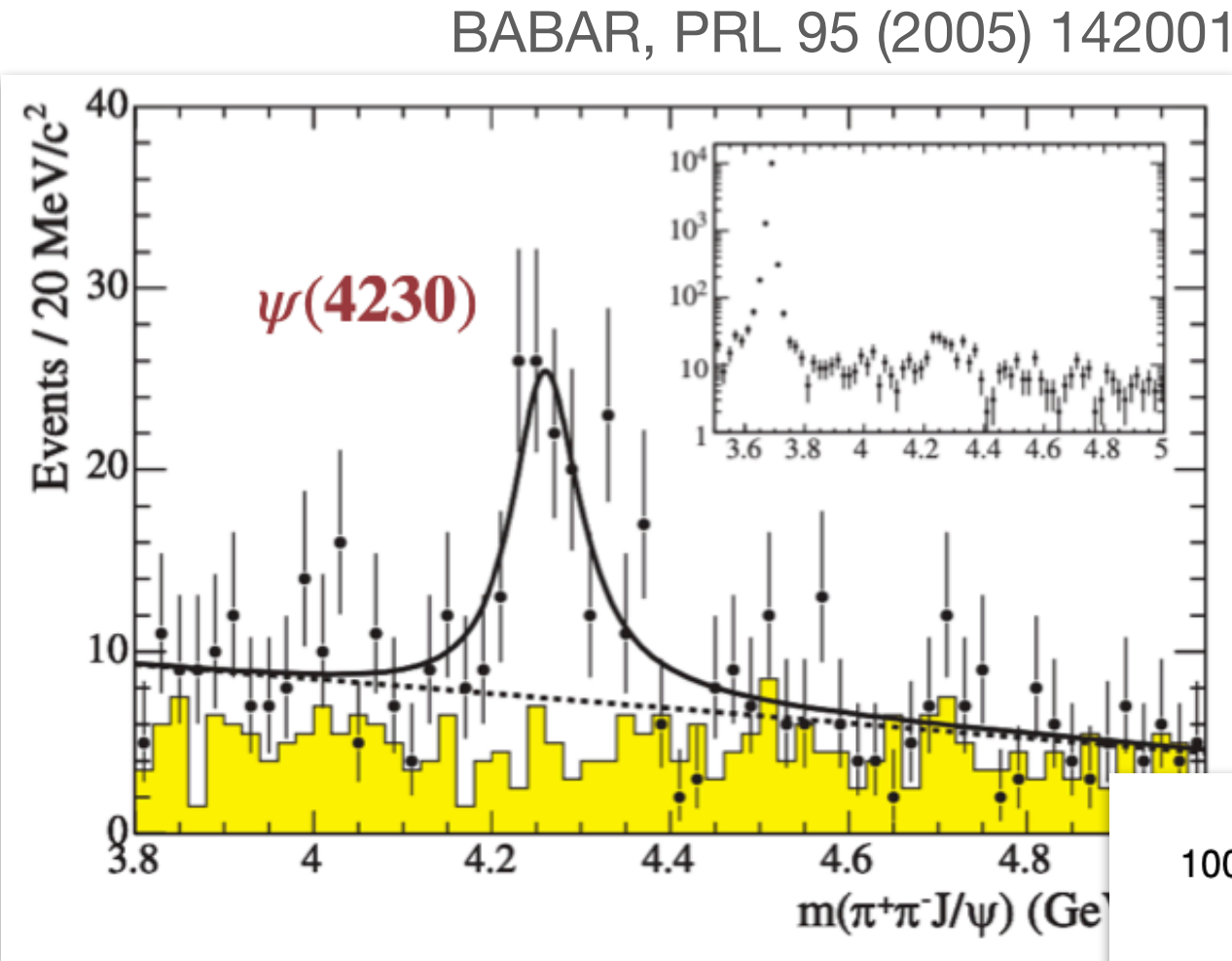
exclusive cross sections such as
 $e^+e^- \rightarrow J/\psi\pi\pi$ show (exotic?) peaks



On $\psi(4230)$ and other vectors

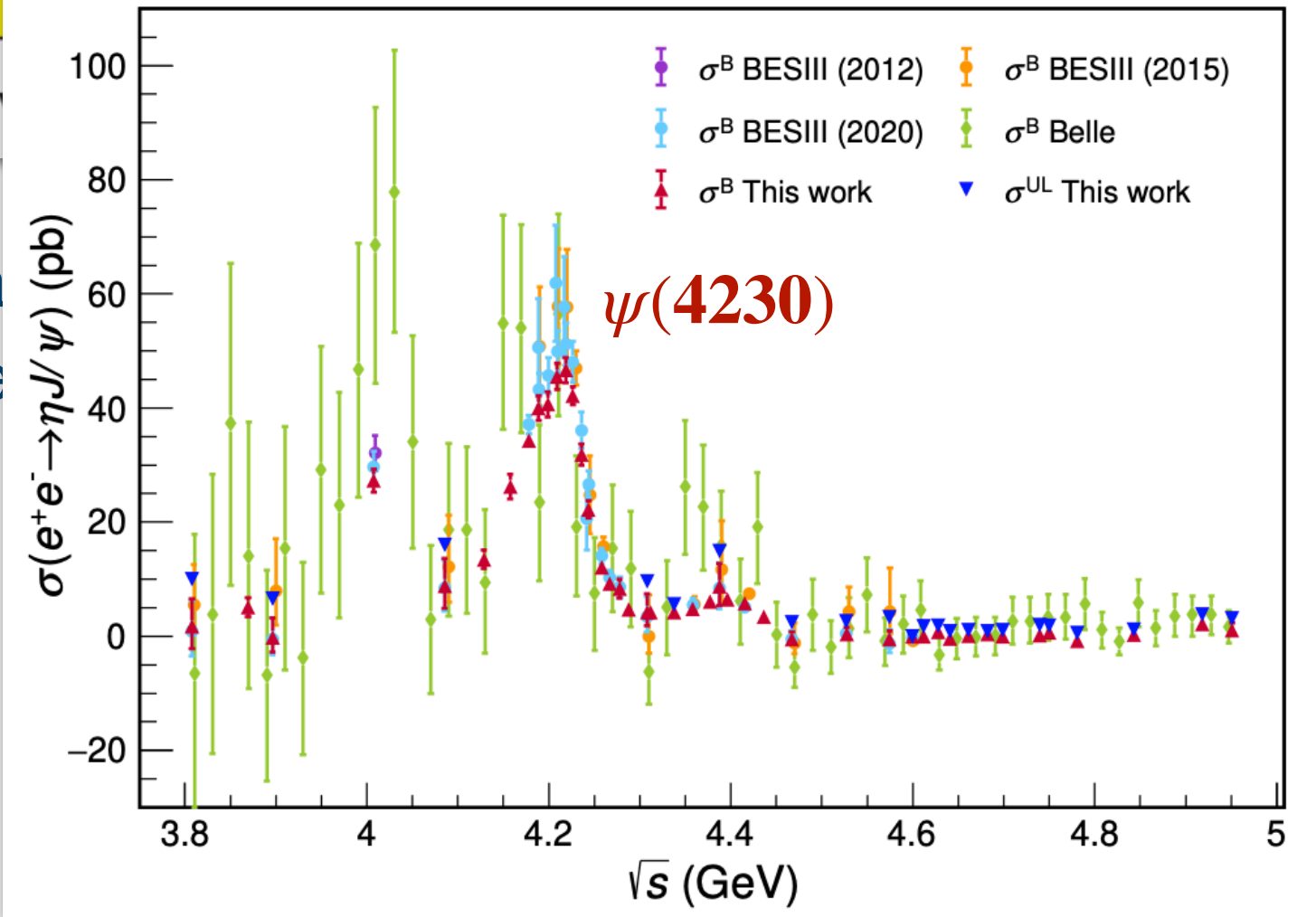


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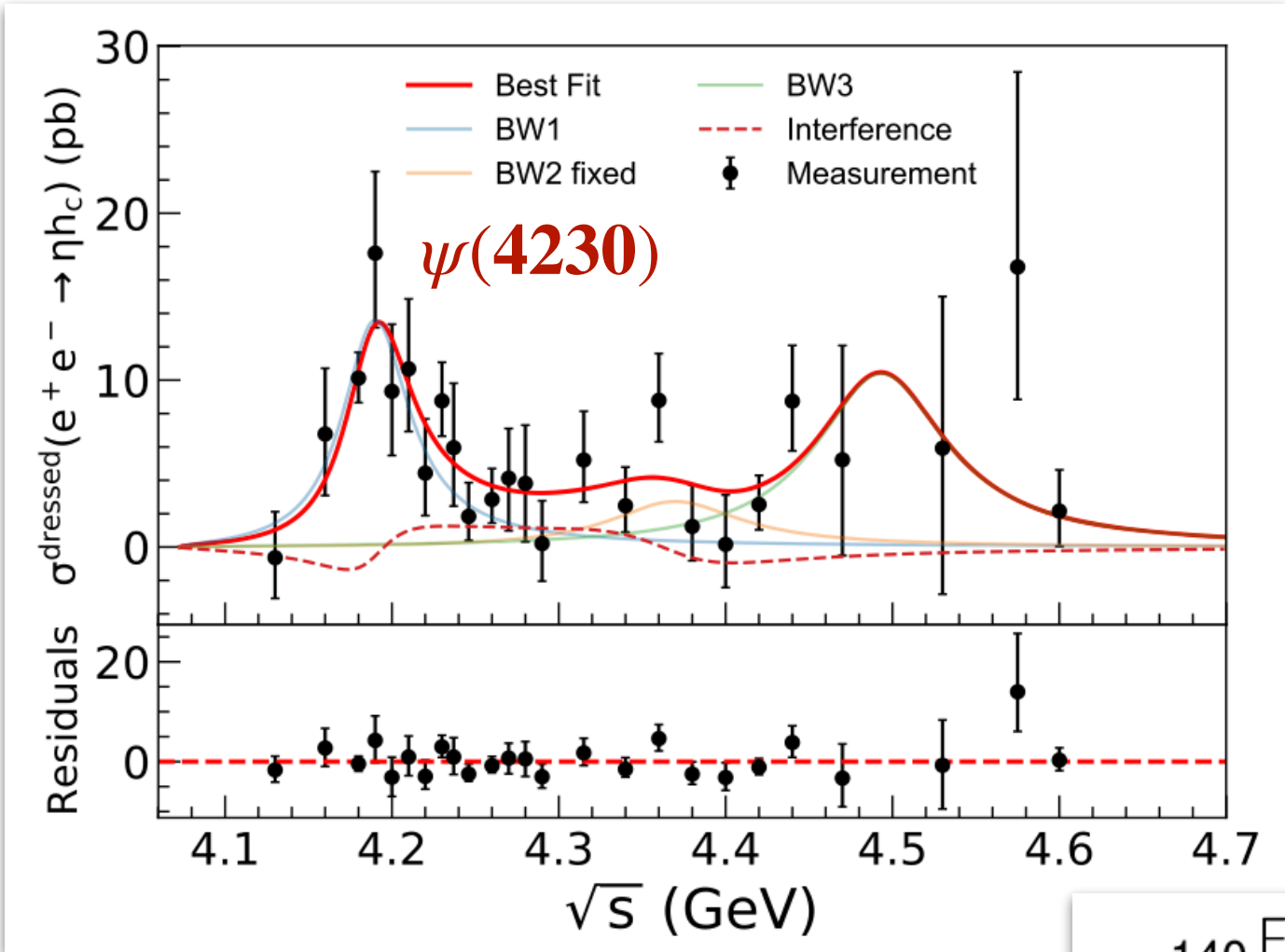


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$$e^+e^- \rightarrow \eta J/\psi$$

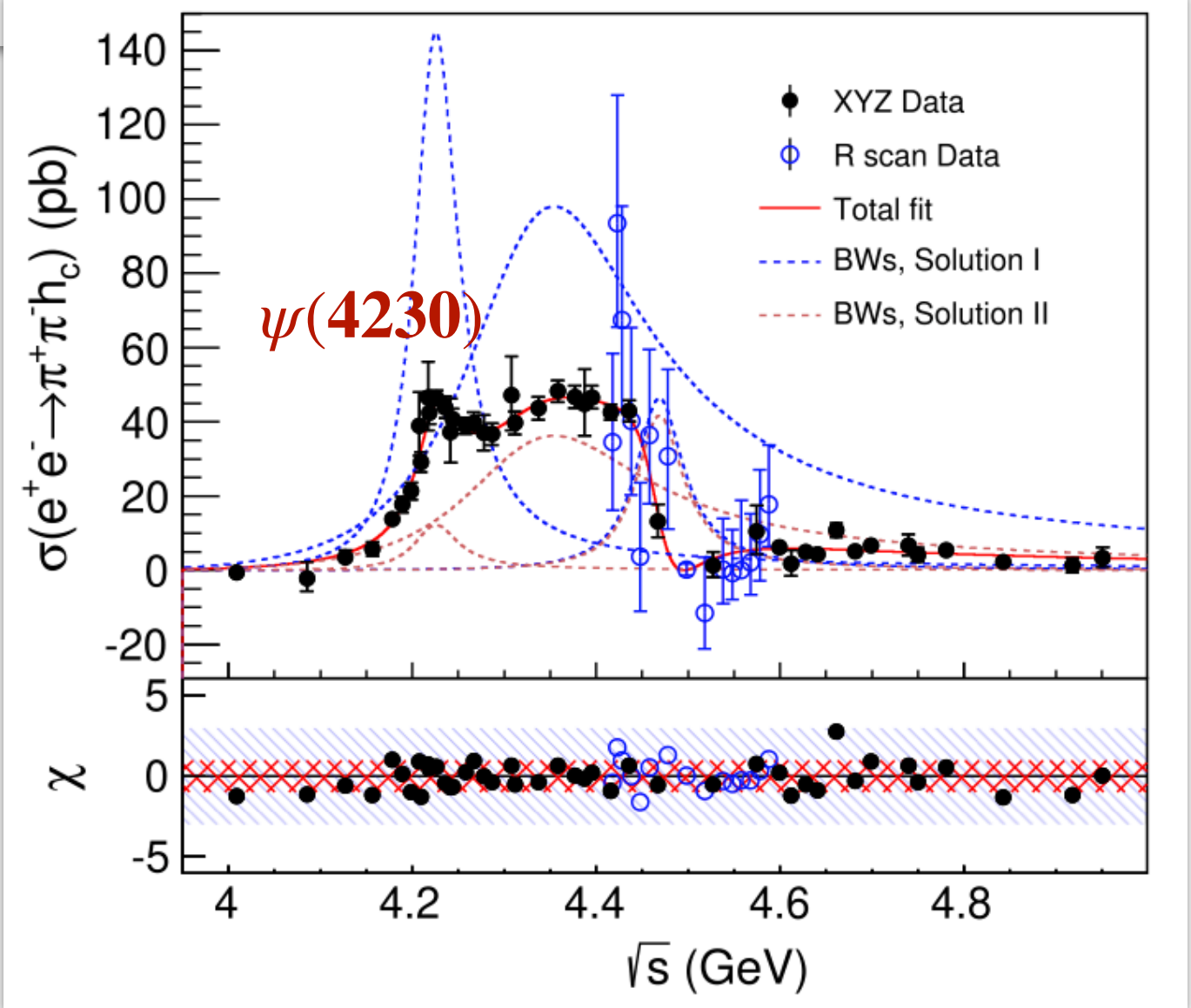


PRD 111, L011101 (2025)

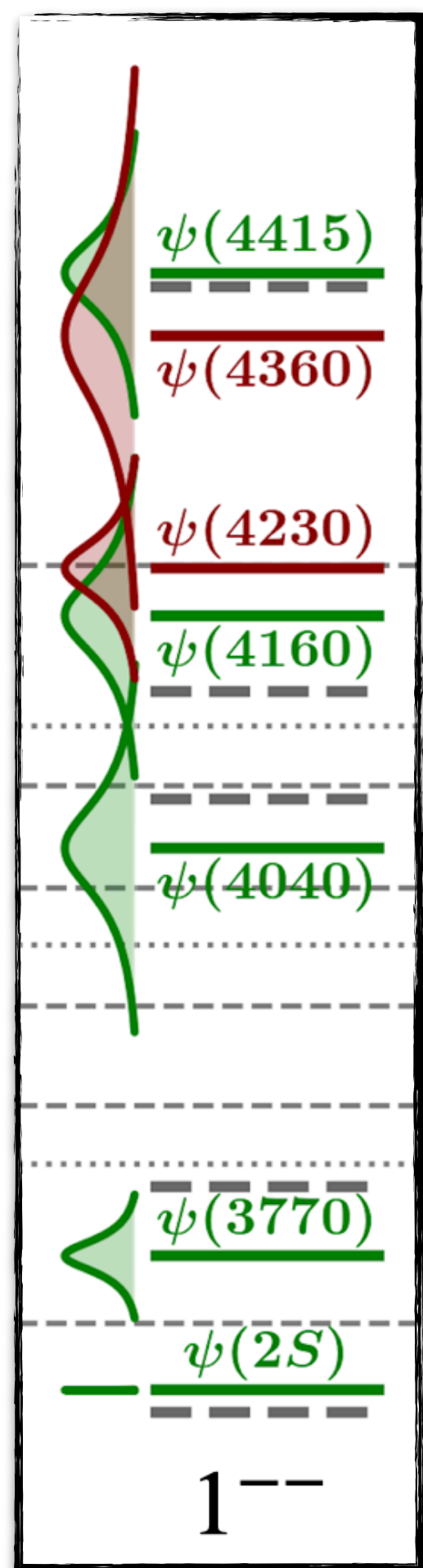


$$e^+e^- \rightarrow \eta h_c$$

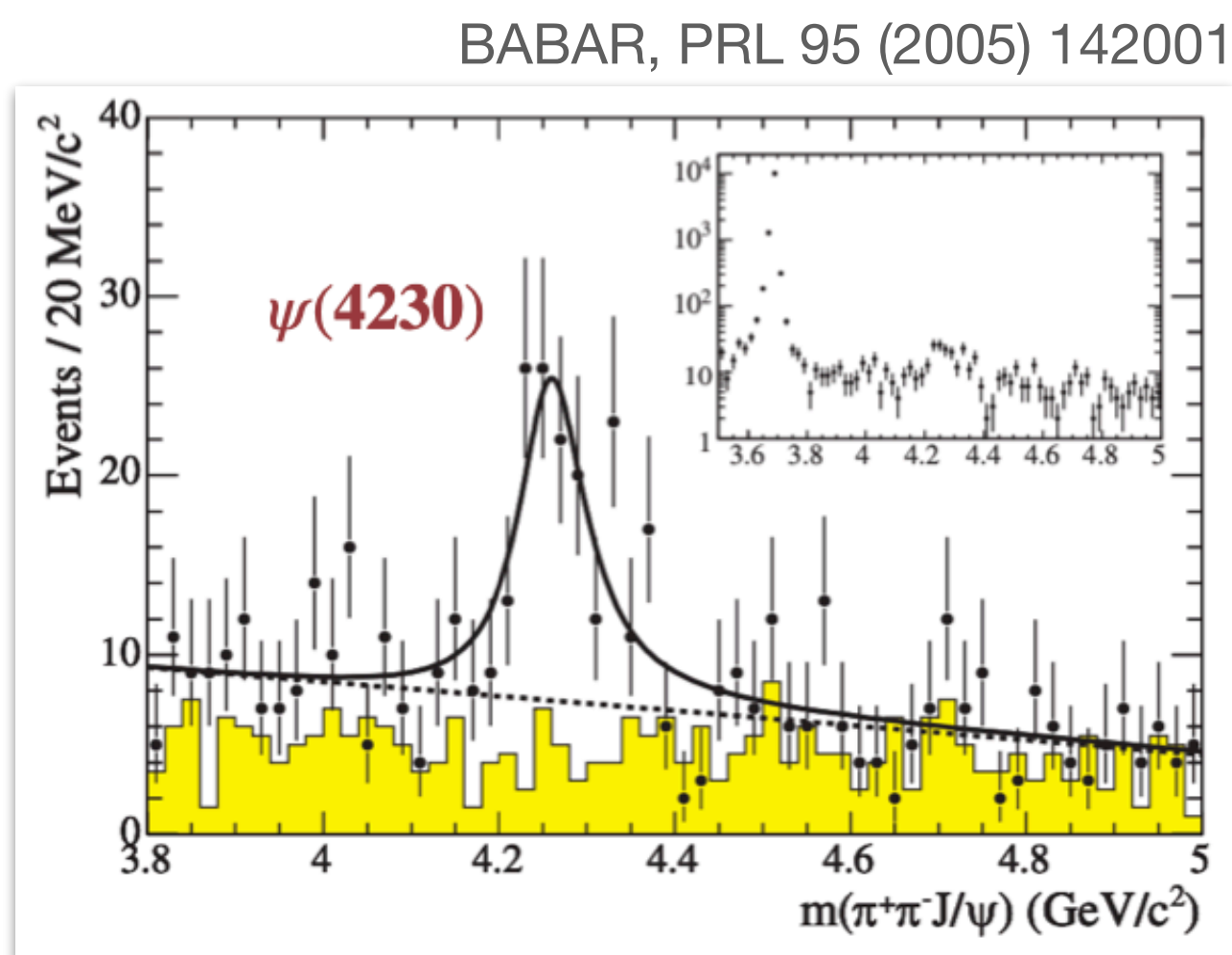
$$e^+e^- \rightarrow h_c \pi^+ \pi^-$$



On $\psi(4230)$ and other vectors



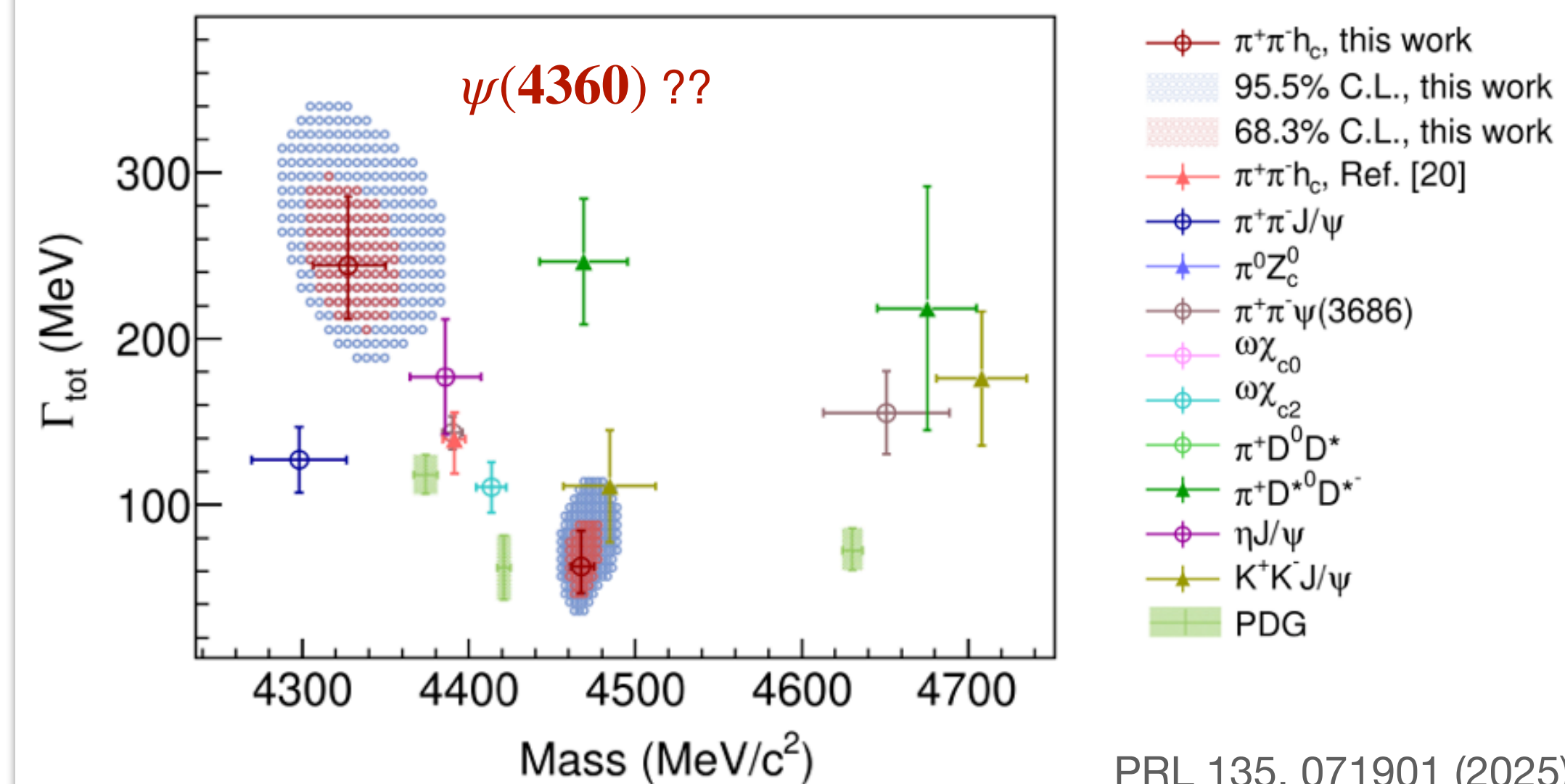
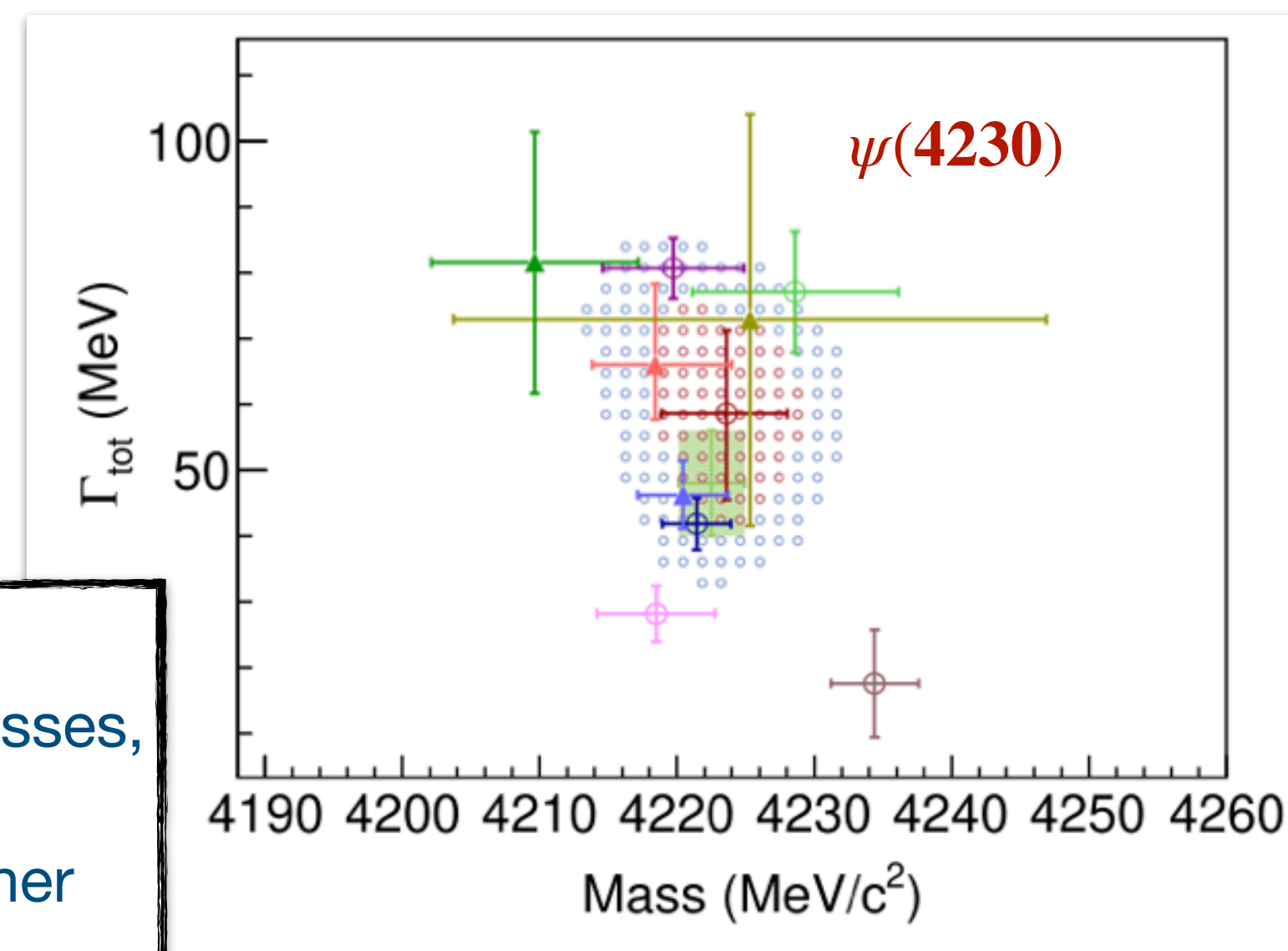
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exclusive cross sections such as $e^+e^- \rightarrow J/\psi\pi\pi$ show (exotic?) peaks

summarizing where we stand:

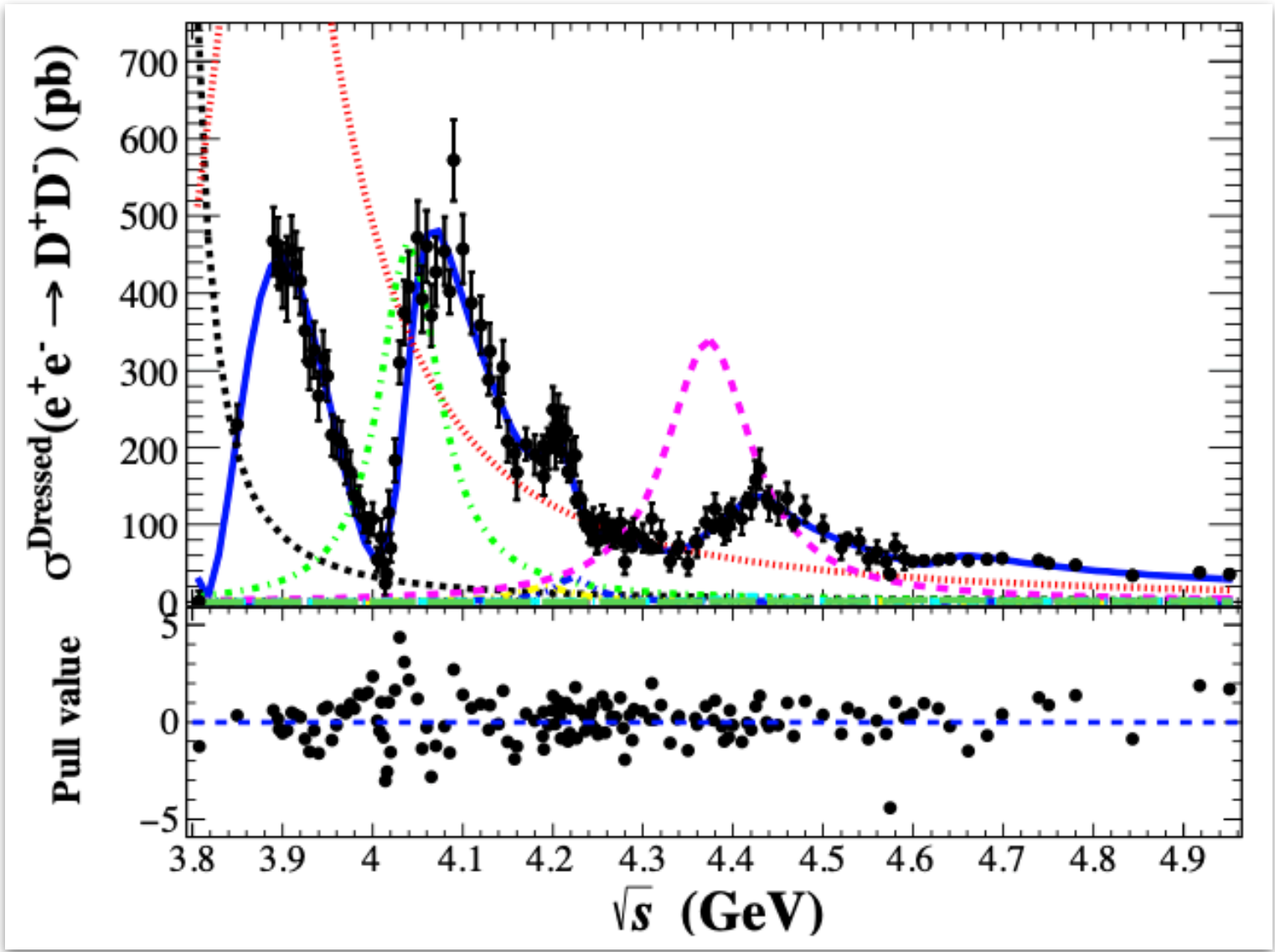
- fairly consistent $\psi(4230)$ masses, inconsistent widths
- very little consistency for higher mass structures



On $\psi(4230)$ and other vectors

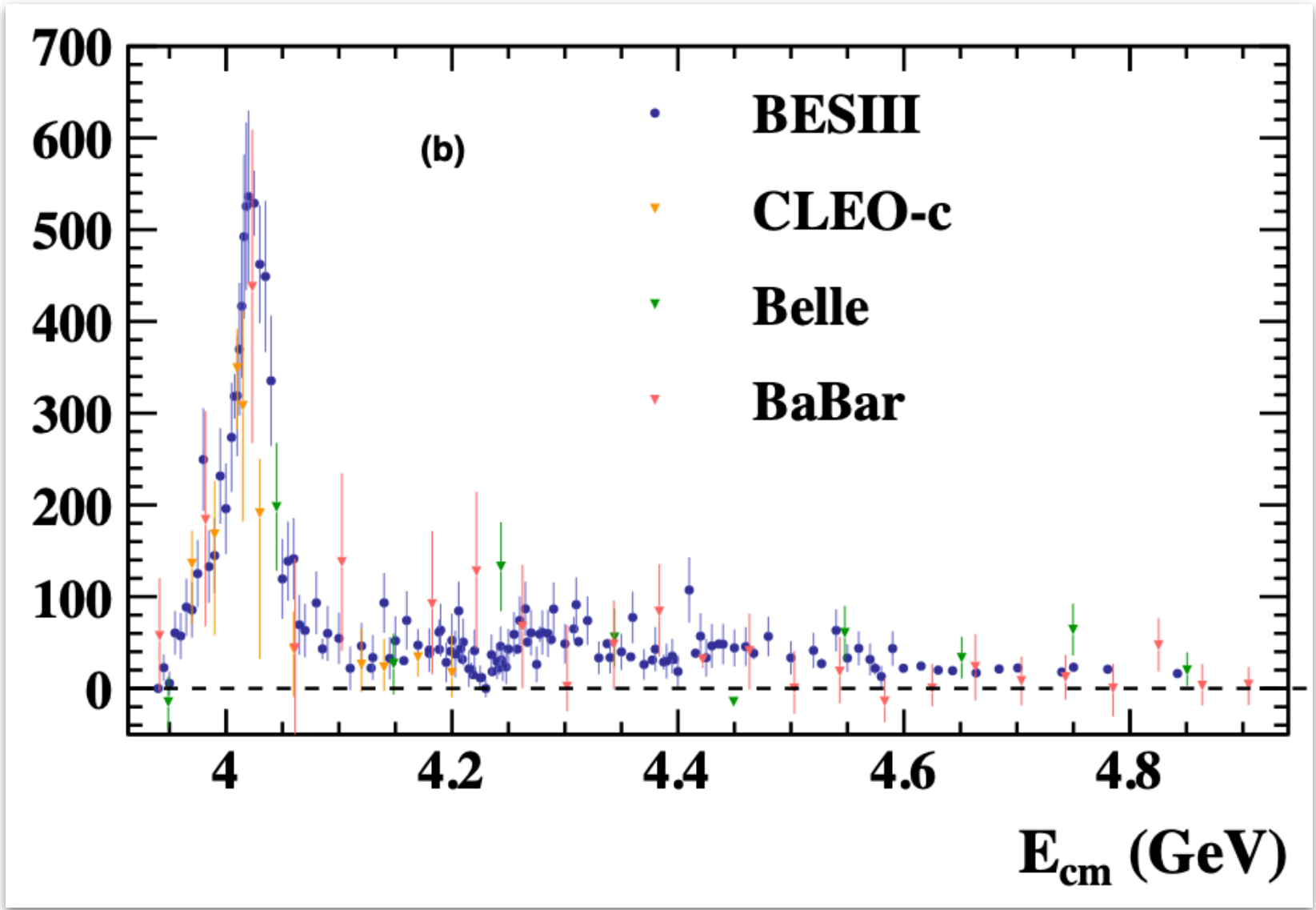
so how about exclusive open-charm cross sections?

$$e^+e^- \rightarrow D\bar{D}$$

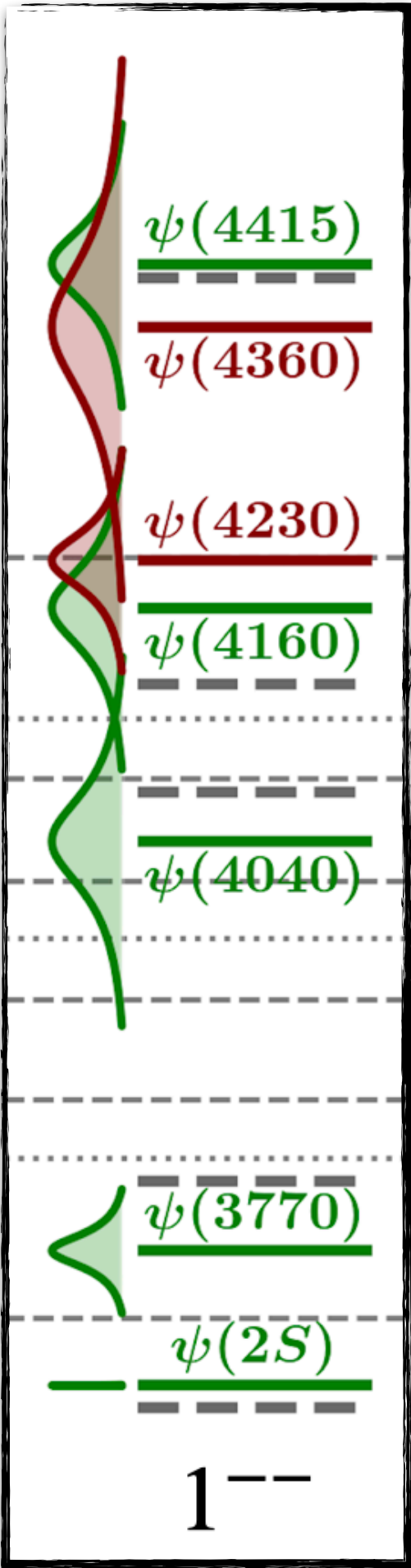


PRL 133 (2024) 8, 081901

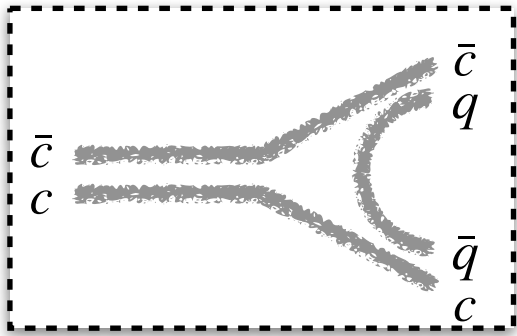
$$e^+e^- \rightarrow D_s\bar{D}_s$$



PRL 133 (2024) 26, 261902



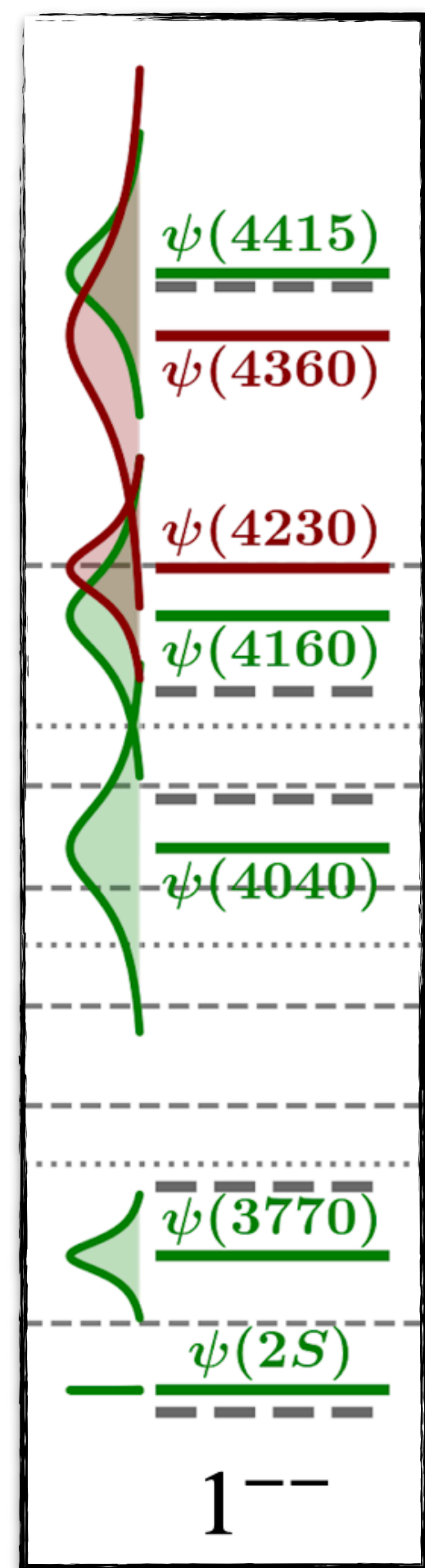
$D\bar{D}$



much larger cross sections, even more complex structure

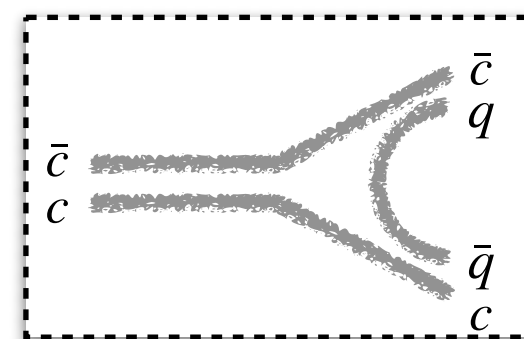
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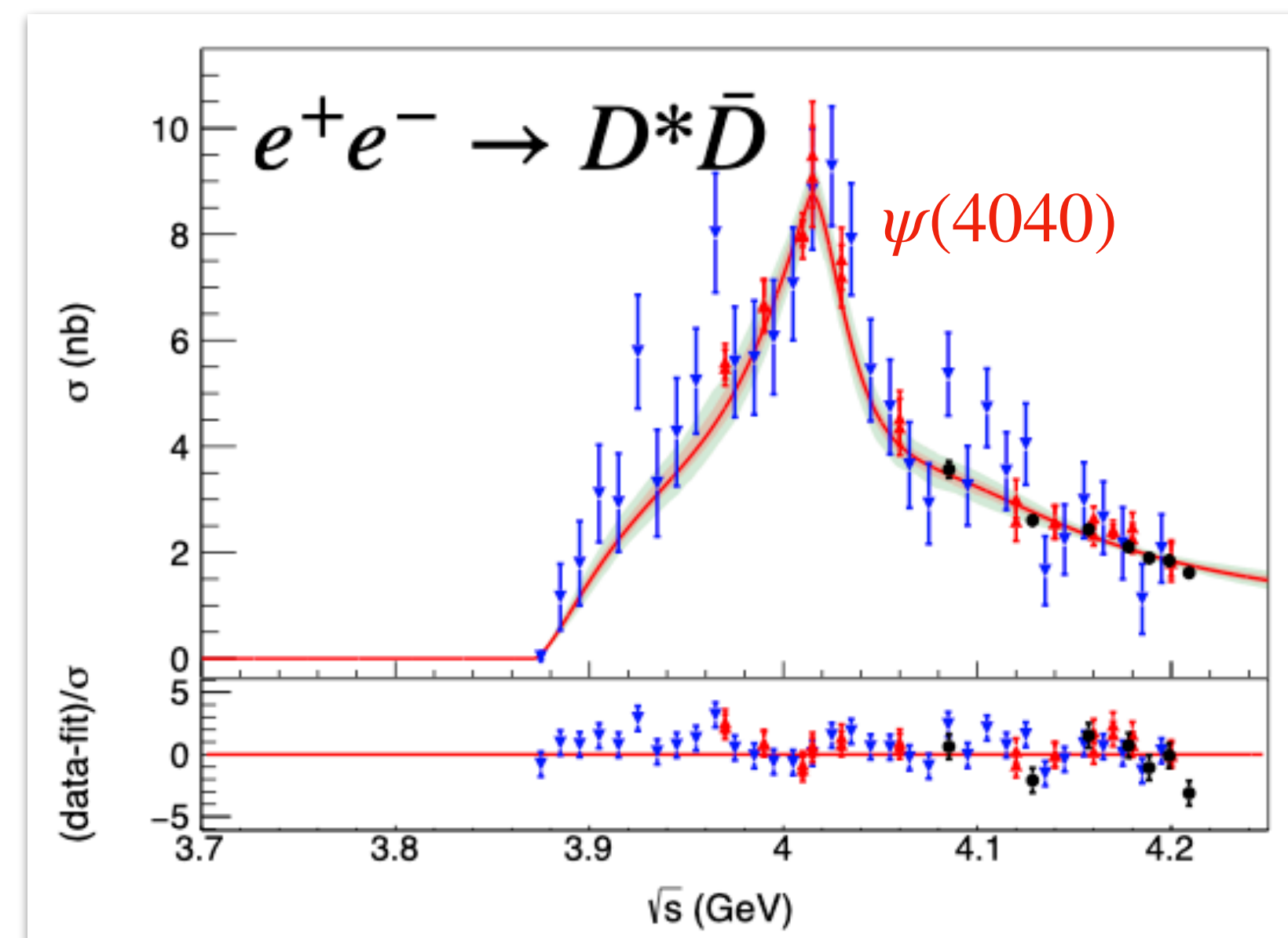
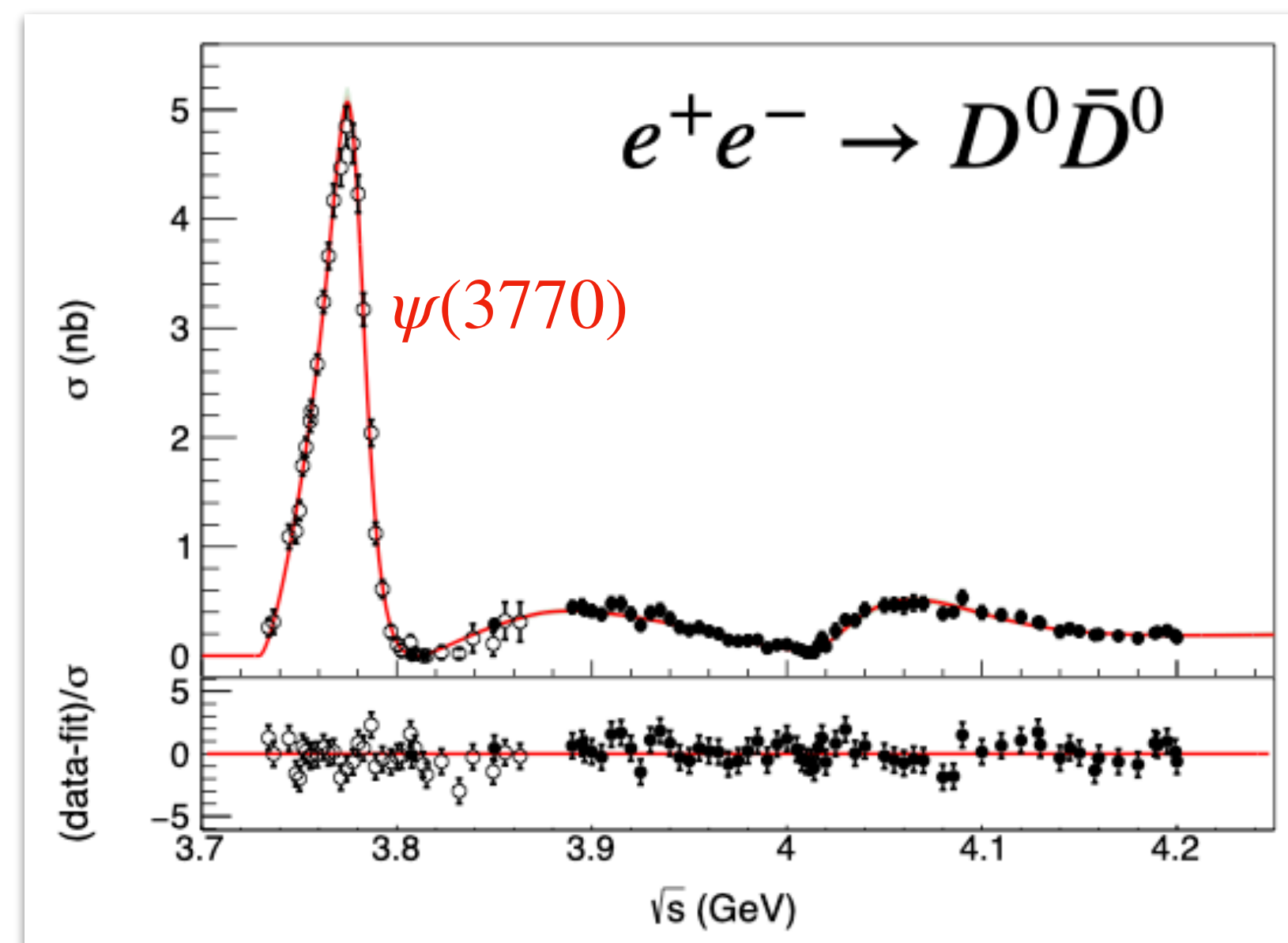


note: this is where e^+e^- machine excel

$D\bar{D}$



interpretation requires global coupled channel analyses



NH et al., PRD 109 (2024) 11, 114010

simultaneous fit of $e^+e^- \rightarrow D\bar{D}, D^*\bar{D}, D^*\bar{D}^*$

one of multiple examples, ongoing effort

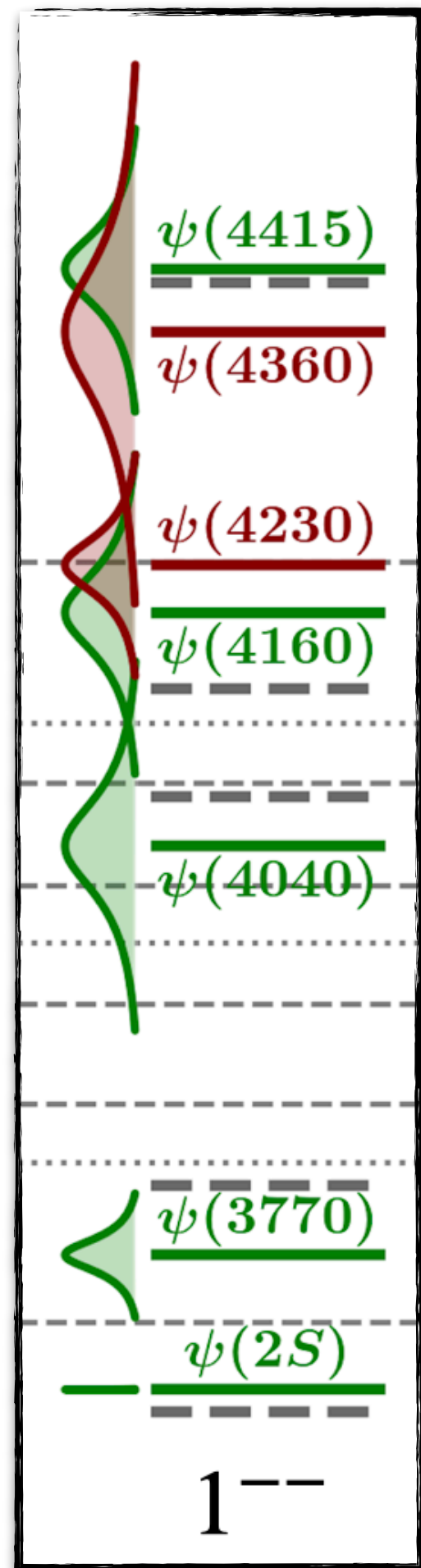
see also: Lin et al., PRL 133, 241903

Nakamura et al., arXiv:2312.17658 [hep-ph]

Cleven et al., PRD 90 (2014) 7, 074039

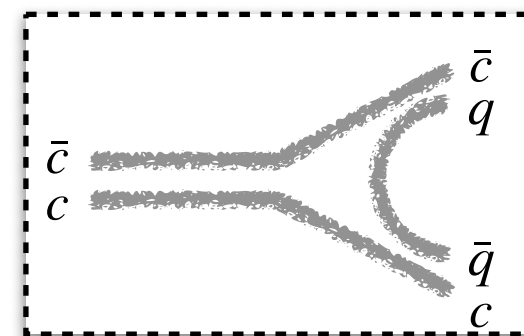
L. von Detten, PRD 109 (2024) 11, 116002

On $\psi(4230)$ and other vectors

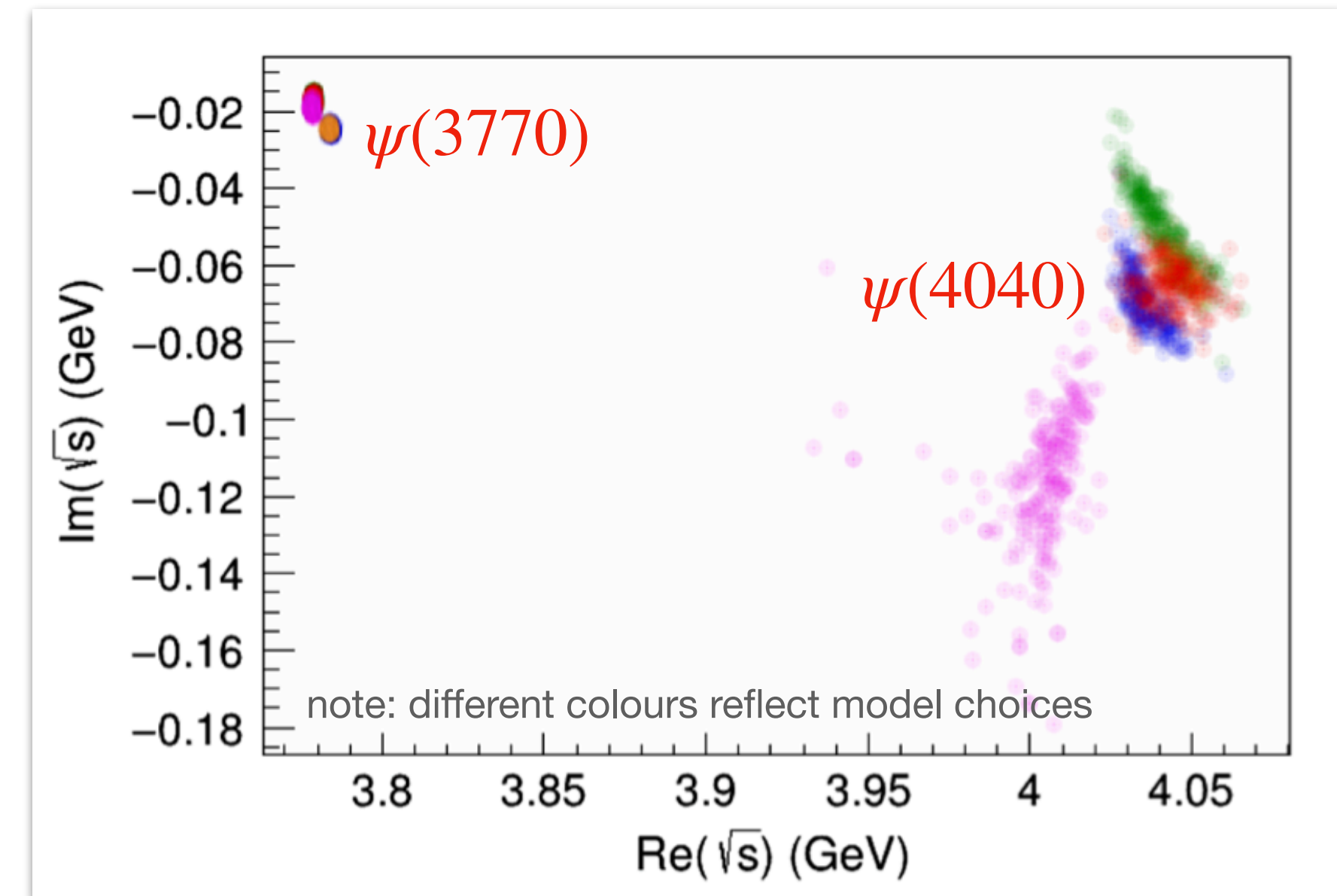
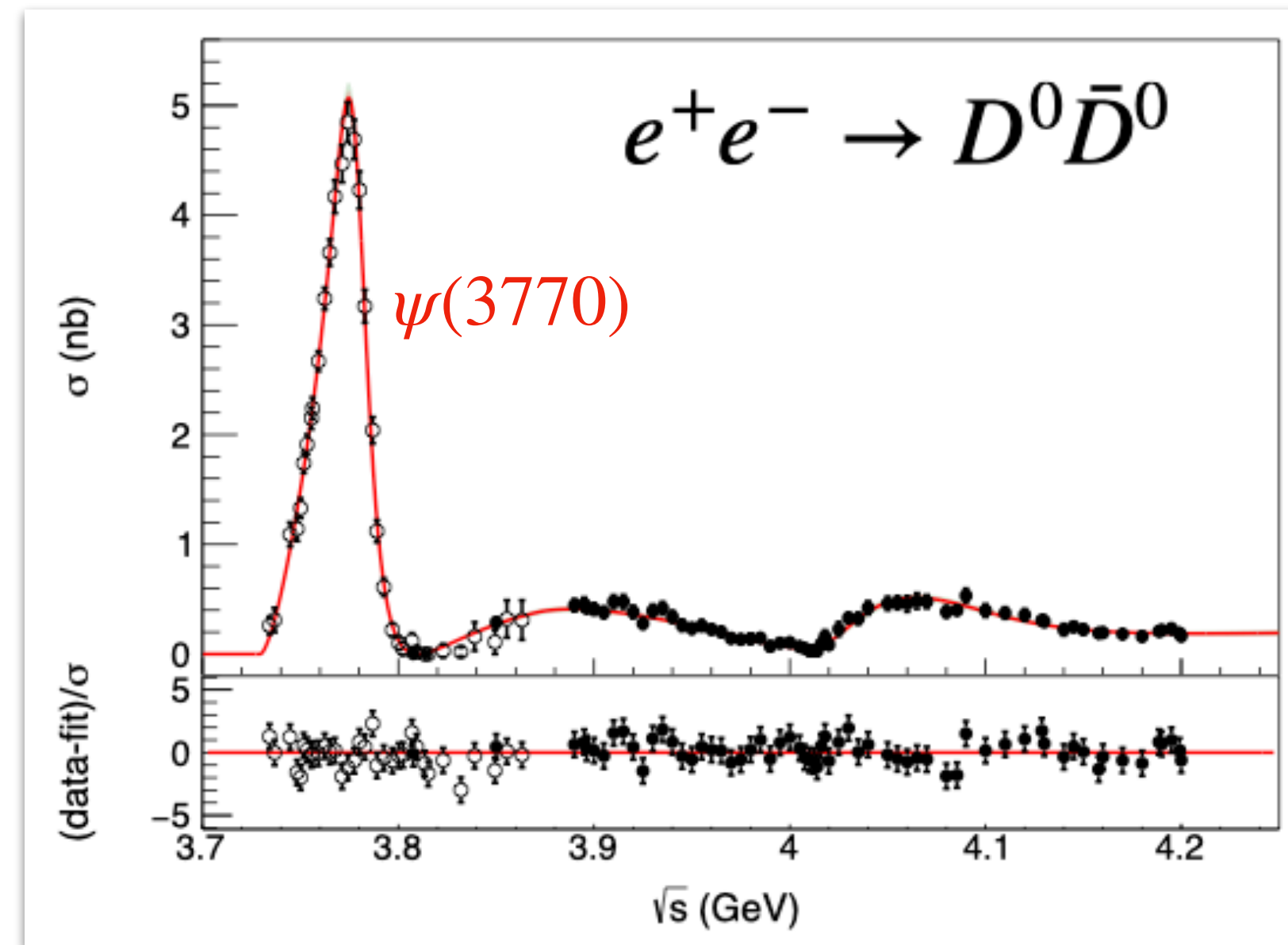


note: this is where e^+e^- machine excel

$D\bar{D}$



interpretation requires global coupled channel analyses



NH et al., PRD 109 (2024) 11, 114010

simultaneous fit of $e^+e^- \rightarrow D\bar{D}, D^*\bar{D}, D^*\bar{D}^*$

one of multiple examples, ongoing effort

see also: Lin et al., PRL 133, 241903

Nakamura et al., arXiv:2312.17658 [hep-ph]

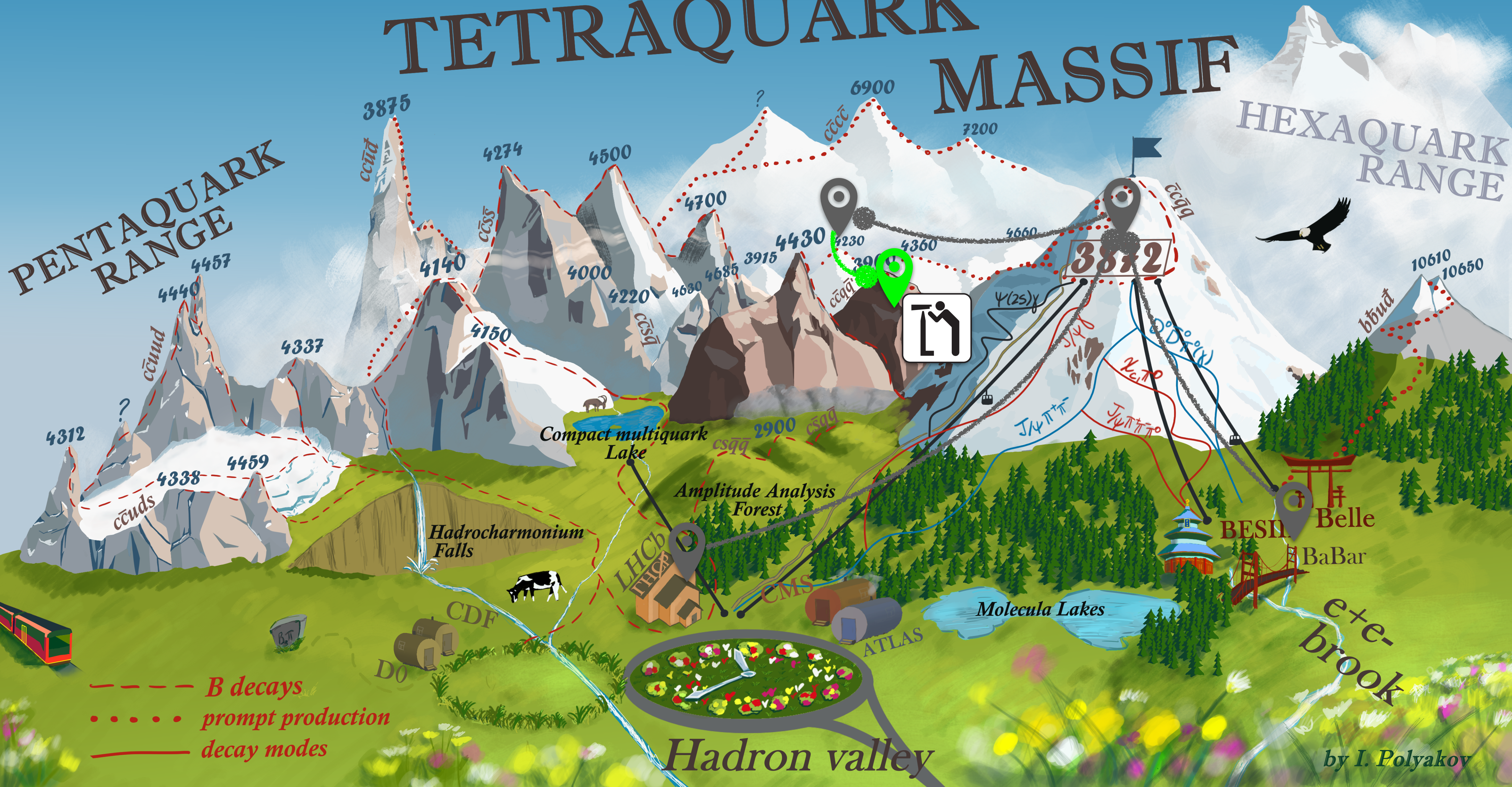
Cleven et al., PRD 90 (2014) 7, 074039

L. von Detten, PRD 109 (2024) 11, 116002

TETRAQUARK MASSIF

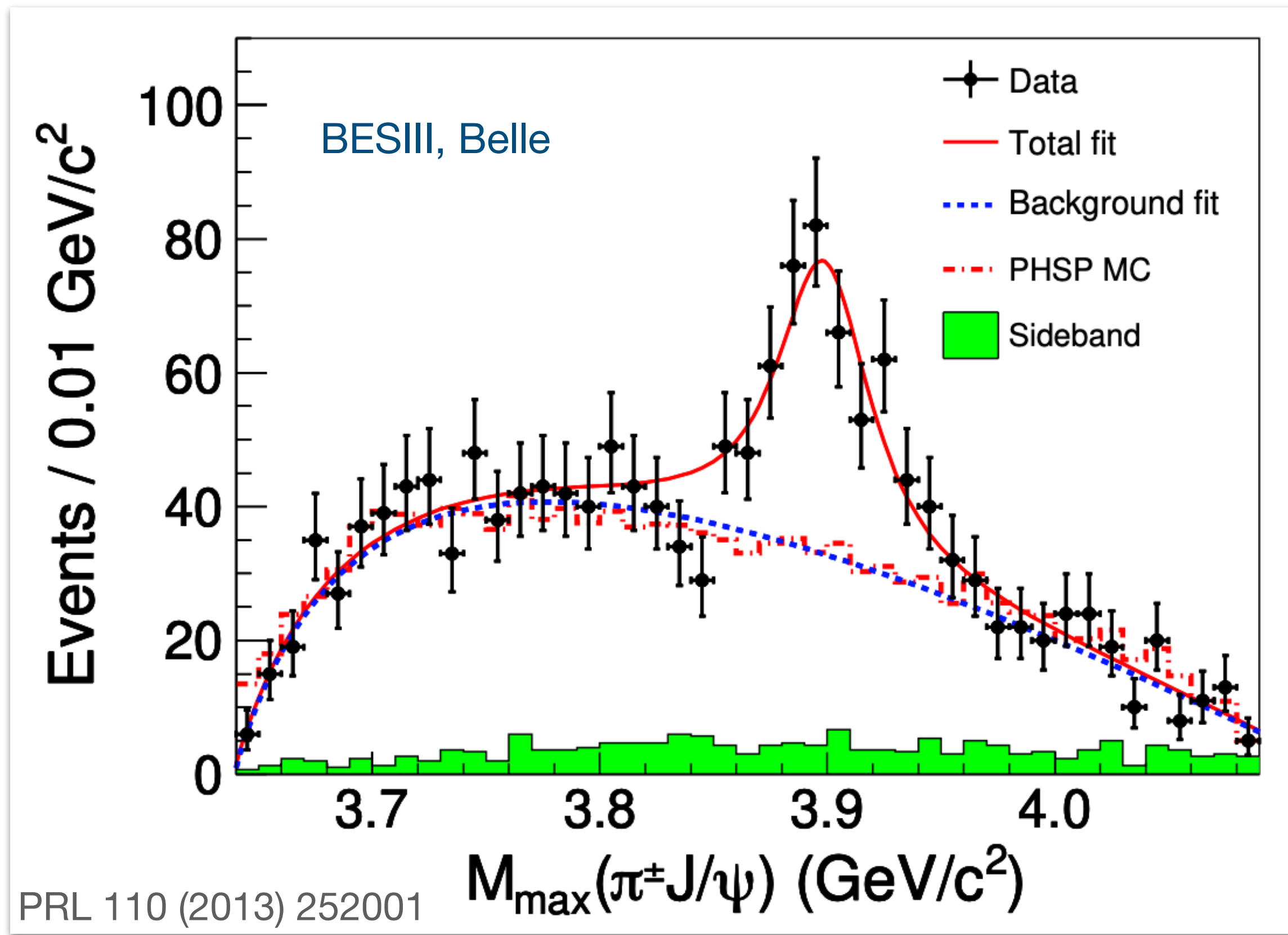
PENTAQUARK RANGE

HEXAQUARK RANGE

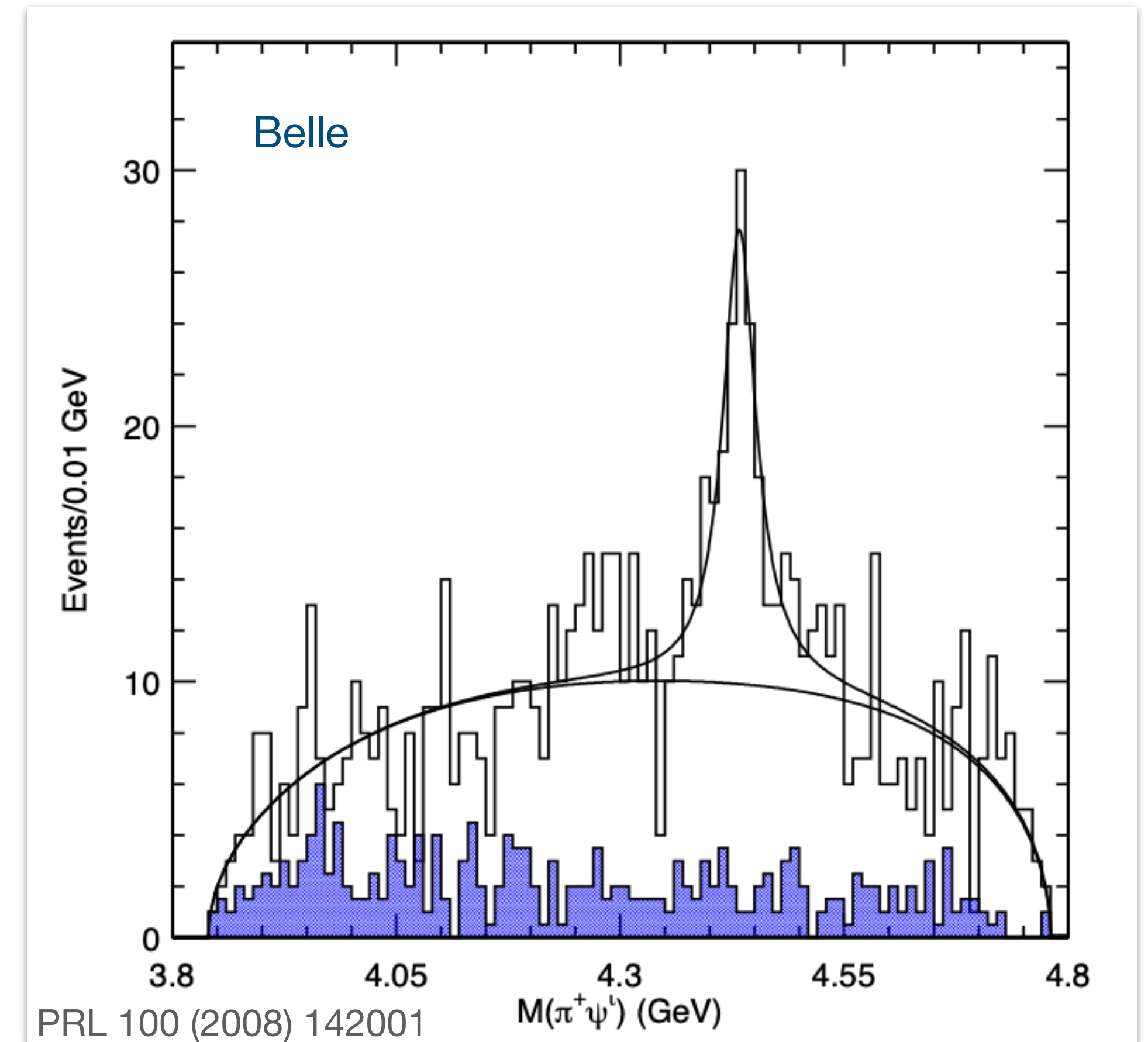


Charged charmonium-like states

$$e^+e^- \rightarrow \pi^\mp Z_c^\pm(3900), \quad Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$$

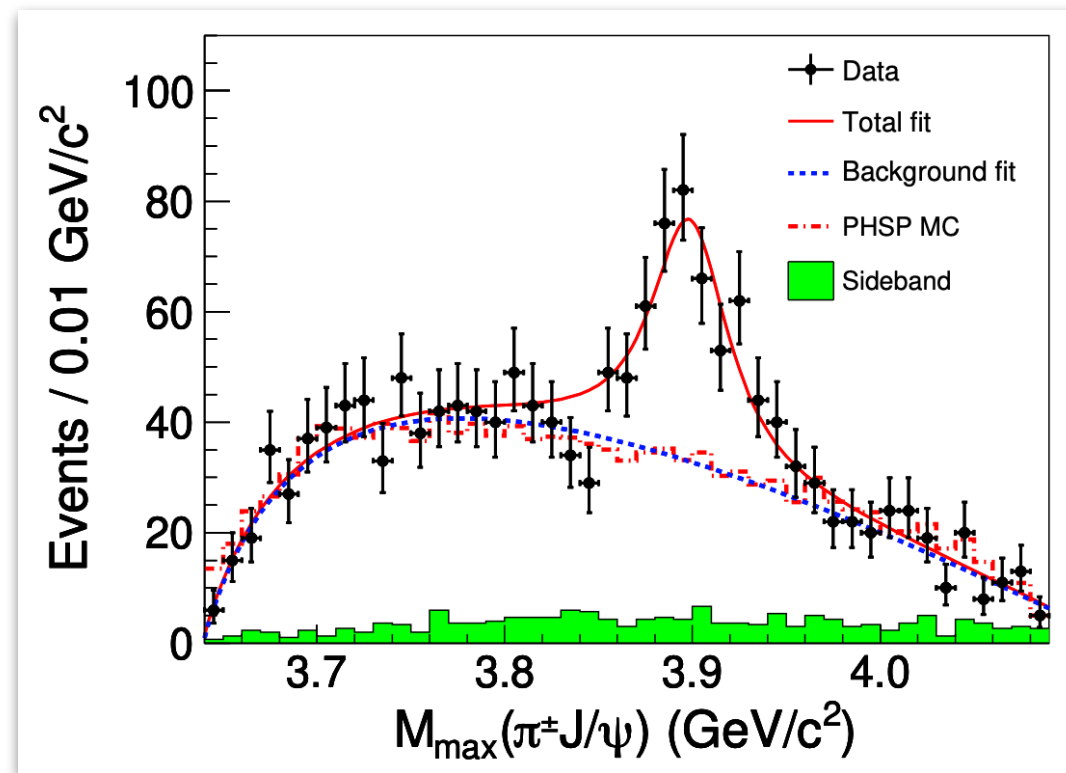


$$B \rightarrow K Z_c^\pm(4430), \quad Z_c^\pm(4430) \rightarrow \psi' \pi^\pm$$

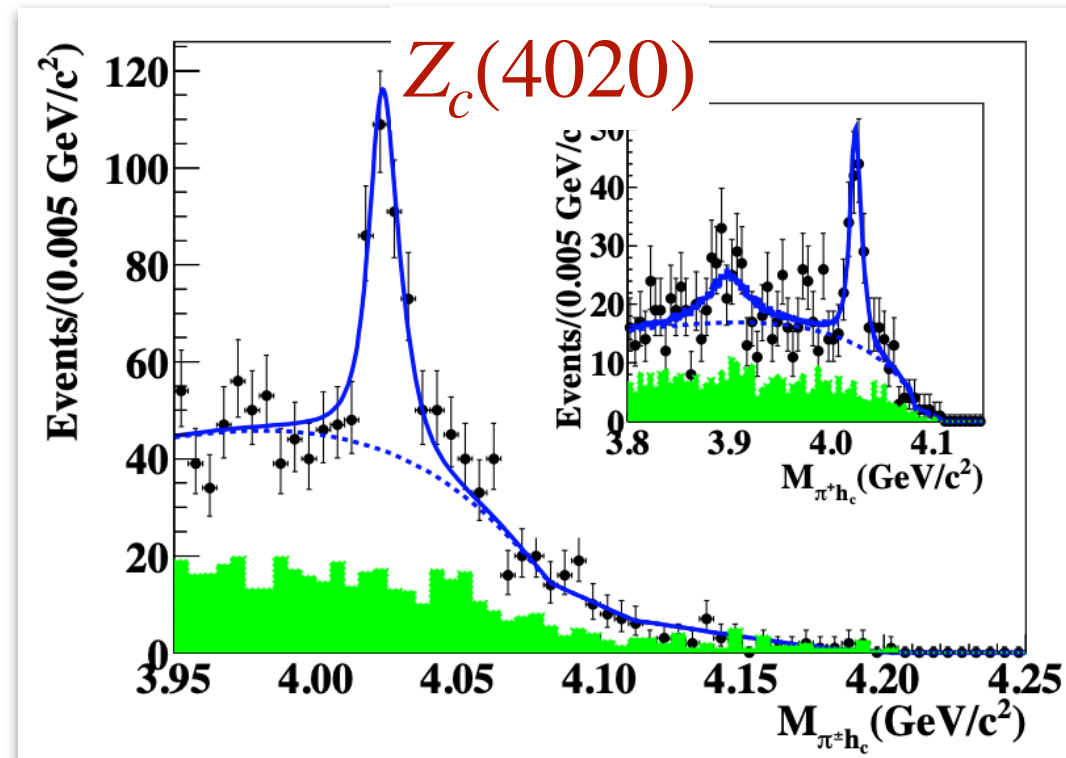


Charged charmonium-like states

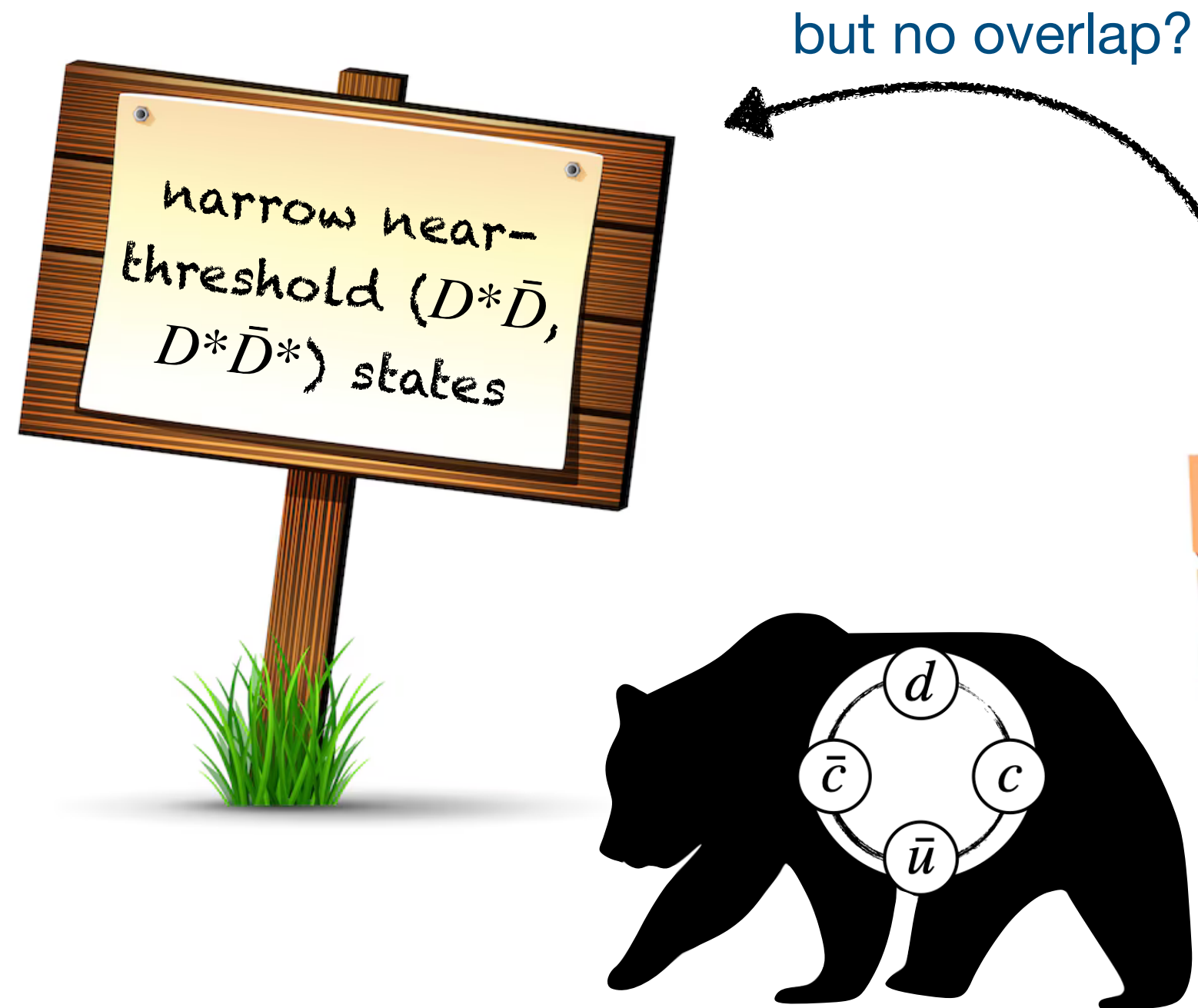
$$e^+e^- \rightarrow \pi^\mp Z_c^\pm(3900), \quad Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$$



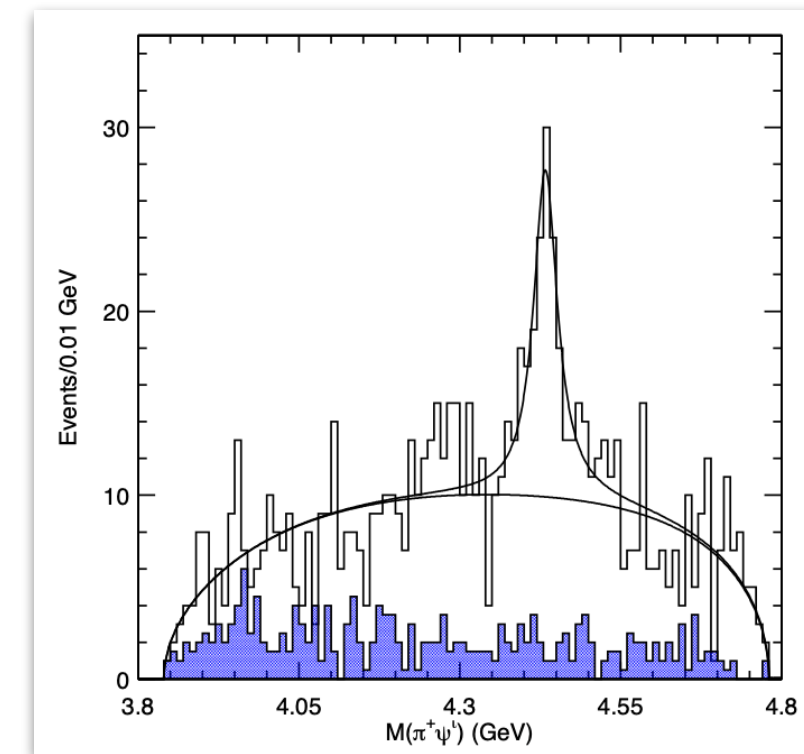
PRL 110 (2013) 252001



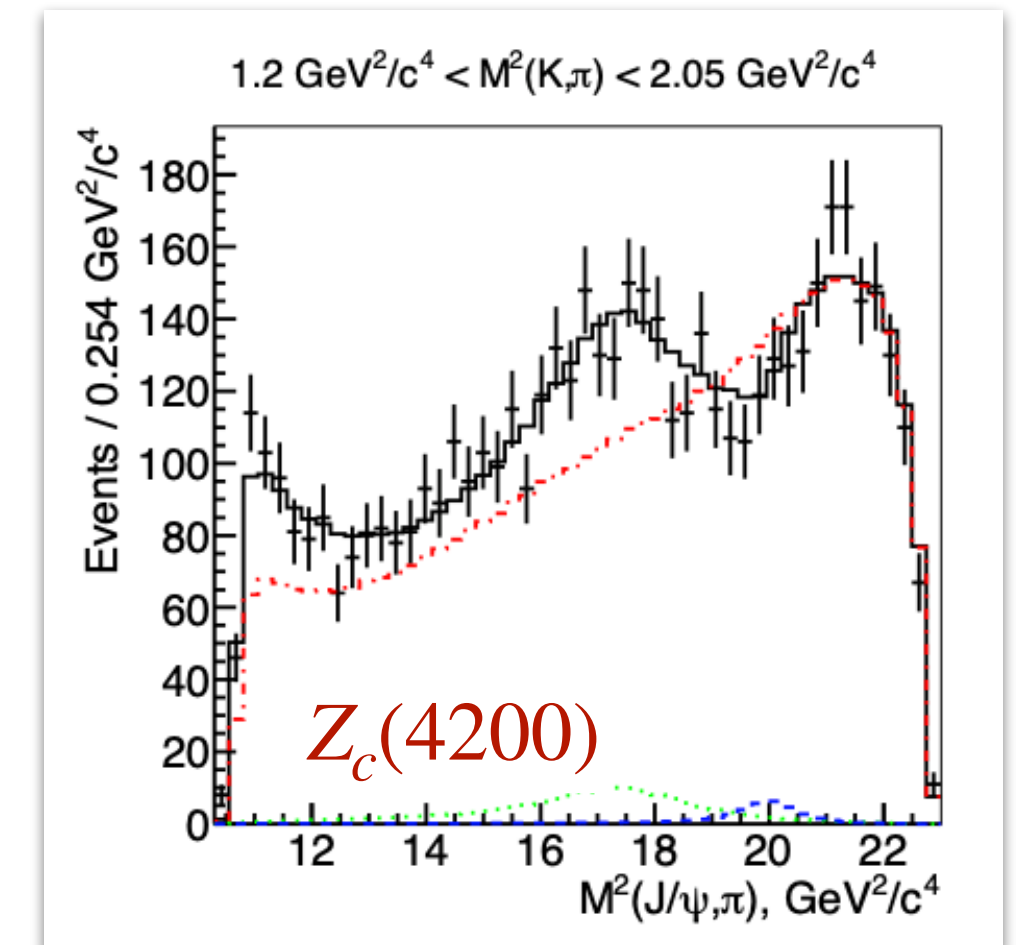
PRL 111 (2013) 24, 242001



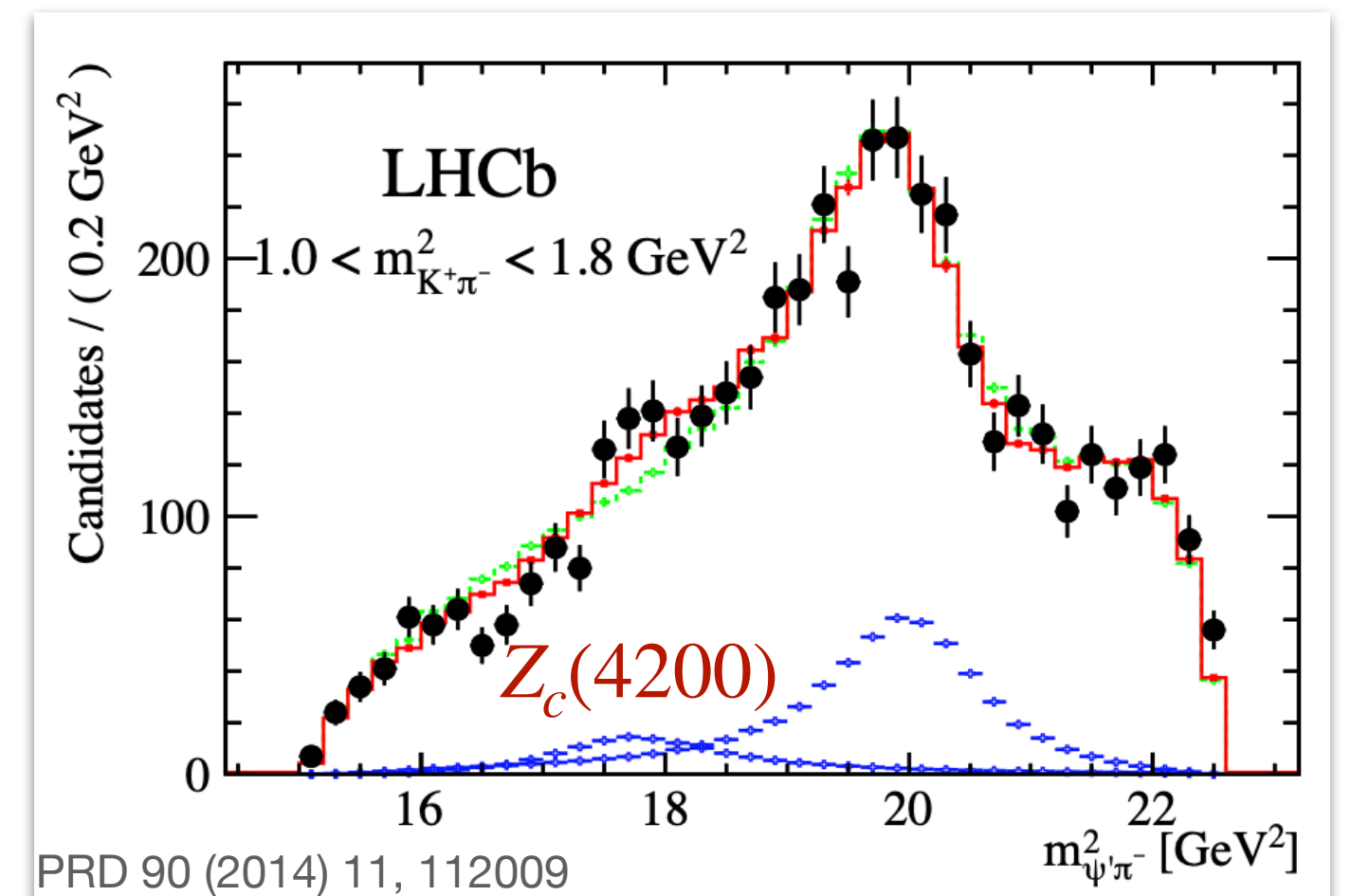
$$B \rightarrow K Z_c^\pm(4430), \quad Z_c^\pm(4430) \rightarrow \psi' \pi^\pm$$



PRL 100 (2008) 142001



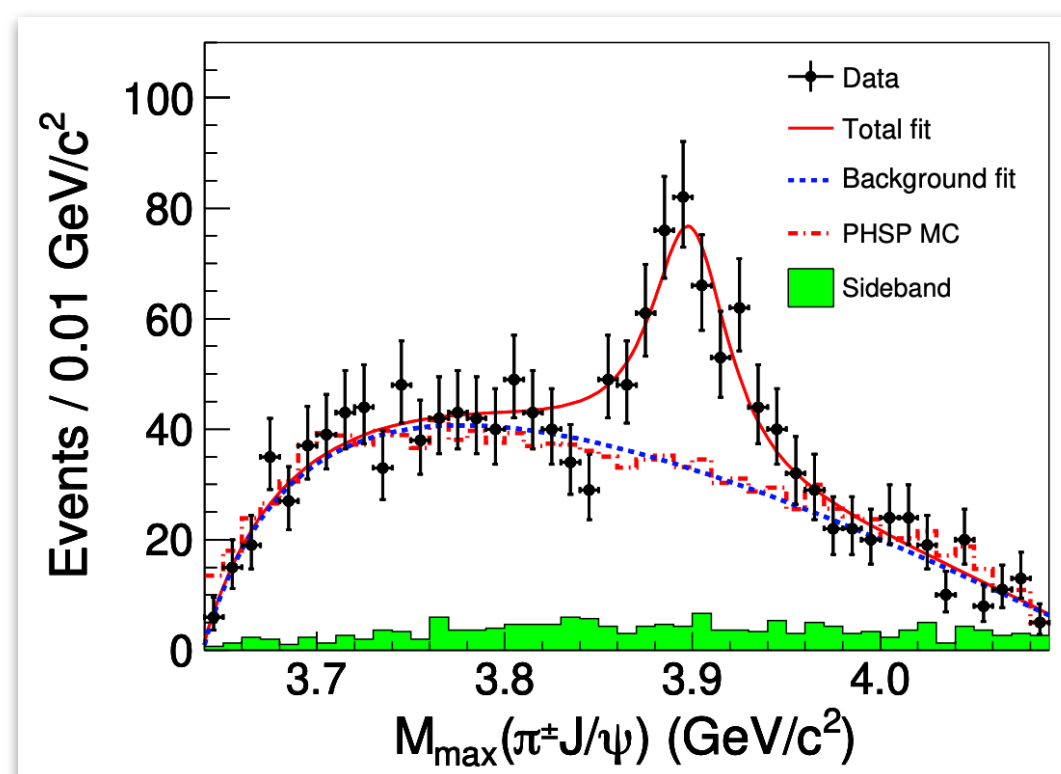
PRD 90 (2014) 11, 112009



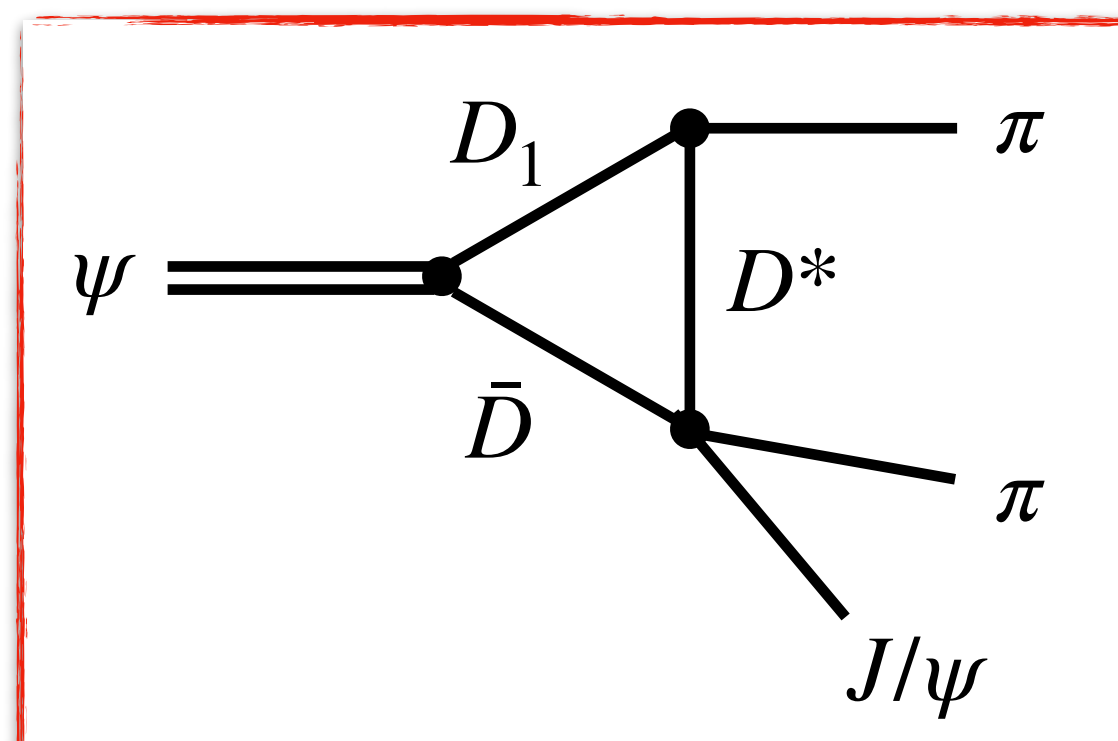
PRD 90 (2014) 11, 112009

Charged charmonium-like states

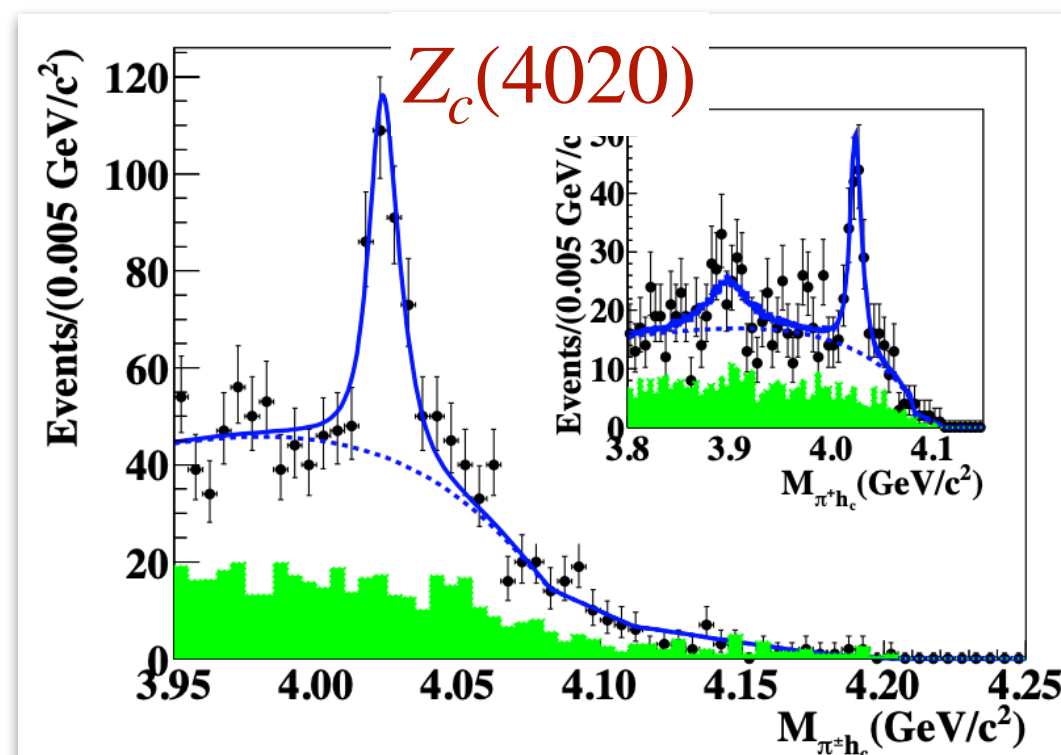
$$e^+e^- \rightarrow \pi^\mp Z_c^\pm(3900), \quad Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$$



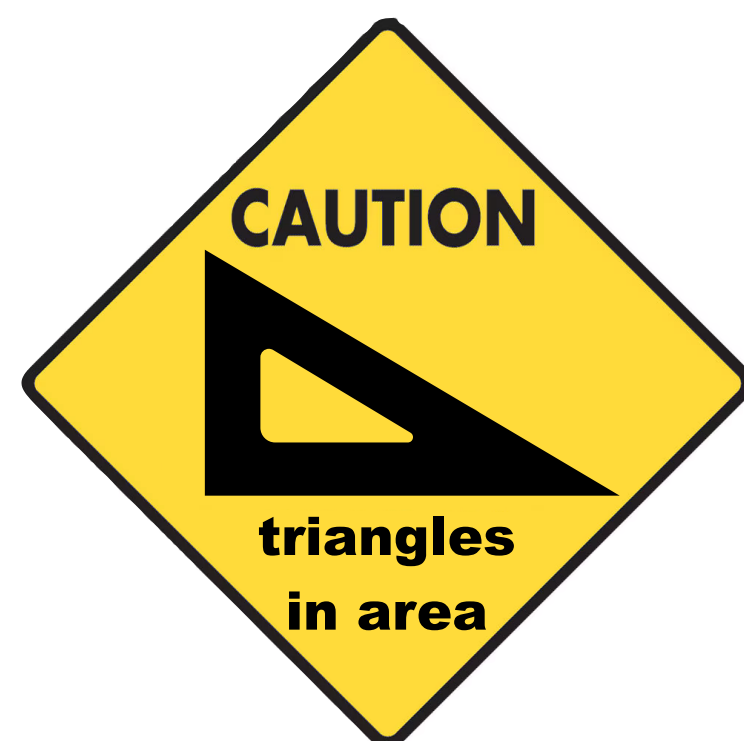
PRL 110 (2013) 252001



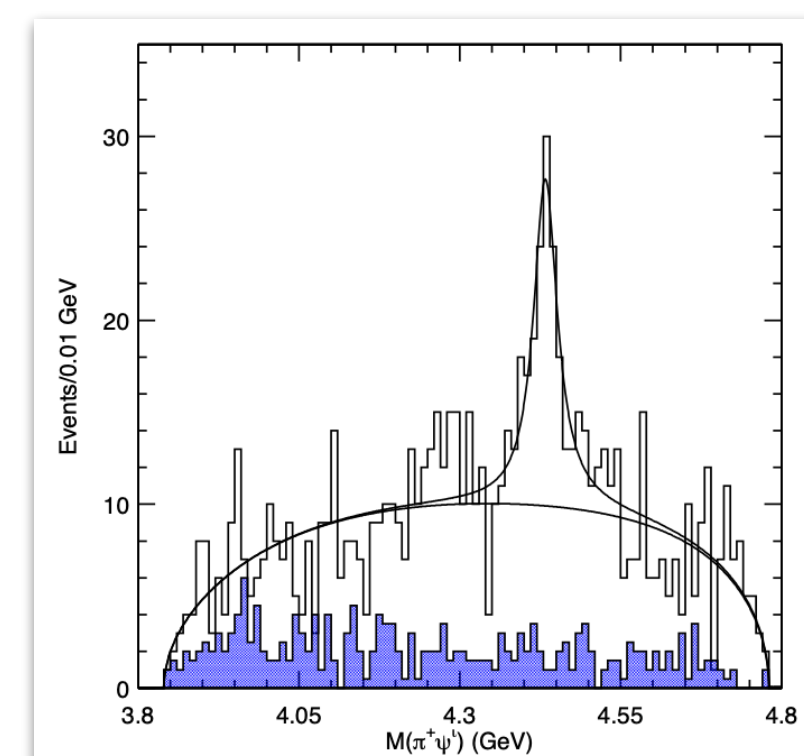
PRL 111 (2013) 13 132003
 PLB 747 (2015) 410
 PLB 755 (2016) 337
 PLB 772 (2017) 200
 EPJ C 80 (2020) 12 1179
 PRD 109 (2024) 11, 116002



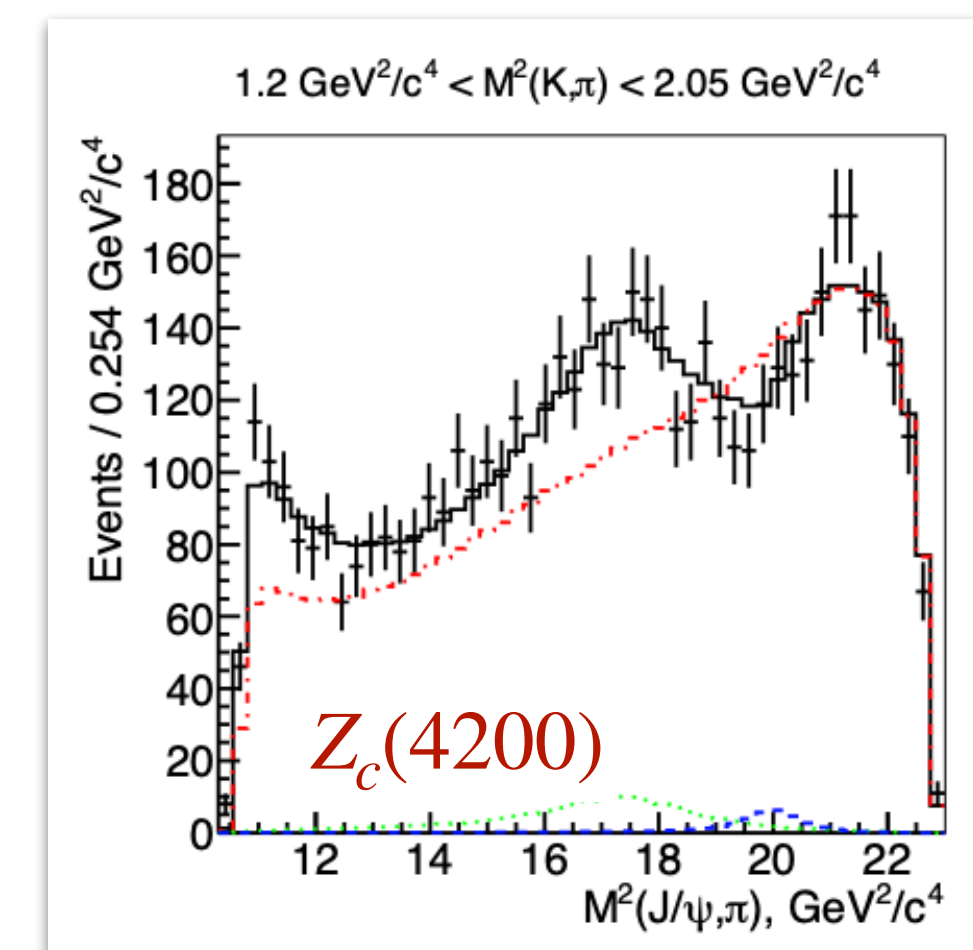
PRL 111 (2013) 24, 242001



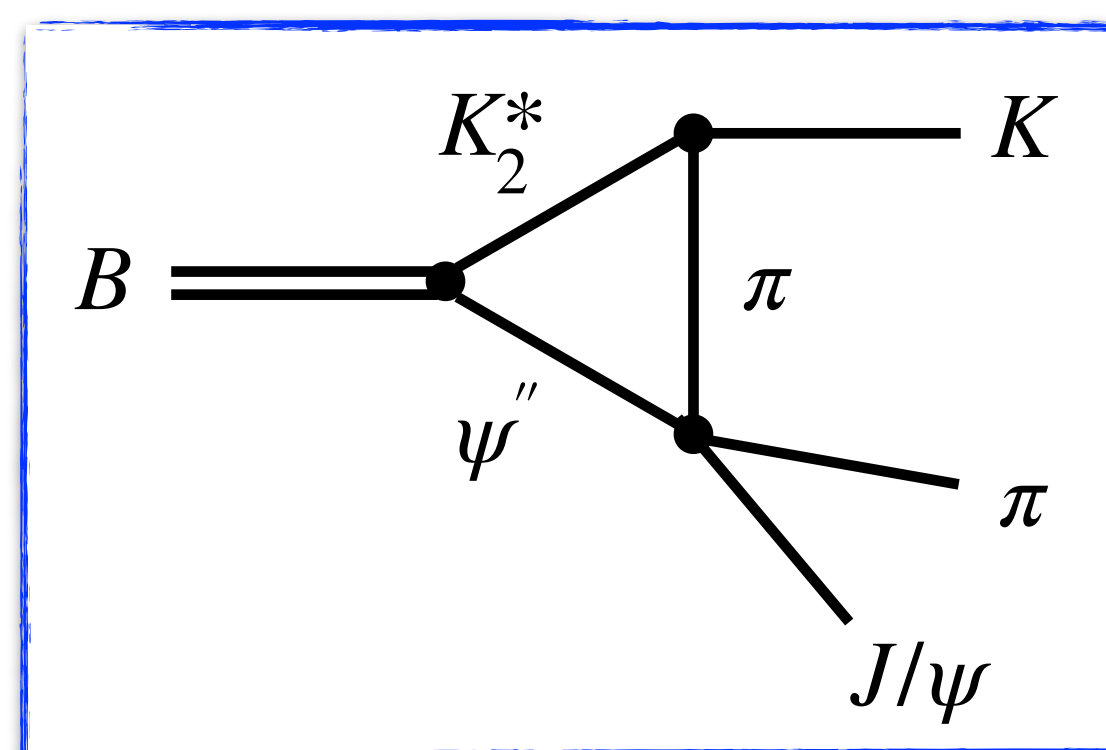
$$B \rightarrow K Z_c^\pm(4430), \quad Z_c^\pm(4430) \rightarrow \psi' \pi^\pm$$



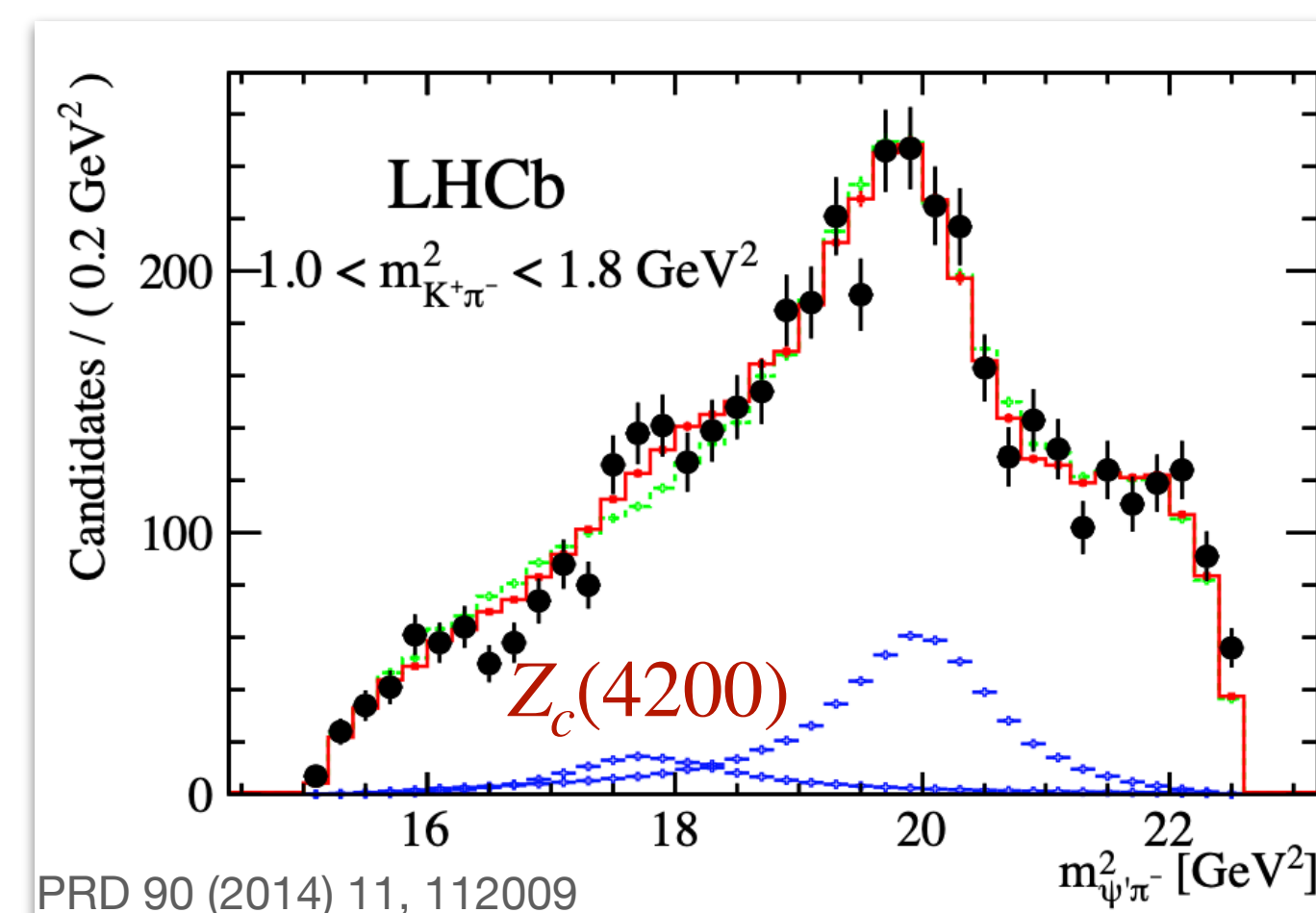
PRL 100 (2008) 142001



PRD 90 (2014) 11, 112009



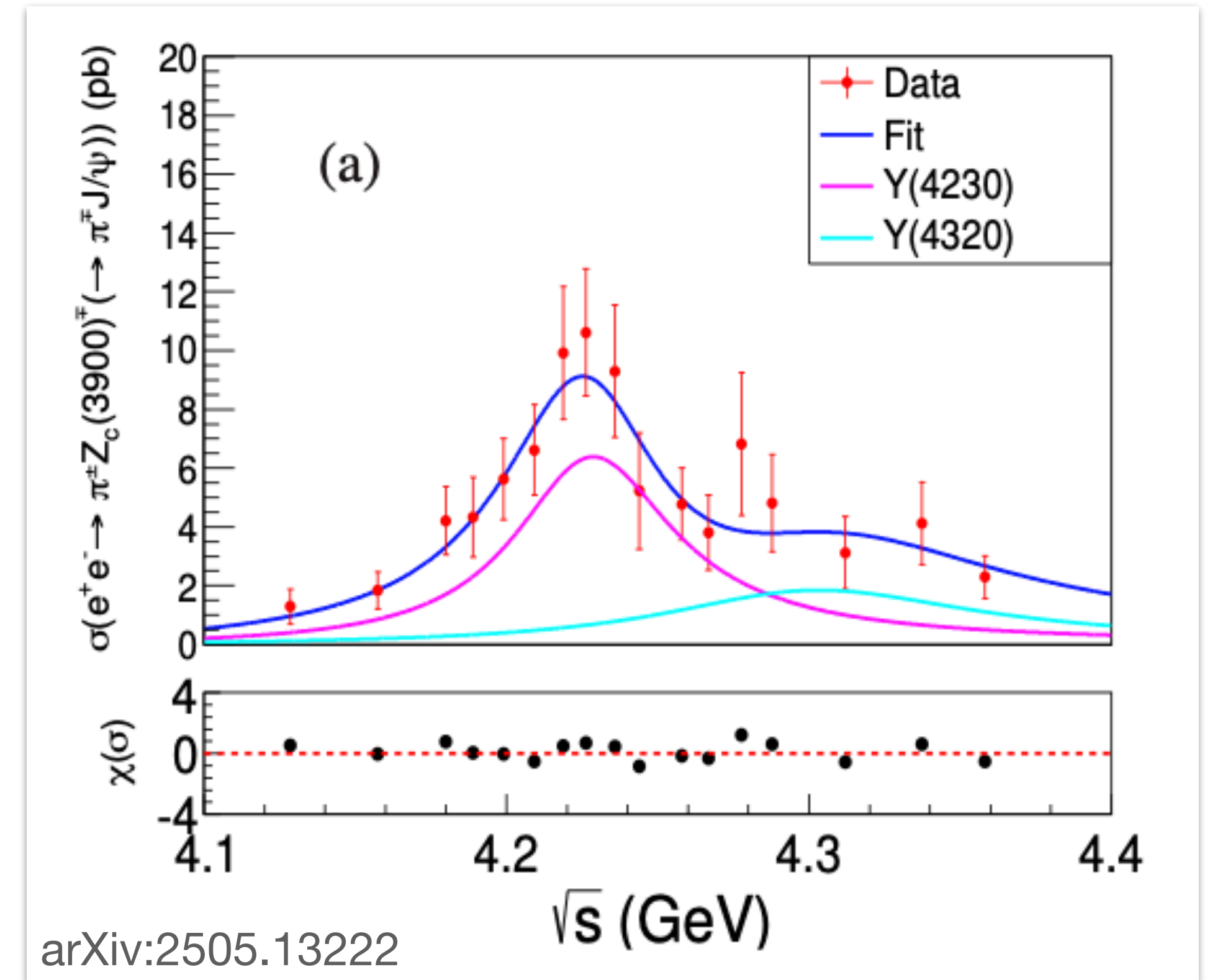
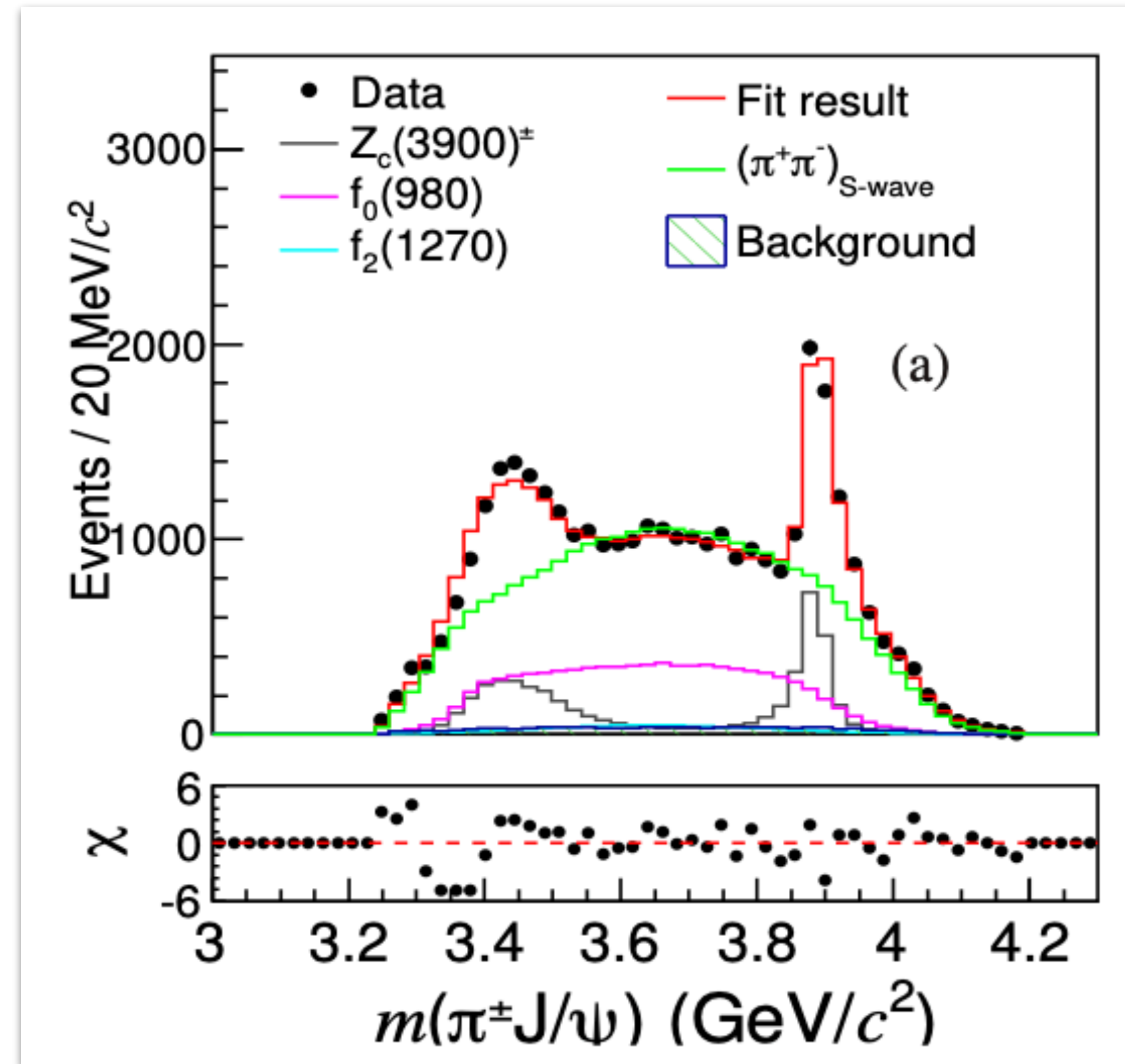
PRD 100 (2019) 1, 011504



PRD 90 (2014) 11, 112009

Detailed study on production in e^+e^-

$$e^+e^- \rightarrow \pi^\mp Z_c^\pm(3900), \quad Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$$

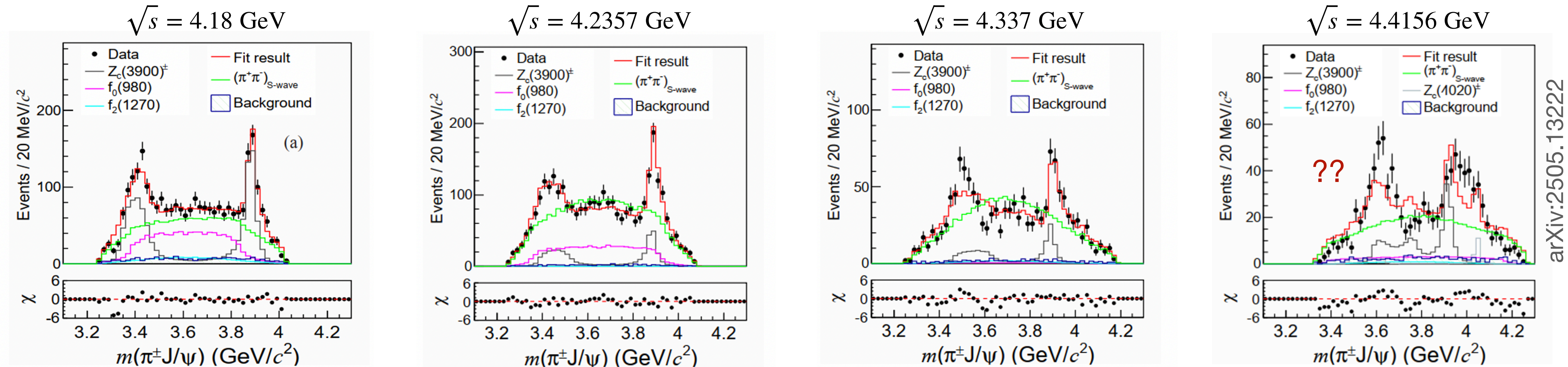


latest work uses all data between 4.1 and 4.4 GeV

$Z_c(3900)$ production near the $\psi(4230)$

Detailed study on production in e^+e^-

$$e^+e^- \rightarrow \pi^\mp Z_c^\pm(3900), \quad Z_c^\pm(3900) \rightarrow J/\psi \pi^\pm$$



acceptance corrected data is made available at 17 different center-of-mass energies

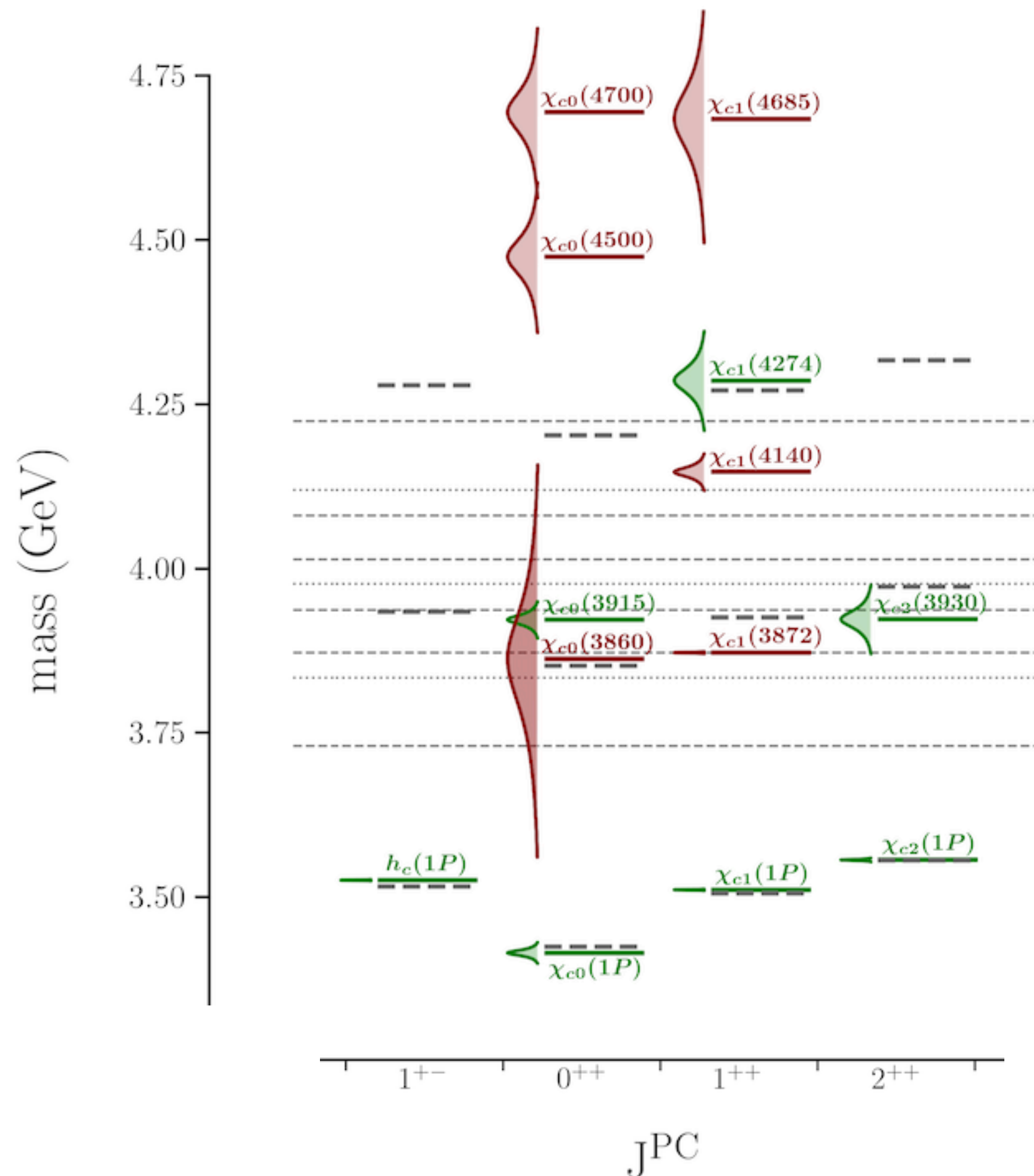
enabling detailed studies of the $Z_c(3900)$ lineshape



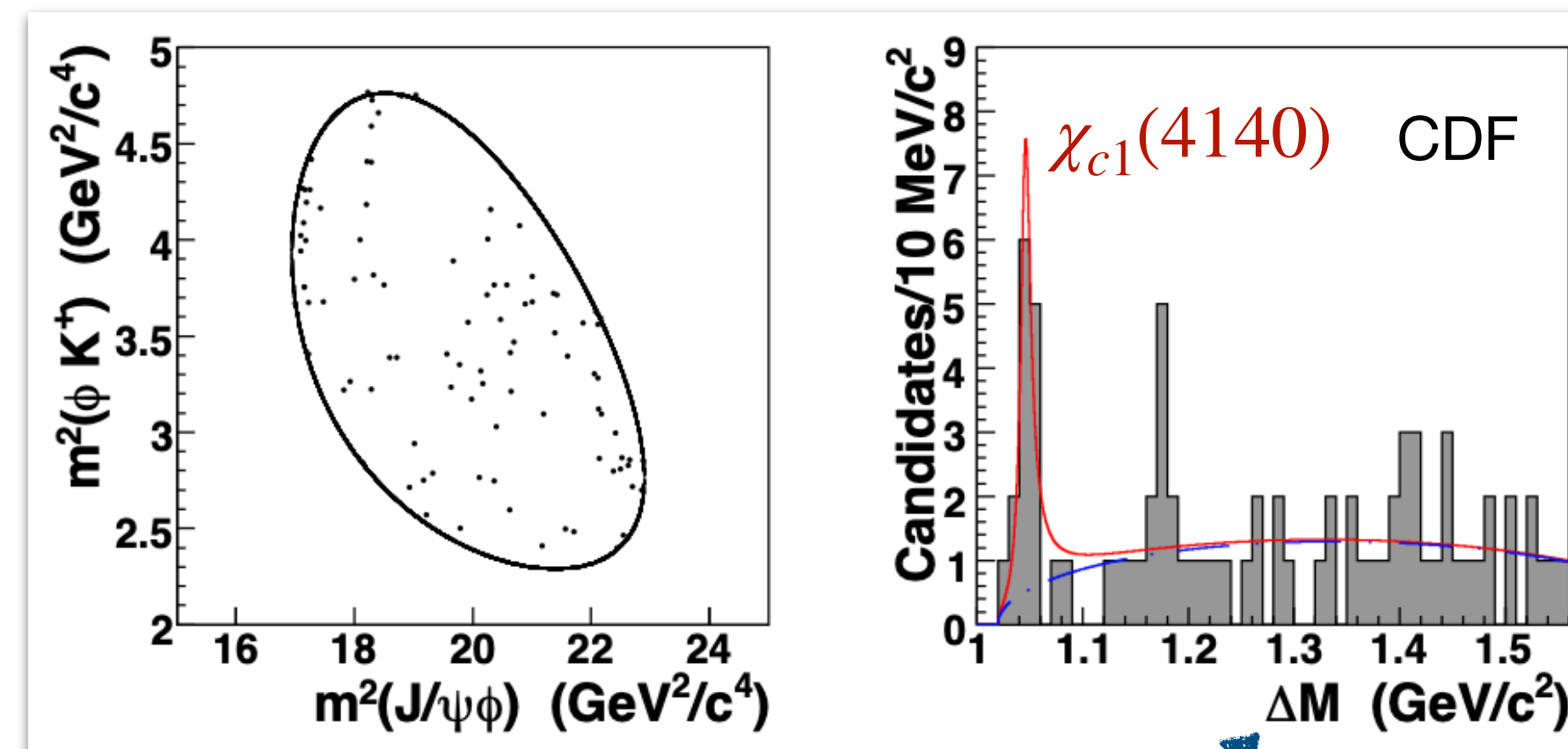
Excited χ_{cJ} states - or not?

interesting open questions for positive-parity charmonium(-like) states:

- which are the radial excitations of the χ_{cJ} ? how does the $X(3872)$ fit in?
- where is the $h_c(2P)$?
- what are the $\chi_{c1}(4140)$ and $\chi_{c1}(4274)$?



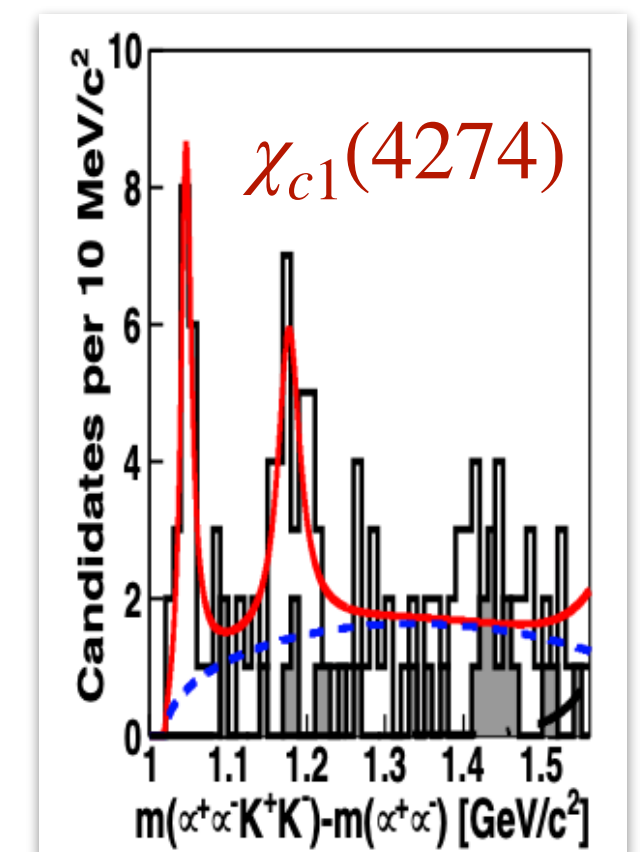
$B \rightarrow J/\psi \phi K$



PRL 102 (2009) 242002

$m(J/\psi \phi) - m(J/\psi)$

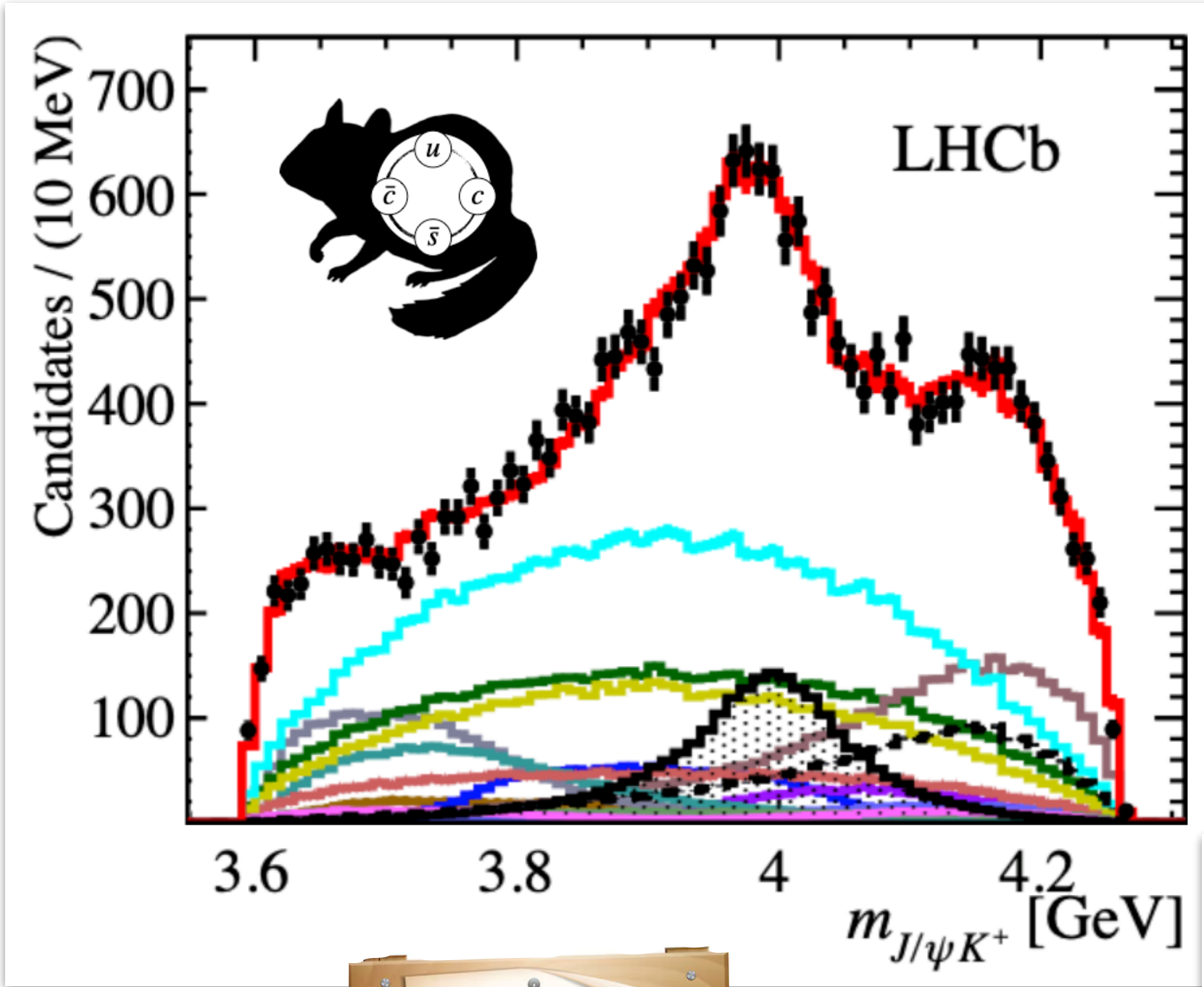
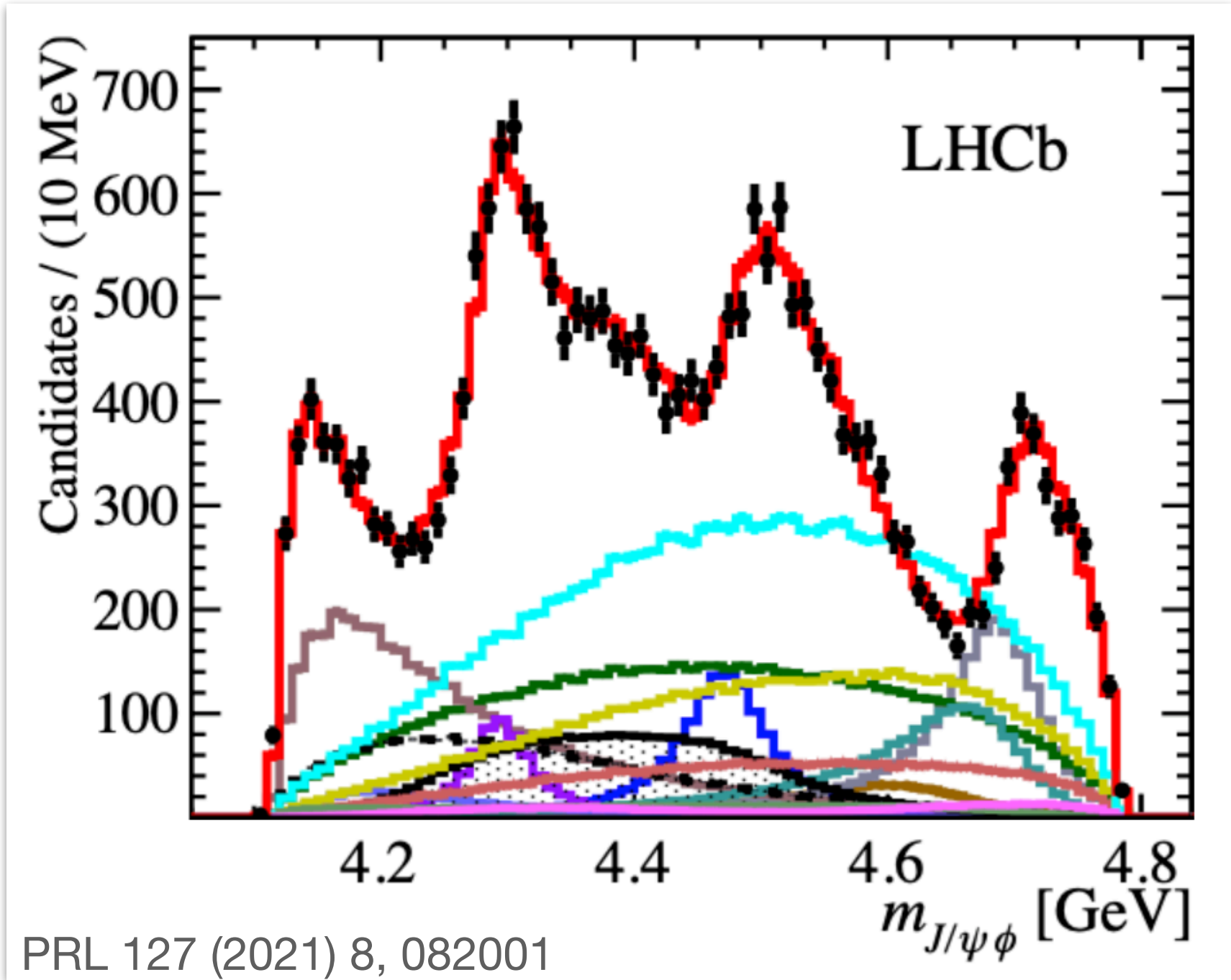
unpublished update



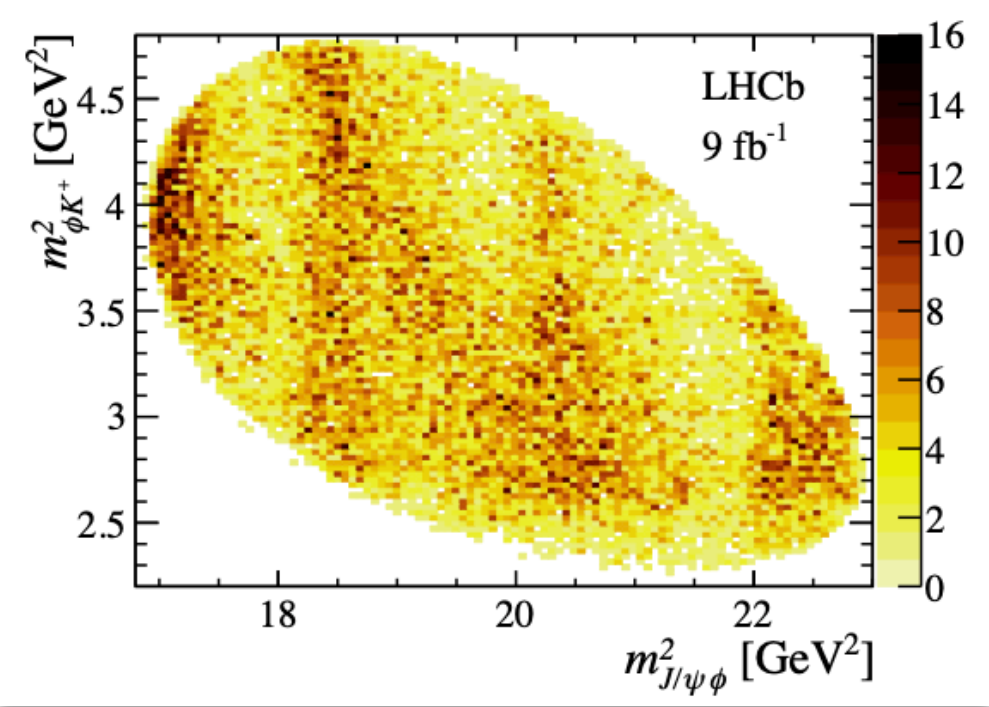
arXiv:1101.6058

Excited χ_{cJ} states - or not?

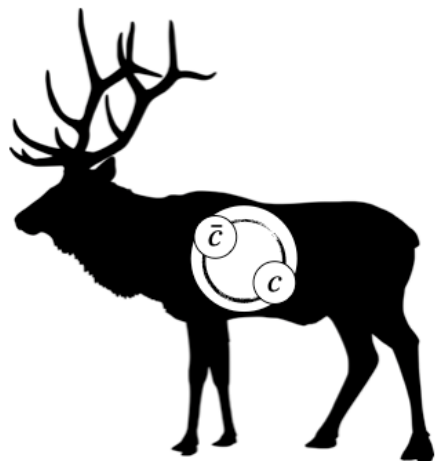
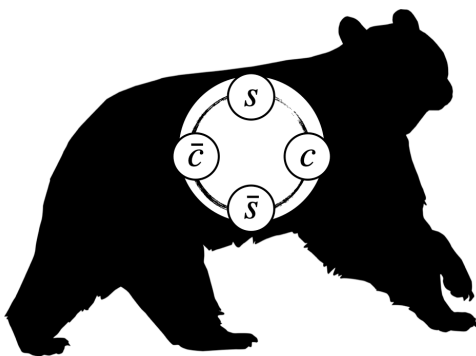
latest LHCb work on $B \rightarrow J/\psi \phi K$



- $X(4630)$
- $X(4500)$
- $X(4700)$
- X_{NR}
- $X(4140)$
- $X(4274)$
- $X(4685)$
- $X(4150)$
- ⋯ $Z_{cs}(4000)$
- - $Z_{cs}(4220)$
- + $K 0^-$
- + $K 1^+$
- + $K 1^-$
- + $K 2^+$
- + $K 2^-$
- - Background
- + Total fit
- + Data 9 fb⁻¹



7 states in
 $X \rightarrow J/\psi \phi$

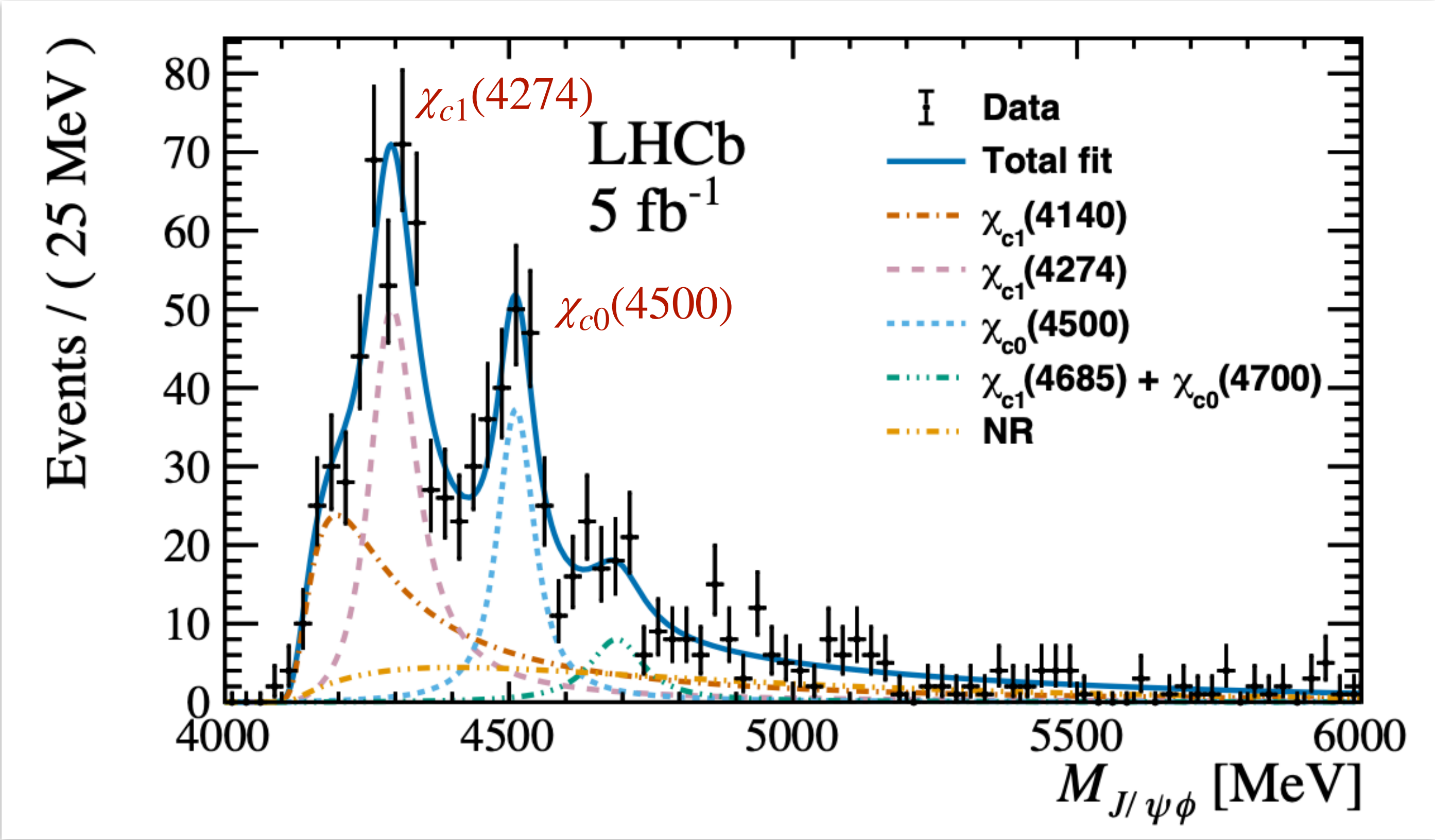


2 Z_{cs}
states

... and 9 more states in ϕK

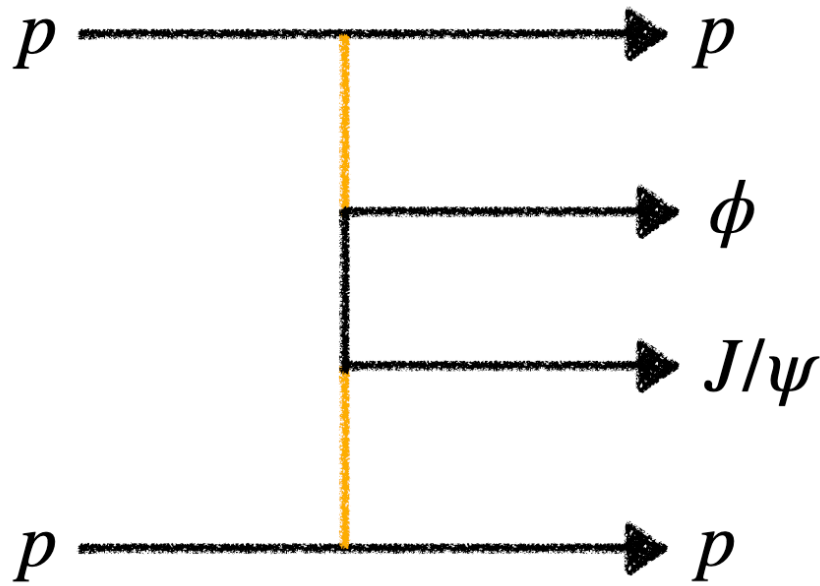
Excited χ_{cJ} states - or not?

$pp \rightarrow ppJ/\psi\phi$



PRL 134 (2025) 3, 031902

- new production process: central exclusive production



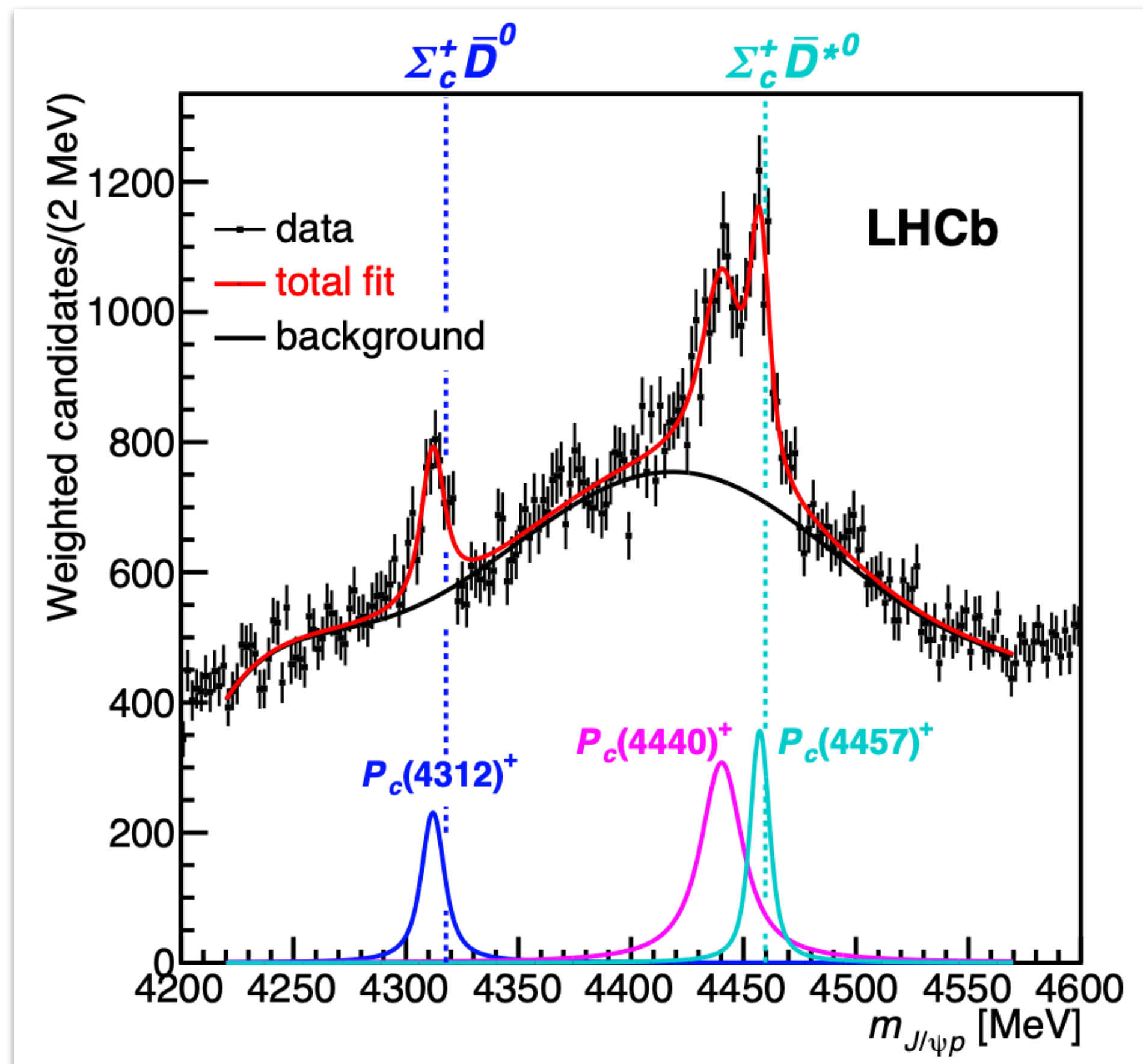
these are events with exclusively $\mu^+\mu^-K^+K^-$ in the vertex detector

- ideally provides additional handle to interpret nature of states observed in $J/\psi\phi$



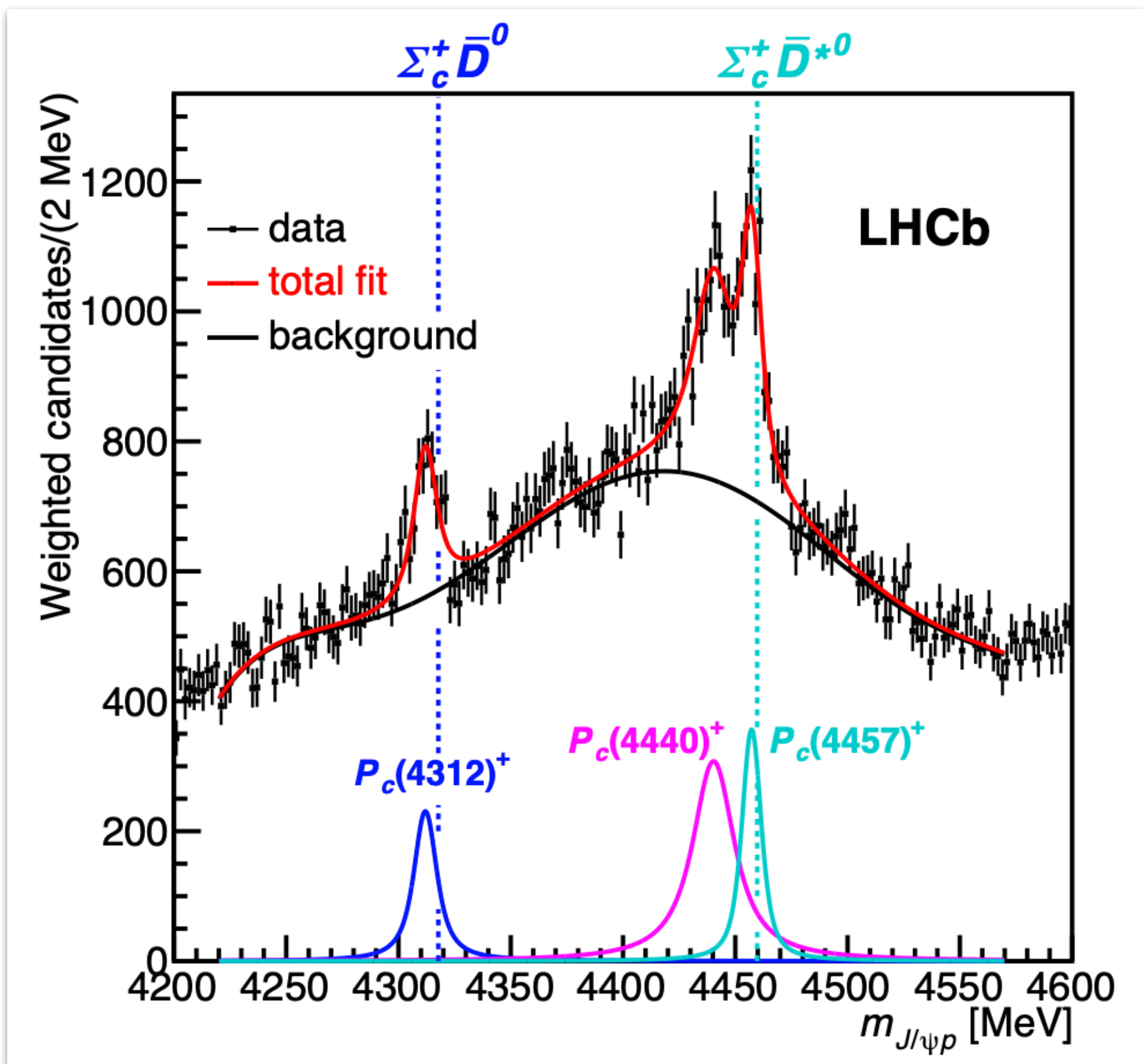
Pentaquark states

$$\Lambda_b \rightarrow J/\psi p K$$



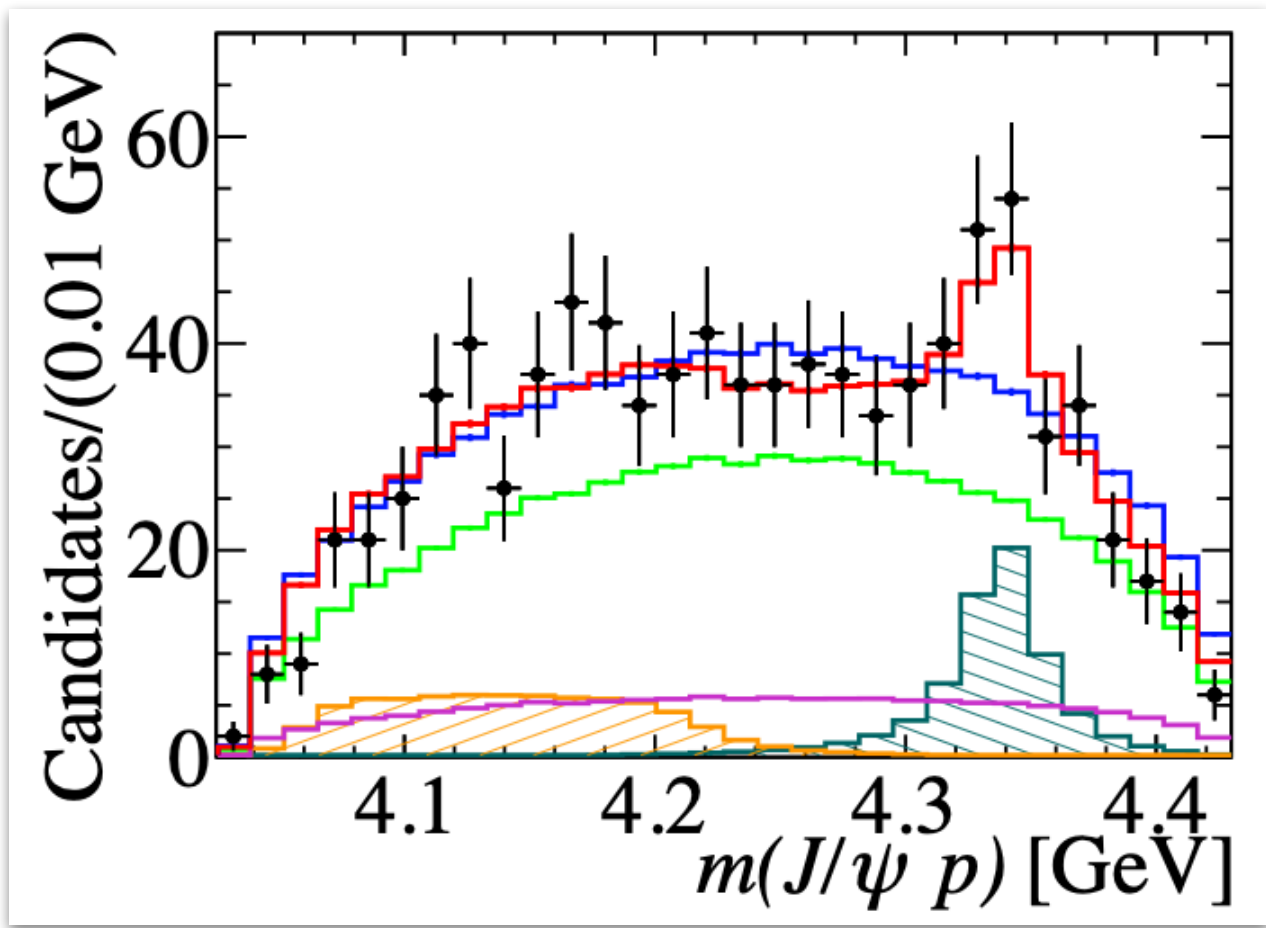
Pentaquark states

$$\Lambda_b \rightarrow J/\psi p K$$



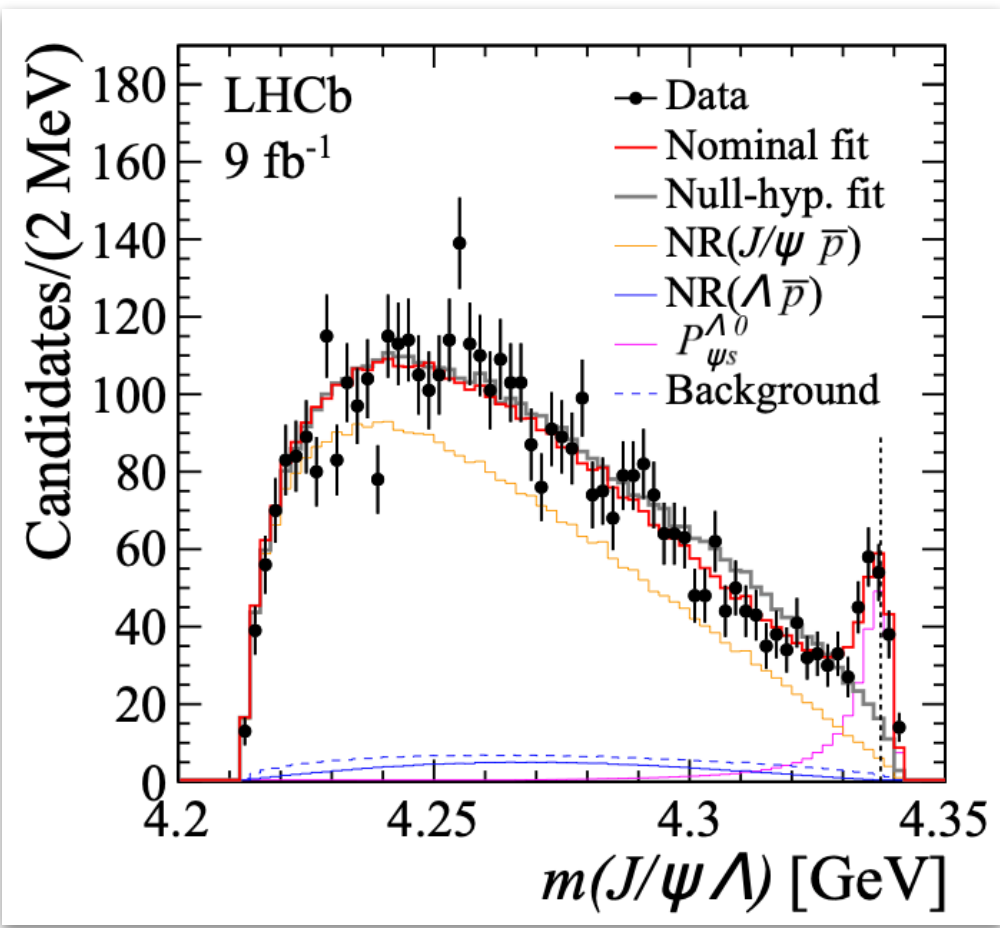
PRL 122 (2019) 22, 222001

$$B_s^0 \rightarrow J/\psi p \bar{p}$$



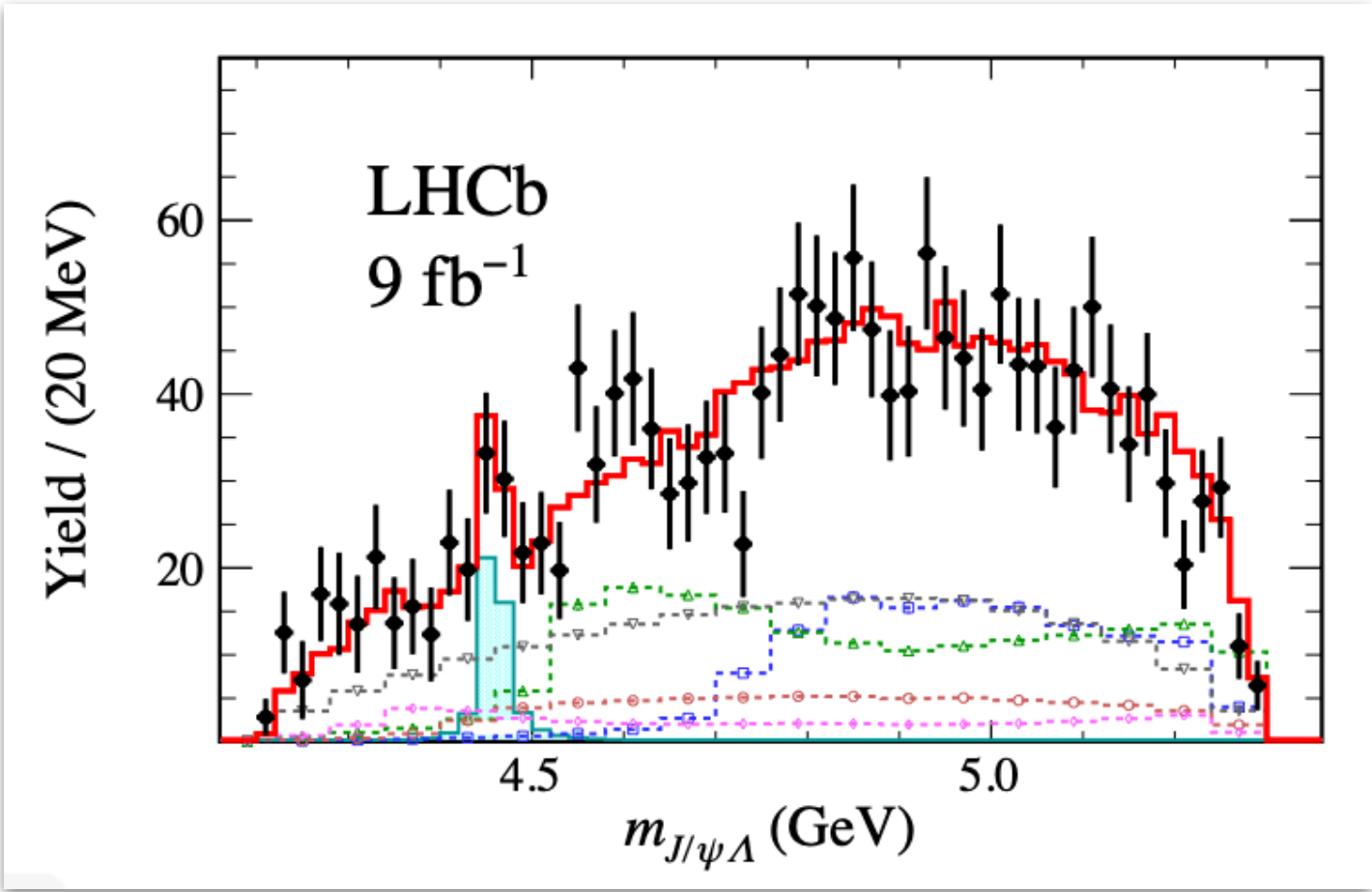
PRL 128 (2022) 6, 062001

$$B^- \rightarrow J/\psi \Lambda \bar{p}$$



PRL 131 (2023) 3, 031901

$$\Xi_b^- \rightarrow J/\psi \Lambda K^-$$

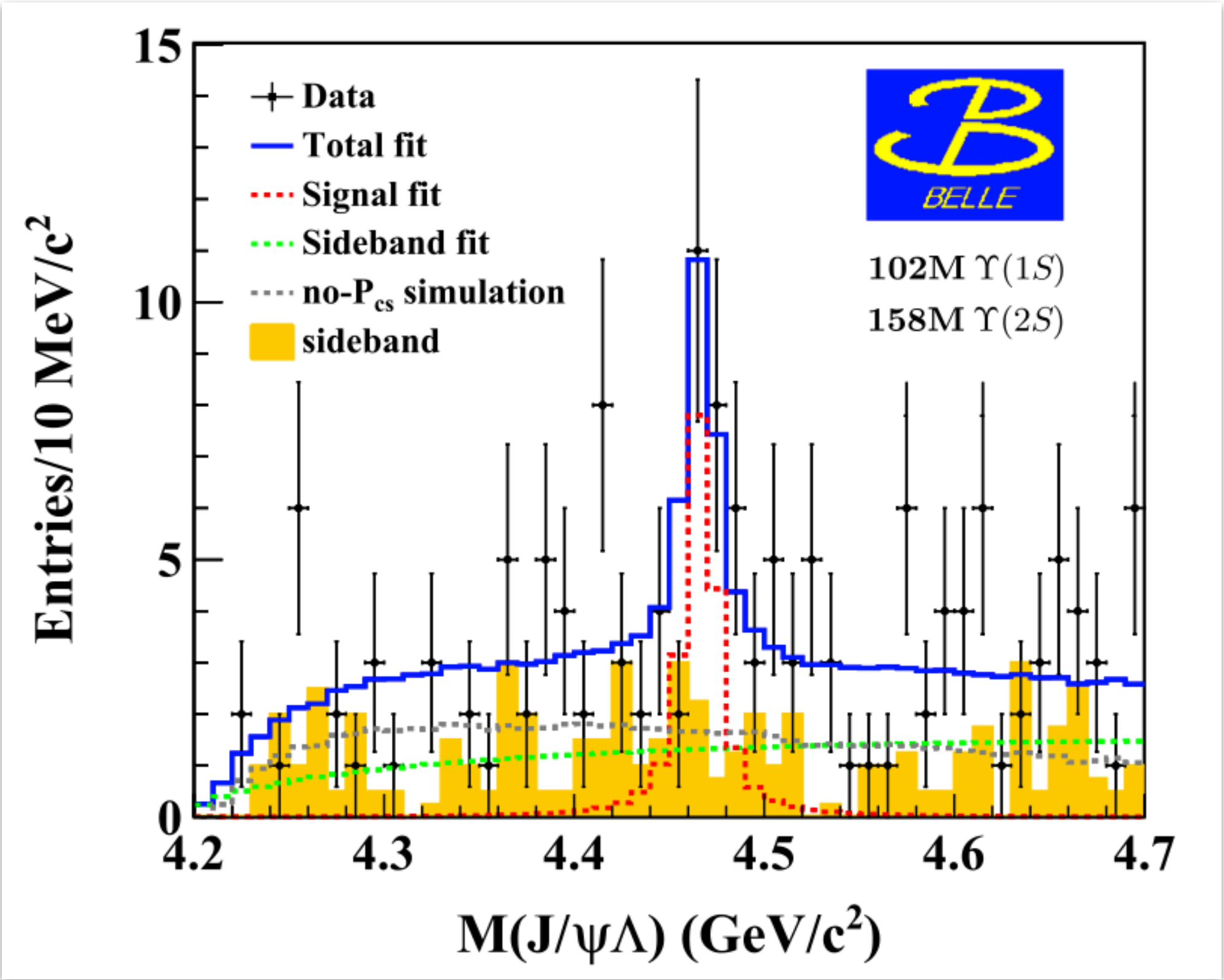


Sci. Bull. 66 (2021) 1278-1287



Pentaquark states

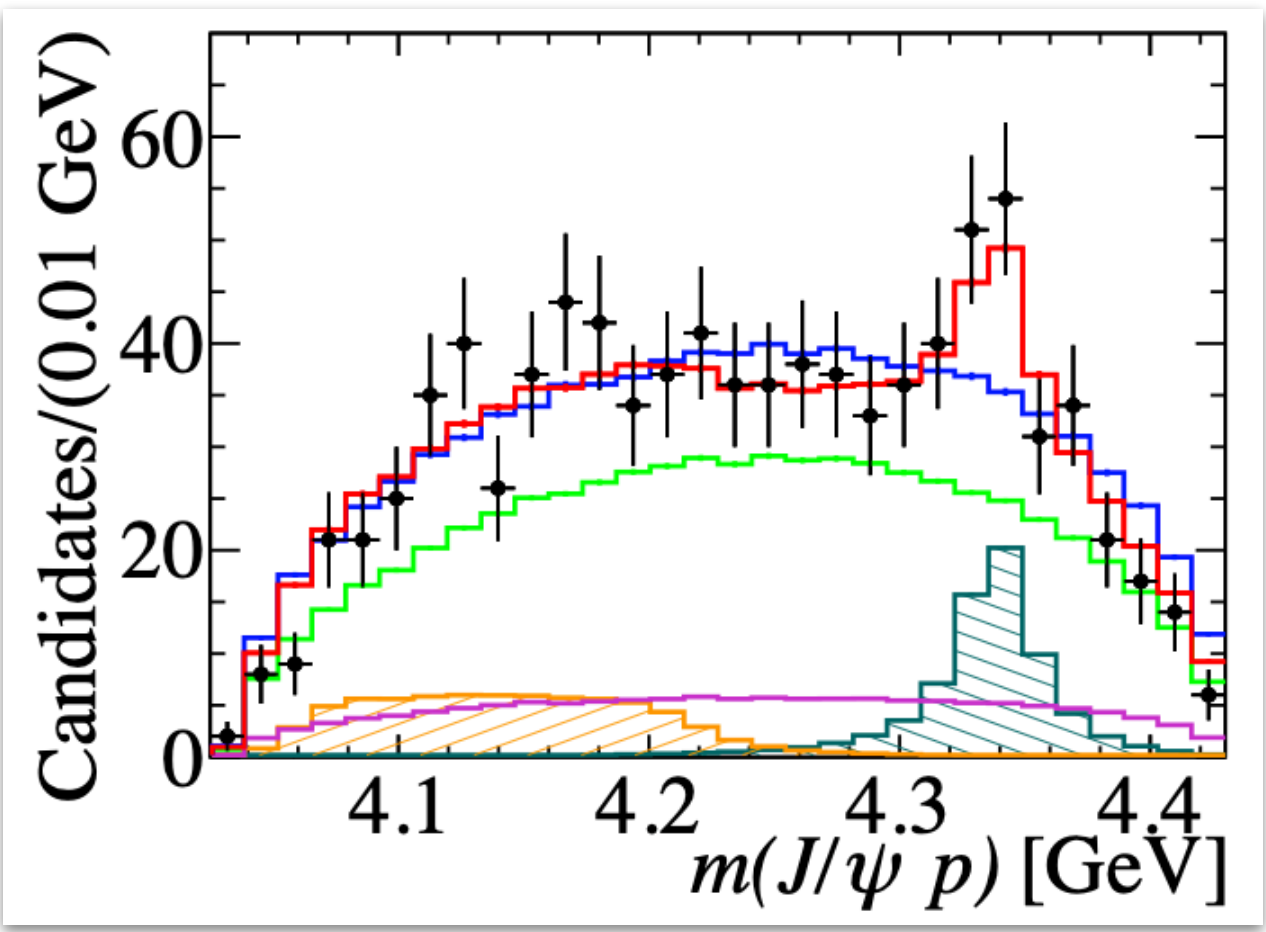
$$\Upsilon \rightarrow J/\psi \Lambda + X$$



PRL 135 (2025) 4, 041901

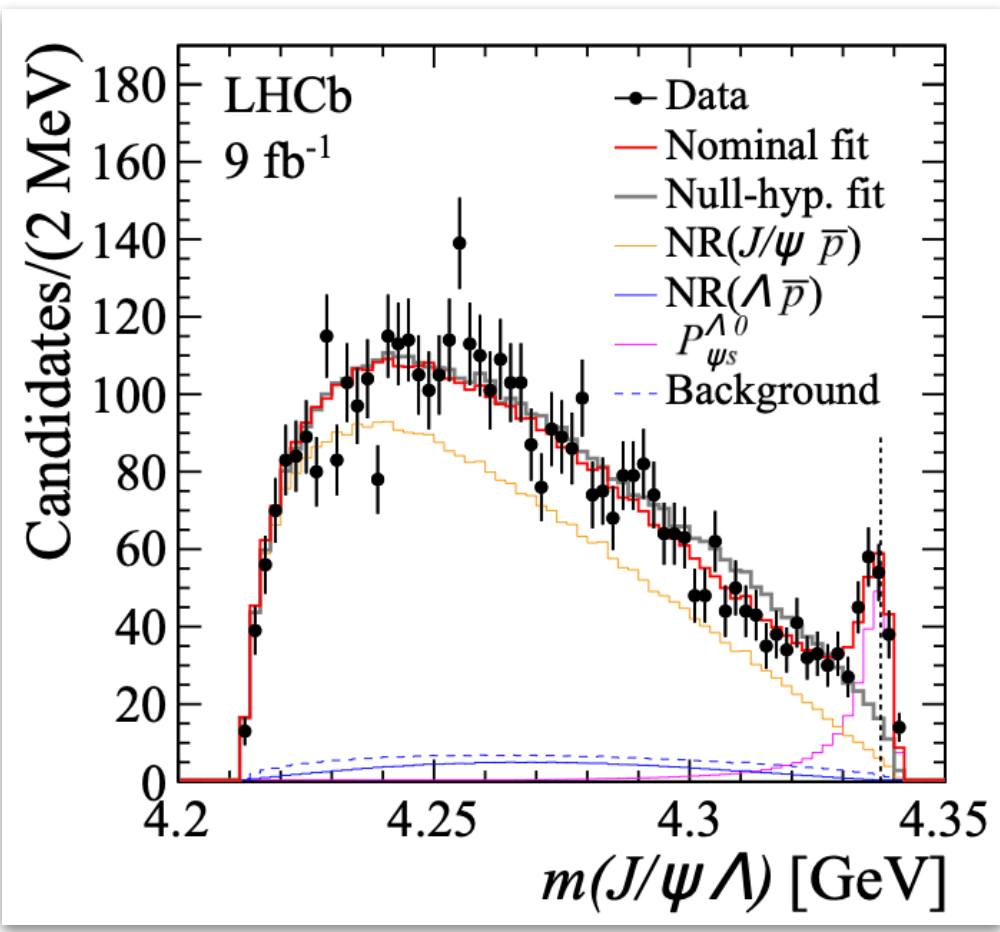
local significance of 3.3σ

$$B_s^0 \rightarrow J/\psi p \bar{p}$$



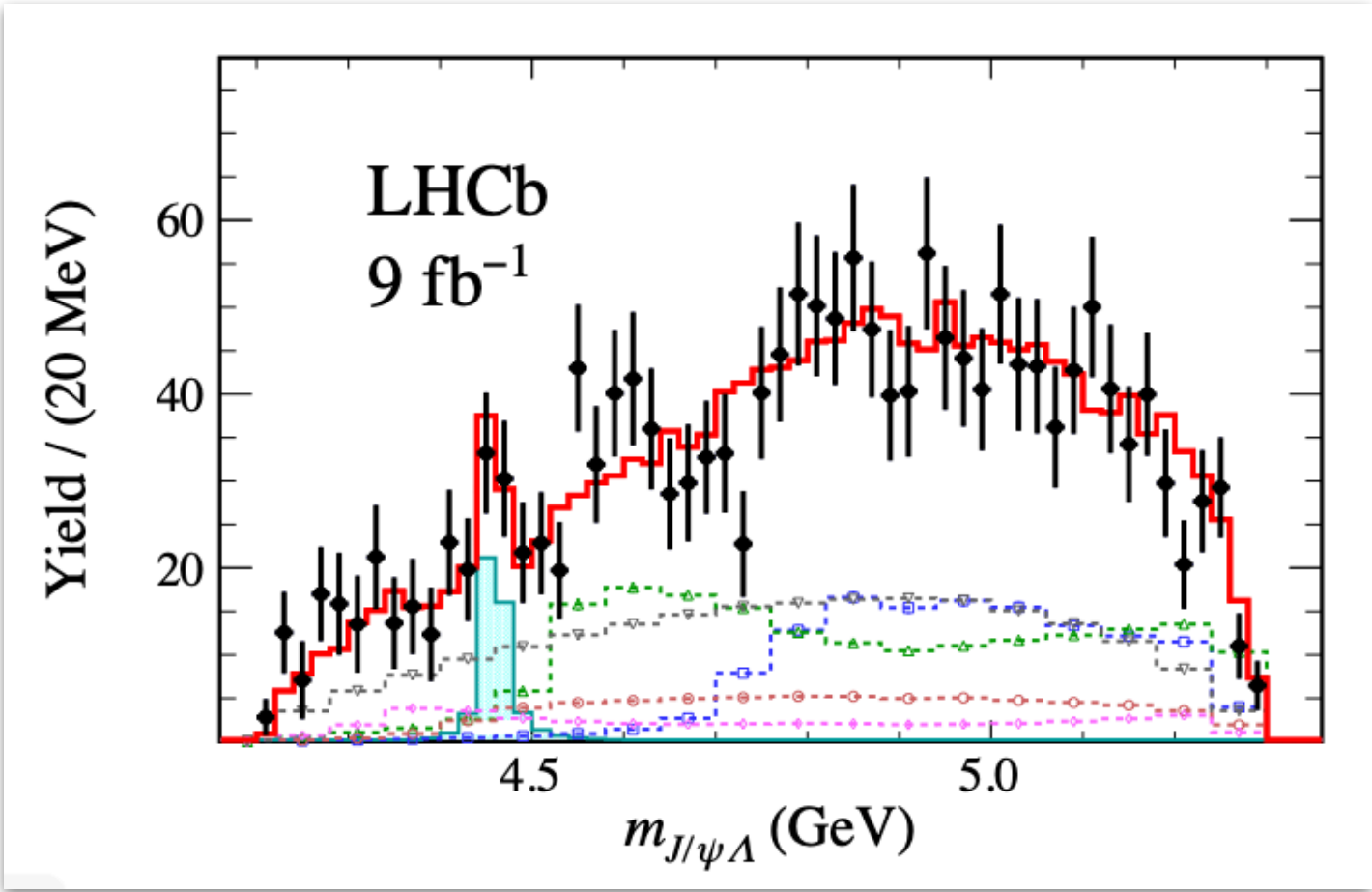
PRL 128 (2022) 6, 062001

$$B^- \rightarrow J/\psi \Lambda \bar{p}$$



PRL 131 (2023) 3, 031901

$$\Xi_b^- \rightarrow J/\psi \Lambda K^-$$

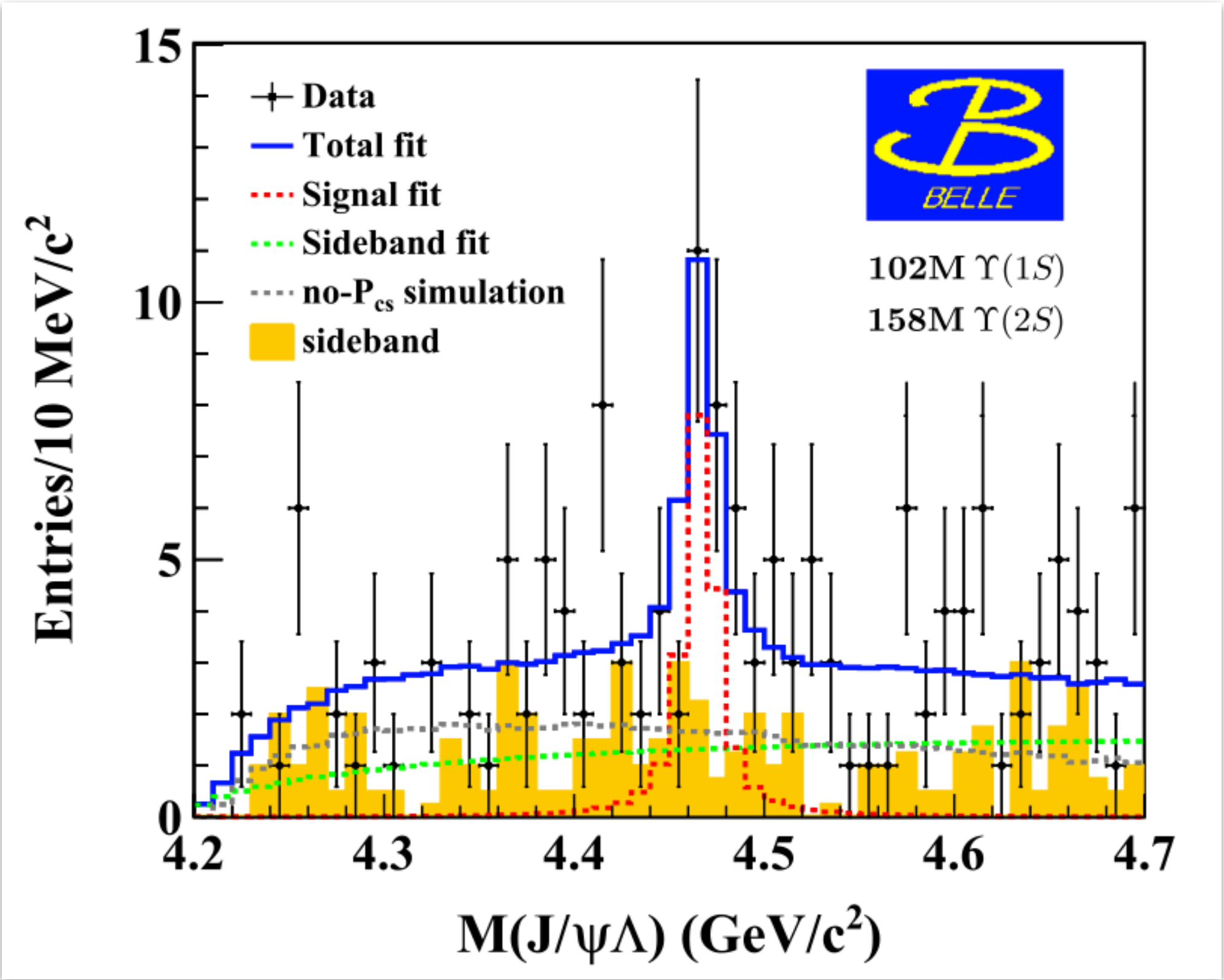


Sci. Bull. 66 (2021) 1278-1287



Pentaquark states

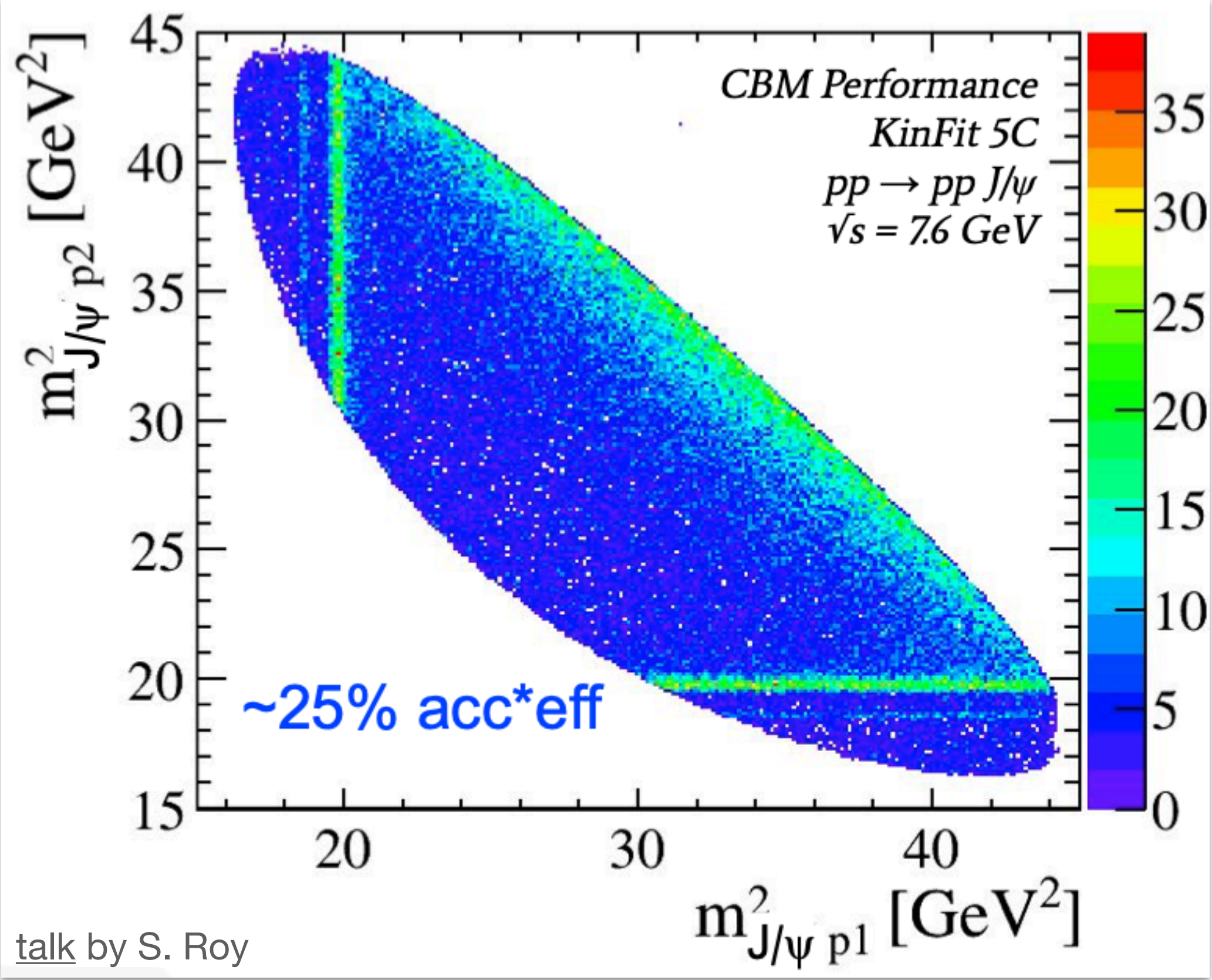
$$\Upsilon \rightarrow J/\psi\Lambda + X$$



PRL 135 (2025) 4, 041901

local significance of 3.3σ

MC simulation of $pp \rightarrow ppJ/\psi$



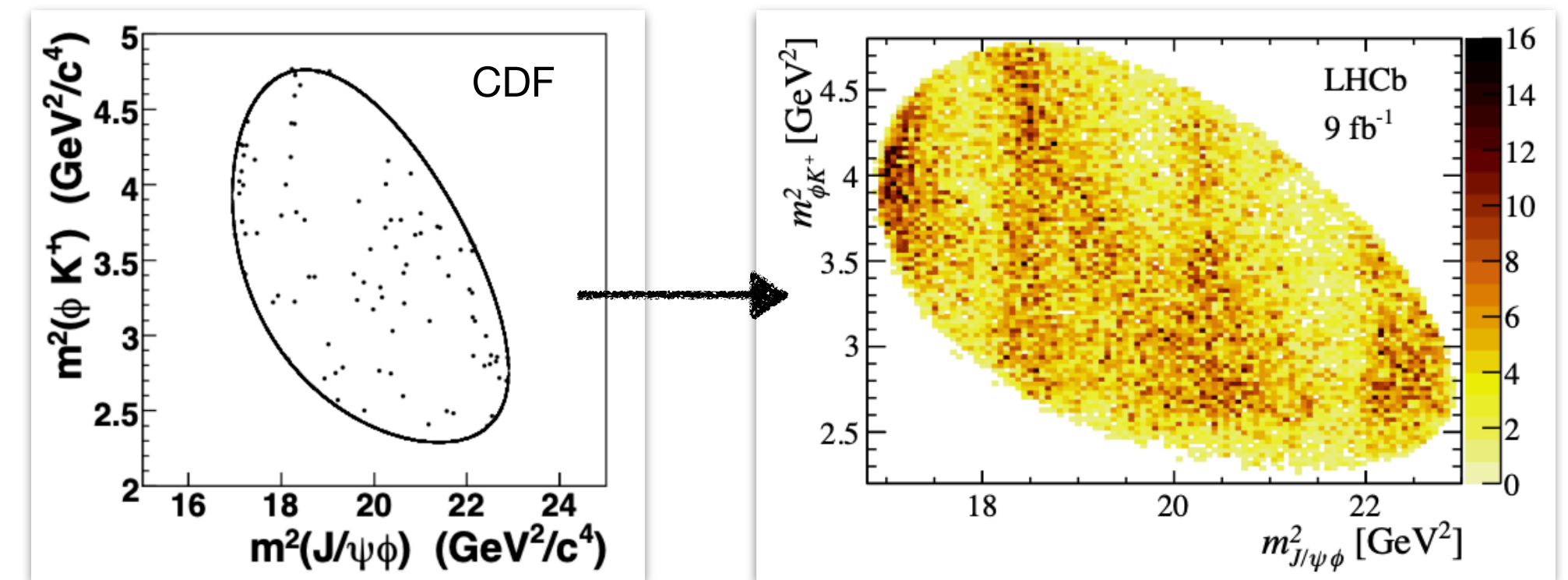
talk by S. Roy

another avenue: J/ψ photo-production (see talk by Farah)

Summary

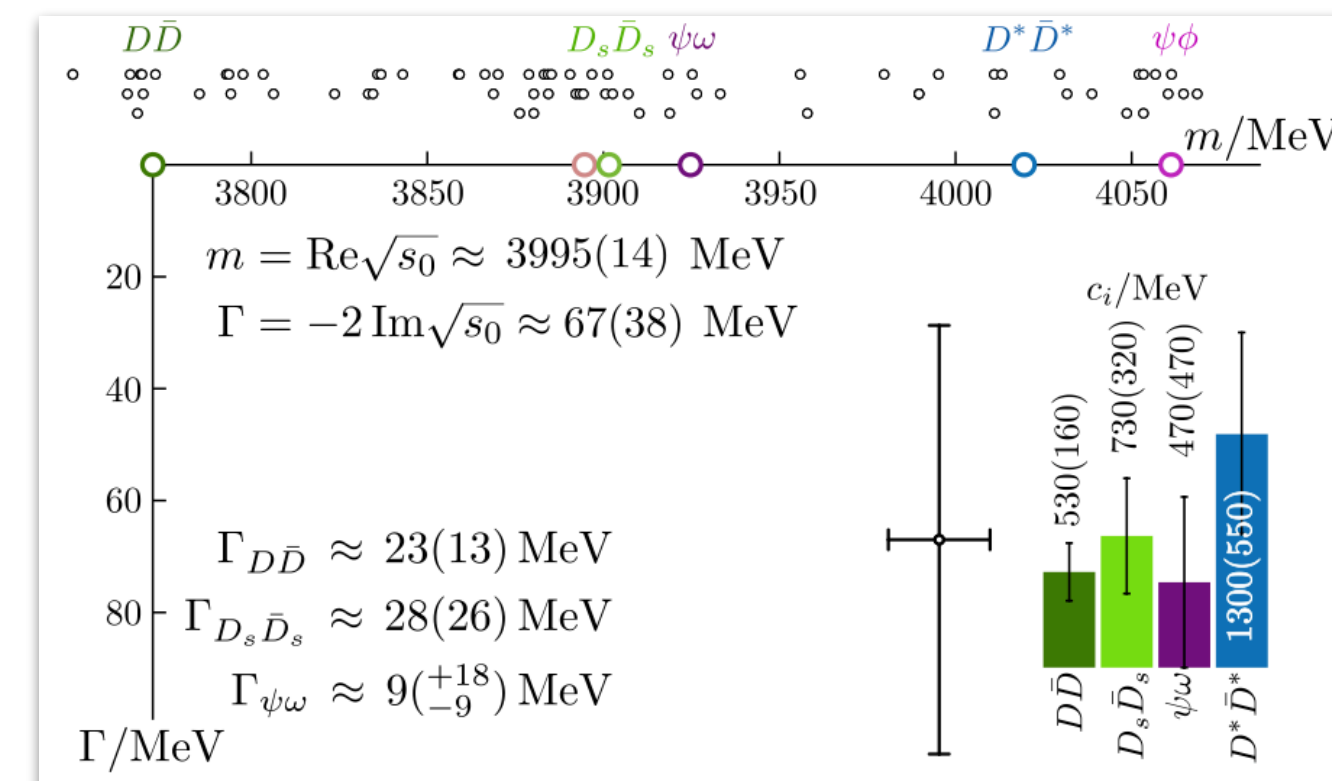
- after discoveries of the charmonium-like XYZ states in the 2000's, now entering era of precision
- continue to discover new states & decay modes from running experiments like LHCb, BESIII and Belle-II
- now have established charmonium-like states with (possible) content of $(c\bar{c}q\bar{q})_{I=0}$, $(c\bar{c}q\bar{q})_{I=1}$, $(c\bar{c}s\bar{q})$, $(c\bar{c}s\bar{s})$, $(c\bar{c}c\bar{c})$, $(c\bar{c}qqq)$ and $(c\bar{c}sqq)$
- interpretation is hard work:
 - experiment: provide as much information as possible: decays, production, ...
 - often multiple possible explanations, need to define key observables
 - kinematic singularities further complicate interpretation
 - more and more lattice-QCD studies will surely help
- many more exciting results available - and a lot more to come!

$$B \rightarrow J/\psi \phi K$$



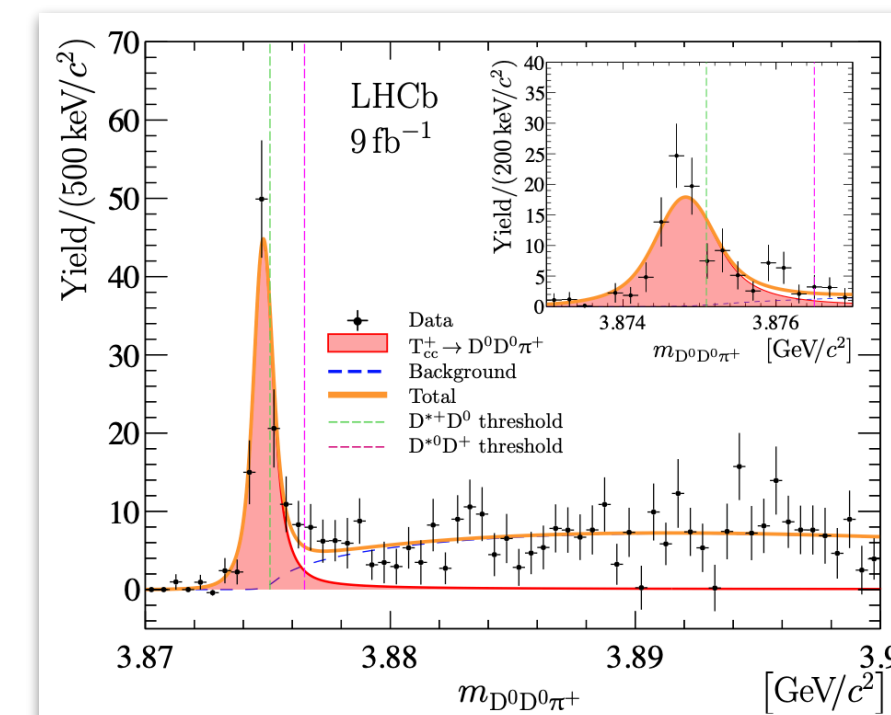
PRL 102 (2009) 242002

PRL 127 (2021) 8, 082001



excited χ_{c0} on the lattice (HadSpec)

PRL 132 (2024) 24, 24



doubly-charmed tetraquark from LHCb

Nature Phys. 18 (2022) 7, 751-754

Thank you for your attention!