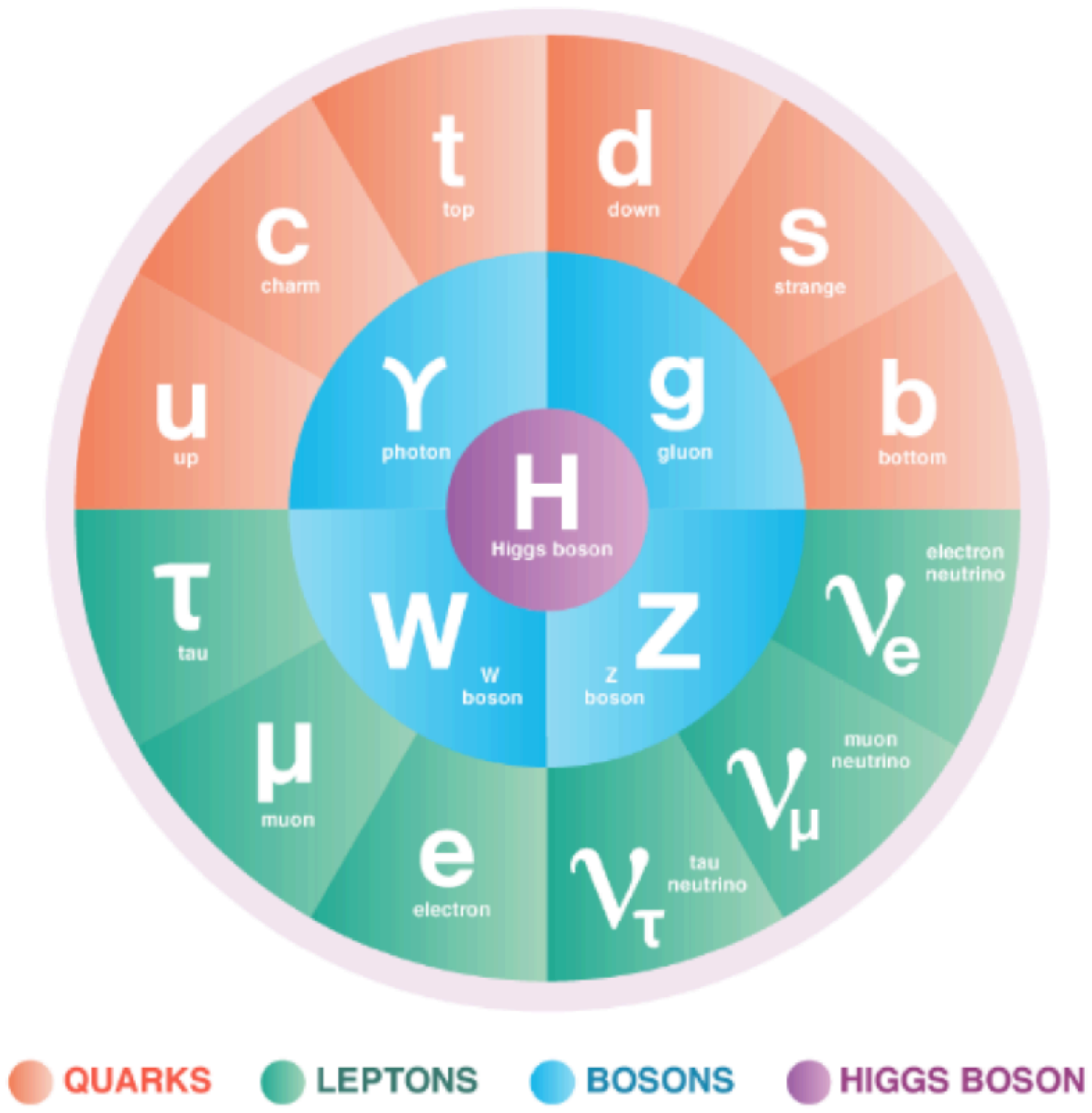
Physics of quarkonia at Belle & Belle II

Speaker: Junhao Yin

The standard model



We know 6 quarks & 6 leptons

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

Quarks spin =1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

We know four types of interactions

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

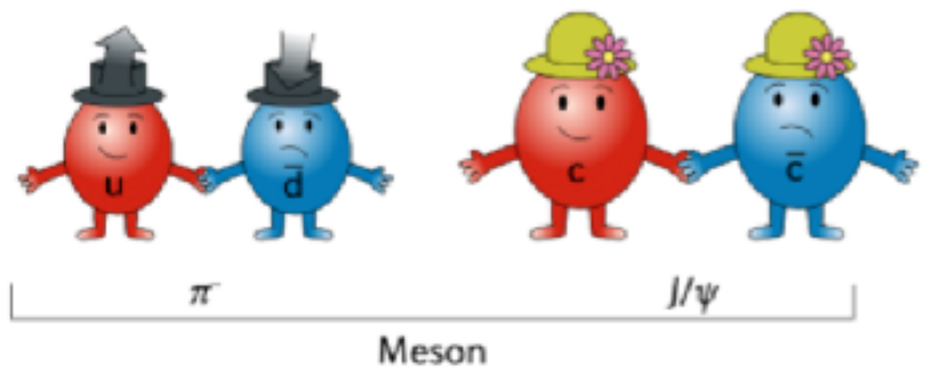
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

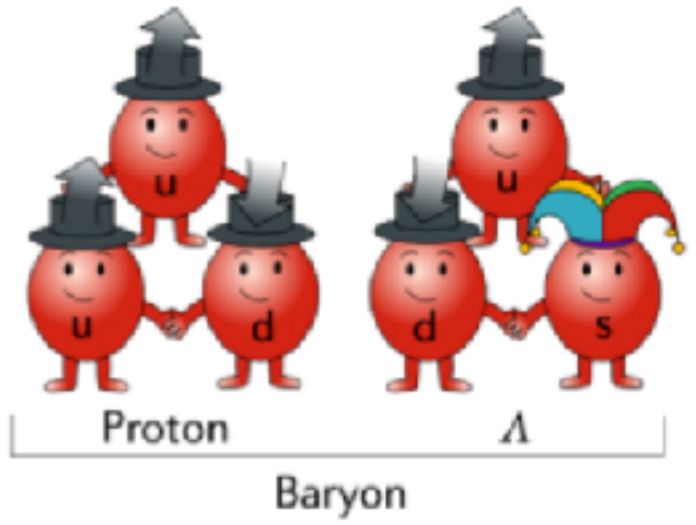
- Gravity is responsible for the structure of the Universe
- Electromegatic interaction ➔ the molecules and atoms
- Weak interaction ➔ the stars shine
- Strong interaction ➔ the structure of the nuclei, nucleons, hadronic matters from the building blocks --- quarks!

but HOW?

Hadrons

- mesons
- baryons





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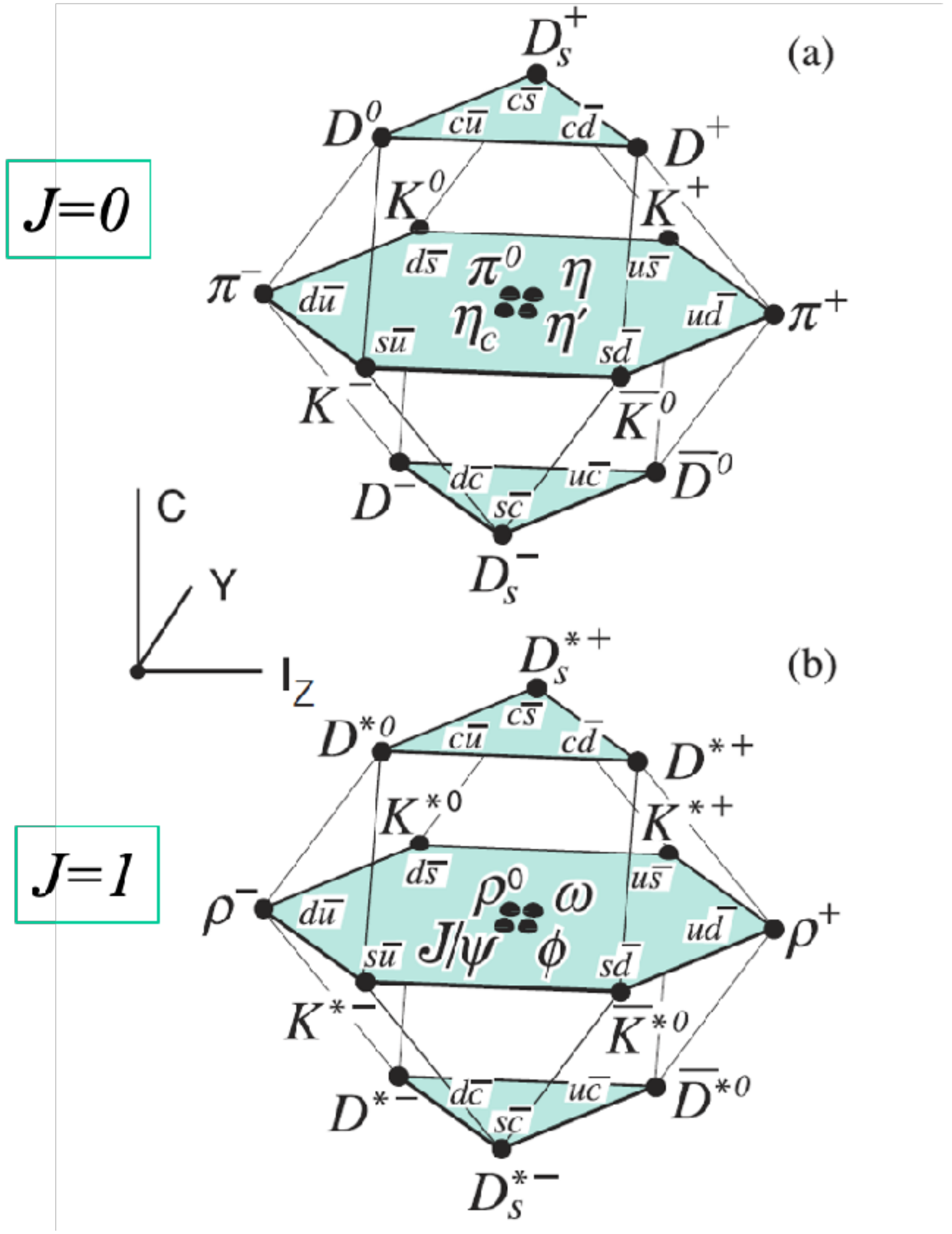
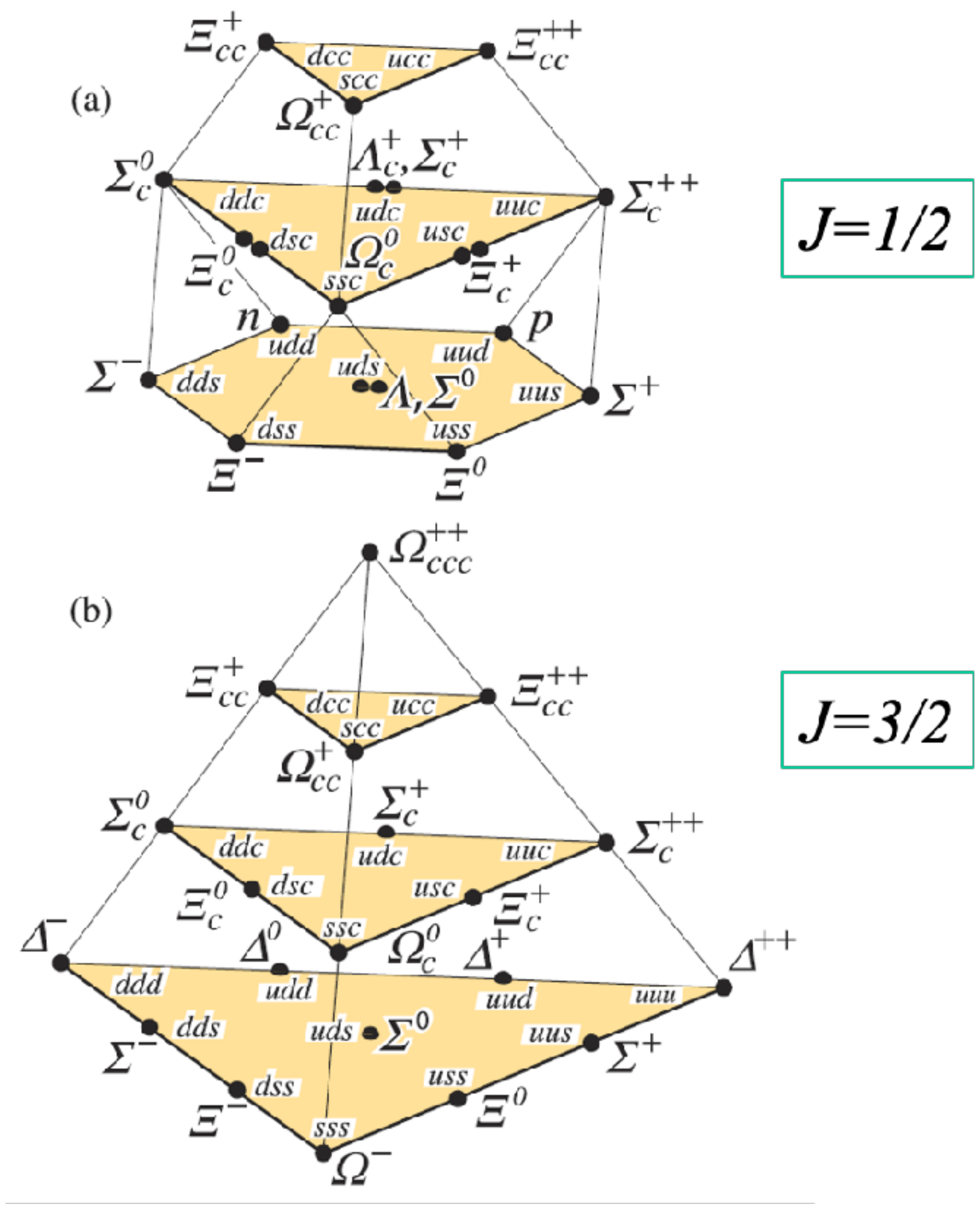
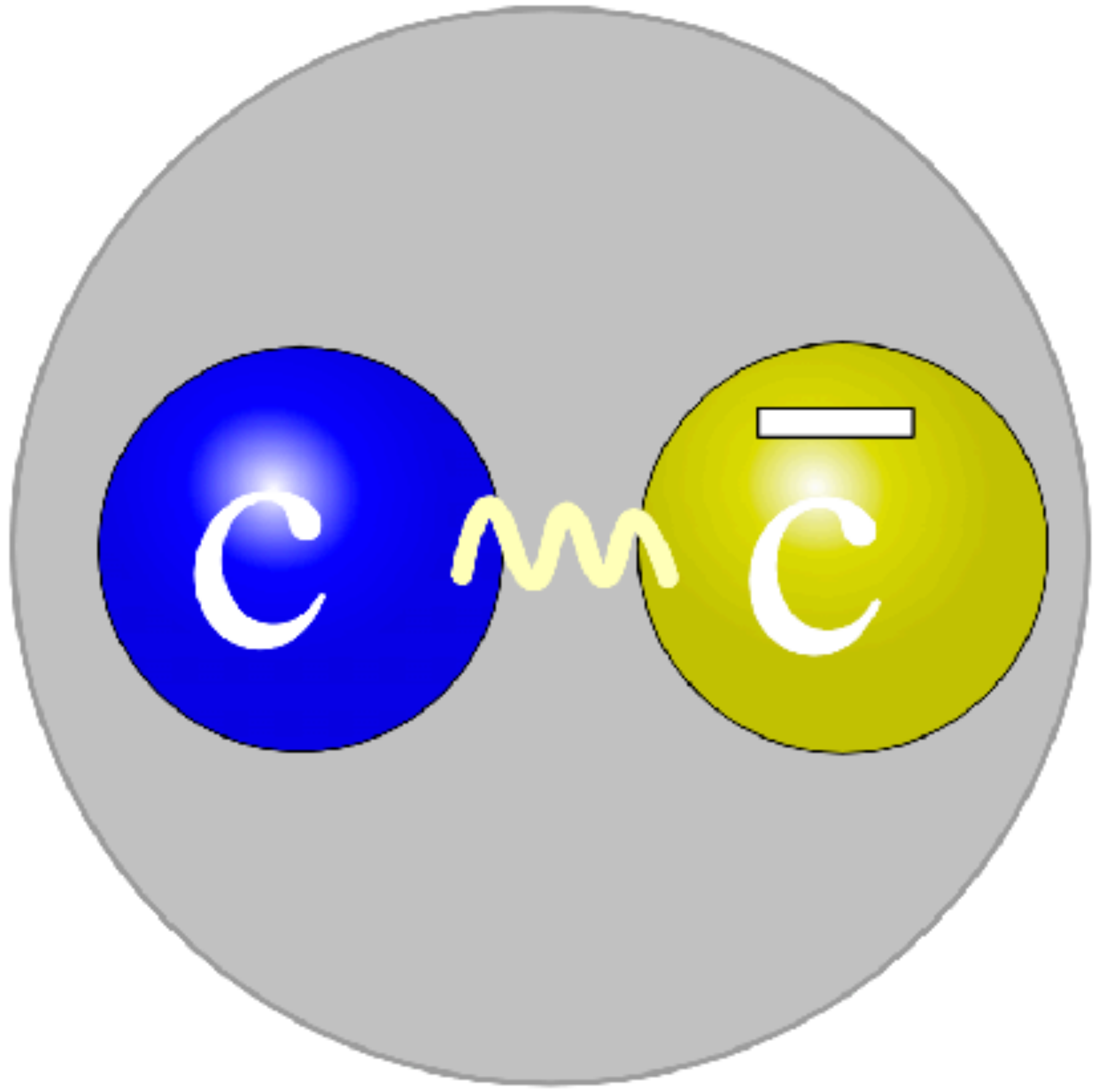
M. Gell-Mann

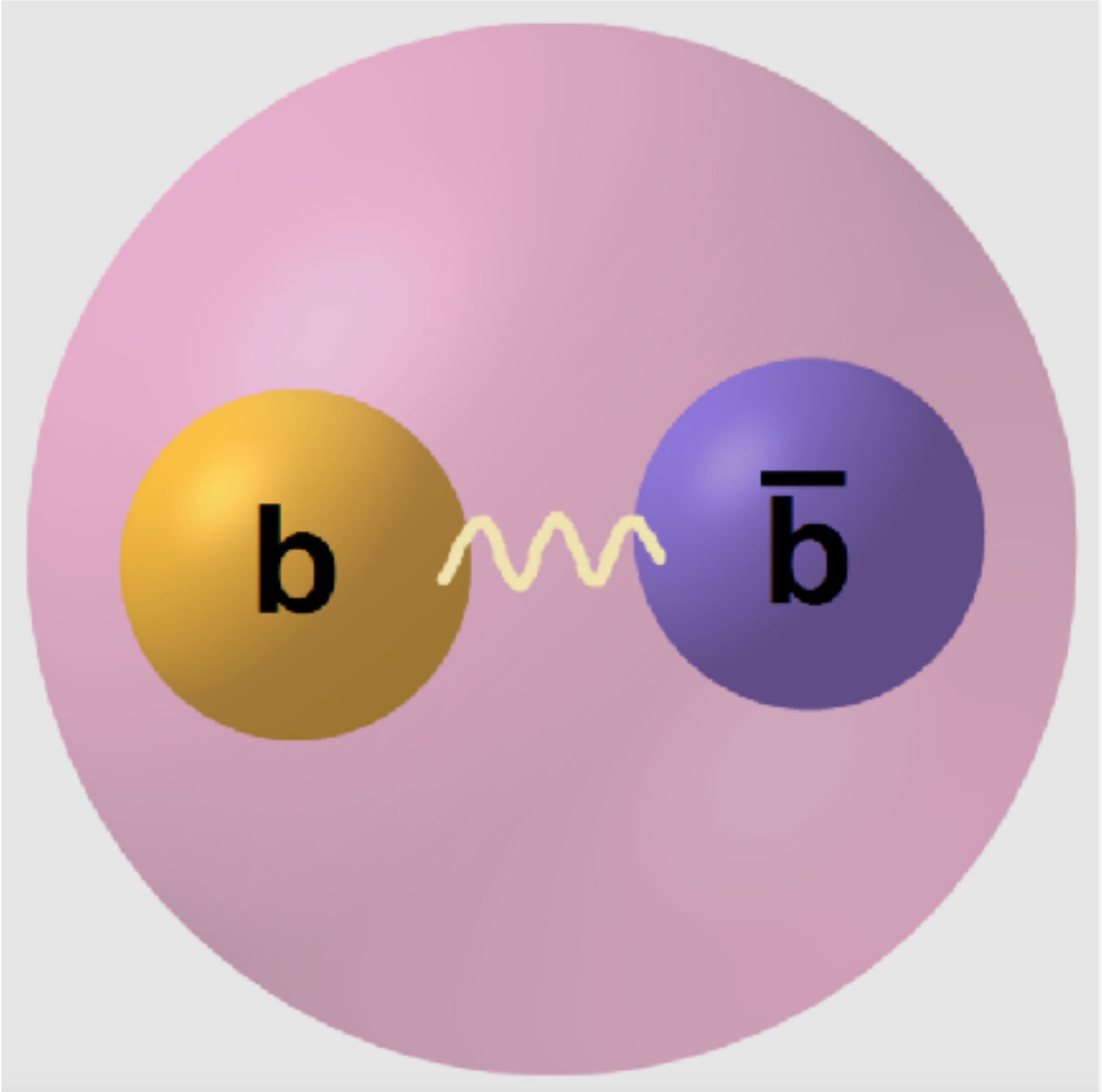
Physics Letters 8, 214 (1964);





We can put (all of) them in a simple picture!





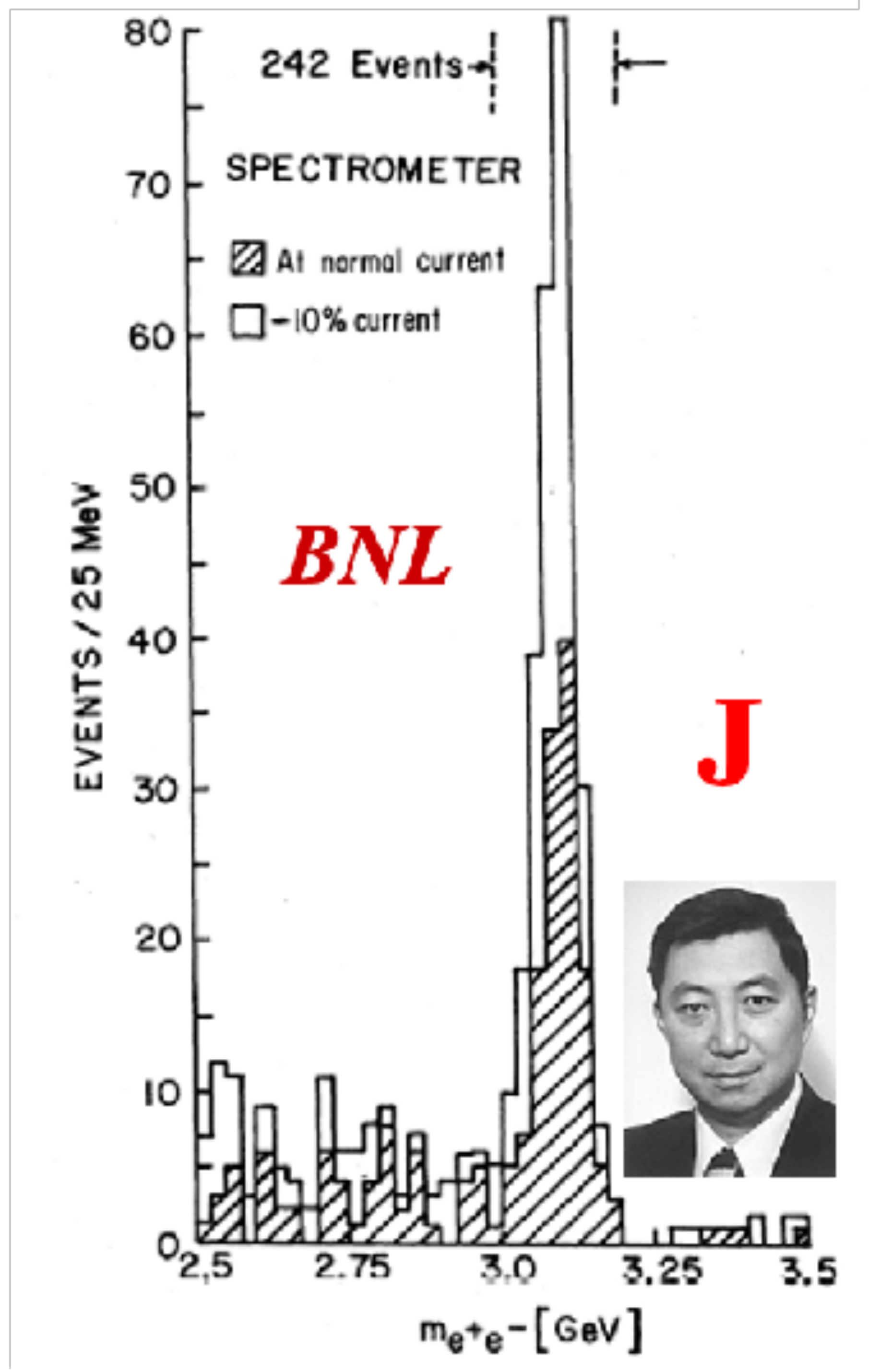
The flavor-changing decays would be strongly suppressed if there were a fourth quark (now called the *charm quark*) that was a complementary counterpart to the strange quark.

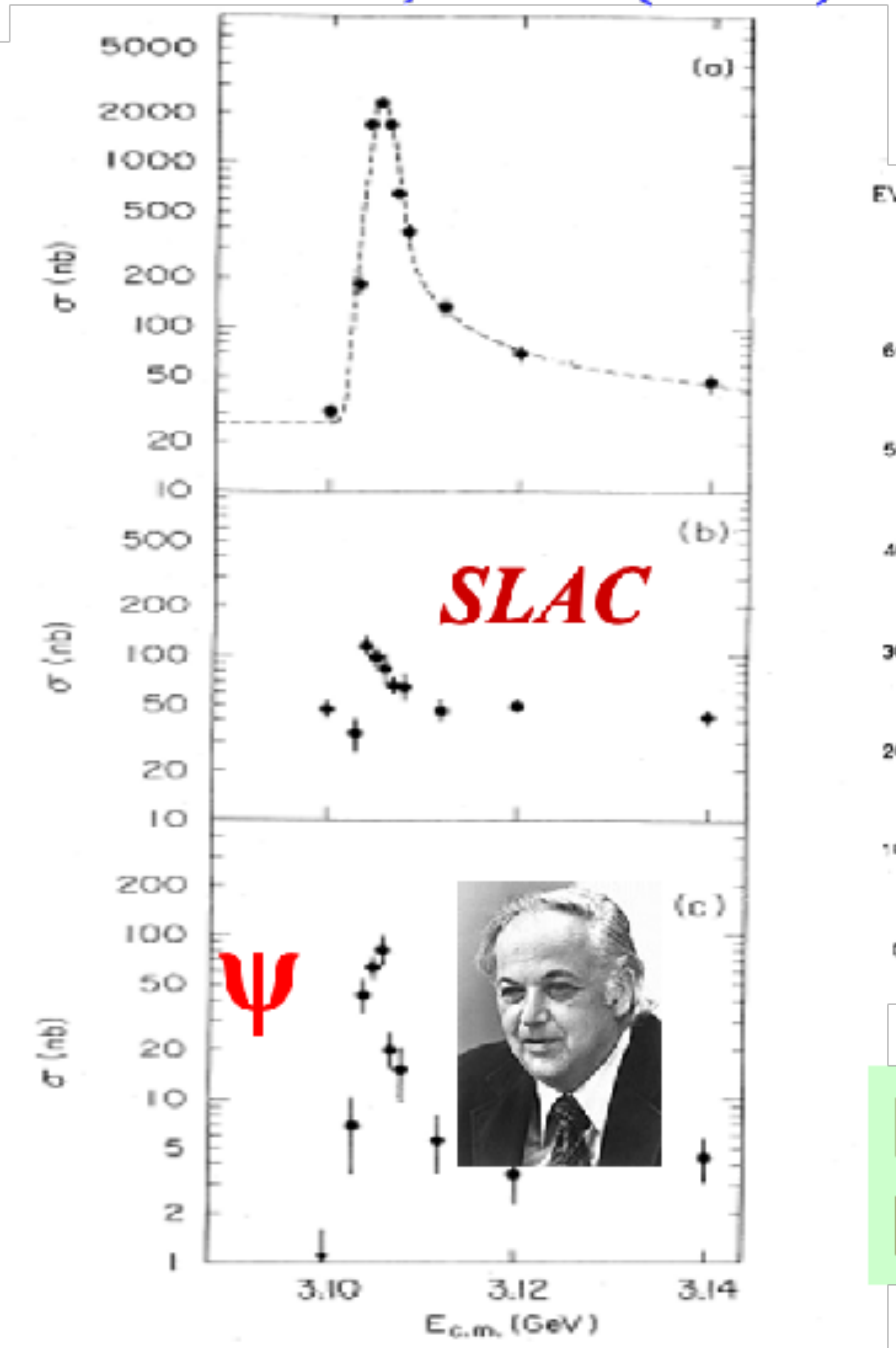
Discovery of the J/ψ

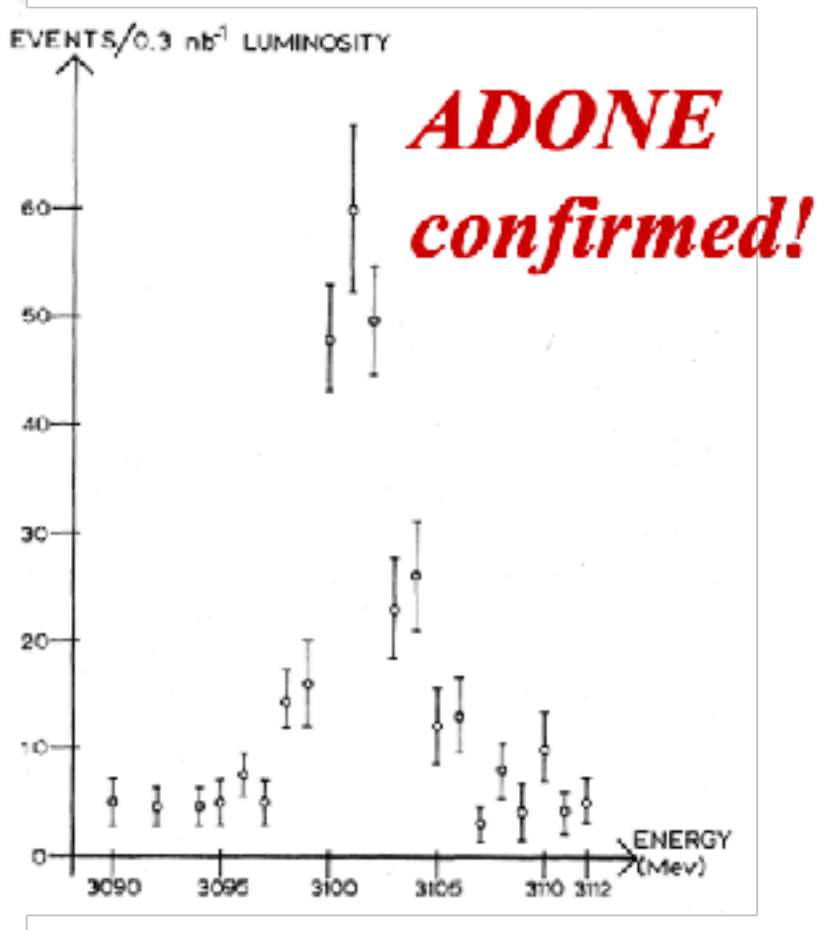
"November Revolution of Particle Physics!"

Charm quark was proposed in 1964, first application in 1970!

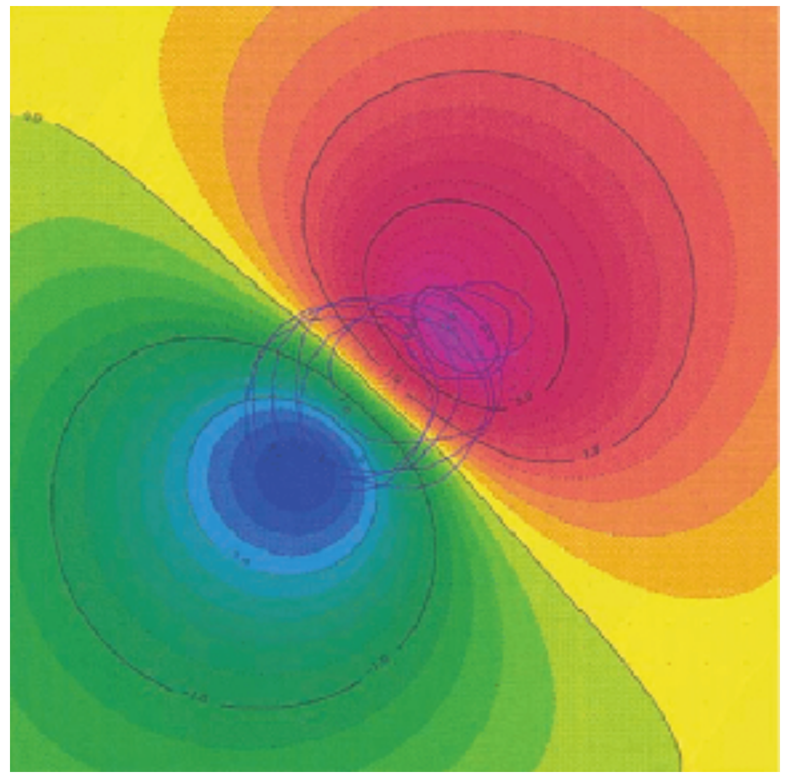
PRL33, 1404 (1974) **PRL33, 1406 (1974)** **PRL33, 1408 (1974)**





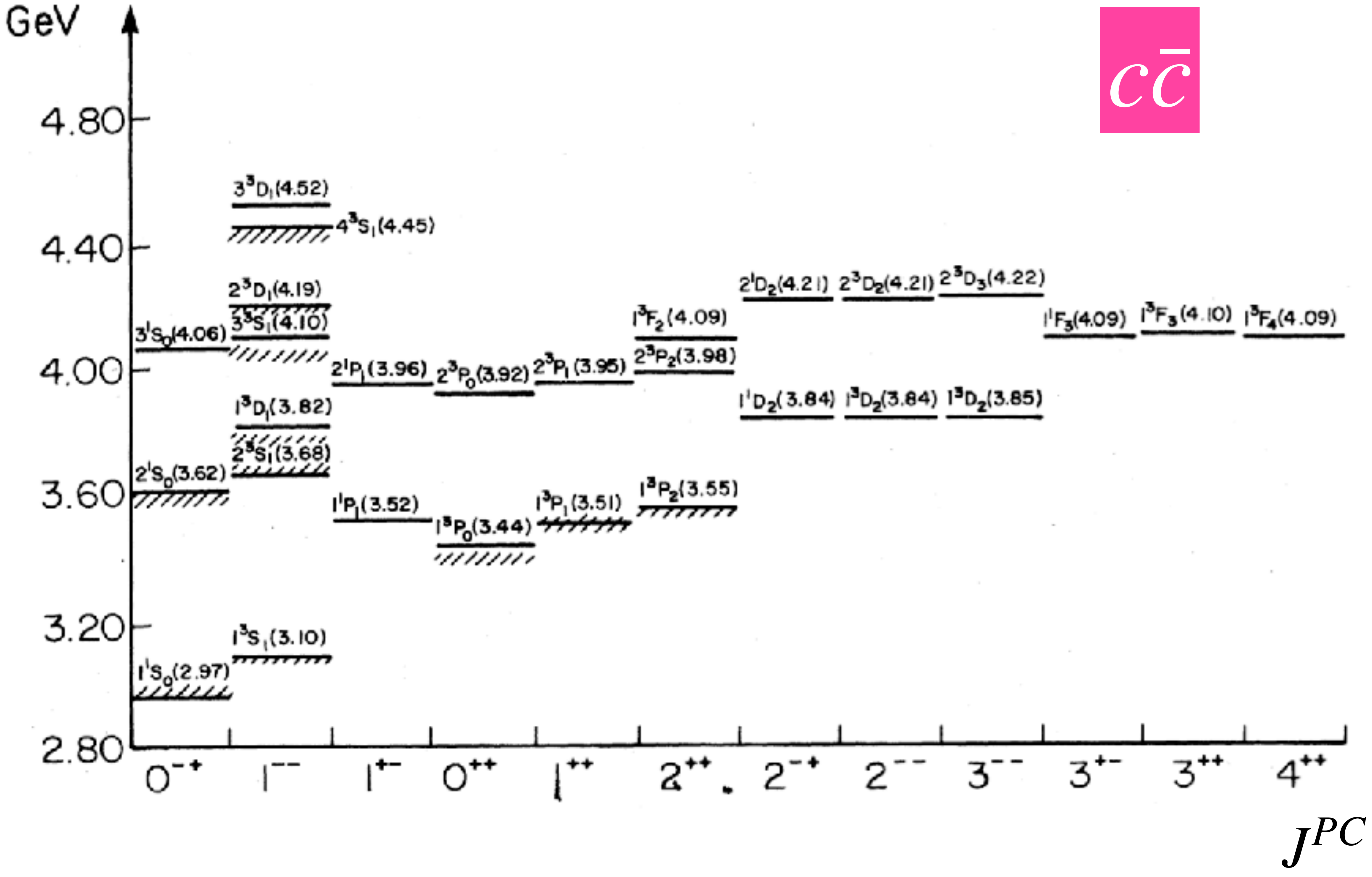


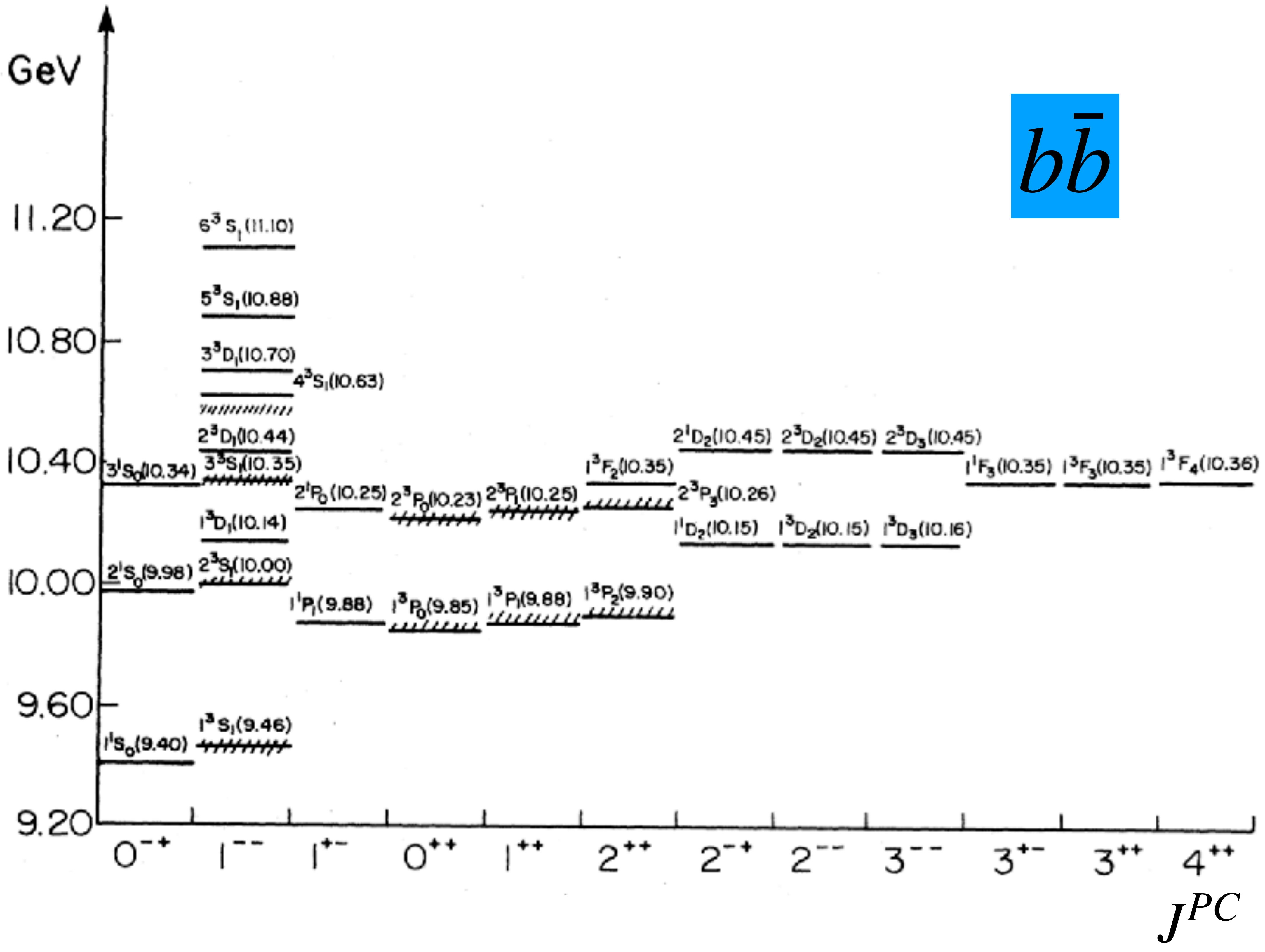
Design:
Max. Ecm~3 GeV!



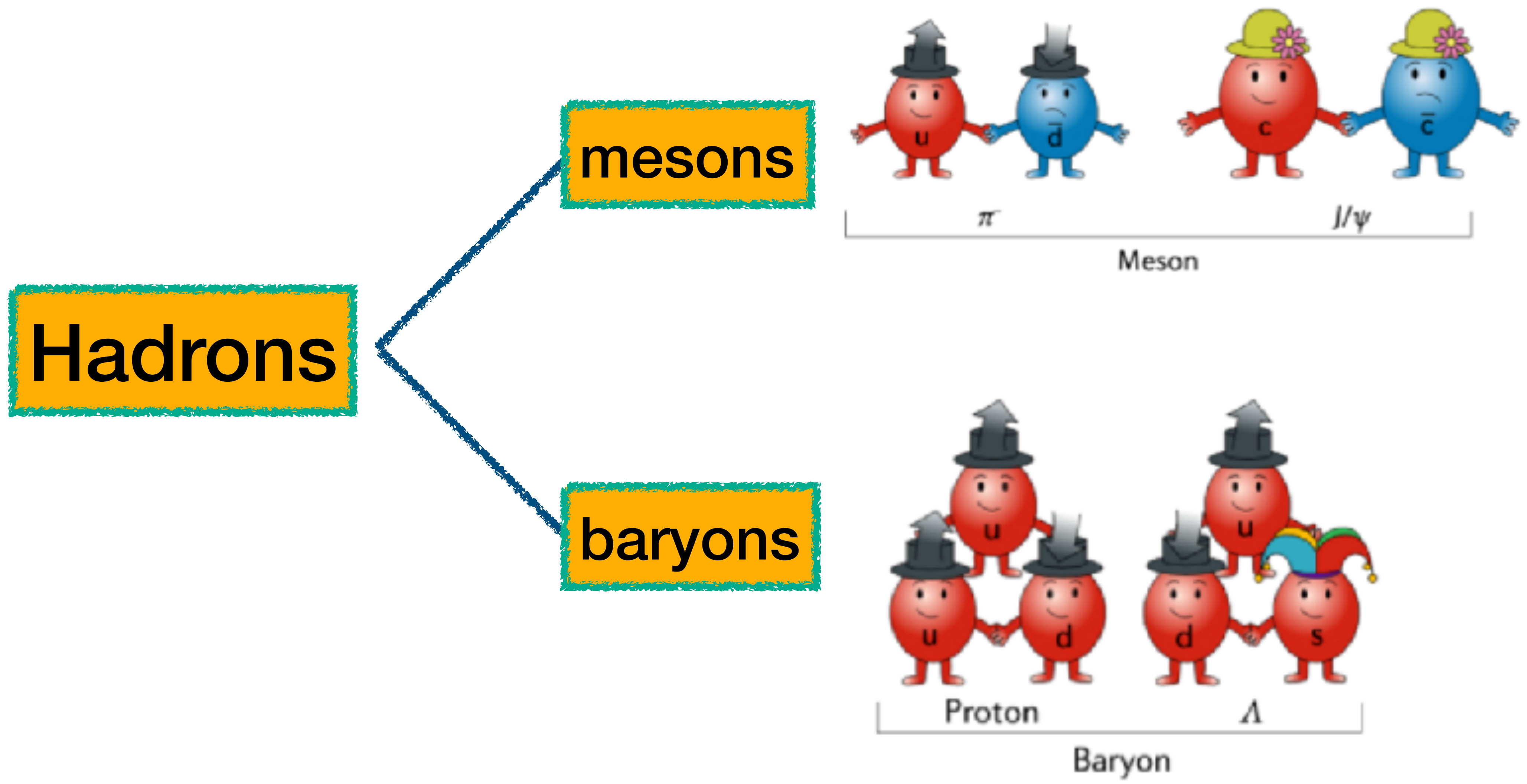
Heavy quark system can be well described by non-relativistic potential model.

Godfrey & Isgur, PhysRevD.32.189 (1985)





The End?



Normal
&
Exotic

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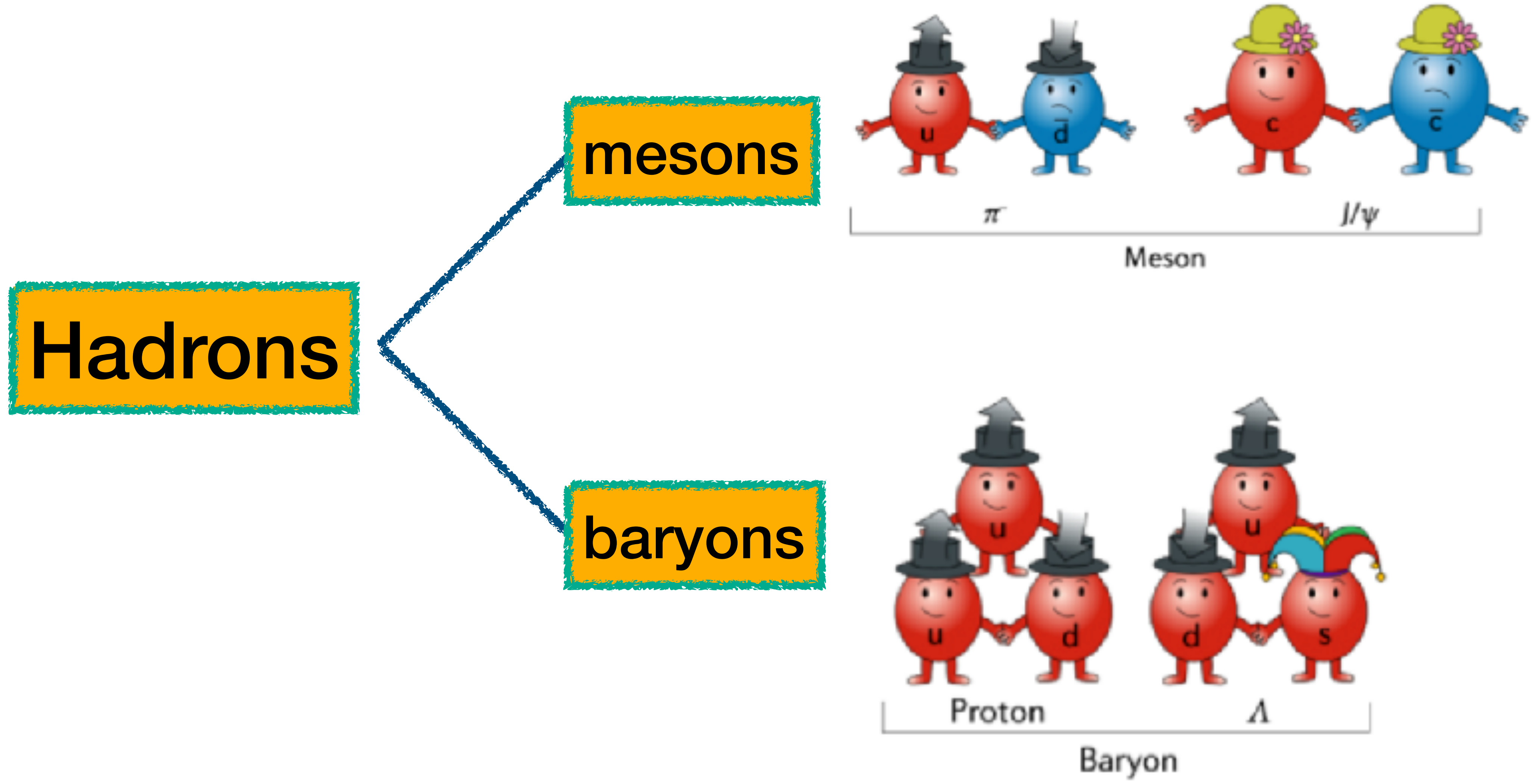
Quark model doesnot forbid hadrons with $N_{\text{quark}} \neq 2,3$!



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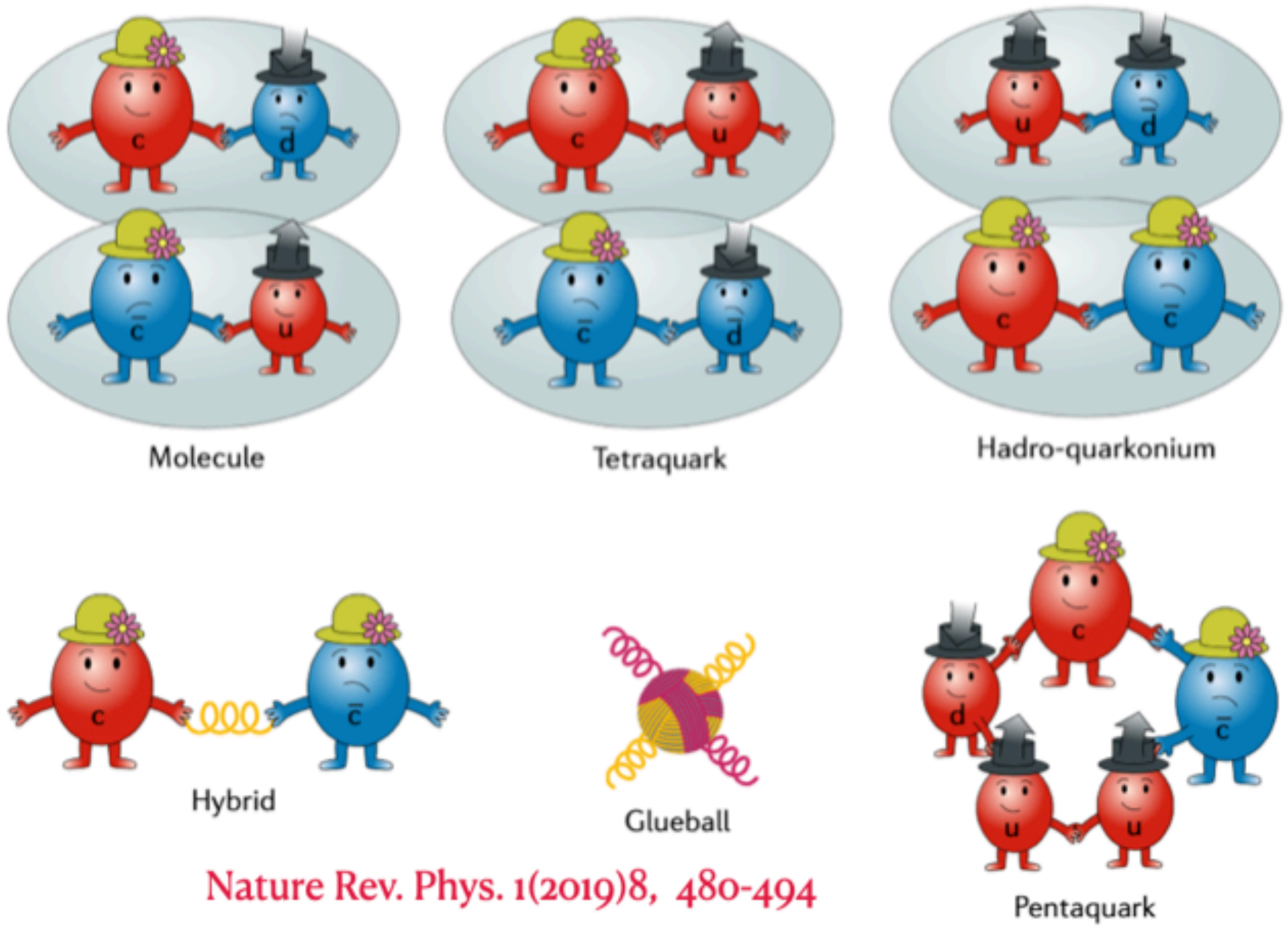

Nature Rev. Phys. 1(2019)8, 480-494

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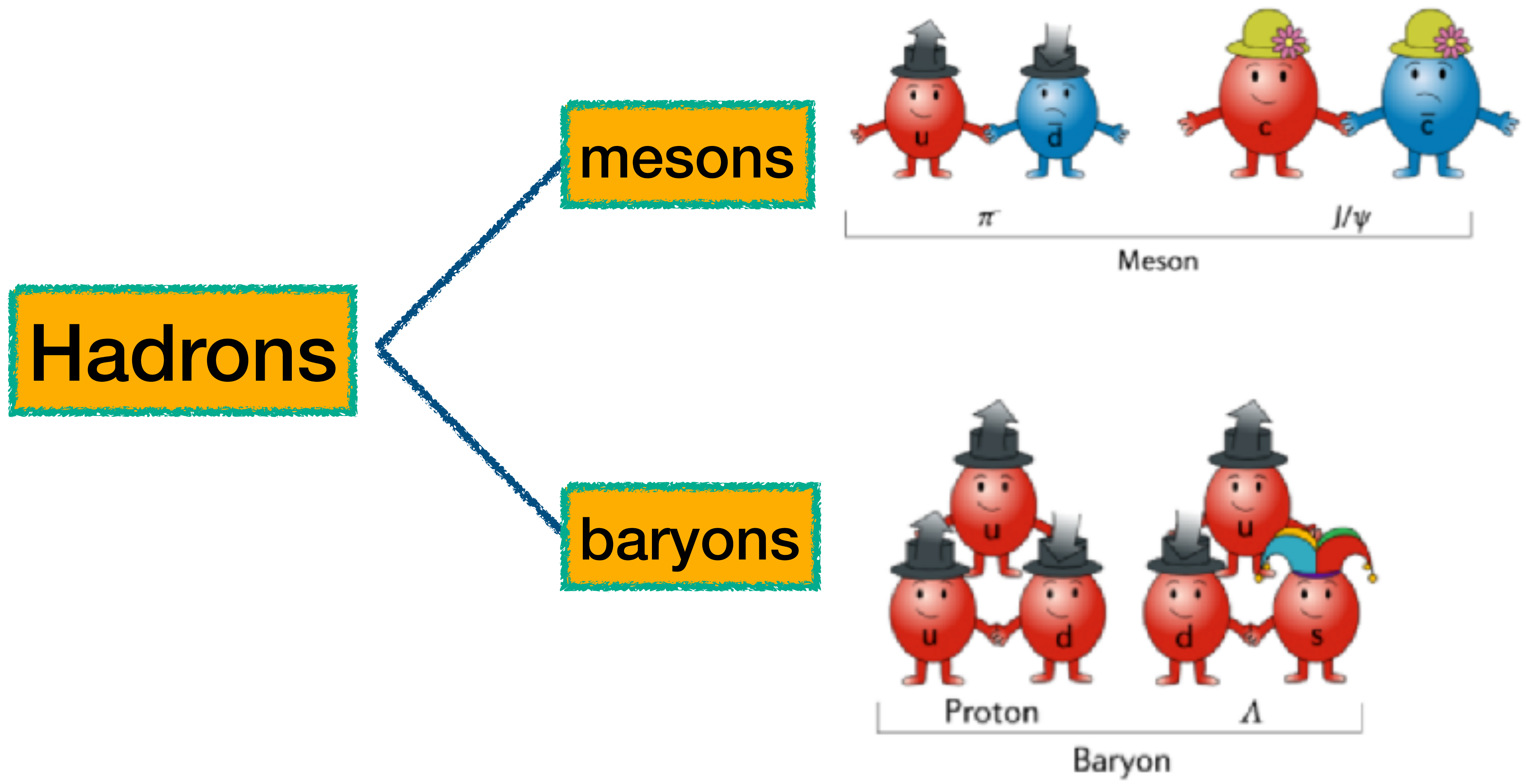

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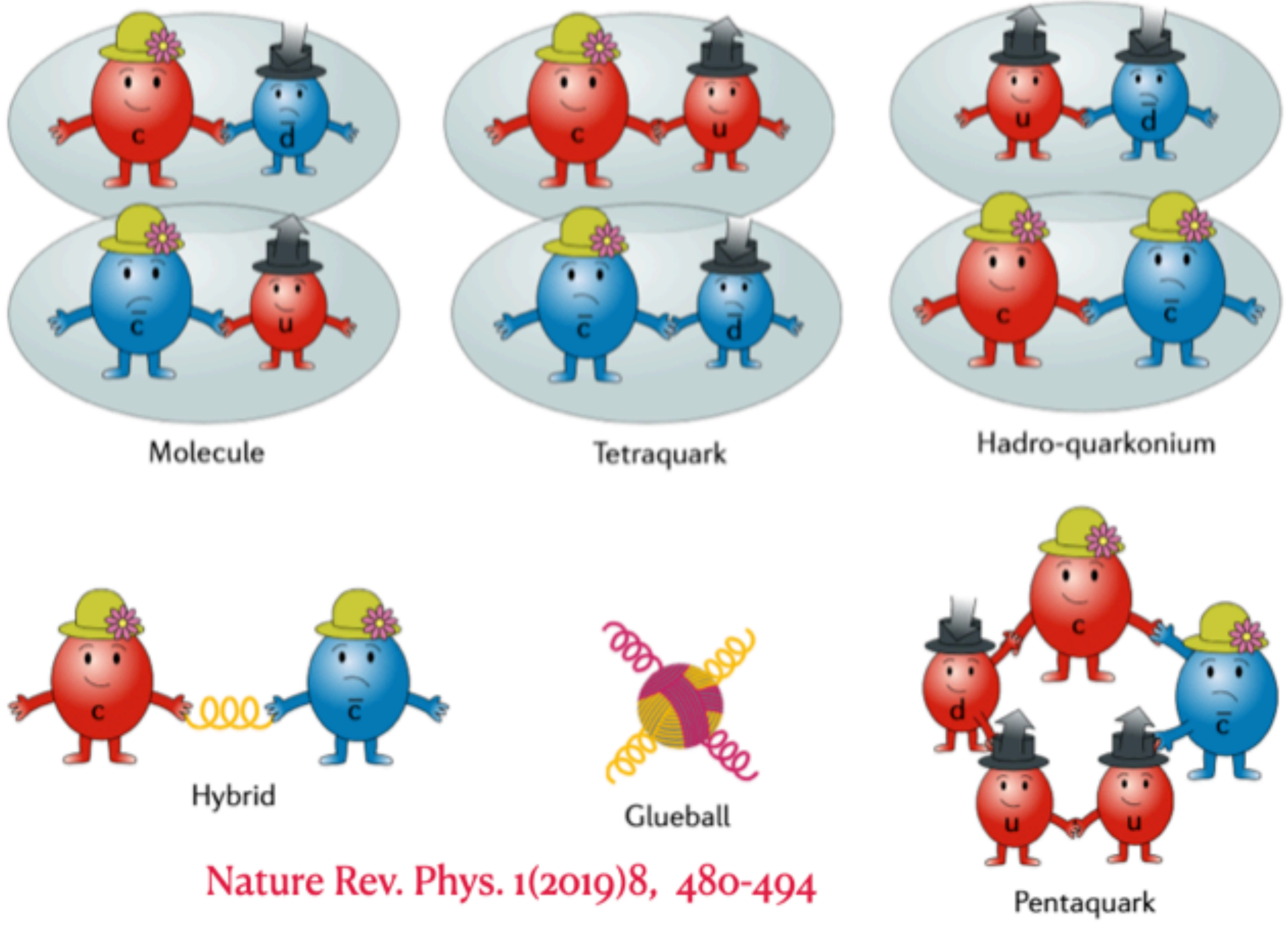

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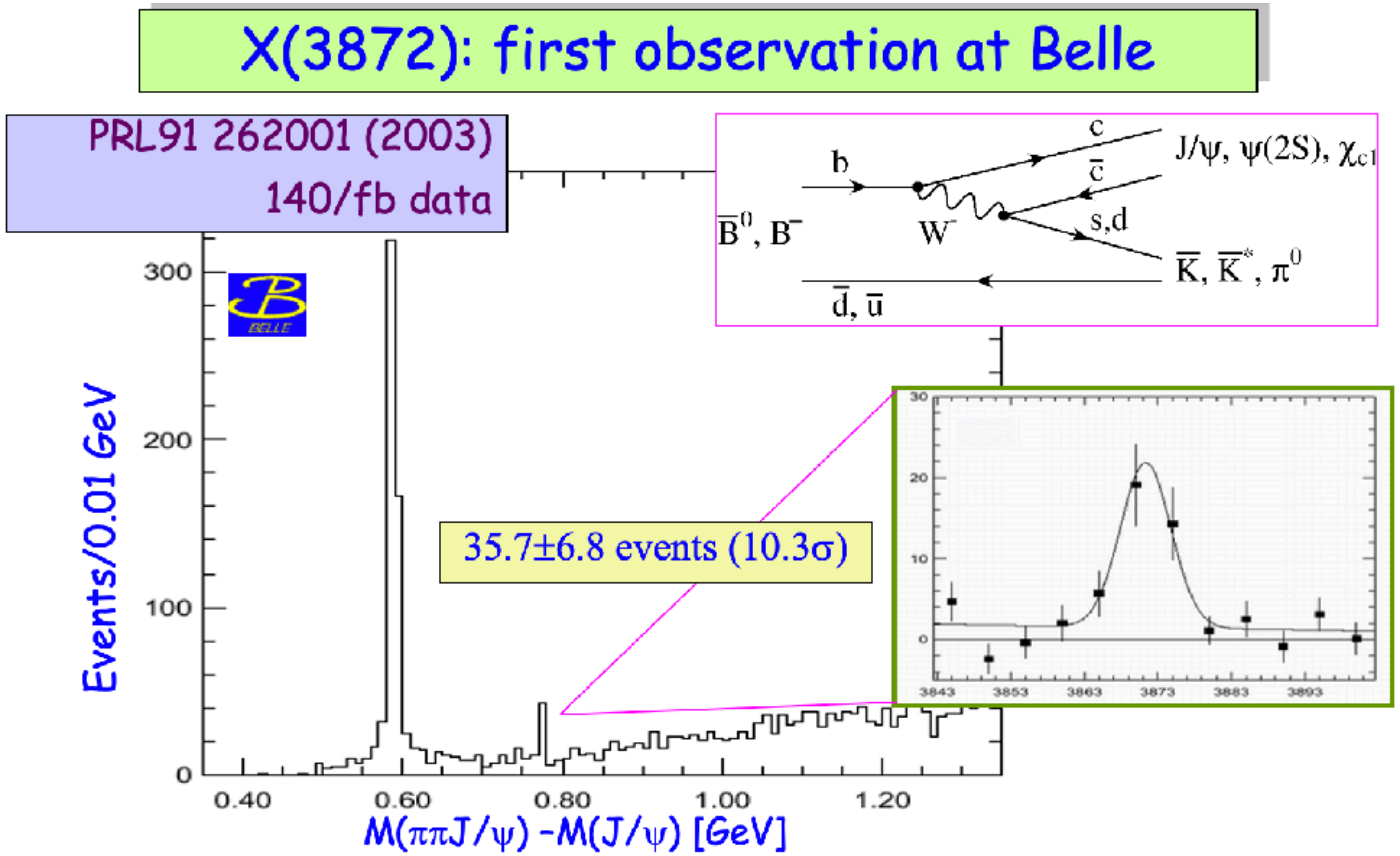
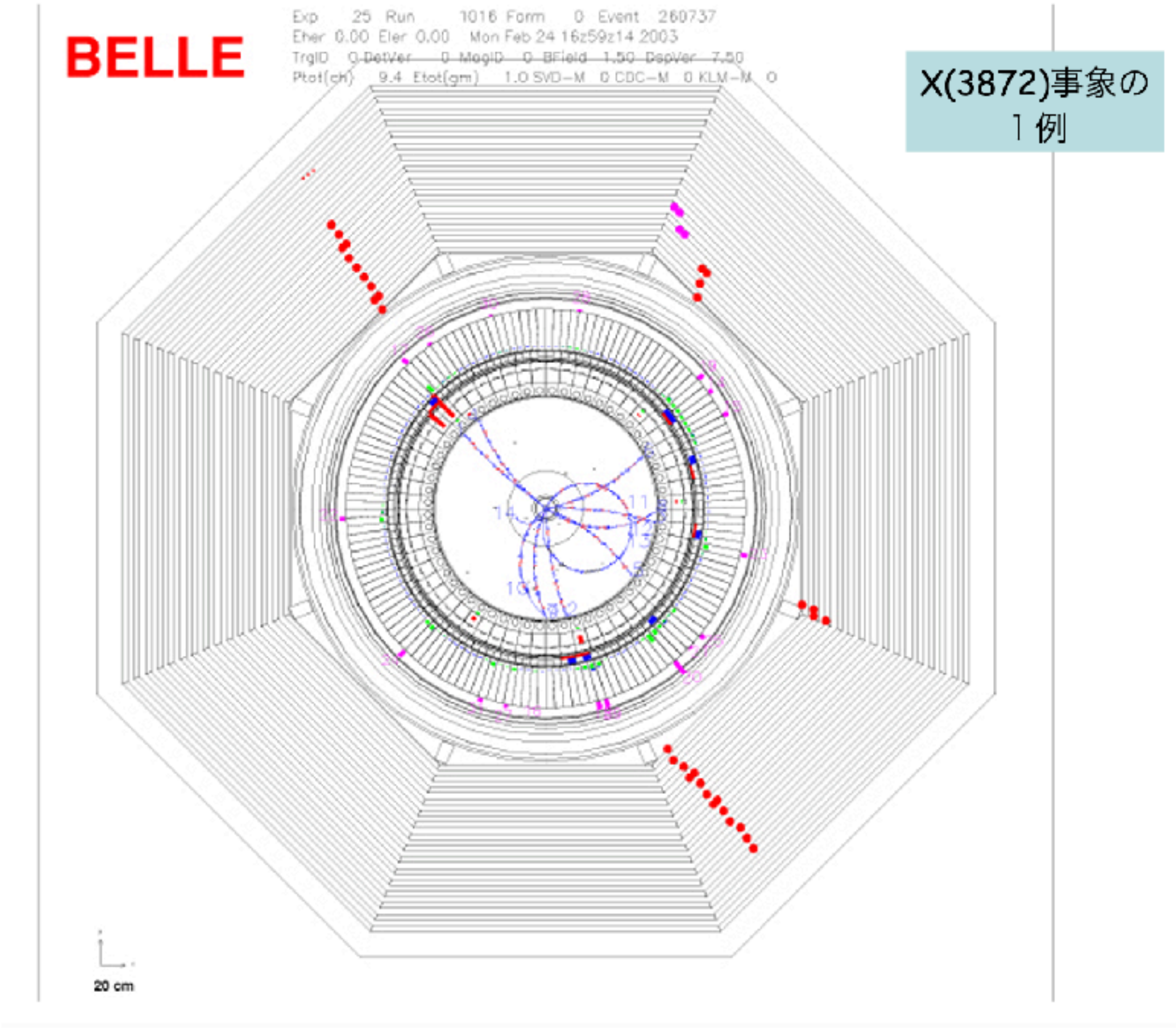
Quark model doesnot forbid hadrons with $N_{\text{quark}} \neq 2,3$!

Where?

2003, Belle observed the first exotic state $X(3872)$

confirmed by BaBar, CDF, D0.





Why $X(3872)$ is exotic?

Mass：

- $3871.65 \pm 0.06\ \mathrm{MeV/c^2}$

Not predicted in the potential model

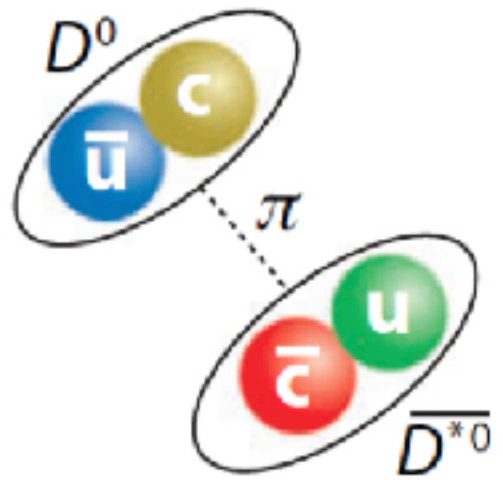
- Mass very close to $m(D^0\bar{D}^{*0})$

Binding energy： $-10 \pm 90\ \mathrm{keV/c^2}$

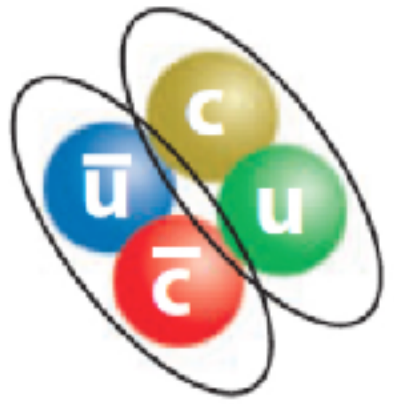
$$E_b = \hbar^2/2\mu a^2$$

$$\langle r \rangle = a/\sqrt{2} \geq 31.7^{+\infty}_{-24.5}\ \mathrm{fm}$$

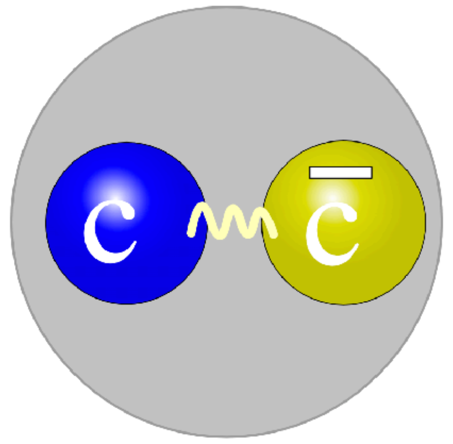
E_b(deuteron) = -2.2 MeV



D^0–$\overline{D^{*0}}$ "molecule"



Diquark–diantiquark



Conventional charmonium

Width：

- $1.19 \pm 0.21\ \mathrm{MeV}$

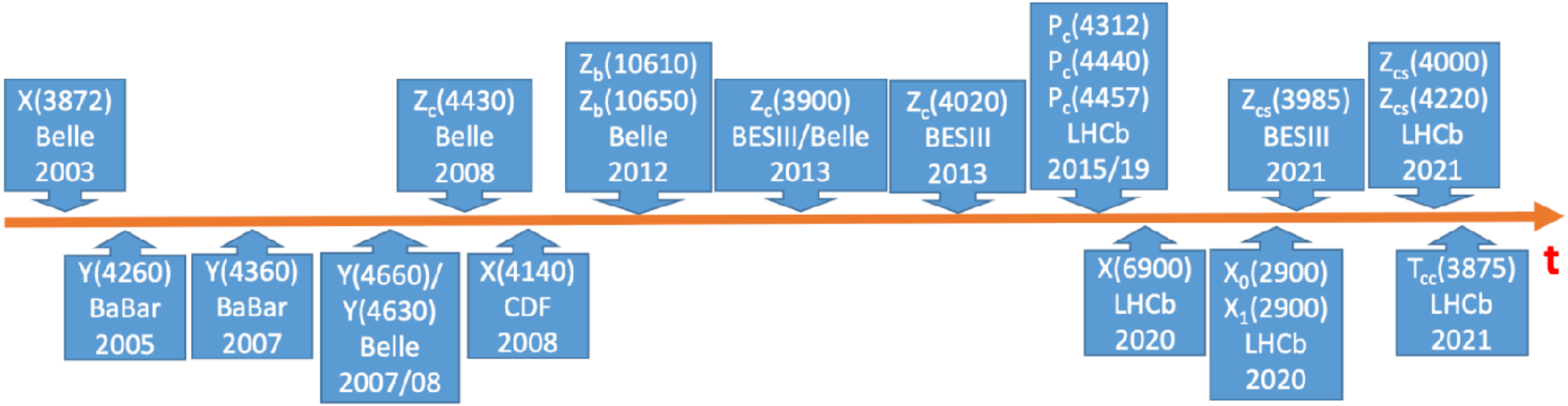
（The short the life, the larger the width）

- Lifetime is 20 times larger than the other charmonia nearby。

Production mechism：

- B decay
- prompt production in pp collision (should be small in case of charmonium)
- e^+e^- radiative decay

Phys.Rev.Lett. 91 (2003) 262001

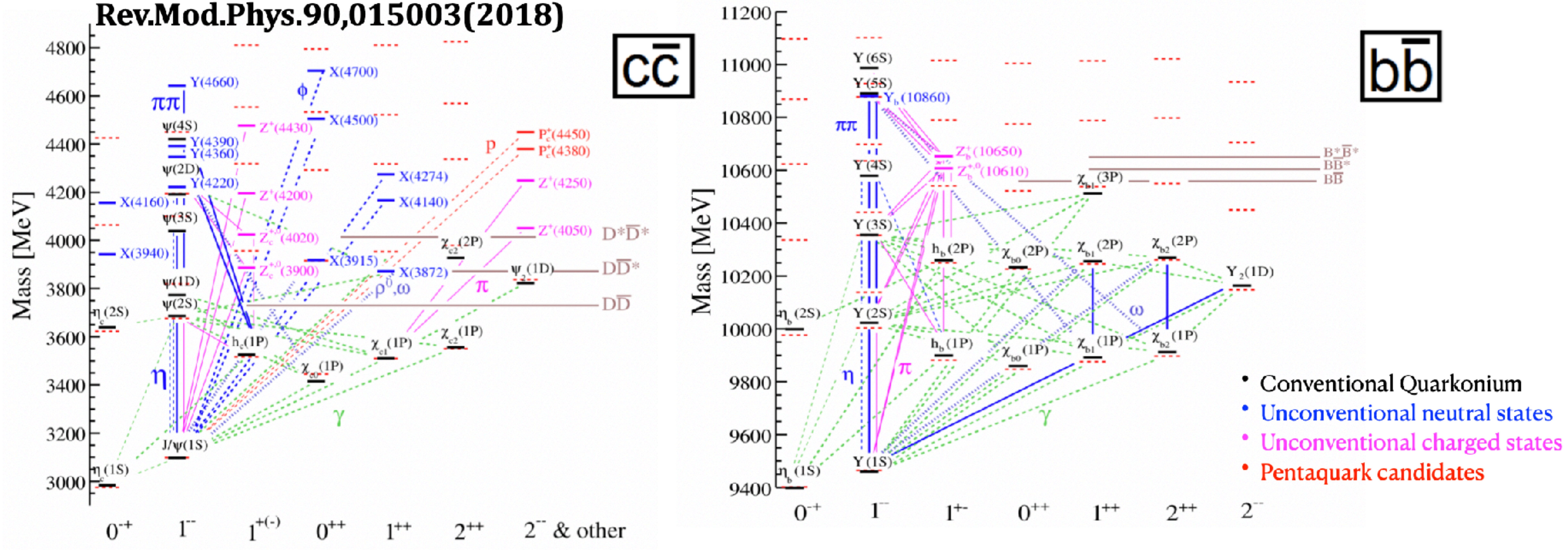


- Ever since the discovery of $X(3872)$, we have a golden era in the discovery of the exotic states.

Quarkonium spectroscopy

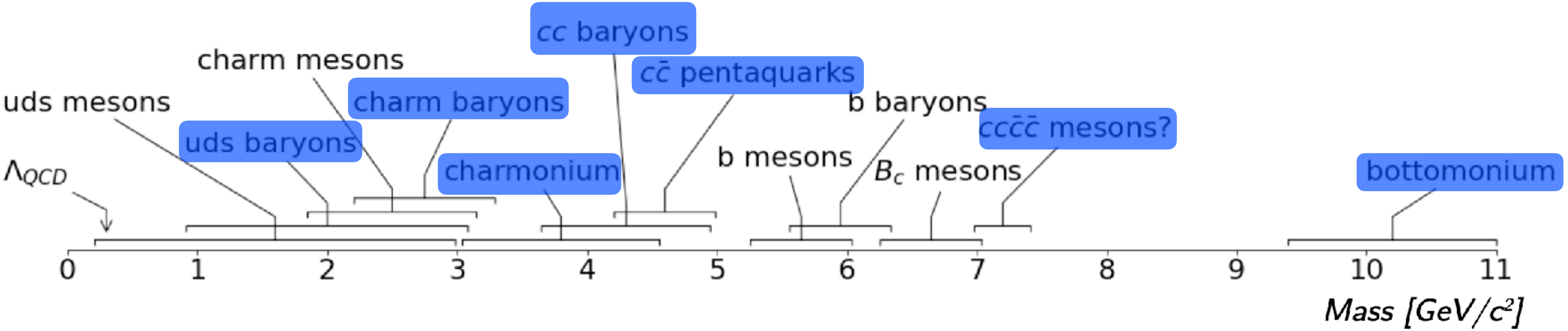
Parallel properties in $c\bar{c}$ and $b\bar{b}$.
Excellent experimental field!

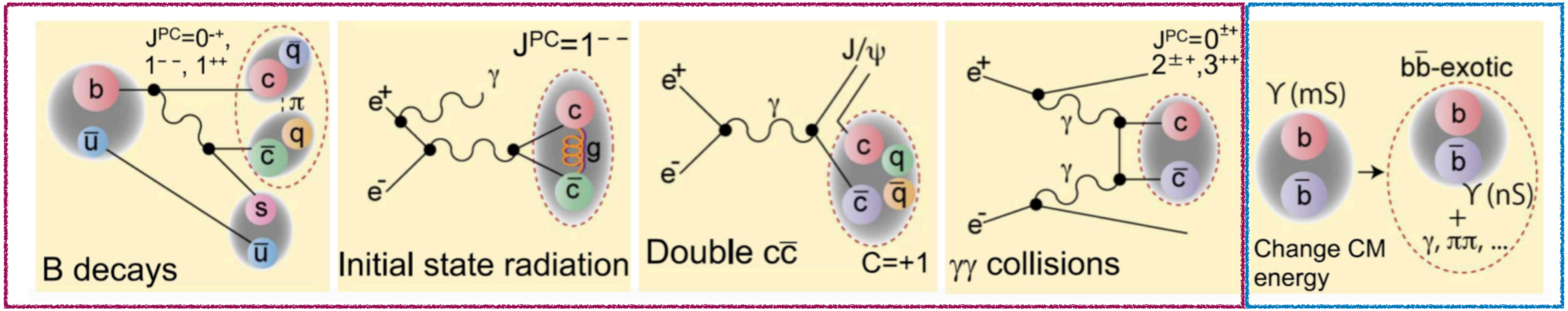
Rev.Mod.Phys.90,015003(2018)



Below $D\bar{D}/B\bar{B}$ threshold: Good agreement!
Above $D\bar{D}/B\bar{B}$ threshold: Unpredicted exotic states!!

Belle&Belle II capabilities on spectroscopy



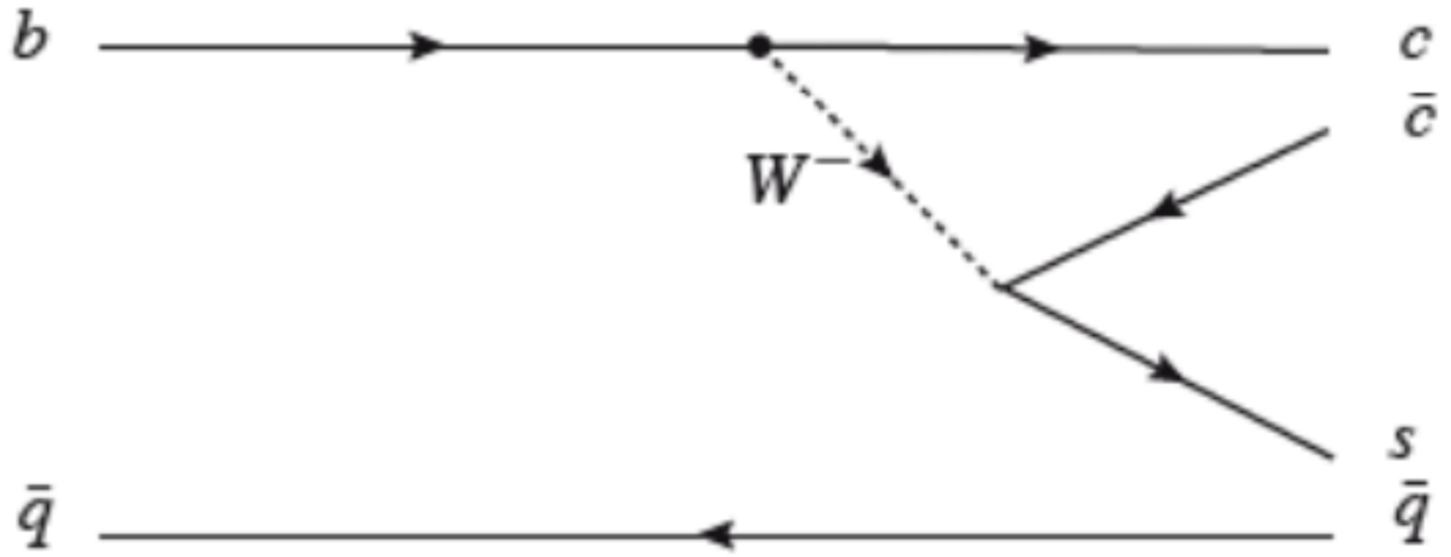


charmonium

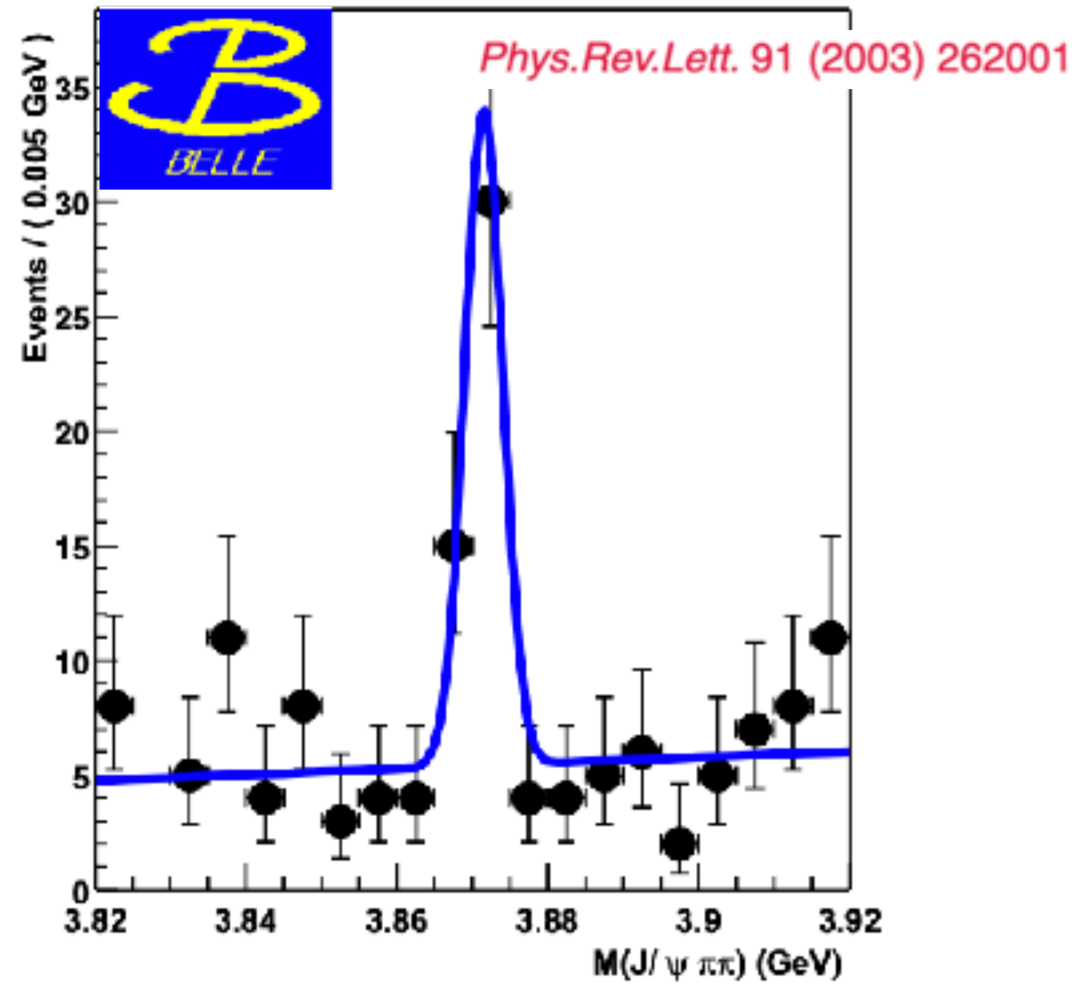
bottomonium

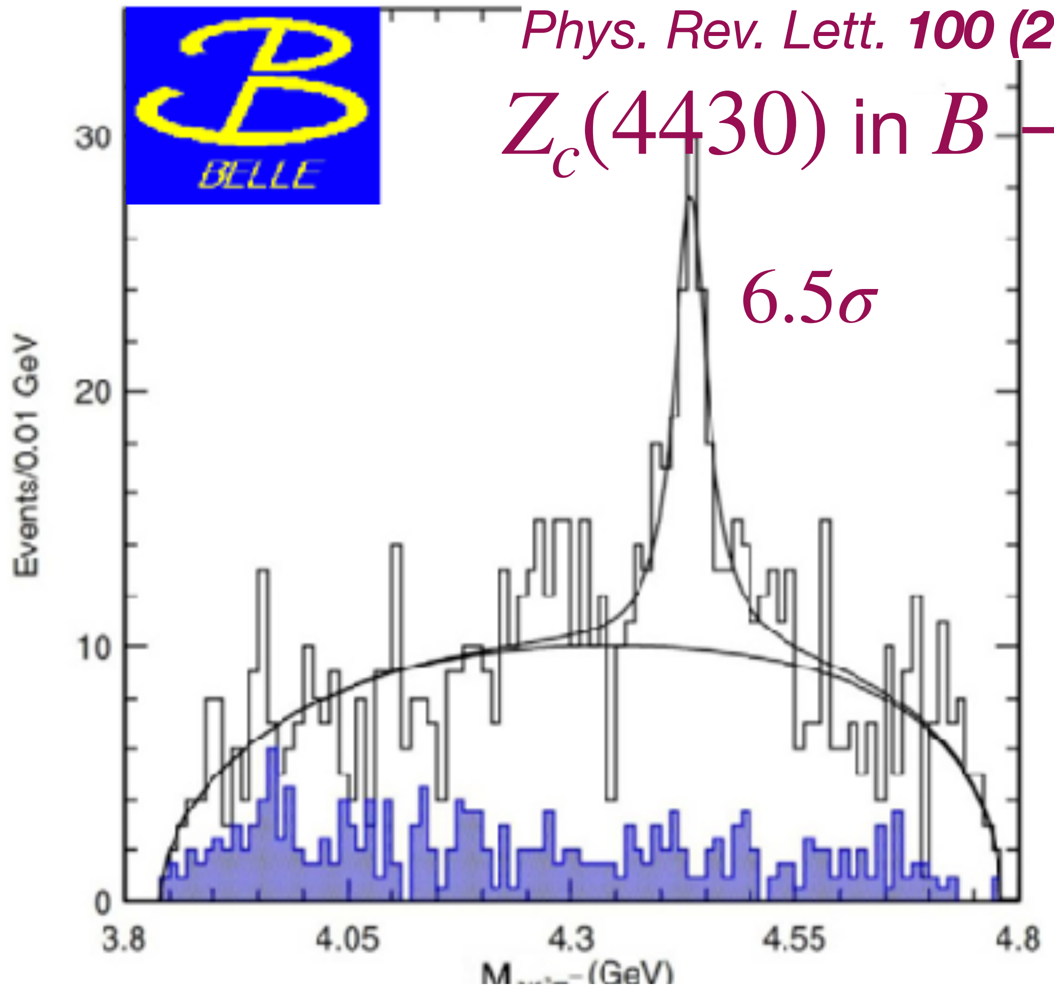
B decays

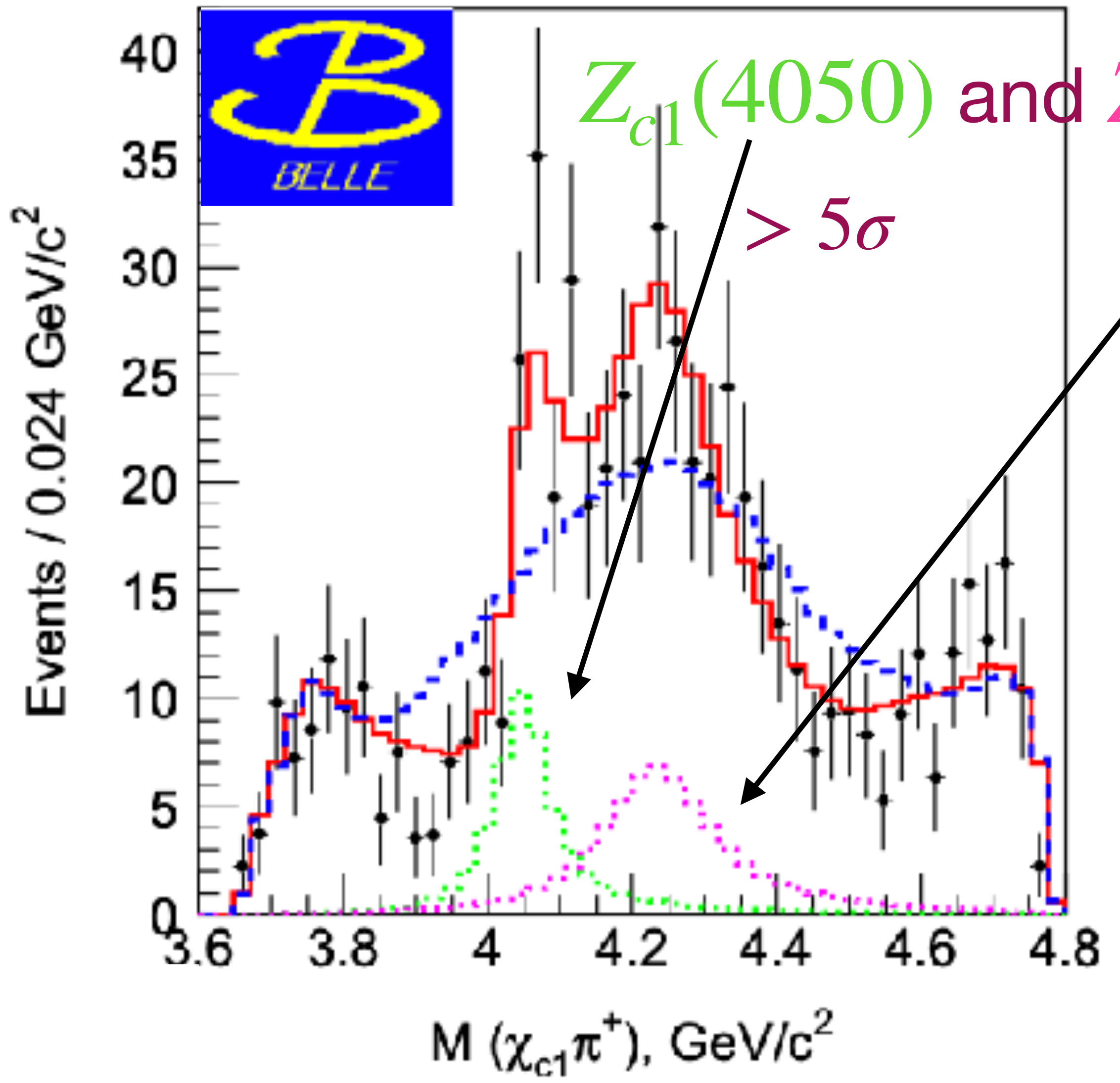
Large production rate provide a solid ground to search for exotics



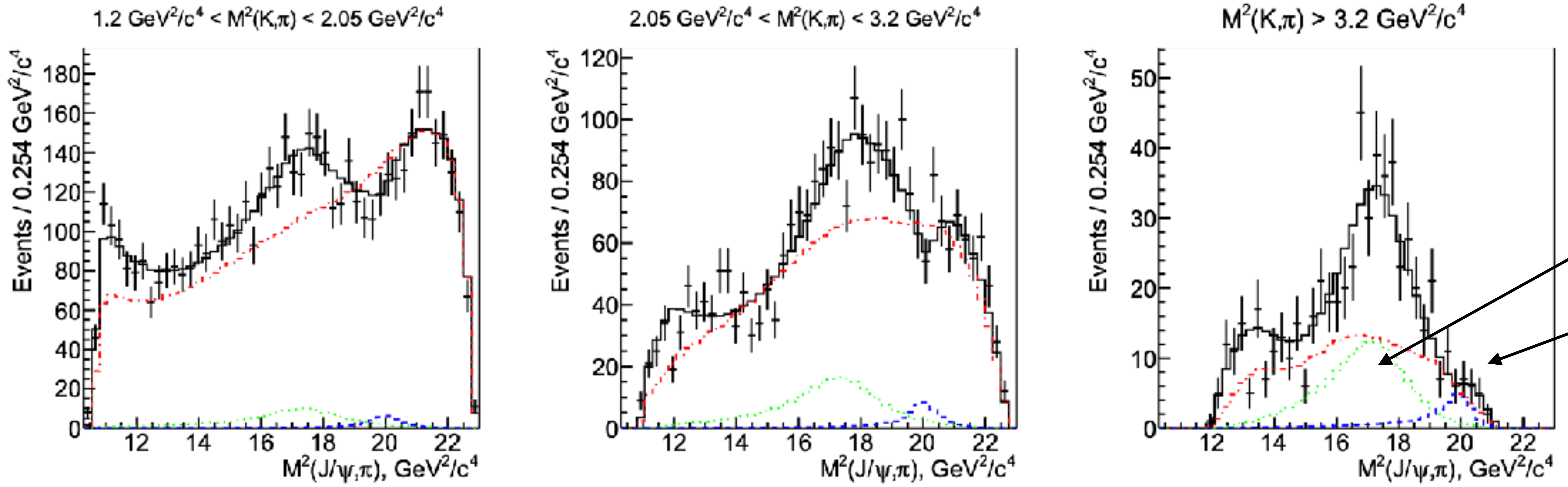
In history: observation of $X(3872)$ & establishment of various Z_c^+ states







Phys.Rev.D 78 (2008) 072004



$Z_c(4200)$ and $Z_c(4430)$ in $B \to K\pi^- J/\psi$

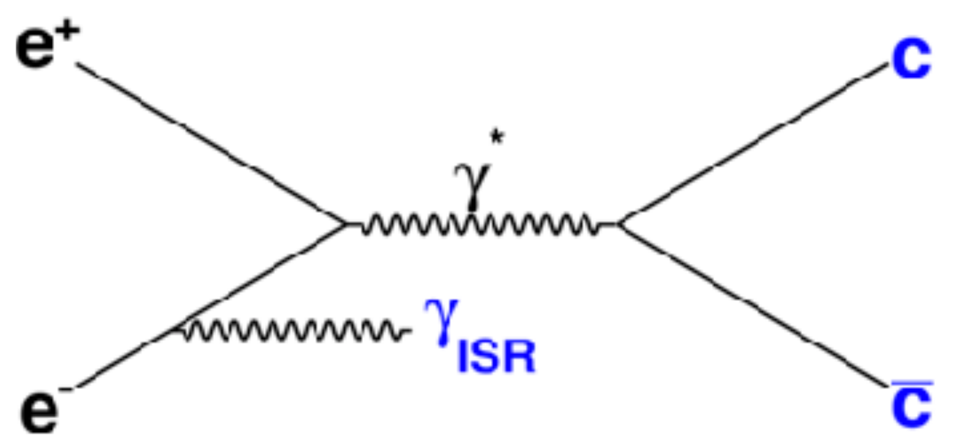
6.2σ

$> 3\sigma$

Phys.Rev.D 90 (2014) 11, 112009

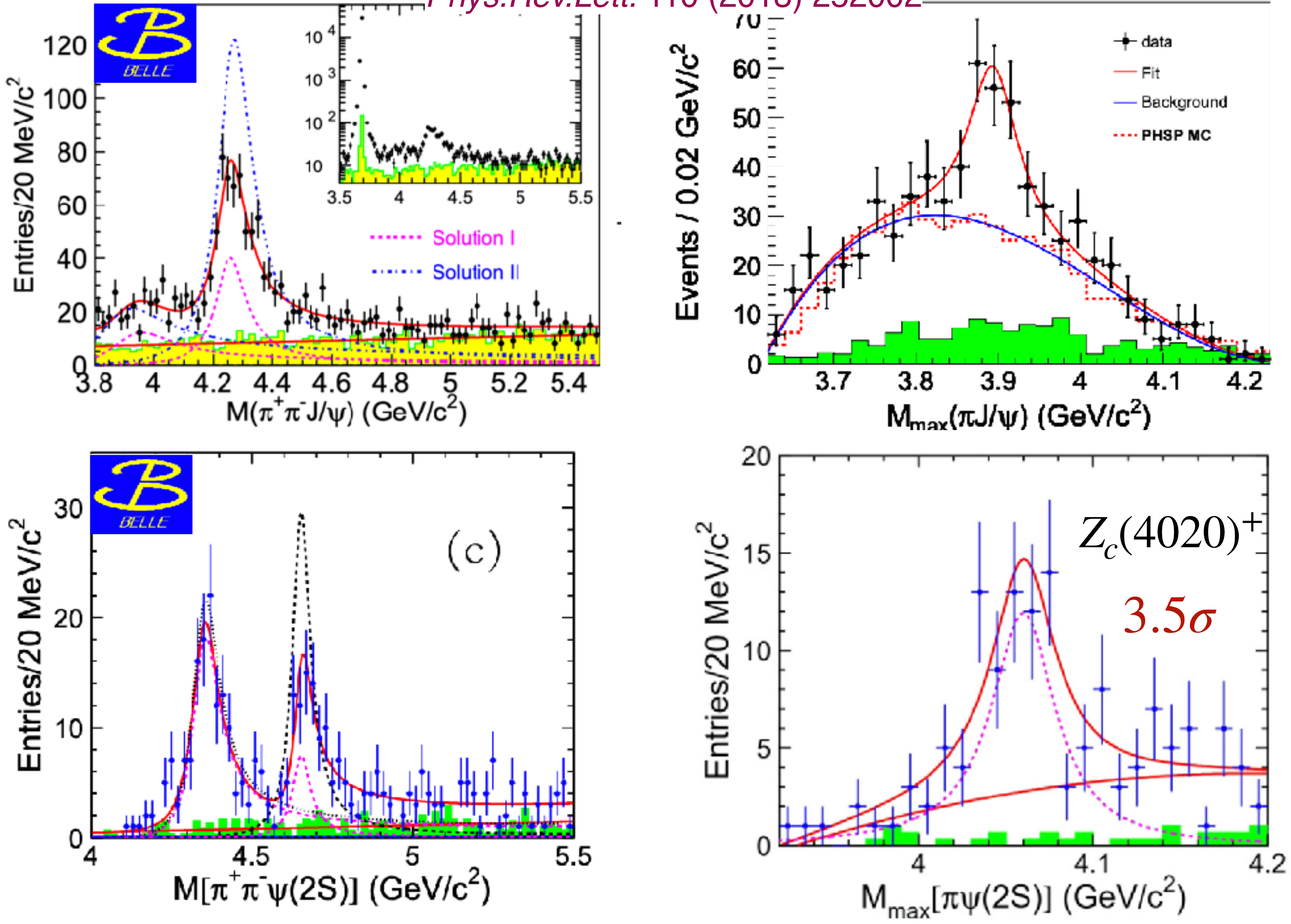
Initial state radiation

Allow us to reach lower c.m. energy "*for free*"

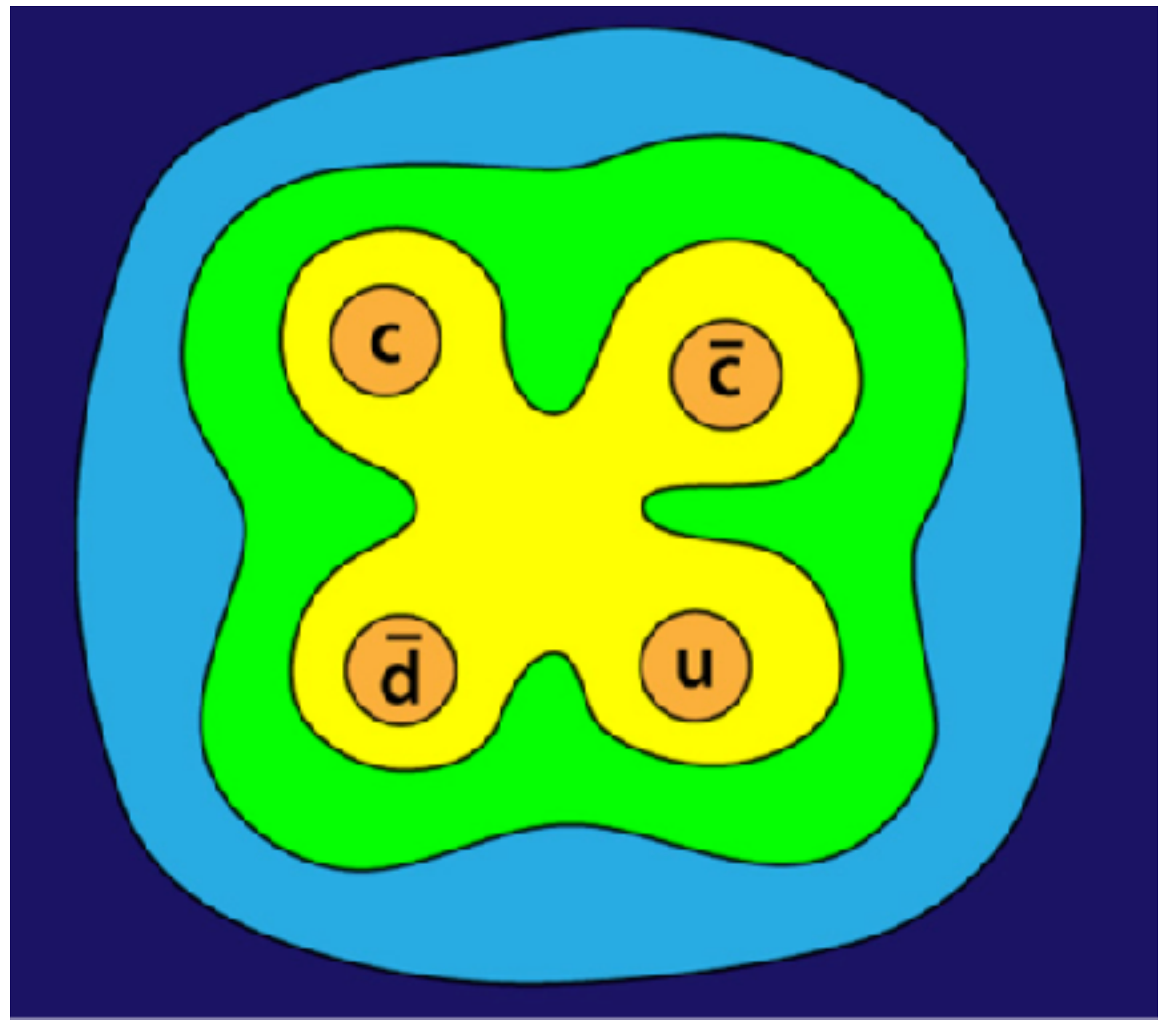


Great achievement in history: Observation of $Z_c(3900)^+$

Phys.Rev.Lett. 110 (2013) 252002



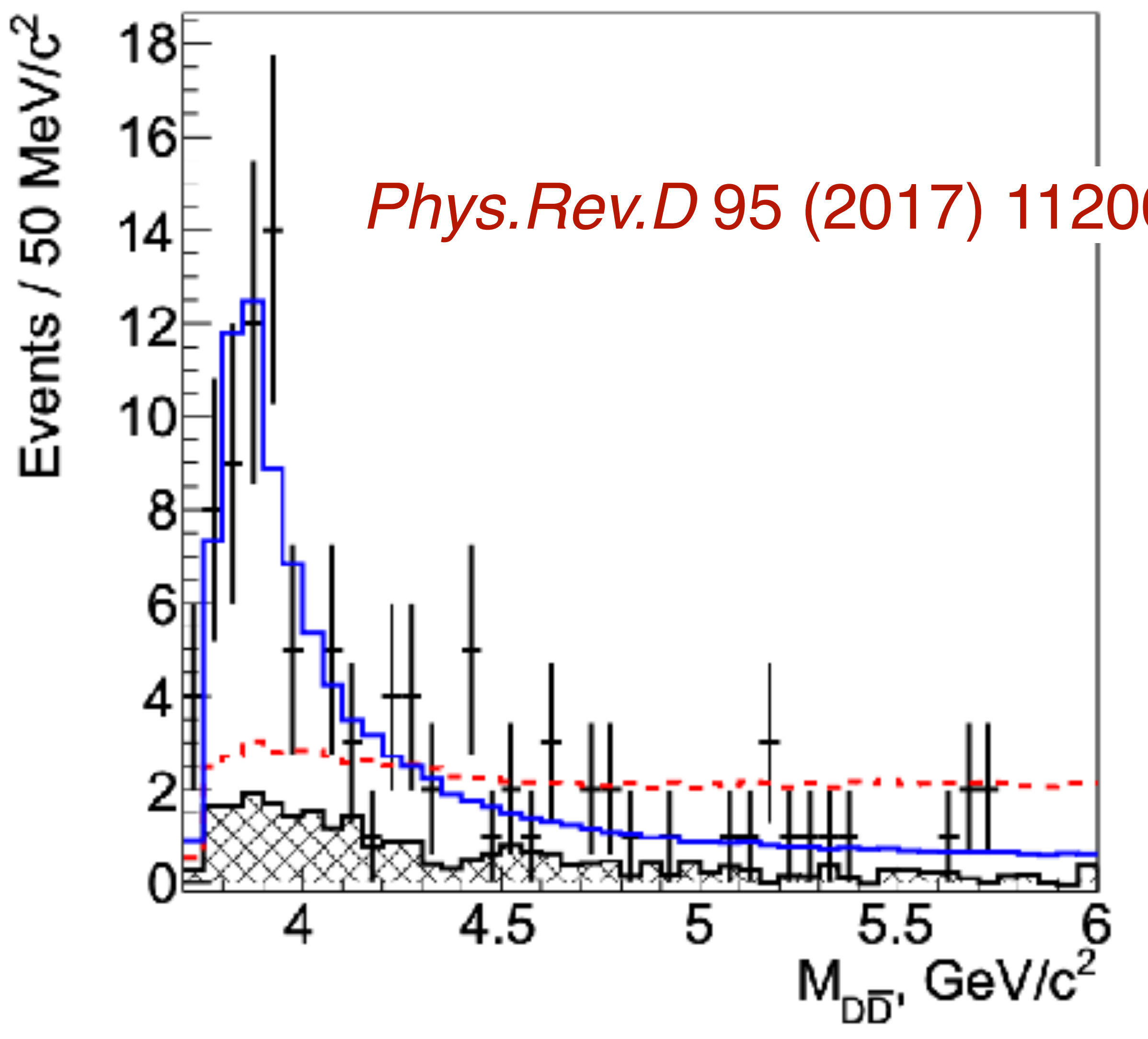
First solid four quark state!



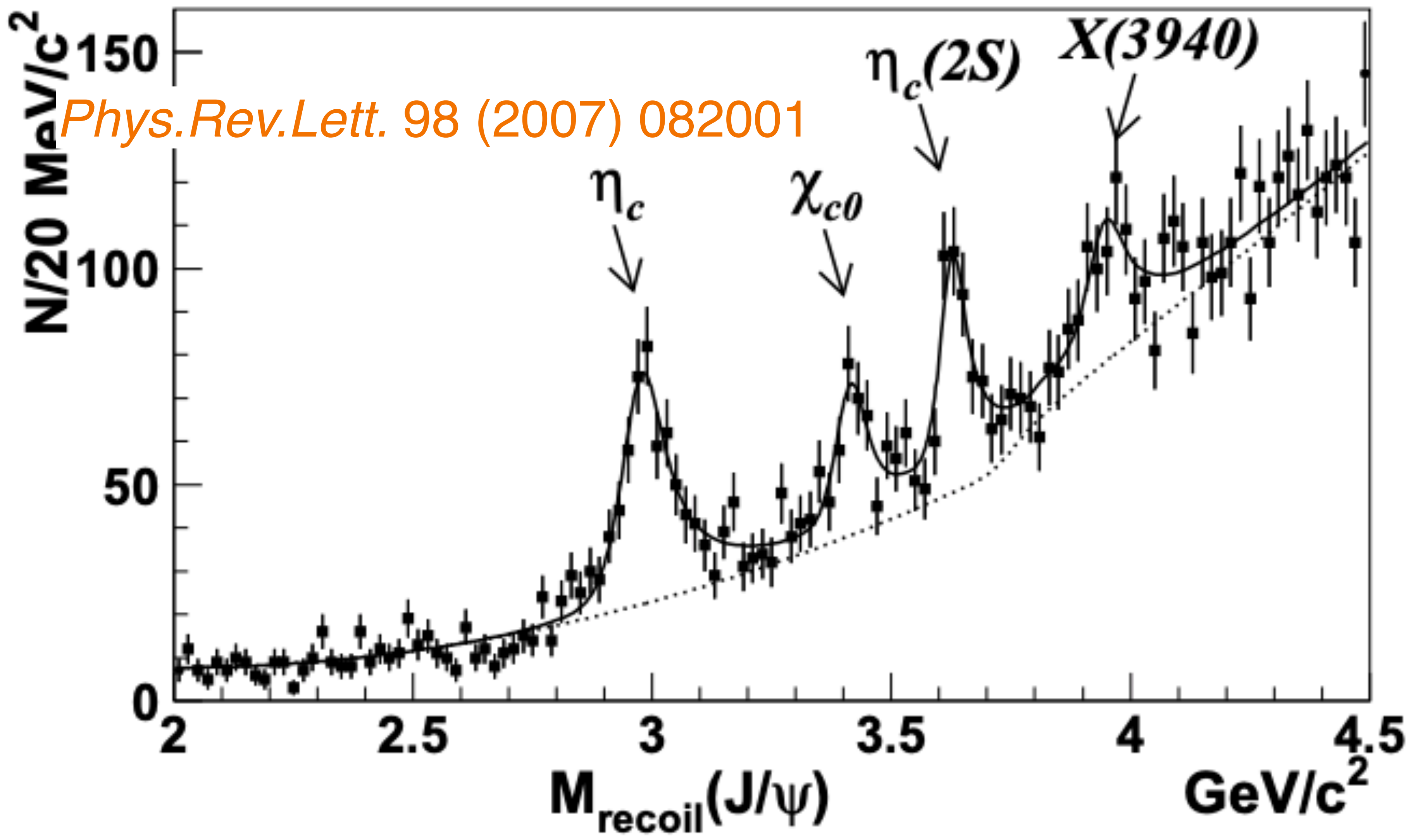
Double charmonium production

Unique field to produce charmonium(-like) particles

Rich resonances produced against J/ψ



Phys.Rev.D 95 (2017) 112003

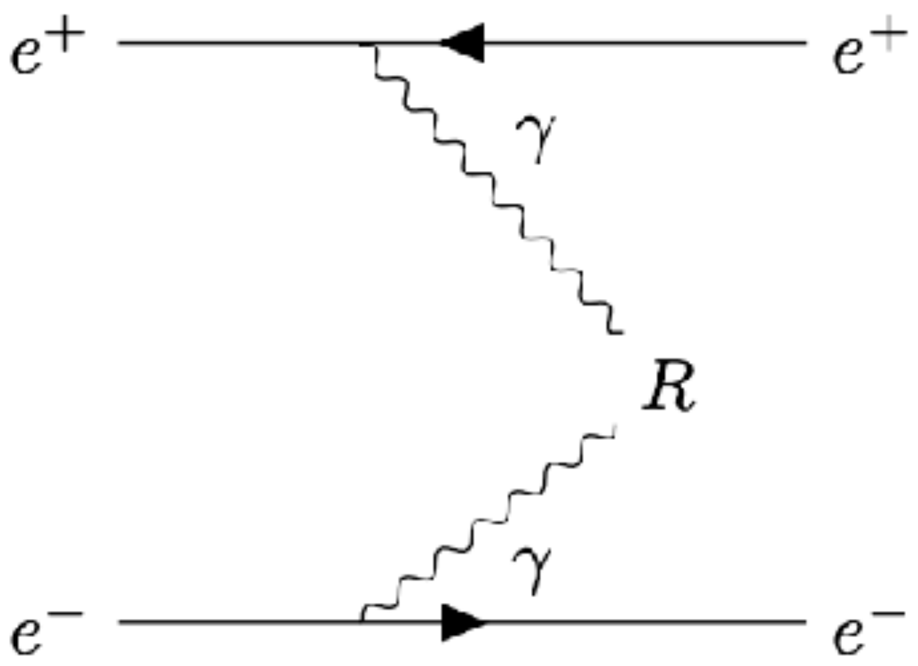


Phys.Rev.Lett. 98 (2007) 082001

$\chi_{c0}(3860)$ was observed in $e^+e^- \to J/\psi D\bar{D}$.
$X(3940)$ was discovered in J/ψ recoiling mass while dominantly decays into $D\bar{D}*$.

Two photon process

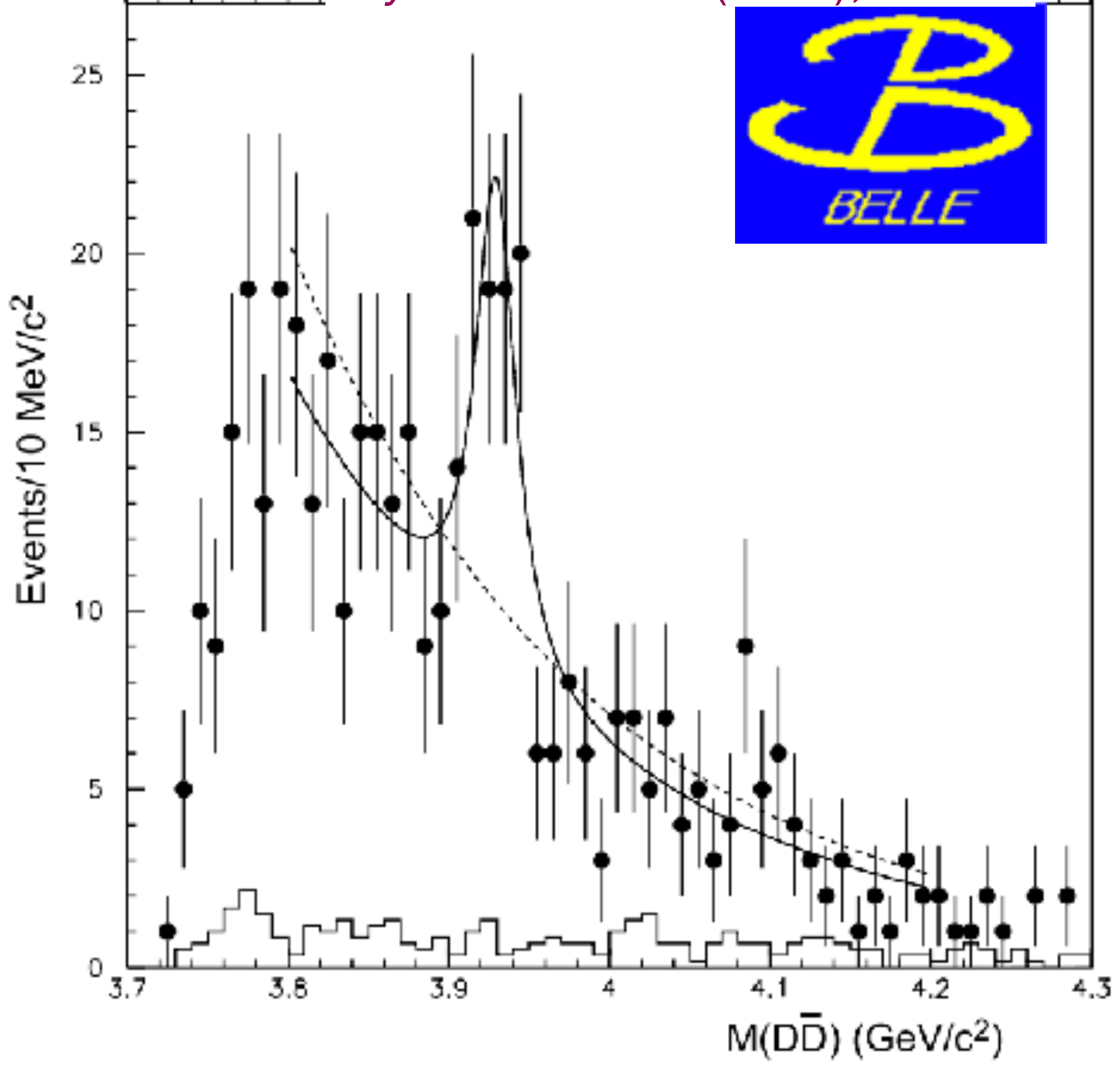
Unique field to produce charmonium(-like) particles



Establishment of exotic states in various final states

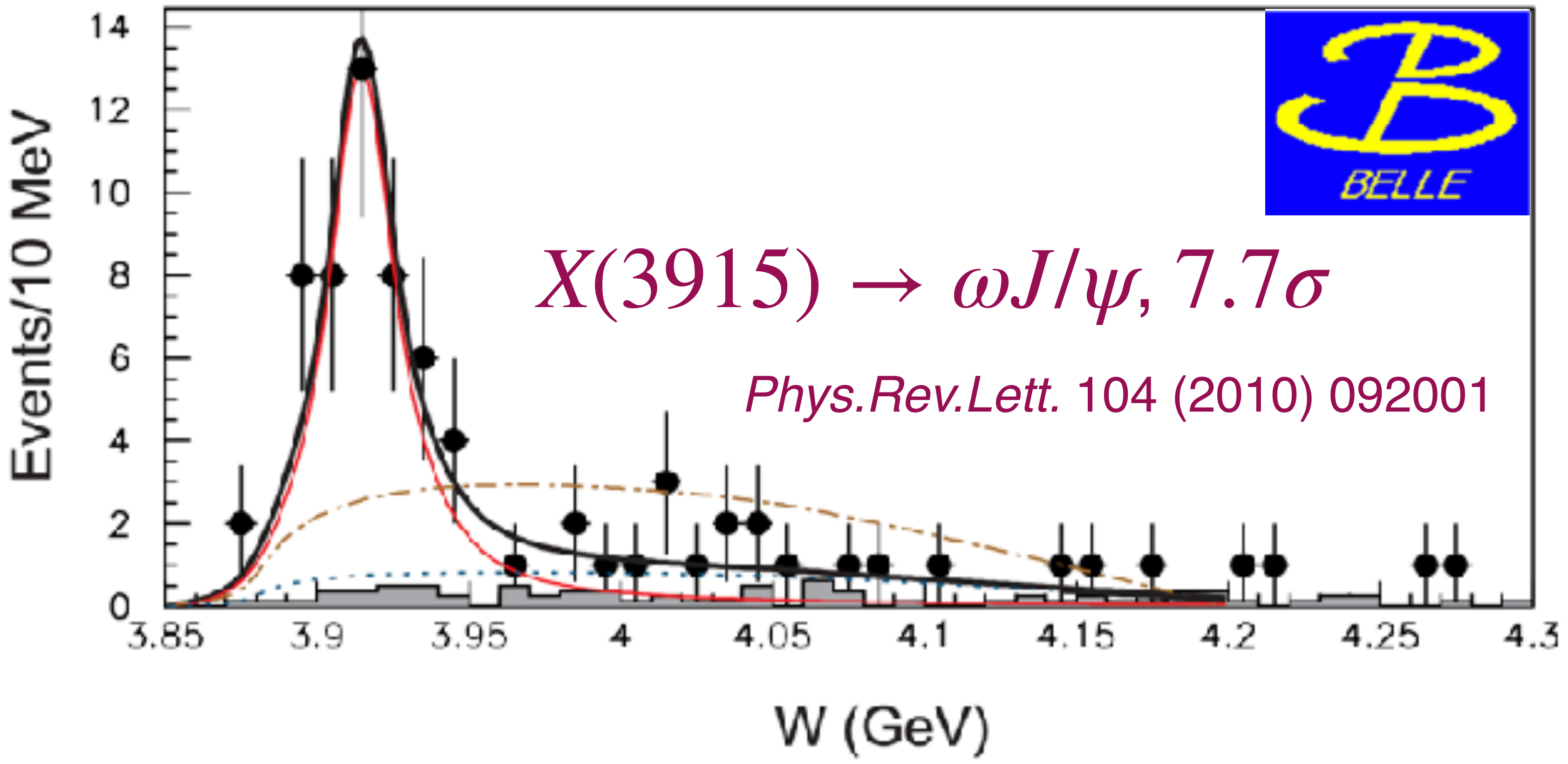
$X(3930) \to D\bar{D}, 5.3\sigma$

Phys.Rev.Lett. 96 (2006), 082003



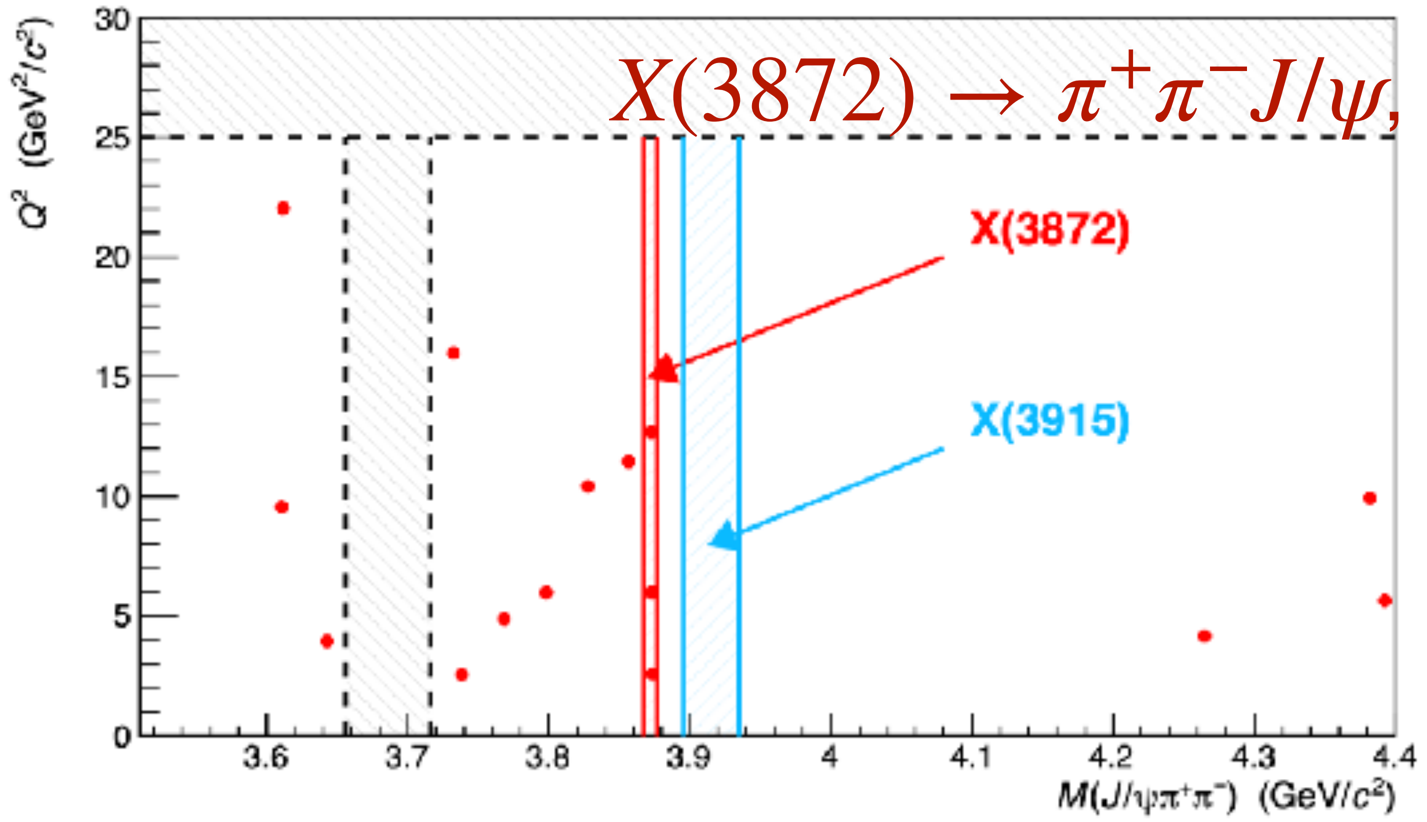
$X(3915) \to \omega J/\psi, 7.7\sigma$

Phys.Rev.Lett. 104 (2010) 092001



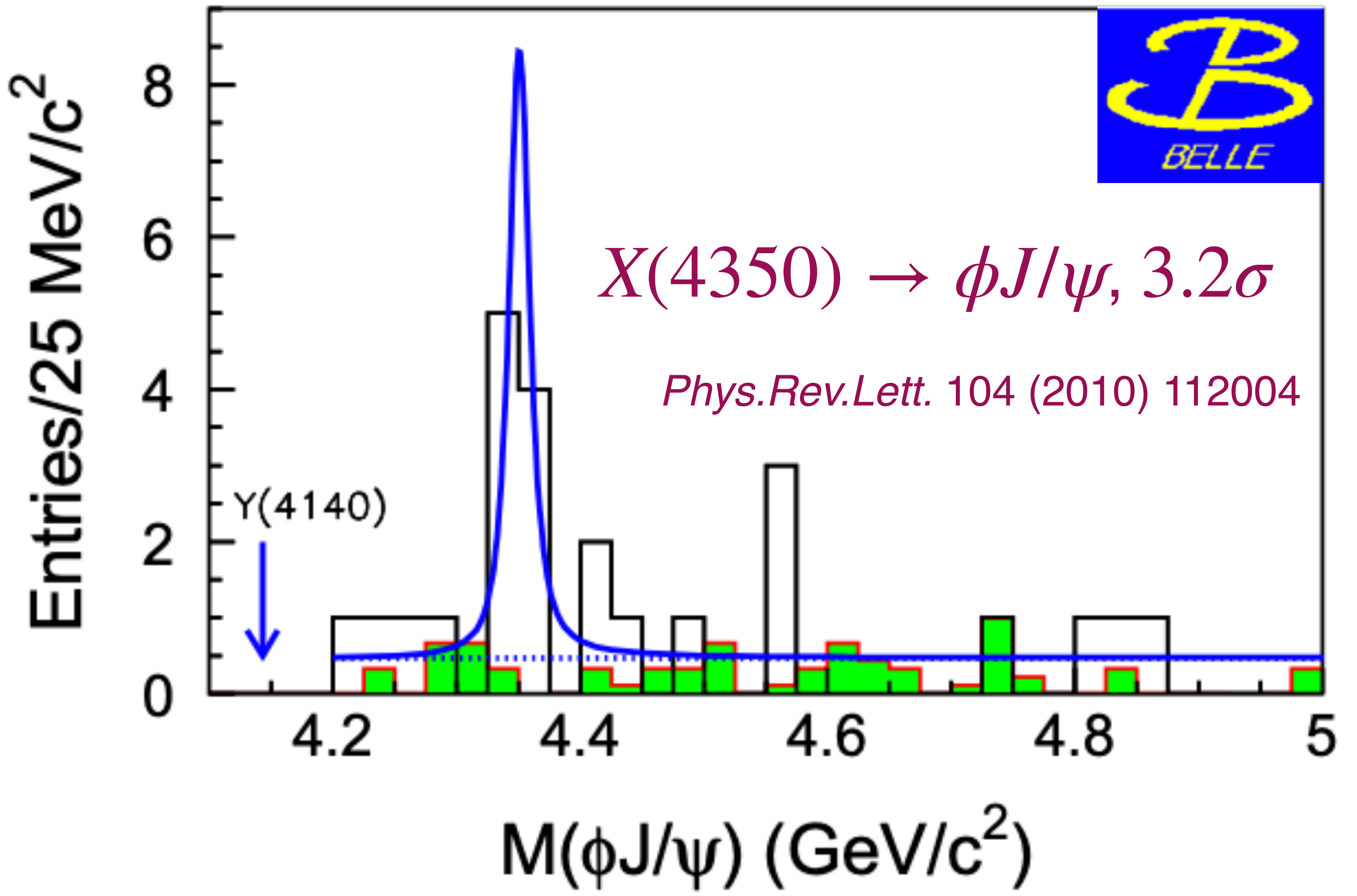
Phys.Rev.Lett. 126 (2021) 12, 122001

$X(3872) \to \pi^+\pi^- J/\psi, 3.2\sigma$

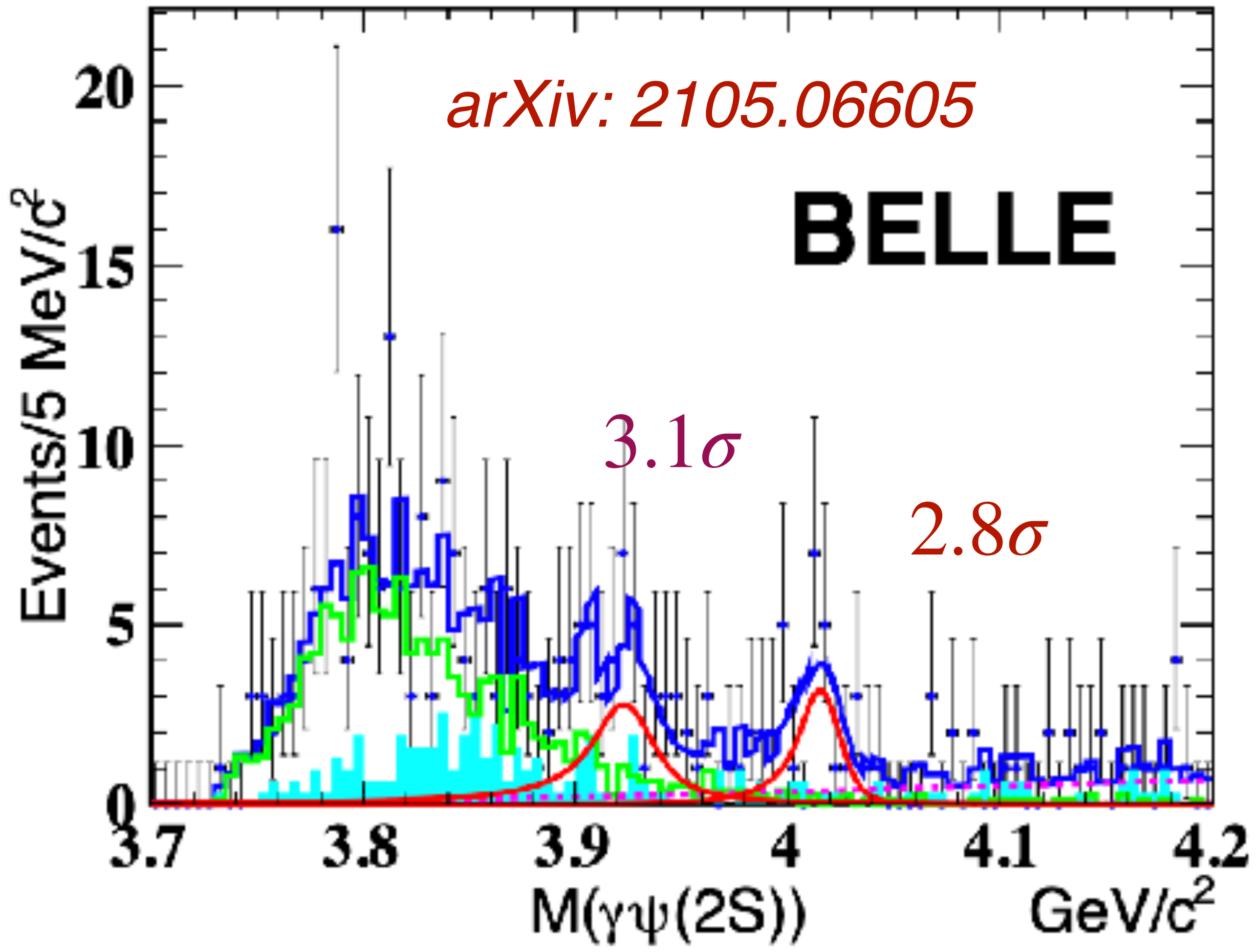


$X(4350) \to \phi J/\psi, 3.2\sigma$

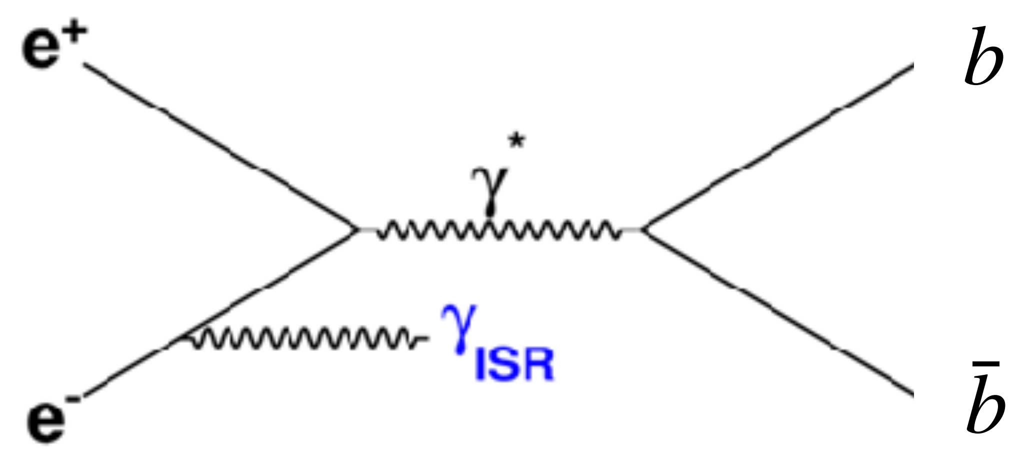
Phys.Rev.Lett. 104 (2010) 112004



arXiv: 2105.06605



Bottomonium production



Excellent play ground of NRQCD & unique properties

Questions raised:* $\Upsilon(5S)$ *mass* & *abnormal transition rate

Phys.Rev.Lett. 100 (2008) 112001

Process	$\Gamma_{\rm total}$	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	110 MeV	0.31 keV	0.59 MeV

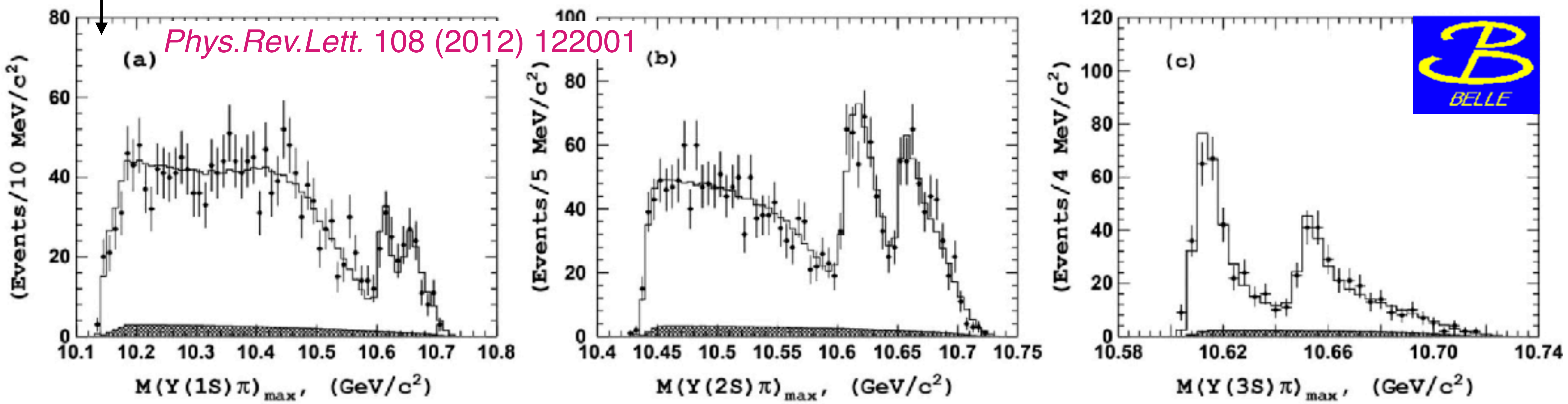
$> 10^2 \times$

$$\frac{\Gamma(\Upsilon(5S) \to h_b(1P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)} = 0.46 \pm 0.08^{+0.07}_{-0.12}$$

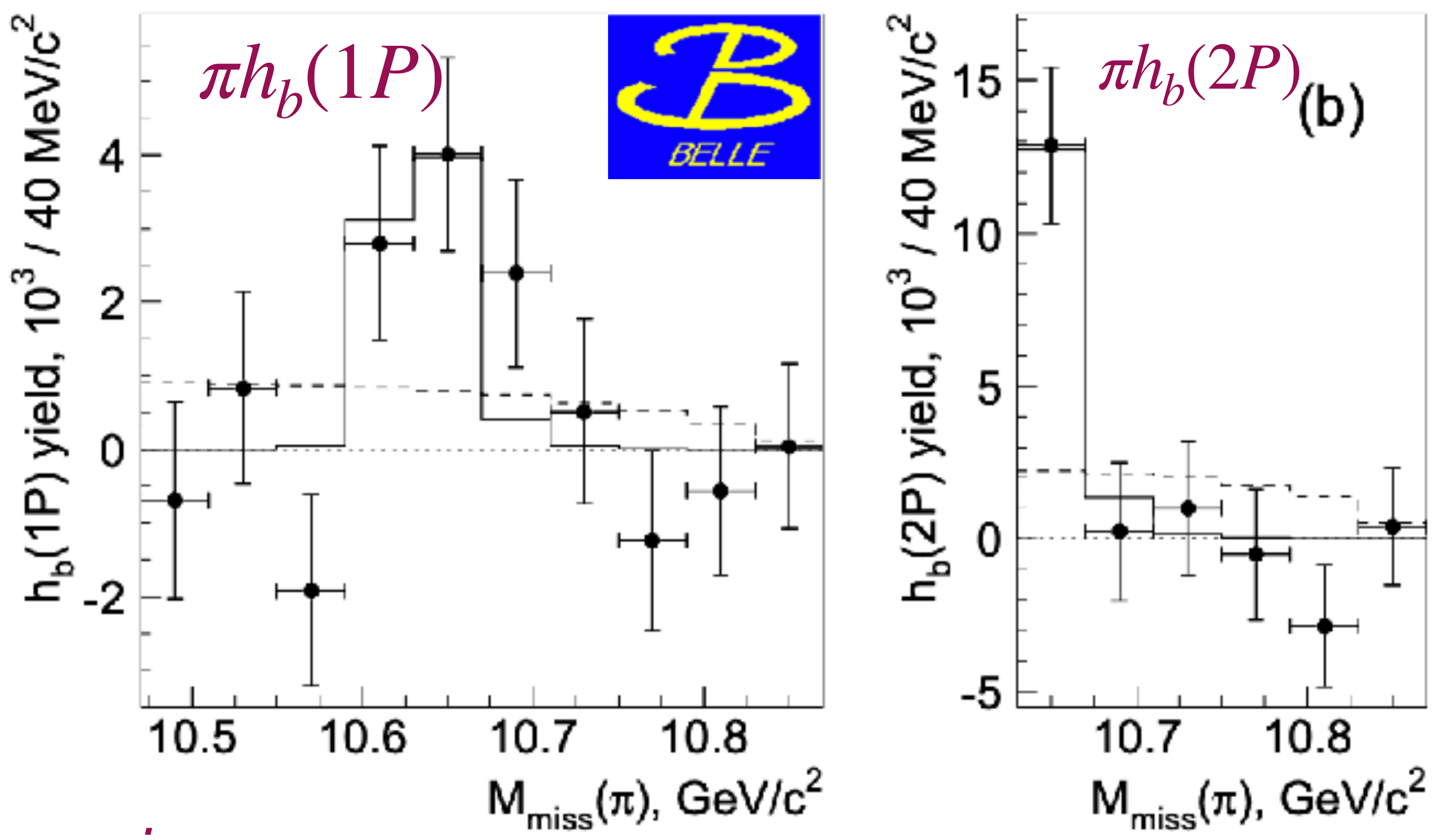
$$\frac{\Gamma(\Upsilon(5S) \to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.77 \pm 0.08^{+0.22}_{-0.17}$$

Observation of $Z_b(10610)^+$ and $Z_b(10650)^+$

Phys.Rev.Lett. 108 (2012) 122001

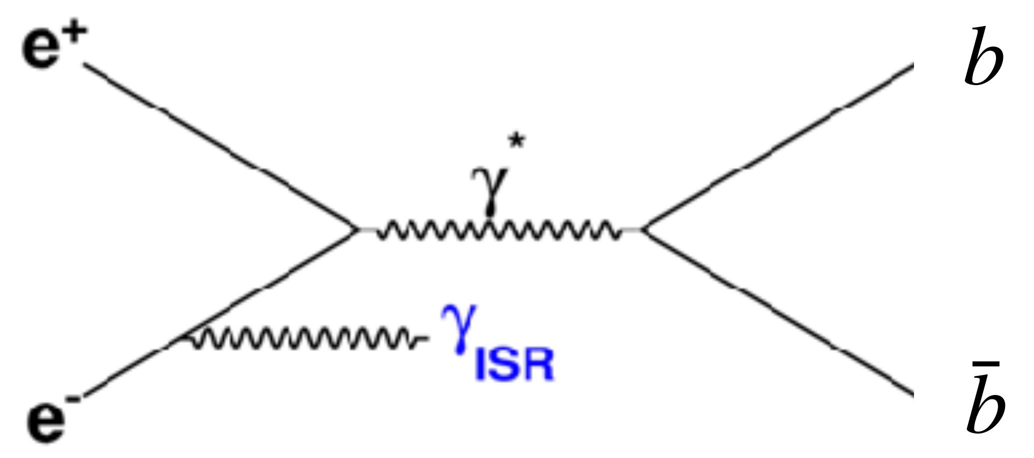


Phys.Rev.Lett. 117 (2016) 14, 142001



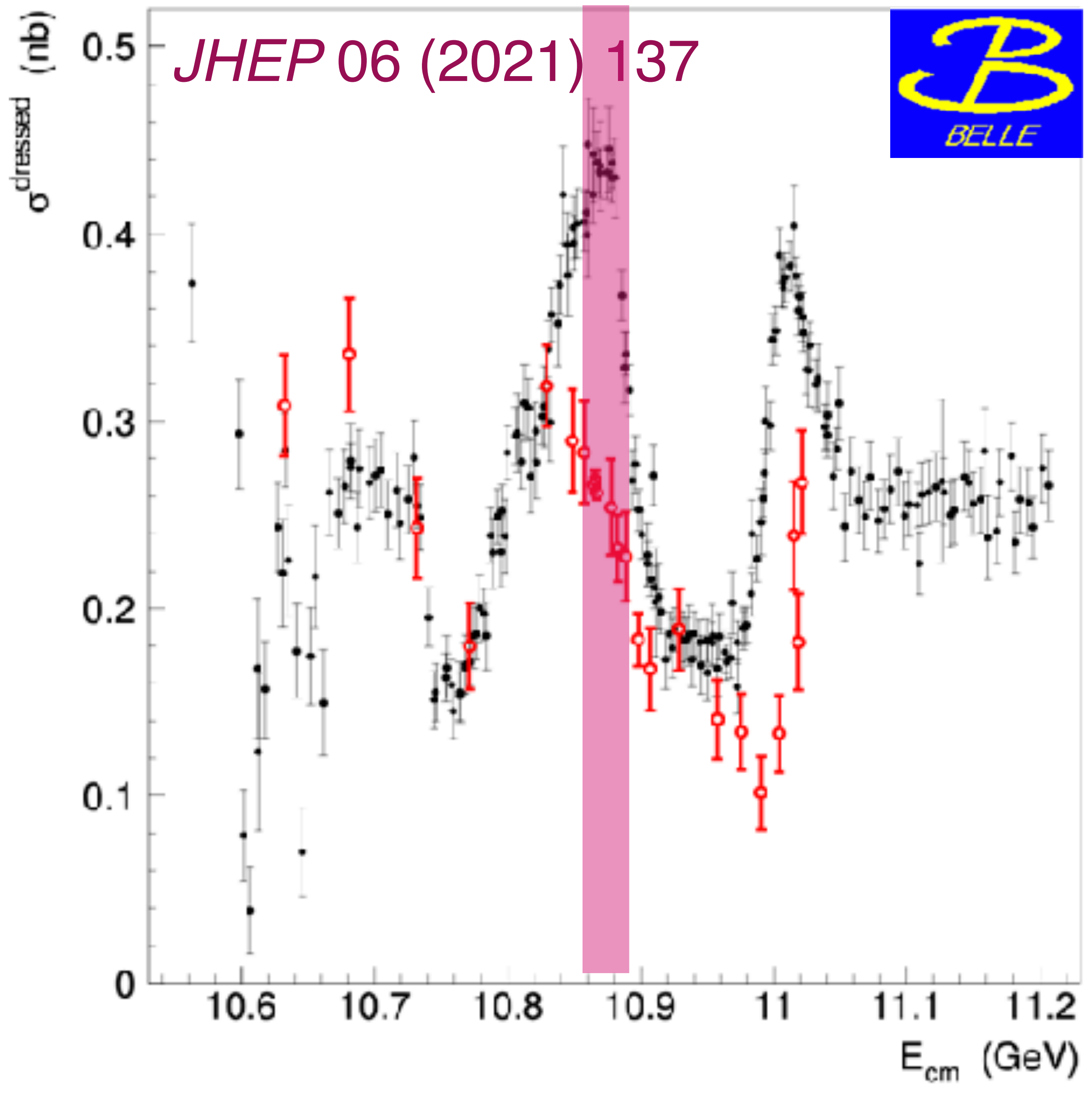
***Similar feature is also found in higher charmonia*

Bottomonium production

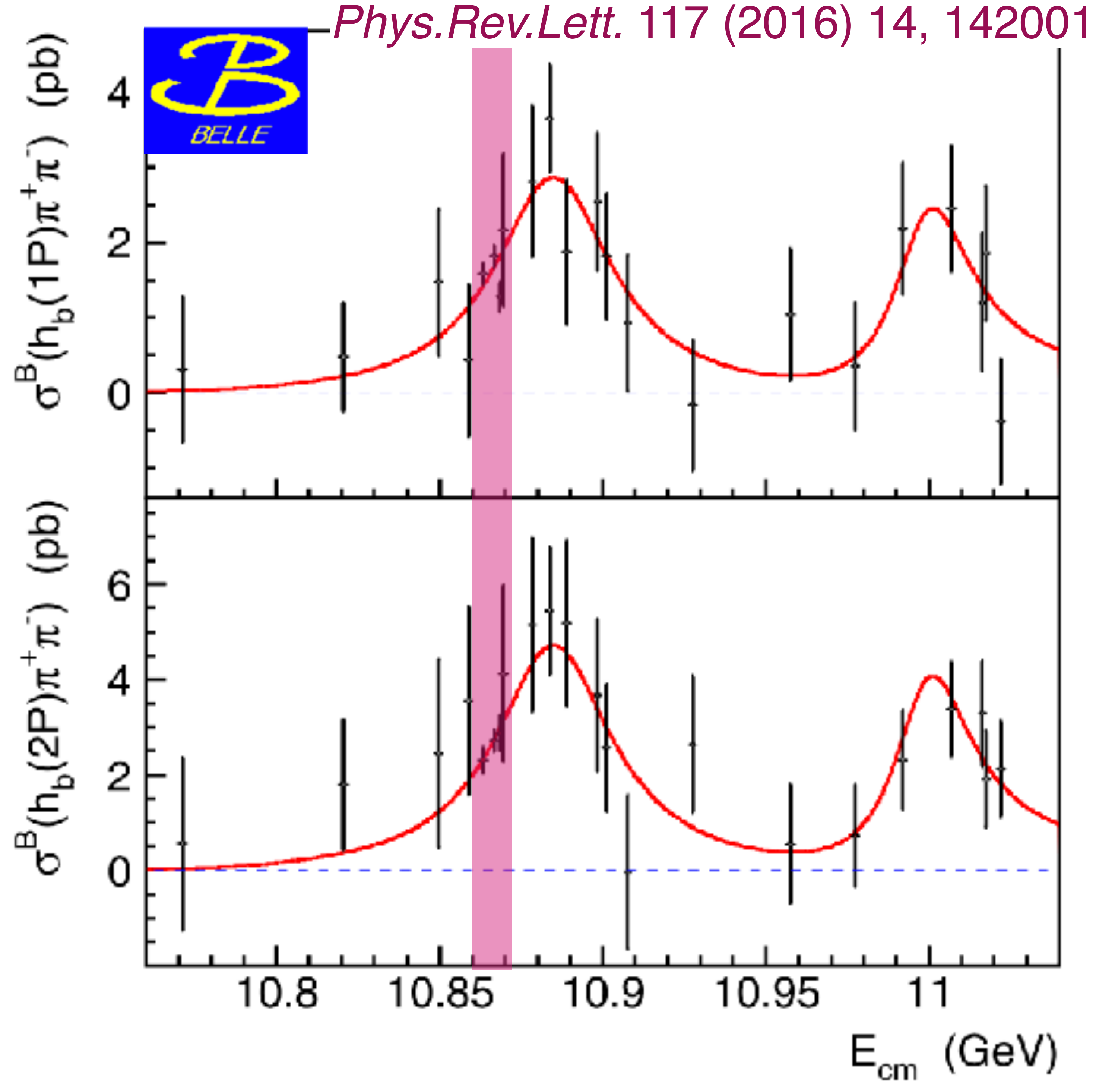


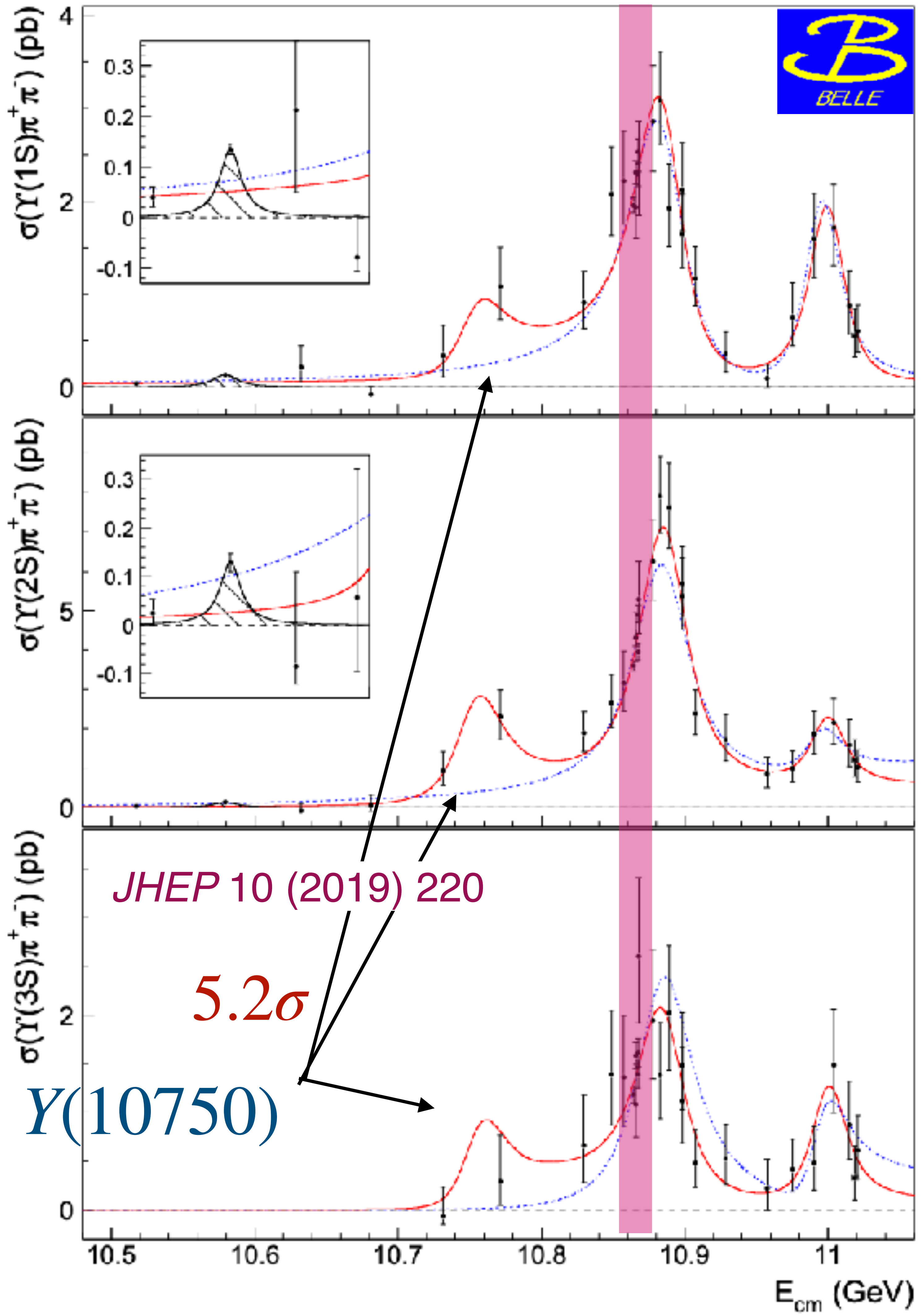
Excellent play ground of NRQCD & unique properties

Questions raised: $\Upsilon(5S)$ mass & abnormal transition rate



Red dots: Measured $\sigma[e^+e^- \to B^{(*)}\bar{B}^{(*)}]$
Black dots: total $b\bar{b}$ dressed cross section
Chin. Phys. C 44, 083001 (2020)

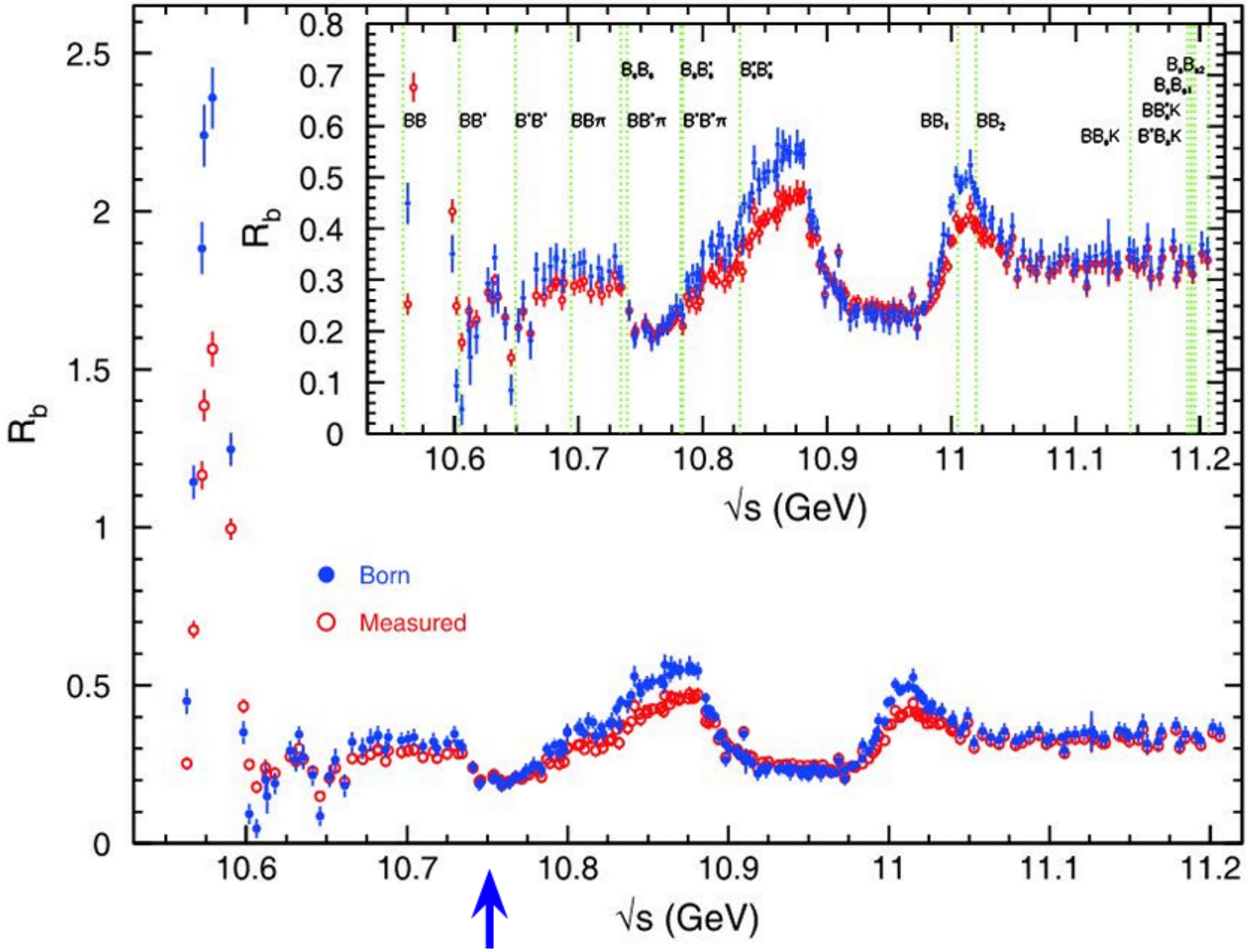




- Excess between $e^+e^- \to b\bar{b}$ and $B^{(*)}\bar{B}^{(*)}$, others?
- Cross sections do not peak at $\Upsilon(5S)$ mass.

A new state: $Y(10750)$

Y(10753): why it's important



$$R_b = \frac{\sigma(e^+e^- \to b\bar{b})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

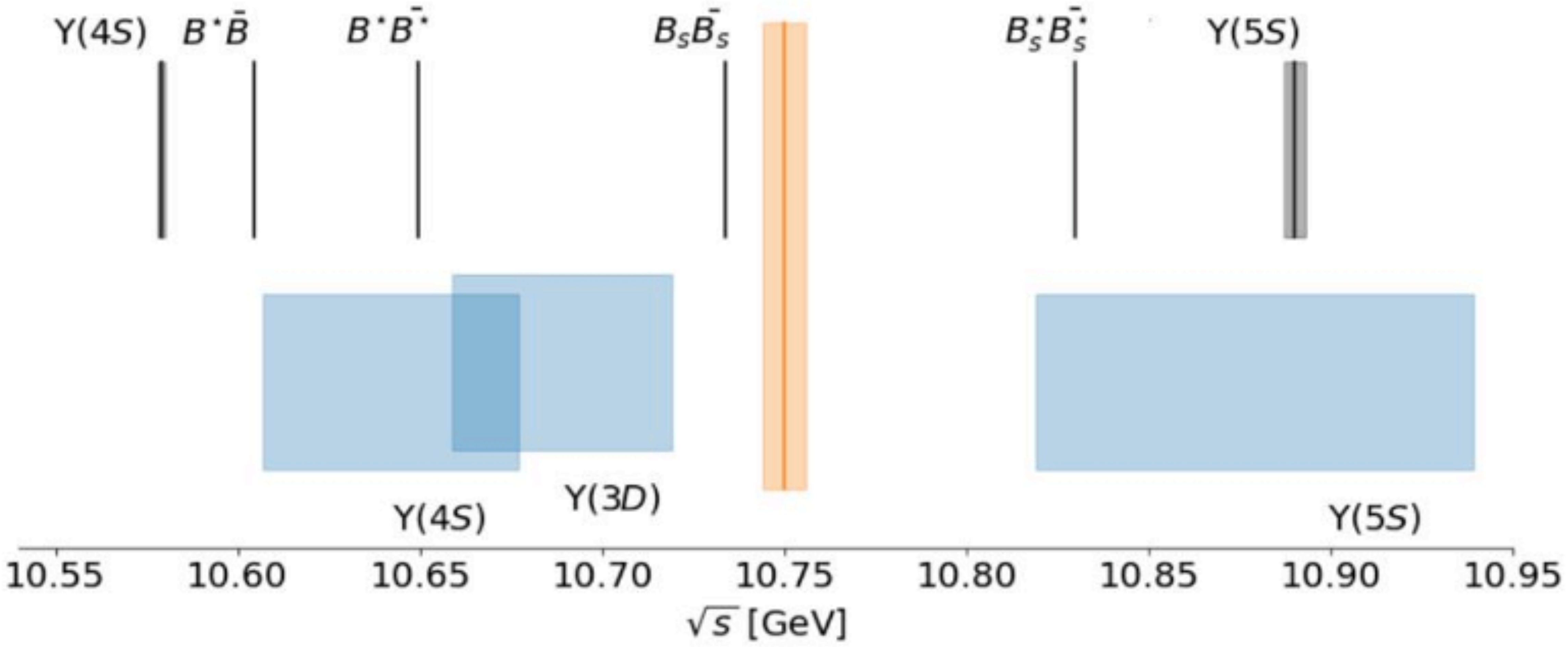
Dip: likely caused by interference between BW and smooth component

Chin. Phys. C 44 (2020) 8, 083001

Υ(10753): why it's important

Uncertain nature:

- No clear conventional $b\bar{b}$ candidate
- Molecule? 10.75 GeV isn't a threshold...
- Tetraquark?



Conventional interpretations:

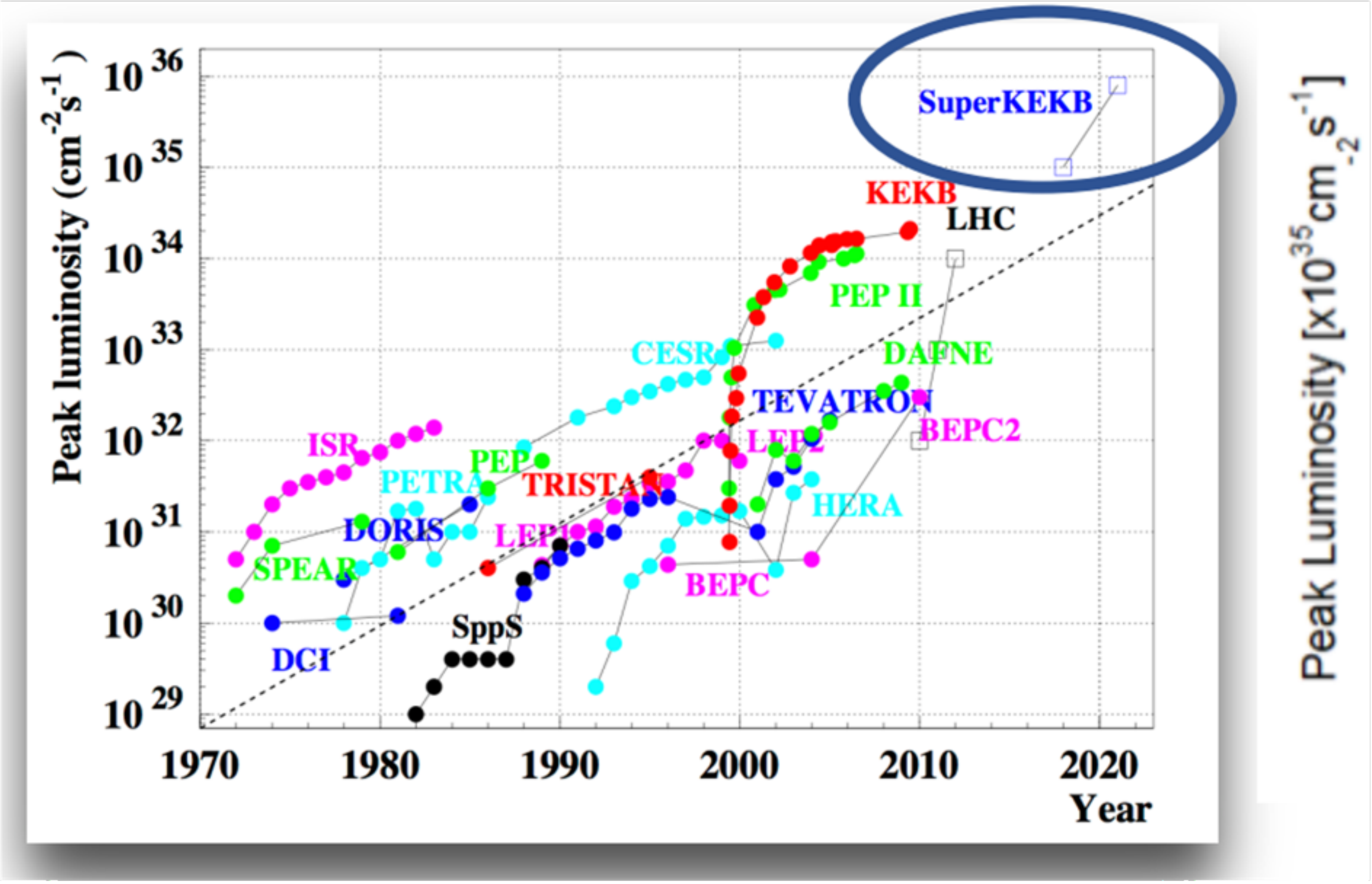
Chen, Zhang & He, PRD 101, 014020 (2020)
Giron & Lebed, PRD 102, 014036 (2020)
Li et al., EPJC 80, 59, (2020)
Li et al., PRD 104, 034036 (2021)
van Beveren & Oset, PPNP 117, 103845 (2021)
Bai et al., PRD 105, 074007 (2022)
Husken, Mitchell & Swanson, arXiv:2204.11915 (2022)
Kher et al., EPJ+ 137, 357 (2022)
Li, Bai & Liu, arXiv:2205.04049 (2022)
Liang, Ikeno & Oset, PLB 803, 135340 (2020)
...

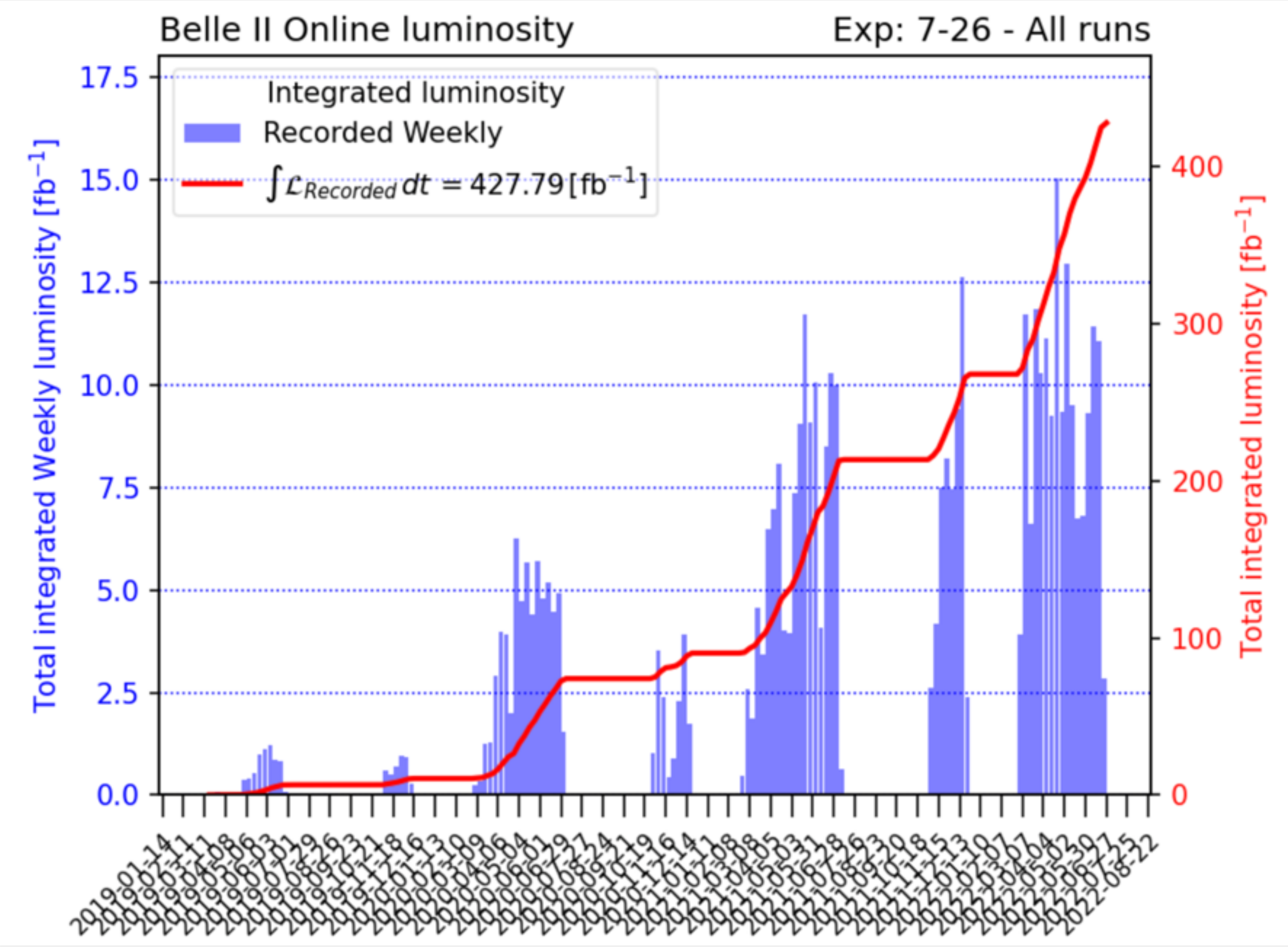
Exotic interpretations:

Wang, CPC 43, 123102 (2019)
Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
Bicudo, Cardoso & Wagner, PRD 103, 074507 (2020)
Castella & Passemar, PRD 104, 034019 (2021)
...

Belle II luminosity

High precision frontier

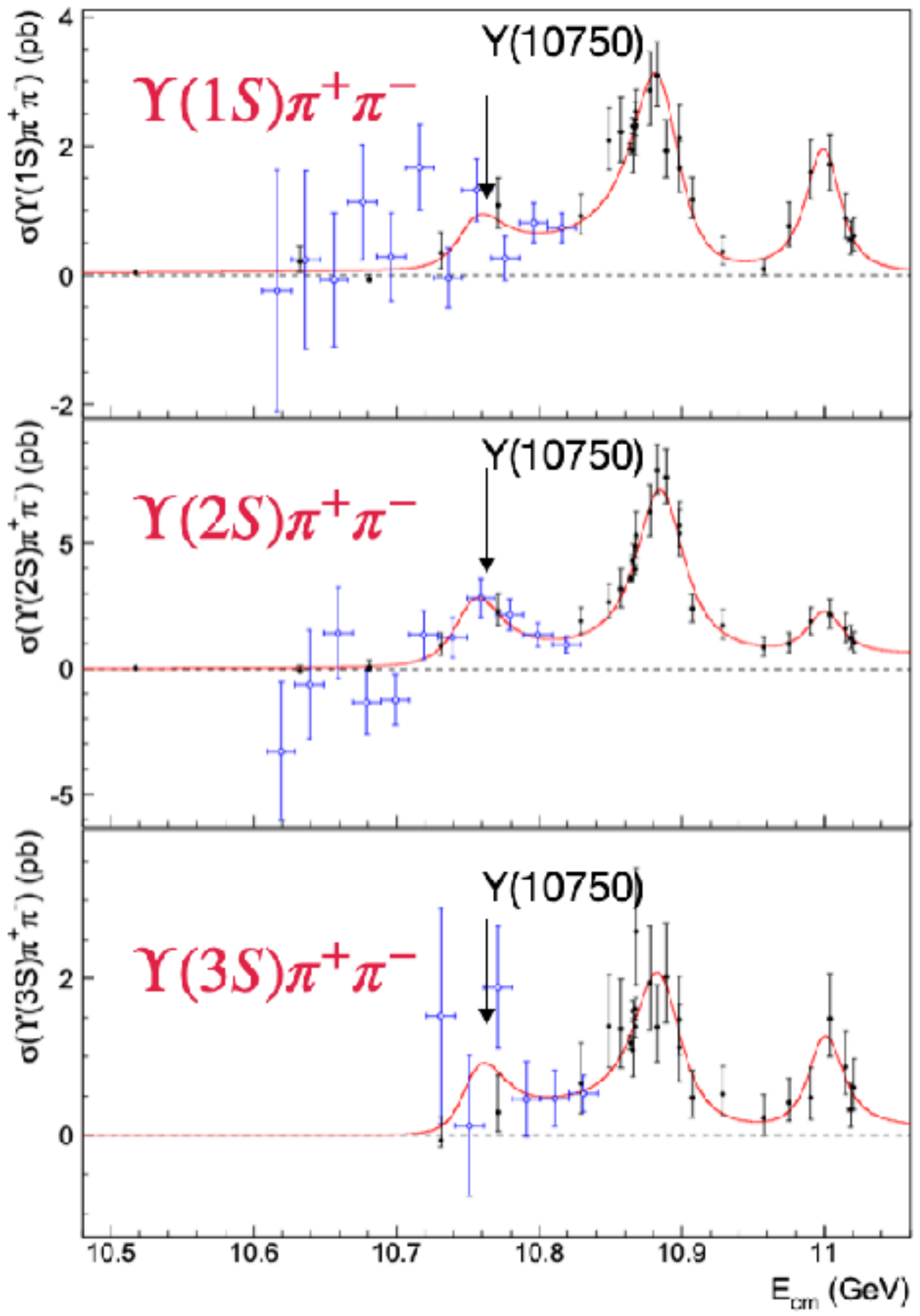




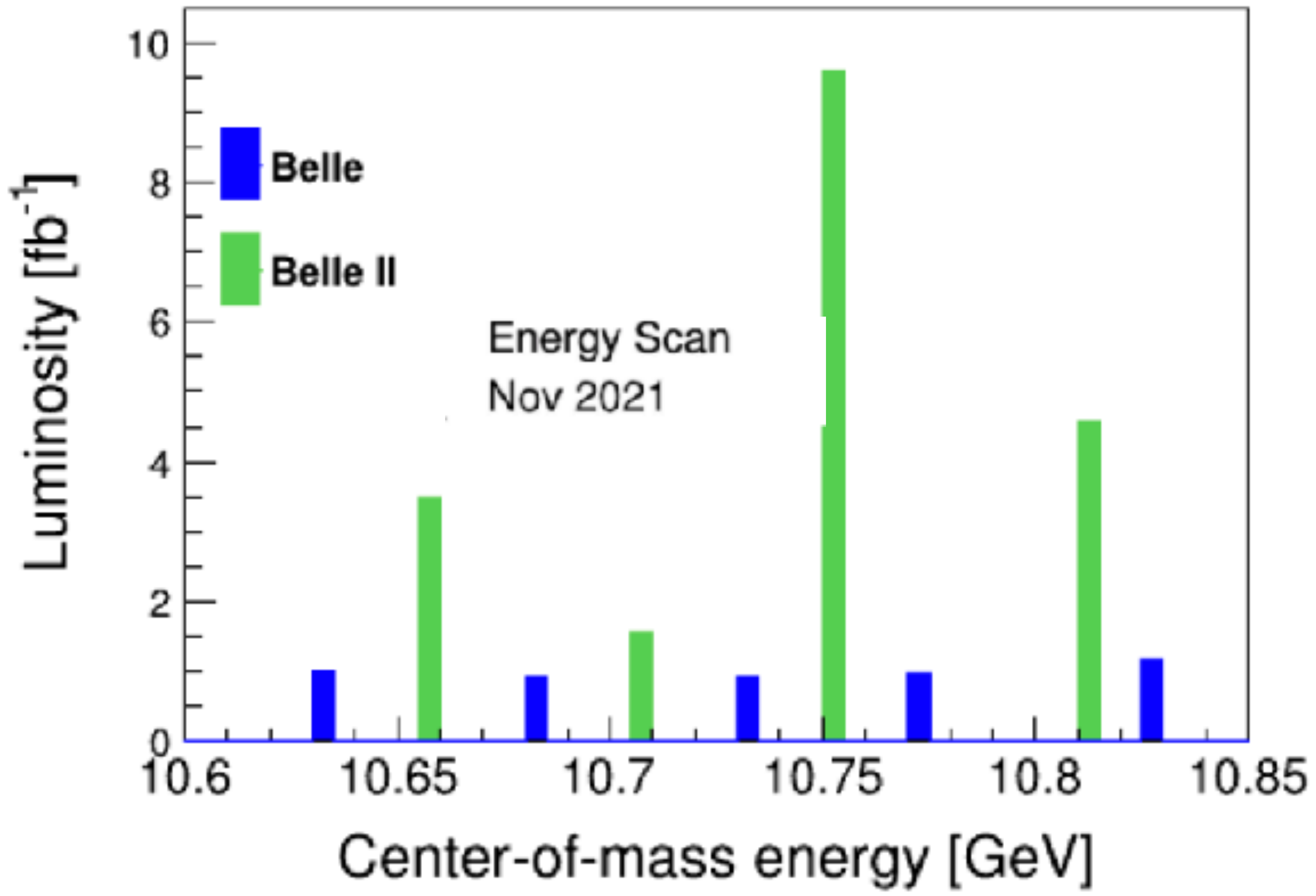
Belle II already achieve the world record instantaneous luminosity: $4.7\times10^{34}/cm^2/s$

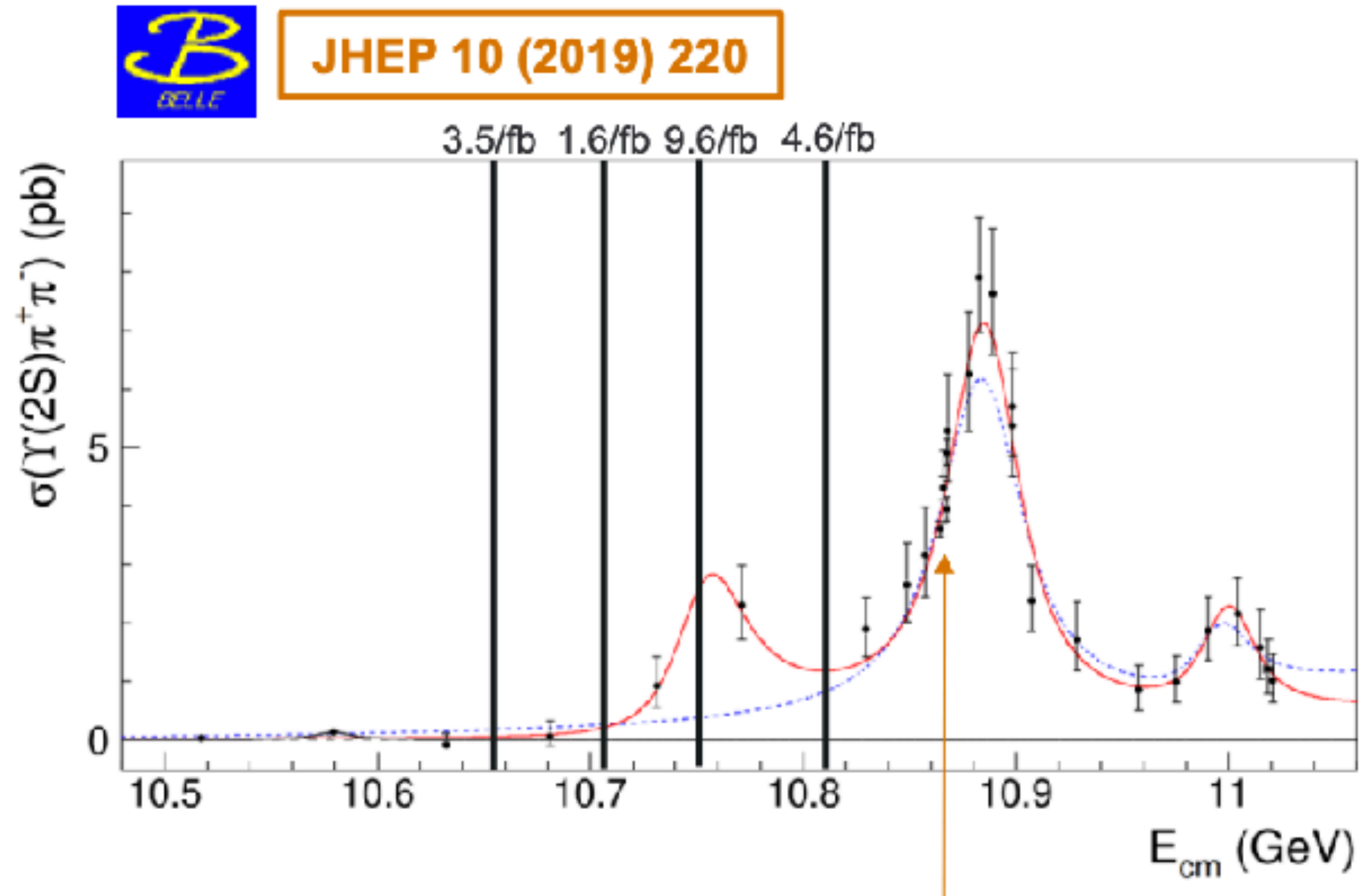
A little data may tell a big story

JHEP 1910, 220 (2019)



Scan data samples with $1\ \text{fb}^{-1}$ at each point on Belle





All points ~1/fb except these (~20+/fb)

- Data collected at 4 energy points around 10.75 GeV
- Physics goal: understand the nature of $Y(10750)$ energy region

Belle II energy scan: new result

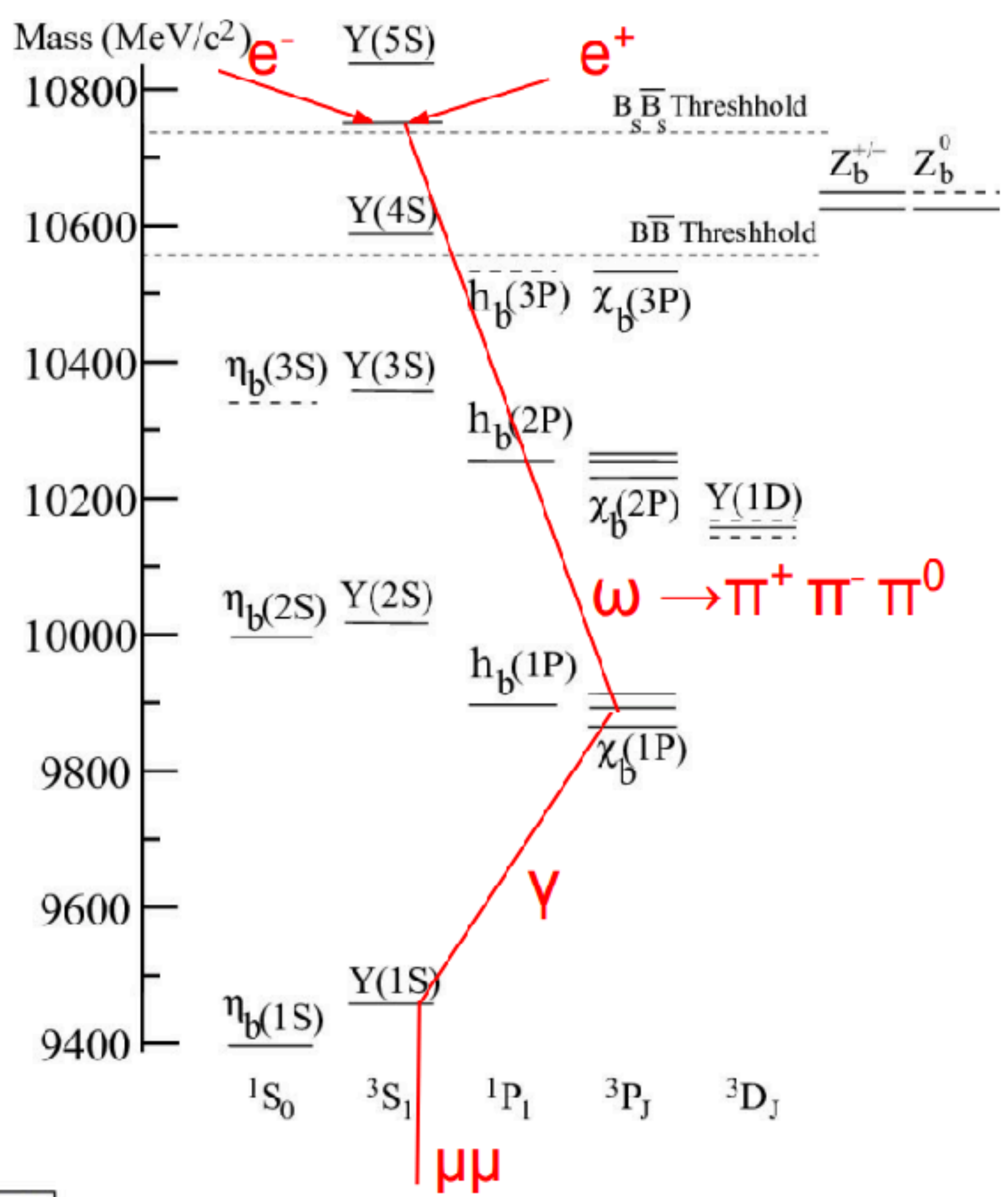
Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

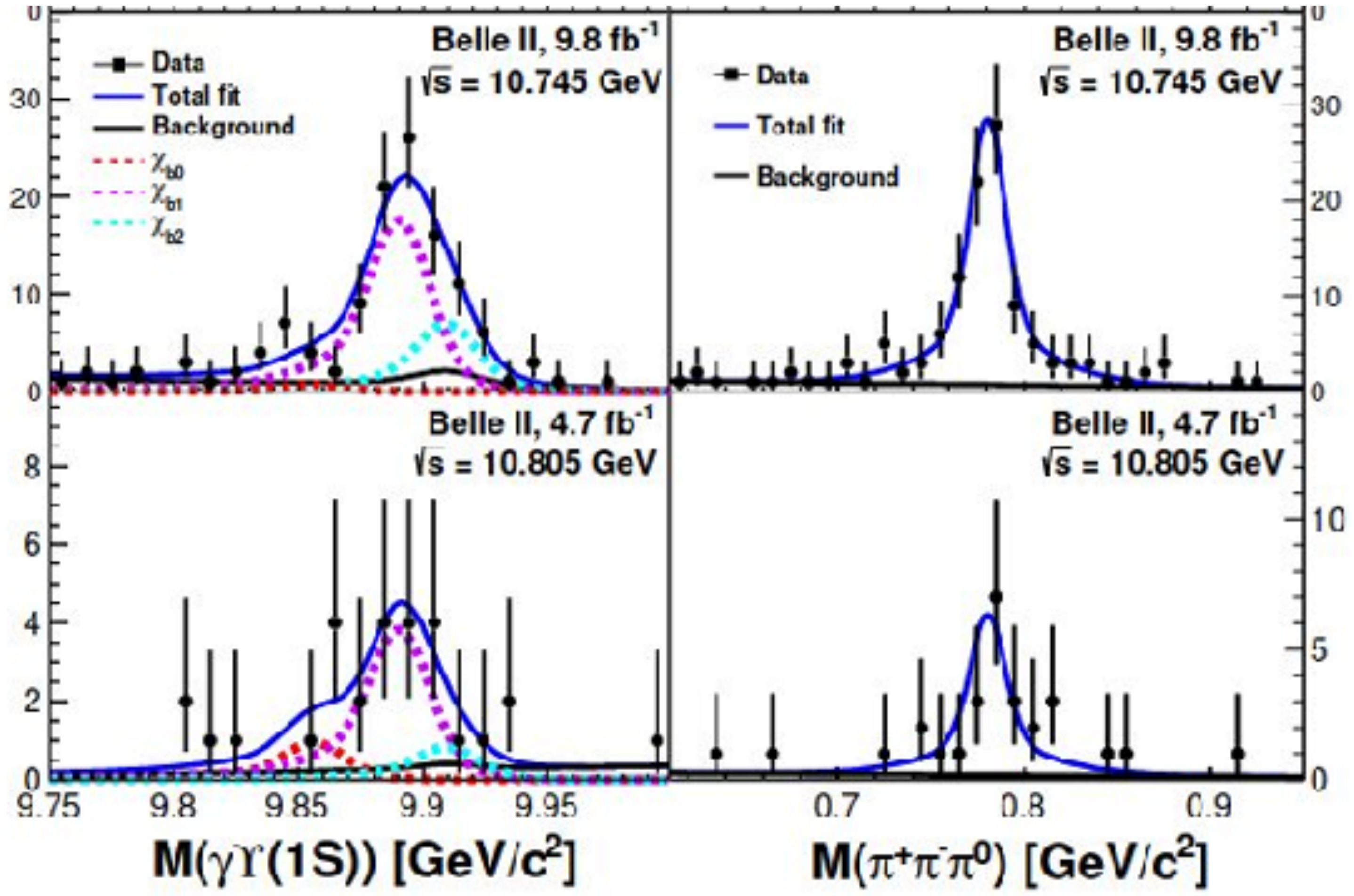
I. Adachi, L. Aggarwal, H. Ahmed, H. Aihara, N. Akopov, A. Aloisio, N. Anh Ky, T. Aushev, V. Aushev, H. Bae, P. Bambade, Sw. Banerjee, J. Baudot, M. Bauer, A. Beaubien, J. Becker, P. K. Behera, J. V. Bennett, E. Bernieri, F. U. Bernlochner, V. Bertacchi, M. Bertemes, E. Bertholet, M. Bessner, S. Bettarini, B. Bhuyan, F. Bianchi, T. Bilka, D. Biswas, D. Bodrov, A. Bolz, A. Bondar, J. Borah, A. Bozek, M. Bračko, P. Branchini, T. E. Browder, A. Budano, S. Bussino, M. Campajola, L. Cao, G. Casarosa, M.-C. Chang, P. Cheema, V. Chekelian, Y. Q. Chen, K. Chilikin, K. Chirapatpimol, H.-E. Cho, K. Cho, S.-J. Cho, S.-K. Choi, S. Choudhury, D. Cinabro, L. Corona, S. Cunliffe, S. Das, F. Dattola, E. De La Cruz-Burelo, S. A. De La Motte, G. De Nardo, M. De Nuccio, G. De Pietro, R. de Sangro, M. Destefanis, S. Dey, A. De Yta-Hernandez, R. Dhamija, A. Di Canto, F. Di Capua, Z. Doležal, I. Domínguez Jiménez, T. V. Dong, M. Dorigo, K. Dort, S. Dreyer, S. Dubey, G. Dujany, M. Eliachevitch, D. Epifanov, P. Feichtinger, T. Ferber, D. Ferlewicz, T. Fillinger, G. Finocchiaro, A. Fodor, F. Forti, B. G. Fulsom, ...

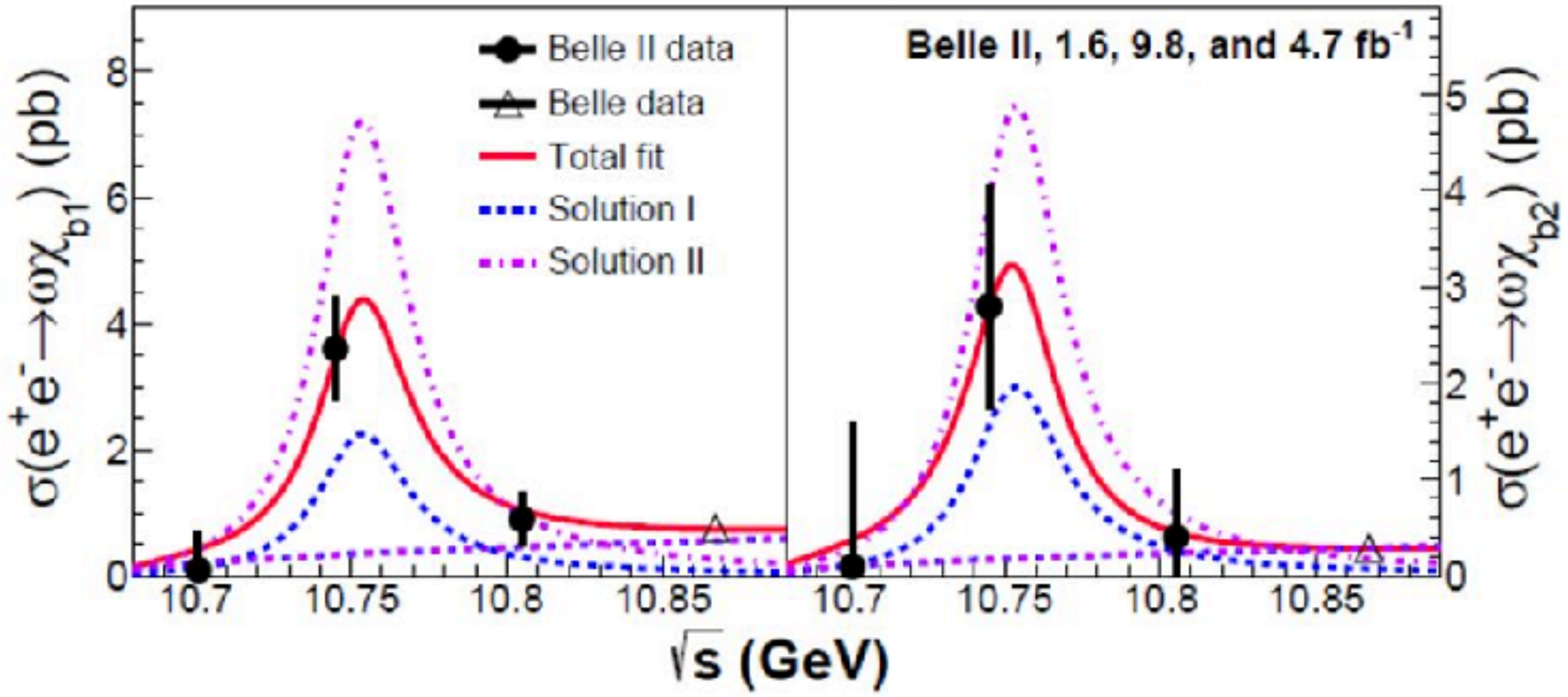
(The Belle II Collaboration)

We study the processes $e^+e^- \to \omega\chi_{bJ}(1P)$ ($J = 0$, 1, or 2) using samples at center-of-mass energies $\sqrt{s} = 10.701$, 10.745, and 10.805 GeV, corresponding to 1.6, 9.8, and 4.7 fb^{-1} of integrated luminosity, respectively. These data were collected with the Belle II detector during a special run of the SuperKEKB collider above the $\Upsilon(4S)$ resonance. We report the first observation of $\omega\chi_{bJ}(1P)$ signals at $\sqrt{s} = 10.745$ GeV. By combining Belle II data with Belle results at $\sqrt{s} = 10.867$ GeV, we find energy dependencies of the Born cross sections for $e^+e^- \to \omega\chi_{b1,b2}(1P)$ to be consistent with the shape of the $\Upsilon(10753)$ state. Including data at $\sqrt{s} = 10.653$ GeV, we also search for the bottomonium equivalent of the $X(3872)$ state decaying into $\omega\Upsilon(1S)$. No significant signal is observed for masses between 10.45 and 10.65 GeV/c^2.

arXiv:2208.13189 [hep-ex]







Confirm the existence of $\Upsilon(10753)$.
Find a new decay mode.

How to identify exotics

- Exotic quantum numbers
  - $J^{PC}=0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$
  - I=2, 5/2
- Minimum quark content >3
  - $s\,s\,\bar{u}\,\bar{d}$, $c\,s\,\bar{u}\,\bar{d}$, $c\,c\,\bar{u}\,\bar{d}$, $uudd\,\bar{s}$, $uudd\,\bar{c}$, …
- Too many states, beyond expectation of quark model
  - Vector charmonia: $N_Y + N_\psi > N_{\psi(3S1)} + N_{\psi(3D1)}$
- State with exotic properties
  - Large mass but very narrow
  - Very close to threshold
  - Strong coupling to heavy quarkonium but charged
  - …

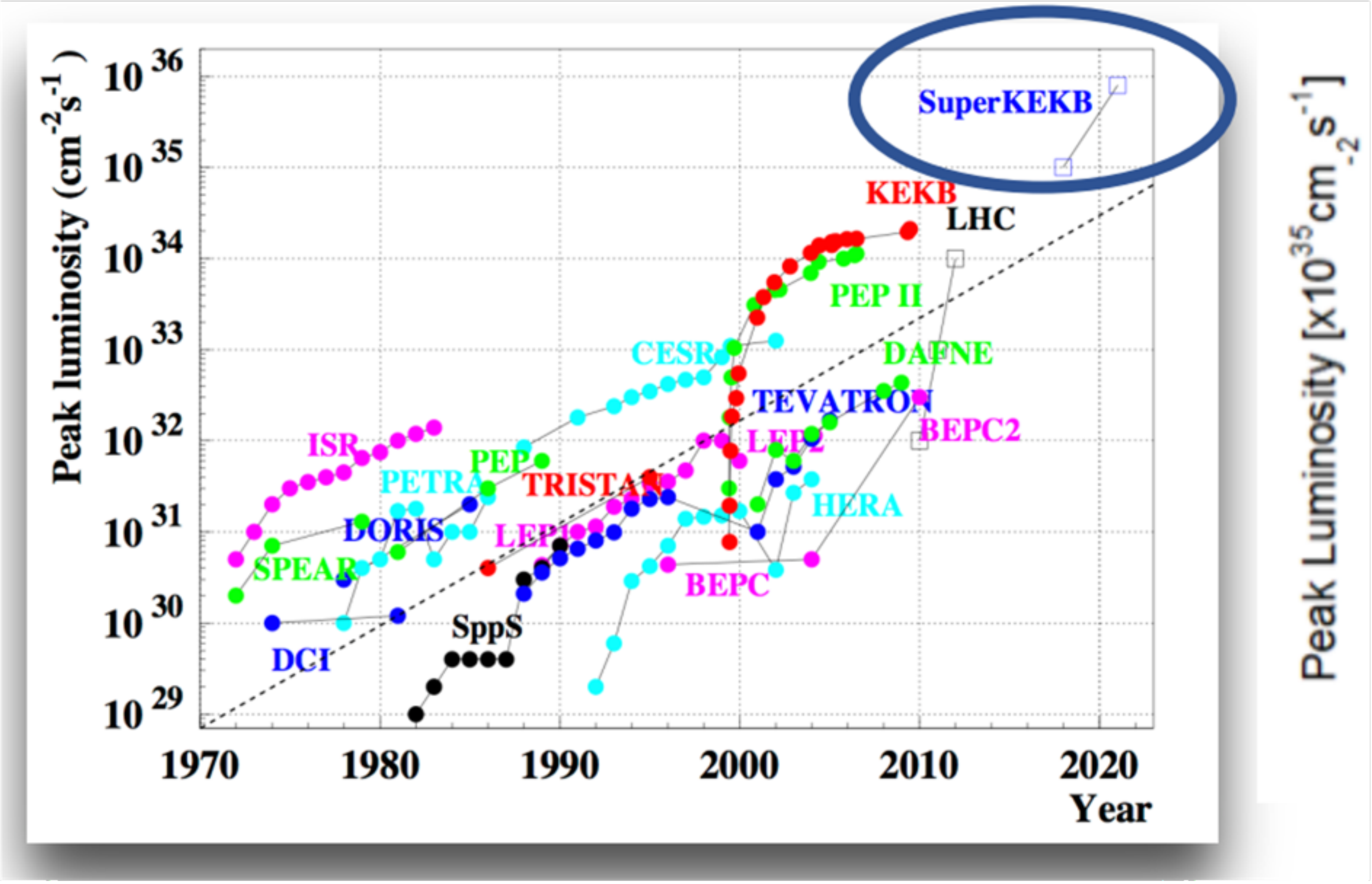
Not so easy…

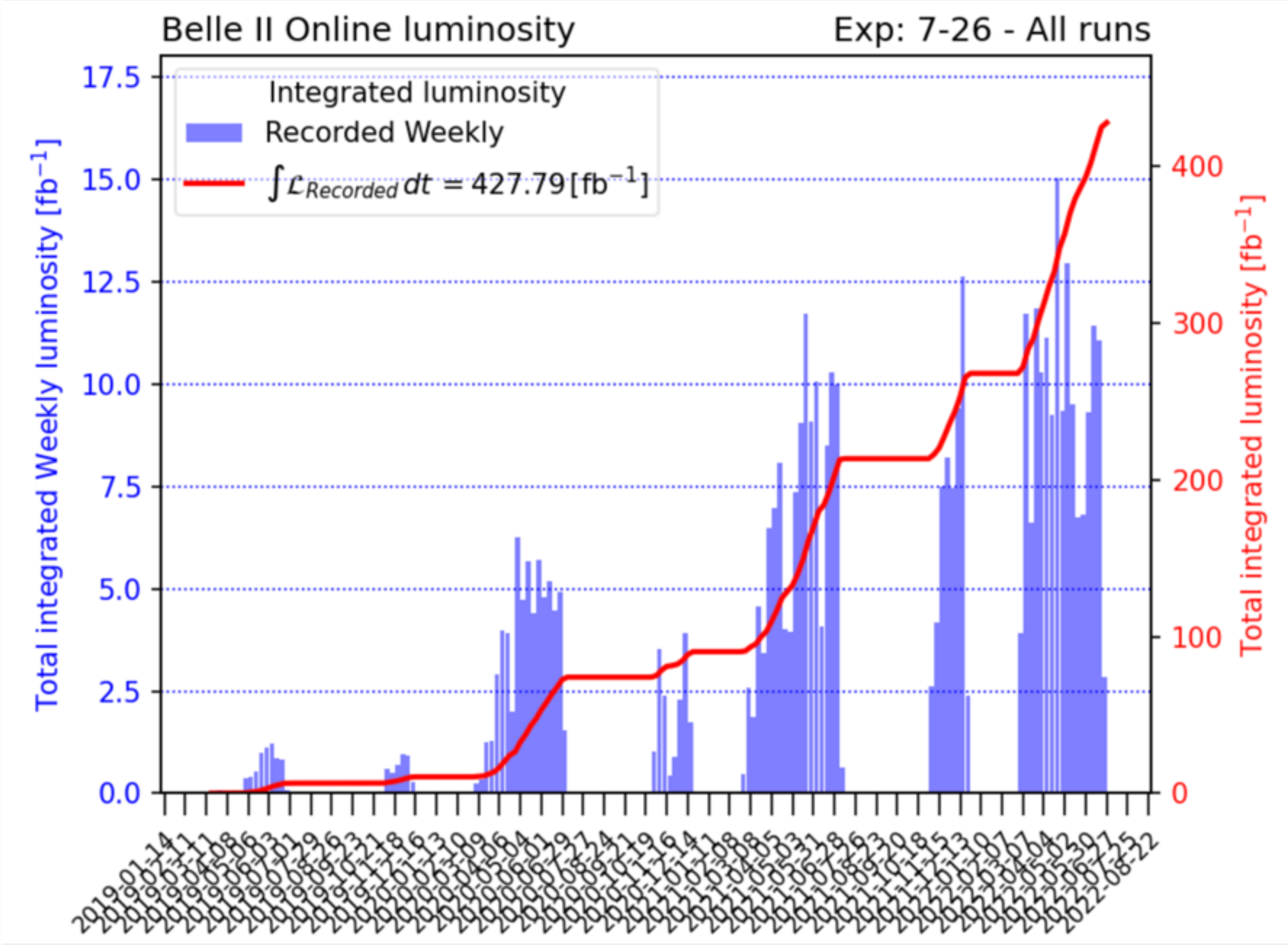
Summary

- Quarkonium spectroscopy is an extraordinary place to test the QCD theory, especially the observation of exotic states, which gives us new insight and shed lights to the understanding of QCD theory.
- Belle II, the next generation B-factory, can make significant impacts in quarkonia study.
    - Precisely measure lineshapes.
    - Determine spin-parities, transitions, and quantum numbers.
    - Search for new decay channels.
    - Test predictions for unobserved states.
    - Unique datasets.
    - …
- The effort goes on with the upgraded facility, SuperKEKB collider, and Belle II detector.

BACK UP

Belle II luminosity High precision frontier

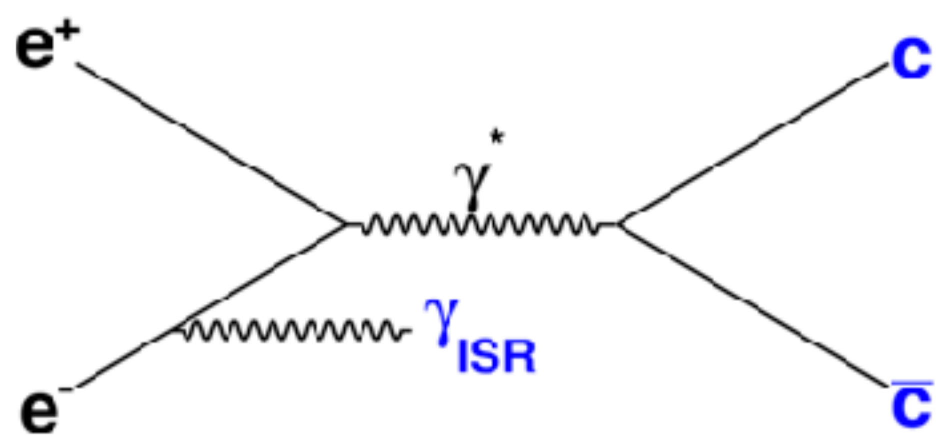




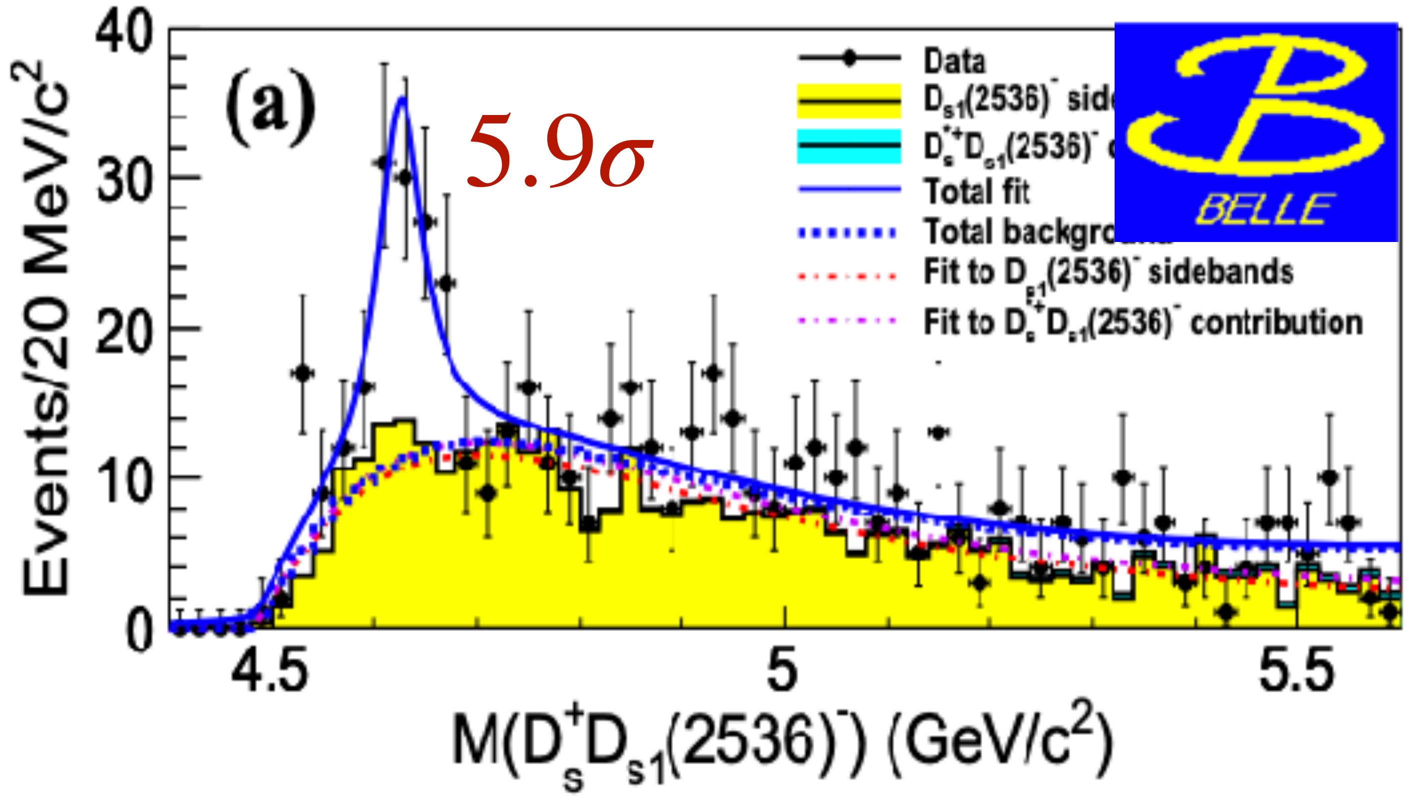
Belle II already achieve the world record instantaneous luminosity: $4.7\times10^{34}/cm^2/s$

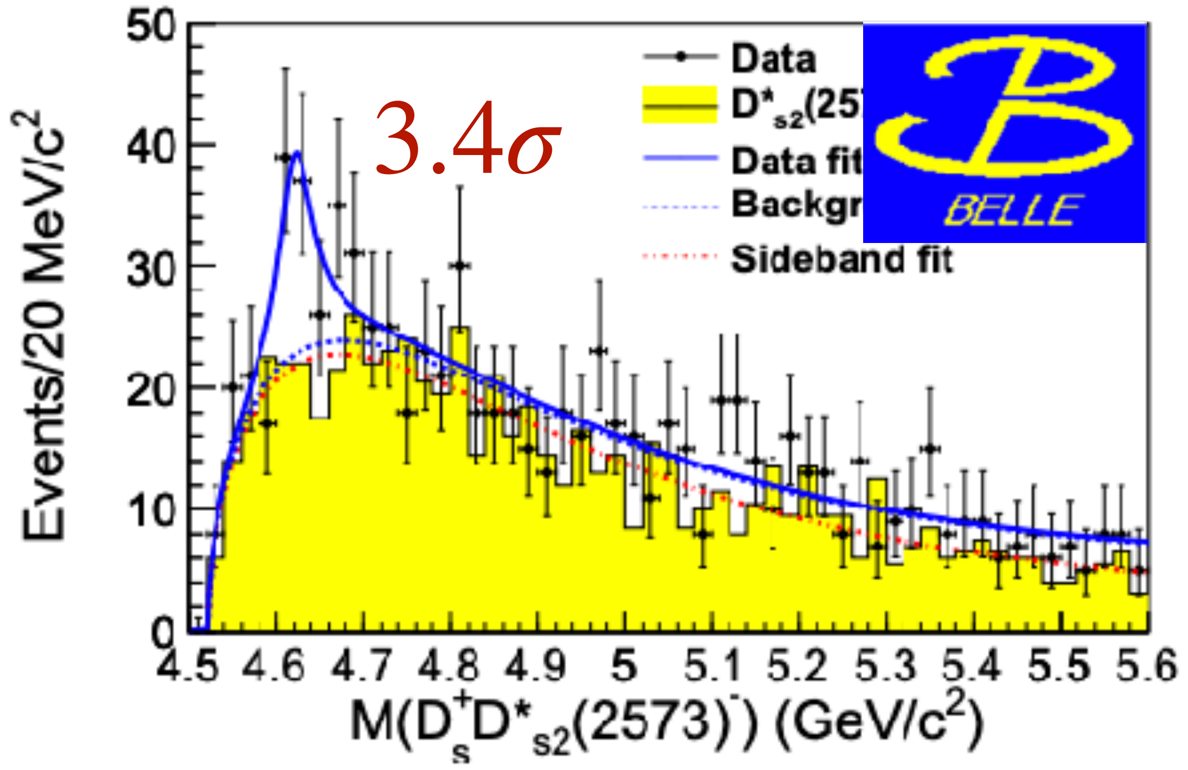
Initial state radiation

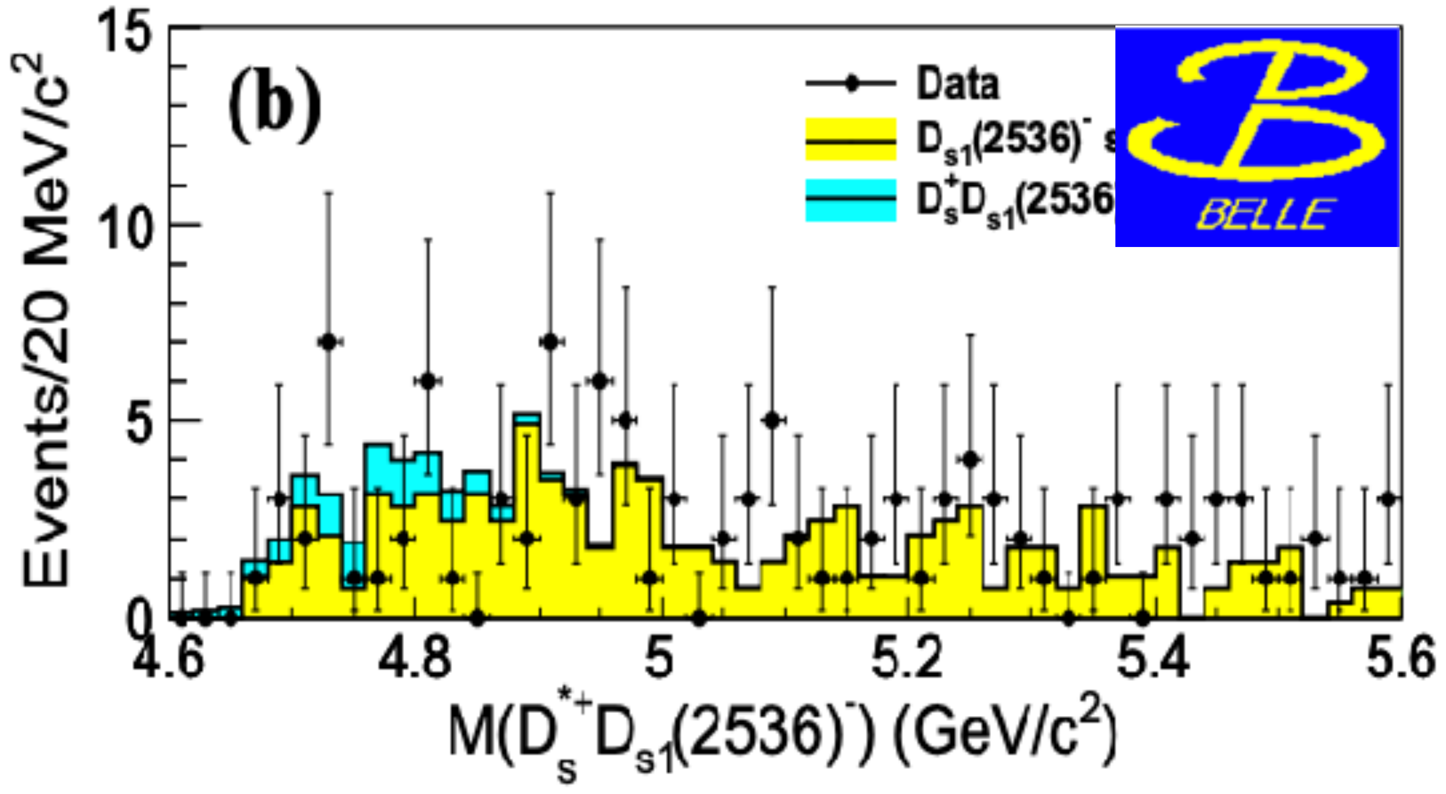
Allow us to reach lower c.m. energy "*for free*"

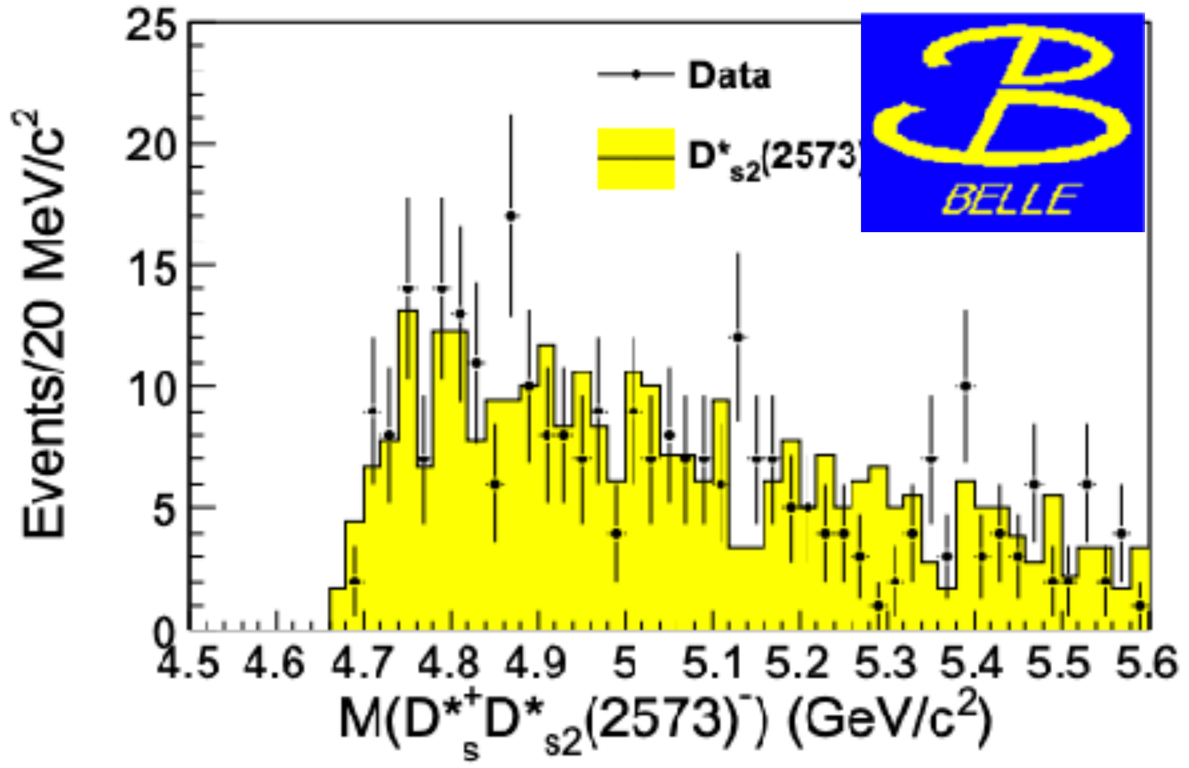


Recent: A new vector state in $e^+e^- \to D_s^+ D_{s1}(2536)^-,\ D_s^+ D_{s2}^*(2573)^-$









Phys.Rev.D 100 (2019) 11, 111103

Phys.Rev.D 101 (2020) 9, 091101

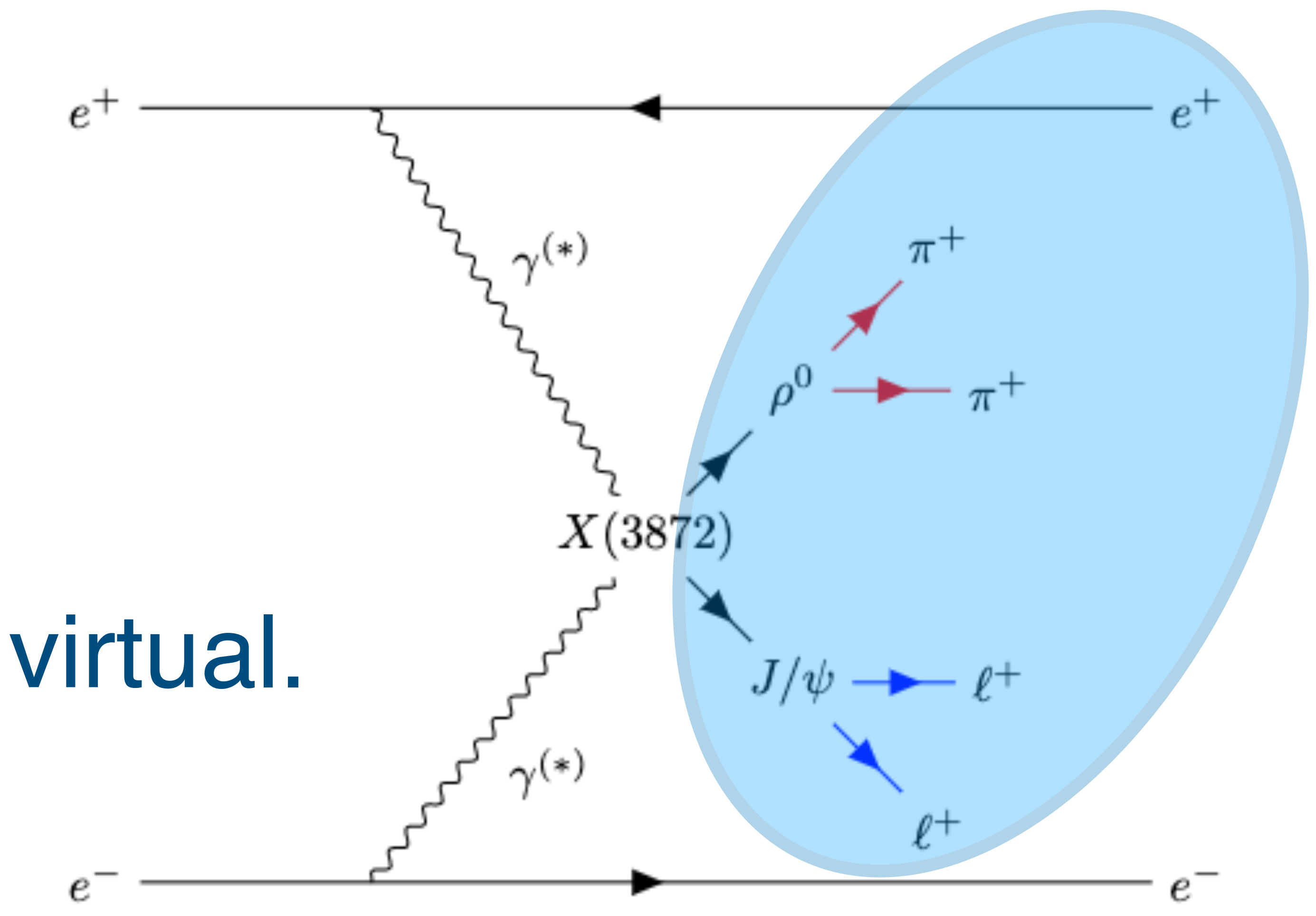
$Y(4620) = Y(4660)$**?**

Experiments	Mass (MeV/c^2)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Belle, $\pi^+\pi^- J/\psi$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi^+\pi^- J/\psi$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$
Belle, $D_s^+ D_{s1}(2536)^-$	$4625.9^{+6.2}_{-6.0} \pm 0.4$	$49.8^{+13.9}_{-11.5} \pm 4.0$
Belle, $D_s^+ D_{s1}^*(2573)^-$	$4619.8^{+8.9}_{-8.0} \pm 2.3$	$47.0^{+31.3}_{-14.8} \pm 4.6$

Evidence of $\gamma\gamma^* \to X(3872)$

Axial-vector particles are forbidden to decay to two real photons.

Mesons with $J^{PC} = 1^{++}$ could be produced is one or both photons are virtual.

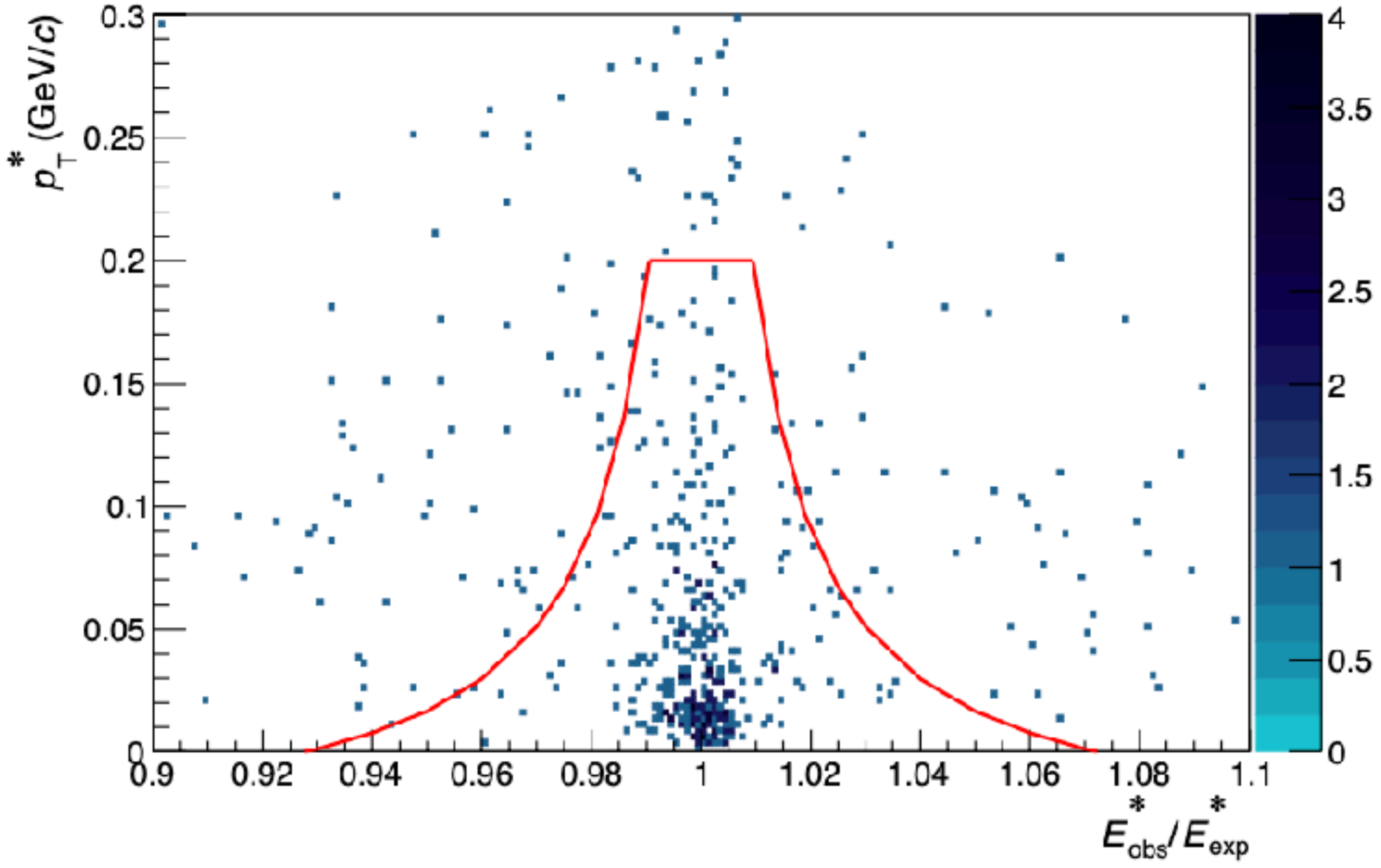


reconstruction:

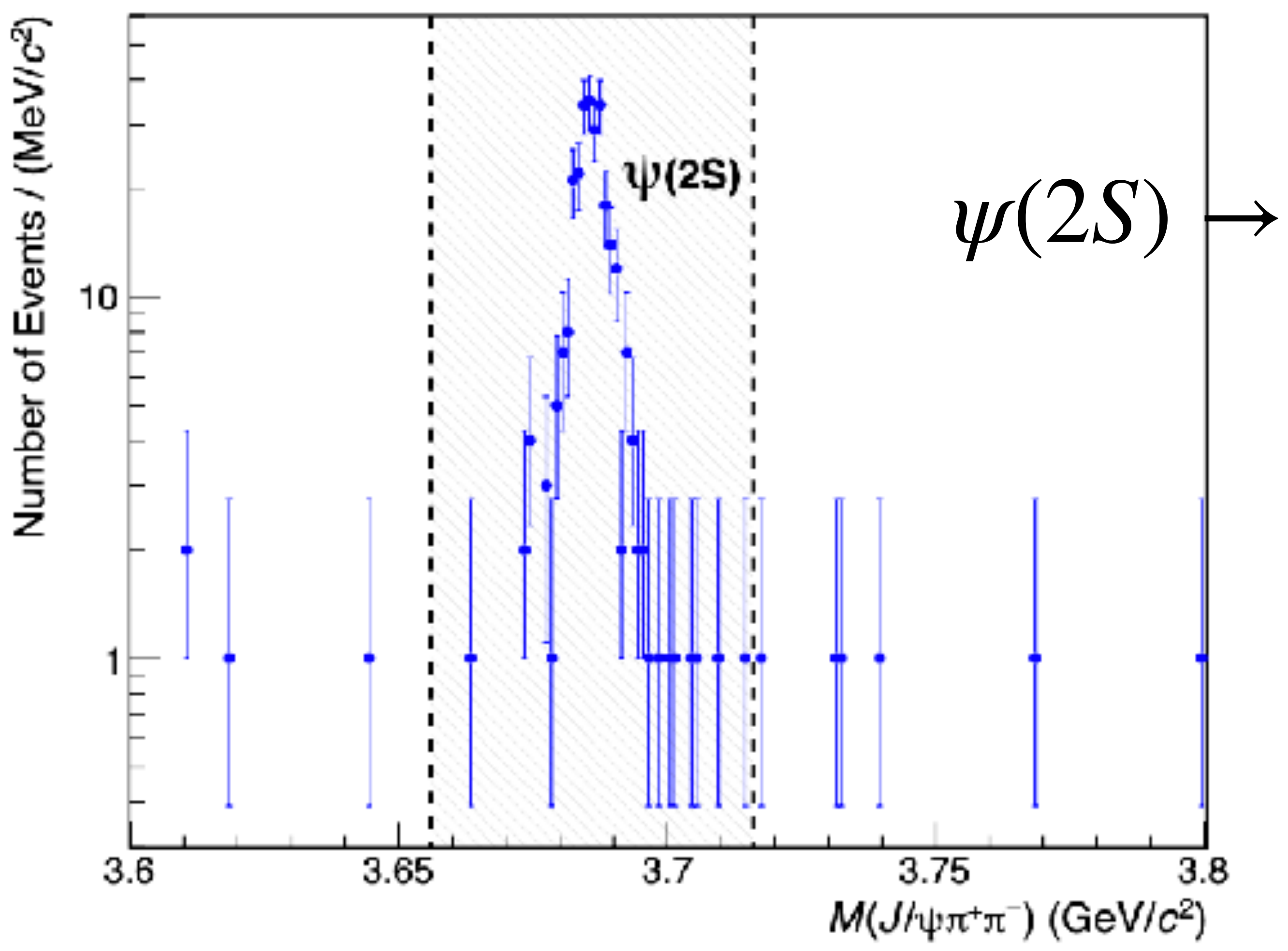
- $N(track) = 5$ with $\sum Q = \pm 1$
  - two pions, two leptons(e/μ)
  - one extra electron/positron (from beam)
  - No photon with $E > 0.4$ GeV or π^0
- $X(3872)$ & tagging electron: back to back
  - azimuthal angle difference within $(\pi \pm 0.1)$
- Visible transverse momentum < 0.2 GeV/c; measured $\pi^+\pi^- J/\psi$ energy $E^*_{\rm obs}$ consistent with the expectation $E^*_{\rm exp}$
- Missing momentum of event projection:

$$p_{z,\rm mis} < -0.4\ {\rm GeV}/c^2\ \text{ for } e^-\text{tag}$$

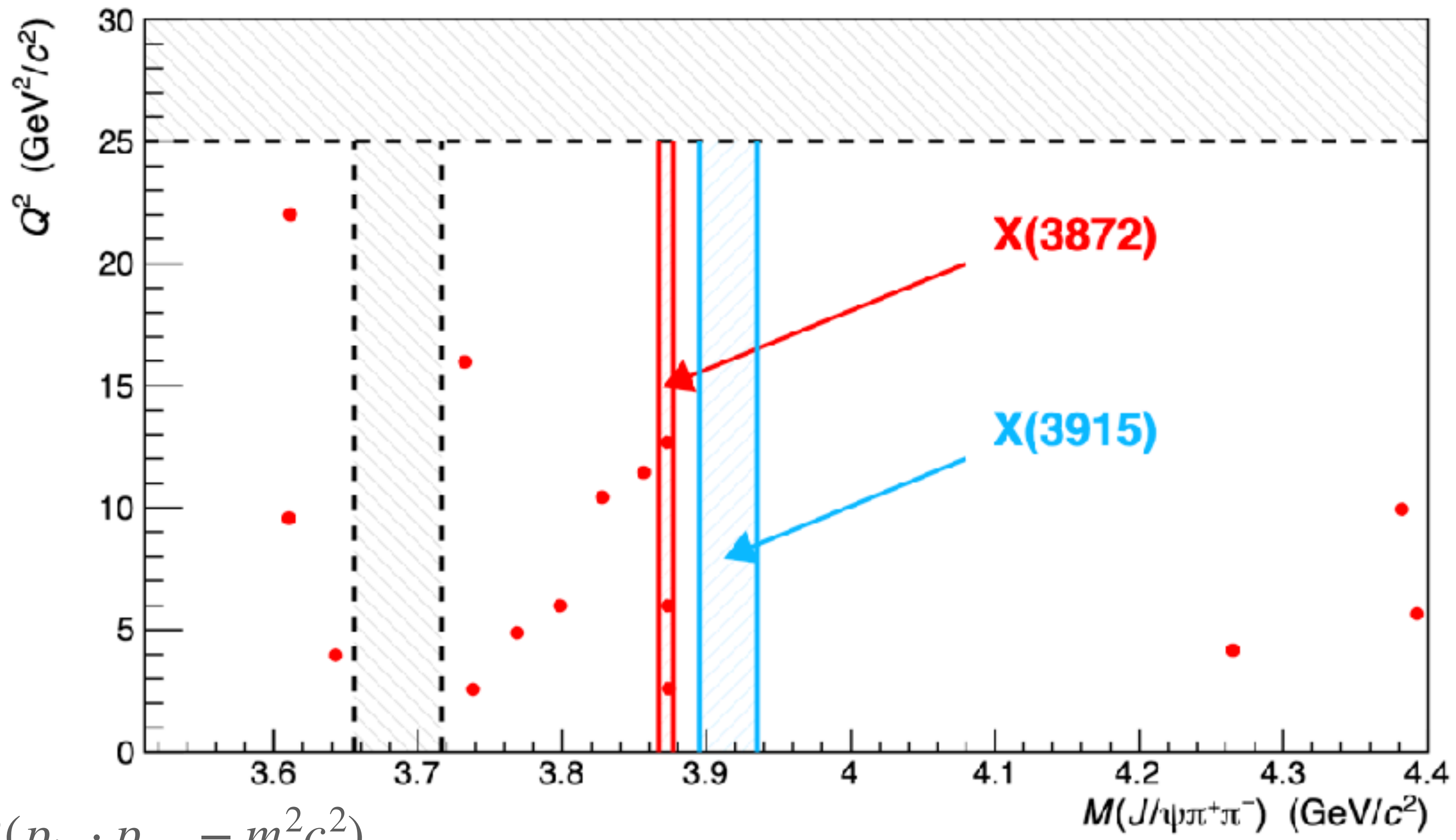
$$p_{z,\rm mis} > +0.4\ {\rm GeV}/c^2\ \text{ for } e^+\text{tag.}$$



Dominate background



$\psi(2S) \to \pi^+\pi^- J/\psi$ ***veto***



$Q^2 = 2(p_{in} \cdot p_{out} - m_e^2 c^2)$,

where $p_{in/out}$ is the momentum of the incoming (beam) electron and outgoing (tagging) electron

expected number of background:

- $(3-5) \times 10^{-2}/(10\ \mathrm{MeV/c^2})$ from internal bremsstrahlung.
- 0.11 ± 0.10 (0.3 for $X(3915)$) extrapolated from fit to the background events

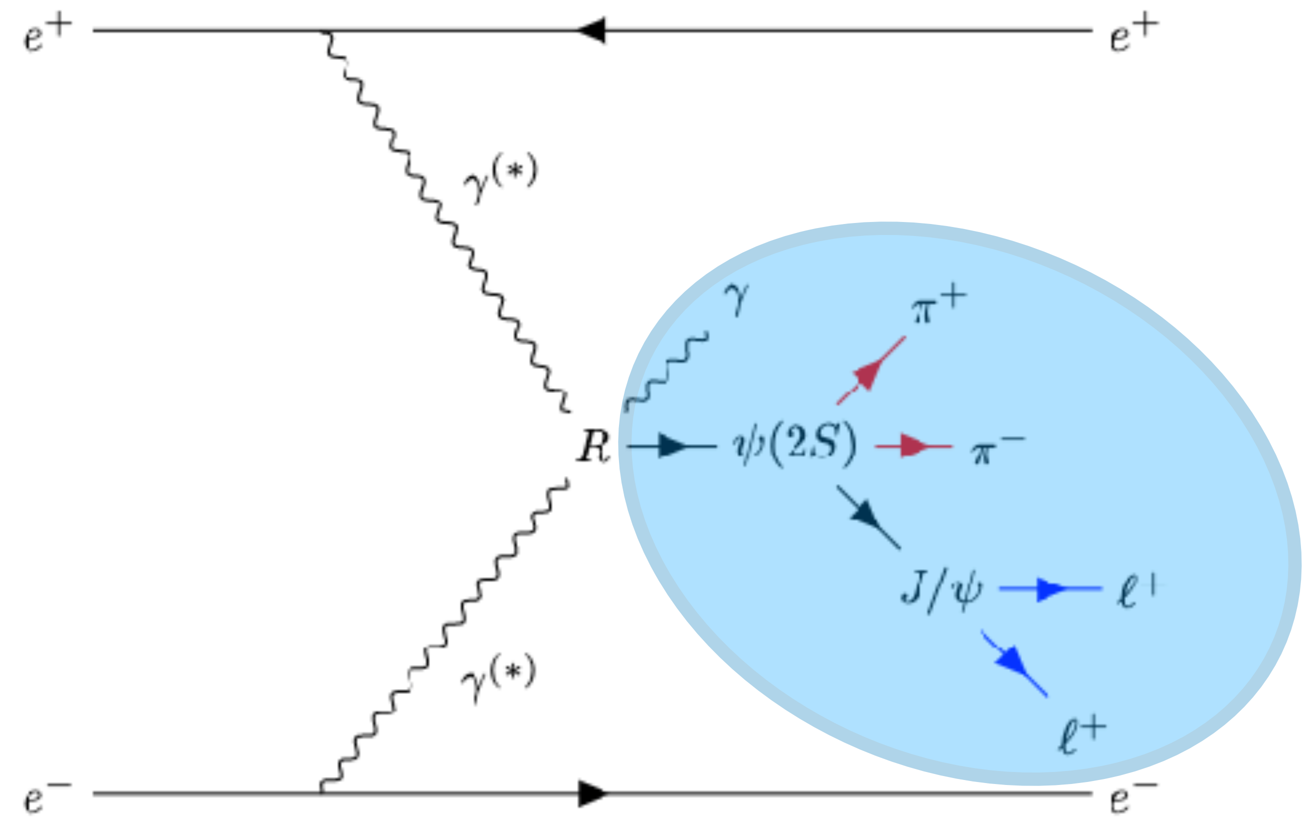
Three events are found in the signal region, with a significance of 3.2σ considering the background.

$N_{\mathrm{sig}} = 2.9^{+2.2}_{-2.0}(\mathrm{stat.}) \pm 0.1(\mathrm{syst.})$ for $X(3872)$, $N_{\mathrm{sig}} < 2.14$ for $X(3915)$

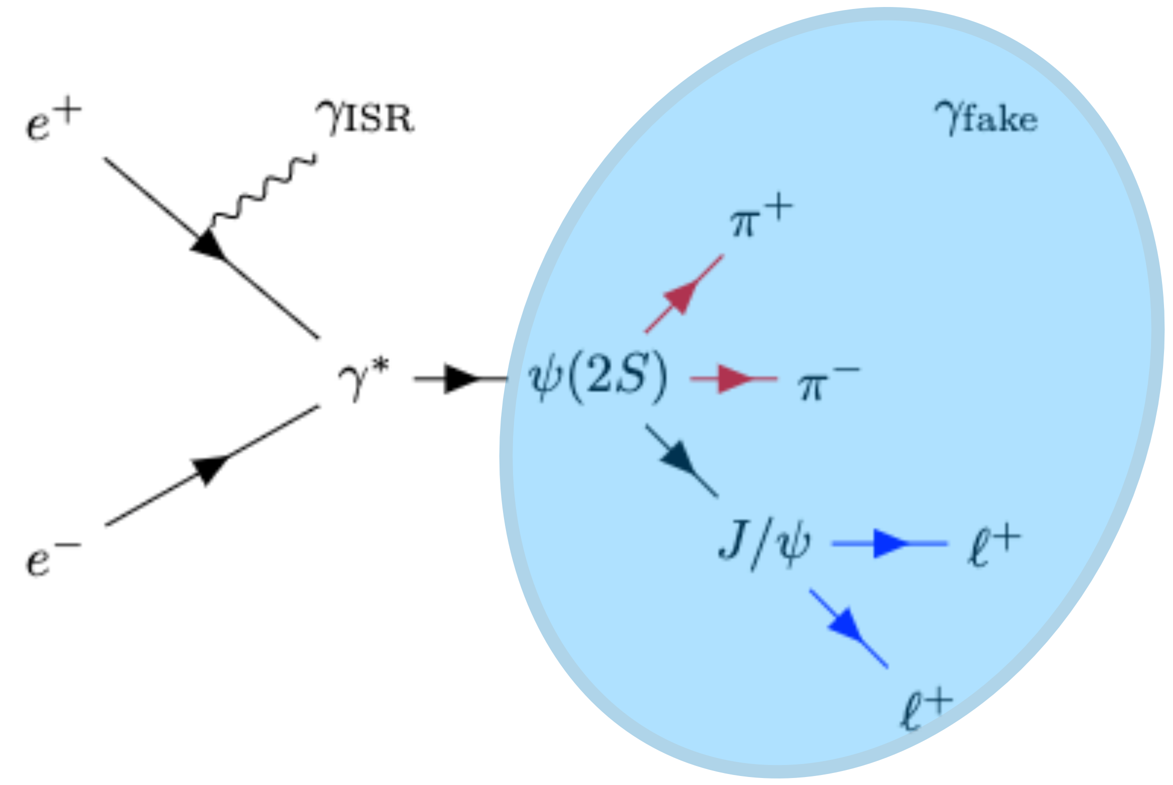
Exotic candidates in $\gamma\gamma \to \gamma\psi(2S)$

Both 0^{++} and 2^{++} could be produced in the two photon collisions, and can radiatively decay to $\psi(2S)$

Signal process



Dominate background: $e^+e^- \to \gamma_{ISR}\psi(2S)$

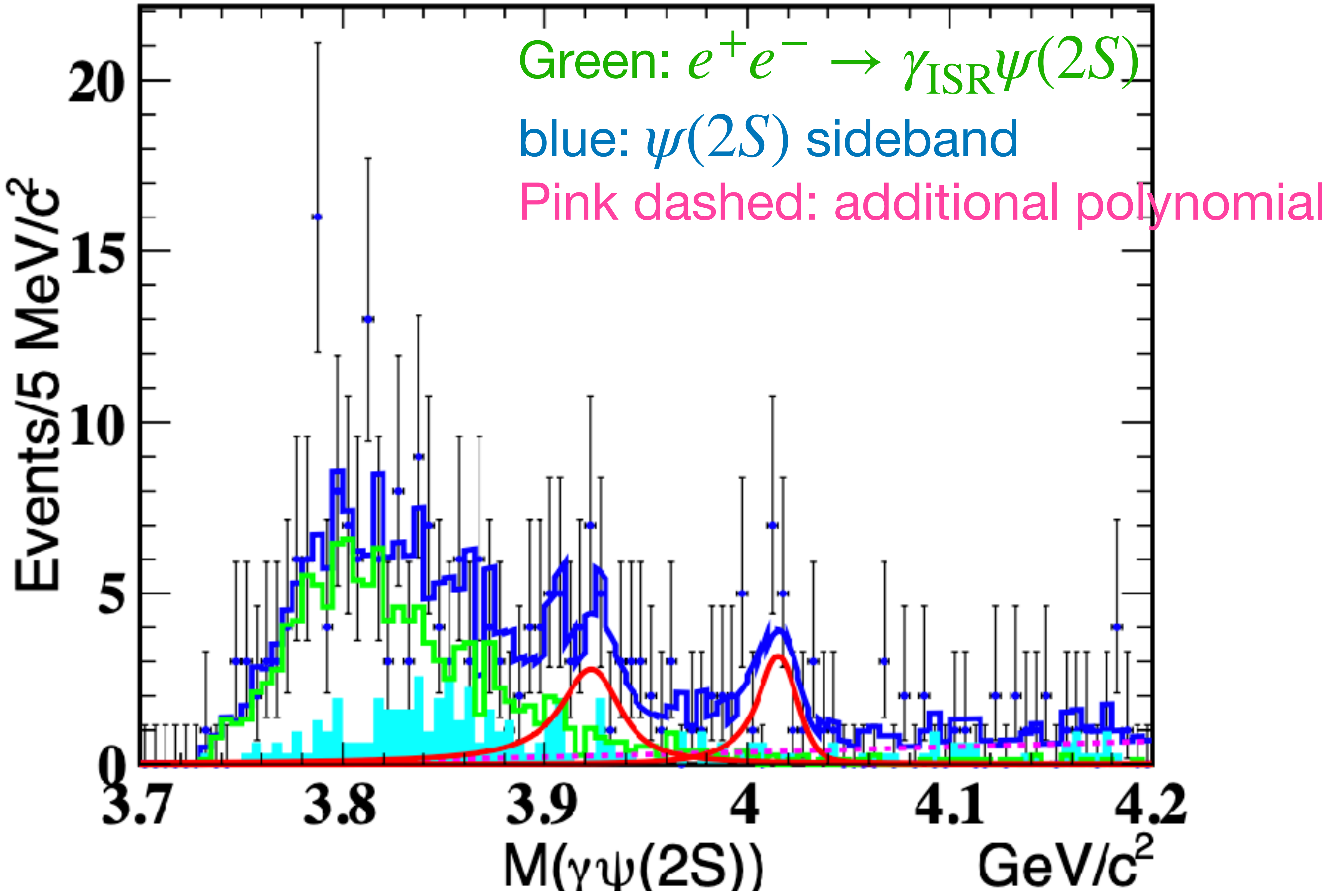


reconstruction:

- Reconstructing $\pi^+\pi^-\ell^+\ell^-$
  - J/ψ reconstructed with two leptons (e/μ)
  - $\psi(2S)$ reconstructed with $\pi^+\pi^-J/\psi$

background suppression:

- Recoiling mass of $\gamma\psi(2S)$
  - $M^2_{\rm rec}(\gamma\psi(2S)) > 10\ ({\rm GeV}/c^2)^2$
- Transverse momentum balances
  - $P_t^*(\psi(2S)) > 0.1\ {\rm GeV}/c$
  - $P_t^*(\gamma\psi(2S)) < 0.2\ {\rm GeV}/c$



Resonant parameters	$J=0$	$J=2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.2$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

Significance of R_1 is 3.1σ considering systematic uncertainty.

Significance of R_2 is 2.8σ after considering LEE.

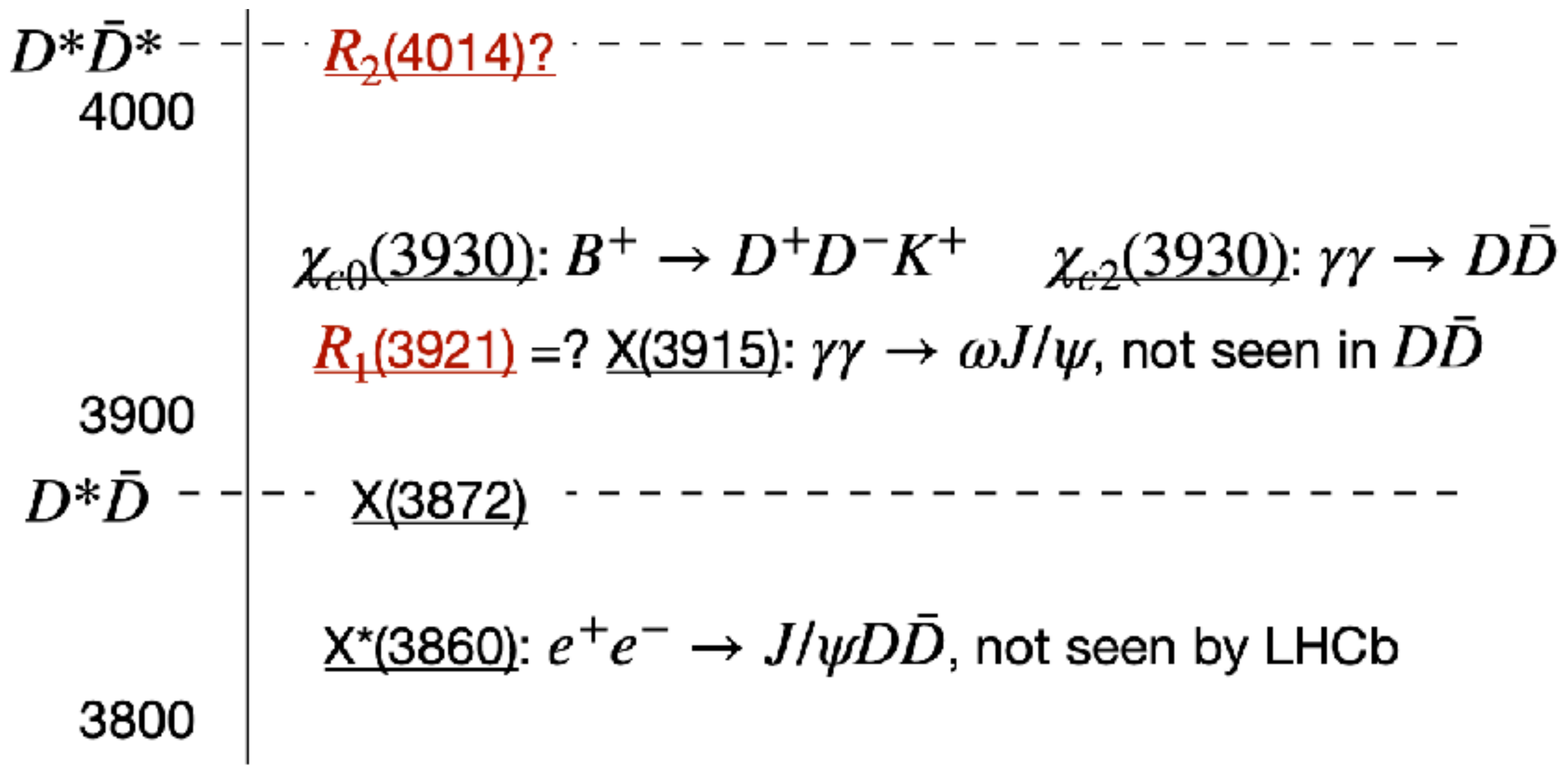
Fitting PDF:

$$f_{\rm sum} = f_{\rm R_1} + f_{\rm R_2} + f_{\rm ISR} + f_{\rm bkg} + f_{\rm SB}$$

$$f_{\rm R} \propto \varepsilon \cdot ({\rm BW} \otimes {\rm CB}).$$

possible interference is ignored

possible nature?



Excess states = exotics?

Observation of $e^+e^- \to \Upsilon(1,2S)\eta$ at 10.866 GeV

For bottomonia below $B\bar{B}$ threshold, predictions of hadronic transition rates are consistent with measurements.

Measured hadronic transition rates between bottomonia above open bottom threshold are higher than predictions.

e.g. $\frac{\Gamma(\Upsilon(5S) \to h_b(1P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)} = 0.46 \pm 0.08^{+0.07}_{-0.12}$ $\frac{\Gamma(\Upsilon(5S) \to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.77 \pm 0.08^{+0.22}_{-0.17}$ Prediction: $\mathcal{O}(10^{-2})$

Analysis of similar processes is crucial for better understanding of the quark structure of bottomonium states above $B\bar{B}$ threshold.

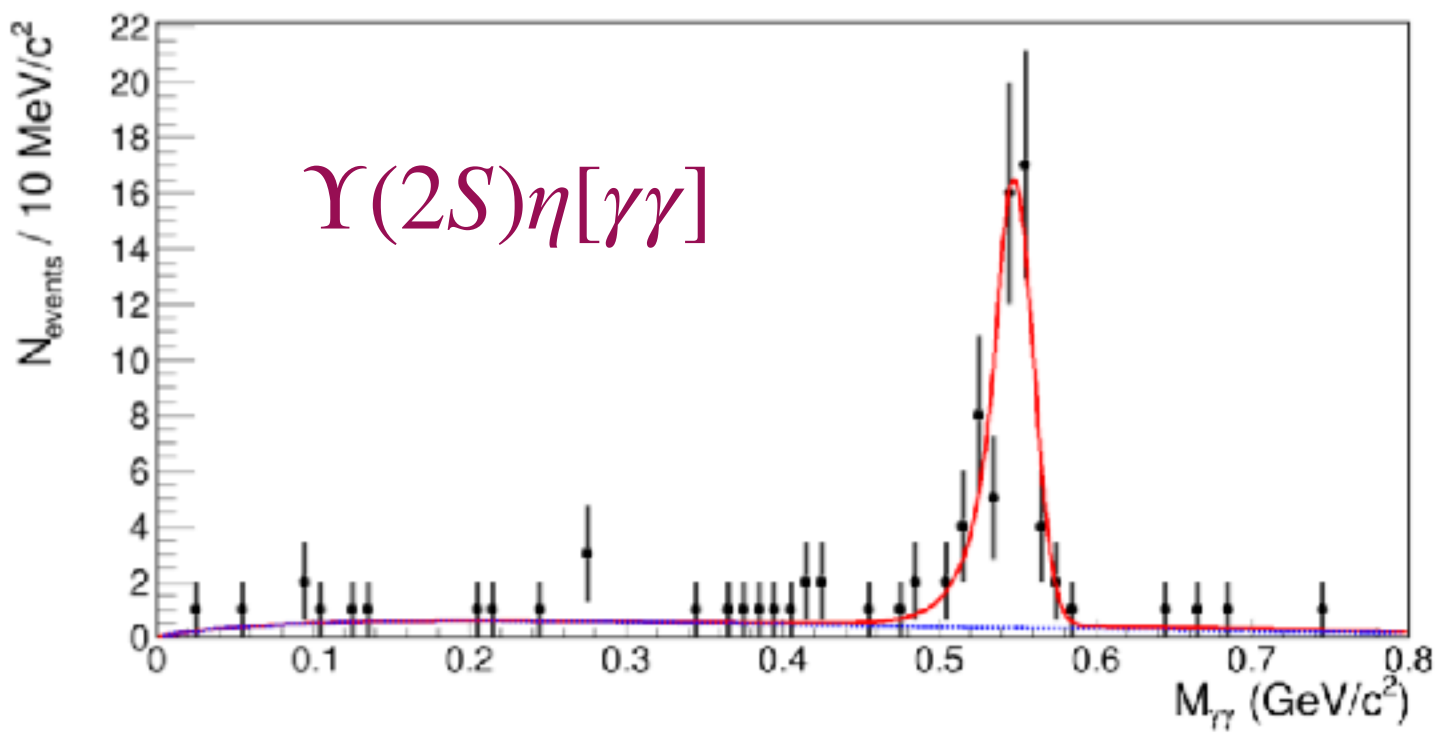
reconstruction:

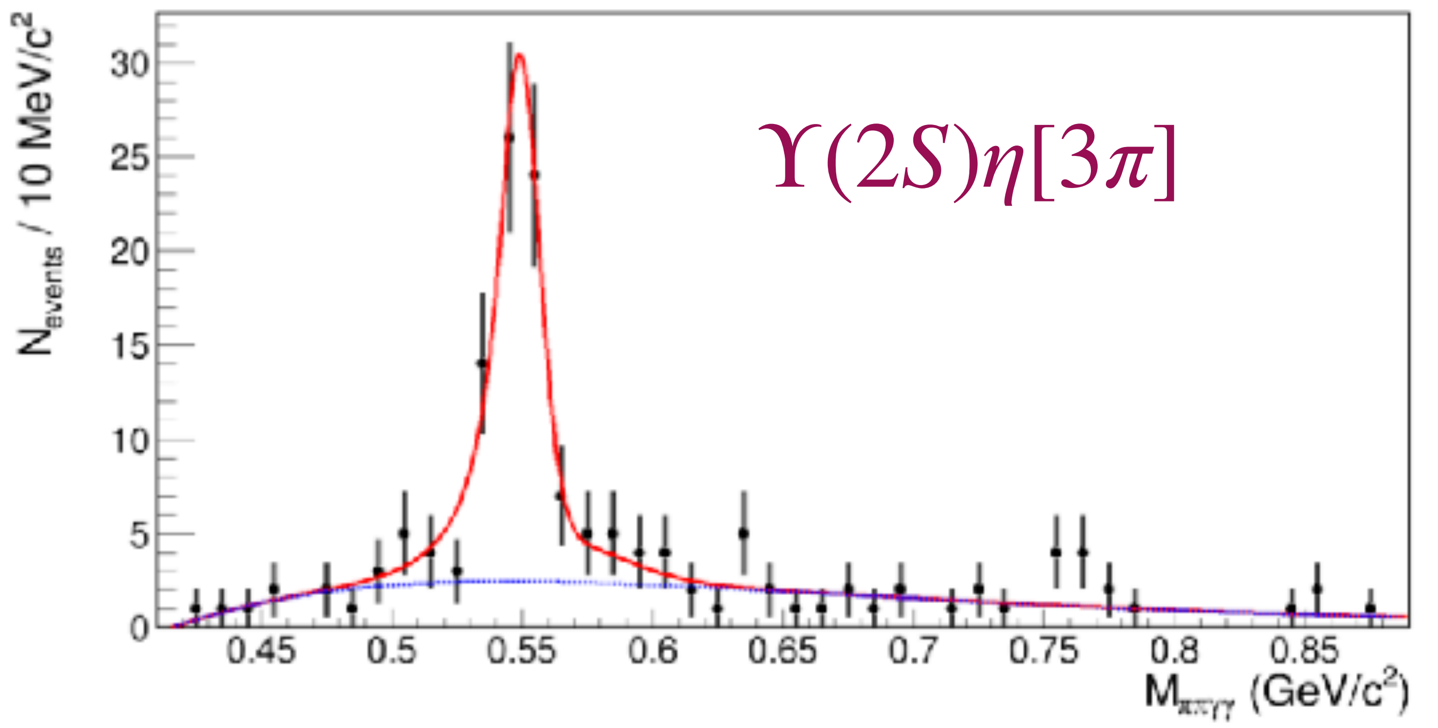
- Final states $\pi^+\pi^-\mu^+\mu^-\gamma(\gamma)$: $\Upsilon(2S)\eta[3\pi]$, $\Upsilon(2S)\eta[\gamma\gamma]$, $\Upsilon(1S)\eta[3\pi]$, $\Upsilon(1S)\eta'[\pi\pi\eta]$, $\Upsilon(1S)\eta'[\gamma\rho]$
- For $\eta \to \gamma\gamma$
  - $\Upsilon(2S)$ reconstructed with $\pi^+\pi^-J/\psi$
- For $\eta \to \pi^+\pi^-\pi^0$
  - $\Upsilon(1,2S)$ reconstructed with two leptons

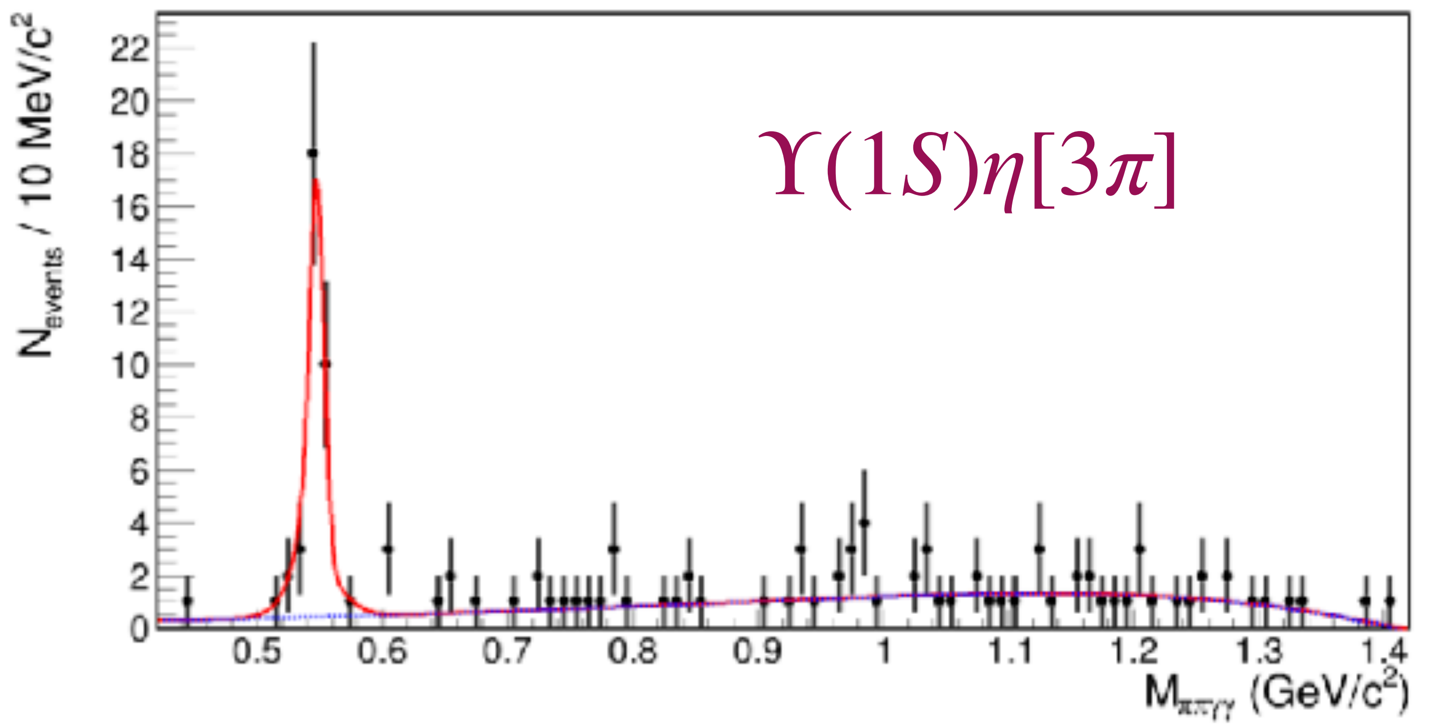
Data sample:

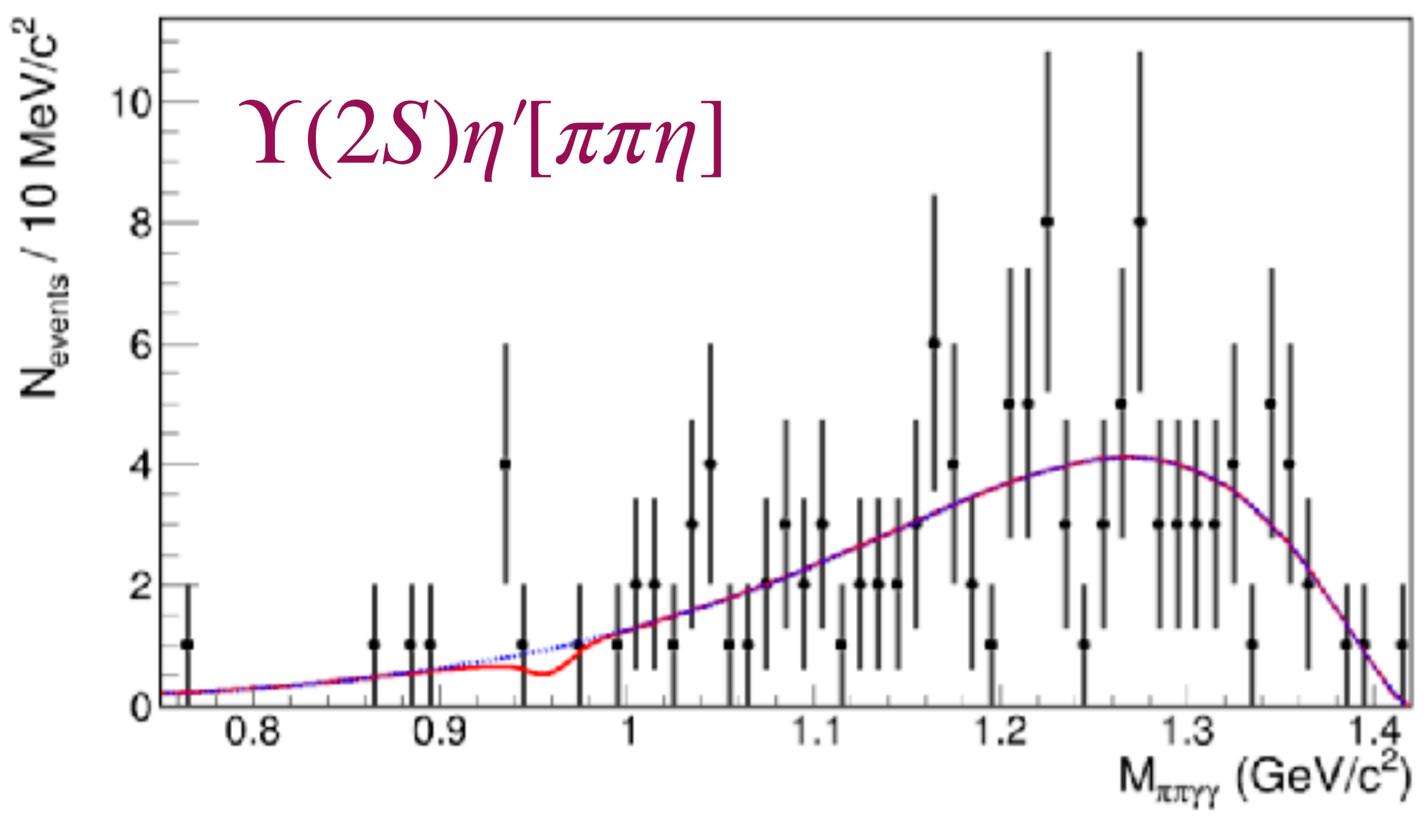
$118\ \mathrm{fb}^{-1}$ **at** $\Upsilon(5S)$

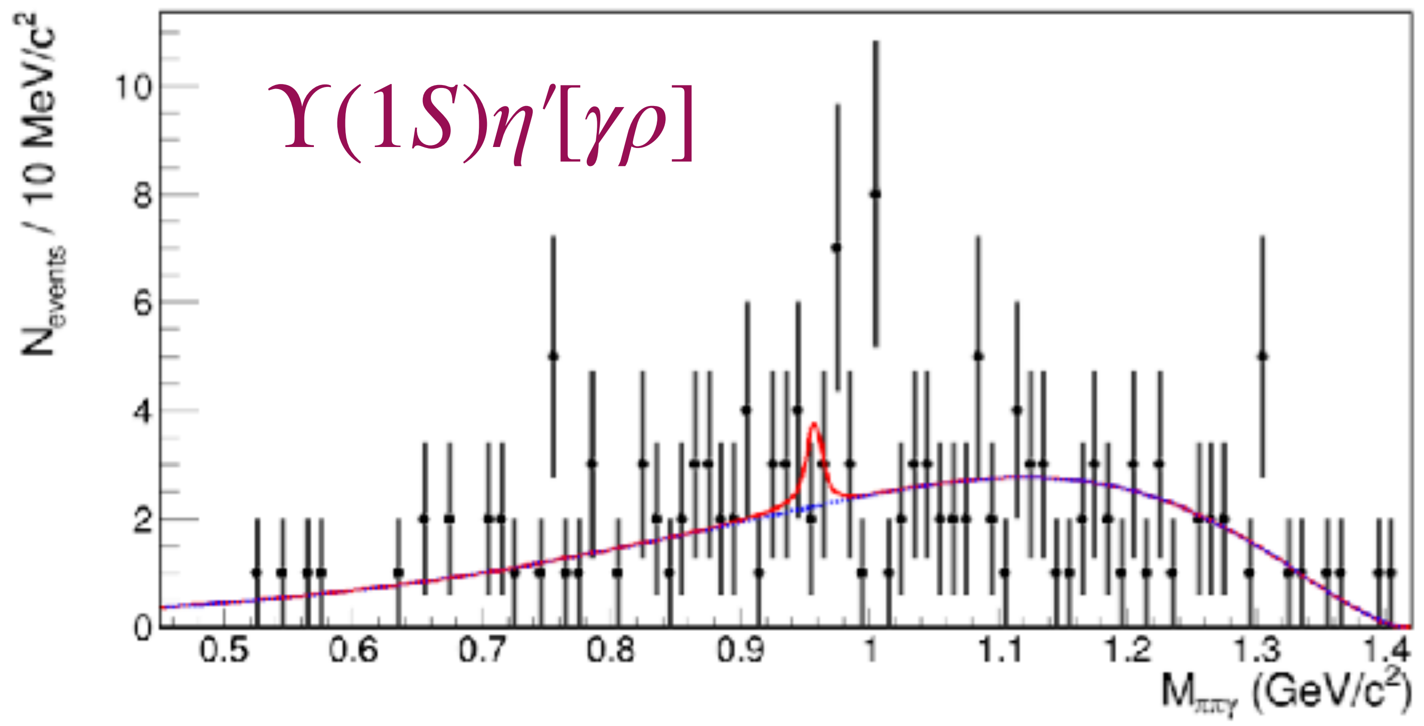
$21\ \mathrm{fb}^{-1}$ **energy scan in** $10.63 \sim 11.02\ \mathrm{GeV}$











Significant $\Upsilon(1S)\eta$ and $\Upsilon(2S)\eta$ signals

- 10.2σ for $e^+e^- \to \Upsilon(1S)\eta$
- 16.5σ for $e^+e^- \to \Upsilon(2S)\eta$

Assuming process only from $\Upsilon(5S)$:

$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta) = (0.85 \pm 0.15 \pm 0.08) \times 10^{-3},$$
$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\eta) = (4.13 \pm 0.41 \pm 0.37) \times 10^{-3},$$
$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta') < 6.9 \times 10^{-5},\ CL = 90\%.$$

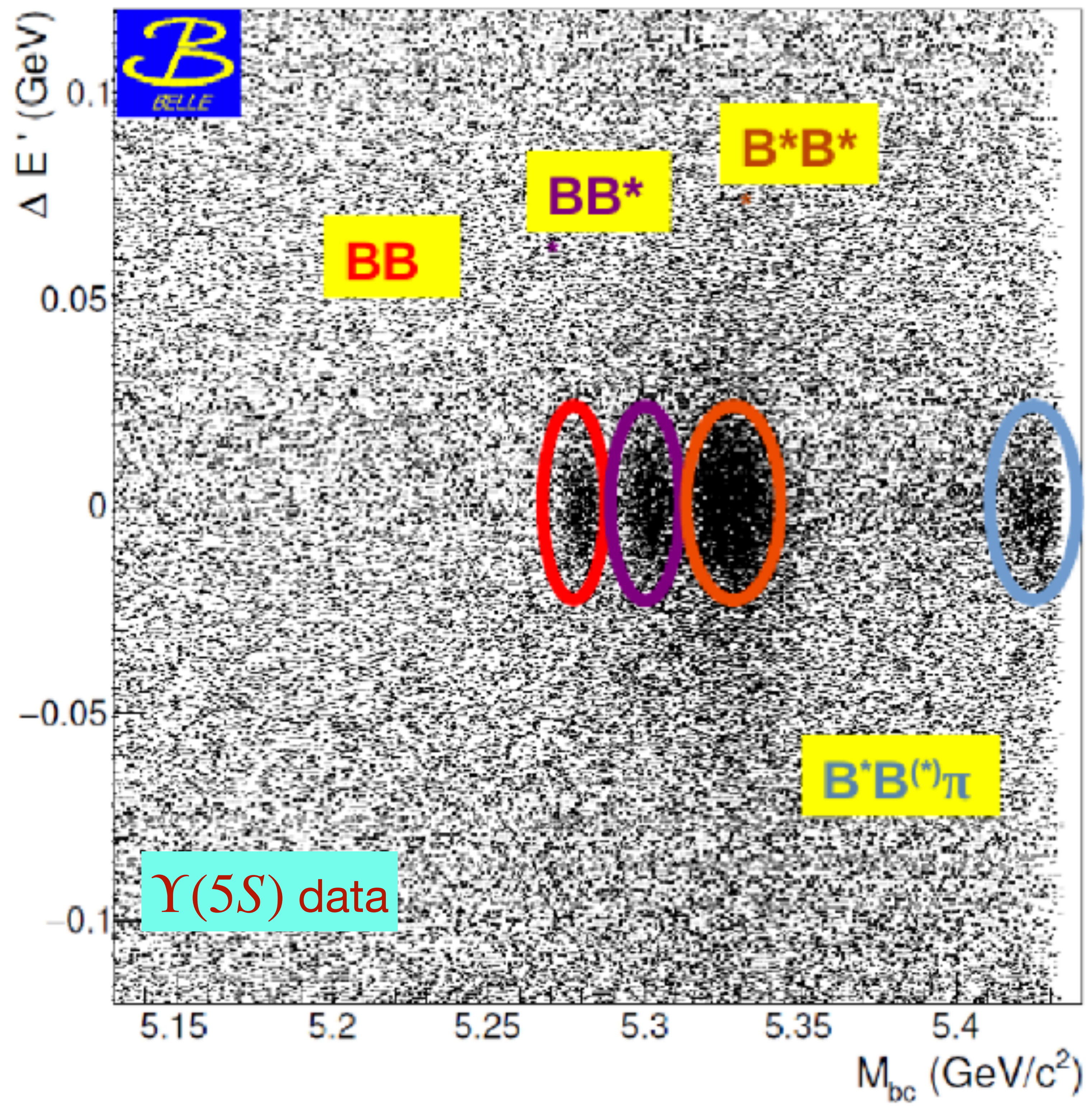
Corresponding fractions are:	Expected
$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)} = 0.52 \pm 0.06$ (stat.)	~ 0.03
$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\pi^+\pi^-)} = 0.18 \pm 0.03$ (stat.)	~ 0.005
$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\eta')}{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\eta)} < 0.14$	~ 12

Cross section of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

Data samples:

- $571\ \mathrm{fb}^{-1}$ on the $\Upsilon(4S)$ resonance
- $121\ \mathrm{fb}^{-1}$ on the $\Upsilon(5S)$ resonance
- $16\ \mathrm{fb}^{-1}$ distributed evenly in 16 points within $10.63 \sim 11.02\ \mathrm{GeV}$

Full reconstruction of one B meson using FEI, a tool developed for tagging B meson in the $\Upsilon(4S) \to B\bar{B}$ decays using multivariate analysis for event selection.
*[Comput. Softw. Big Sci. **3**, 6 (2019)]*

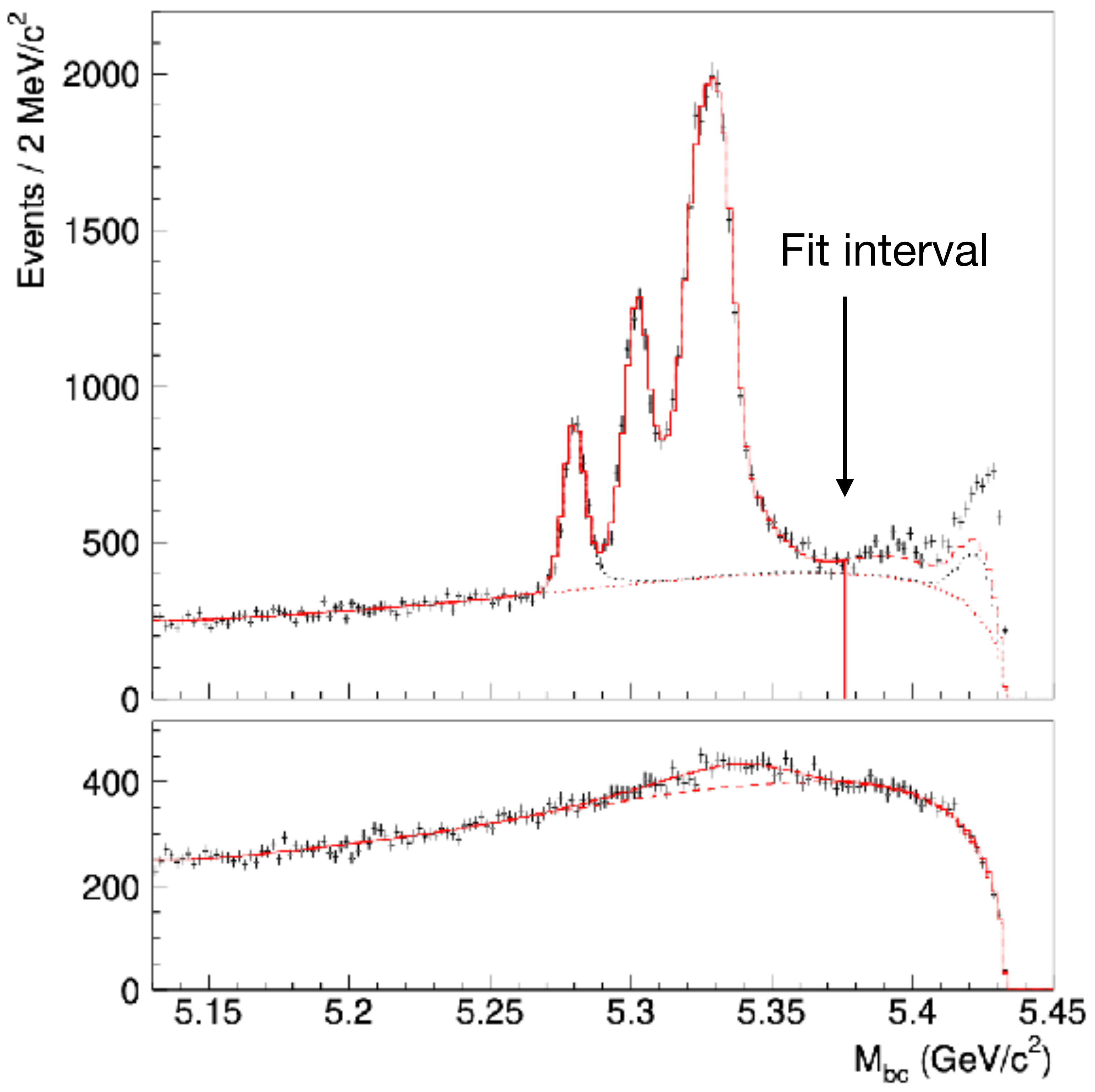


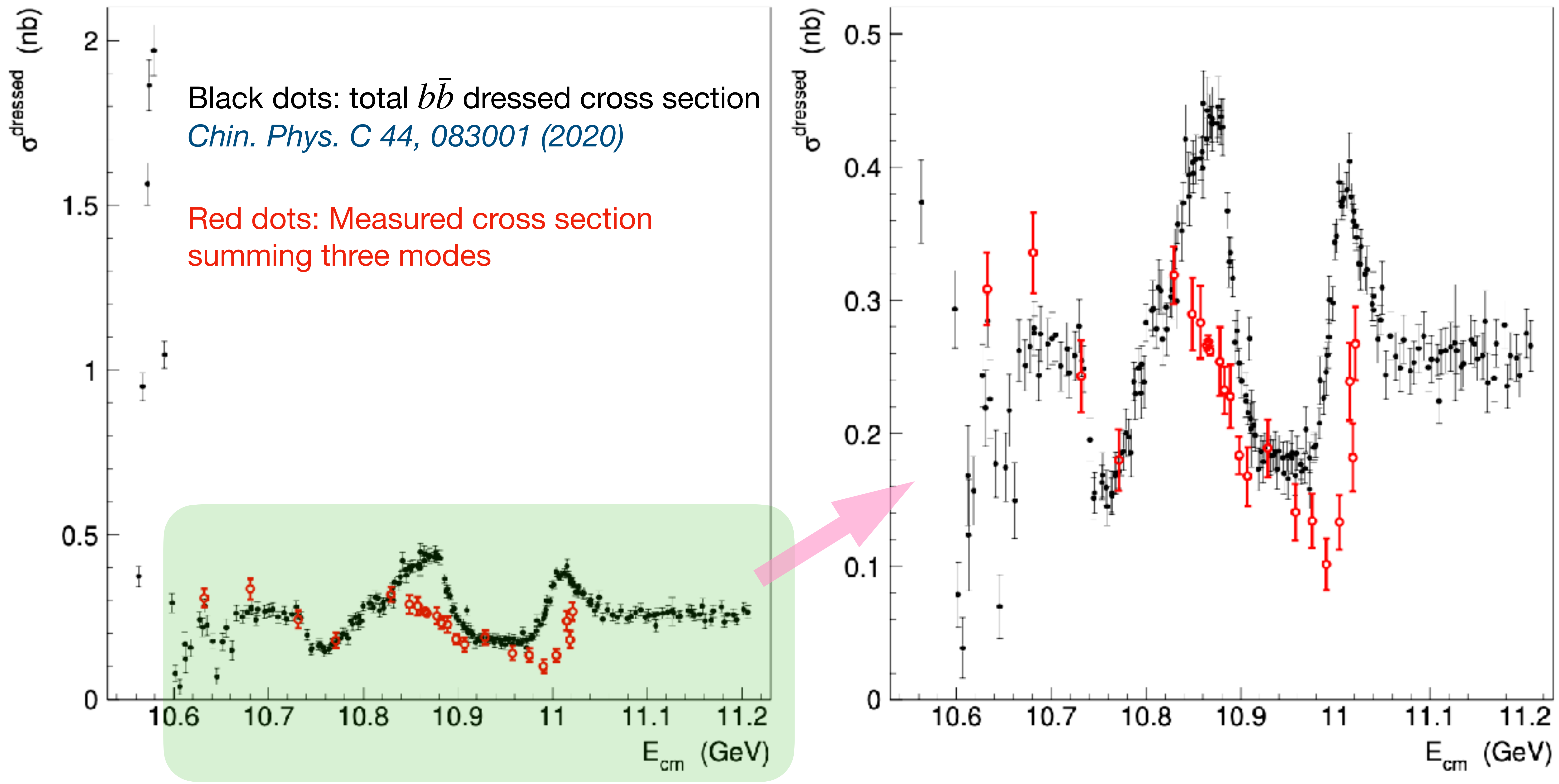
$$M_{bc} \equiv \sqrt{(E_{beam,CM})^2 - (p_{B,CM})^2}$$

$$\Delta E' \equiv \Delta E - M_{bc} + M_B$$

where

$$\Delta E \equiv E_{B,CM} - E_{beam,CM}$$





- Fit M_{bc} distributions, selected in ΔE` signal region and ΔE` side-bands, for data taken at $\Upsilon(5S)$
- A similar fit is done for all 16 data points in the scan, to study the energy dependence of the cross sections

$$\sigma^{\text{dressed}} = \frac{N}{(1+\delta_{\text{ISR}})\,L\,\varepsilon},$$

- No clear $\Upsilon(5S)$ signals from cross section measurement of $B^{(*)}\bar{B}^{(*)}$
- Excess is $B_s^{(*)}\bar{B}_s^{(*)}$, $B^{(*)}\bar{B}^{(*)}n\pi$, bottomonia + light hadrons, which contradicts expectation of $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}$ dominantly.
- Cross sections do not peak at $\Upsilon(5S)$ mass.

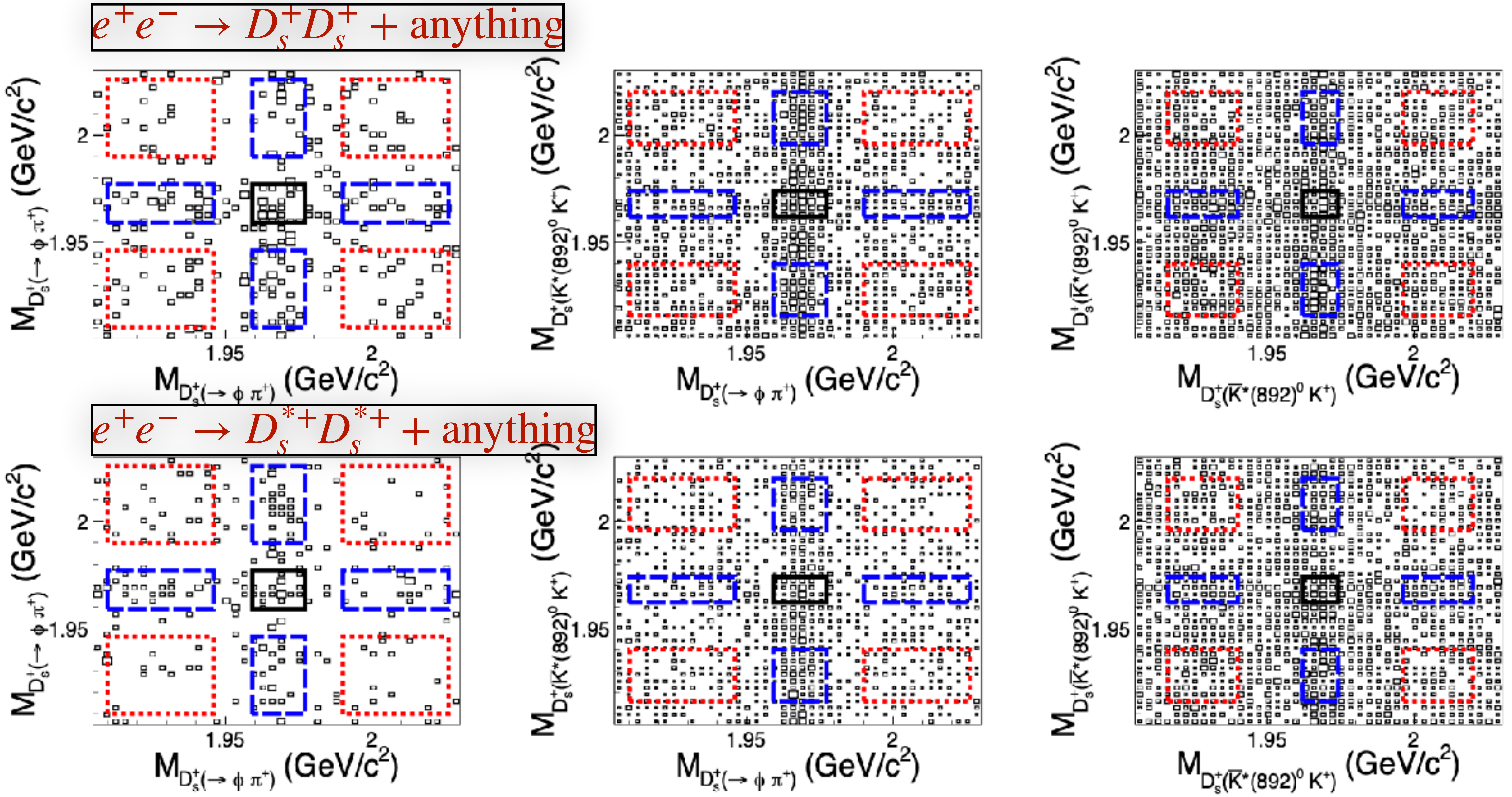
Search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_s^+ D_s^+$, $D_s^{*+} D_s^{*+}$

predictions

Mode	IJ^P	Mass (MeV/c^2)	Width (MeV)
$X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+$	00^+	4902	3.54
$X_{cc\bar{s}\bar{s}} \to D_s^{*+} D_s^{*+}$	02^+	4821	5.58
	02^+	4846	10.68
	02^+	4775	23.26

Data samples:

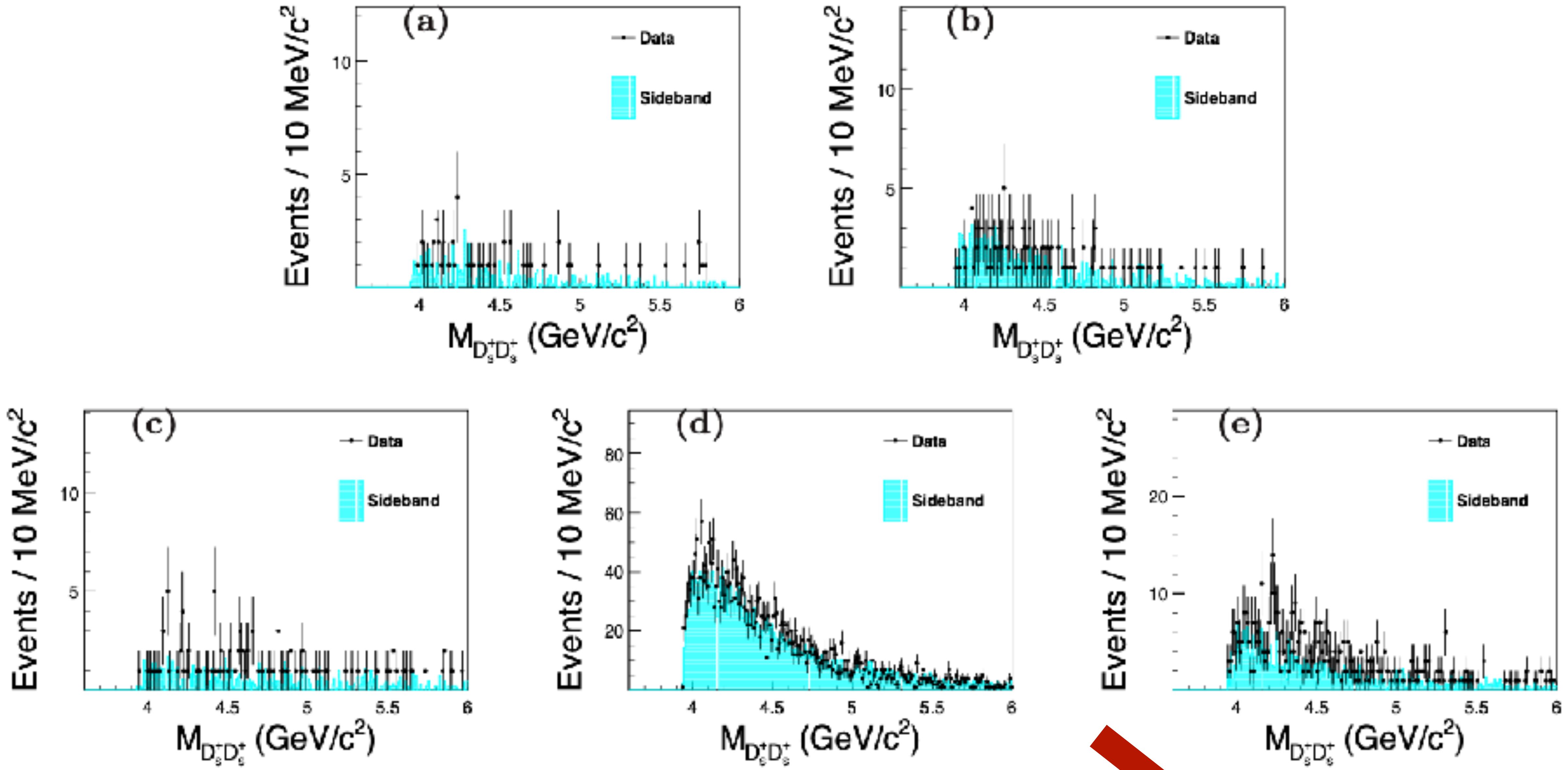
a. $5.74\ \text{fb}^{-1}$ on the $\Upsilon(1S)$ resonance
b. $24.7\ \text{fb}^{-1}$ on the $\Upsilon(2S)$ resonance
c. $89.5\ \text{fb}^{-1}$ at $\sqrt{s} = 10.52$ GeV
d. $711\ \text{fb}^{-1}$ at $\sqrt{s} = 10.58$ GeV
e. $121.4\ \text{fb}^{-1}$ at $\sqrt{s} = 10.867$ GeV



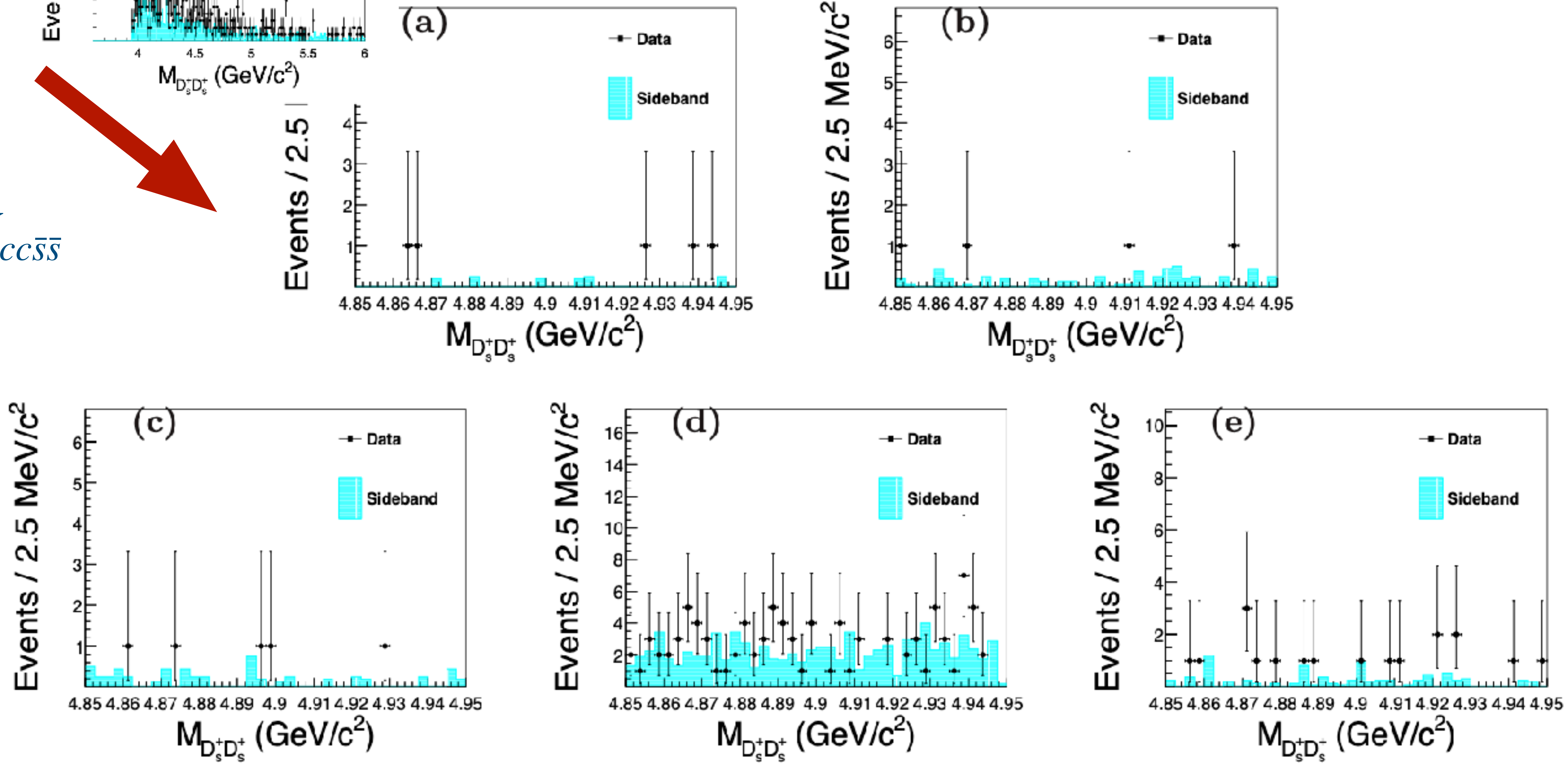
Use two modes to reconstruct D_s^+
- $D_s^+ \to K^*(892) K^+$
- $D_s^+ \to \phi \pi^+$

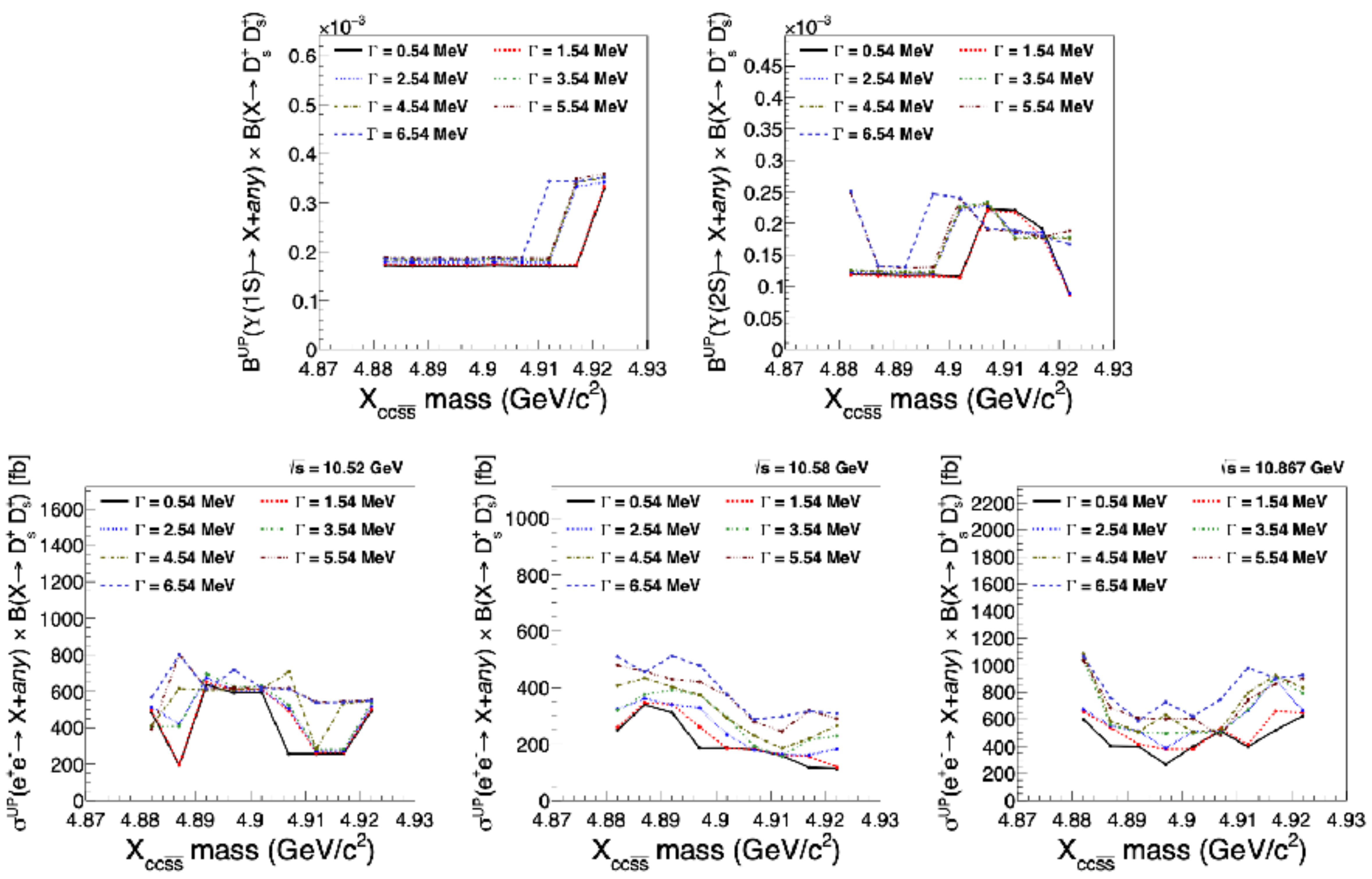
$e^+e^- \to D_s^+ D_s^+ + \text{anything}$

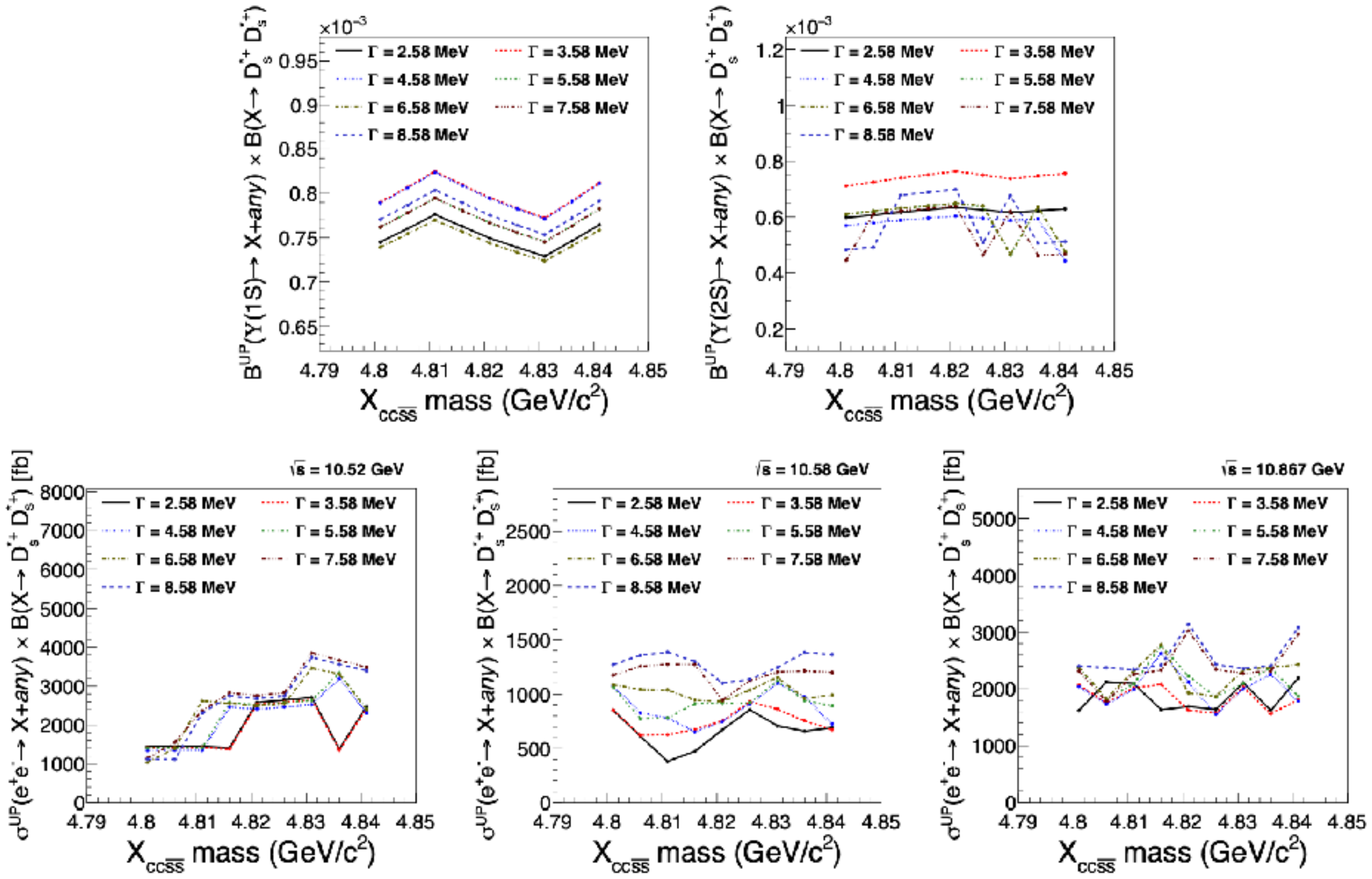
No peaking background in ***sideband***



Focus on prediction regions for $X_{cc\bar{s}\bar{s}}$







No evident signal from $D_s^+D_s^+$ or $D_s^{*+}D_s^{*+}$.

Upper limits in 90% C.L. are estimated in different mass and width assumptions.

Others

Search for $\eta_{c2}(1D)$ in the $e^+e^- \to \gamma\eta_{c2}(1D)$

Phys.Rev.D 104 (2021) 012012

Study of $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$ at Belle

arXiv: 2108.03497

Search for a doubly-charged DDK bound state

Phys.Rev.D 102 (2020) 11, 112001

Evidence of $\Omega_c \to \pi^+ \Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$

- (Belle 2018) observation of $\Omega(2012)^- \to K^-\Xi^0,\ K_S^0\Xi^-$
- Interpretations?
  - Is it a $(\bar{K}\Xi(1530))^-$ molecule, or not?
  - If molecule ➔ large decay width of $\Omega(2012)^- \to (\bar{K}\pi\Xi)^-$
- Prediction
  - $\Omega(2012)^-$ would be much more visible in $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$

PHYS. REV. D **102**, 076009 (2020)

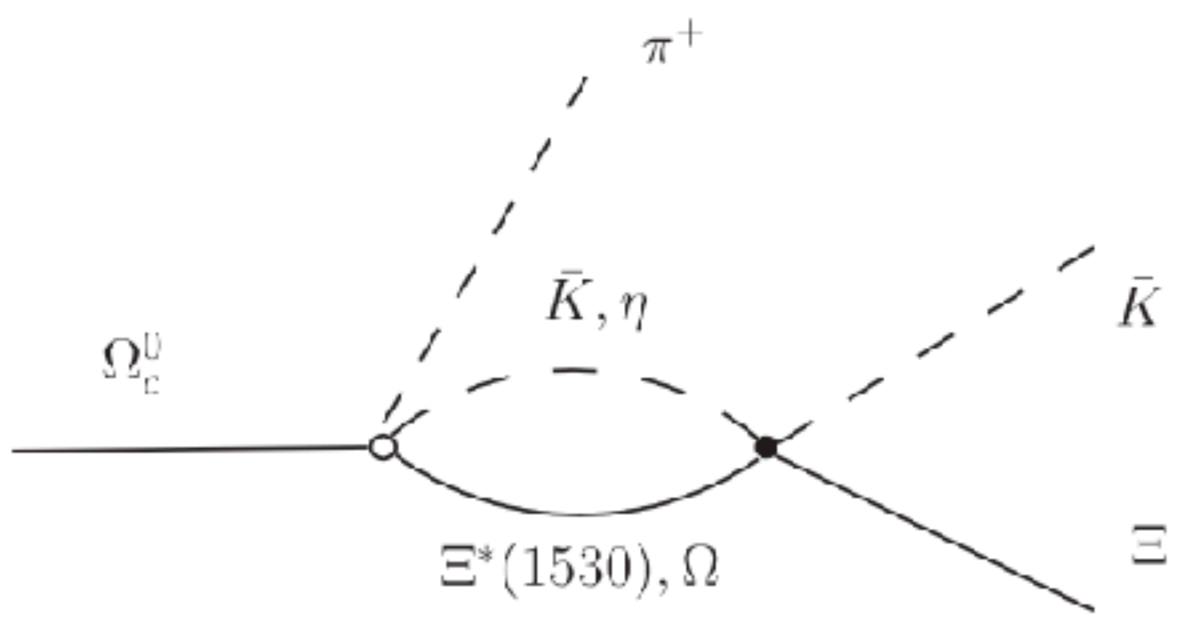


FIG. 2. Diagram for the meson-baryon final-state interaction for the $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ decay.

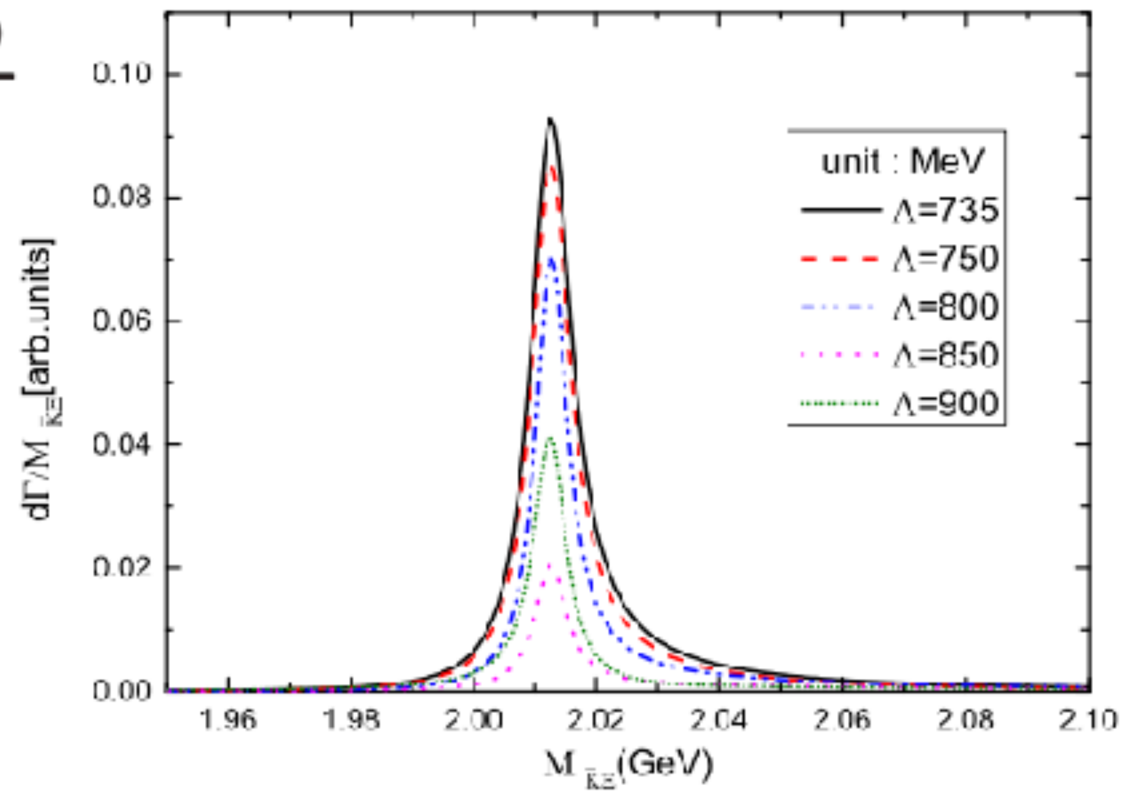


FIG. 3. $\bar{K}\Xi$ invariant mass distributions of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ decay.

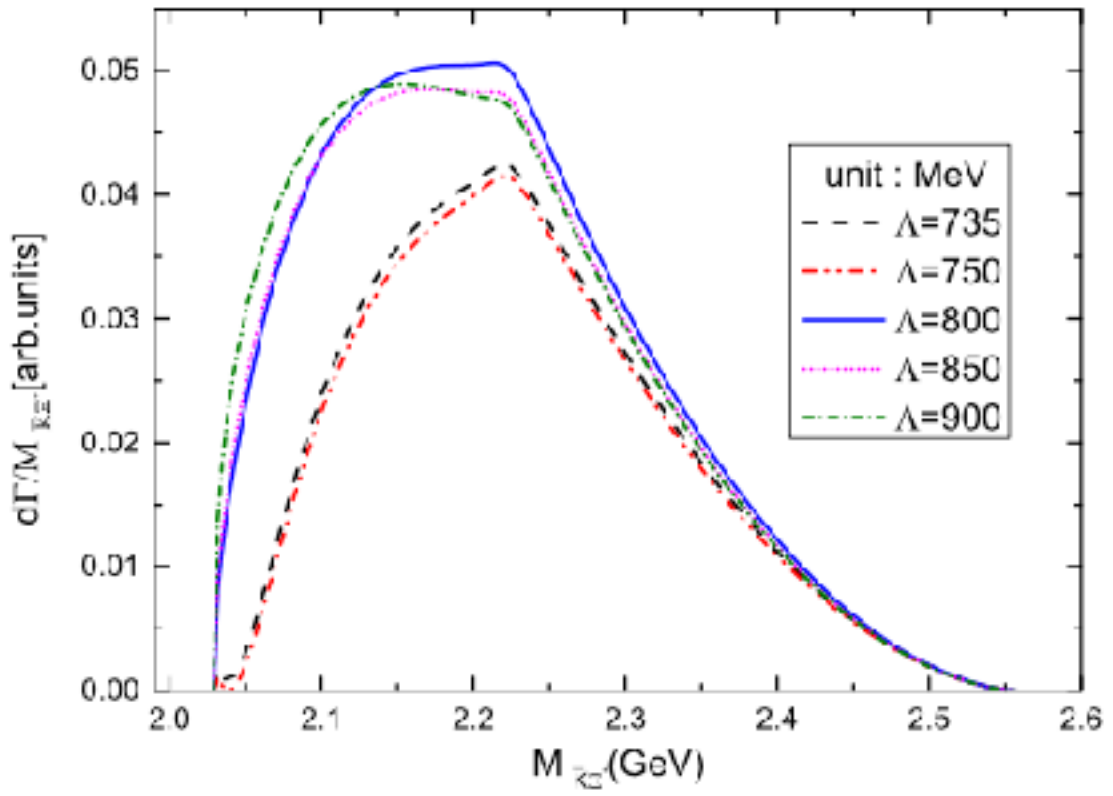
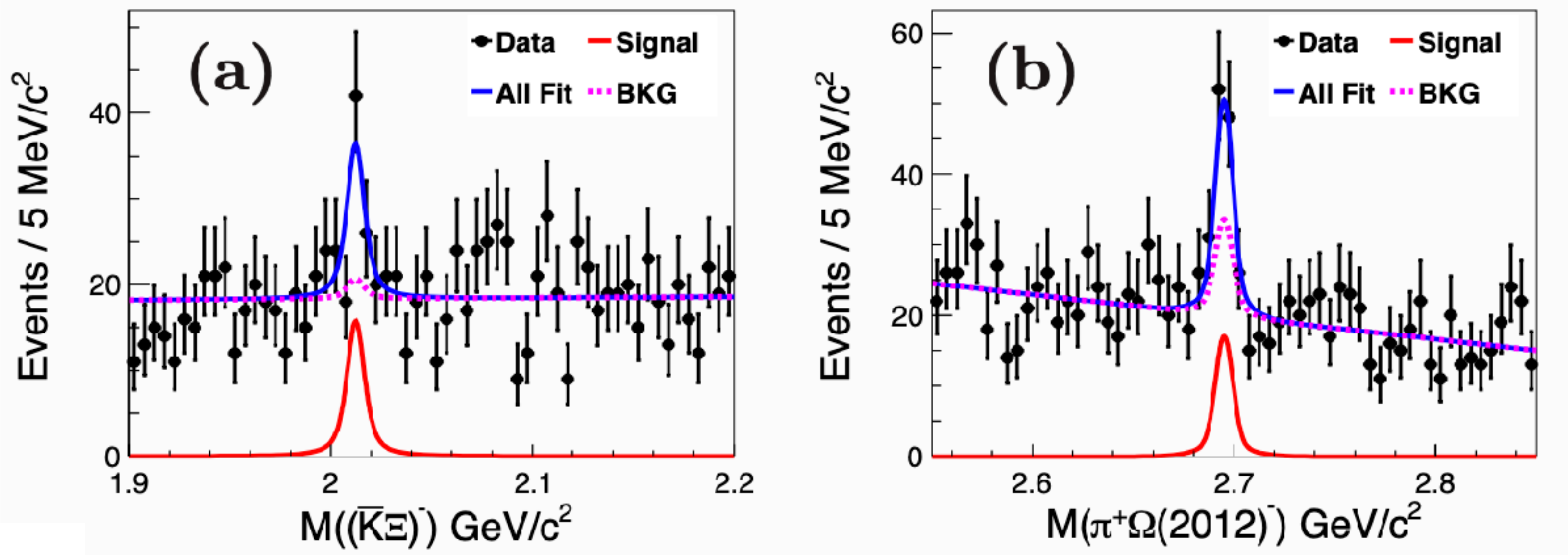


FIG. 4. $\bar{K}\Xi^*$ invariant mass distribution of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi^*)$ decay.

Phys.Rev.D 104 (2021) 5, 052005

2D fit to $M(\bar{K}\Xi)$ vs $M(\pi^+\Omega(2012)^-)$ simultaneously for $M(K^-\Xi^0)$ and $M(K_S^0\Xi^-)$.

Entire Belle data—$980\ \mathrm{fb}^{-1}$



$N_{fit} = 46.6 \pm 12.3$

Signal significance: 4.2σ
(including systematic uncertainties)

$$\frac{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\overline{K}\Xi)^-)}{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega^-)} = 0.220 \pm 0.059 \pm 0.035$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+K^-\Xi^0)}{\mathcal{B}(\Omega_c^0 \to \pi^+K^-\Xi^0)} = (9.6 \pm 3.2 \pm 1.8)\%$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+K_S^0\Xi^-)}{\mathcal{B}(\Omega_c^0 \to \pi^+K_S^0\Xi^-)} = (5.5 \pm 2.8 \pm 0.7)\%$$

Spin parity of $\Xi_c(2970)^+$

- ∃ no determination of spin-parity of Ξ_c baryons

Ξ_c^+ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

J^P has not been measured; $\frac{1}{2}^+$ is the quark-model prediction.

Mass $m = 2467.71 \pm 0.23$ MeV (S = 1.3)
Mean life $\tau = (456 \pm 5) \times 10^{-15}$ s

$\Xi_c(2970)$ $I(J^P) = \frac{1}{2}(?^?)$

was $\Xi_c(2980)$

$\Xi_c(2970)^+$ $m = 2964.3 \pm 1.5$ MeV (S = 3.9)
$\Xi_c(2970)^0$ $m = 2967.1 \pm 1.7$ MeV (S = 6.7)

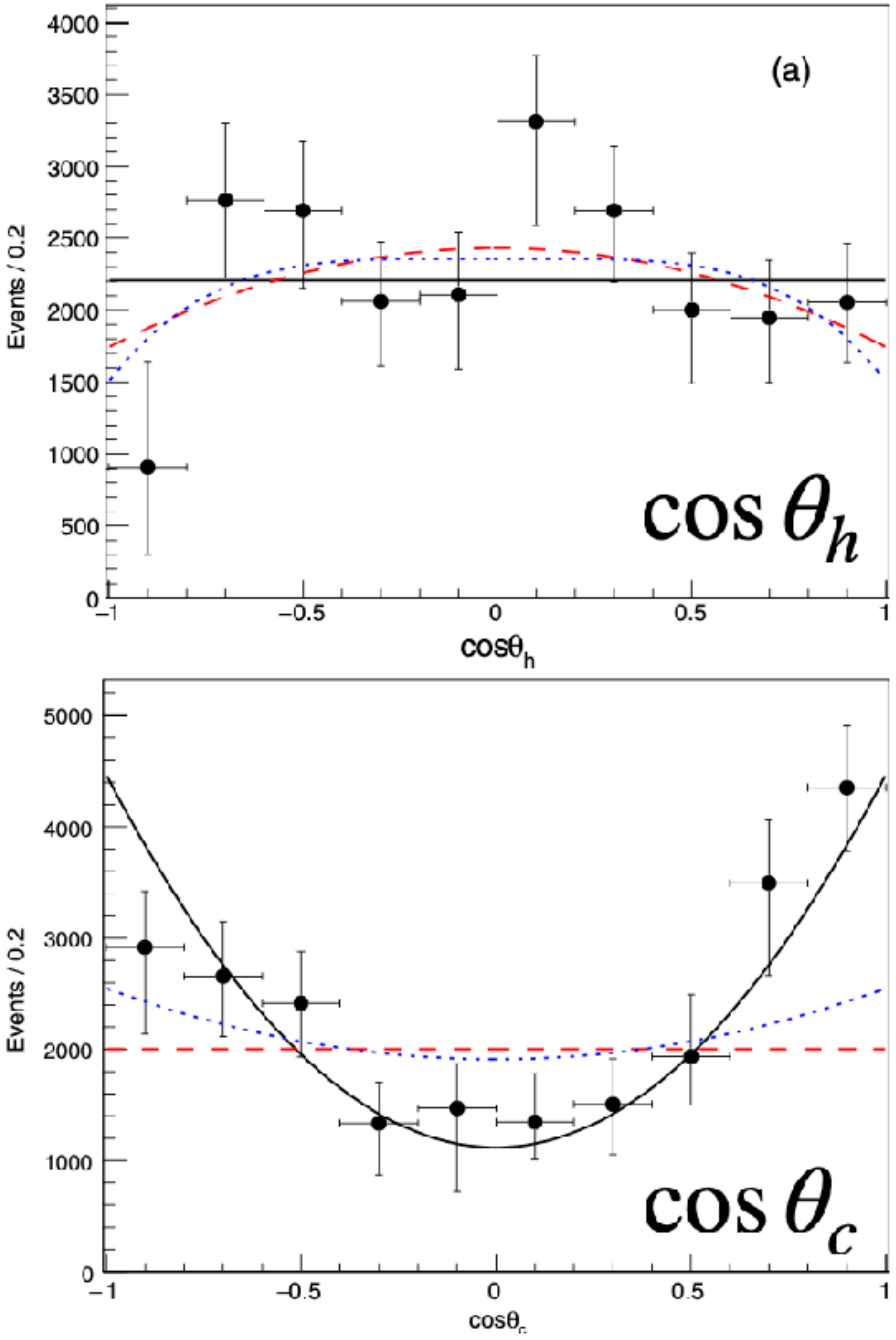
- We study $\Xi_c(2970)^+$ because
  - J^P has not been assigned by PDG
  - Belle, with high-stat. $\Xi_c(2970)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^+\pi^-$ and clean e^+e^- setting, is an ideal place to measure J^P of $\Xi_c(2970)^+$

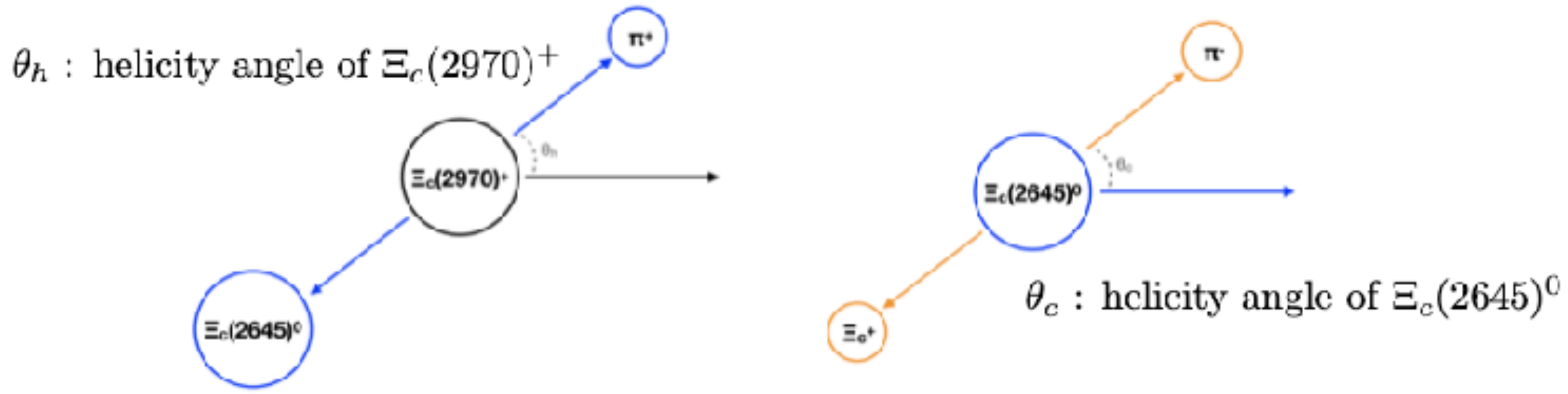
• wide variety (of J^P) and controversial
• many predicted states within ~50 MeV

- ∃ many theory predictions
  - $J^P = 1/2^+, 3/2^+, 5/2^+, 5/2^-$, and even predictions of (−) parity
  - so, we want to measure it and help decipher the nature of the state

Spin & Parity of $\Xi_c(2970)^+$

Phys.Rev.D 103 (2021) 11, L111101





J^P	Partial wave	$W(\theta_c)$
$1/2^+$	P	$1 + 3\cos^2\theta_c$
$1/2^-$	D	$1 + 3\cos^2\theta_c$
$3/2^+$	P	$1 + 6\sin^2\theta_c$
$3/2^-$	S	1
$5/2^+$	P	$1 + (1/3)\cos^2\theta_c$
$5/2^-$	D	$1 + (15/4)\sin^2\theta_c$

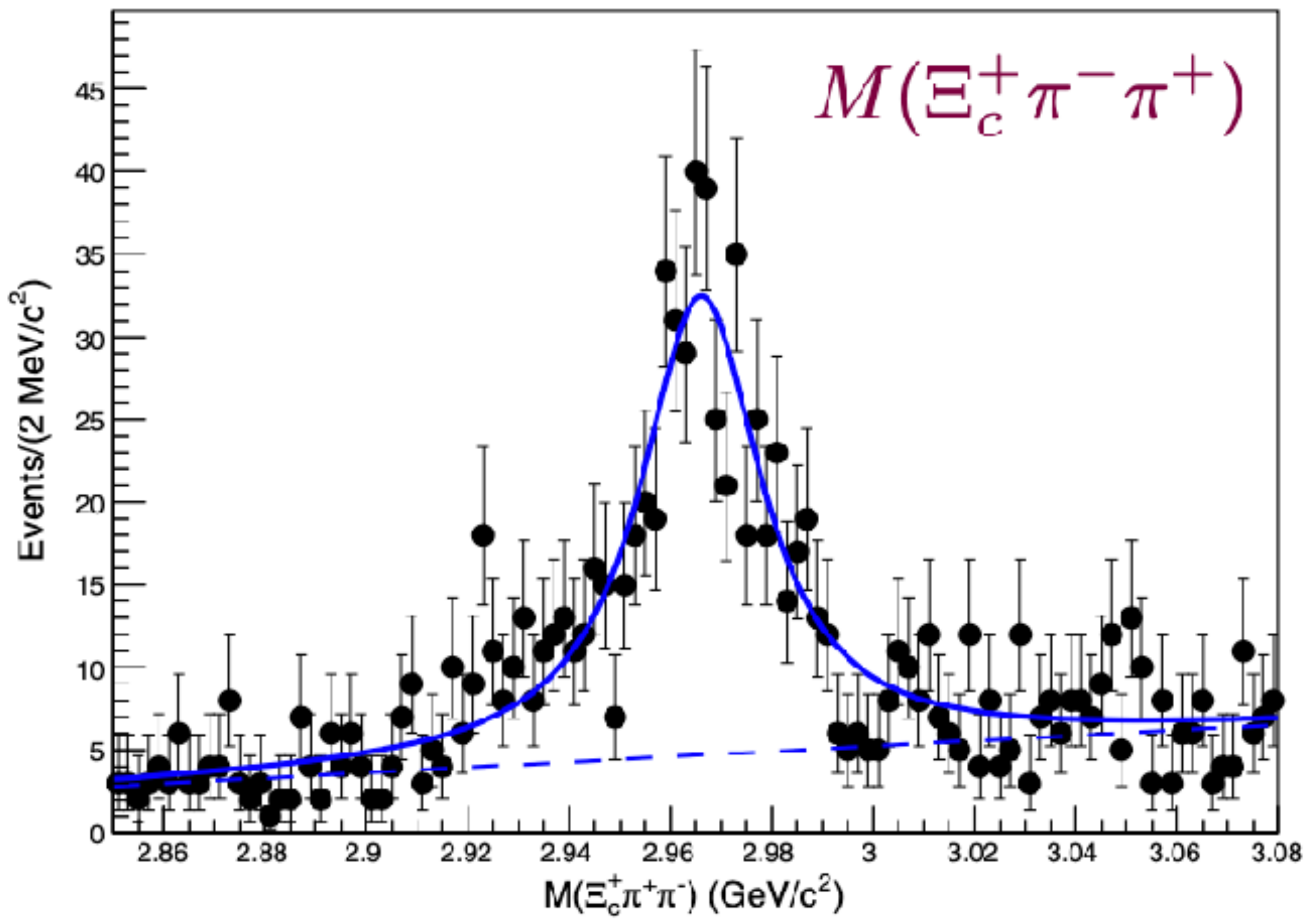
J^P	$1/2^\pm$	$3/2^-$	$5/2^+$
χ^2/n.d.f.	6.4/9	32.2/9	22.3/9
Exclusion level (s.d.)	$\cdots$	5.5	4.8

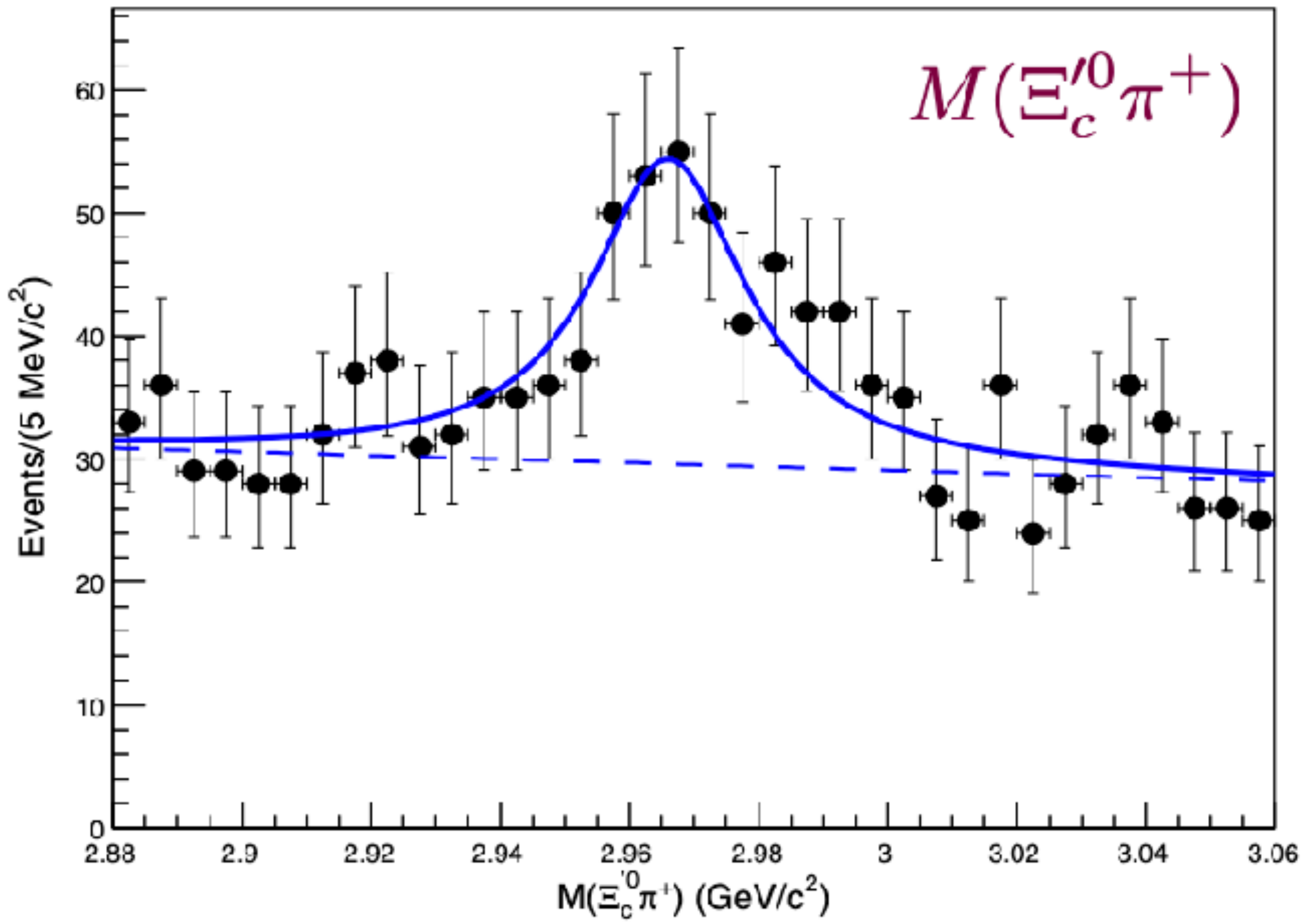
- most consistent with spin=1/2 hypothesis
- also excludes $\Xi_c(2645)$ spin of 1/2 ($\because$ $\cos\theta_c$ not flat)

Spin & Parity of $\Xi_c(2970)^+$

Phys.Rev.D 103 (2021) 11, L111101

$$R = \frac{\mathcal{B}[\Xi_c(2970)^+ \to \Xi_c(2645)^0\pi^+]}{\mathcal{B}[\Xi_c(2970)^+ \to \Xi_c'^0\pi^+]}$$ — sensitive to parity





$$R = 1.67 \pm 0.29^{+0.15}_{-0.09} \pm 0.25 \ (\text{IS})$$

Heavy-quark spin sym. prediction

Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	$\ll 1$

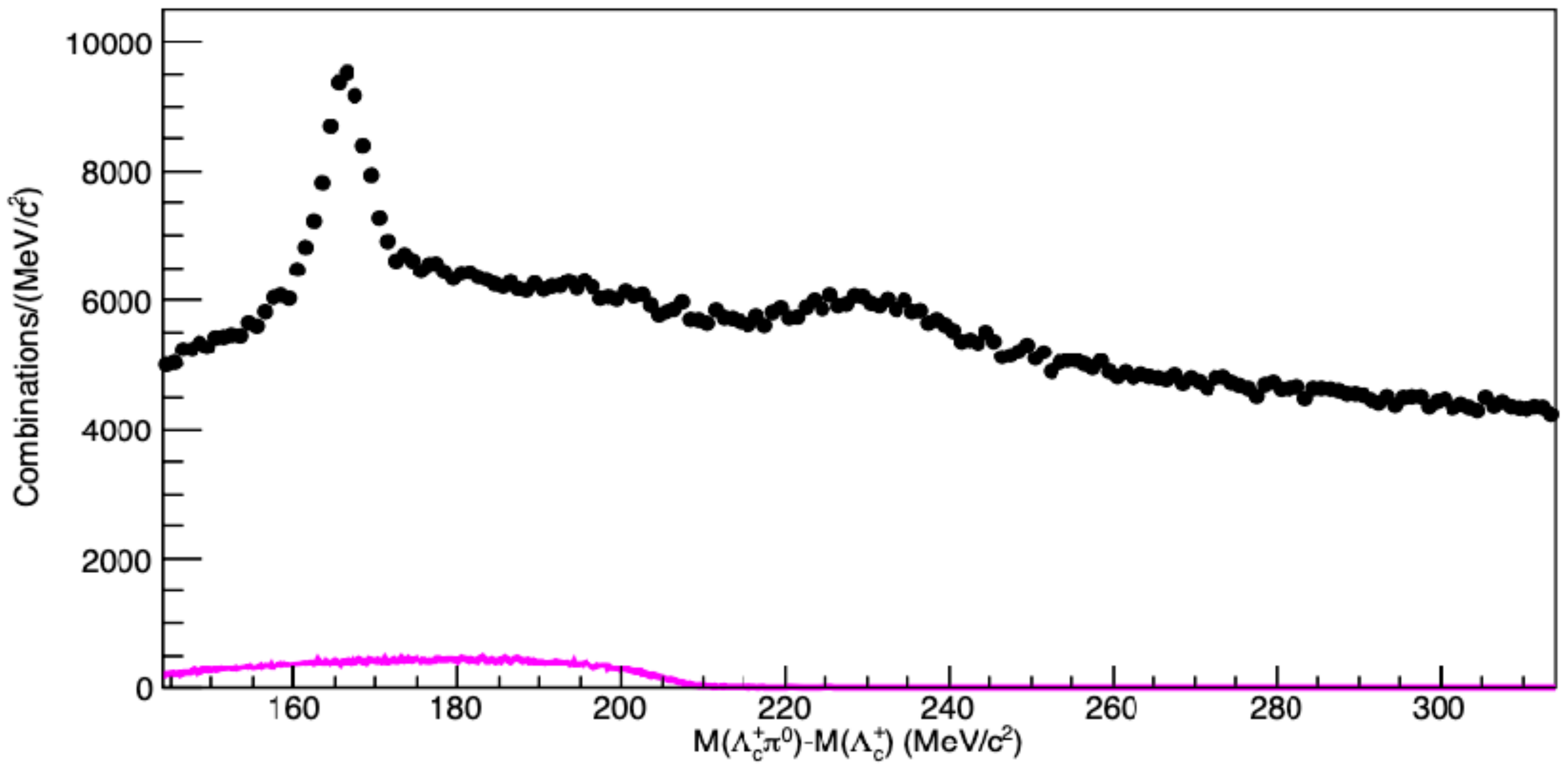
∴ **(+) parity assignment is favored**

Mass and width of $\Sigma_c^{(*)+}$

- Σ_c baryons = a c quark + spin-1 light diquark (uu, ud or dd)
  - lowest : $\Sigma_c(2455)$ triplet, with $J^P = (1/2)^+$ ➔ decay to $\Lambda_c^+\pi$
  - next up: $\Sigma_c(2520)$ triplet, with $J^P = (3/2)^+$ ➔ decay to $\Lambda_c^+\pi$
  - $\Sigma_c^{++/0}$ mass, width — well measured for both charges, but
  - Σ_c^+ — mass only from CLEO II, and limit only for widths
- Mass measurements of the two isotriplets
  - allow tests of models of isospin mass splittings
- Predictions
  - most mass models: $m(\Sigma_c^+) < m(\Sigma_c^{0/++})$
  - natural width models: $\Gamma(\Sigma_c^+) > \Gamma(\Sigma_c^{0/++})$

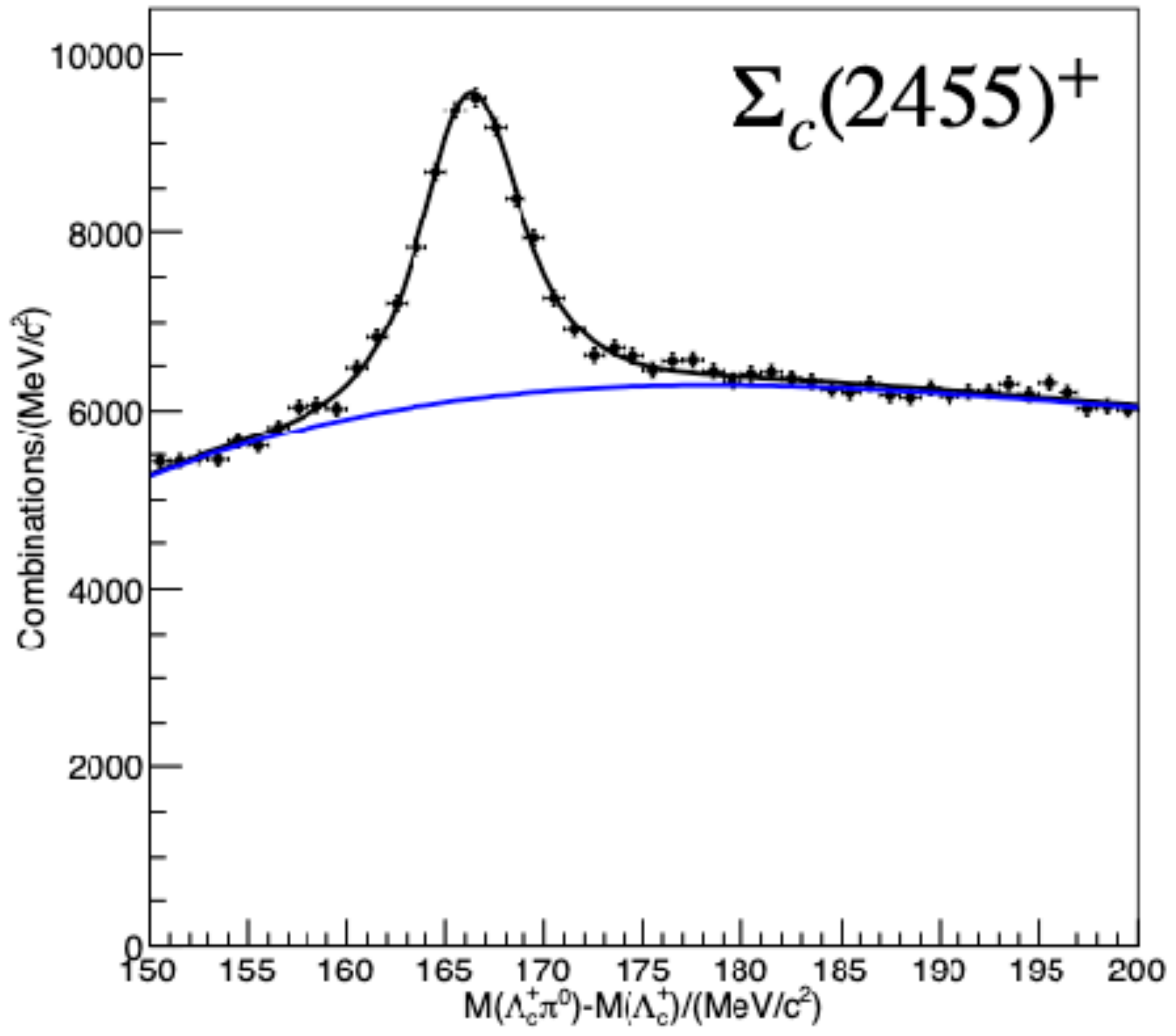
[4] G.-S. Yang and H.-C. Kim, Phys. Lett. B **808**, 135619 (2020).

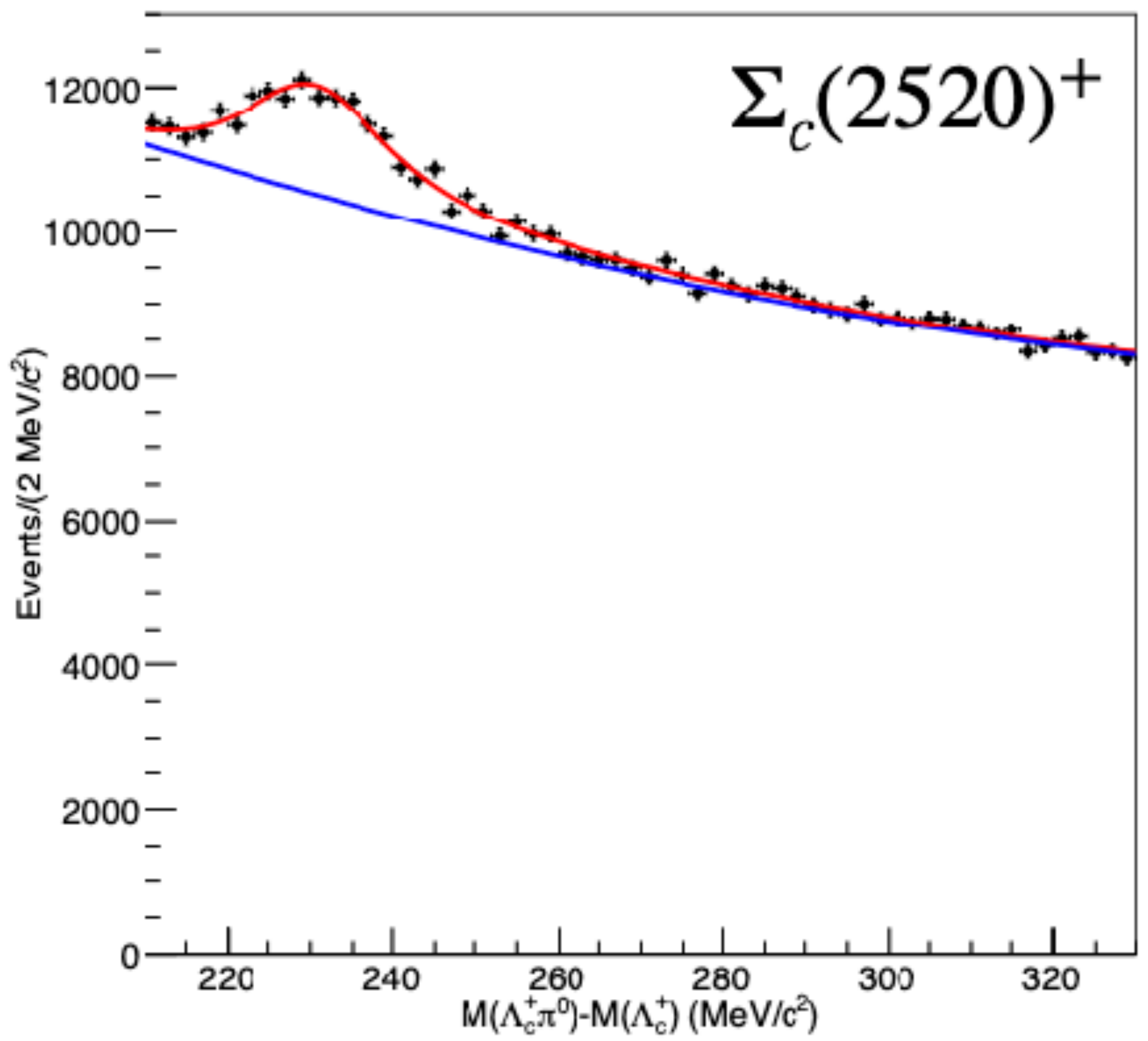
$$\Sigma_c(2455/2520)^+ \to \pi^0 \Lambda_c^+ \to \pi^0 (pK^- \pi^+)$$



Phys.Rev.D 104 (2021) 5, 052003

	$\Sigma_c(2455)^+$	$\Sigma_c(2520)^+$
ΔM [MeV/c^2]	$166.17 \pm 0.05^{+0.16}_{-0.07}$	$230.9 \pm 0.5^{+0.5}_{-0.1}$
Γ [MeV/c^2]	$2.3 \pm 0.3 \pm 0.3$	$17.2^{+2.3+3.1}_{-2.1-0.7}$



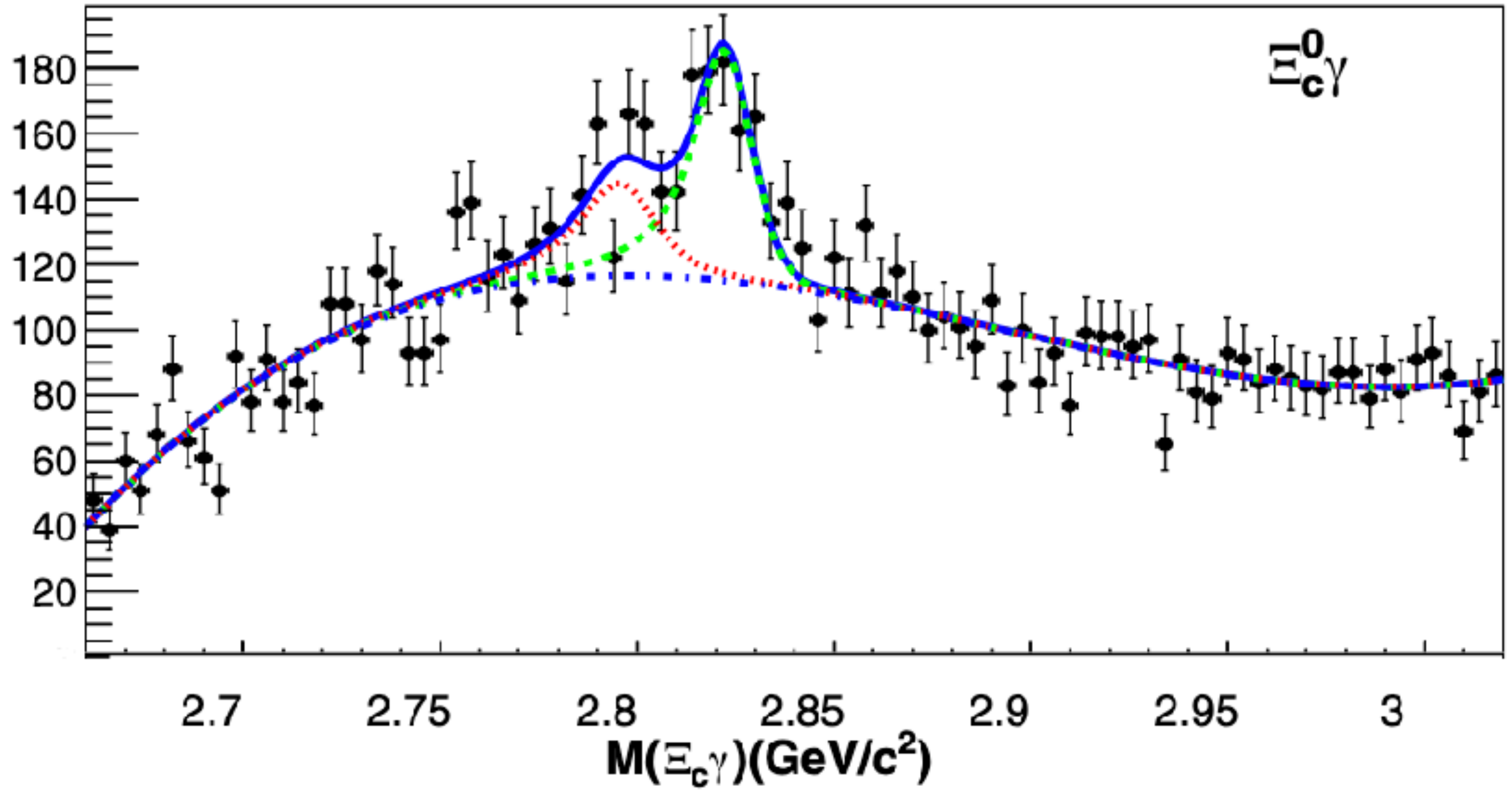


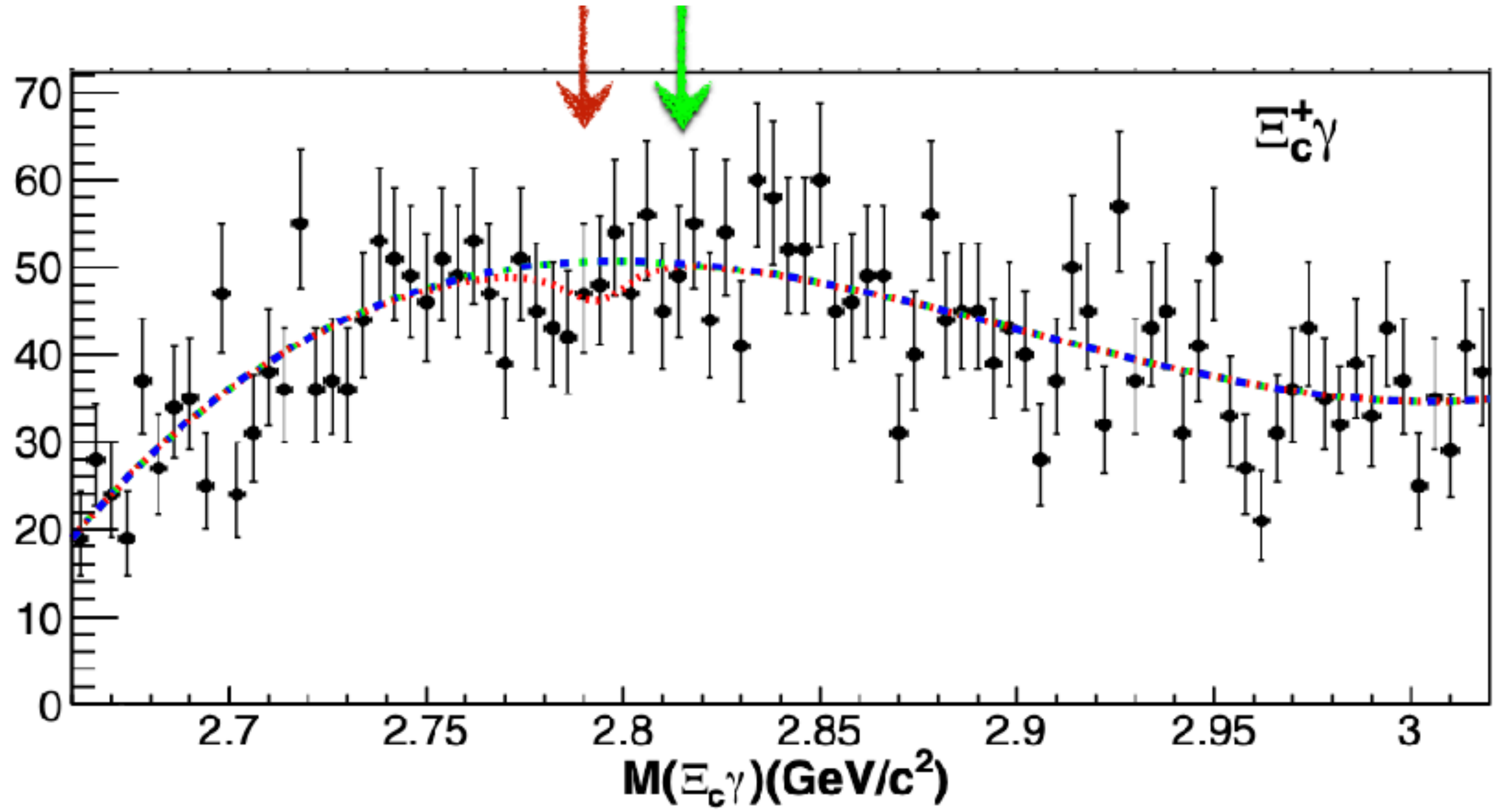
- First measurement of widths of $\Sigma_c(2455)^+$, $\Sigma_c(2520)^+$
- Much improved precision of $m(\Sigma_c(2455)^+)$, $m(\Sigma_c(2520)^+)$
- Measured masses and widths are consistent with theory predictions

Radiative decay of $\Xi_c(2790/2815)$

- Recently measured $\Xi_c(2790)^{+/0}$ & $\Xi_c(2815)^{+/0}$ masses and widths
  - In the picture of $(c + ud, us)$, these are typically interpreted as $L = 1$ orbital excitations ("λ").
  - The nature of these states are identified by mass spectra and decay modes.
- Excited charmed baryons mostly decay via strong interactions.
  - the only observed EM decays : $\Xi_c' \to \Xi_c \gamma,\ \Omega_c(2770) \to \Omega_c \gamma$
- Wang, Yao, Zhong, Zhao (PRD 96, 116016 (2017)) predicts
  - assuming λ excitations, large widths of $\Xi_c(2790)^0 \to \Xi_c^0 \gamma,\ \Xi_c(2815)^0 \to \Xi_c^0 \gamma$ $(\Gamma \gtrsim 200\ \mathrm{keV})$
  - assuming ρ excitations (between the two light quarks), much smaller widths $(< 10\ \mathrm{keV})$ for the Ξ_c^+ baryons

Phys.Rev.D 102 (2020) 7, 071103





$$R^0_{2790} = \frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$$

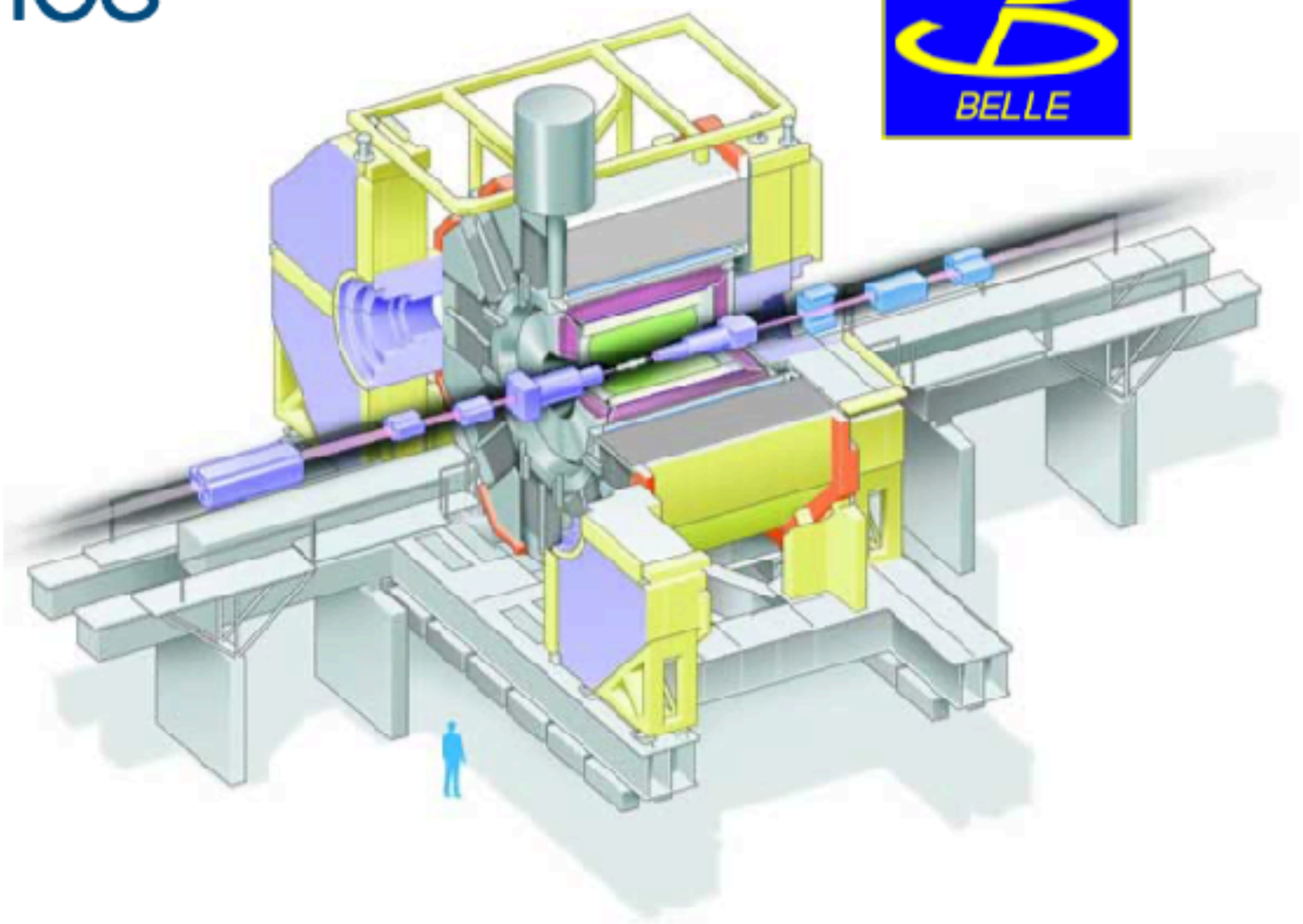
$$R^+_{2790} = \frac{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+]} < 0.06 \text{ @ } 90\% \text{ C.L.}$$

$$R^0_{2815} = \frac{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-]} = 0.41 \pm 0.05 \pm 0.03$$

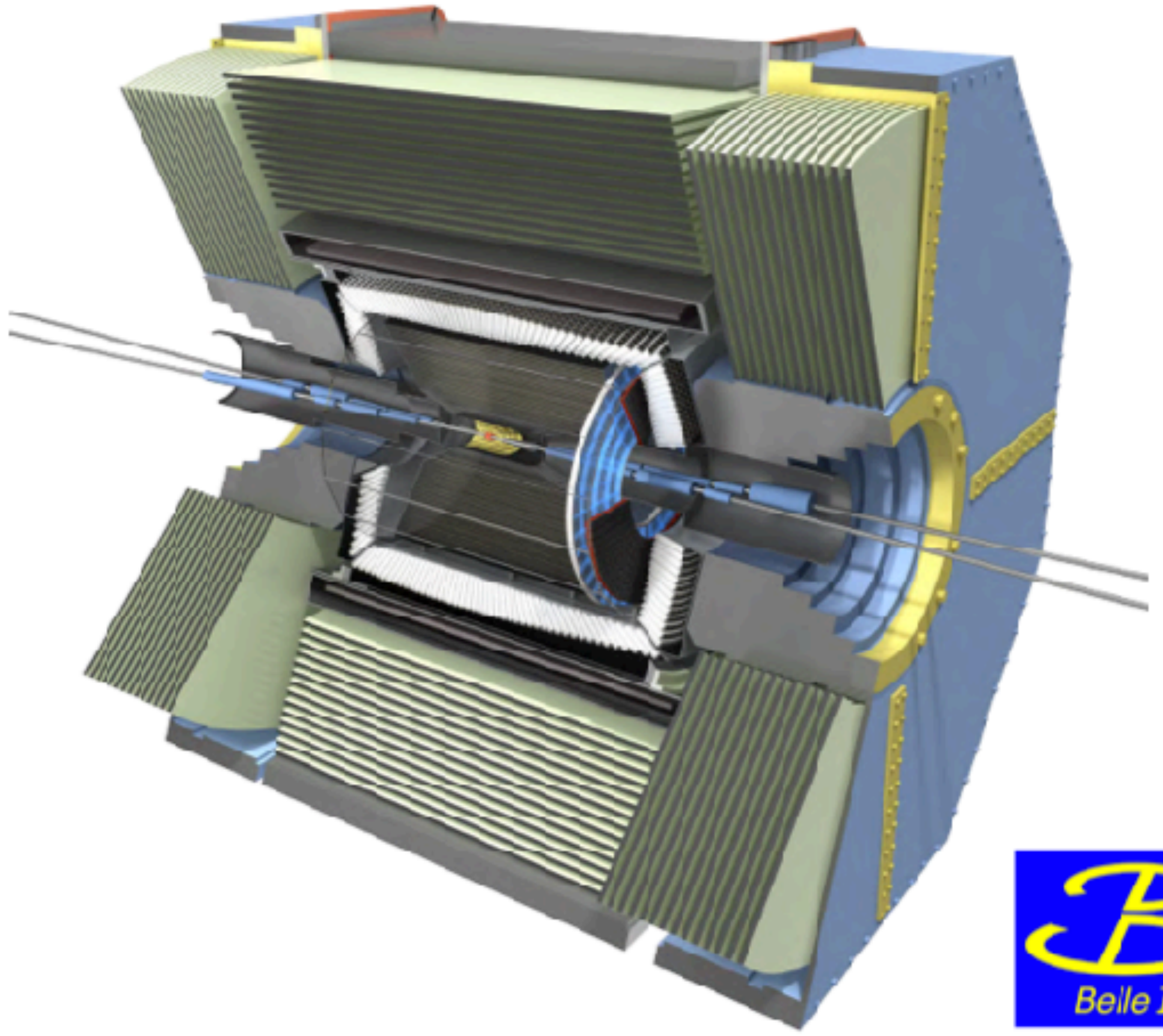
$$R^+_{2815} = \frac{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^+\pi^-]} < 0.09 \text{ @ } 90\% \text{ C.L.}$$

- First observation of radiative decays of orbitally excited Ξ_c

Benefits of hadron spectroscopy at B-factories

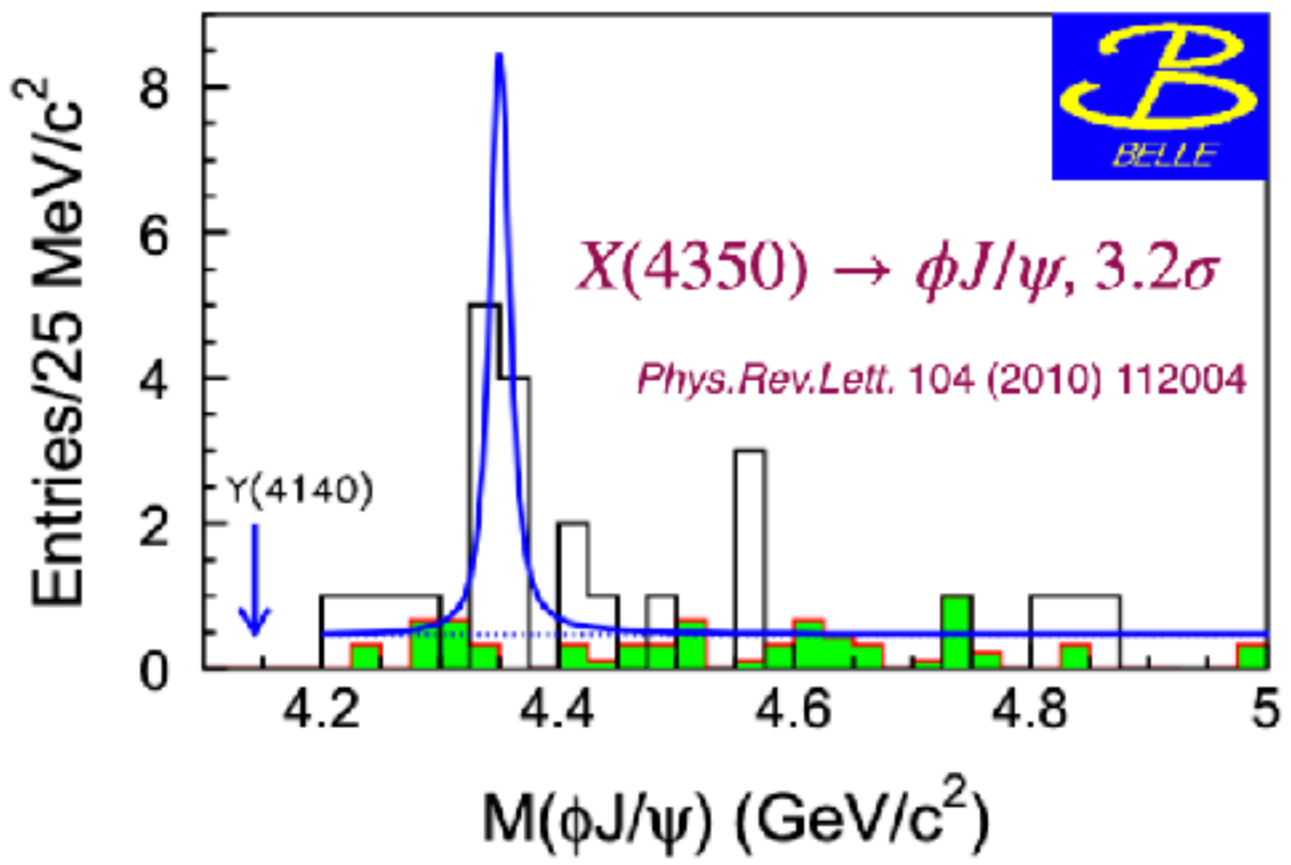


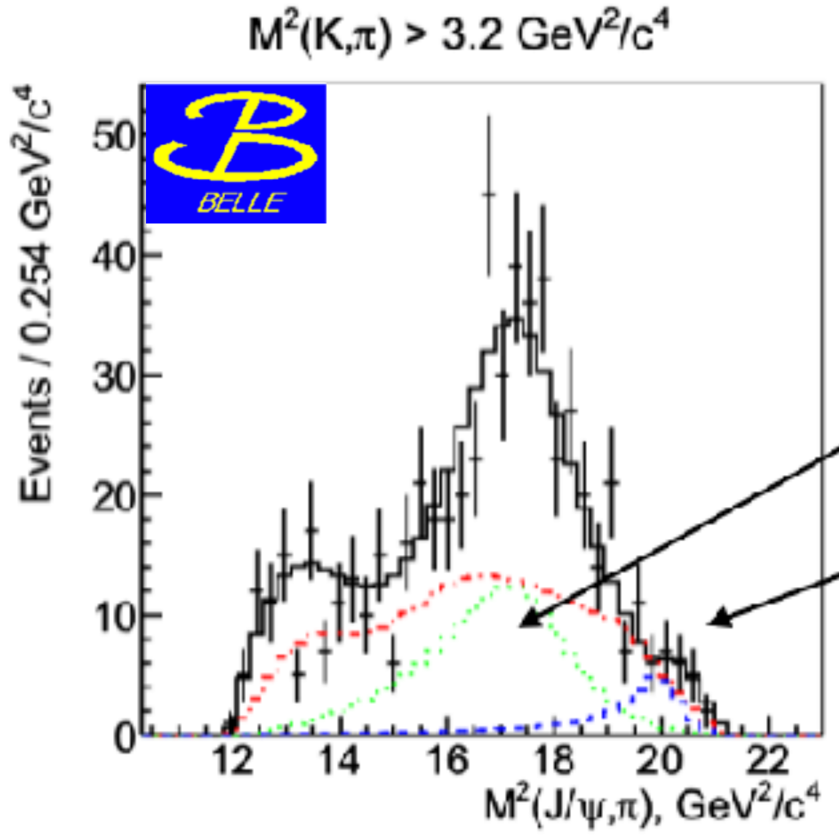
- ☑ Efficient reconstruction of neutrals (π^0, η, ...)
- ☑ Fully reconstruction or recoil system
- ☑ Variety of production mechanisms
- ☑ Large production rate of $b \to c\bar{c}$
- ☑ Unique dataset



Prospect

Evidence could be clarified, e.g.



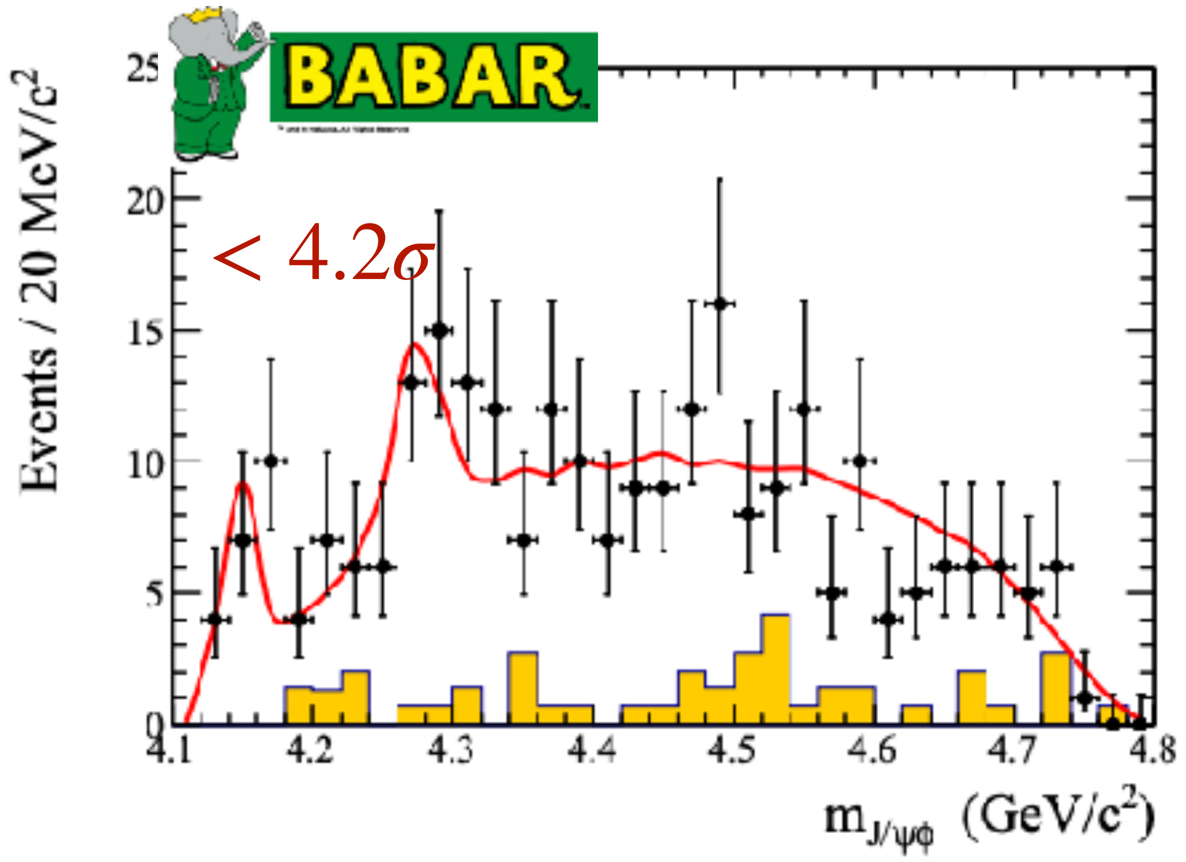


$Z_c(4200)$ and $Z_c(4430)$ in $B \to K\pi^- J/\psi$

6.2σ

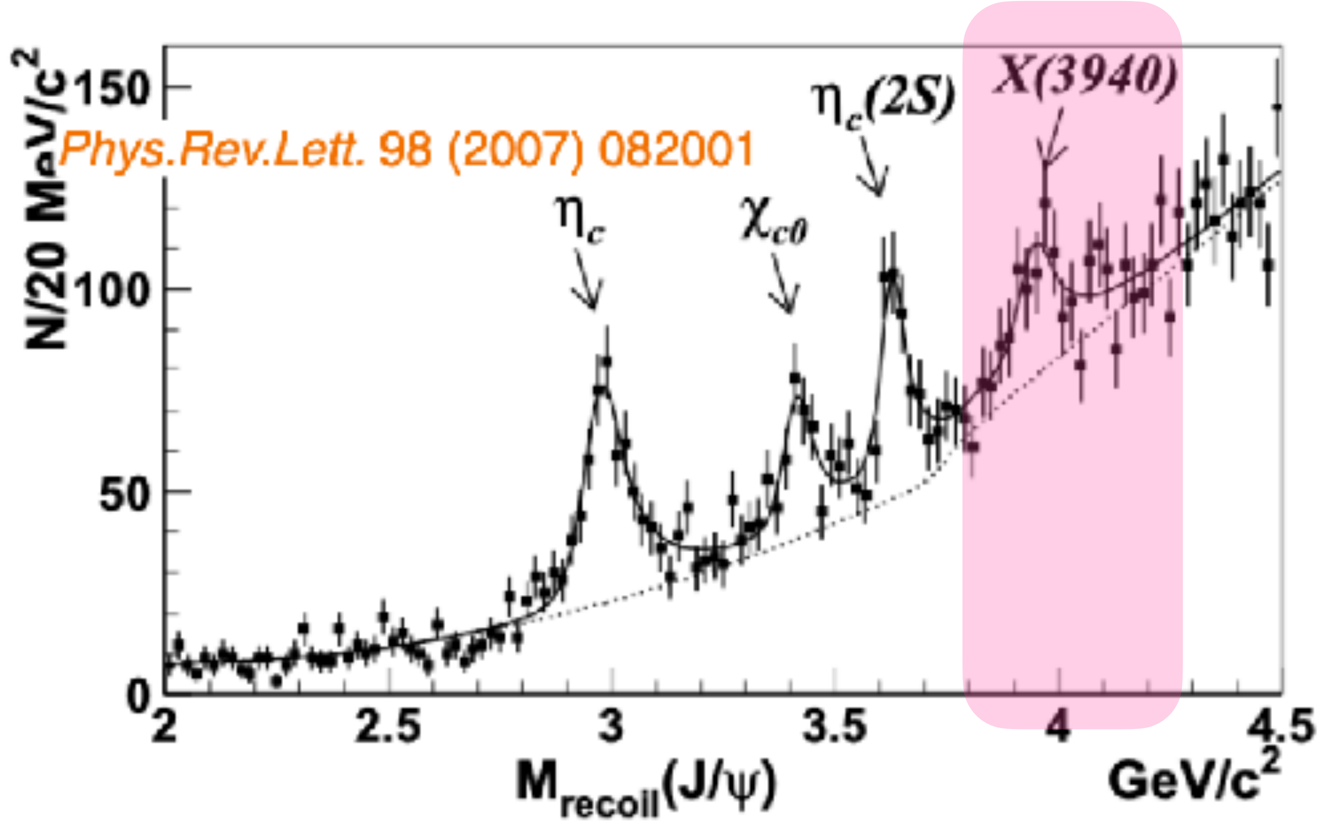
$> 3\sigma$

Phys.Rev.D 90 (2014) 11, 112009



$X(4014)$ in $B \to K\phi J/\psi$

Properties measurements with dedicated analysis

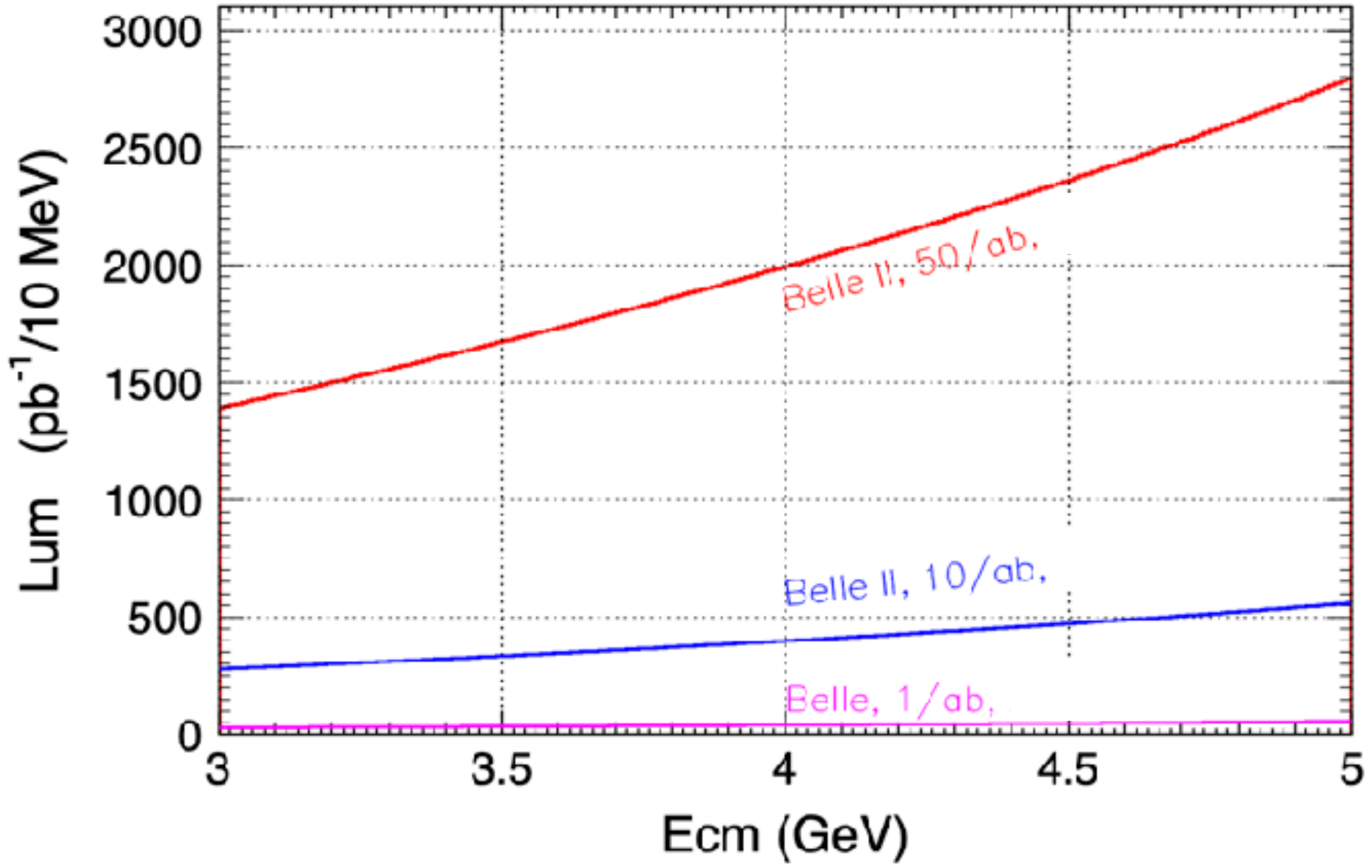


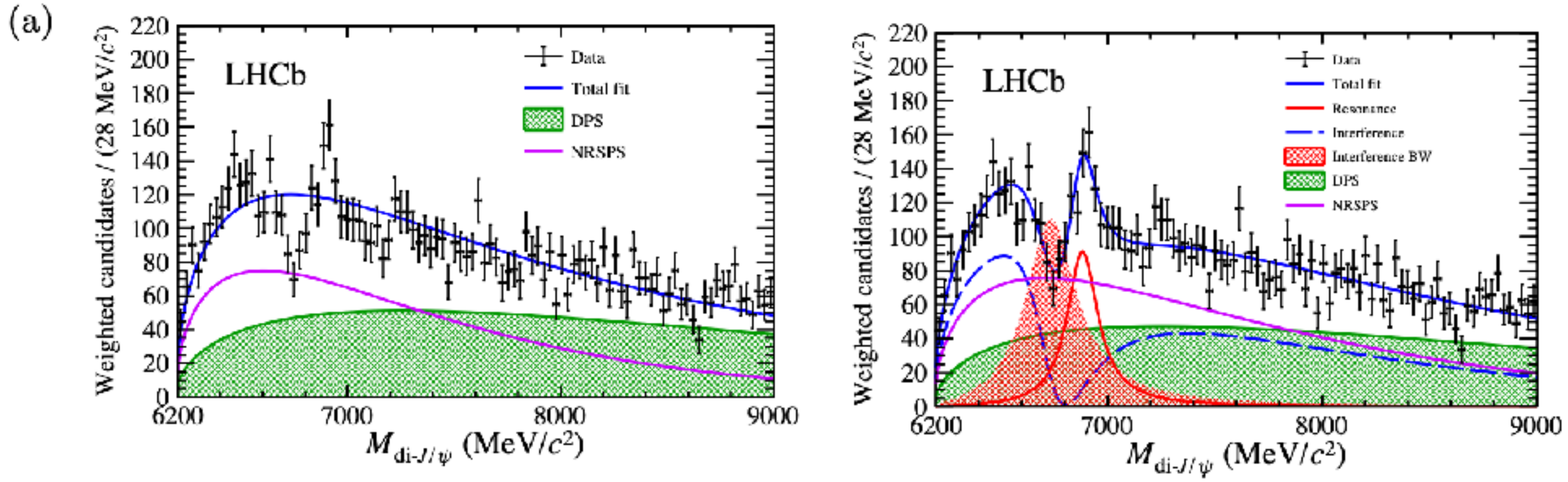
$X(3940)$ $\quad I^G(J^{PC}) = ?^?(?^{??})$

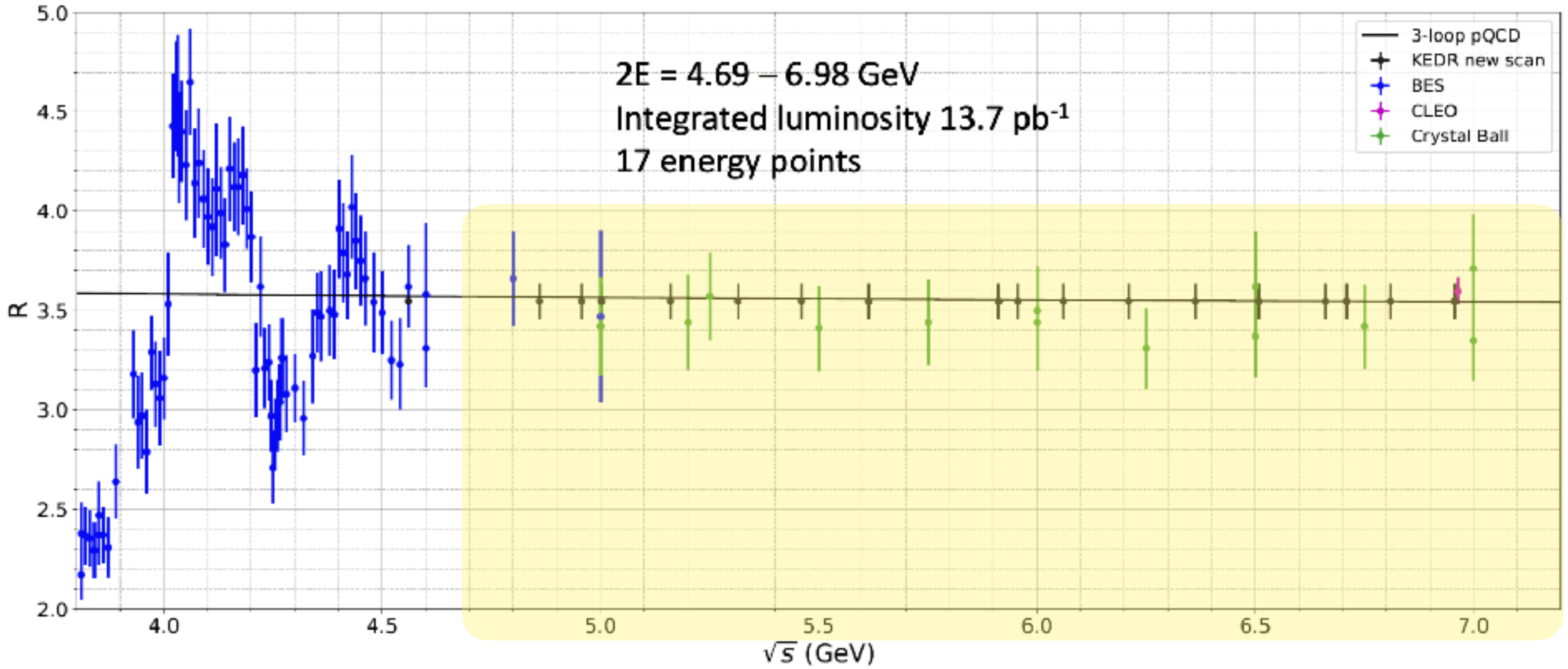
Quantum number of $X(3940)$ remains unknown.

Prospect

Fully cover charmonium region with ISR







- Dedicated study to $e^+e^- \to \pi^+\pi^- J/\psi$, $K\bar{K}J/\psi$, etc.
- Z_c production in both e^+e^- annihilation and B decays.
- Doubly charmonium state in, e.g. $e^+e^- \to \eta_c J/\psi, \chi_c J/\psi$

Other prospects at Belle II

- Very high statistics samples of $\Upsilon(4S)$
  - Dedicate study of $X(3872)$ decays to final states with neutrals, i.e. $D^0\bar{D}^{*0}$.
  - Searching for new charmonium(-like) states in various productions.
- Higher statistics samples of $\Upsilon(5S)$ and $\Upsilon(6S)$
  - Investigate Z_b states: quantum numbers, neutral partners, decay modes…
  - Search for new states
  - Potential laboratory for other bottomonium states like $h_b(3P)$, $\Upsilon(D)$
- Potential to reach higher E_{cms}
- Reach charmonium(-like) states via ISR with huge datasets