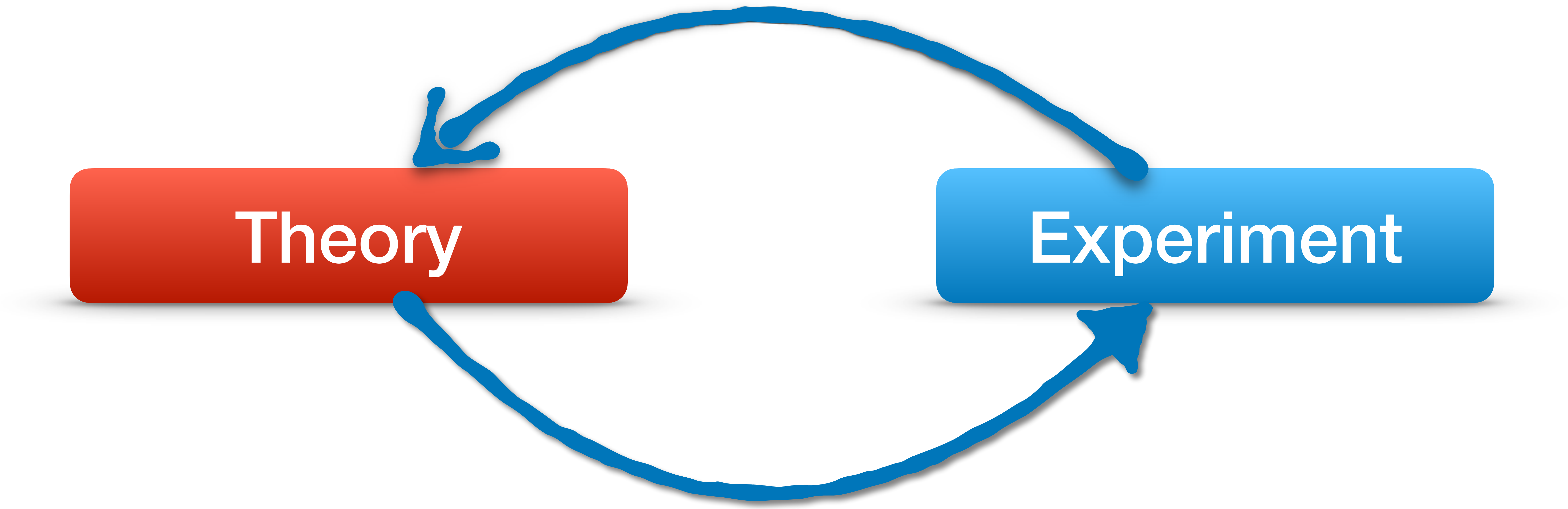
Overview of hadron spectroscopy at Belle and Belle II

Speaker: Junhao Yin (on behalf of Belle and Belle II collaborations)

Inspire



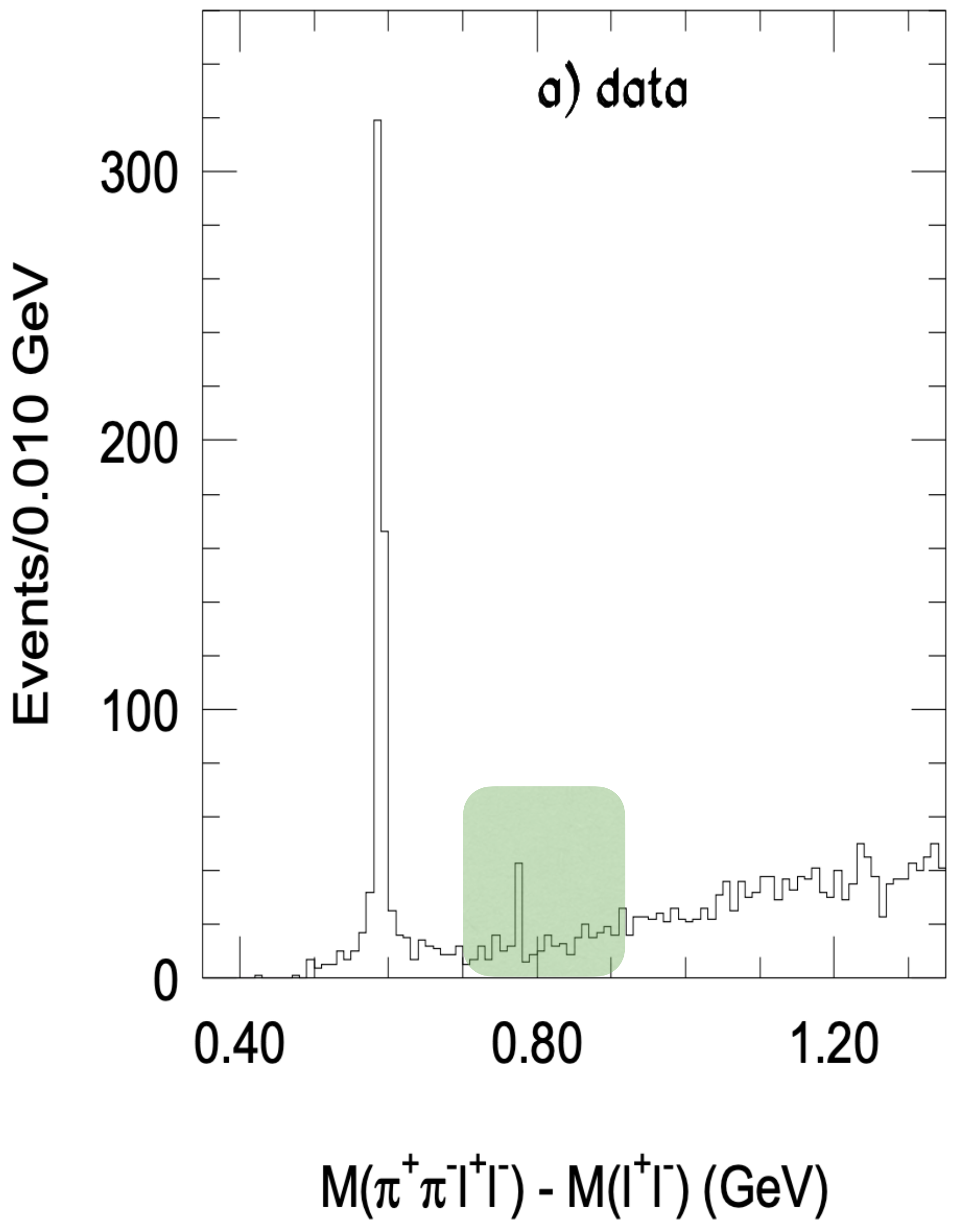
For years this circulation works well

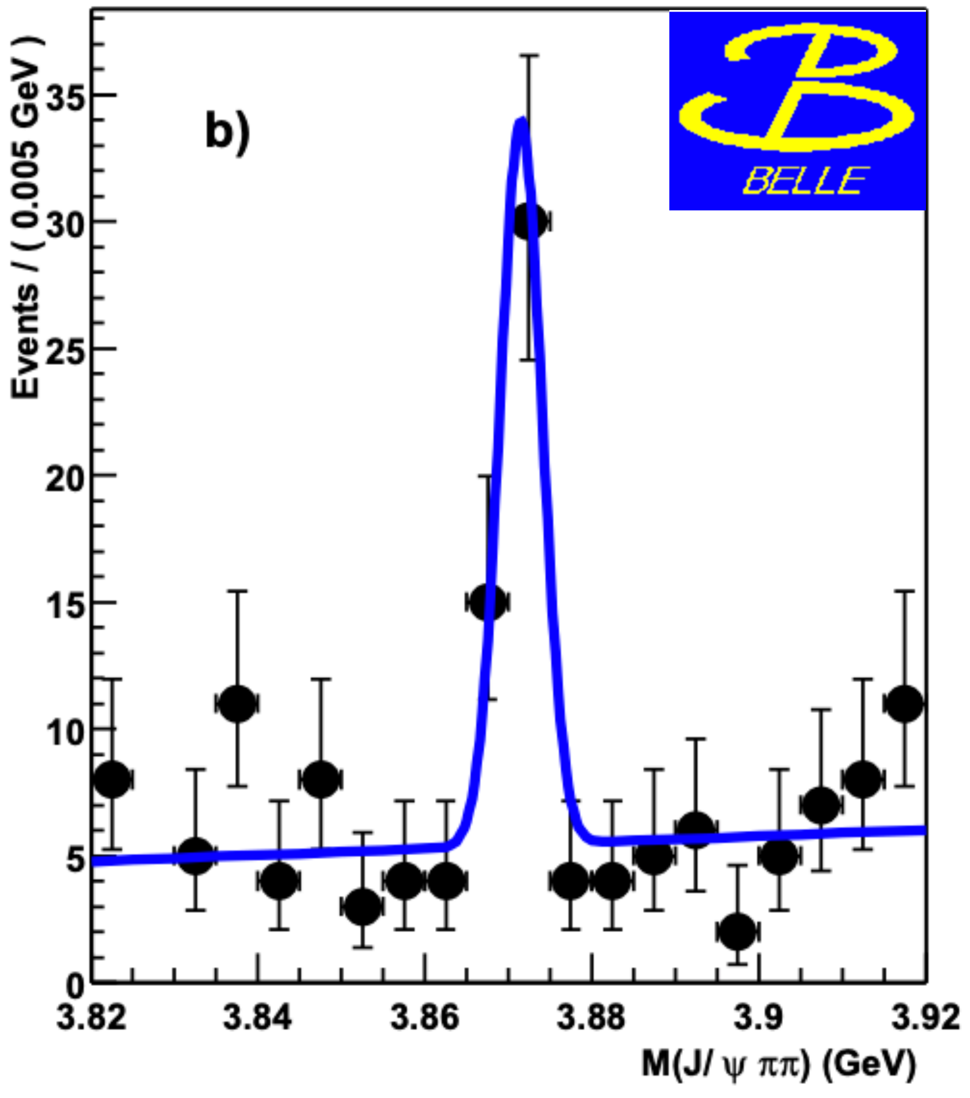
Inspire

For years this circulation works well

Unpredicted features, particles discovered since this century

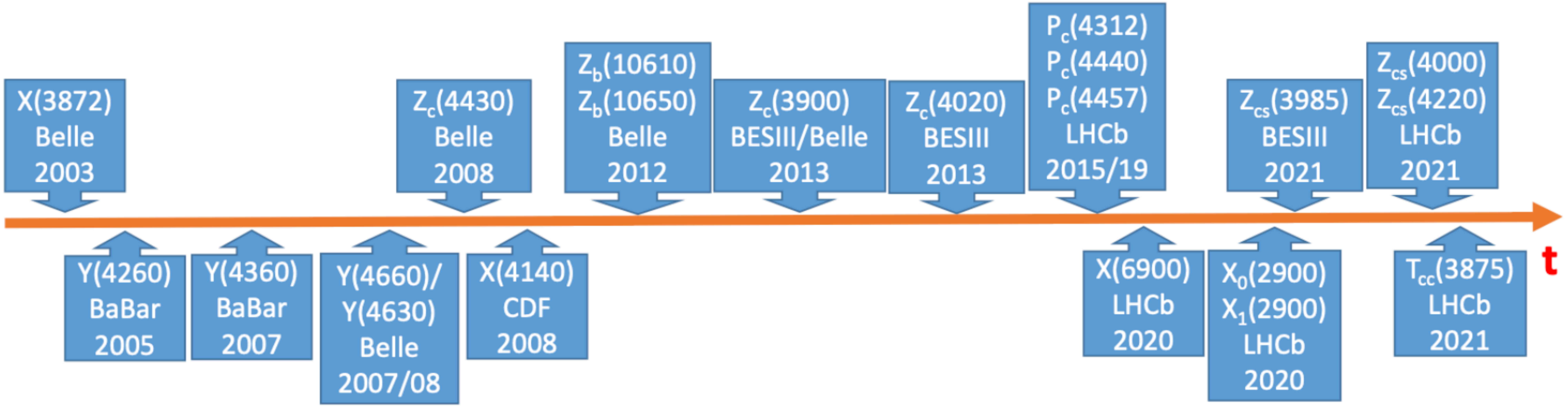
Unexpected mass&Unique properties.



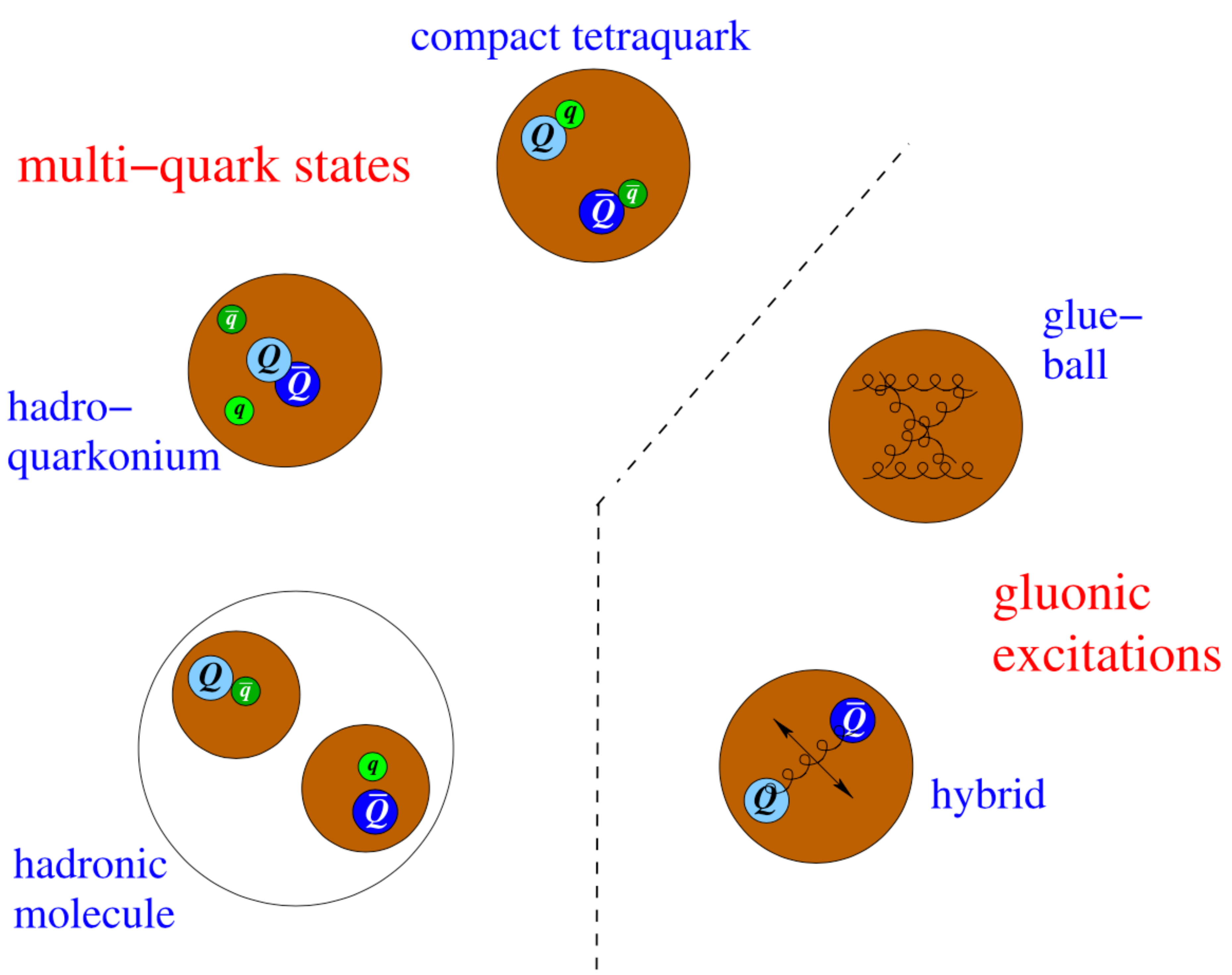


- Ever since the discovery of $X(3872)$, we have a golden era in the discovery of the exotic states.
- No solid explanations for these exotics.

Phys.Rev.Lett. 91 (2003) 262001 *Most cited Belle paper!*

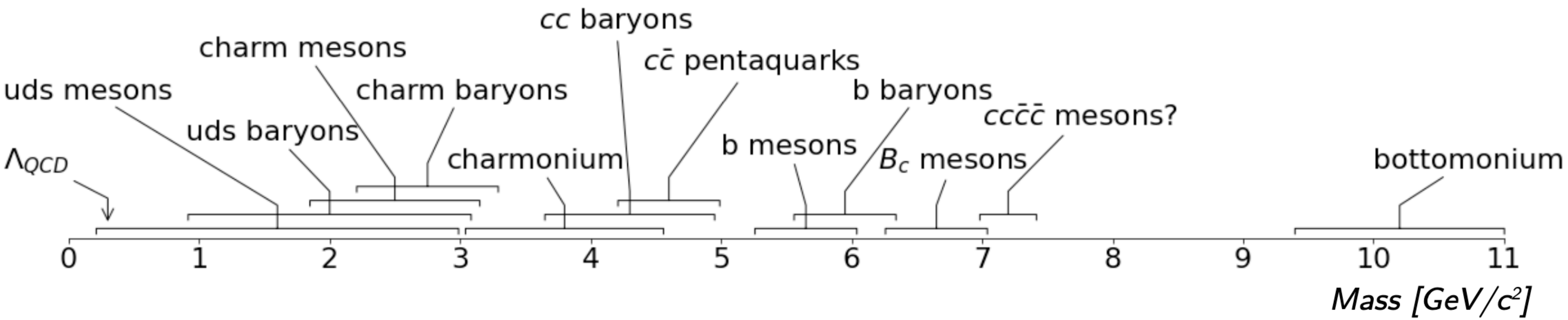


N. Brambilla, S. Eidelman, C. Hanhart et al. / Physics Reports 873 (2020) 1–154

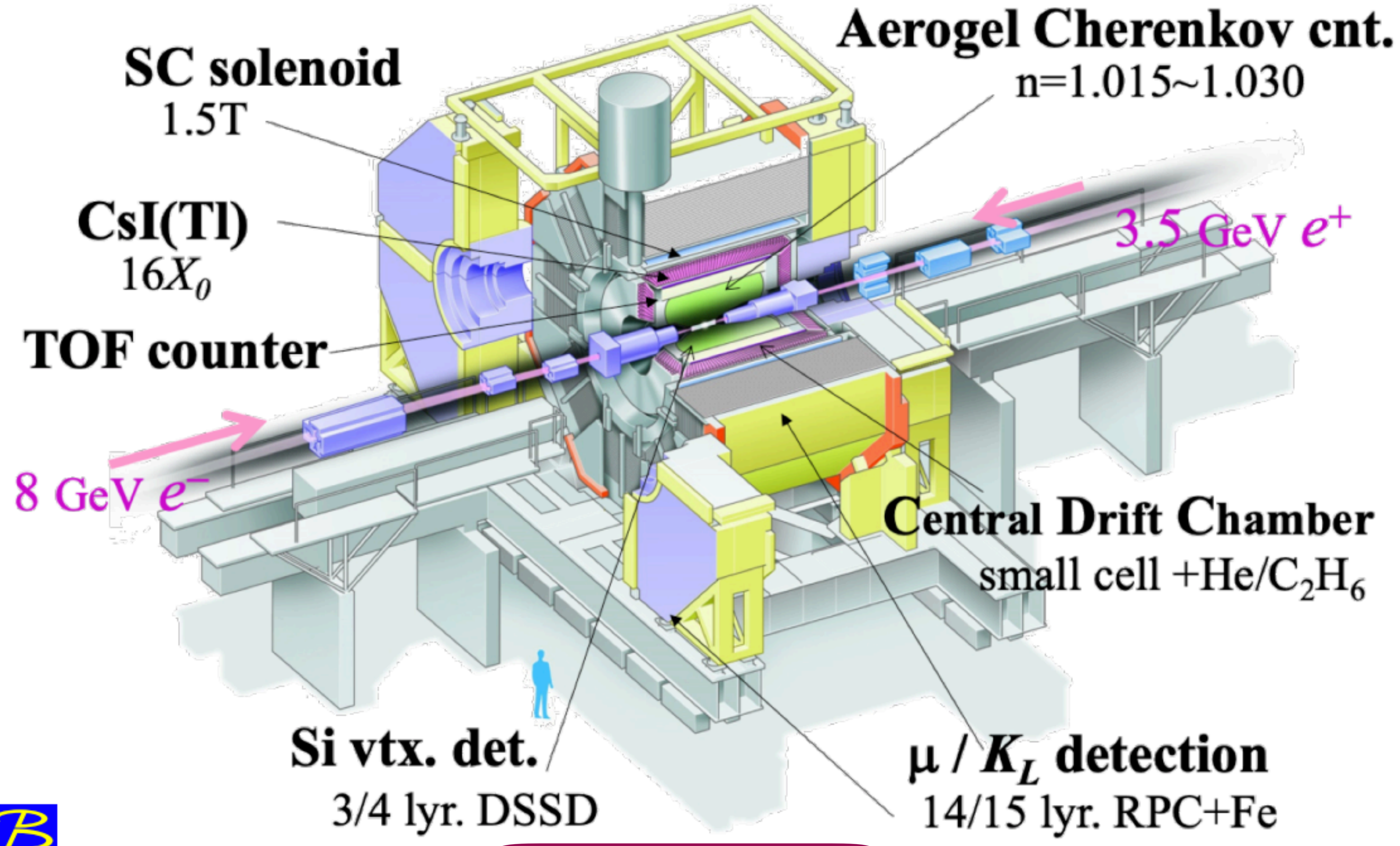


hadron spectroscopy

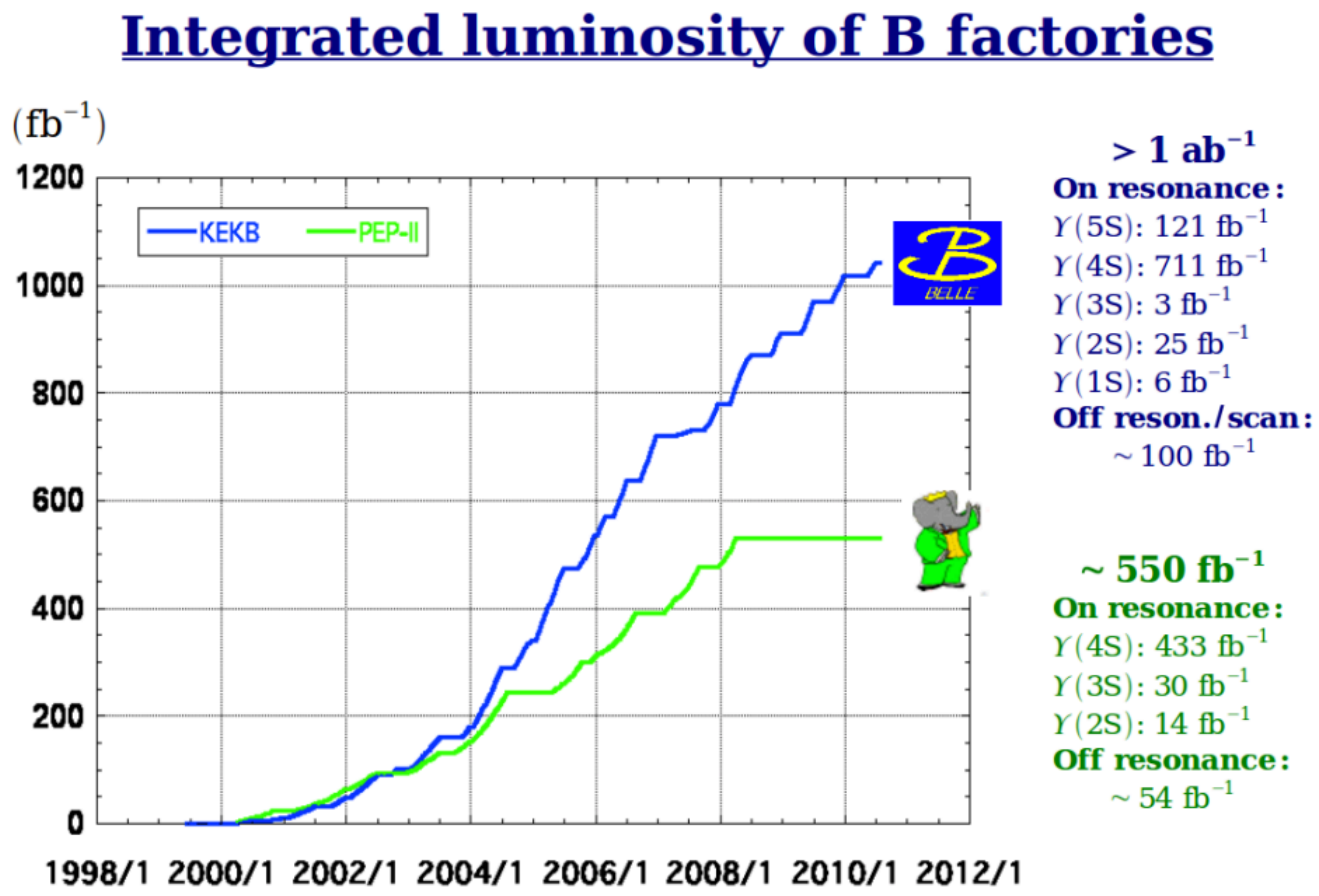
- New knowledge feeds back to theory.
- Perfect ground to test theoretical models.
- New viewing angle towards QCD.



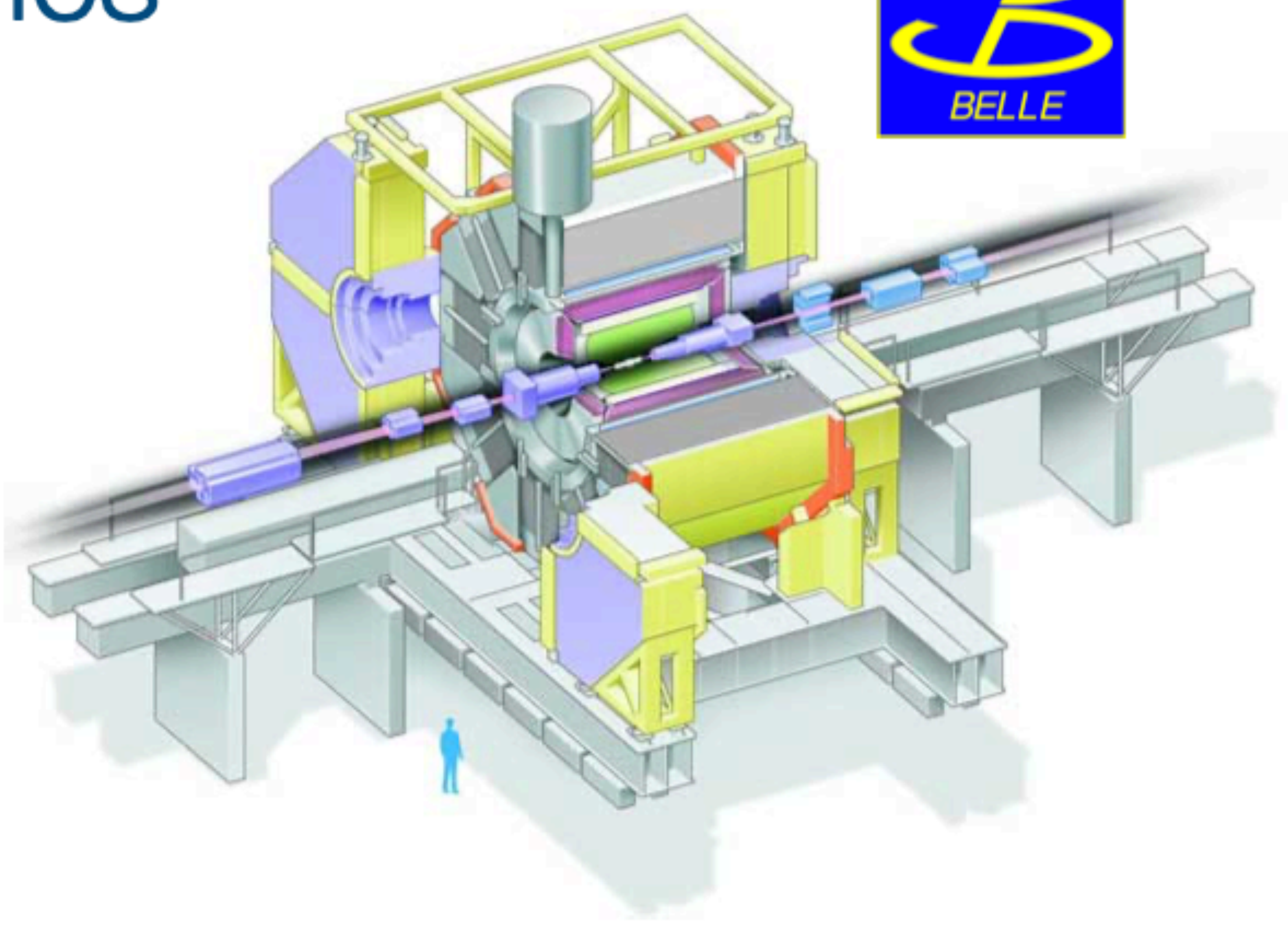
- KEKB is an asymmetric-energy e^+e^- collider operating near $\Upsilon(4S)$ mass peak (~ 10.58 GeV$/c^2$, $>B\bar{B}$ threshold).
- Belle detector has good performances on momentum/vertex resolution; particle identification, etc.
- Accumulated data set of ~ 1 ab^{-1}: not only a large $B\bar{B}$ sample (B-factory); but also a large charm sample to study charm physics.

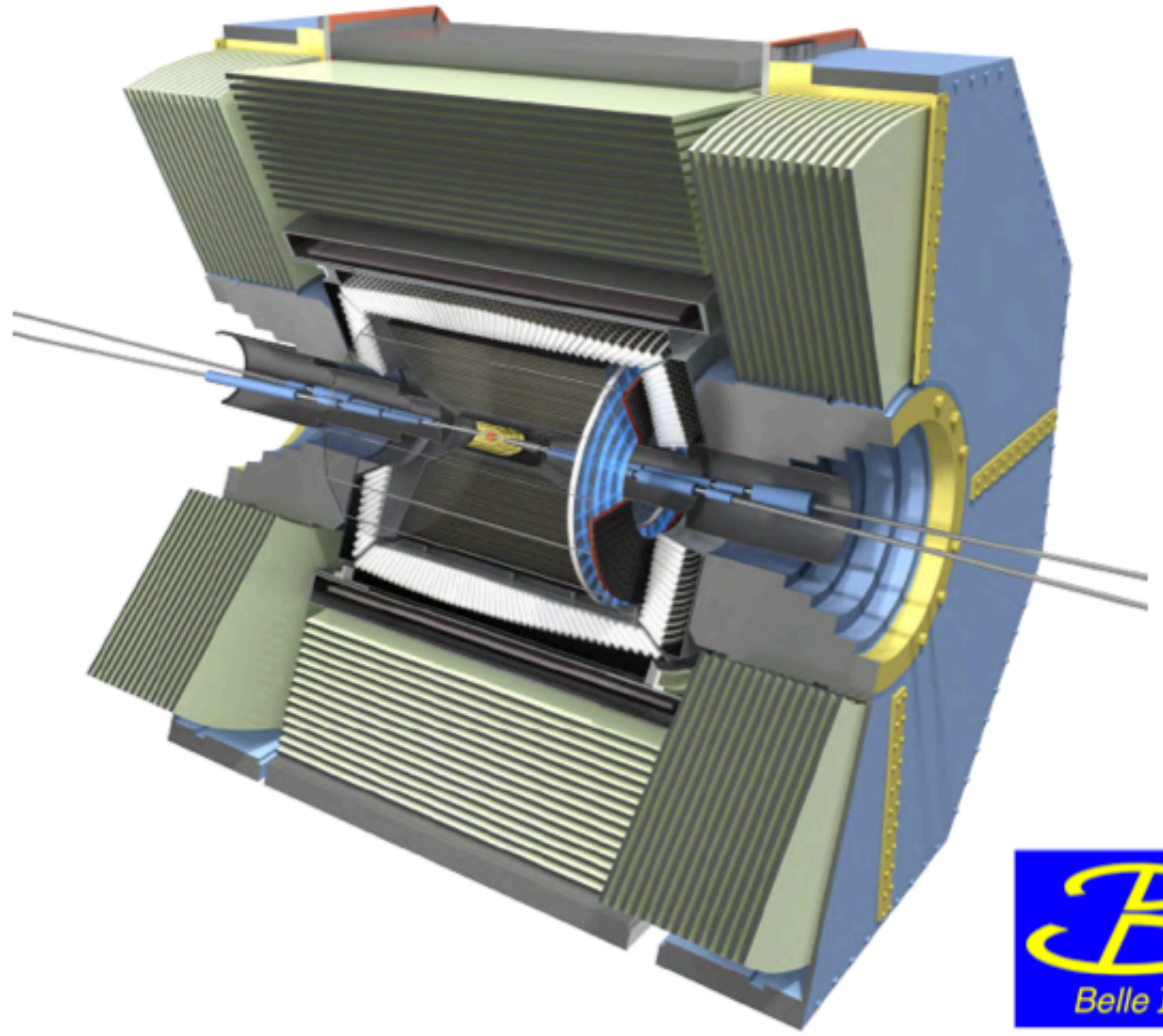


World record:
L = 2.1 x 10^{34}/cm^2/sec



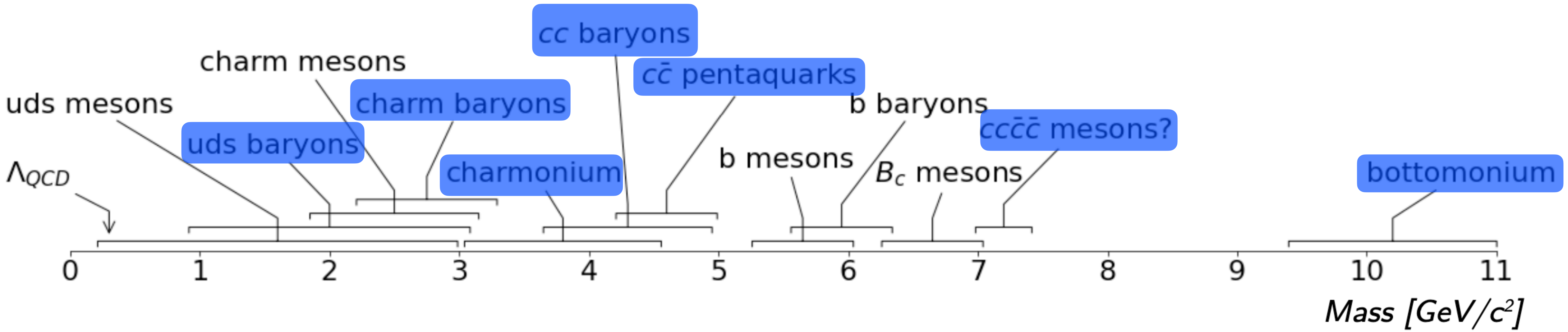
Benefits of hadron spectroscopy at B-factories

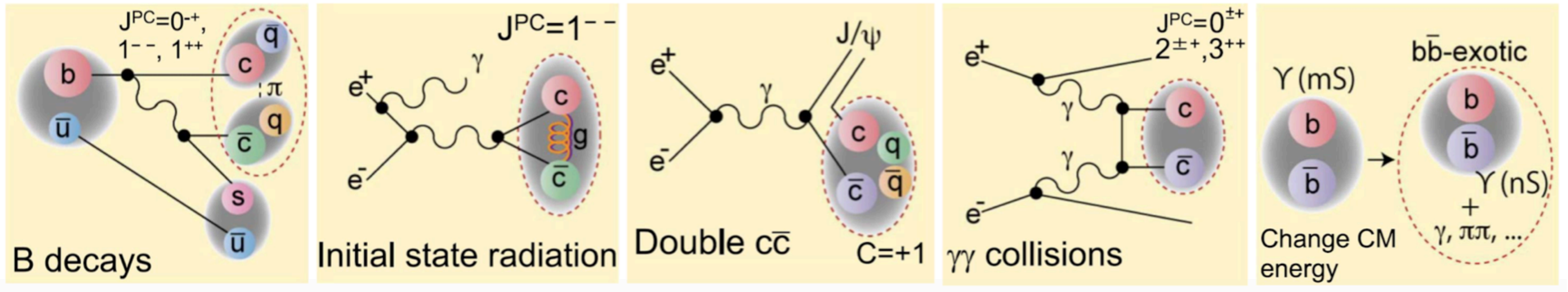




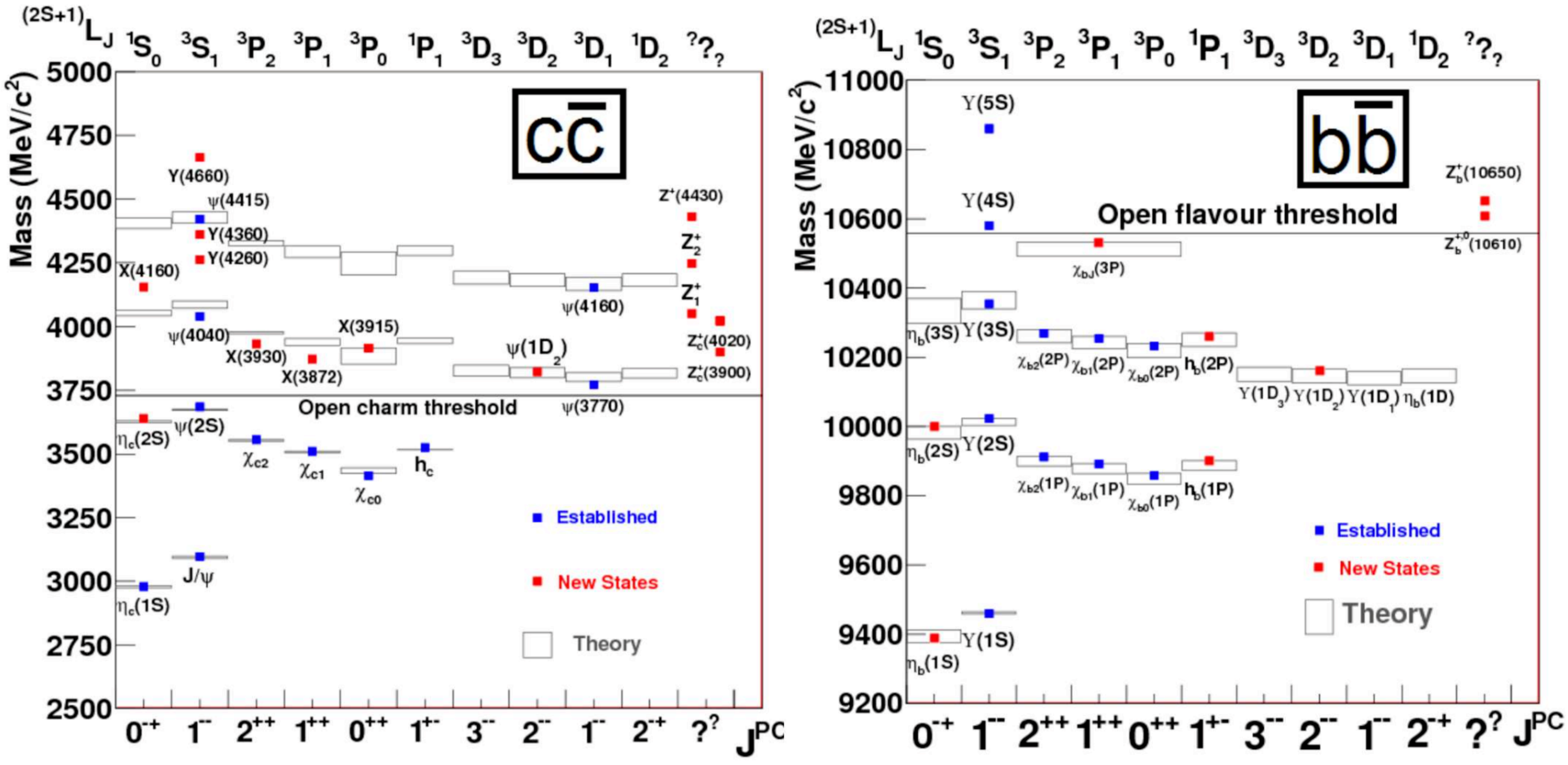
- ☑ Efficient reconstruction of neutrals (π^0, η, …)
- ☑ Fully reconstruction or recoil system
- ☑ Variety of production mechanisms
- ☑ Large production rate of $b \to c\bar{c}$
- ☑ Unique dataset

Belle&Belle II capabilities on spectroscopy





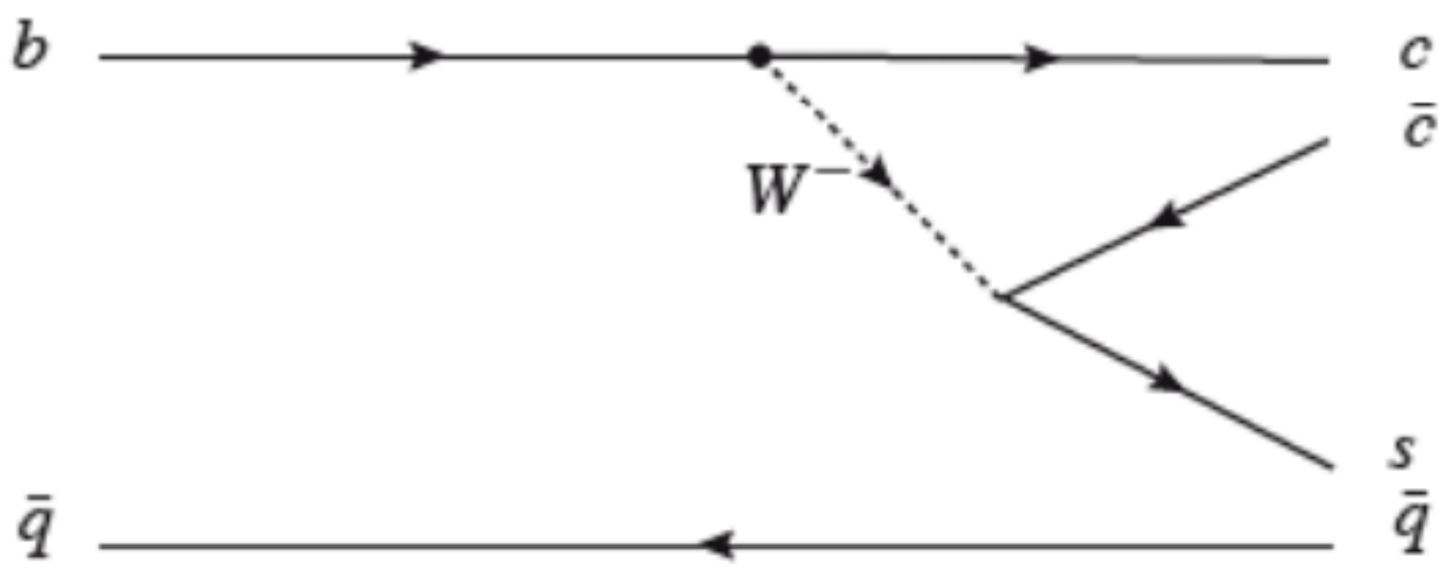
Quarkonium spectroscopy



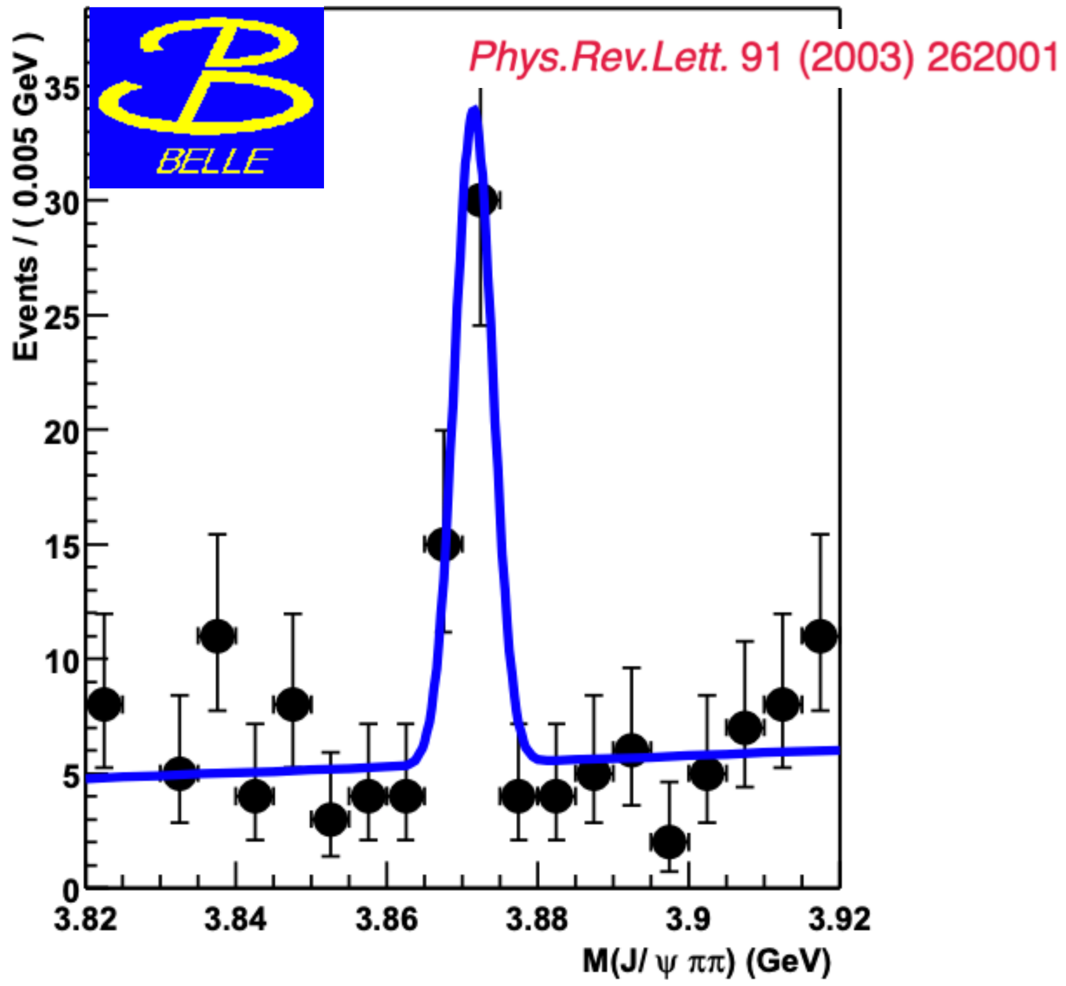
Good agreement with potential model below open flavor threshold
Exotic states, so called XYZ states, discovered above open flavor threshold.

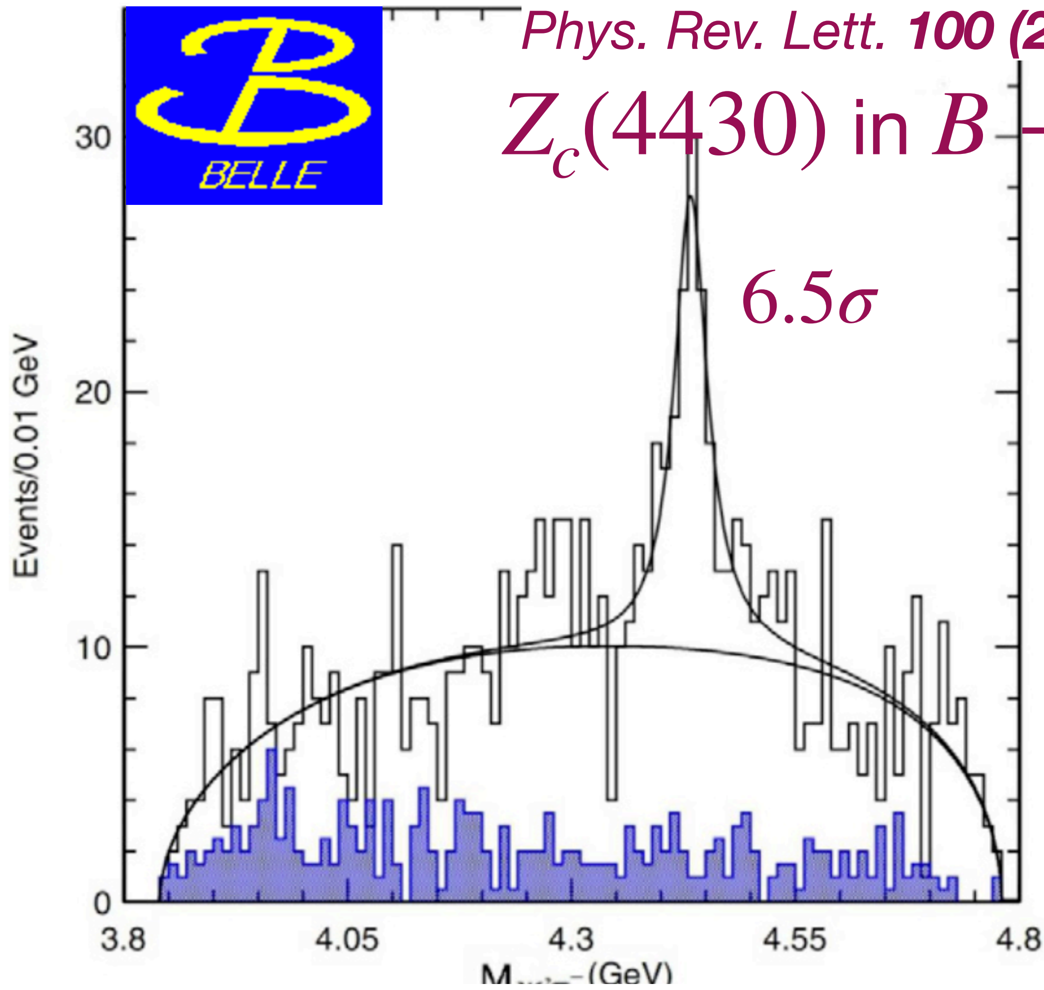
B decays

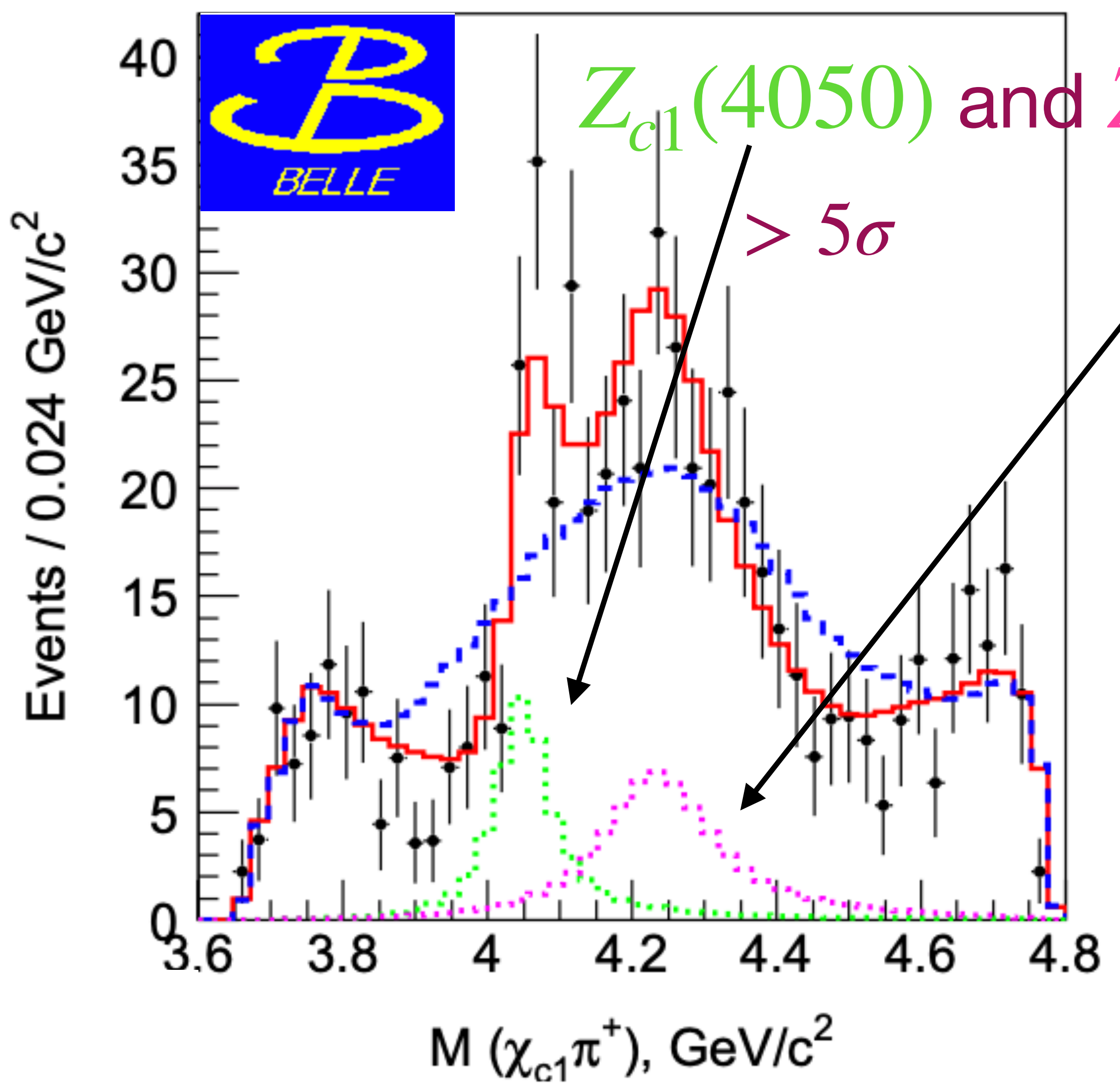
Large production rate provide a solid ground to search for exotics

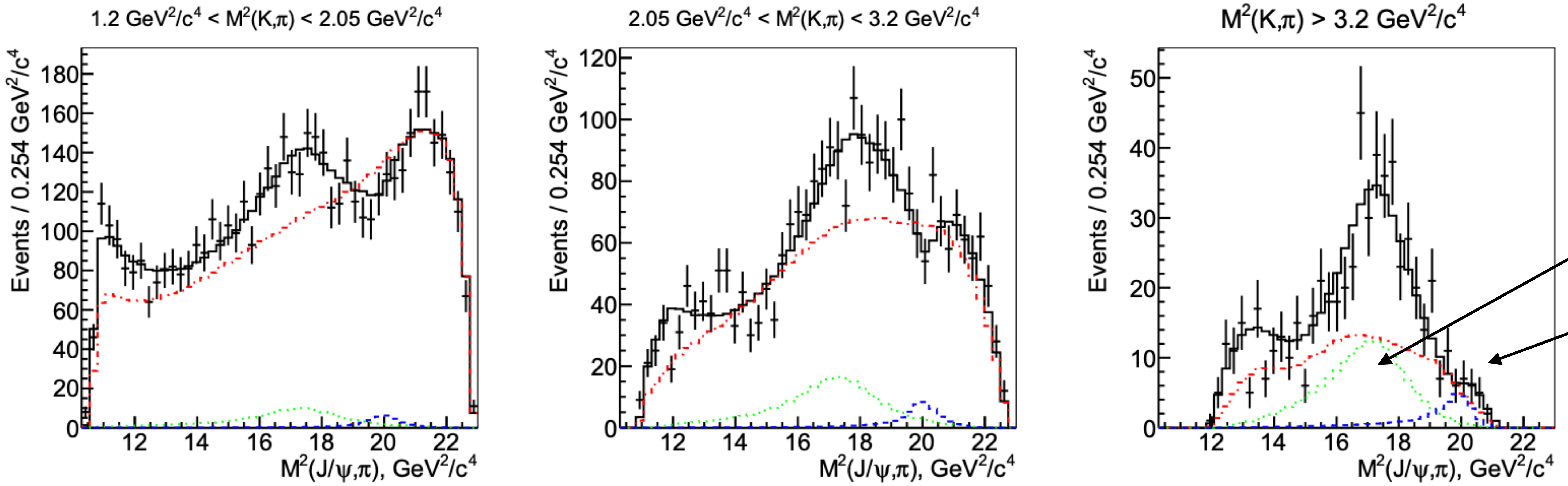


In history: observation of $X(3872)$ & establishment of various Z_c^+ states









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

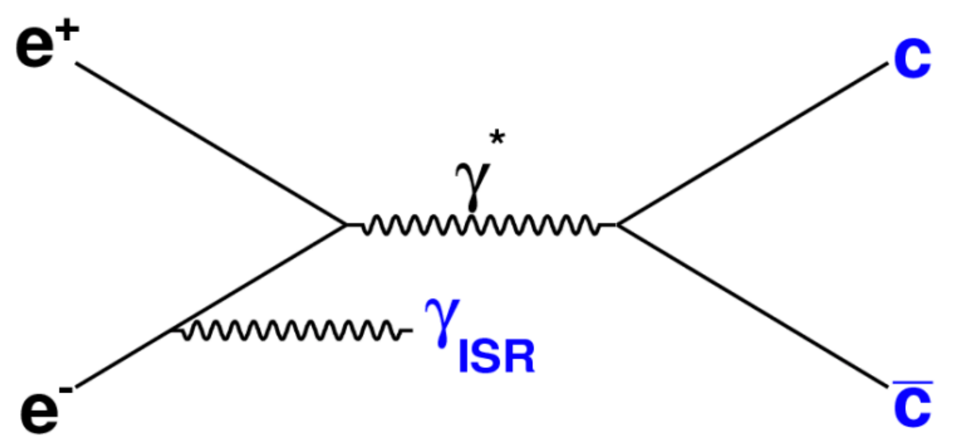
6.2σ

$> 3\sigma$

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

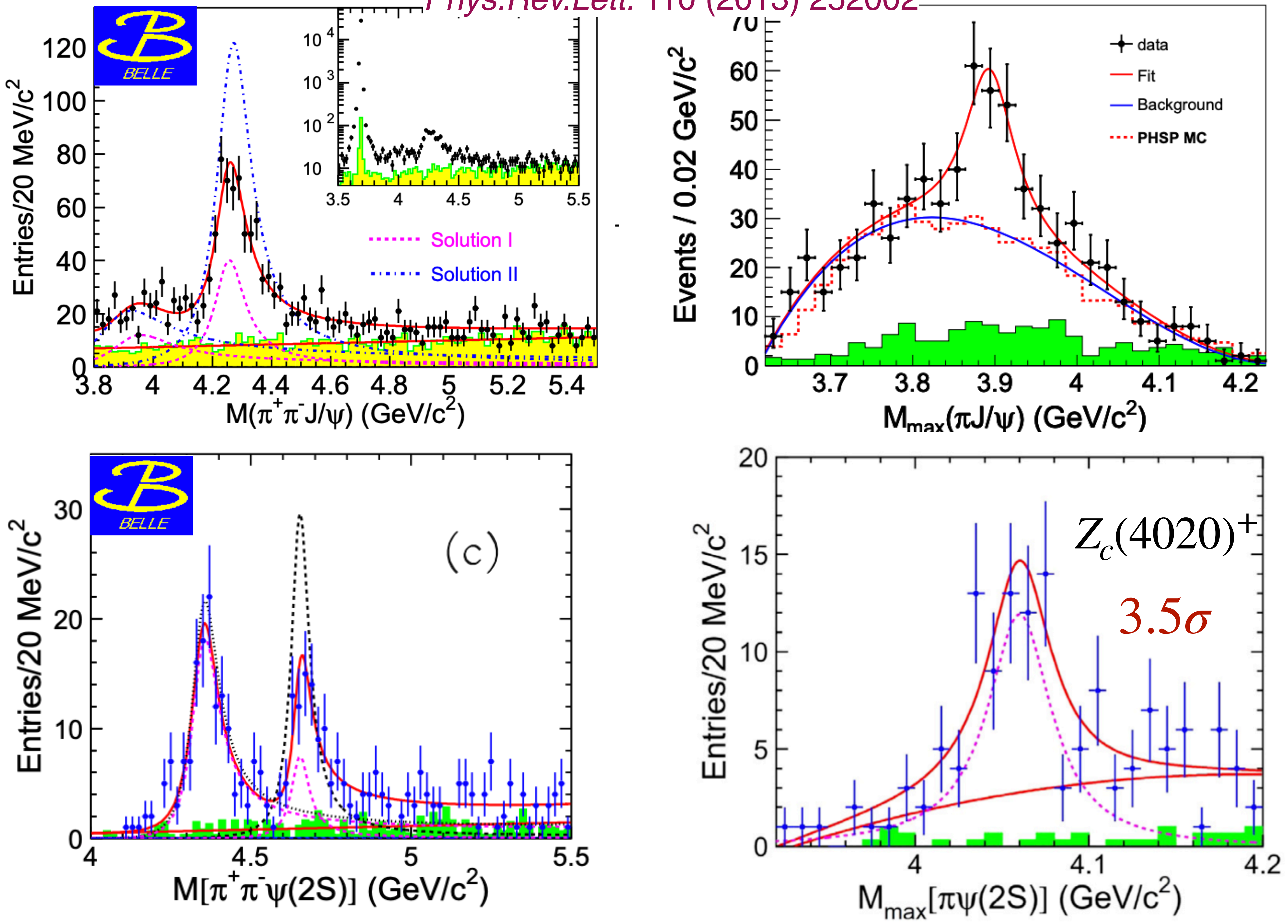
Initial state radiation

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

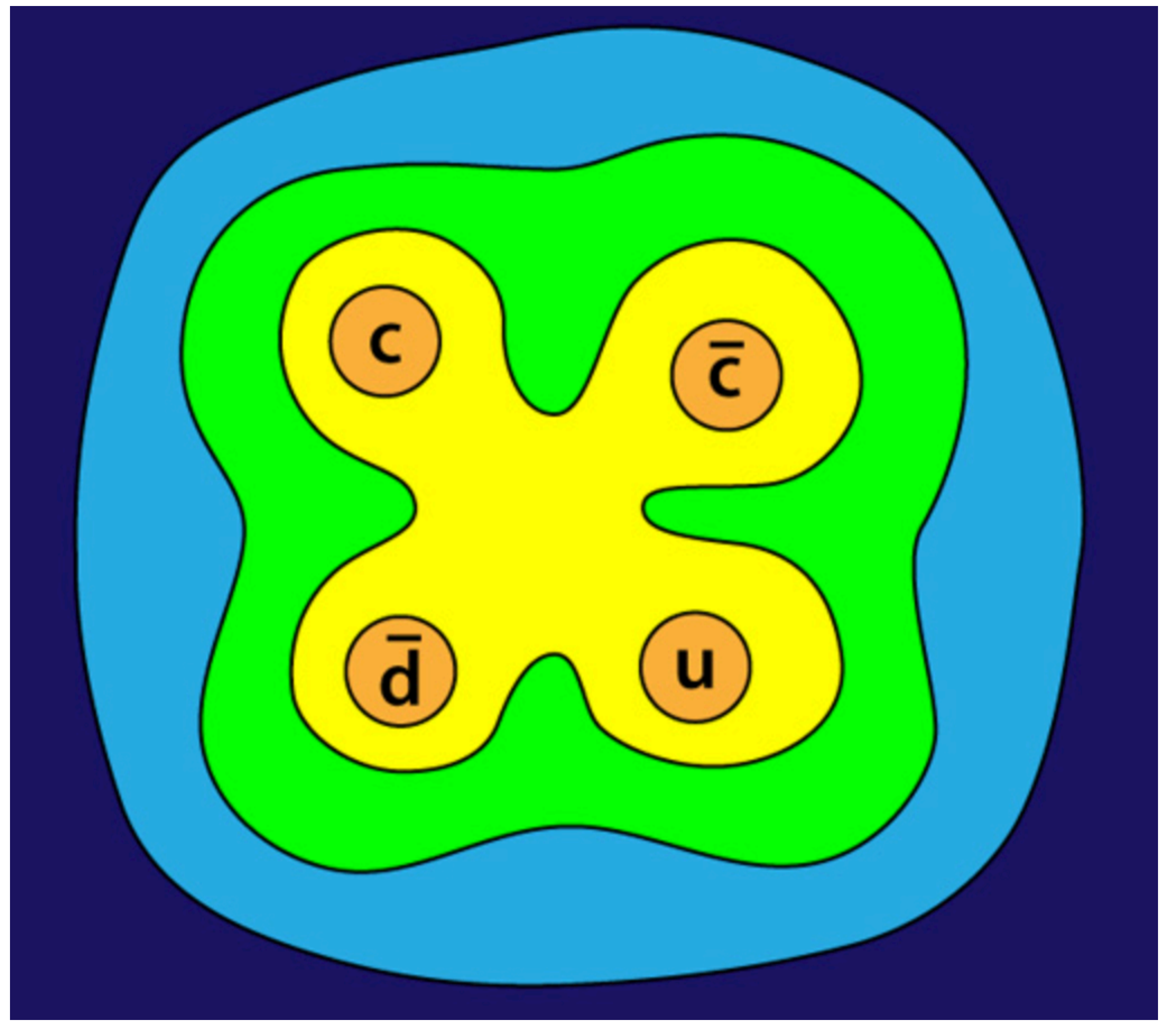


Great achievement in history: Observation of $Z_c(3900)^+$

Phys.Rev.Lett. 110 (2013) 252002

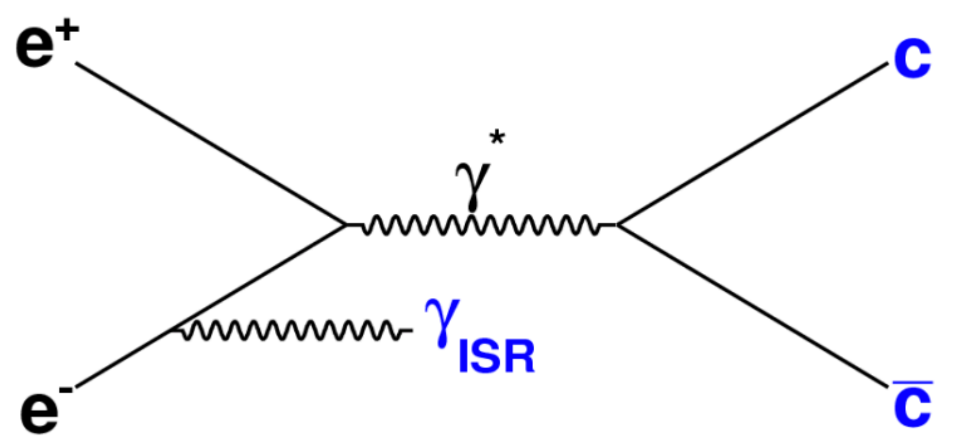


First solid four quark state!

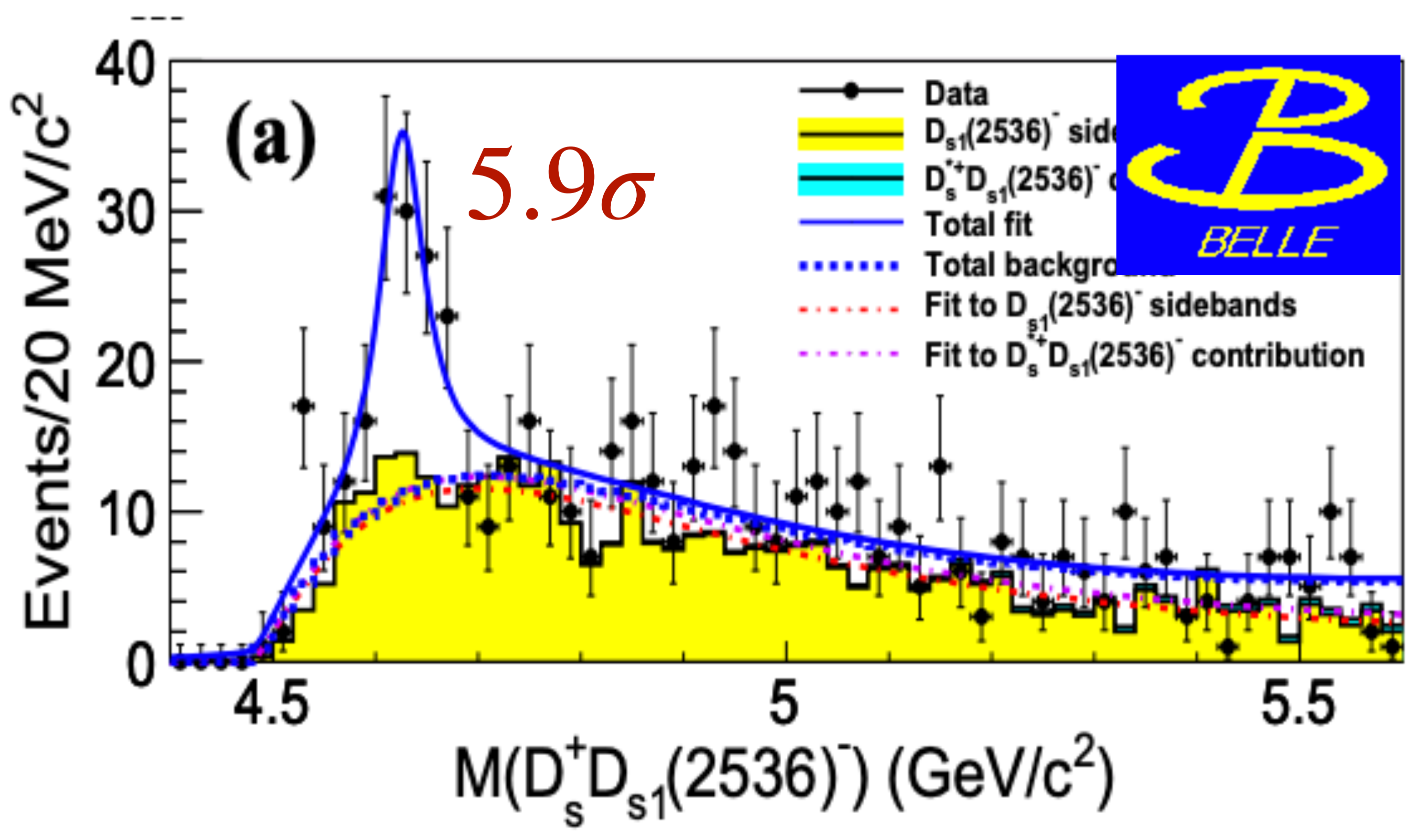


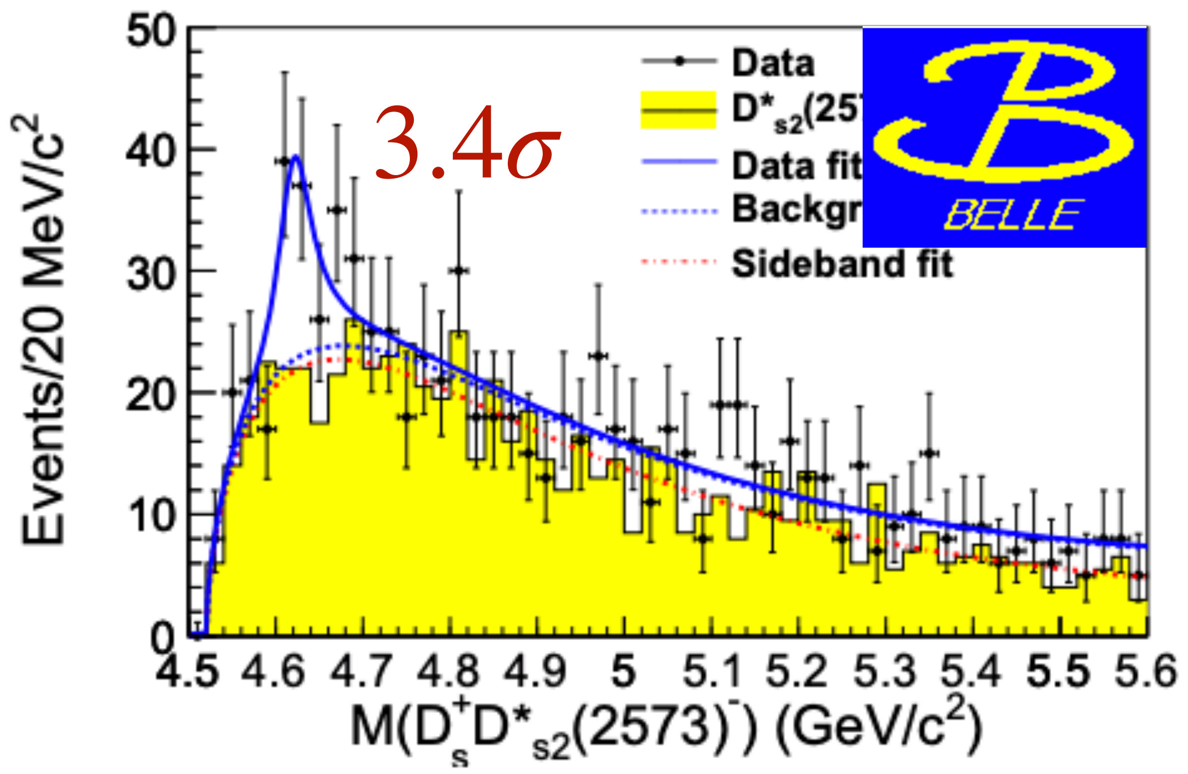
Initial state radiation

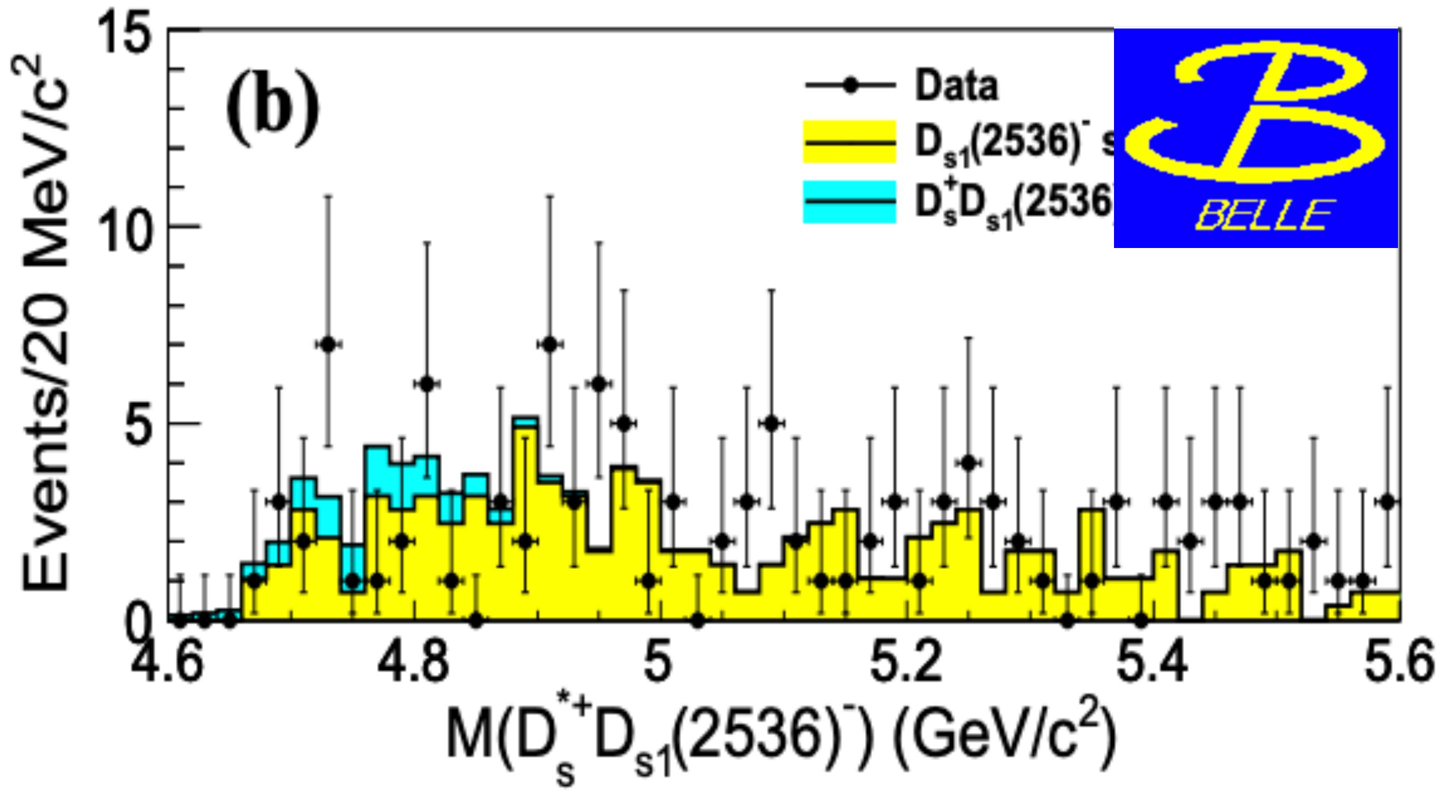
Allow us to reach lower c.m. energy “*for free*”

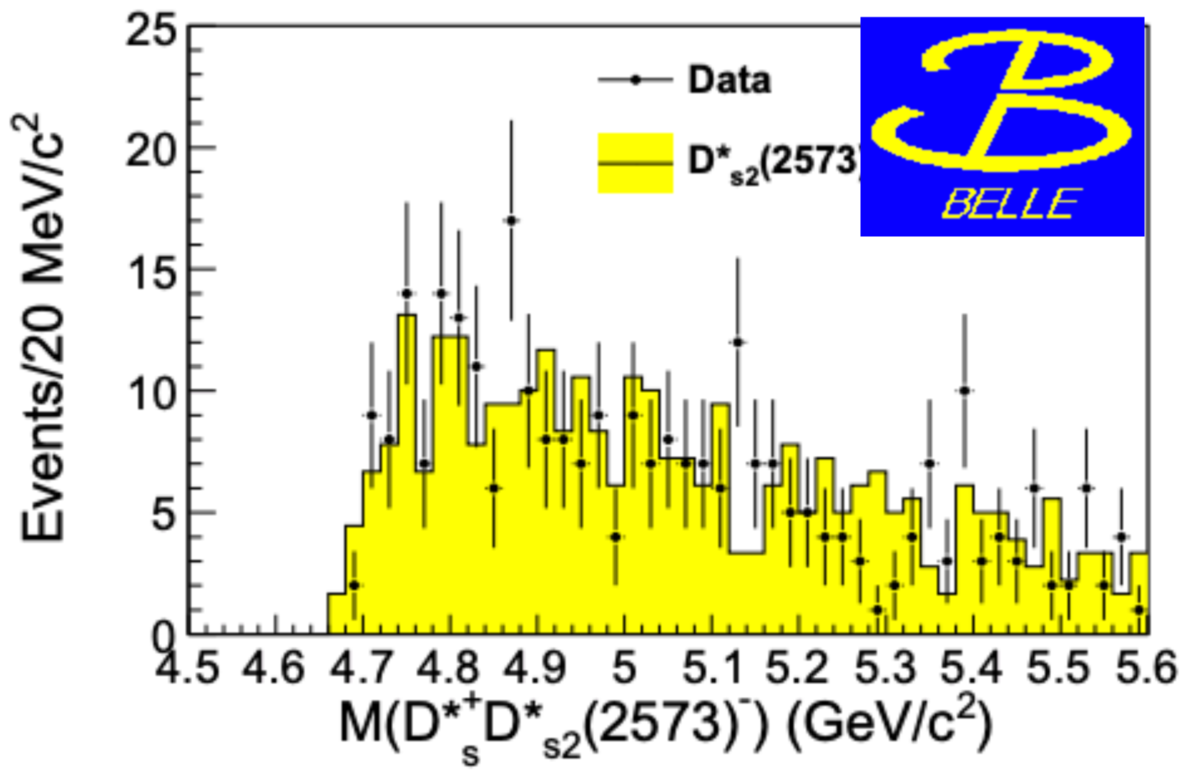


Recent: A new vector state in $e^+e^- \to D_s^+ D_{s1}(2536)^-,\ D_s^+ D_{s2}^*(2573)^-$









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

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

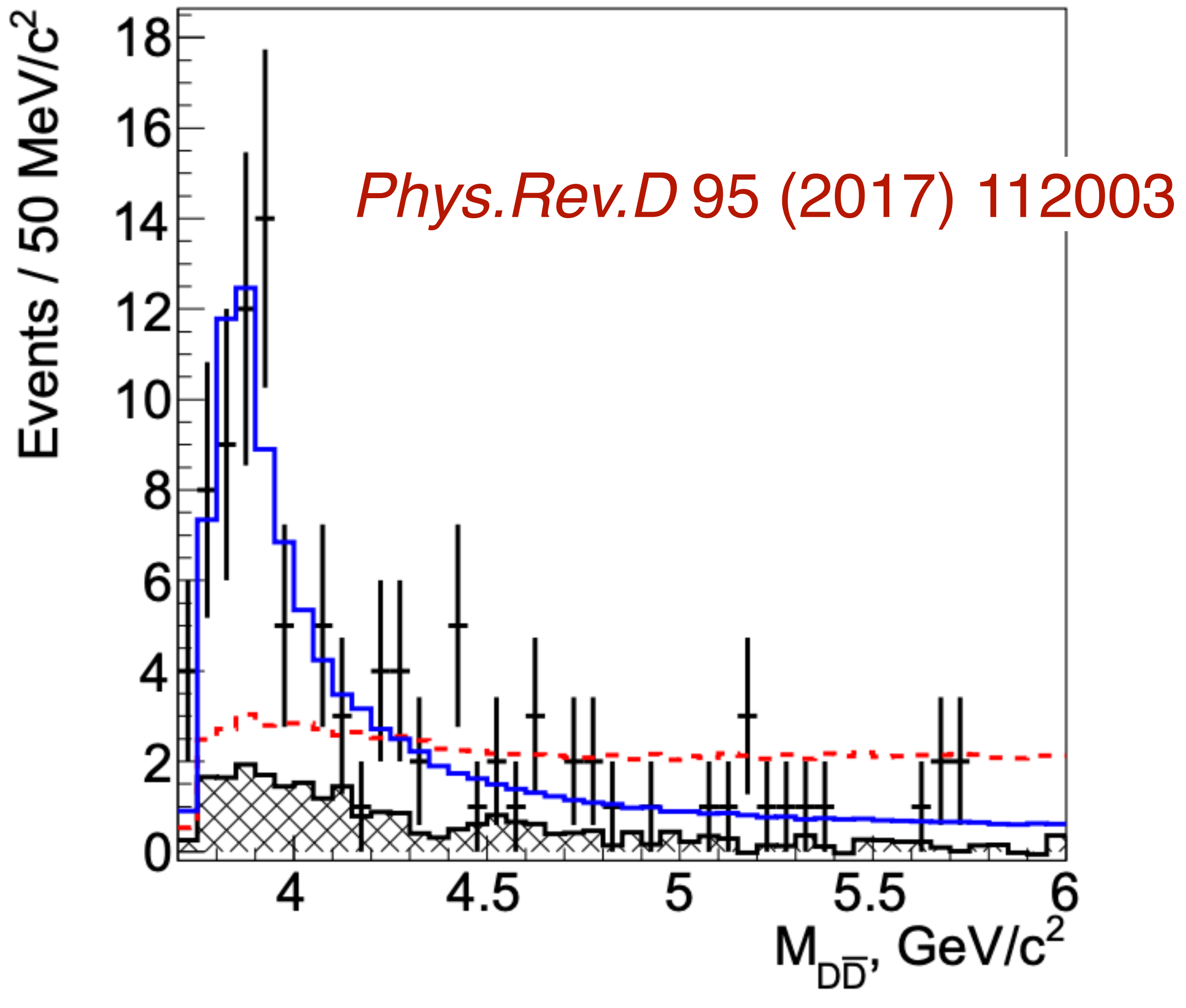
$Y(4620) = Y(4660)$**?**

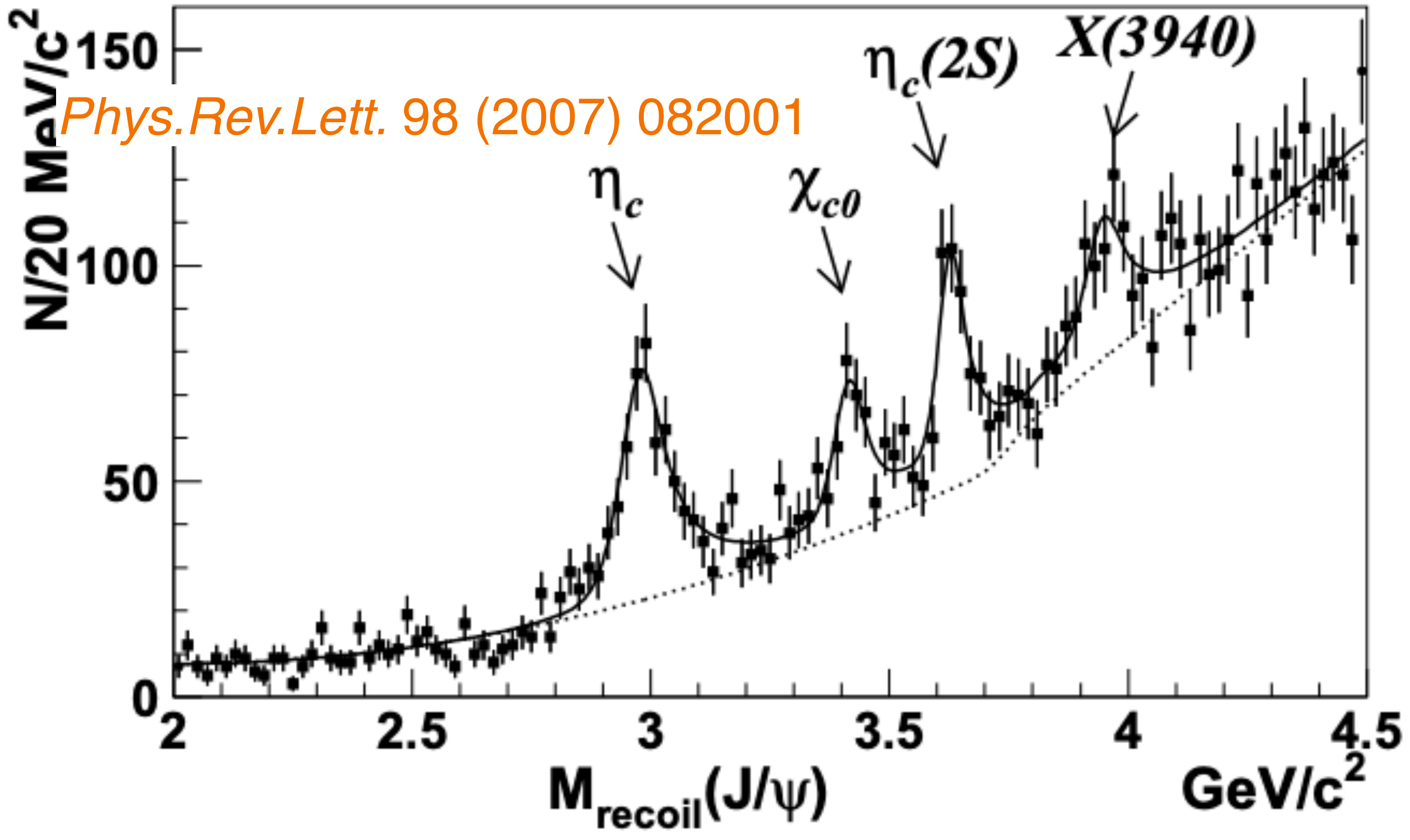
Experiments	Mass (MeV/c^2)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Belle, $\pi^+\pi^-J/\psi$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi^+\pi^-J/\psi$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$
Belle, $D_s^+D_{s1}(2536)^-$	$4625.9^{+6.2}_{-6.0} \pm 0.4$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

Double charmonium production

Unique field to produce charmonium(-like) particles

Rich resonances produced against J/ψ

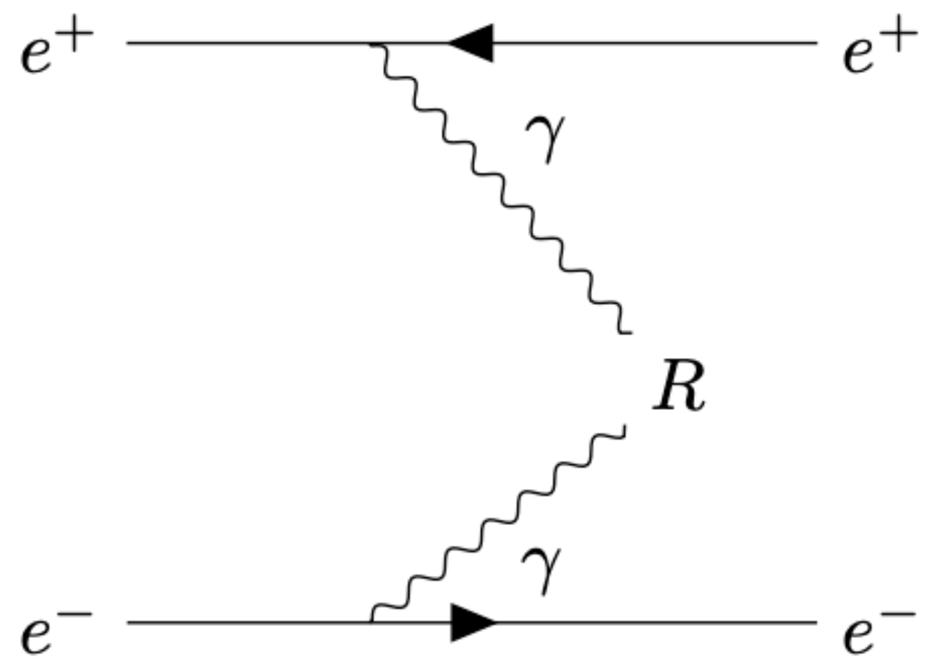




$\chi_{c0}(3860)$ was observed in $e^+e^- \to J/\psi D\bar{D}$.

$X(3940)$ was discovered in J/ψ recoiling mass while dominantly decays into $D\bar{D}^*$.

Cross section of $e^+e^- \to J/\psi c\bar{c}$ was measured to be 0.74 ± 0.08 pb [*PRD* 79 (2009) 071101]



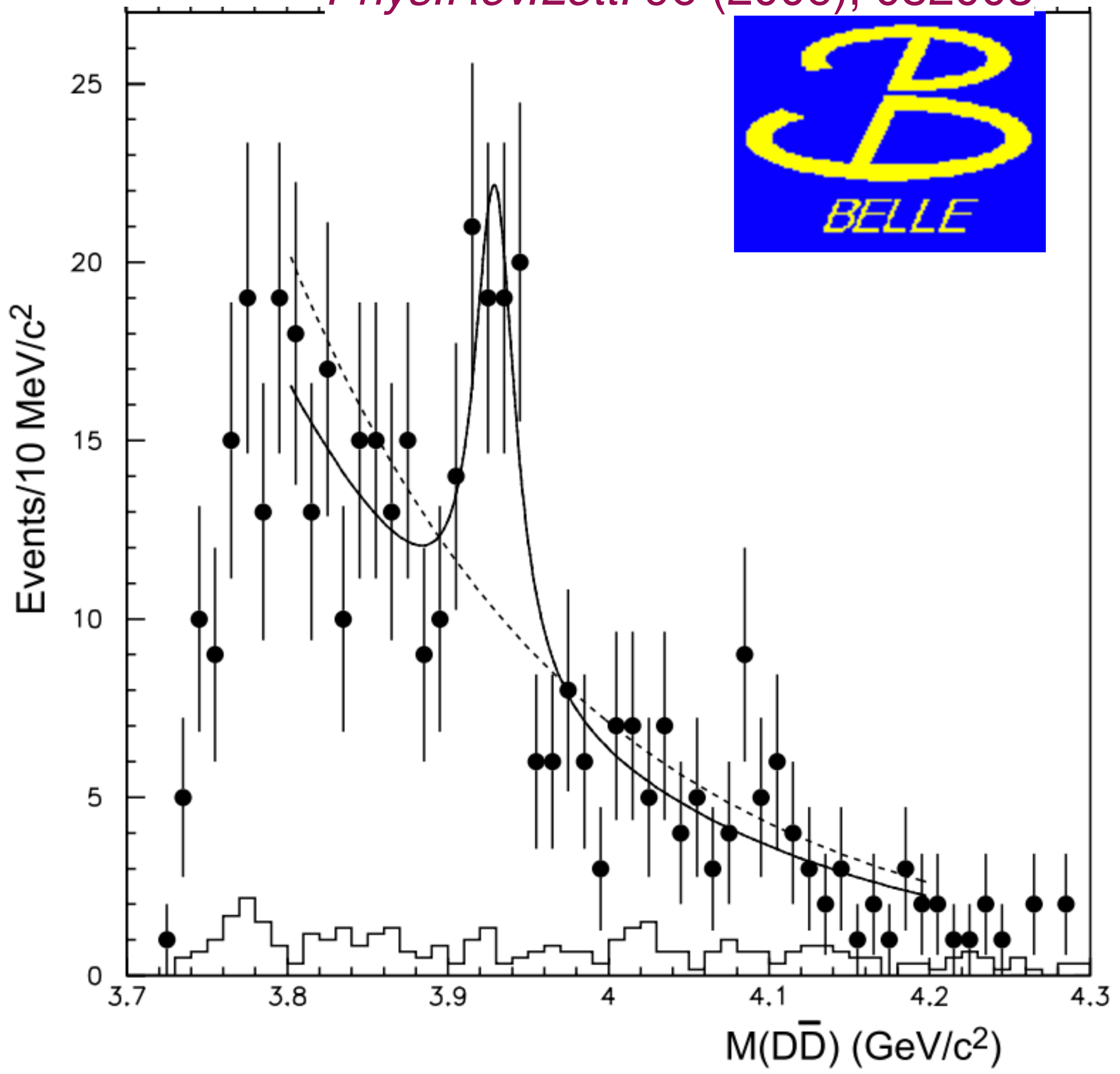
Two photon process

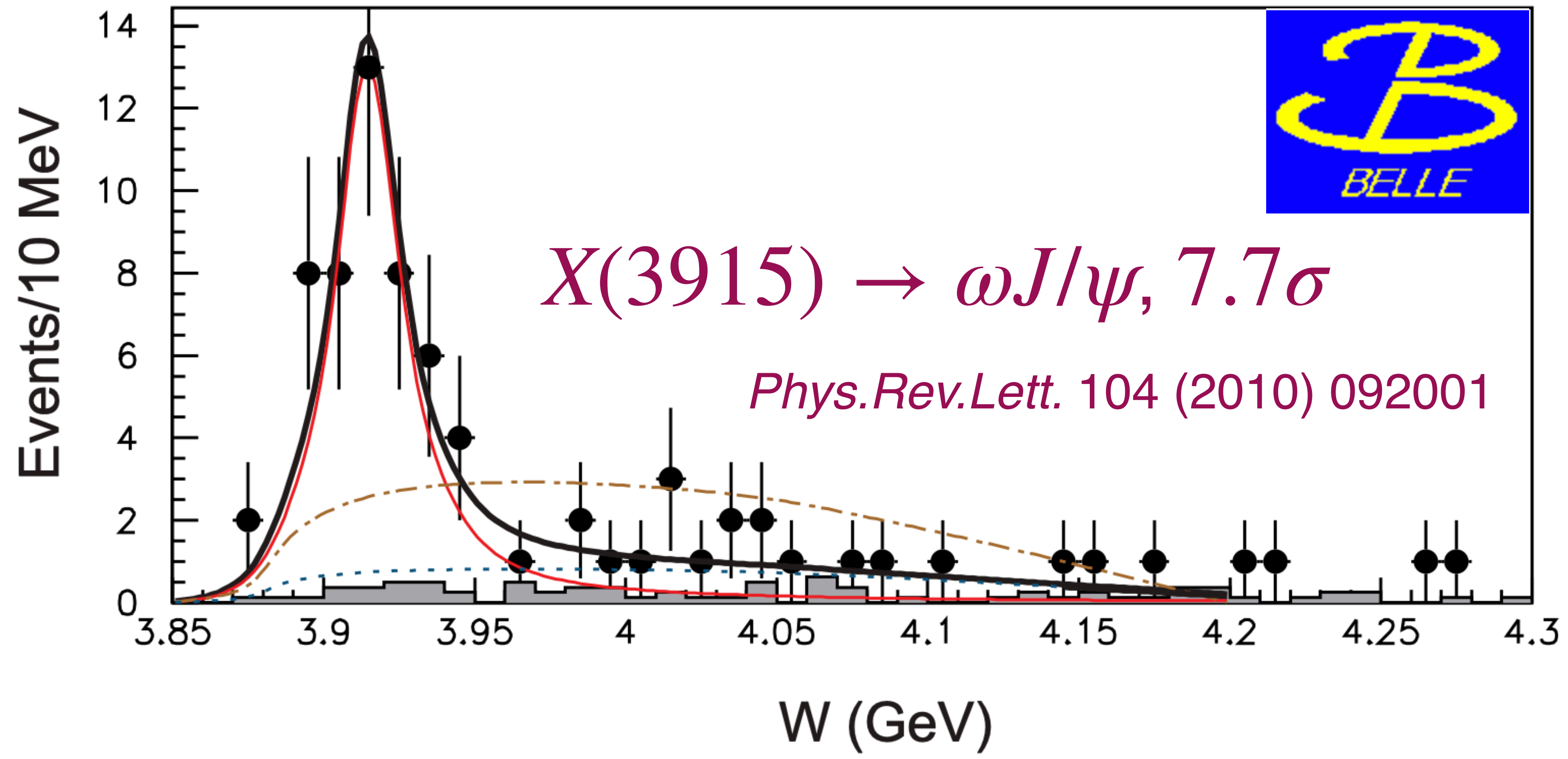
Unique field to produce charmonium(-like) particles

Establishment of exotic states in various final states

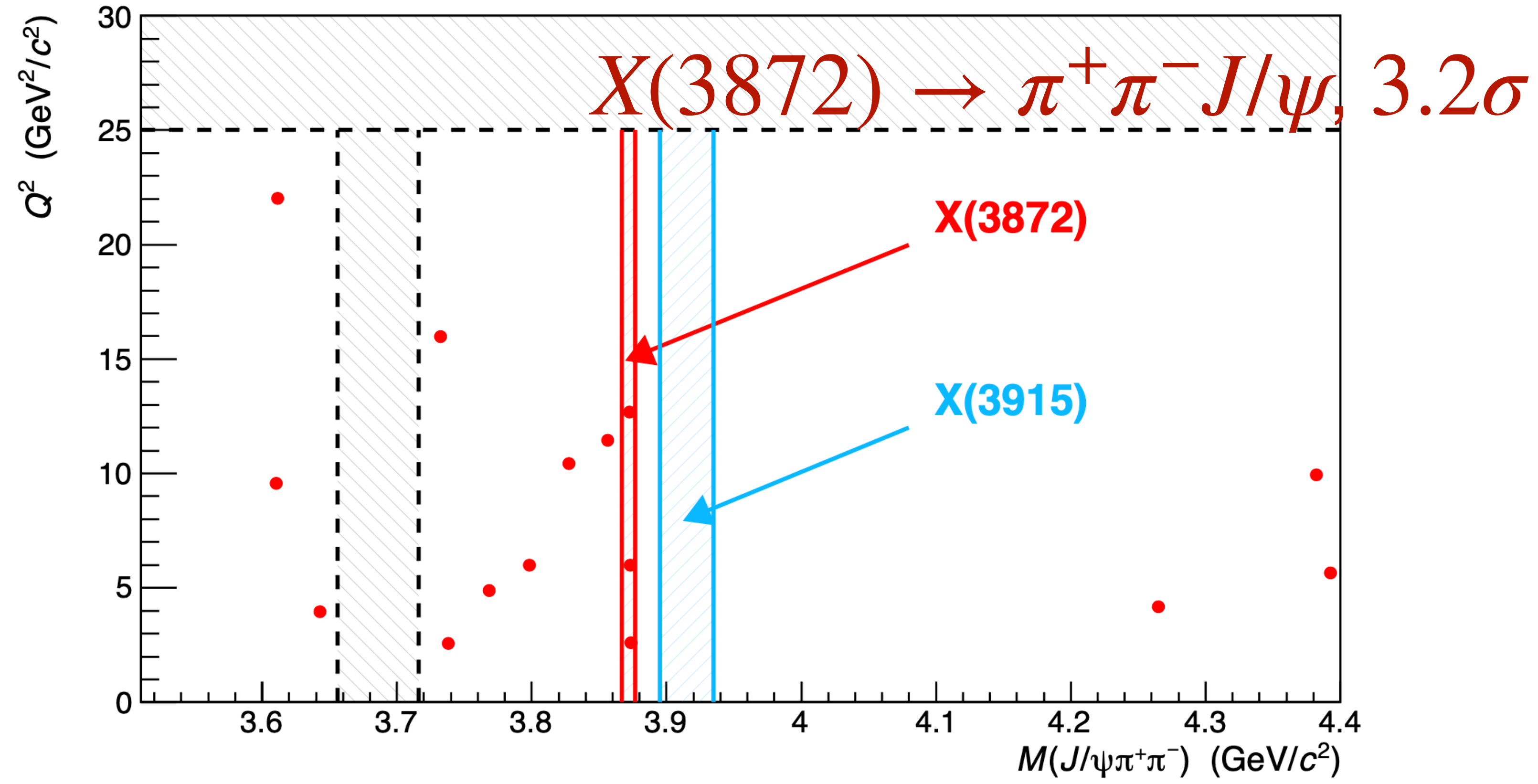
$X(3930) \to D\bar{D}$, 5.3σ

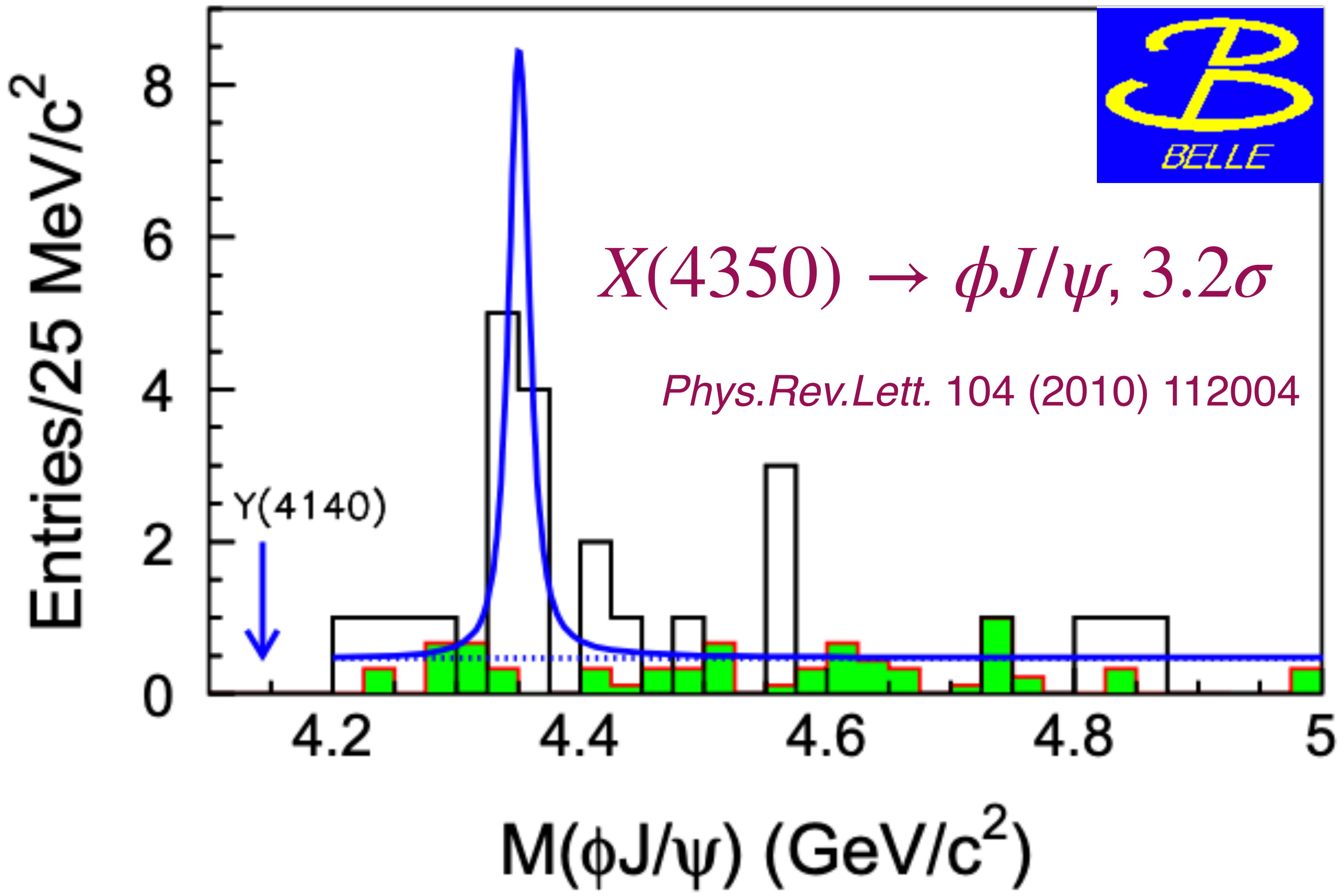
Phys.Rev.Lett. 96 (2006), 082003

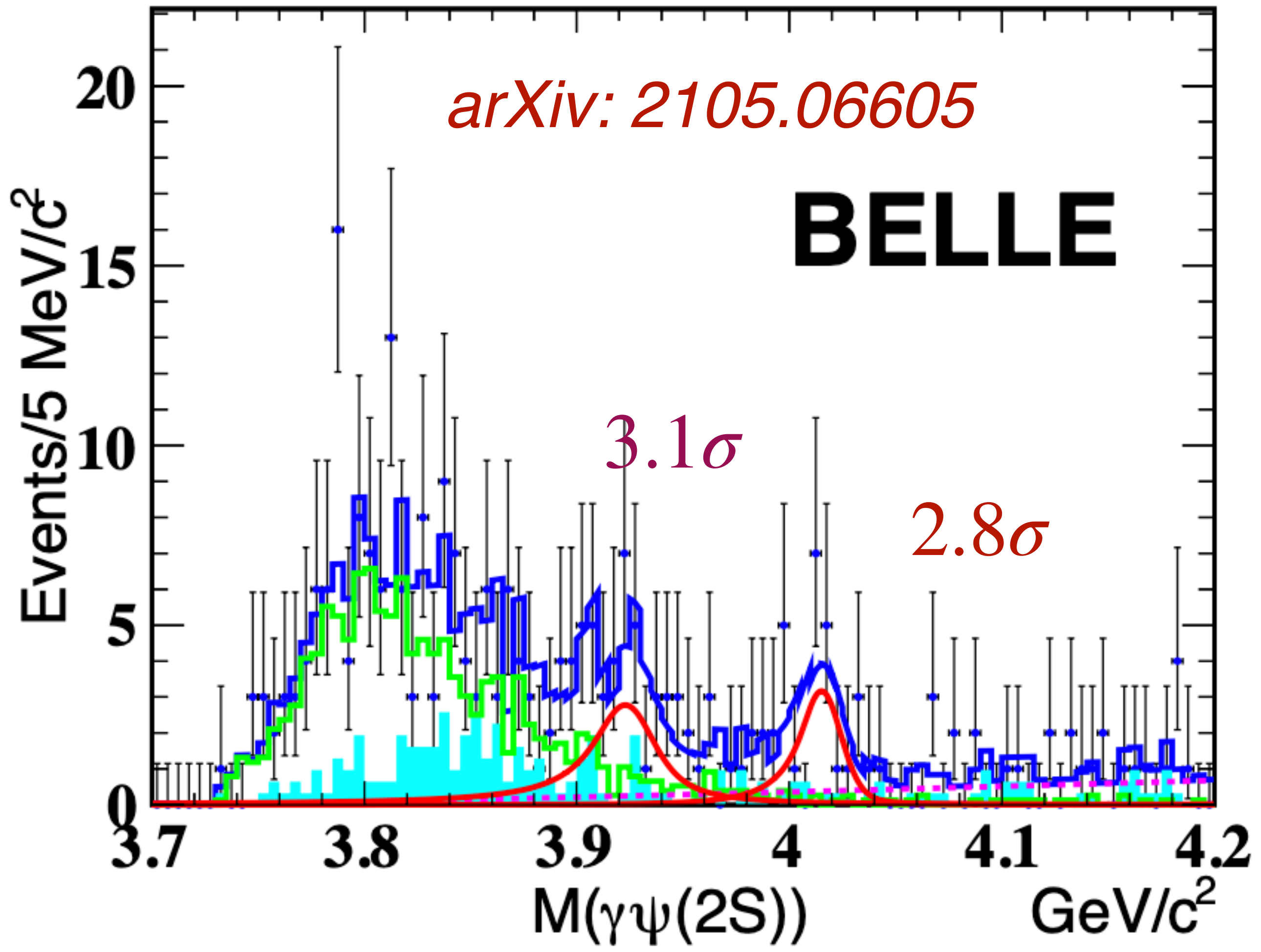




Phys.Rev.Lett. 126 (2021) 12, 122001

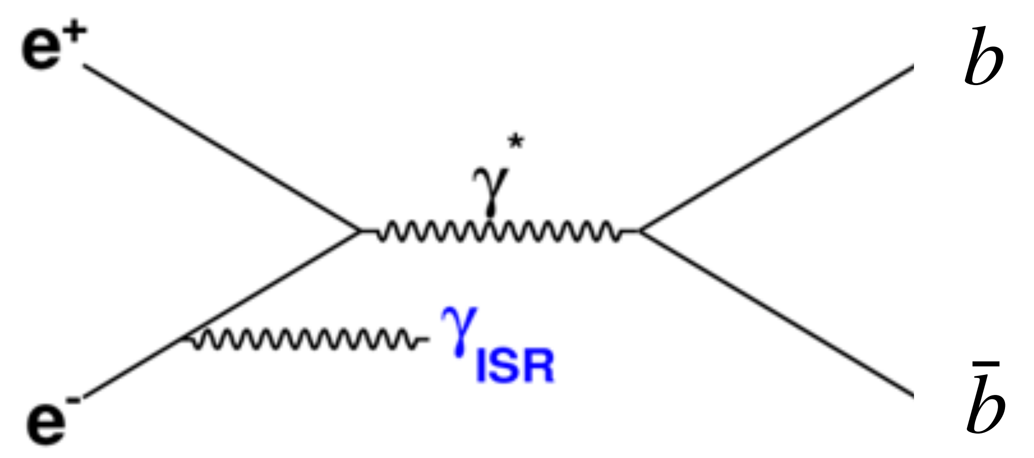




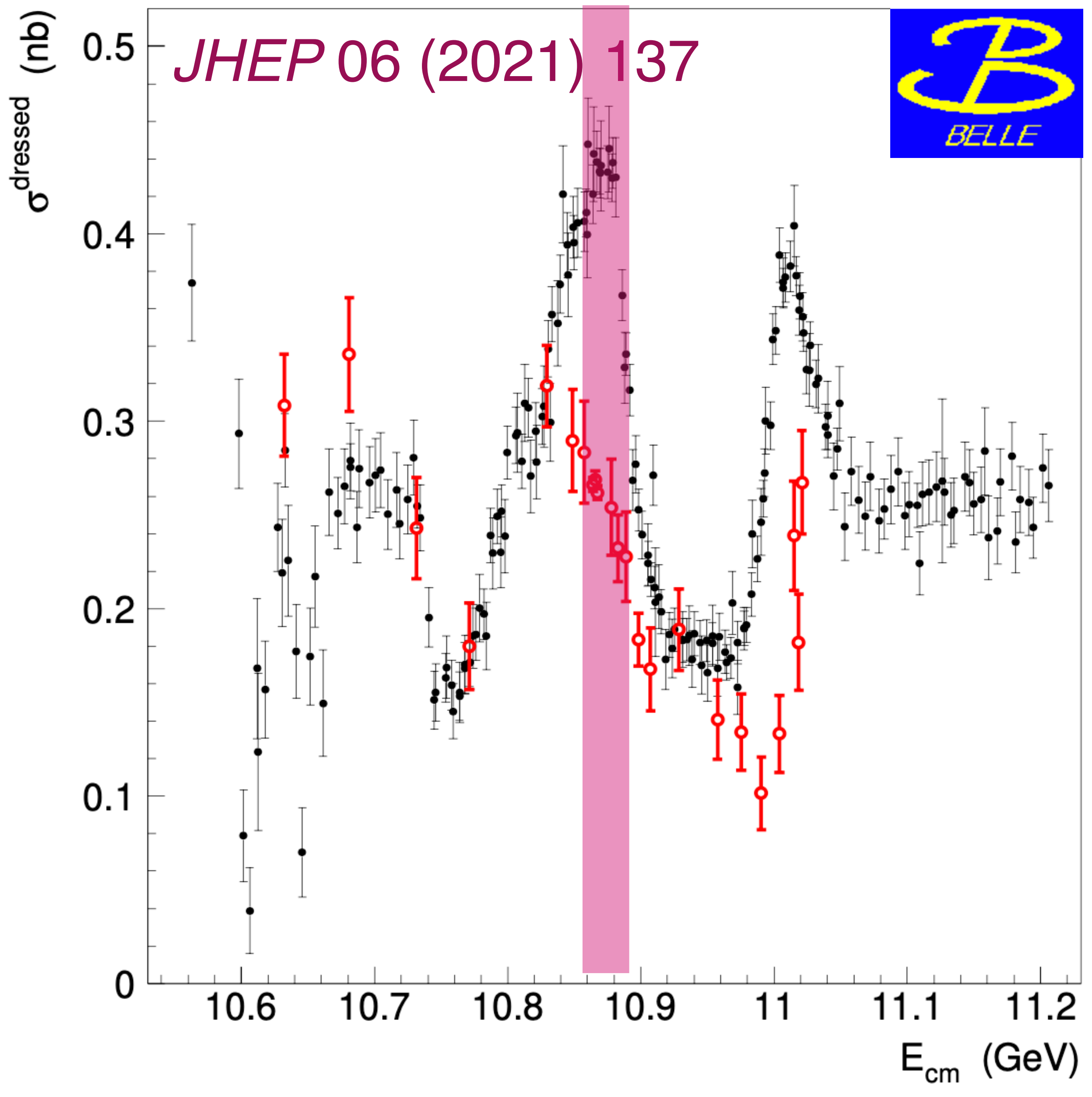


Bottomonium production

Excellent play ground of NRQCD & unique properties



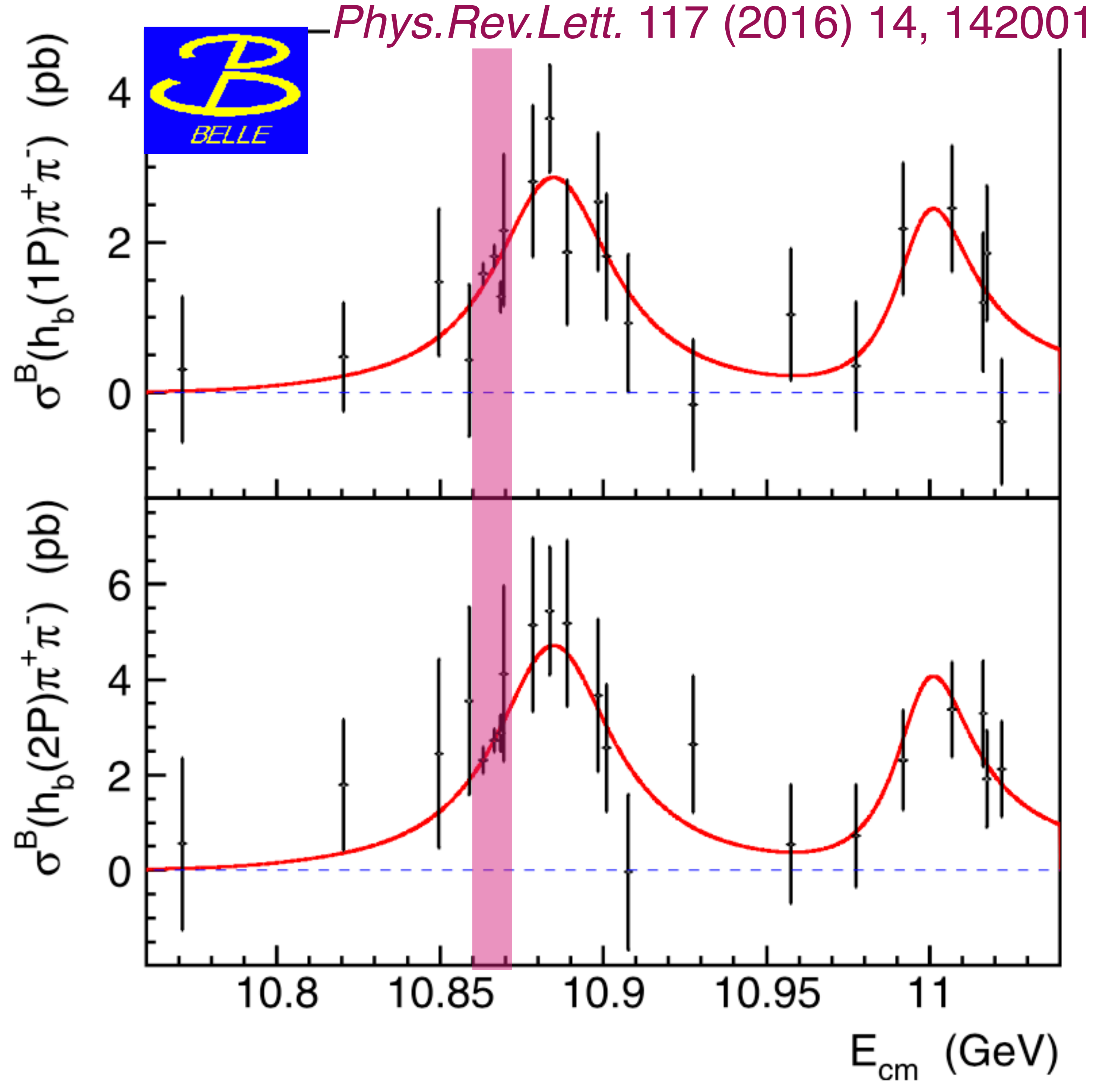
Questions raised: $\Upsilon(5S)$ ***mass &*** ***abnormal transition rate***

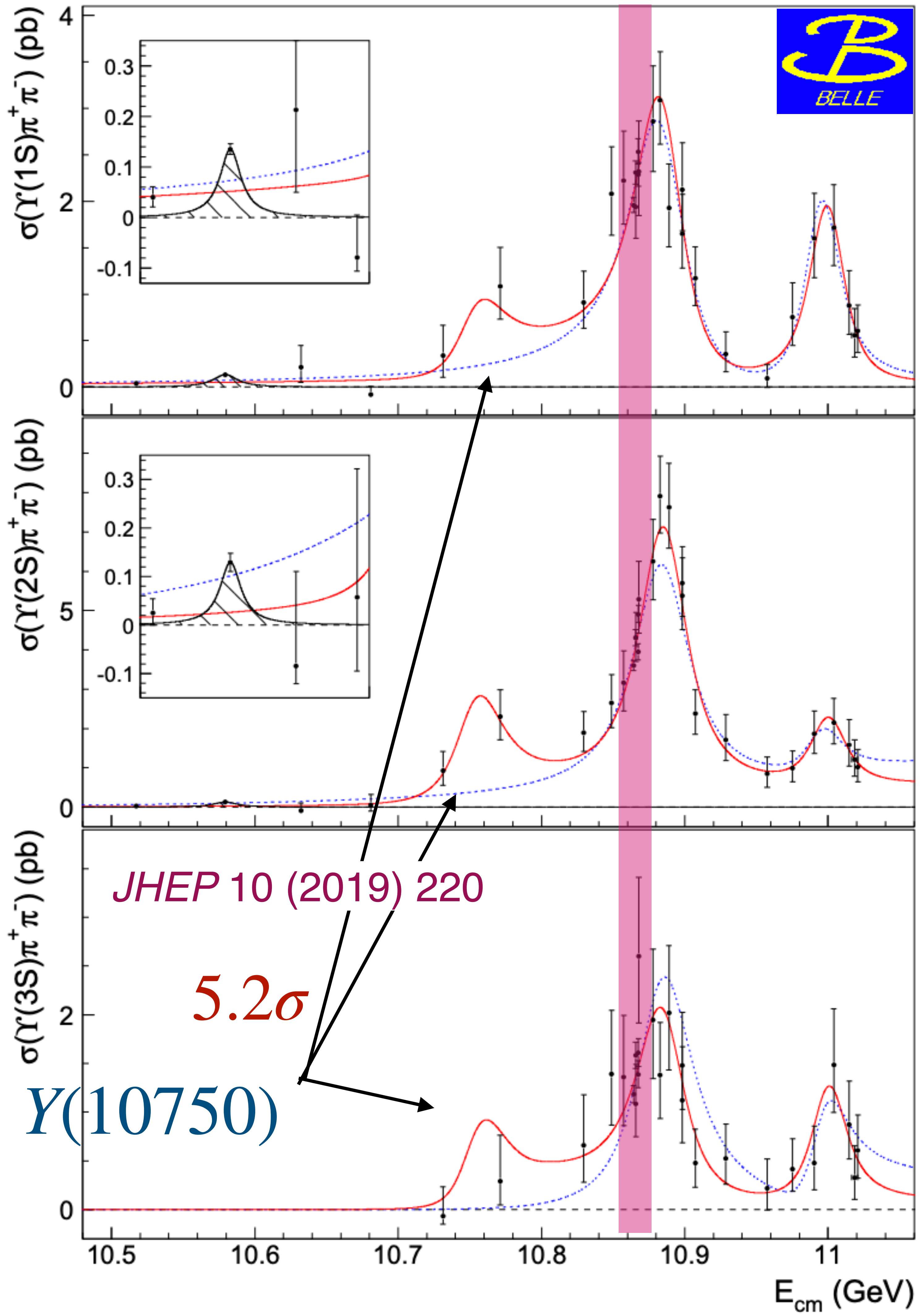


Red dots: Measured $\sigma[e^+e^- \to B^{(*)}\bar{B}^{(*)}]$

Black dots: total $b\bar{b}$ dressed cross section

Chin. Phys. C 44, 083001 (2020)



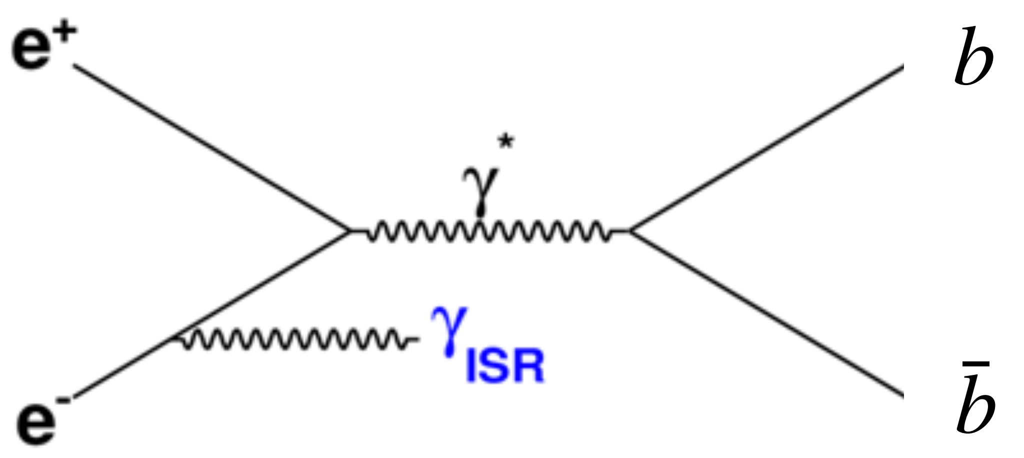


- Excess between $e^+e^- \to b\bar{b}$ and $B^{(*)}\bar{B}^{(*)}$, others?
- Cross sections do not peak at $\Upsilon(5S)$ mass.

A new state: $Y(10750)$

Bottomonium production

Excellent play ground of $NRQCD$ & unique properties



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

Phys.Rev.Lett. 100 (2008) 112001

Process	Γ_{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

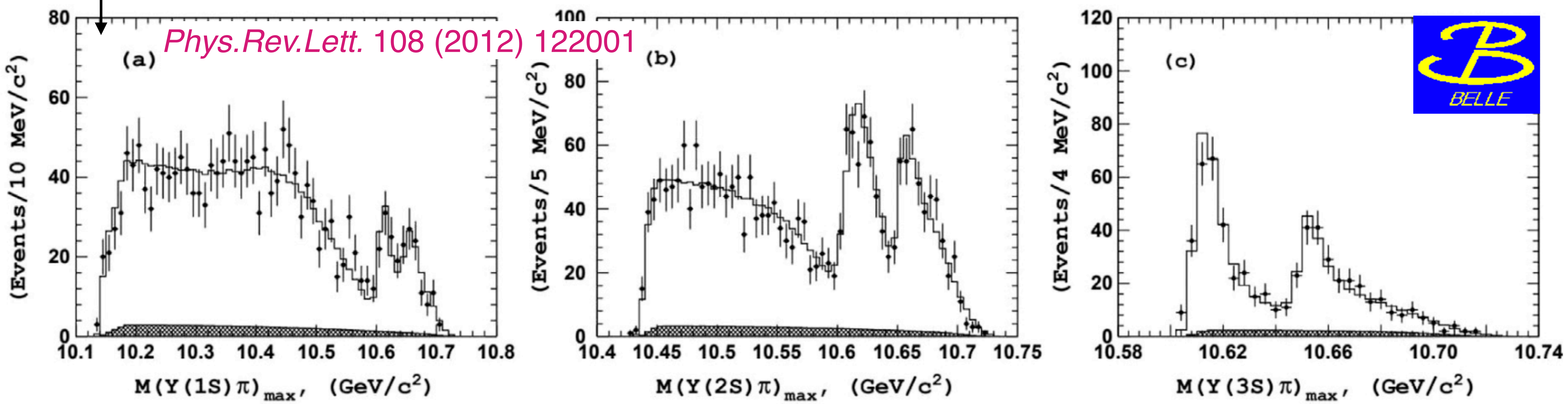
$> 10^2 \times$

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

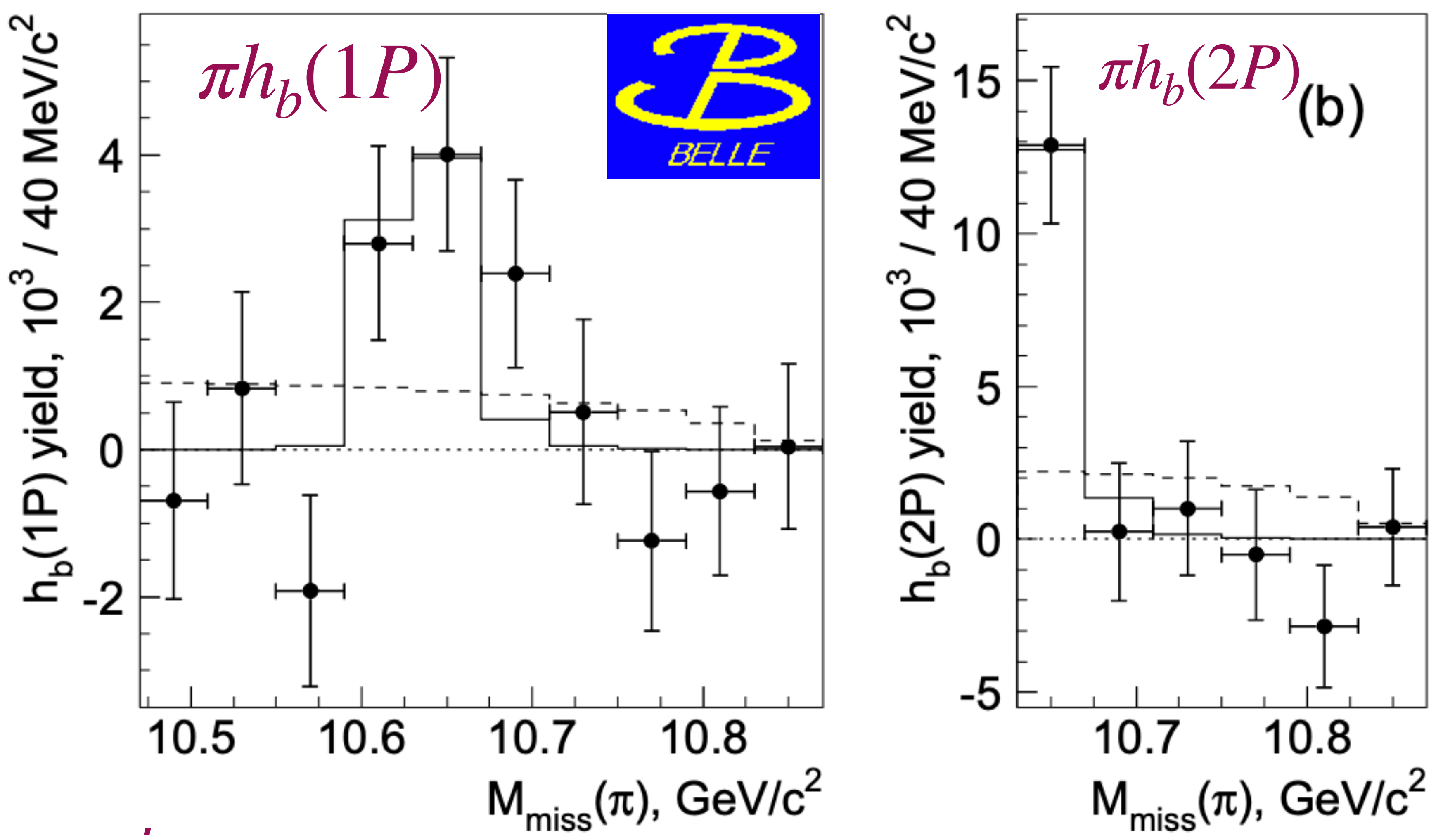
$$\frac{\Gamma(\Upsilon(5S) \to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.77 \pm 0.08^{+0.22}_{-0.17}$$

Observation of $Z_b(10610)$ ***and*** $Z_b(10650)$

Phys.Rev.Lett. 108 (2012) 122001

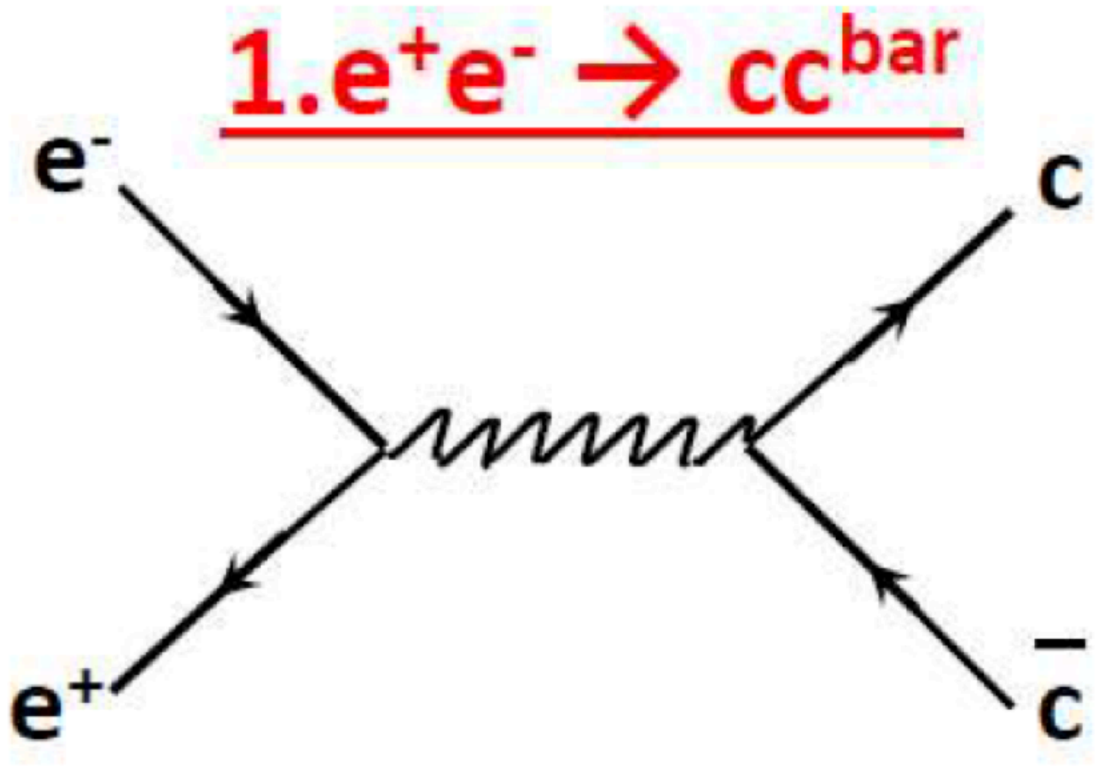


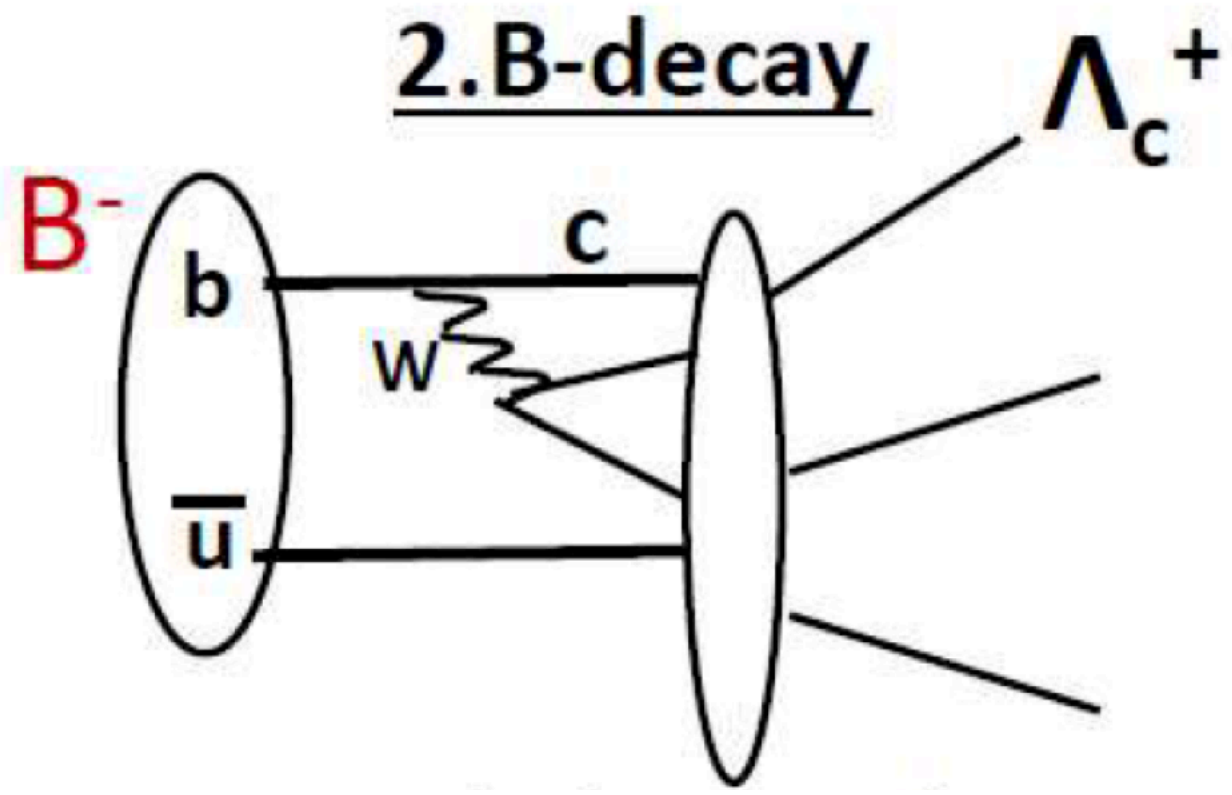
Phys.Rev.Lett. 117 (2016) 14, 142001



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

Baryon spectroscopy





Production:

- fragmentation
- B-decays

Normally we donnot separate them experimentally

Focus:

- Searching for new states
- Properties measurement

Fruitful results recently

- Weak decays
  - $\Xi_c^0 \to \Lambda K_S^0,\ \Sigma^0 K_S^0,\ \Sigma^+ K^-$ — arXiv:2111.08981
  - $\Xi_c^0 \to \Lambda \overline{K}^{*0},\ \Sigma^0 \overline{K}^{*0},\ \Sigma^+ K^{*-}$ — JHEP 2106, 160 (2021)
  - $\Lambda_c^+ \to p\omega$ (BF) — PRD 104, 072008 (2021)
  - ✓ $\Omega_c^0 \to \pi^+ \Omega(2012)^- \to \pi^+ (\bar{K}\Sigma)^-$ — PRD 104, 052005 (2021)
  - $\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu)$ and asym. of $\Xi_c^0 \to \Xi^- \pi^+$ — PRL 127, 121803 (2021)
  - $\Lambda_c^+ \to p\eta,\ p\pi^0$ — PRD 103, 072004 (2021)
  - $\Xi_c^0 \to \Xi^0 K^+ K^-$ — PRD 103, 112002 (2021)
  - ✓ $\Lambda_c^+ \to \eta\Lambda\pi^+,\ \eta\Sigma^0\pi^+,\ \Lambda(1670)\pi^+,\ \eta\Sigma(1385)^+$ — PRD 103, 052005 (2021)

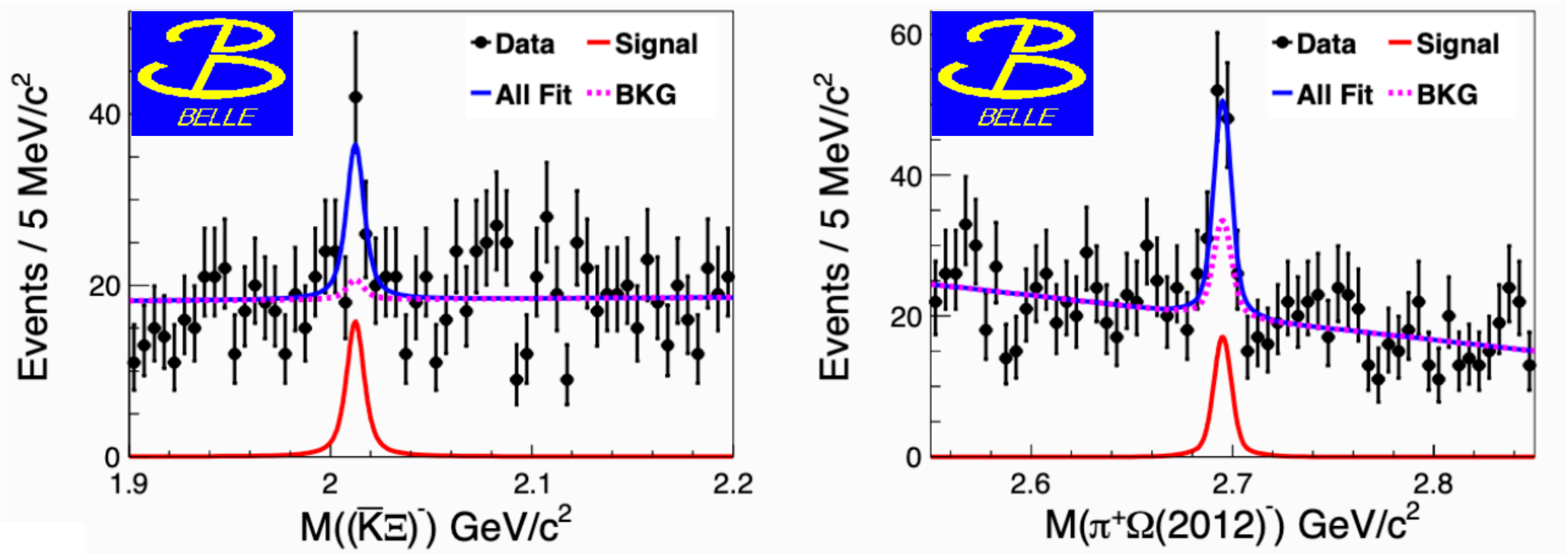
- Hadronic properties & radiative decays
  - ✓ mass, width of $\Sigma_c(2455)^+$, $\Sigma_c(2520)^+$ — PRD 104, 052003 (2021)
  - ✓ $\Xi_c(2815)^0 \to \Xi_c^0\gamma,\ \Xi_c(2790)^0 \to \Xi_c^0\gamma,$ — PRD 102, 071103 (2020)
  - ✓ Spin-parity of $\Xi_c(2970)^+$ — PRD 103, L111101 (2021)
  - B baryonic decays, $B \to \Lambda_c \Xi_c$ — PRD 100, 112010 (2019)
  - $\Xi(1620)^0$ & $\Xi(1690)^0$ in $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ — PRL 122, 072501 (2019)
  - ...
  - Excited Ω^- observations — PRL 121, 052003 (2018)
  - Excited Ω_c (obs. 4 states) — PRD 97, 051102 (2018)

Searching for new states

Various production mechanism create massive baryons
Lower backgrounds
Efficient neural reconstructions

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

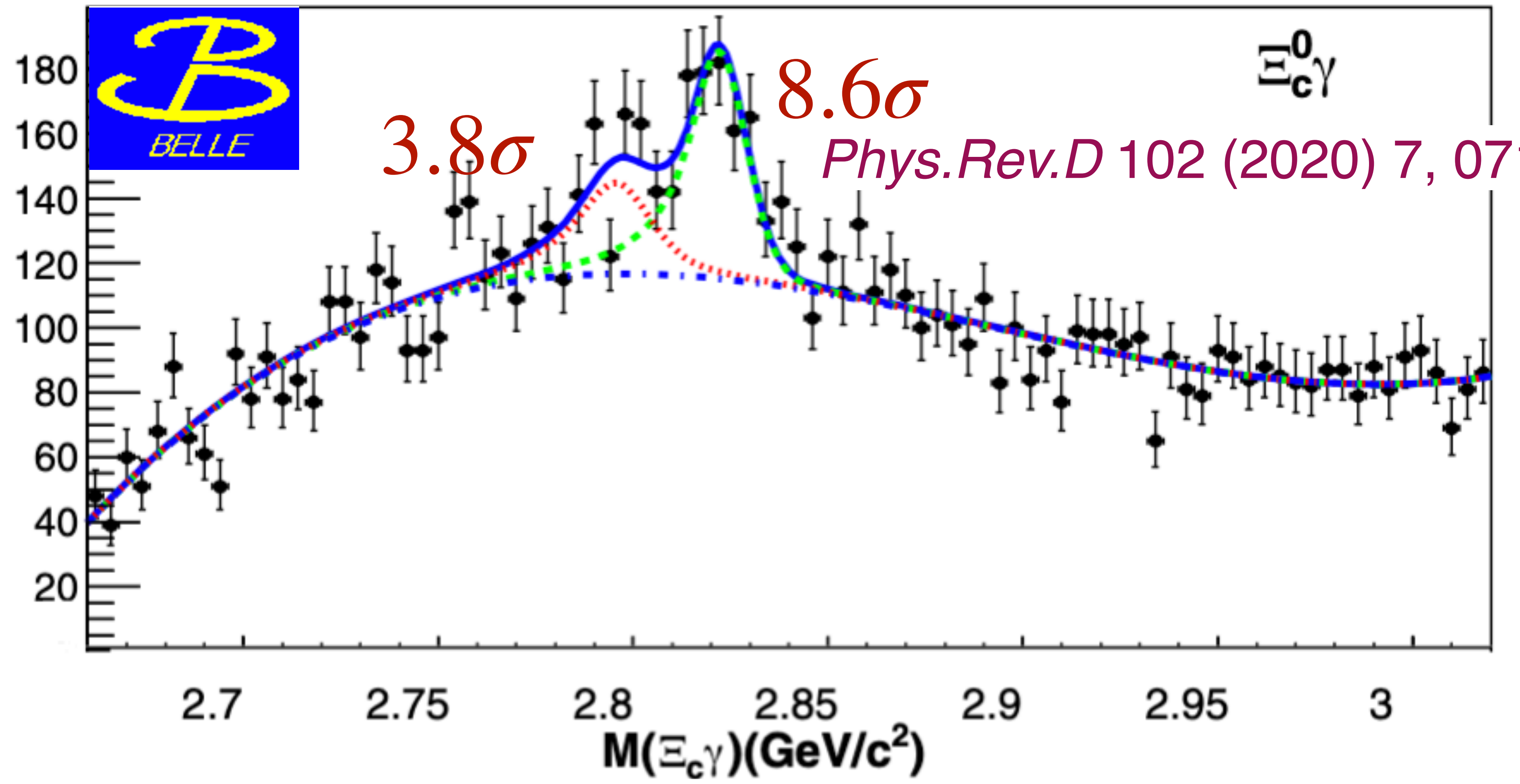
Entire Belle data—$980\ \mathrm{fb}^{-1}$ 4.2σ *Phys.Rev.D* 104 (2021) 5, 052005

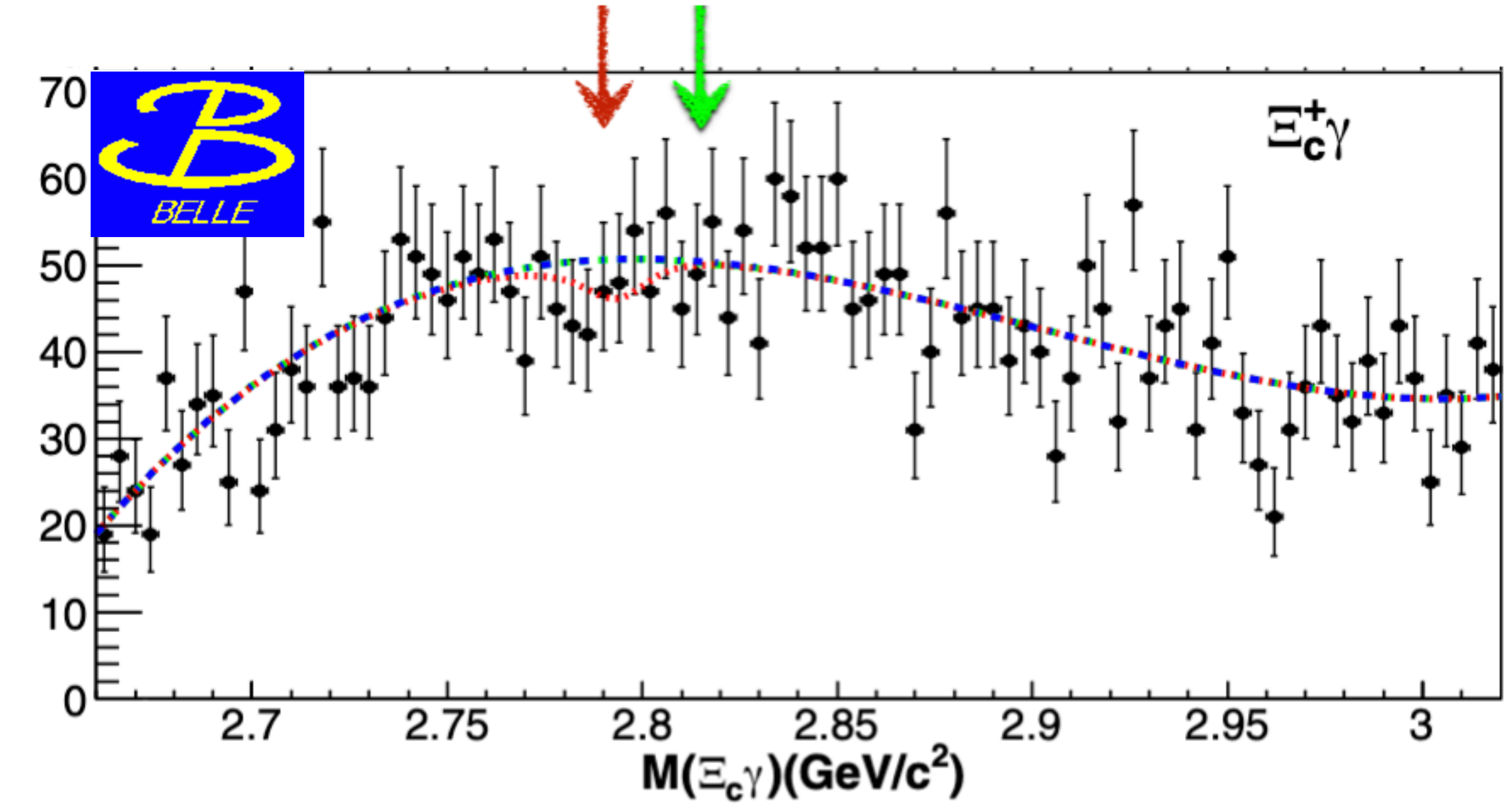


If $\Omega(2012)$ is a $(\bar{K}\Xi(1530))$ molecule, could be much more visible in $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$

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

3.8σ 8.6σ *Phys.Rev.D* 102 (2020) 7, 071103





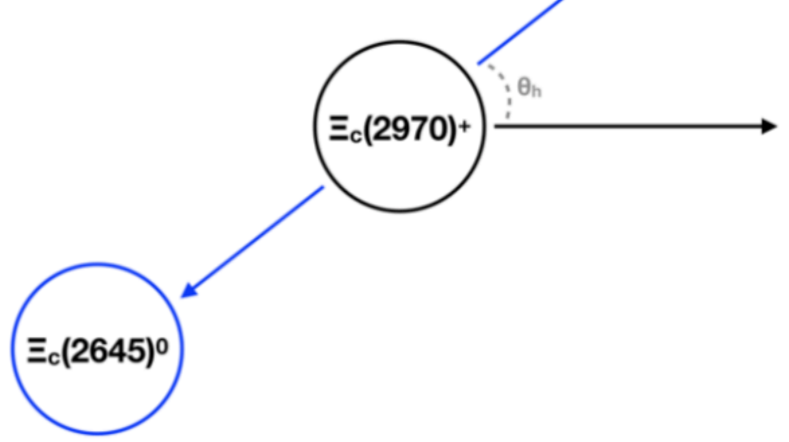
Properties measurements

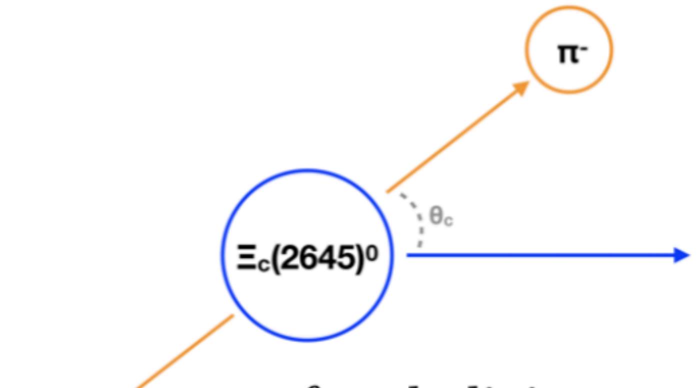
Various production mechanism create massive baryons
Lower backgrounds
Efficient neural reconstructions

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

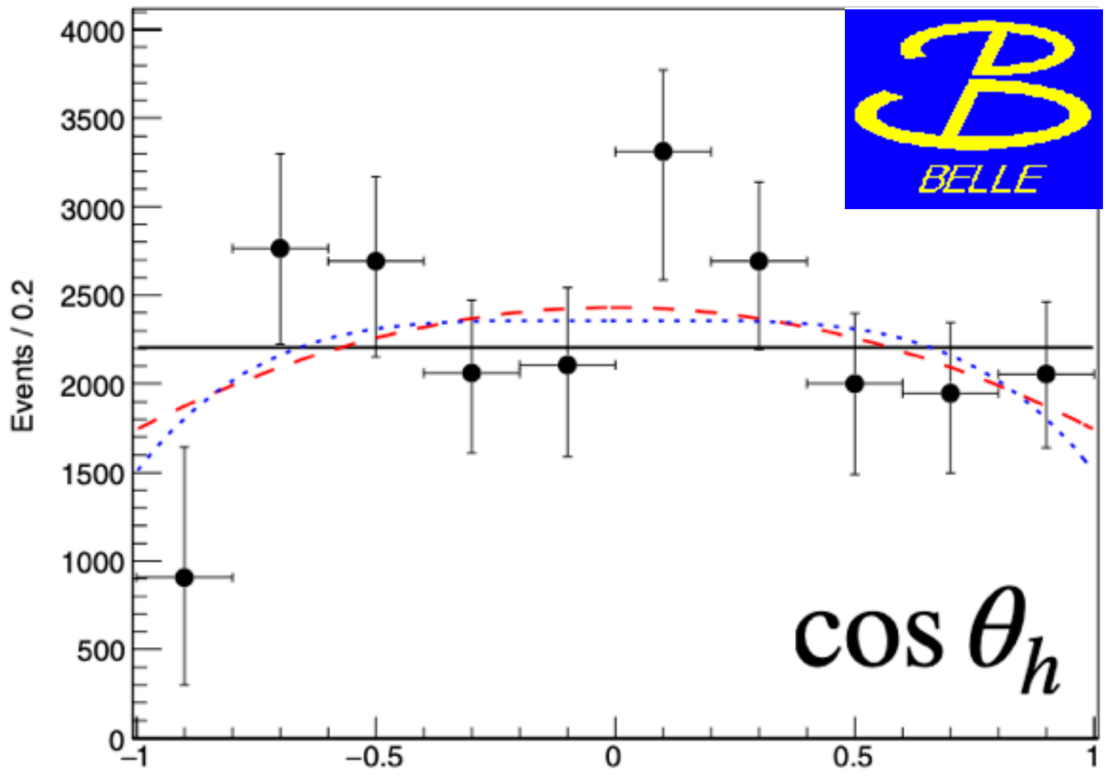
Phys.Rev.D 103 (2021) 11, L111101

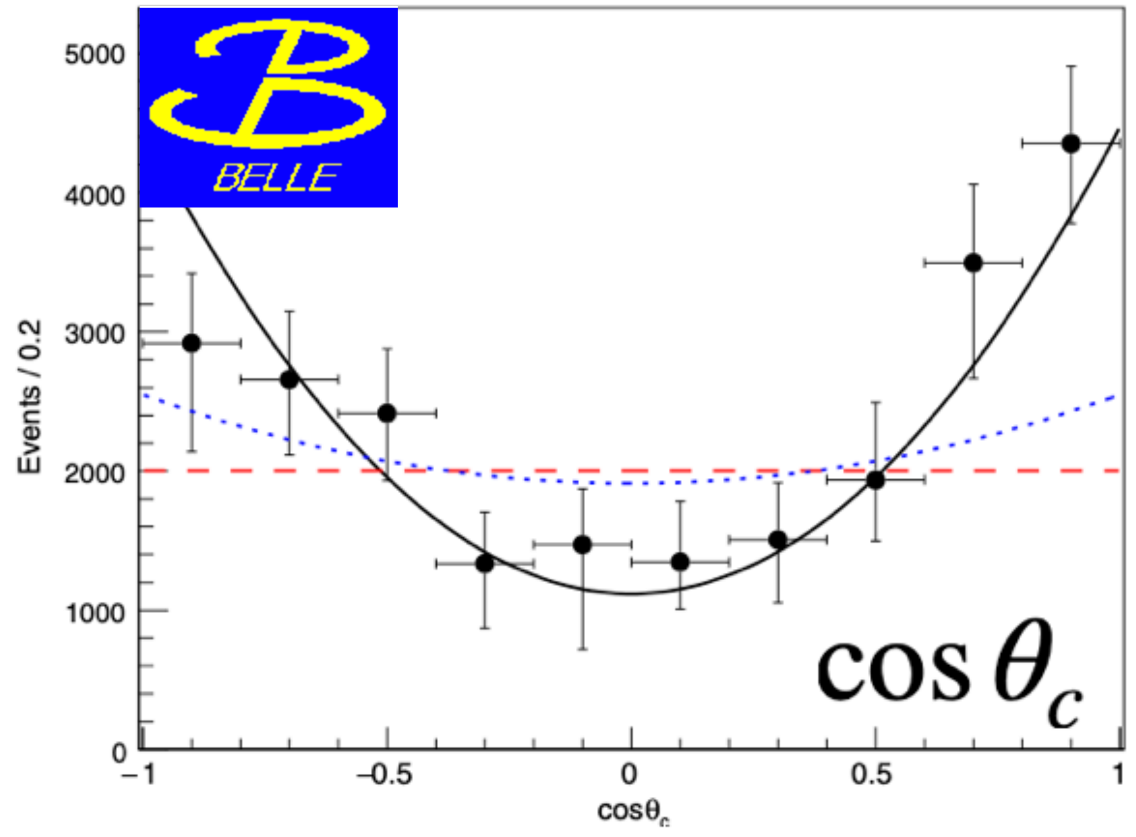
θ_h : helicity angle of $\Xi_c(2970)^+$





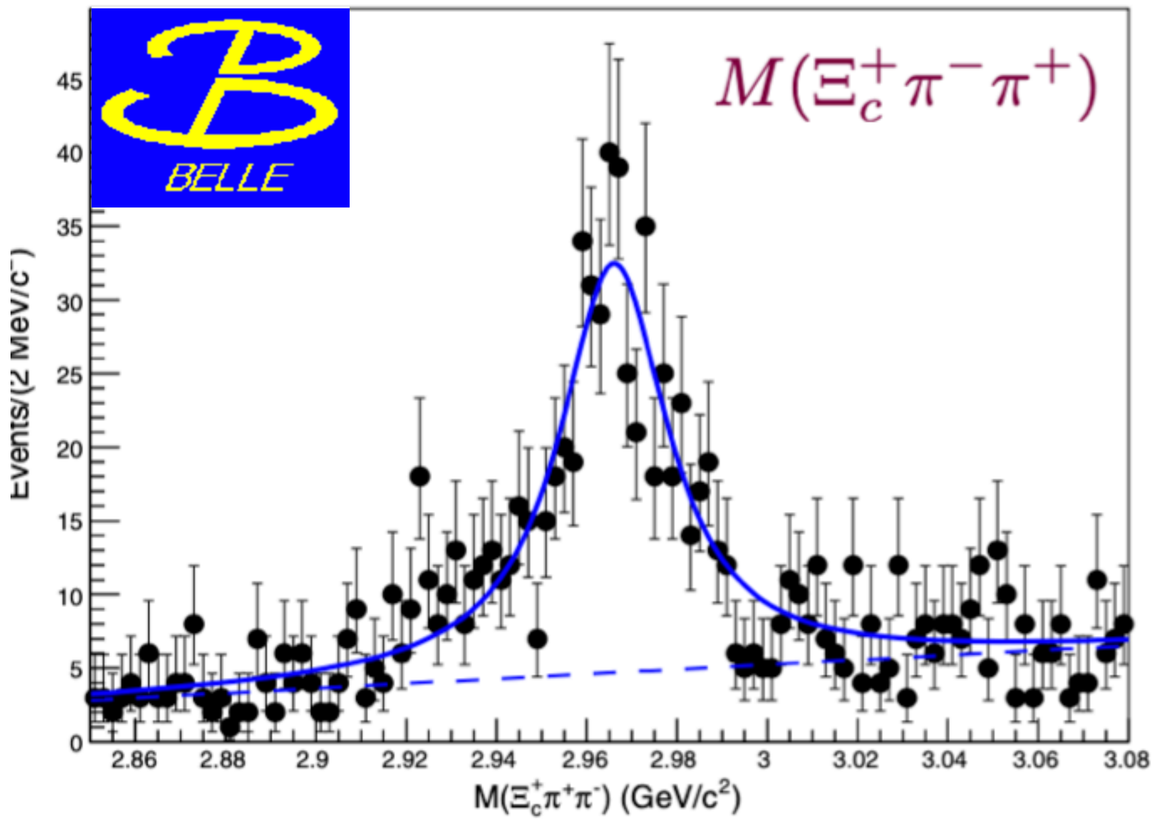
θ_c : helicity angle of $\Xi_c(2645)^0$

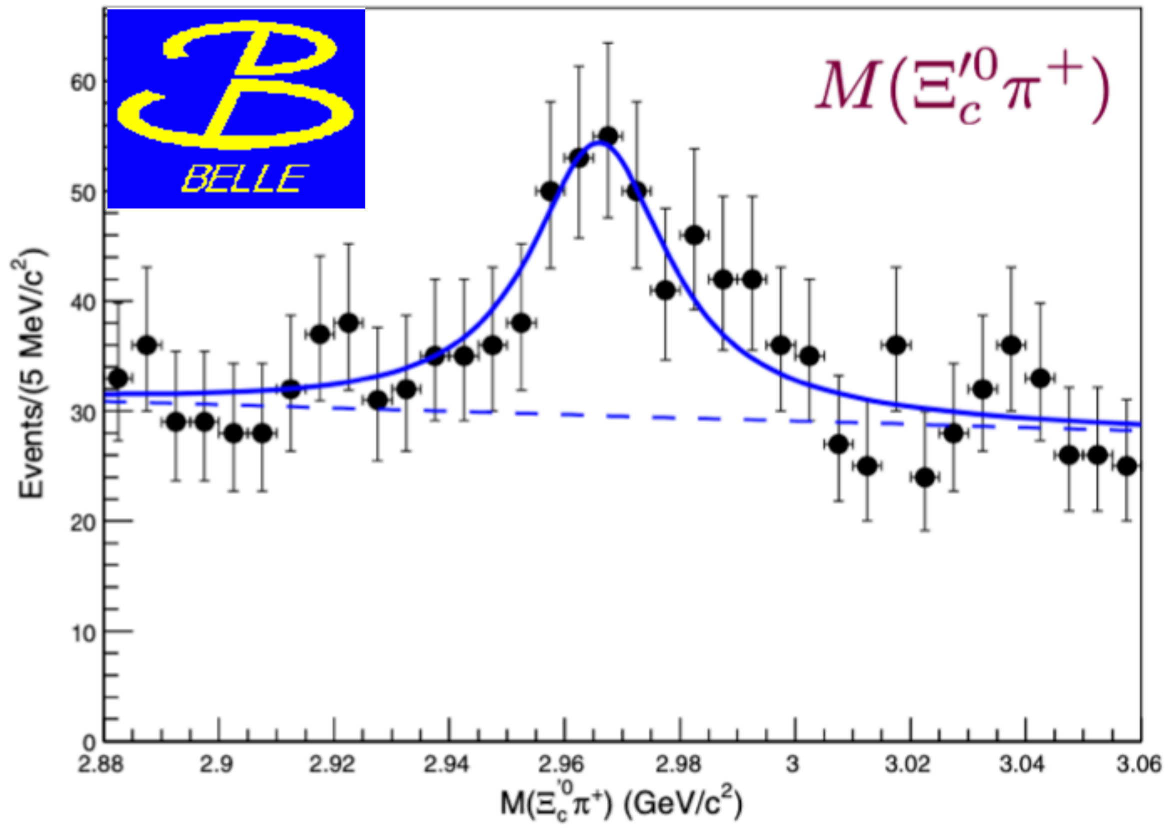




- most consistent with spin=1/2 hypothesis
- also excludes $\Xi_c(2645)$ spin of 1/2 ($\because \cos\theta_c$ not flat)

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





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

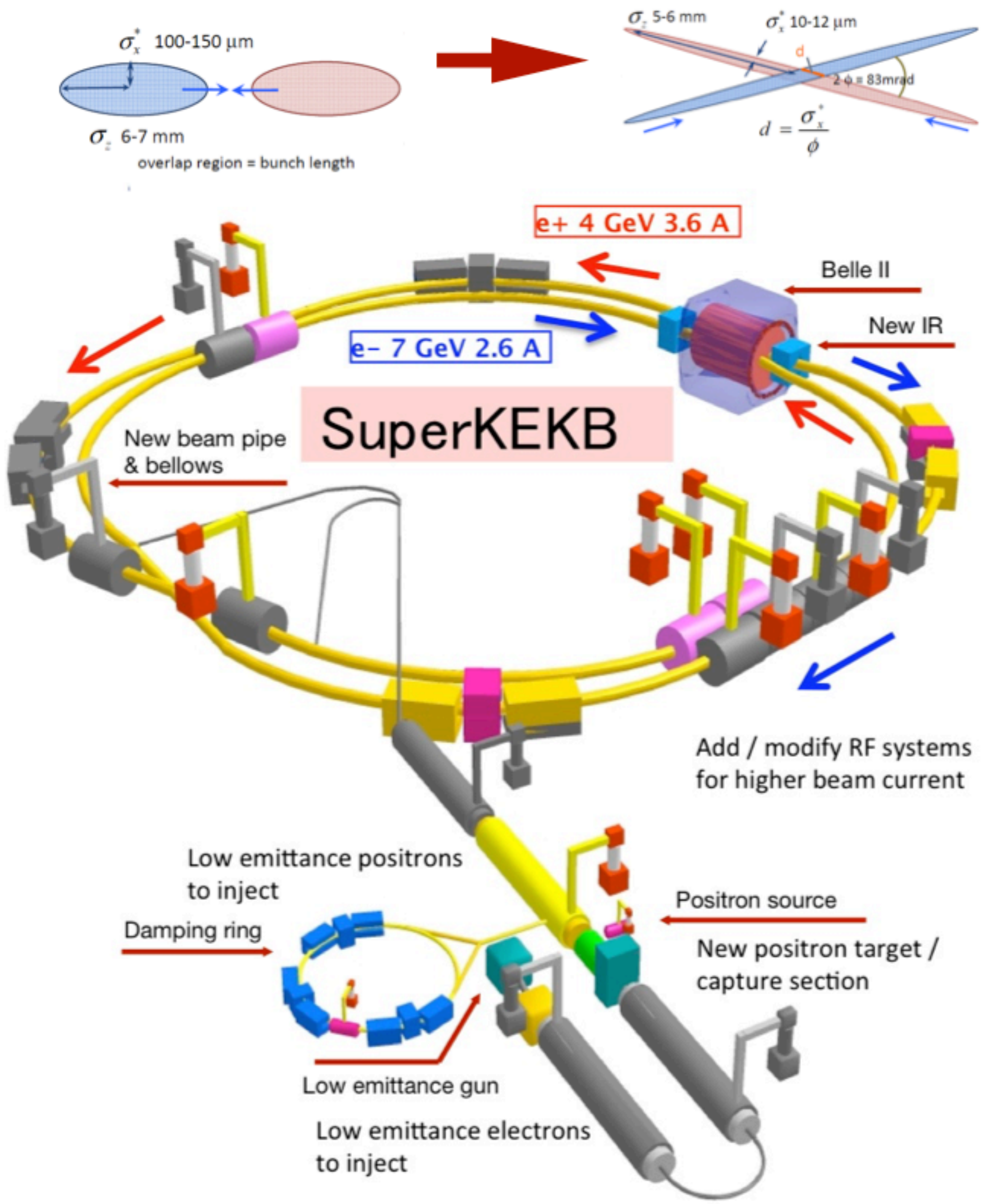
Heavy-quark spin sym. prediction

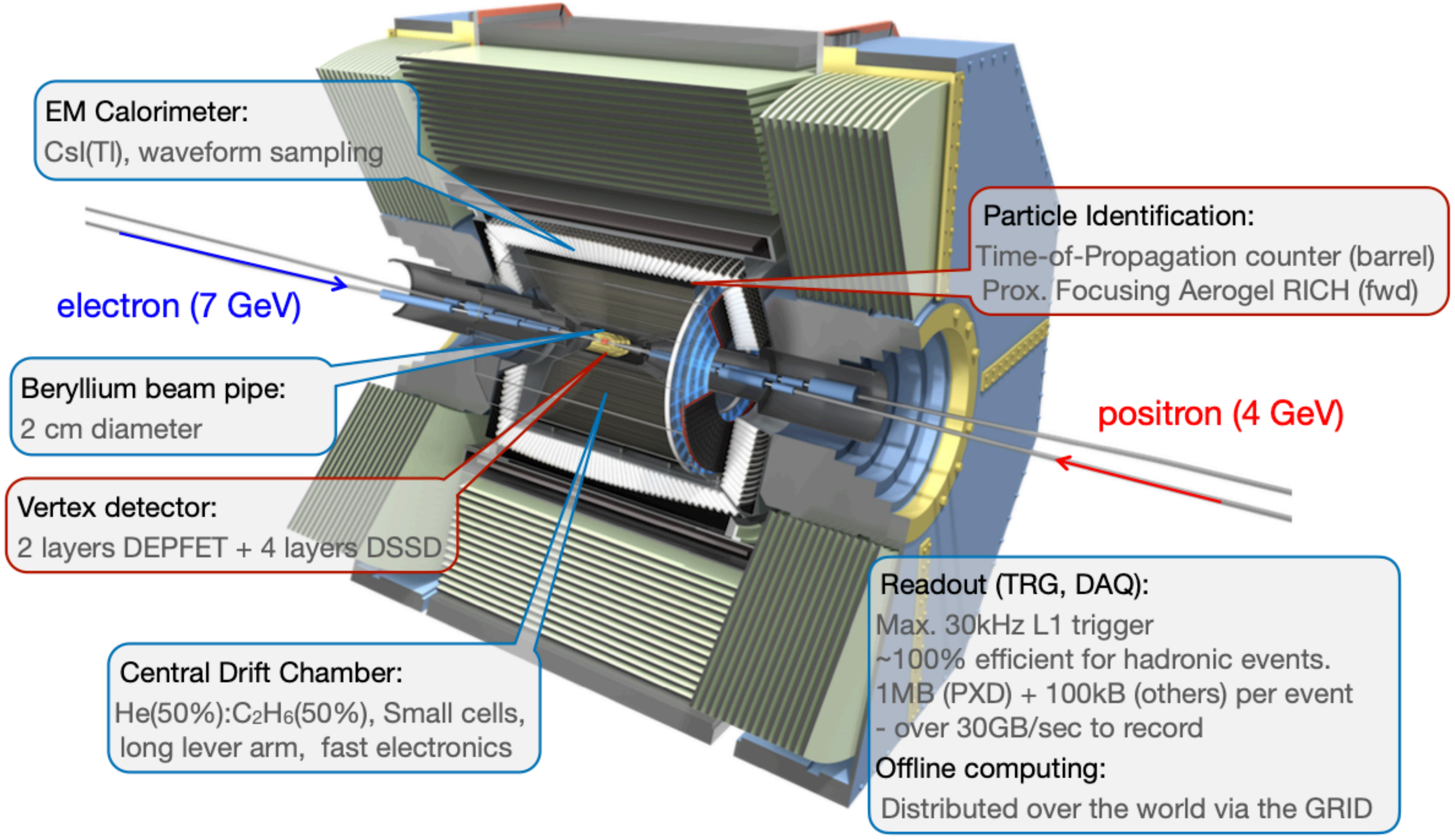
Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	≪1

∴ (+) parity assignment is favored

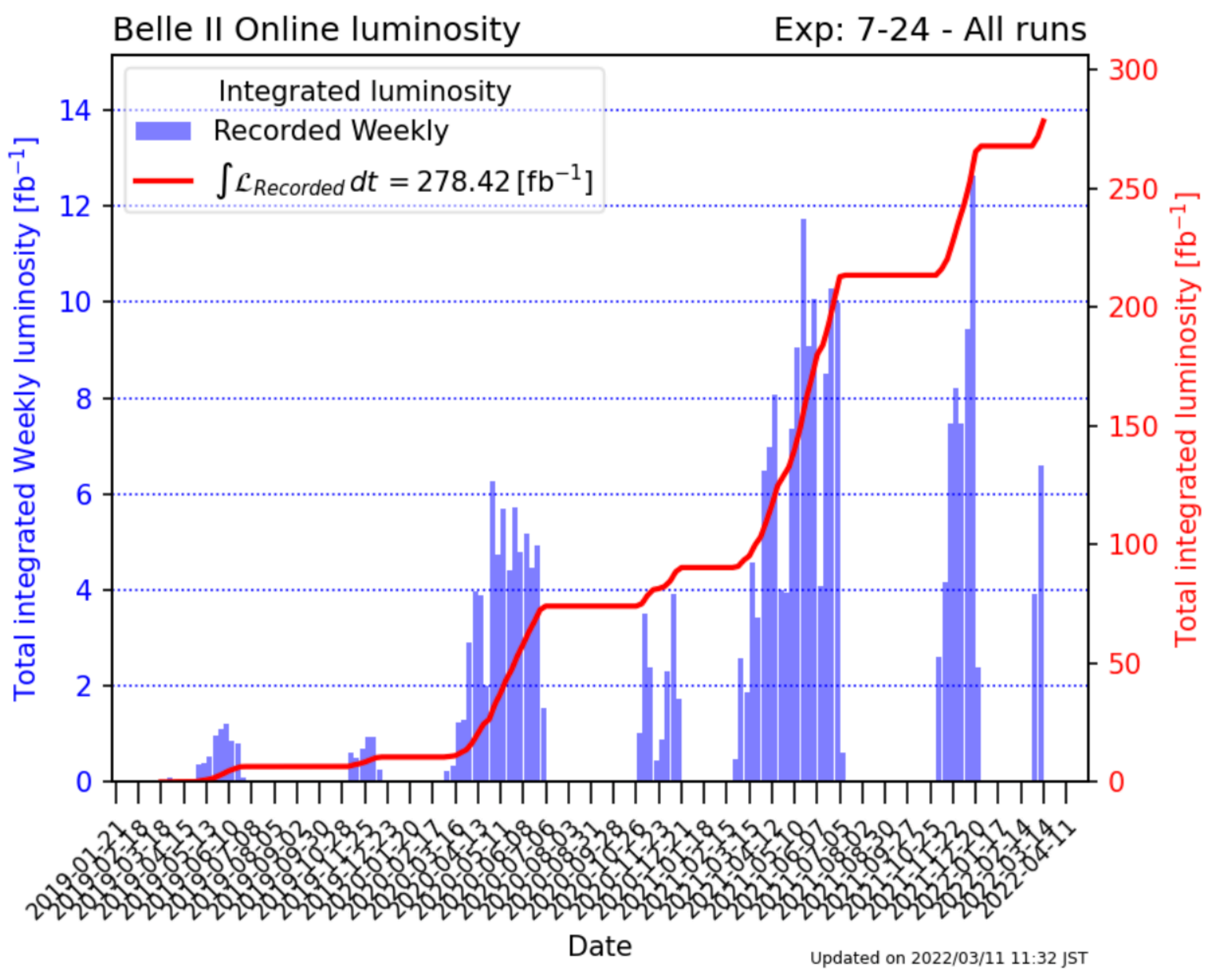
SuperKEKB and Belle II: The next generation B-factory

Upgraded detector and accelerator





arXiv:1011.0352 [physics.ins-det]



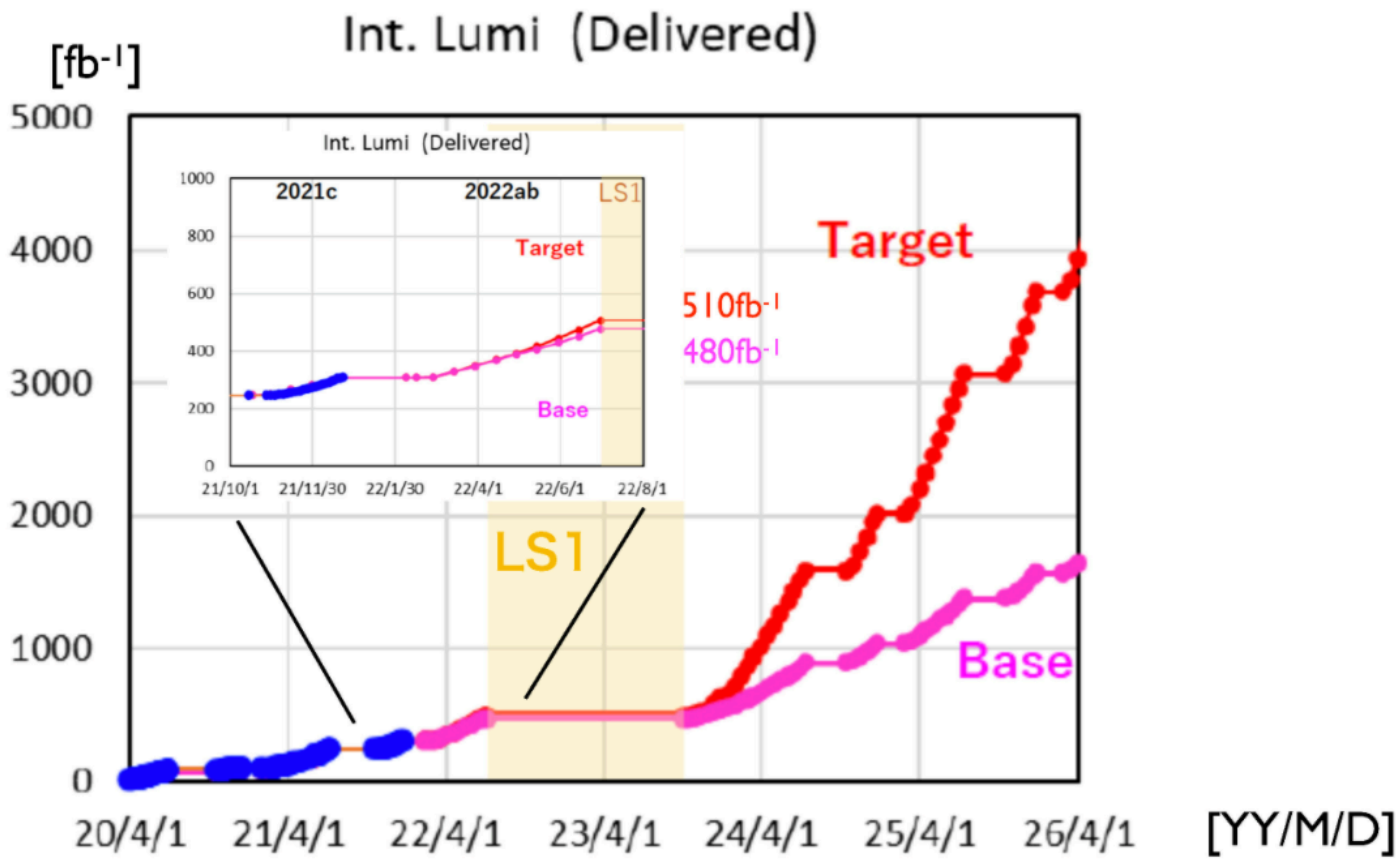
Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run

Increasing by $1 \sim 1.5\ \mathrm{fb}^{-1}$ per day

We reached $> 250\ \mathrm{fb}^{-1}$!

Luminosity record: $3.8 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

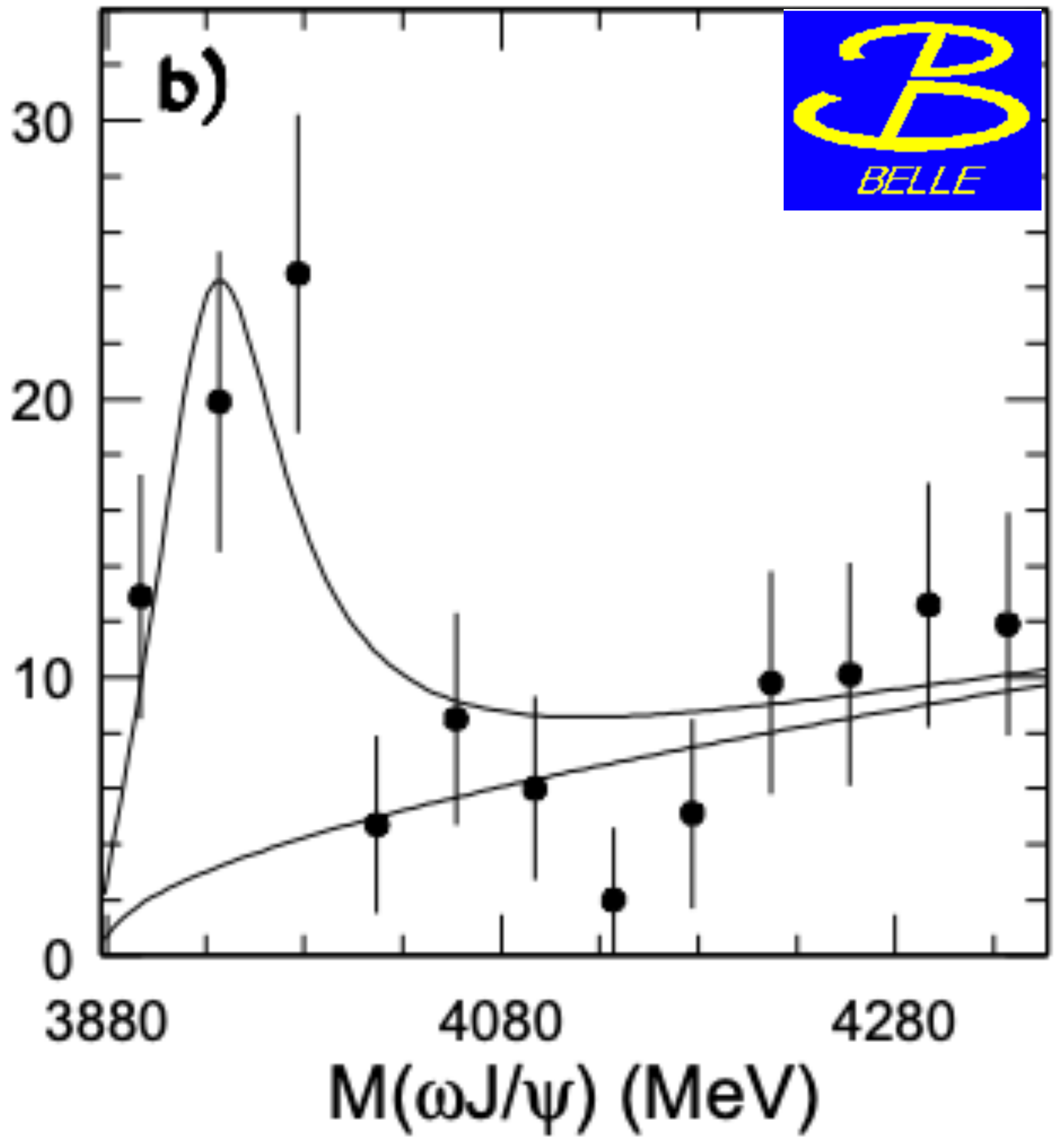


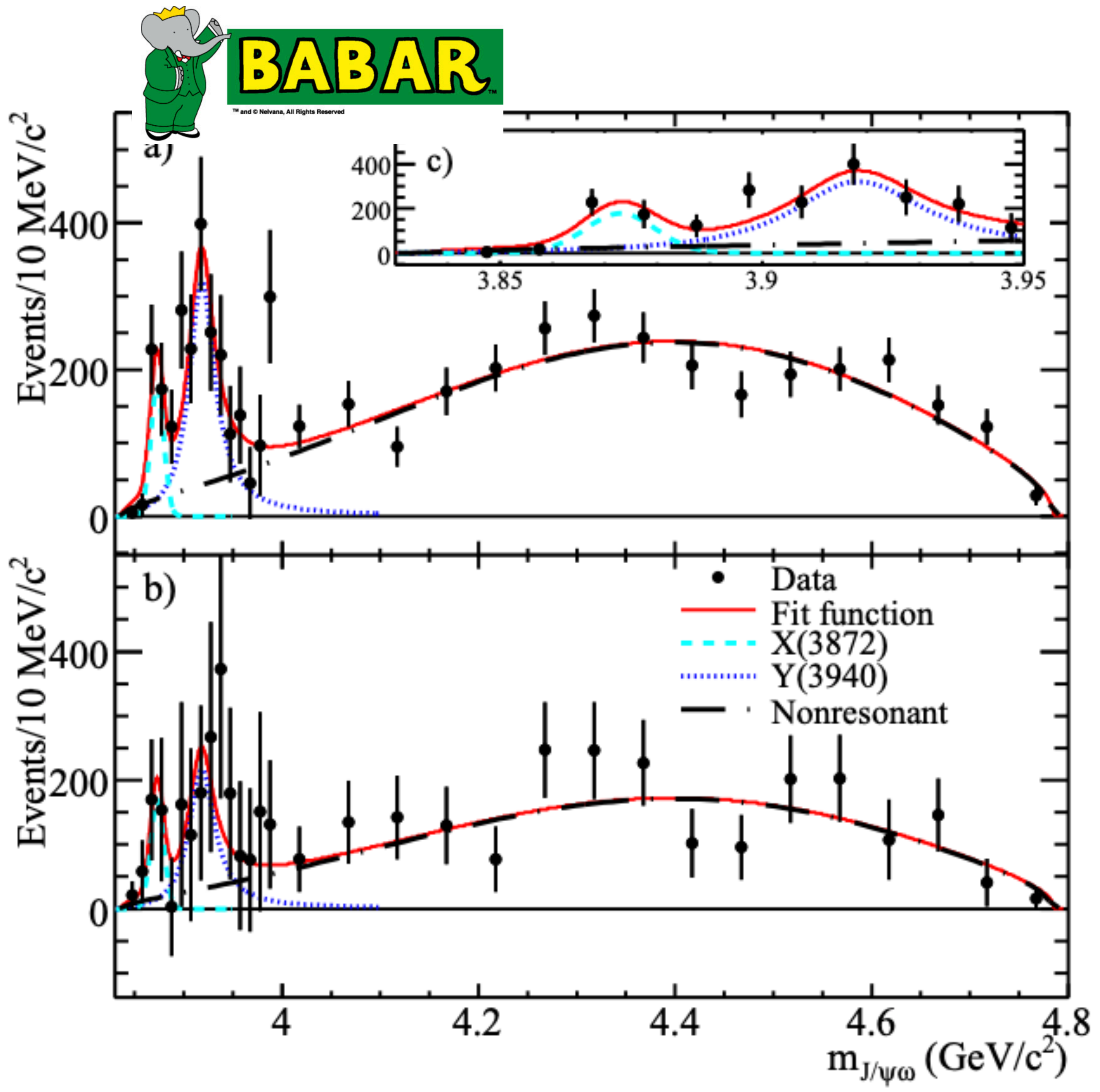
Prospect

In short term

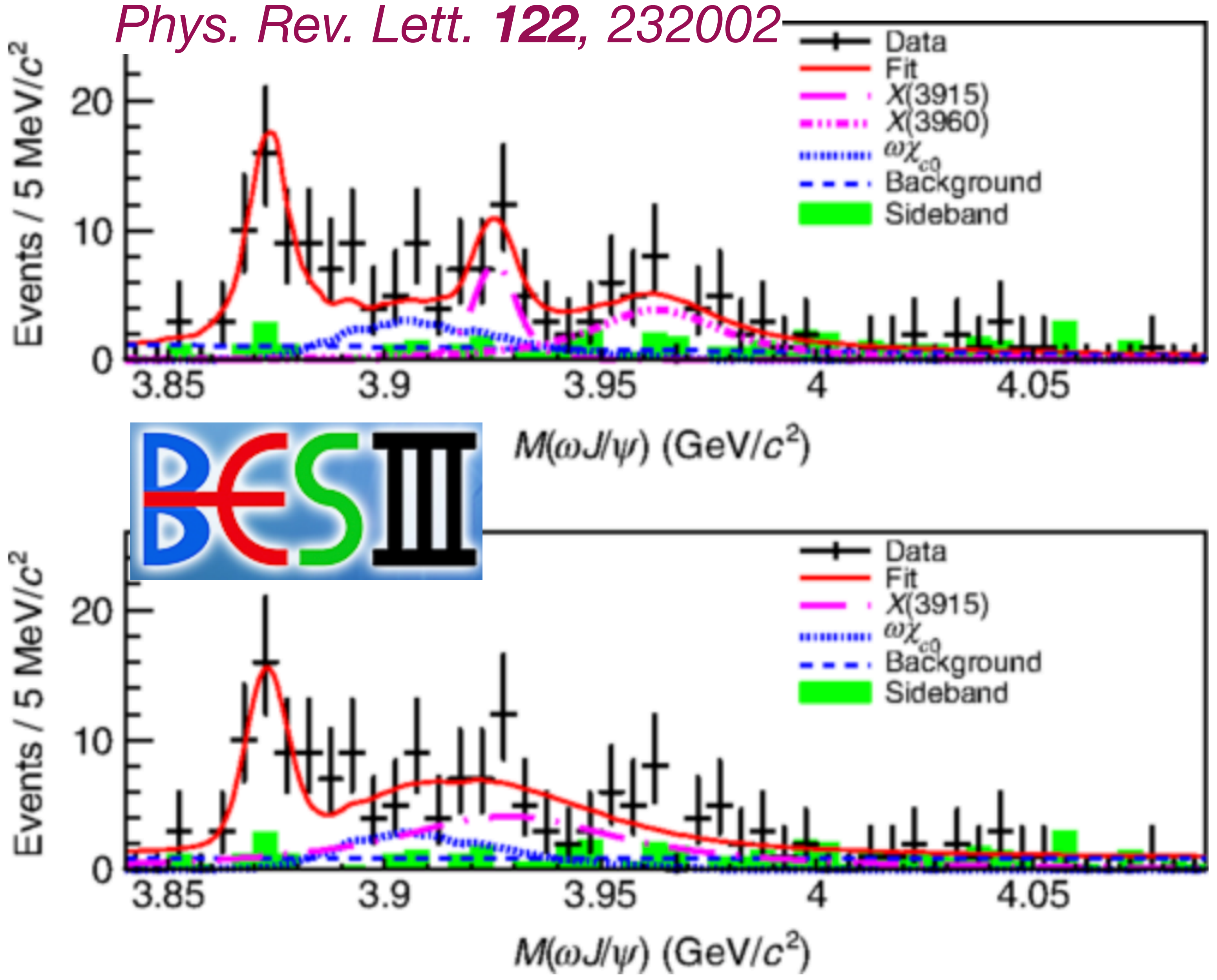
Accumulate ~500/fb $\Upsilon(4S)$ data before long shutdown in summer 2022.

May not bring a significant change to the arena, but Belle + Belle II data may at least clarify some puzzles, e.g.





Phys. Rev. Lett. ***122****, 232002*



An external resonance beside $X(3872)$ on $M(\omega J/\psi)$. Is this same one in $\gamma\gamma \to X(3915) \to \omega J/\psi$?

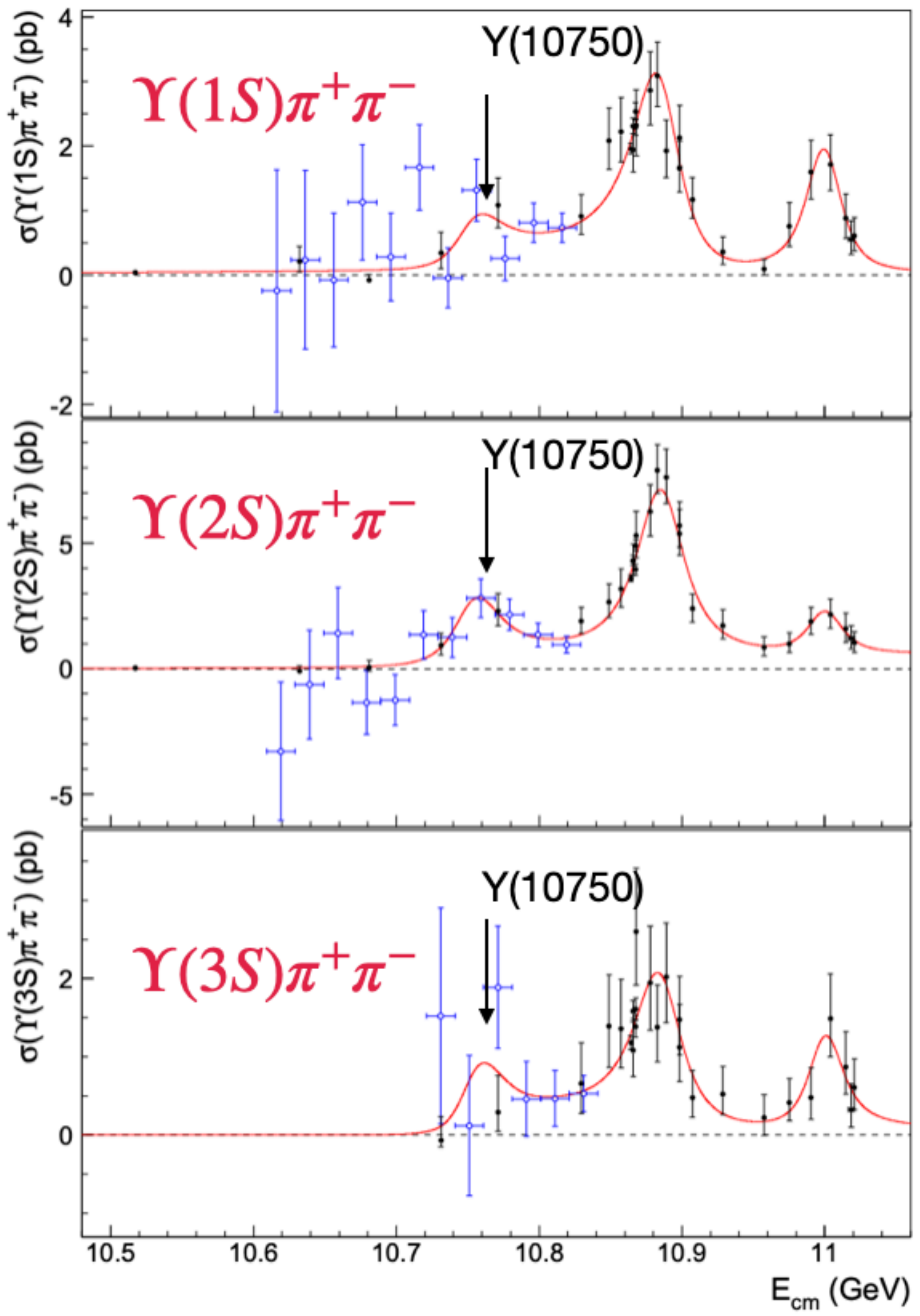
Prospect

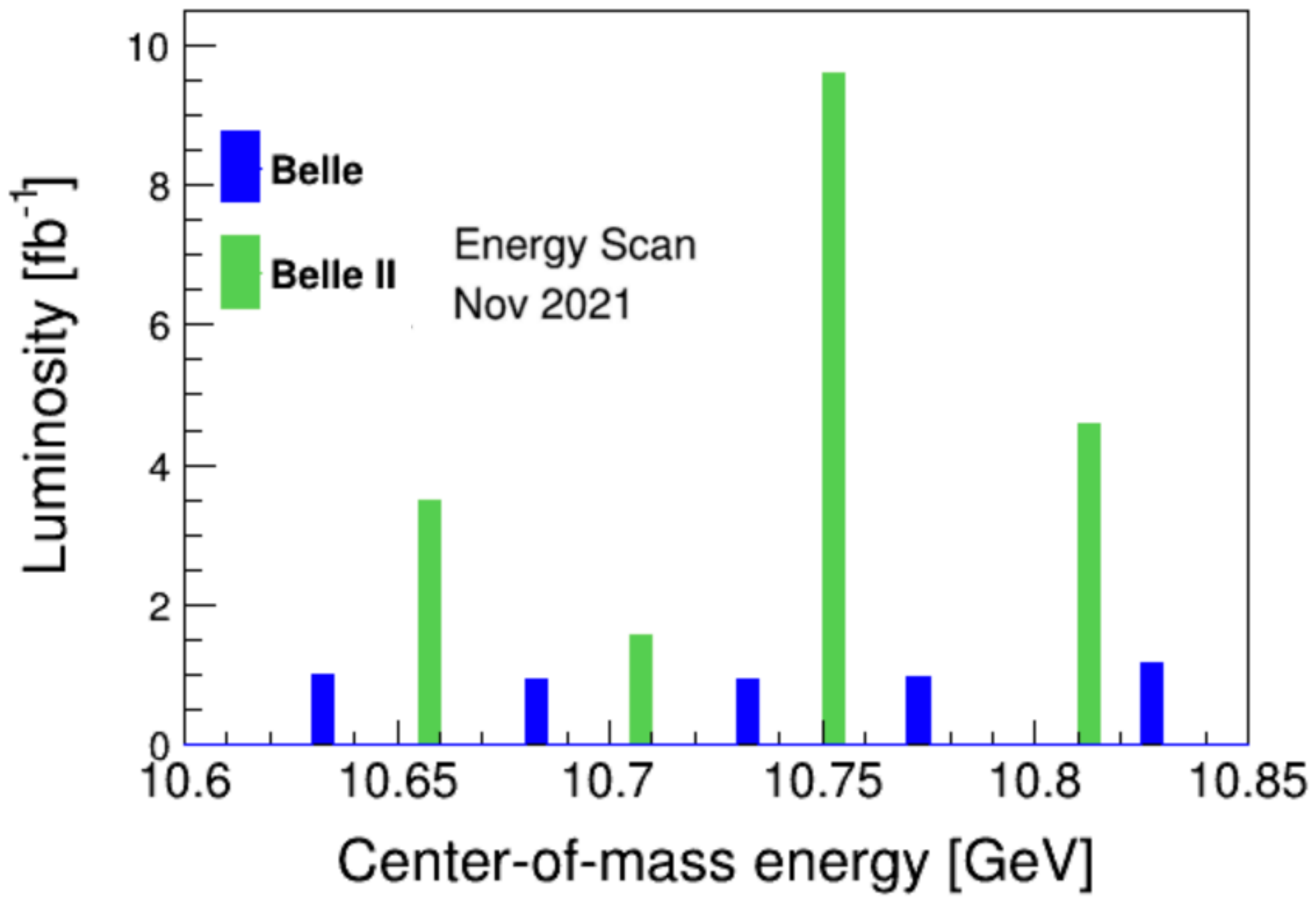
In short term

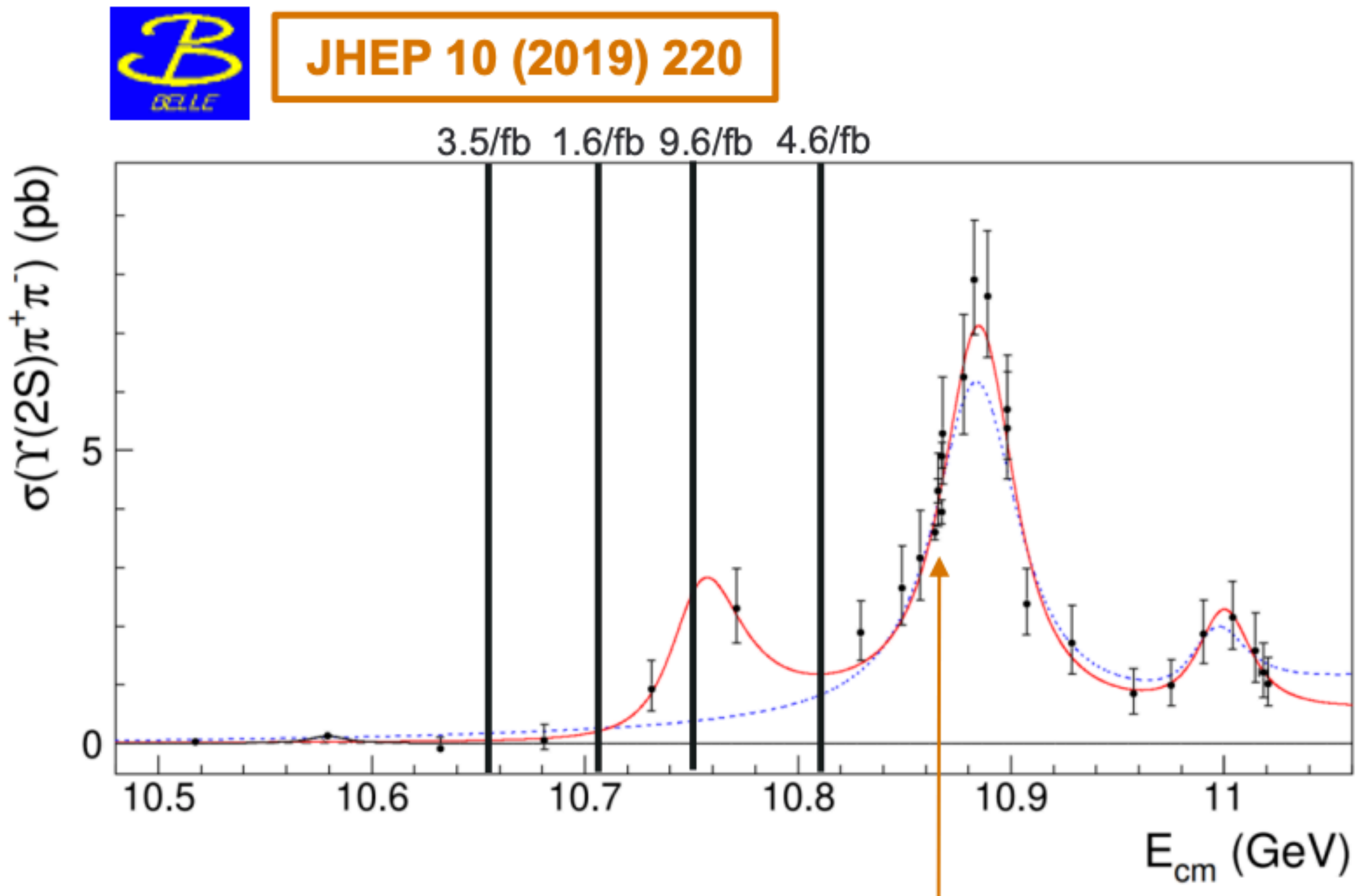
Scan data samples with 1 fb^{-1} at each point on Belle

A little data may tell a big story

JHEP 1910, 220 (2019)







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

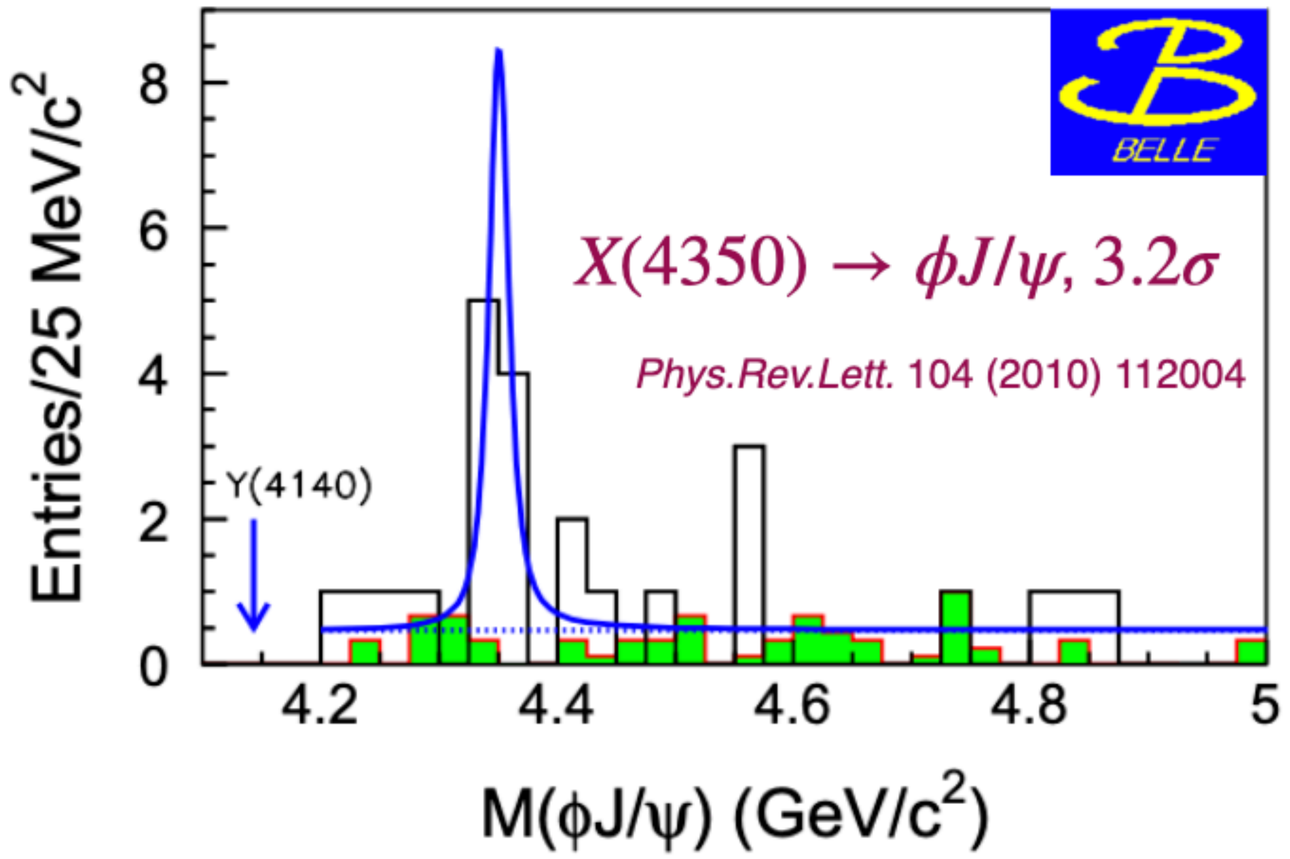
- Data collected at 4 energy points around 10.75 GeV
- Physics goal: understand the nature of $Y(10750)$ energy region
- Potential: $e^+e^- \to \pi\pi\Upsilon(nS)$, $\omega\chi_{bJ}$, $B^{(*)}\bar{B}^{(*)}$, γX_b, etc.

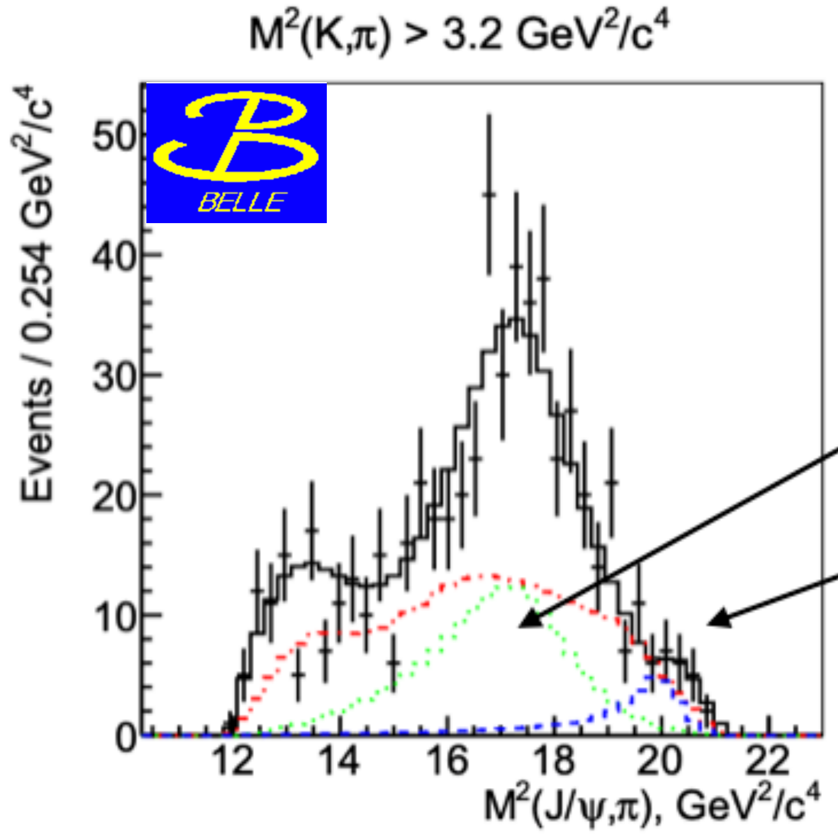
Coming soon!

Prospect

With $10\ \mathrm{ab}^{-1}$

Evidence could be clarified, e.g.





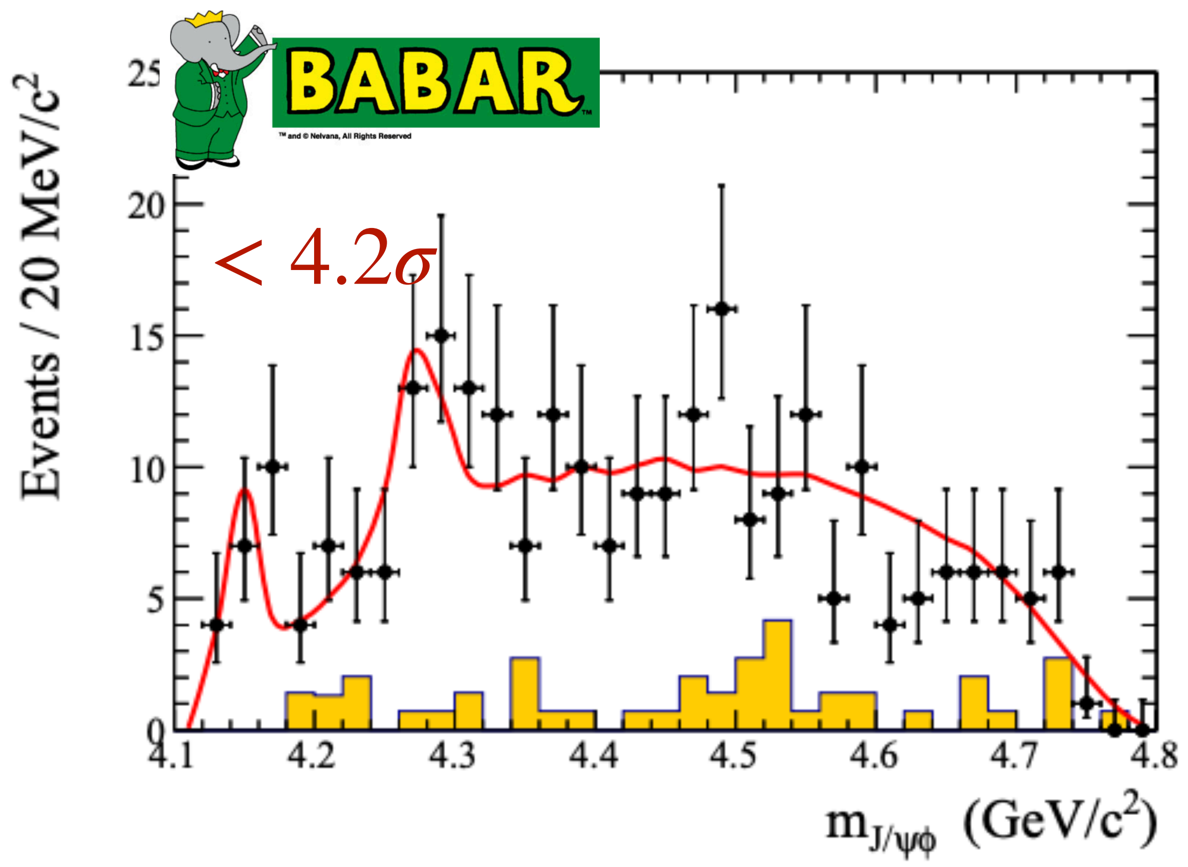
$Z_c(4200)$ and $Z_c(4430)$ in $B \to K\pi^- J/\psi$

6.2σ

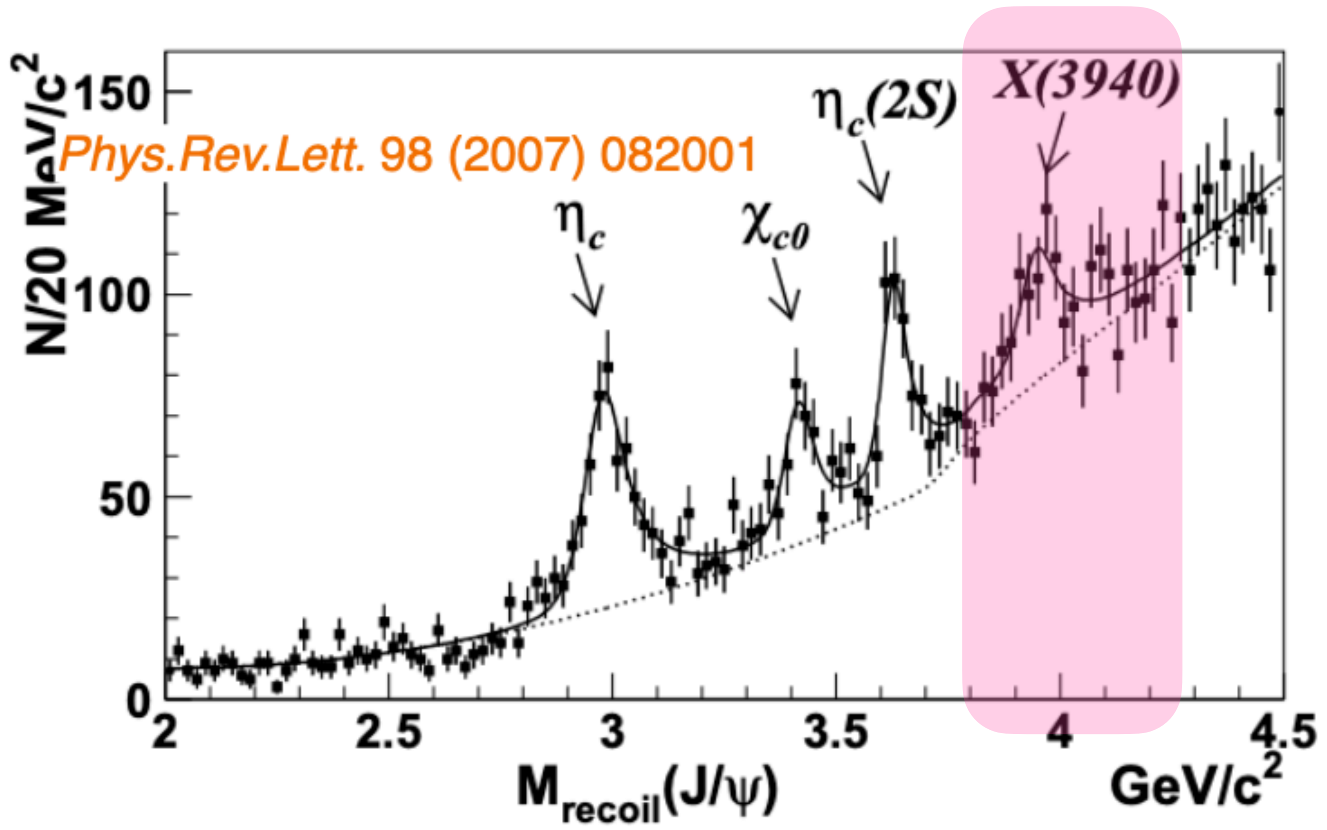
$> 3\sigma$

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

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



Properties measurements with dedicated analysis



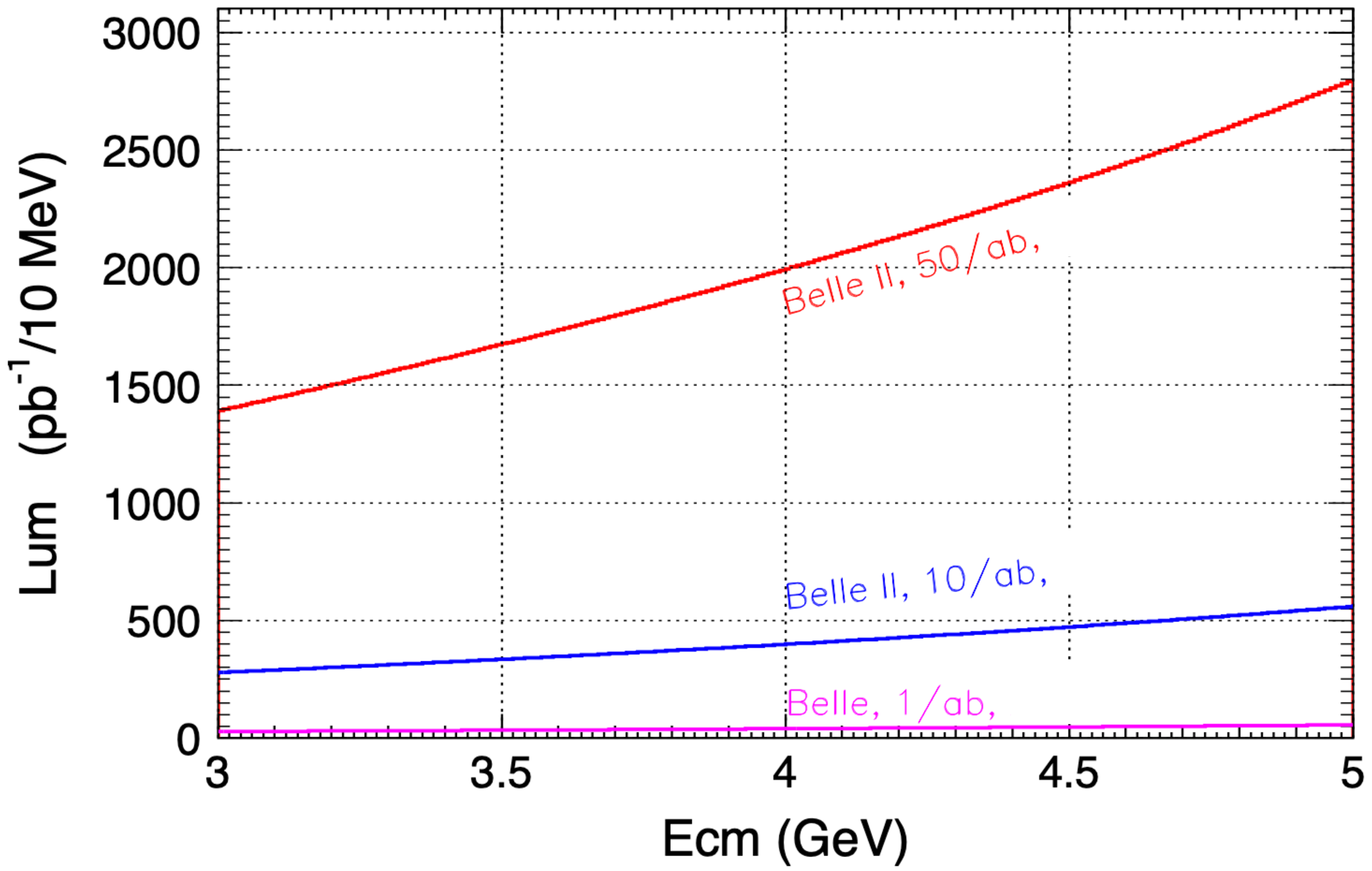
$X(3940)$ $\quad I^G(J^{PC}) = ?^?(?^{??})$

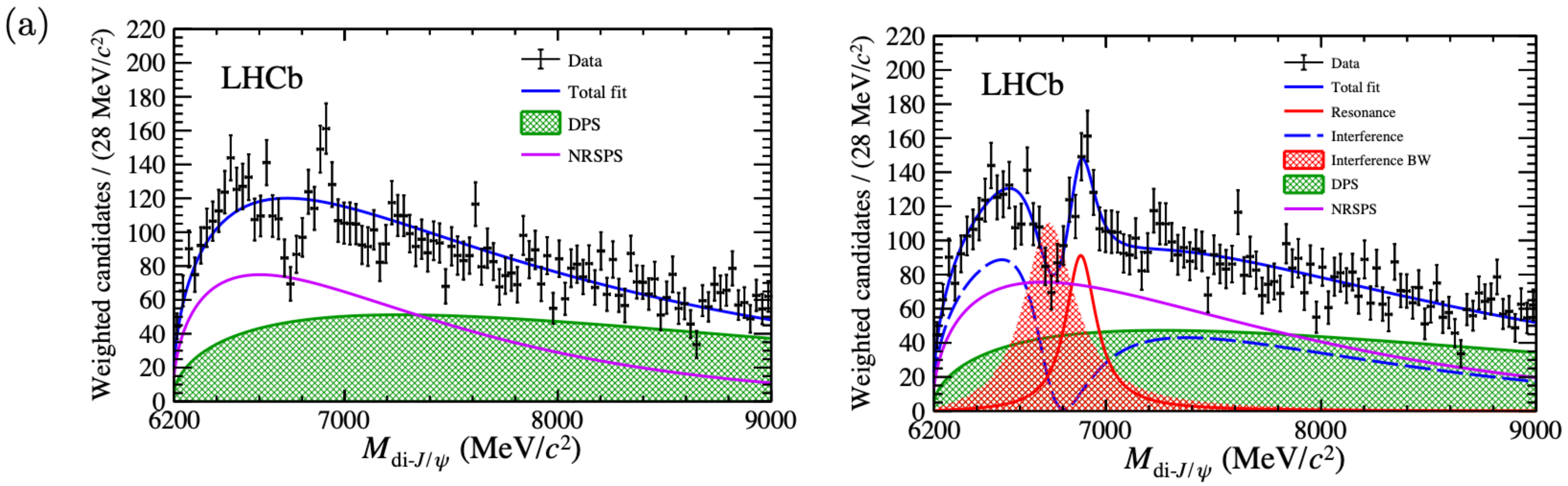
Quantum number of $X(3940)$ remains unknown.

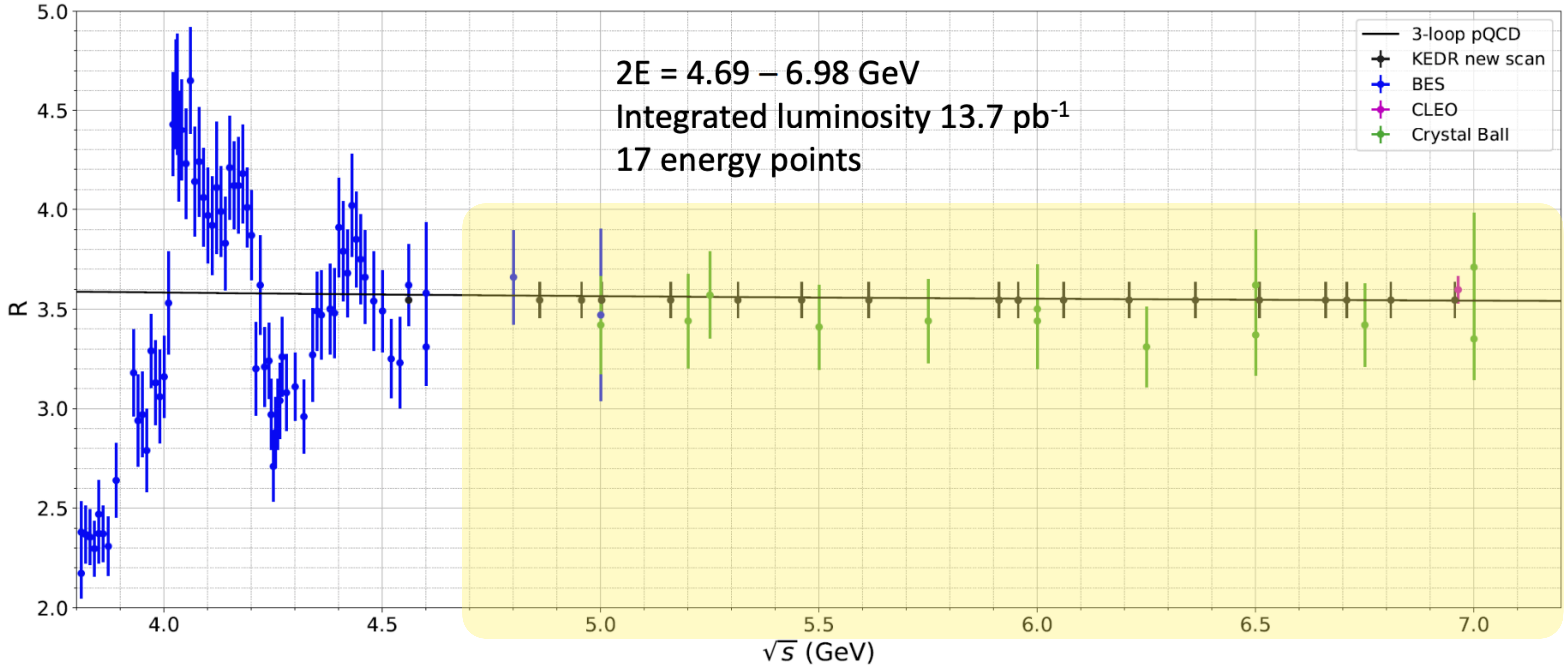
Prospect

With $50\ \mathrm{ab}^{-1}$

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. $D^0\bar{D}^{*0}$. (See more details in Sören's talk.)
  - 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

Summary

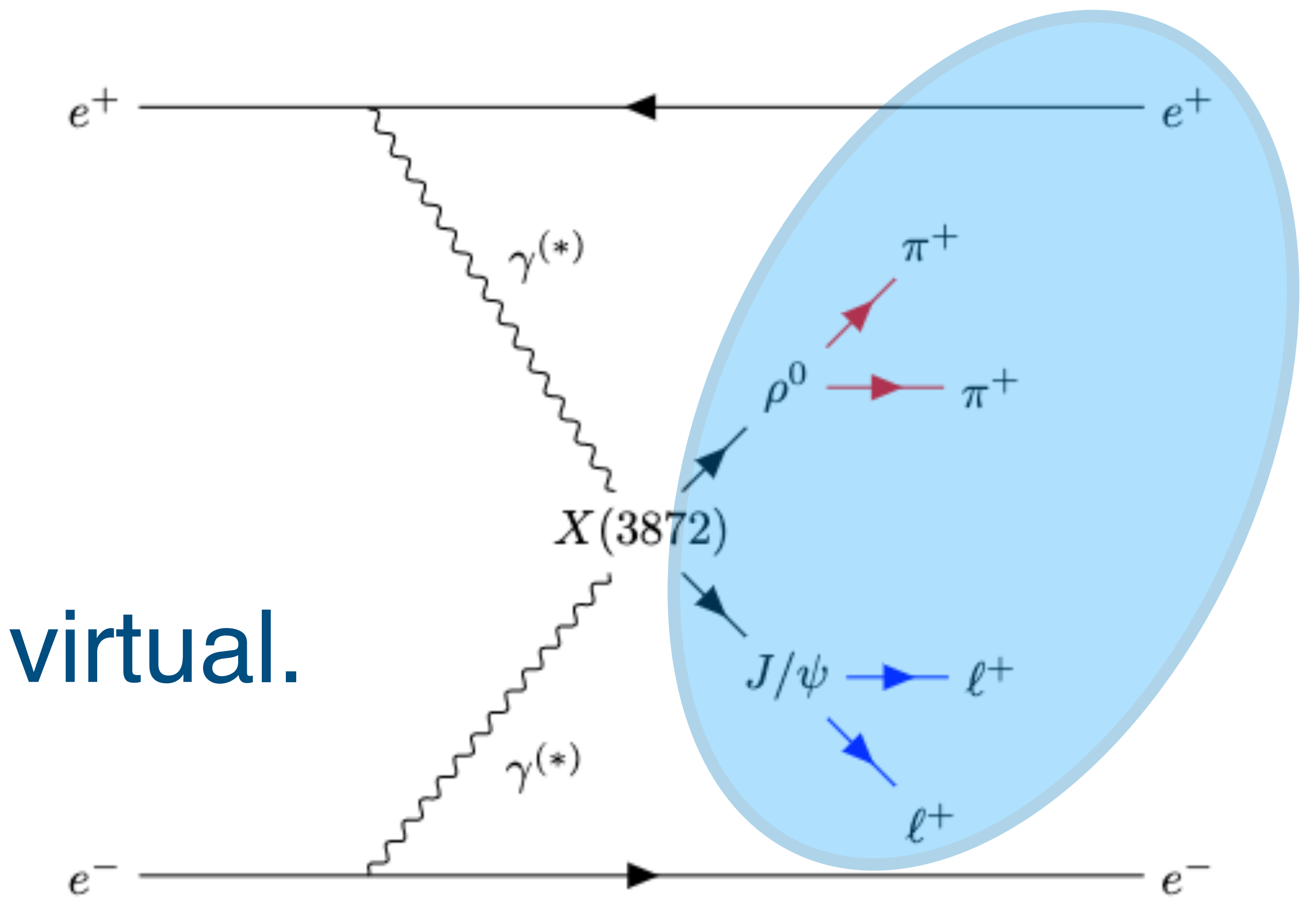
- Even a decade after data taking finished, the Belle experiment is producing interesting and important results.
- Belle II, the next generation B-factory, can make significant impacts in spectroscopy.
  - Precisely measure lineshapes.
  - Determine spin-parities, transitions, and quantum numbers.
  - 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

Outline

- Introduction
- Belle achievement
  - Quarkonium(-like) states
  - Baryons
- Belle II
  - What we have
  - Prospect
- Summary

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

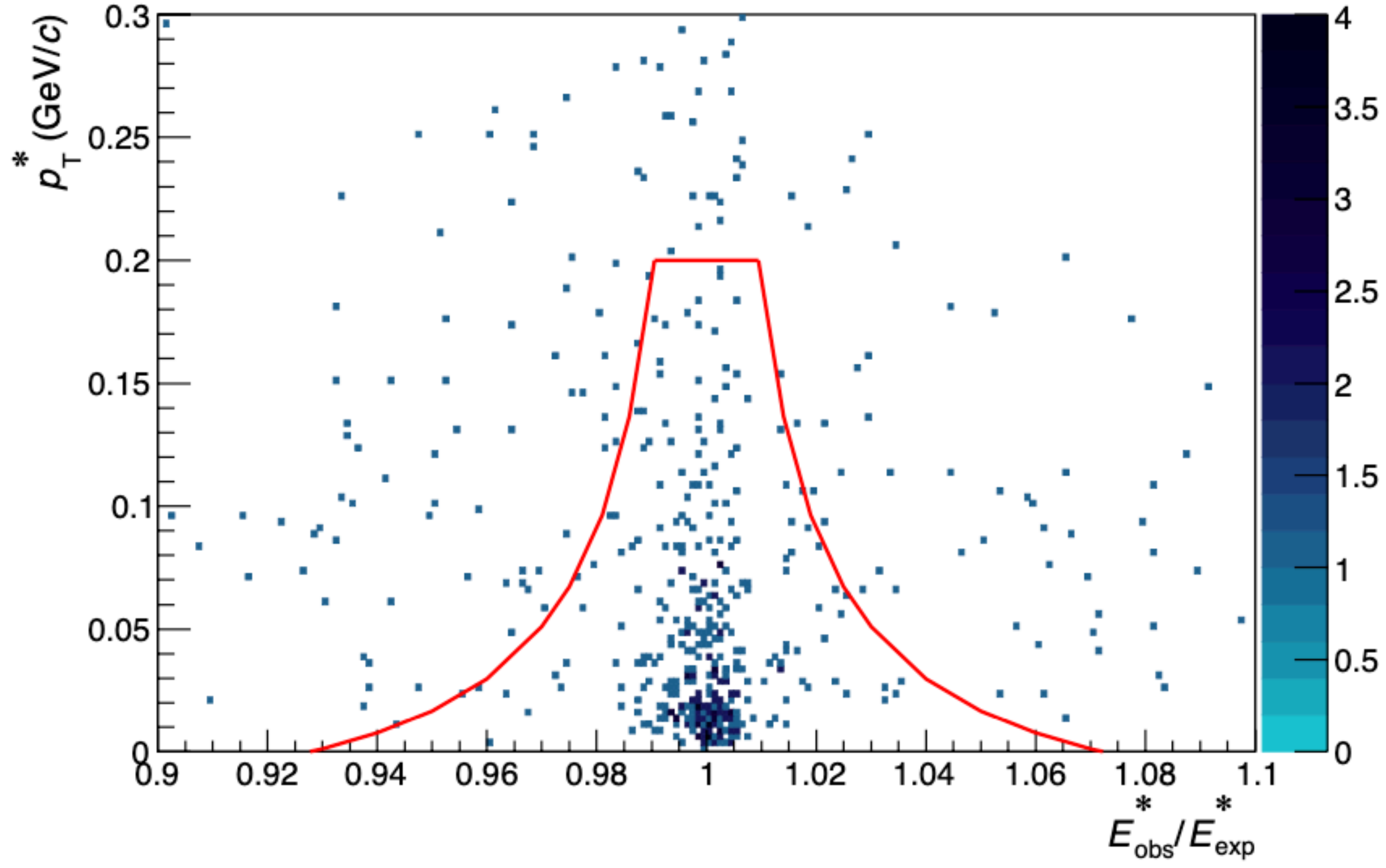


Axial-vector particles are forbidden to decay to two real photons.

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

reconstruction:

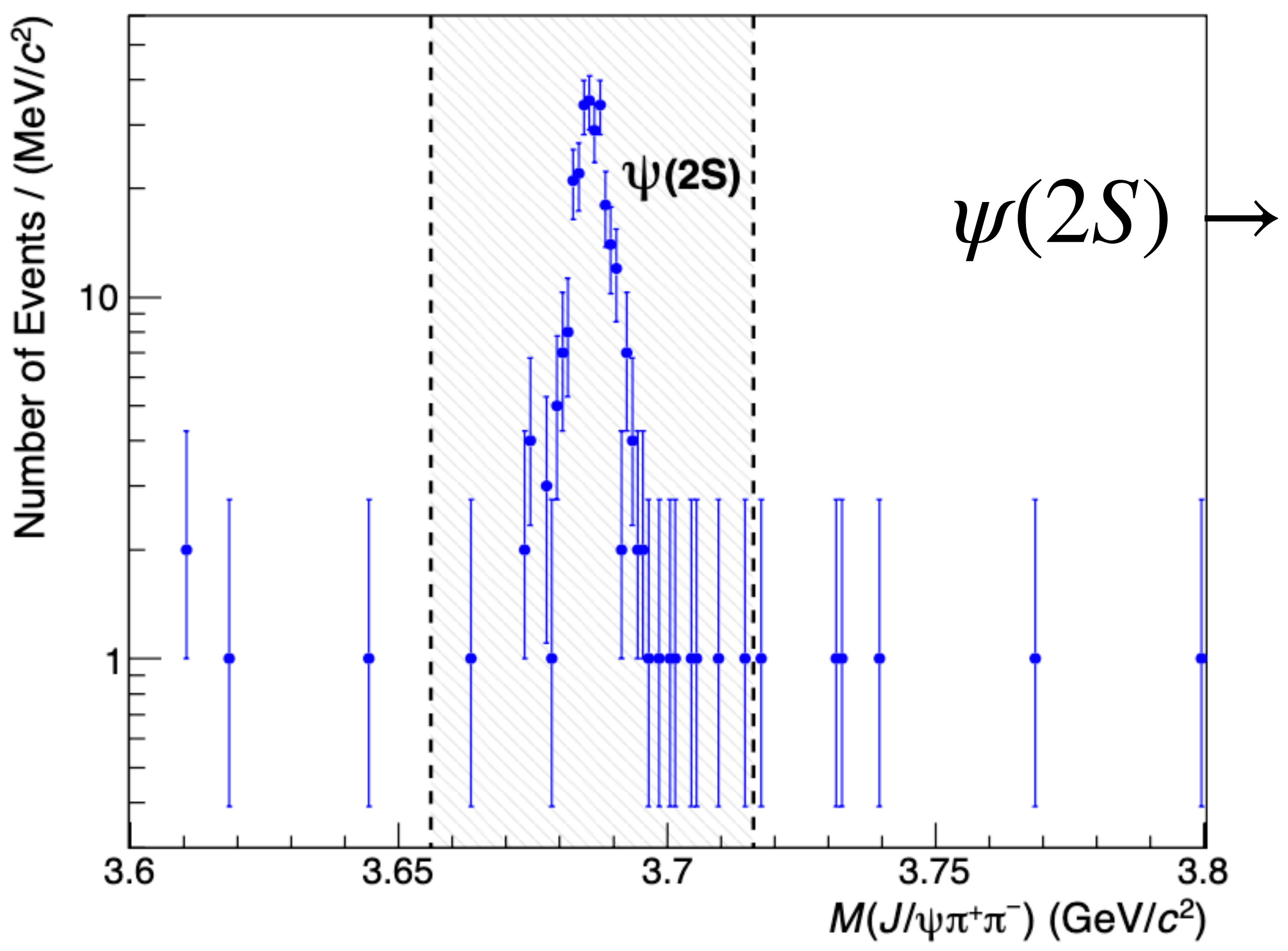
- $N(track) = 5$ with $\sum Q = \pm 1$
  - two pions, two leptons(e/μ)
  - one extra electron/positron (from beam)
  - No photon with $E > 0.4$ GeV or π^0
- $X(3872)$ & tagging electron: back to back
  - azimuthal angle difference within $(\pi \pm 0.1)$
- Visible transverse momentum < 0.2 GeV/c; measured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



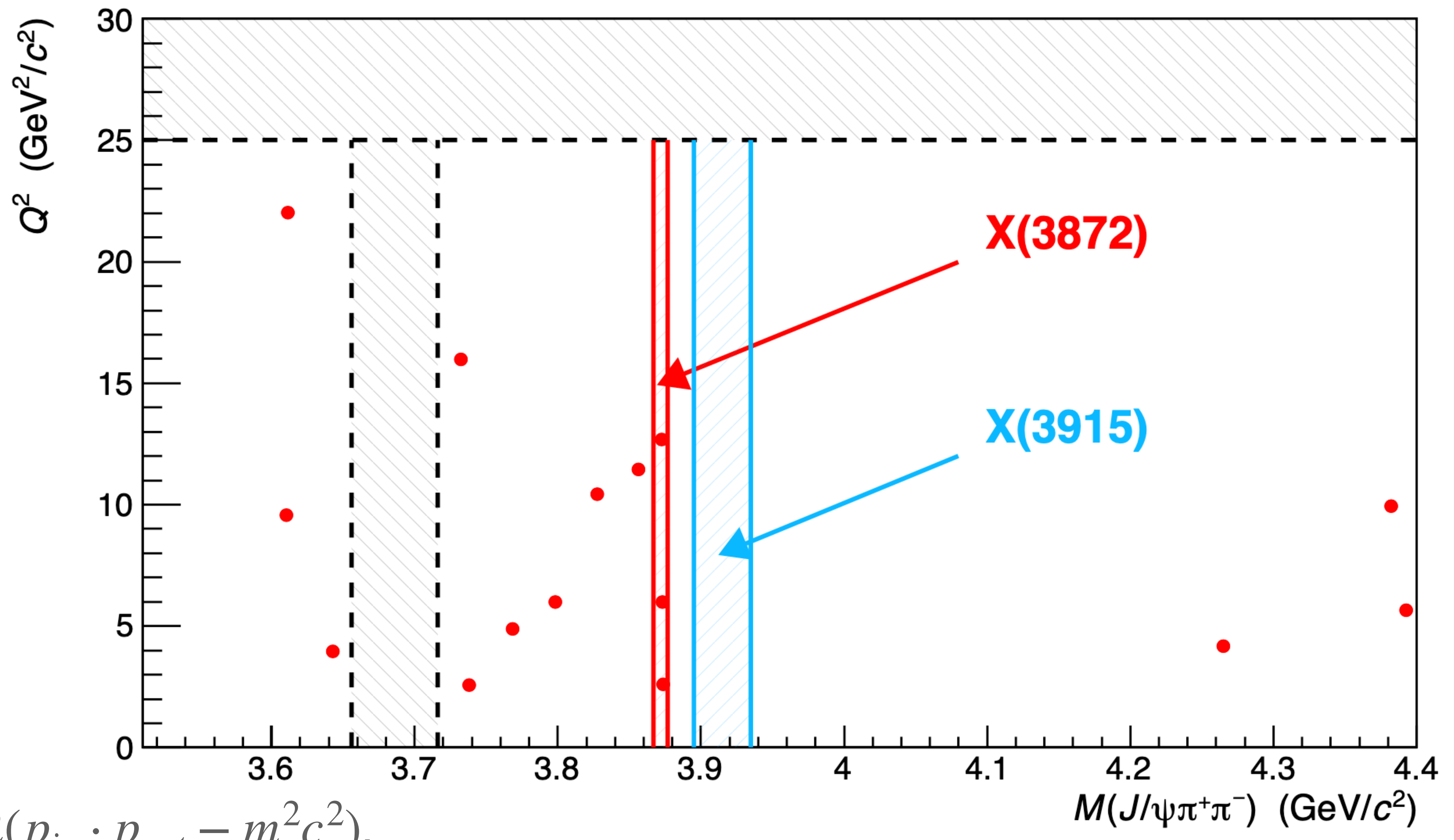
$$p_{z,\text{mis}} < -0.4 \text{ GeV}/c^2 \text{ for } e^-\text{tag}$$

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

Dominate background



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

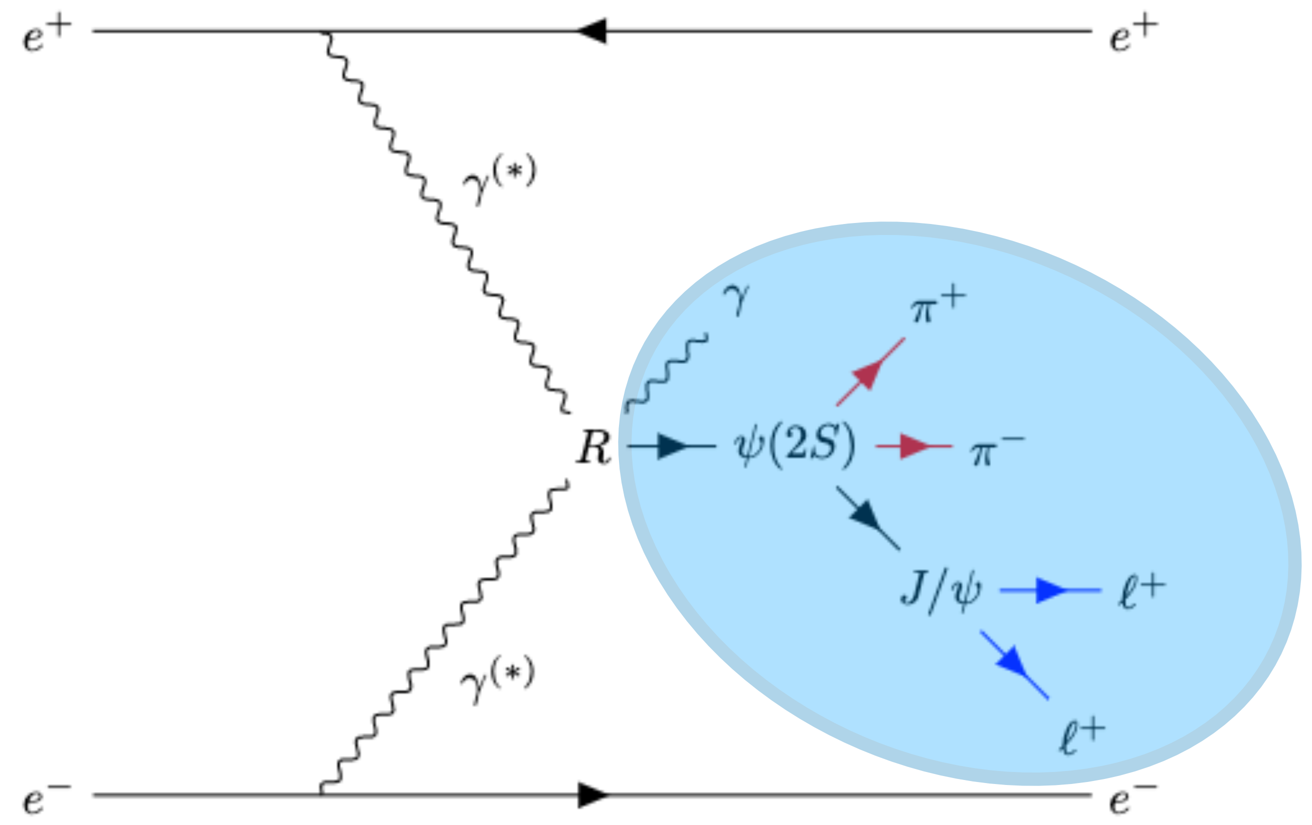
Three events are found in the signal region, with a significance of 3.2σ considering the background.

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

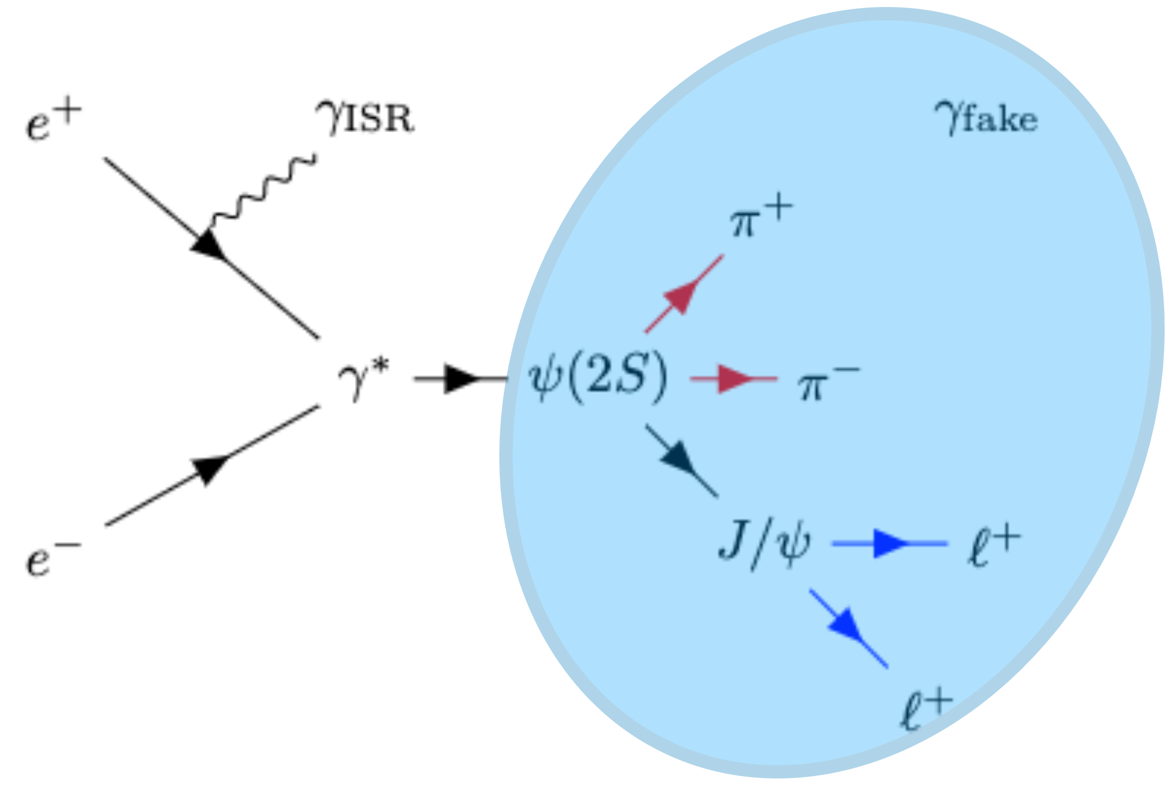
Exotic candidates in $\gamma\gamma \to \gamma\psi(2S)$

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

Signal process



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

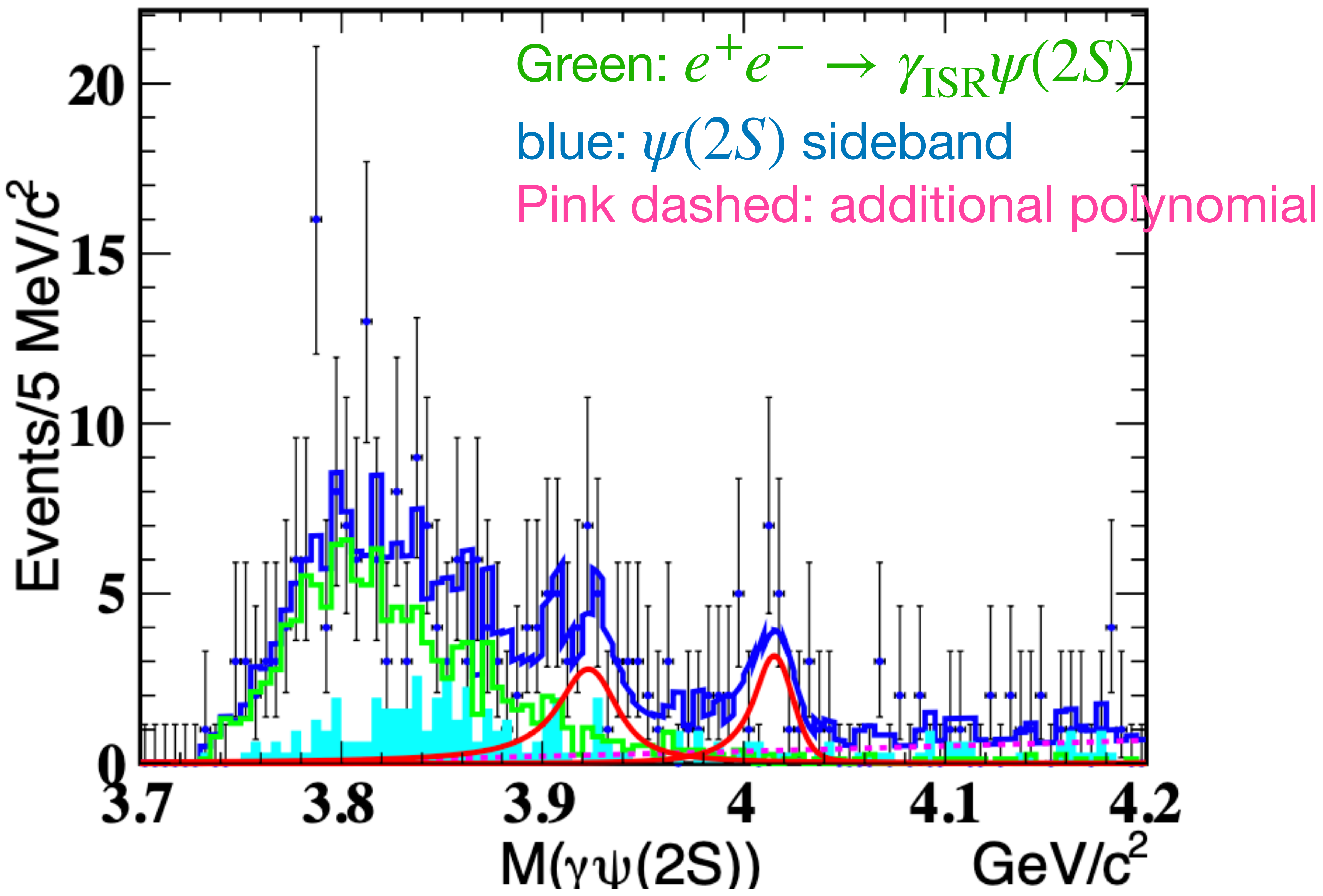


reconstruction:

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



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?

$D^*\bar{D}^*$ - - - R_2(4014)? - - - - - - - -

4000

χ_{c0}(3930): $B^+ \to D^+D^-K^+$ χ_{c2}(3930): $\gamma\gamma \to D\bar{D}$

R_1(3921) =? X(3915): $\gamma\gamma \to \omega J/\psi$, not seen in $D\bar{D}$

3900

$D^*\bar{D}$ - - - X(3872) - - - - - - - -

X*(3860): $e^+e^- \to J/\psi D\bar{D}$, not seen by LHCb

3800

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. $$\frac{\Gamma(\Upsilon(5S) \to h_b(1P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)} = 0.46 \pm 0.08^{+0.07}_{-0.12} \qquad \frac{\Gamma(\Upsilon(5S) \to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.77 \pm 0.08^{+0.22}_{-0.17}$$

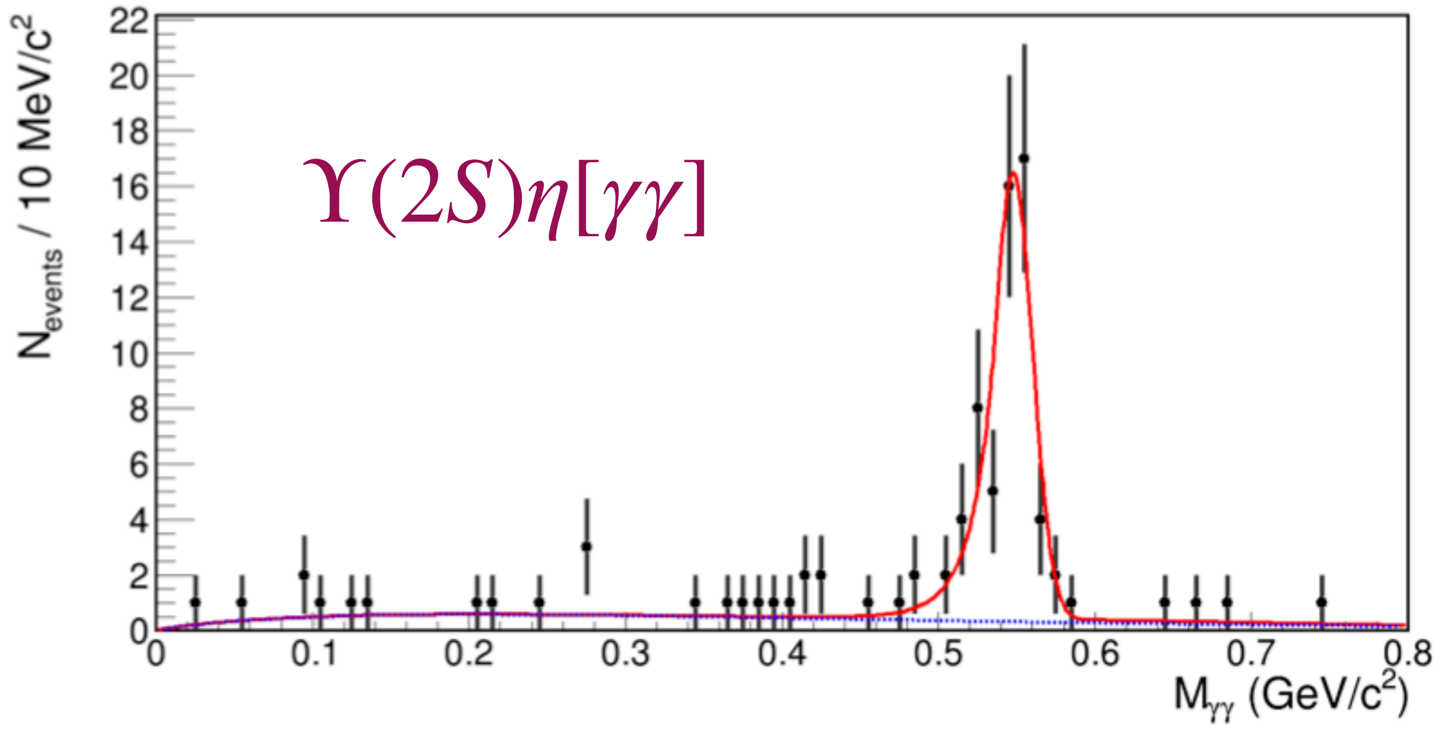
Prediction: $\mathcal{O}(10^{-2})$

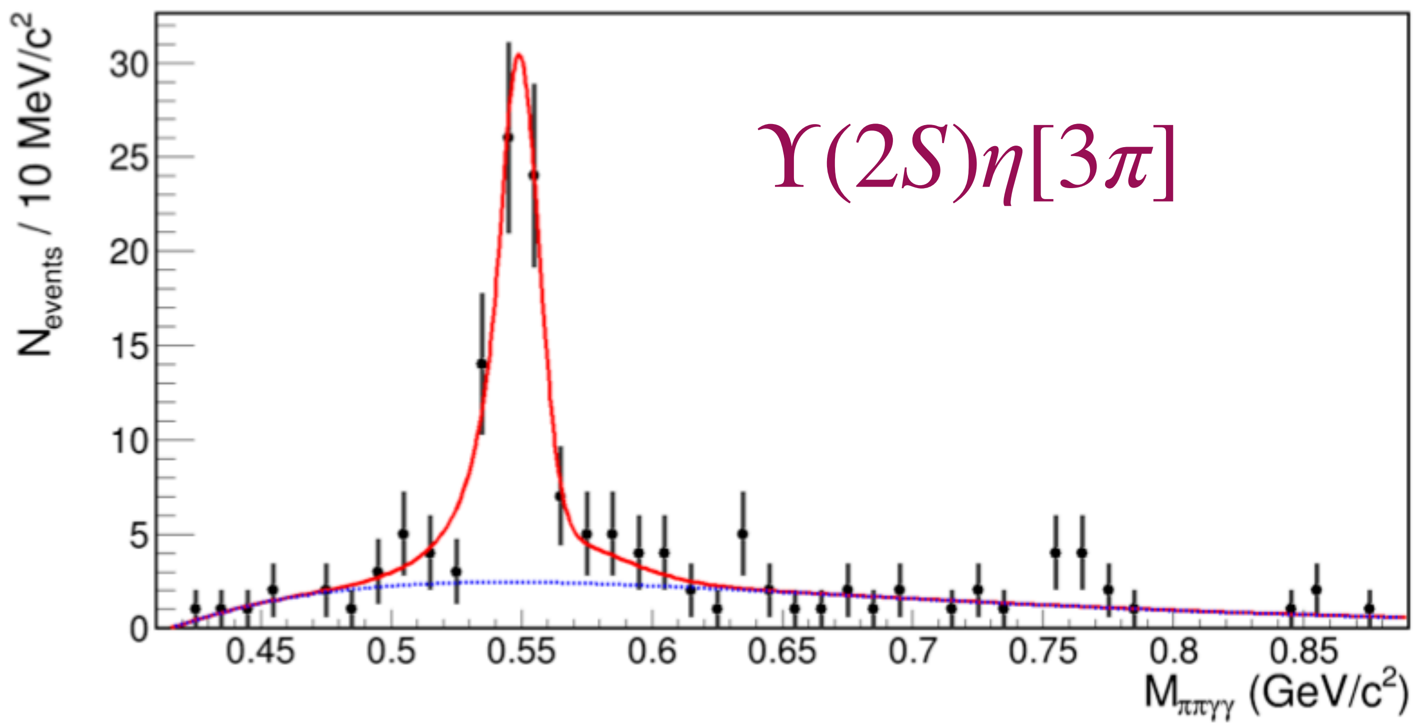
Analysis of similar processes is crucial for better understanding of the quark structure of bottomonium states above $B\bar{B}$ threshold.

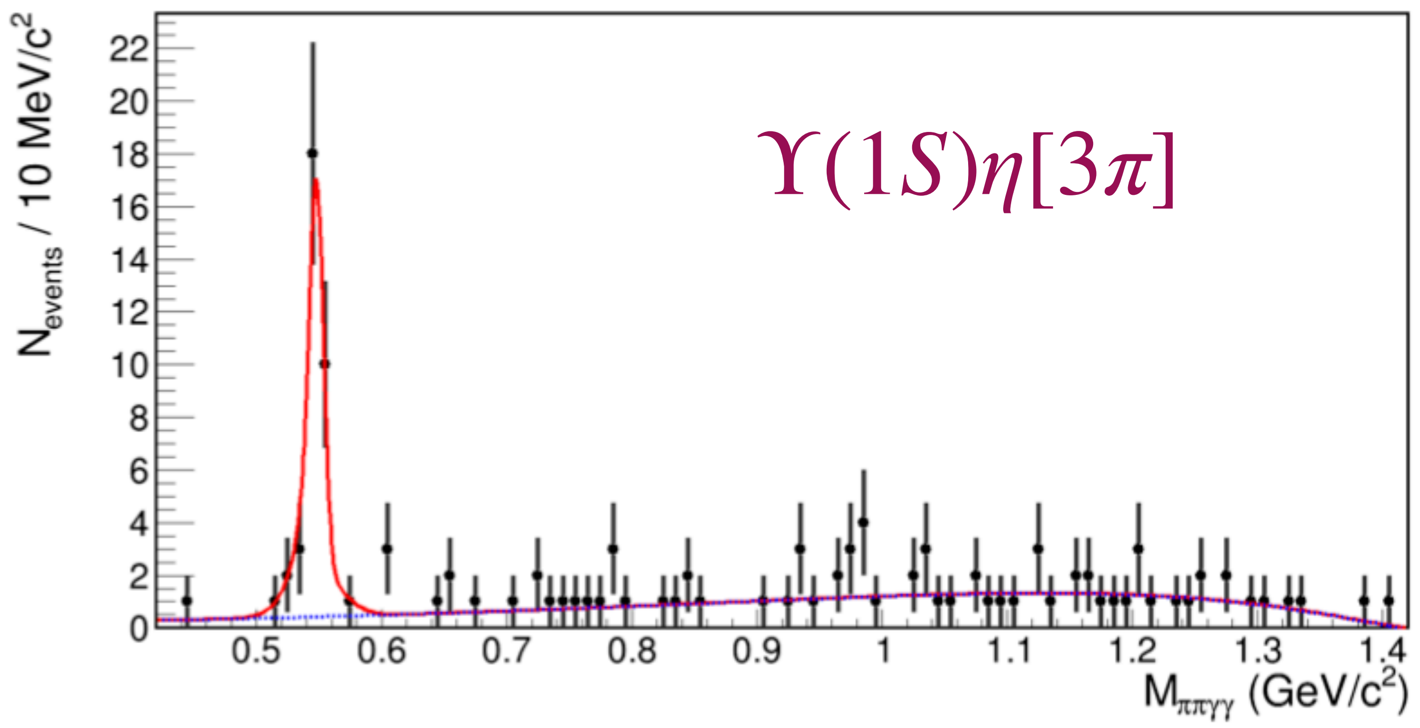
reconstruction:

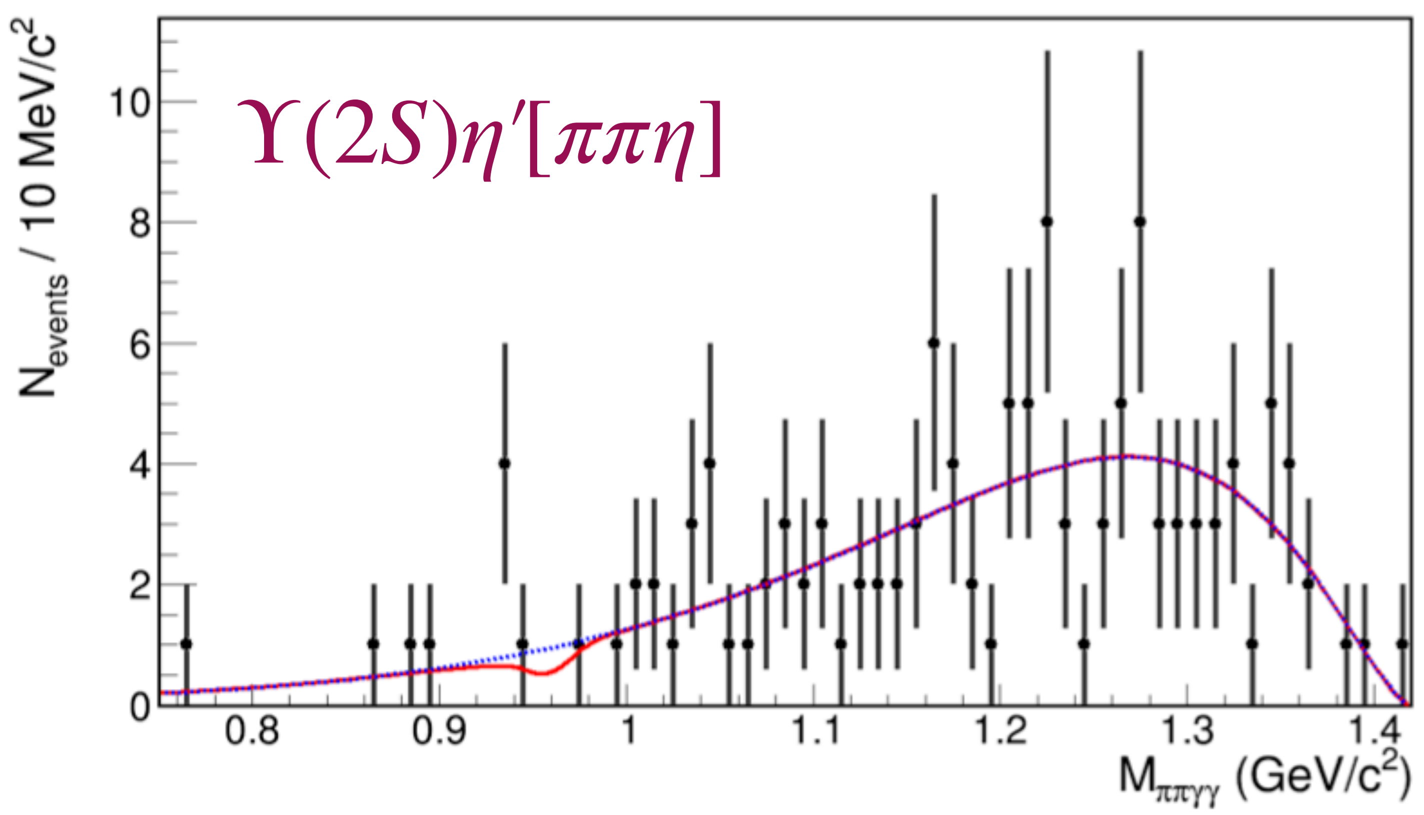
- Final states $\pi^+\pi^-\mu^+\mu^-\gamma(\gamma)$: $\Upsilon(2S)\eta[3\pi]$, $\Upsilon(2S)\eta[\gamma\gamma]$, $\Upsilon(1S)\eta[3\pi]$, $\Upsilon(1S)\eta'[\pi\pi\eta]$, $\Upsilon(1S)\eta'[\gamma\rho]$
- For $\eta \to \gamma\gamma$
  - $\Upsilon(2S)$ reconstructed with $\pi^+\pi^-J/\psi$
- For $\eta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

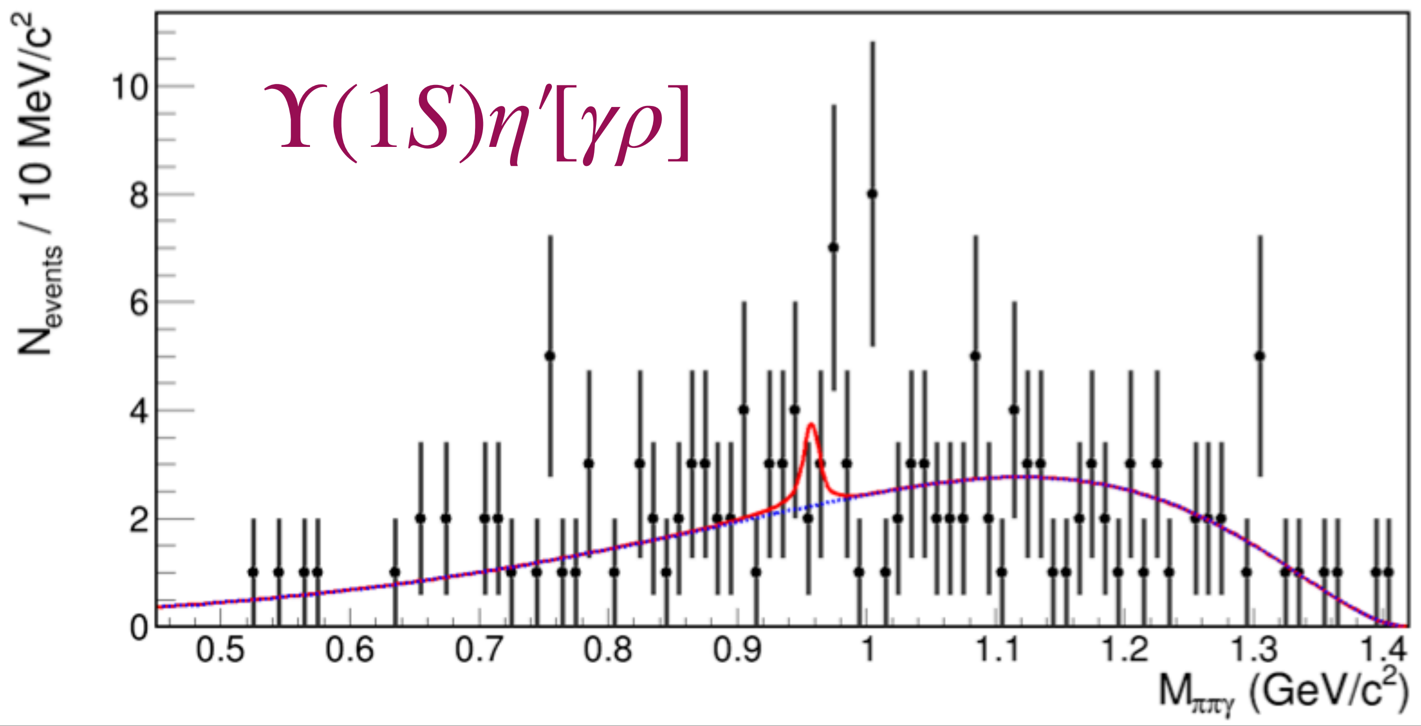
Data sample:
$118\ \mathrm{fb}^{-1}$ **at** $\Upsilon(5S)$
$21\ \mathrm{fb}^{-1}$ **energy scan in** $10.63 \sim 11.02\ \mathrm{GeV}$











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 $\Upsilon(5S)$:

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

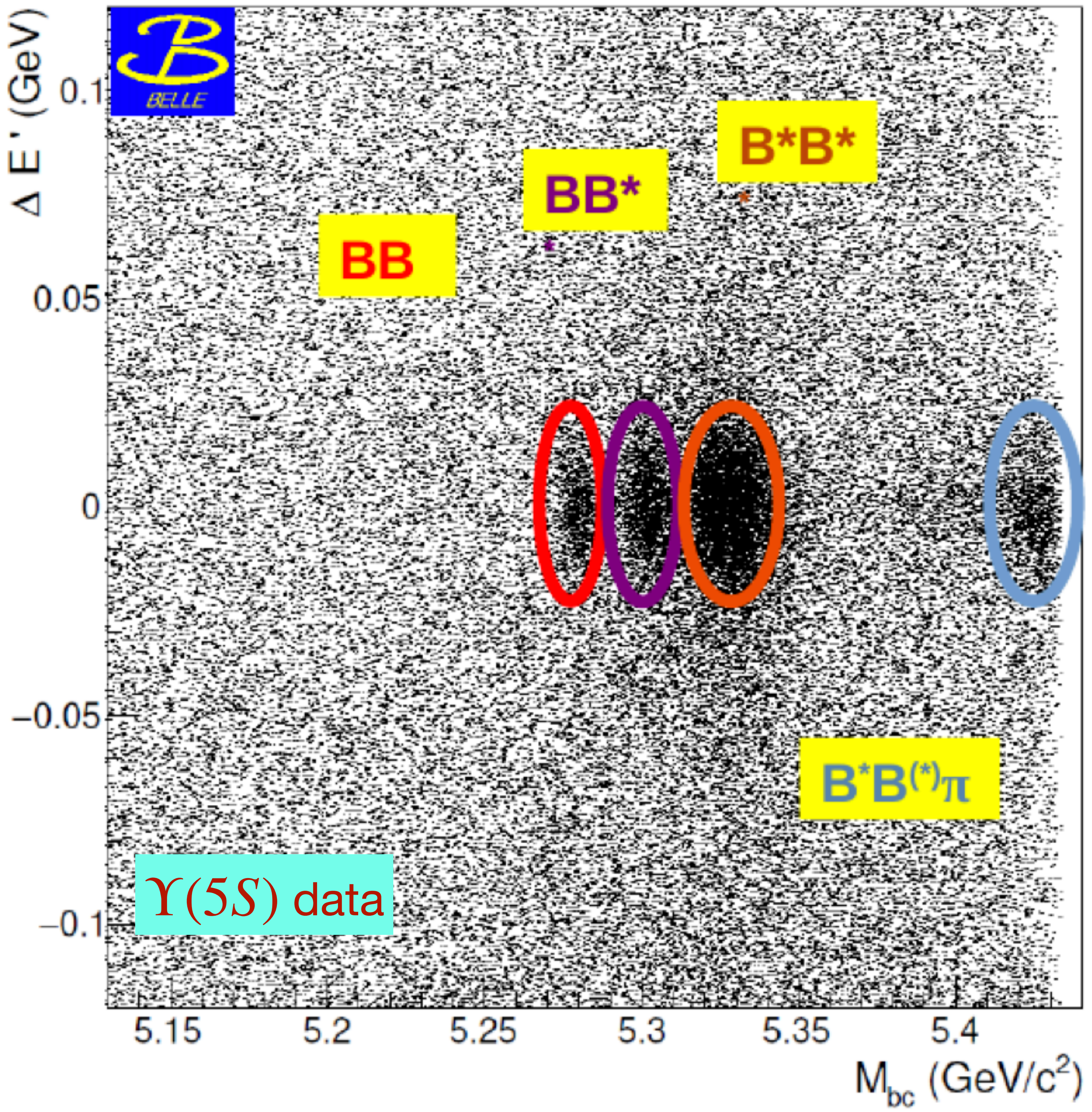
Corresponding fractions are:	Expected
$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)} = 0.52 \pm 0.06$ (stat.)	~ 0.03
$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\pi^+\pi^-)} = 0.18 \pm 0.03$ (stat.)	~ 0.005
$\frac{\Gamma(\Upsilon(5S)\to\Upsilon(1S)\eta')}{\Gamma(\Upsilon(5S)\to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

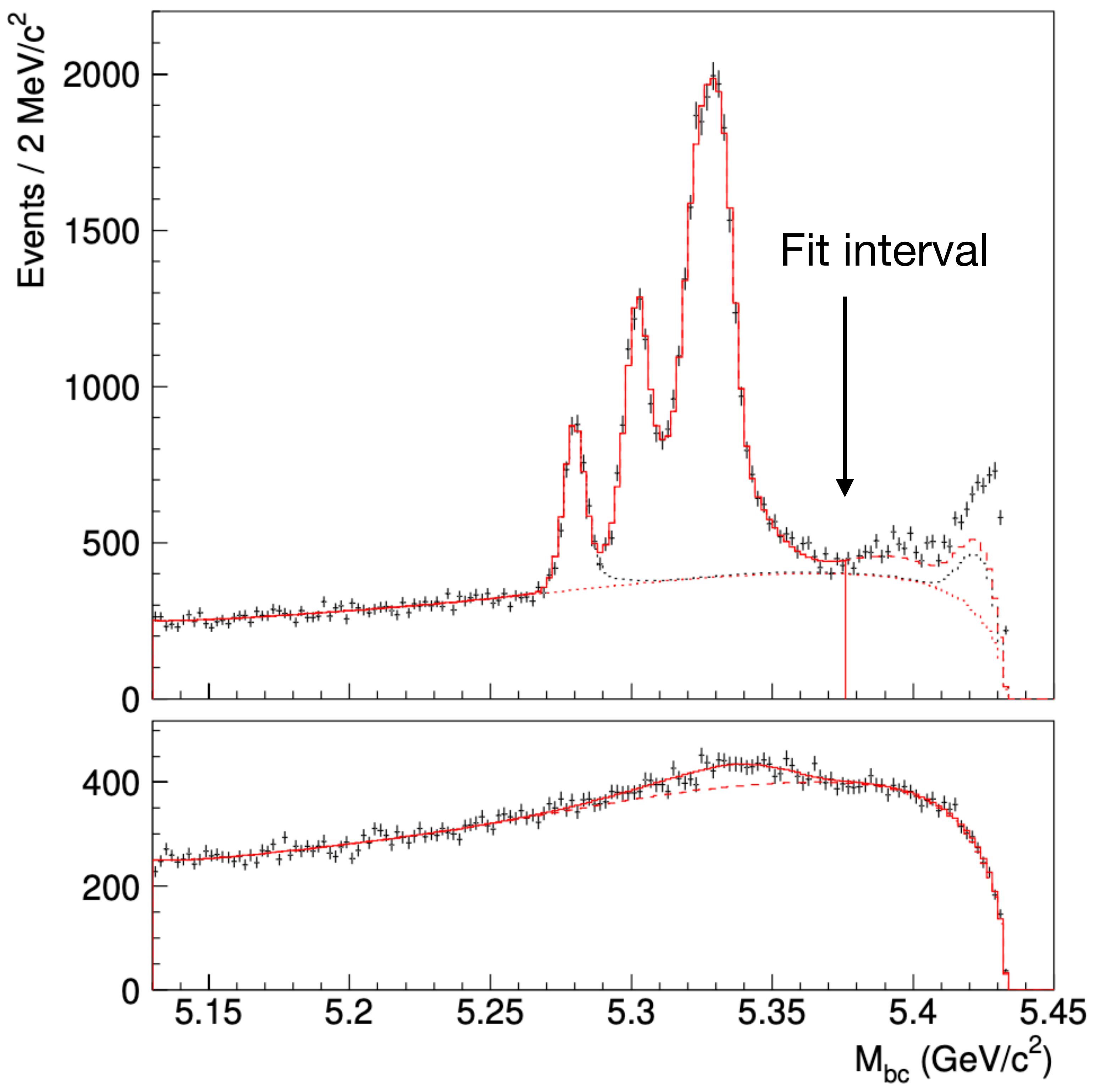


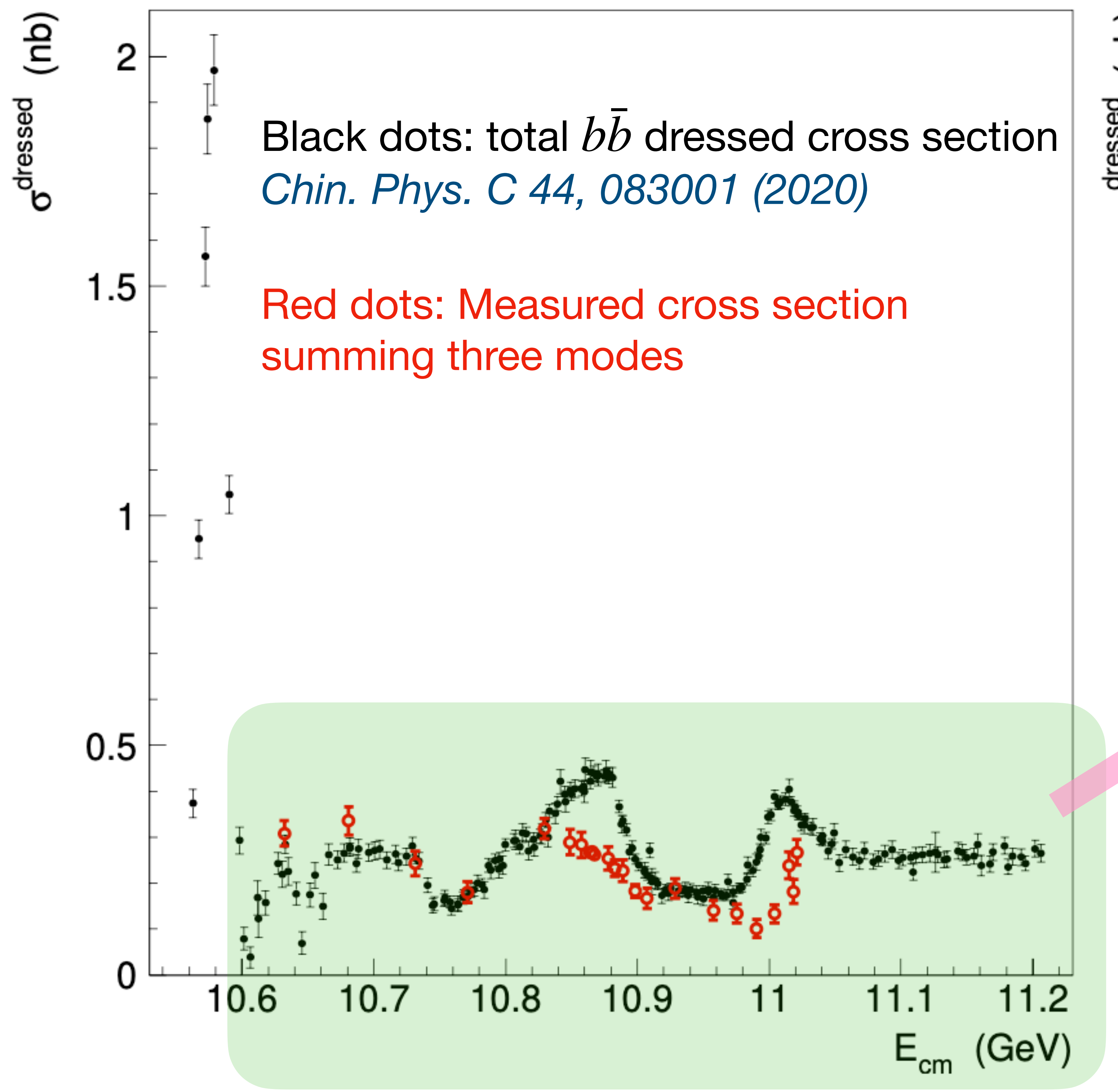
$$M_{bc} \equiv \sqrt{(E_{beam,CM})^2 - (p_{B,CM})^2}$$

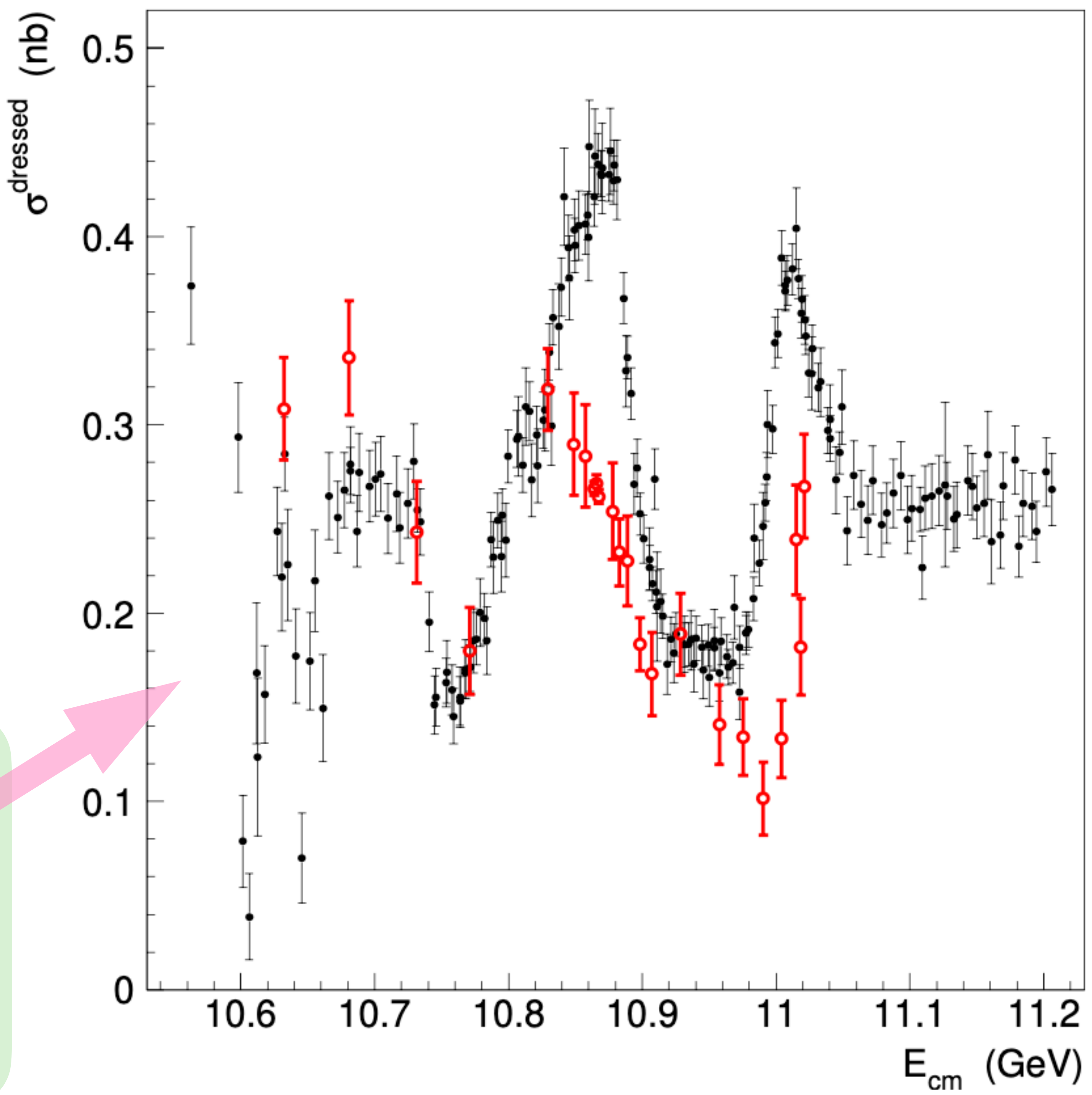
$$\Delta E' \equiv \Delta E - M_{bc} + M_B$$

where

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







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

- 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

- 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.

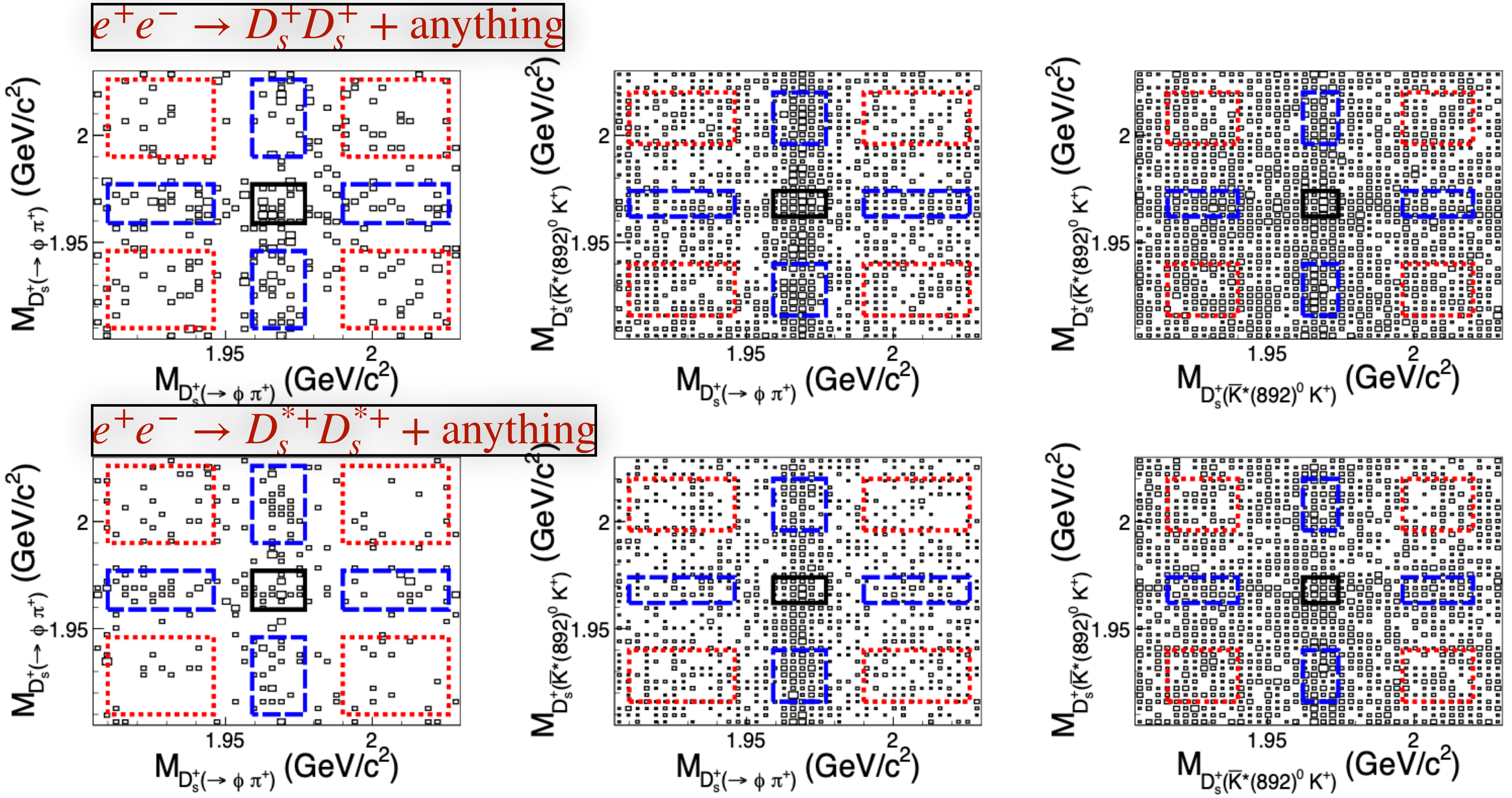
Search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_s^+D_s^+$, $D_s^{*+}D_s^{*+}$

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

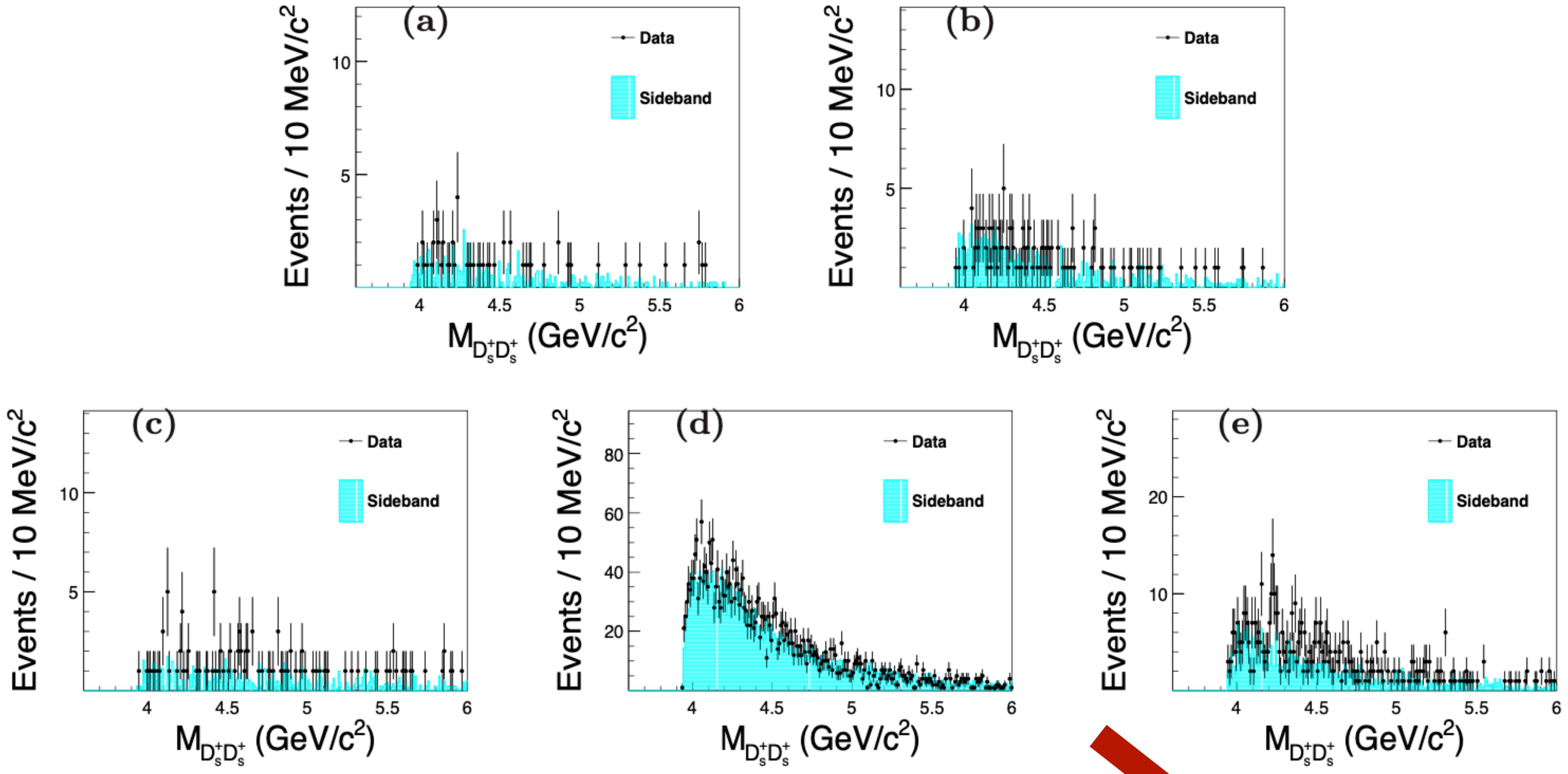


Use two modes to reconstruct D_s^+

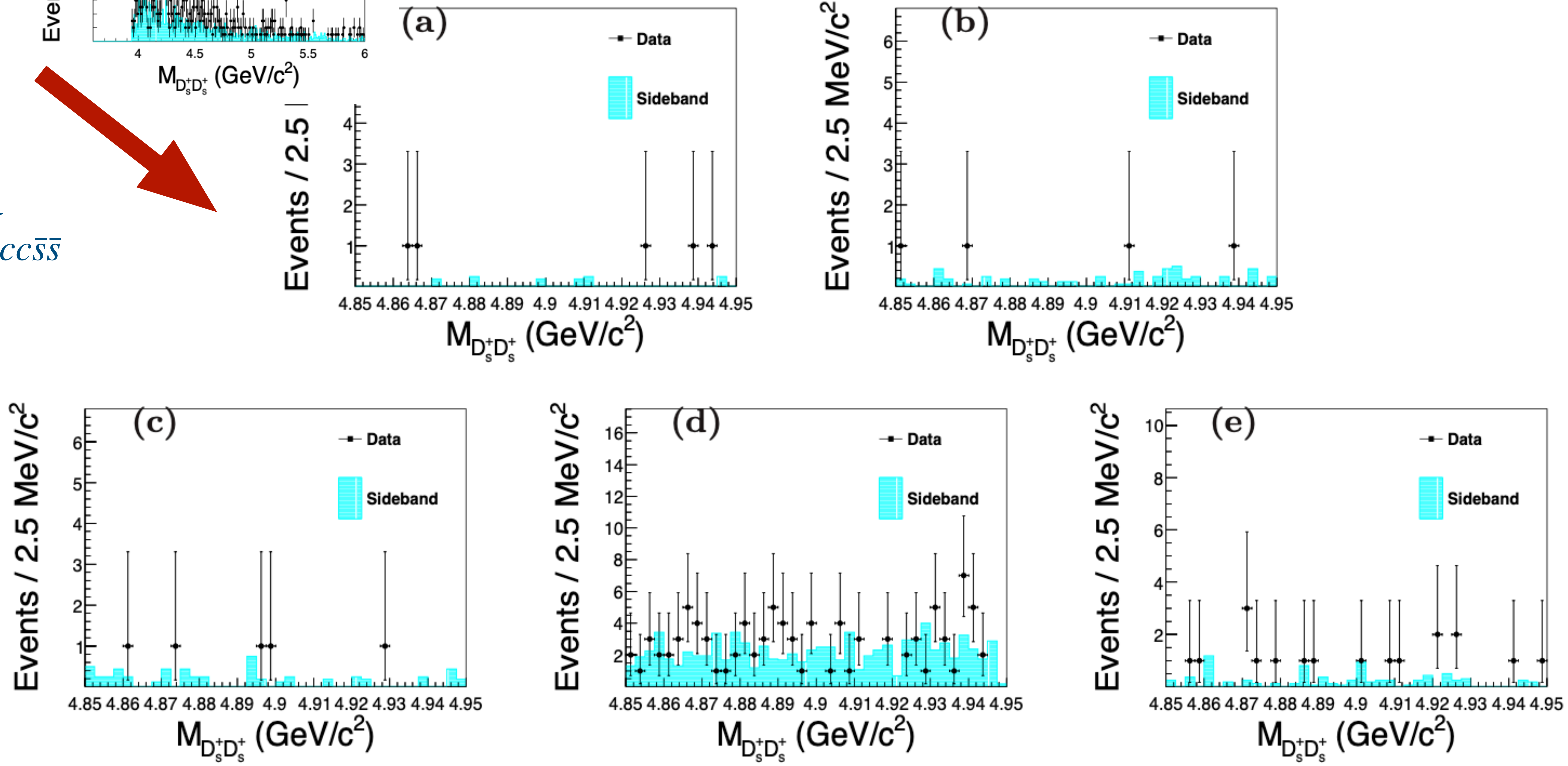
- $D_s^+ \to K^*(892)K^+$
- $D_s^+ \to \phi\pi^+$

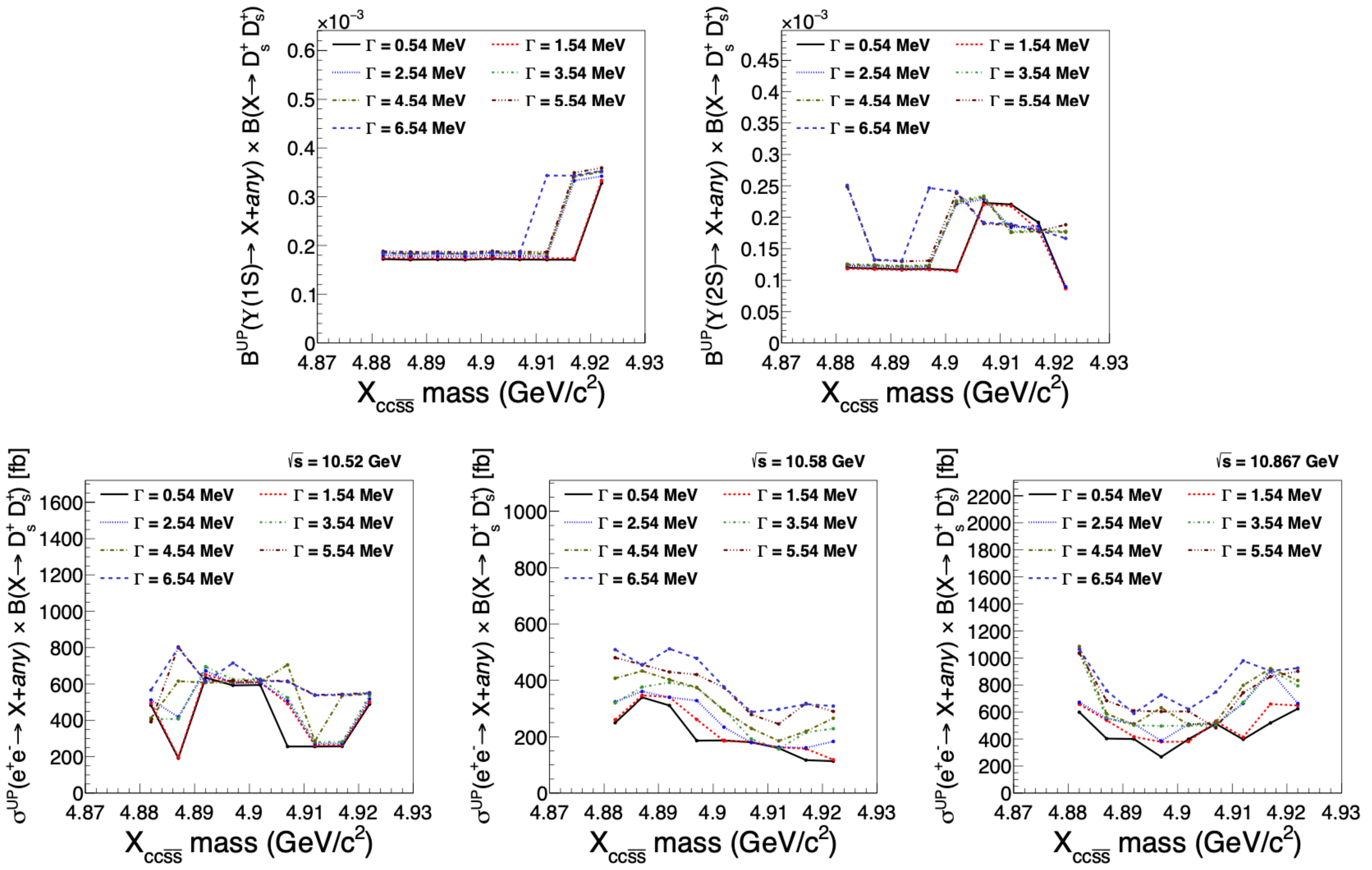
$e^+e^- \to D_s^+D_s^+ + \text{anything}$

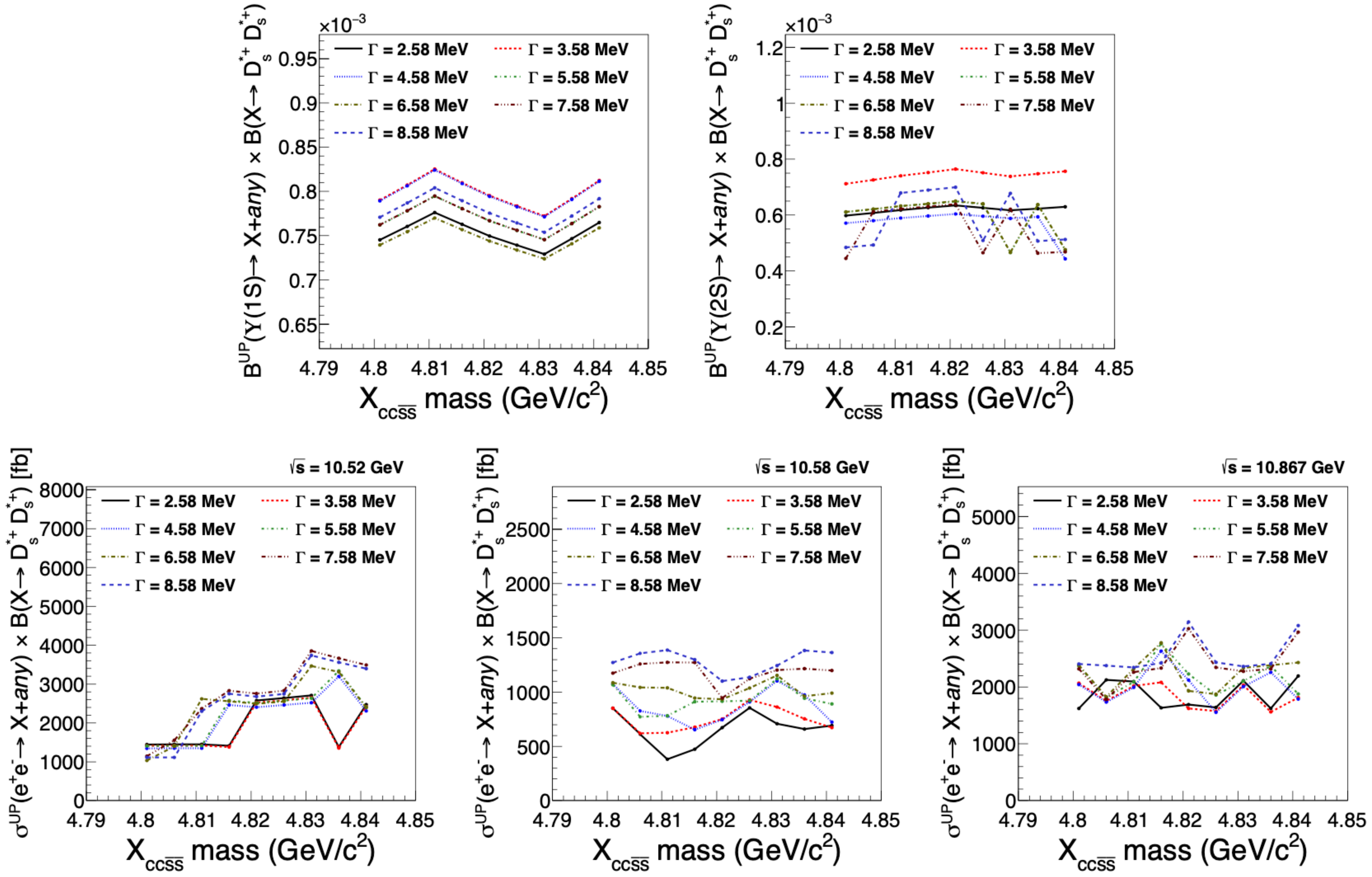
No peaking background in ***sideband***



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)

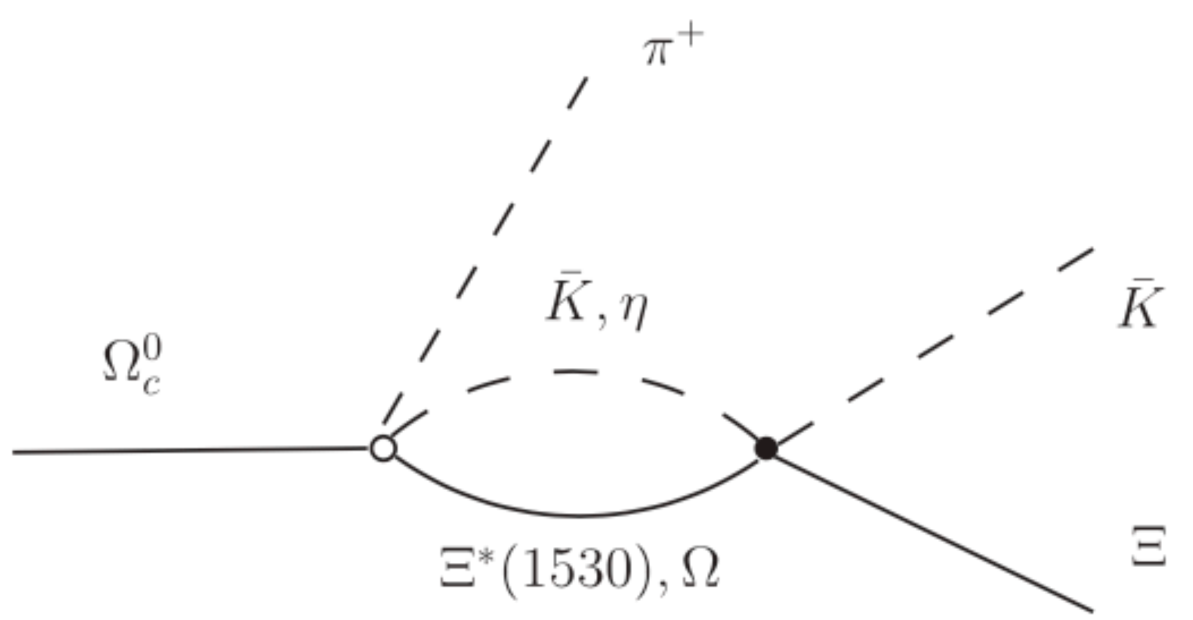


FIG. 2. Diagram for the meson-baryon final-state interaction for the $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ decay.

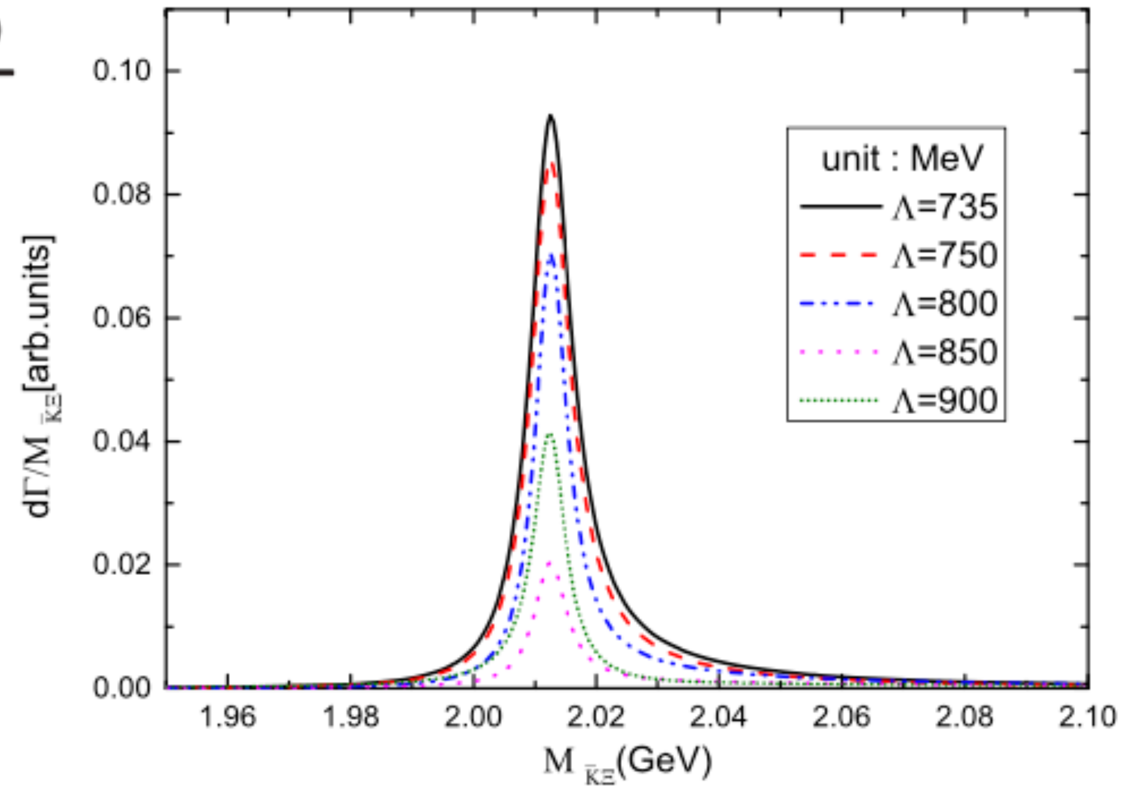


FIG. 3. $\bar{K}\Xi$ invariant mass distributions of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ decay.

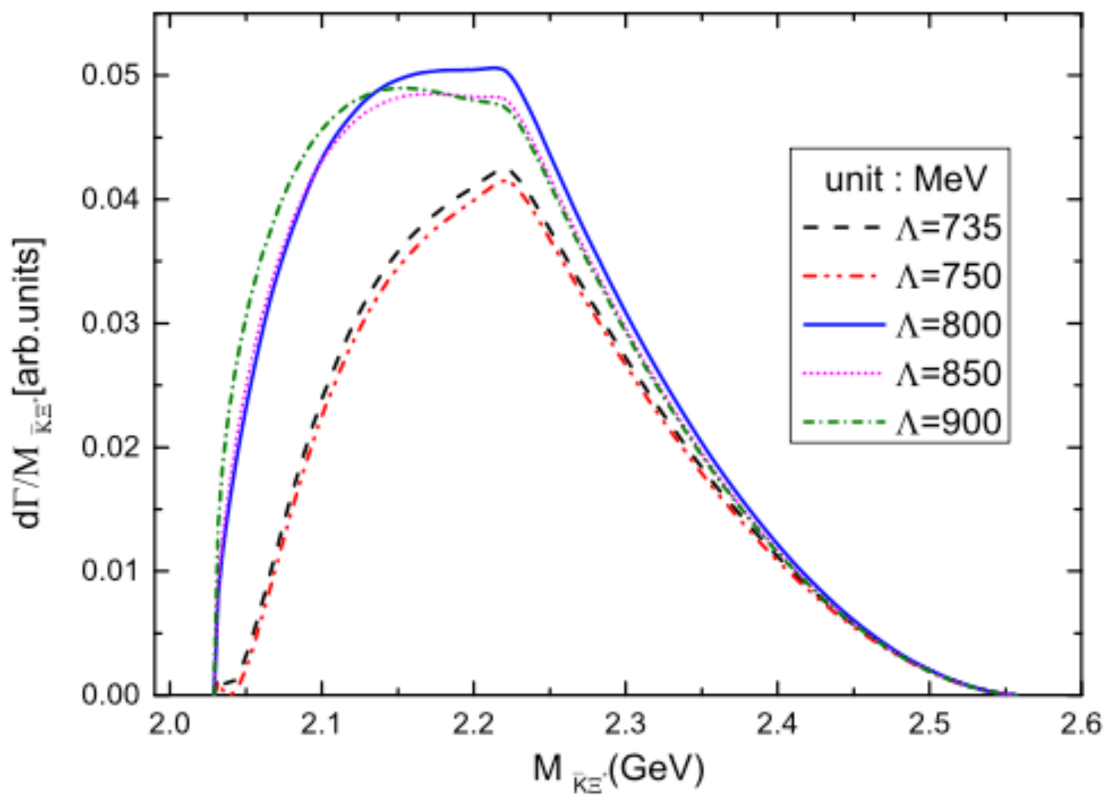


FIG. 4. $\bar{K}\Xi^*$ invariant mass distribution of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi^*)^-$ decay.

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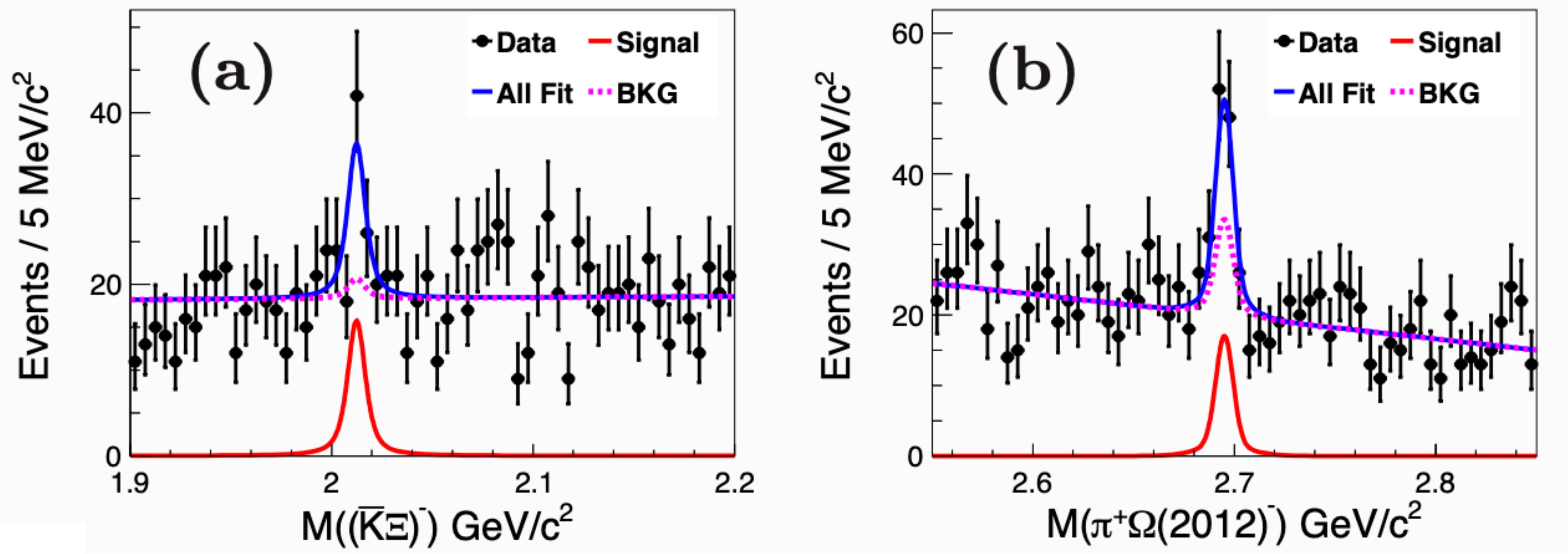
2D fit to $M(\bar{K}\Xi)$ vs $M(\pi^+\Omega(2012)^-)$ simultaneously for $M(K^-\Xi^0)$ and $M(K_S^0\Xi^-)$.

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



$N_{fit} = 46.6 \pm 12.3$

Signal significance: 4.2σ
(including systematic uncertainties)

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

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

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

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

- $\exists$ 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

- $\exists$ 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 $\Xi_c(2970)^+$

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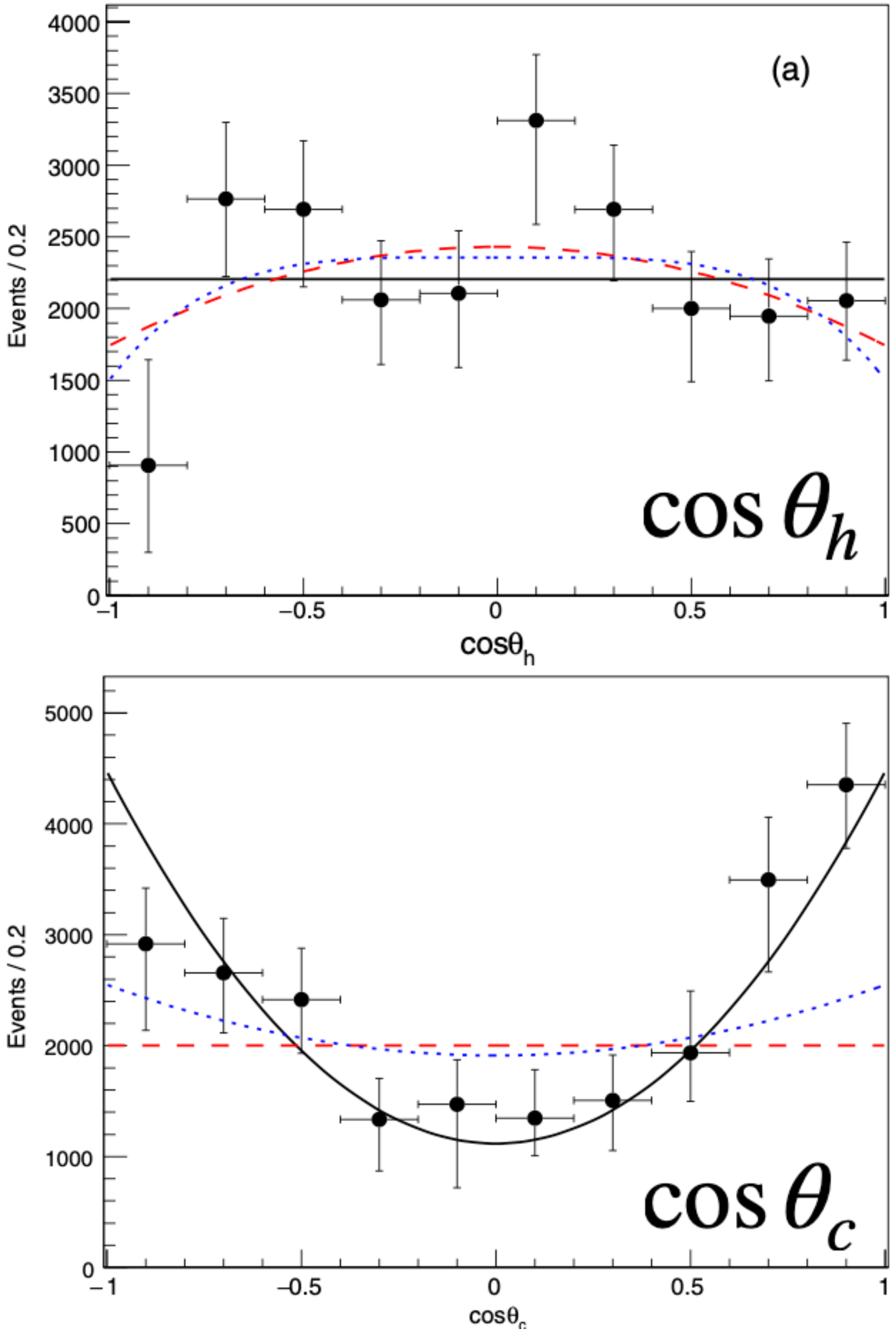

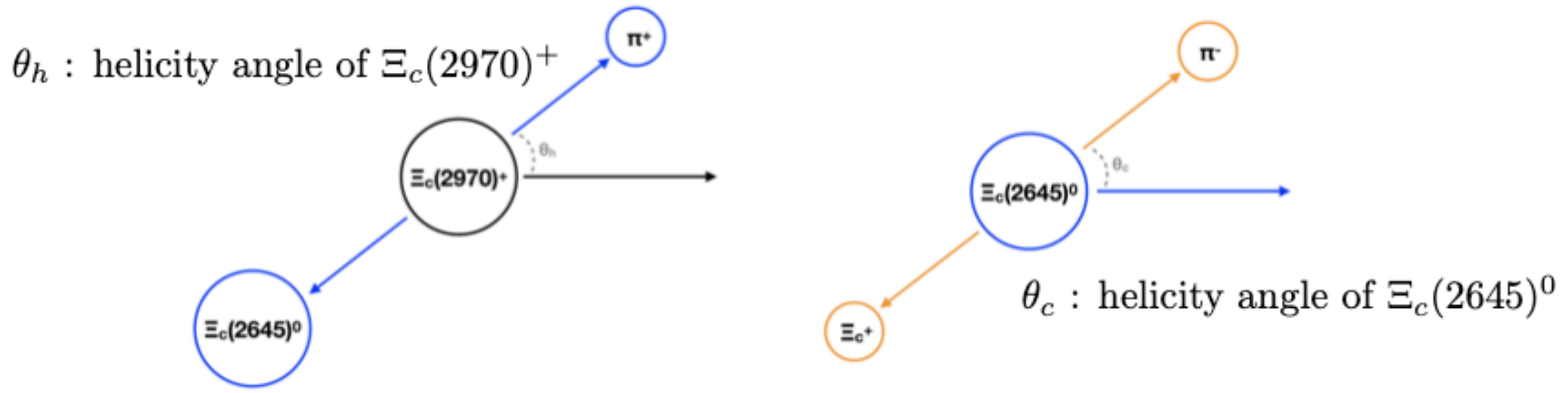

J^P	Partial wave	$W(\theta_c)$
$1/2^+$	P	$1 + 3\cos^2\theta_c$
$1/2^-$	D	$1 + 3\cos^2\theta_c$
$3/2^+$	P	$1 + 6\sin^2\theta_c$
$3/2^-$	S	1
$5/2^+$	P	$1 + (1/3)\cos^2\theta_c$
$5/2^-$	D	$1 + (15/4)\sin^2\theta_c$

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 $\Xi_c(2970)^+$

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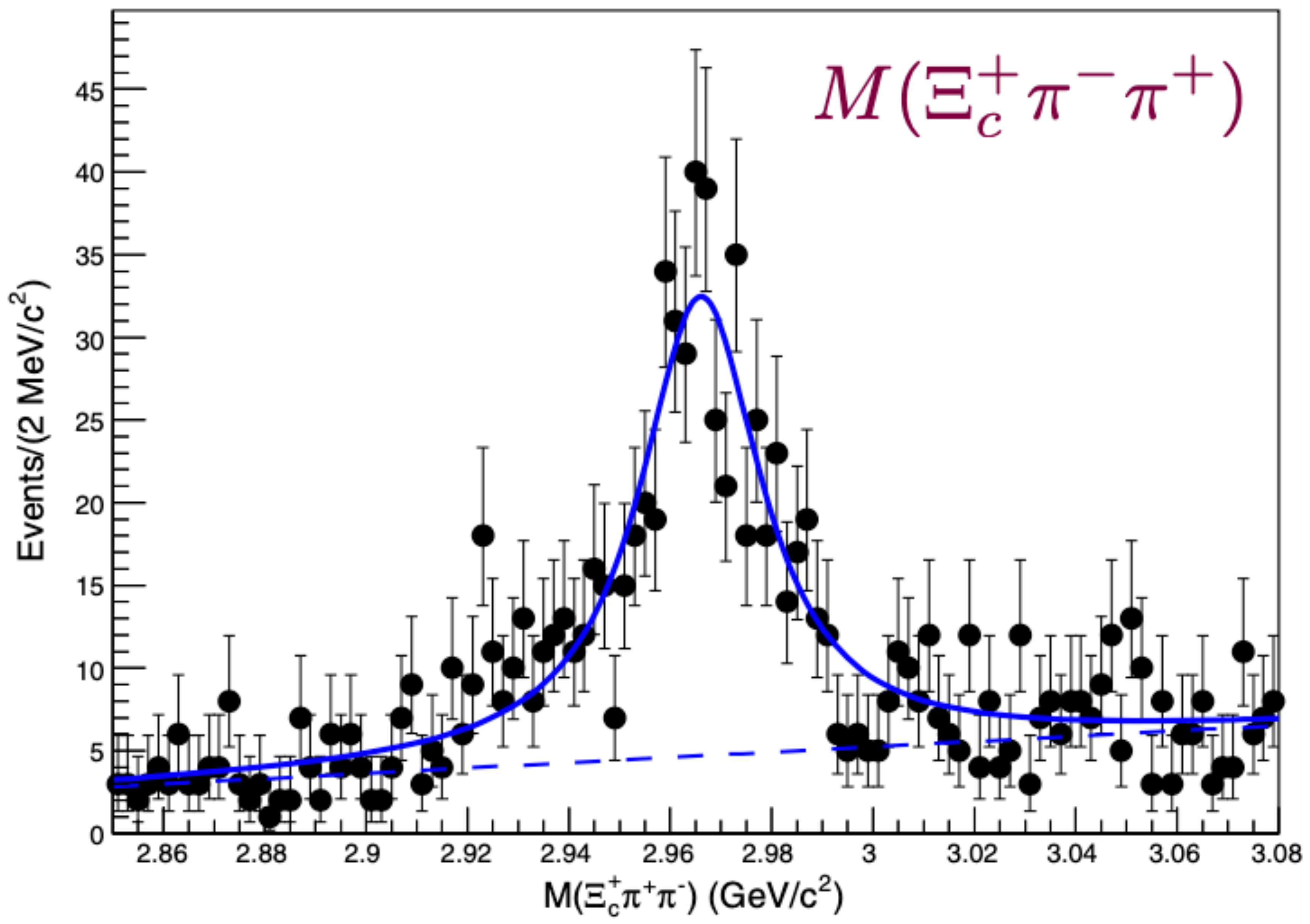
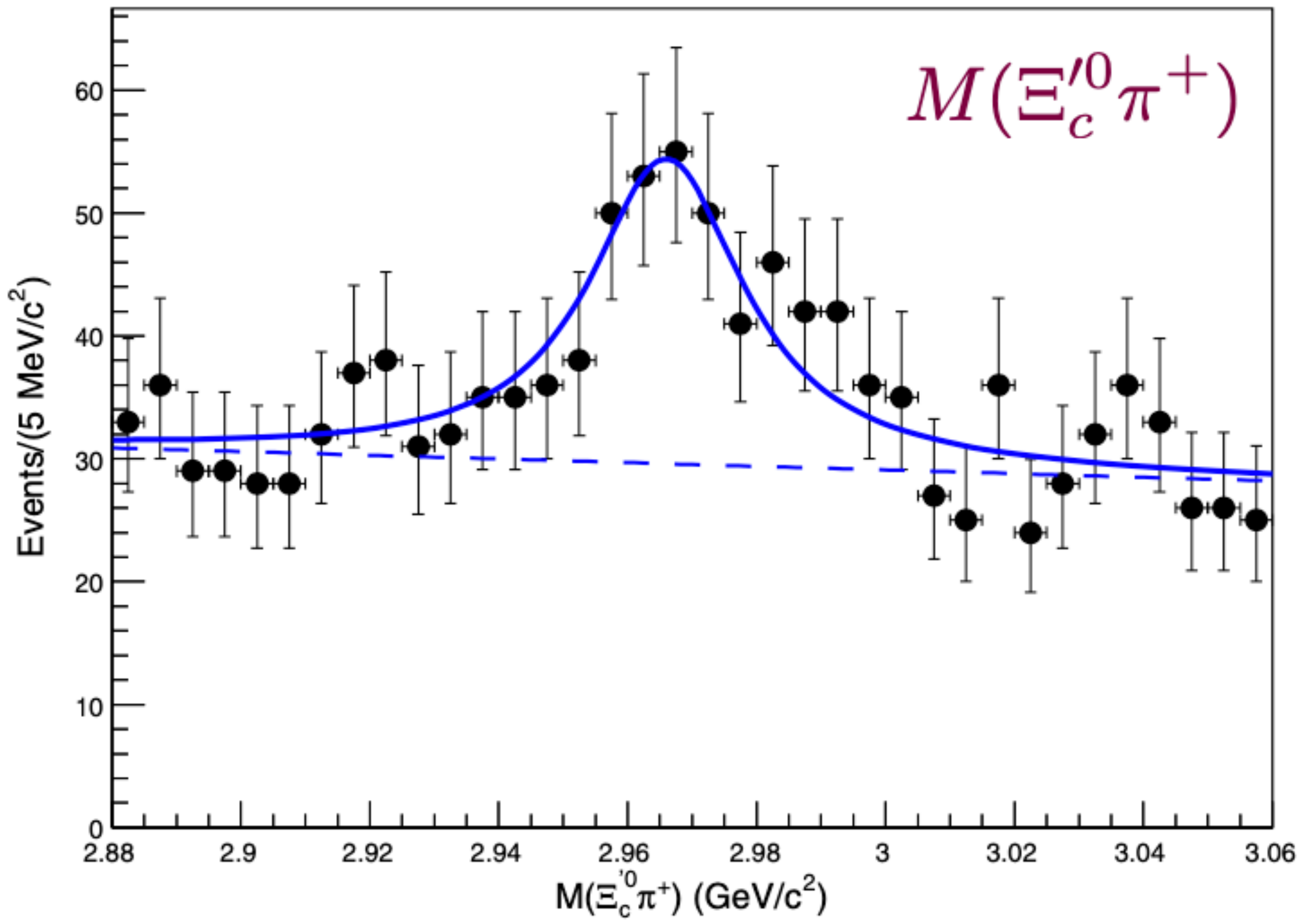
$$R = \frac{\mathcal{B}[\Xi_c(2970)^+ \to \Xi_c(2645)^0\pi^+]}{\mathcal{B}[\Xi_c(2970)^+ \to \Xi_c'^0\pi^+]}$$ — sensitive to parity





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

Heavy-quark spin sym. prediction

Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	≪1

∴ (+) parity assignment is favored

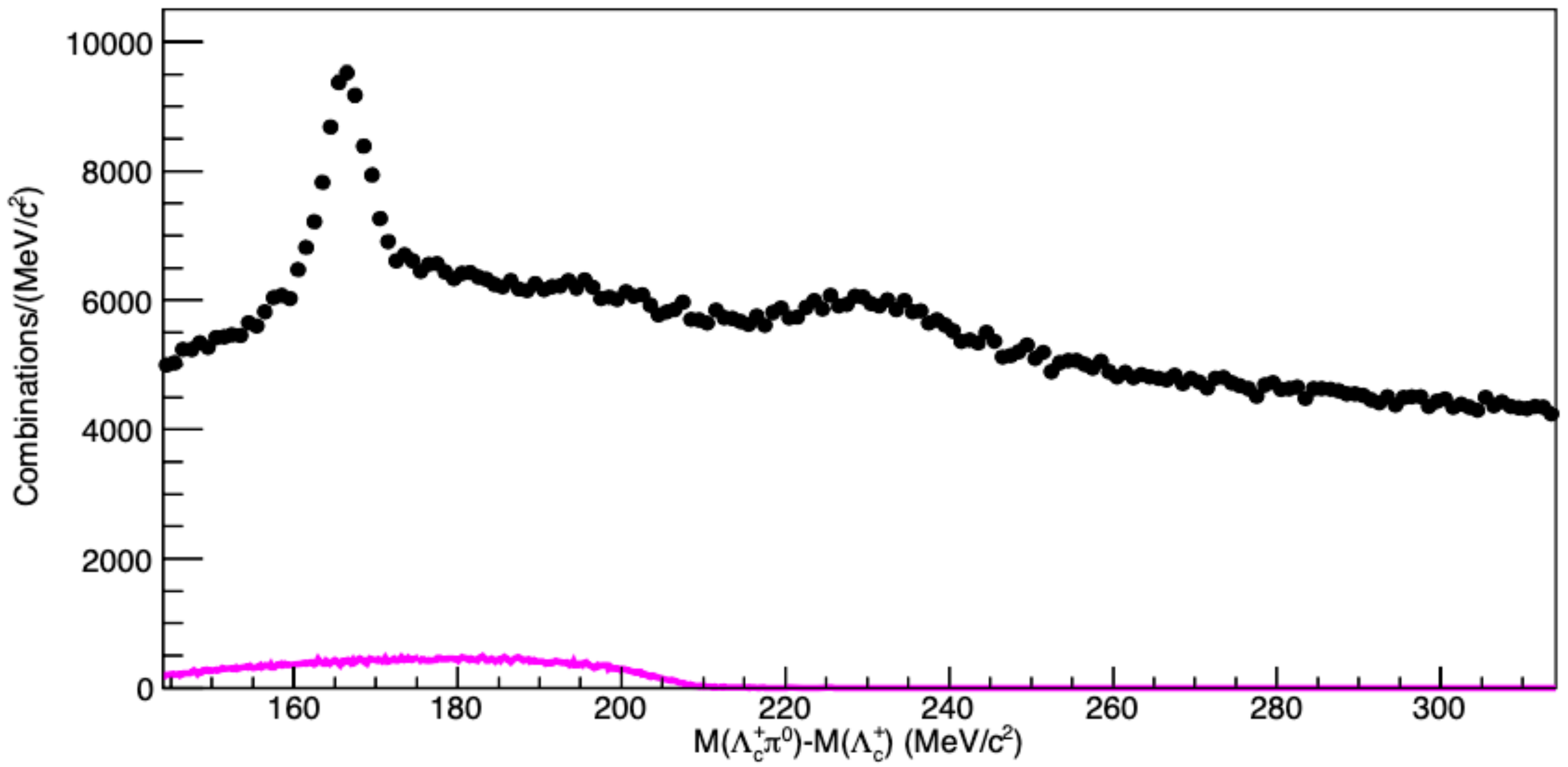
Mass and width of $\Sigma_c^{(*)+}$

- 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).

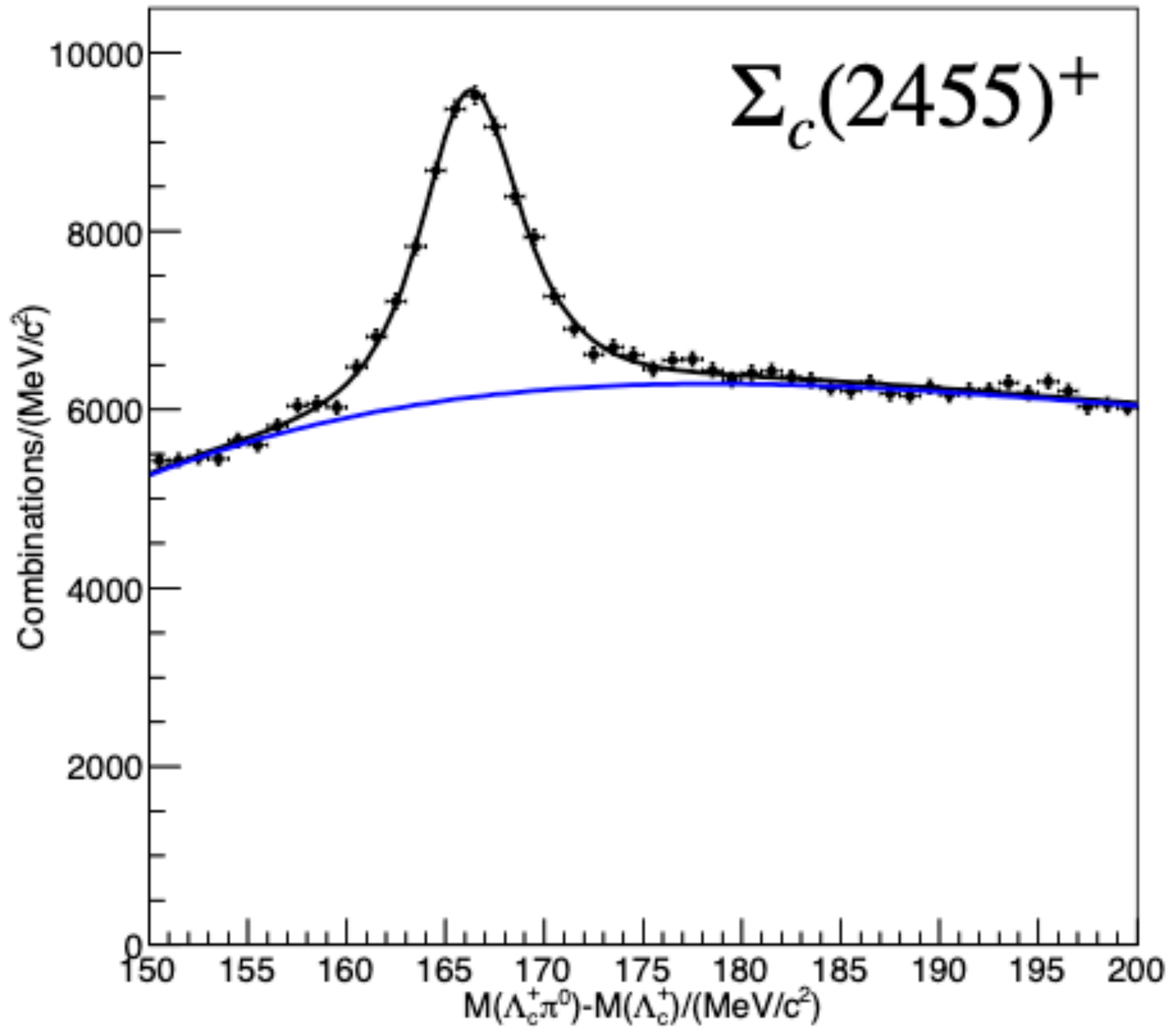
$$\Sigma_c(2455/2520)^+ \to \pi^0\Lambda_c^+ \to \pi^0(pK^-\pi^+)$$

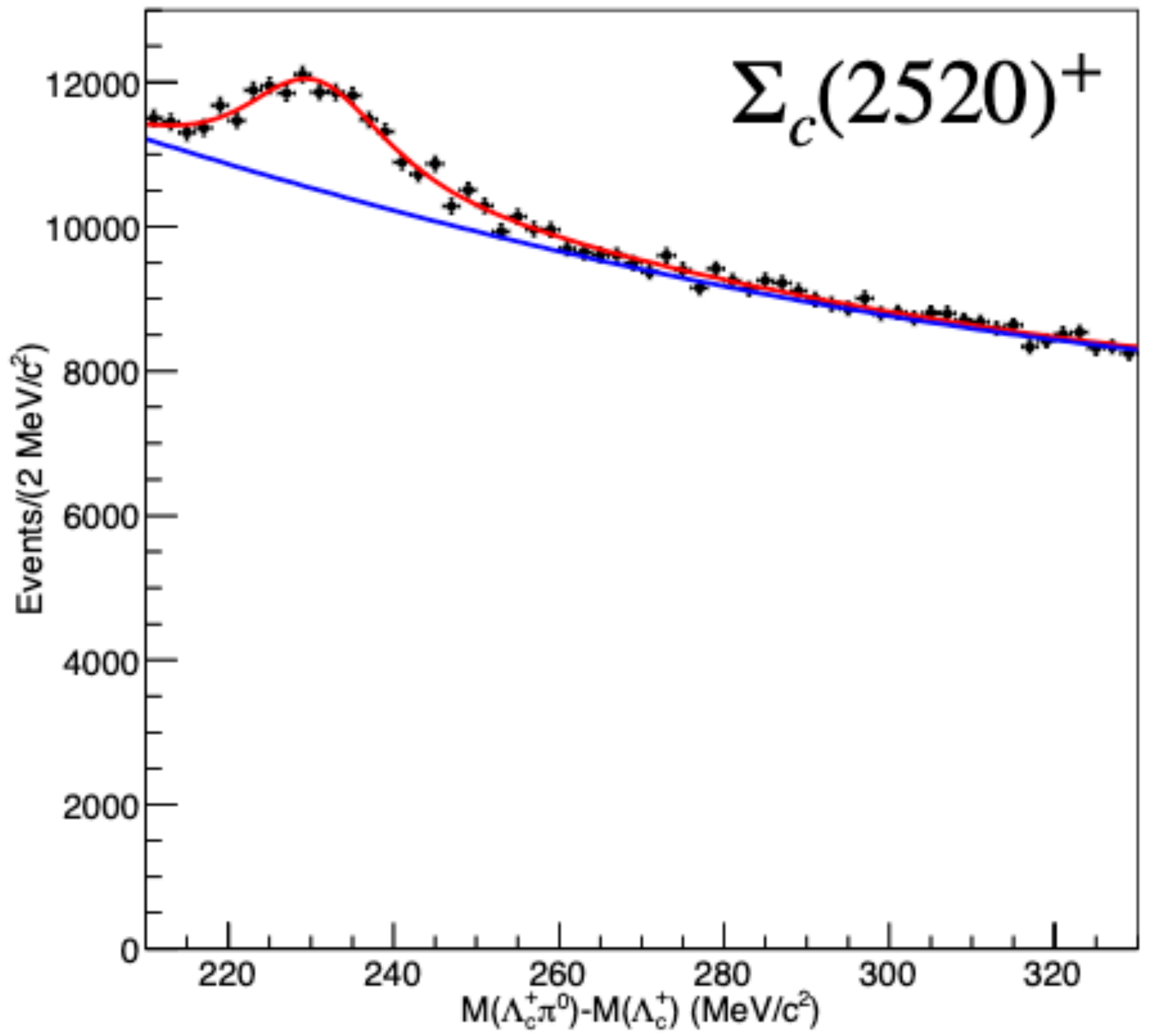
Phys.Rev.D 104 (2021) 5, 052003



	$\Sigma_c(2455)^+$	$\Sigma_c(2520)^+$
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

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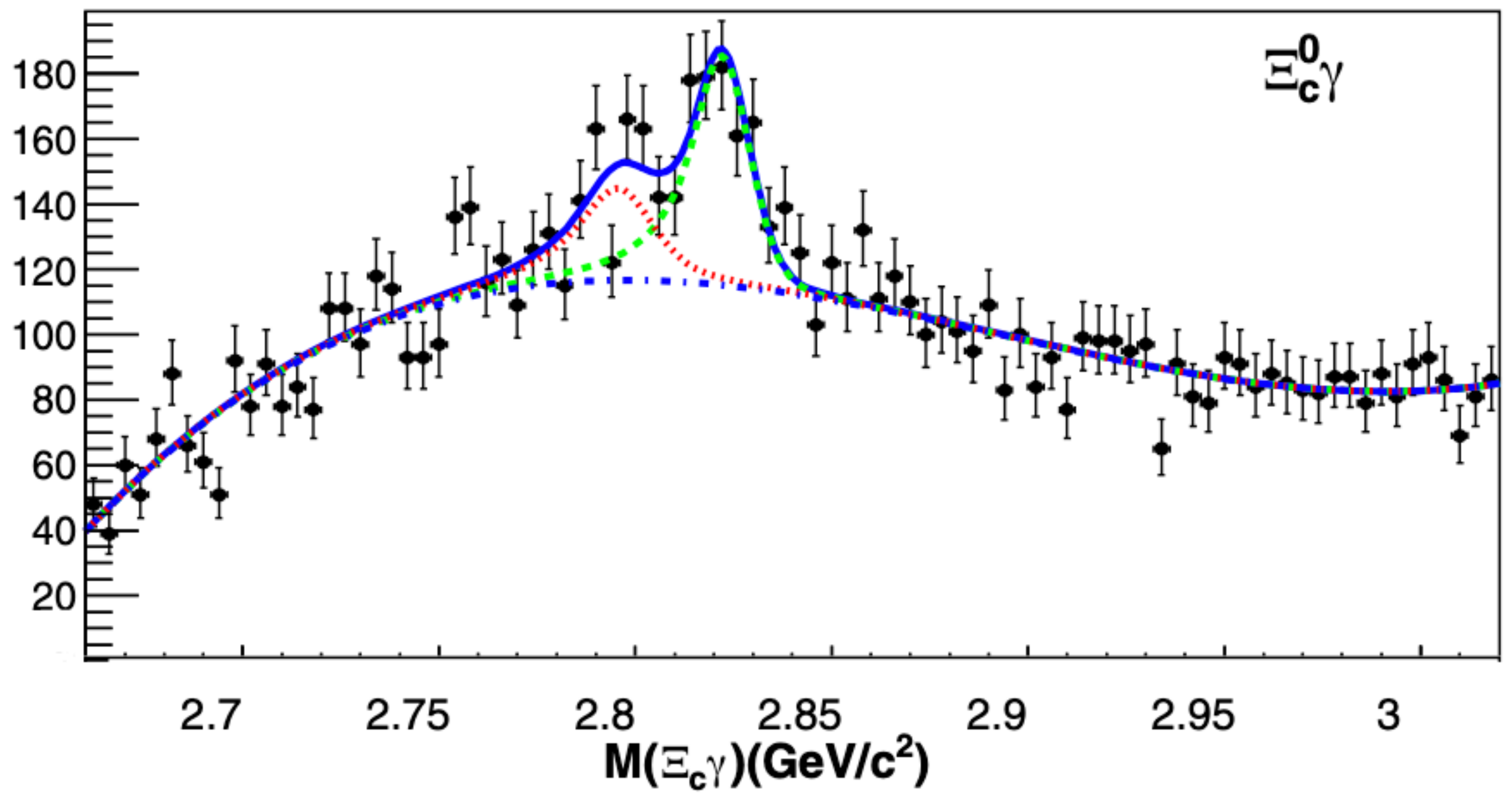

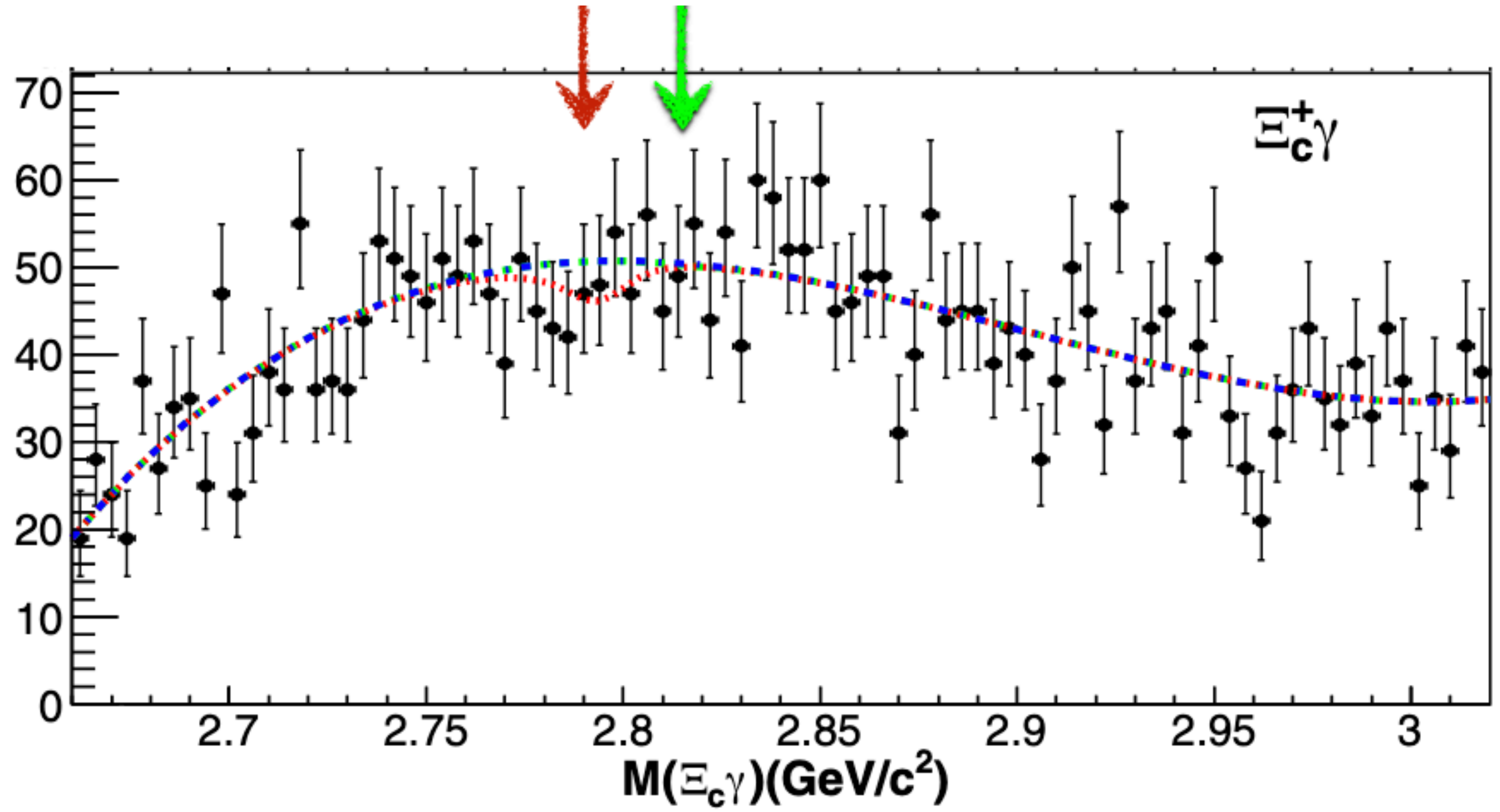

$$R^0_{2790} = \frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$$

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

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

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

- First observation of radiative decays of orbitally excited Ξ_c