

Overview of Quarkonium results on Belle II

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on behalf of Belle II Collaboration

Discovery of Upsilon

January, 1976

Fermi Lab, E288, $ee1$

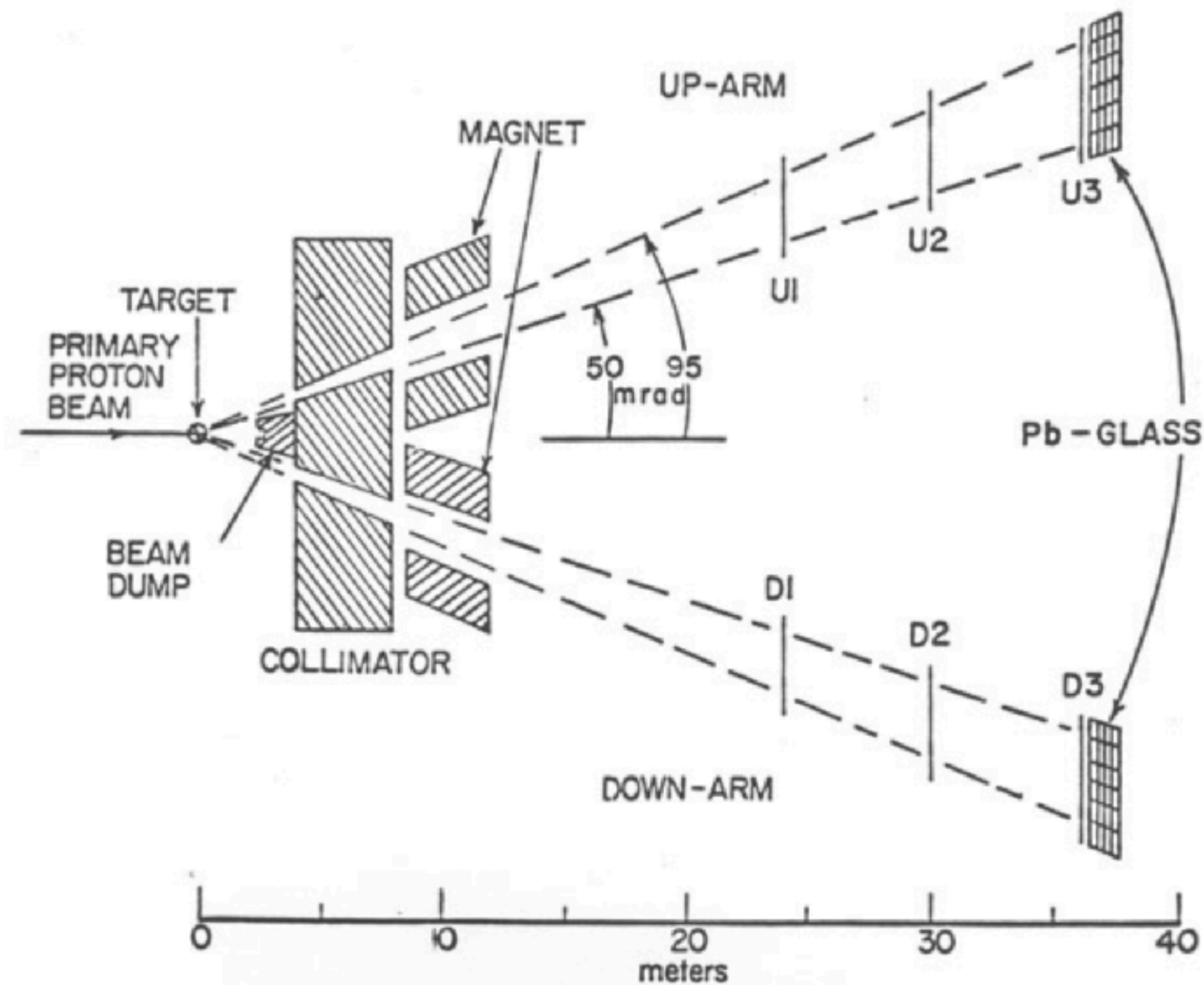


Fig. 1: Schematic Diagram of the Apparatus: U1-3 and D1-3 are sets of scintillation trigger counters, proportional wire chambers, and scintillation hodoscopes.

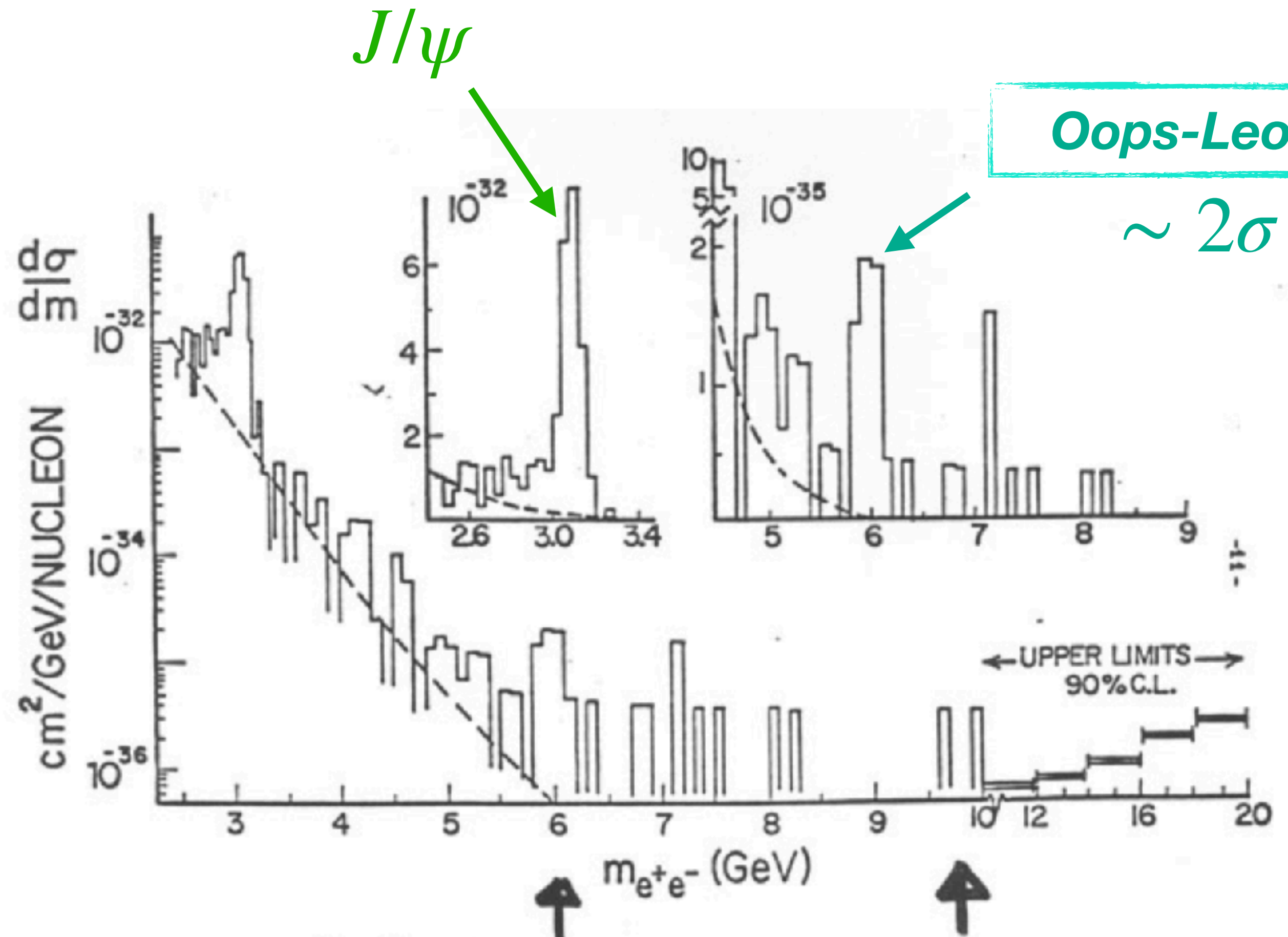
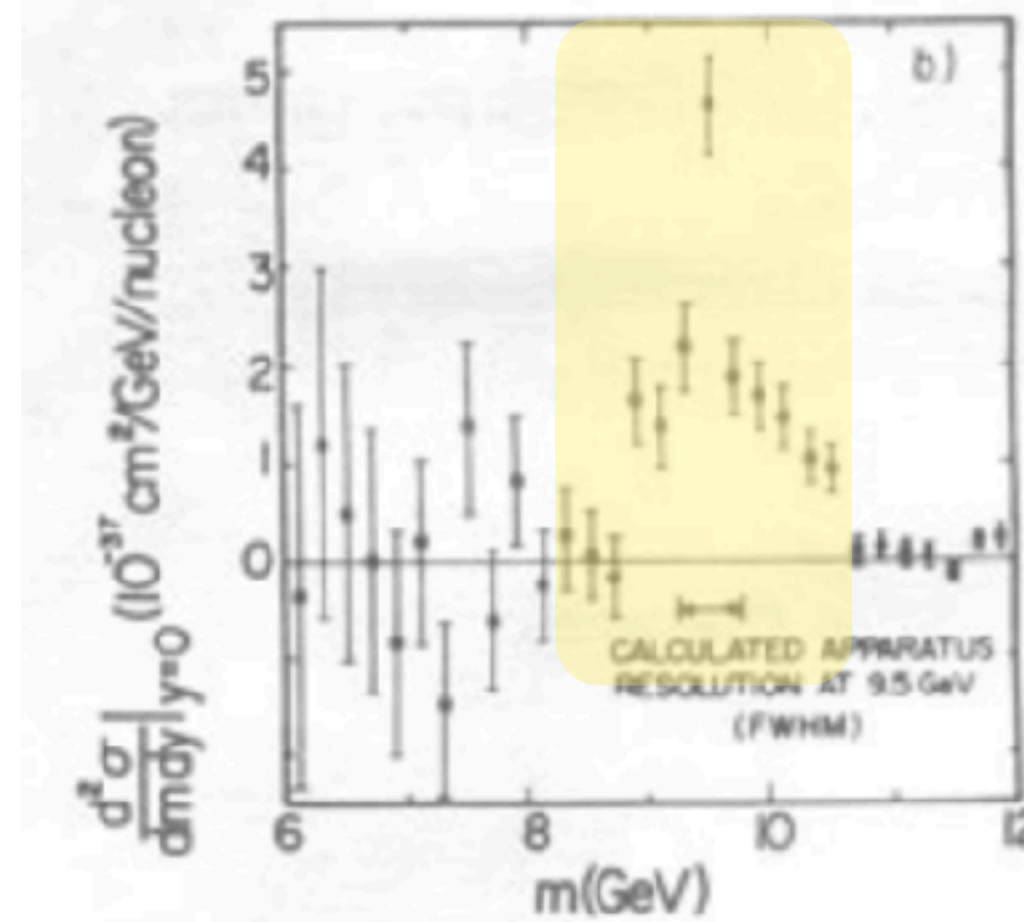
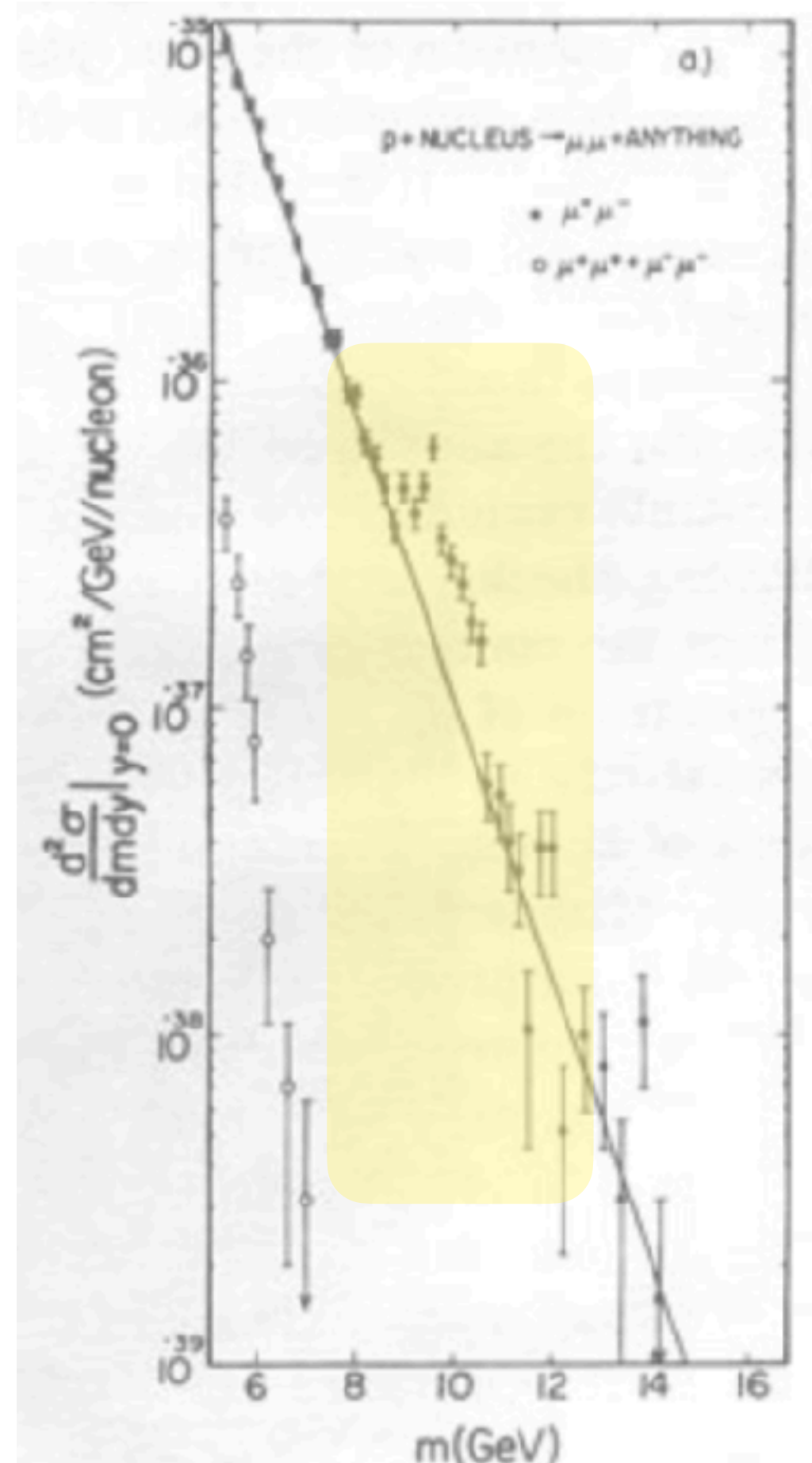
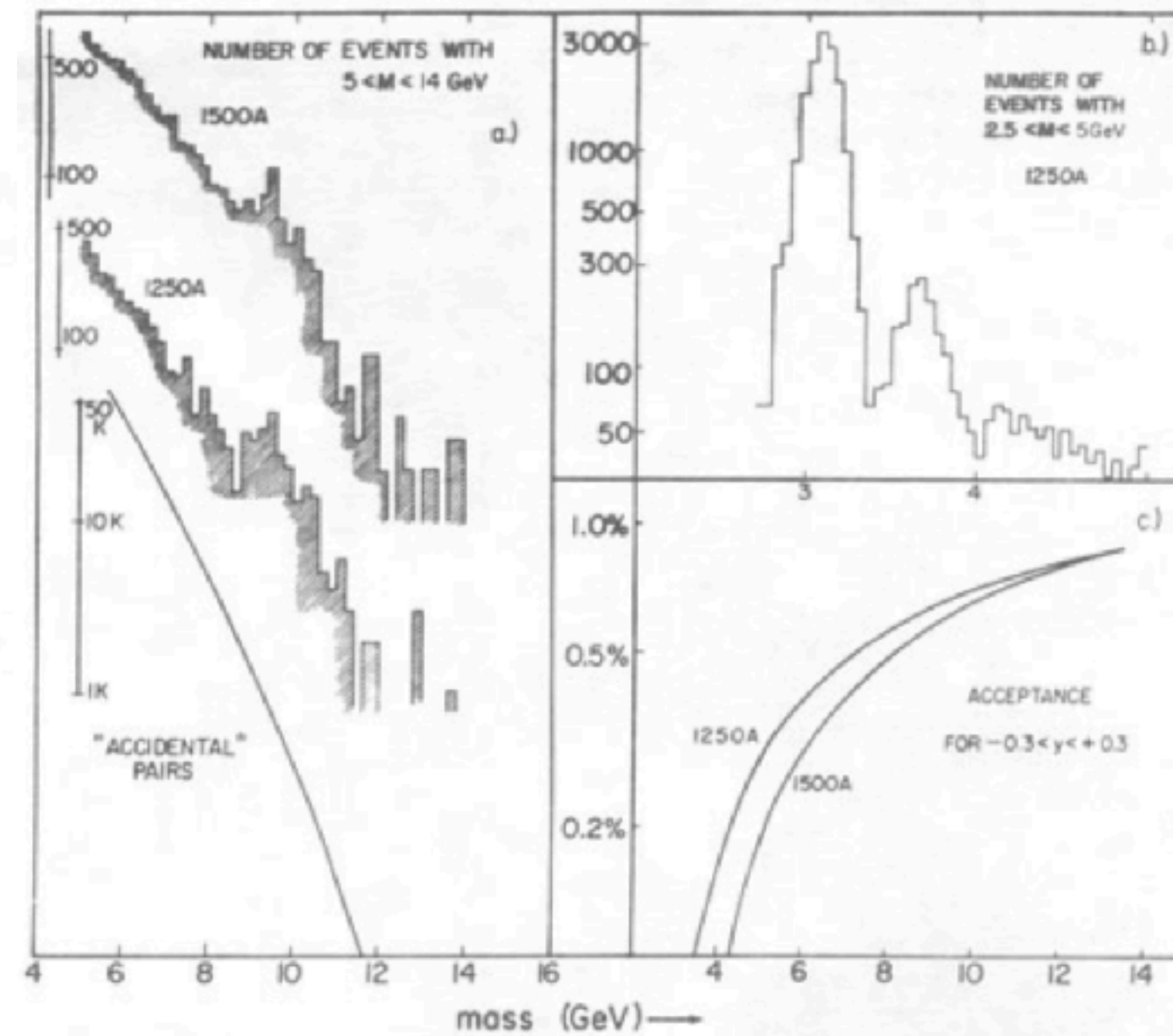
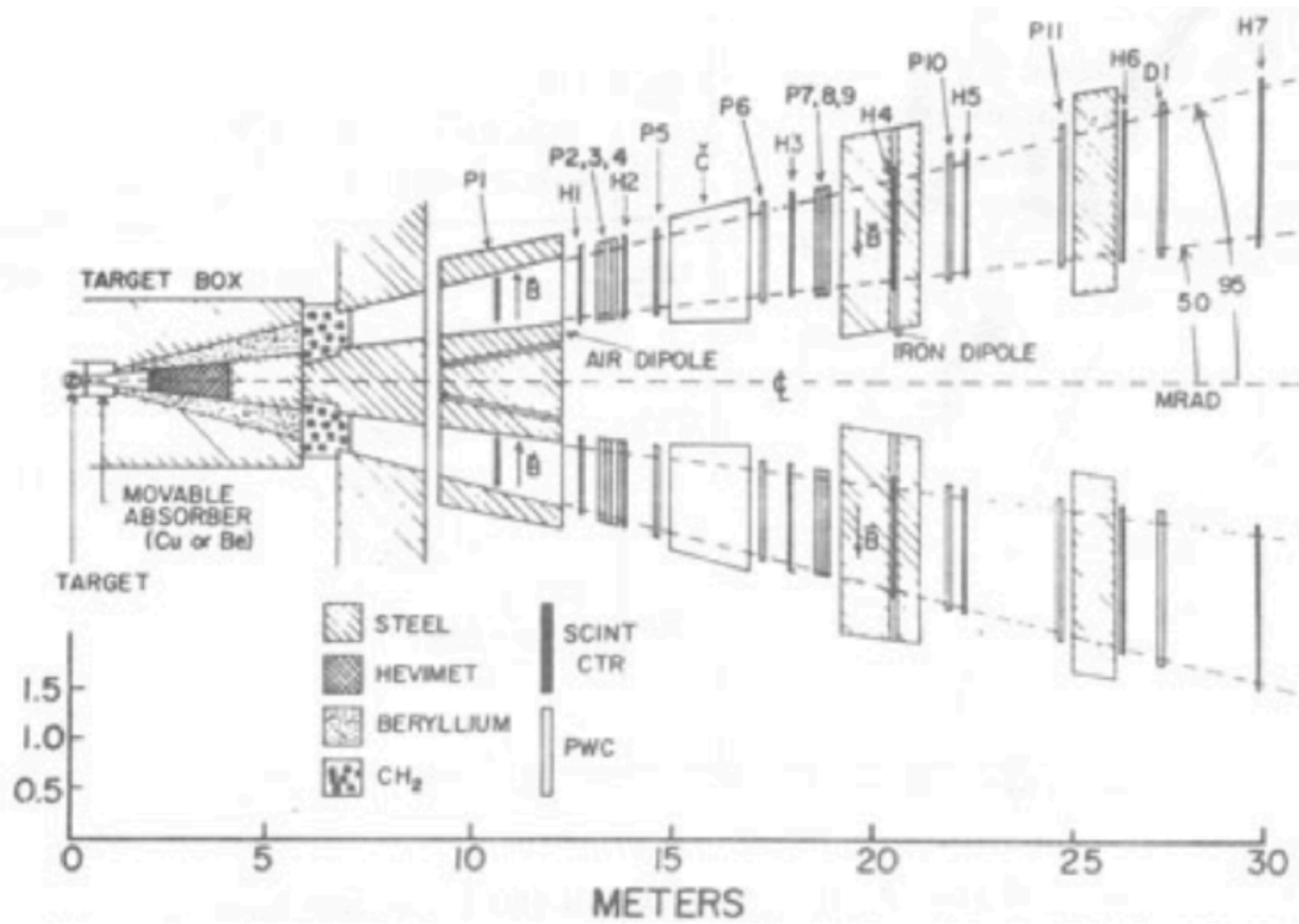


Fig. 2: Electron-Positron Mass Spectrum: $d\sigma/dm$ per nucleon versus the effective mass. A linear A -dependence is assumed. Note bin width changes.

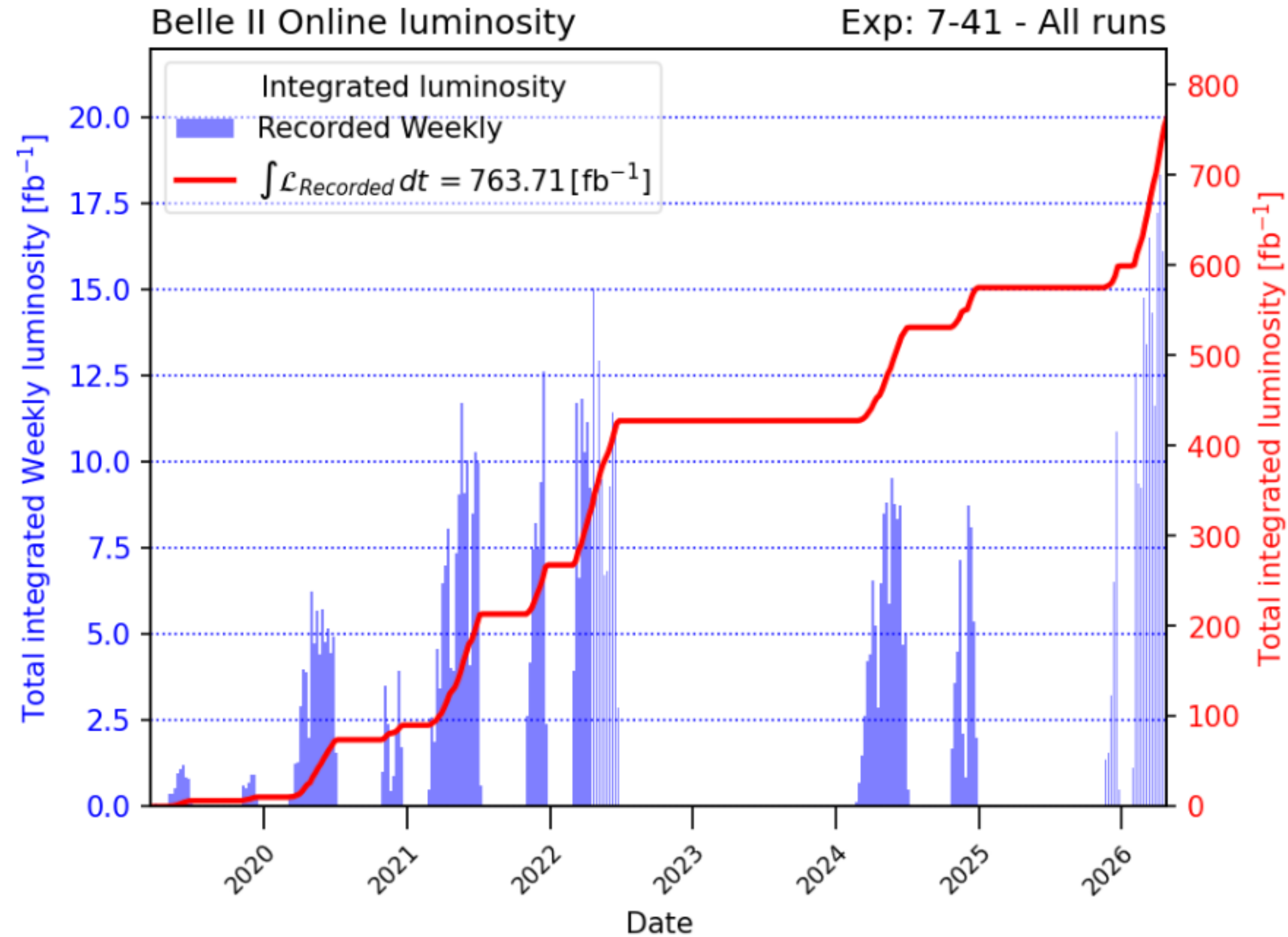
Discovery of Upsilon

Fermi Lab, E288, $\mu\mu 2$



3 years after November revolution
July 1, 1977

RUN-I & II (2019-2025)



The only collider can collect pure Υ data!

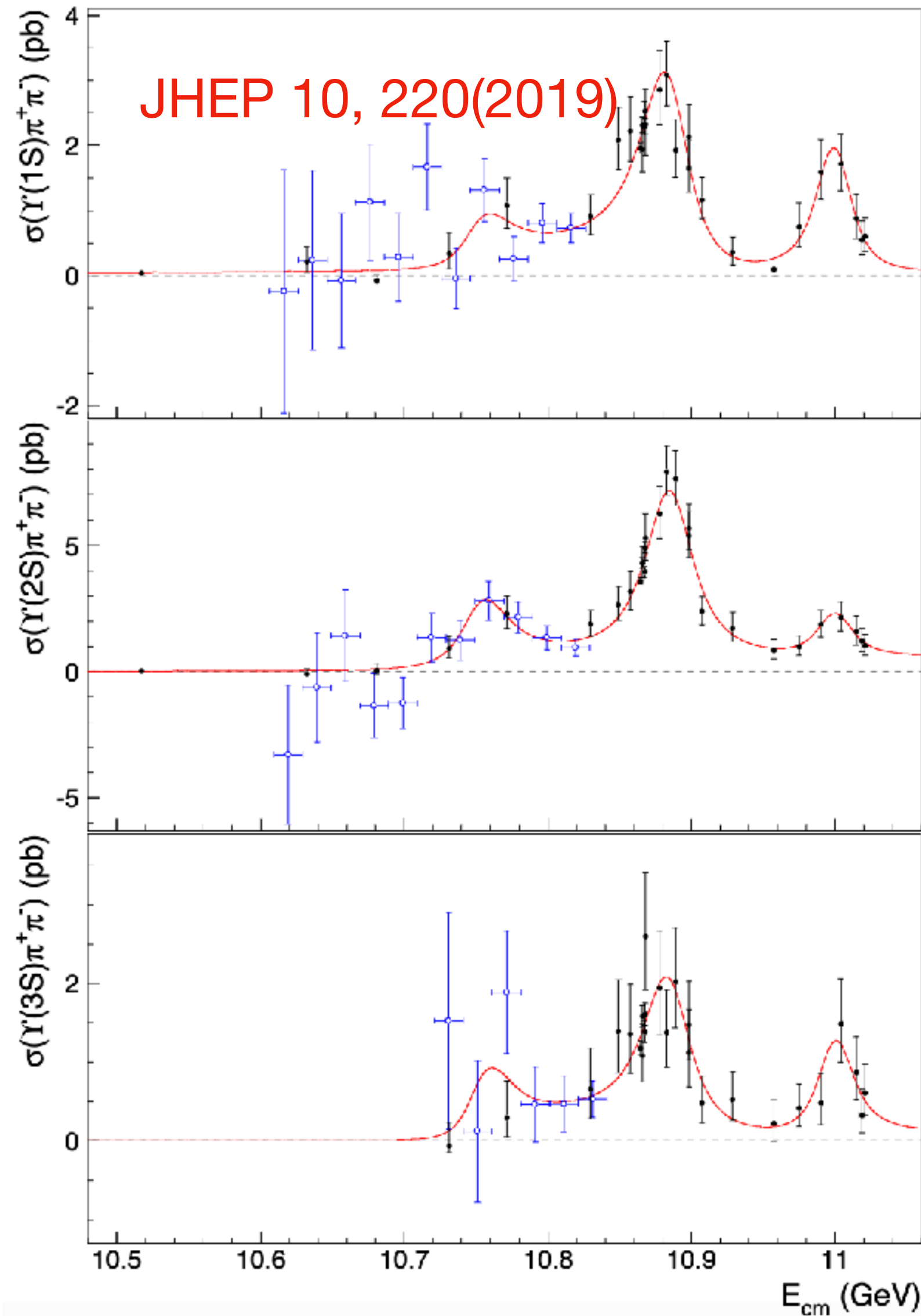
- $\sim 20/\text{fb}$ near $\Upsilon(10753)$
- $\sim 700/\text{fb}$ at $\Upsilon(4S)$
- $\sim 42/\text{fb}$ at 10.52 GeV for continuum

Run 2 of experiment started Jan 29th 2024

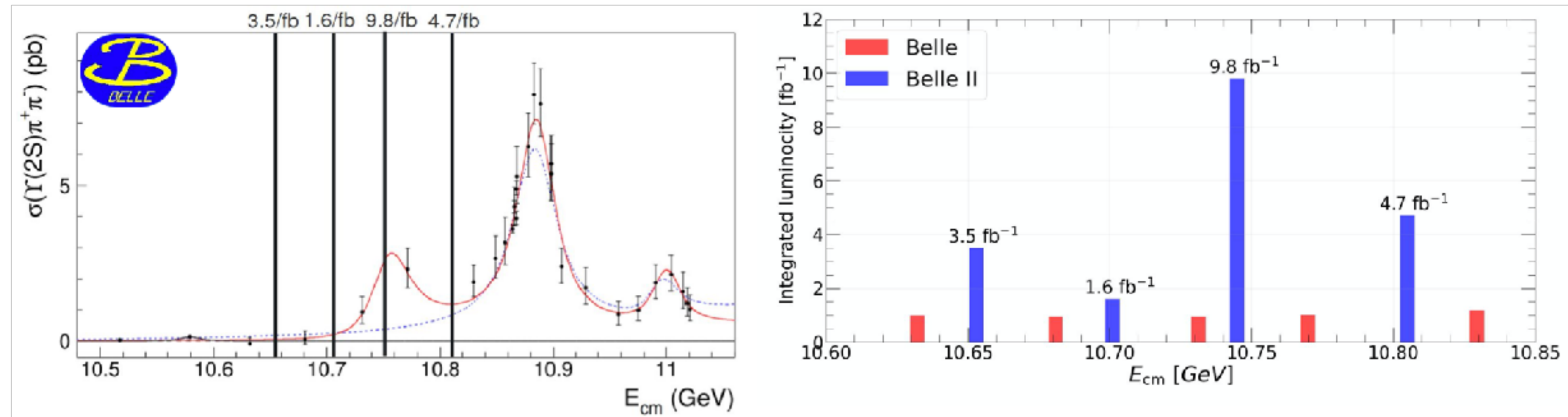
Collected ca. 0.55/ab = BaBar

→ During **Run 1**: Achieved world record inst. luminosity of $4.71 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

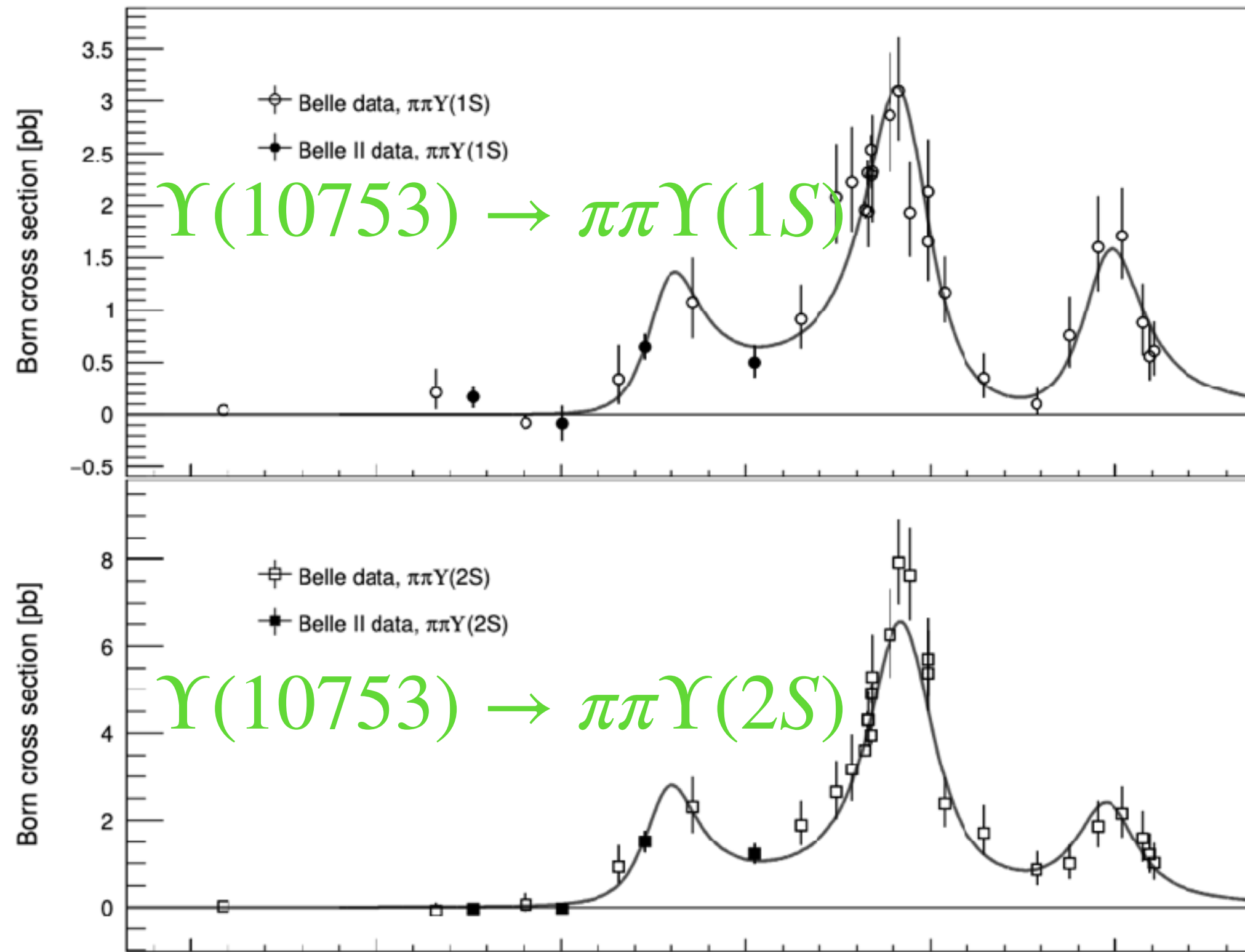
$\Upsilon(10753)$ – discovery and studies



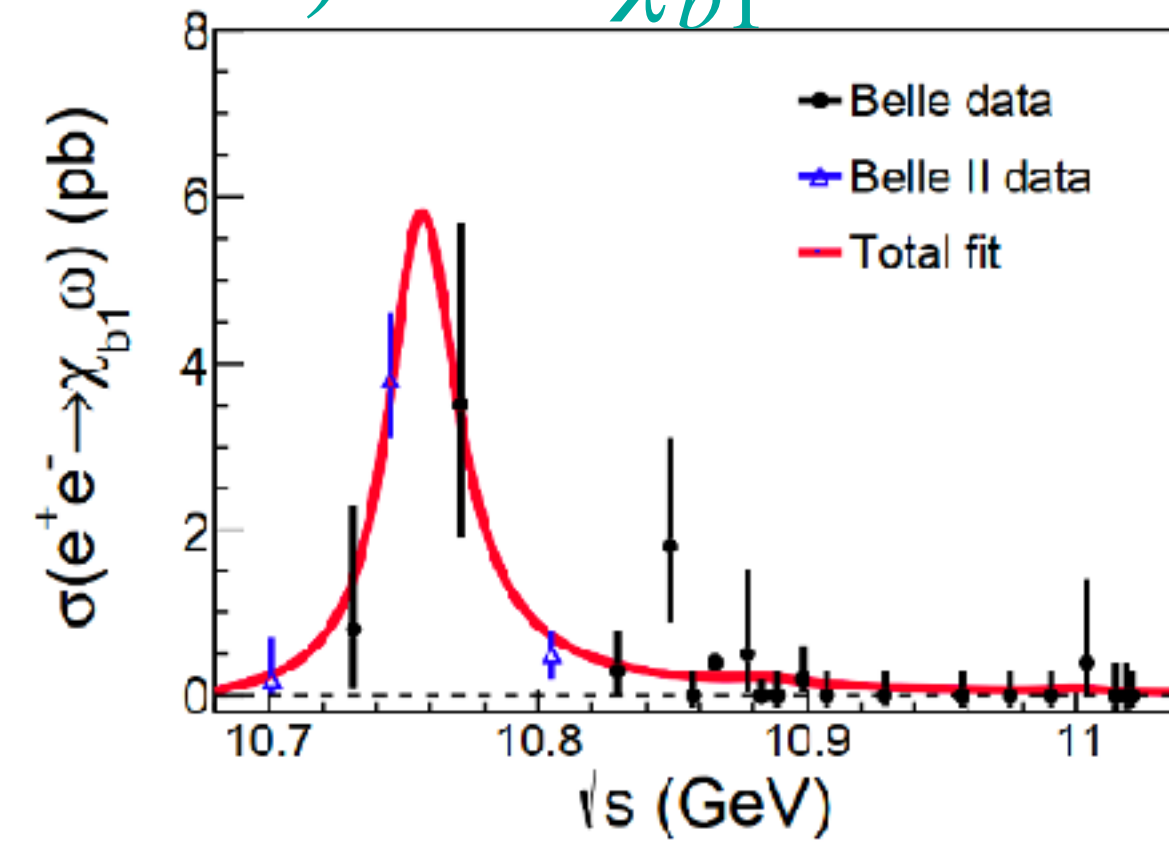
- $\Upsilon(10753)$ was firstly observed at Belle in the process of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ ($n = 1,2,3$).
- Many hypotheses to this new particle
 - Hybrid, tetraquark, mixed bottomonium, etc.
- Scan data on Belle II to study its properties to reveal its nature



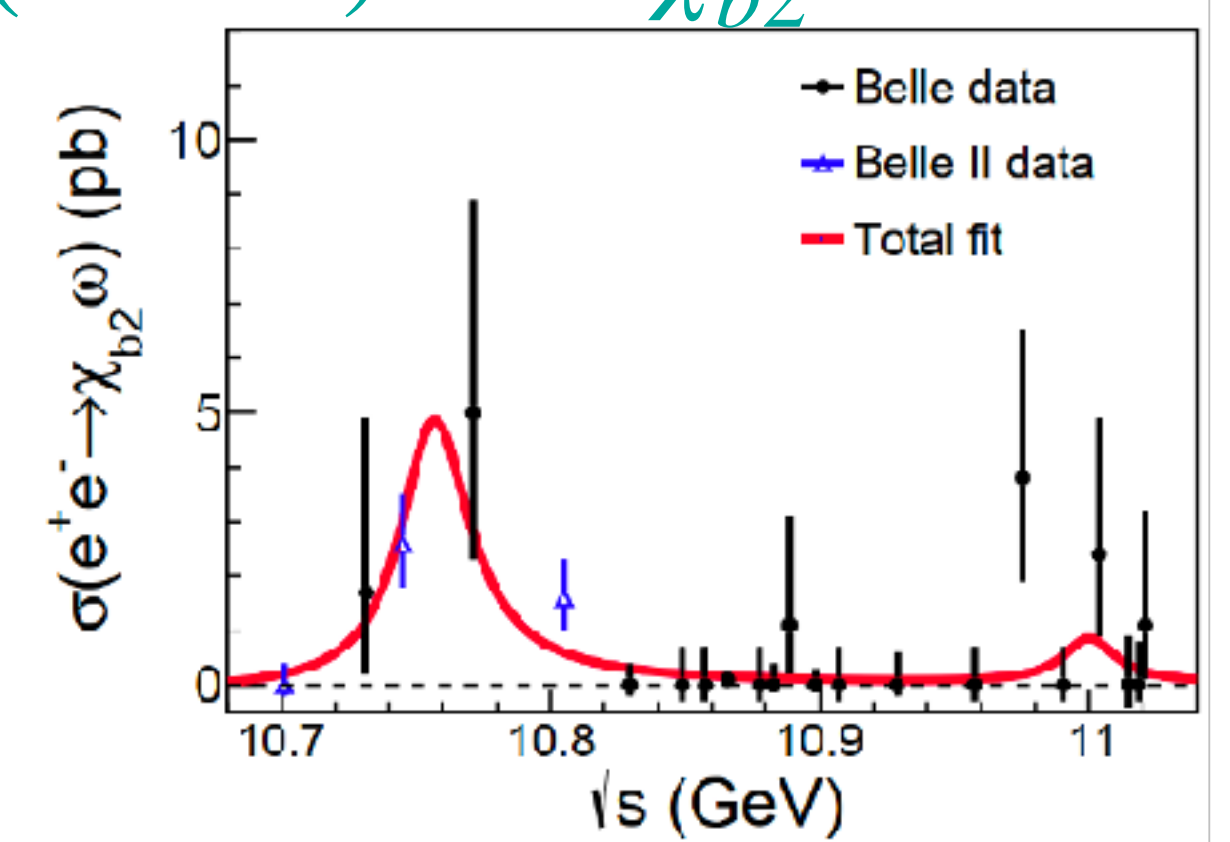
$\Upsilon(10753)$ – mass and width



$\Upsilon(10753) \rightarrow \omega\chi_{b1}$



$\Upsilon(10753) \rightarrow \omega\chi_{b2}$



$$M = 10756.1 \pm 4.3 \text{ MeV}/c^2$$

$$\Gamma = 32.2 \pm 18.7 \text{ MeV}$$

$$M = 10756.3 \pm 2.7_{(stat.)} \pm 0.6_{(syst.)} \text{ MeV}/c^2$$

$$\Gamma = 29.7 \pm 8.5_{(stat.)} \pm 1.1_{(syst.)} \text{ MeV}$$

$$M = 10756.1 \pm 2.3 \text{ MeV}/c^2$$

$$\Gamma = 30.1 \pm 7.8 \text{ MeV}$$

Agree with previous Belle measurement.

Improve uncertainties ~2 times smaller

$\Upsilon(10753)$ — decays

We have searched for

$$\Upsilon(10753) \rightarrow \pi\pi\Upsilon(2S)^{**}$$

$$\Upsilon(10753) \rightarrow \omega\chi_{bJ}^{**}$$

$$\Upsilon(10753) \rightarrow \eta\Upsilon(2S)^*$$

$$\Upsilon(10753) \rightarrow \pi^+\pi^-\pi^0\chi_{bJ}$$

$$\Upsilon(10753) \rightarrow \eta\Upsilon(1S)$$

$$\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon_2(1D)$$

$$\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon_3(1D)$$

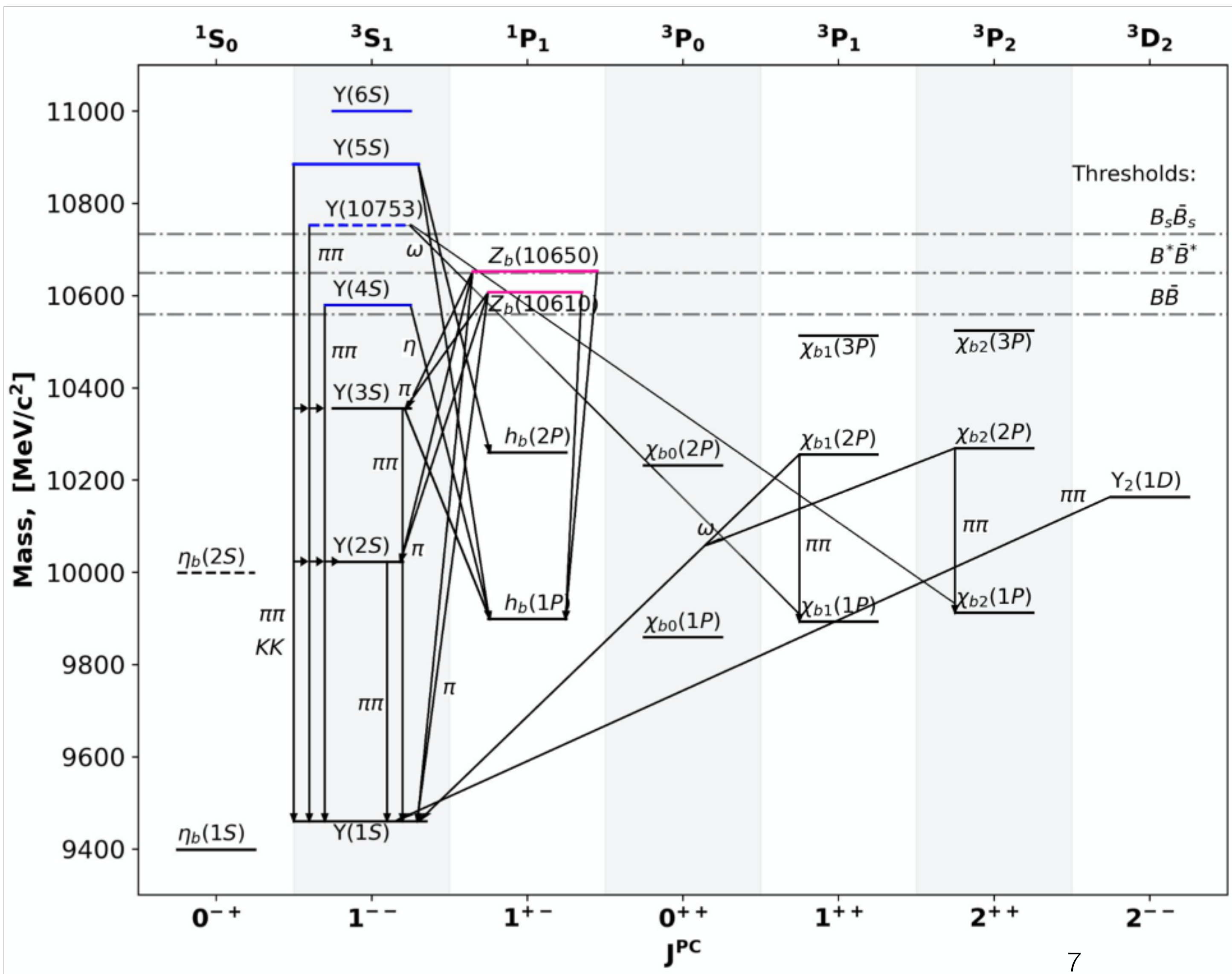
$$\Upsilon(10753) \rightarrow \pi\pi\Upsilon(1S)^*$$

$$\Upsilon(10753) \rightarrow \pi\pi\Upsilon(2S)$$

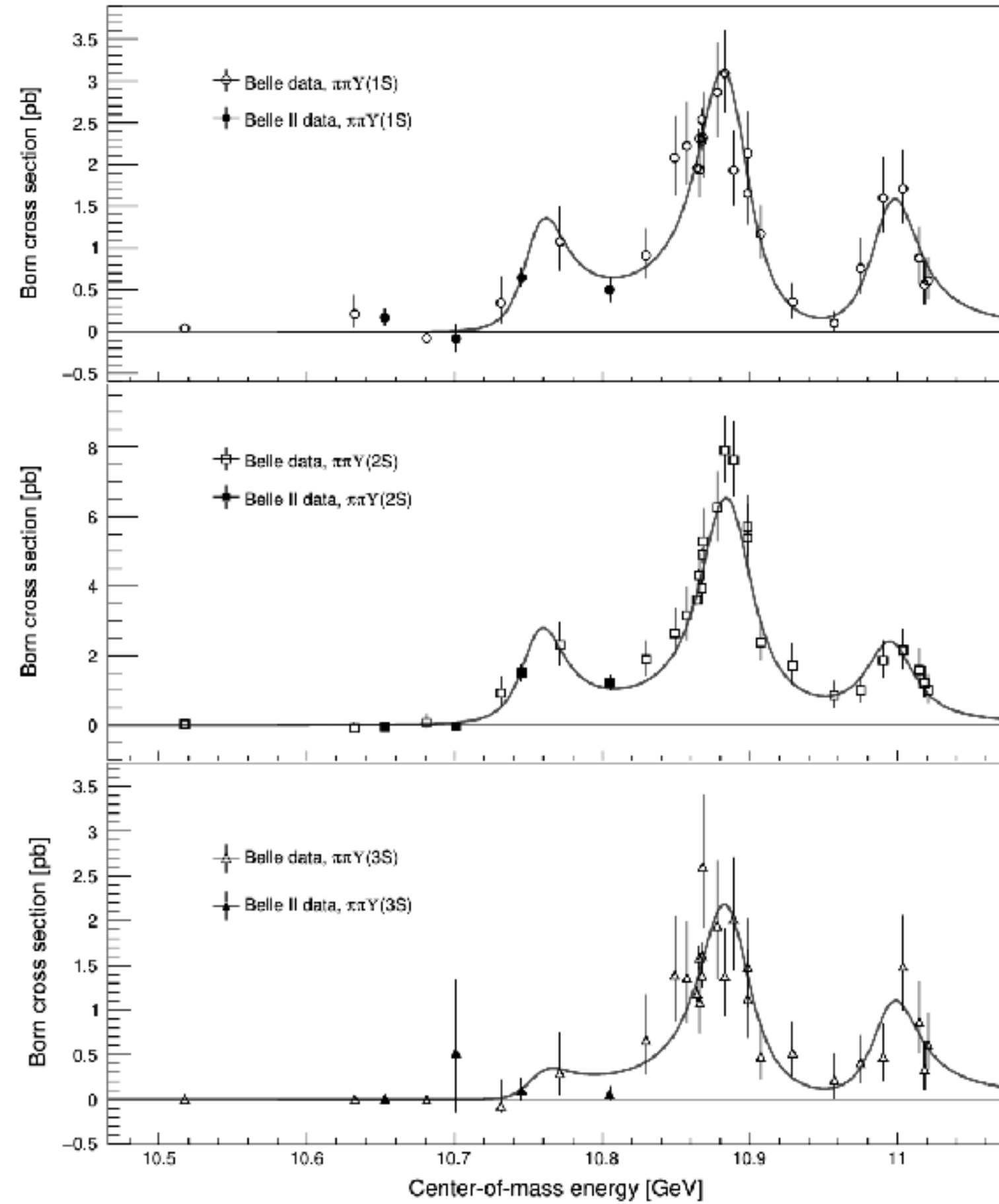
$$\Upsilon(10753) \rightarrow \omega\eta_b$$

$$\Upsilon(10753) \rightarrow \gamma\chi_{bJ}$$

$$\Upsilon(10753) \rightarrow \pi^\pm Z_b^\mp$$



$\Upsilon(10753) \rightarrow \pi\pi\Upsilon(nS)$



Extract relative ratios:

$$\frac{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(1S)}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(2S)} = 0.46^{+0.15}_{-0.12}$$

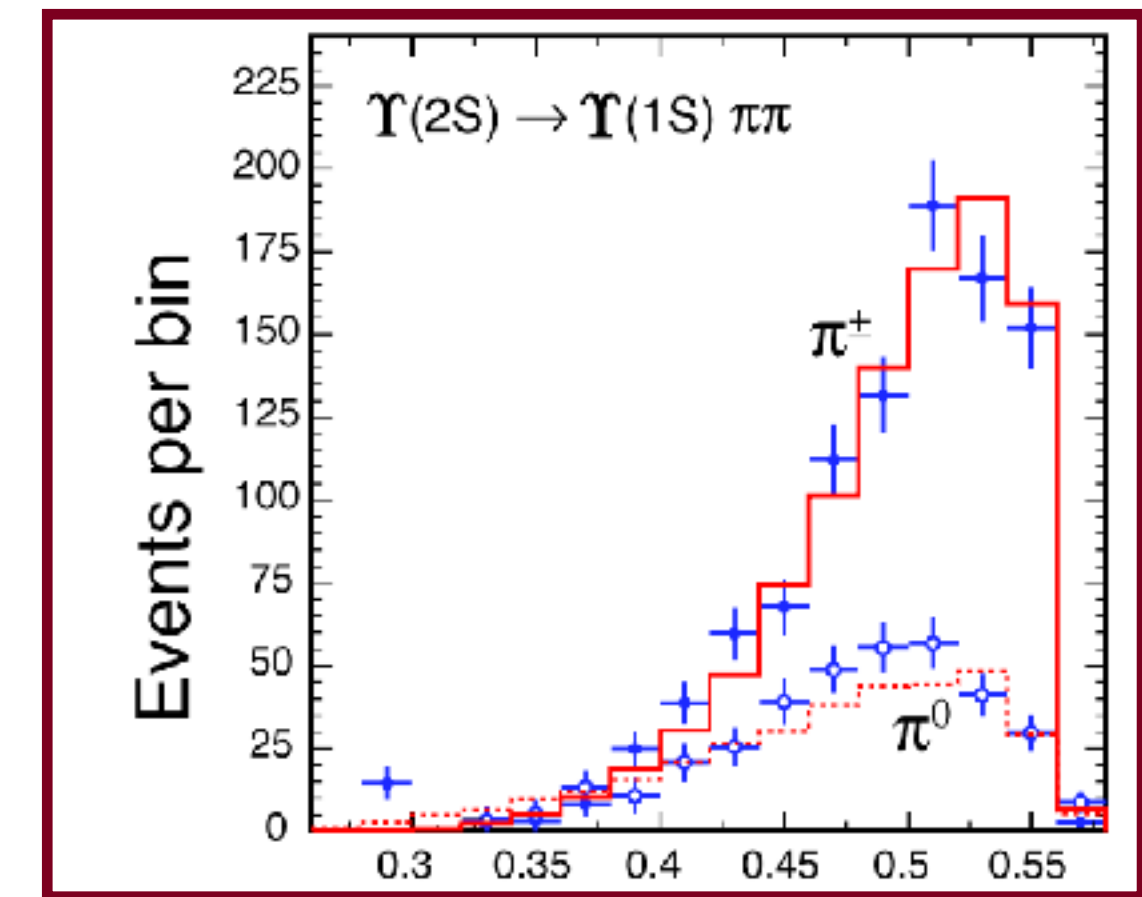
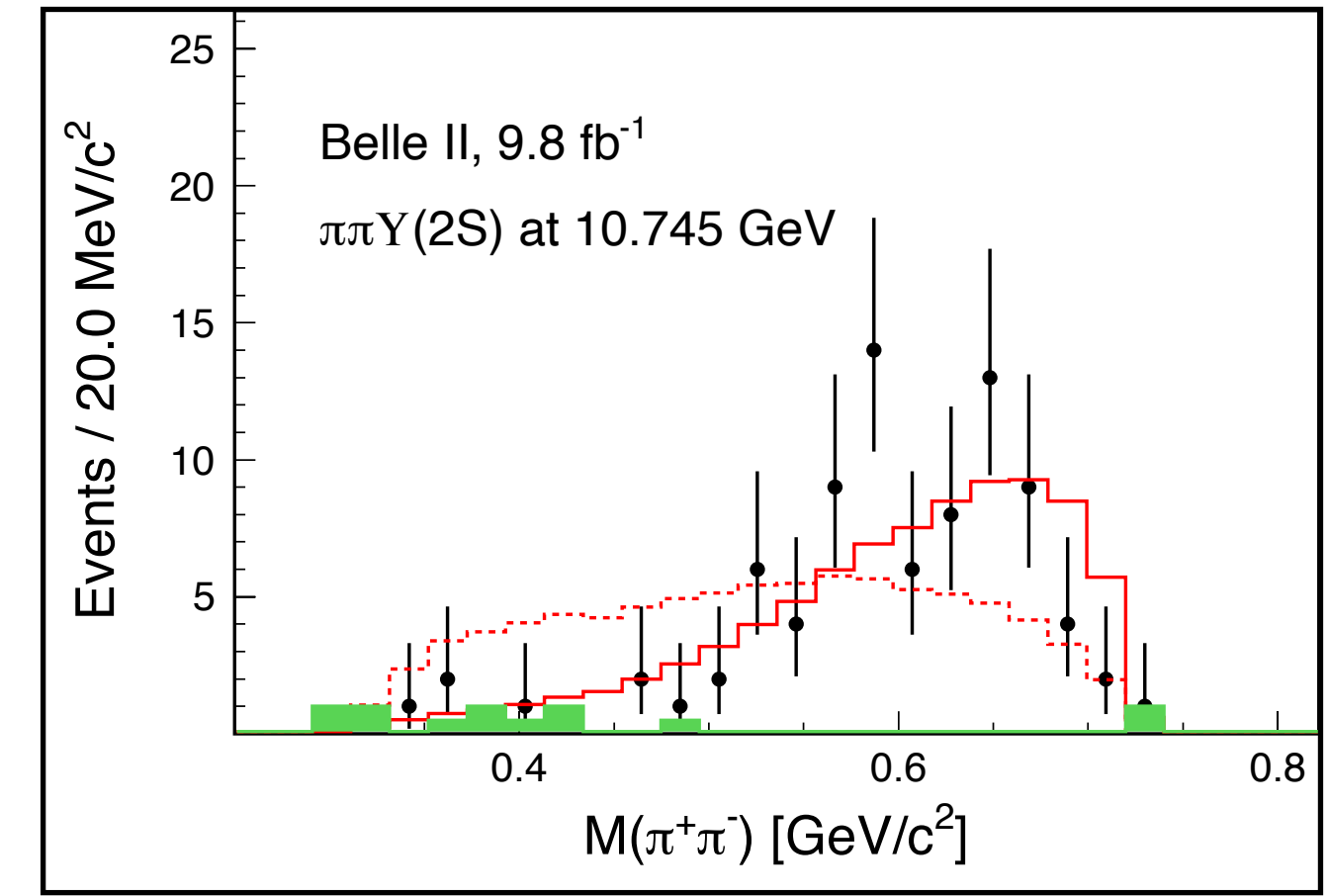
$$\frac{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(3S)}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(2S)} = 0.10^{+0.05}_{-0.04}$$

$$\frac{\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(1S)} = 0.45 \pm 0.04$$

$$\frac{\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(2S)}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(2S)} = 0.32^{+0.04}_{-0.03}$$

$$\frac{\Upsilon(6S) \rightarrow \pi^+\pi^-\Upsilon(1S)}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(1S)} = 0.64^{+0.23}_{-0.13}$$

$$\frac{\Upsilon(6S) \rightarrow \pi^+\pi^-\Upsilon(2S)}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(2S)} = 0.41^{+0.16}_{-0.12}$$



Mass spectrum of $\pi^+\pi^-$ similar as $\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$

No significant $\Upsilon(10753) \rightarrow \pi\pi\Upsilon(3S)$

Similarity between $\Upsilon(10753)$, $\Upsilon(5S)$, $\Upsilon(6S)$

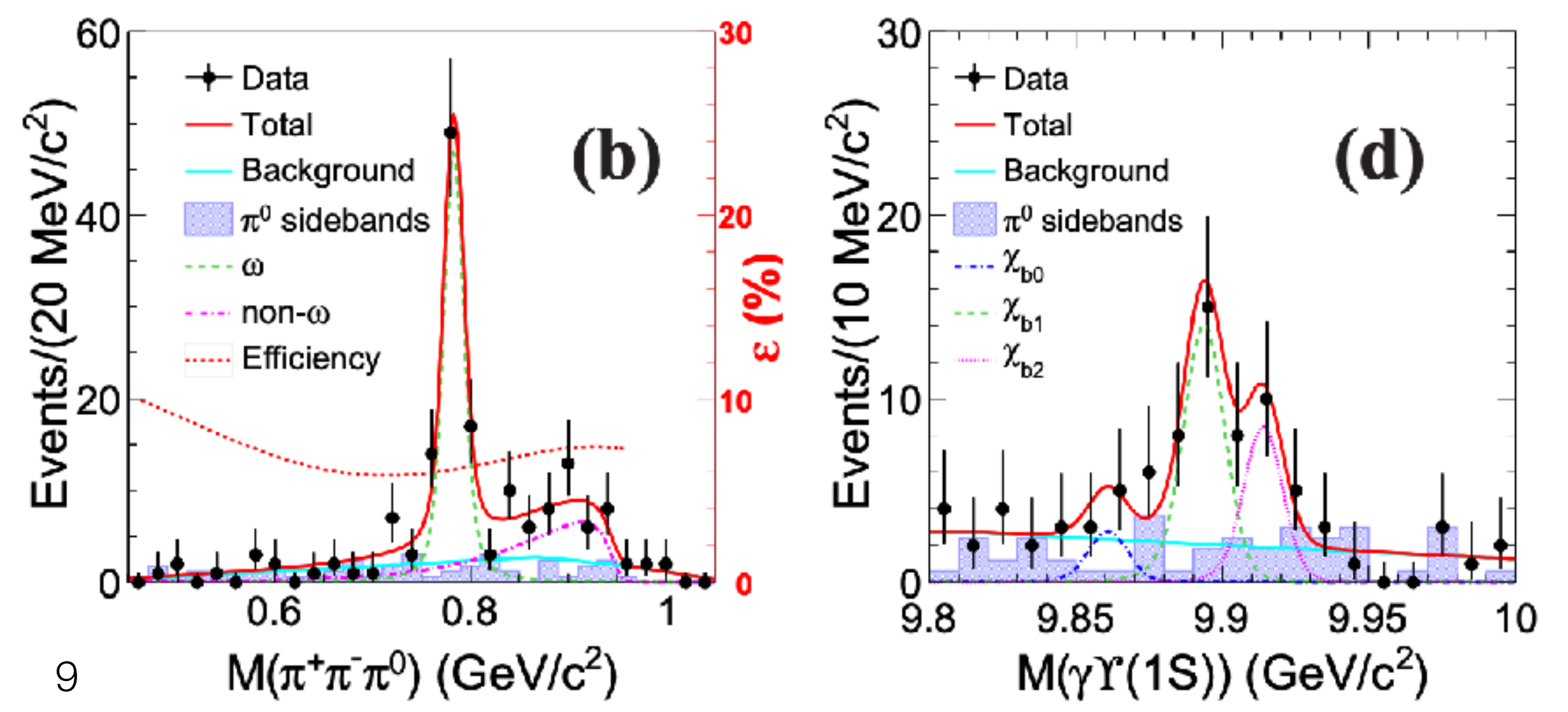
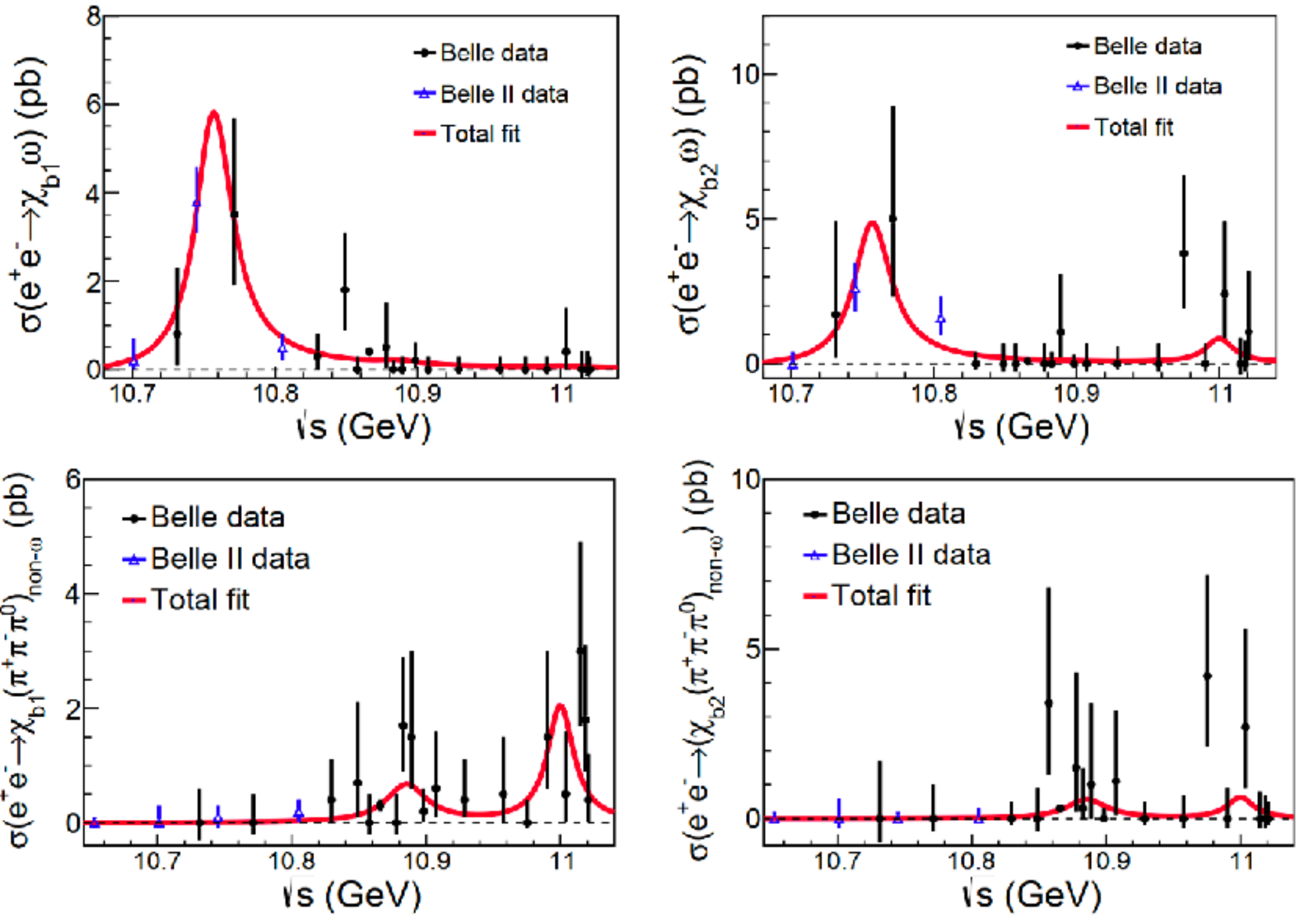
$\Upsilon(10753) \rightarrow \omega\chi_{bJ}$

$$\frac{\Upsilon(10753) \rightarrow \omega\chi_{bJ}}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)} \sim 1.5 @ 10.75 \text{ GeV}$$

$$\frac{\Upsilon(10753) \rightarrow \omega\chi_{bJ}}{\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)} \sim 0.15 @ 10.81 \text{ GeV}$$

Indicate different inner structure between $\Upsilon(10753)$ and $\Upsilon(5S)$

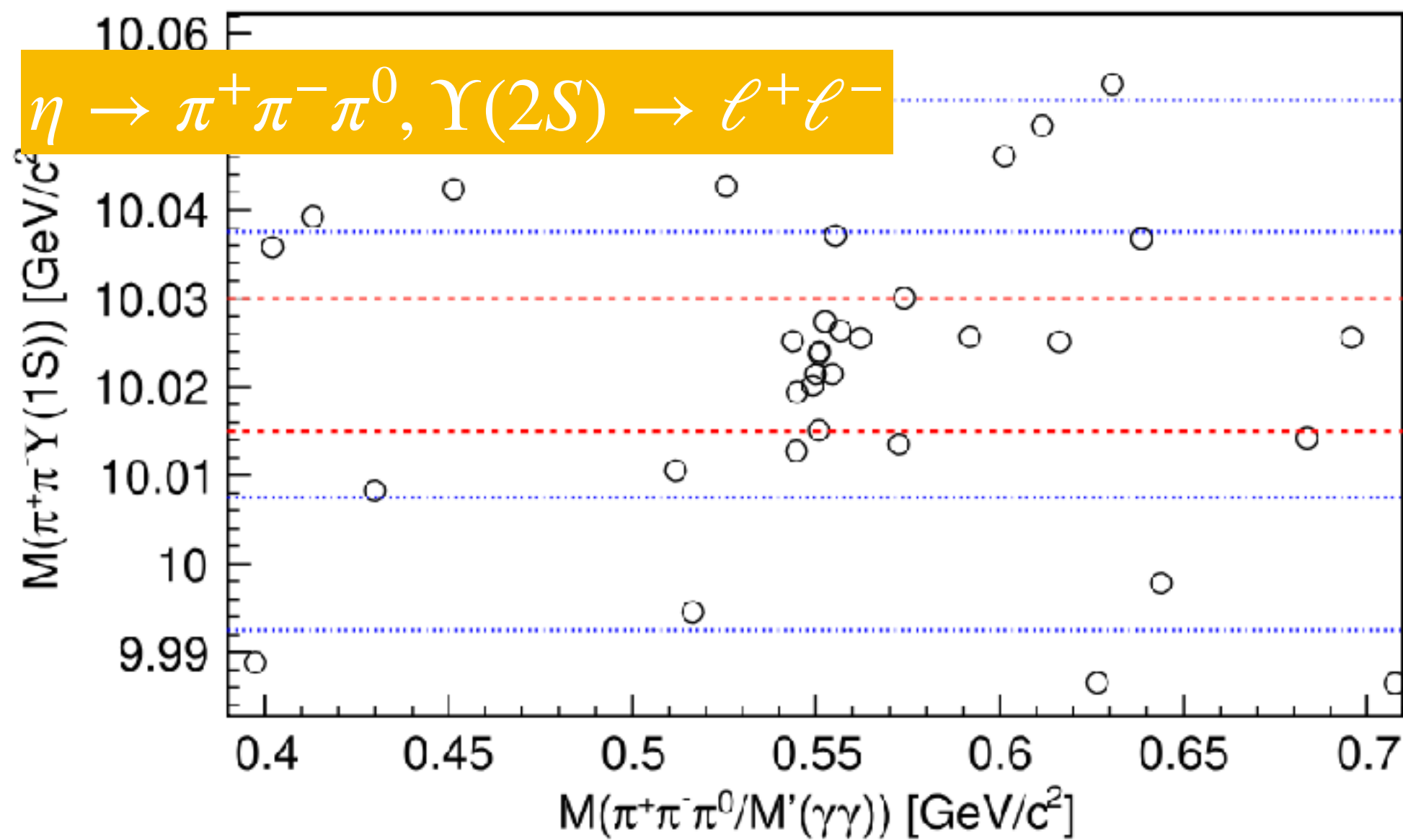
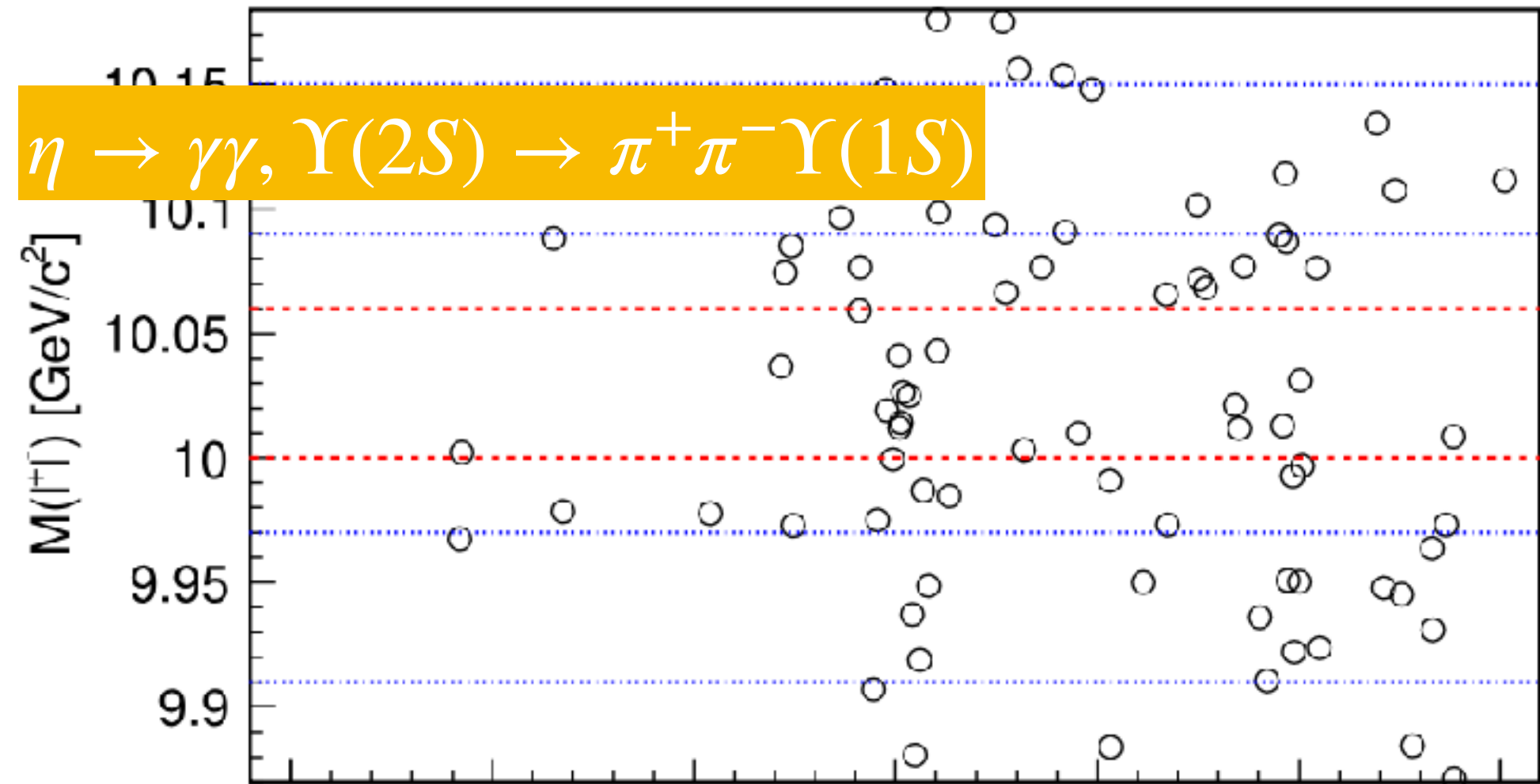
$$\frac{\Upsilon(10753) \rightarrow \omega\chi_{b1}}{\Upsilon(10753) \rightarrow \omega\chi_{b2}} = 1.13 \pm 0.38 \pm 0.34$$



The $(\pi^+\pi^-\pi^0)_{(non-\omega)}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(5S,6S) \rightarrow Z_b\pi \rightarrow [\chi_{bJ}\rho]\pi$ [PRD 90, 014036 (2014)].

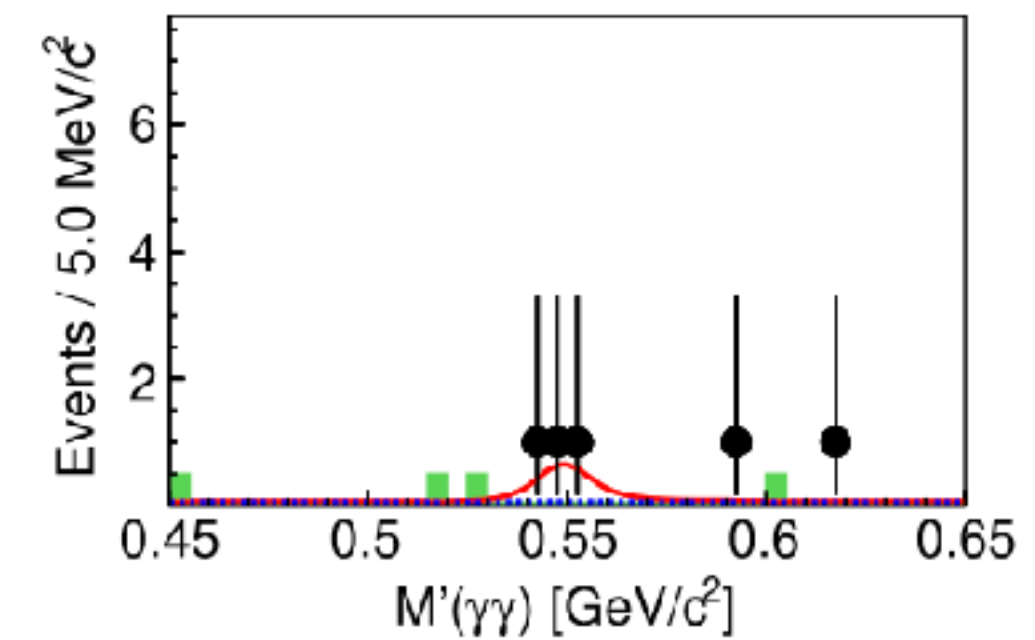
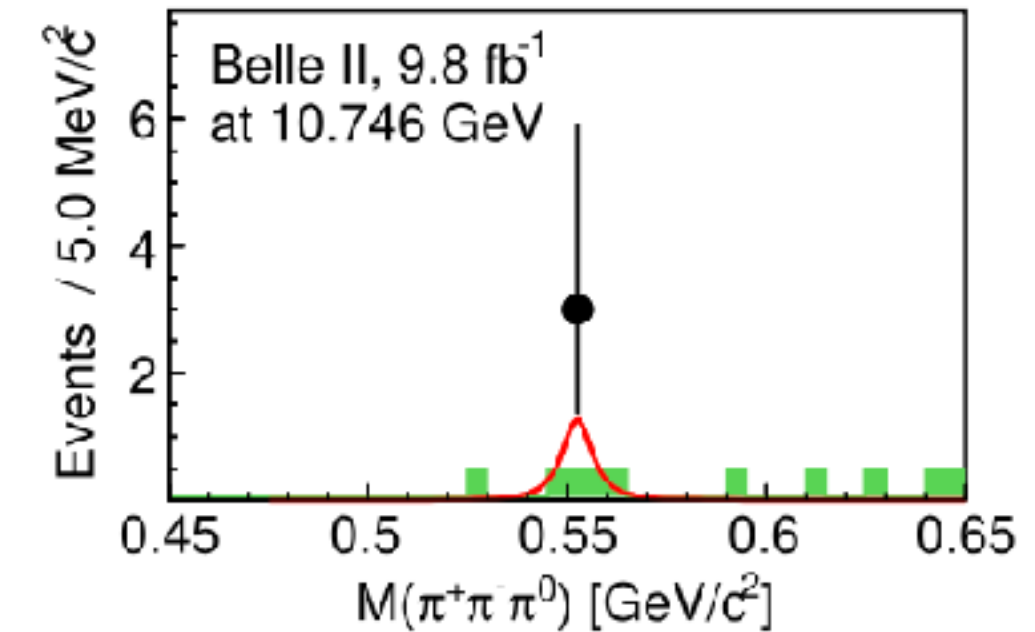
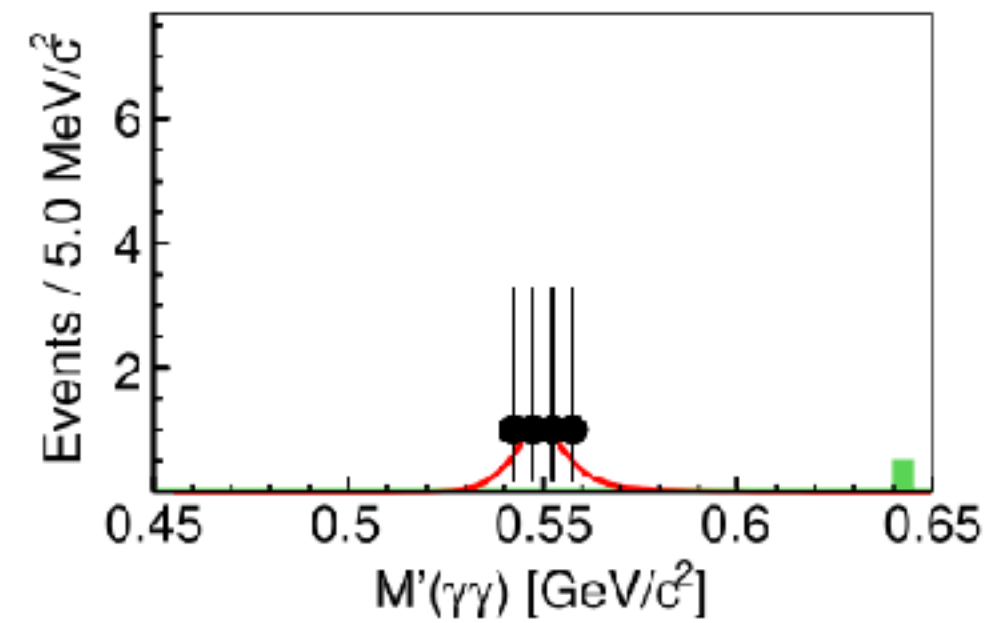
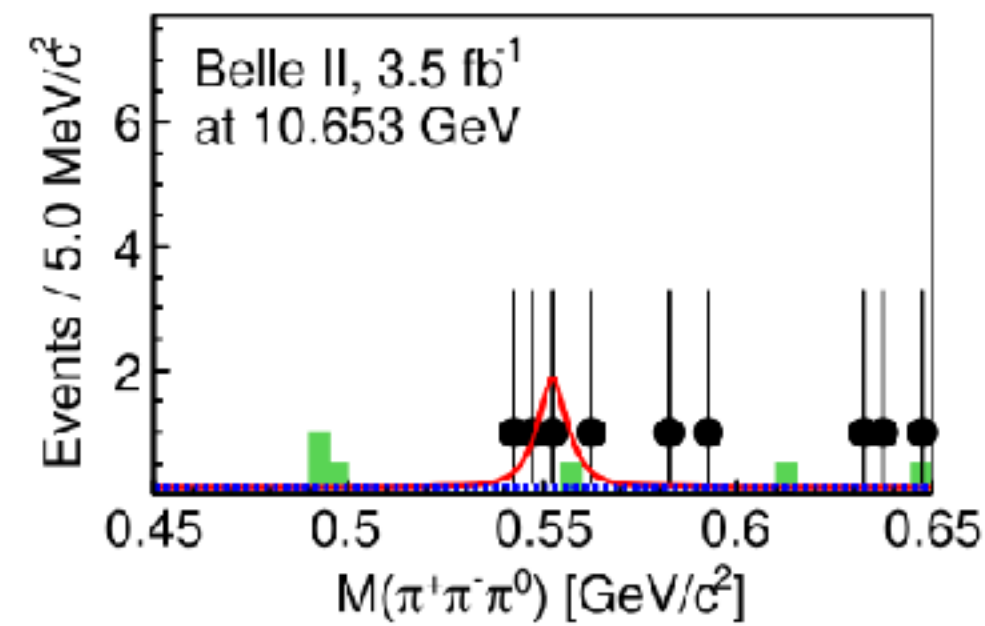
$\Upsilon(10753) \rightarrow \eta \Upsilon(2S)$

Belle II, $L_{\text{int}} = 19.6 \text{ fb}^{-1}$



Clear signal is seen.

Equivalent signal yields at 10.610 GeV as 10.75 GeV but much less luminosity.

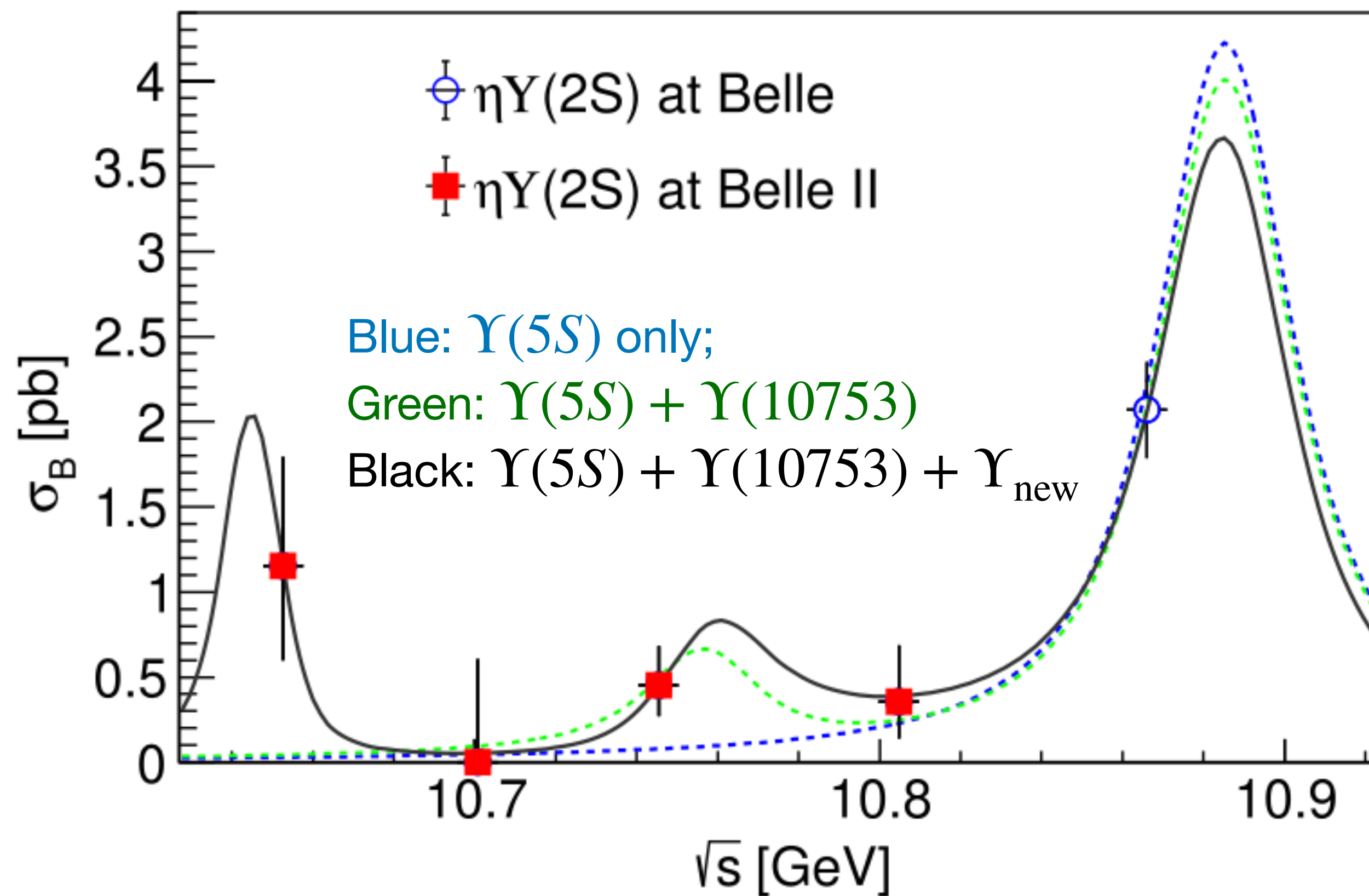


$$\frac{e^+e^- \rightarrow \eta \Upsilon(2S)}{e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)} > 23 \text{ @ } 10.65 \text{ GeV}, \sim 0.31 \text{ @ } 10.75 \text{ GeV}$$

Strong violation of HQSS, comparing with $\mathcal{O}(10^{-3})$ for $\Upsilon(1,2S)$

Possibility of a new $B^*\bar{B}^*$ bound state?

Unbinned maximum likelihood fit to the σ^{Born} together with Belle measurement.

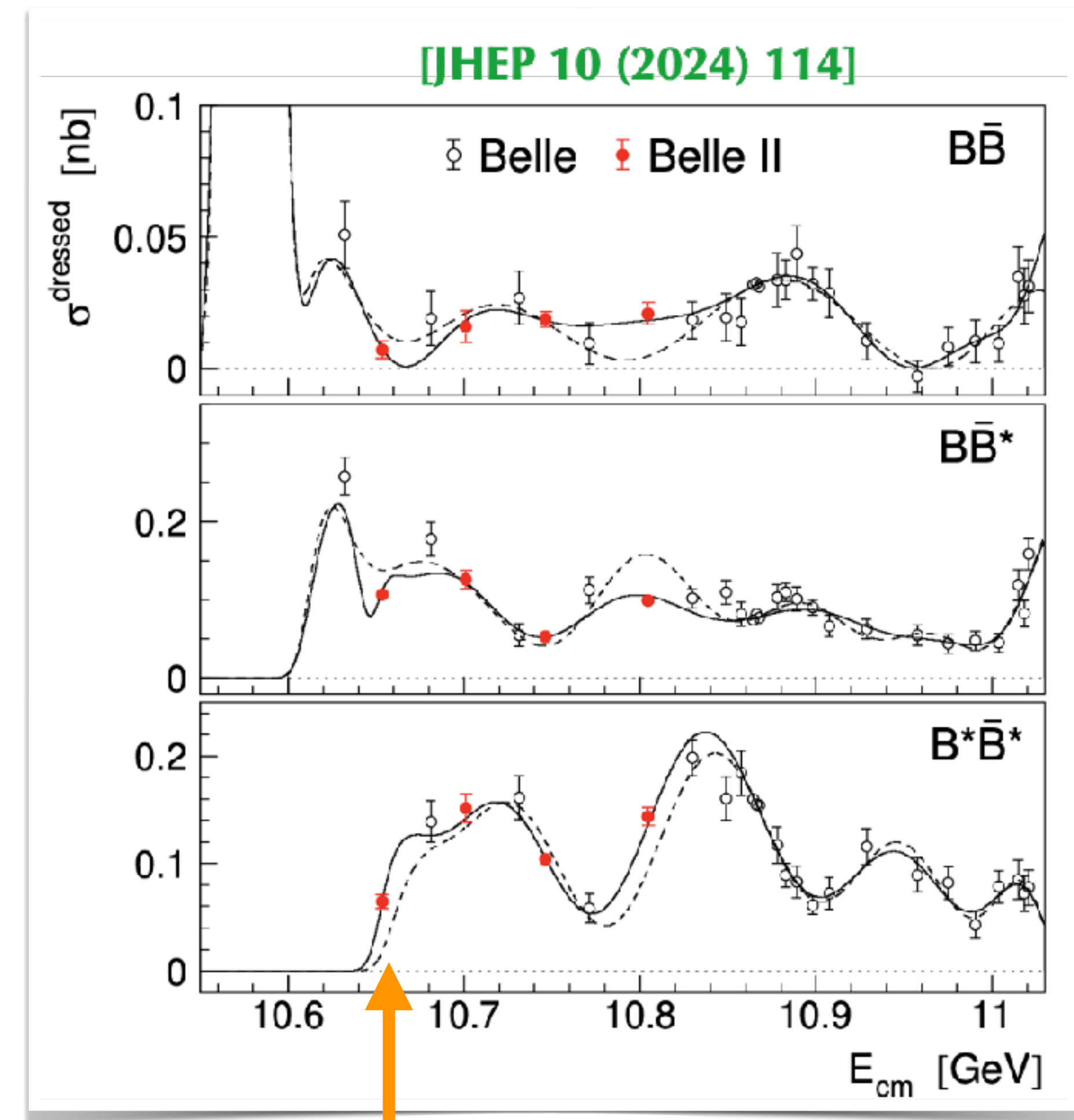


Parameters of Y_{new} fixed to:

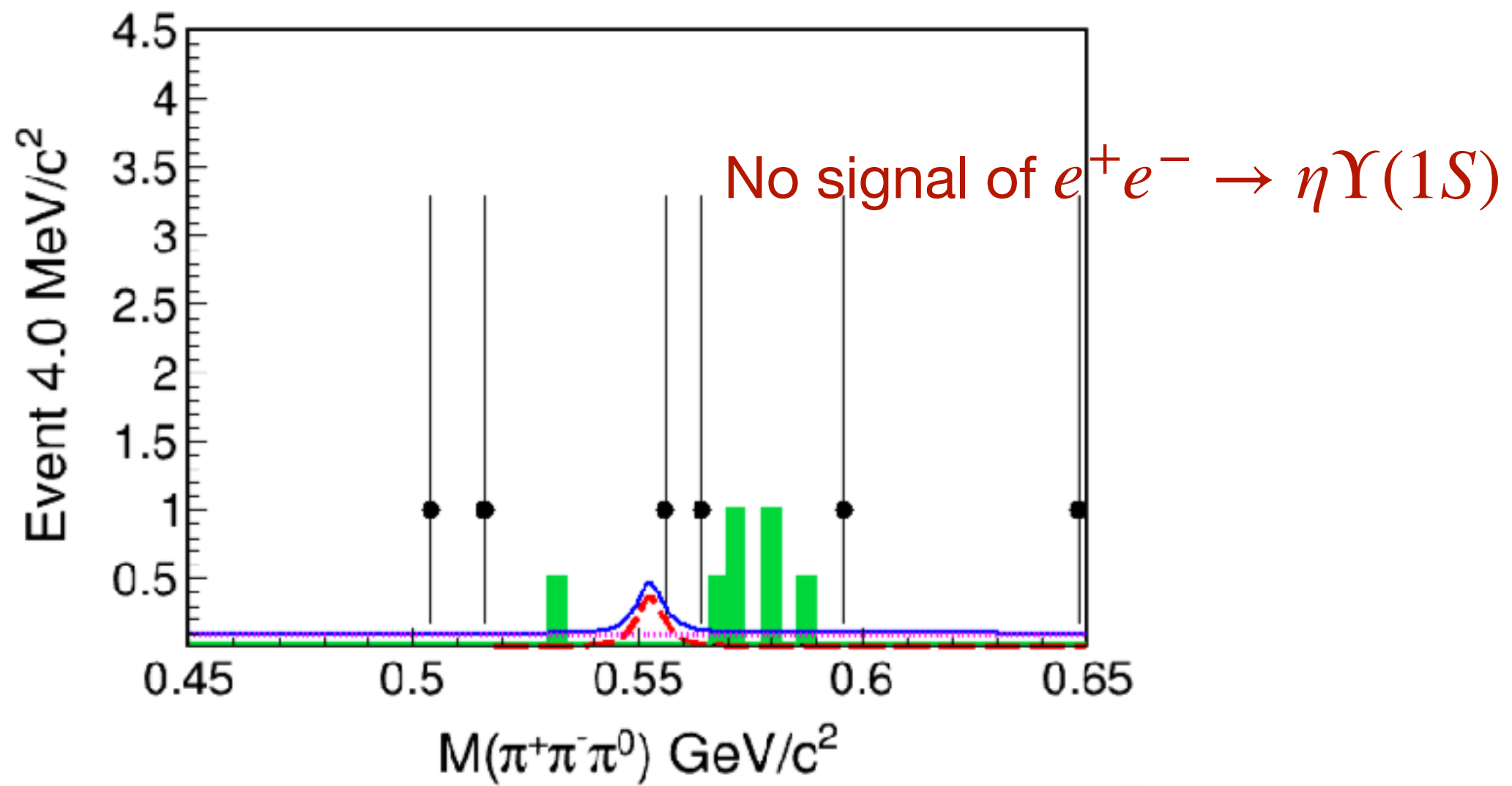
$m = 10645 \text{ MeV}/c^2$, $\Gamma = 9 \text{ MeV}$ obtained from $e^+e^- \rightarrow B^{(*)}\bar{B}^{(*)}$.

Only Hint of Y_{new} is found.

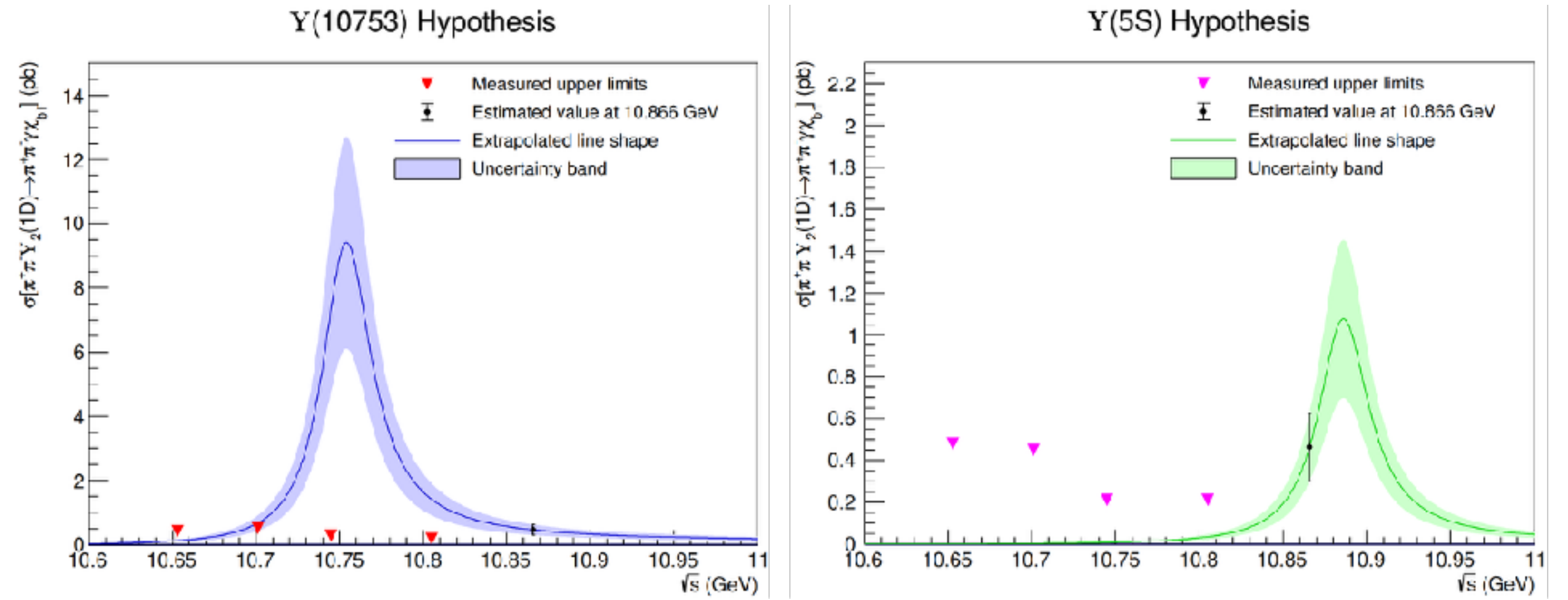
$Y_b(10650)$ is predicted in Refs. [[arXiv:2505.02742](https://arxiv.org/abs/2505.02742), [arXiv:2508.11127](https://arxiv.org/abs/2508.11127), [arXiv:2505.03647](https://arxiv.org/abs/2505.03647)].



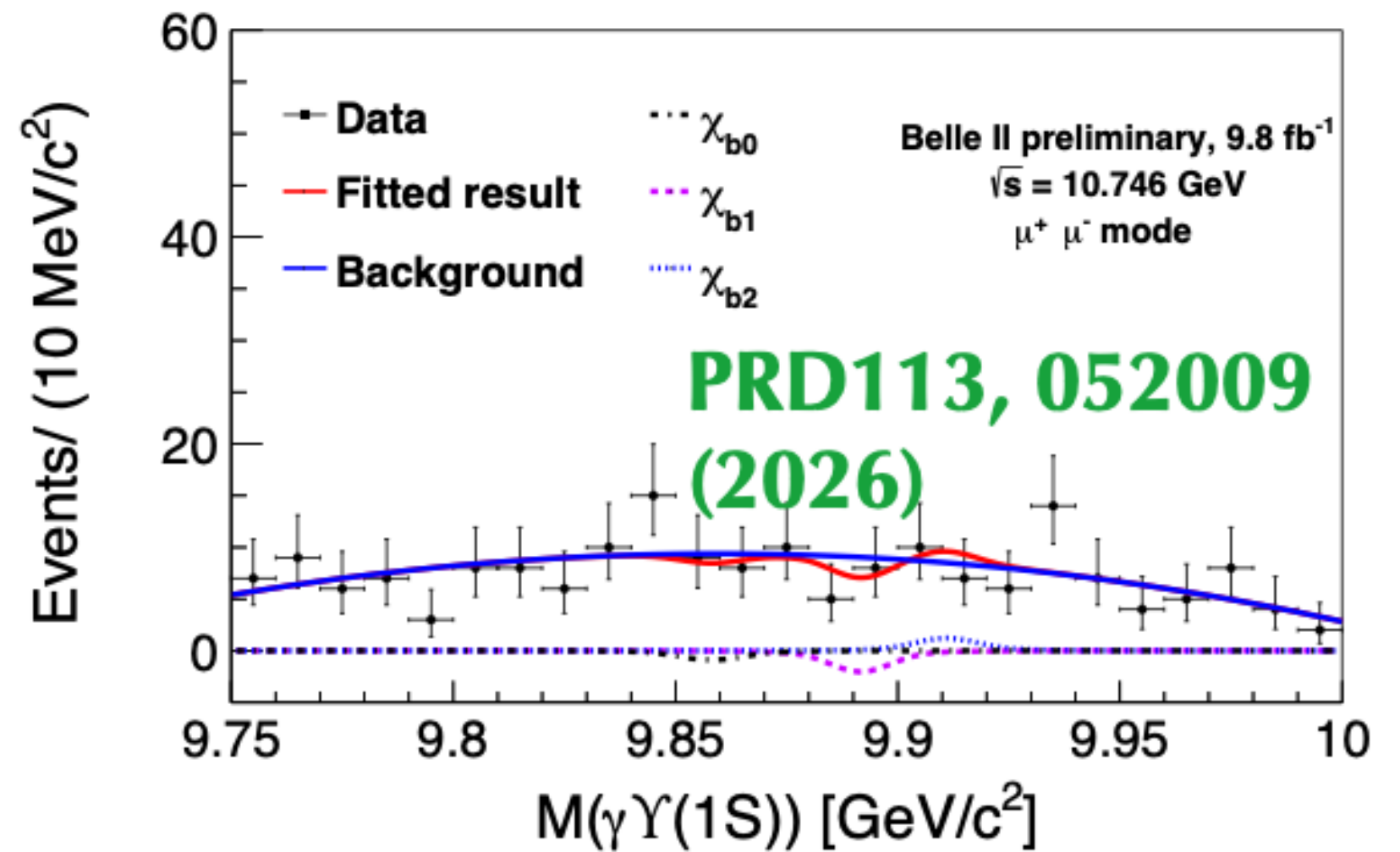
Rapid increase of $\sigma(B^*\bar{B}^*)$ just above the threshold



$$Y(10753) \rightarrow \pi^+ \pi^- Y_2(1D)$$



No signal of $e^+e^- \rightarrow \gamma \chi_{bJ}$

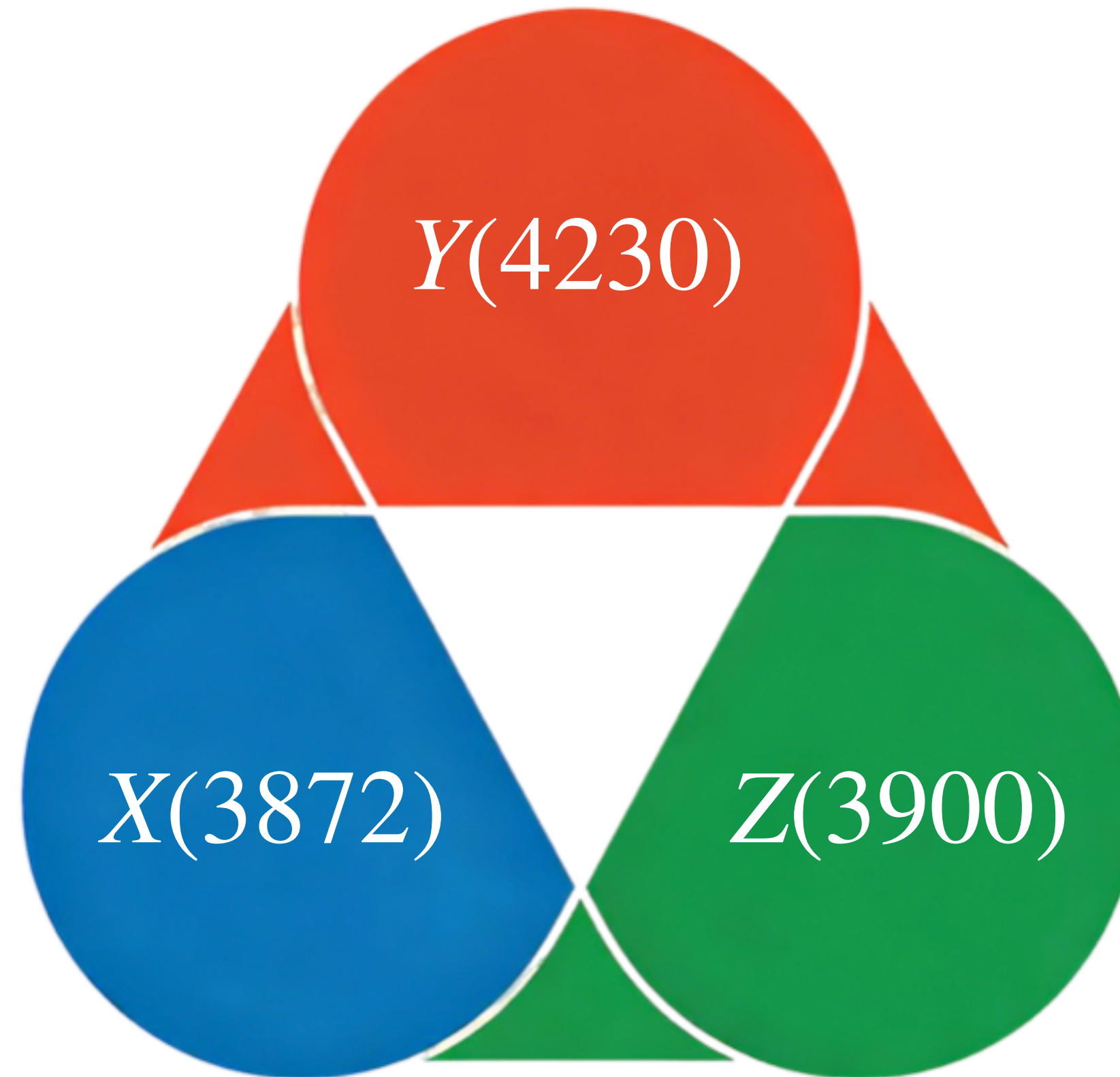


No signal of $e^+e^- \rightarrow \pi^+ \pi^- Y_{2/3}(1D)$.

The upper limits do not conflict with the $Y(5S)$ line shape.

Much smaller Born cross sections than $e^+e^- \rightarrow \omega \chi_{bJ}$ and $e^+e^- \rightarrow \pi^+ \pi^- Y(nS)$

$\Upsilon(10753)$ correlation to XYZ?

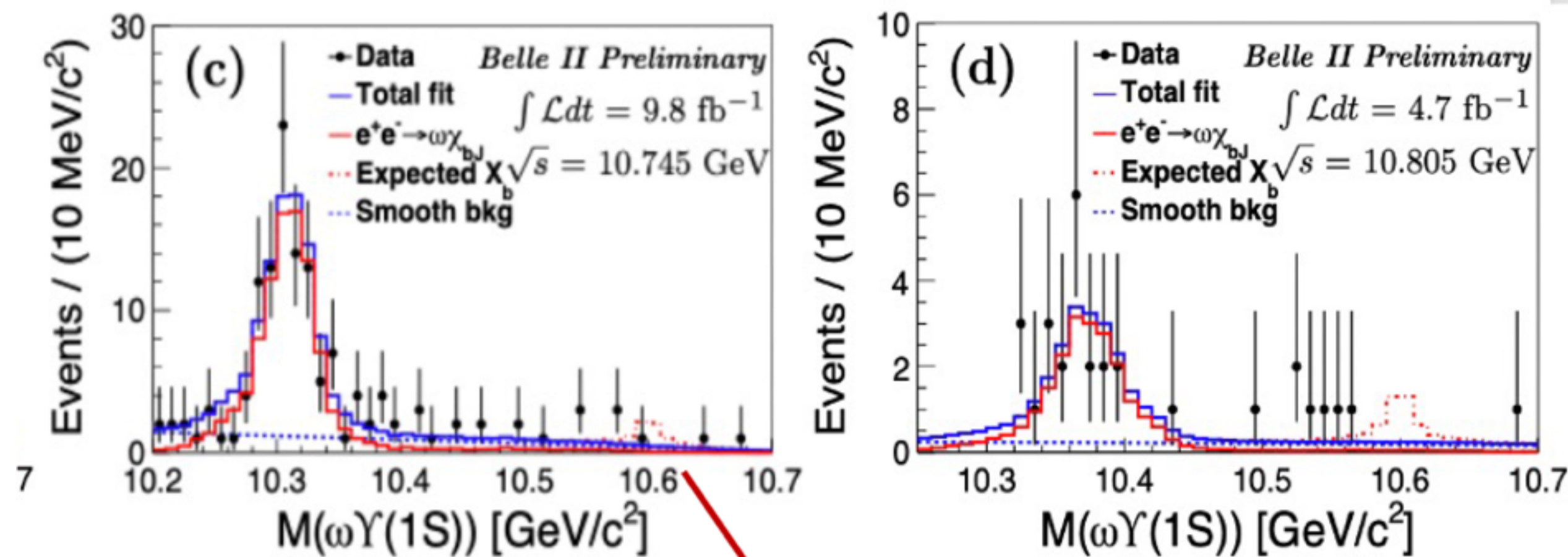


$Y(4230)$, another quarkonium-(like) state which was also found in $e^+e^- \rightarrow \pi\pi J/\psi$ and $\omega\chi_{c0}$.

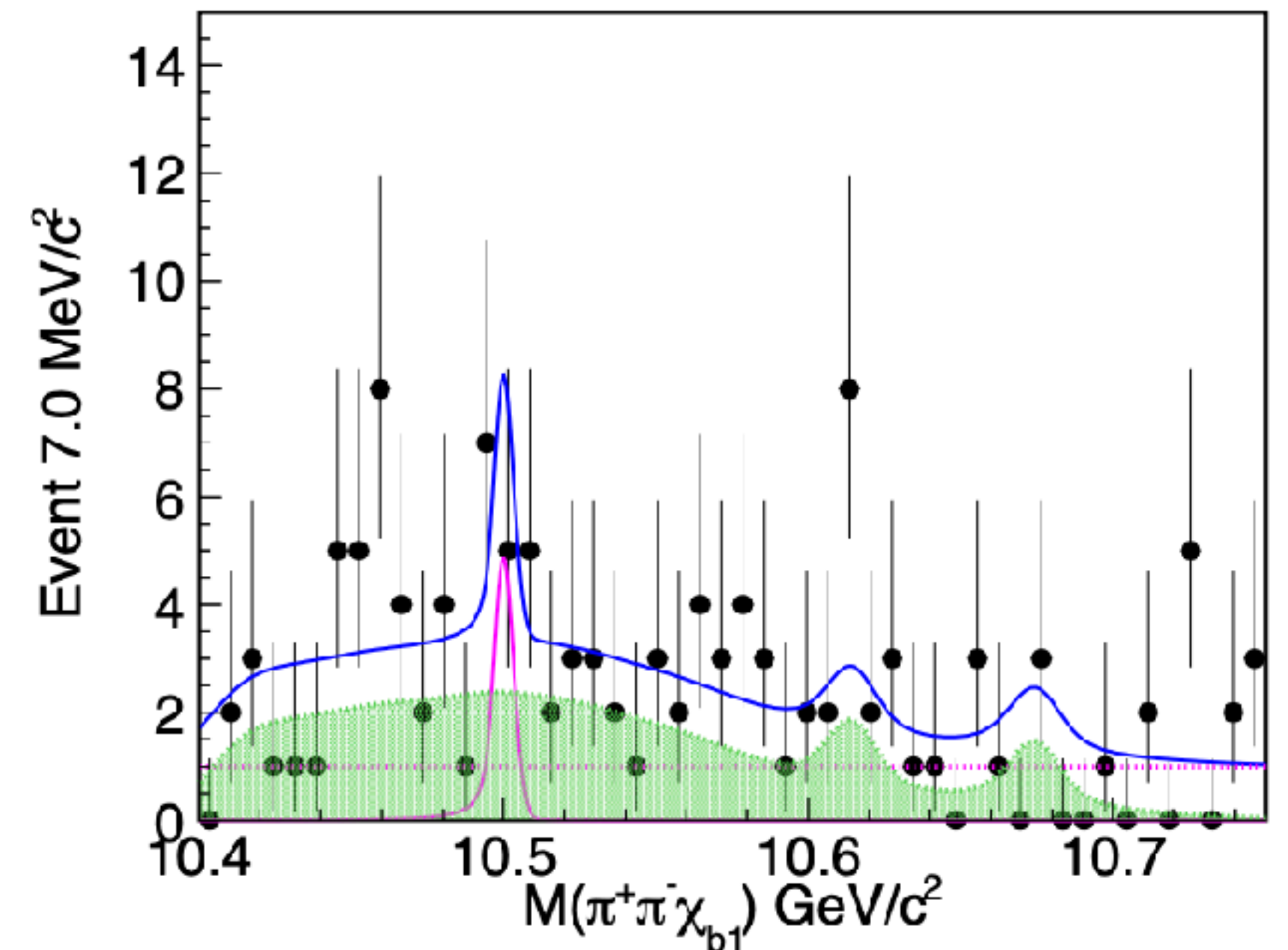
$\Upsilon(10753)$ may also have a strong coupling to X_b or Z_b .

$$\Upsilon(10753) \rightarrow \gamma X_b$$

The partner of $X(3872)$ in bottomonium sector, namely X_b , is predicted to decay to $\omega\chi_{bJ}$, $\pi\pi\chi_{bJ}$, $\pi\pi\Upsilon(nS)$, etc.

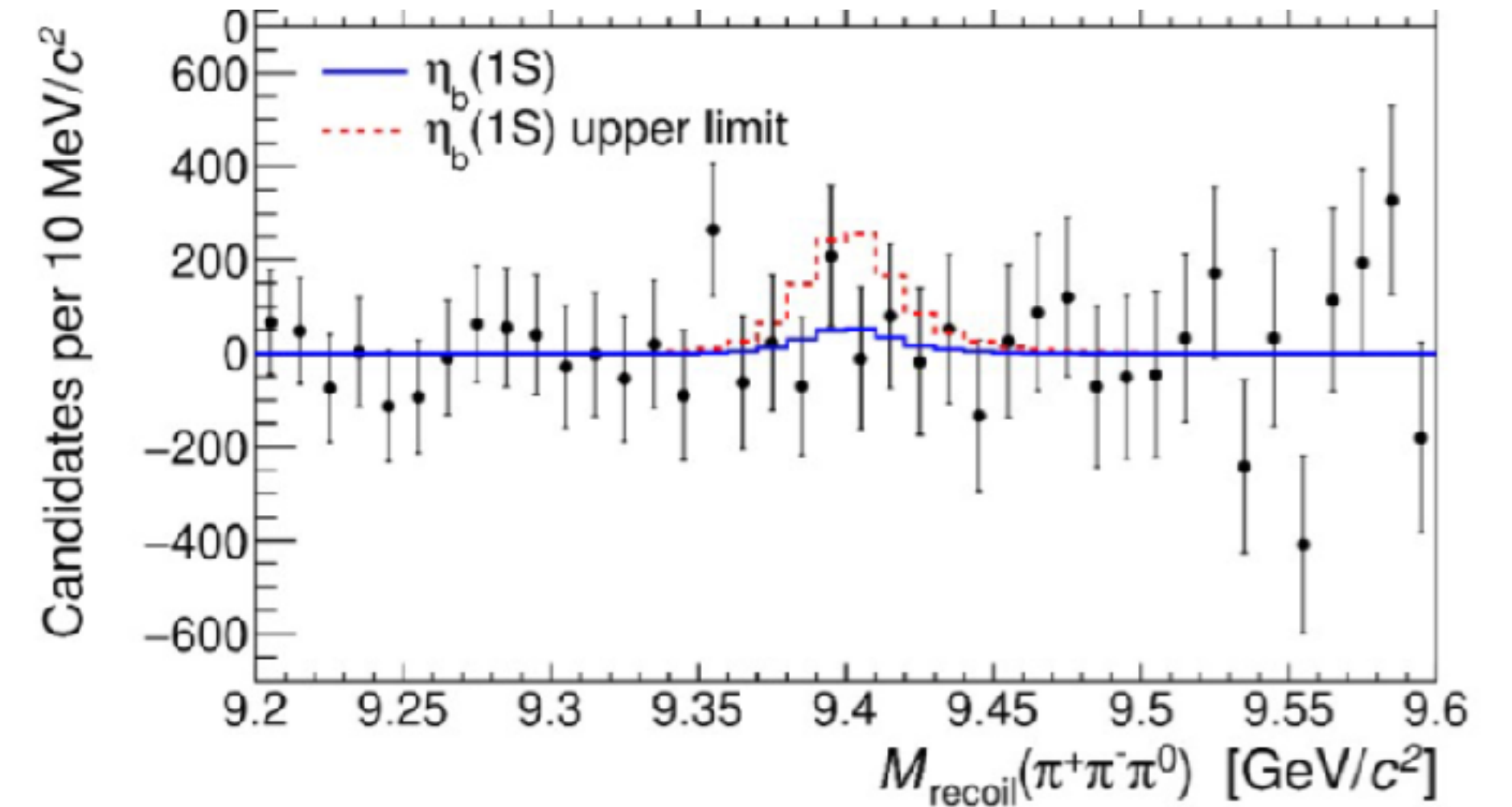
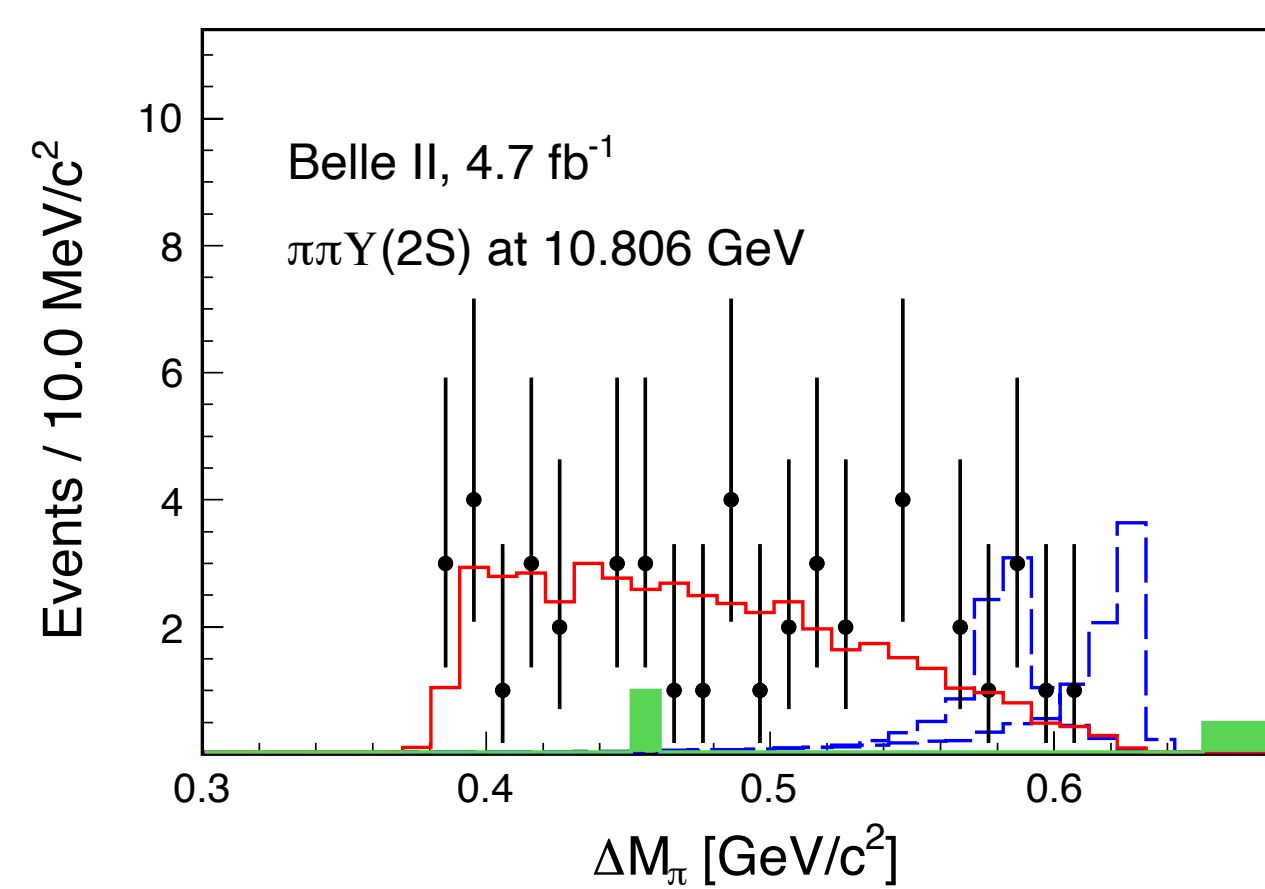
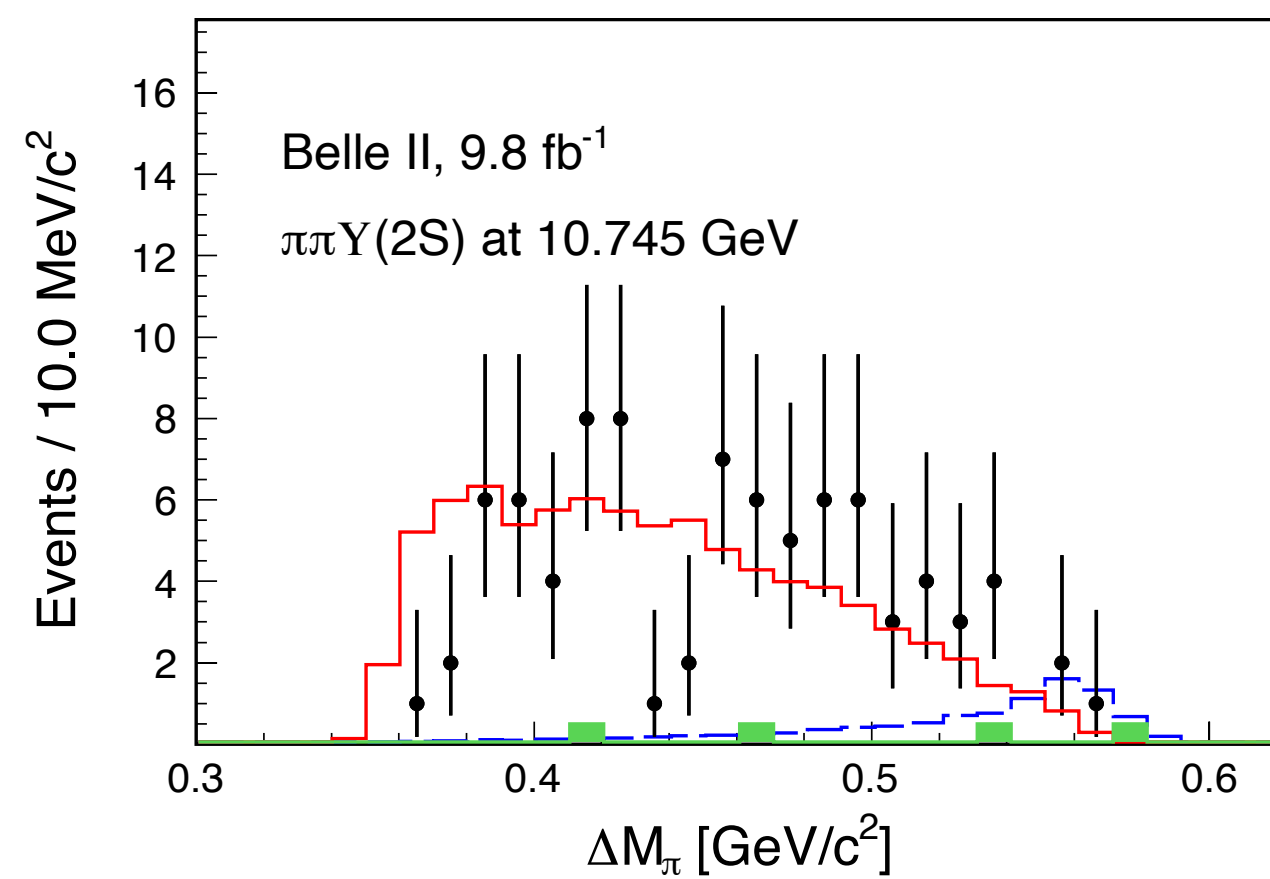
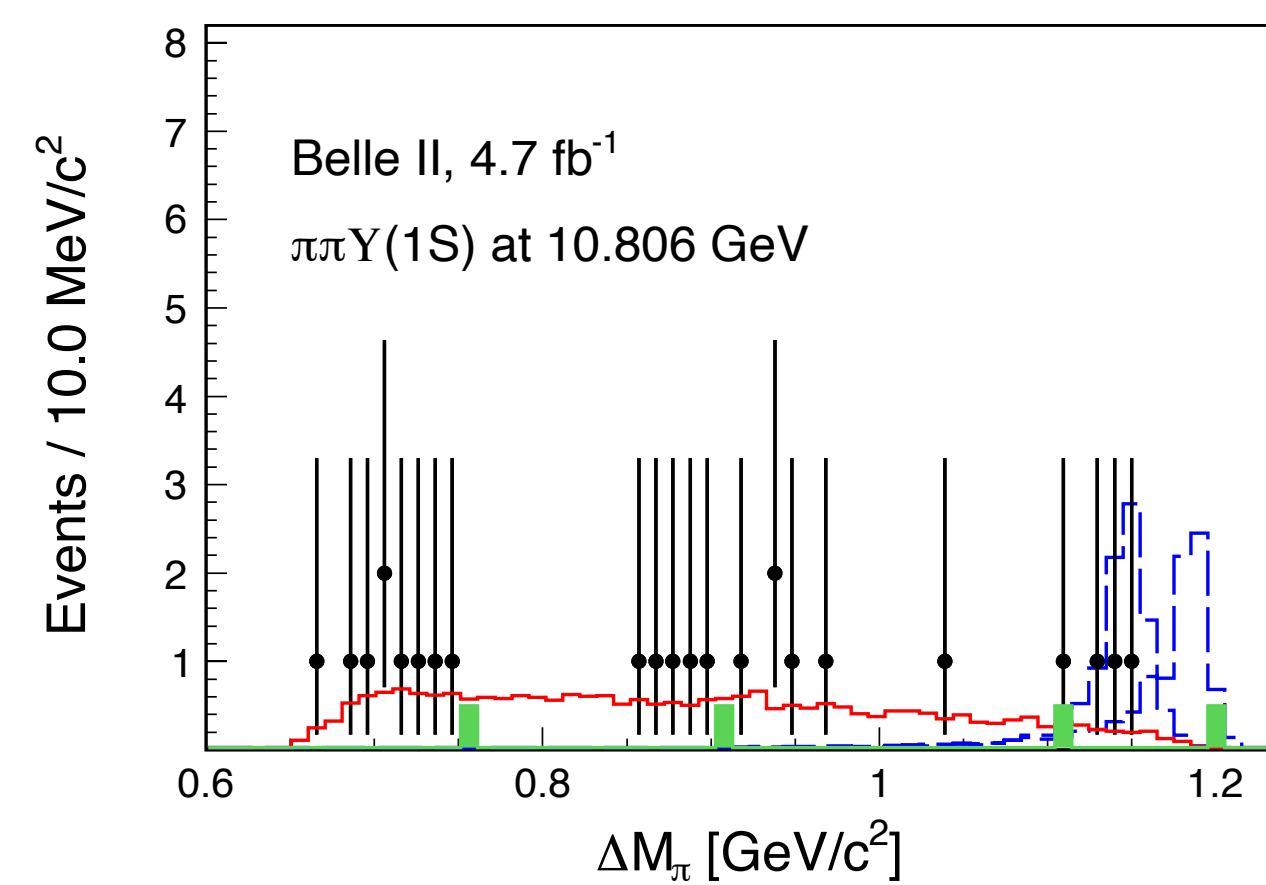
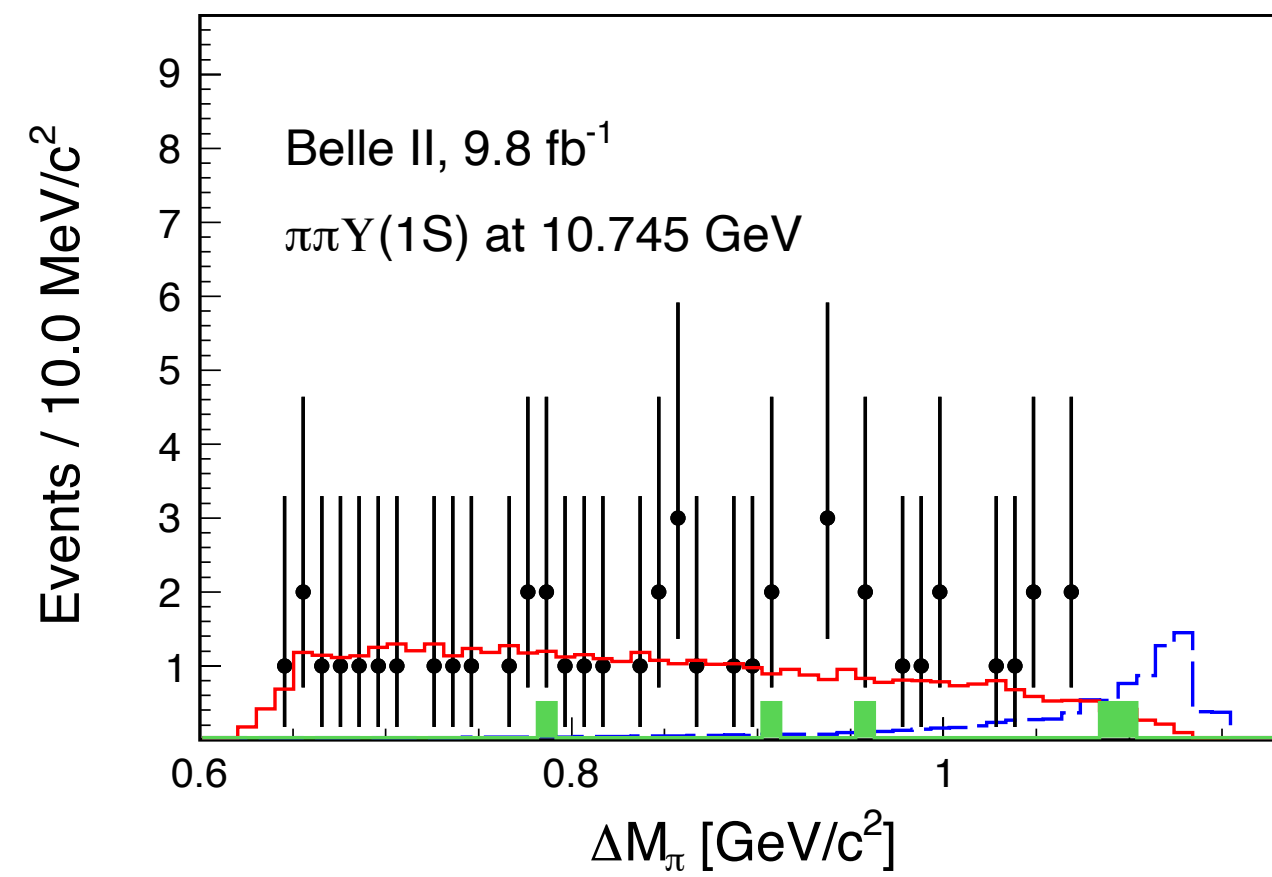


From simulated events with $m(X_b) = 10.6 \text{ GeV}/c^2$
The yield is fixed at the upper limit at 90% C.L.



No evidence is found in neither $X_b \rightarrow \omega\chi_{bJ}$ nor $X_b \rightarrow \pi^+\pi^-\chi_{bJ}$

$$\Upsilon(10753) \rightarrow \pi^\mp Z_b^\pm$$

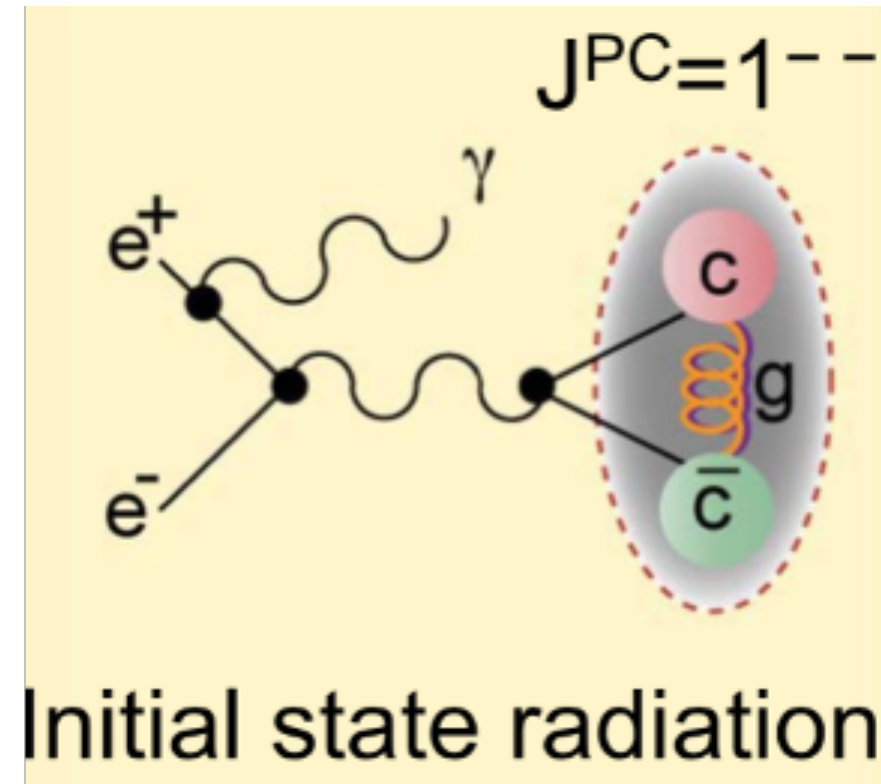


Spin flip if exotic nature inside,
leads to possible large BF of
 $\Upsilon(10753) \rightarrow \omega\eta_b$ [CPC 43, 123102(2019)].

No evidence found.

No Evidence of $Z_b(10610/10650)$.

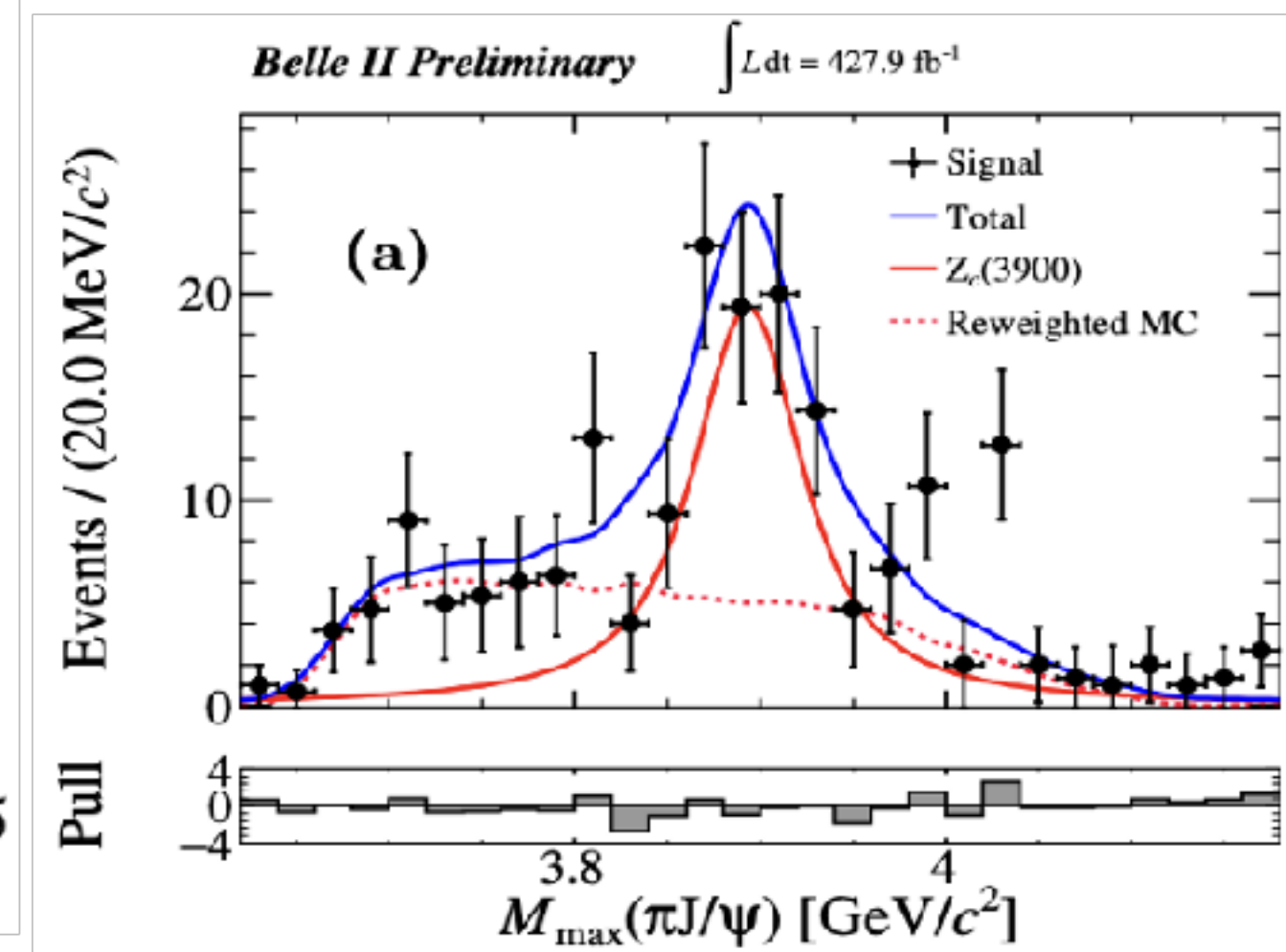
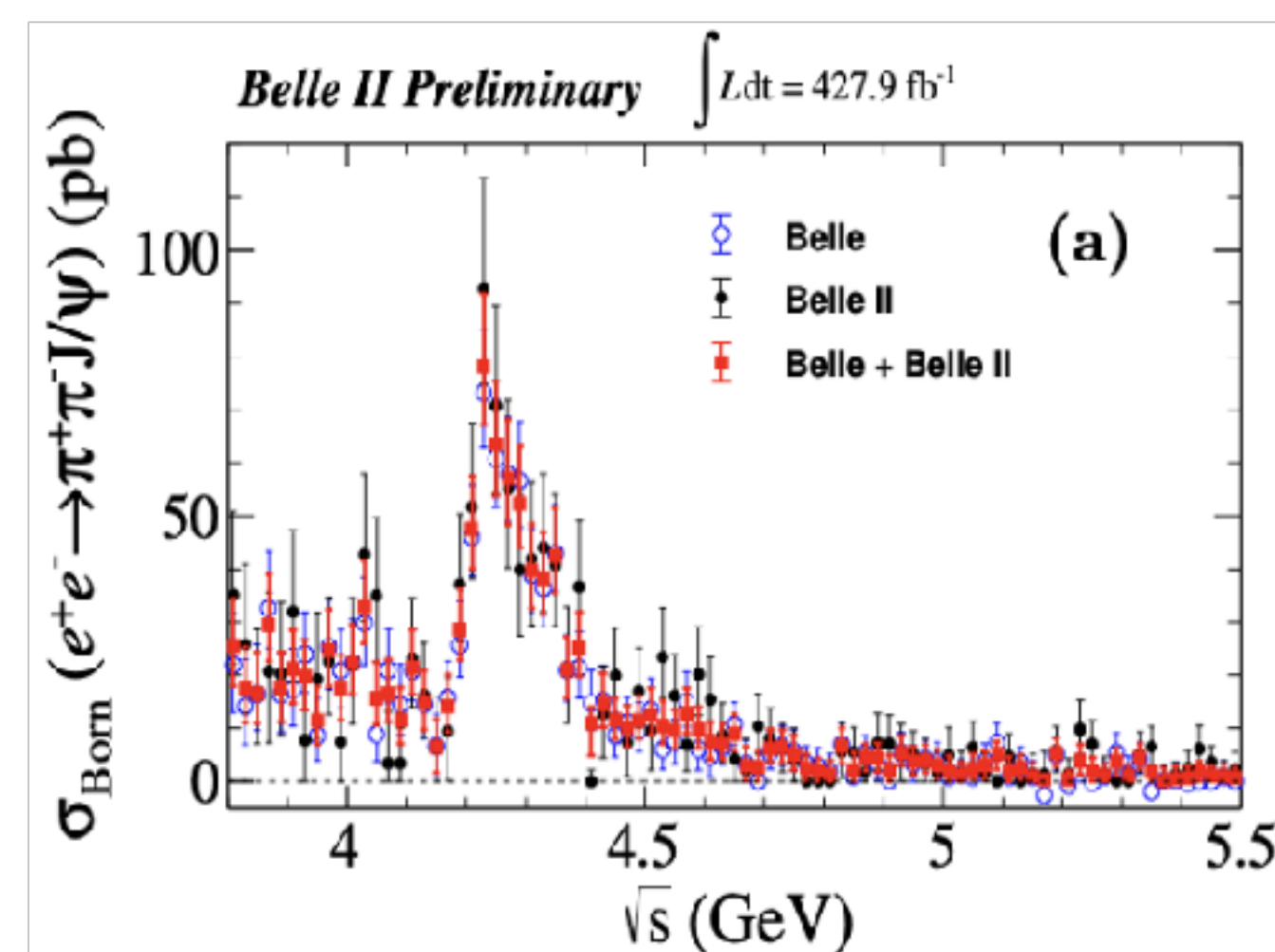
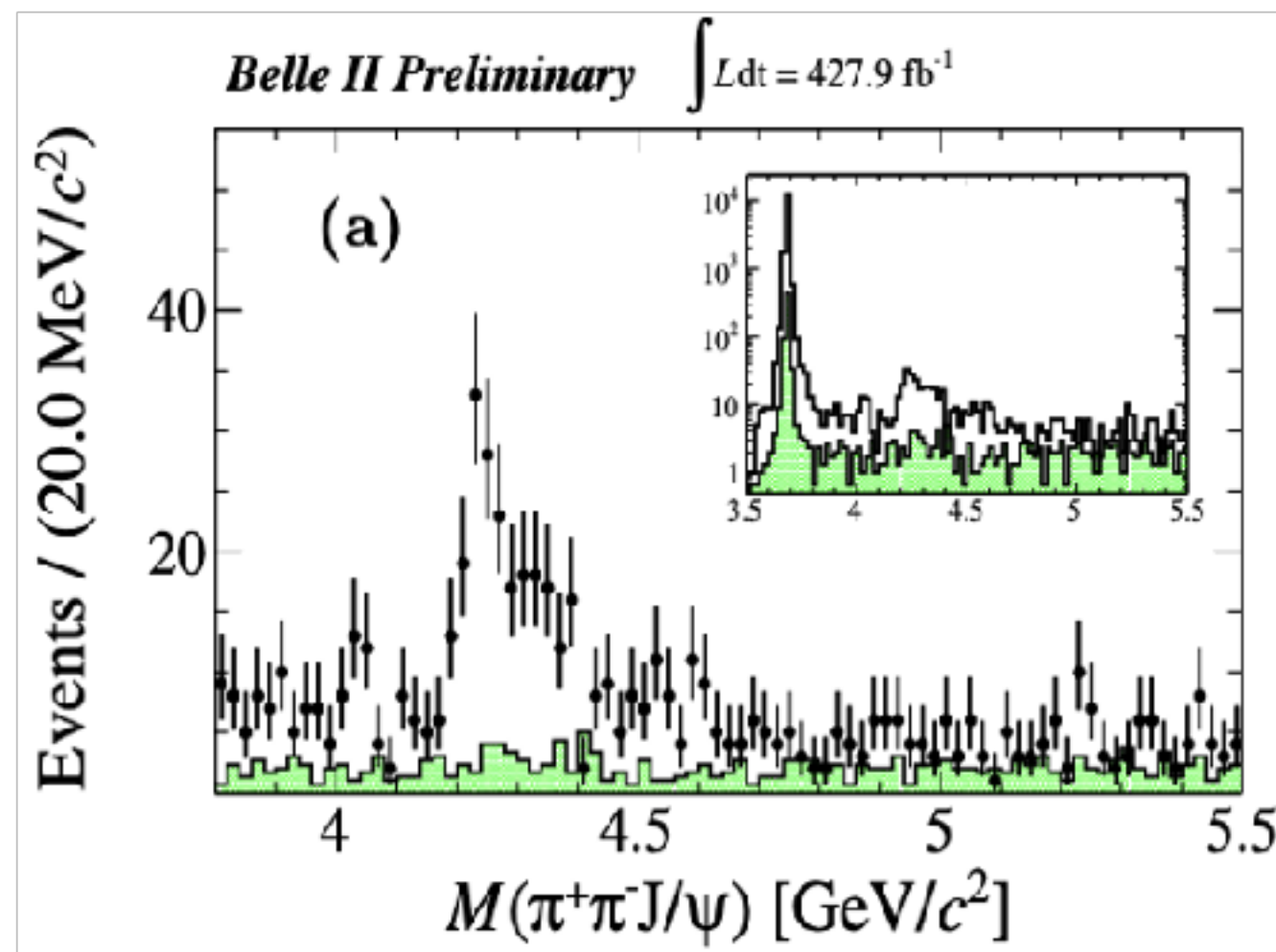
Other spectroscopy studies



Advantages of ISR:

Allows to study energies below E_{cms} .

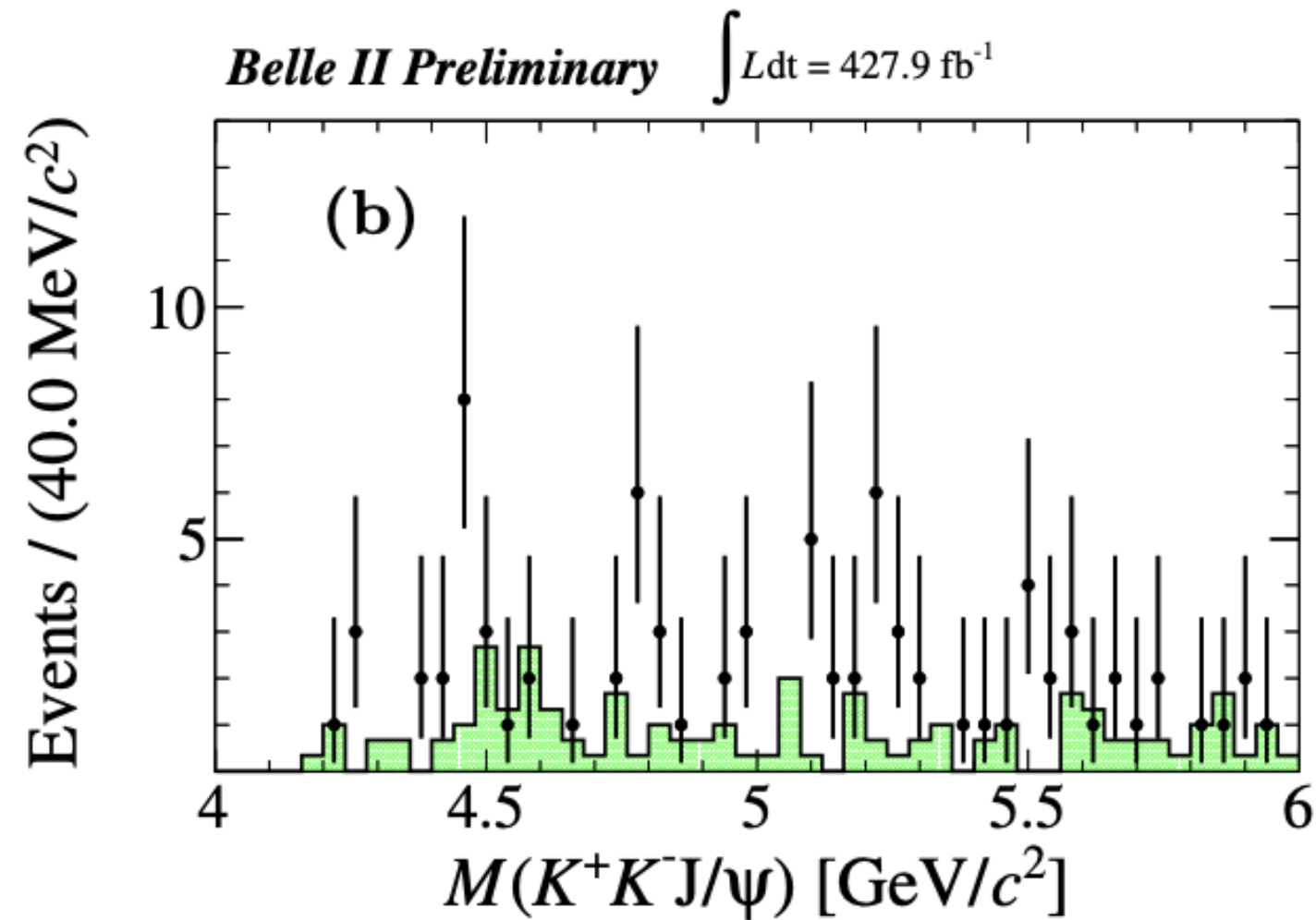
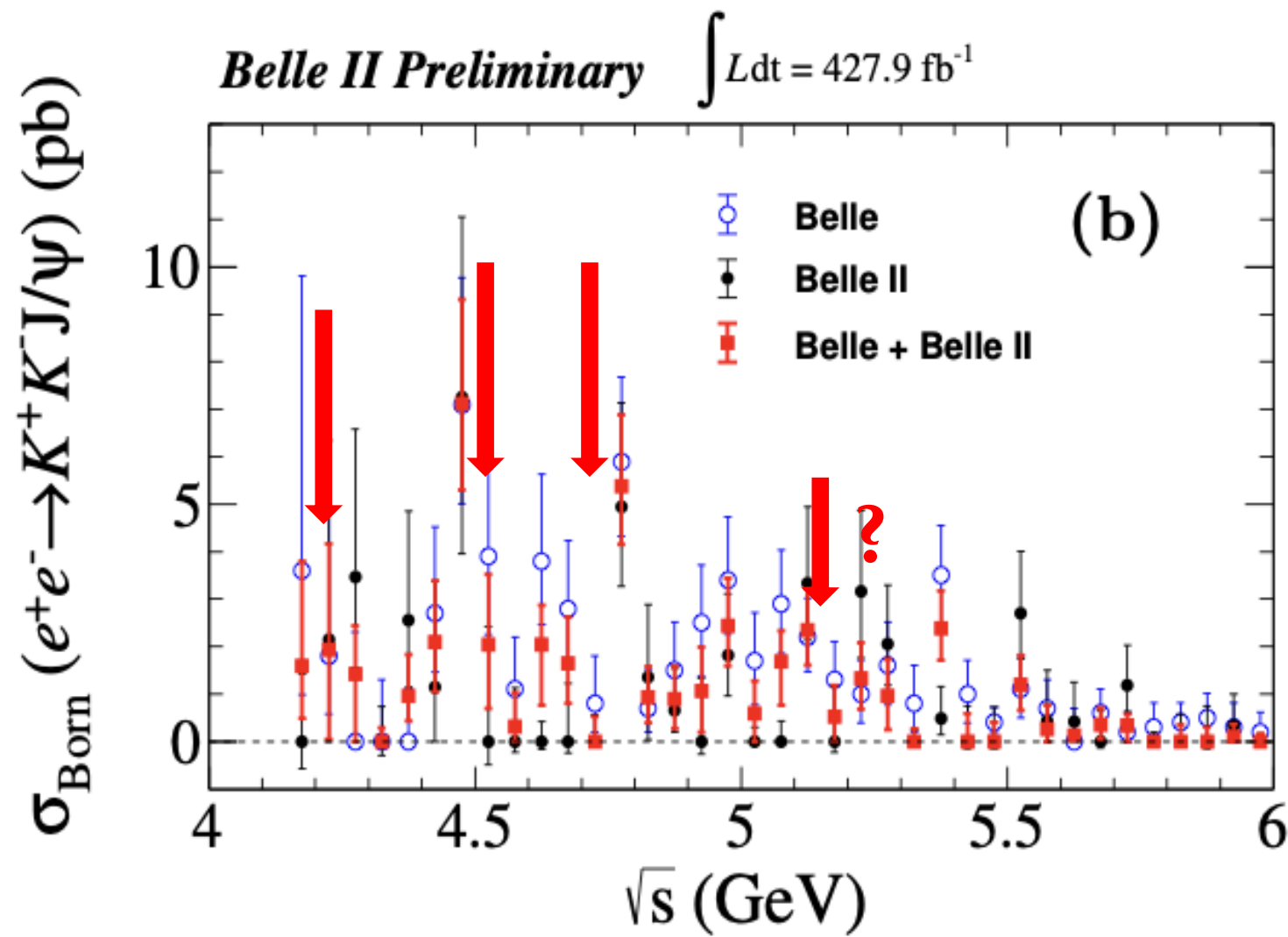
Wide energy range available.



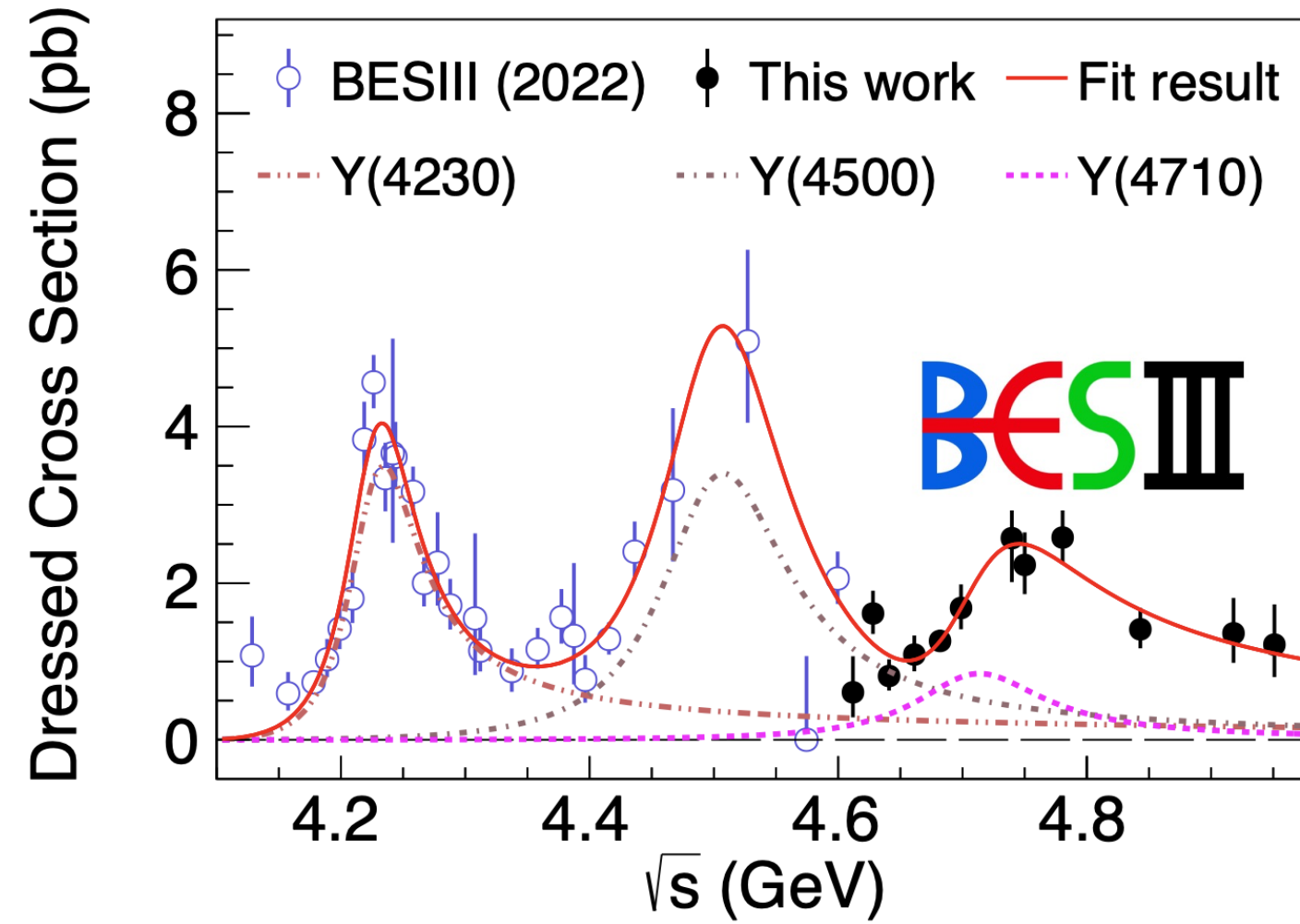
We can see the $Y(4008)$ evidence and $Y(4230/4320)$ signal.

The significance of $Z_c(3900)$ is 5.3σ , showing Belle II's potential of charmonium-(like) states studies.

$e^+e^- \rightarrow K^+K^-J/\psi$ via ISR:



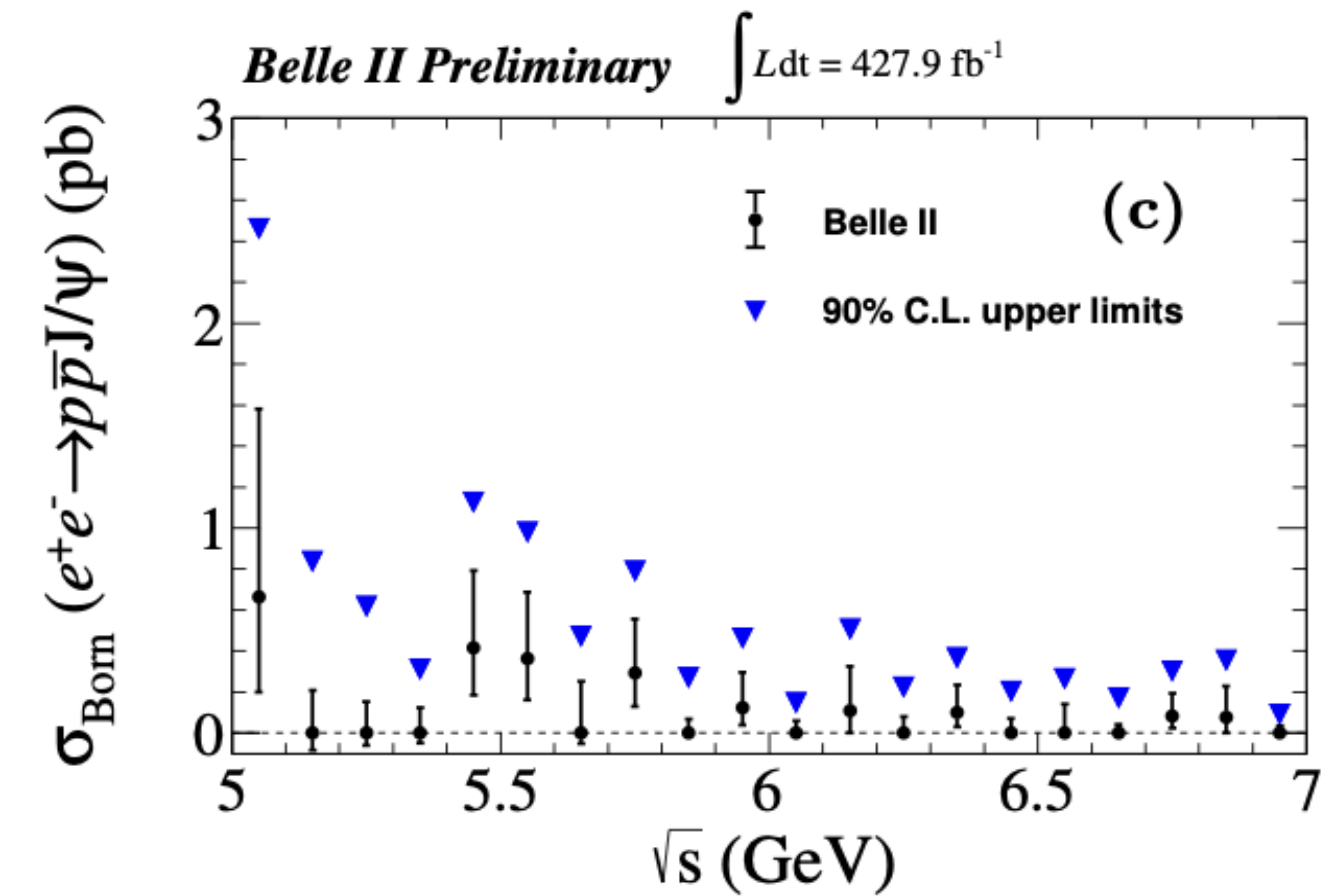
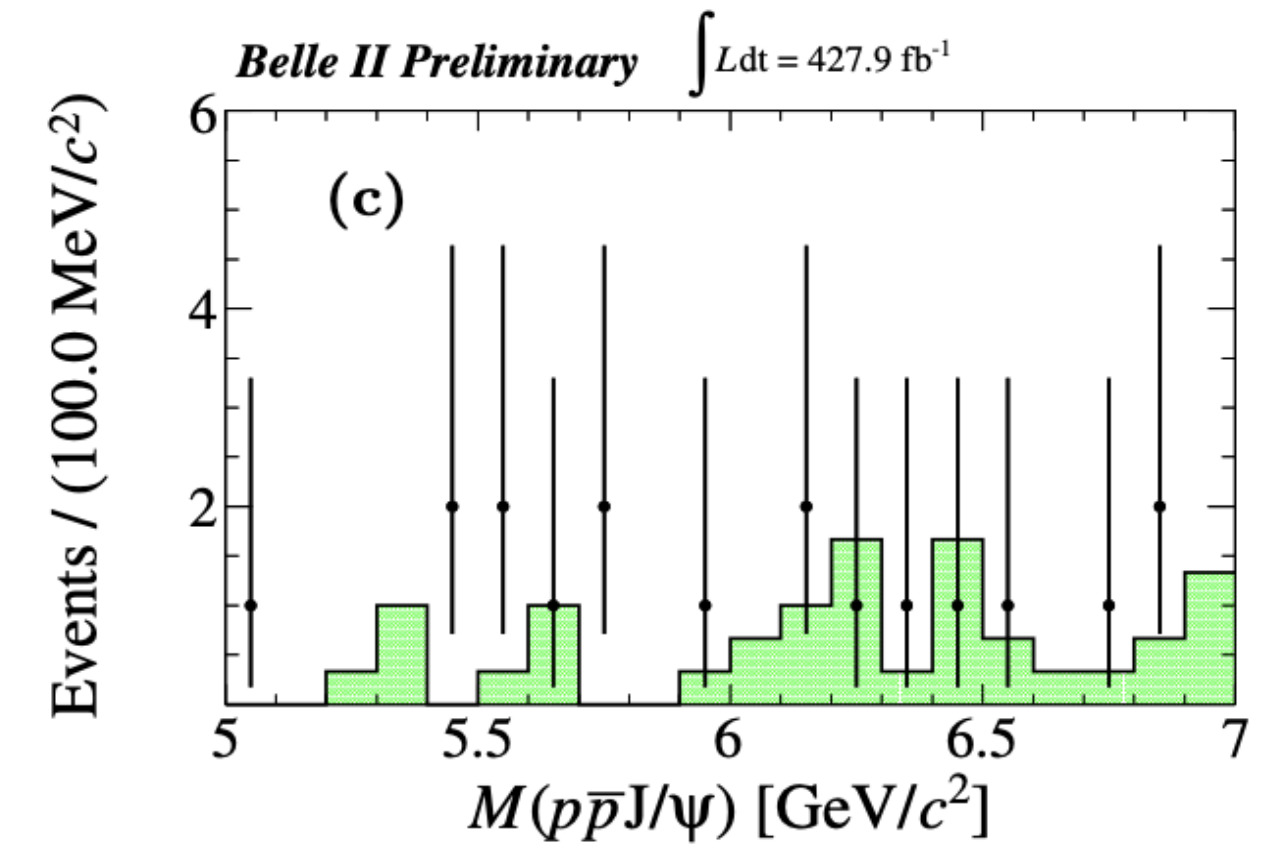
PRL 131, 211902 (2023)



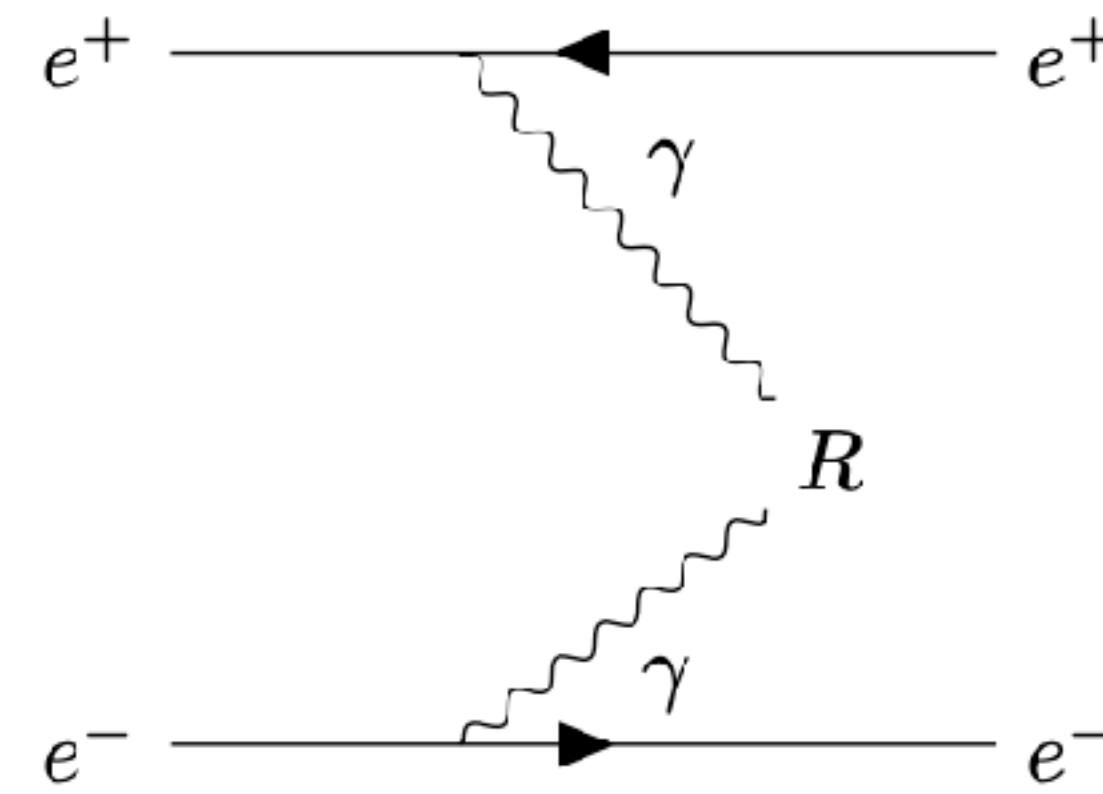
- No clear signals were observed at Belle II.
- More data are needed.

$e^+e^- \rightarrow p\bar{p}J/\psi$ via ISR:

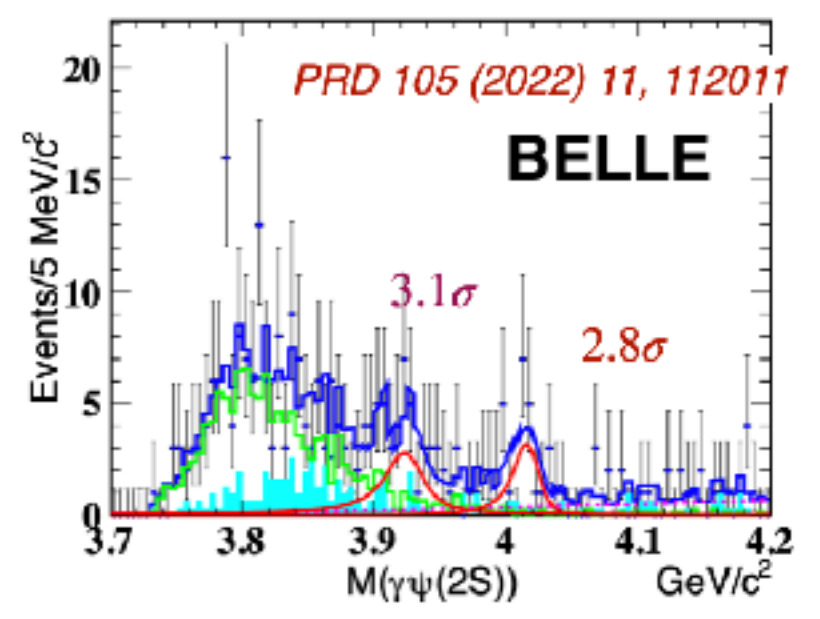
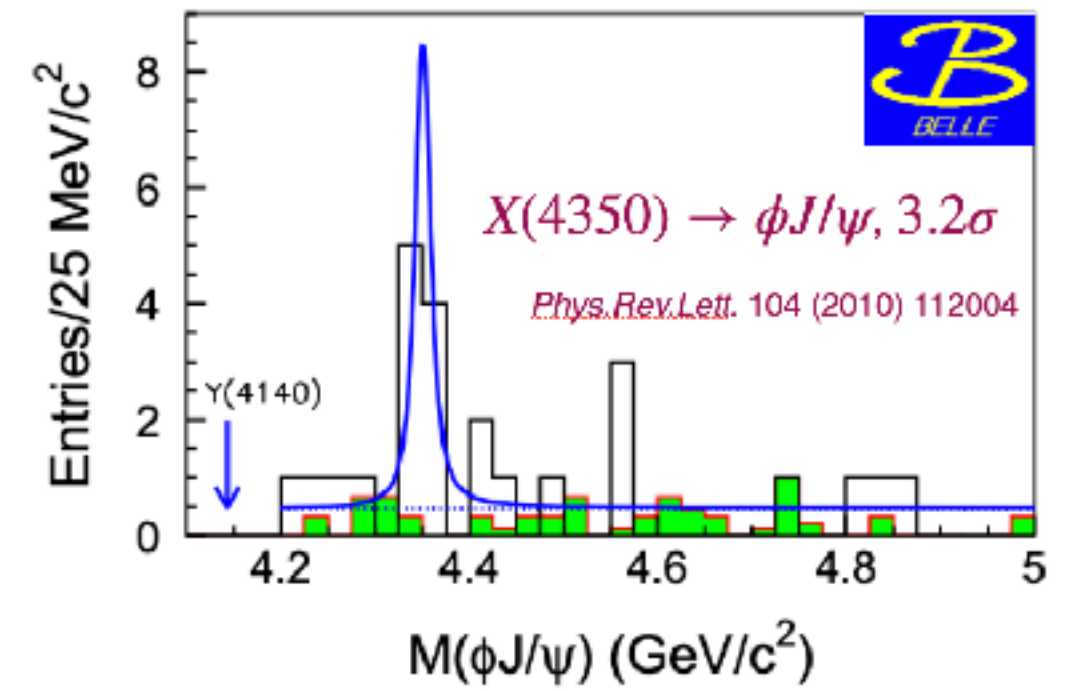
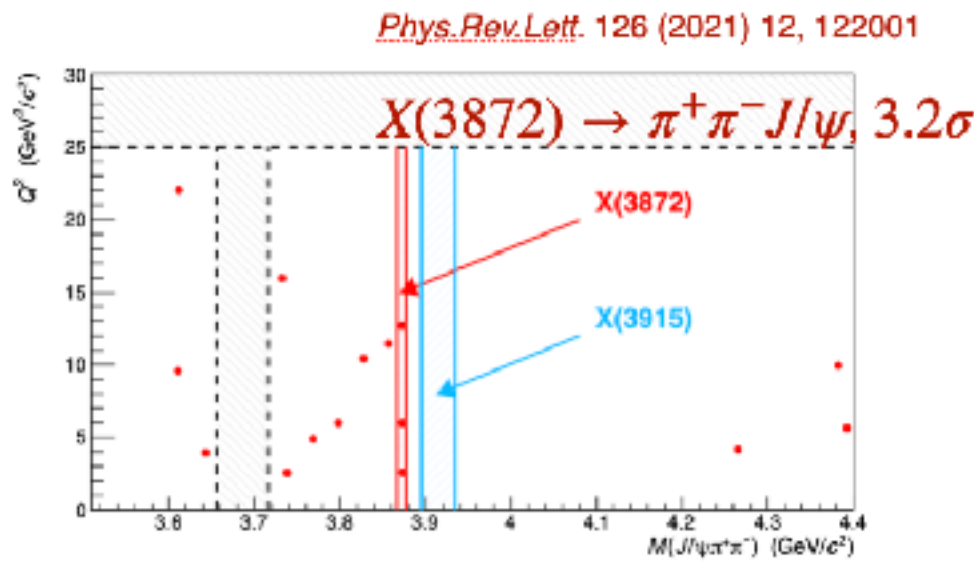
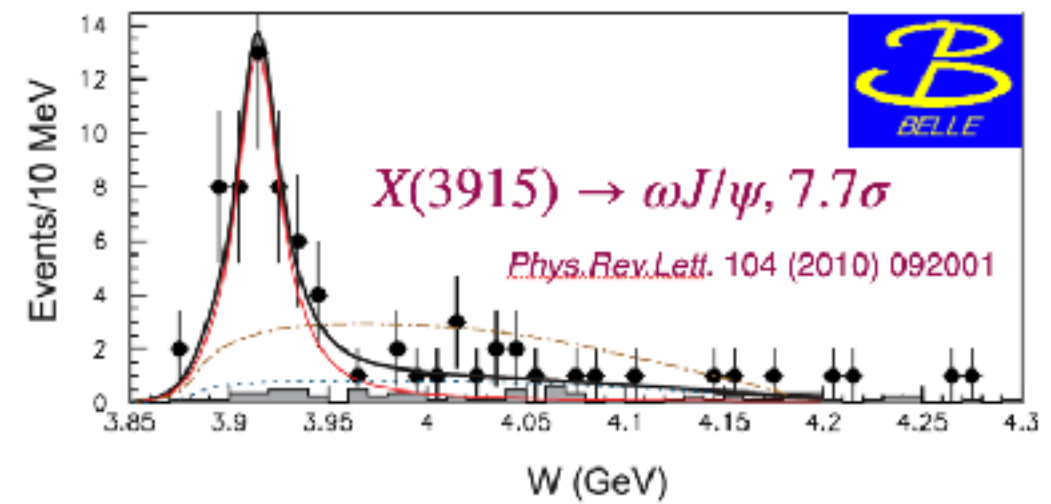
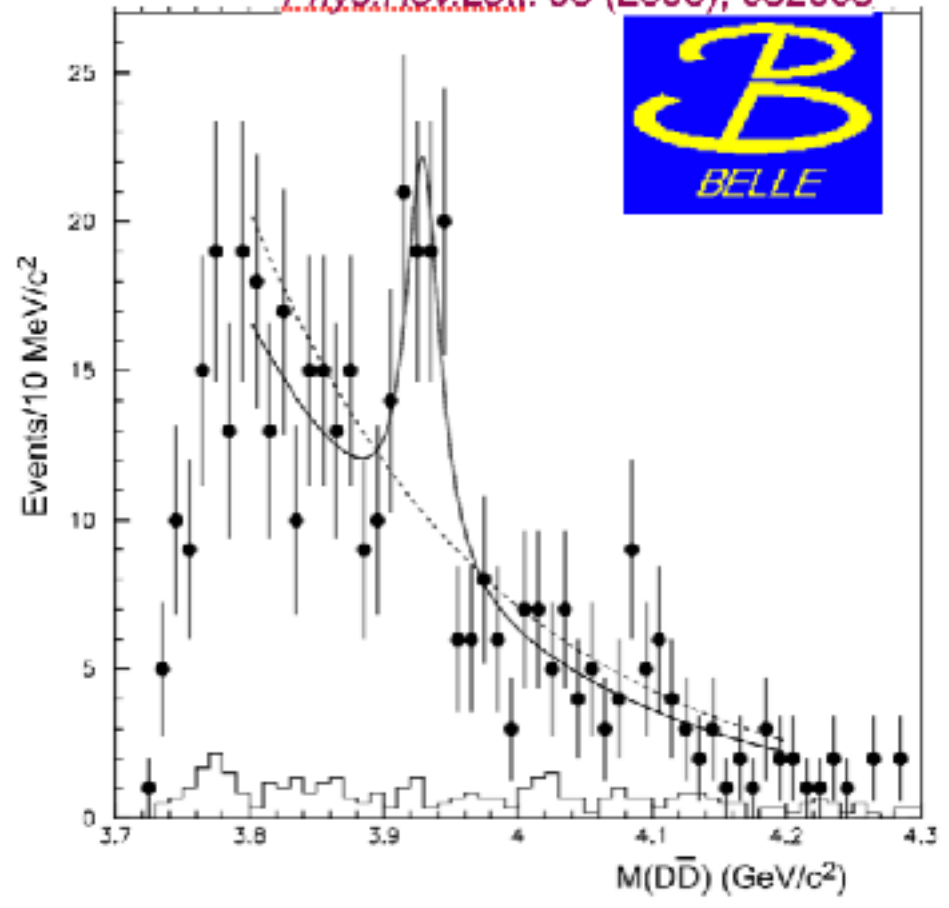
The cross section for $e^+e^- \rightarrow P_c\bar{p}$ is estimated to be $\lesssim \mathcal{O}(0.1 \text{ pb})$ [arXiv: 2508.08694].



Two photon process



$X(3930) \rightarrow D\bar{D}, 5.3\sigma$
Phys.Rev.Lett. 96 (2006), 082003

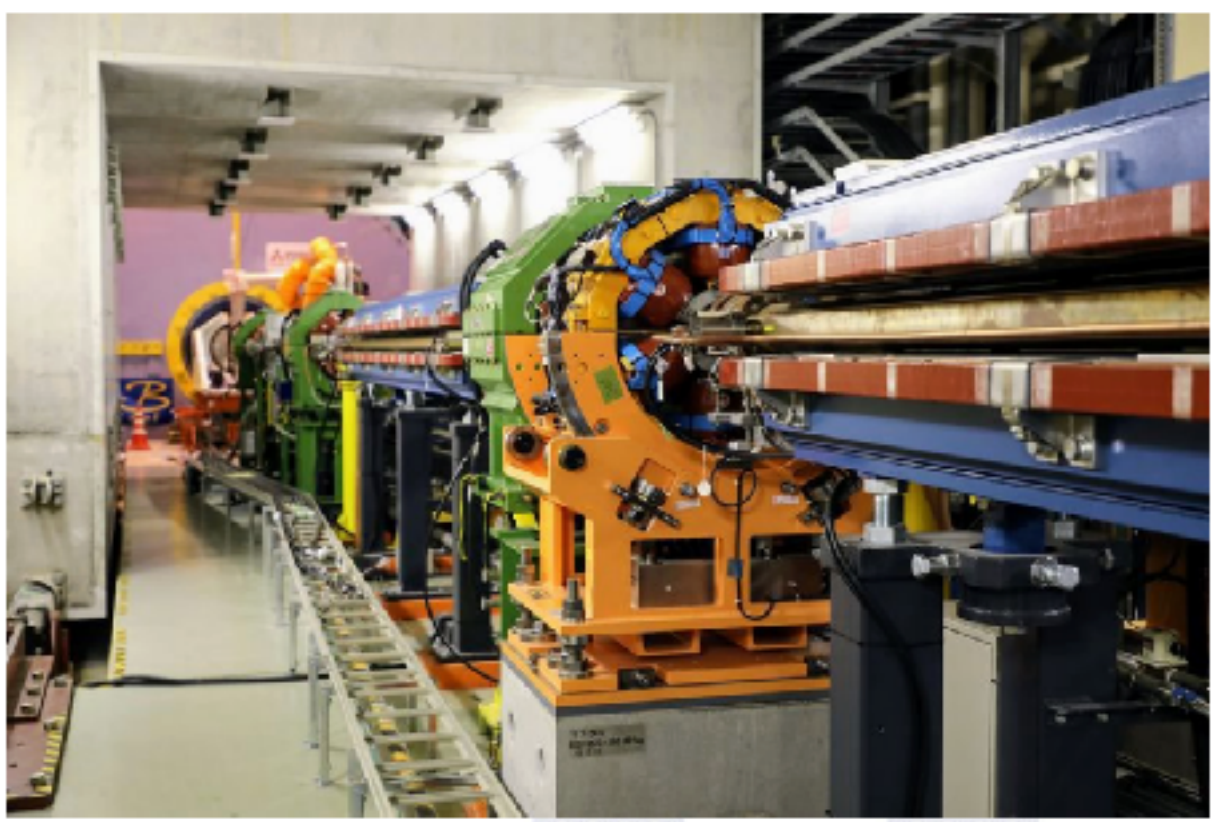


Unique field to produce charmonium(-like) particles. Important in various QCD measurements.

Long suffered from high background from continuum background and low efficiency.

*A new detector to tag two photon process is proposed by Fudan University:
 "Workshop for Two Photon Process and New Detection Technology"
 May 16-17 in Fudan University.*

<https://indico.ihep.ac.cn/event/29263/>



Dipole magnet near the Belle II detector

Summary

- Belle II is the only detector working in bottomonium energy region. Unique data provide unique results!
- New data, upgraded detector, more intelligent tools, more importantly, brighter beams.
- Belle II is targeting $\sim 1/\text{ab}$ till this summer. Will bring more interesting results, not only in quarkonium but also other area.

谢谢！

$$\Upsilon(10753) \rightarrow \pi^+ \pi^- \Upsilon(1,2,3S)$$

$$\Upsilon(10753) \rightarrow \eta \Upsilon(1,2S)$$

$$\Upsilon(10753) \rightarrow \gamma X_b$$



$$\Upsilon(10753) \rightarrow \omega \chi_{bJ}$$

$$\Upsilon(10753) \rightarrow \omega \eta_b$$

$$\Upsilon(10753) \rightarrow \pi \pi \Upsilon_3(1D)$$