# Recent quarkonium results from Belle & Belle II

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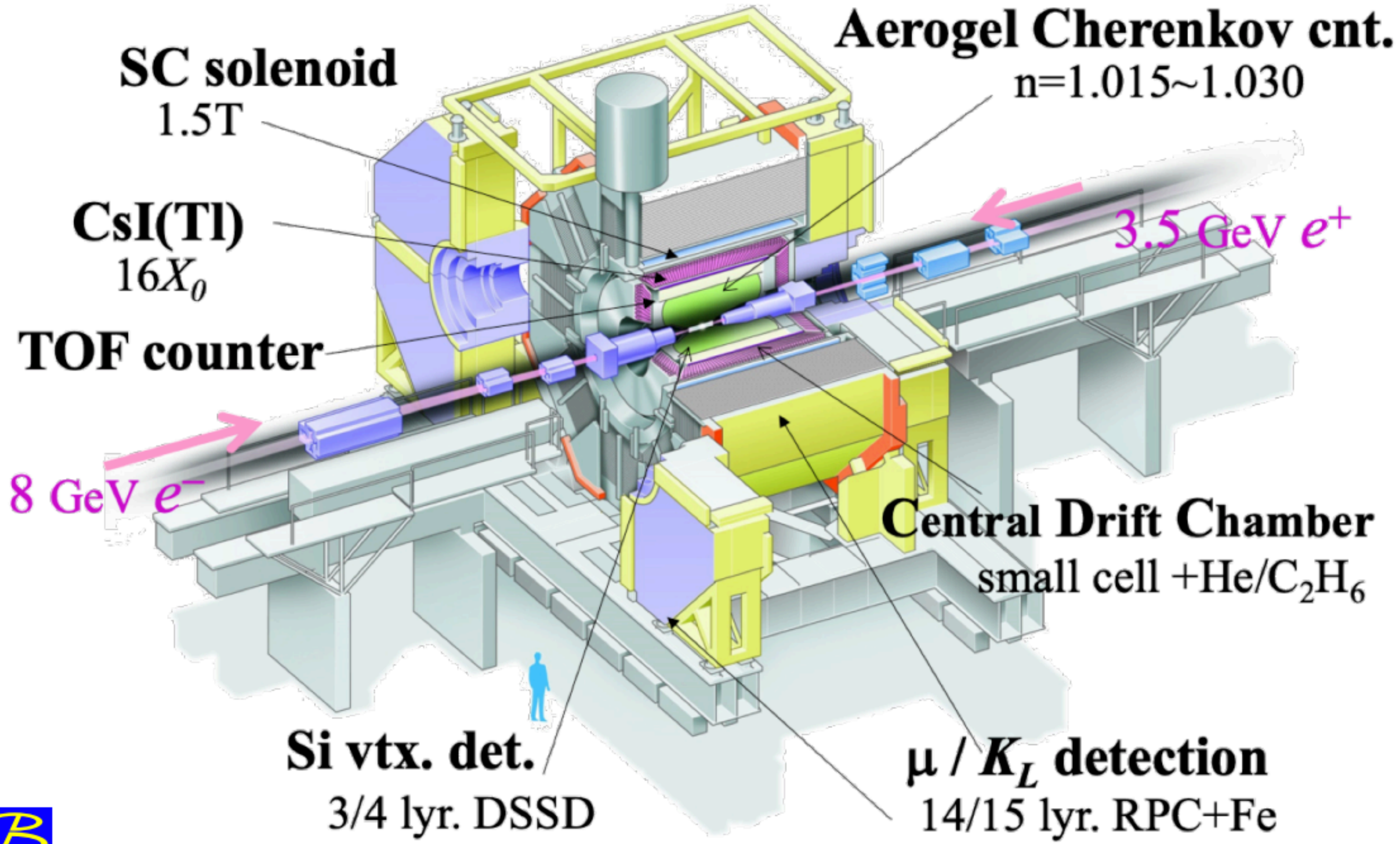
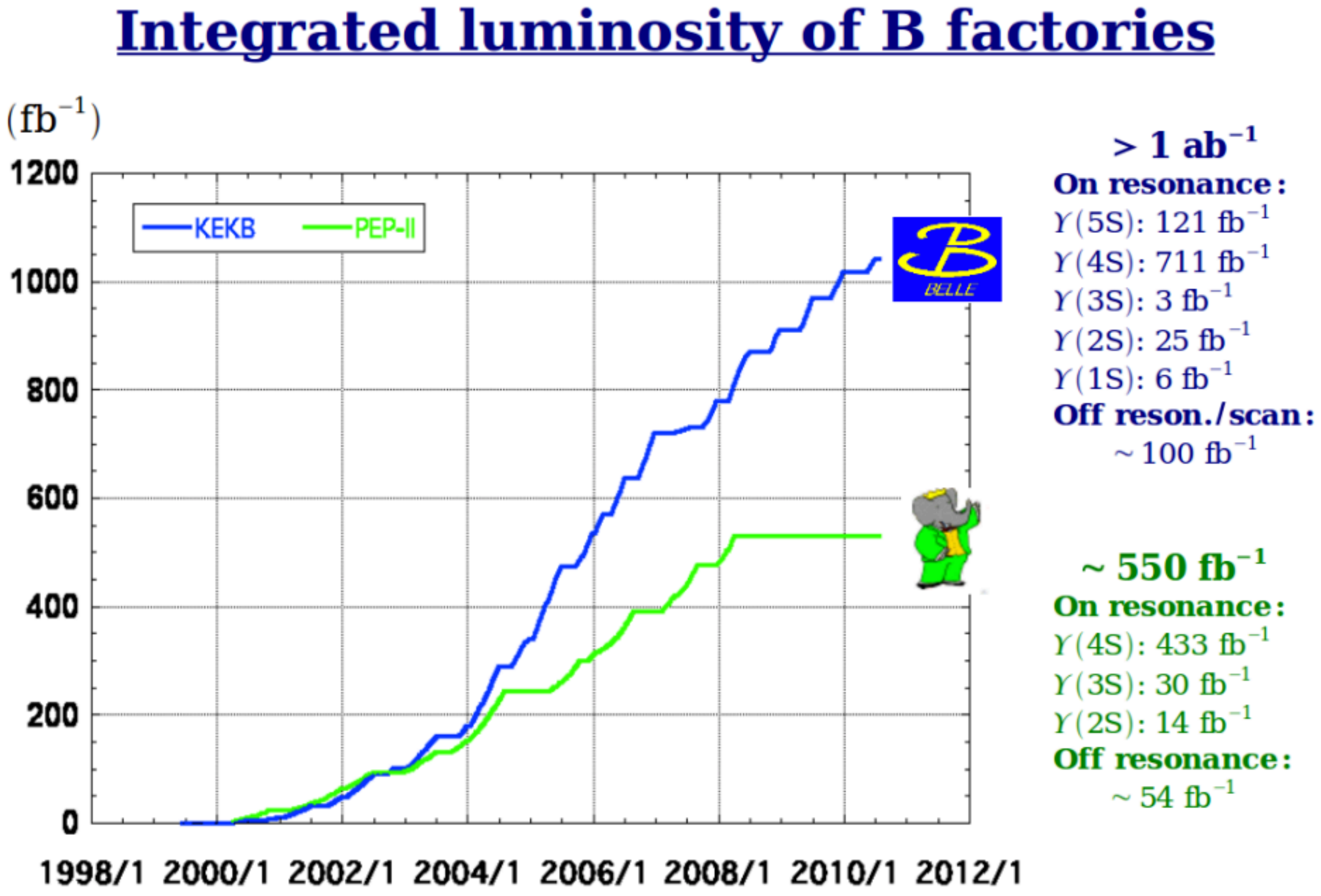
# Belle experiment at KEKB

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

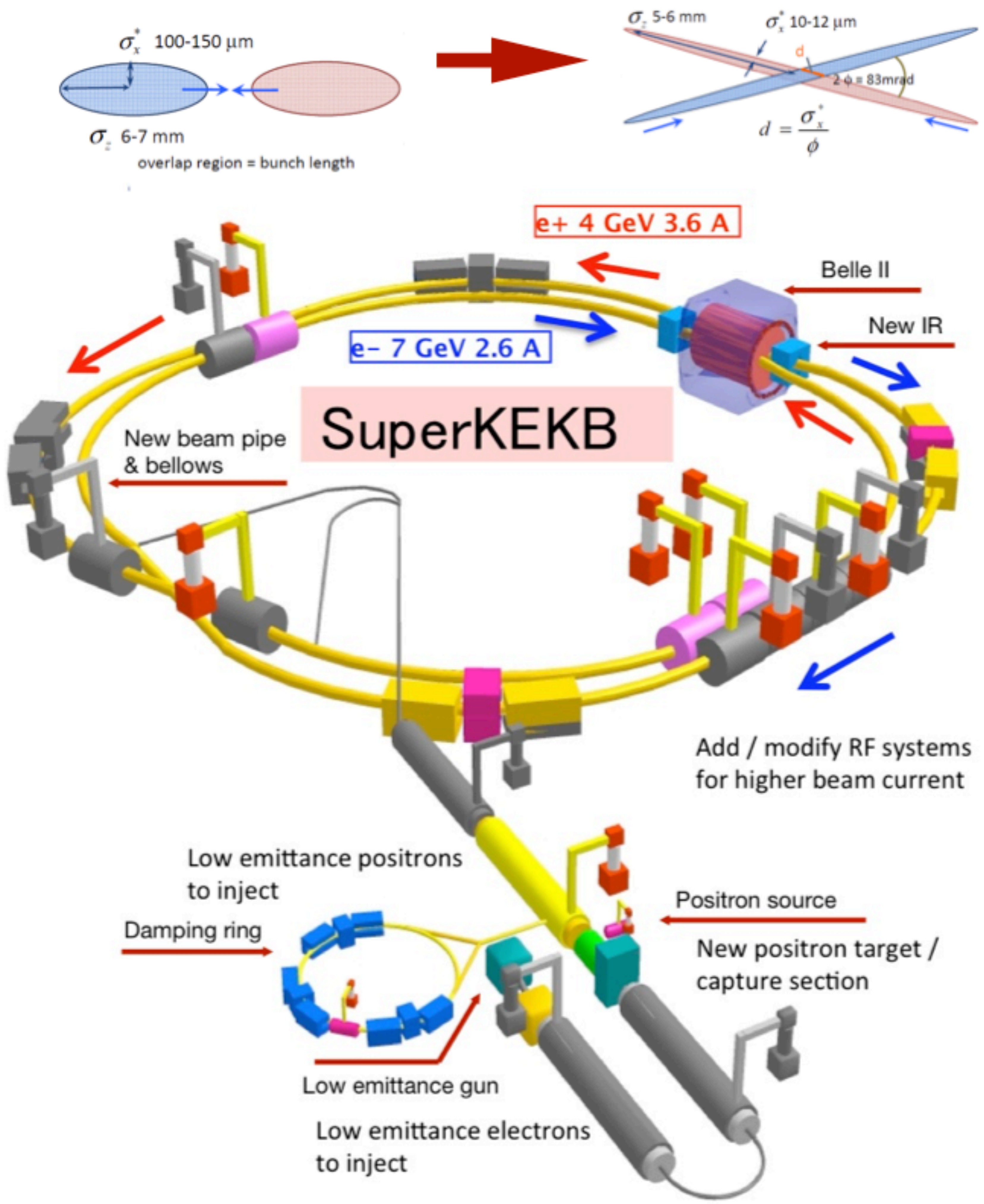


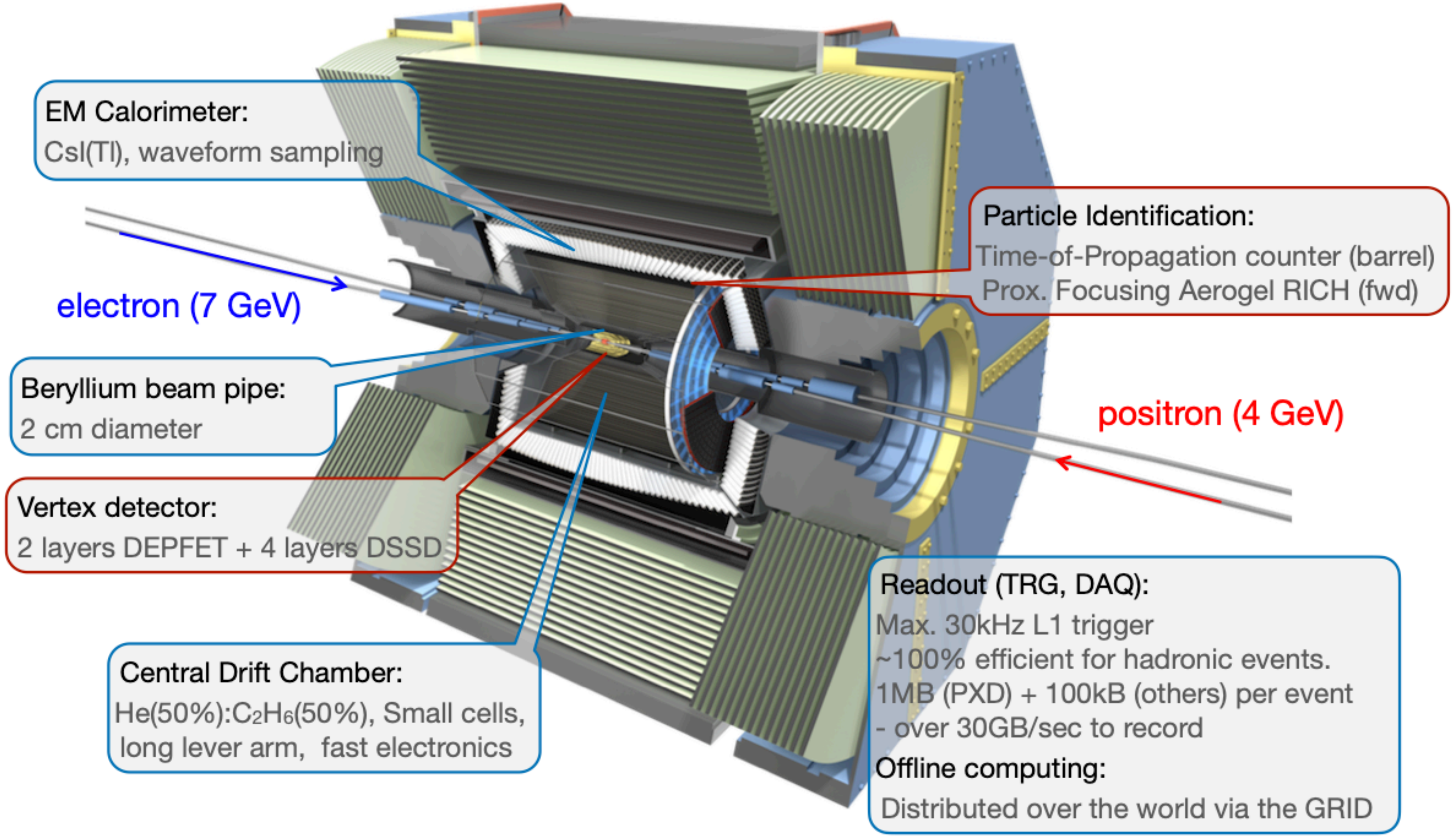

PEAK
L = 2.1 x $10^{34}$/cm$^2$/sec



# SuperKEKB and Belle II: The next generation B-factory

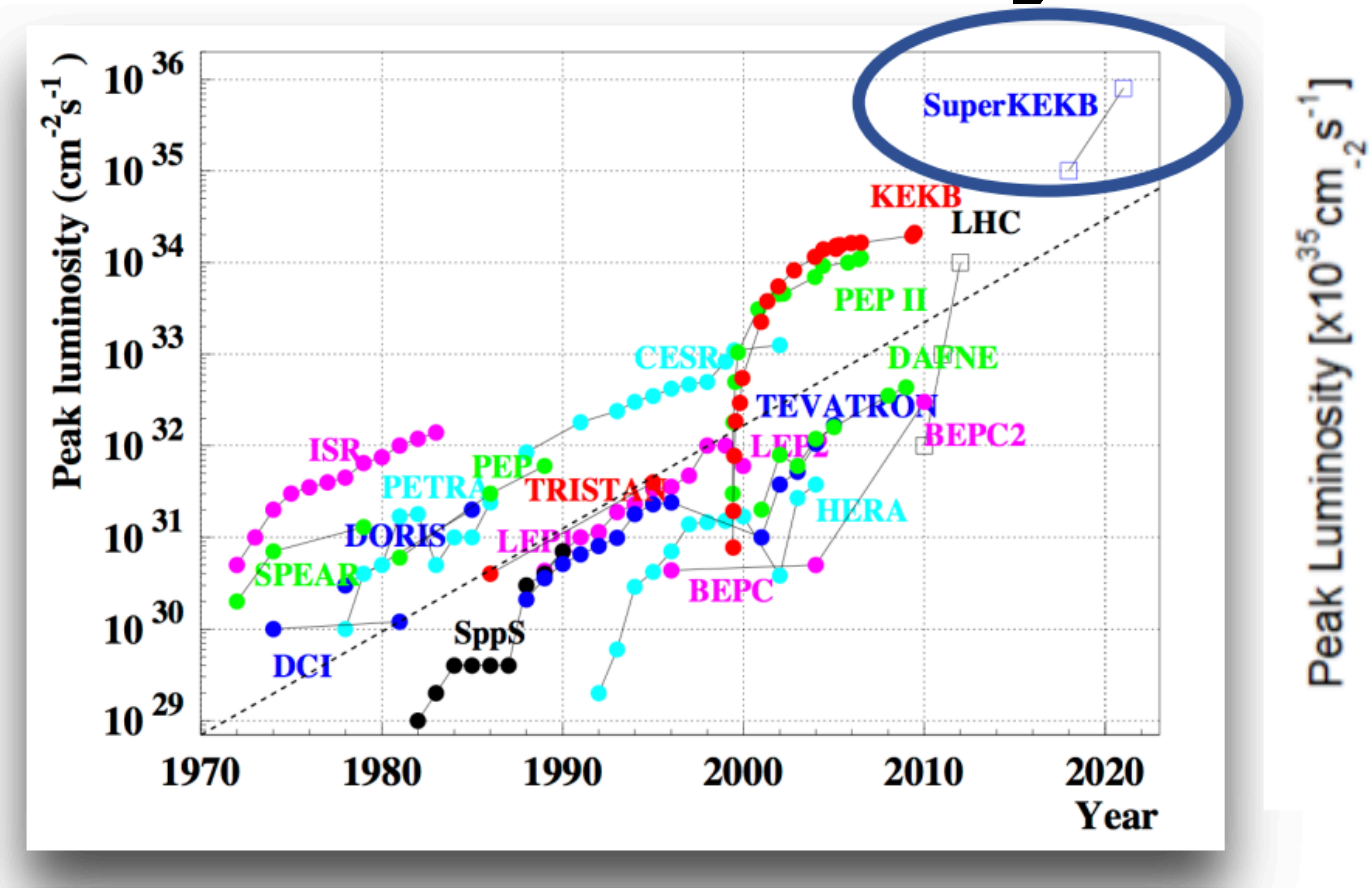
## Upgraded detector and accelerator

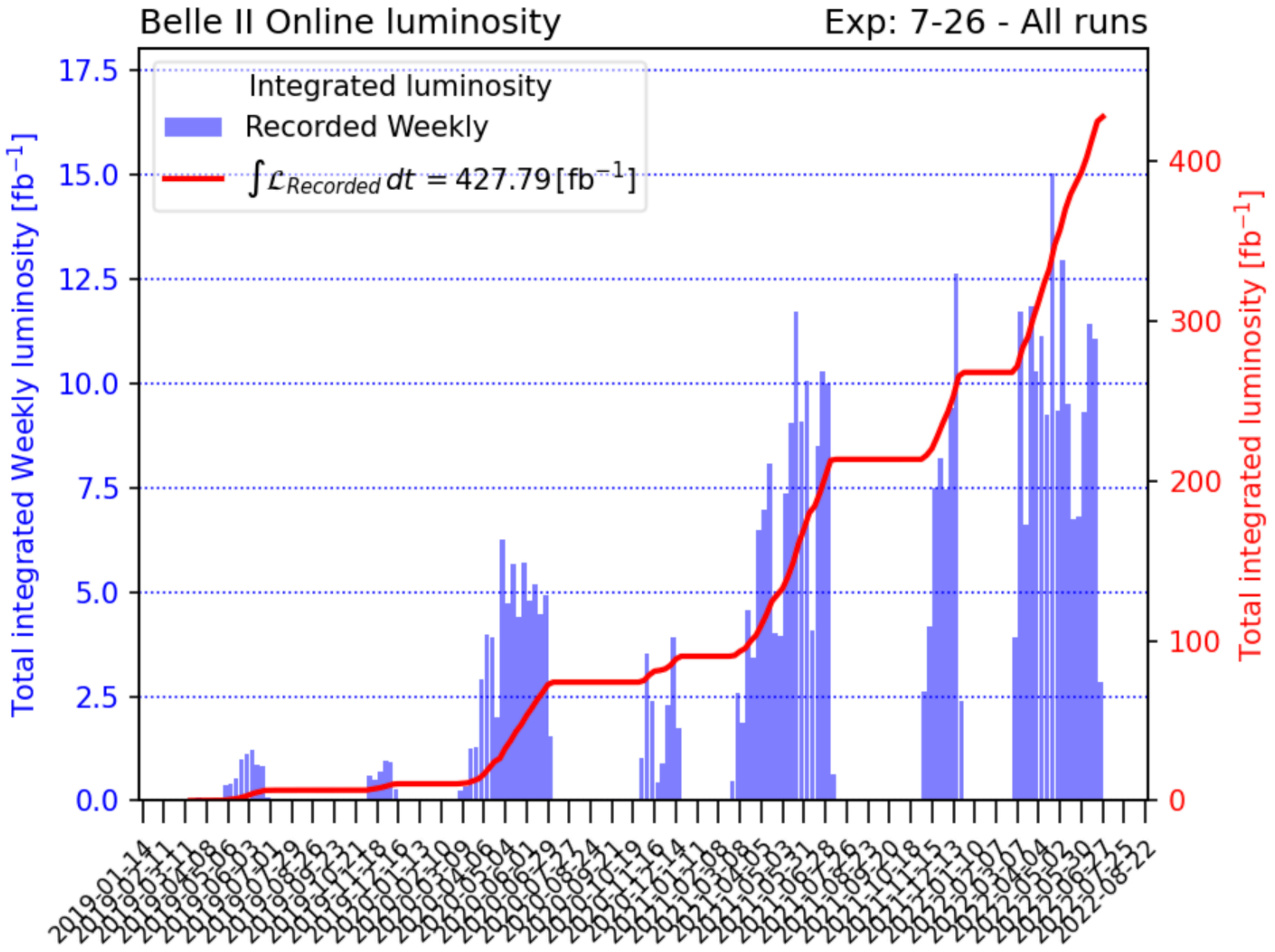



arXiv:1011.0352 [physics.ins-det]

# Belle II luminosity



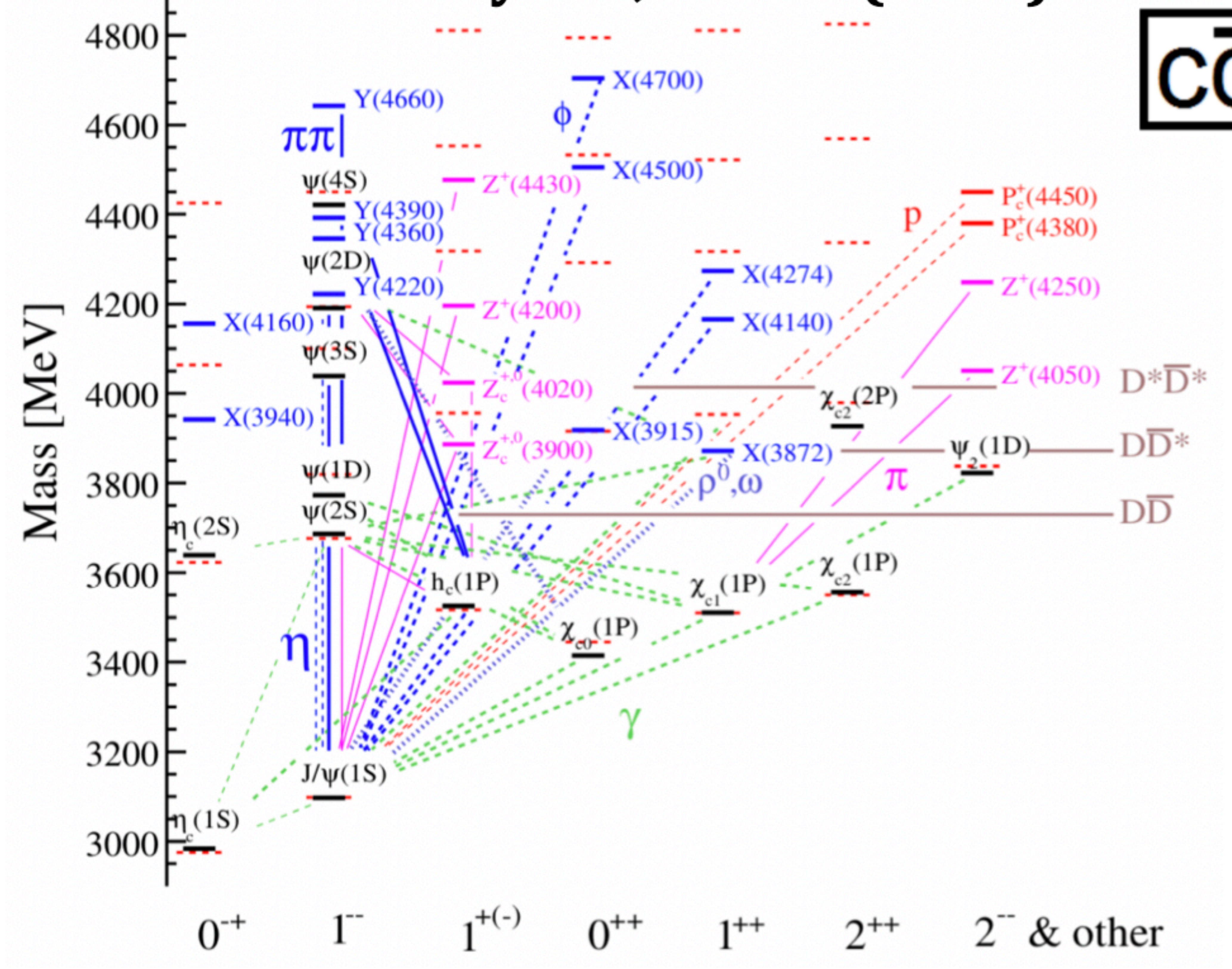



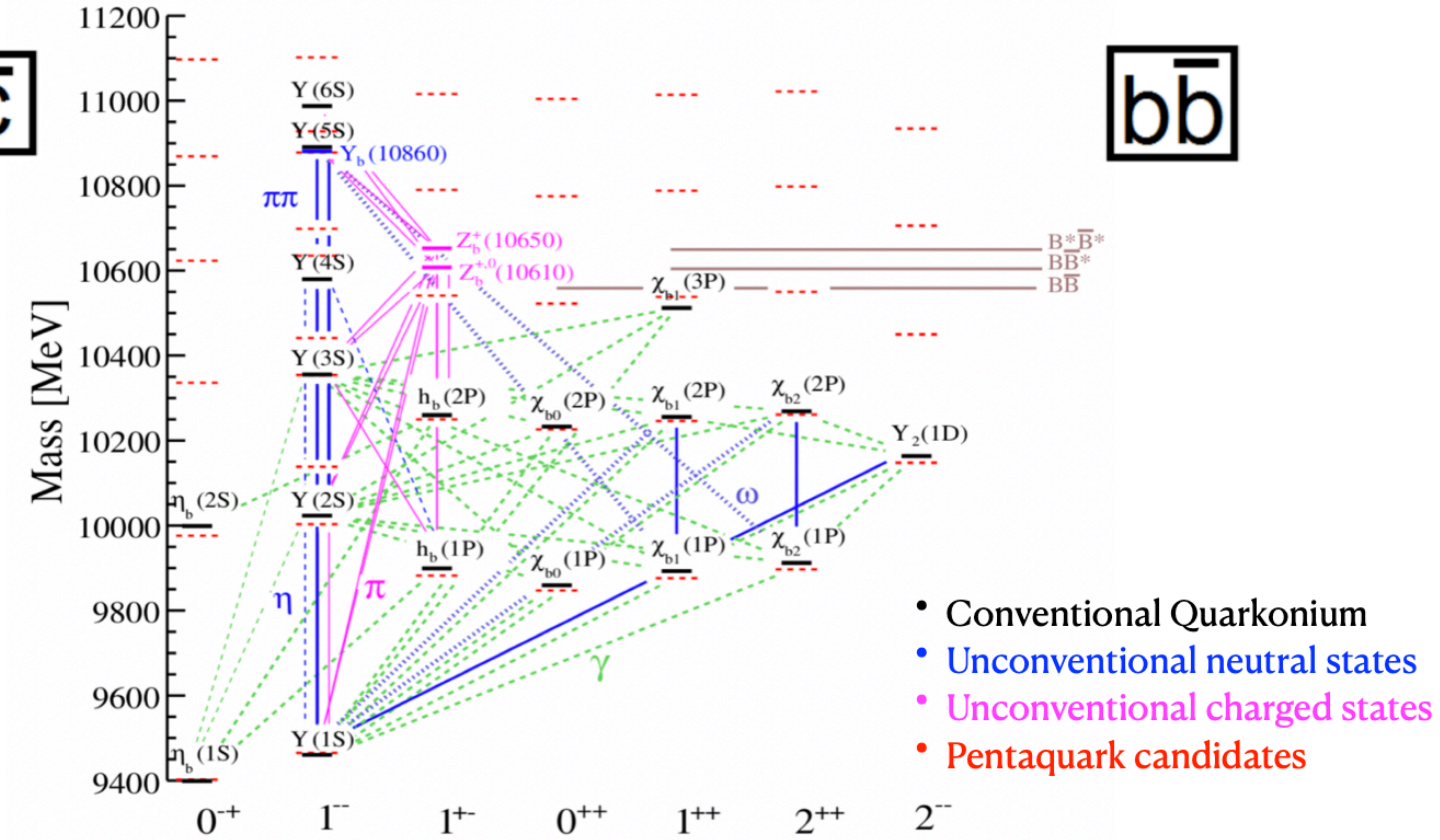

Belle II already achieve the world record instantaneous luminosity: $4.7 \times 10^{34}/cm^2/s$

Integrated luminosity: $427.79\ \mathrm{fb}^{-1}$

# Quarkonium spectroscopy

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



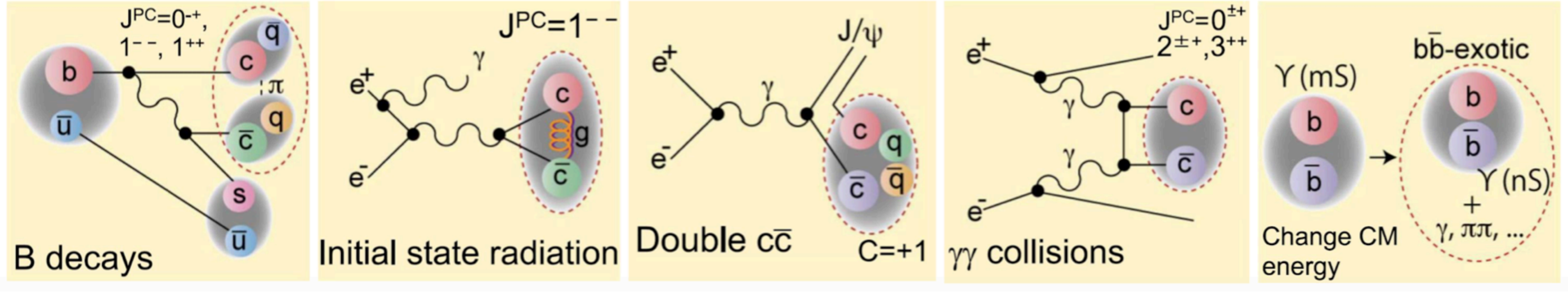

Below $D\bar{D}/B\bar{B}$ threshold: Good agreement!

Above $D\bar{D}/B\bar{B}$ threshold: Exotic states!!

Parallel properties in $c\bar{c}$ and $b\bar{b}$.

Excellent experimental field!

# Quarkonium production mechanisms




***Recent publications:***

***…***

***New vector state in*** $e^+e^- \to D_s^+ D_{s1}(2536)^-,\ D_s^+ D_{s2}^*(2573)^-$***; [PRD 100 (2019) 11, 111103, PRD 101 (2020) 9, 091101]***

***First evidence of*** $\gamma\gamma \to X(3872)$***; [Phys.Rev.Lett. 126 (2021) 12, 122001]***

***Evidence of*** $\gamma\gamma \to \chi_c(3930) \to \gamma\psi(2S)$***; [Phys.Rev.D 105 (2022) 11, 112011]***

***Observation of*** $\Upsilon(5S) \to \eta\Upsilon(1,2S)$***; [Phys.Rev.D 104 (2021) 11, 112006]***

***Lineshape study of*** $e^+e^- \to B^{(*)}B^{(*)}$***; [JHEP 06 (2021) 137]***

***Searching for*** $X(3872) \to \pi^+\pi^-\pi^0$***; [arXiv: 2206.08592]***

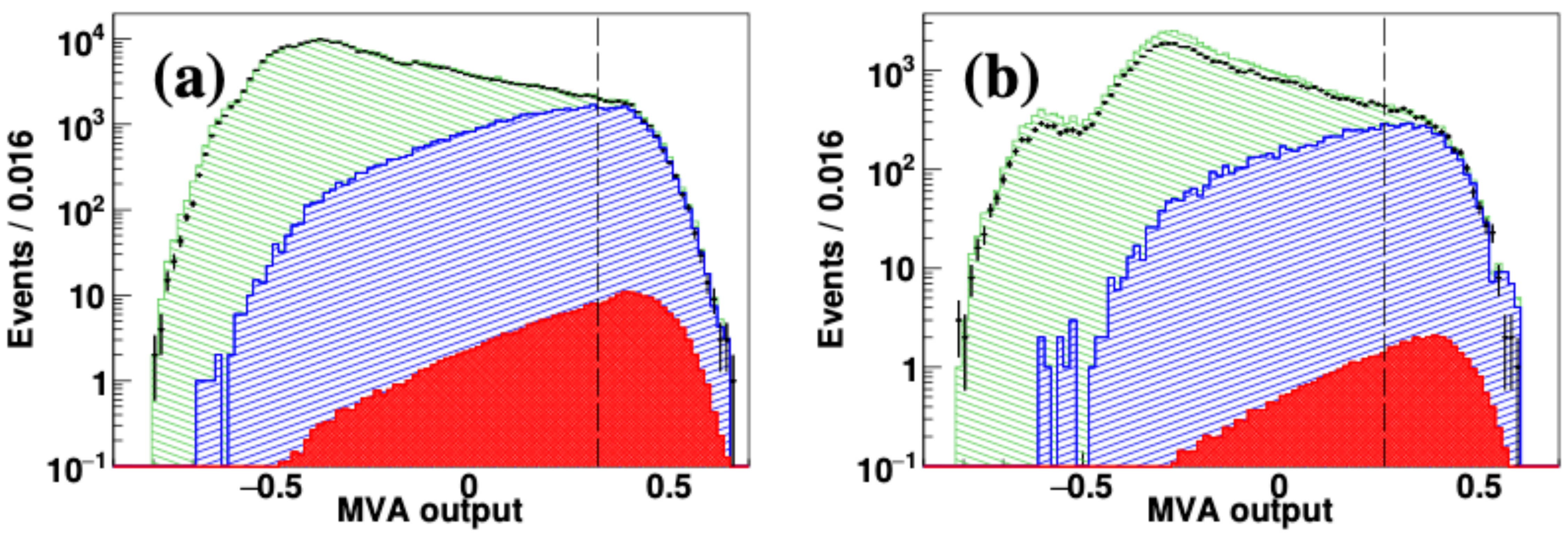
***Observation of*** $\Upsilon(10750) \to \omega\chi_{b1,2}$***; [preliminary]***

# Search for $X(3872) \to \pi^+\pi^-\pi^0$

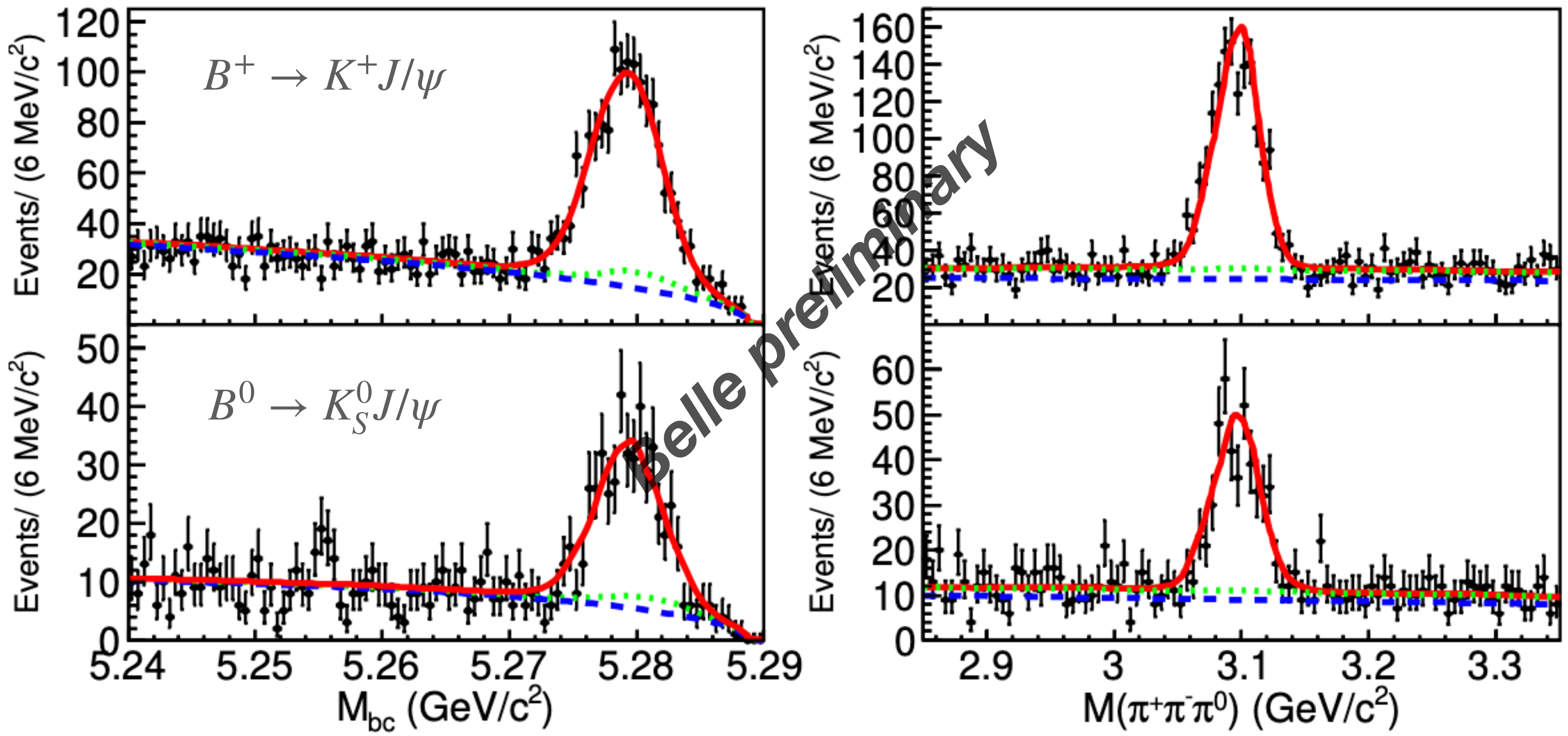
arXiv: 2206.08592

**Based on $772 \times 10^6$ $B\bar{B}$ events on Belle, in $B \to KX(3872)$**

Nearly 99% of continuum background could be removed with MVA




Validate with $B \to KJ/\psi$, $J/\psi \to \pi^+\pi^-\pi^0$




A two dimensional simultaneous fit to the charged and neutral mode and result

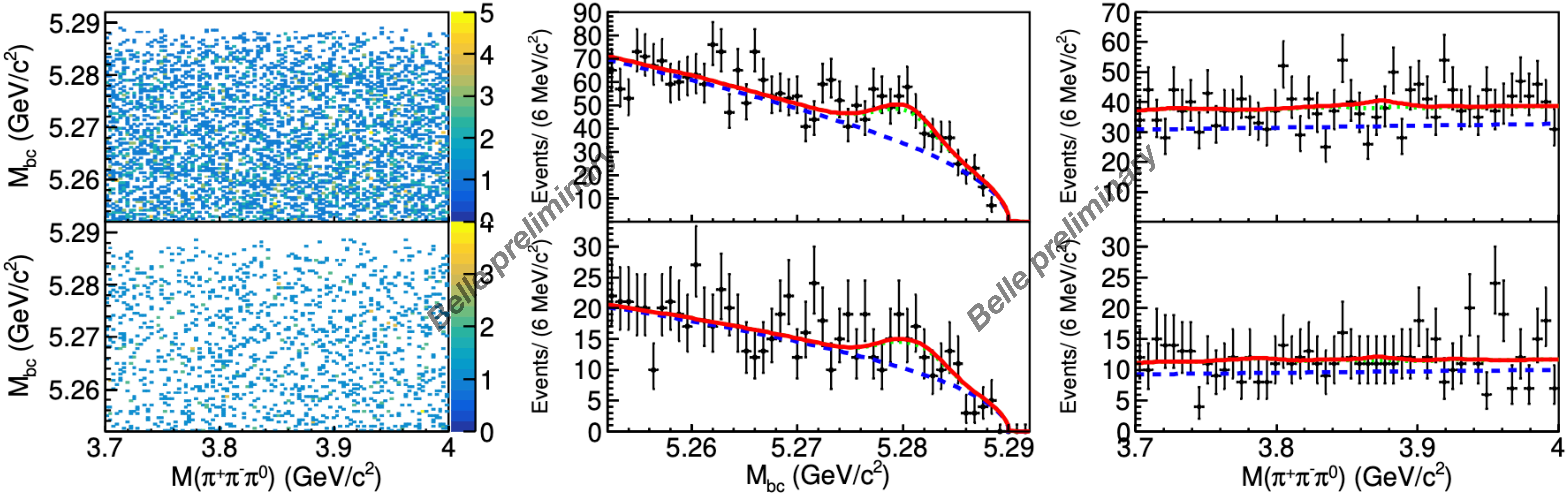
$$\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0) = (2.10 \pm 0.06)\ \% \text{ (stat. only)}$$

consistent with PDG: $(2.10 \pm 0.08)\ \%$ within uncertainties.

# Search for $X(3872) \to \pi^+\pi^-\pi^0$

arXiv: 2206.08592

Signal is searched for in the assumption of $X(3872) \to \pi^+\pi^-\pi^0$ uniformly [*named as: case I*]



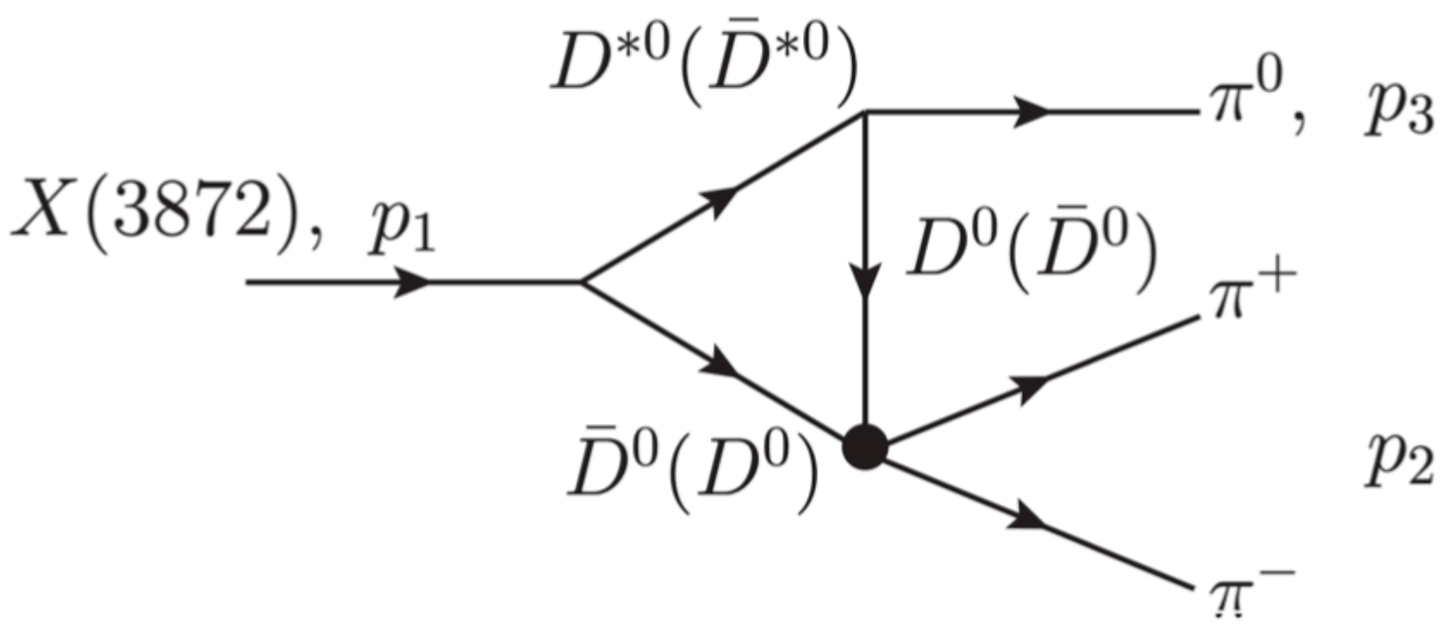

Upper limit is estimated at 90% C.L. $< 1.3\,\%$ .

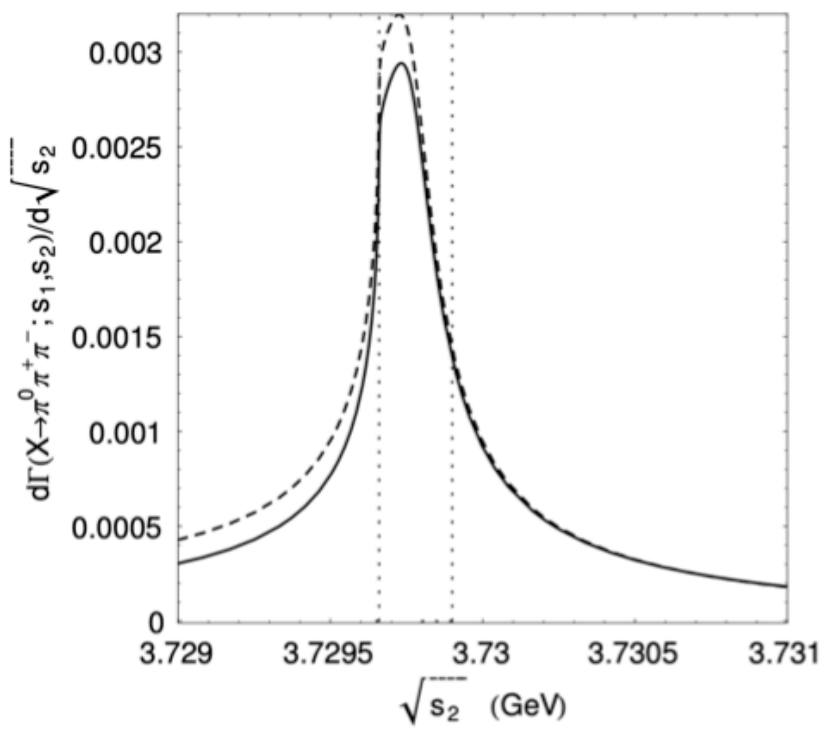
Quote $\mathscr{B}(B \to KX(3872))$ from ***PRD 100, 094003 (2019)***.

# Search for $X(3872) \to \pi^+\pi^-\pi^0$

arXiv: 2206.08592

Phys. Rev. D 99, 116023 (2019)

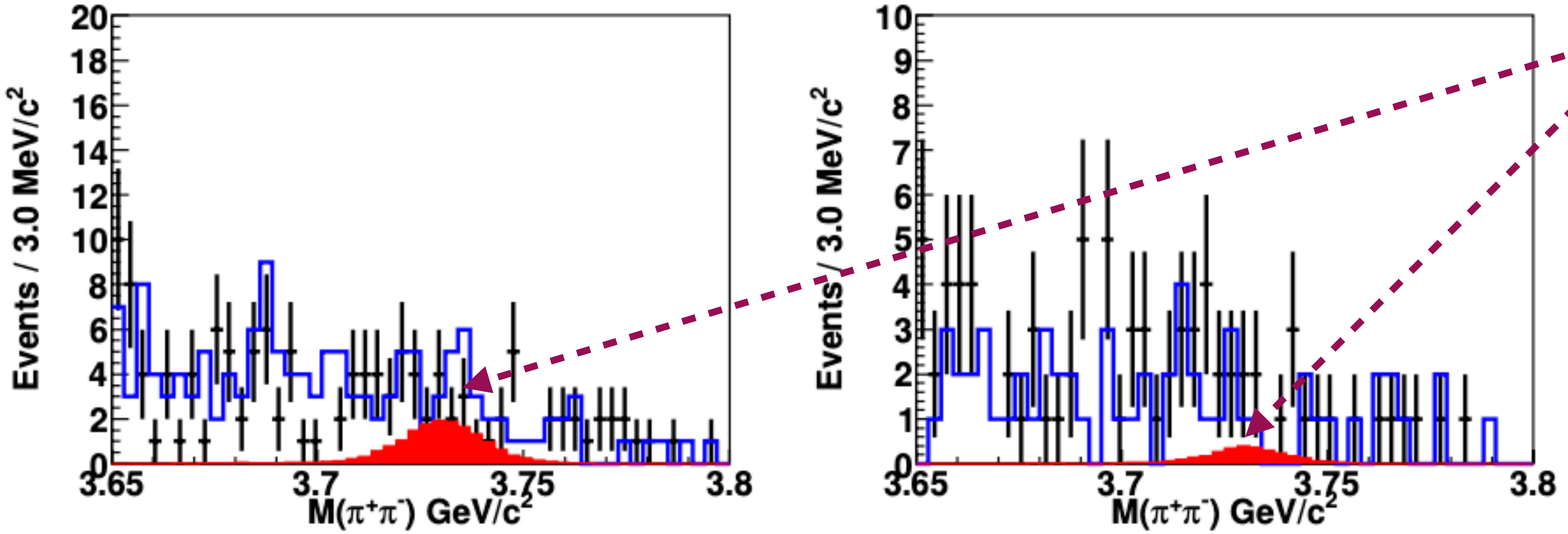



BF is predicted at the level of $10^{-3} \sim 10^{-4}$

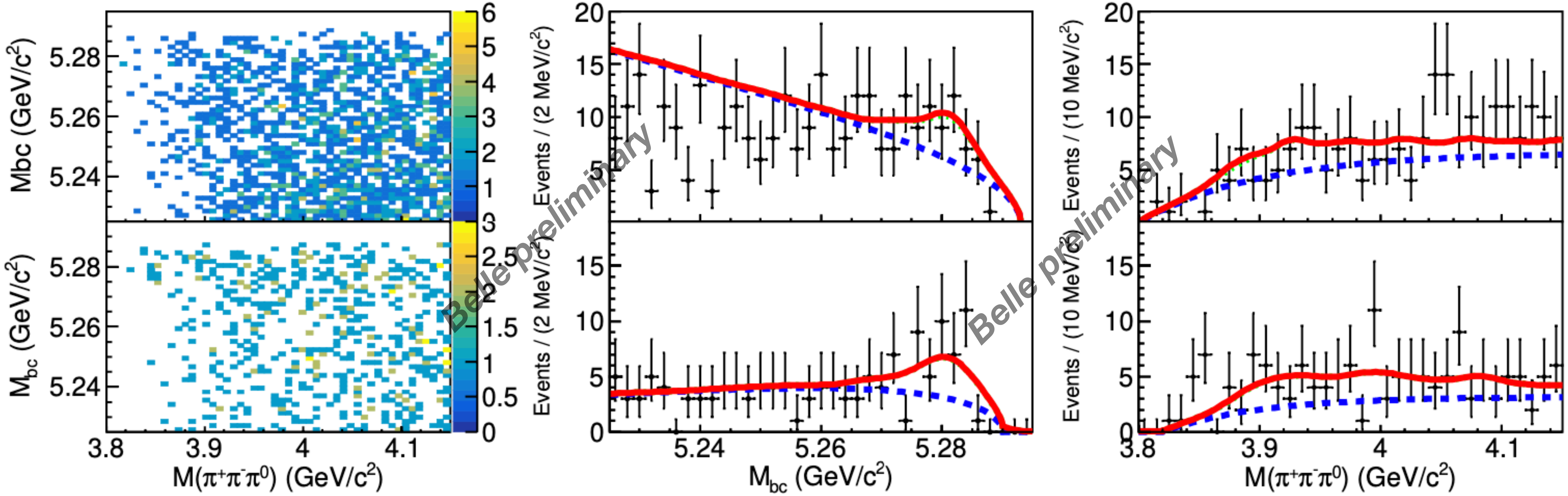
Mass of $\pi^+\pi^-$ accumulate around $M(D^0\bar{D}^0)$

Additional requirement [named as case II]:
$M(\pi^+\pi^-) \in [3.7,\ 3.75]\ \mathrm{GeV/c^2}$




Signals are normalized with
$\mathscr{B}(X \to 3\pi) = 10^{-3}$

No enhancement is found on $M(3\pi)$



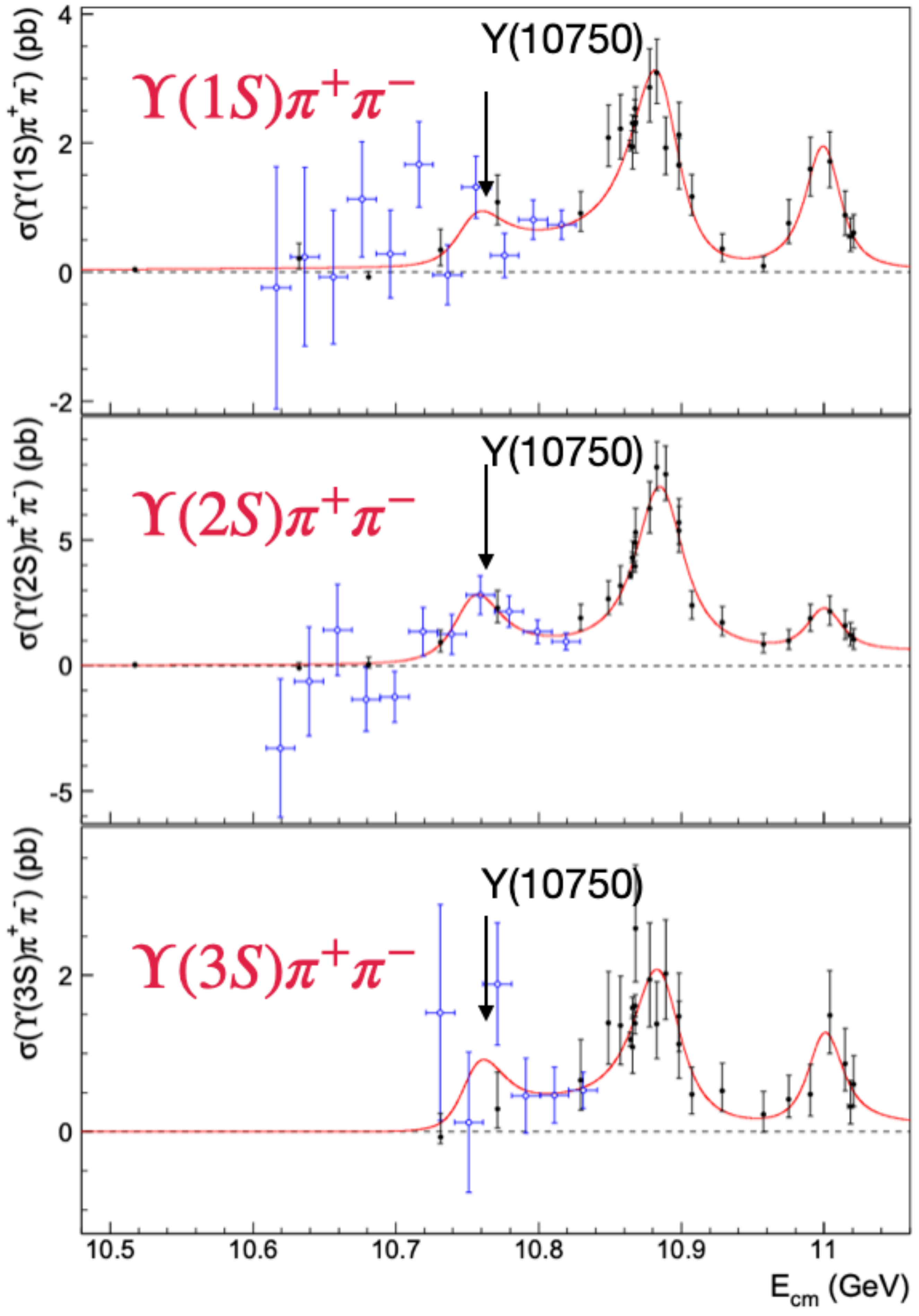

Upper limit of the joint BF is also estimated:

| channel | case I | case II |
|---|---|---|
| $B^{\pm} \to K^{\pm} X(3872),\ X(3872) \to \pi^+\pi^-\pi^0$ | $< 1.9 \times 10^{-6}$ | $< 1.5 \times 10^{-7}$ |
| $B^0 \to K^0 X(3872),\ X(3872) \to \pi^+\pi^-\pi^0$ | $< 1.5 \times 10^{-6}$ | $< 1.8 \times 10^{-7}$ |
| $X(3872) \to \pi^+\pi^-\pi^0$ | $< 1.3\%$ | $< 1.2 \times 10^{-3}$ |

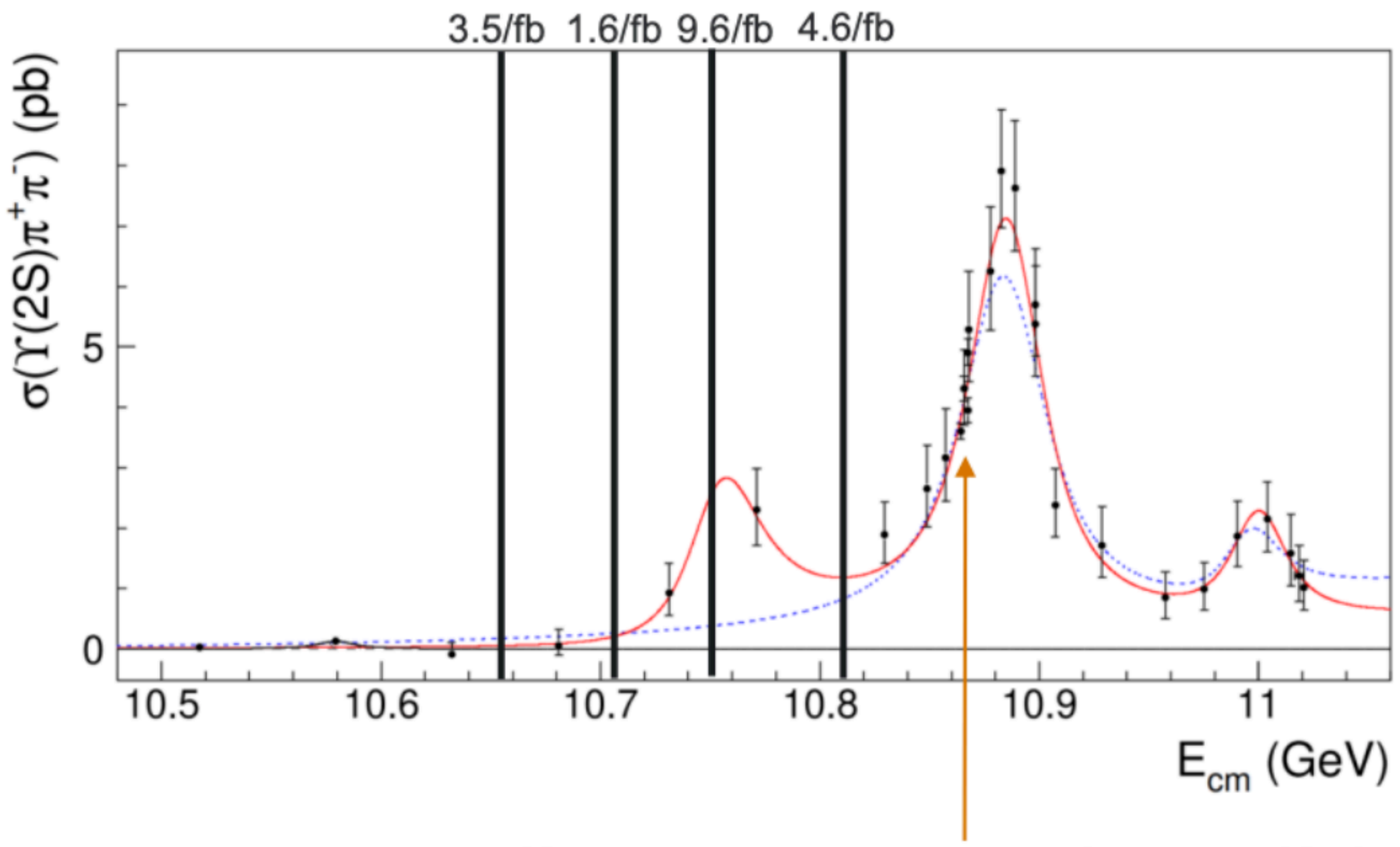
Could be used to provide constraints on the triangle logarithmic singularity of $X(3872) \to D^0\bar{D}^{*0} \to D^0\bar{D}^0\pi^0$.

# Unique scan data near $\sqrt{s} = 10.75$ GeV

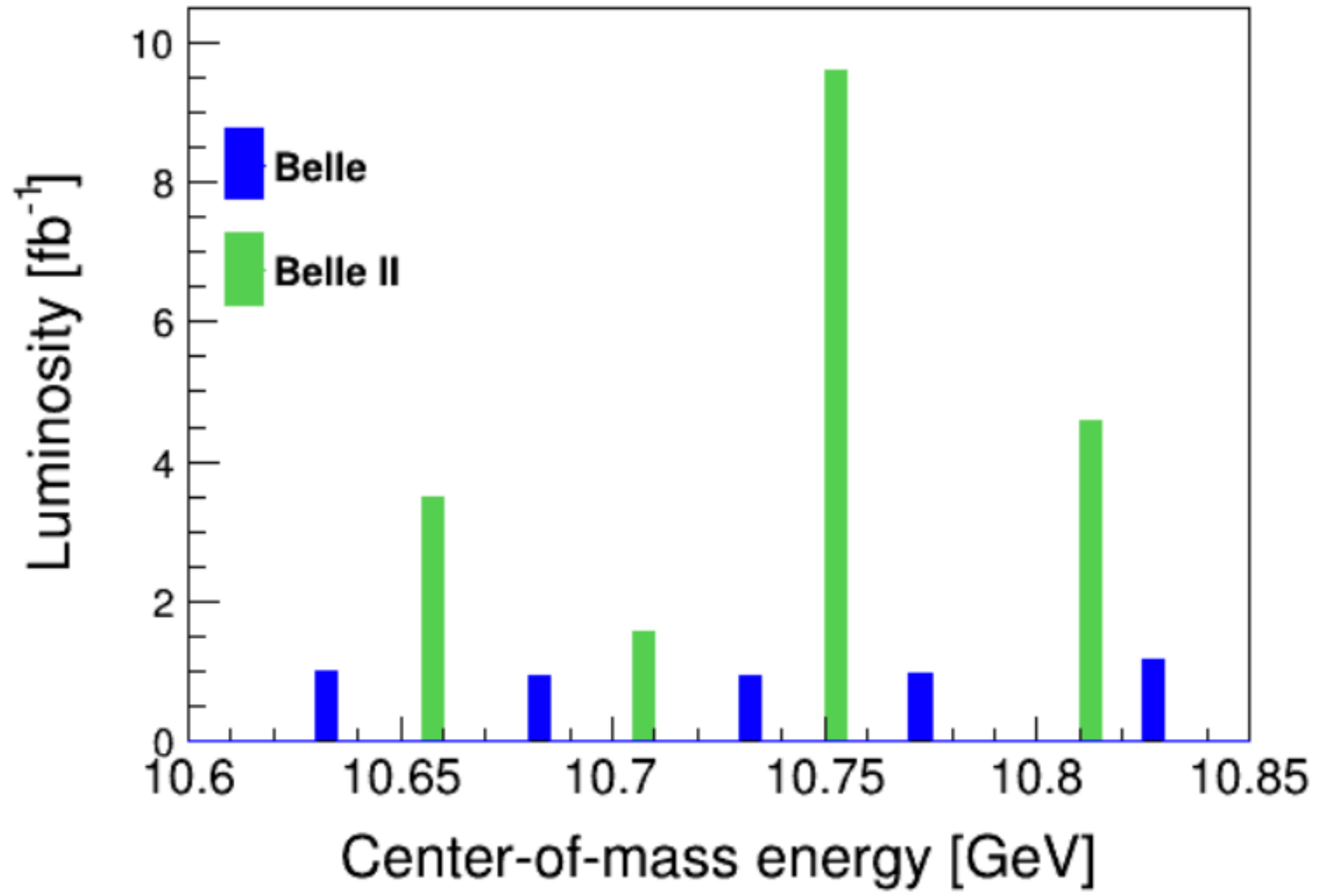
JHEP 1910, 220 (2019)




- In November 2021, Belle II collected $19 \text{fb}^{-1}$ of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV
- Physics goal: understand the nature of the $Y(10753)$.



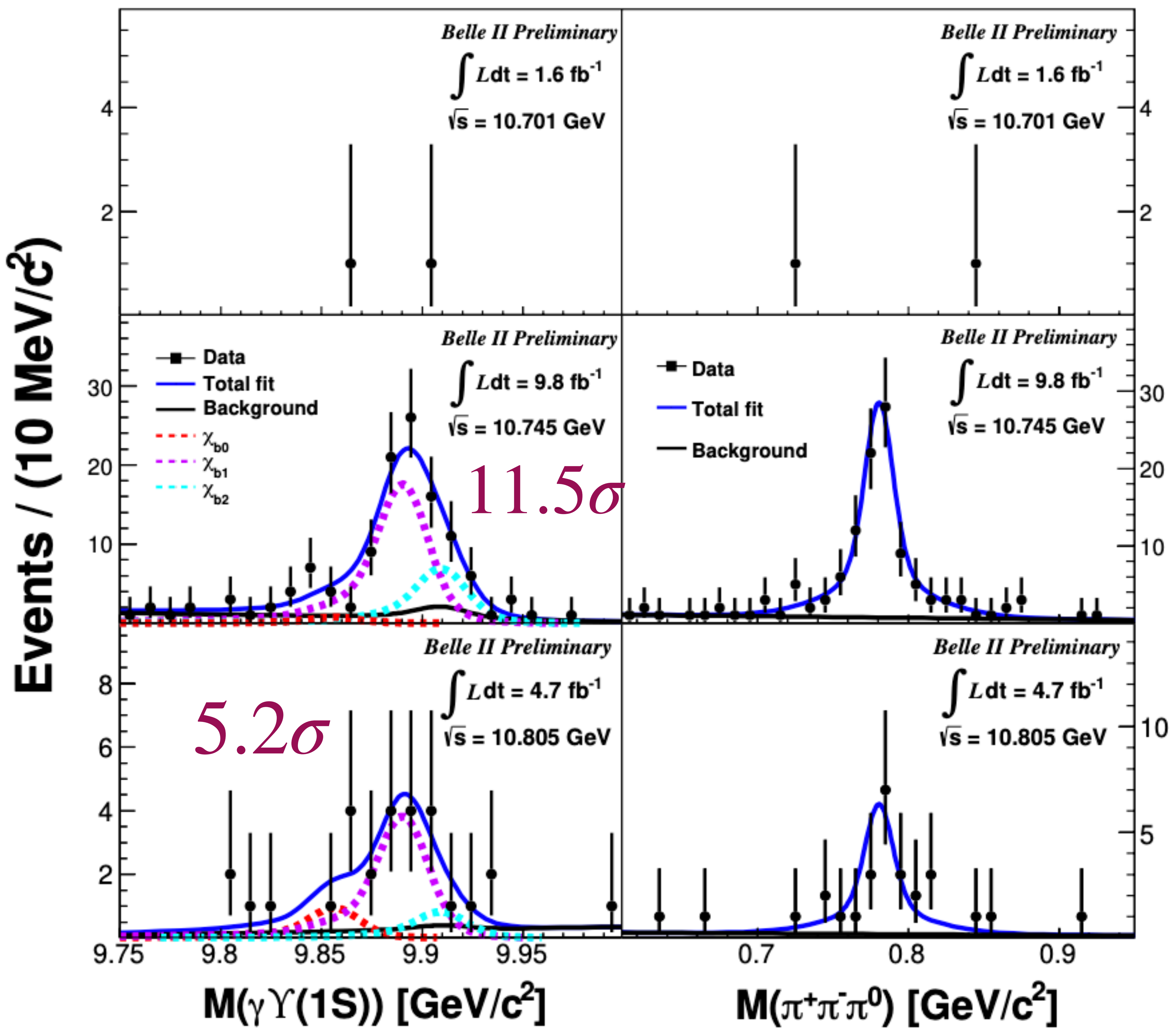

All points ~1/fb except these (~20+/fb)

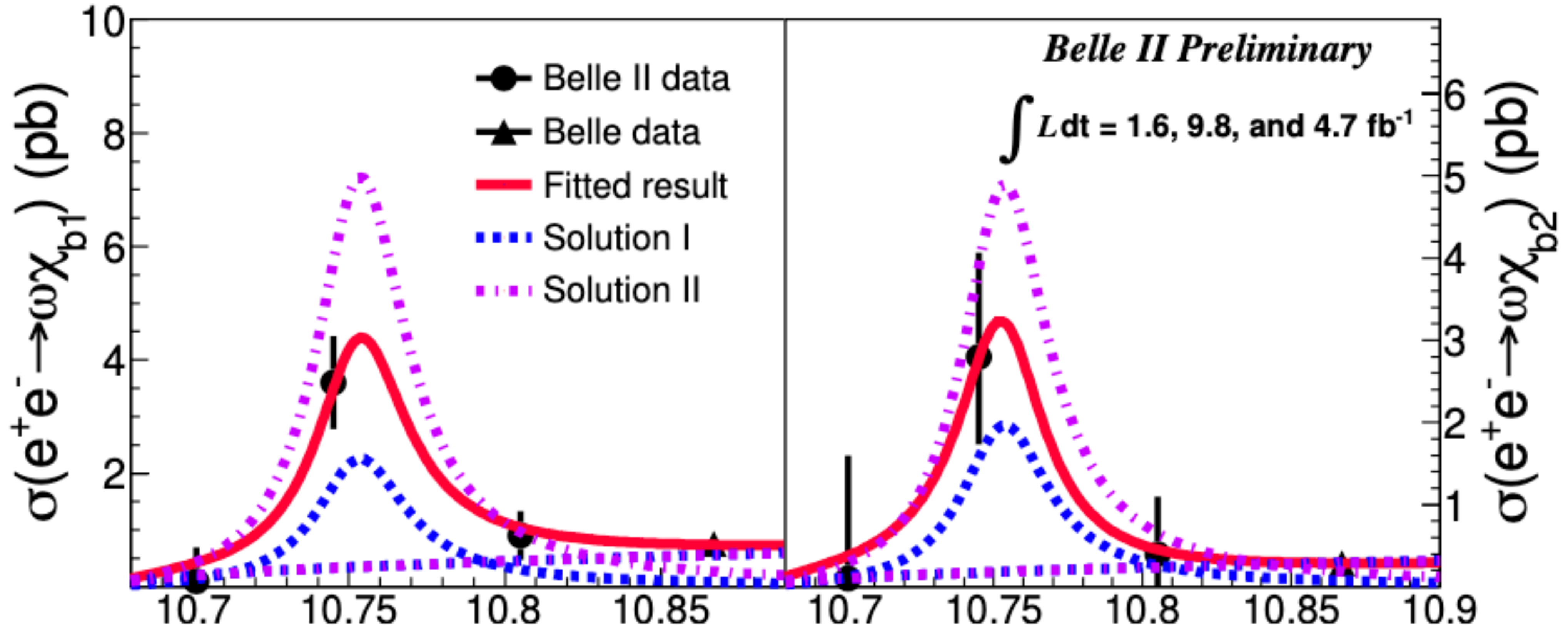


*NEW from Belle II*

# Observation of $Y(10750) \to \omega\chi_{bJ}$ in $e^+e^- \to \gamma\omega\Upsilon(1S)$

With the ***new*** scan data around $\sqrt{s} = 10.75$ GeV



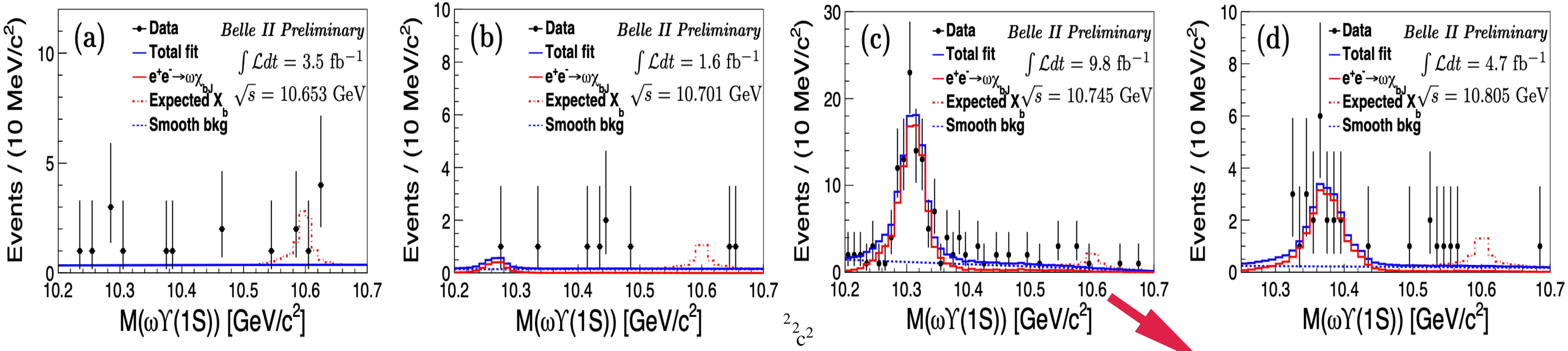

| $\Gamma_{ee}\mathcal{B}_f$ | Solution I | Solution II |
|---|---|---|
| $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$ | $(0.63 \pm 0.39 \pm 0.20)$ eV | $(2.01 \pm 0.38 \pm 0.76)$ eV |
| $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$ | $(0.53 \pm 0.46 \pm 0.15)$ eV | $(1.32 \pm 0.44 \pm 0.55)$ eV |

- $\frac{\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})}{\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})} \sim 1.0$ agrees with the expectation for HQET[3]
- $\frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))^{[2]}} \sim 1.5$ for $\Upsilon(10753)$ and $\sim 0.1$ for $\Upsilon(10870)$

[1]PRL 113, 142001(2014); [2]. JHEP 10, 220(2019); [3]. arXiv:hep-ph/9908366;

Implying a $\omega\chi_b$ hadro-bottomonium/hybrid interpretation of $Y(10750)$

# Search for $X_b \to \omega\Upsilon(1S)$ in $e^+e^- \to \gamma\omega\Upsilon(1S)$




- No significant $X_\mathrm{b}$ signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{\mathrm{bJ}}$

From simulated events with $M(X_\mathrm{b}) = 10.6\ \mathrm{GeV/c^2}$
The yield is fixed at the upper limit on 90% C.L.

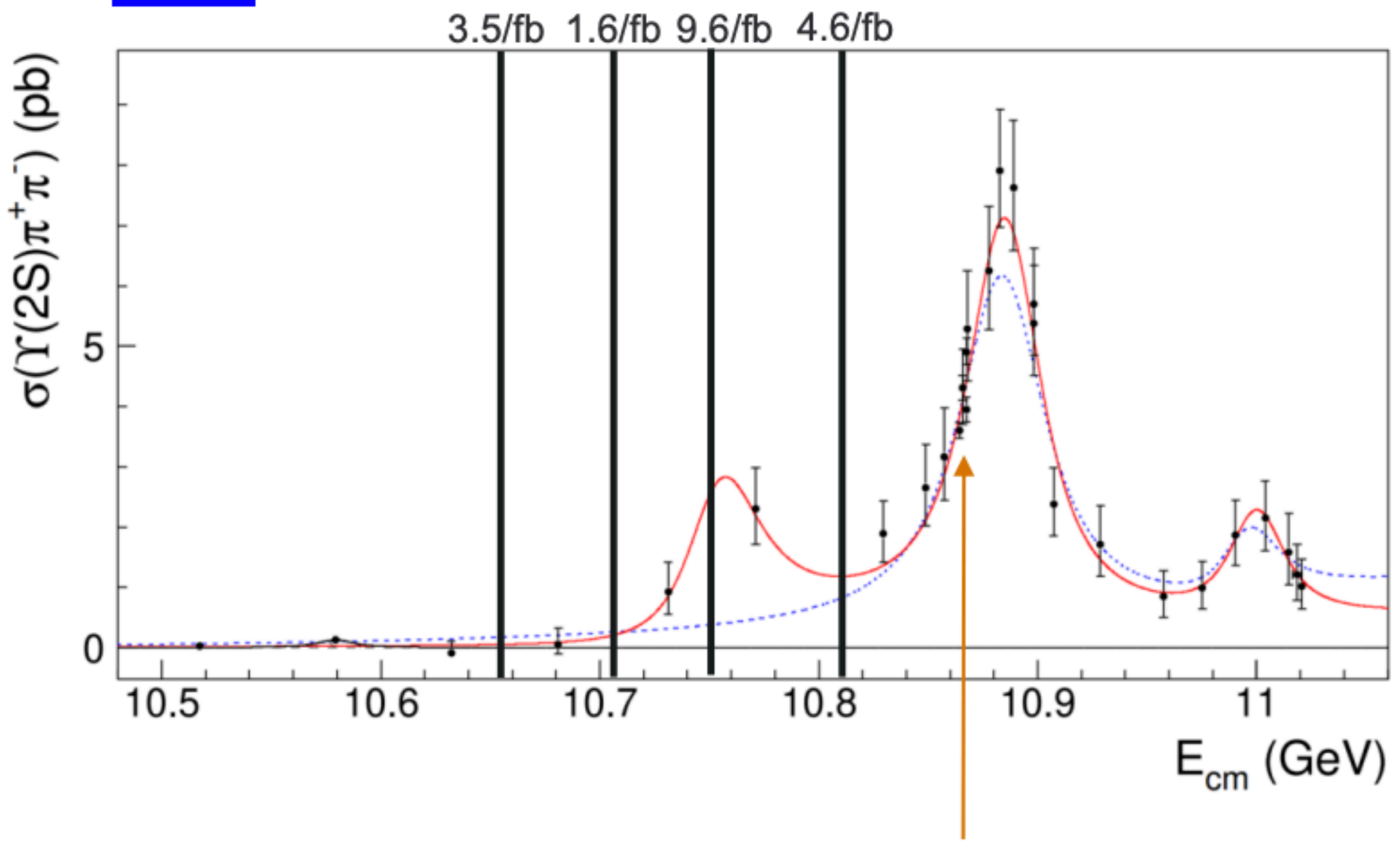
| Upper limits of $\sigma_\mathrm{B}(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$ | $\sqrt{s}$ (GeV) | 10.653 | 10.701 | 10.745 | 10.805 |
|---|---|---|---|---|---|
| | $M(X_\mathrm{b}) = 10.6\ \mathrm{GeV/c^2}$ | 0.45 | 0.33 | 0.10 | 0.14 |

# Prospect

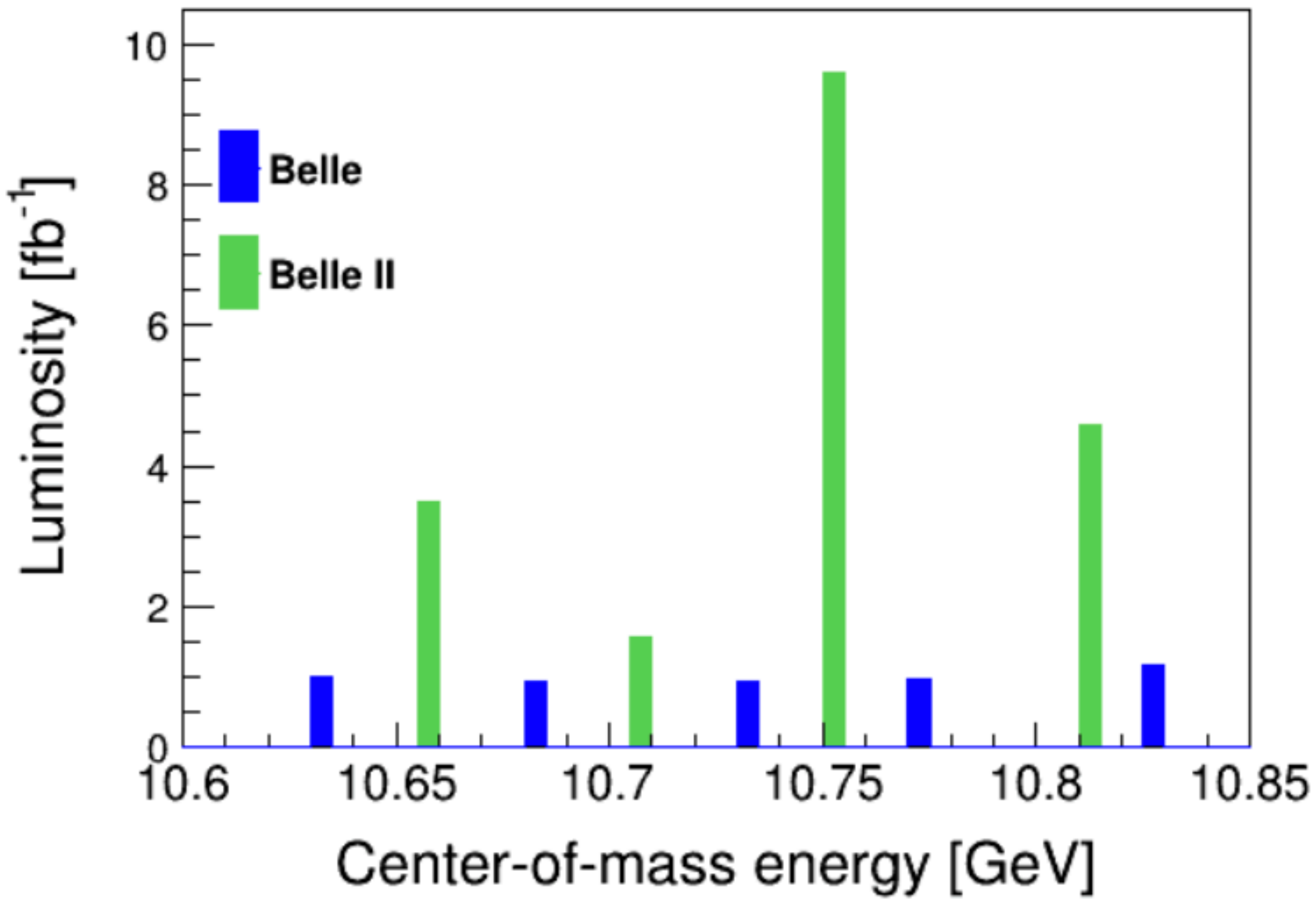
*In short term*

## *What is $\Upsilon(10750)$?*
## *—A little data may tell a big story*

JHEP 10 (2019) 220




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

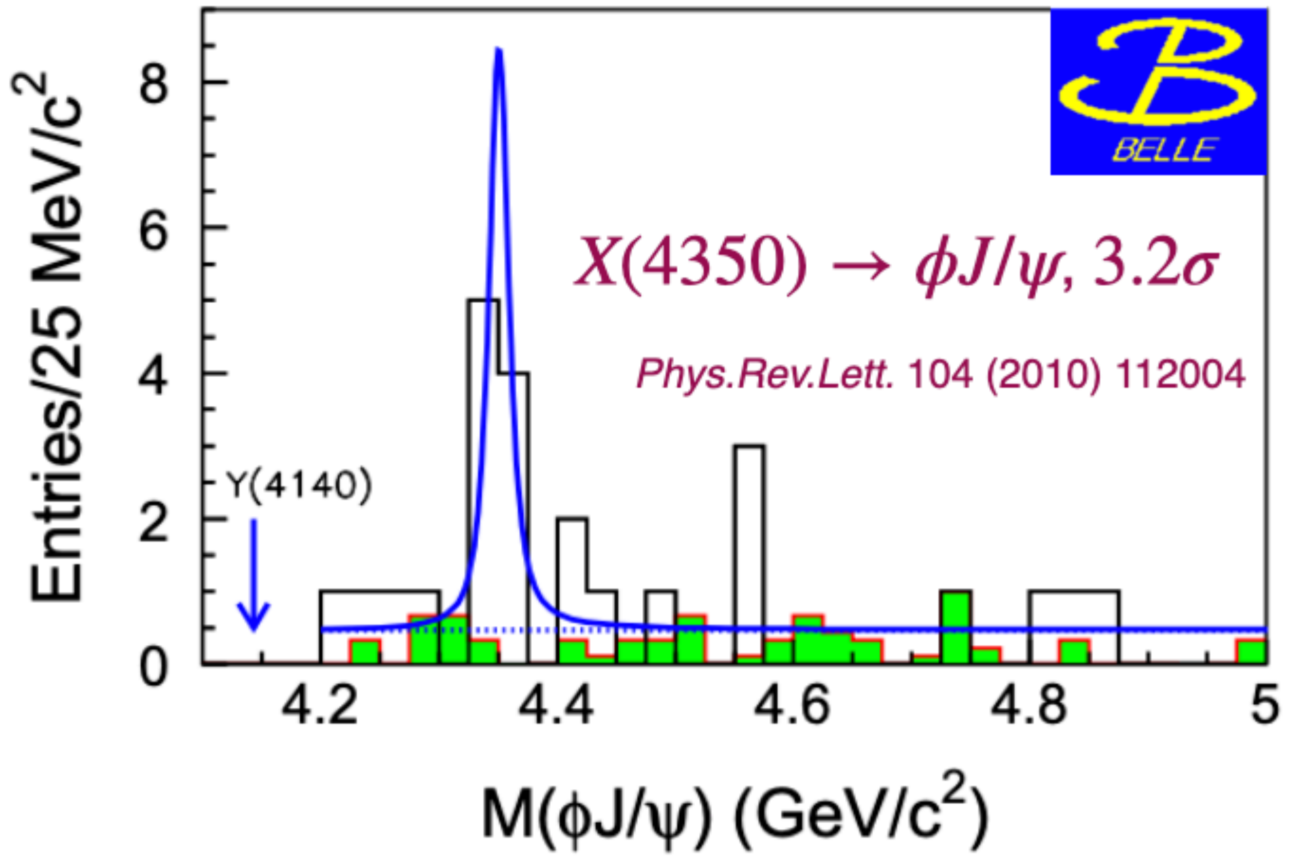


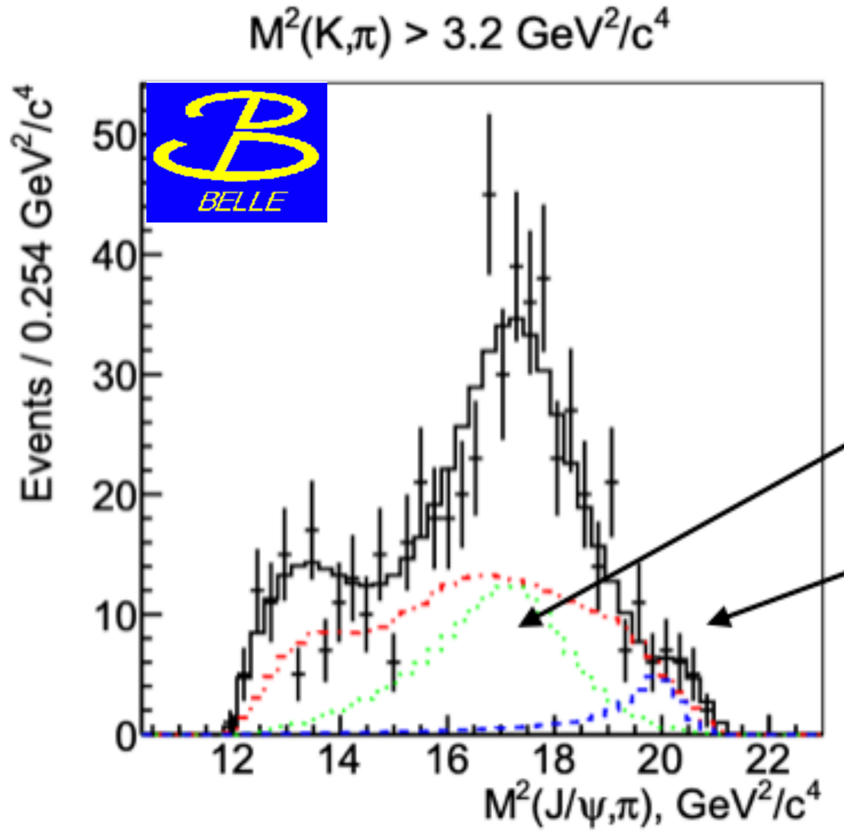

Already presented $\Upsilon(10750) \to \omega\chi_{bJ}$; more studies coming on the way

- $e^+e^- \to \pi\pi\Upsilon(nS)$, $B^{(*)}\bar{B}^{(*)}$, $\gamma X_b$, $\eta\Upsilon(nS)$ etc.
- Combine with Belle data.

# Prospect *With* $10\ \mathrm{ab}^{-1}$

## ***Evidence could be clarified, e.g.***



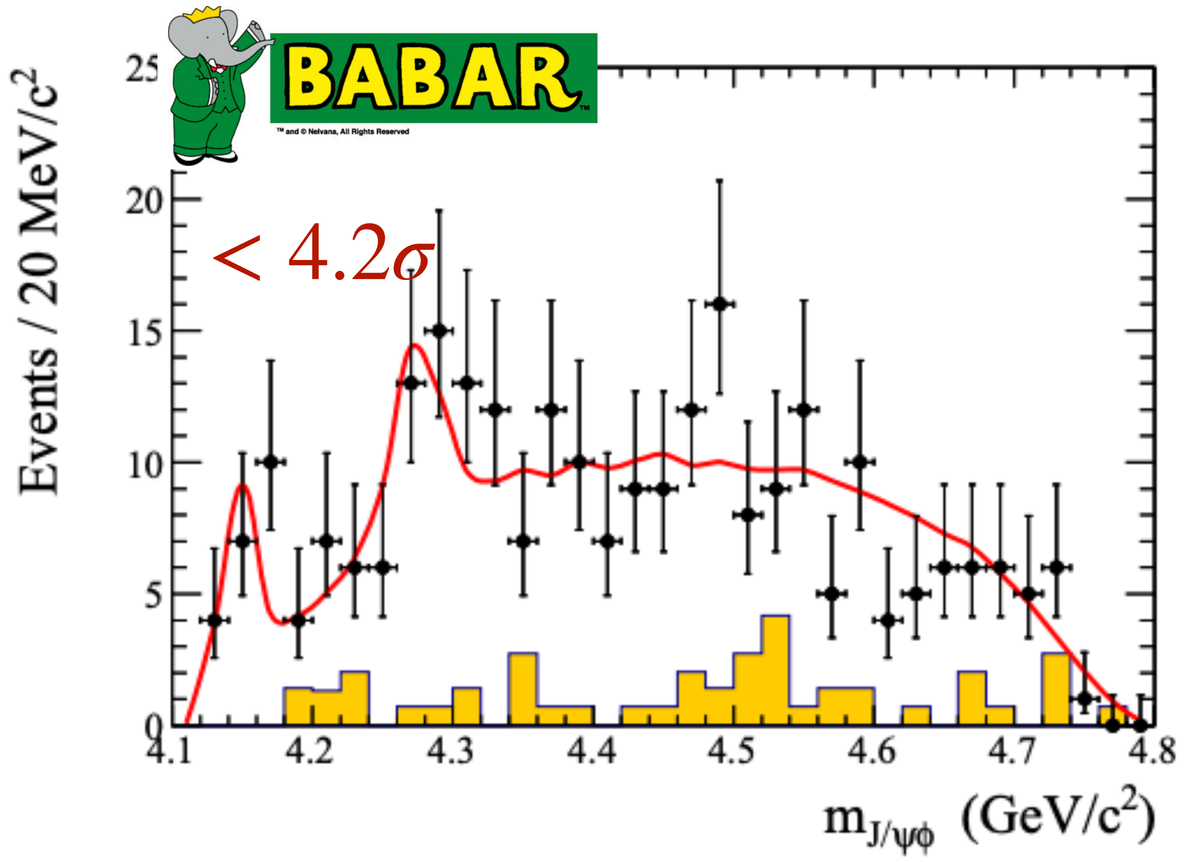

$Z_c(4200)$ and $Z_c(4430)$ in $B \to K\pi^- J/\psi$

$6.2\sigma$

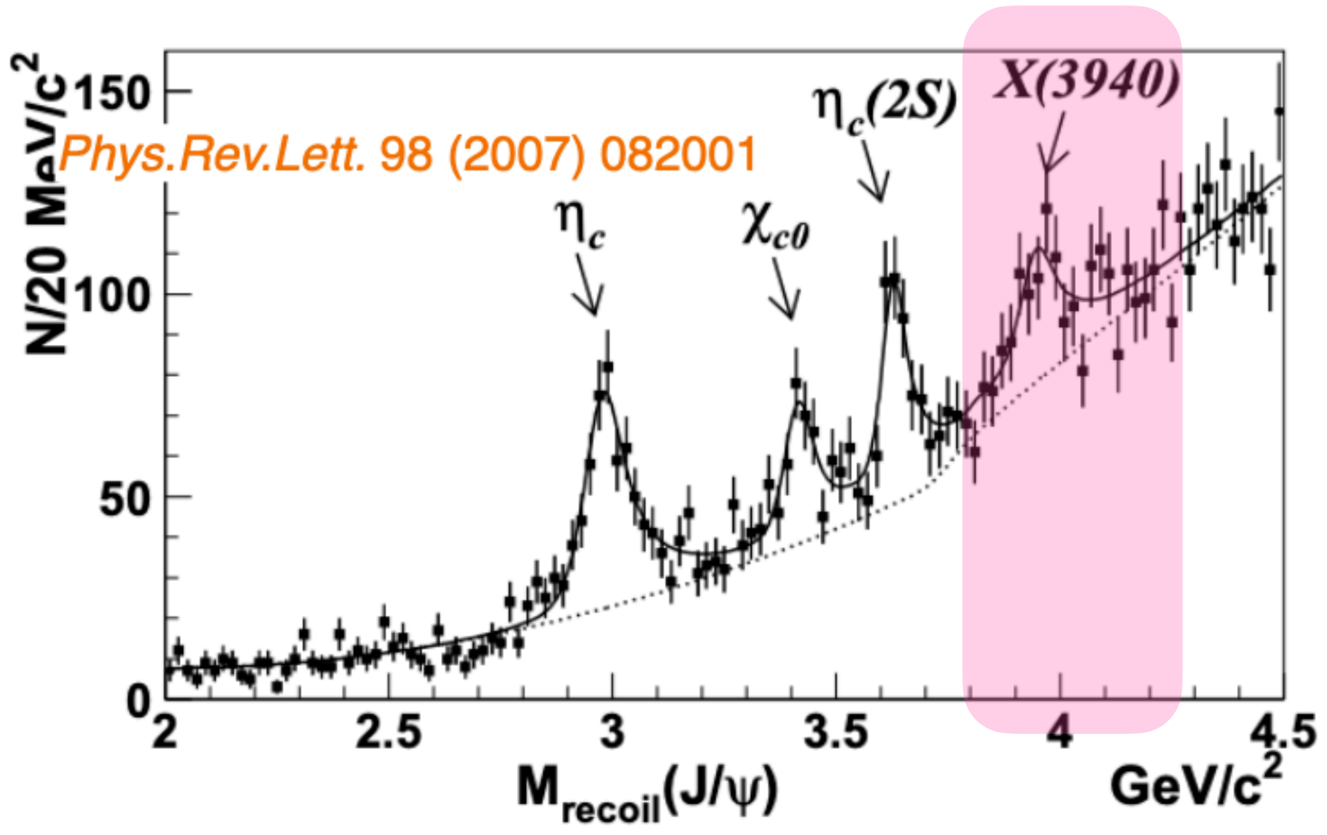
$> 3\sigma$

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

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




## ***Properties measurements with dedicated analysis***



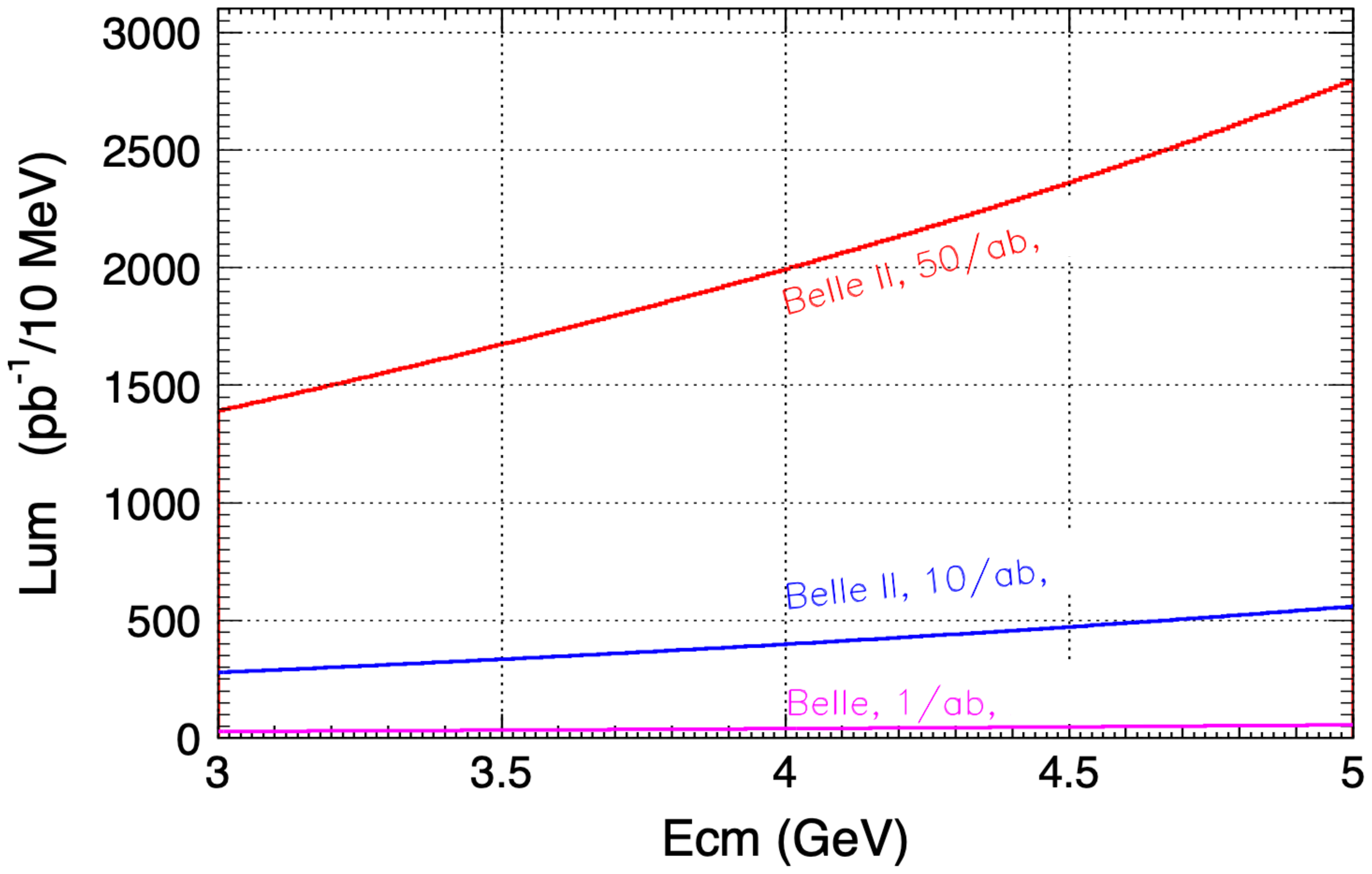

$X(3940)$ $\quad I^G(J^{PC}) = ?^?(?^{??})$

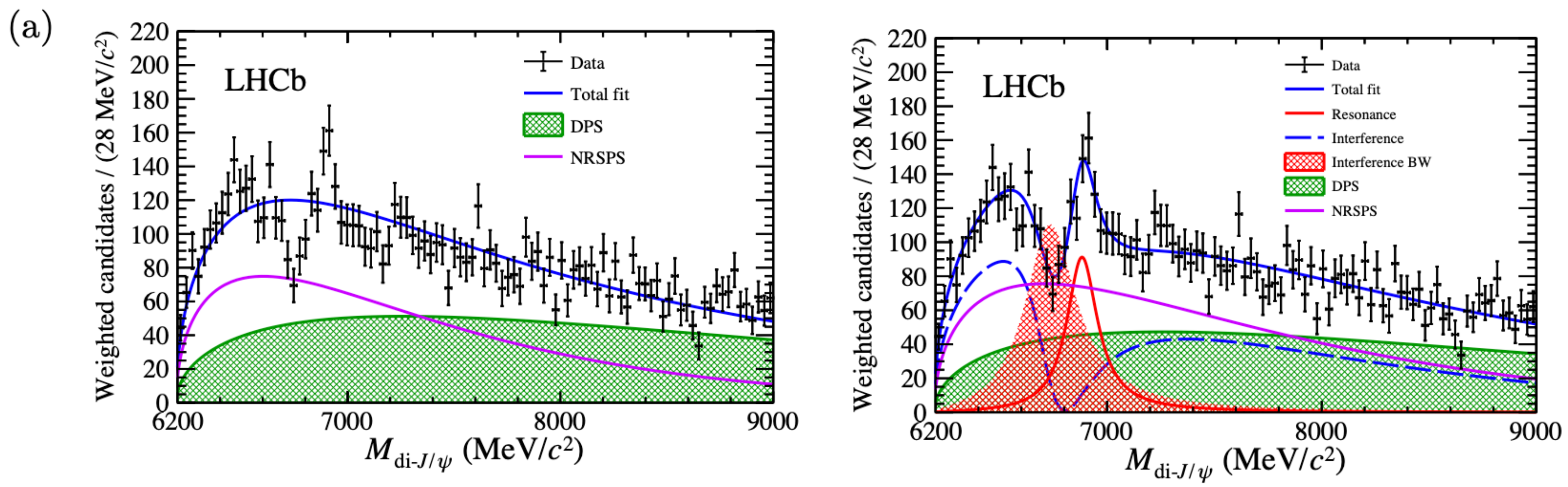
Quantum number of $X(3940)$ remains unknown.
Amplitude analysis could be implemented to tell the possible multiple resonances apart.

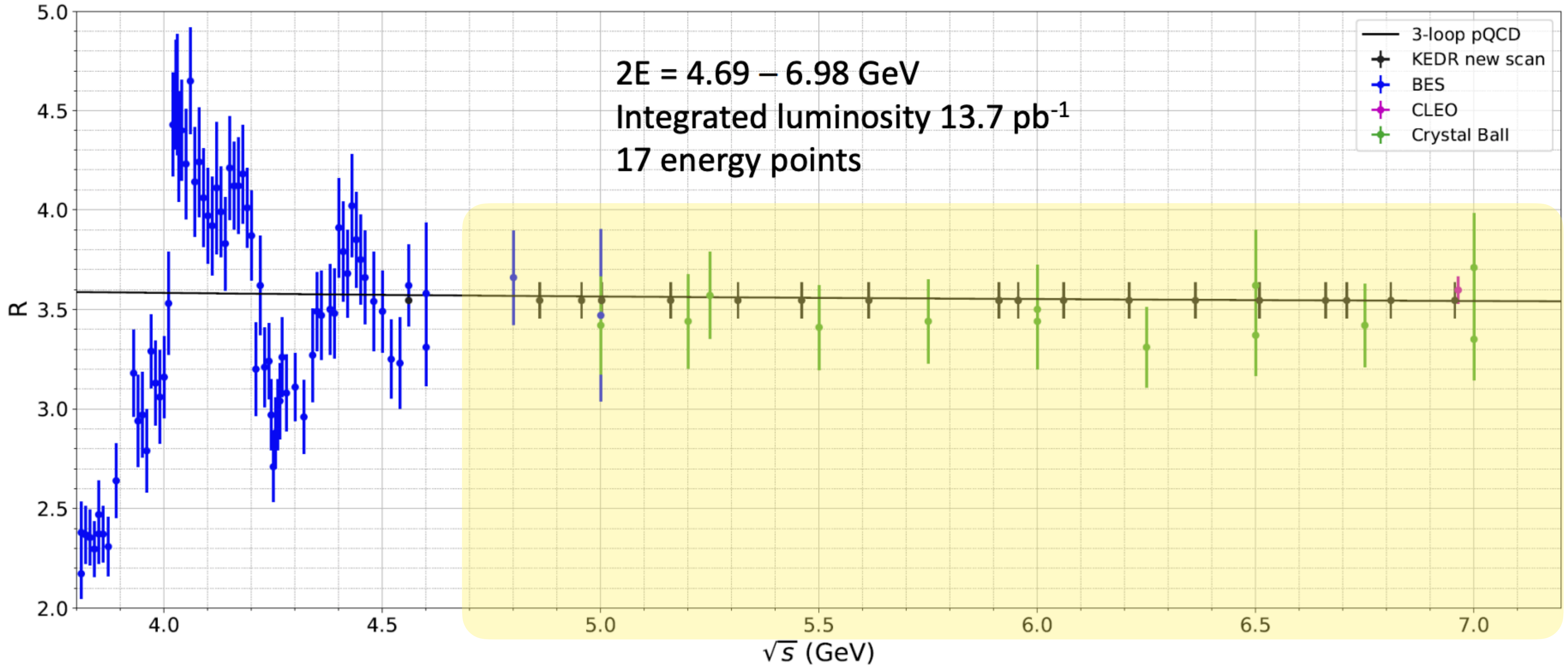
# Prospect

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

### *Fully cover charmonium region with ISR*



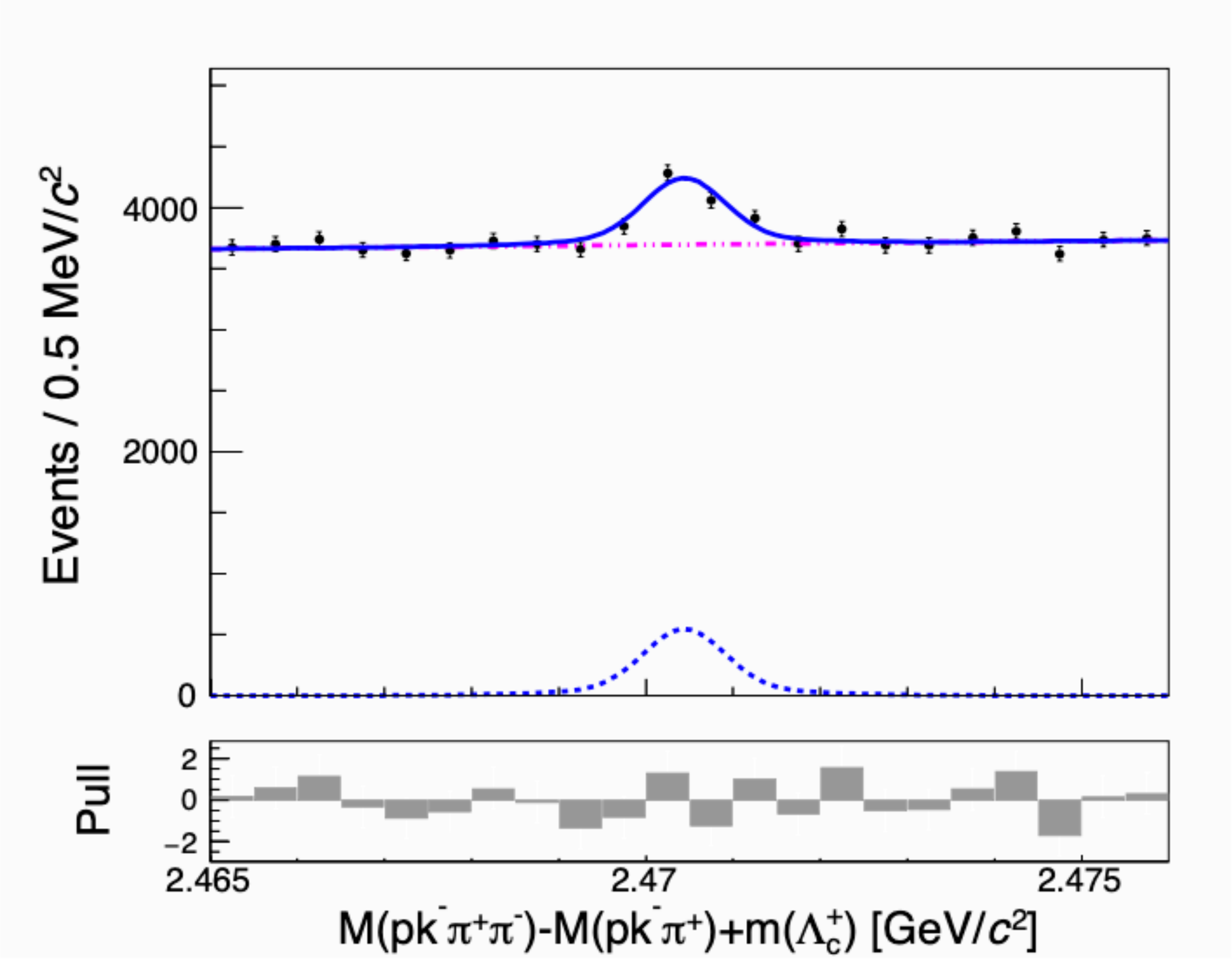

- Dedicated study to $e^+e^- \to \pi^+\pi^- J/\psi$, $K\bar{K}J/\psi$, etc.
- $Z_c$ production in both $e^+e^-$ annihilation and $B$ decays.
- Doubly charmonium state in, e.g. $e^+e^- \to \eta_c J/\psi, \chi_c J/\psi$ via ISR

# Summary and outlook

- Belle and Belle II provide unique and fertile physics environment.
- 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.
  - Precise measurement;
  - Spin-parities, transitions, and quantum numbers determination;
  - New decays searching;
  - Prediction/model/theory testing
  - …
- Belle II with $> 400\ \mathrm{fb}^{-1}$ data, including unique $\Upsilon(10750)$ scan data, can already provide physics output on the level of its predecessors.

# Back up

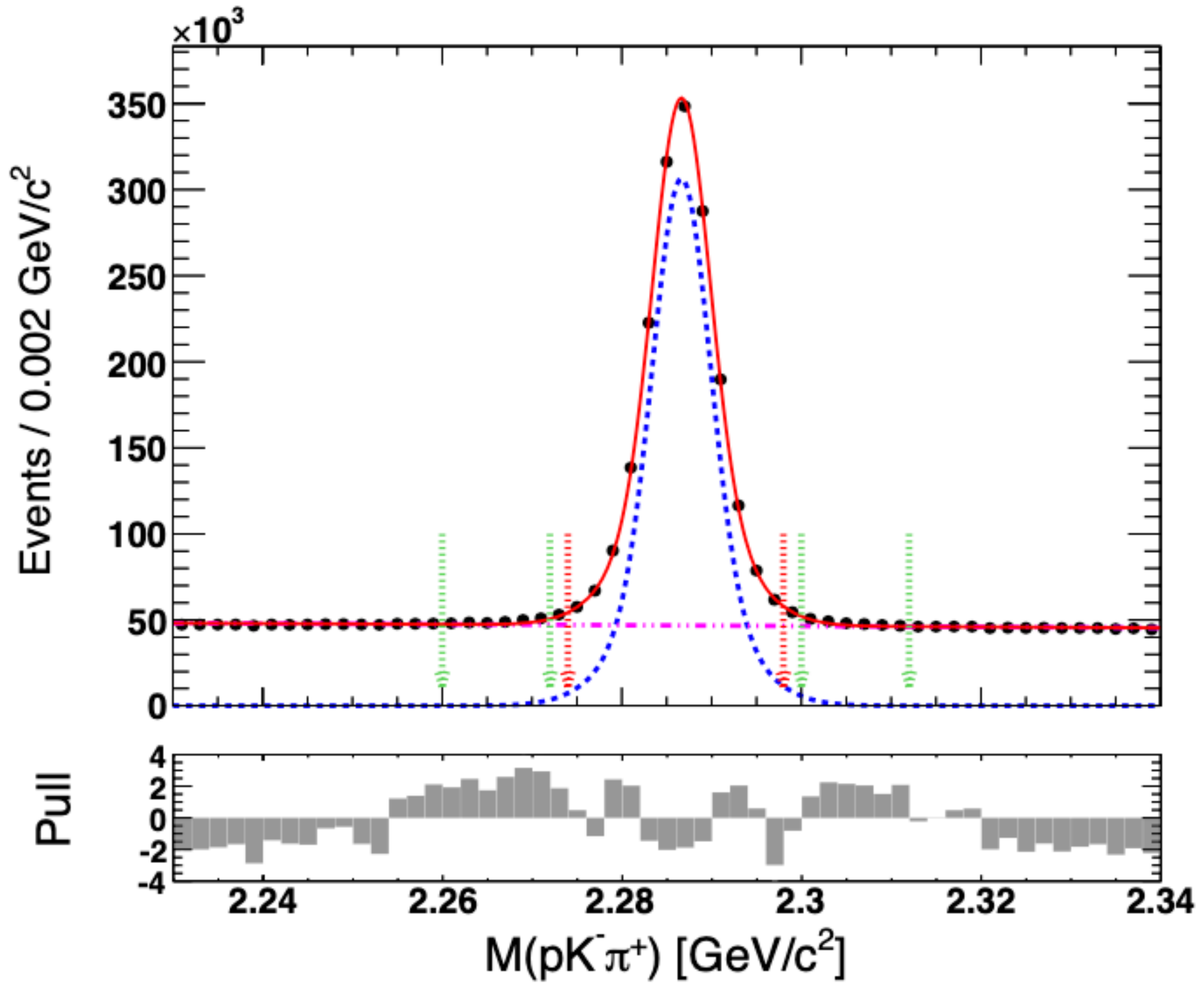
# Measurement of $\Xi_c^0 \to \Lambda_c^+ \pi^-$

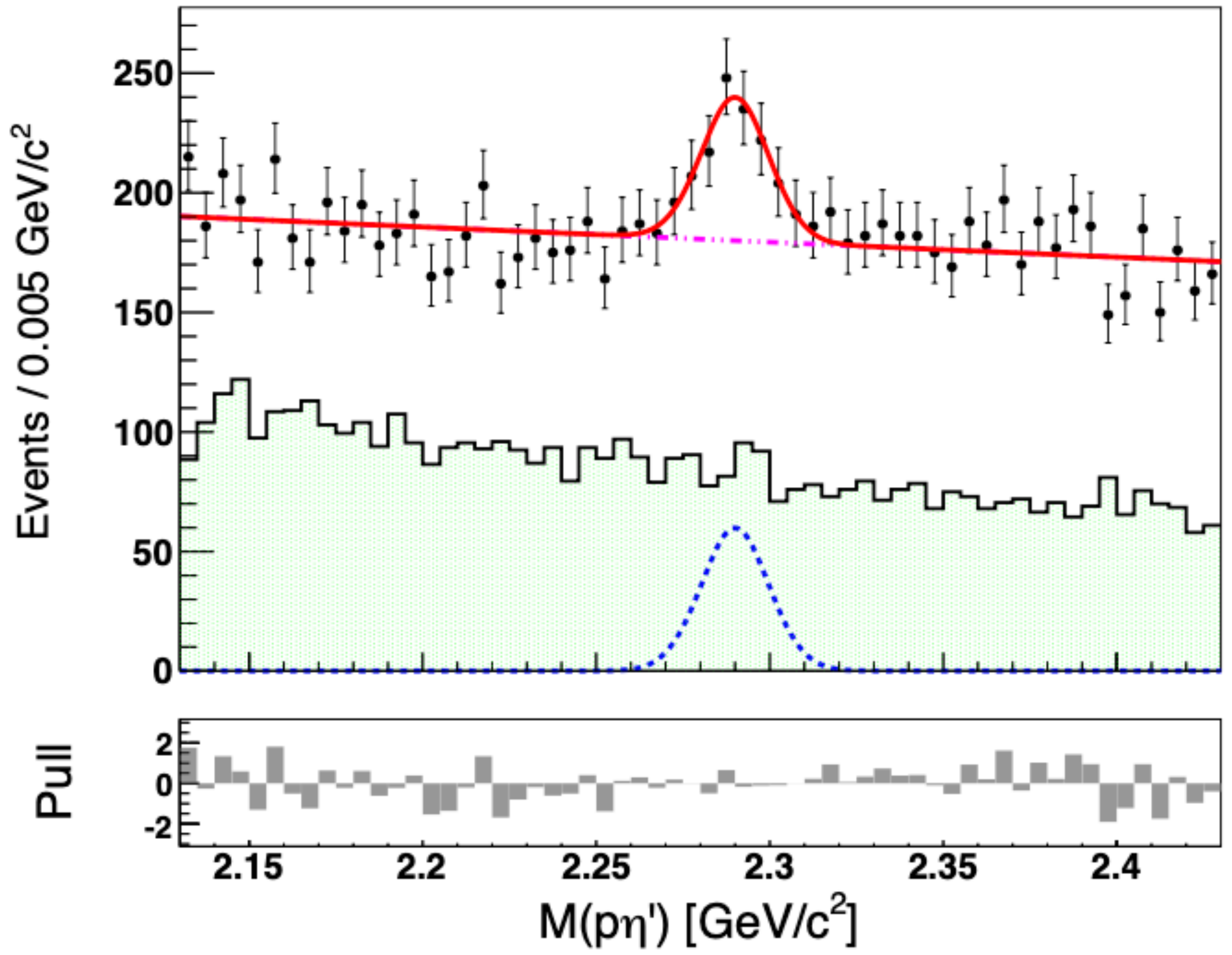


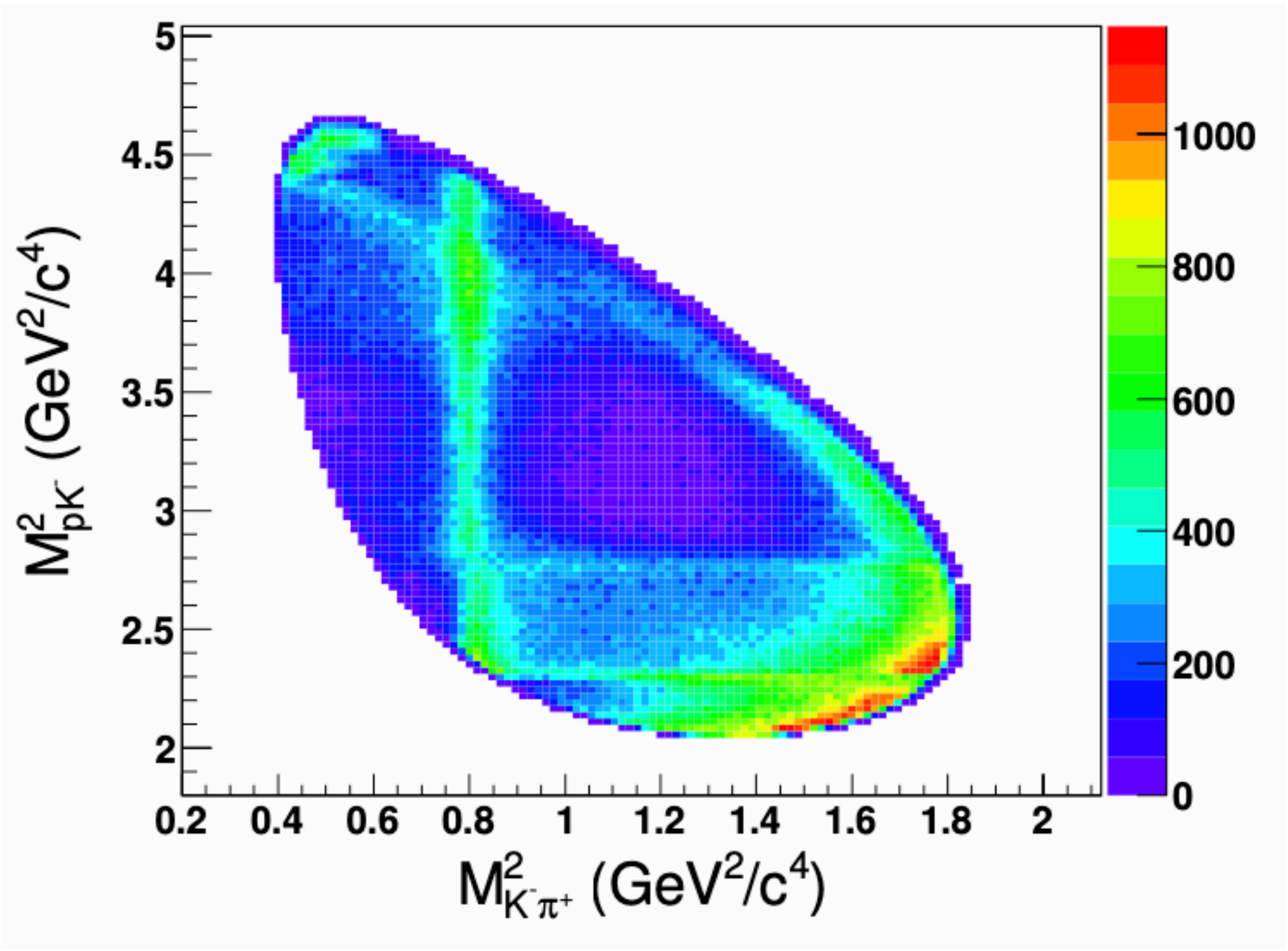

$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = \frac{N_{\Lambda_c\pi} \times \epsilon_{\Xi\pi}^{\rm ref} \times \mathcal{B}(\Xi^- \to \Lambda\pi^-) \times \mathcal{B}(\Lambda \to p\pi^-)}{N_{\Xi\pi} \times \epsilon_{\Lambda_c\pi}^{\rm sig} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$
$$= 0.38 \pm 0.04(\text{stat.}) \pm 0.04(\text{syst.}),$$

arXiv: 2206.08527

# Measurement of $\Lambda_c^+ \to p\eta'$




$$\frac{\mathcal{B}(\Lambda_c^+ \to p\eta')}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.54 \pm 1.32 \pm 0.73) \times 10^{-3},$$

arXiv: 2112.14276