Belle II

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Exotic ~~and conventional~~

Quarkonium(-like) Physics Prospects at Belle II

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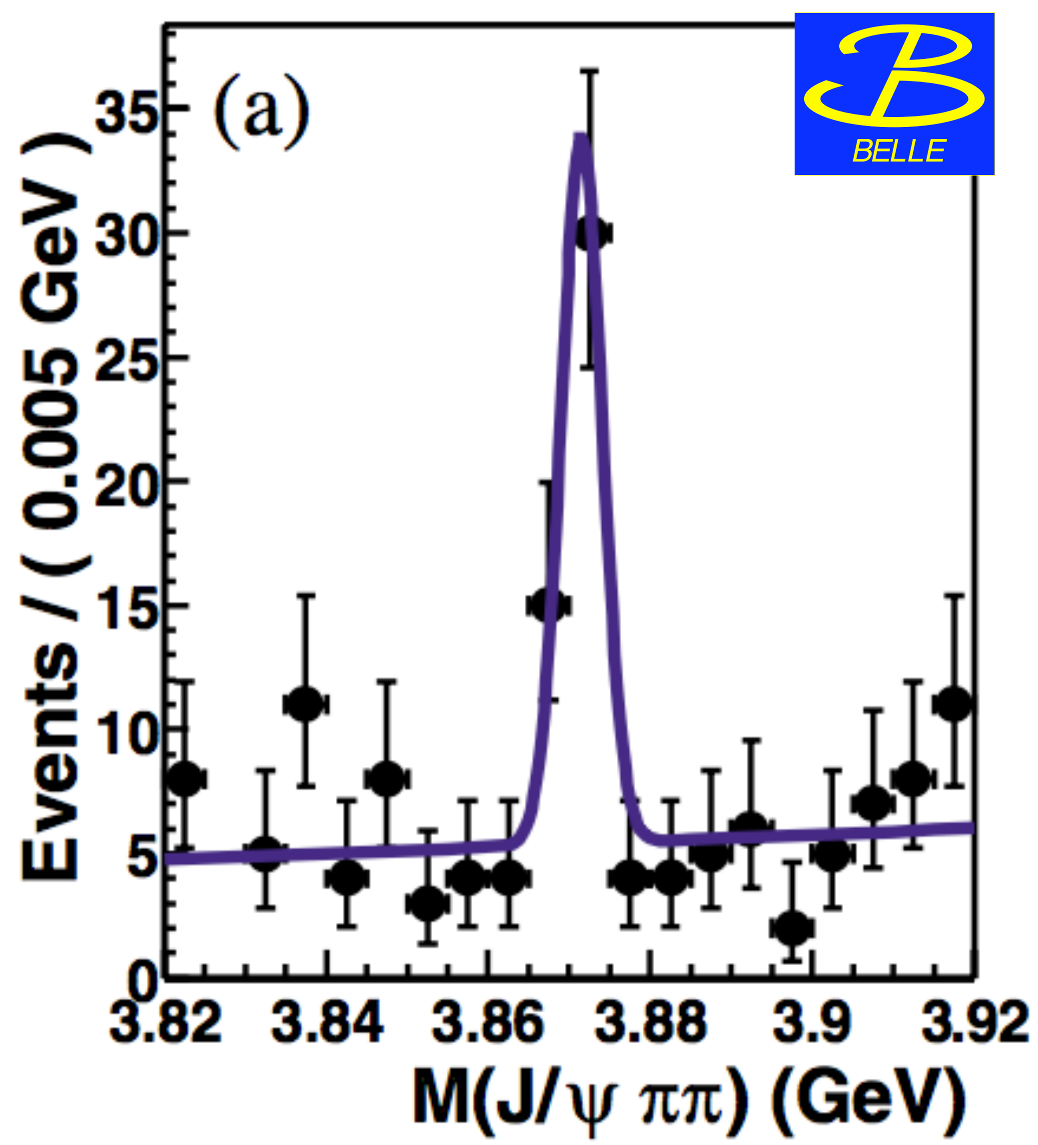
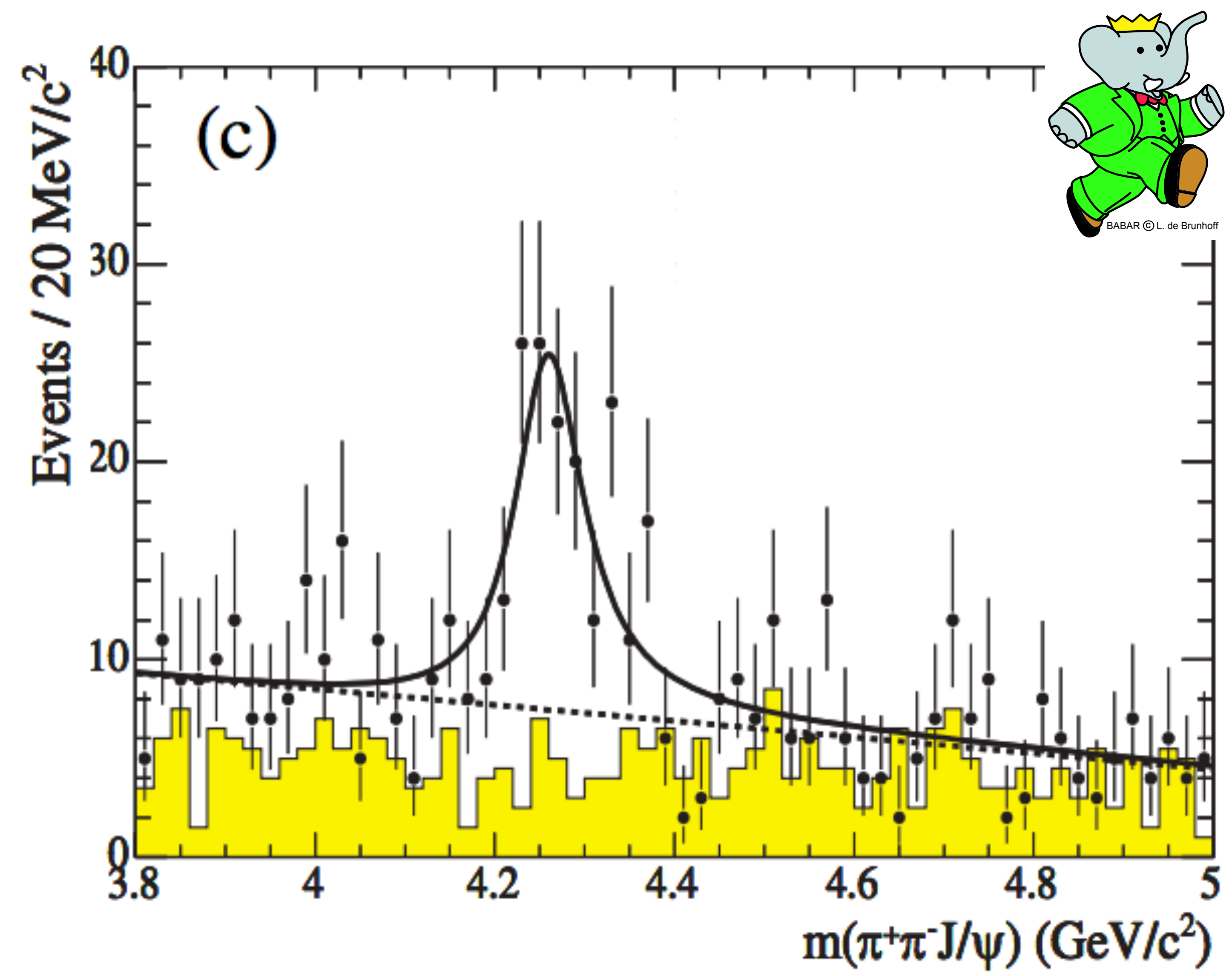
"X Y Z" – *the beginning*



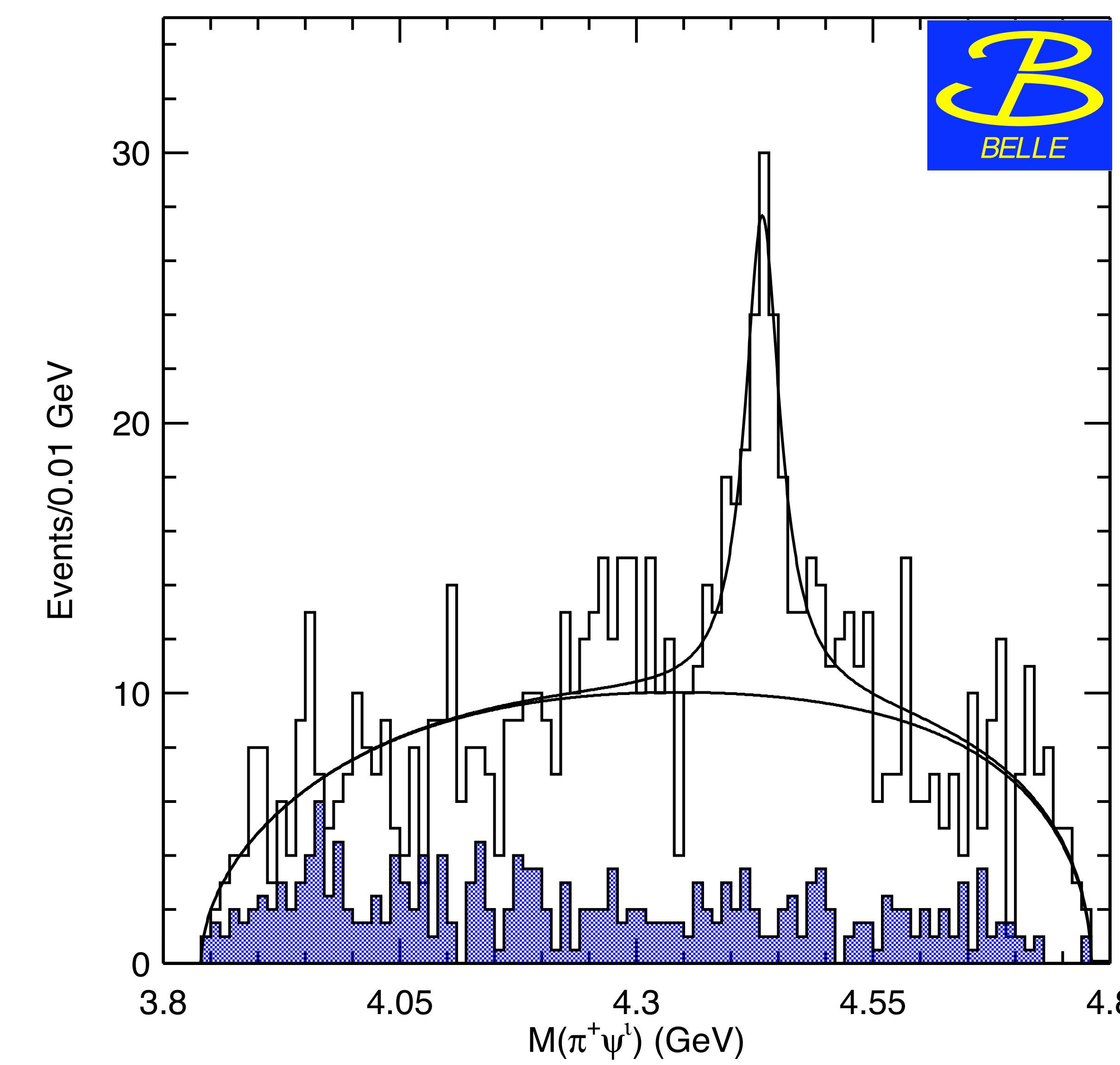
$X(3872)$
PRL 91, 262001 (2003)

$$B^{\pm} \to K^{\pm}[\pi^{+}\pi^{-} J/\psi]$$



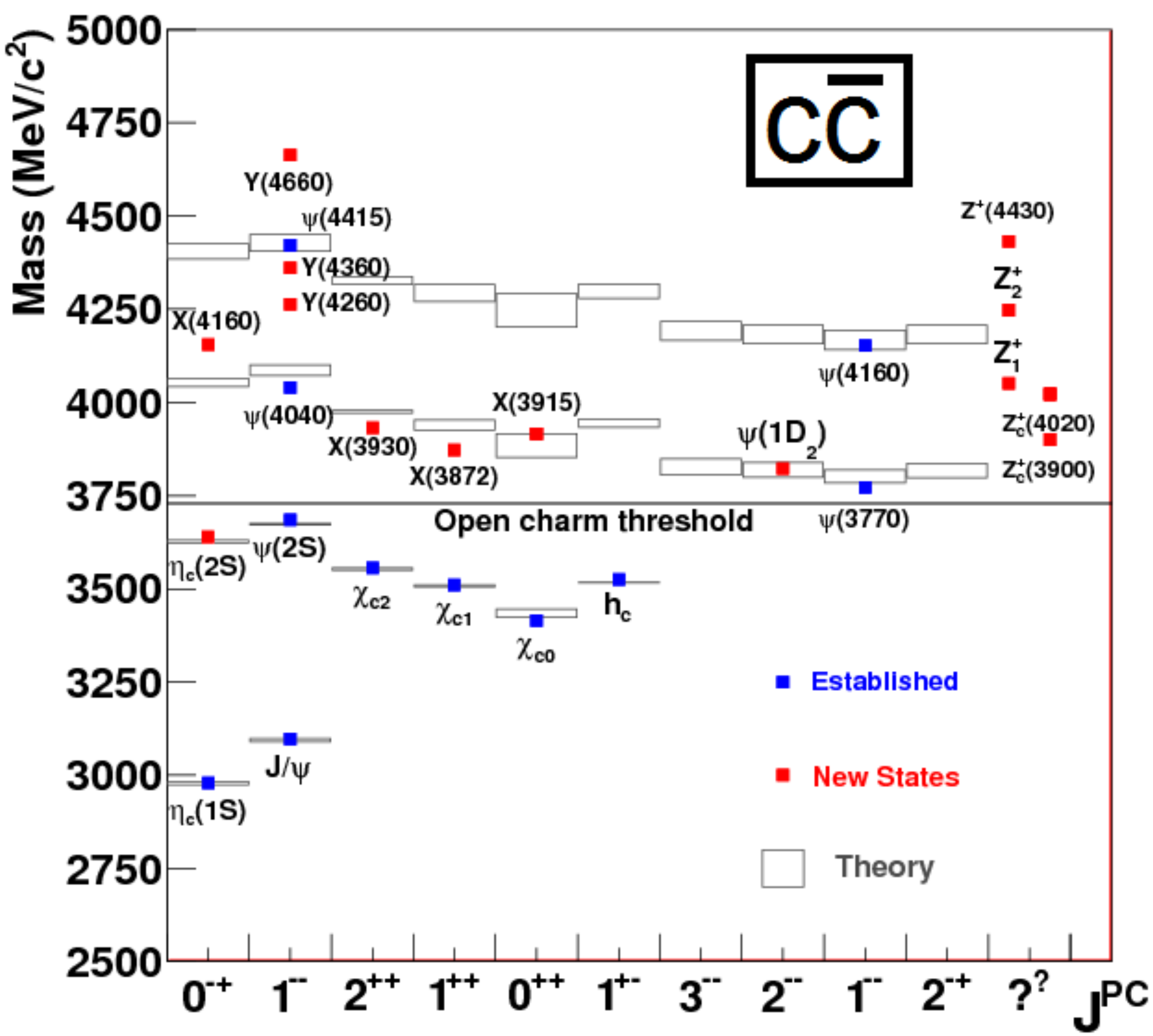
$Y(4260)$
PRL 95, 142001 (2005)

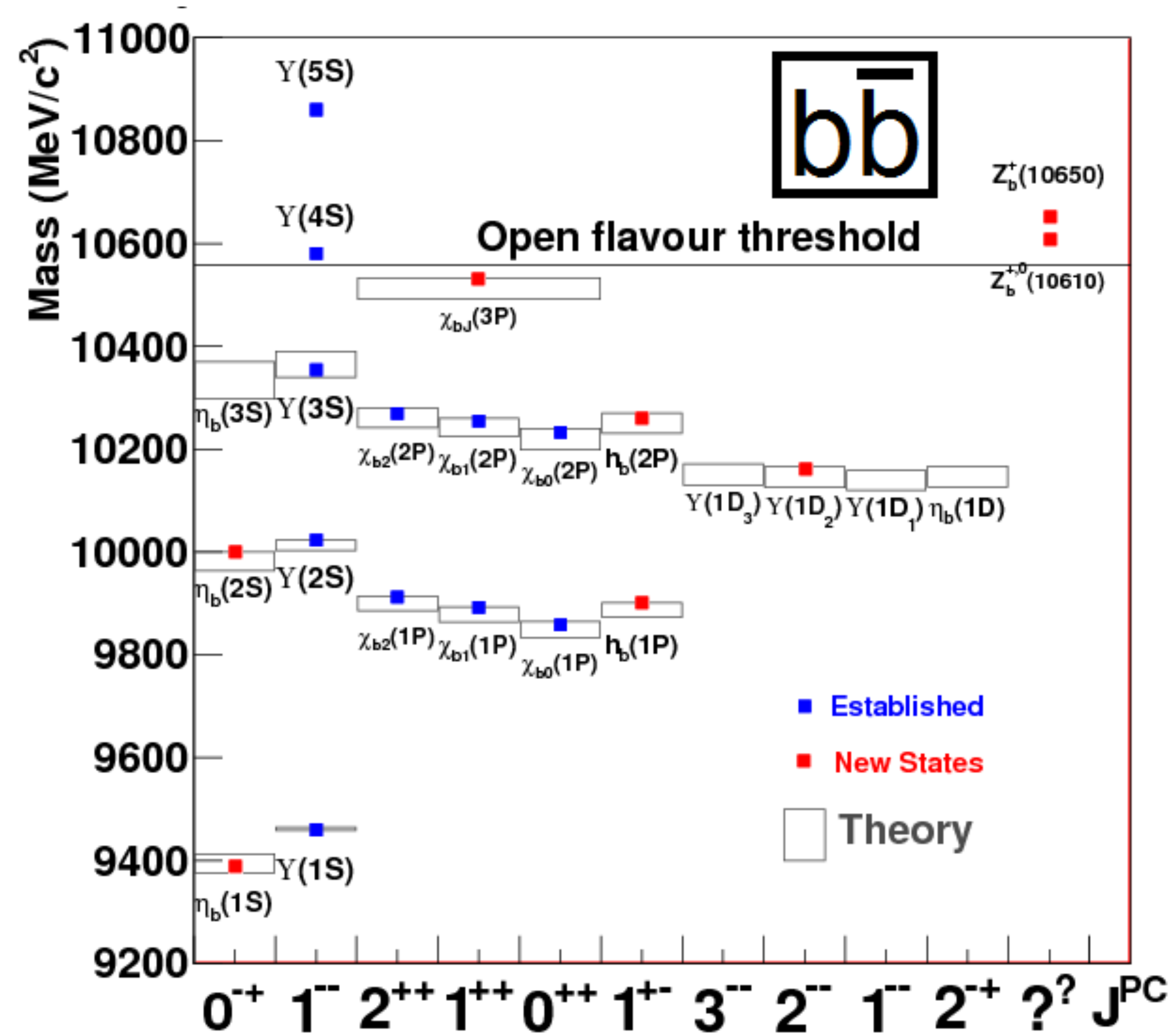
$$e^{+}e^{-} \to \gamma[\pi^{+}\pi^{-} J/\psi]$$



$Z_c(4430)^{\pm}$
PRL 100, 142001 (2008)

$$B \to K[\pi^{\pm}\psi']$$

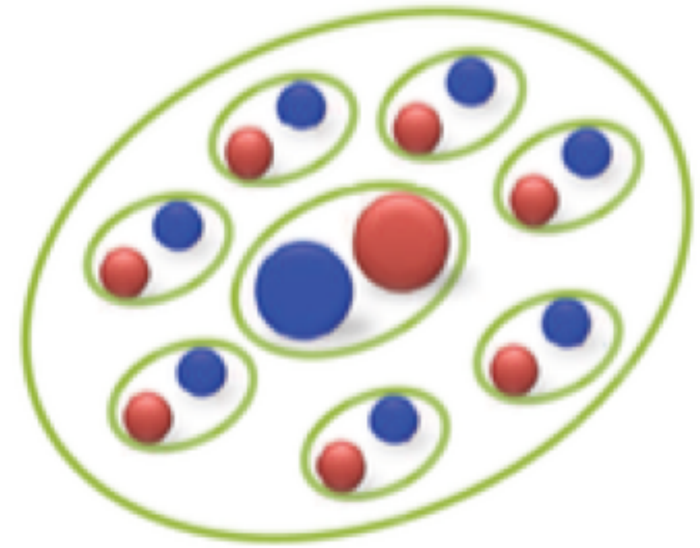




If I could remember the names of all these particles, I'd be a botanist.

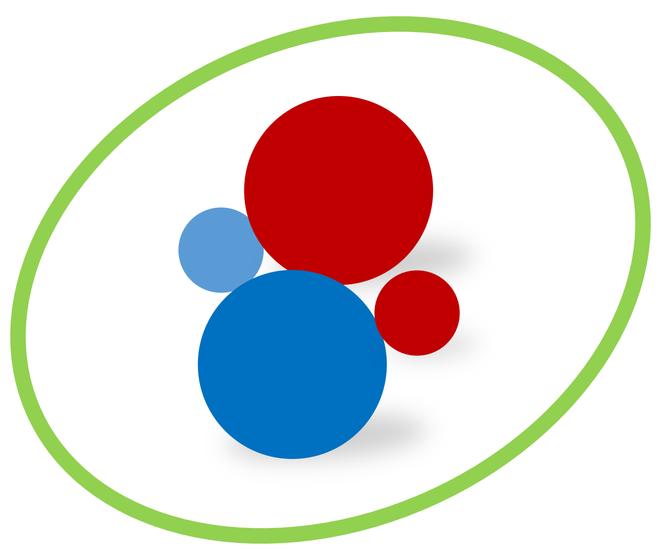
- E. Fermi

Various interpretations of the exotic states



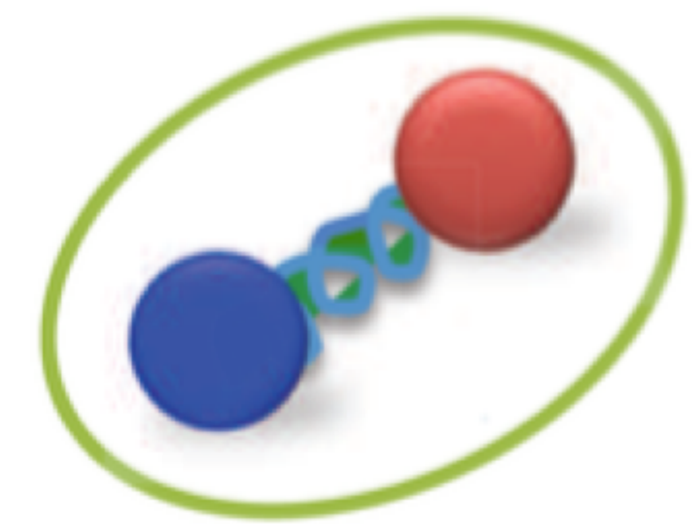
hadroquarkonium

diquark-diantiquark



tetra-quark

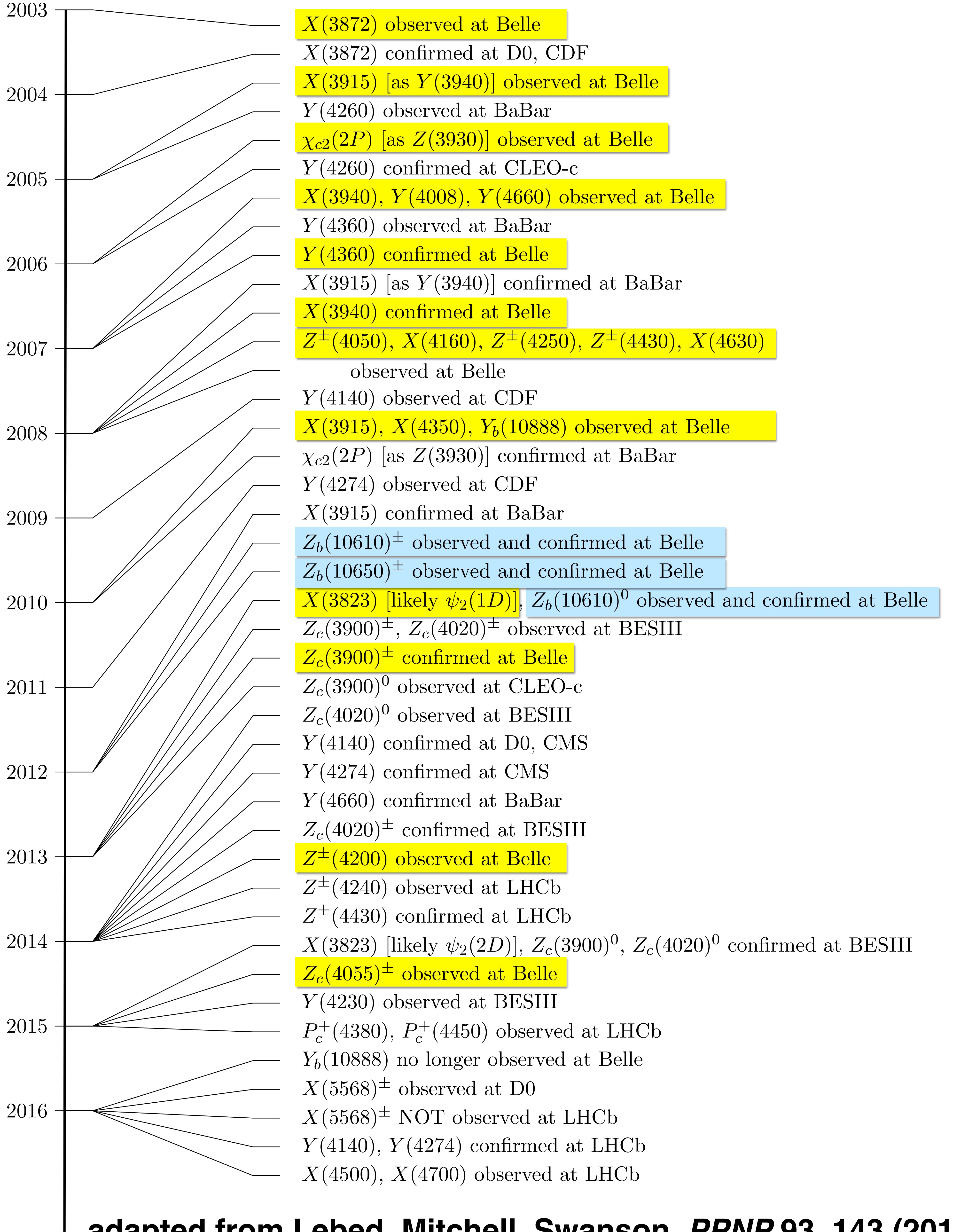
q$\bar{q}$-gluon “hybrid”



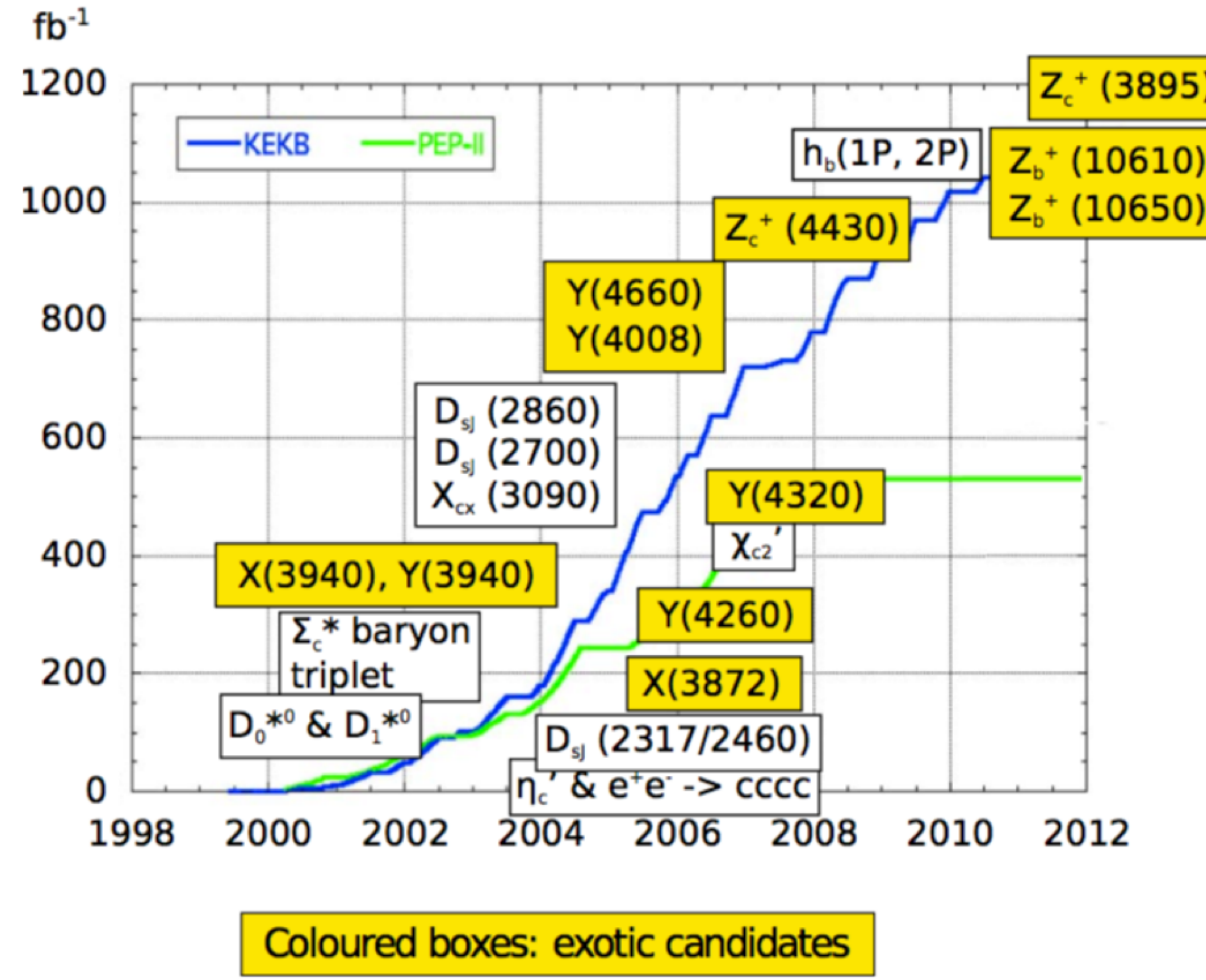
D-$\bar{D}$* “molecule”

Notable question on the exotic states

- What are the nature of these states? Quantum numbers?
- Why are they surprisingly narrow, even though they are above threshold?



adapted from Lebed, Mitchell, Swanson, *PPNP* 93, 143 (2017)



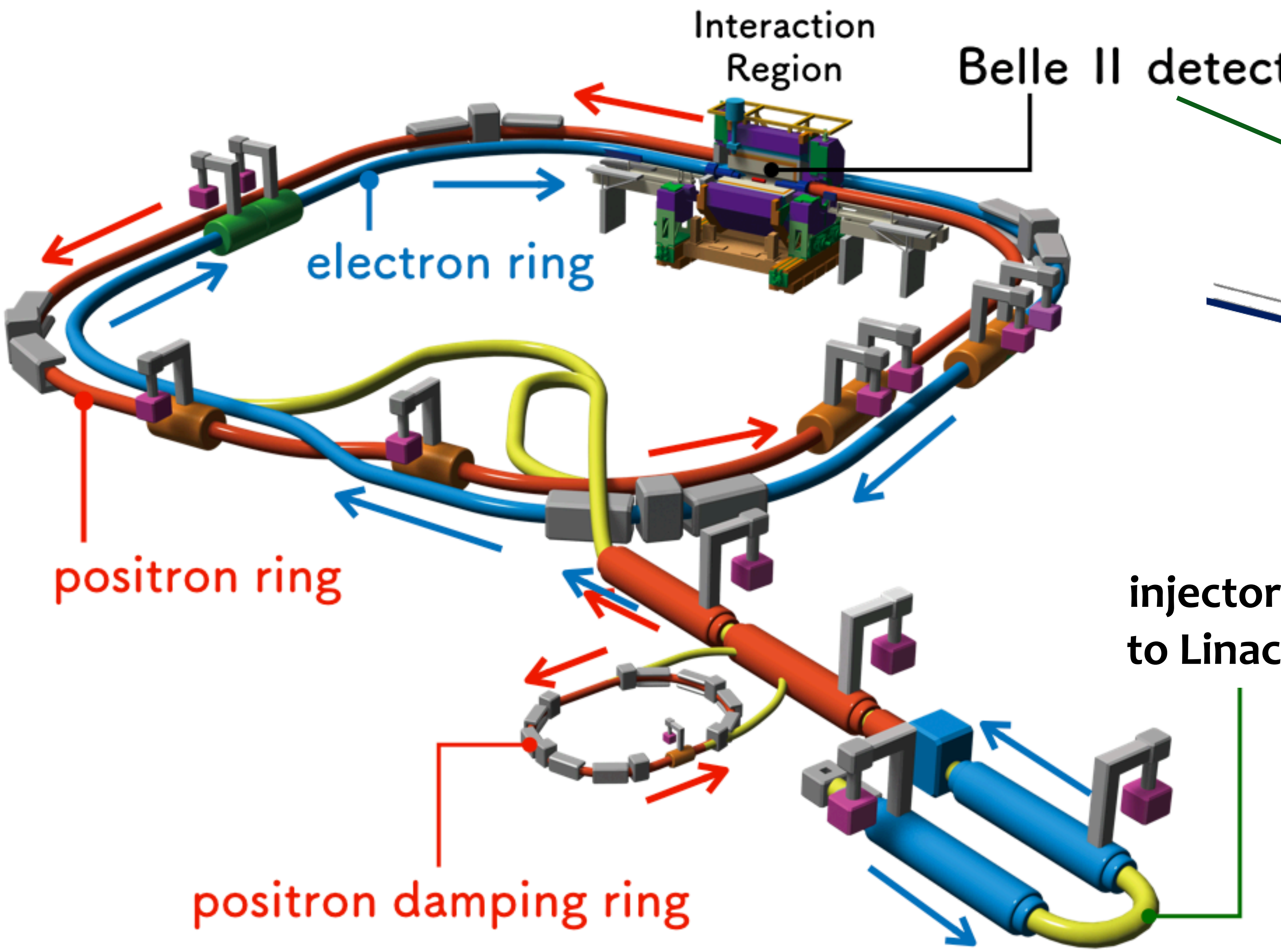
- History of the quarkonium-like exotic states
- Belle accounts for ~1/2 of the discoveries, including the very first one, X(3872)

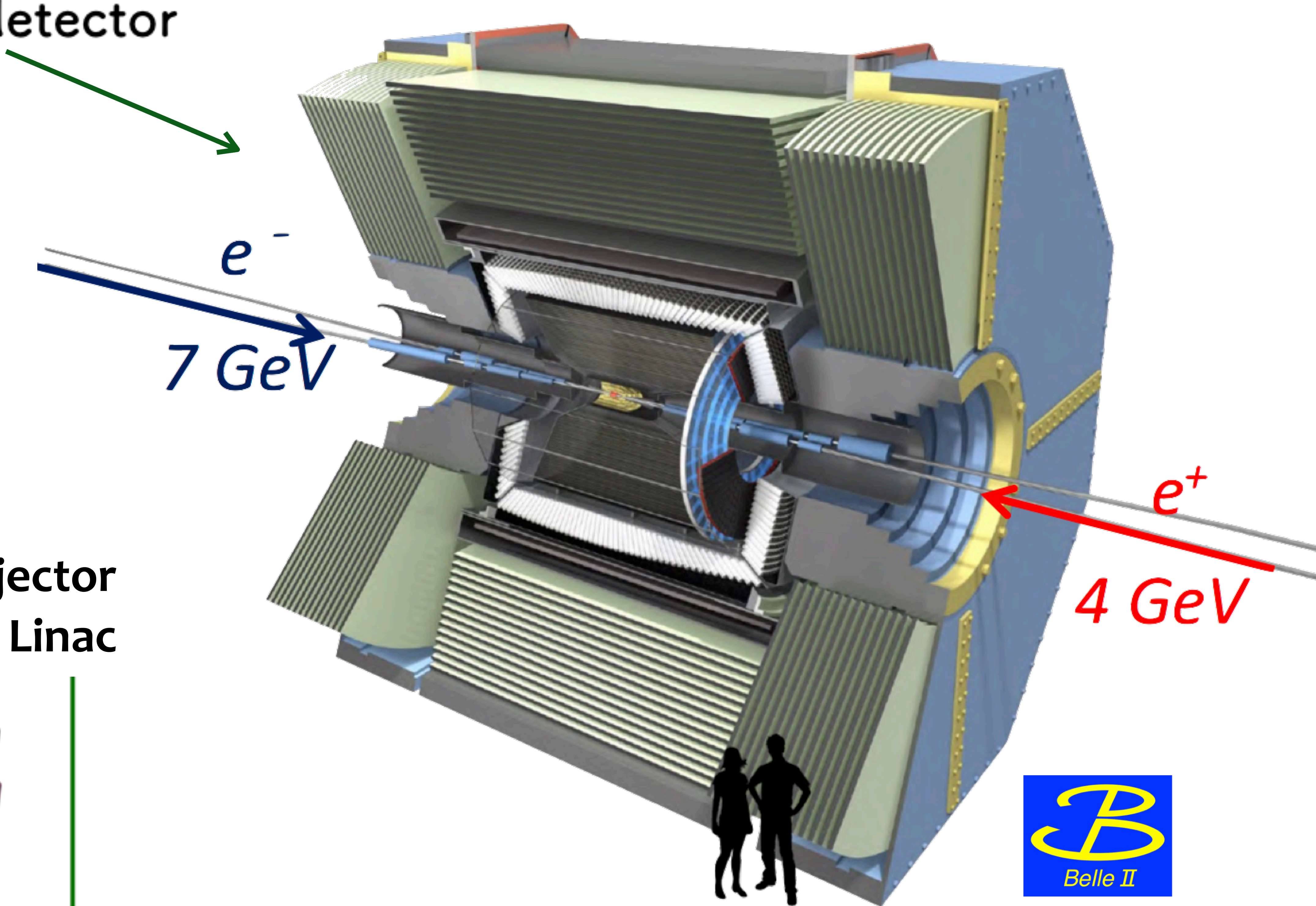
Overview

- **Introduction**
- **Action items for Belle II**
  - Charmonium-like exotics
  - Bottomonium-like exotics
- **Closing remarks**

SuperKEKB

Belle II





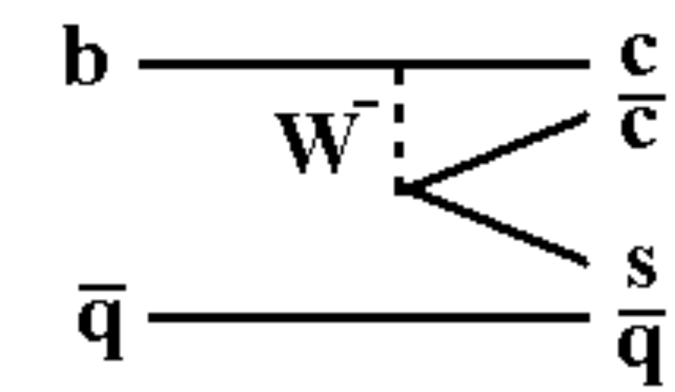
$$e^- \xrightarrow{\mathbf{7\ GeV}} (\star) \xleftarrow{\mathbf{4\ GeV}} e^+$$

$$\mathcal{L}^{\text{peak}} = 40 \times \mathcal{L}^{\text{peak}}_{\text{Belle}}$$

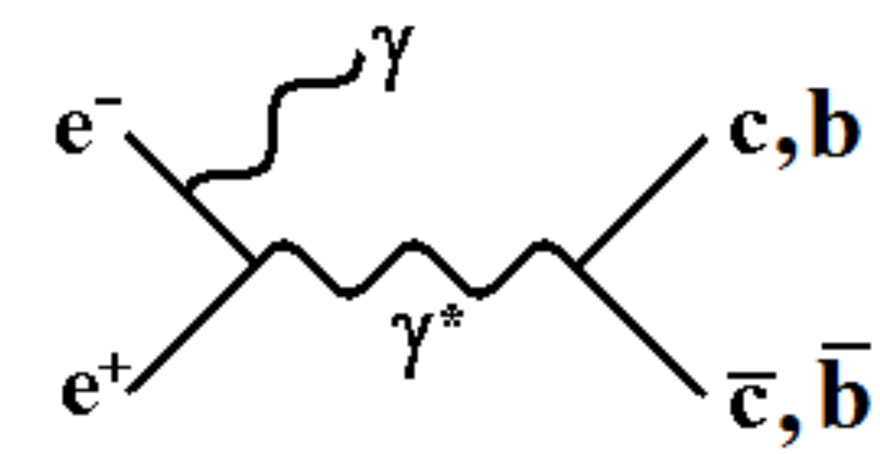
$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1} = 50 \times \mathcal{L}^{\text{int}}_{\text{Belle}}$$

Quarkonium production in e^+e^-

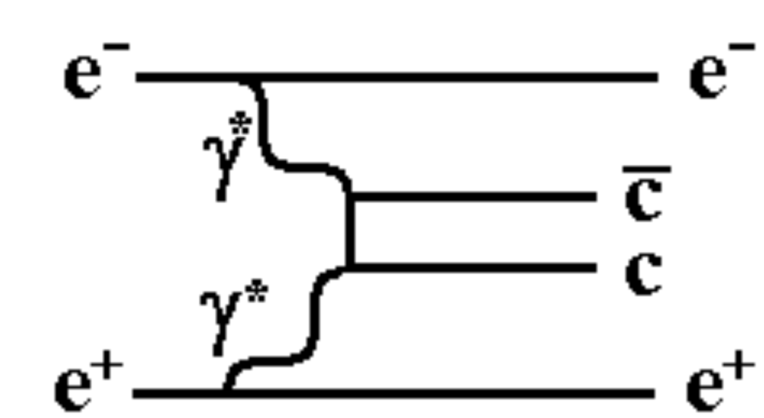
- **B decays**
  - $(c\bar{c})$ only
  - all quantum numbers



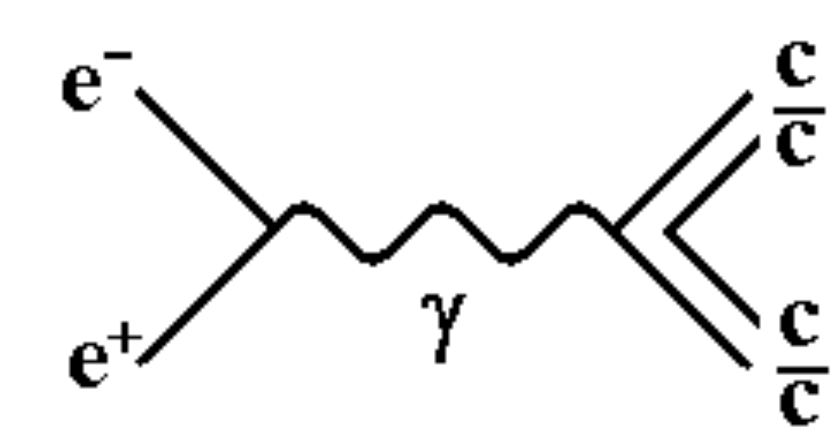
- **Initial-state radiation (ISR)**
  - $J^{PC} = 1^{--}$



- **two-photon process**
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$



- **double charmonium**
  - e.g. $e^+e^- \to J/\psi X(3940)$ Belle, PRL 98, 082001 (2007)



- **quarkonium transitions**

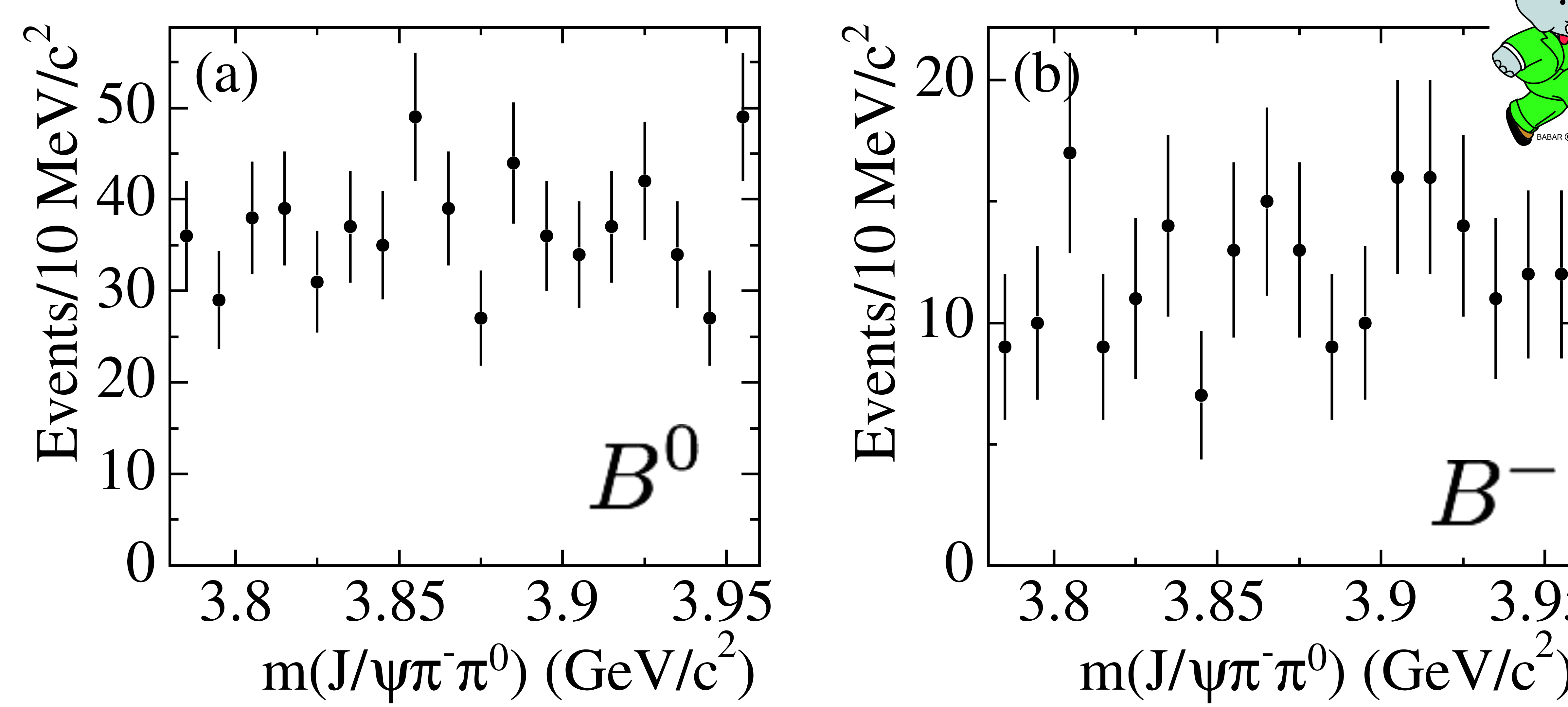
Charmonium-like exotics

X(3872) — action items for Belle II

Nature of X(3872)?

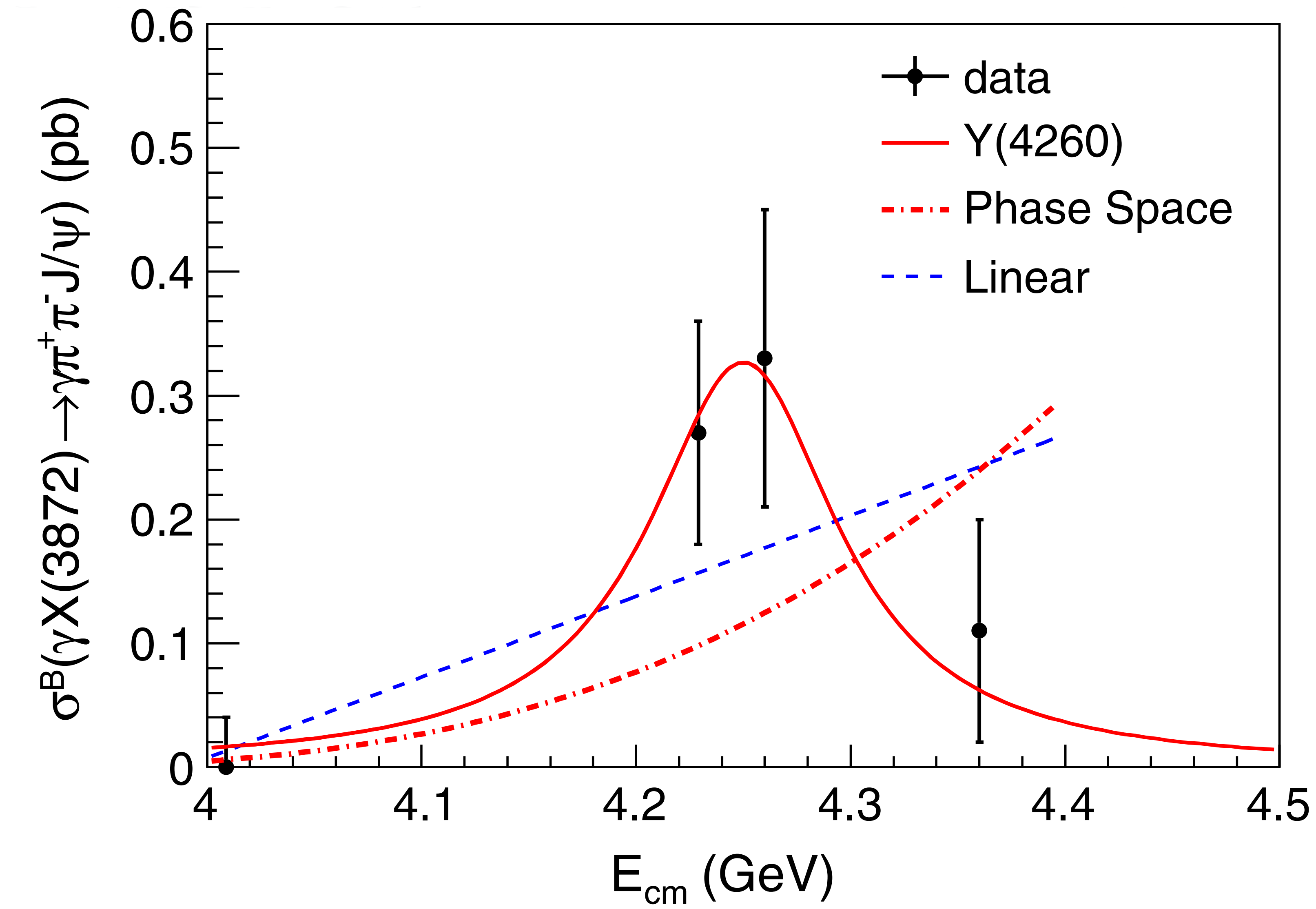
- Search for a charged partner of X(3872)
- can give crucial input, if found, for the nature of X(3872)
- existing search (and null results) by BaBar
- isovector hypothesis of X(3872) is excluded;
  null hypothesis over isovector by a factor 1.1×10^4

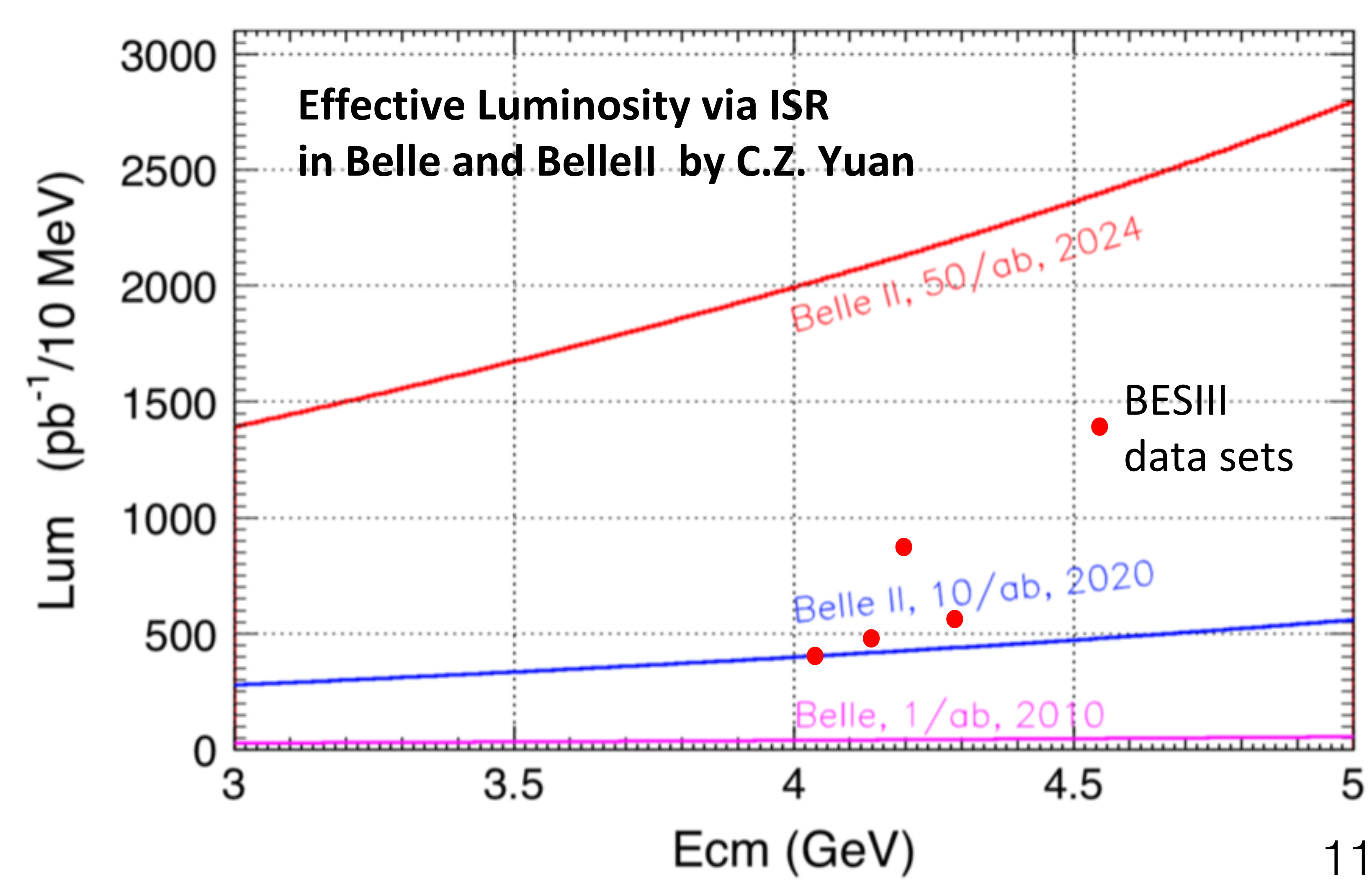
$$X^- \to J/\psi\pi^-\pi^0$$



X(3872) — action items for Belle II

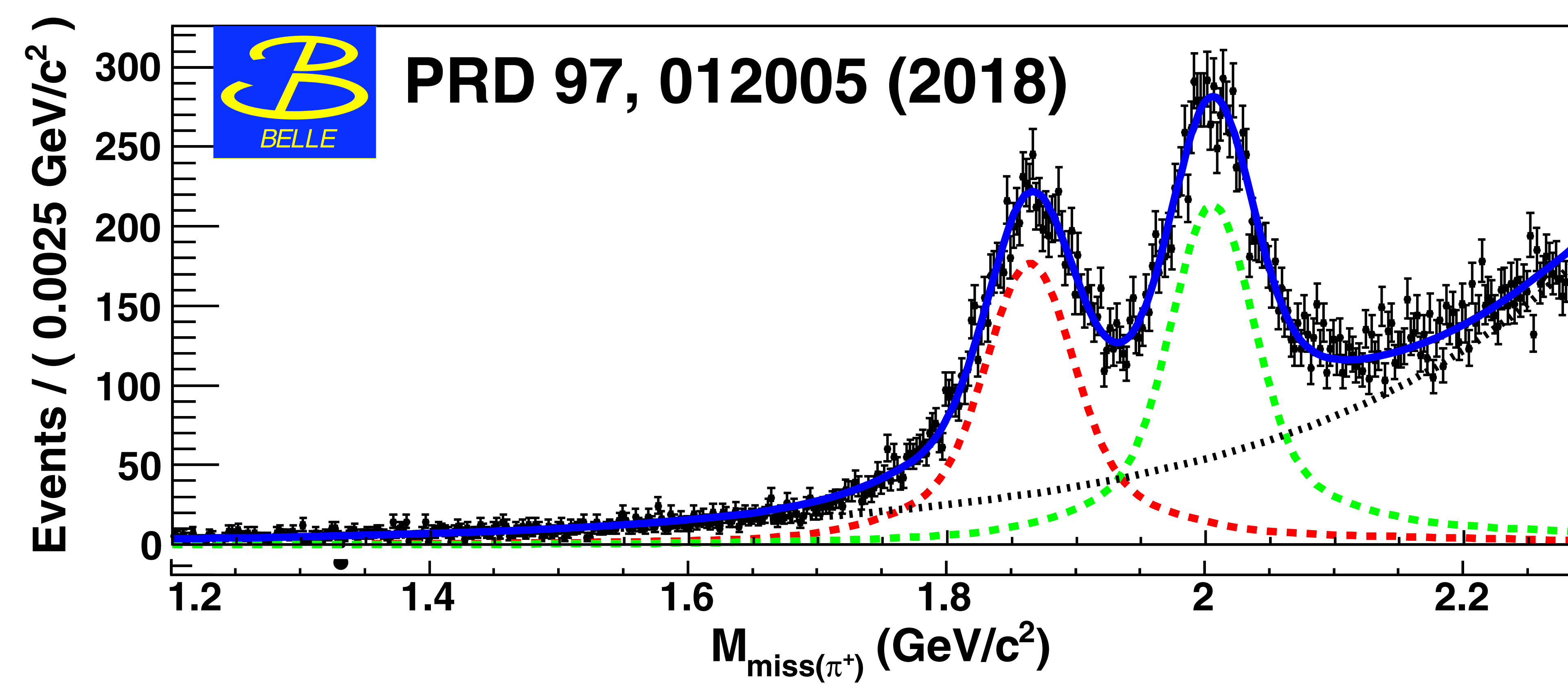
- Nature of X(3872)?
- **Connection with Y(4260)?**
  - Y(4260) ➔ $Z_c(3900)^{\pm}$ $\pi^{\mp}$ is observed
  - Y(4260) ➔ γ X(3872) studied by BESIII
  - Detailed study of these by Belle II is necessary
  - ×4 effective luminosity from Belle II with $50ab^{-1}$





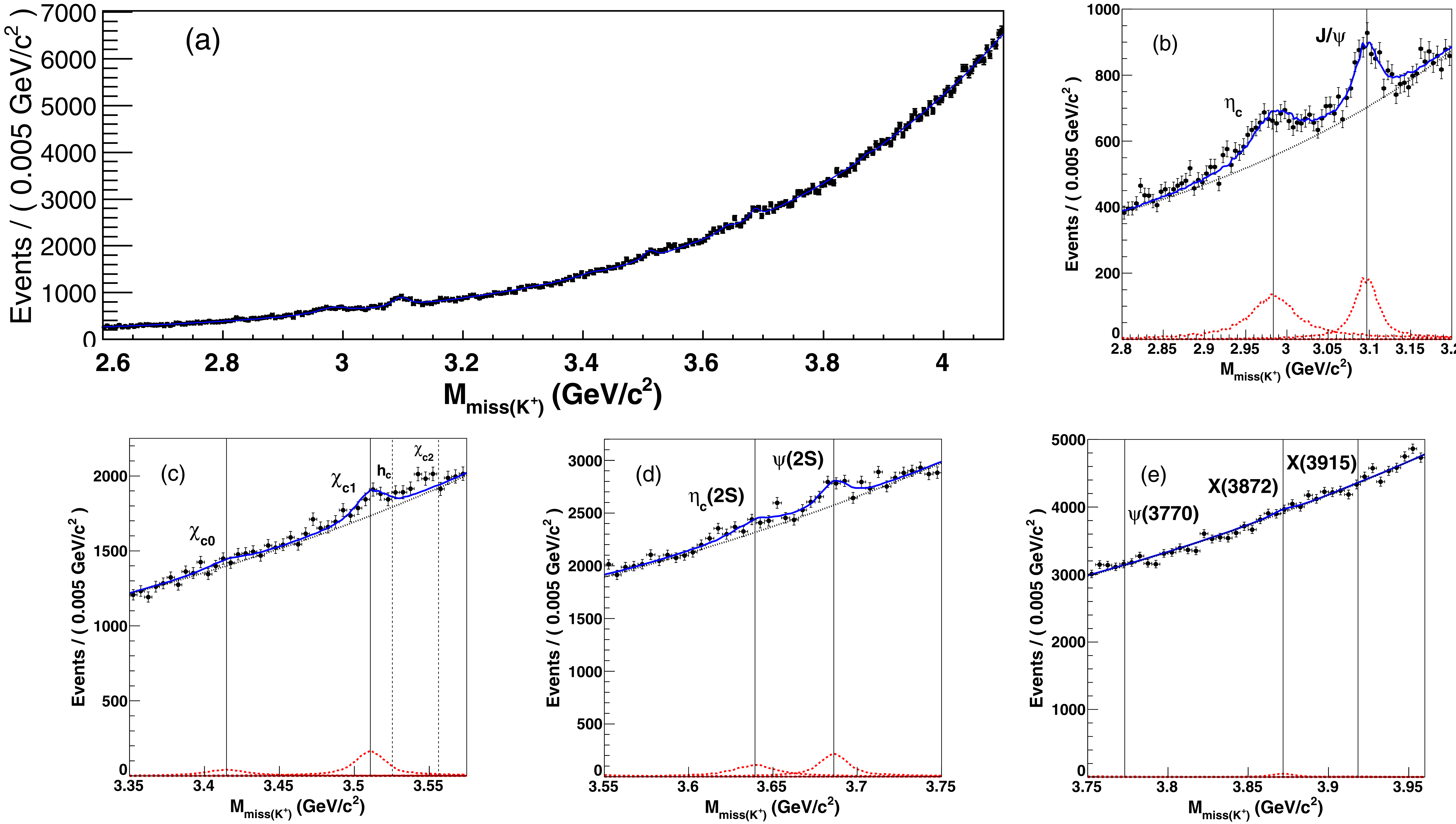
X(3872) — action items for Belle II

- Nature of X(3872)?
- Connection with Y(4260)?
- **Absolute branching fractions?**
  - Absolute measurement of BF($B^+ \to X(3872)\ K^+$) is useful to obtain BF of $X(3872)$ to a specific final state, hence understand its properties.
  - This can be done in e^+e^- B-factory, by M_{miss}.
  - Proof of principle by BF($B^+ \to D^{(*)}\ \pi^+$)



PRD 97, 012005 (2018)

$B^+ \to X_{c\bar{c}} K^+$ by $M_{\rm miss}$



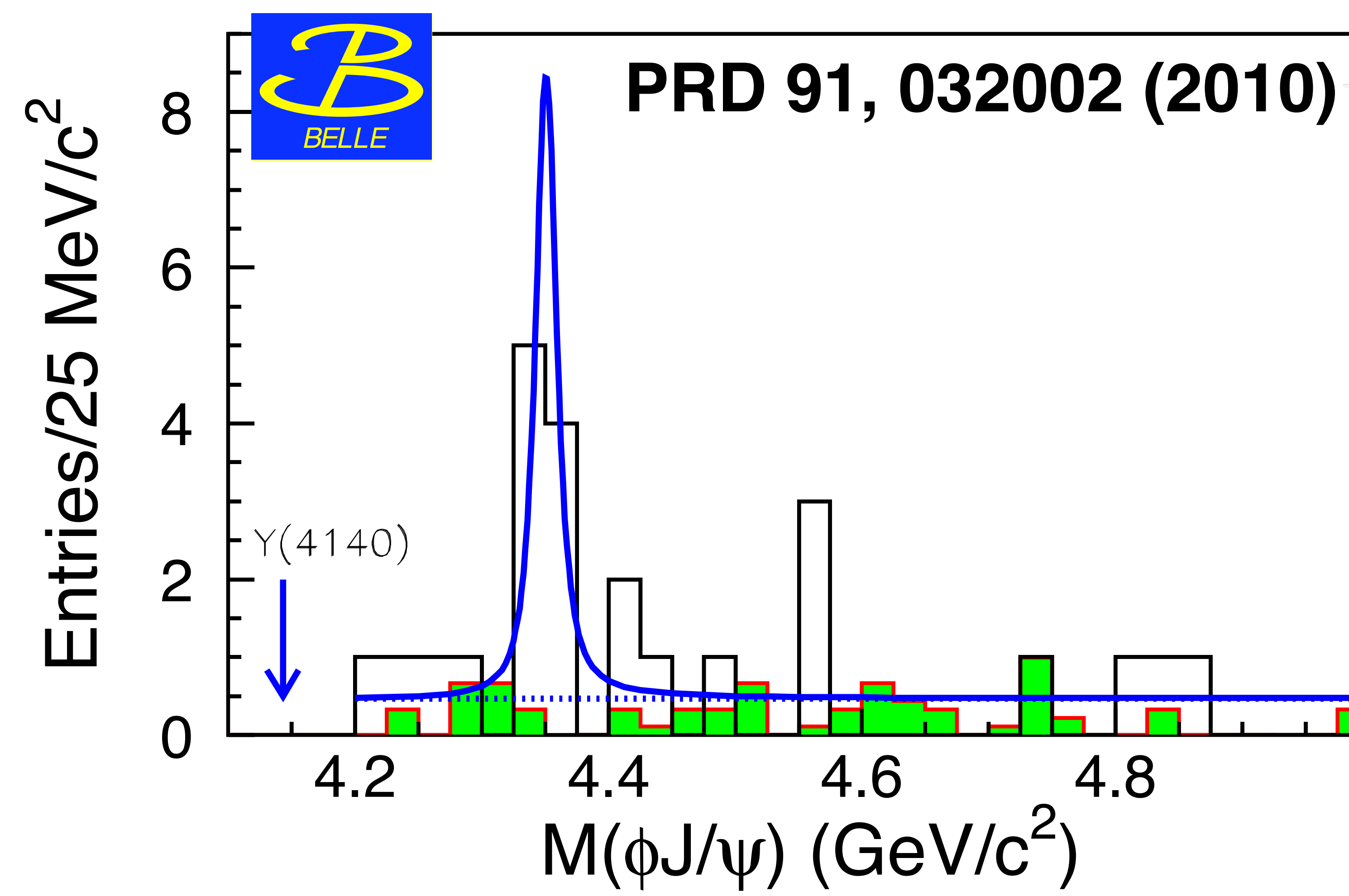
$$\mathcal{B}(B^+ \to \eta_c(2S)K^+) = (4.8 \pm 1.1 \pm 0.3) \times 10^{-4} \qquad \mathcal{B}(B^+ \to X(3872)K^+) < 2.6 \times 10^{-4}$$

X(3872) — action items for Belle II

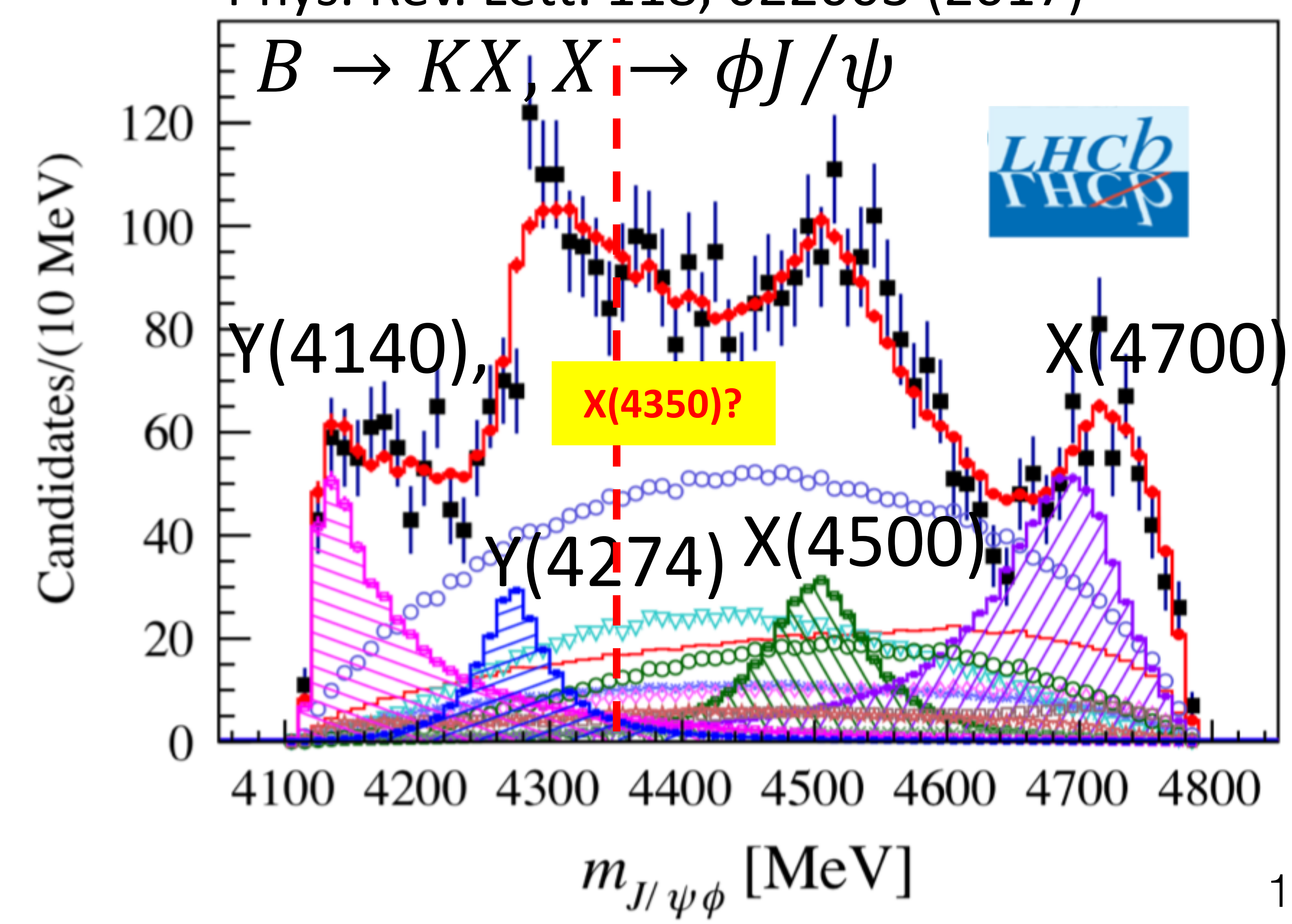
- Nature of X(3872)?
- Connection with Y(4260)?
- Absolute branching fractions?
- **For other exotics**
  - Lineshape, e.g. for Y(4260)
  - Determine J^{PC} (not determined for many exotic states)
  - dependence on production mechanism?

Production mechanism?

- **Belle two-photon**
  - observed X(4350) in γγ ➔ J/ψ ϕ
- **LHCb amplitude analysis of B ➔ J/ψ ϕ K**
  - several resonant structures: Y(4140), Y(4274), X(4500), X(4700)
  - but did not see X(4350)
- **Belle II should revisit this mode in all ways possible (*B*, ISR, 2γ)**

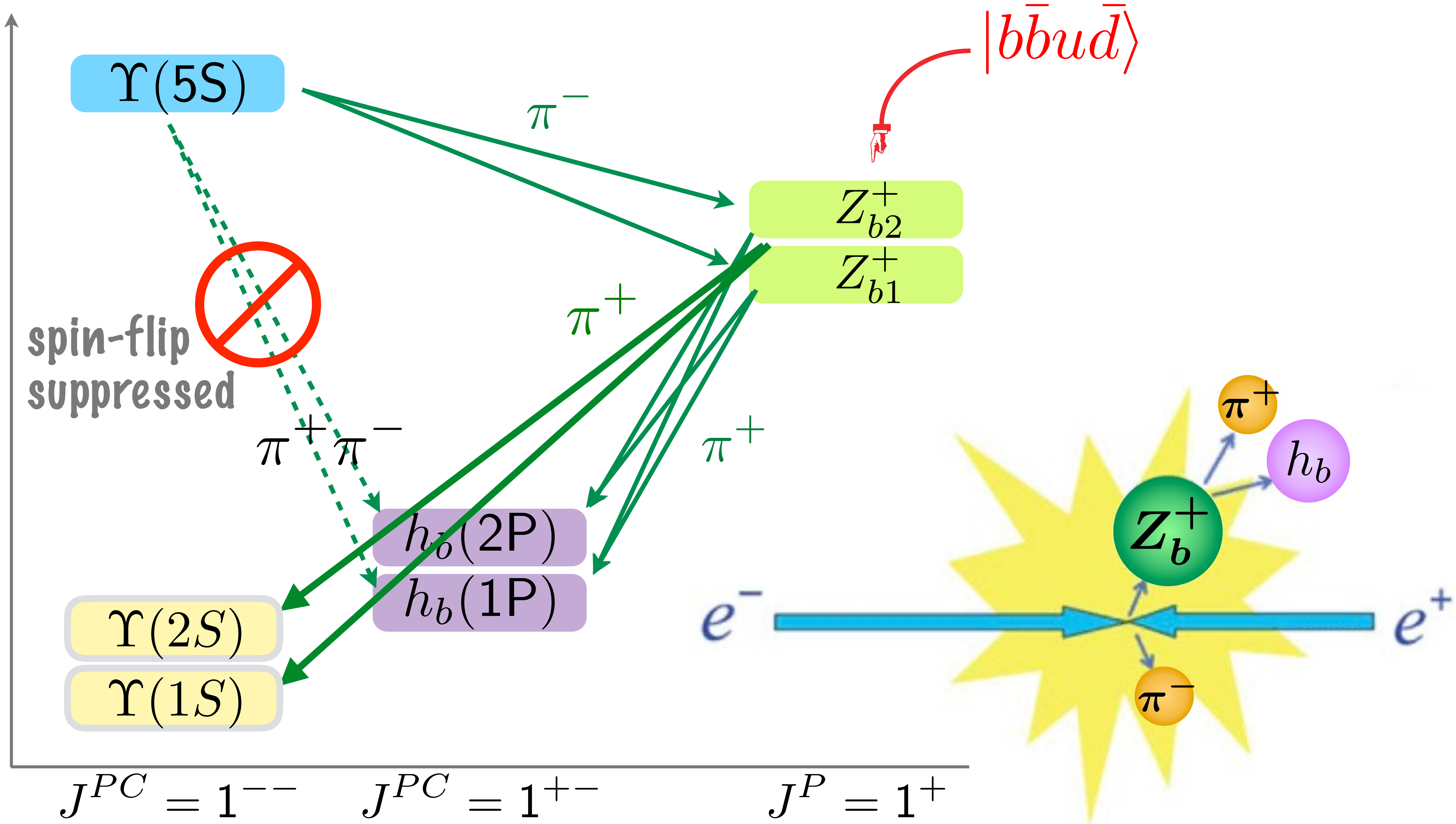


Phys. Rev. Lett. 118, 022003 (2017)



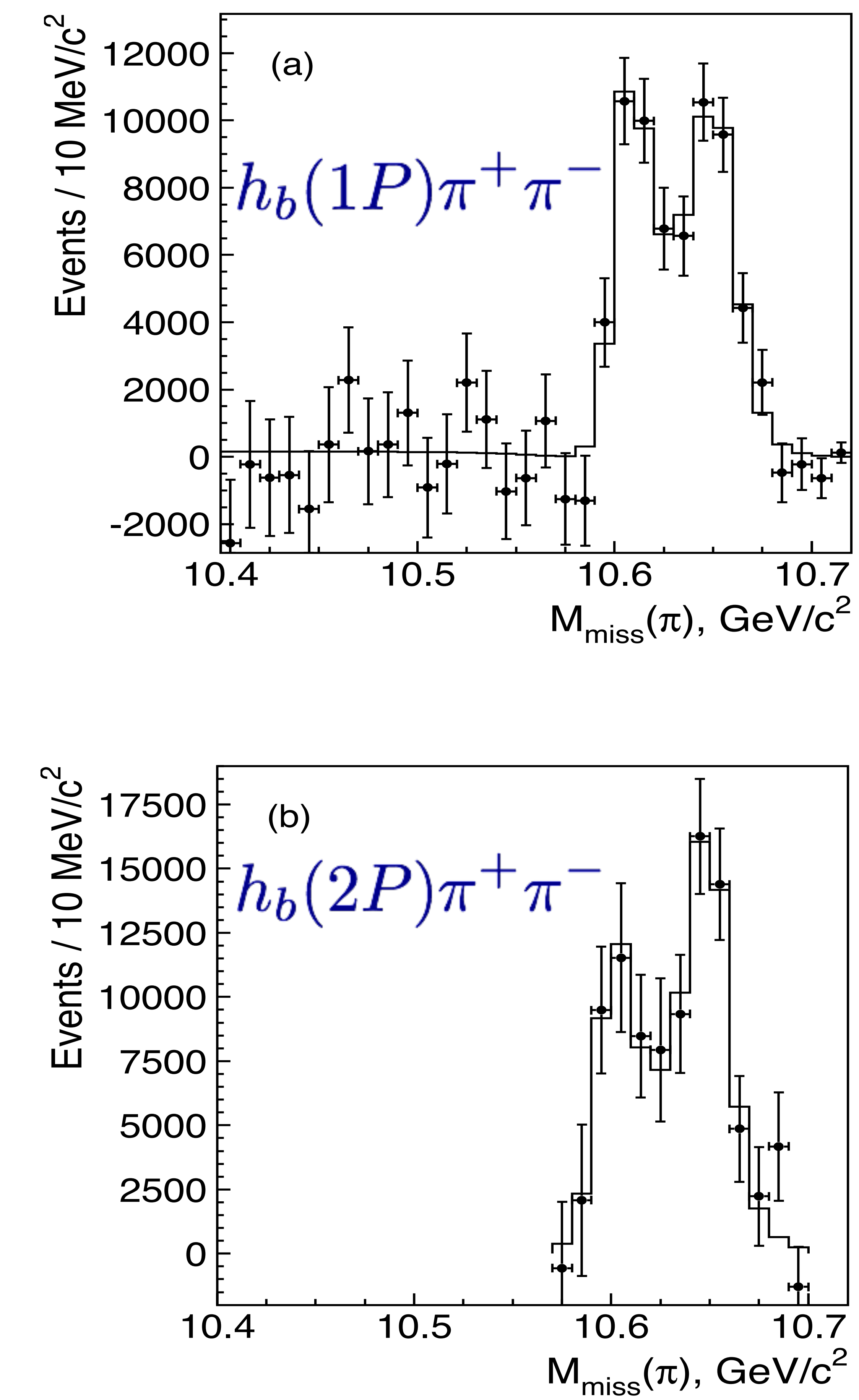
Bottomonium-like exotics

exotic states: $Z_b(10610)$, $Z_b(10650)$



Note: $\Upsilon(5S)$ is an ***h_b*-factory!**

BELLE PRL 108, 122001 (2012)



$\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$

Bottomonia from e^+e^- *B*-factories

Important past contributions

- discovery of h_b, η_b
- anomalous $\pi\pi$ and η transitions
- discovery of Z_b: exotic (charged), around $B^{(*)}\bar{B}^*$ threshold

Operation energies

Existing datasets in fb^{-1} (M events)

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5

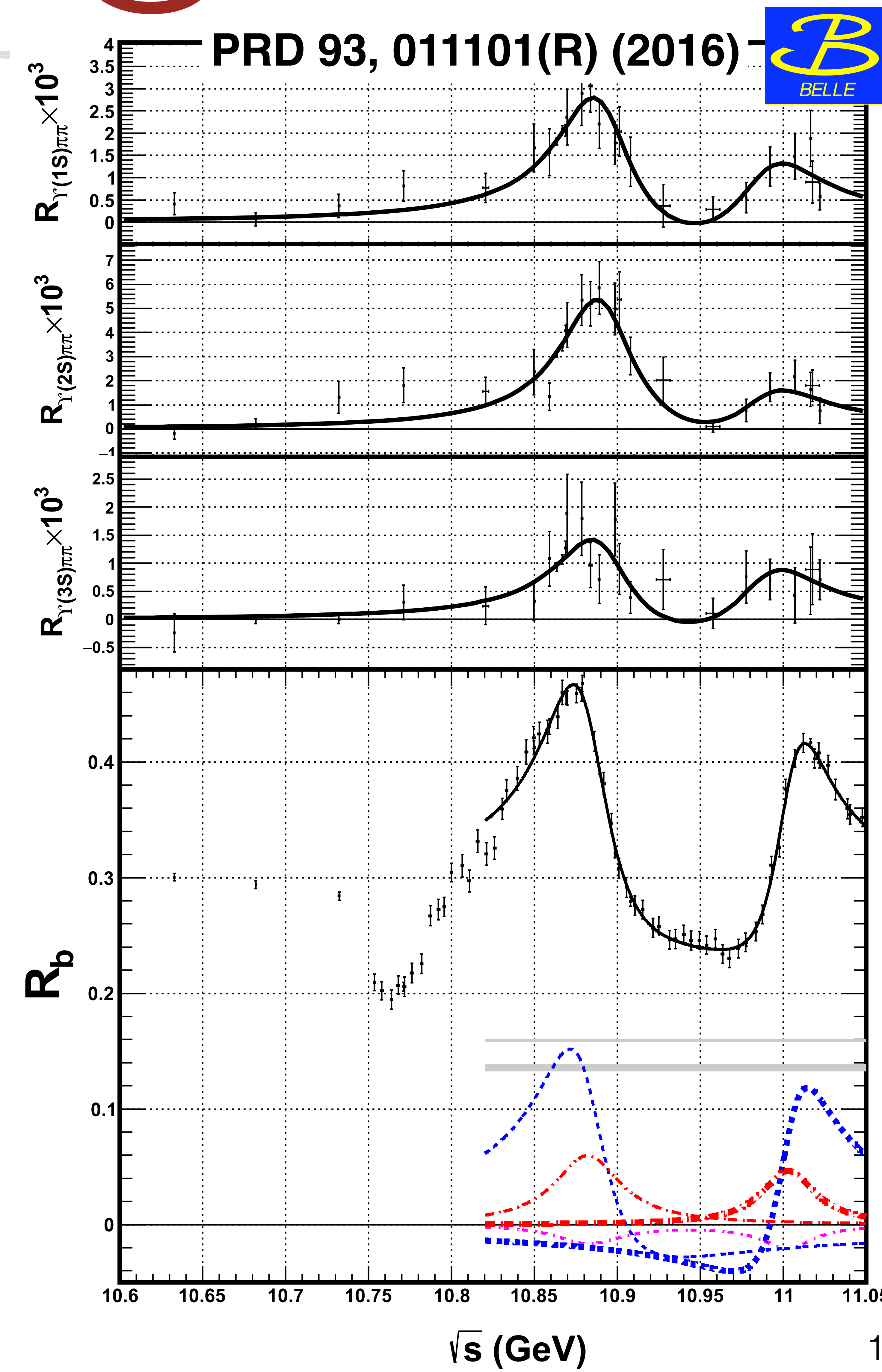
- With $\sim$1.5 ab^{-1} @ $\Upsilon(4S)$ existing, it might be sensible to run for non-B physics in early Belle II operations

action items for $b\bar{b}$-like @ Belle II

Energy scan — motivations

- $\Upsilon(10860)$ has been interpreted to be a pure S-wave, $J^{PC} = 1^{--}$
- But ∃ several questions to this:

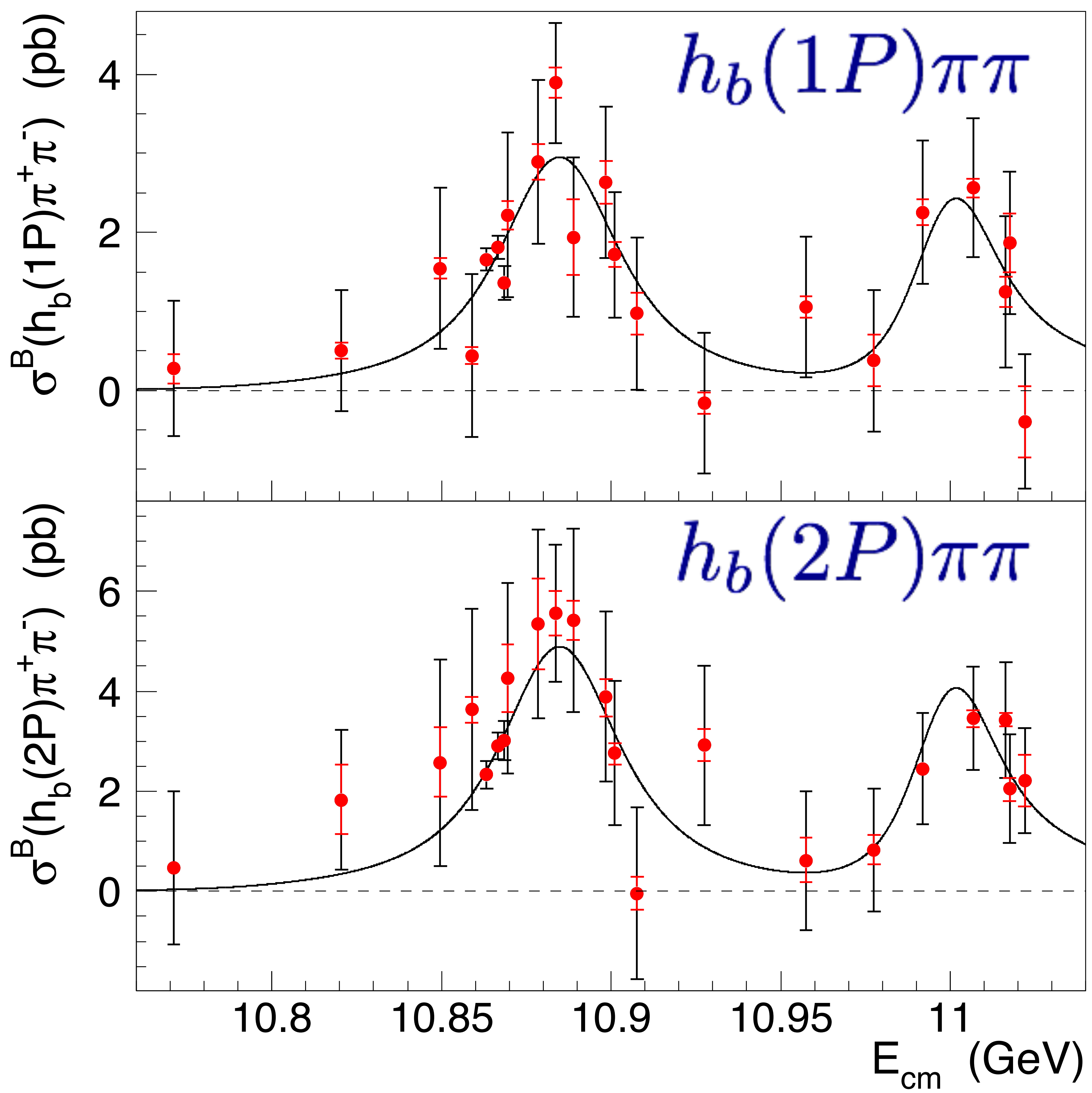
  peak shifts, anomalously high rates to $\Upsilon(nS)\pi\pi$, non-suppression of spin-flip processes, etc.
- Moreover, all cross sections around $\Upsilon(10860)$ and $\Upsilon(11020)$ show similar structure
  - ✓ Just two peaks — "5S" and "6S"
  - ✓ This difference, to charmonia, is not understood
- The exclusive scan results (top 3) are certainly limited by statistics

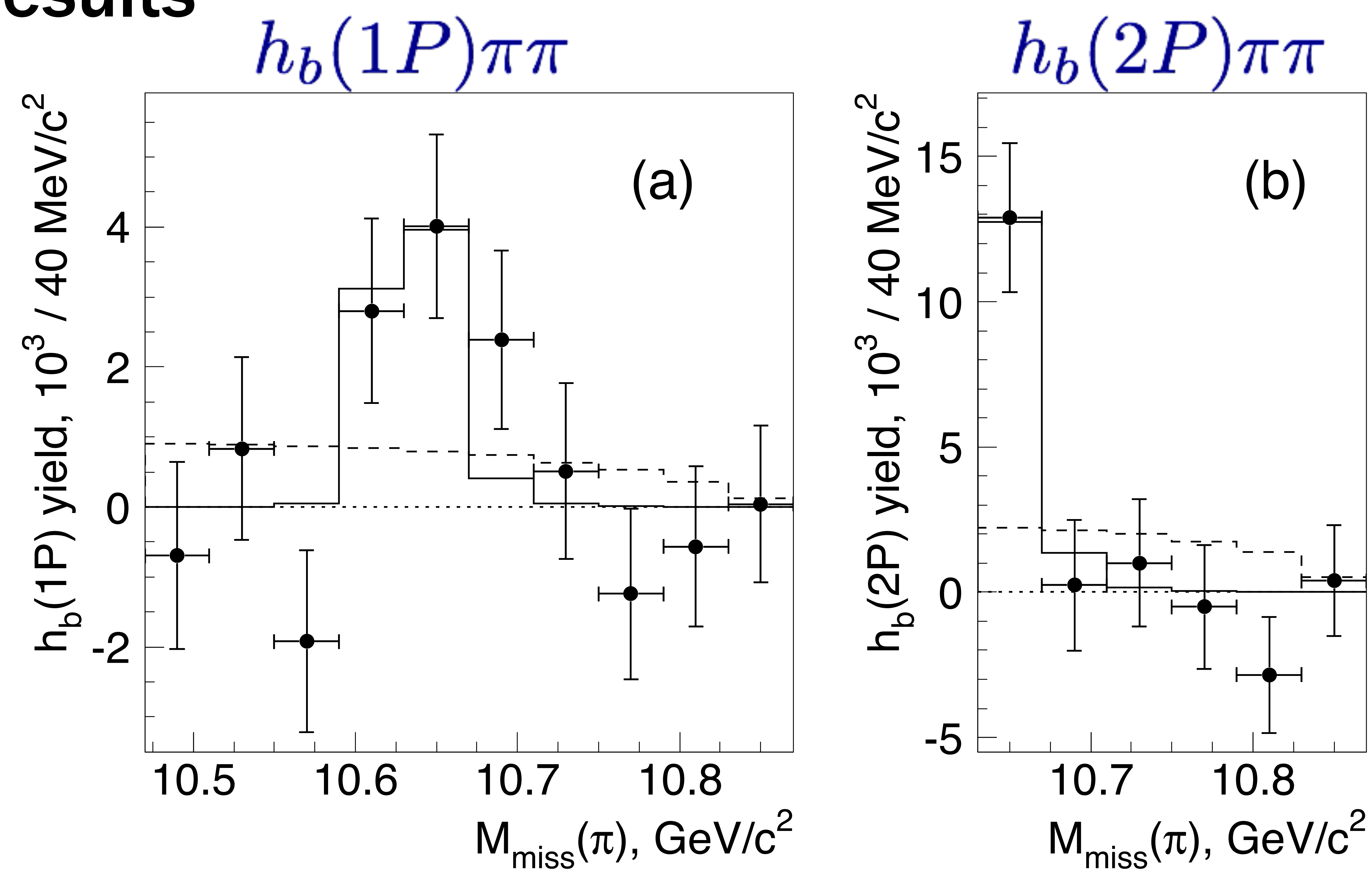


action items for $b\bar{b}$-like @ Belle II

PRL 117, 142001 (2016)

- **Energy scan — recent Belle results**





single $Z_b(10610)$ hypothesis is excluded at 3.3σ

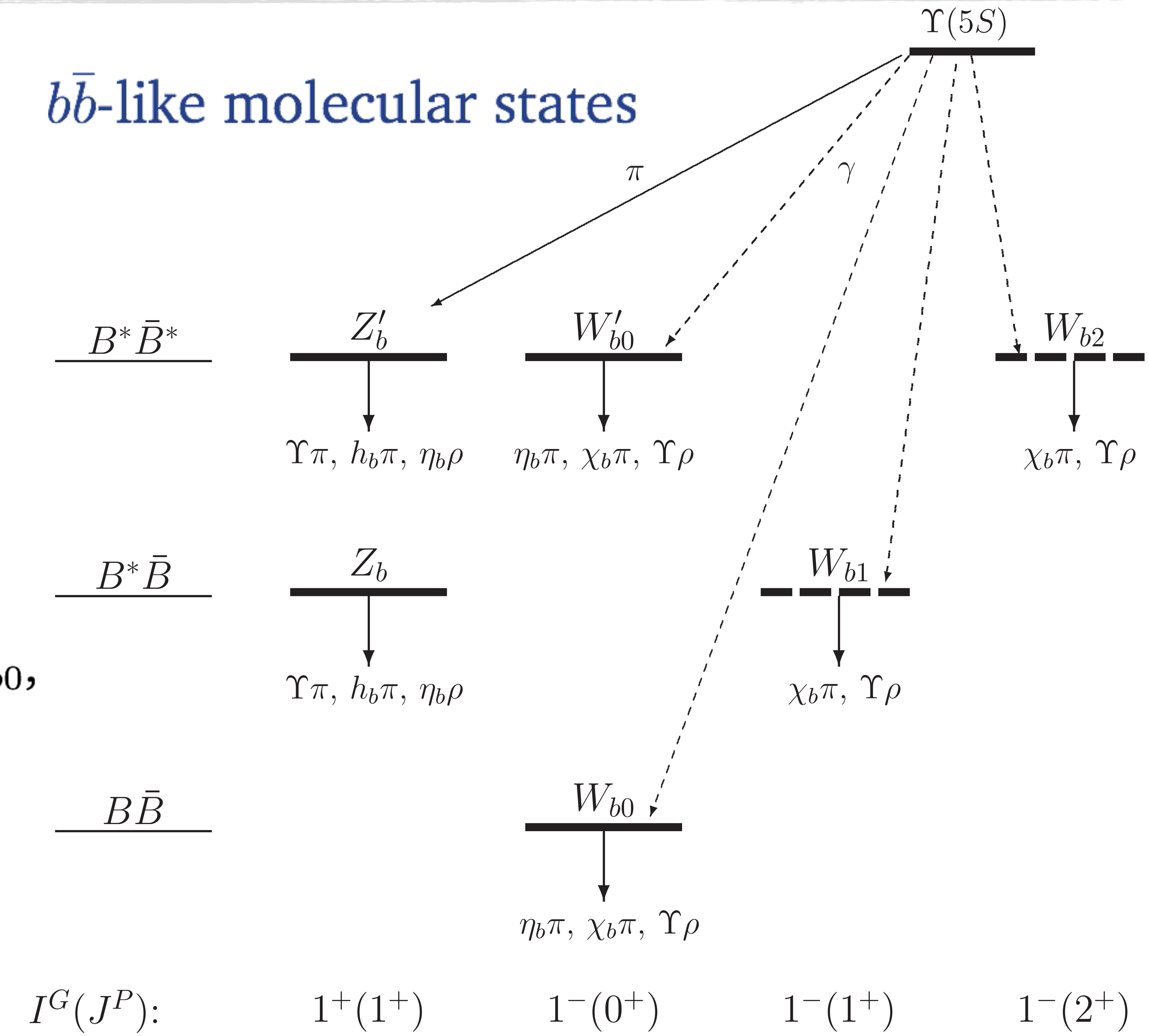
single $Z_b(10650)$ hypothesis is *not* excluded

For more on Belle energy scan results (esp. 1806.06203), see L. Piilonen talk.

action items for $b\bar{b}$-like @ Belle II

- Energy scan
- **Run at 6S**

- Understand $\Upsilon(6S) \to Z_b$ processes
  - * $\Upsilon(6S) \to \pi^+\pi^- h_b(mP),\ \pi^+\pi^-\Upsilon(nS)$
  - * transitions with $\pi^0\pi^0$?
- Search for W_b, molecular partner of Z_b
  - * $\Upsilon(5S,6S) \to \gamma W_{b0}$, $\Upsilon(6S) \to \pi^+\pi^- W_{b0}$, where $W_{b0} \to \eta_b\pi, \chi_b\pi, \Upsilon\rho$



from Voloshin, *PRD* 93, 143 (2017)

action items for $b\bar{b}$-like @ Belle II

- Energy scan
- Run at 6S
- "Energy frontier" (> 11.24 GeV)
    - Previously unexplored
    - To study potentially interesting baryon-antibaryon dynamics
      $\exists\ \Lambda_b\bar{\Lambda}_b$ threshold at $\sim$ 11.24 GeV
    - Transitions from new vector states possibly provide a way of producing partners of X(3872), Z_b(106*0), etc.

      Necessary to go beyond ~11.5 GeV to access such transitions kinematically

      But, it requires a Linac upgrade, which costs a lot.

action items for $b\bar{b}$-like @ Belle II

- Energy scan
- Run at 6S
- "Energy frontier" (> 11.24 GeV)
- Full amplitude analyses to determine J^P of exotics

Closing remarks

- There is no consensus about the interpretation for the observed exotic states, and different assumed structures lead to different predictions.

  ∴ A lot of work is waiting for Belle II, to complete our experimental knowledge of the exotic states.

- Belle II shall search for missing quarkonia and for expected partners of exotic states, search for new decay channels of known states, and detailed measurement of all accessible properties, including J^P, absolute BF, line-shapes, etc.

Back-up

$b\bar{b}$-like molecular states

$I^G(J^P)$	Name	Content	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z_b'	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W_{b0}'	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X_{b1}'	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$
$0^+(0^+)$	X_{b0}'	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$