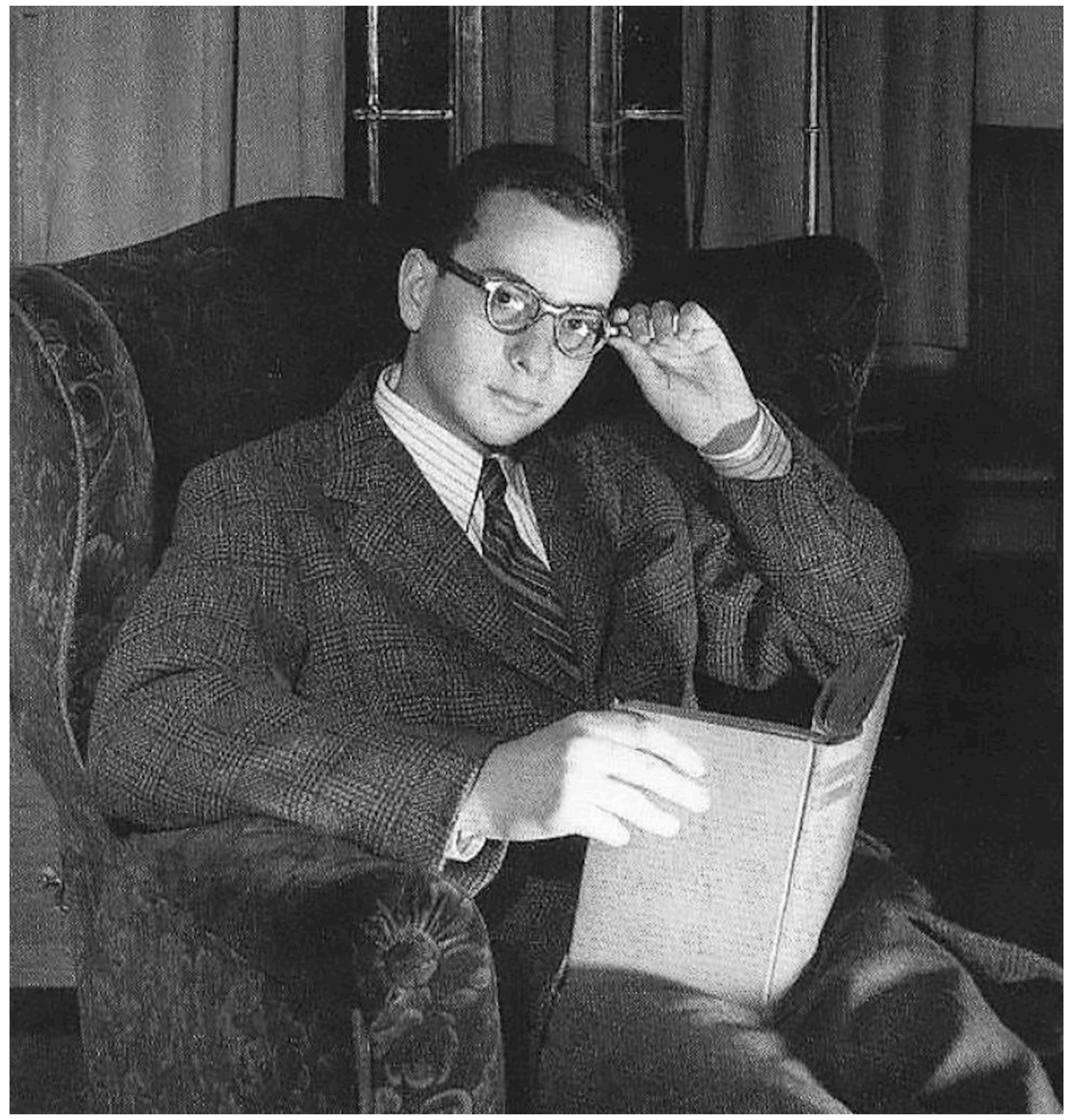
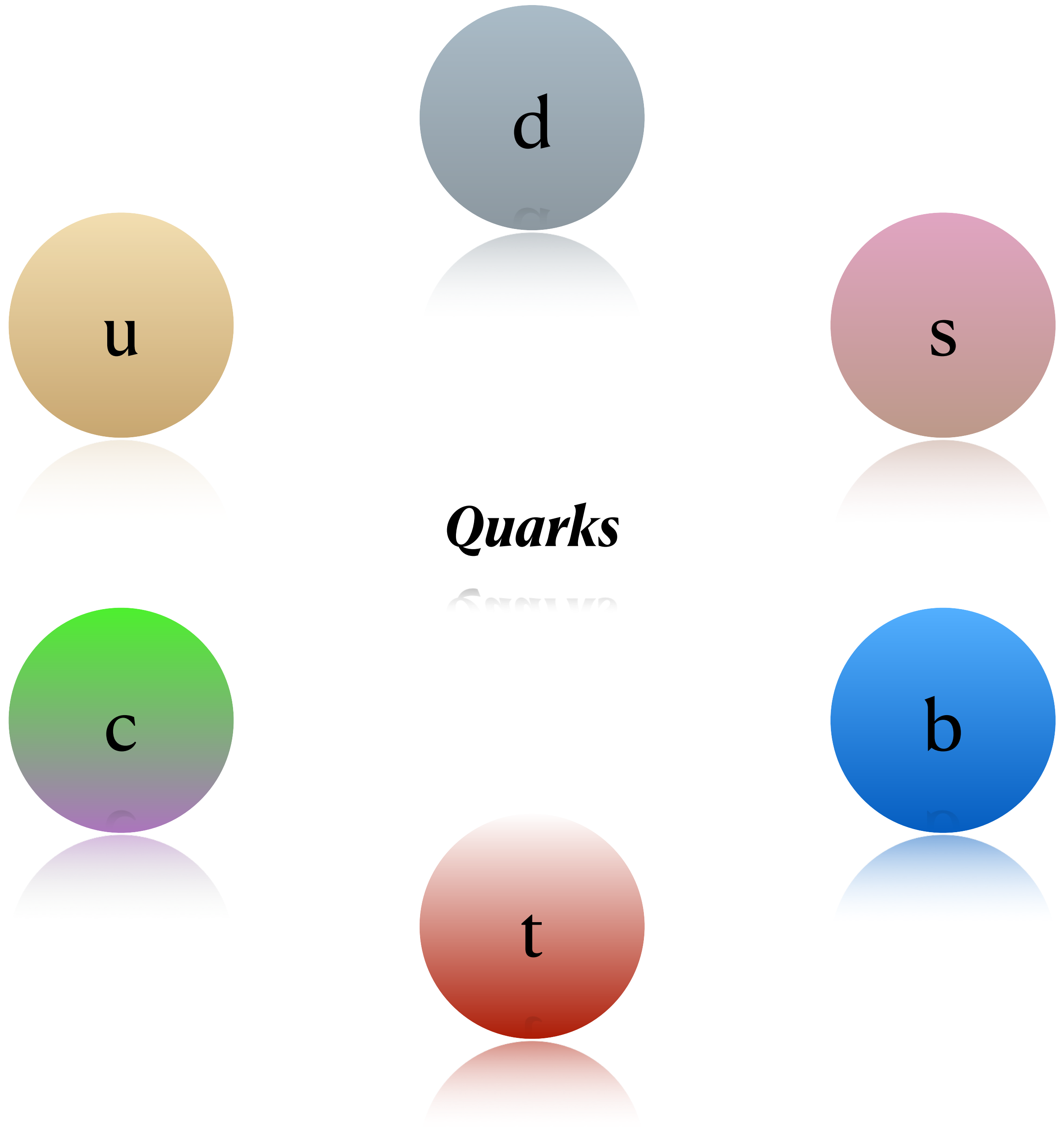
Quarkonium at Belle II

Speaker: Junhao Yin, on behalf of Belle II Collaboration



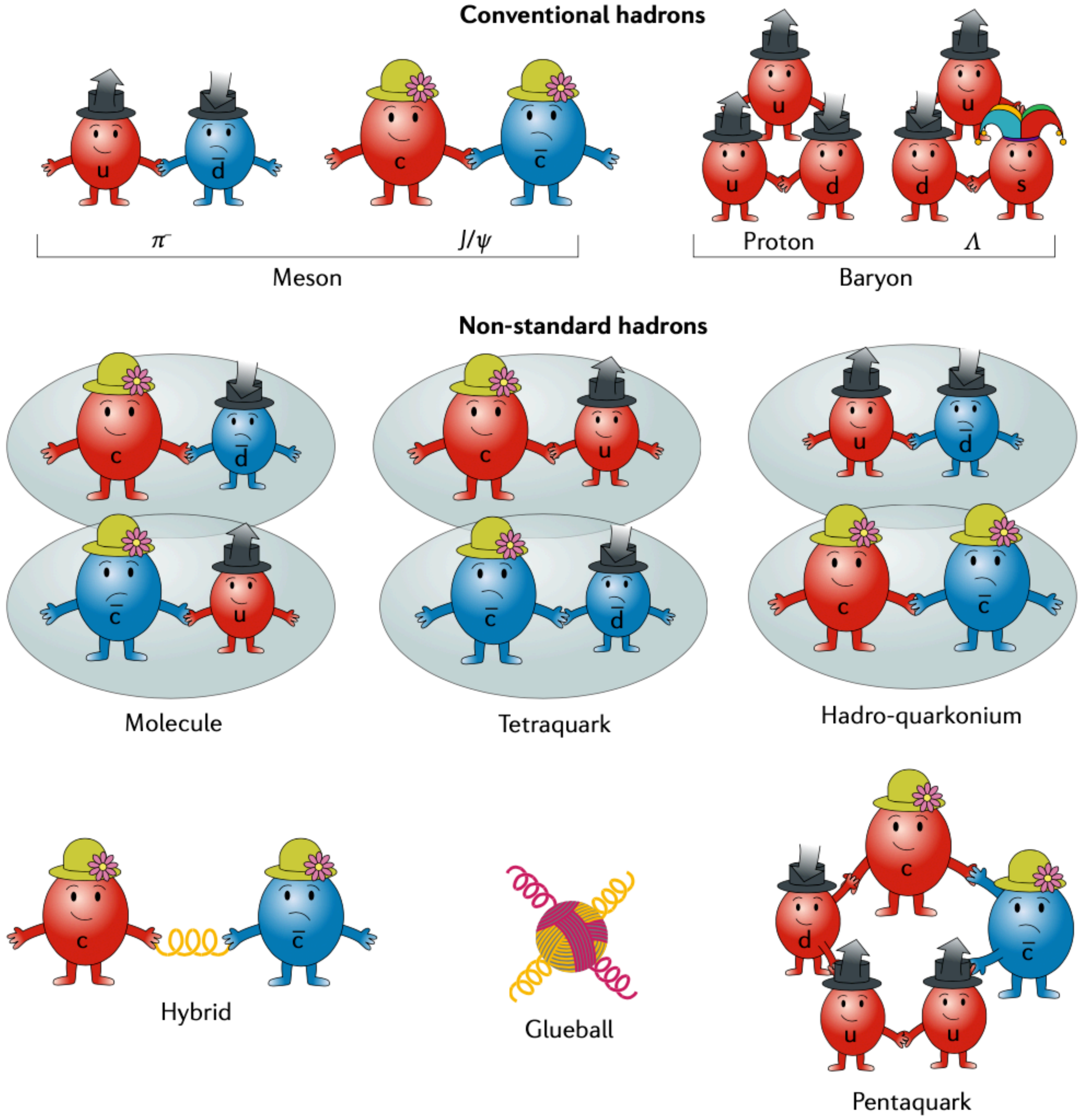


In 1963, Murry Gell-mann proposed the quark model.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Published in Physics Letters 8, 214 (1964);
Similar idea by G. Zweig, CERN-TH-401 (1964).

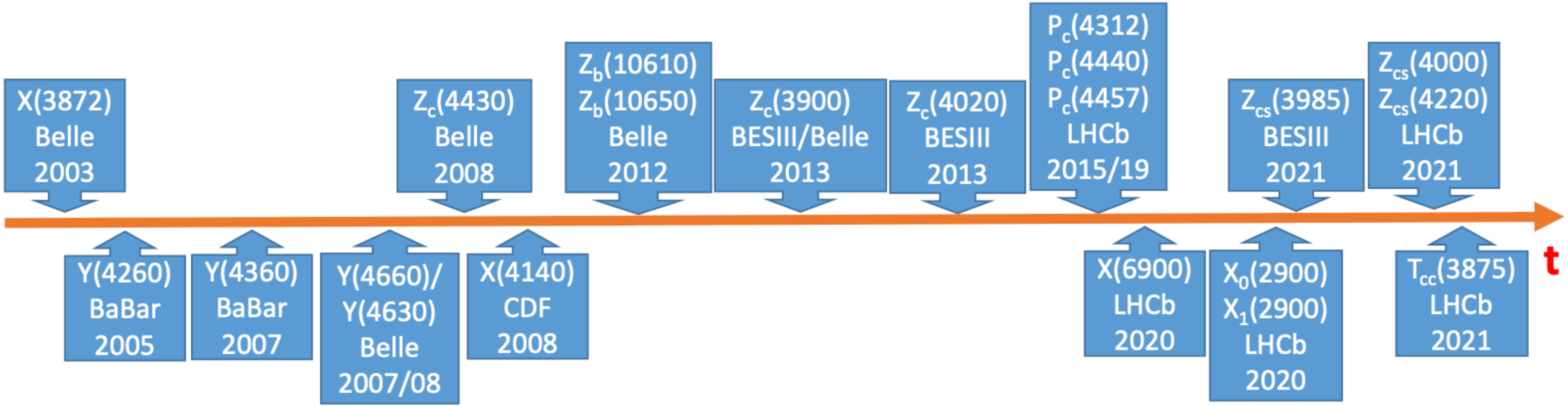
QCD does not forbid hadrons with $N_{quark} \neq 2,3$!!



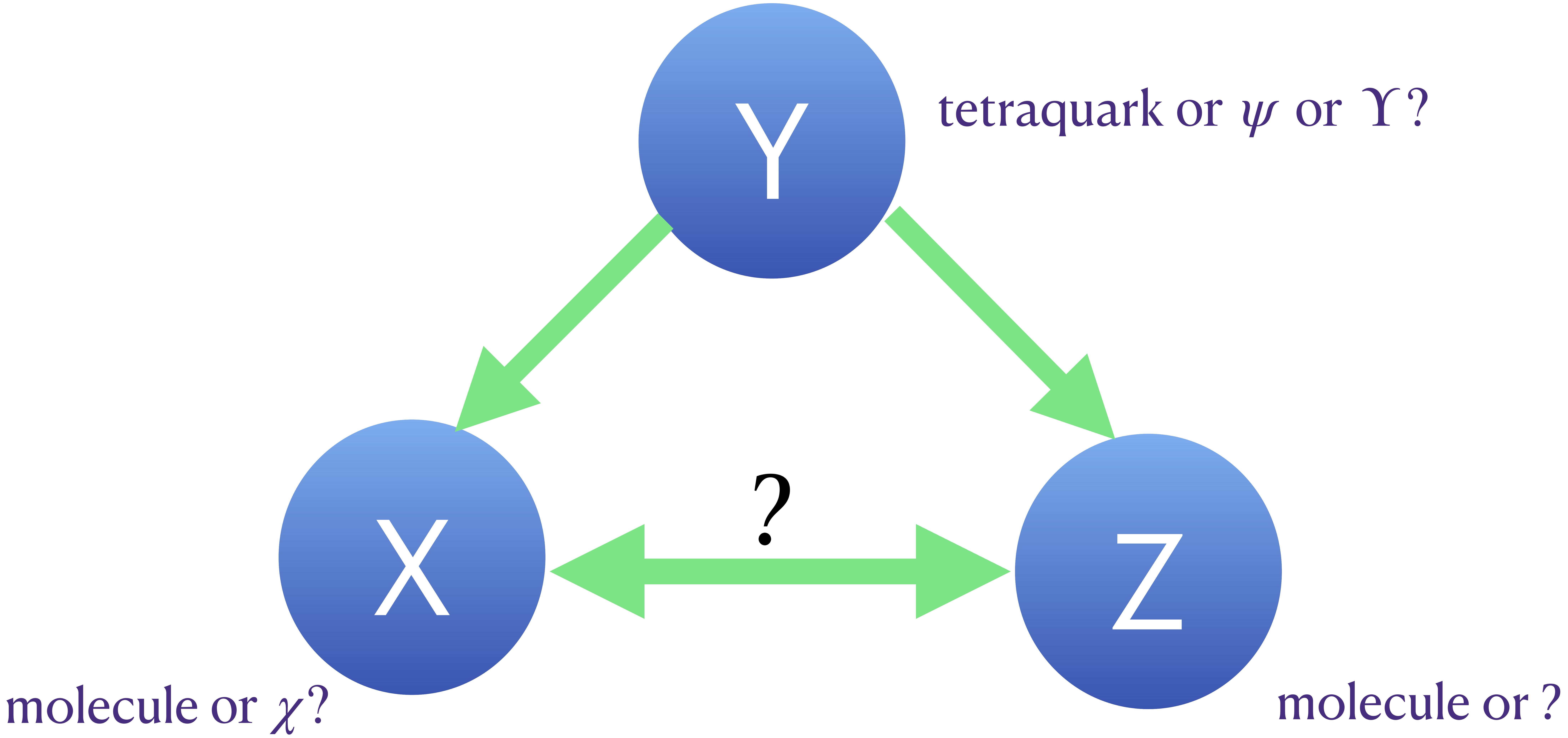
Nature Rev. Phys. 1(2019)8, 480-494, C. Z. Yuan and S. L. Olsen,

No solid evidence for exotic states until 2003, the observation of $X(3872)$
Since then, we have a golden era on the discovery of the exotic state.

Phys.Rev.Lett. 91 (2003) 262001

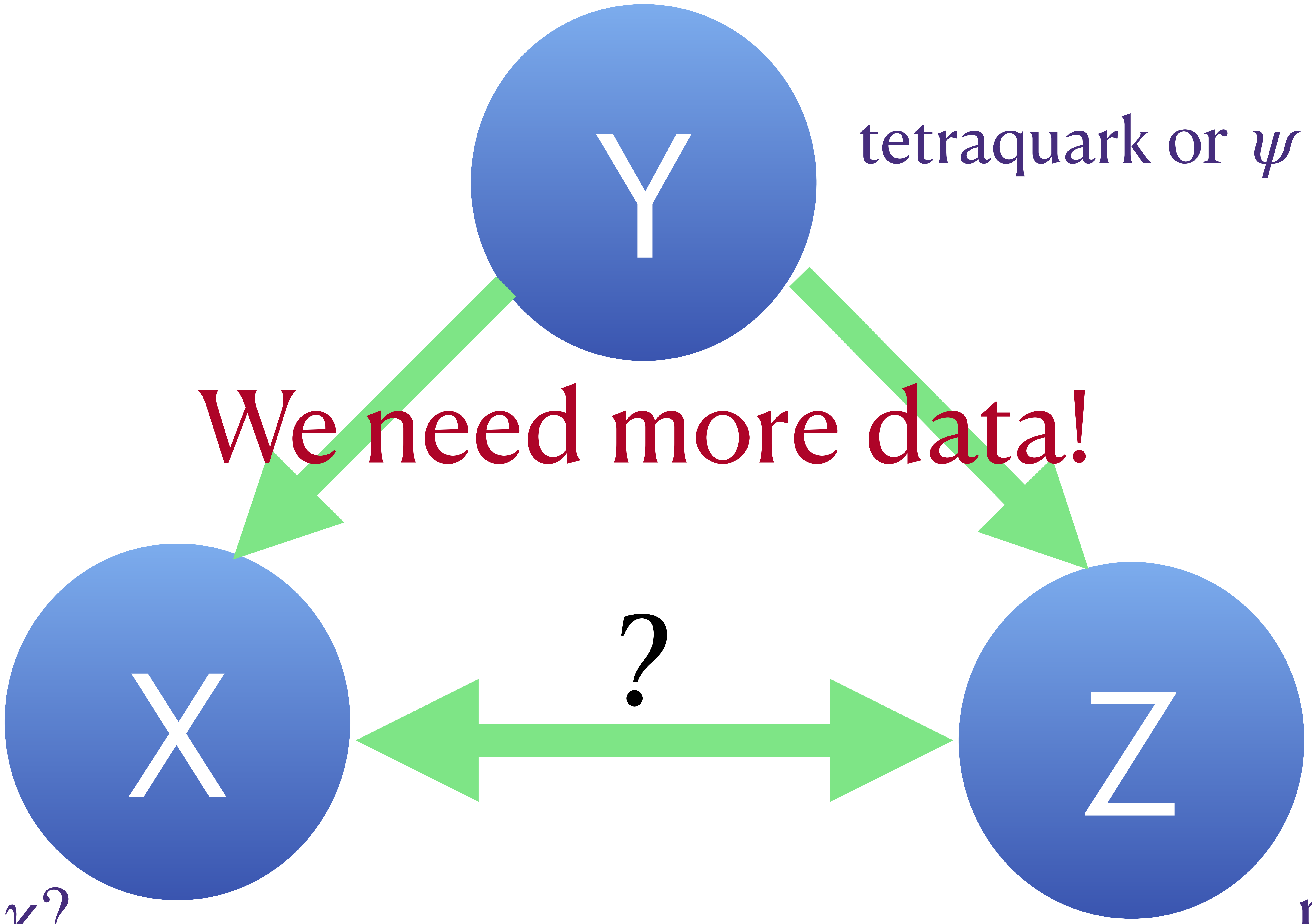


What are they?



What are they?

tetraquark or ψ or Υ?



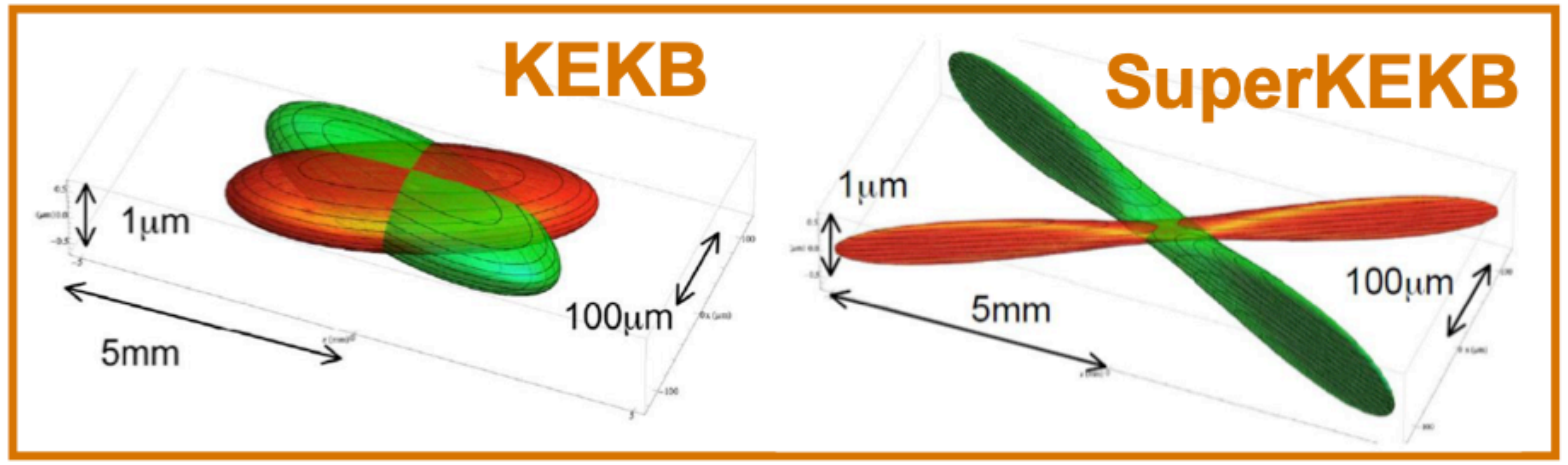
We need more data!

molecule or χ?

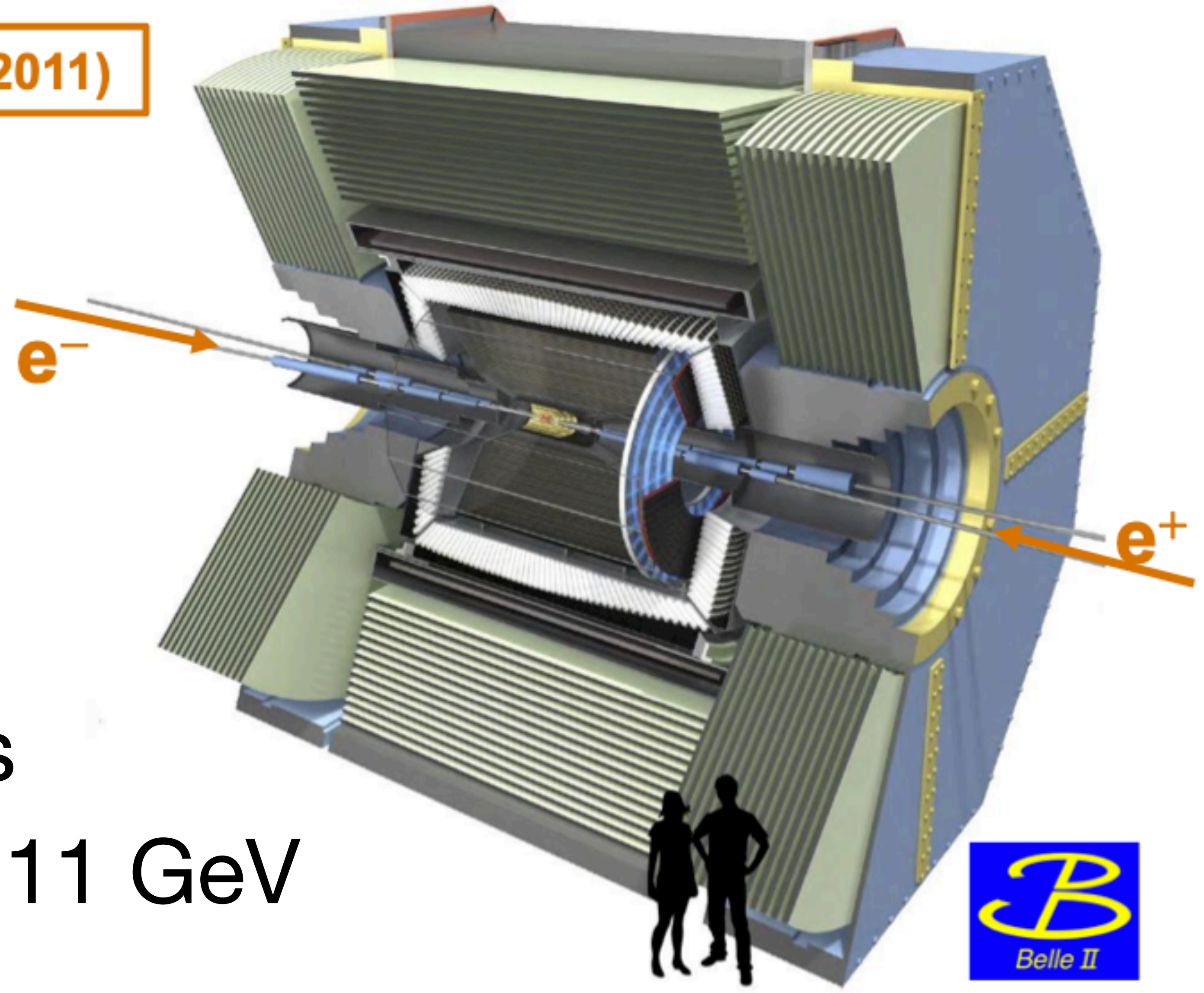
molecule or ?

Belle II Capabilities

PTEP 2019 123C01 (2019)



arXiv:1011.0352 (2011)

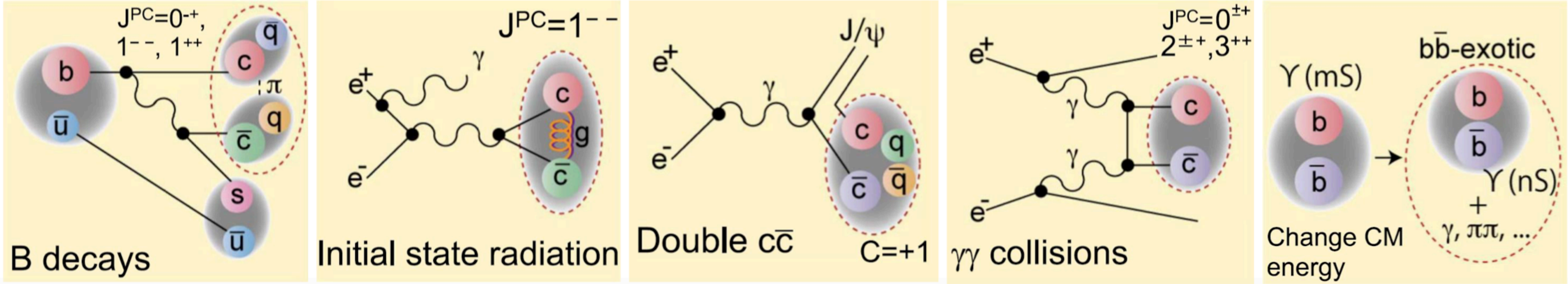


Belle II is the next generation B-factory

- Upgraded detector and accelerator
- 1107 members, 123 institutions, 26 nations
- ~10-years program ongoing since 2019

Advantages

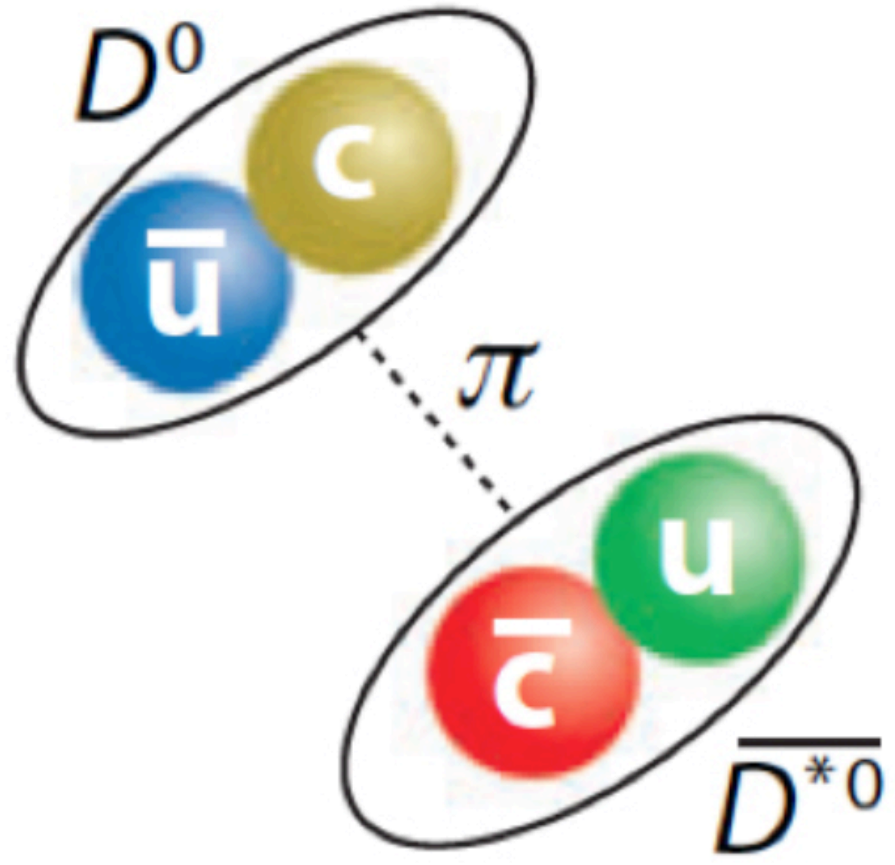
- ~30x instantaneous and integrated luminosity
- Full events reconstruction, decays with neutral/soft particles
- Nominal $\sqrt{s} = 10.58\ \mathrm{GeV} \equiv \mathrm{m}(\Upsilon(4S))$, potential reach ~11 GeV



X(3872)

Most concerned particle in charmonium sector!

- Highest citation in Belle (~1900)!
- molecule of $D^0\bar{D}^{*0}$?
  - production
  - decay
  - lineshape
- Belle II capability
  - Branching fraction measurement
  - Lineshape determination



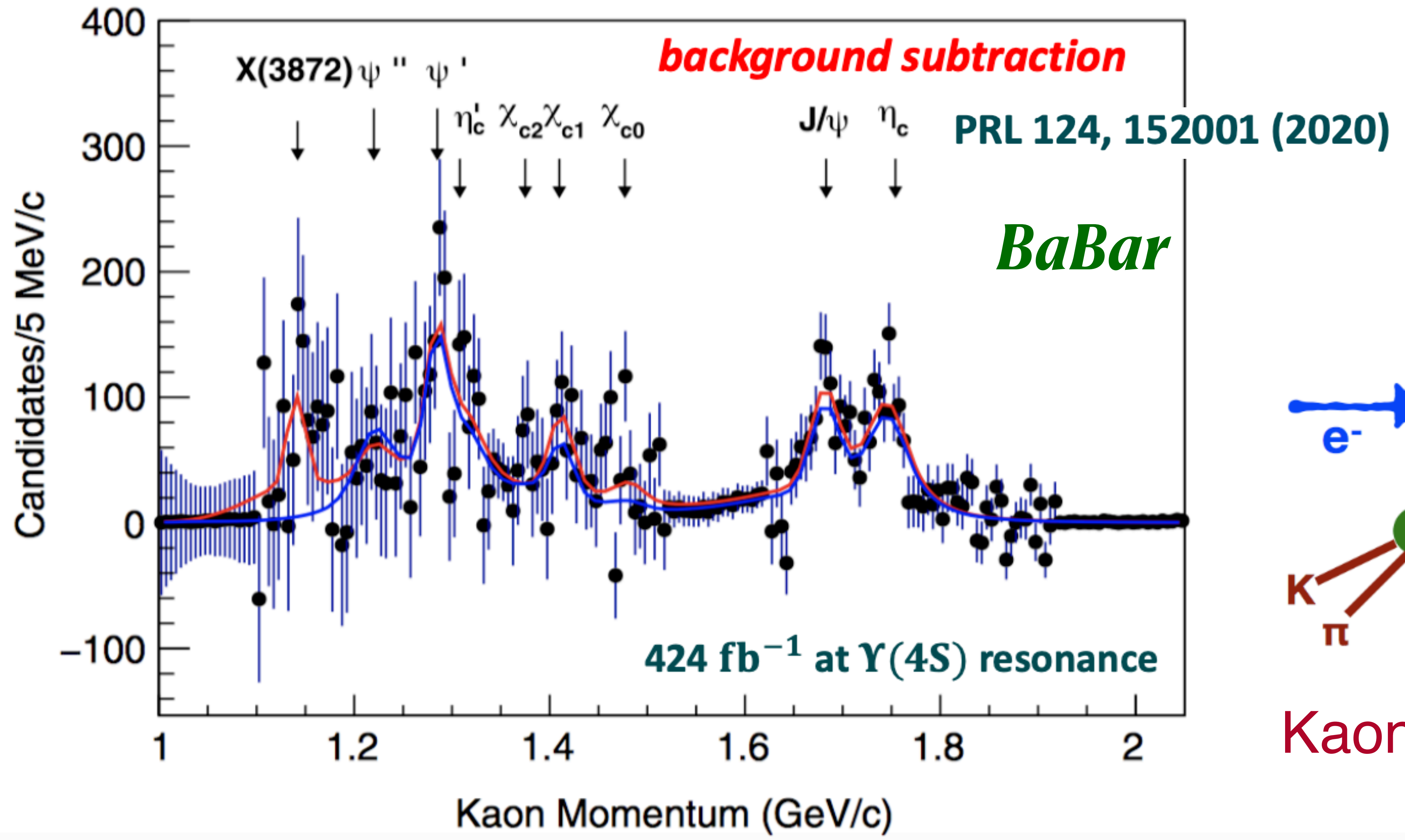
$$M[X(3872)] = 3871.65 \pm 0.06\ \text{MeV}$$

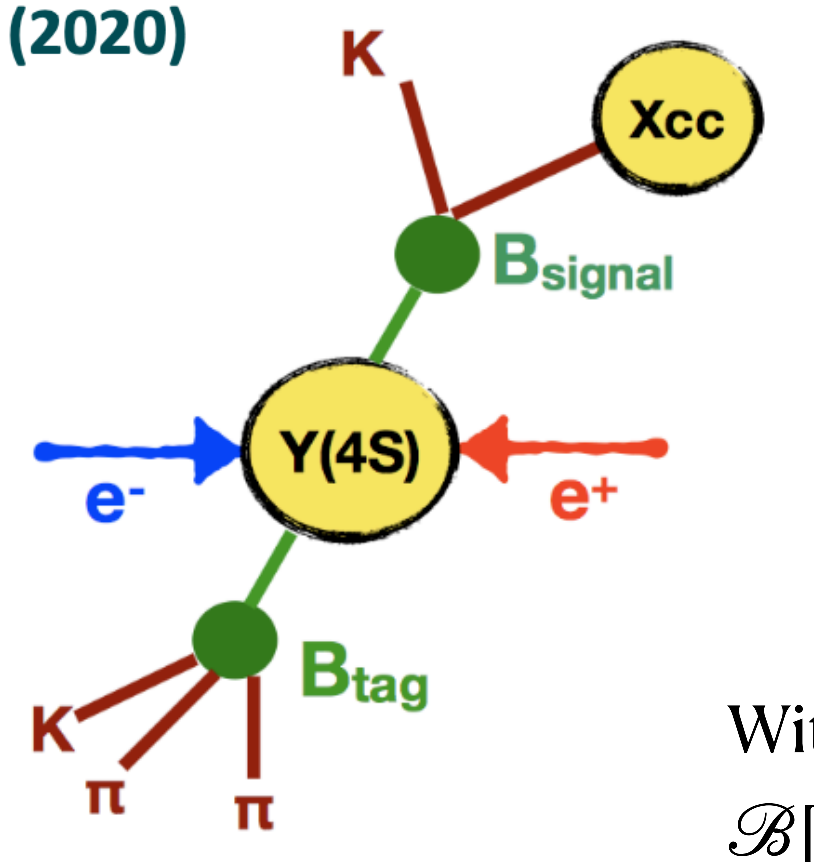
$$M[D^0\bar{D}^{*0}] = 3871.69 \pm 0.11\ \text{MeV}$$

binding energy: $0.04 \pm 0.12\ \text{MeV}$

**bound energy of deuteron: $2.2\ \text{MeV}$

Radius $> 5\ \text{fm}$ for a molecular hypothesis





Evidence of $X(3872)$ with a significance of 3σ;
For $B \to KX(3872)$

$$\mathcal{B} = (2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$$

With the absolute branching fraction of $B \to KX(3872)$, $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]$ could be extracted.

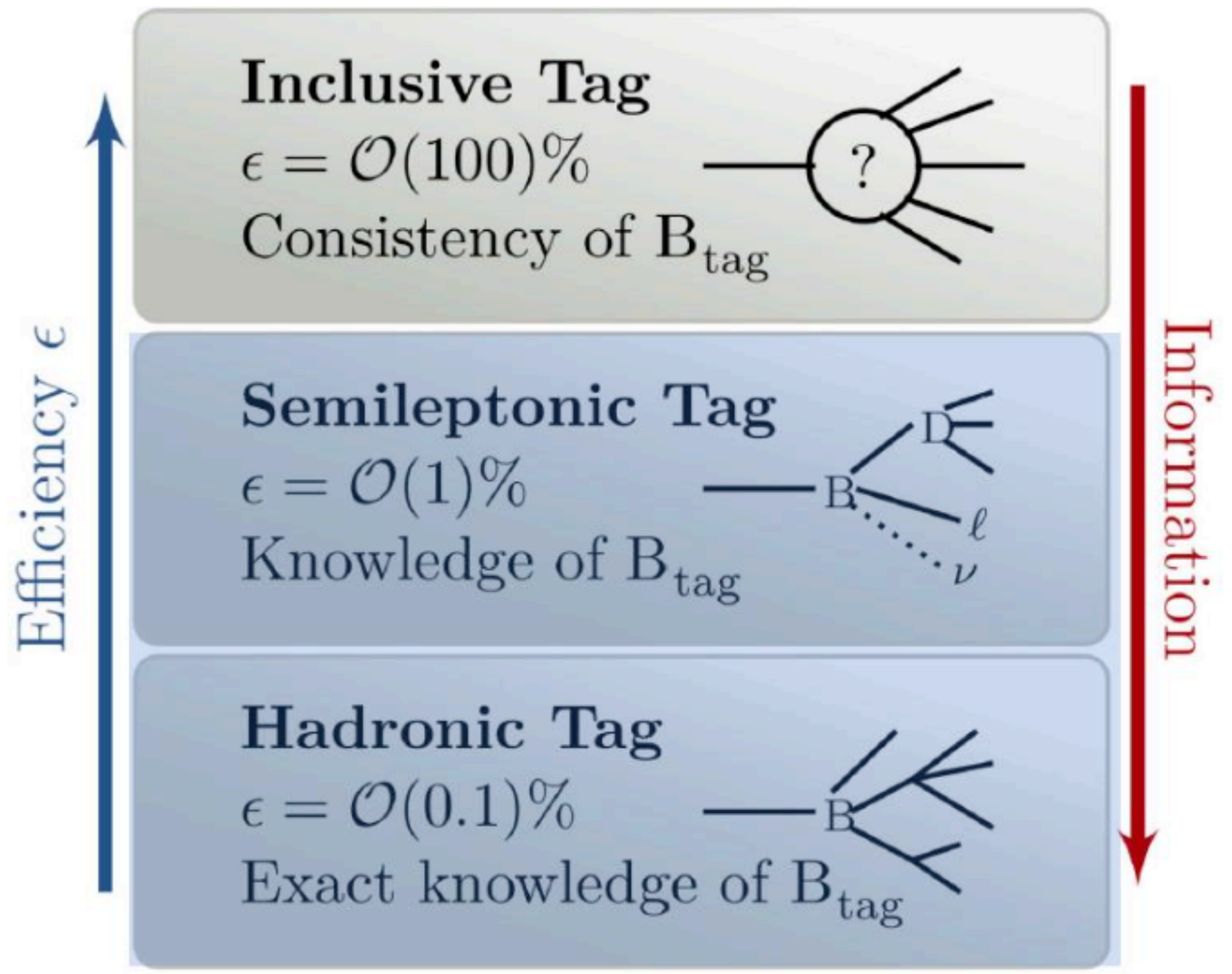
Kaon momentum is directly related to the recoil mass

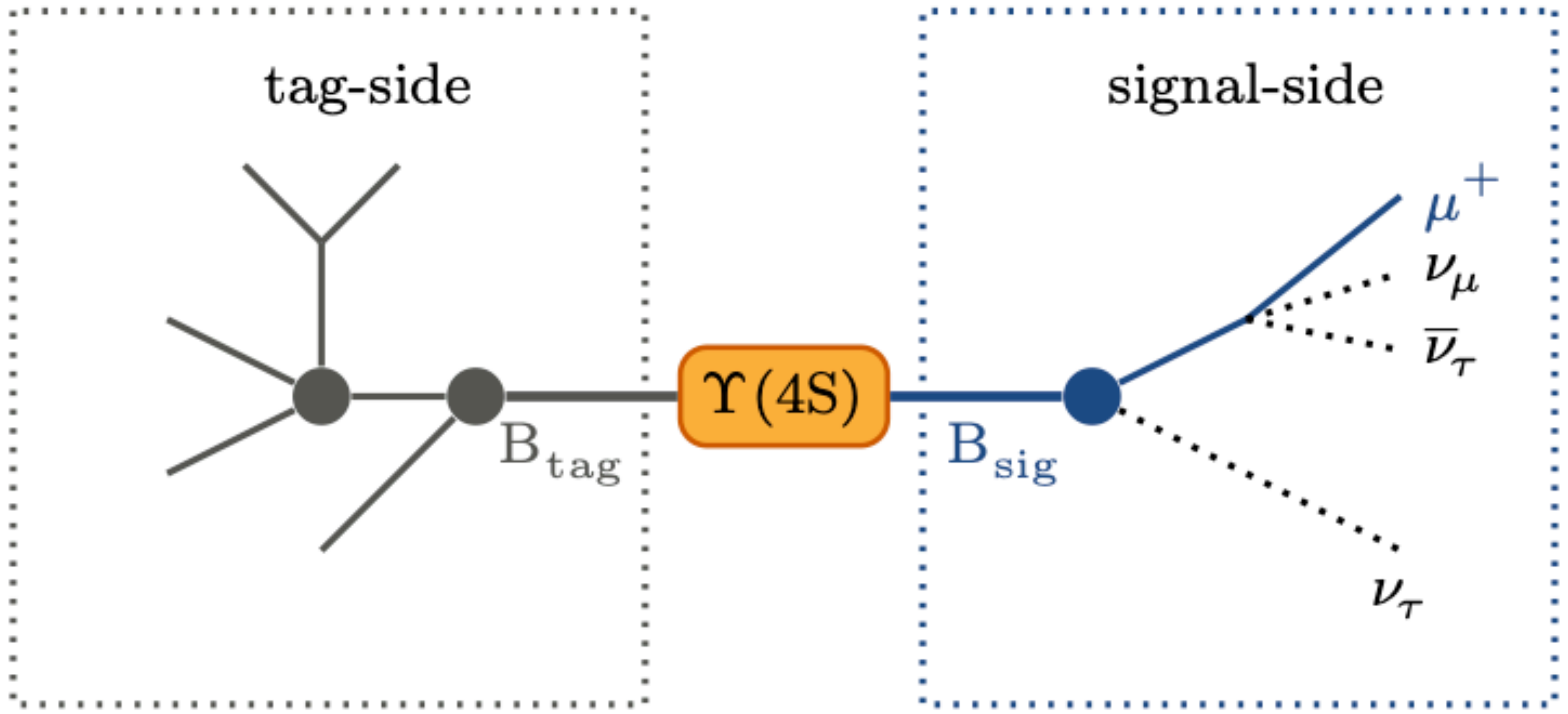
At Belle II, we need improve the measurements related with X(3872) decays [reduce the background level; improve B tagging efficiency]

Full Event Interpretation (FEI) is designed:

- Reconstruction of ~10,000 modes
- Extensive use of ML
- semileptonic and hadronic tag modes
- Increase in efficiency, and comparable purity.

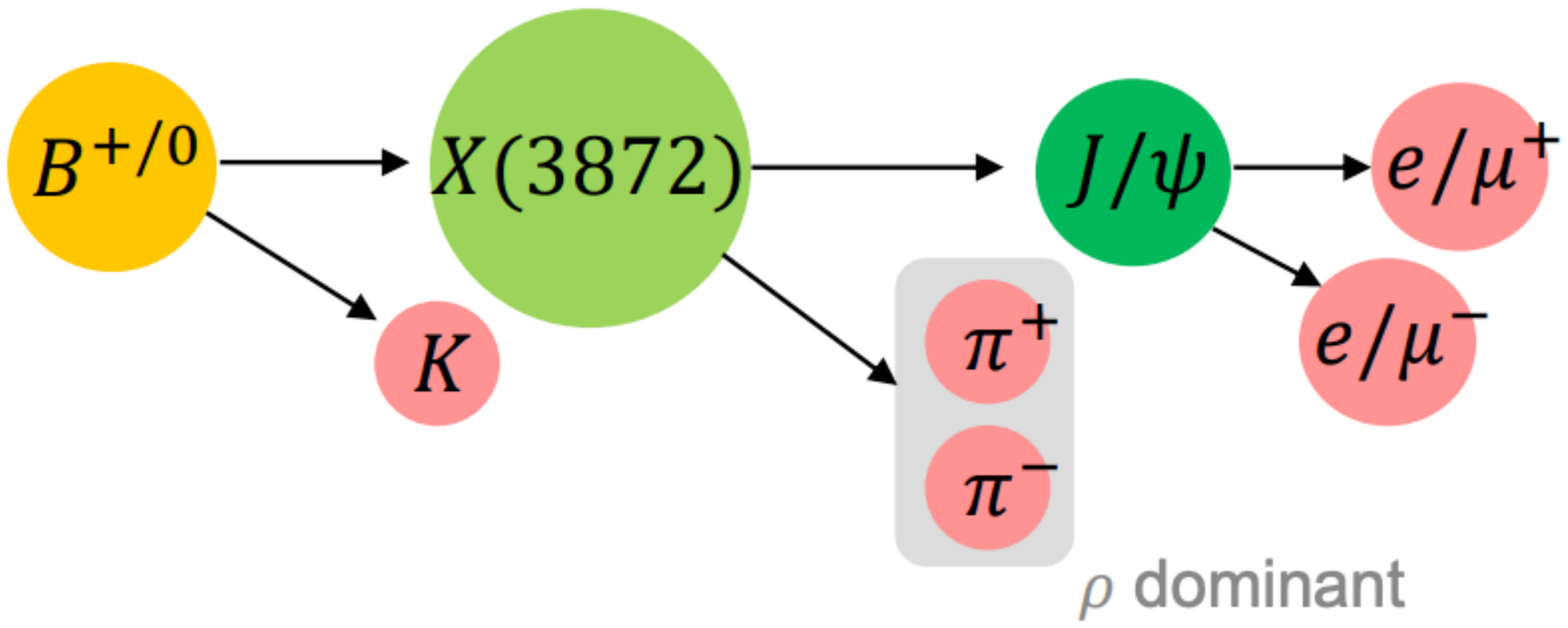
Improve up to 50 % efficiency





arXiv: 1807.08680 [hep-ex]
Comput. Softw. Big Sci. 3 (2019) 1, 6

Early measurement of $X(3872)$

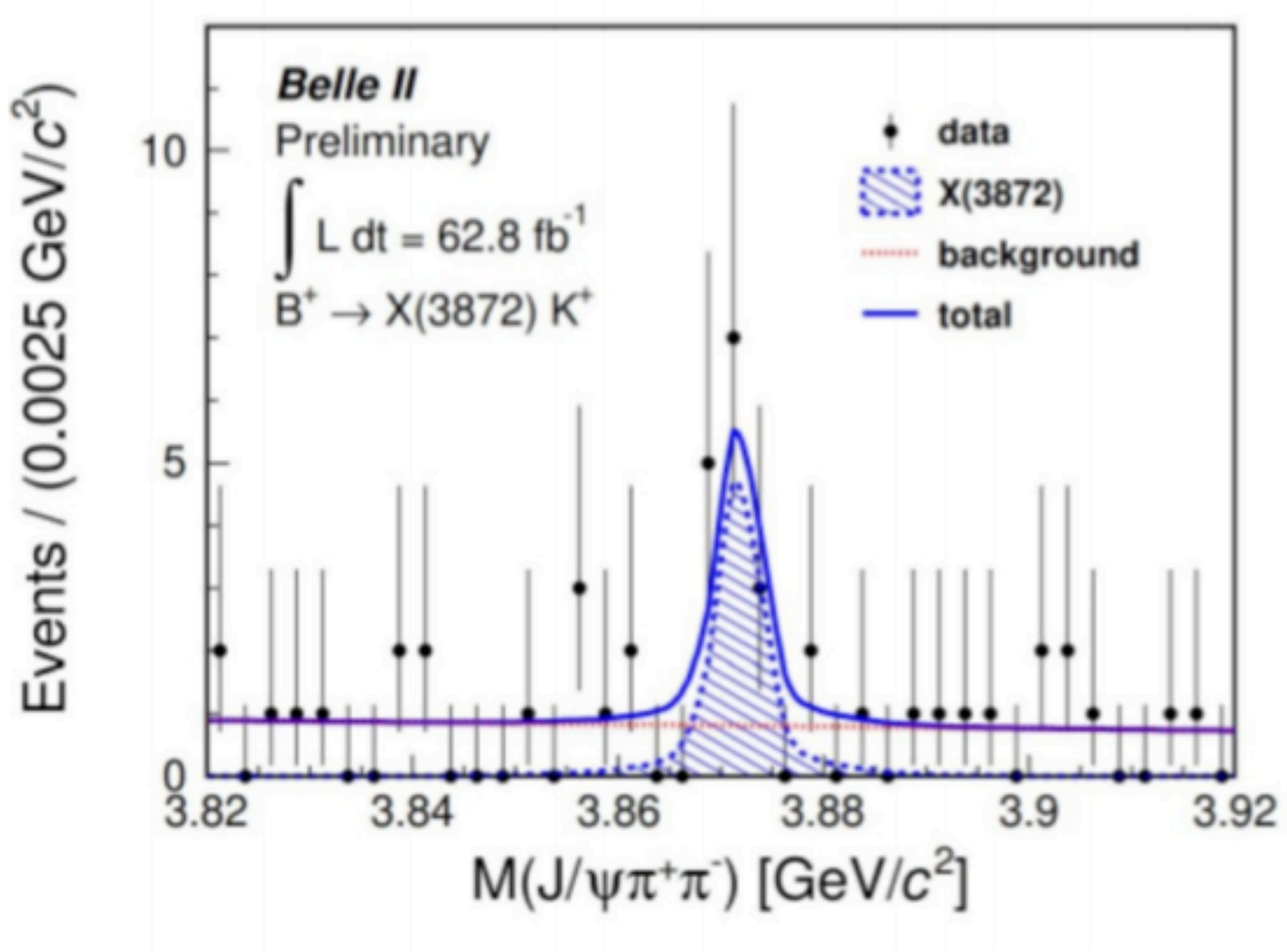


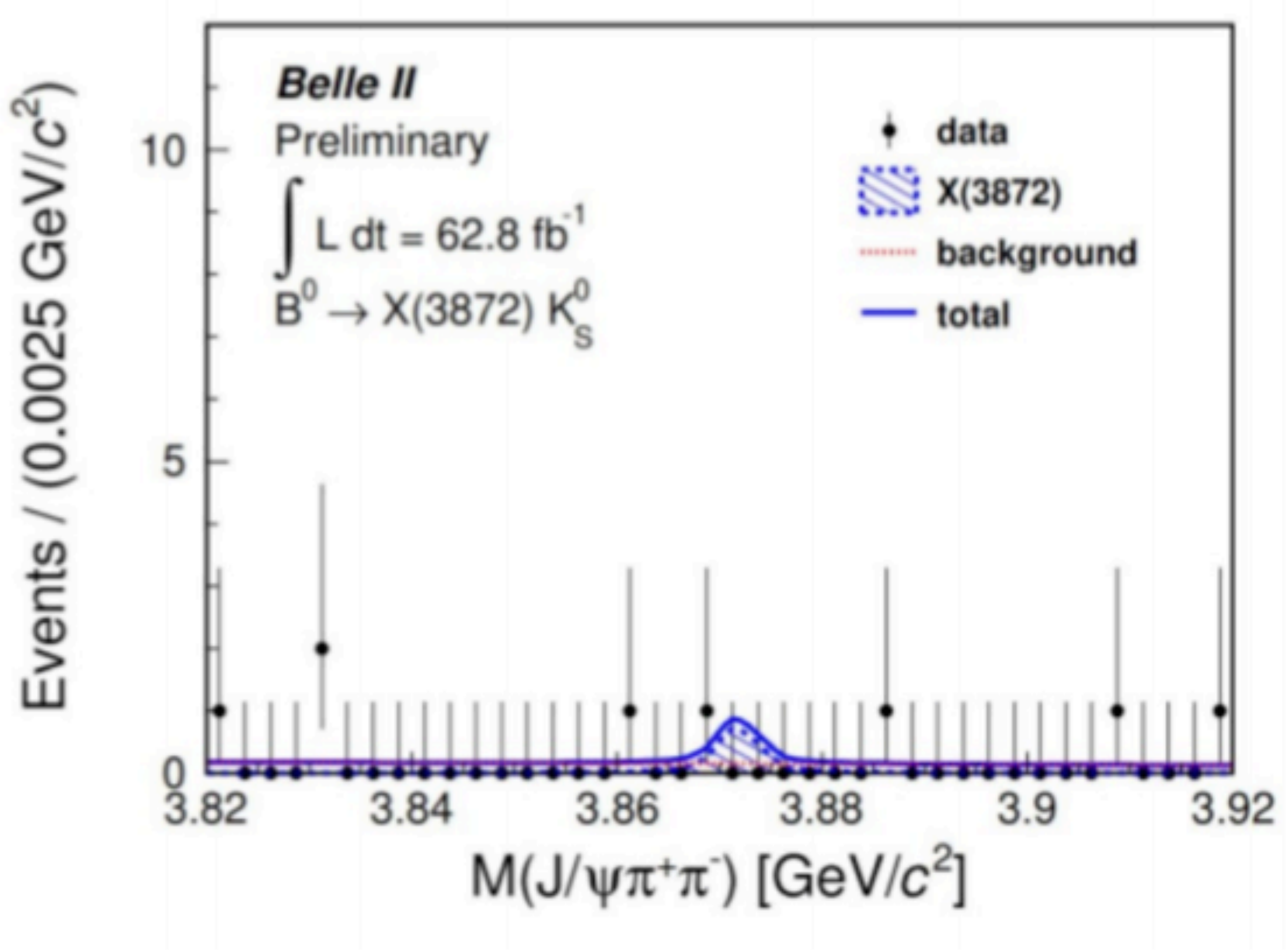
Reconstruction of final states

- $B^{\pm} \to \pi^+\pi^- J/\psi(l^+l^-)K^{\pm}$
- $B^0 \to \pi^+\pi^- J/\psi(l^+l^-)K_S$

Selection criteria

- Particle identification
- continuum suppression
- kinematics criteria: M_{bc}, $|\Delta E|$





$$\frac{B^0 \to X(3872)K^0}{B^{\pm} \to X(3872)K^{\pm}} = 0.5 \text{ is assumed}$$

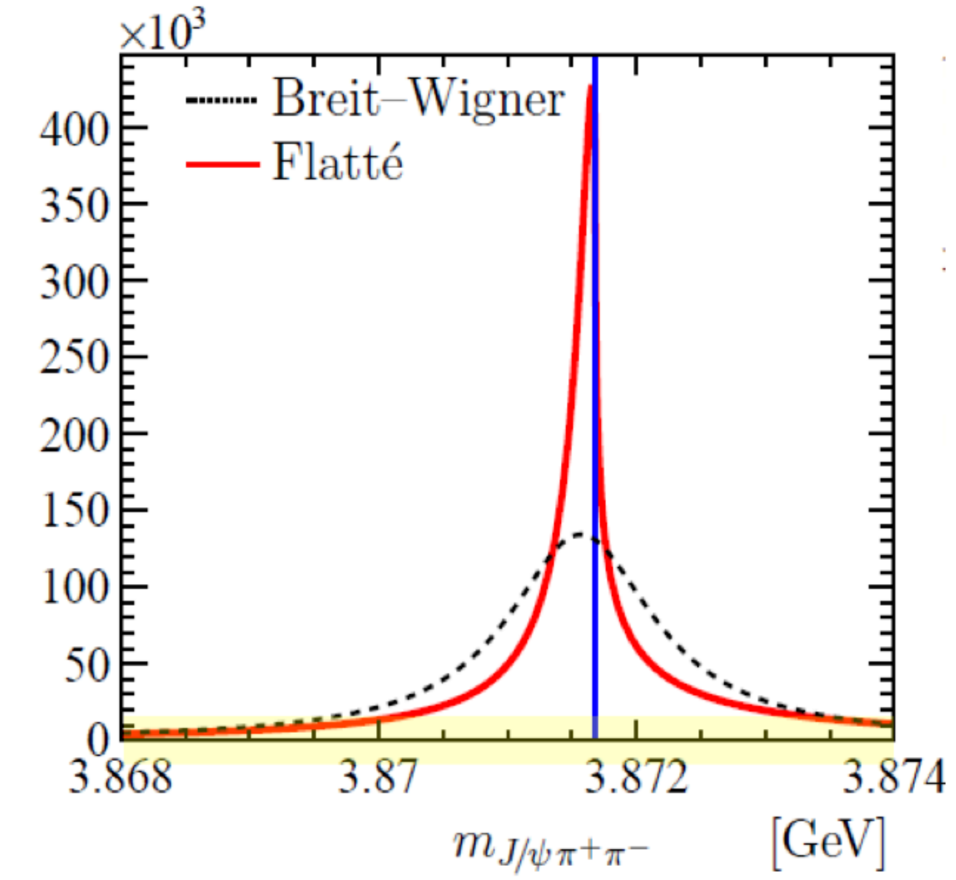
First $X(3872)$ at Belle II:

$N_{sig} = 14.4 \pm 4.6$

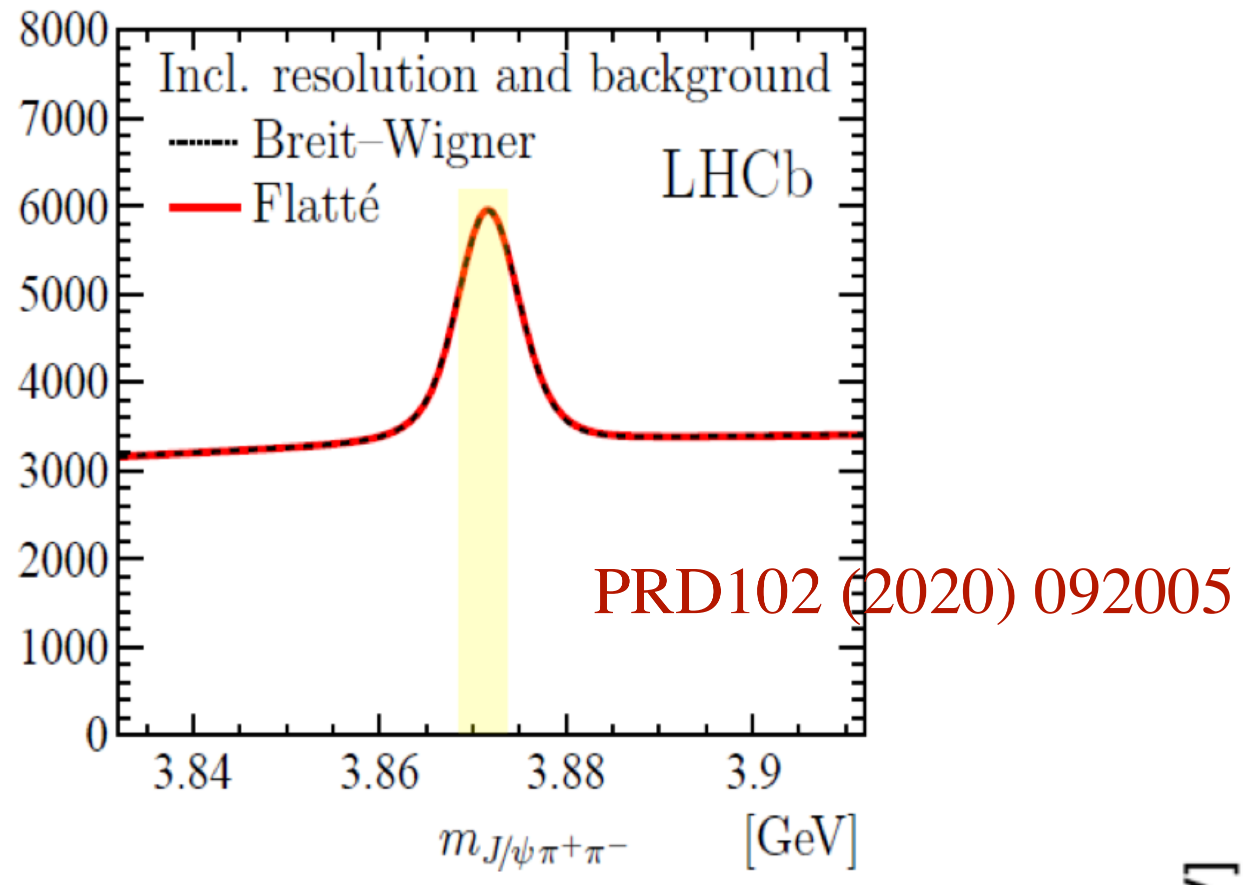
Evidence of $X(3872)$ with 4.6σ

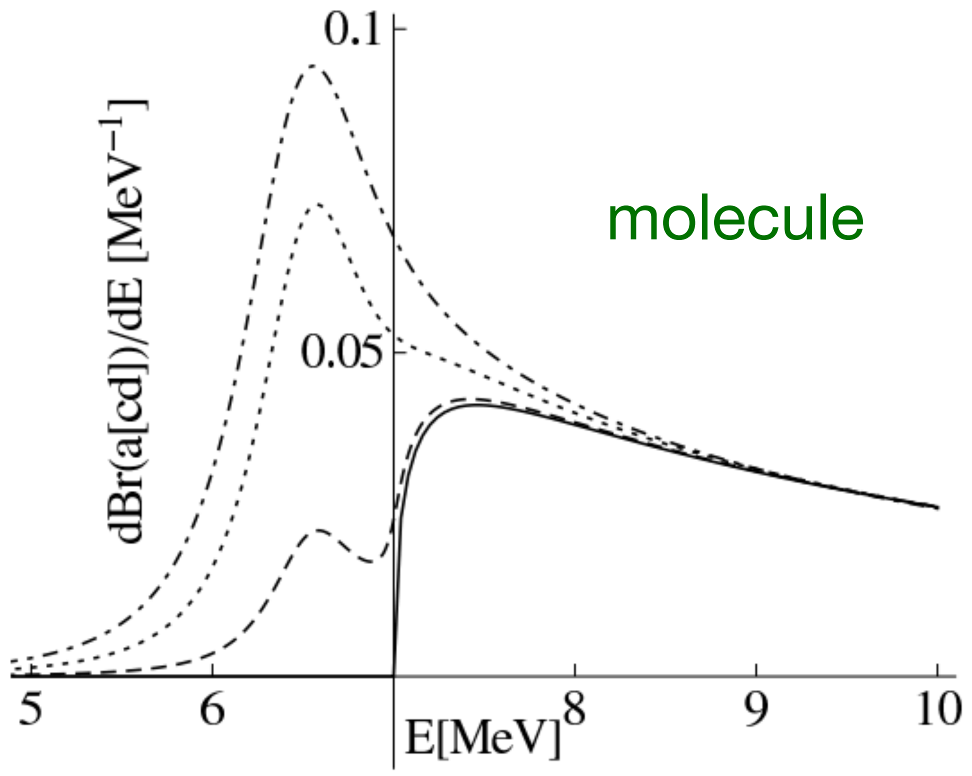
Lineshape measurement of $X(3872)$

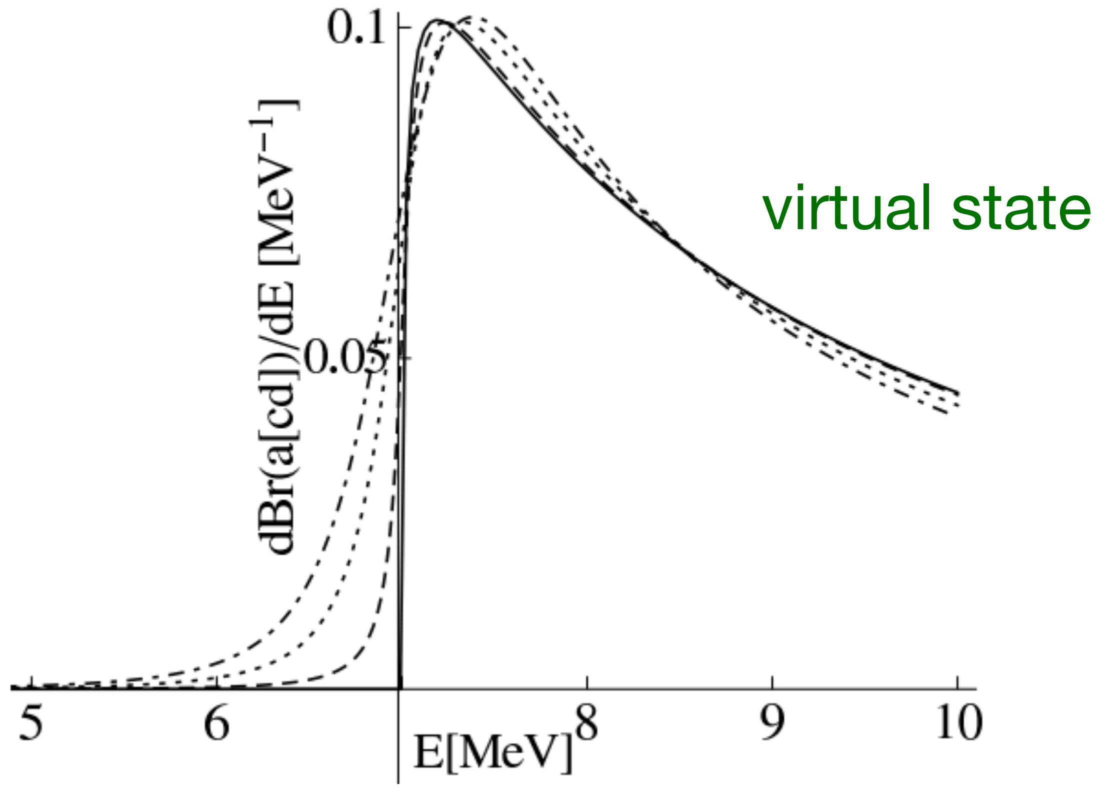
Original lineshapes



Lineshapes with resolution

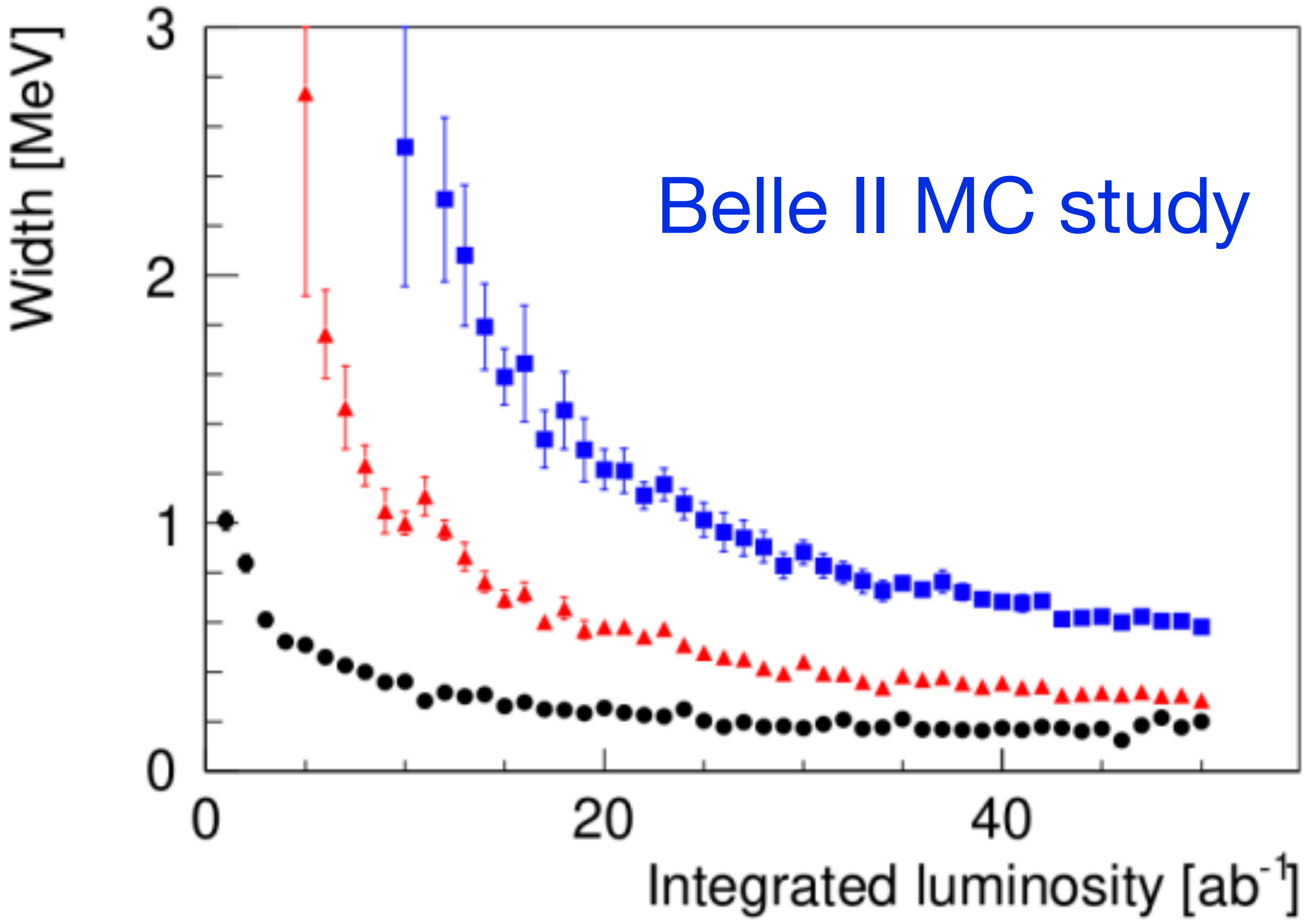






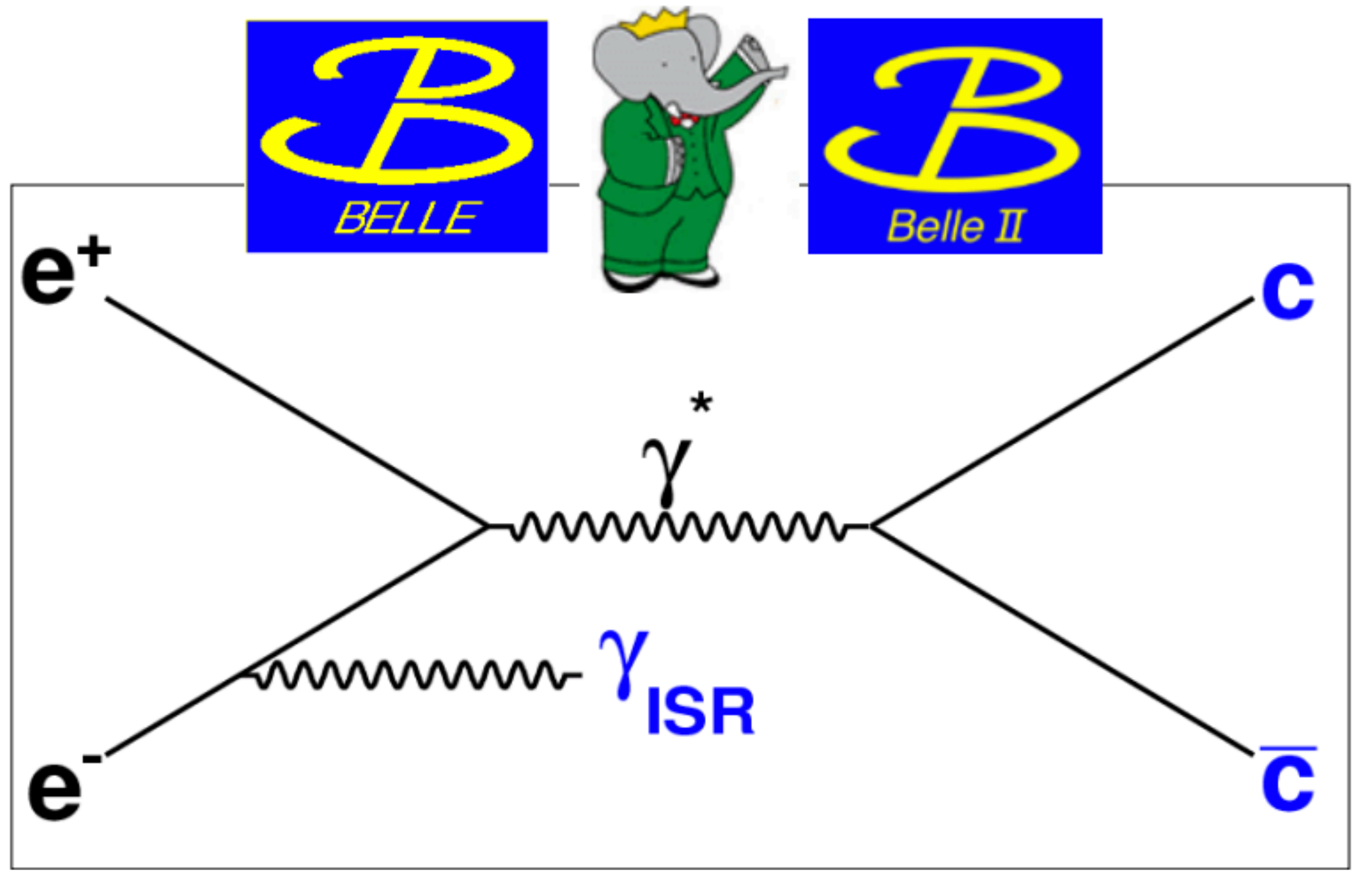
PRD 81 (2010) 094028

- LHCb measured the mass and width with $X(3872) \to \pi^+\pi^- J/\psi$
- Difficult to distinguish BW or Flatté
- The line-shape is more sensitive to $D^0\bar{D}^{*0} + c.c.$

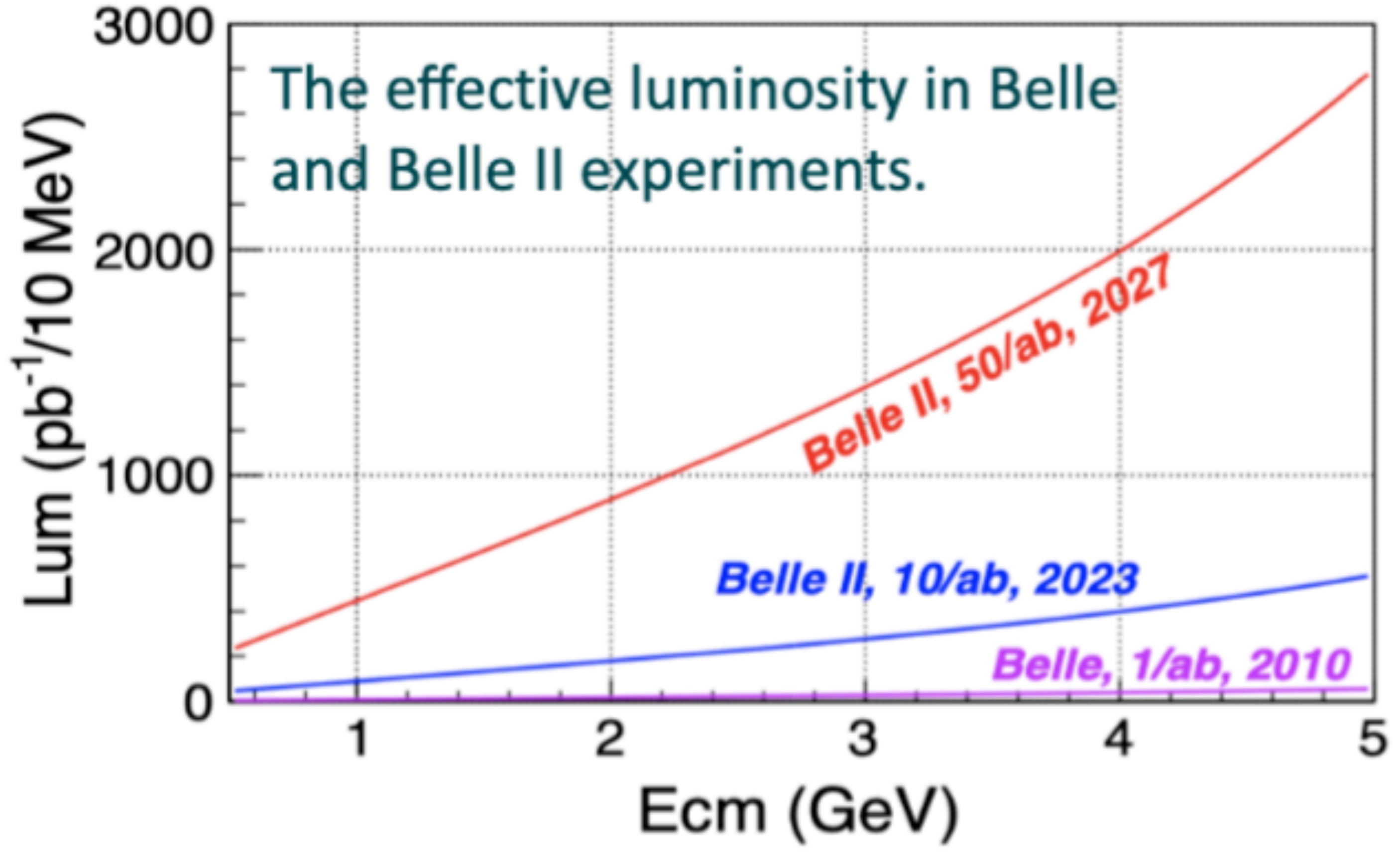


Resolution: 684 ± 8 keV
Width down to 280 keV

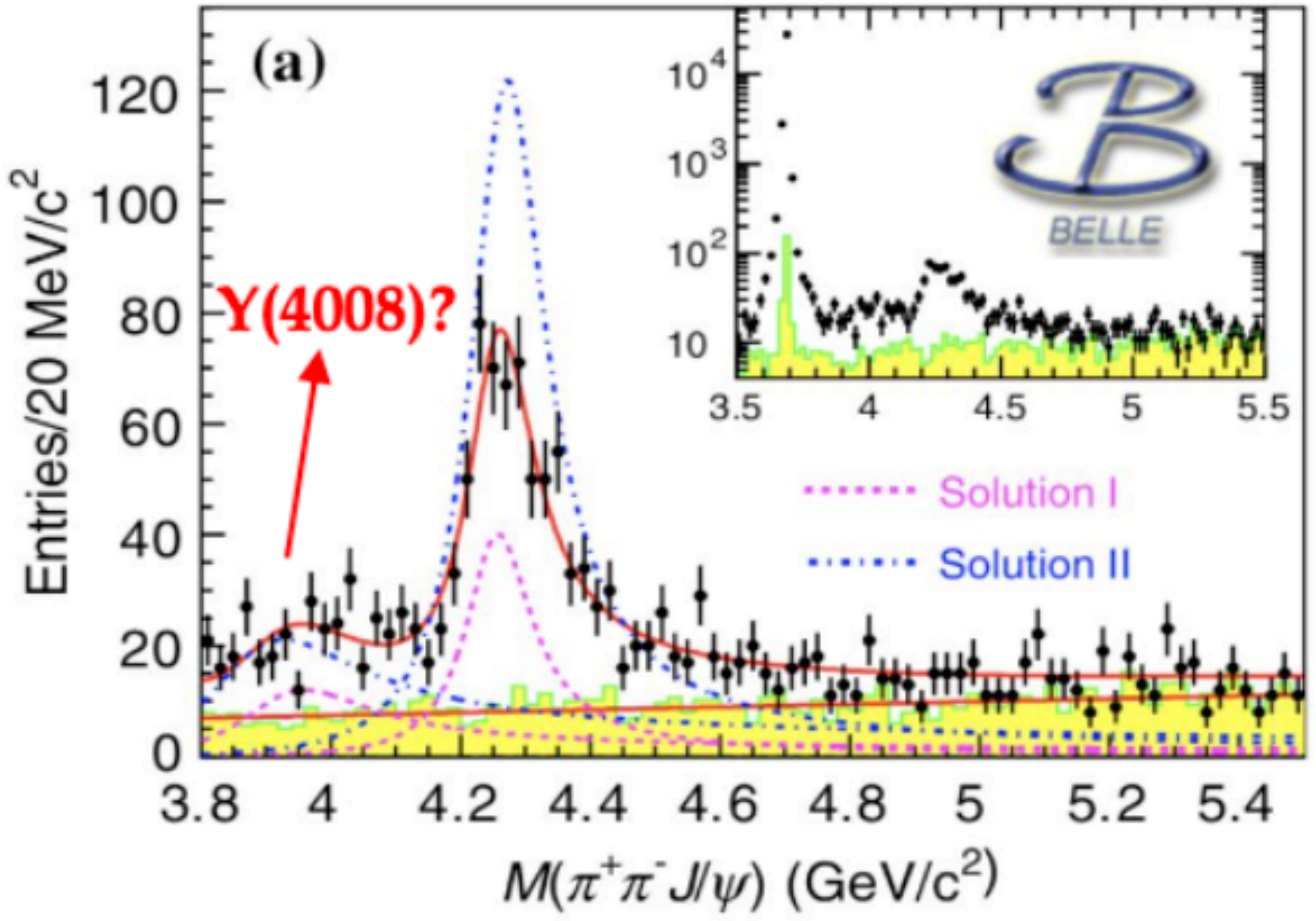
Search for exotics using initial state radiation



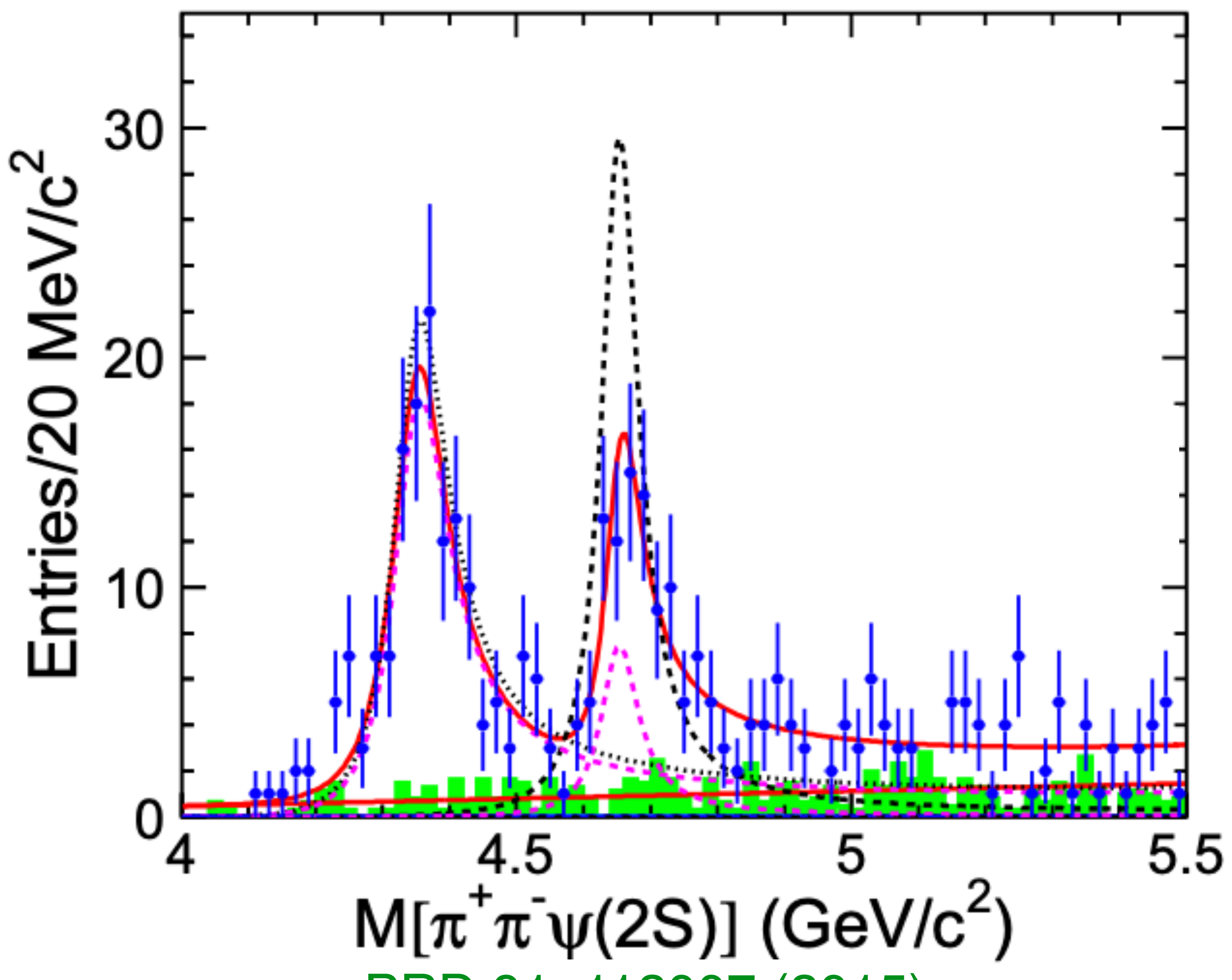
ISR = initial state radiation



- ISR technique can explore $J^{PC} = 1^{--}$ states far away from e^+e^- collision energy.
- The whole hadron spectrum is visible.
- The effective luminosity and detection efficiency are relatively low.



PRL 110, 252002 (2013)



PRD 91, 112007 (2015)

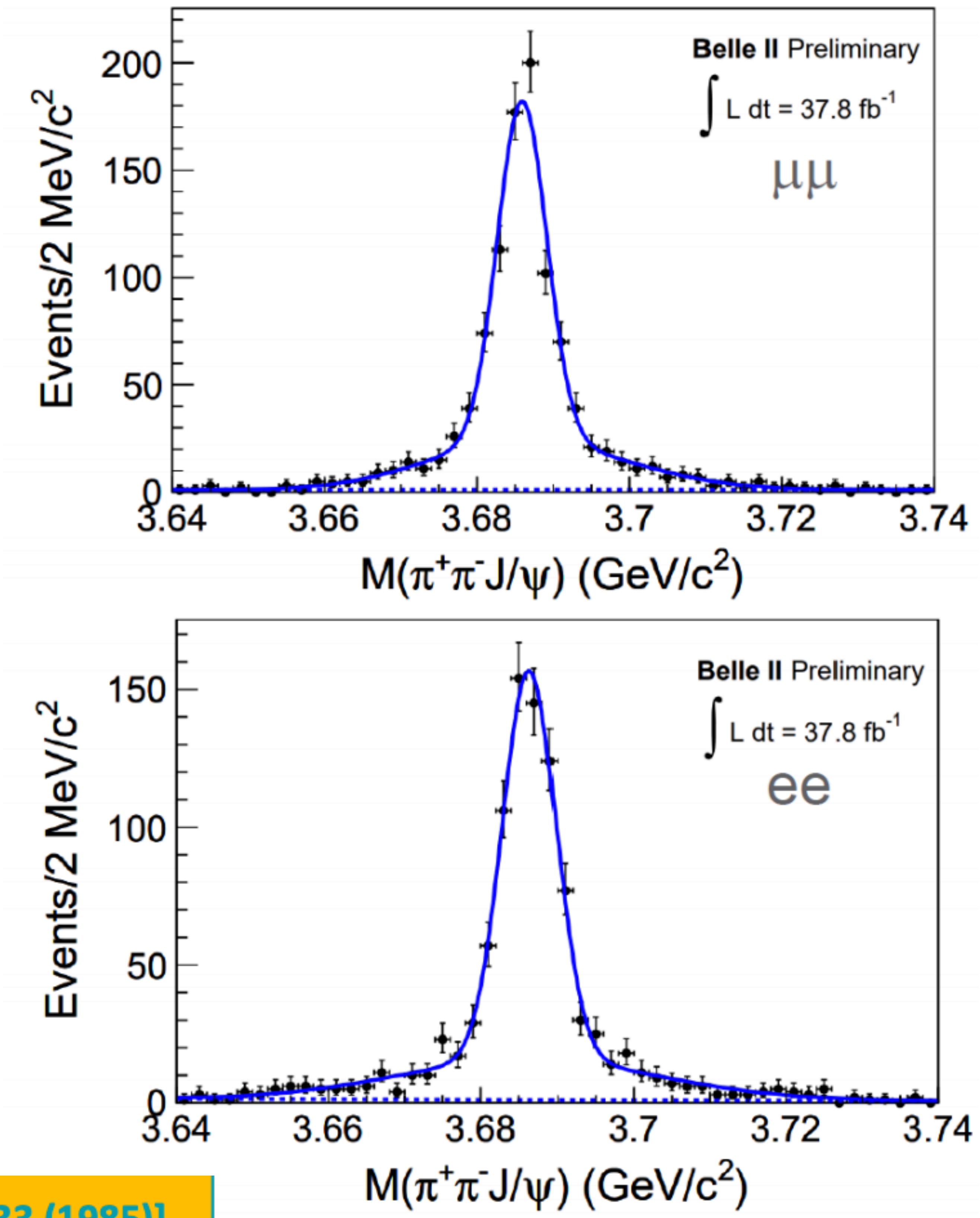
With the technique of ISR, Belle achieve fruitful results, i.e. $Y(4230)$, $Y(4660)$ etc.

Control sample of $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

- $e^+e^-\gamma_{ISR} \rightarrow \pi^+\pi^- J/\psi(\ell^+\ell^-)$ final states
  - Nominal PID requirements
  - $|M(J/\psi)\text{-}M(PDG)| < 75$ MeV
  - ISR photon not required (high efficiency)
  - $|MM^2(\pi^+\pi^- J/\psi)| < 2\ GeV^2$

- Clear observation of ISR $\psi(2S)$ signals

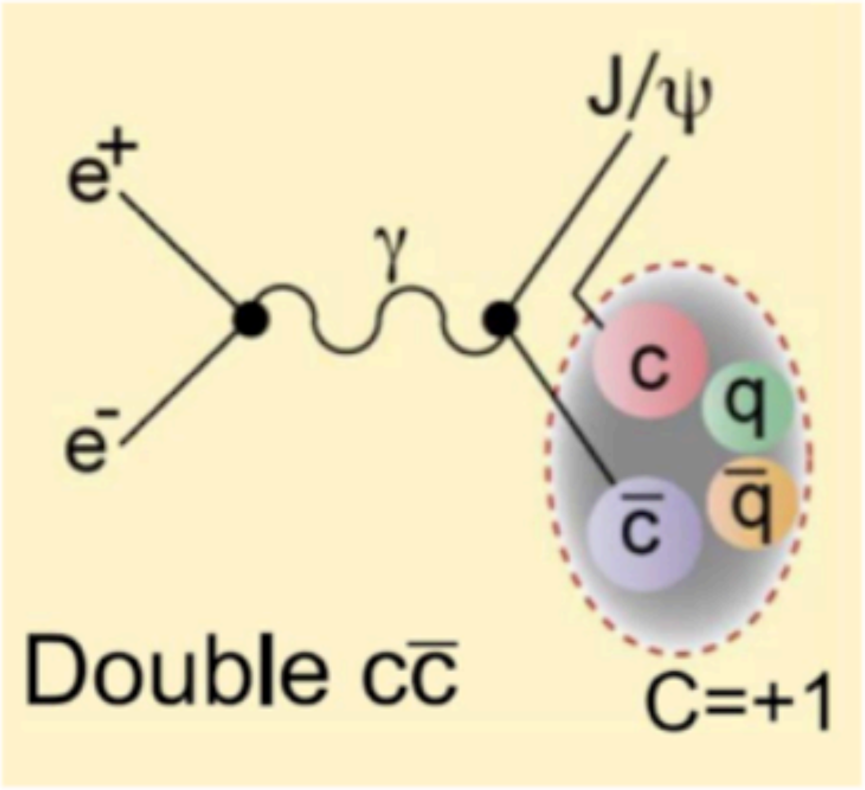
- Next step: “Y(4260)” rediscovery
  - Expect ~60 total events per 100 fb^{-1}



Mode	Our measurements	Theoretical calculation [Yad. Fiz. 41, 733 (1985)]
$J/\psi \rightarrow \mu^+\mu^-$	(12.0 ± 1.2) pb	(14.1 ± 0.3) pb
$J/\psi \rightarrow e^+e^-$	(13.0 ± 1.2) pb	

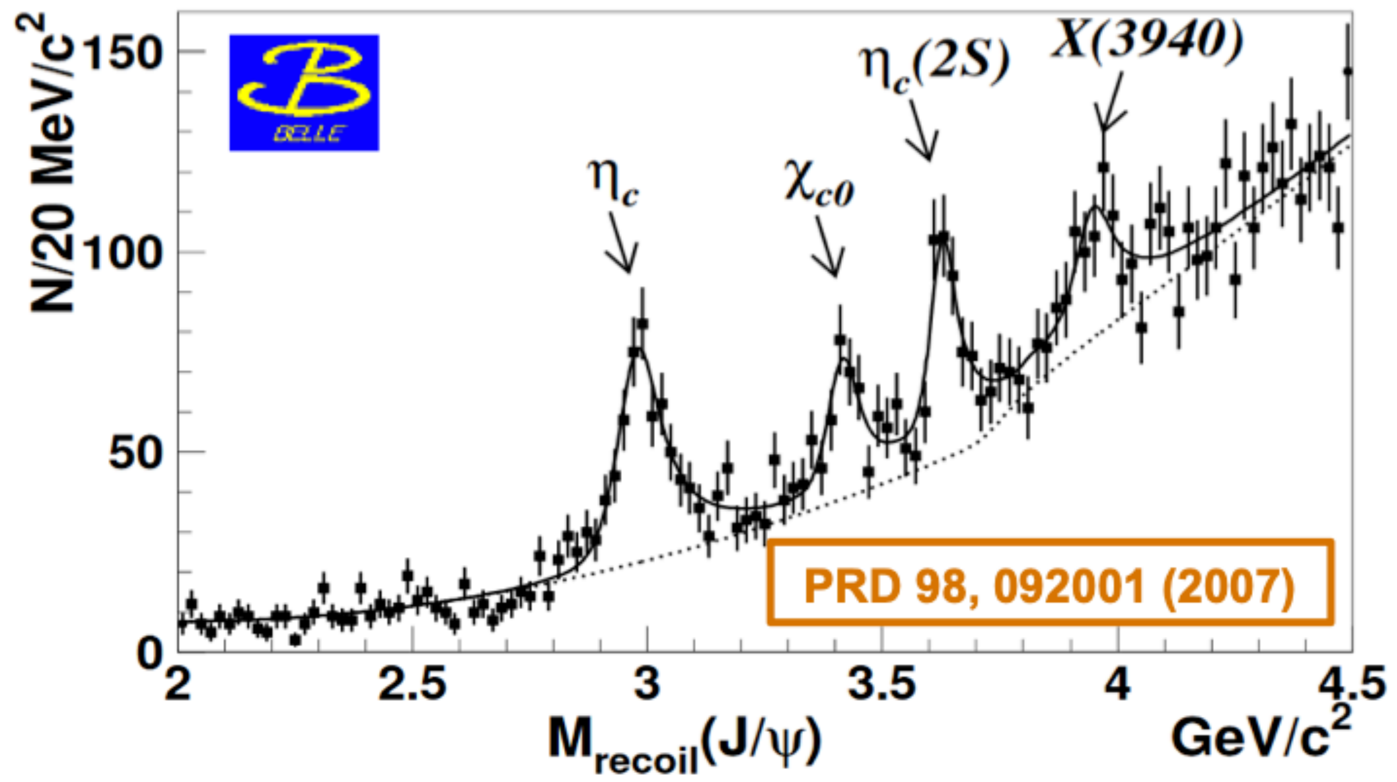
consistent with the theoretical calculation

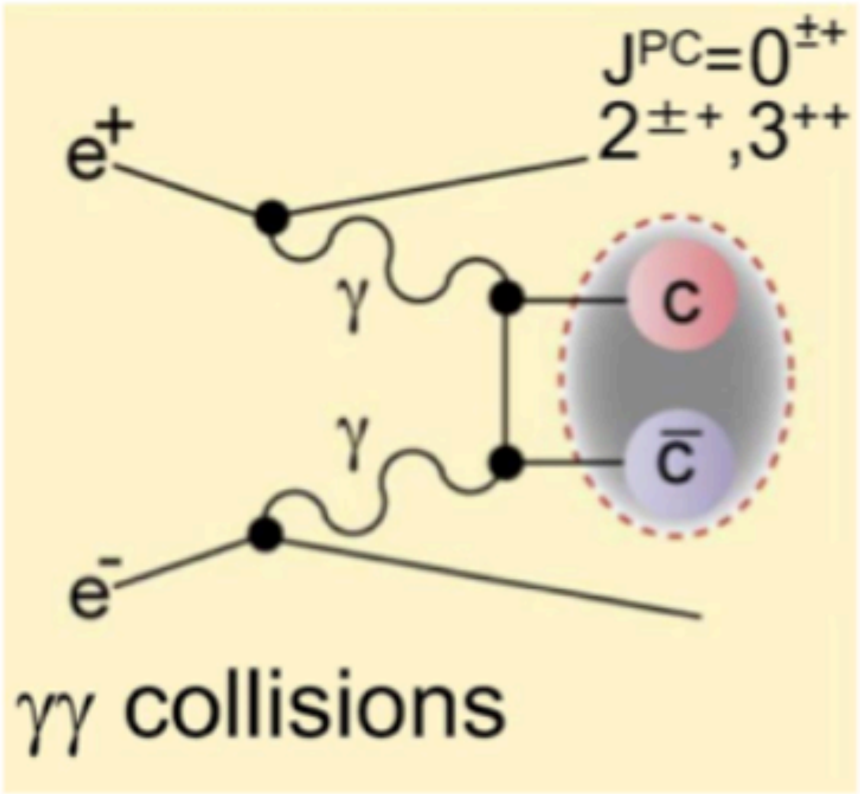
Other productions



Double charmonium production:

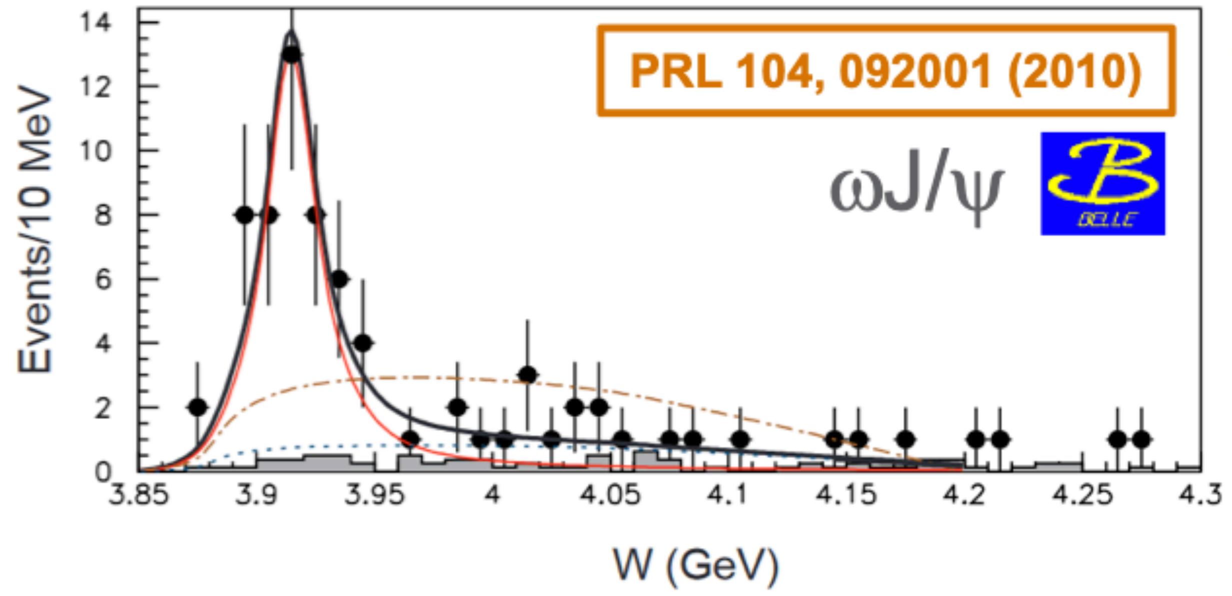
- $\sigma_{\text{theory}} \ll \sigma_{\text{measure}}$, rich resonances
- Discovery of $X(3940)$, $\chi_{c0}(2P)$
- Expand to other $c\bar{c}$, search for new states

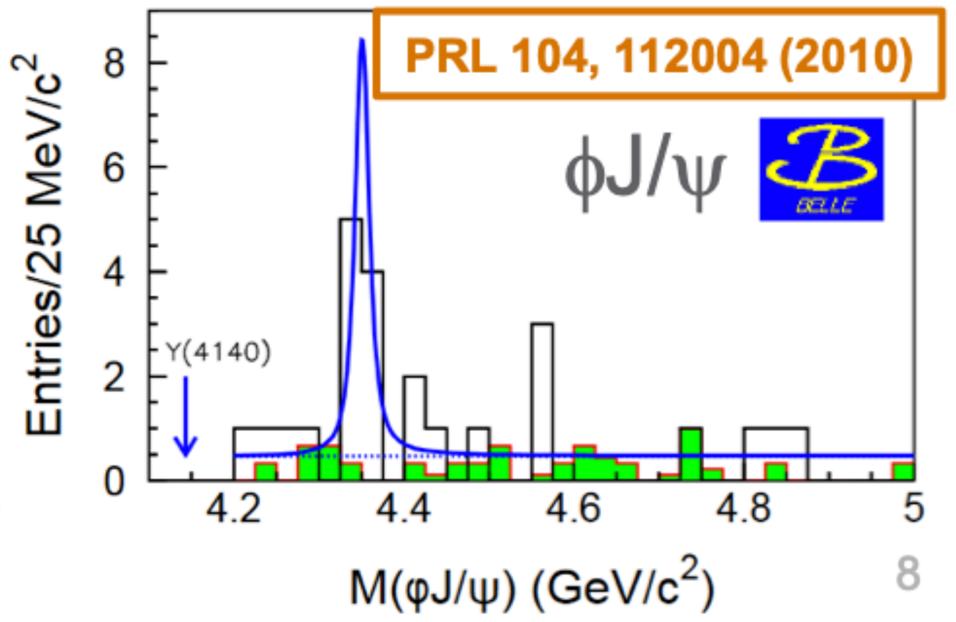


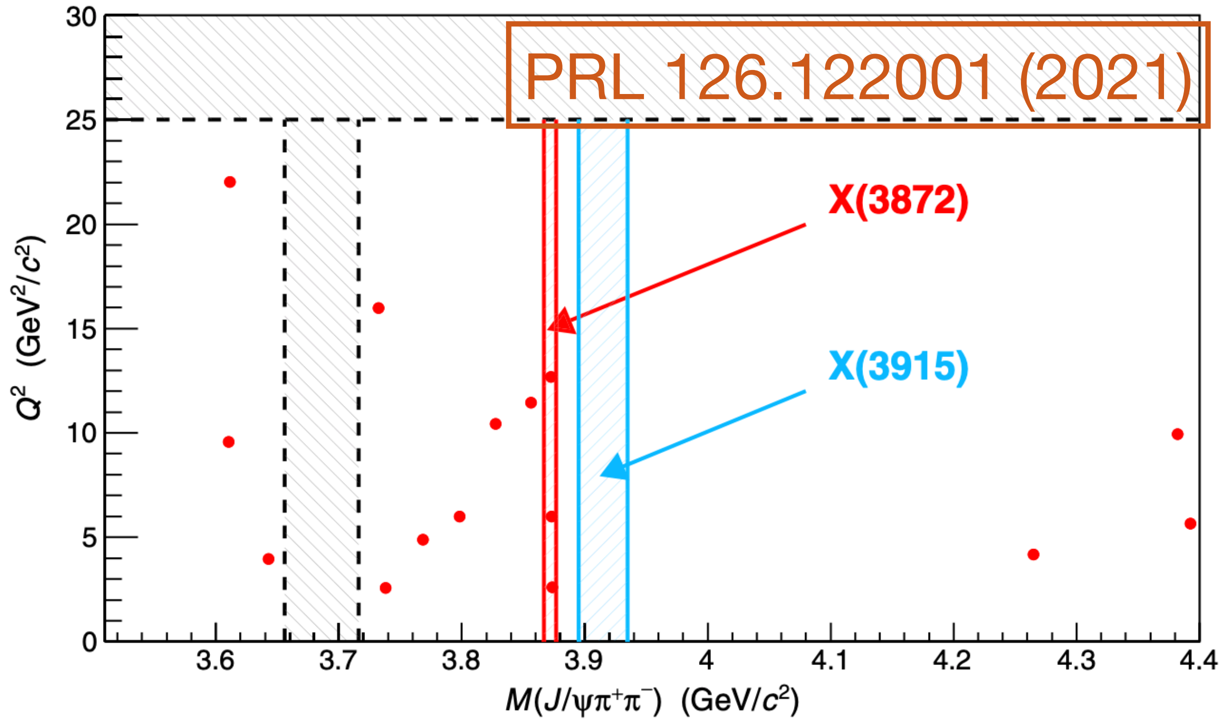


Two-photon:

- J^{PC} of $X(3915)$
- Confirm $\phi J/\psi$ state
- Confirm $X(3872)$







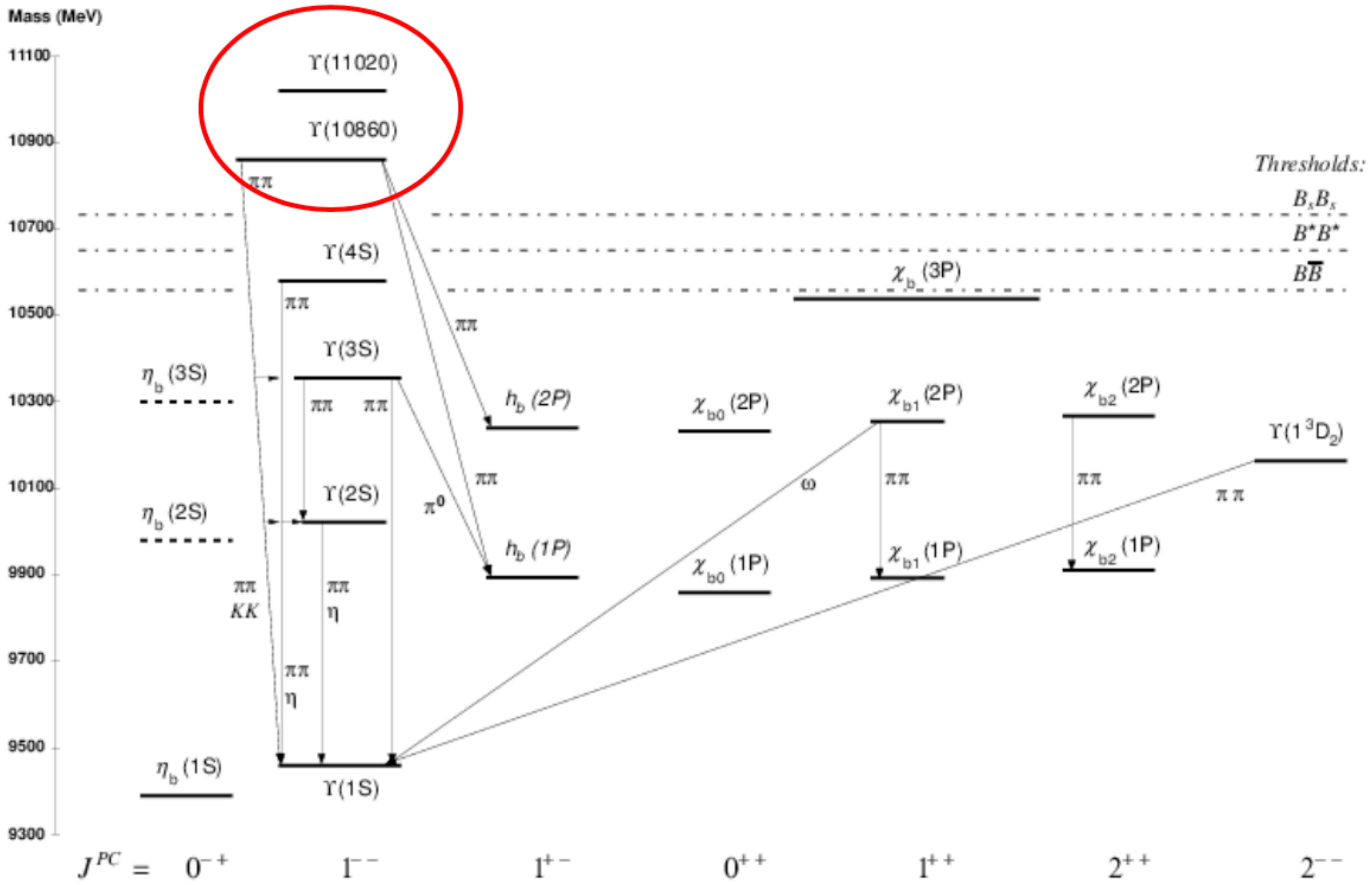
Bottomonia at Belle II

Unique study on Belle & Belle II

$\Upsilon(5,6S)$:

- Study of Z_b: branching ratios, decays...
- Search for new/predicted resonances
- $\Upsilon(5,6S)$ transitions are different
  - hint for non $b\bar{b}$ nature?

An extra resonance around 10.750 GeV?



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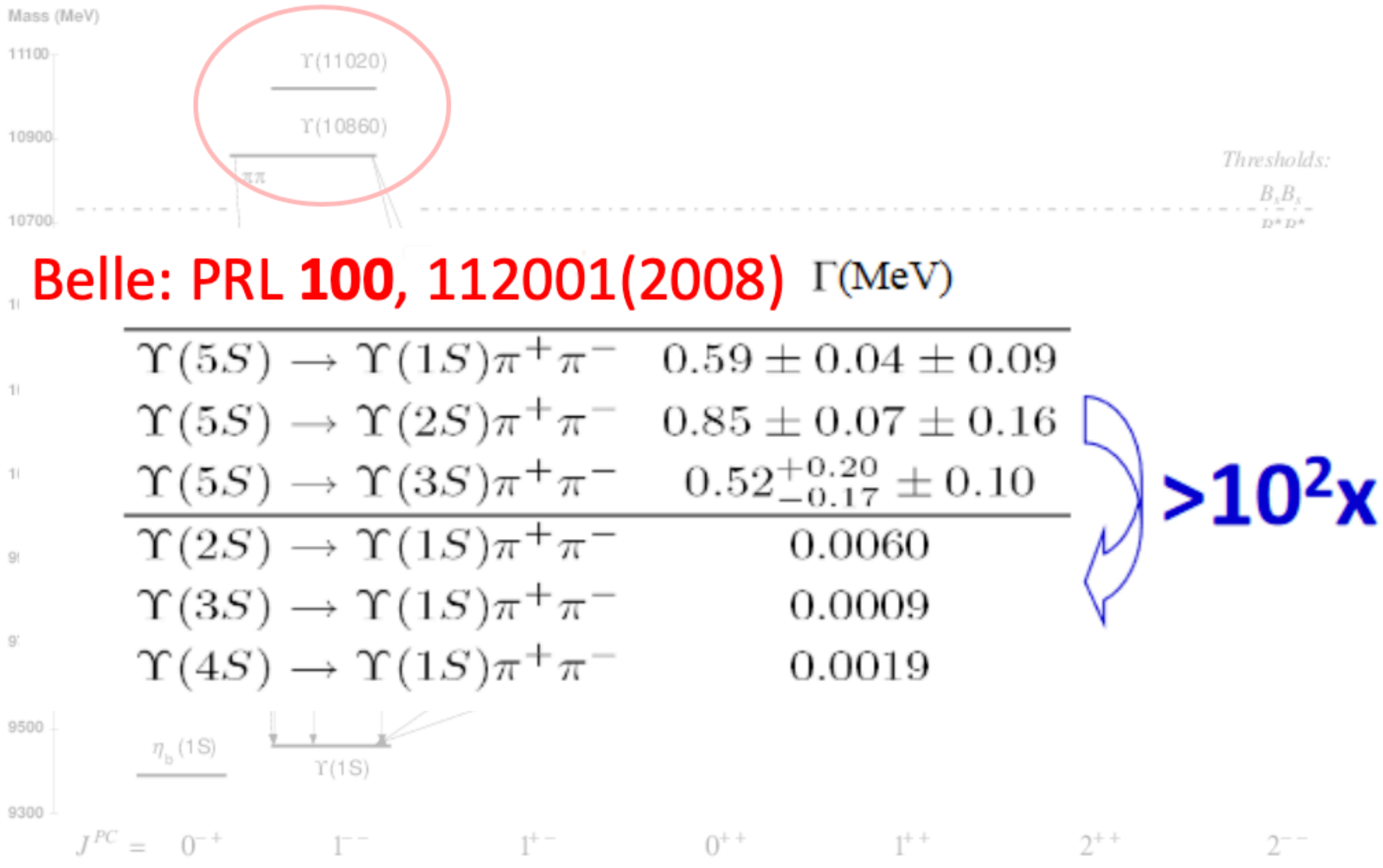

Belle: PRL 100, 112001(2008)

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

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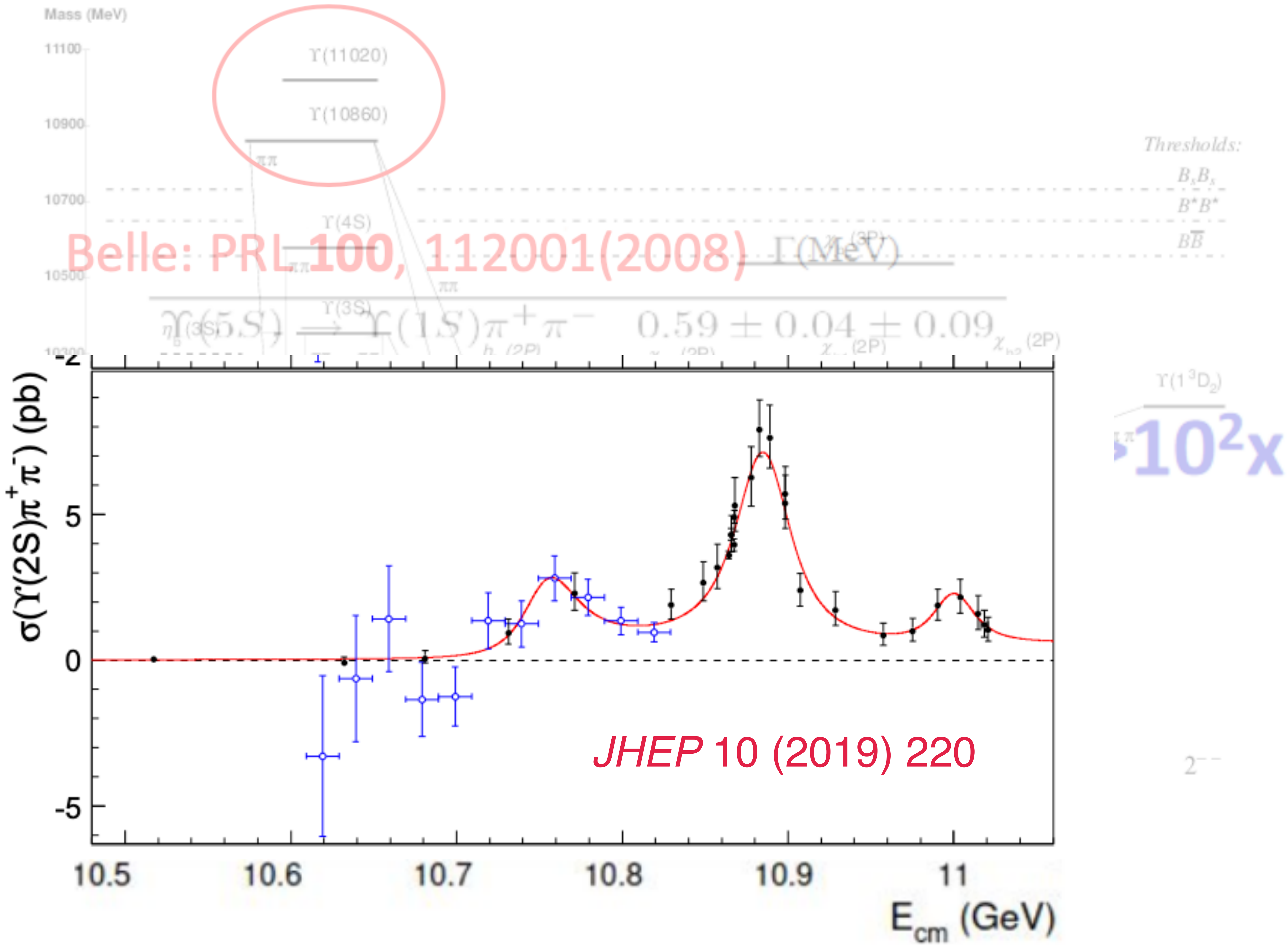


Observation of $Y(10750)$

JHEP 1910, 220 (2019)

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

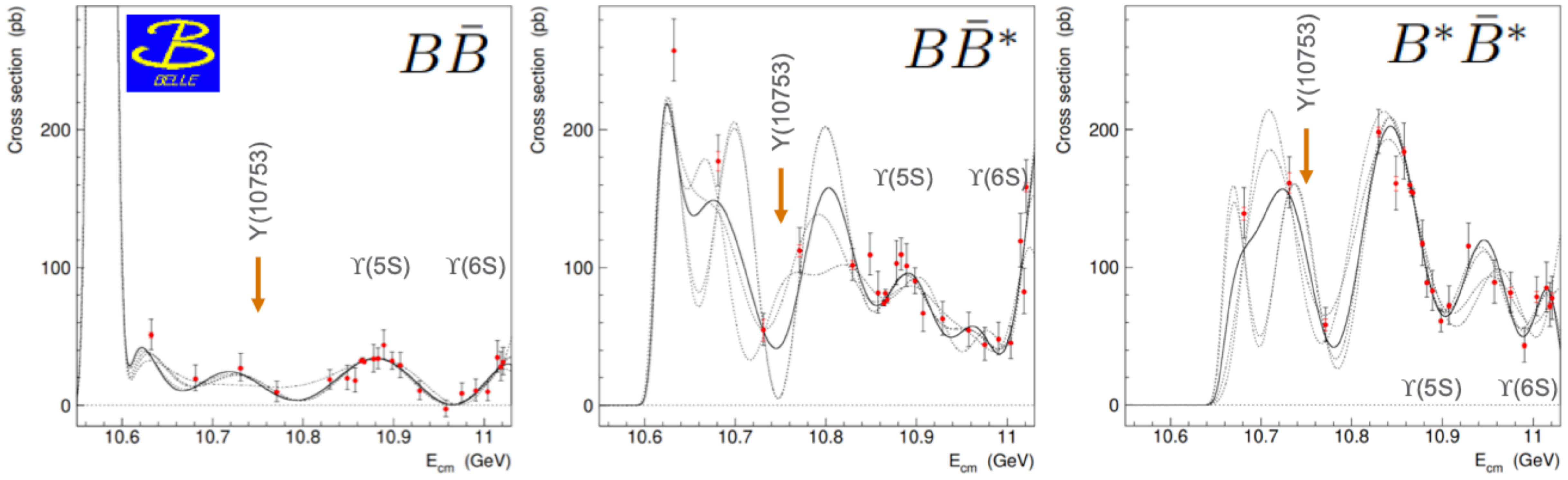
In the final state of $\pi^+\pi^-\Upsilon(1,2,3S)$:

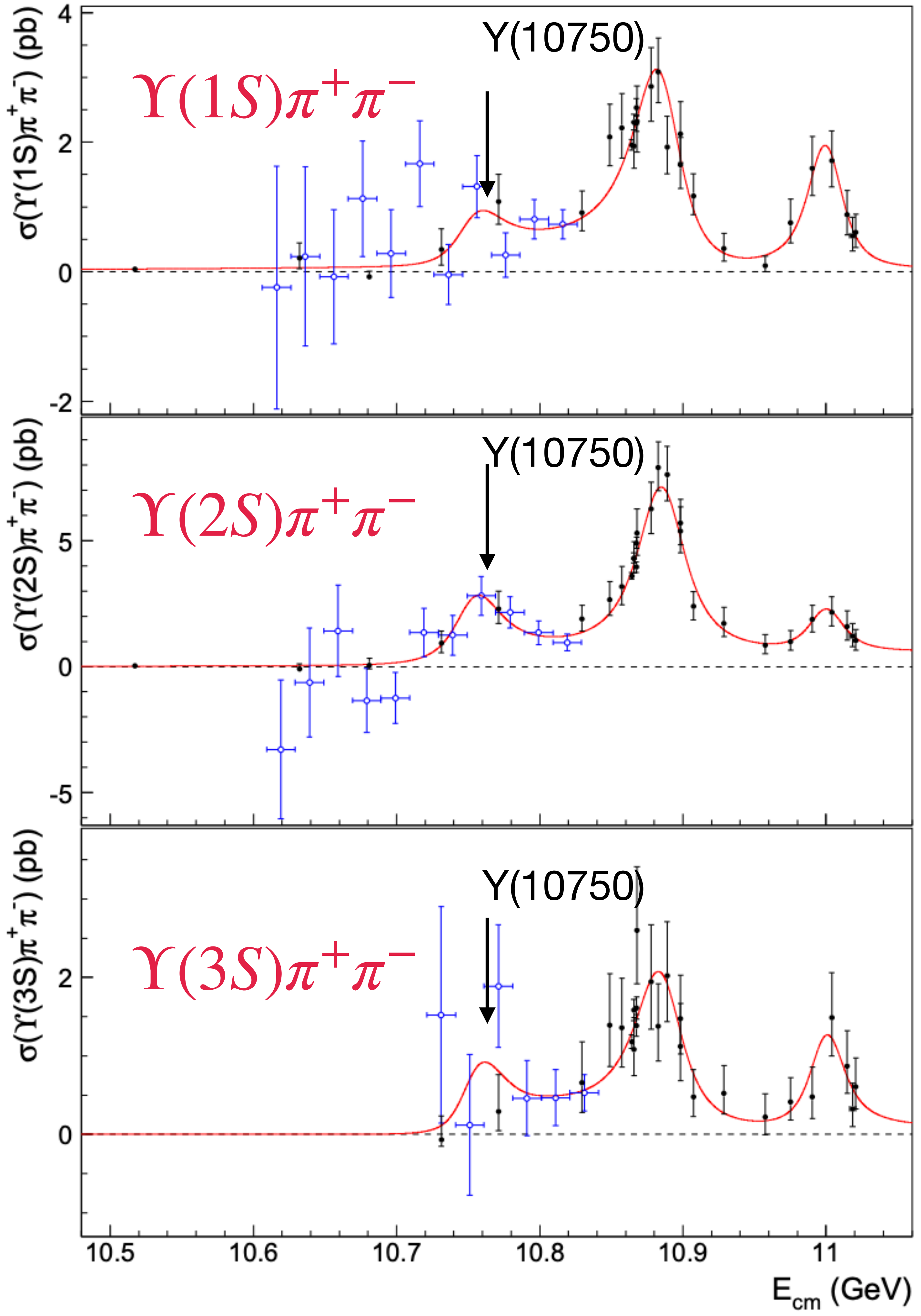
A resonant structure is observed with 5.2σ

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5 ^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9 ^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

- Varying $B\bar{B}$ cross sections

JHEP 06 (2021) 137



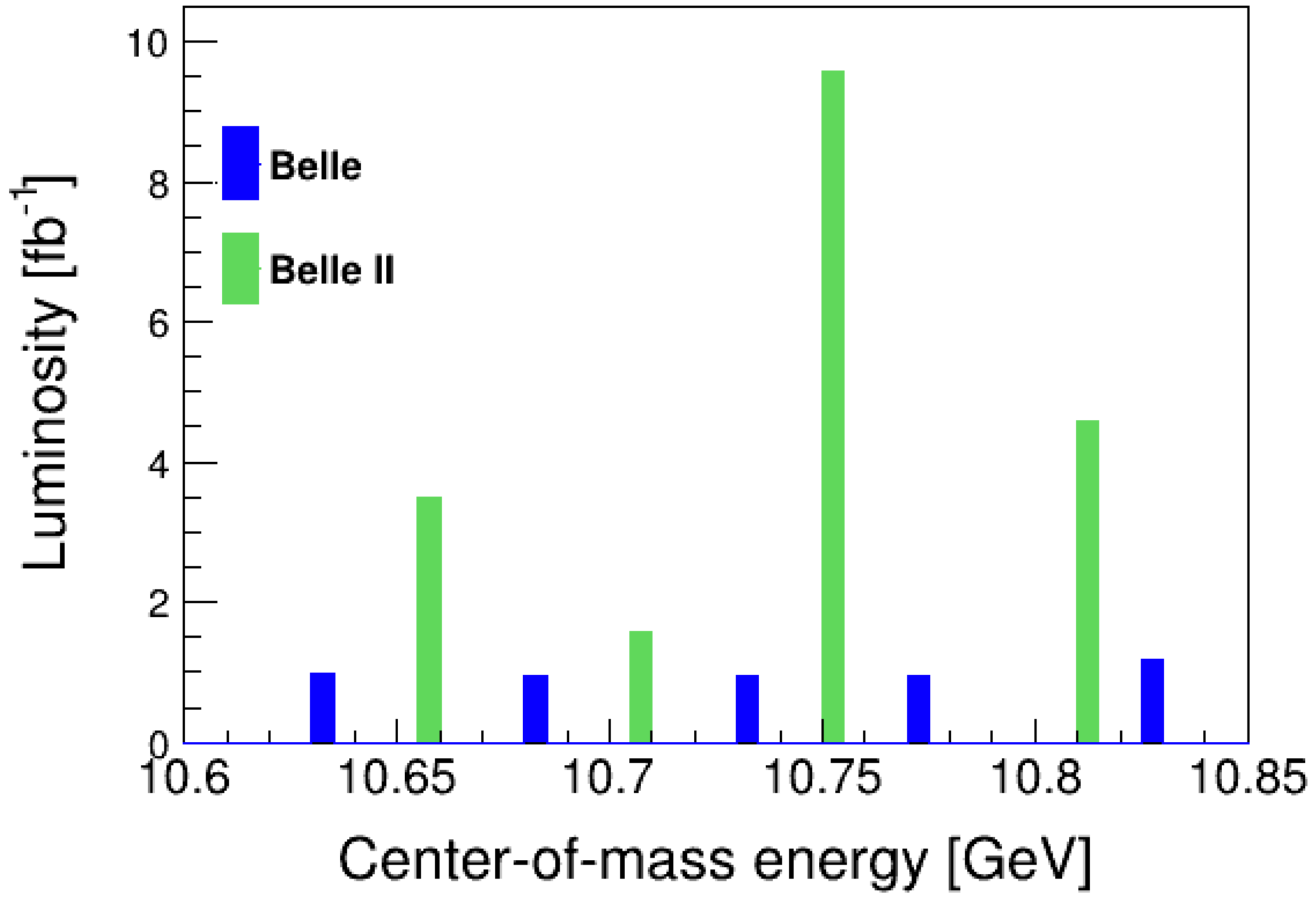


Interpretation of the Y(10750)

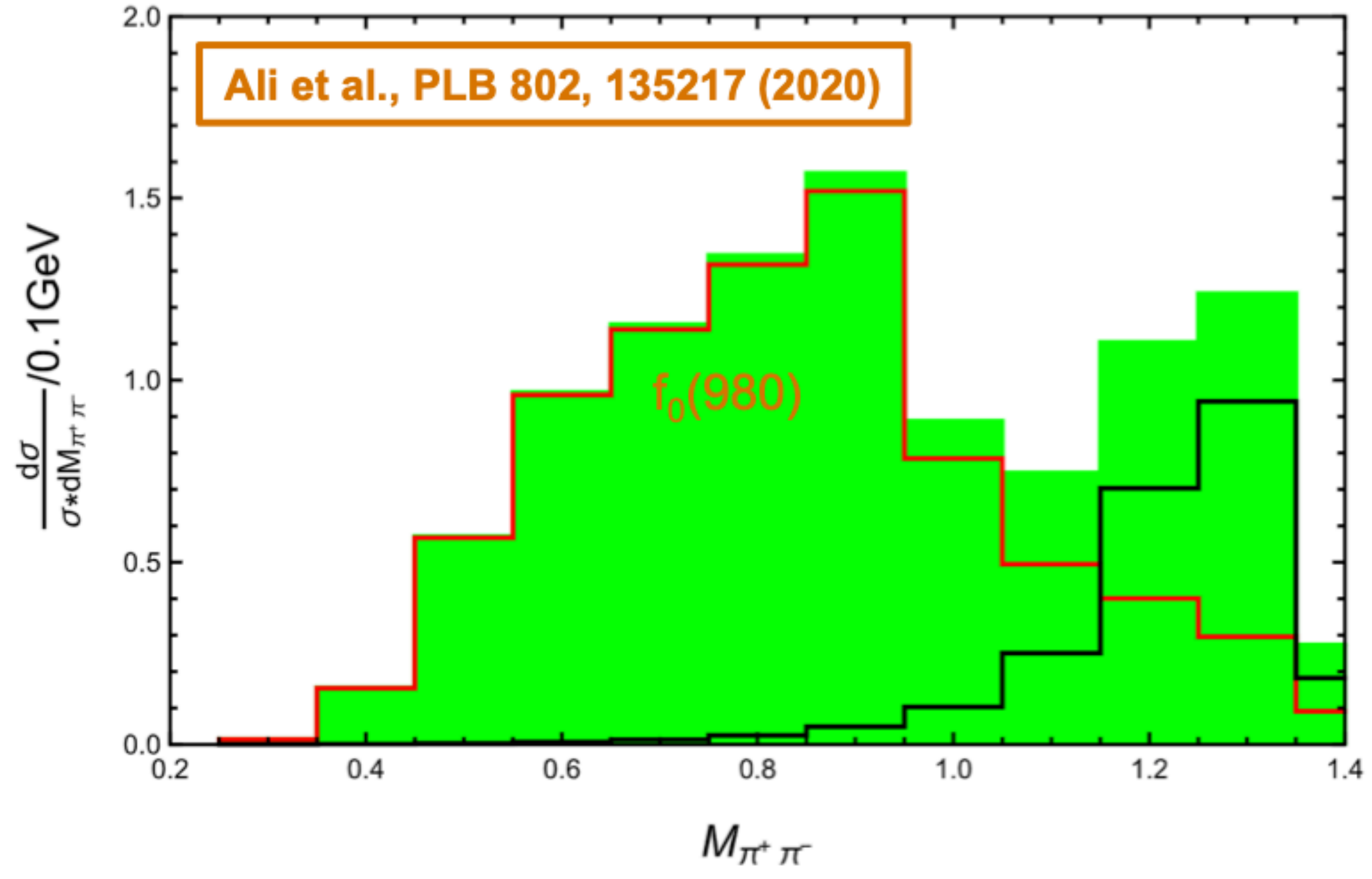
- D-wave bottomonium
  - B. Chen, A.L. Zhang, J. He, arXiv:1910.06065, Bottomonium spectrum in the relativistic flux tube model (3D)
  - Q. Li, M.S. Liu, Q.F. Lü, L.C. Gui, X.H. Zhong, arXiv:1905.10344, Canonical interpretation of Y(10750) and Y(10860) in the Y family (4D)
- $\bar{B}^{(*)}B^{(*)}$ dynamically generated pole
  - P. Bicudo, M. Cardoso, N. Cardoso, M. Wagner, arXiv:1910.04827, Bottomonium resonances with I=0 from lattice QCD correlation functions with static and light quarks
- Hybrid
  - J. T. Castellà, arXiv:1908.05179, Spin Structure of heavy-quark hybrids
- Tetraquark state
  - A. Ali, L. Maiani, A. Y. Parkhomenko, W. Wang, arXiv:1910.07671, Interpretation of Yb (10753) as a tetraquark and its production mechanism
  - Z.G. Wang, arXiv:1905.06610, Vector hidden-bottom tetraquark candidate: Y(10750)

A little data may tell a big story

- Data collected at 4 energy points around 10.75 GeV
- Physics goal: understand the nature of $Y(10750)$ energy region
- The mechanism of $Y(10750) \to \pi^+\pi^-\Upsilon(1S)$ in tetraquark interpretation:



Tetraquark $m_{\pi\pi}$ prediction



Mode	$\mathcal{B}(4q)$ (%)	$\mathcal{B}(b\bar{b})$ (%)
$B\bar{B}$	$39.3^{+38.7}_{-22.9}$	21.3
$B\bar{B}^*$	$\sim$0.2	14.3
$B^*\bar{B}^*$	$52.3^{+54.9}_{-31.7}$	64.1
$B_s\bar{B}_s$	-	0.3
$\omega\eta_b$	$7.9^{+14.0}_{-5.0}$	-
$\omega\chi_{bJ}$	-	$\sim$0.3
$f_0(1370)\Upsilon$	$0.2^{+0.6}_{-0.2}$	-
$\eta\Upsilon$	-	$\sim$0.2
$\eta'\Upsilon$	-	$\sim$0.06
ηh_b	-	$\sim$0.2

Selected predictions

Wang, CPC 12, 123102 (2019)
Ali et al., PLB 802, 135217 (2020)
Chen et al., PRD 101, 014020 (2020)
Giron & Lebed, PRD 102, 014036 (2020)
Li et al., EPJC 80, 59 (2020)
Liang et al., PLB 803, 135340 (2020)
Bicundo et al., PRD 103, 074507 (2021)
Li et al., arXiv:2106.14123 (2021)

Summary

- We are at the beginning of a long program of quarkonium physics
  - Many opportunities for world-leading physics
- Early measurements display the foundations we will build upon.
- The legacy of Belle&Babar inspire us; LHCb&BESIII will push us as well.
  - Expectation of great achievement in hadronic spectroscopy
    - Dedicated study of known XYZ states
    - Search for new particle via ISR, two photon production, double charmonium production…
    - Bottomonium search through $\Upsilon(nS)$
    - etc…