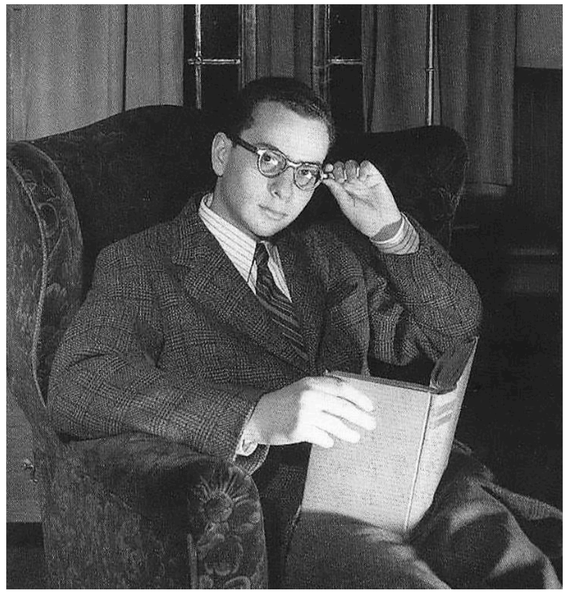
Quarkonium at Belle II

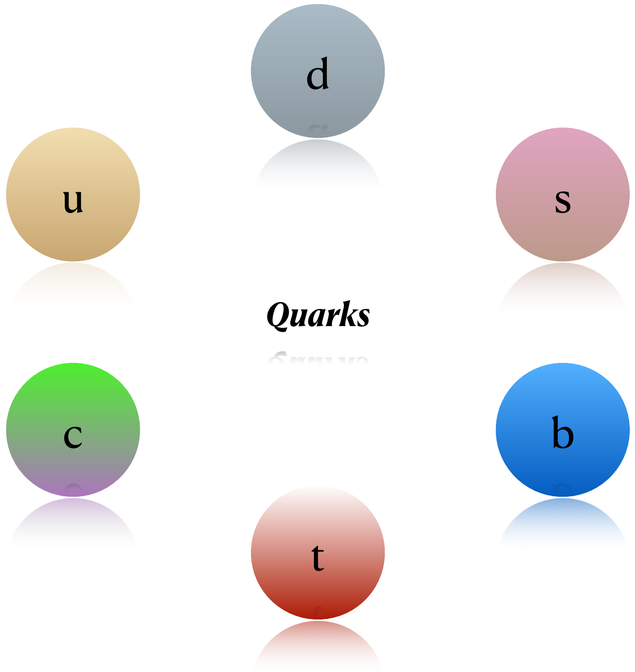
Speaker: Junhao Yin, on behalf of Belle II Collaboration

Junhao Yin, July 2021

outline

- Introduction
  - Quarkonium and the exotics
  - Questions
- The Belle II experiment
- Searching for exotics on Belle II
  - Re-discoveries with “early Phase III data”
  - Prospect
- Summary





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

Hadrons with more than 3 quarks were predicted.

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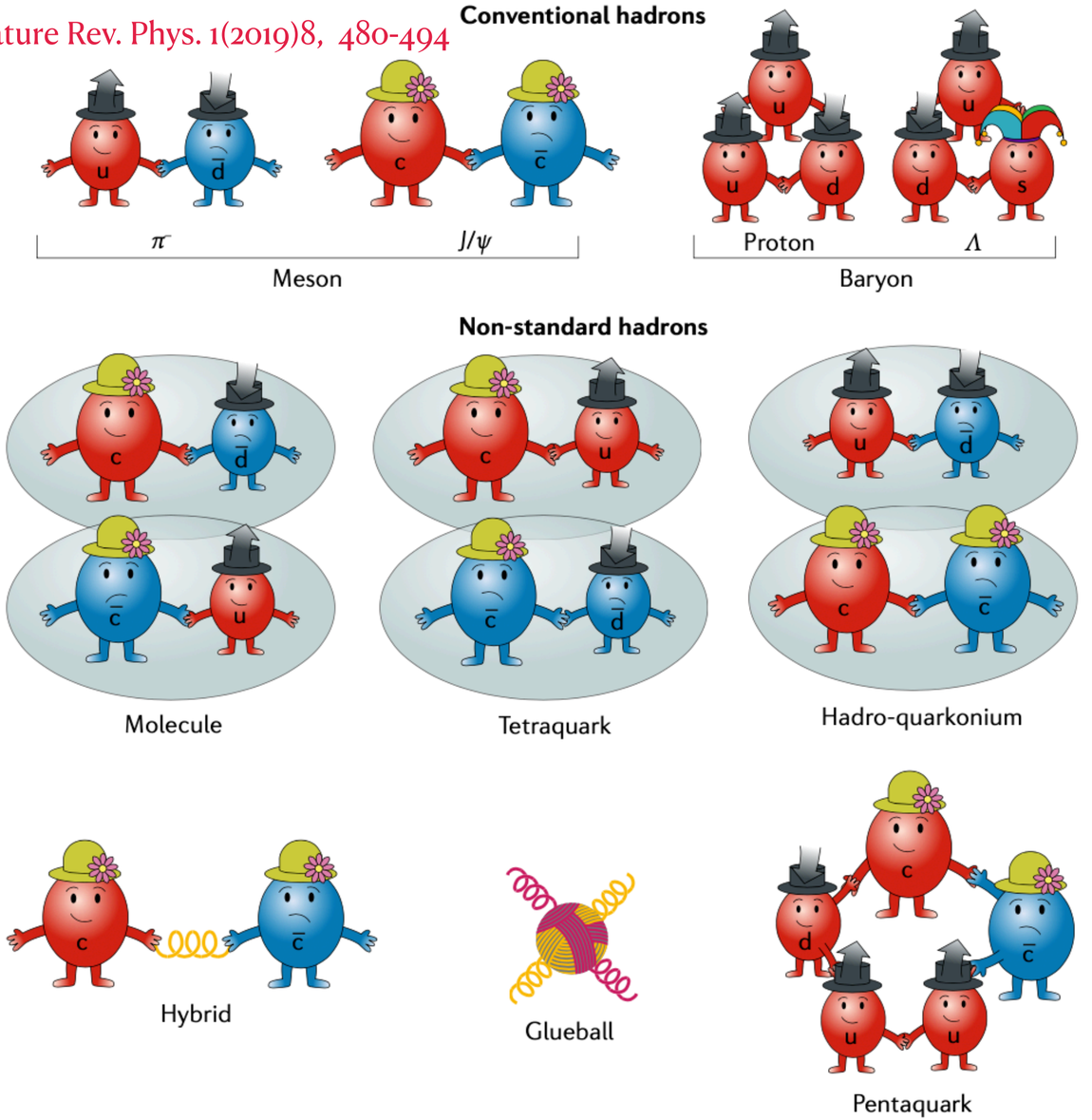
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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



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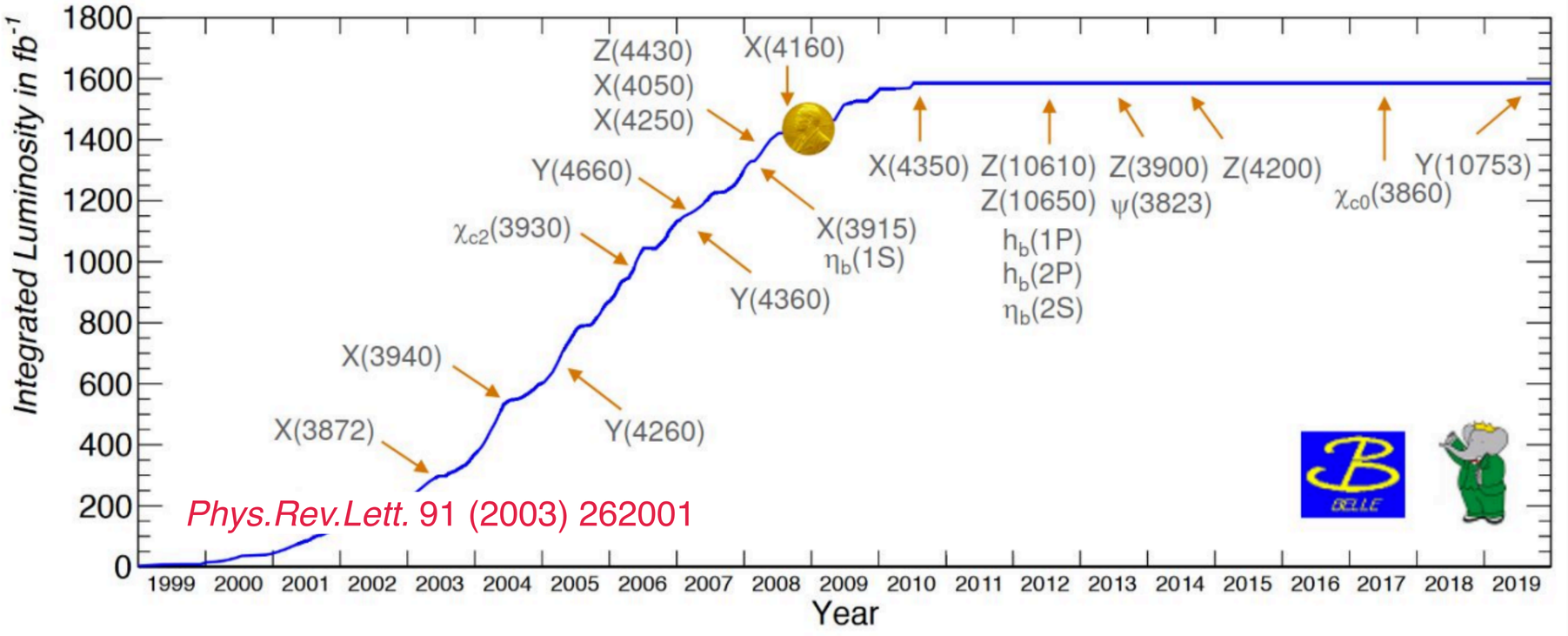
No solid evidence until 2003, the observation of $X(3872)$
Since then, we have a golden era on the discovery of the exotic state.



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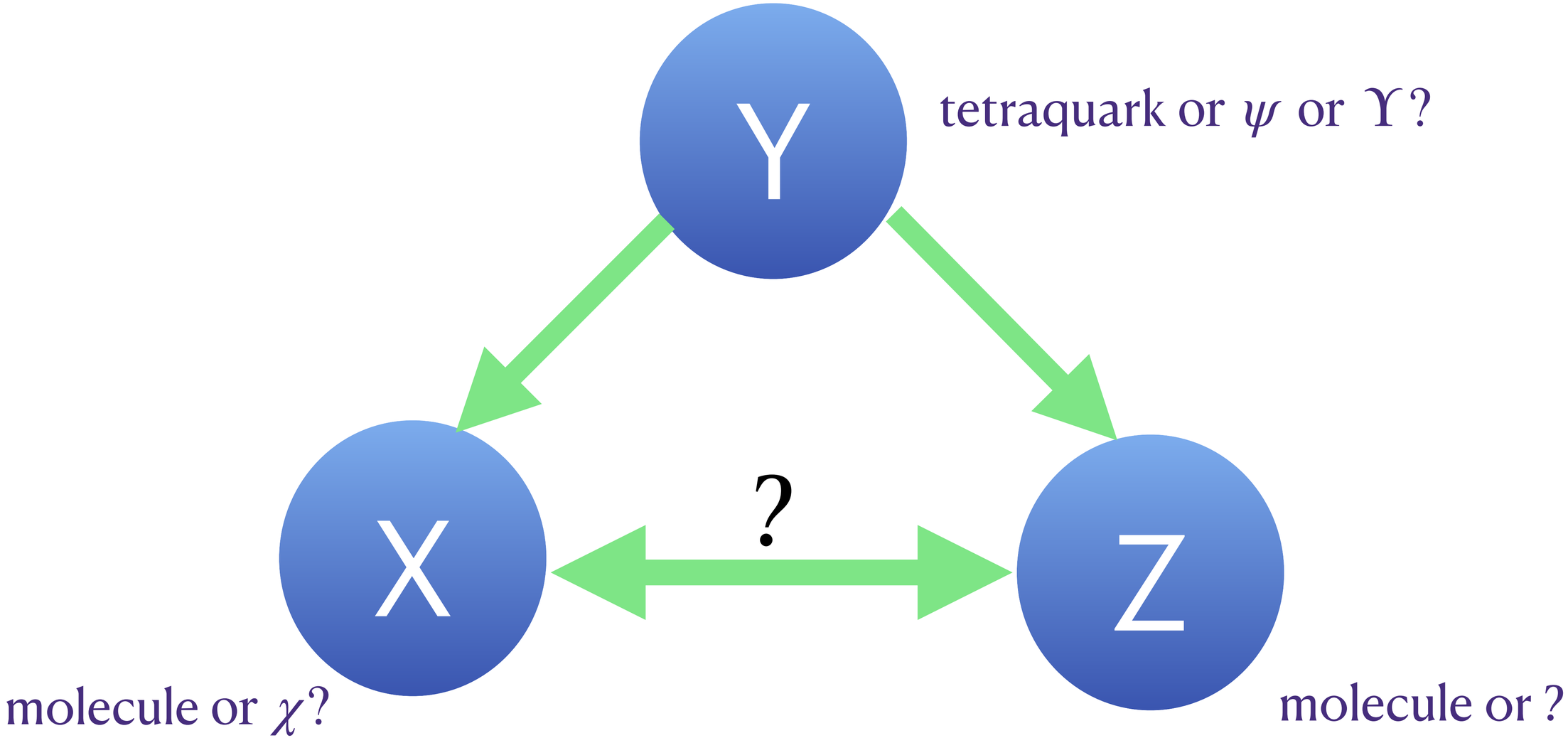
What are they?



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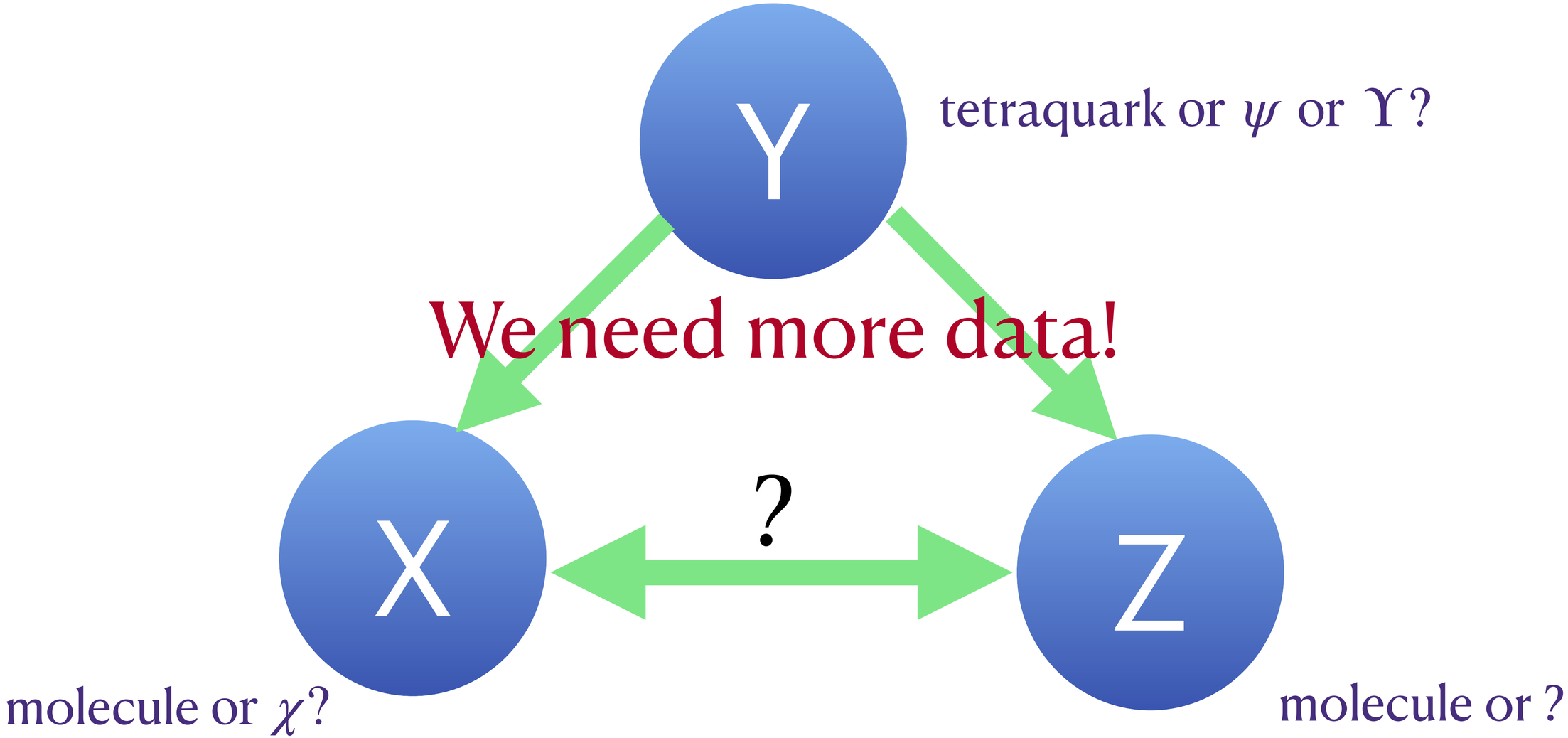
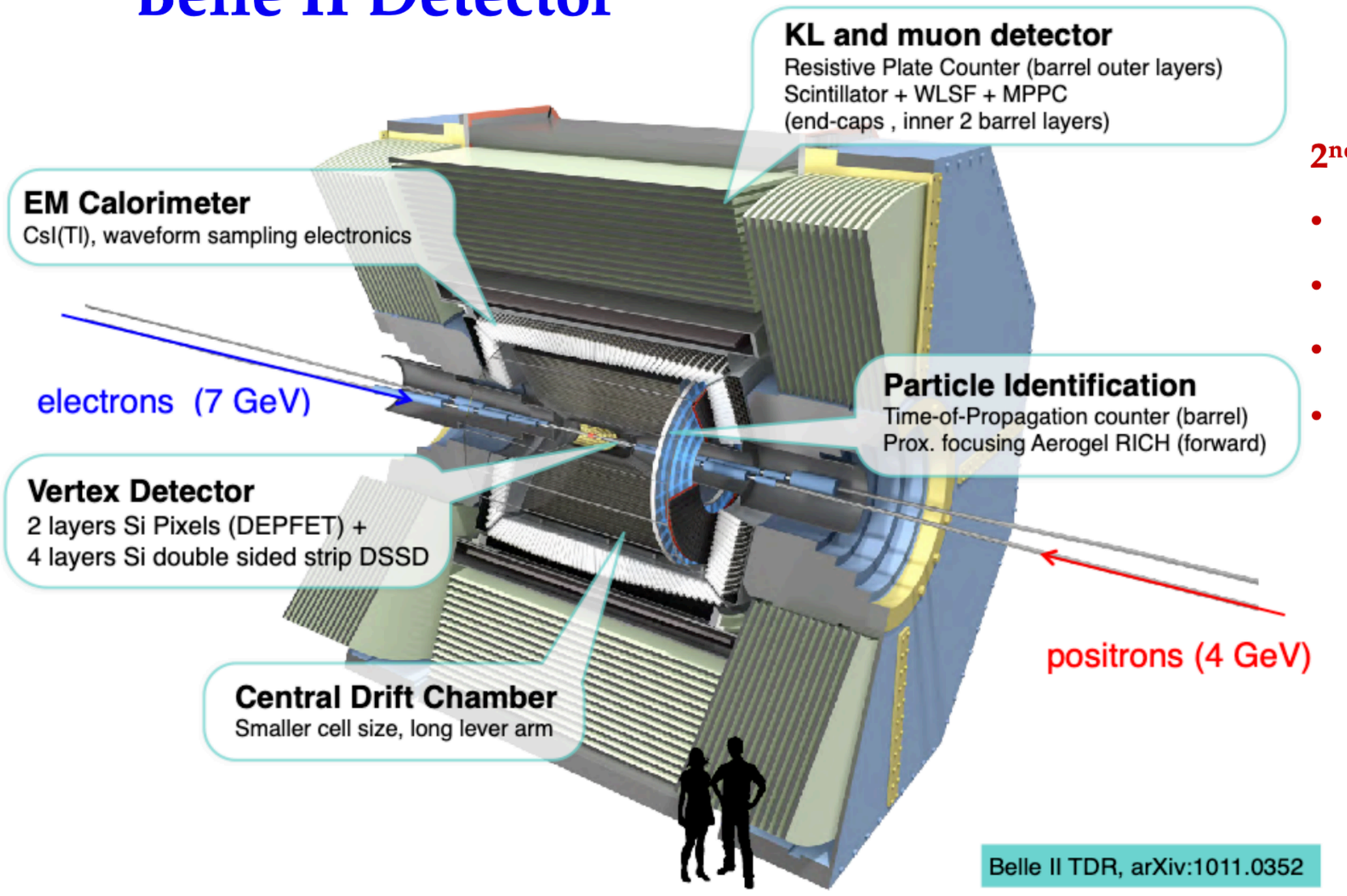
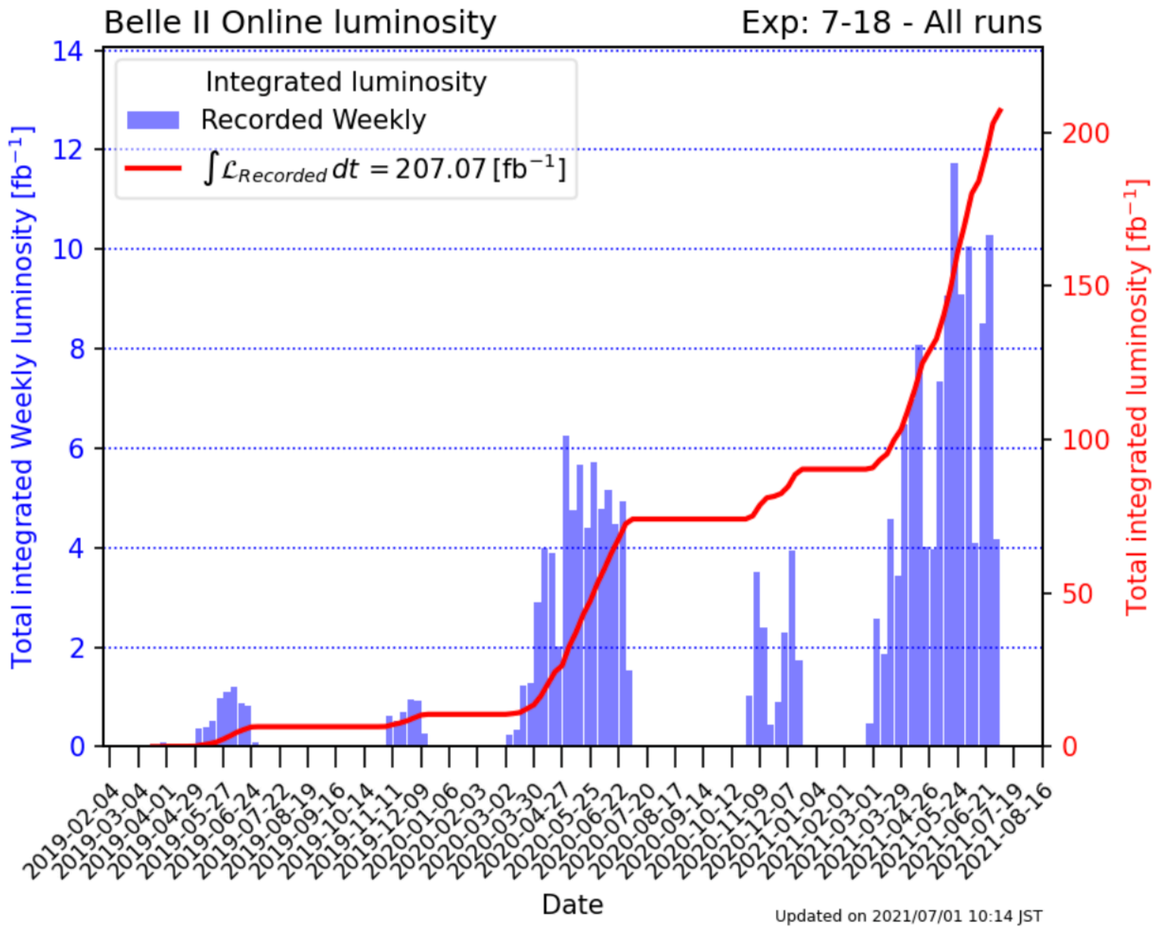


Belle II Detector



2nd Generation B-Factory Detector

- High-luminosity performance
- Much improved vertexing
- Novel Cherenkov PID (TOP)
- Other upgrades…



Corona-pandemic affected activity at KEKB

BUT

we are very active and data taking is ongoing!

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

We reached 200 fb^{-1} !

Luminosity record: $3.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Goal: $65 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Will accumulate around 50 ab^{-1} around 2031.

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X(3872)

Most concerned particle in charmonium sector!

- Highest citation in Belle!
- Still many puzzles.
  - decays ratios?
  - lineshape?
  - Real nature?

Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays #1

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)

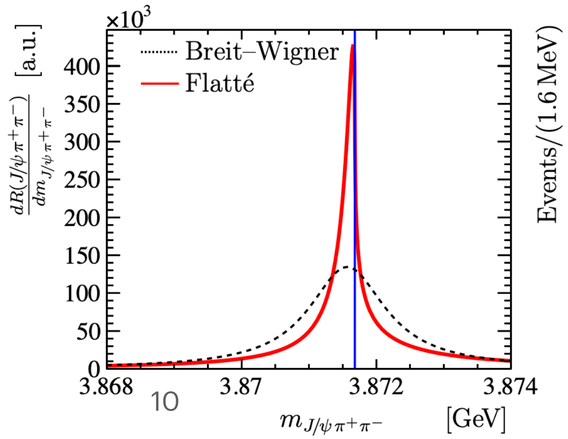
Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

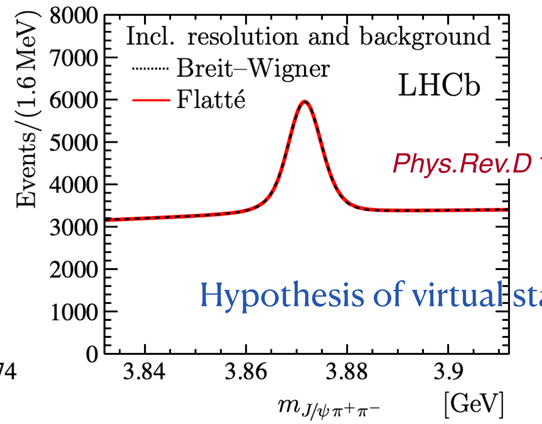
pdf links DOI cite 1,953 citations

Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \to$ unknown	$(31.9^{+18.1}_{-31.5})\%$

Strong coupling to $D^0\bar{D}^{*0} + c.c.$

Phys.Rev.D 100 (2019) 9, 094003

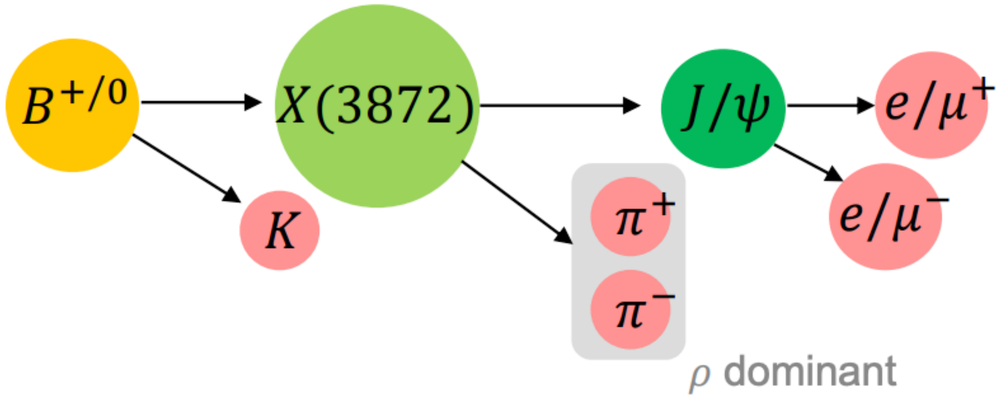


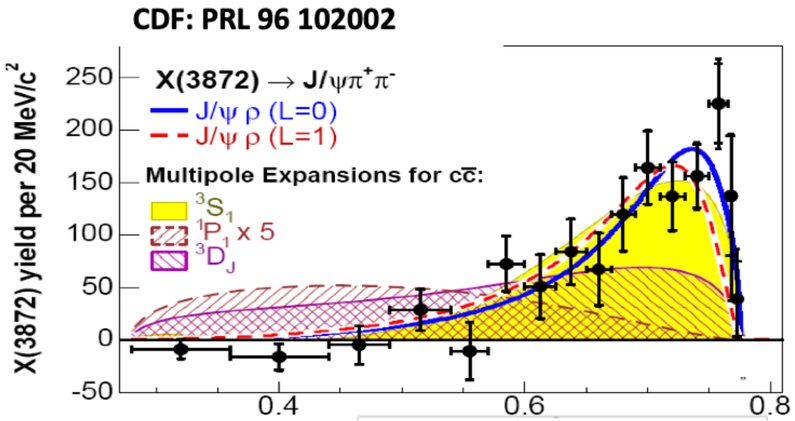


Phys.Rev.D 102 (2020) 9, 092005

Hypothesis of virtual state is not 100% rejected

Rediscovery 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}, $|\Delta E|$

$M(\pi^+\pi^-) > M(\pi^+\pi^- l^+l^-) - m(J/\psi) - 0.150\ \mathrm{GeV/c^2}$

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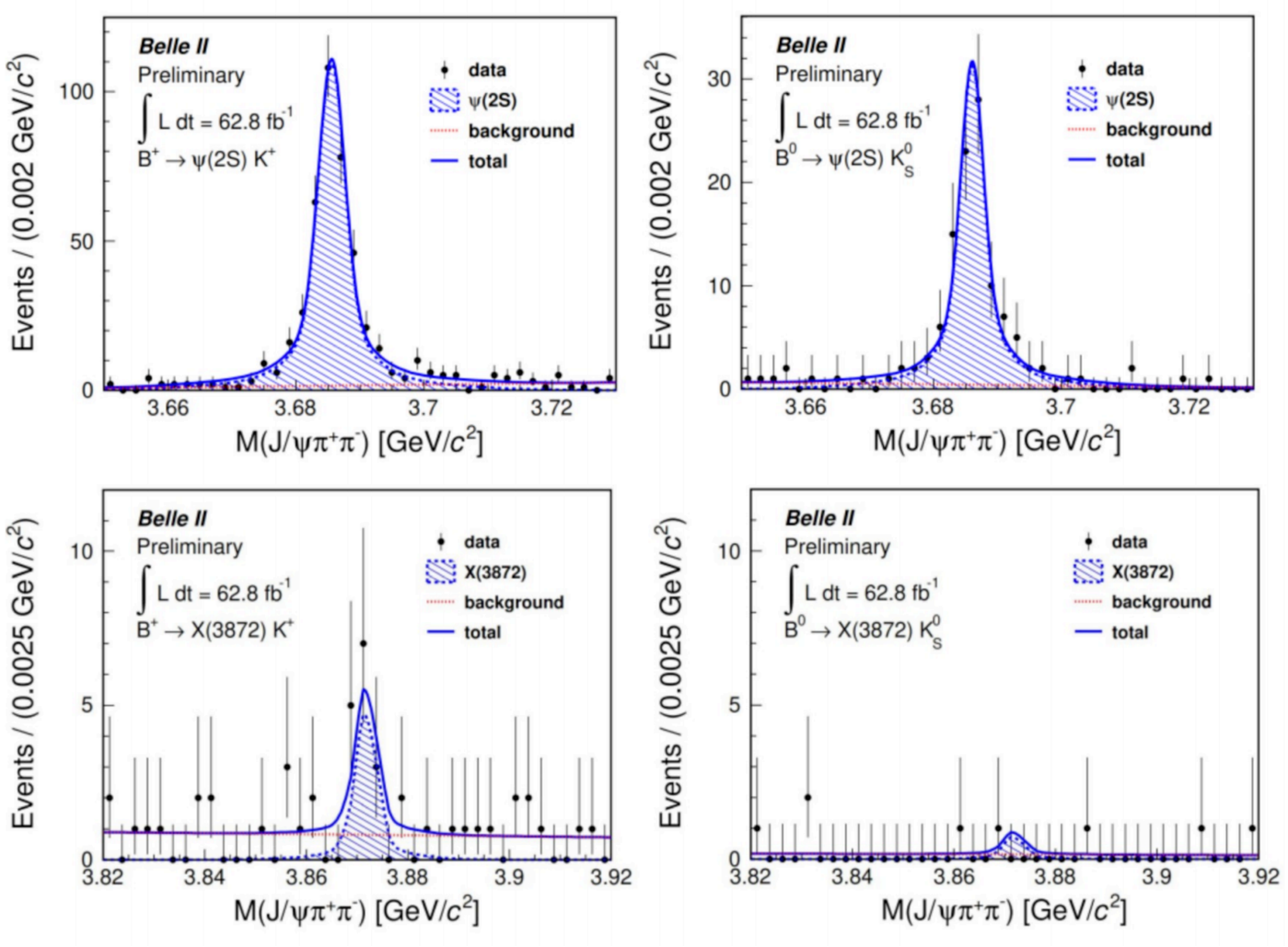
Rediscovery of $X(3872)$



Significant $\psi(2S)$
A good control sample

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

First $X(3872)$ at Belle II:

$N_{\text{sig}} = 14.4 \pm 4.6$

Evidence of $X(3872)$ with 4.6σ

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ISR preliminary studies

Goal:

- Exotic states with $J^{PC} = 1^{--}$ and their decays

assumed errors

Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$

50 ab^{-1}

10 ab^{-1}

Advantage:

- ISR is a “free energy scan”!
- Reach a really low energy region

Competition:

- BESIII: > 0.5 fb^{-1} each point $\in [4.13, 4.70]$ GeV

Need really huge dataset!!

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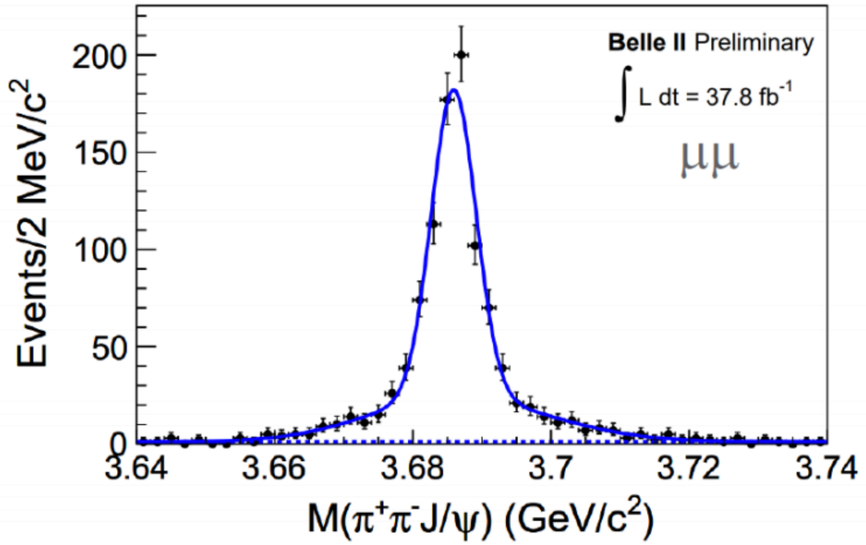
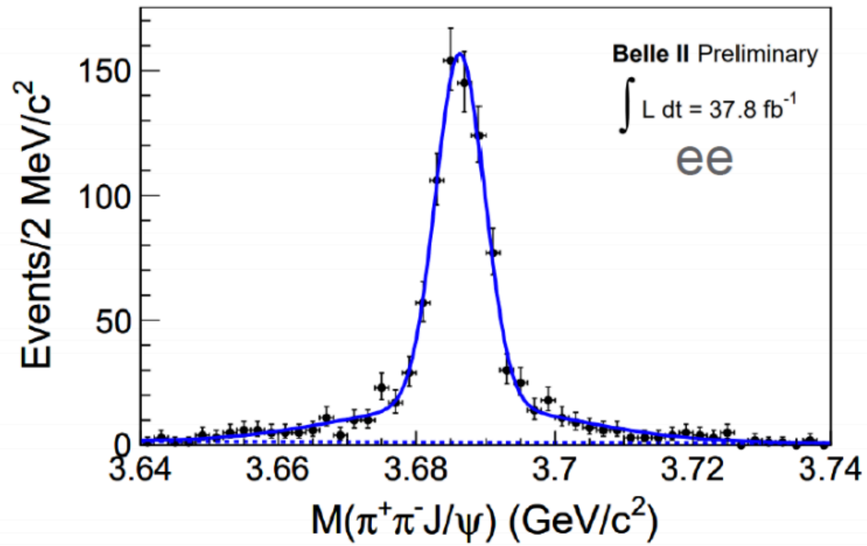
ISR preliminary studies

- $e^+e^-\gamma_{ISR} \rightarrow \pi^+\pi^- J/\psi(\ell^+\ell^-)$ 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}





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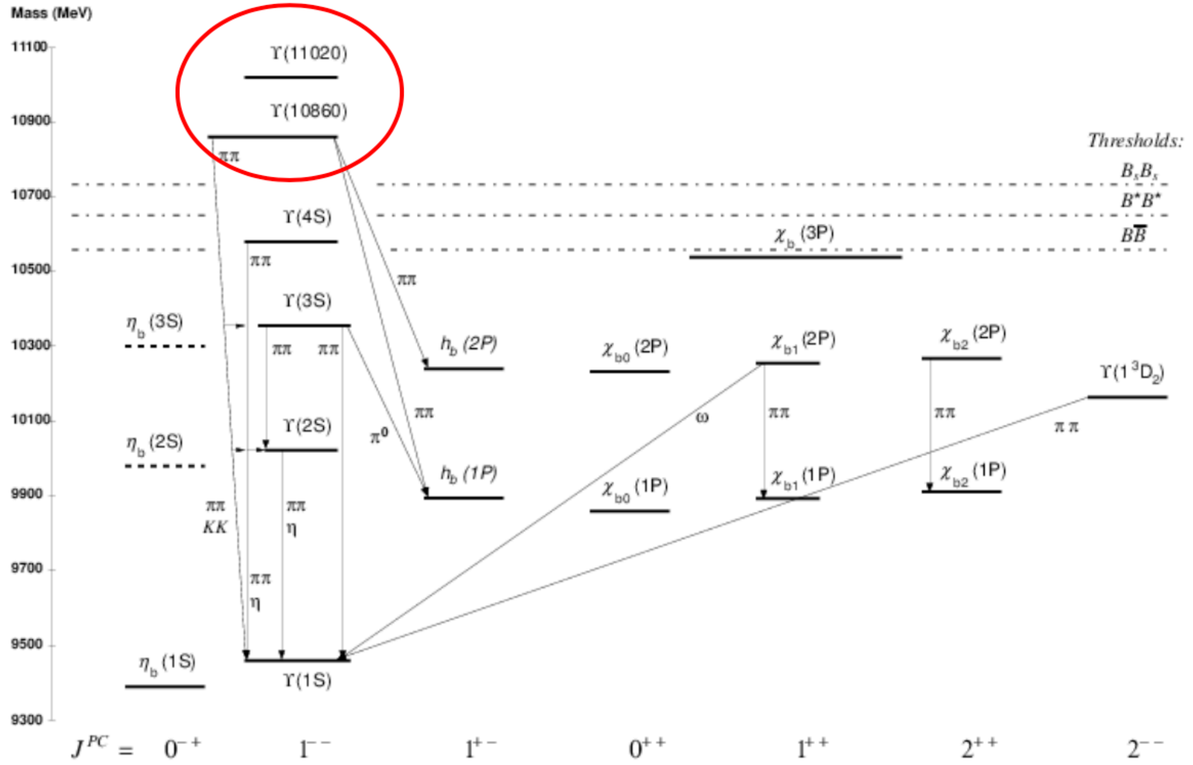
Bottomonia at Belle II

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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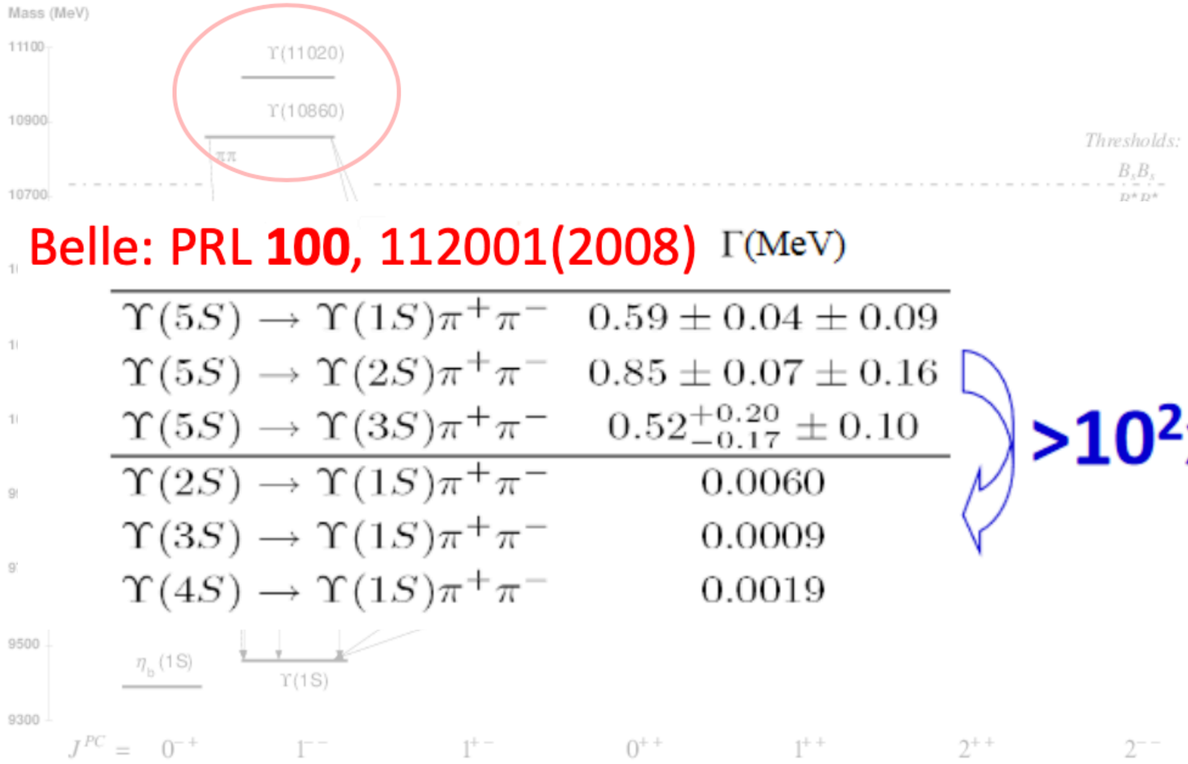

Belle: PRL **100**, 112001(2008)

	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

>10^2x

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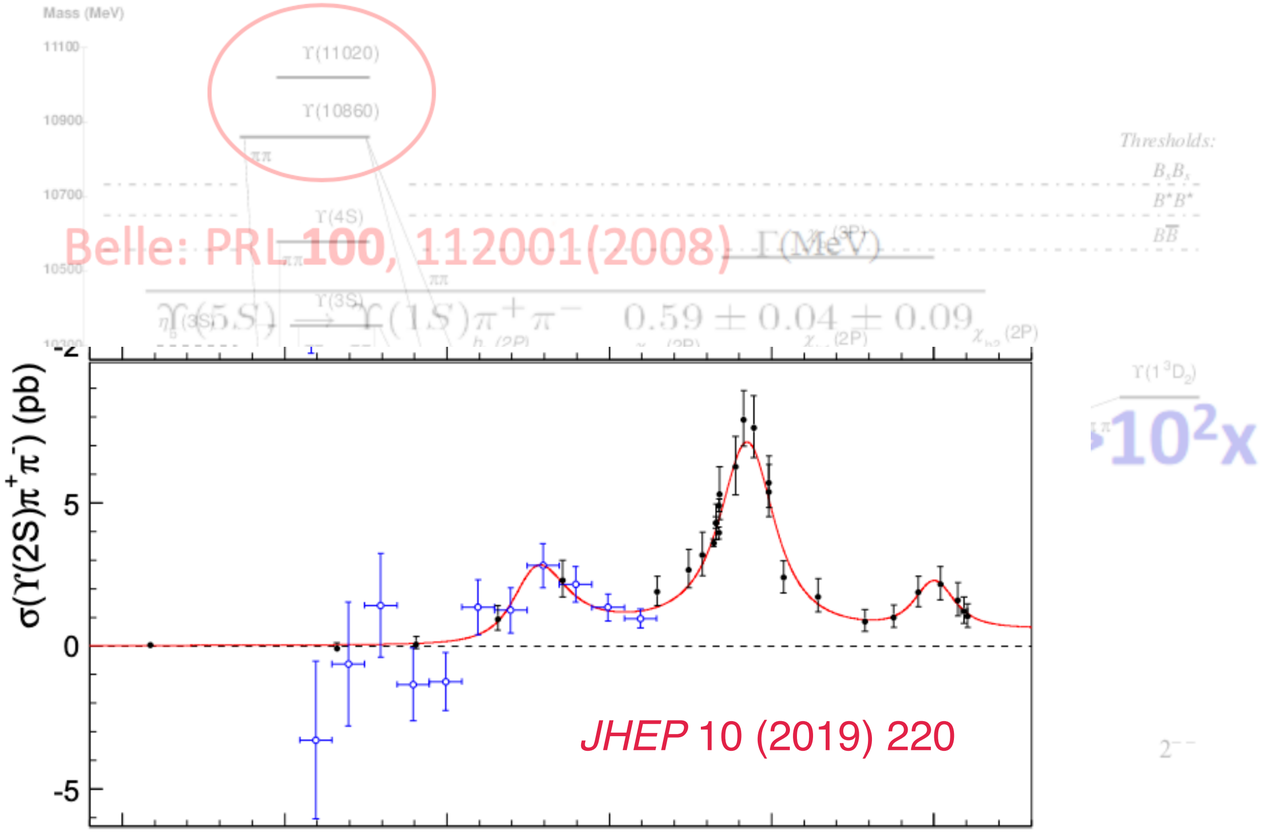

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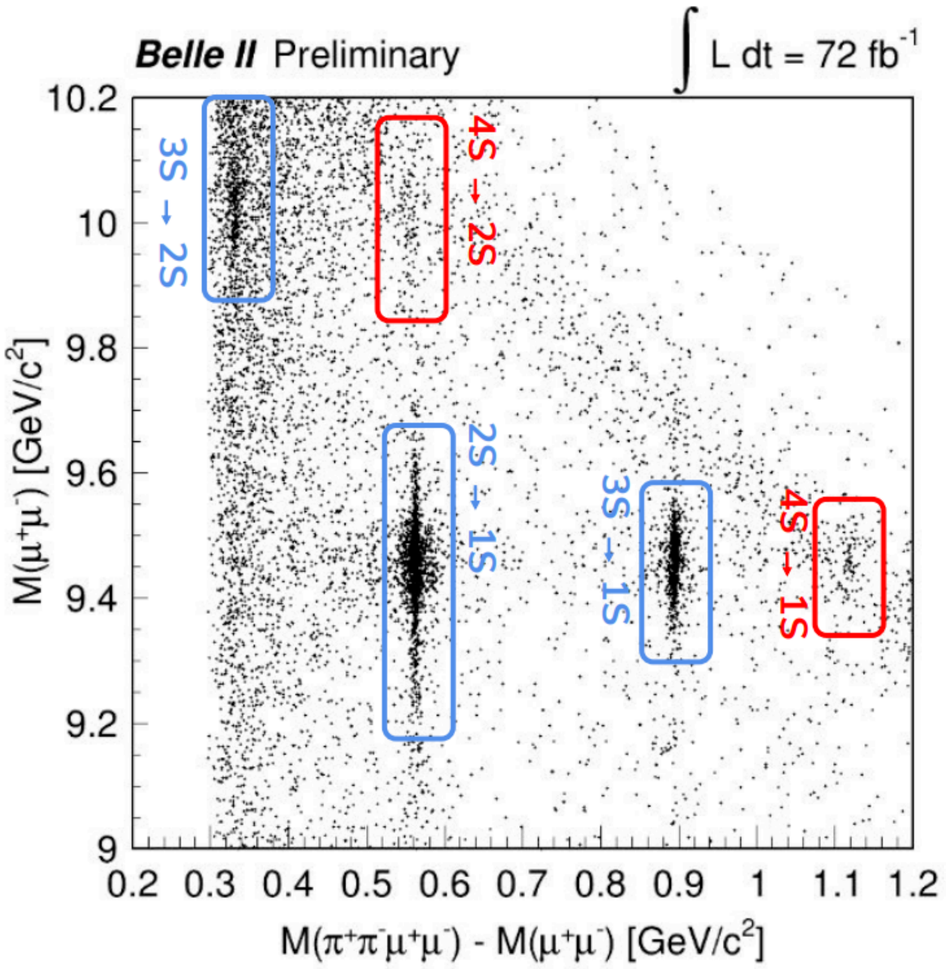
Dipion transition among bottomonia



Study $e^+e^- \to \pi^+\pi^- \mu^+\mu^-$ (+γ undetected)

- **$\Upsilon(4S) \to \pi^+\pi^- \Upsilon(nS)$**
- $e^+e^- \to \gamma_{ISR}\, \Upsilon(mS)$, $\Upsilon(mS) \to \pi^+\pi^- \Upsilon(nS)$

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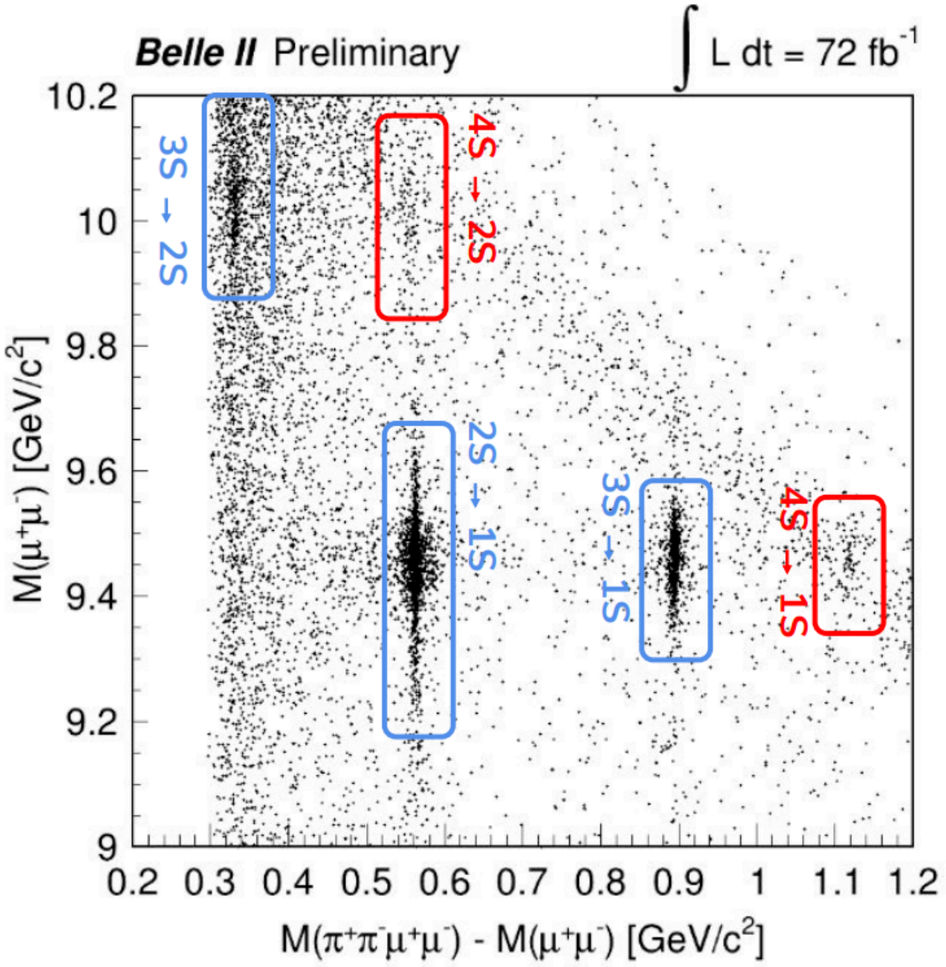
Dipion transition among bottomonia



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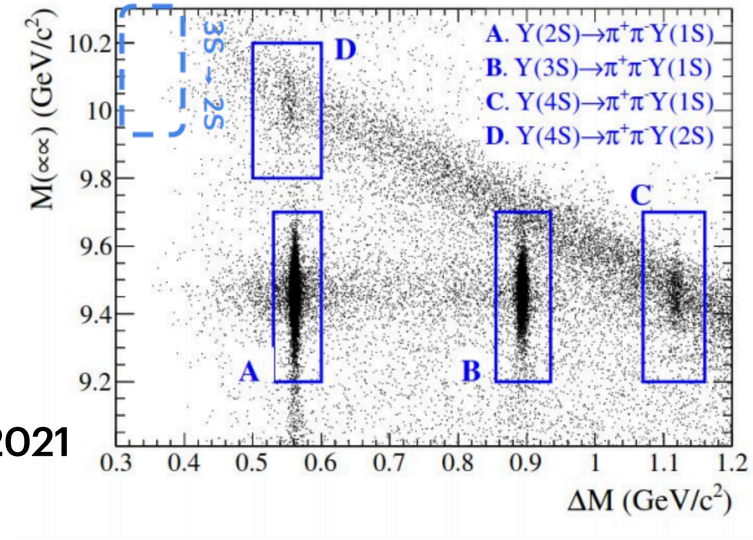
Compared with Belle, 496 fb^{-1}



Belle

PRD 96 (2017) 5, 052005

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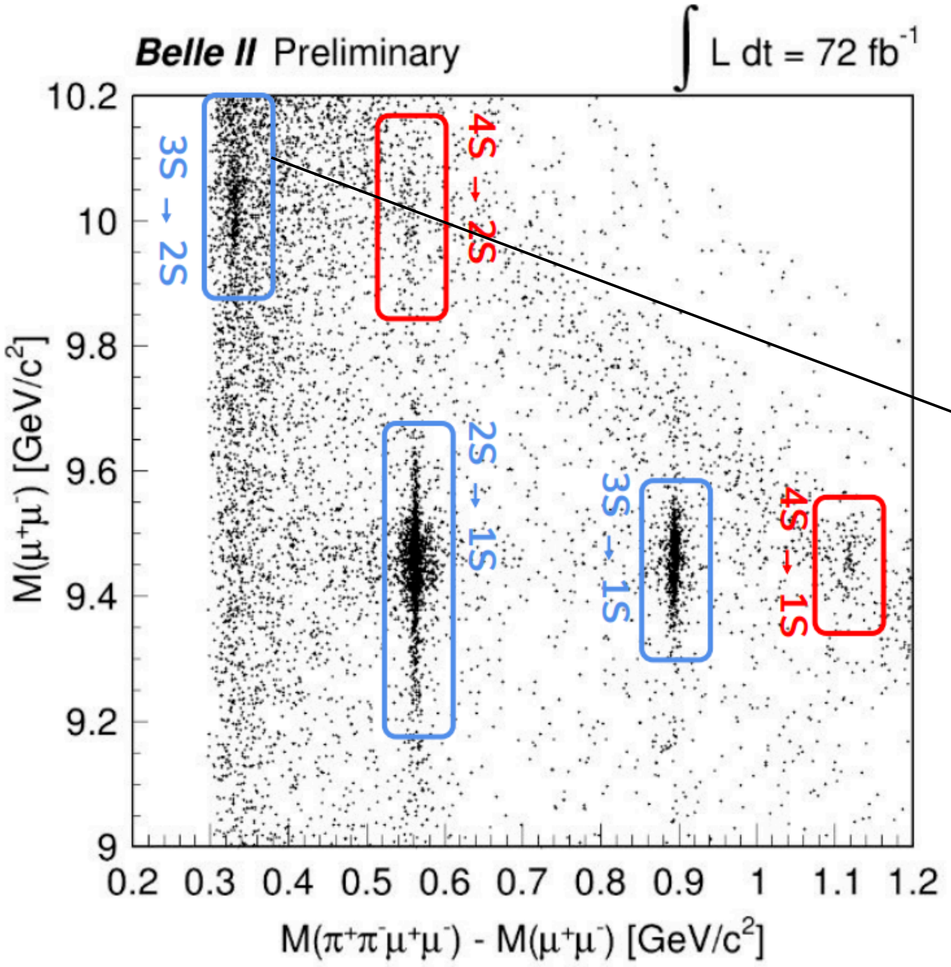
Dipion transition among bottomonia



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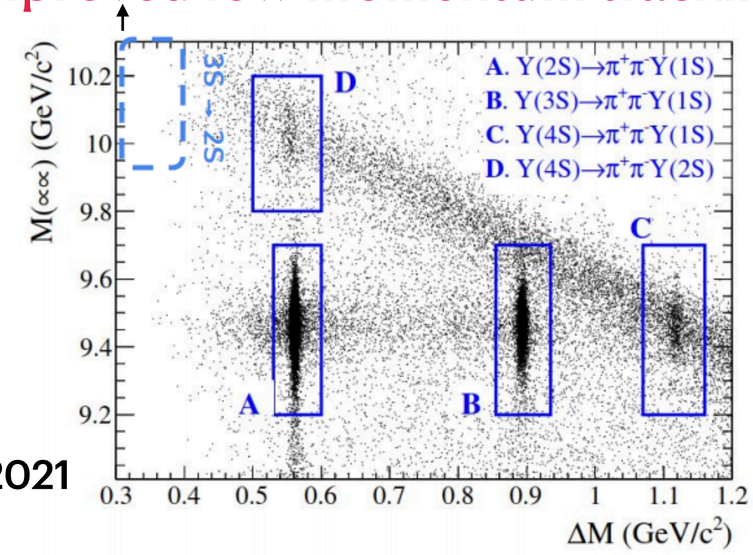
Compared with Belle, 496 fb^{-1}

improved low momentum tracking



Belle

PRD 96 (2017) 5, 052005

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Near term plan

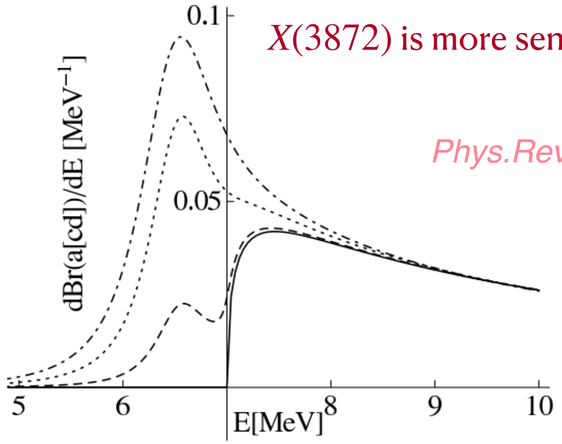
Many analysis already ongoing, just waiting for more data!

Charmonium

- X(3872) lineshape combining Belle and Belle II dataset
- Full amplitude analysis of B → charmonium modes
- Inclusive B → K ($c\bar{c}$)

Bottomonium sector

- Dalitz analysis of Υ(4S) → $\pi^+\pi^-$ Υ(nS)
- h_b(1P) and η_b(1S) exclusive decays



$X(3872)$ is more sensitive to $D^0\bar{D}^{*0} + c.c.$

Phys.Rev.D 81 (2010) 094028

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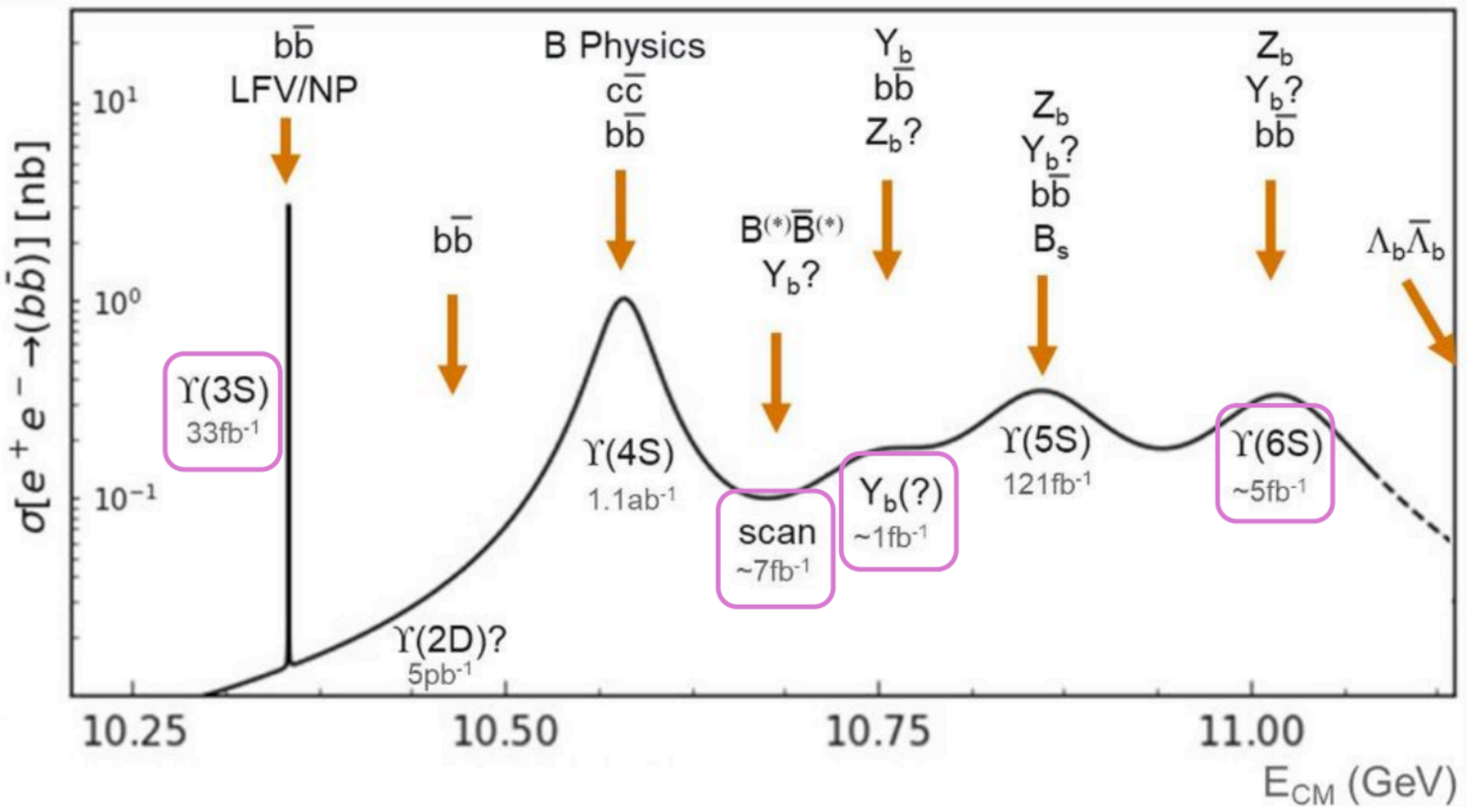
Outside Y(4S) even small data sets can make a difference

Currently available data sets in the bottomonium region



Data taken around 10.750 GeV is approved!

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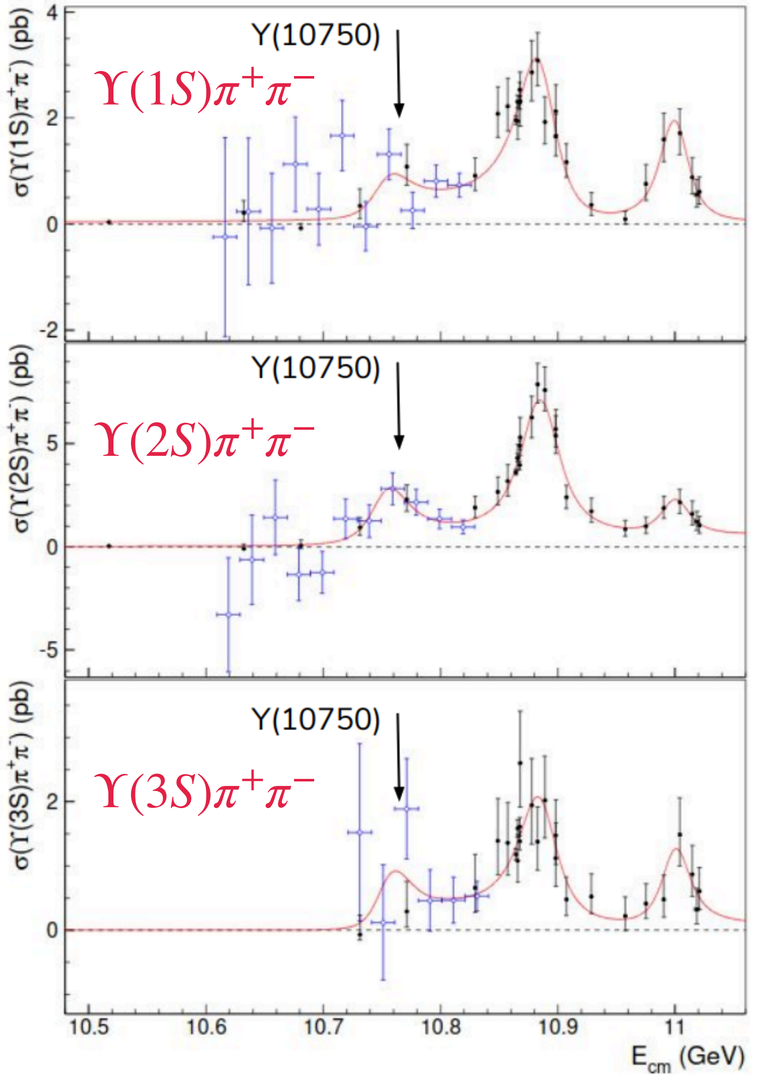
Why it's important?

JHEP10(2019)220 (*Belle*):

- "High-stat" scan points: 1 fb^{-1} each
- 1 point "on resonance"
- 2-3 points in the region of interest
- Significance: 5.2 σ

Parameters:

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



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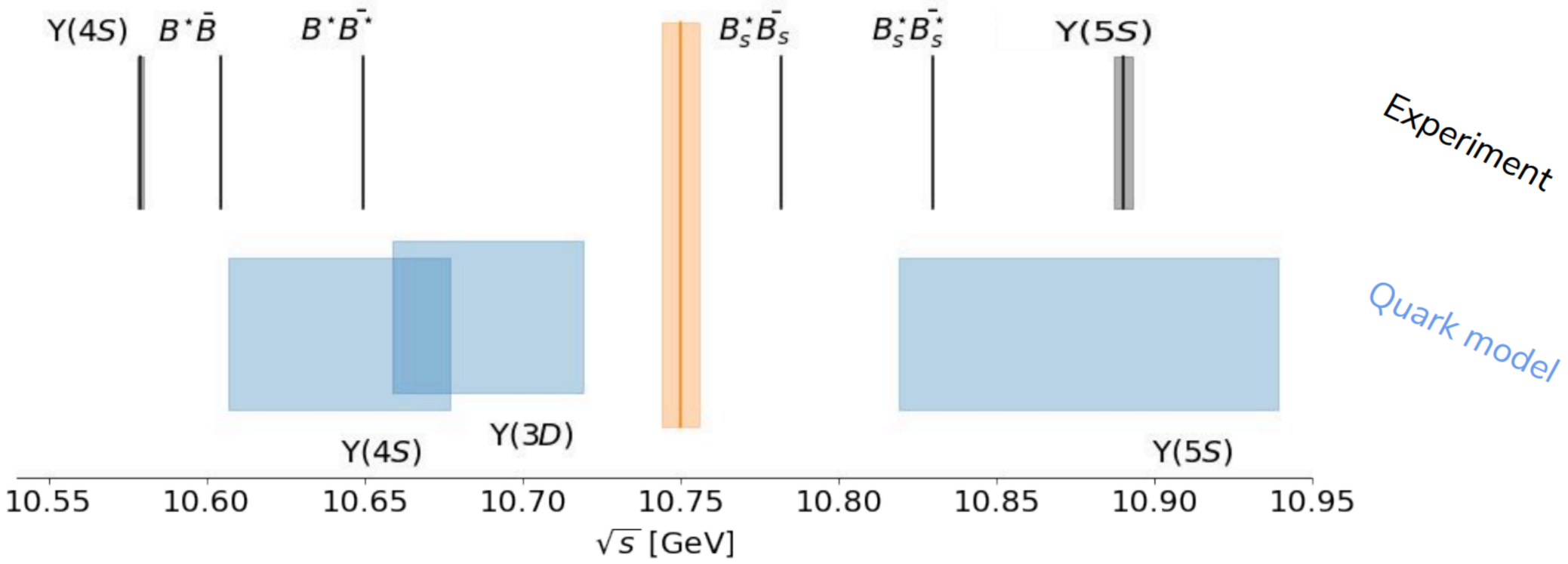
Why it's important?

- Unlikely to be a molecule as it's far from any S- threshold
- No direct matching to conventional states (but may be an S-D mixing?)



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Summary

- We are at the beginning of a long program of quarkonium physics
  - Many opportunities for world-leading physics
- Rediscoveries display the foundations we will build upon.
- The legacy of Belle&Babar inspire us; LHCb&BESIII will push us as well.
  - 50 ab^{-1} integrated luminosity at Belle II in around 2031.
  - 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...

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