Exotic States at Belle (II) Experiment

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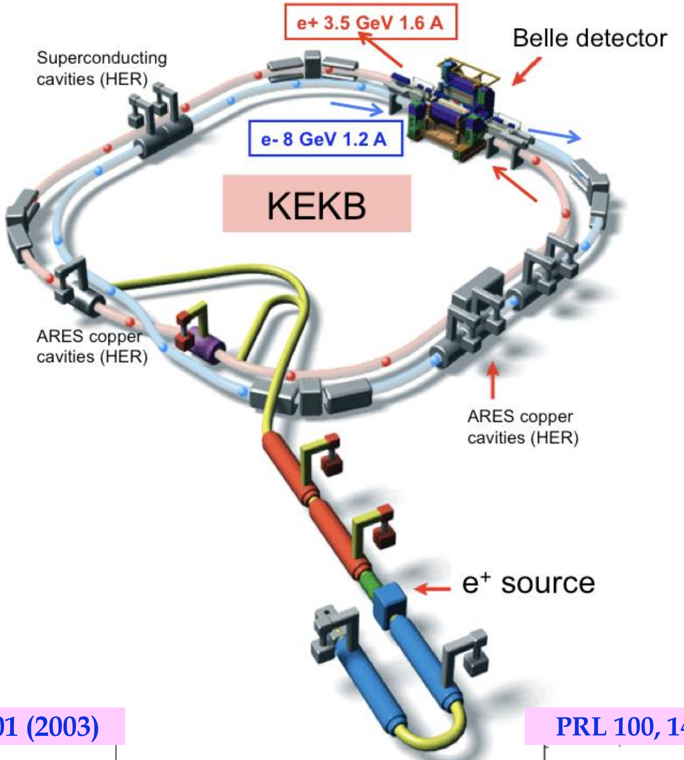
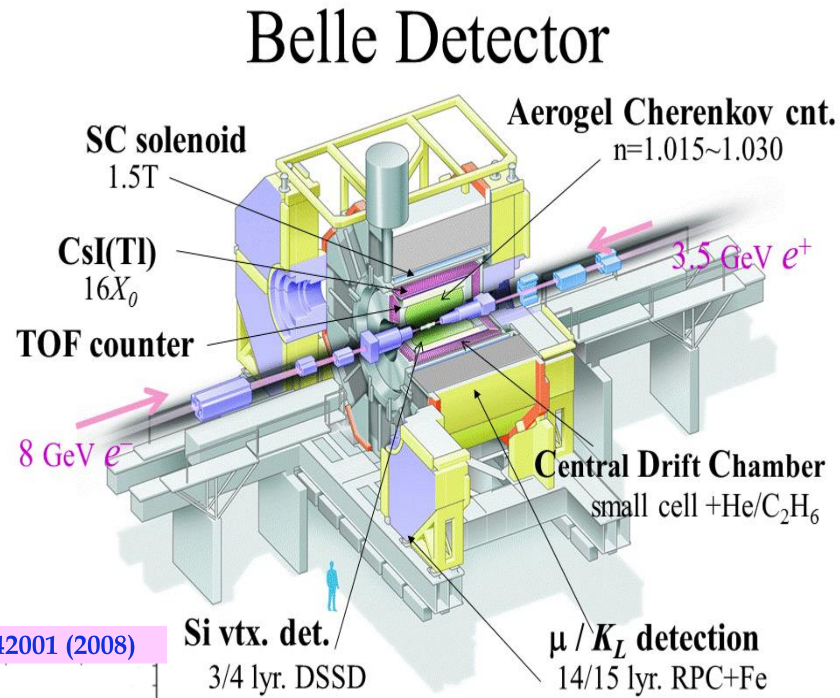
EIC-Asia workshop 2024/07/03

KEKB and Belle

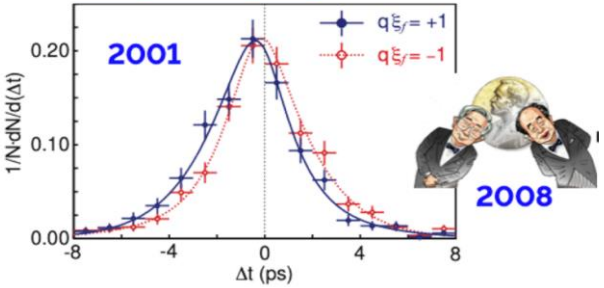
Peak luminosity: $2.11 \times 10^{34} \mathrm{cm}^{-1}\mathrm{s}^{-1}$
Integrated luminosity (~980 fb^{-1} in total):
$\Upsilon(5S)$: 121 fb^{-1}, $\Upsilon(4S)$: 711 fb^{-1}, $\Upsilon(3S)$: 3 fb^{-1},
$\Upsilon(2S)$: 25 fb^{-1}, $\Upsilon(1S)$: 6 fb^{-1}, continuum: 90 fb^{-1}



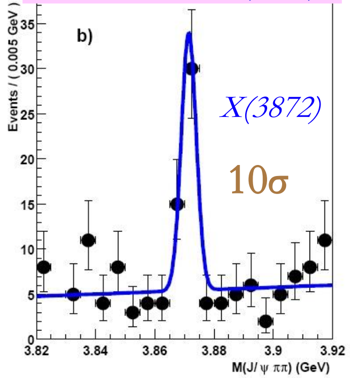


$\sqrt{s} \sim 10.6$ GeV

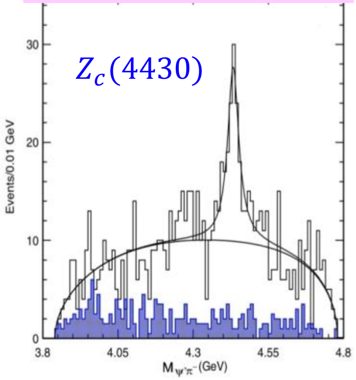
PRL 87, 091802 (2001)



PRL 91, 262001 (2003)

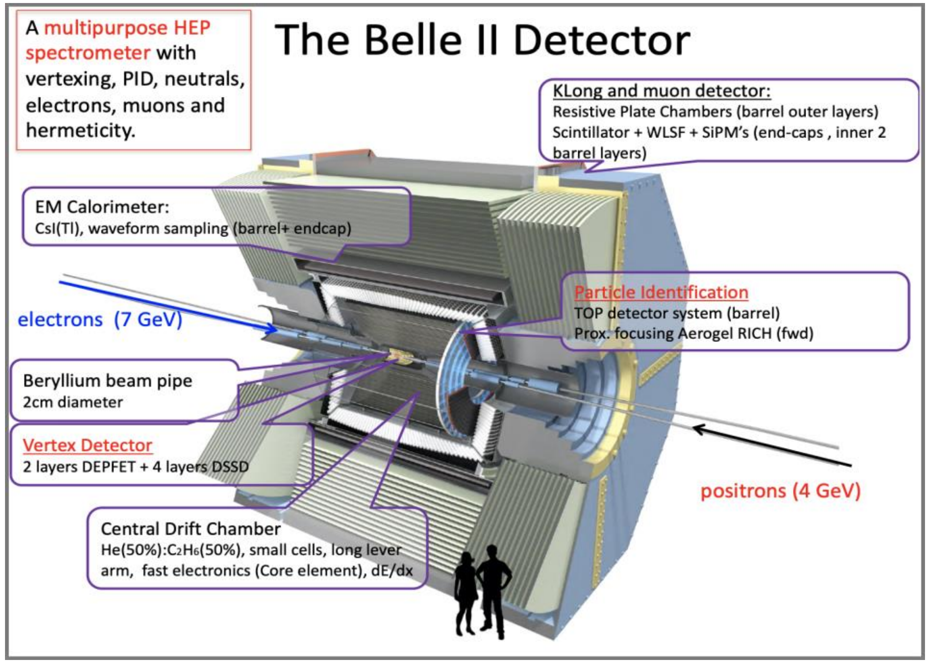


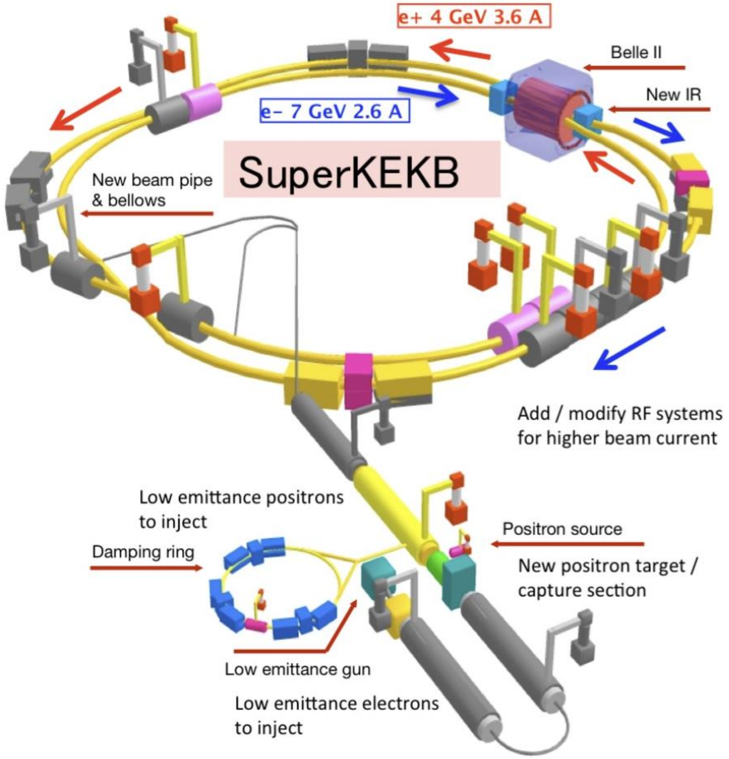
PRL 100, 142001 (2008)

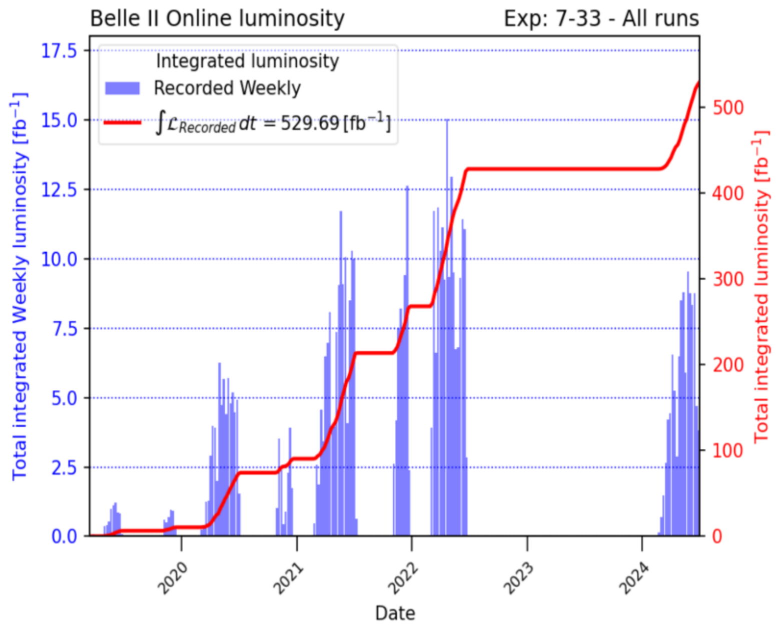


SuperKEKB and Belle II

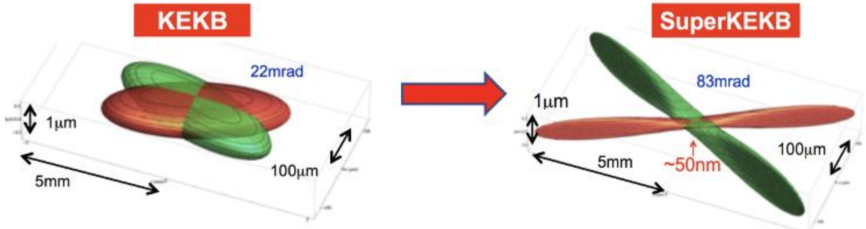
- Achieved peak luminosity: $4.7\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Integrated luminosity: 530/fb







New detector:
tracker, PID, calorimeters electronics…



Nano-beam design:
Beam squeezing: ×20 smaller
Target luminosity: KEKB×40

What are Exotic States

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

Where are they??

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been discussed only by abstracting the properties from a formal field theory model based on fundamental entities [3] from which the baryons and mesons are built up. [...] ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

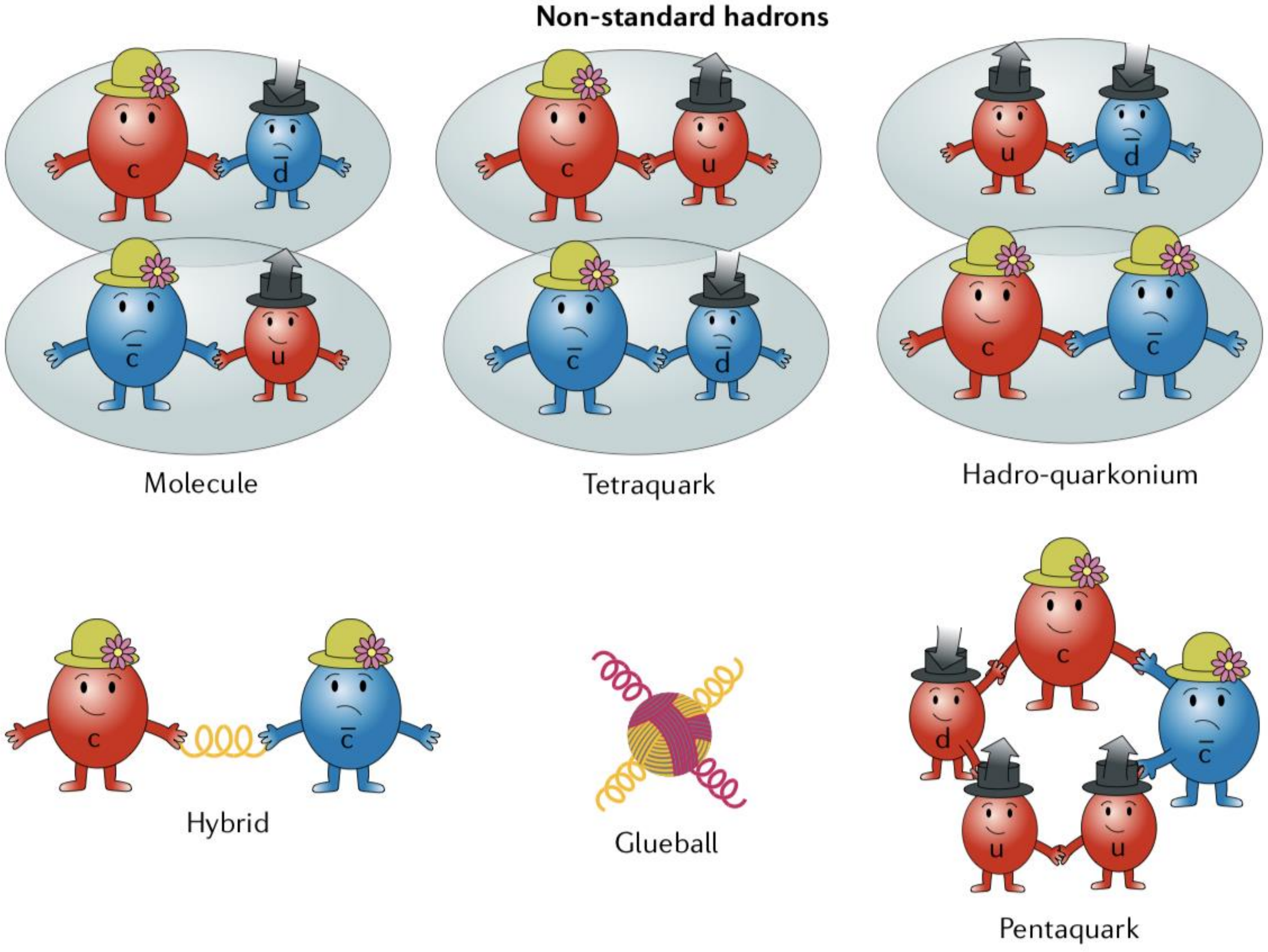
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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**.

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

- **Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks**
- **QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$**

Gell-Mann in his quark model paper has mentioned "exotic states" since 1964. After that, many experiments focused on finding exotic hadrons.

Various interpretations of the exotic states



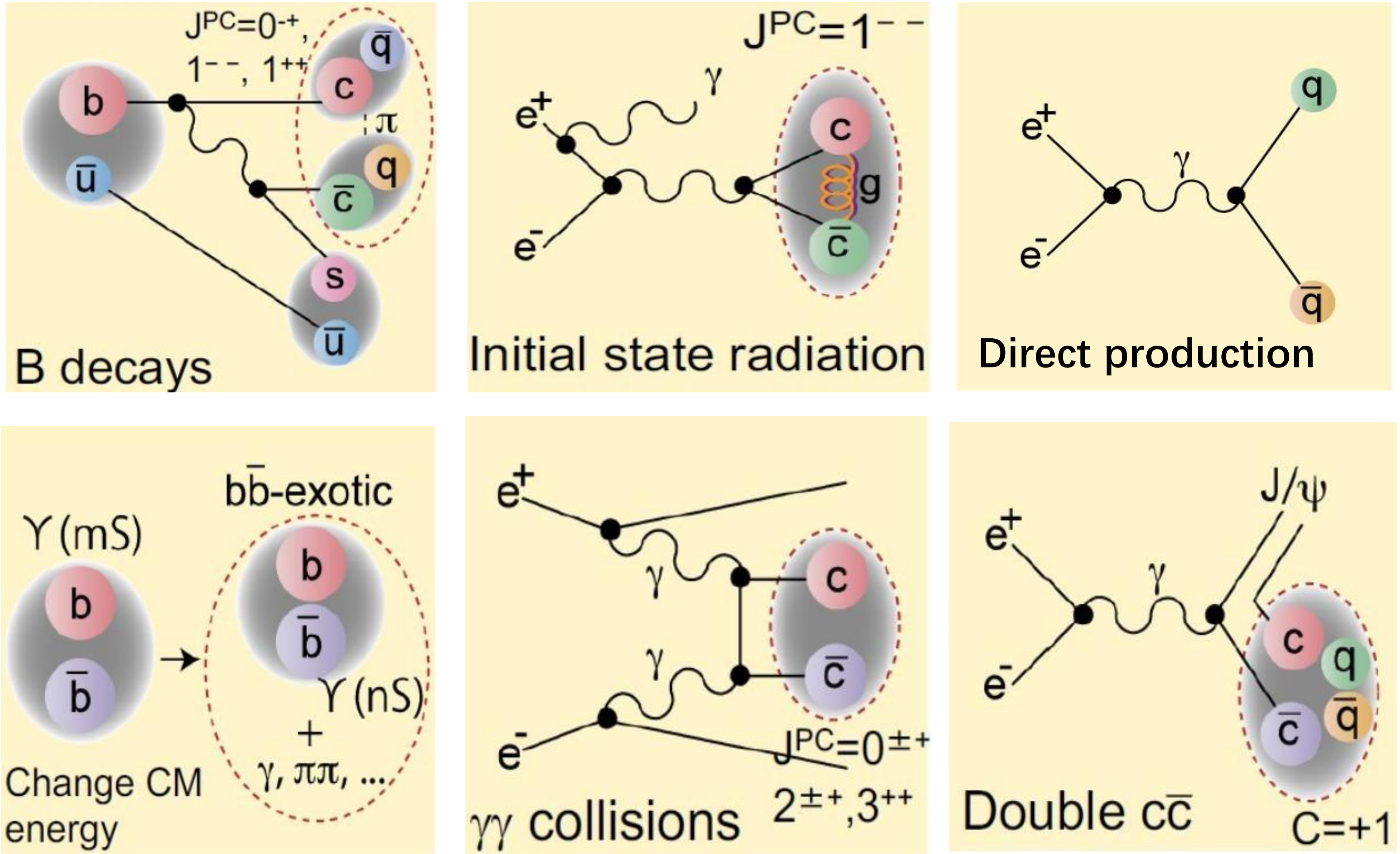
Nature Reviews Physics 1, 480 (2019)

Glueball: N_{quarks} = 0 (gg, ggg, …)
Hybrid: N_{quarks} = 2 (or more) + excited gluon
Multiquark state: N_{quarks} > 3
Molecule: bound state of more than 2 hadrons

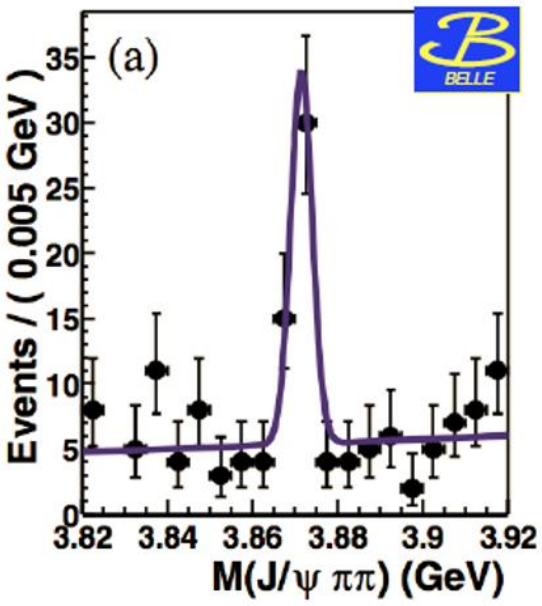
Study of exotic hadrons can

- provide new insights into internal structure and dynamics of hadrons
- act as a unique probe to non-perturbative behavior of QCD

XYZ production mechanism @B factory:



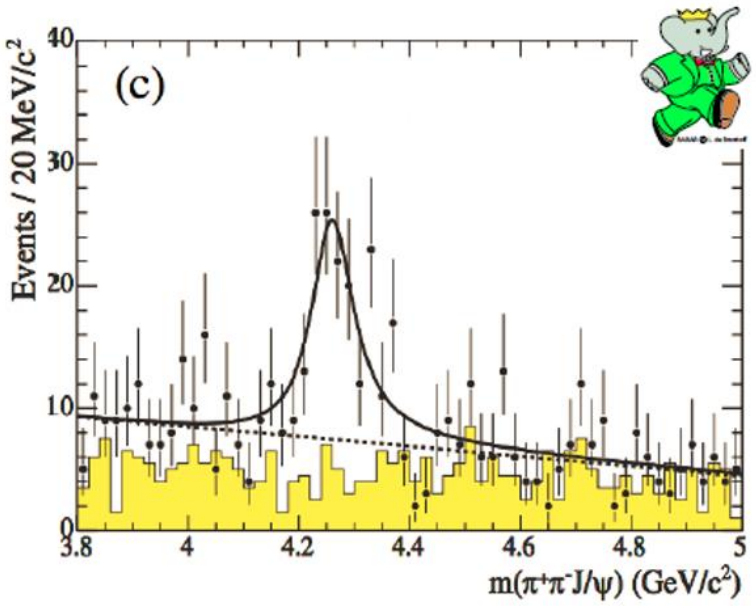
The start of the journey



$X(3872)$

PRL 91, 262001 (2003)

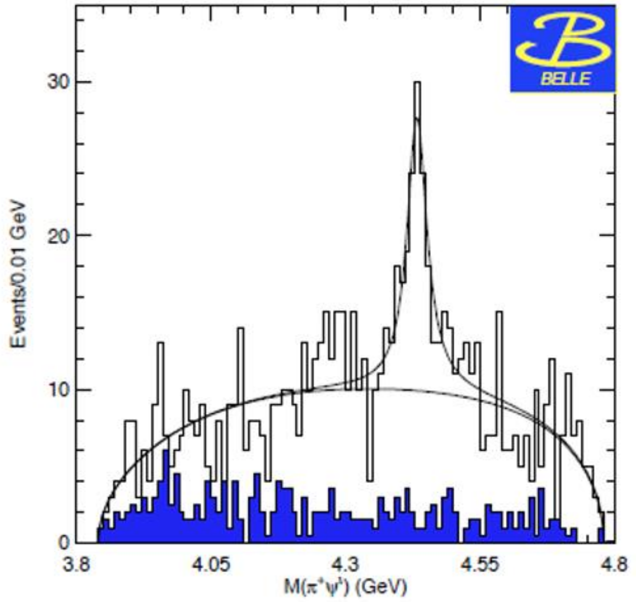
$B^{\pm} \to K^{\pm}[\pi^+\pi^- J/\psi]$



$Y(4260)$

PRL 95, 142001 (2005)

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



$Z_c(4430)^{\pm}$

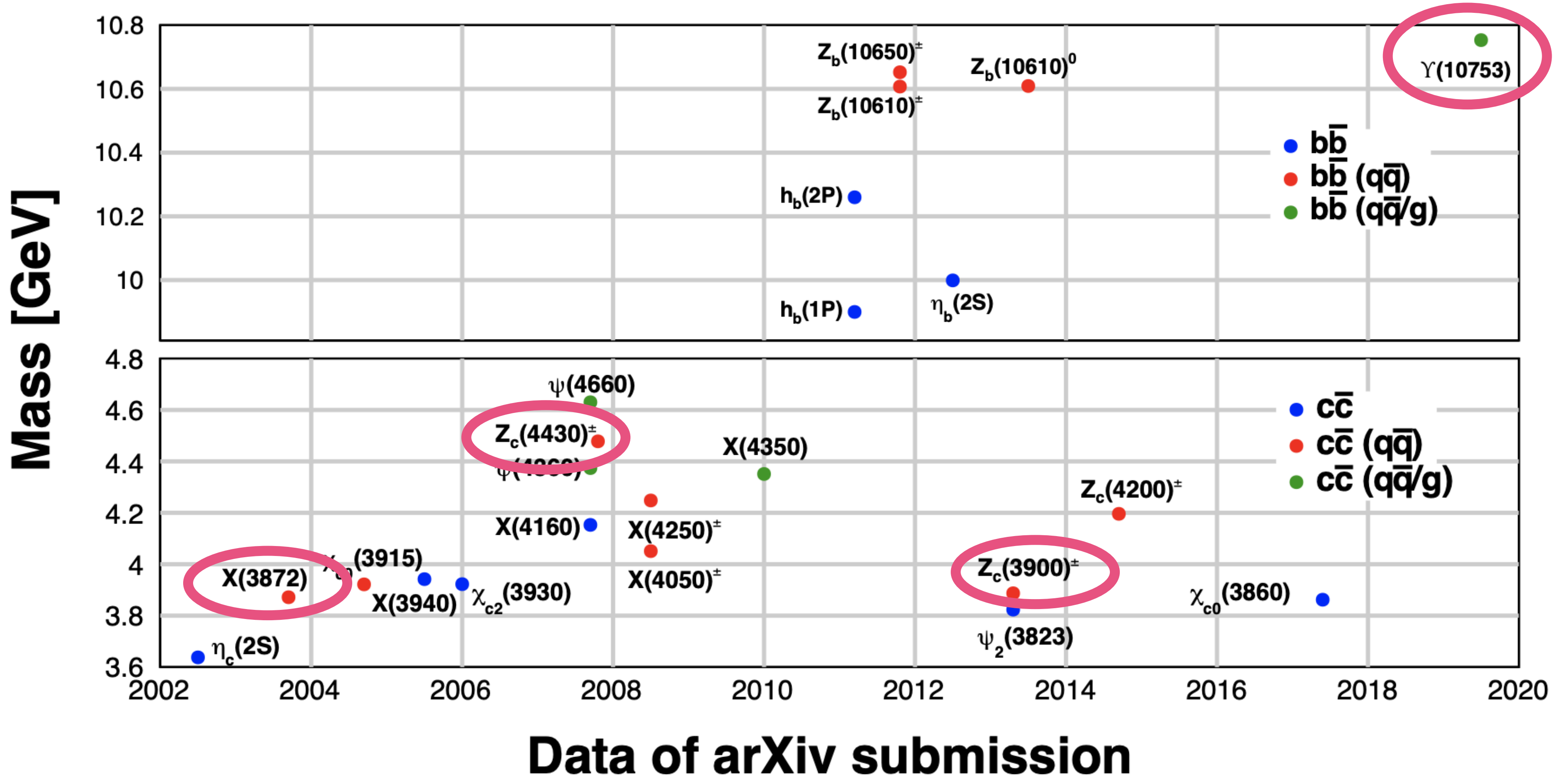
PRL 100, 142001 (2008)

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

Classification: $Q\bar{Q}q\bar{q}$

X: Neutral, $J^{PC} \neq 1^{--}$; Y: Neutral, $J^{PC} = 1^{--}$; Z: Charged

Quarkonium(-like) states observed by Belle as a function of the year of observation



> 20 new (exotic) hadrons were first observed by Belle, including **the first XYZ state X(3872)**, **the first charged charmonium-like state $Z_c(4430)$**, and **the only two bottononium-like state of $Z_b(10610)$ and $Z_b(10650)$.**

X(3872)

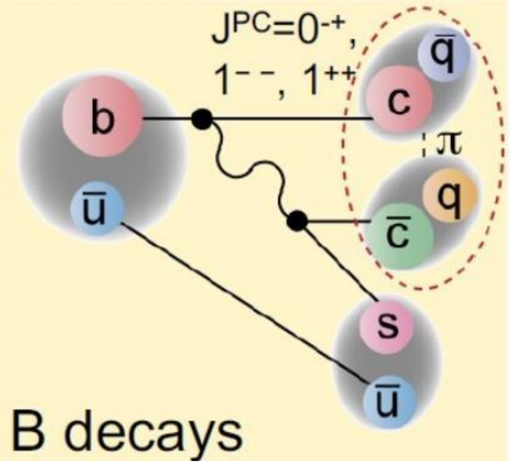
$B^{\pm} \to K^{\pm}[\pi^{+}\pi^{-}J/\psi]$

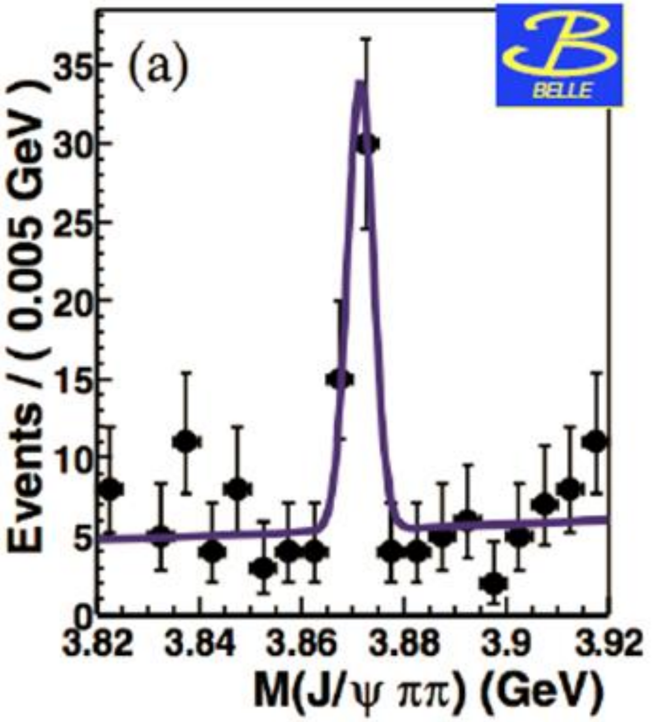
Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays #1

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 claim reference search 2,498 citations

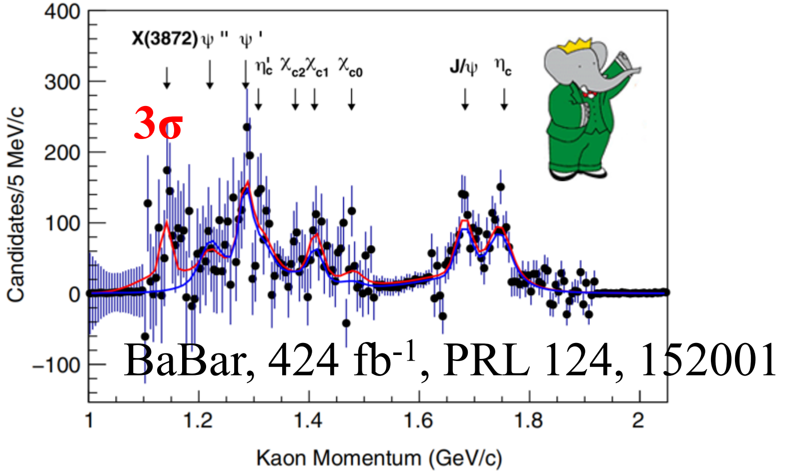




The most-cited article at Belle: >2000

First observed by Belle in $B \to K\,J/\psi\pi^{+}\pi^{-}$

- M_X close to $D^0\bar{D}^{*0}$ threshold M = (3871.68±0.17) MeV
- Surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% C.L.



BaBar, 424 fb^{-1}, PRL 124, 152001

$B(B^{\pm}\to X(3872)K^{\pm}) = (2.1\pm0.6\pm0.3)\times10^{-4}$

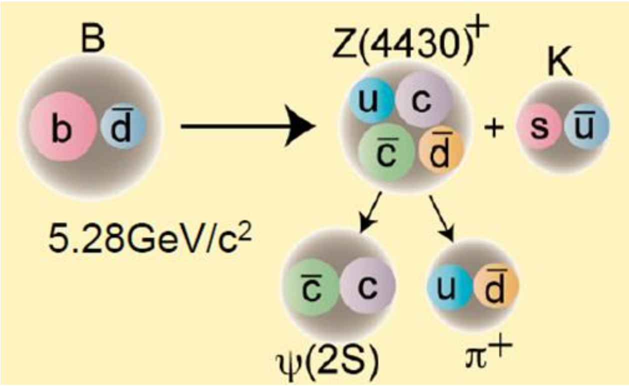
Branching fraction	Structure
$\mathcal{B}(X(3872)\to J/\psi\pi^{+}\pi^{-})$ $\sim 50\%$	Tetraquark State [PRD 71, 014028 (2005)]
$\mathcal{B}(X(3872)\to J/\psi\pi^{+}\pi^{-})$ $< 10\%$	Molecular state [PRD 72, 054022 (2005), PRD 69, 054008 (2004)]

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

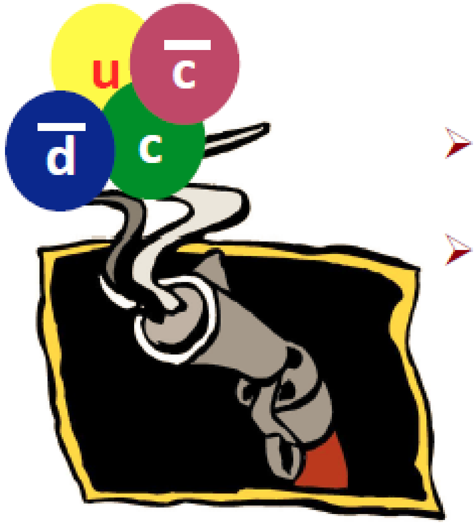
Belle II can give more precise result

Zc(4430) and Zc(3900)

The $Z(4430)^+ \rightarrow \pi^+ \psi'$

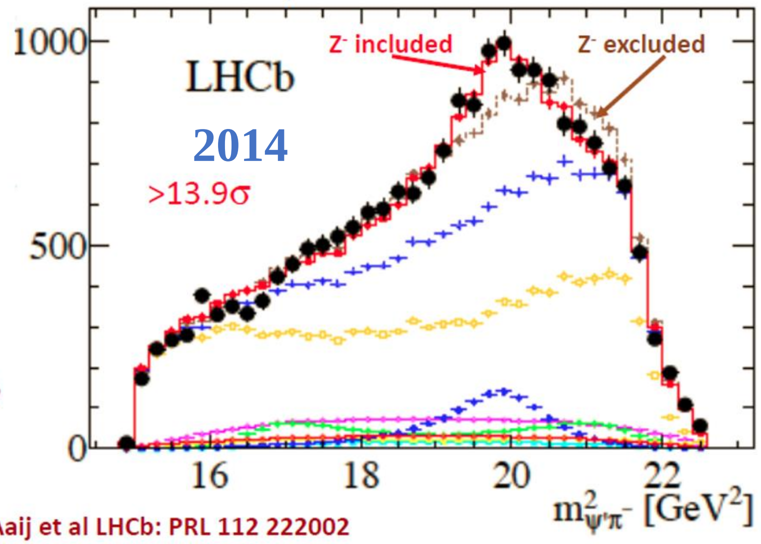


"smoking gun" evidence for a 4-quark meson



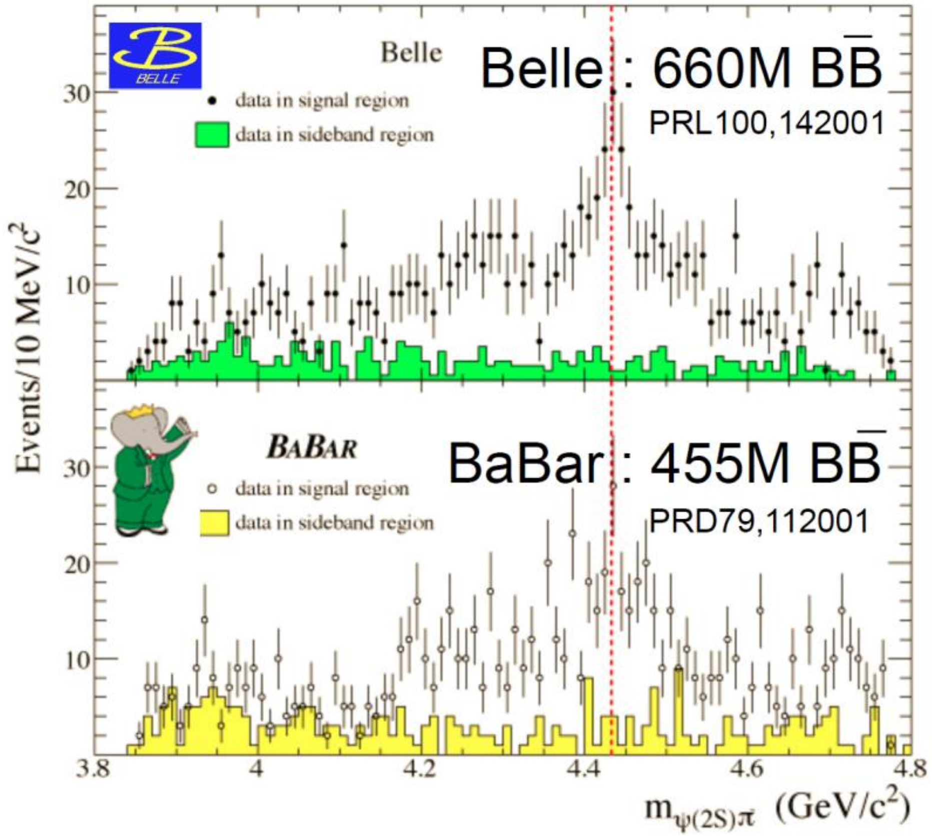
- decays to ψ' ➔ must contain $c\bar{c}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

$B \rightarrow K^+\pi^- \psi'$ 4-dim amplitude analysis



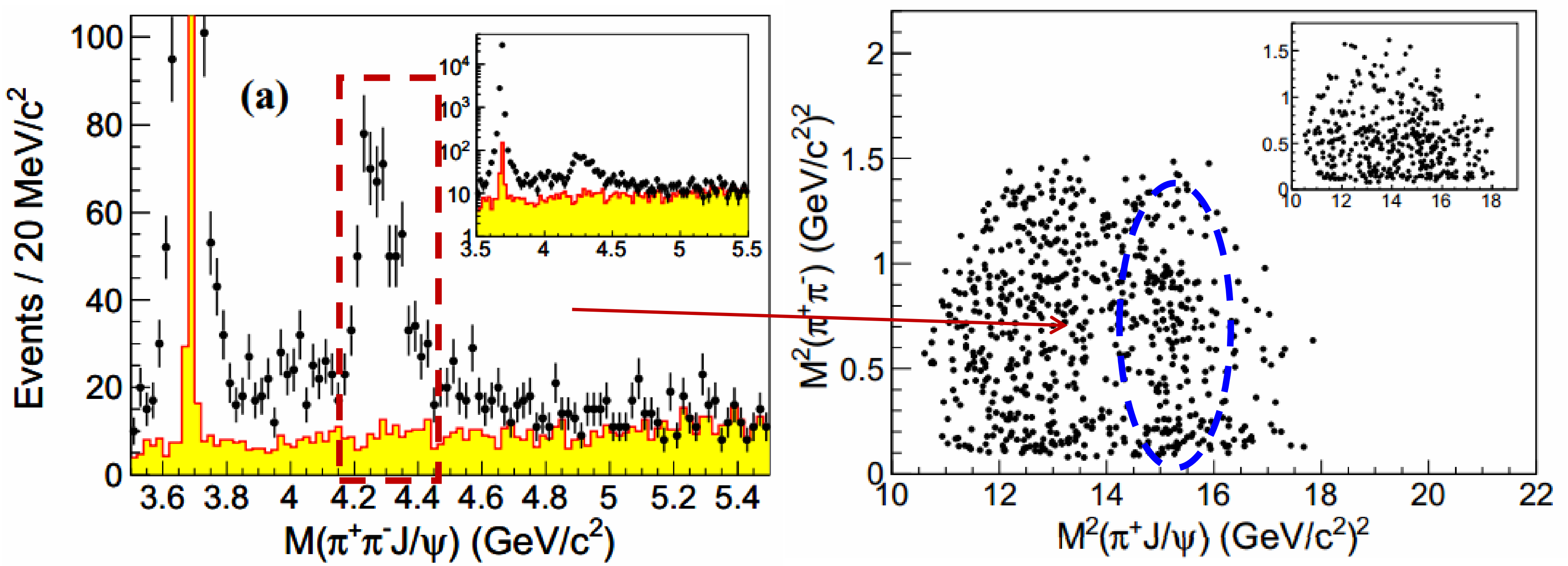
R. Aaij et al LHCb: PRL 112 222002

Good agreement with Belle,
(with smaller errors)



Phys.Rev.D 79 (2009) 112001

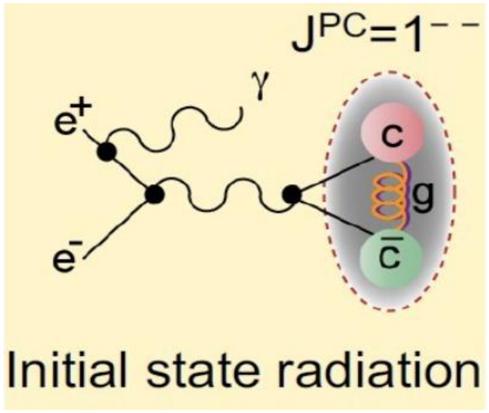
Zc(4430) and Zc(3900)



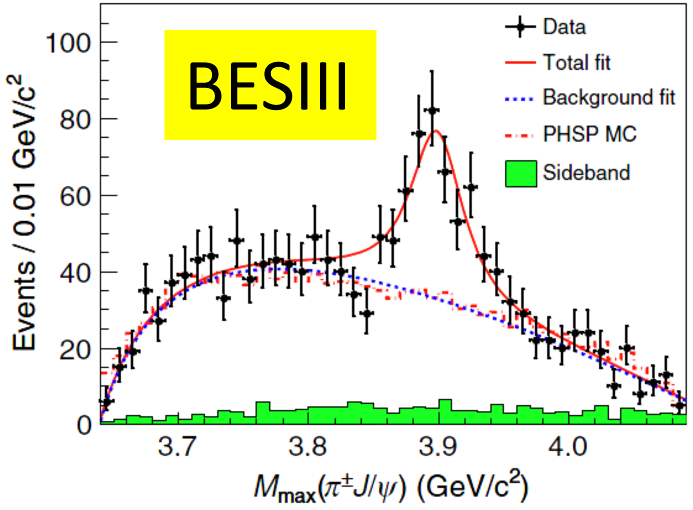
1. Almost full Belle data sample used: Lum=967 fb^{-1} data.
2. Using ISR photon non-tagged method, Y(4260) was observed significantly.
3. 4.15<$M(\pi^+\pi^- J/\psi)$<4.45 GeV to select Y(4260) resonance.
4. Dalitz plot also shows structures.

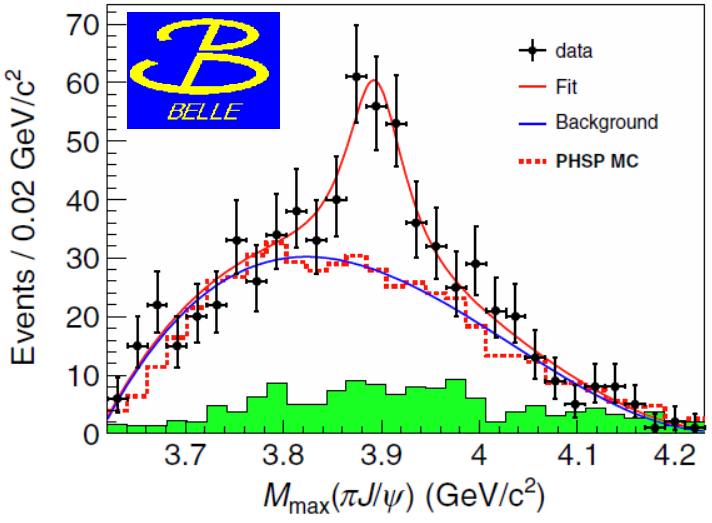
Zc(4430) and Zc(3900)

$Zc(3900)^{\pm}$ from Belle



PRL 110, 252001 (2013)





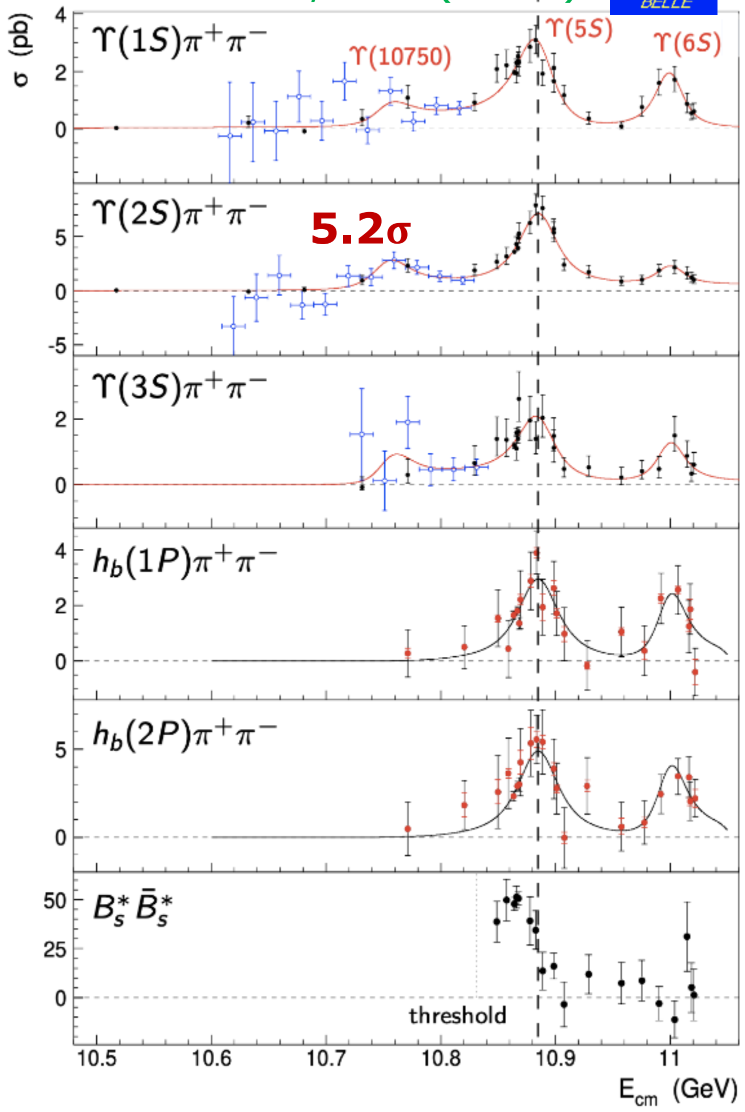
PRL 110, 252002 (2013)

1. S-Wave BW, p*q phase space factor, efficiency applied, to fit $M_{max}(\pi J/\psi)$ distribution
2. Belle observed 689 events, with 139 background.
3. M=(3894.5±6.6±4.5) MeV;
   G=(63±24±26) MeV.
4. Significance:5.2σ.

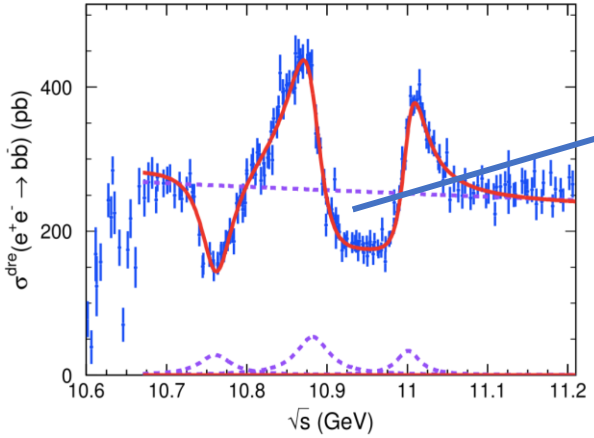
Comment: Since Zc(3900) is charged and can decay into πJ/ψ, it must have at least four quarks.

$\Upsilon(10750)$ state observed in $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

JHEP 10, 220 (2019)

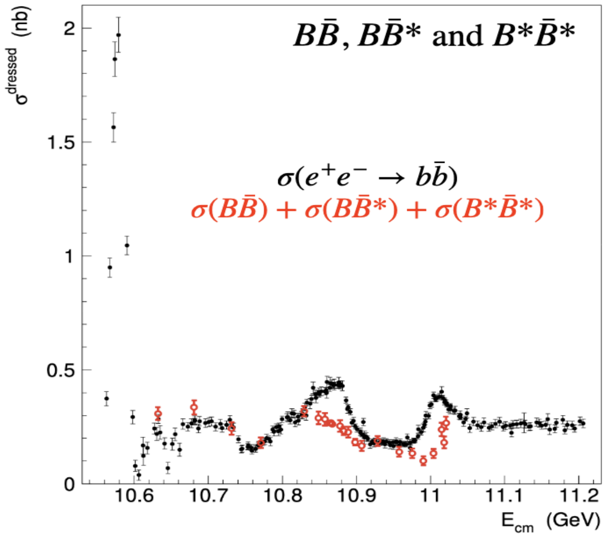


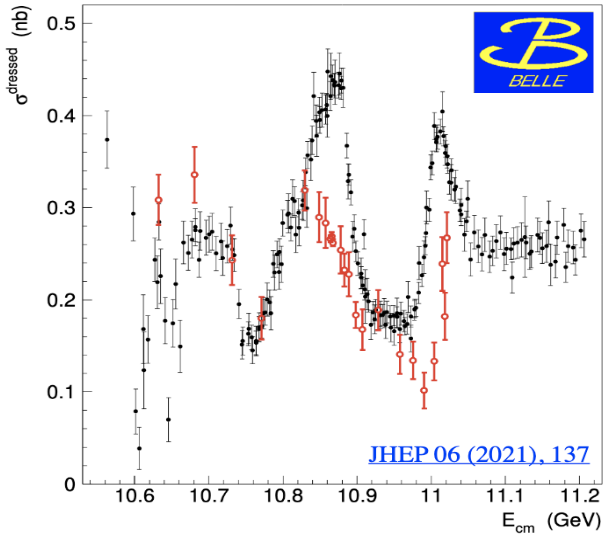
CPC 44 (2020) 8, 083001



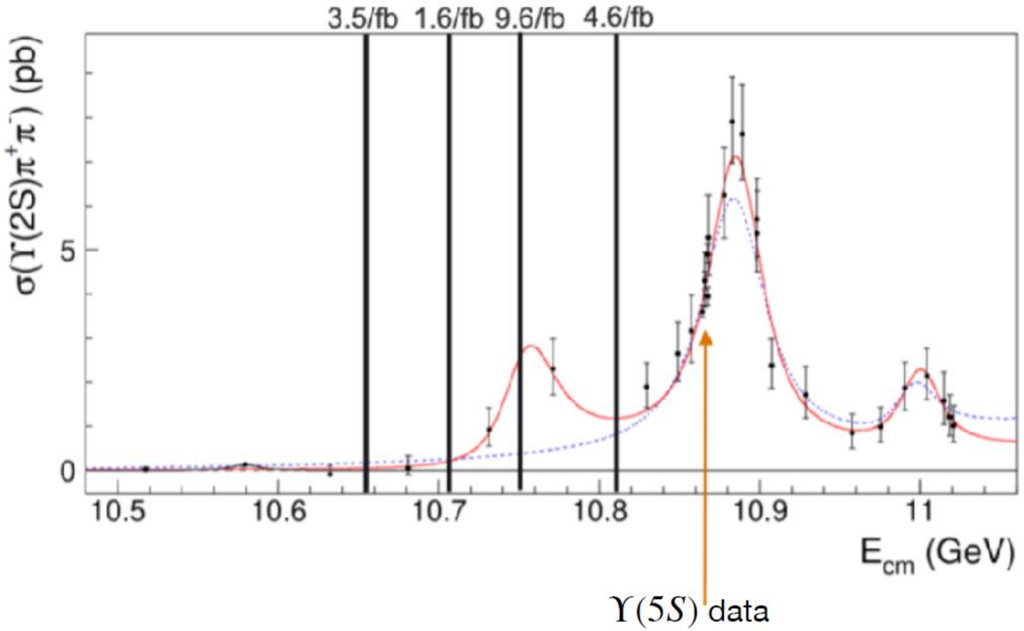
A dip at 10.75 GeV may correspond to $\Upsilon(10753)$.

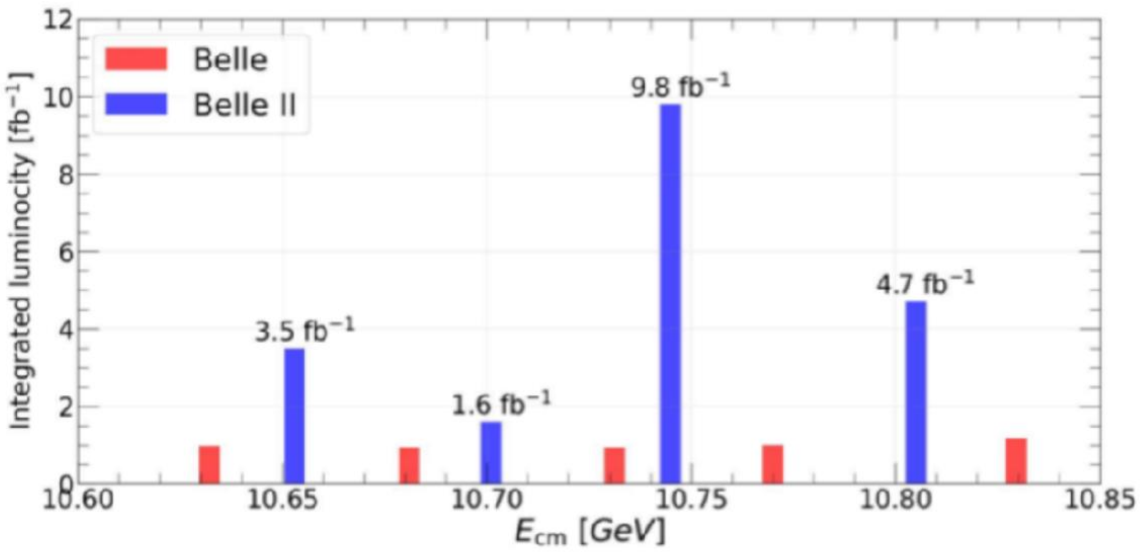
The individual cross sections contain more information than sum





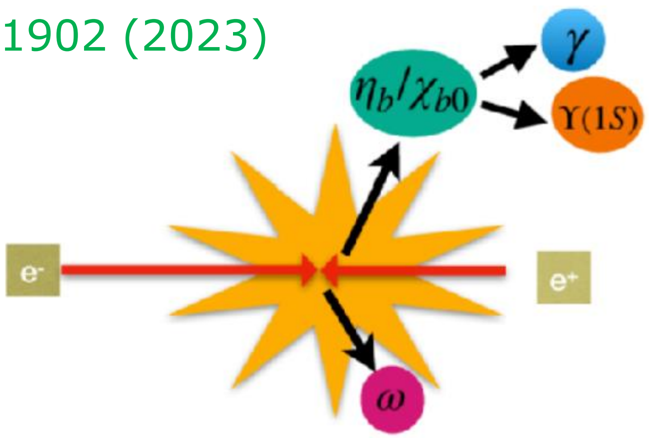
- In Nov. 2021, Belle II collected ~20/fb of unique scan data at energies near 10.75 GeV
  - Fill the gaps in Belle Scan data
  - Physics goal is to understand the nature of $\Upsilon(10753)$





9

$\Upsilon(10753) \to \omega\chi_{bJ}$ and $X_b \to \omega\Upsilon(1S)$ PRL 130, 091902 (2023)

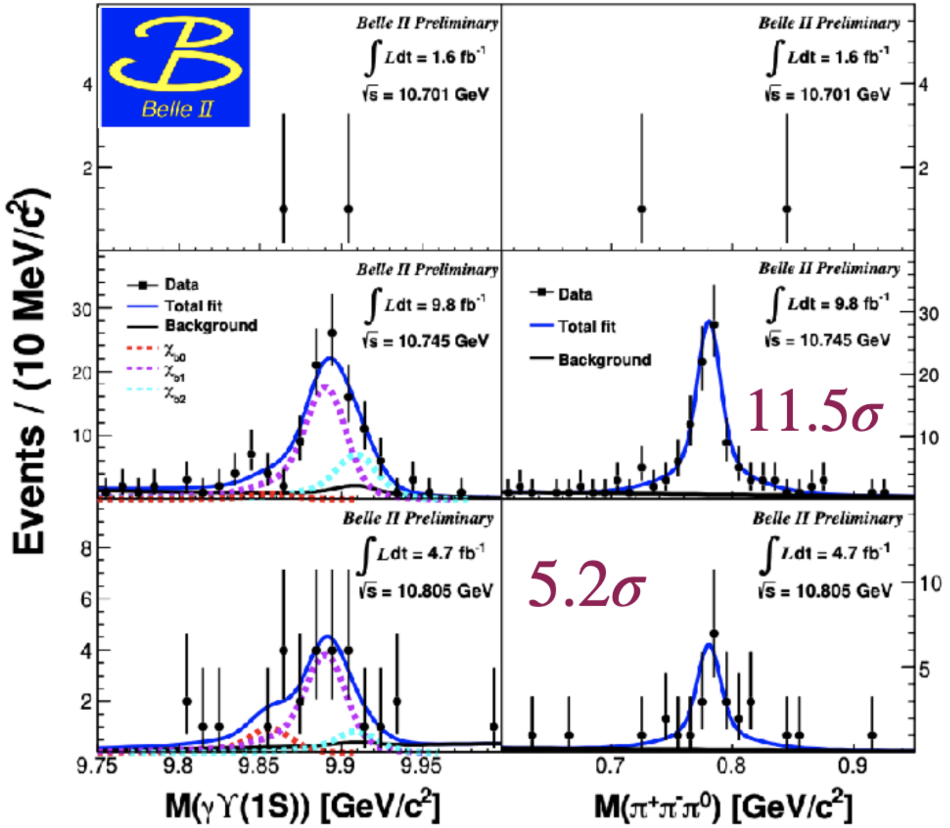


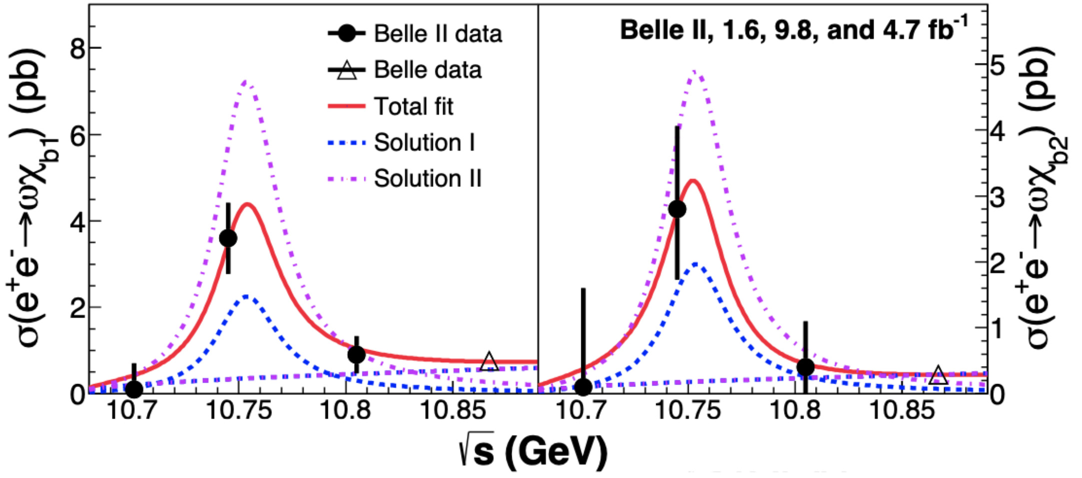
Theory: $\mathcal{B}(\Upsilon(10753) \to \omega\chi_{bJ})$ and $\mathcal{B}(\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS))$ are $\sim 10^{-3}$

if $\Upsilon(10753)$ is $\Upsilon(4S)$ - $\Upsilon(3D)$ mixing state

[PRD 104, 034036]
[PRD 105, 074007]

Clear $\omega\chi_{bJ}$ signals at $\sqrt{s} = 10.745$ and 10.805 GeV



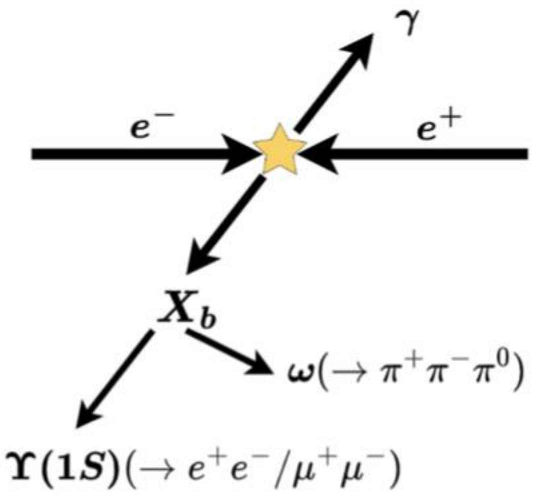


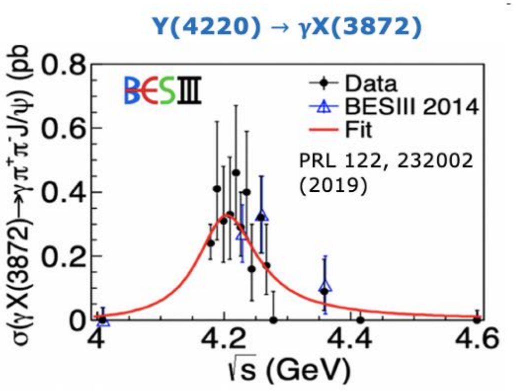
$\frac{\sigma(e^+e^- \to \chi_{b1}\omega)}{\sigma(e^+e^- \to \chi_{b2}\omega)} \sim 1$: consistent with HQFT

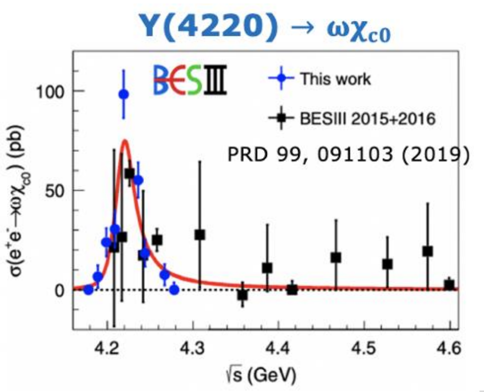
$\frac{\sigma(e^+e^- \to \chi_{b1}\omega)}{\sigma(e^+e^- \to \pi\pi\Upsilon(2S))} \begin{cases} \sim 1.5 & @\Upsilon(10753) \\ \sim 0.1 & @\Upsilon(5S) \end{cases}$:

difference in the internal structures $\Upsilon(5S)$ and $\Upsilon(10753)$

$\Upsilon(10753) \to \omega\chi_{bJ}$ and $X_b \to \omega\Upsilon(1S)$ PRL 130, 091902 (2023)

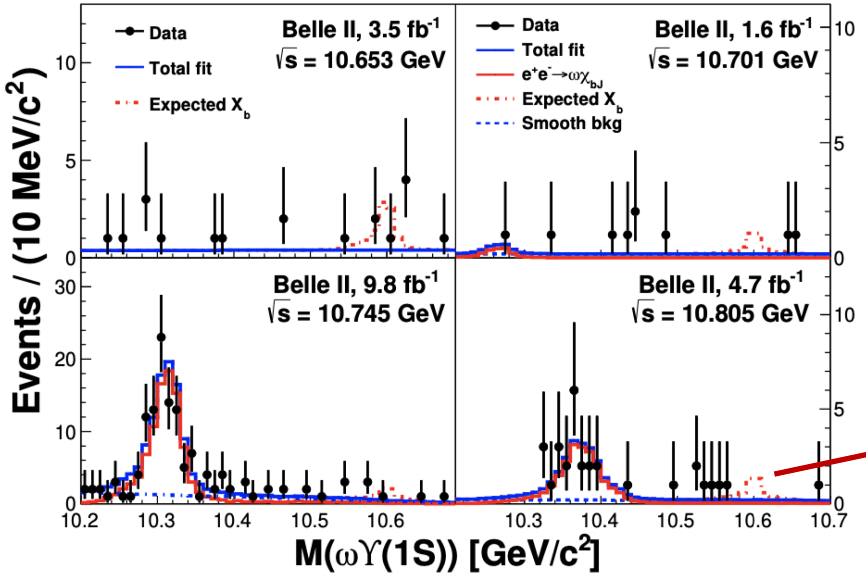






$Y(4220) \to \gamma X(3872)$ and $\omega\chi_{c0}$ observed by BESIII.

So we expect the observations of $\Upsilon(10753) \to \gamma X_b$ and $\omega\chi_{bJ}$.



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

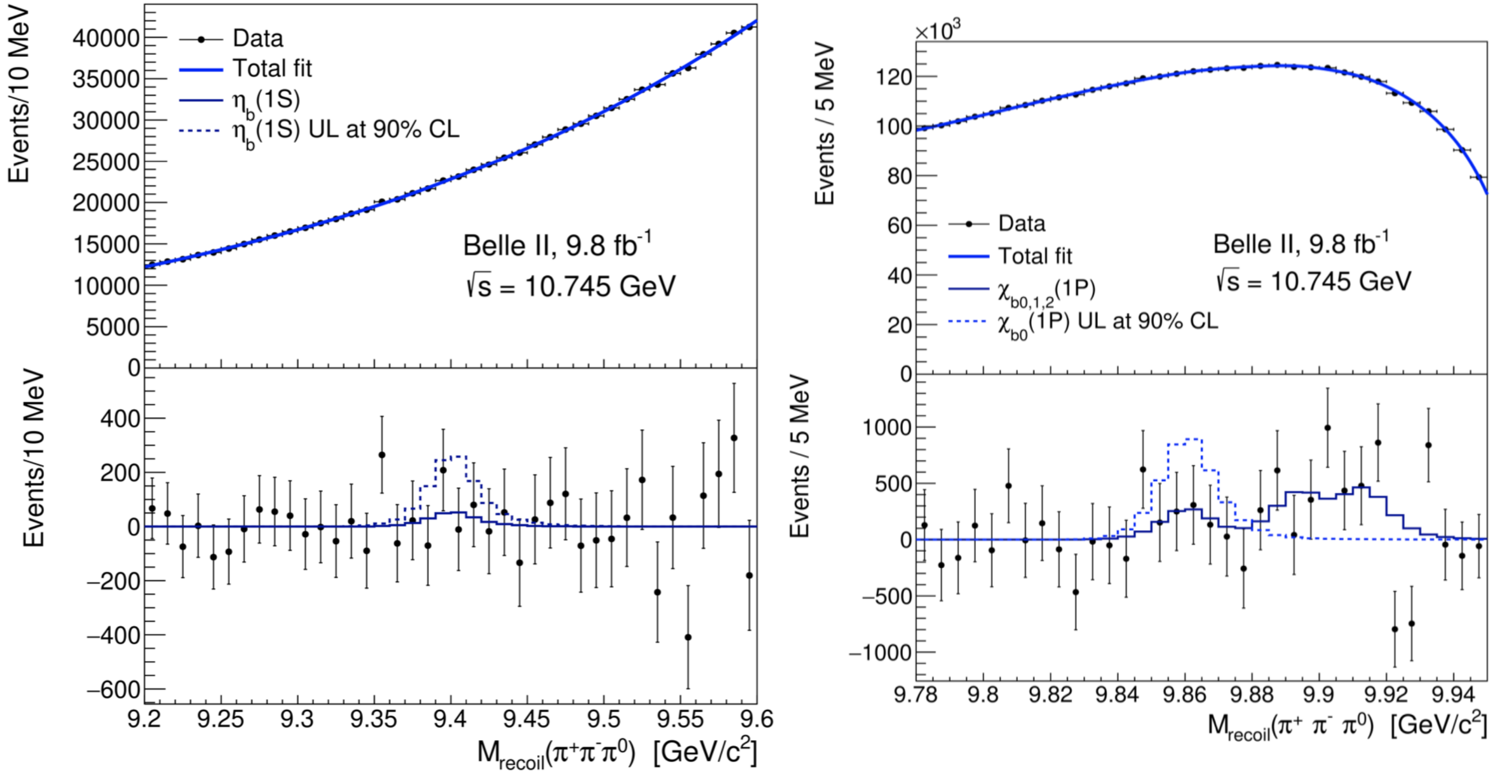
From simulated events with $m(X_b) = 10.6$ GeV/c^2
The yield is fixed at the upper limit at 90% C.L.

Search for $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$ preliminary

- Tetraquark (diquark-antidiquark) interpretation
  enhancement of $\Upsilon(10753) \to \omega\eta_b(1S)$ transition

$$\frac{\Gamma(\eta_b\,\omega)}{\Gamma(\Upsilon\,\pi^+\pi^-)} \sim 30$$

[Chin. Phys. C 43, 123102 (2019)].



Recoiling the ω

The yields for $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ are fixed [PRL 130, 091902 (2023)].

Tetraquark model in Ref. [CPC 43, 123102]:

$$\Gamma(\Upsilon(10753) \to \eta_b(1S)\omega) = 2.64^{+4.70}_{-1.69}\ \text{MeV}$$
$$\Gamma(\Upsilon(10753) \to \Upsilon\pi^+\pi^-) = 0.08^{+0.20}_{-0.06}\ \text{MeV}$$

This measurement and JHEP 10, 220 (2019):

$$\sigma^B(\Upsilon(10753) \to \eta_b(1S)\omega) < 2.5\ \text{pb}$$
$$\sigma^B(\Upsilon(10753) \to \Upsilon(2S)\pi^+\pi^-) \approx (3 \pm 1)\ \text{pb}$$

No clear $\eta_b(1S)$ and $\chi_{b0}(1P)$ signals are observed.
not support the prediction

Update of the cross section of $e^+e^- \to \pi\pi\Upsilon(nS)$

preliminary

Fit with three coherent BW, convoluting a Gaussian modeling energy spread:

$$\sigma \propto |\sum_i^3 \frac{\sqrt{12\pi\Gamma_i\mathcal{B}_i}}{s - M_i + iM_i\Gamma_i} \cdot \sqrt{\frac{f(\sqrt{s})}{f(M_i)}} e^{i\phi_i}|^2 \otimes G(0, \delta E)$$

All parameters are free, except $\delta E = 0.0056$ GeV

Parameters of $\Upsilon(10753)$:

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

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

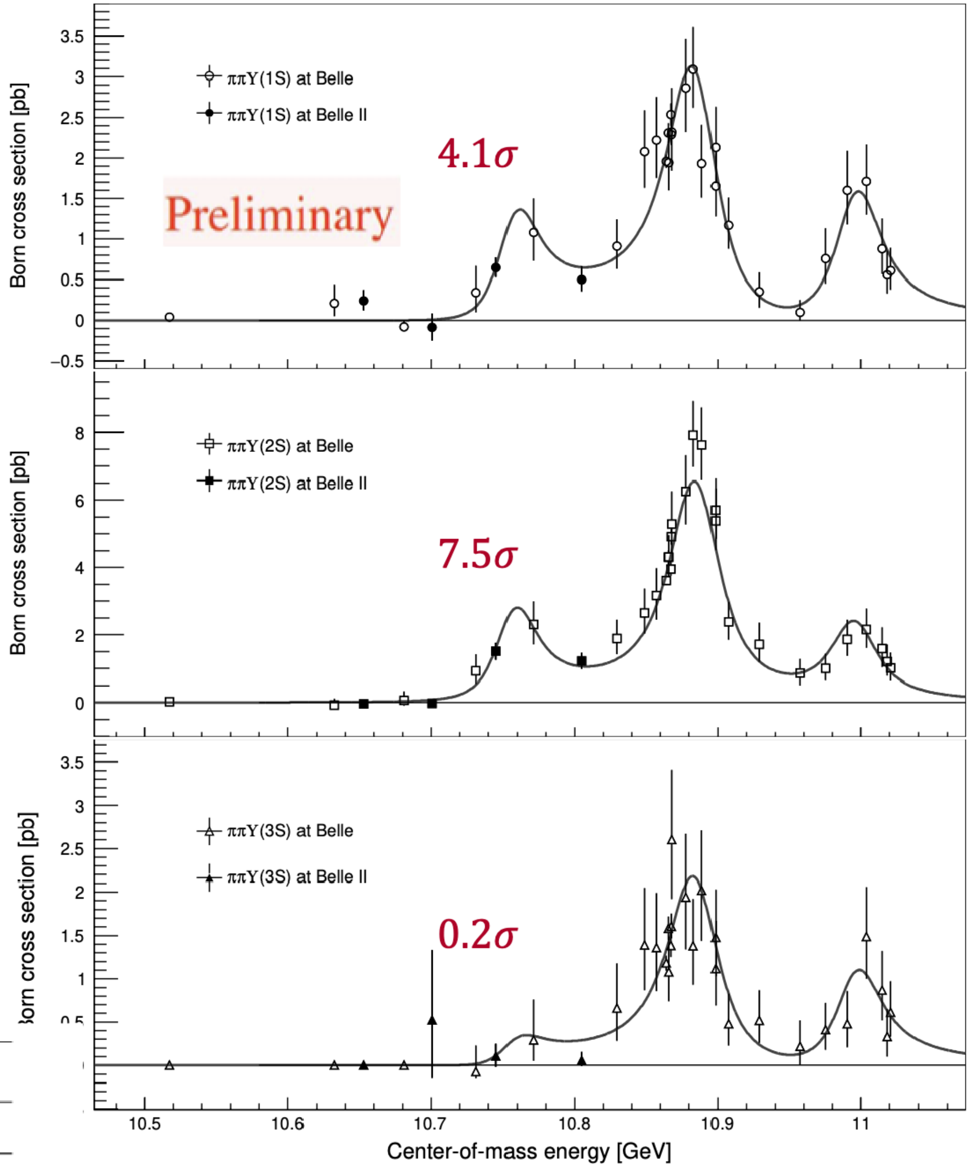
Previous:

$10752.7 \pm 5.9 {}^{+0.7}_{-1.1}$

$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$

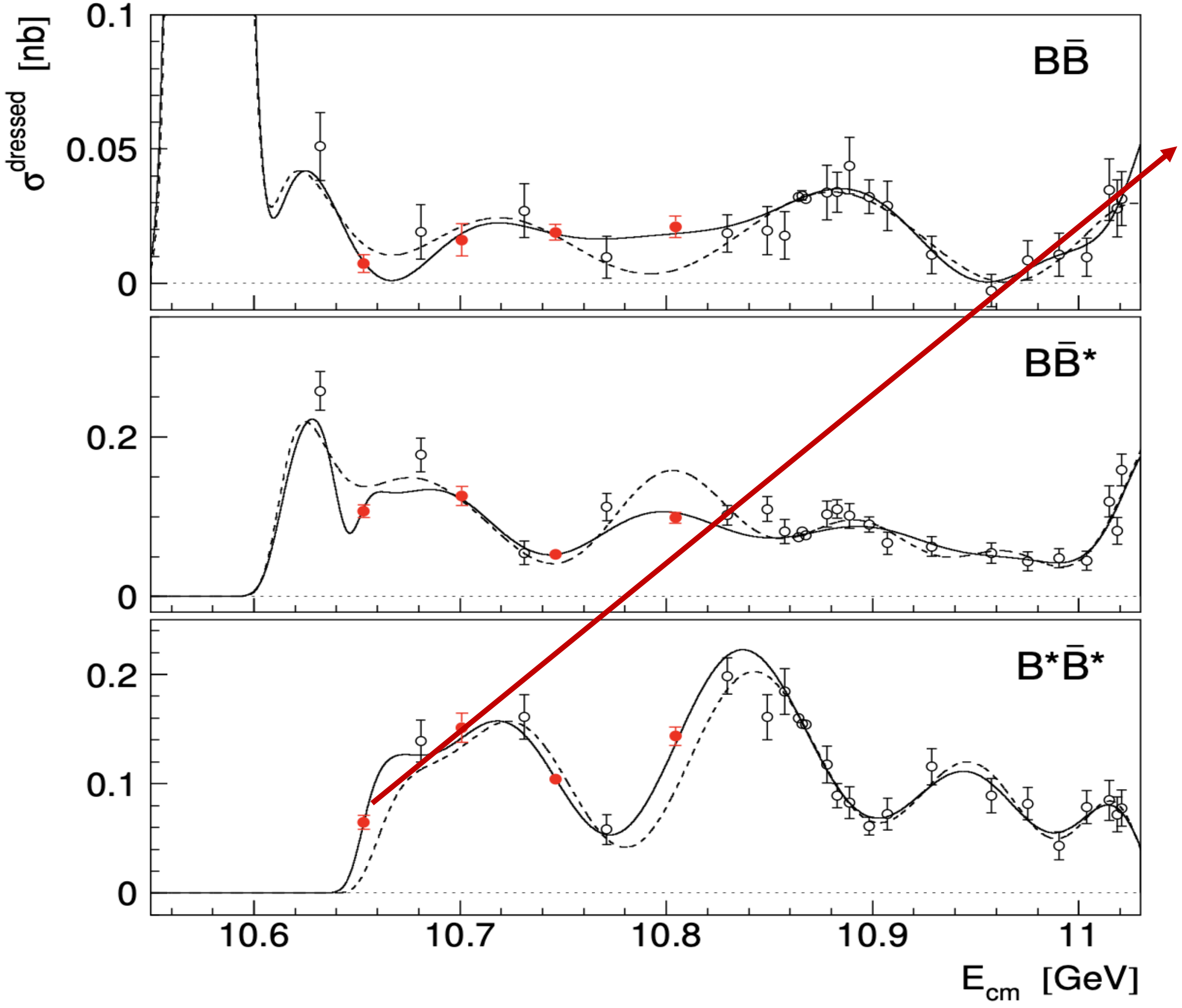
Relative ratios of cross section at different resonance peaks

	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$
Ratios	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$	$0.45^{+0.04}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.64^{+0.23}_{-0.13}$	$0.41^{+0.16}_{-0.12}$



The $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections

arXiv: 2405.18928

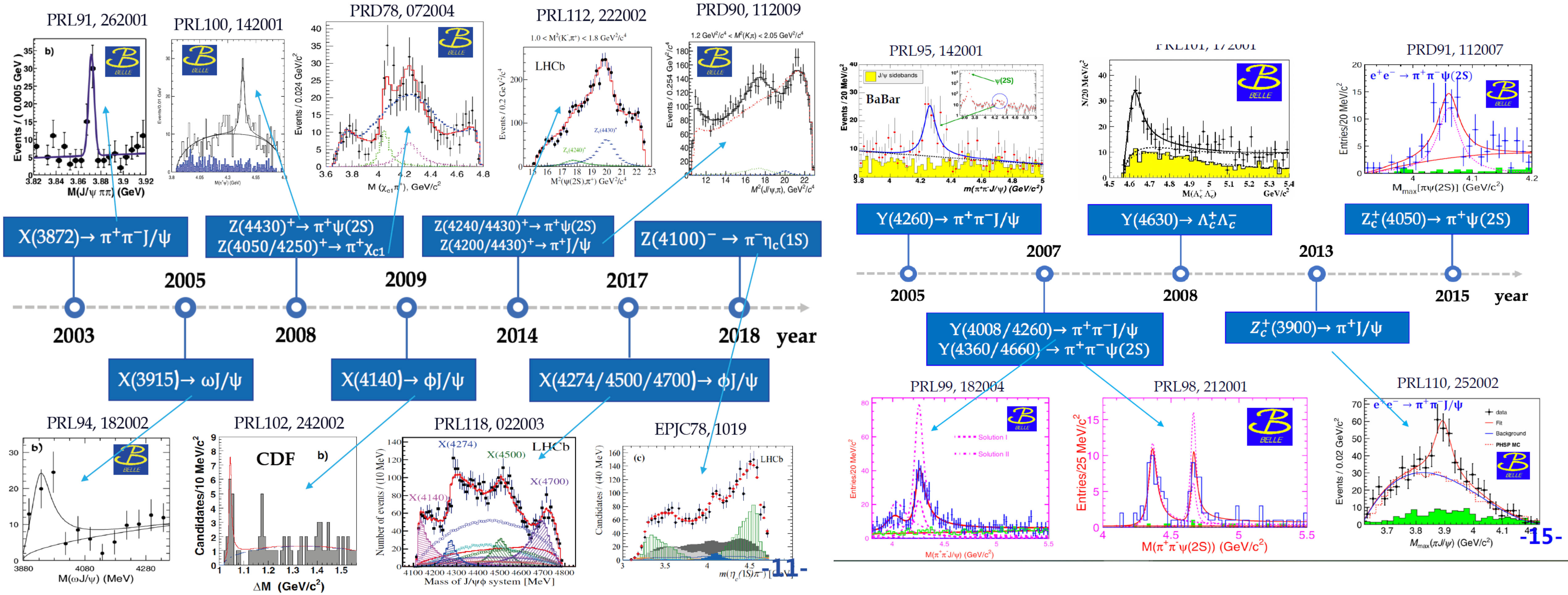


New: rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold

- Similar behaviour was seen for $D^*\bar{D}^*$ cross section (PRD 97, 012002 (2018))
- Possible interpretation: resonance or bound state ($B^*\bar{B}^*$ or $b\bar{b}$) near threshold (MPL A 21, 2779 (2006))
- Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by destructive interference between $e^+e^- \to B\bar{B}^*$ and $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$
- **Need more data to fill the gaps**

Solid curve: fit to Belle + Belle II data
Dashed curve: fit to Belle data fit only

Summary



PRL91, 262001
PRL100, 142001
PRD78, 072004
PRL112, 222002
PRD90, 112009
LHCb
X(3872)→ π⁺π⁻J/ψ
Z(4430)⁺→ π⁺ψ(2S)
Z(4050/4250)⁺→ π⁺χc1
Z(4240/4430)⁺→ π⁺ψ(2S)
Z(4200/4430)⁺→ π⁺J/ψ
Z(4100)⁻ → π⁻ηc(1S)
2003
2005
2008
2009
2014
2017
2018
year
X(3915)→ ωJ/ψ
X(4140)→ ϕJ/ψ
X(4274/4500/4700)→ ϕJ/ψ
PRL94, 182002
PRL102, 242002
CDF
PRL118, 022003
EPJC78, 1019
-11-
PRL95, 142001
BaBar
PRD91, 112007
Y(4260)→ π⁺π⁻J/ψ
Y(4630)→ Λc⁺Λc⁻
Zc⁺(4050)→ π⁺ψ(2S)
2005
2007
2008
2013
2015
year
Y(4008/4260)→ π⁺π⁻J/ψ
Y(4360/4660) → π⁺π⁻ψ(2S)
Zc⁺(3900)→ π⁺J/ψ
PRL99, 182004
PRL98, 212001
PRL110, 252002
-15-

Summary

The Belle II quarkonium program includes

→ 50 ab^{-1} for charmonium ISR, double charmonium, $B \to c\bar{c}X$ ...

→ 500 fb^{-1} of scan above Υ(5S)

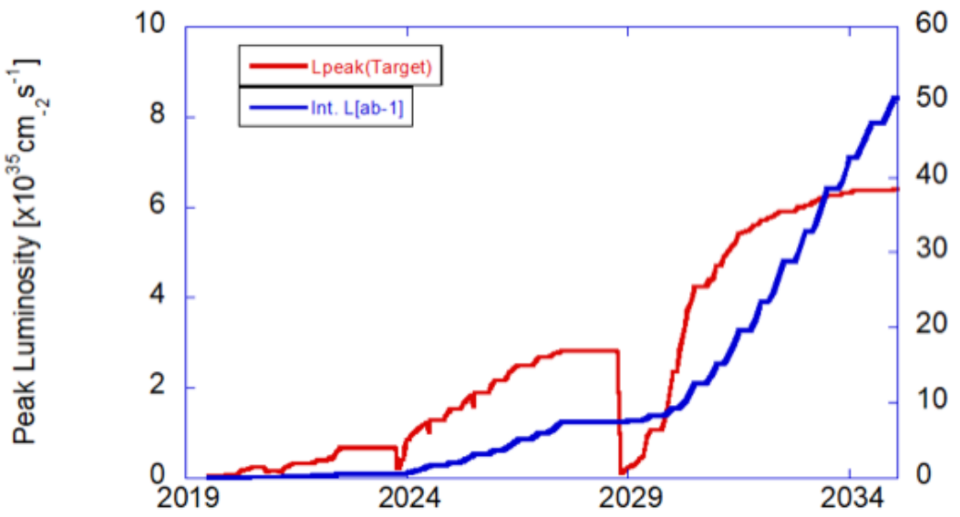
→ 300 fb^{-1} of Υ(3S)

→ 100 fb^{-1} of Υ(6S)

→ 1 ab^{-1} of Υ(5S)

Searching for explanation of families of exotic particle

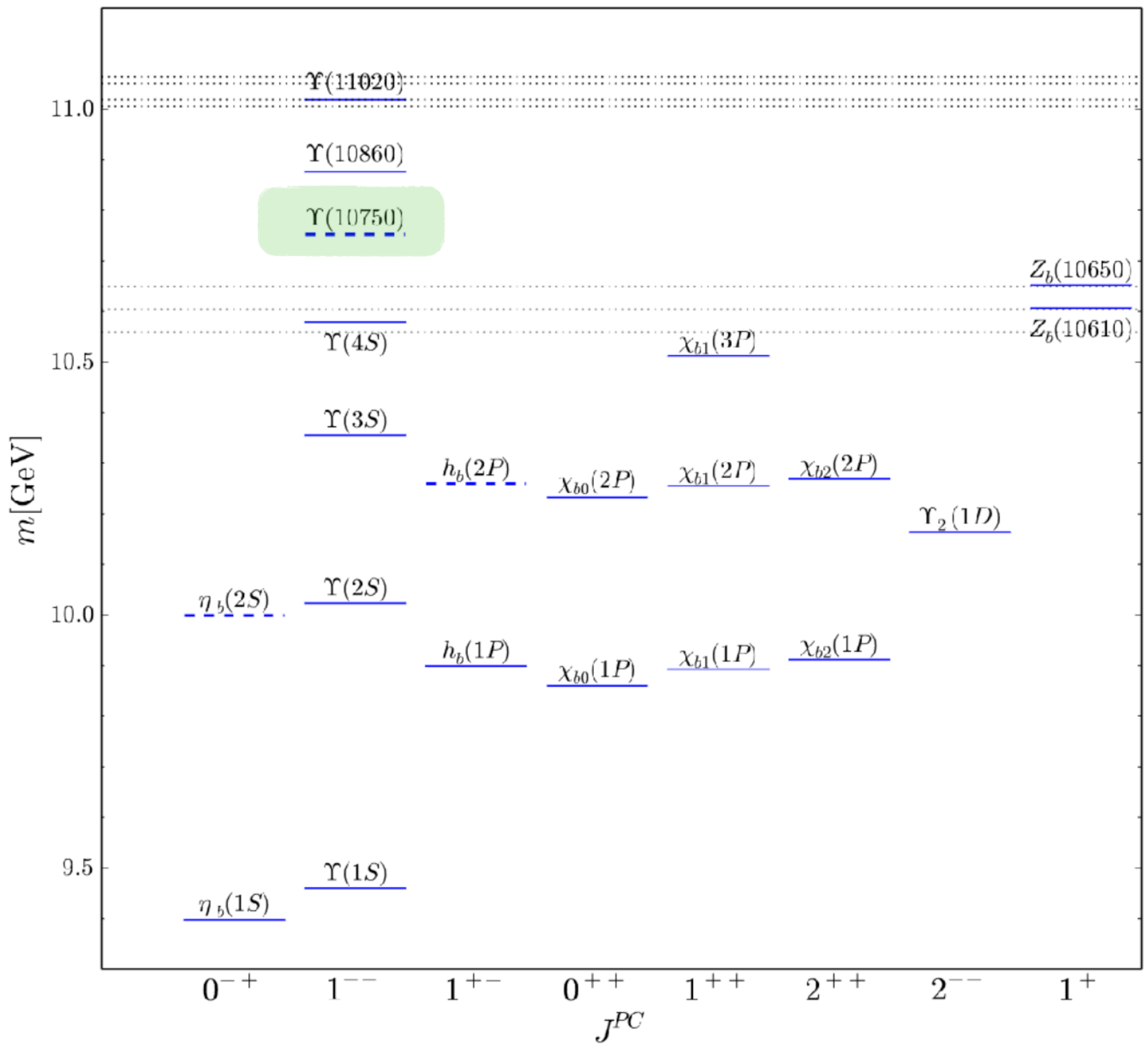
The results of XYZ are on the way!!!



Thank you!

XYZ particles: review articles, books, & web pages

- H.-X. Chen et al., The hidden-charm pentaquark and tetraquark states, Phys. Rept. 639 (2016) 1
- A. Hosaka et al., Exotic hadrons with heavy flavors: X, Y, Z, and related states, PTEP 2016 (2016) 062C01
- J.-M. Richard, Exotic hadrons: review and perspectives, Few Body Syst. 57 (2016) 1185
- R. F. Lebed, R. E. Mitchell, E. Swanson, Heavy-quark QCD exotica, PPNP 93 (2017) 143
- A. Esposito, A. Pilloni, A. D. Polosa, Multiquark resonances, Phys. Rept. 668 (2017) 1
- A. Ali, J. S. Lange, S. Stone, Exotics: Heavy pentaquarks and tetraquarks, PPNP 97 (2017) 123
- F. K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Hadronic molecules, RMP 90 (2018) 015004
- S. L. Olsen, T. Skwarnicki, Nonstandard heavy mesons and baryons: Experimental evidence, RMP 90 (2018) 015003
- Y.-R. Liu et al., Pentaquark and tetraquark states, PPNP107 (2019) 237
- N. Brambilla et al., The XYZ states: experimental and theoretical status and perspectives, Phys. Rept. 873 (2020) 1
- Y. Yamaguchi et al., Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners, JPG 47 (2020) 053001
- F. K. Guo, X.-H. Liu, S. Sakai, Threshold cusps and triangle singularities in hadronic reactions, PPNP 112 (2020) 103757
- G. Yang, J. Ping, J. Segovia, Tetra- and penta-quark structures in the constituent quark model, Symmetry 12 (2020) 1869
- C. Z. Yuan, Charmonium and charmoniumlike states at the BESIII experiment, Natl. Sci. Rev. 8 (2021) nwab182
- H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, An updated review of the new hadron states, RPP 86 (2023) 026201
- L. Meng, B. Wang, G.-J. Wang, S.-L. Zhu, Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules, Phys. Rept. 1019 (2023) 1
- A. Ali, L. Maiani, A. D. Polosa, Multiquark Hadrons, Cambridge University Press (2019)
- QWG: https://qwg.ph.nat.tum.de/exoticshub/



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Bottomonium?

Phys. Rev. D 101, 014020 (2020)

Phys. Lett. B 803, 135340 (2020)

Eur. Phys. J. C 80, 59 (2020)

Phys. Rev. D 102, 014036 (2020)

Prog. Part. Nucl. Phys. 117, 103845 (2021)

Phys. Rev. D 104, 034036 (2021)

Phys. Rev. D 105, 074007 (2022)

etc…

Hybrid?

Phys. Rept. 873, 1 (2020)

Phys. Rev. D 104, 034019 (2021)

etc…

Tetraquark?

Phys. Lett. B 802, 135217 (2020)

Chin. Phys. C 43, 123102 (2019)

Phys. Rev. D 103, 074507 (2021)

Phys. Rev. D 107, 094515 (2023)

etc…