First analysis of Belle II energy scan data

Sen Jia (Fudan University)
on behalf of the Belle II Collaboration

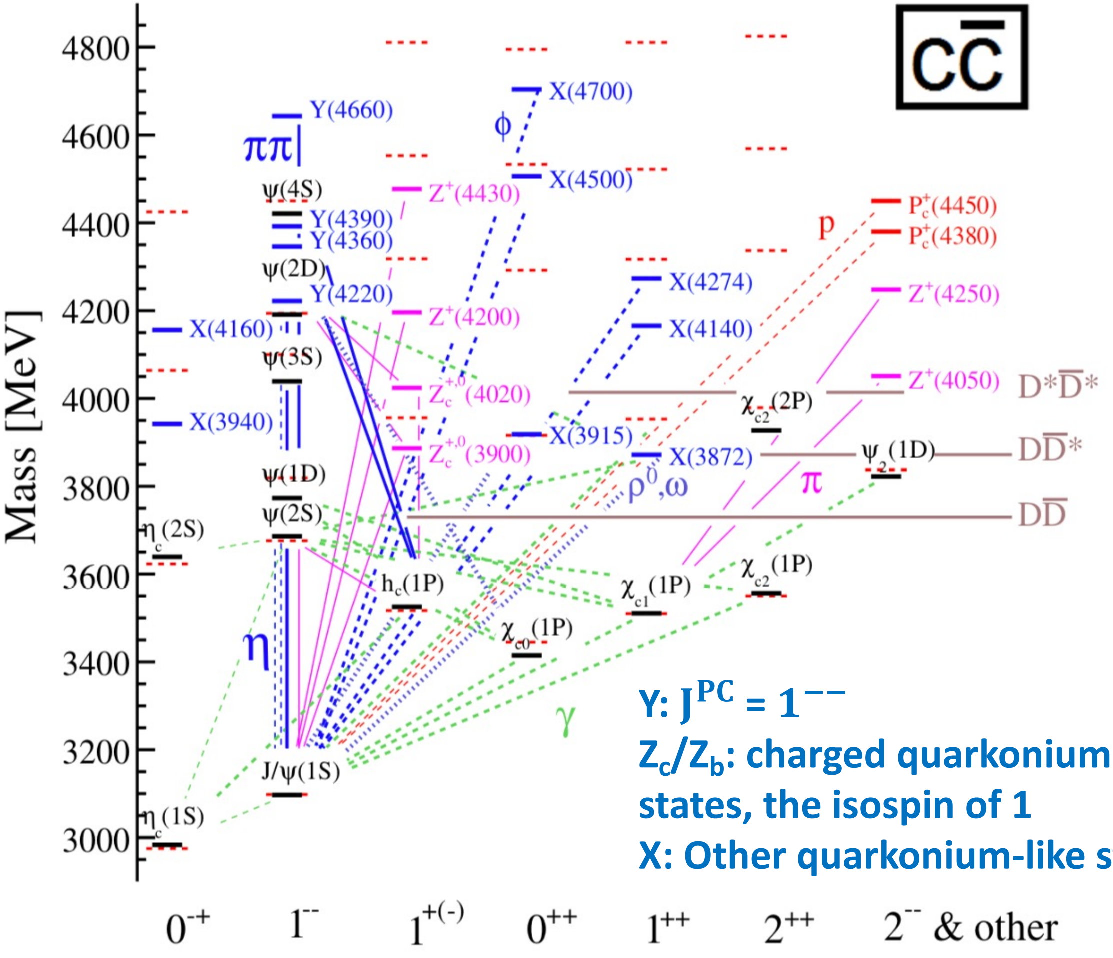
QCD22 25th HIGH-ENERGY PHYSICS
INTERNATIONAL CONFERENCE
IN QUANTUM CHROMODYNAMICS

MONTPELLIER
4-7 july 2022

QCD
22
MONTPELLIER FRANCE • 4-7 july 2022

Quarkonium

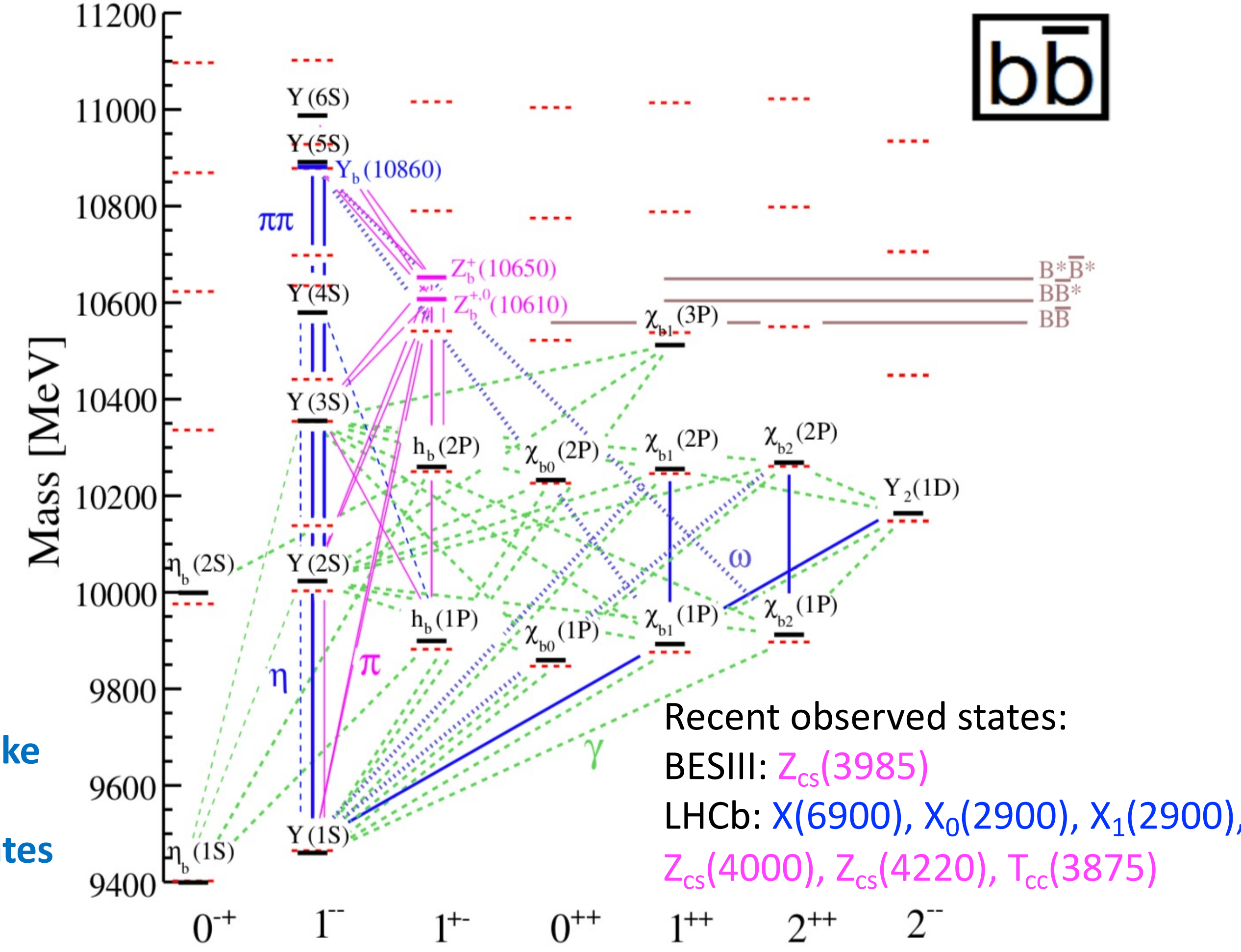
Rev. Mod. Phys. 90, 015003 (2018)



Y: $J^{PC} = 1^{--}$

Z_c/Z_b: charged quarkonium-like states, the isospin of 1

X: Other quarkonium-like states



Recent observed states:
BESIII: Z_{cs}(3985)
LHCb: X(6900), X_0(2900), X_1(2900),
Z_{cs}(4000), Z_{cs}(4220), T_{cc}(3875)

- Conventional quarkonium
- Unconventional neutral states
- Unconventional charged states
- Pentaquark candidates

- Below $D\bar{D}/B\bar{B}$ thresholds − charmonium and bottomonium are successful stories of QCD.
- 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 states.

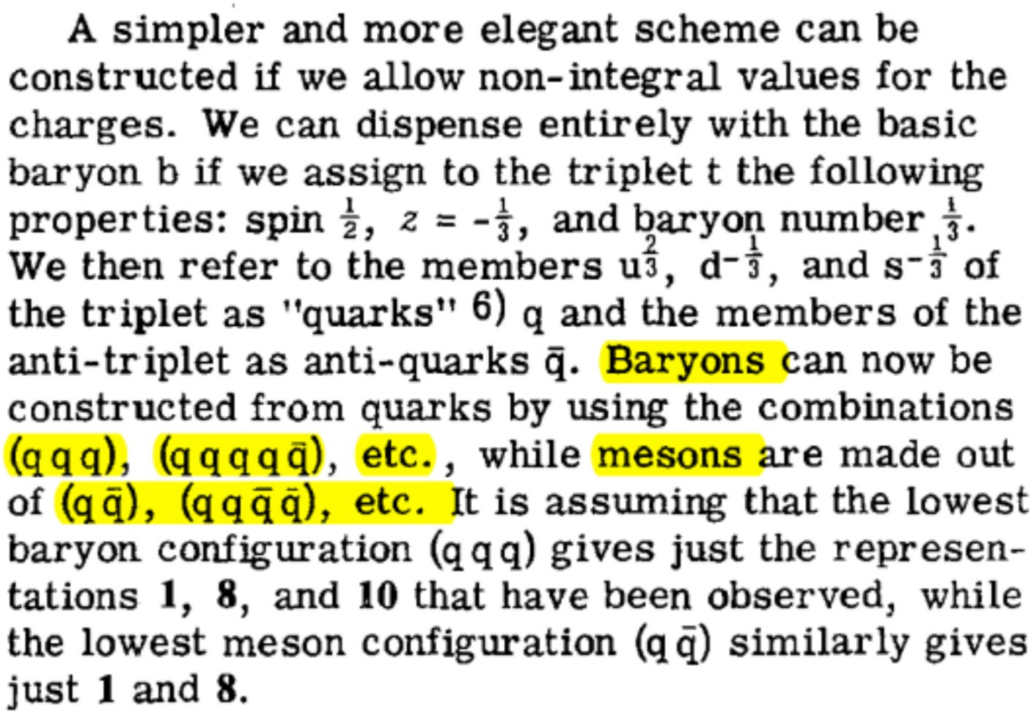
Exotic interpretations

Nature Reviews Physics 1, 480 (2019)
Physics Reports 873, 1 (2020)

In 1963 Gell-Mann proposed the quark model:

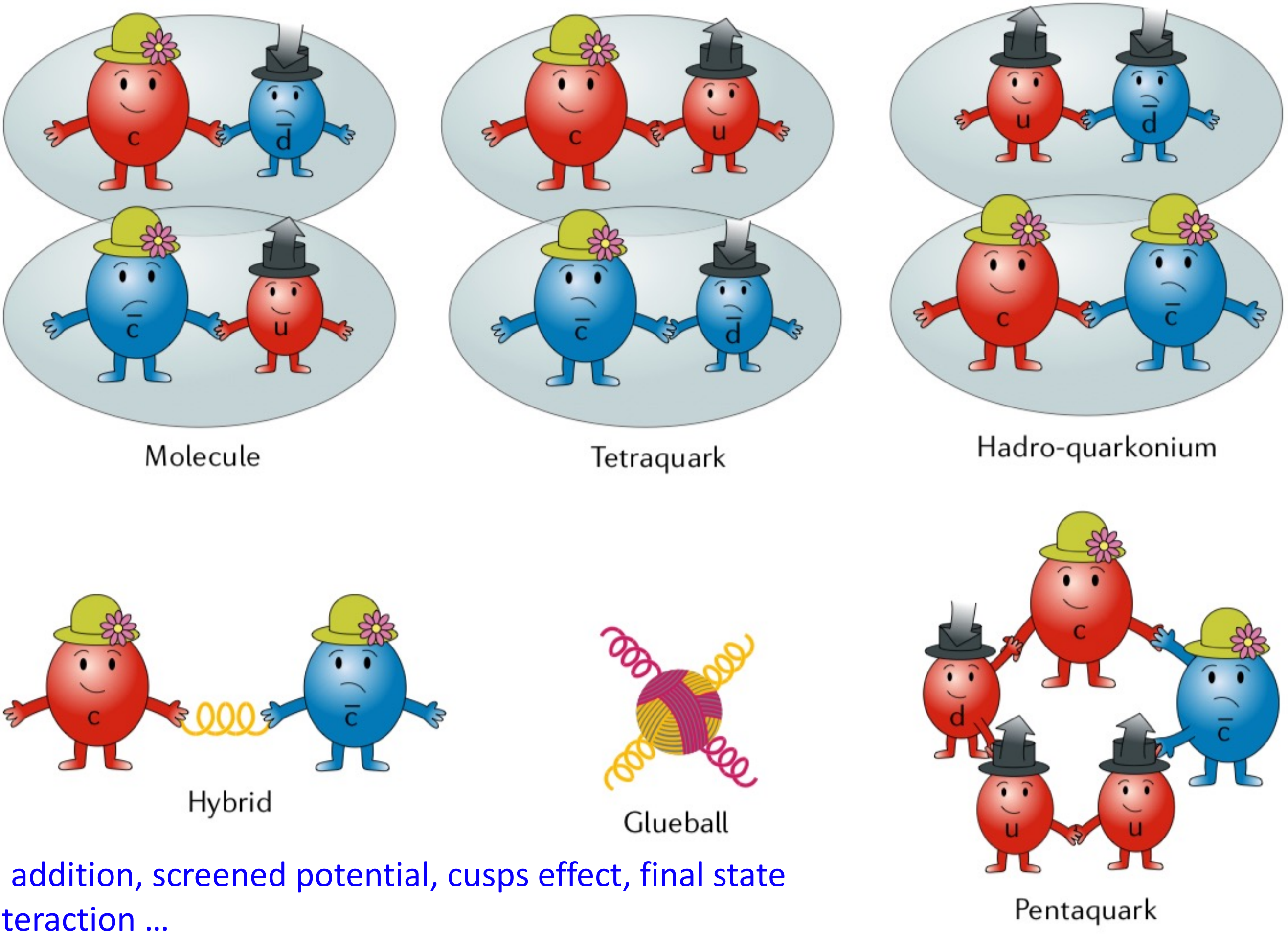
- Conventional hadrons: mesons (2 quarks) and baryons (3 quarks)
- QCD does not forbid hadrons with > 3 quarks!!

Physics Letters 8, 214 (1964).



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**.

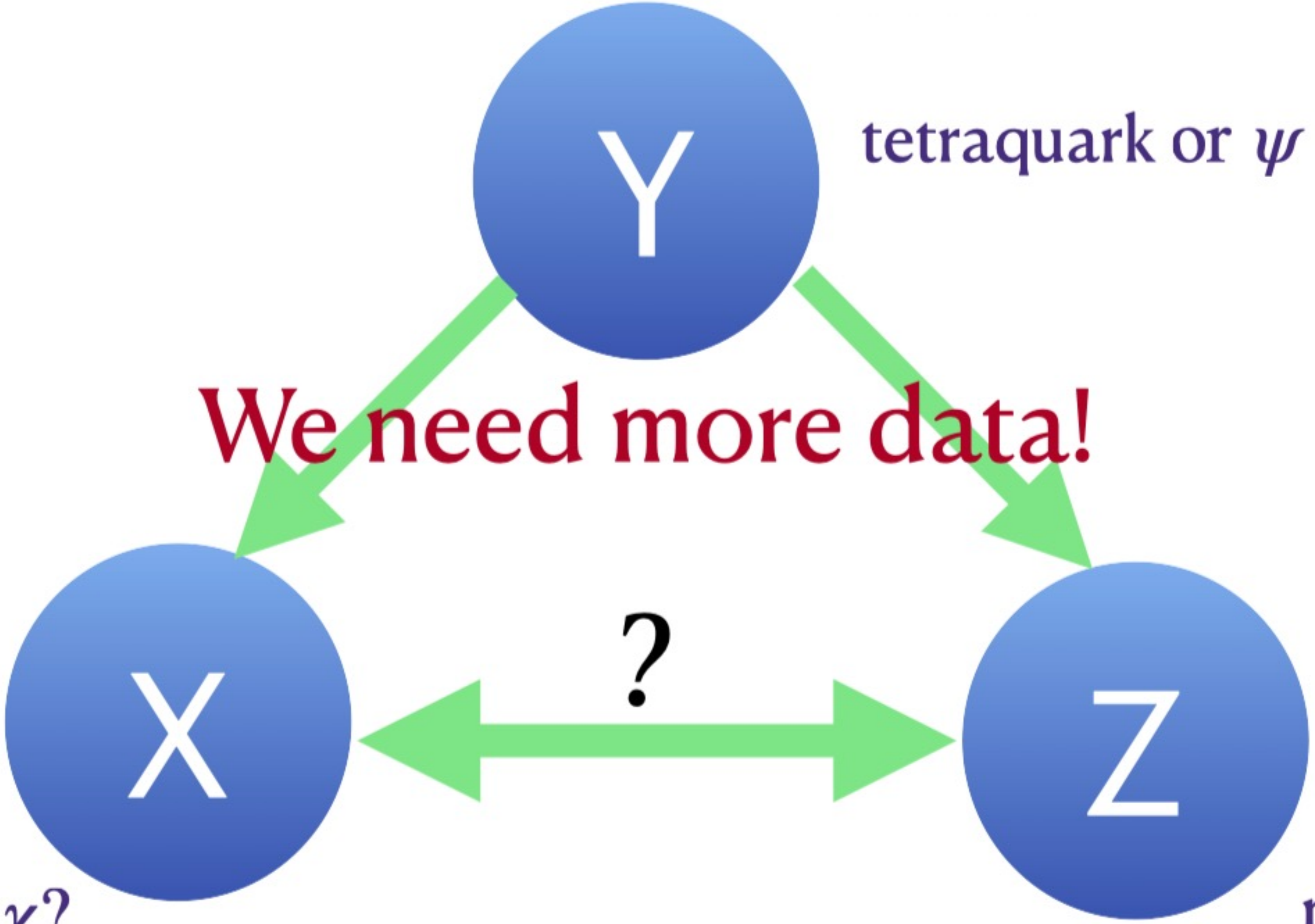
Non-standard hadrons



In addition, screened potential, cusps effect, final state interaction …

High priority: seek unified picture describing all XYZ states, not state-by-state

What are they?



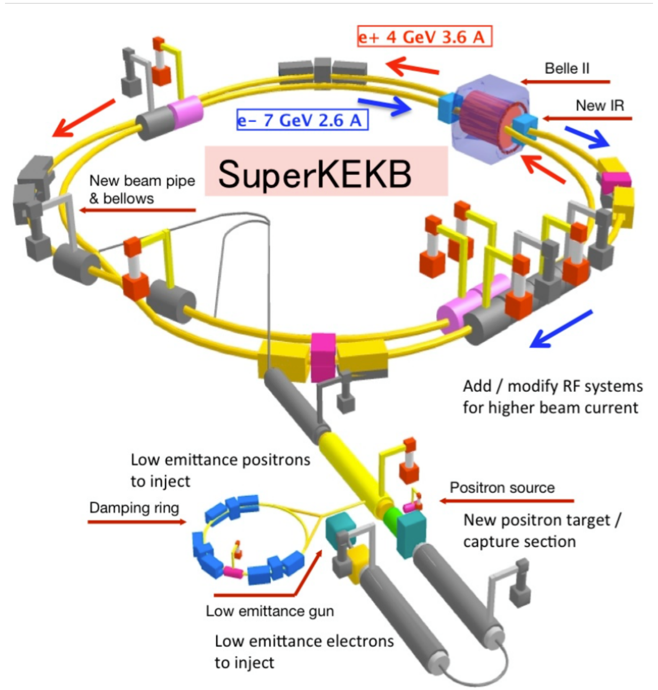
tetraquark or ψ or Υ?

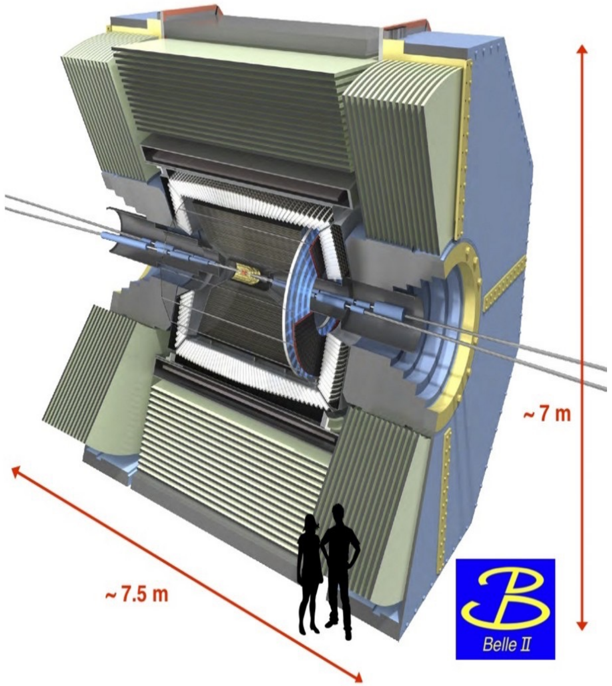
We need more data!

molecule or χ?

molecule or ?

SuperKEKB and Belle II





- Asymmetric energy e^+e^- (4 & 7 GeV) collider in Tsukuba, Japan
- Much higher luminosity than predecessor
- Upgraded detectors (better vertex and particle identification performances)
- Achieved peak luminosity: 4.7×10^{34} $cm^{-2}s^{-1}$
- Integrated luminosity: ~424/fb

- Charmonium production mechanisms: B decays, initial-state radiation, two-photon collisions, and double charmonium production.
- Bottomonium production mechanisms: direct production from e^+e^-, initial-state radiation, and hadronic/radiative transitions.

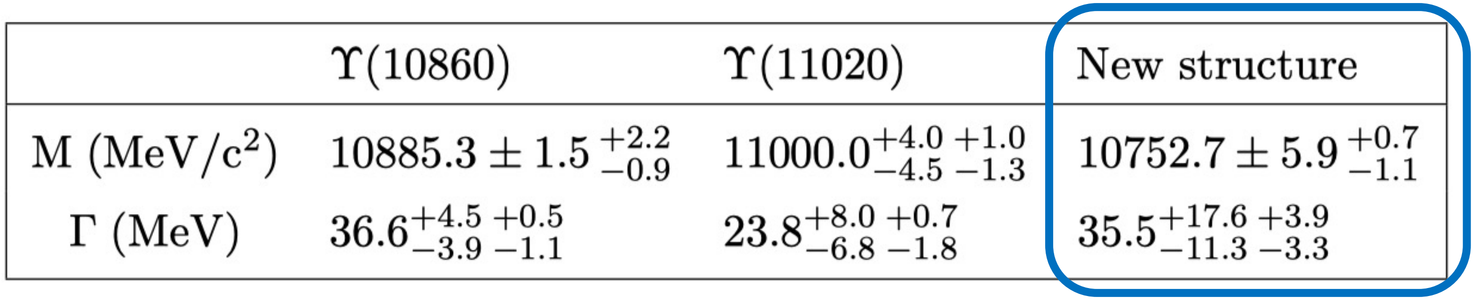
New result

Observation of $e^{+}e^{-} \to \omega\chi_{bJ}$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

Motivation: $\Upsilon(10753)$

JHEP 10, 220 (2019)

- Belle: several ~1fb^{-1} scan points below Y(5S)
- New structure observed in $\pi^+\pi^-\Upsilon(nS)$ transitions



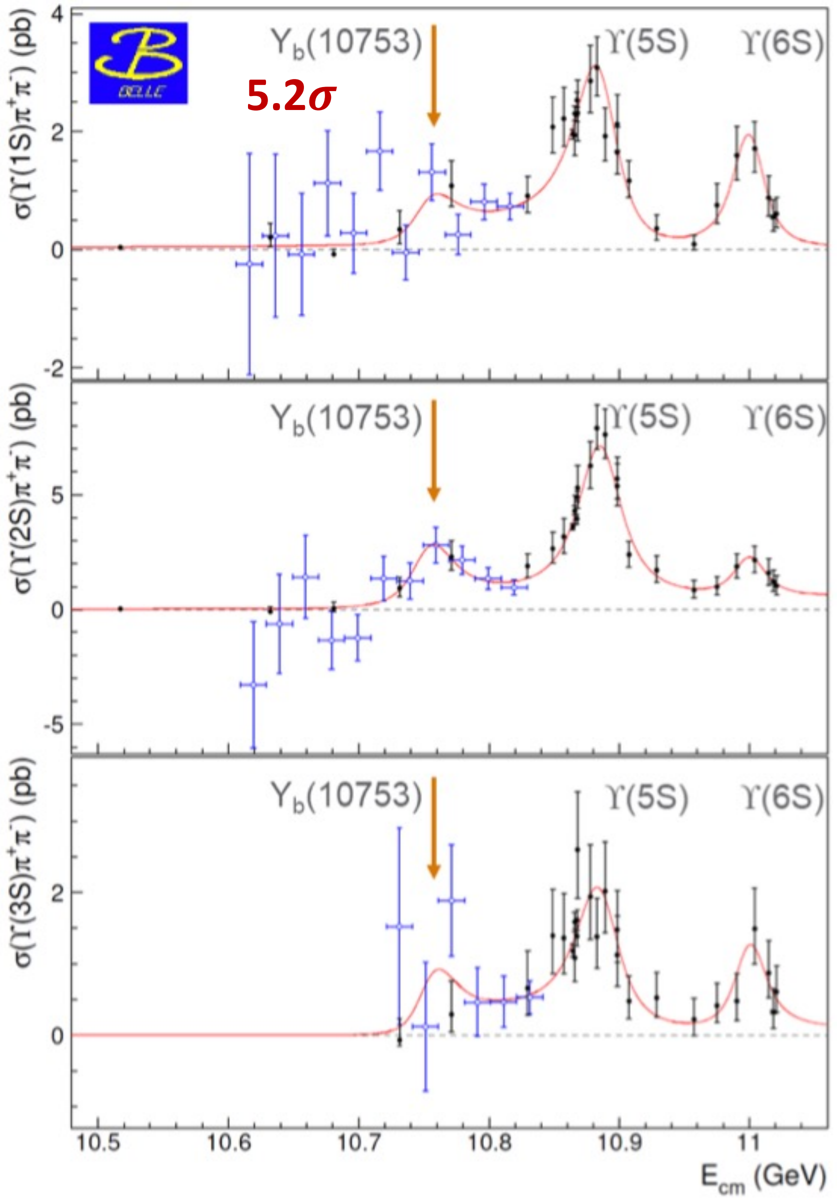
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

- Theoretical interpretations

Conventional D- or S-D mixed bottomonium:
PRD 105, 074007 (2022), PRD 104, 034036 (2021)
EPJC 80, 59 (2020), PRD 101,397 014020 (2020)
PRD 102, 014036399 (2020), EPJP 137, 357 (2022)
PRD 105, 114041 (2022), PLB 803, 135340 (2020)
arXiv:2204.11915, Prog. Part. Nucl. Phys. 117, 103845 (2021)

A tetraquark:
PLB 802, 135217 (2020)
PRD 103, 074507 (2021
arXiv:2205.11475
Chin. Phys. C 43, 123102 (2019)

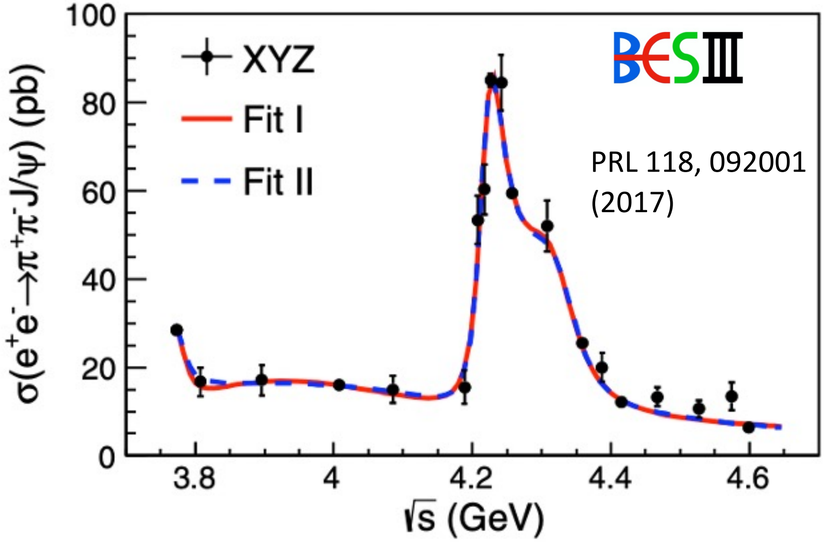
- $\Upsilon(10753)$ is predicted to decay into $\omega\chi_{bJ}$ with a BF of 10^{-3} based on the mixing of the conventional states 4S and 3D [PRD 104, 034036 (2021)].



X_b: Bottomonium counterpart of X(3872)?

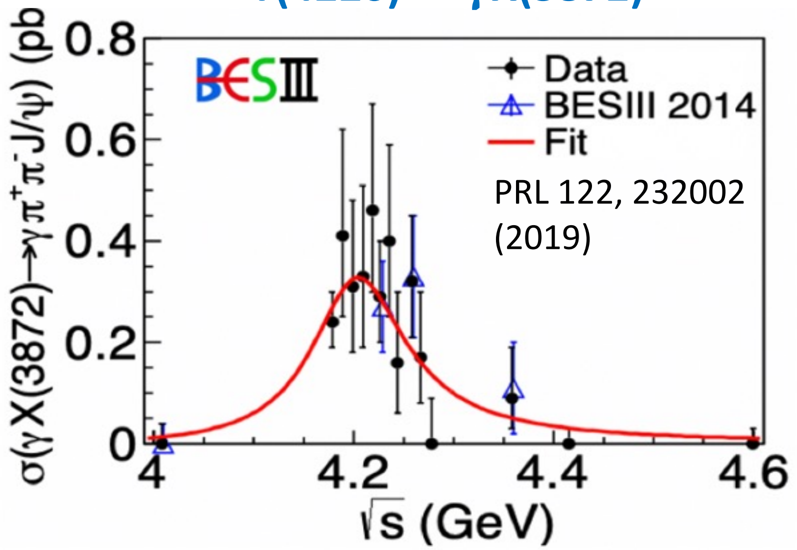
- Two close peaks observed in the cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII[1] and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ by Belle[2], respectively, may suggest similar nature.
- Y(4220) → $\gamma X(3872)$[3] and $\omega\chi_{c0}$[4] observed by BESIII.
- So expect the $\Upsilon(10753)$ state to decay into γX_b with $X_b \to \omega\Upsilon(1S)$, as well as a potential resonance in the line shape of $\sigma(e^+e^- \to \omega\chi_{bJ})$.

Y(4220)/Y(4320) → $\pi^+\pi^- J/\psi$



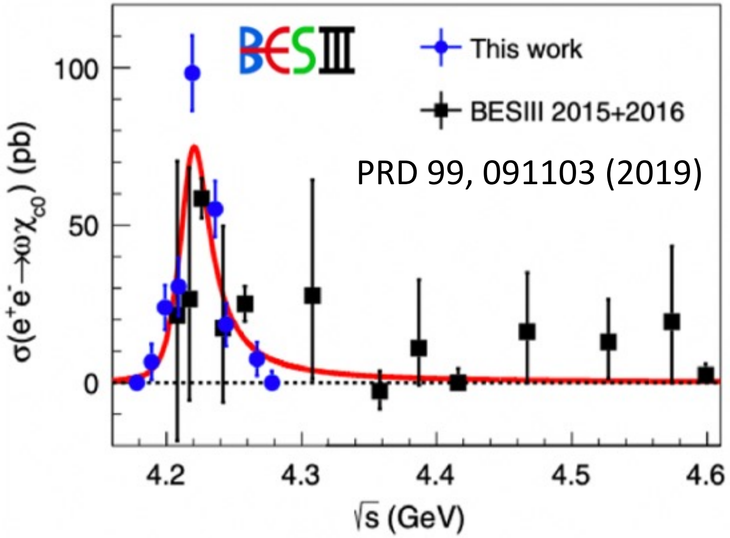
PRL 118, 092001 (2017)

Y(4220) → $\gamma X(3872)$



PRL 122, 232002 (2019)

Y(4220) → $\omega\chi_{c0}$

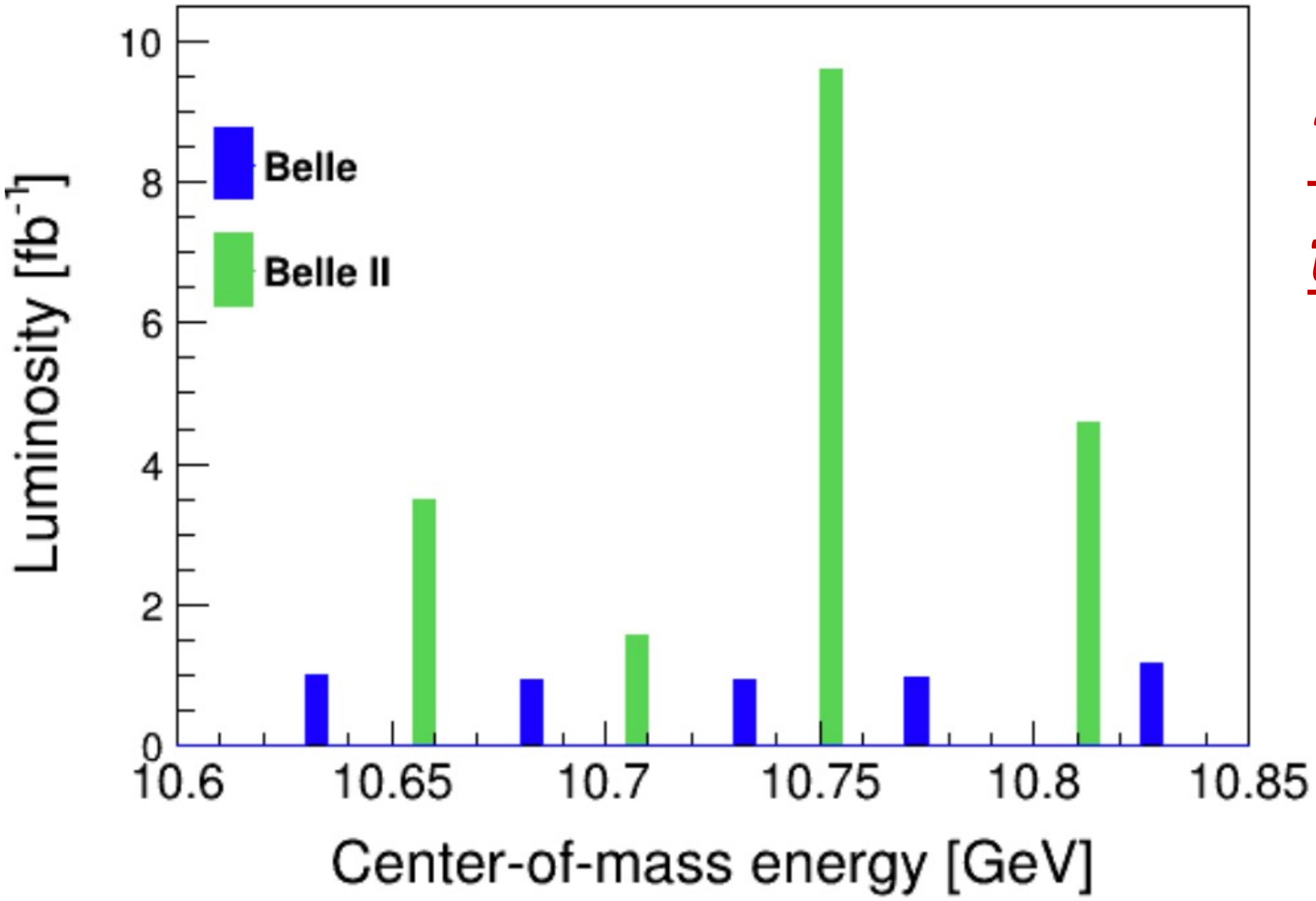


PRD 99, 091103 (2019)

[1] PRL 118, 092001 (2017); [2] JHEP 10, 220 (2019); [3] PRL 122, 232002 (2019); [4] PRD 99, 091103 (2019)

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

- In November 2021, Belle II collected 19 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 $\Upsilon(10753)$ energy region.



This is the first showing of these results.

New result

Analysis goals

$e^+e^- \to \omega\chi_{bJ}$:

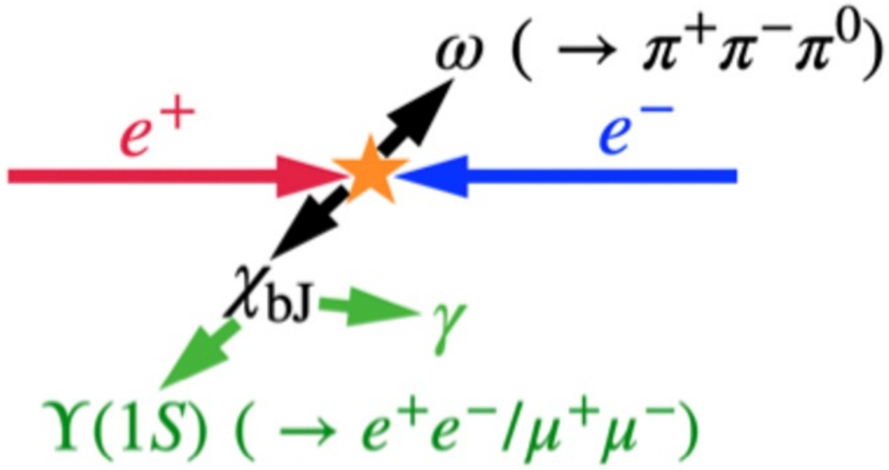
- Determine the Born cross section for $e^+e^- \to \omega\chi_{bJ}$ using unique scan data samples at $\sqrt{s}$ = 10.701, 10.745 and 10.805 GeV.
- Study the energy dependence of Born cross section for $e^+e^- \to \omega\chi_{bJ}$ by combining with Belle data at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)].

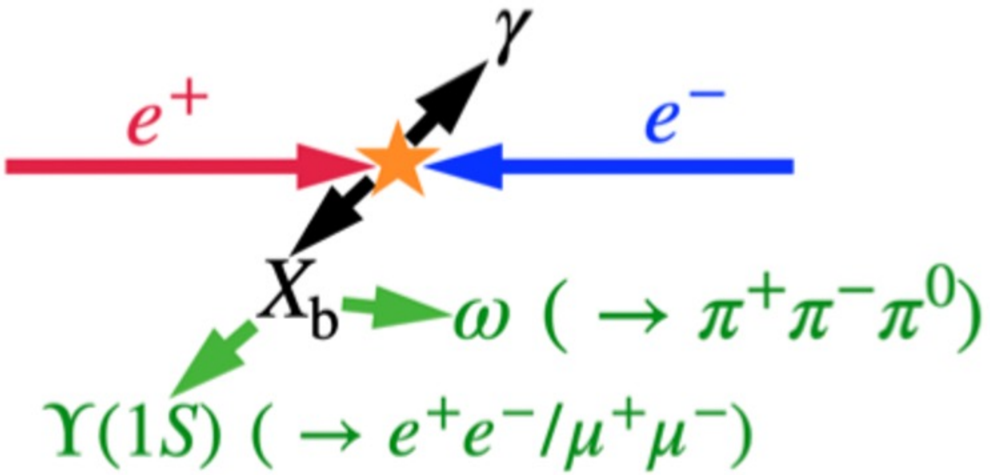
$e^+e^- \to \gamma X_b$:

- Search for the X_b using unique scan data samples at $\sqrt{s}$ = 10.653, 10.701, 10.745 and 10.805 GeV.

Analysis overview

New result





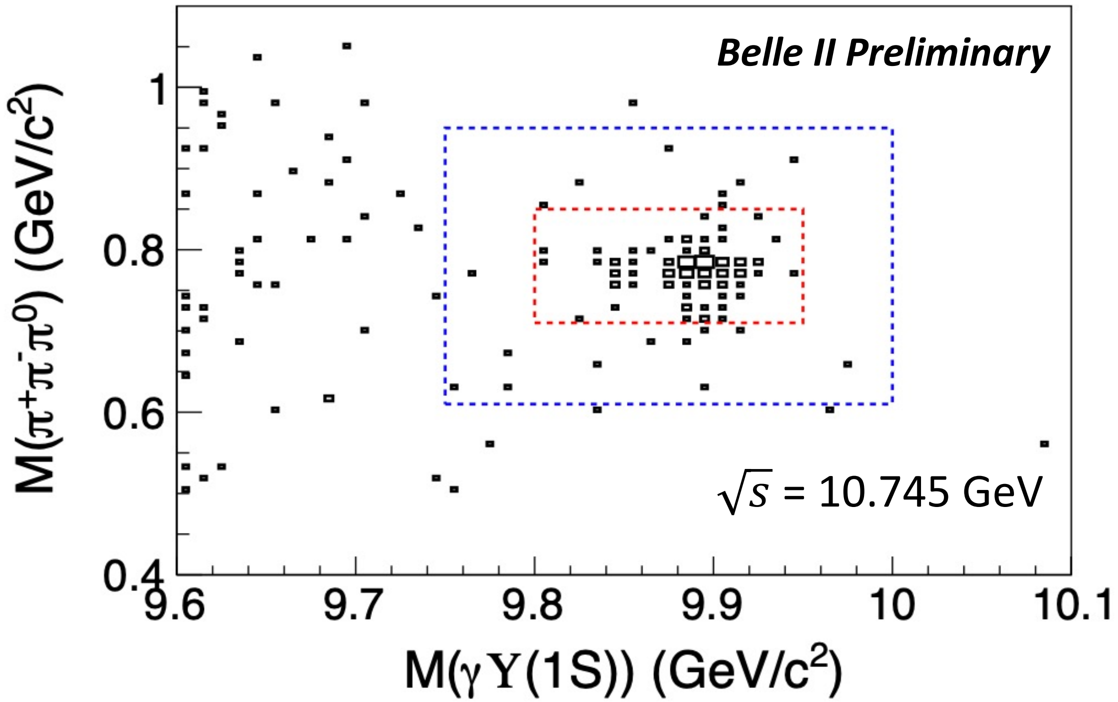
\- Event selection criteria

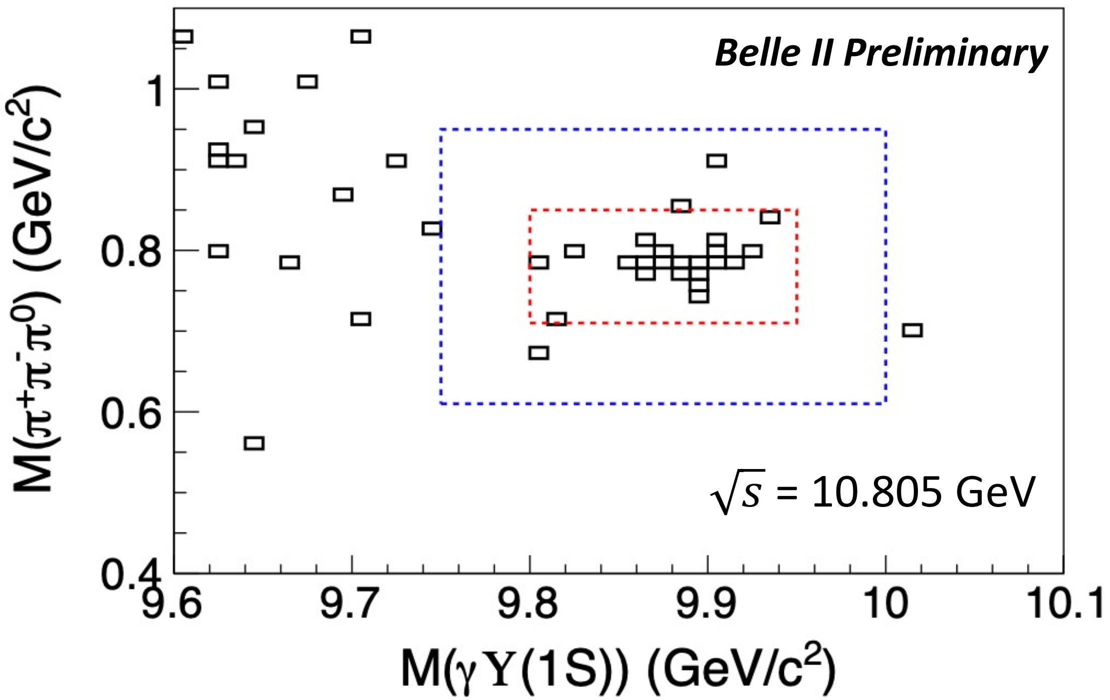
- 4 or 5 charged particles
- standard Belle II PID: 90-95% efficiency with 1-5% misID
- χ_{bJ} photon energy > 50 MeV
- $0.105 < M(\gamma\gamma) < 0.150$ GeV/c^2 (90% efficiency)
- constrained kinematic fit to $\pi^+\pi^-\pi^0\gamma e^+e^-/\mu^+\mu^-$ final states
- best candidate based on fit quality

\- Data driven corrections and systematics from control samples

Mass distributions

New result

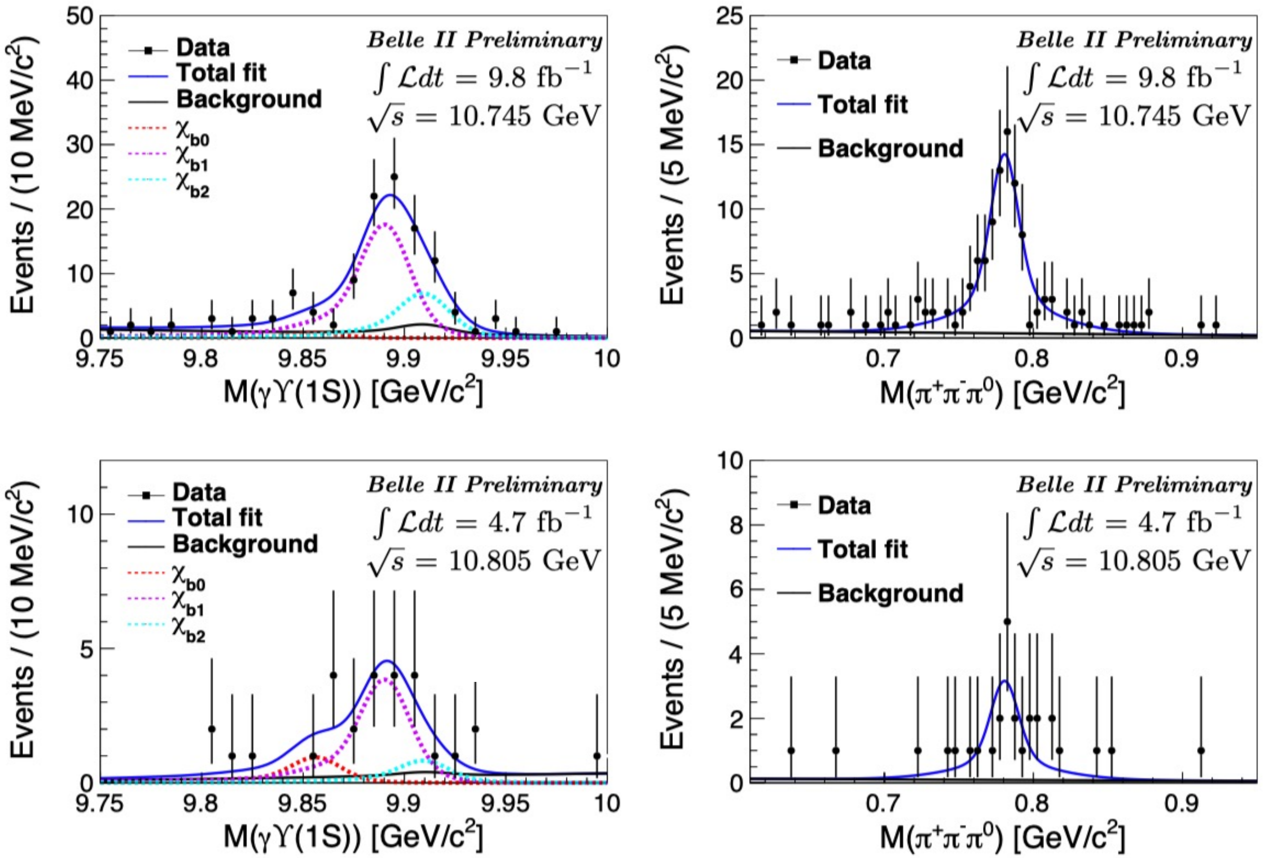




- Red box contains 95% of signals
- Blue box defines one-dimensional projection ranges

Observation of $e^+e^- \to \omega\chi_{bJ}$

New result



Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

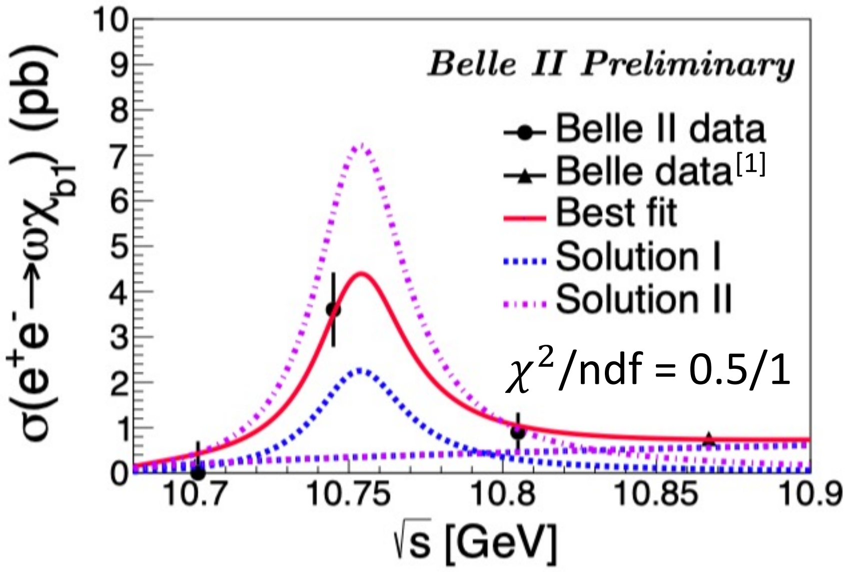
Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma^{(UL)}_{Born}$ (pb)
$\omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.4$
$\omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.5$
$\omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	1.6 @90% C.L.
$\omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	1.5 @90% C.L.

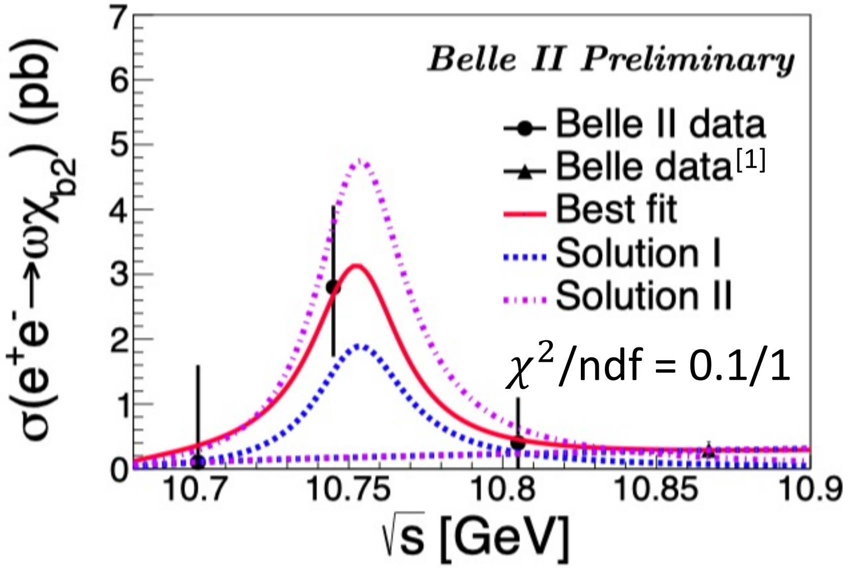
The total χ_{bJ} signal significances are 11.5σ and 5.2σ at $\sqrt{s}$ = 10.745 and 10.805 GeV.

Note that the $\sigma_{\mathrm{Born}}(e^+e^- \to \omega\chi_{b1}/\omega\chi_{b2})$ is only (0.76±0.11±0.11)/(0.29±0.11±0.08) pb at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001(2014)].

Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$

New result





The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$, while no obvious peak at $\Upsilon(10860)$ is found!

Combine Belle II measurements with Belle measurement[1] to fit cross section with function:

$$\sigma_{e^+e^-\to\omega\chi_{b1}}(\sqrt{s}) = \left|\sqrt{PS_2(\sqrt{s})} + \mathrm{BW}(\sqrt{s})e^{i\phi}\right|^2, \mathrm{BW}(\sqrt{s}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 + iM\Gamma}\sqrt{\frac{PS_2(\sqrt{s})}{PS_2(M)}}$$

M and Γ of $\Upsilon(10753)$ are fixed according to Ref. [3].

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

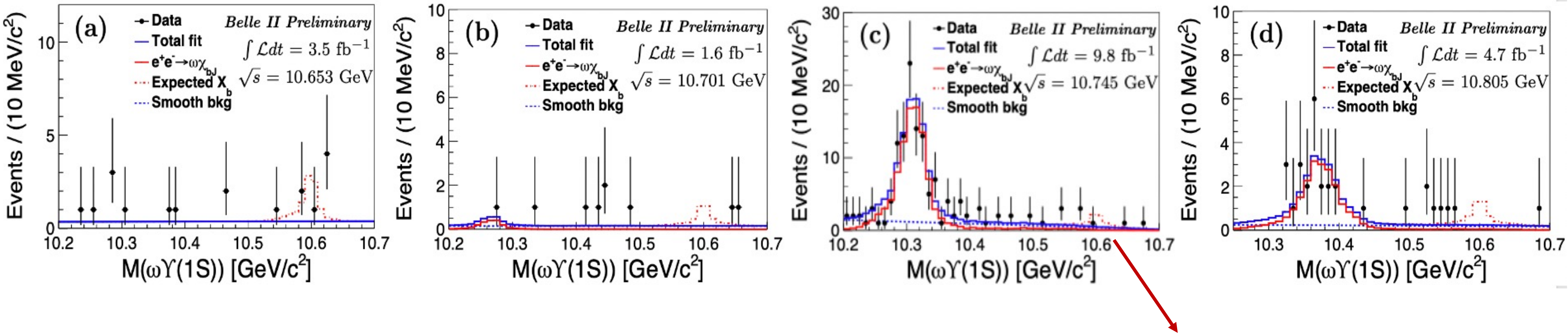
- $\frac{\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})}{\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})}$ ~ 1 agrees with the expectation for HQET[2]
- $\frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/b2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))^{[3]}}$ ~ 1.5 for $\Upsilon(10753)$ and 0.1 for $\Upsilon(10860)$

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

Search for X_b

New result

$e^+e^- \to \gamma X_b(\to \omega\Upsilon(1S))$



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

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

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b)\cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
	$m(X_b) = 10.6$ GeV/c^2	0.45	0.33	0.10	0.14
	$m(X_b) = (10.45, 10.65)$ GeV/c^2	(0.14, 0.54)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.36)

Belle II potential – 10.75 GeV

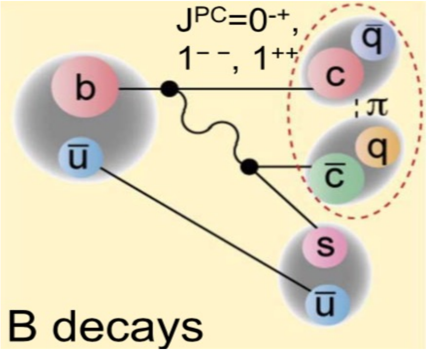
Other active ongoing analyses based on unique scan data at Belle II:

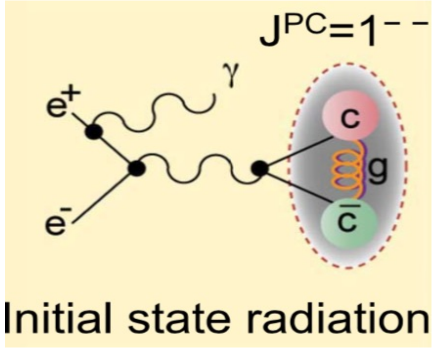
Channel
$B\overline{B}$ decomposition
$e^+e^- \to \gamma X_b$
$e^+e^- \to \omega\eta_b(1S)$
$e^+e^- \to \Upsilon(1S) + X$
$e^+e^- \to \pi^+\pi^- h_b(nP)$
$e^+e^- \to \pi^+\pi^- \Upsilon_2(1D)$
$e^+e^- \to \pi^+\pi^- \Upsilon(nS)$
$e^+e^- \to \eta h_b(1P)$
$e^+e^- \to \phi\eta_b(1S)$

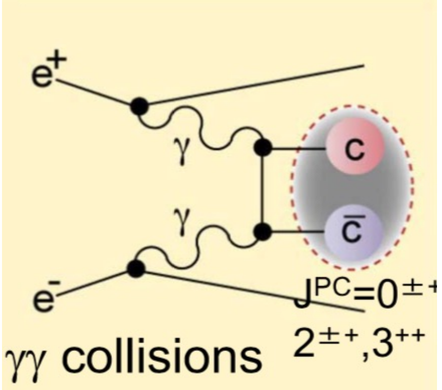
- Quarkonium spectroscopy (conventional and exotic)
- Hadronic and radiative transitions
- Annihilations in exclusive final states
- Precision study of the vector states using ISR
- New physics in Bottomonia
- …

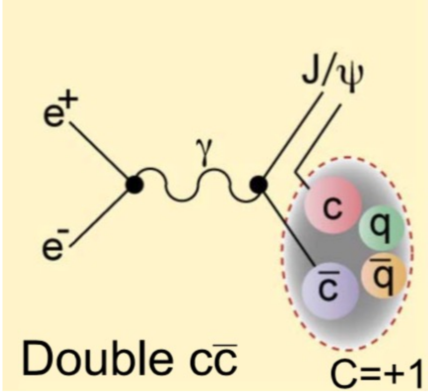
Charmonium(-like) states

- B decay ($B \to KX_{c\bar{c}}$)
  - CKM favored process, large BFs
  - $J^{PC} = 0^{-+}, 1^{--}, 1^{++}, \ldots$
- Initial-state radiation (ISR)
  - $J^{PC} = 1^{--}$
- Two-photon process
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}, \ldots$
- Double charmonium









Belle II capability

- Absolute Branching fraction measurement
- Lineshape determination

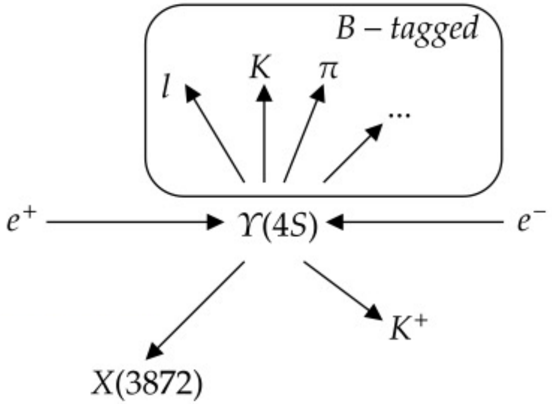
Belle II might measure these values not only for X(3872), but also for other states.

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



Summary

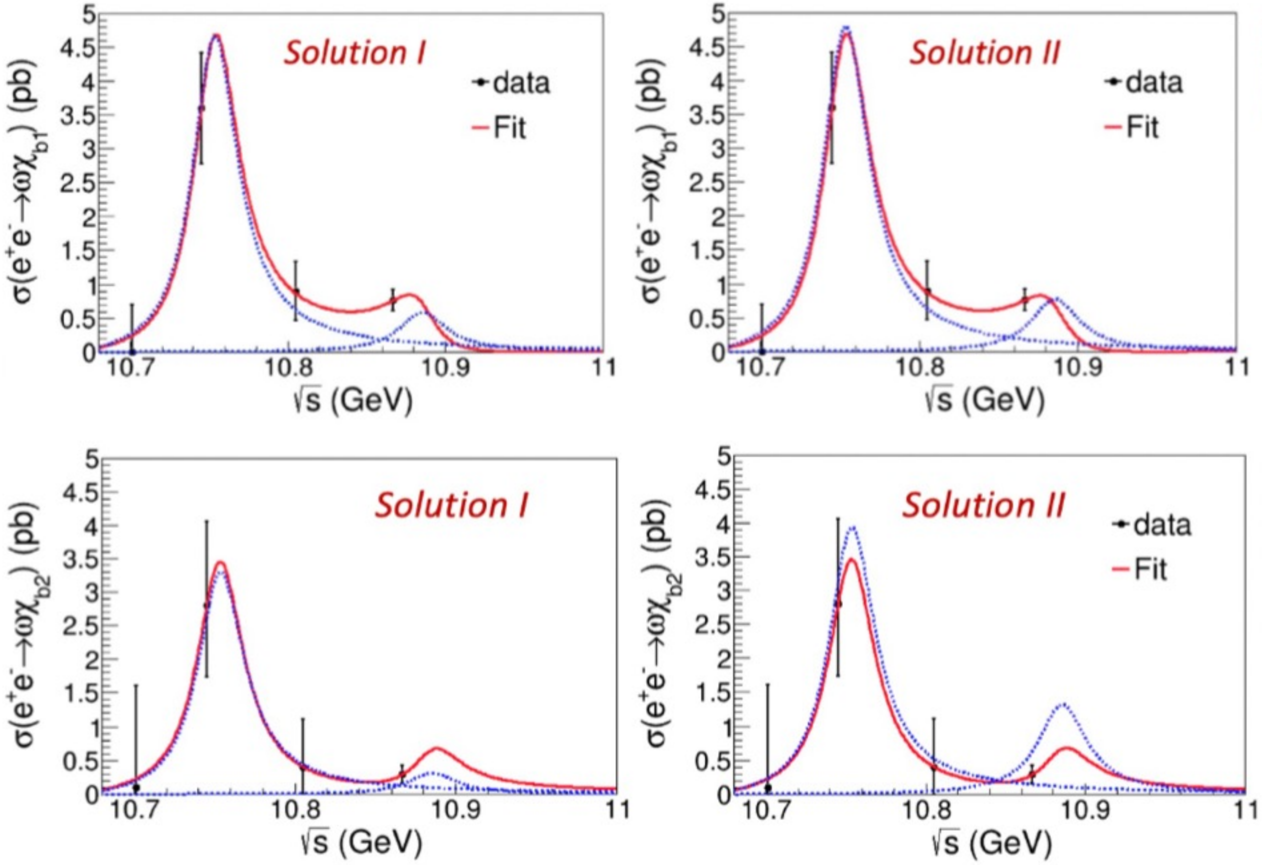
Today first showing of energy-scan data results!

- We are at the beginning of a long program of quarkonium physics.
- The unique scan data near $\sqrt{s}$ = 10.75 GeV at Belle II provide an opportunity to understand the nature of the $\Upsilon(10753)$ energy region, as well as the quarkonium spectroscopy.
- New decay modes of $\Upsilon(10753) \rightarrow \omega\chi_{bJ}$ are observed for the first time.
- No significant X_b signal is observed with a mass around 10.6 GeV/c^2, and the upper limits at 90% C.L. are set.
- Quarkonium Belle II program is not limited to bottomonium: setting up a program to determine precisely absolute BF and lineshape of X(3872).

Thanks for your attention!

Backup slides

Alternative fit for $\sigma(e^+e^- \to \omega\chi_{bJ})$



$$\sigma_{\omega\chi_{c1/2}}(\sqrt{s}) = |BW_{\Upsilon(10753)} + BW_{\Upsilon(10806)}e^{i\phi}|^2$$

M and Γ are fixed referring to Ref. [1][2]

$$\frac{\Gamma_{ee}B(\Upsilon(10753) \to \omega\chi_{b1})}{\Gamma_{ee}B(\Upsilon(10753) \to \omega\chi_{b2})}$$

Solution I: $\dfrac{1.24 \pm 0.56(\text{stat.})}{0.92 \pm 0.37(\text{stat.})}$

Solution II : $\dfrac{1.28 \pm 0.57(\text{stat.})}{1.09 \pm 0.40(\text{stat.})}$

$\chi^2/\text{ndf} = 0.4$ and 0.1 for $\omega\chi_{b1}$ and $\omega\chi_{b2}$

Ref: [1]. JHEP 10, 220(2019);

[2]. PDG 2022