First result of scan data at around 10.75 GeV at Belle II

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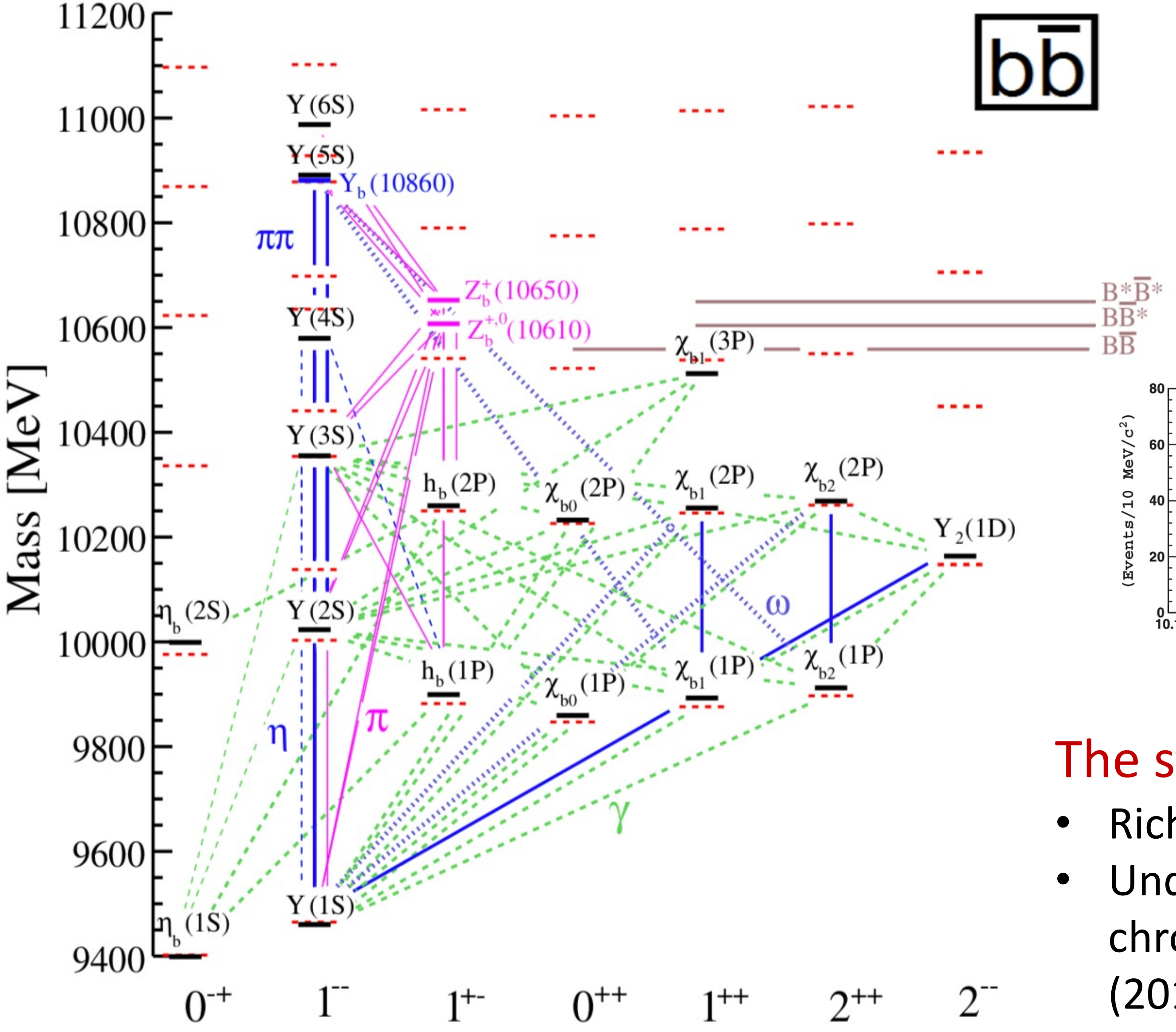
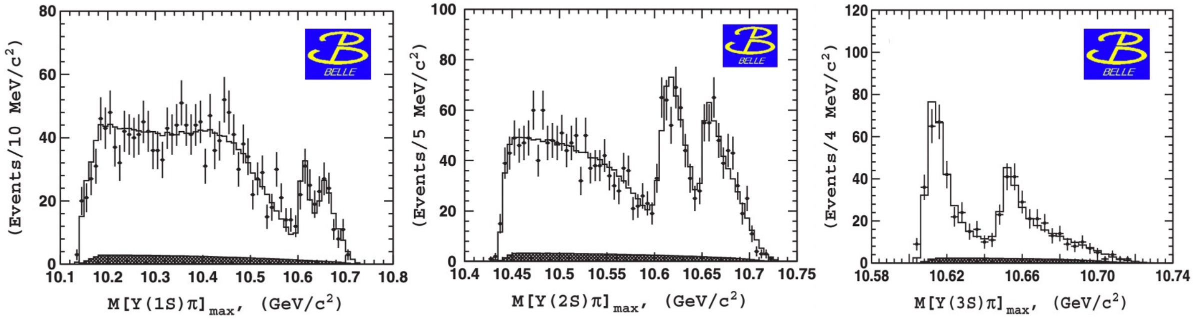
Bottomonium

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



- Conventional bottomonium
- Unconventional charged states

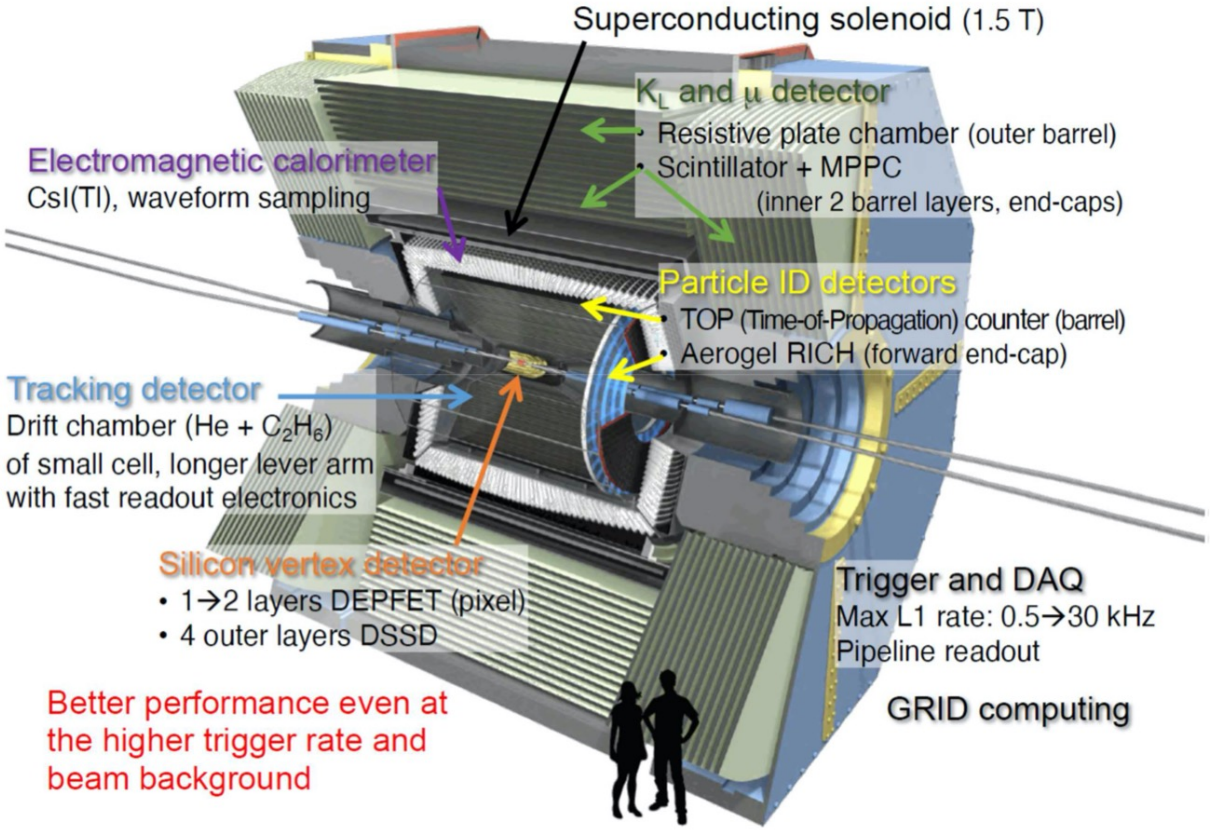
Only two bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ [PRL 108, 122001 (2012)]:



The study of bottomonium states:

- Rich the bottomonium spectroscopy
- Understand the nonperturbative behavior of quantum chromodynamics [EPJC 71, 1534 (2011), EPJC 74, 2981 (2014), PRD 93, 074027 (2016)]

Belle II detector

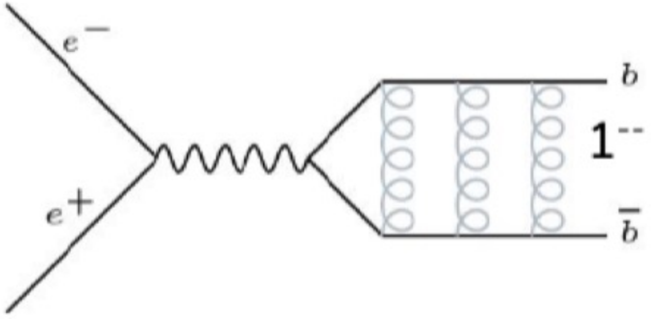


- Asymmetric energy e^+e^- collider operating near $\Upsilon(4S)$ mass peak
- Much higher luminosity than predecessor
- Upgraded detectors (better vertex and particle identification performances)
- Achieved peak luminosity: 4.7×10^{34} $cm^{-2}s^{-1}$
- Current integrated luminosity: ~424/fb (~Babar ~0.5 Belle)

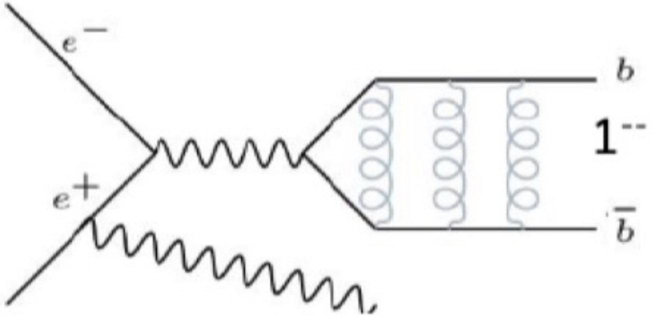
Bottomonium(-like) prospects at Belle II

Four ways to access bottomonia:

- Direct production from e^+e^-: $J^{PC} = 1^{--}$: $\Upsilon(nS)$



- ISR production: $J^{PC} = 1^{--}$: $\Upsilon(nS)$

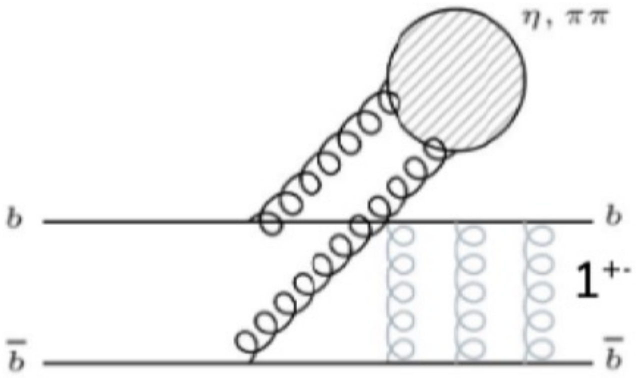


- Hadronic transitions from $\Upsilon(nS)$ through η, ππ, etc

$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}$ … : $\Upsilon(nS)$, $h_b(nS)$, …

- Radiative transitions from $\Upsilon(nS)$

$J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{++}$: $\eta_b(nS)$, χ_b



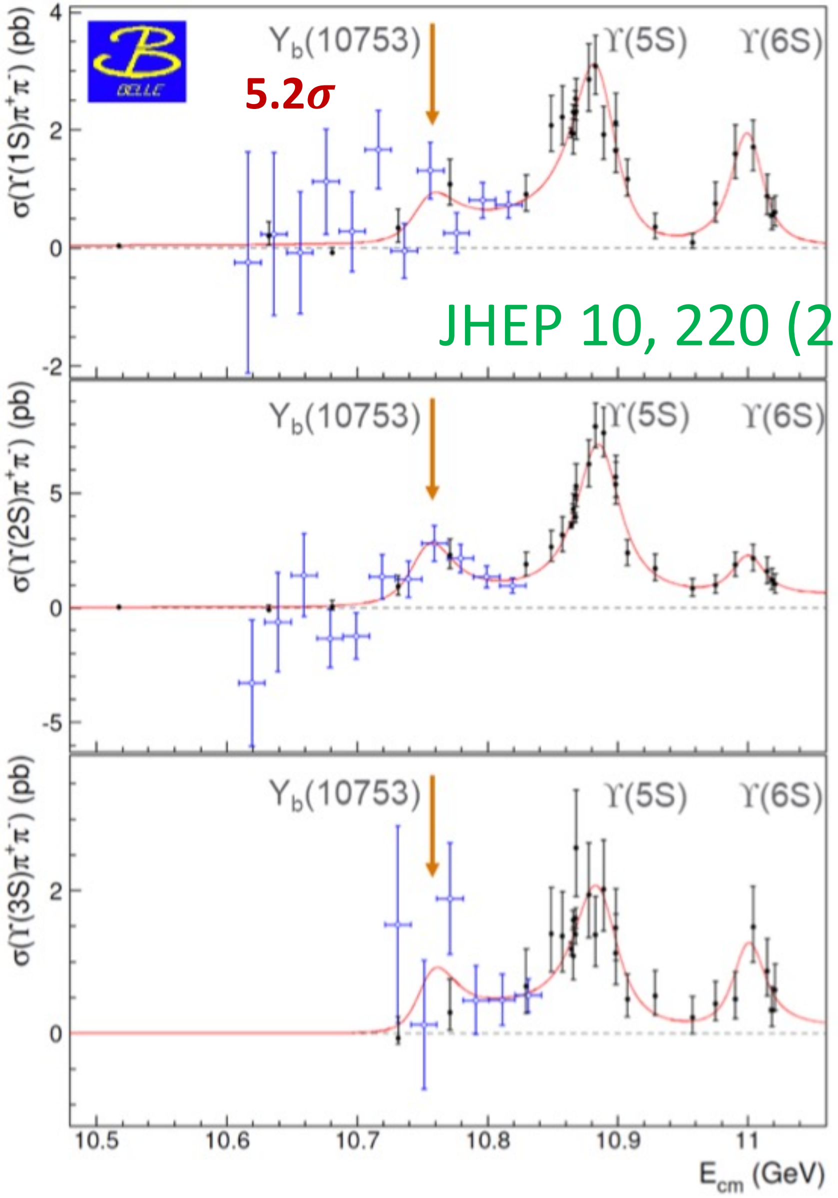
Observation of $e^+e^- \to \omega\chi_{bJ}$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

[arXiv: 2208.13189]

Motivation: $\Upsilon(10753)$

- Belle: several ~1 fb^{-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)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$



JHEP 10, 220 (2019)

- Theoretical interpretations

Conventional D- or S-D mixed bottomonium:
PRD 105, 074007 (2022), PRD 104, 034036 (2021)
EPJC 80, 59 (2020), PRD 101, 014020 (2020)
PRD 102, 014036 (2020), EPJP 137, 357 (2022)
PRD 105, 114041 (2022), PLB 803, 135340 (2020)
PRD 106, 094013 (2022)
Prog. Part. Nucl. Phys. 117, 103845 (2021)

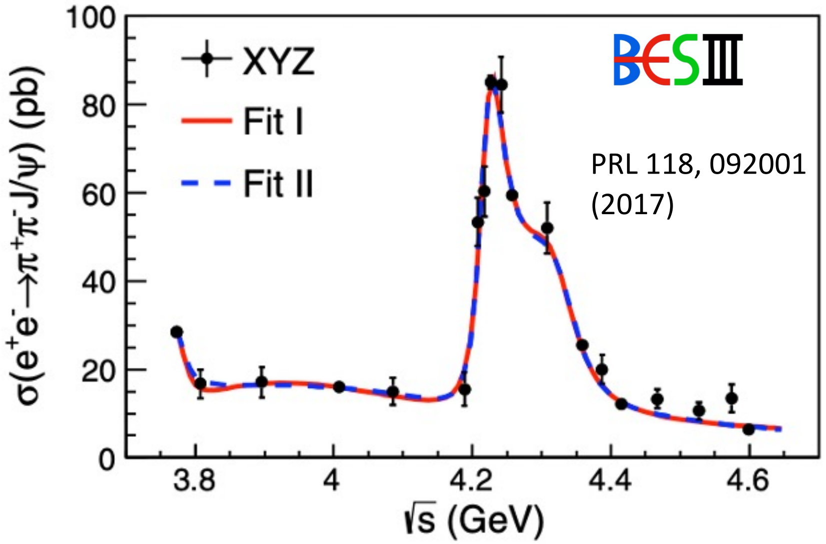
Tetraquark:
PLB 802, 135217 (2020)
PRD 103, 074507 (2021)
arXiv:2205.11475
CPC 43, 123102 (2019)
arXiv: 2210.16250

- Interpretations as an admixture of the conventional 4S and 3D state predict comparable branching fractions of 10^{-3} for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(10753) \to \omega\chi_{bJ}$ [PRD 104, 034036 (2021), PRD 105, 074007 (2022)].

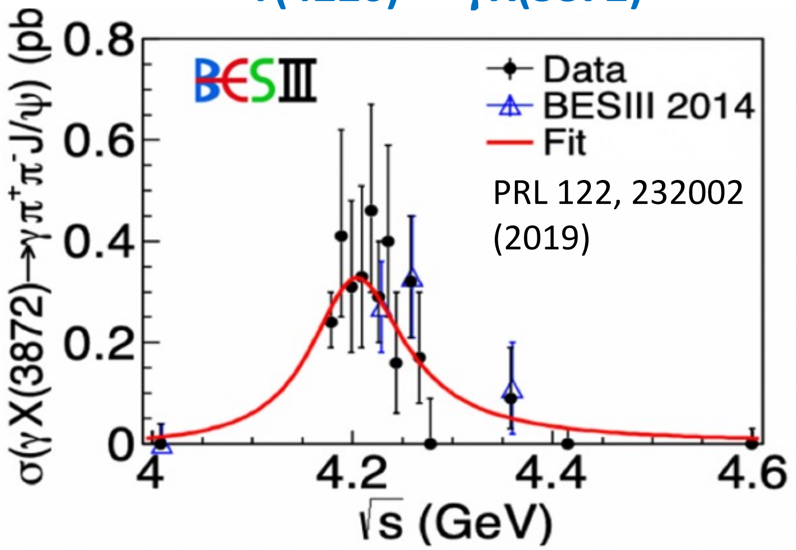
X_b: Bottomonium counterpart of X(3872)?

- 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) $\to \gamma$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 $\sigma(e^+e^- \to \omega\chi_{bJ})$.

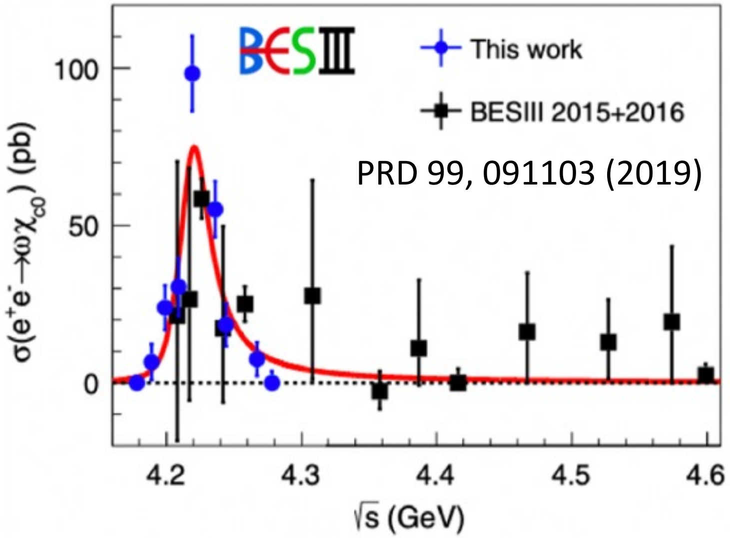
Y(4220)/Y(4320) → $\pi^+\pi^- J/\psi$



Y(4220) → γX(3872)



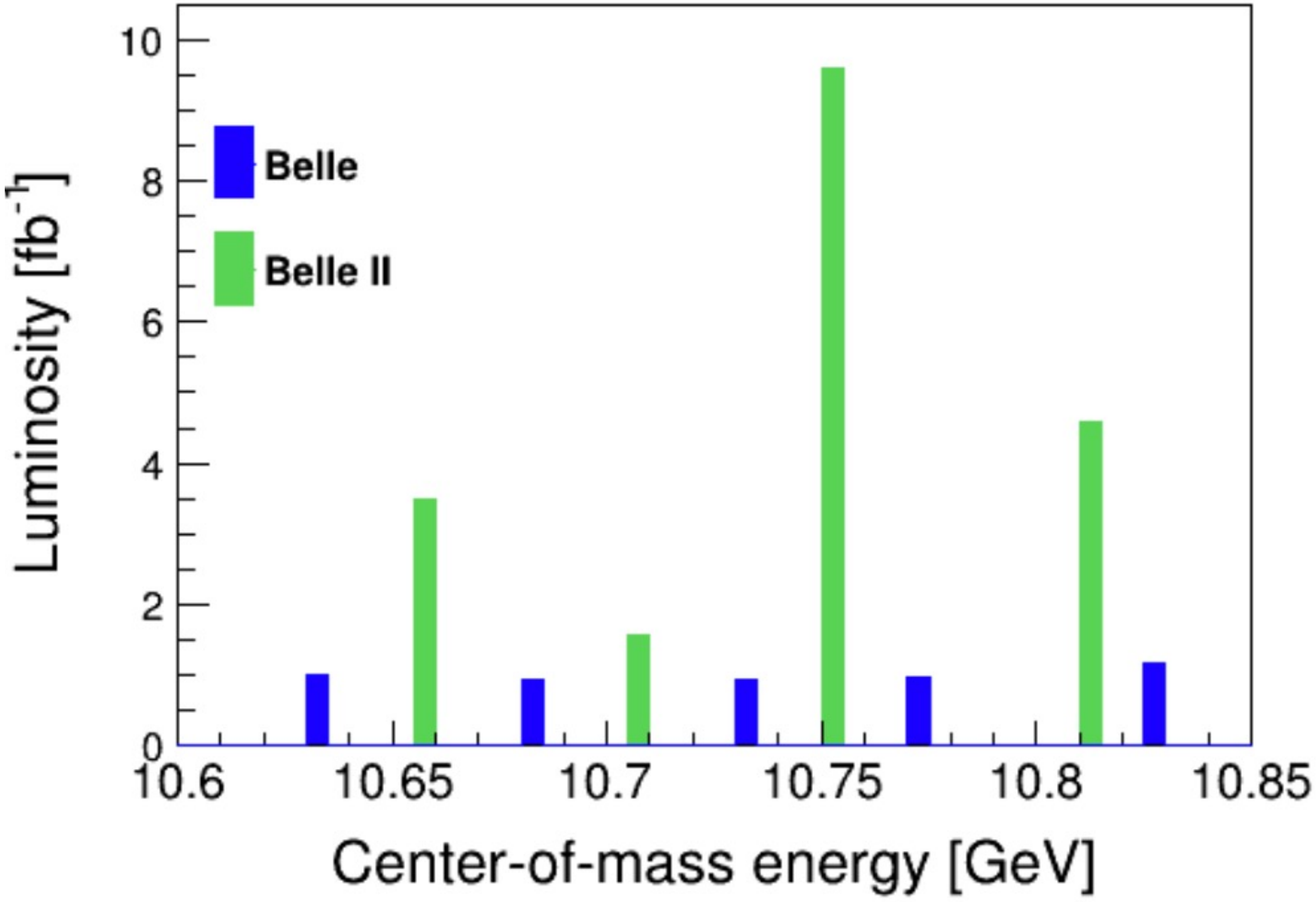
Y(4220) → $\omega\chi_{c0}$



[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.



Analysis goals

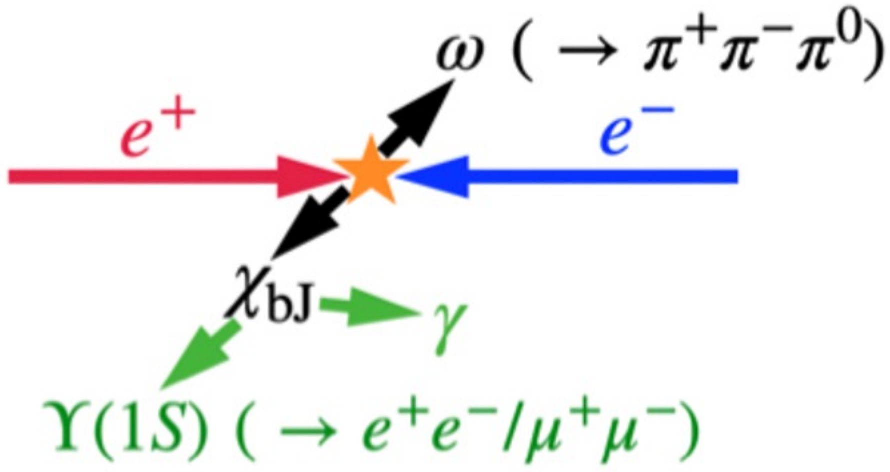
$e^+e^- \to \omega\chi_{bJ}$:

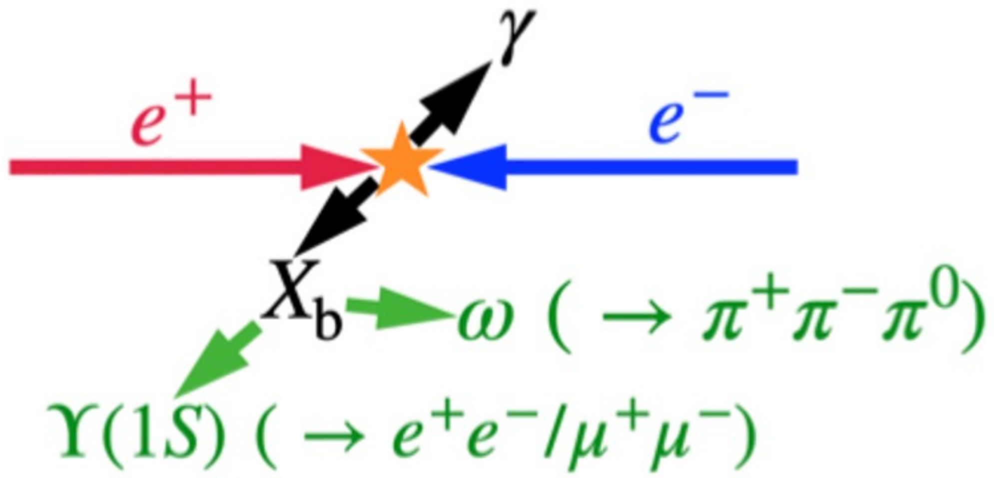
- Determine the Born cross section for $e^+e^- \to \omega\chi_{bJ}$ using unique scan data samples at $\sqrt{s}$ = 10.701, 10.745 and 10.805 GeV.
- Study the energy dependence of Born cross section for $e^+e^- \to \omega\chi_{bJ}$ by combining with Belle data at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001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



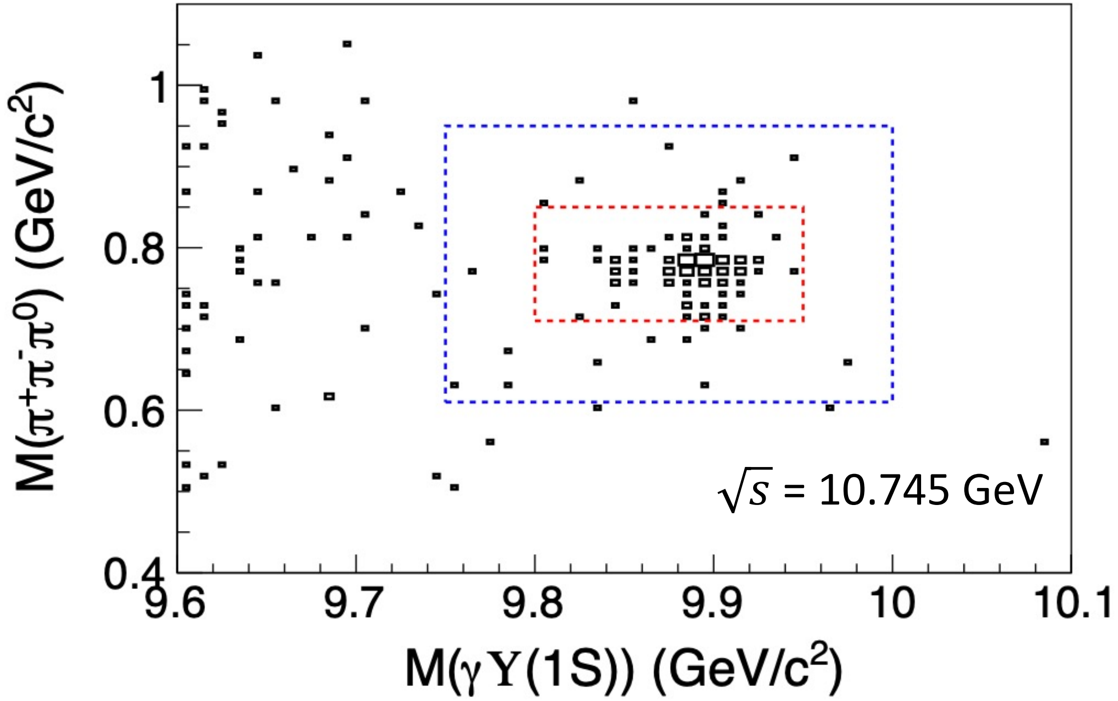


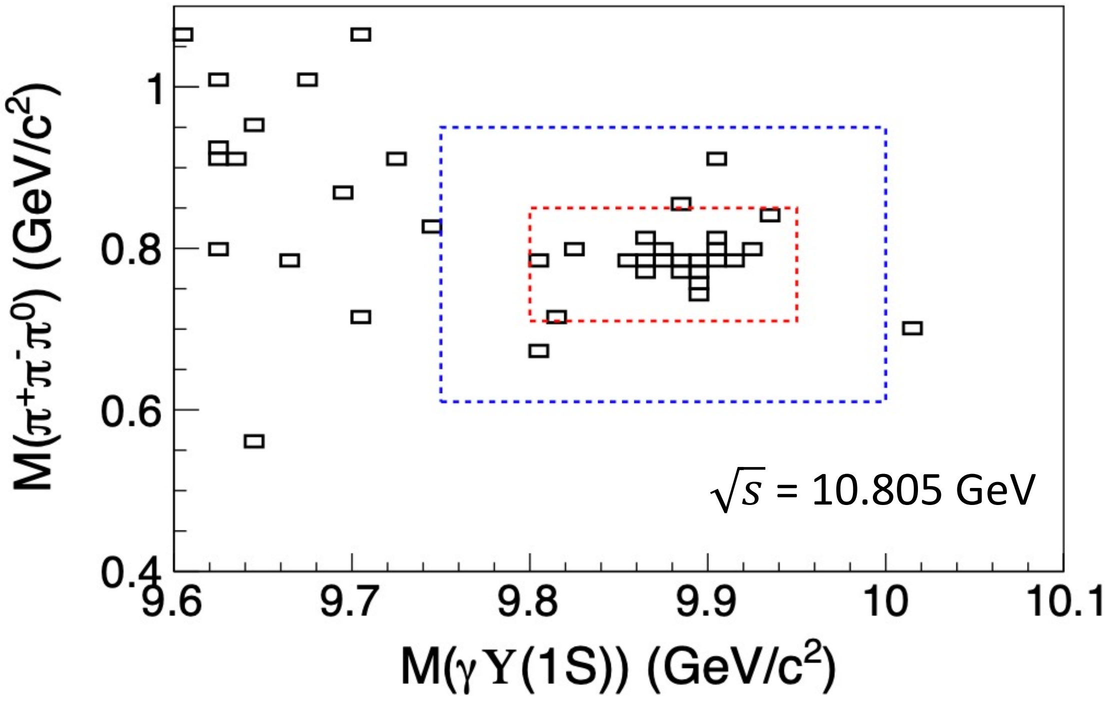
- Event selection criteria

- 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 for π^0 (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

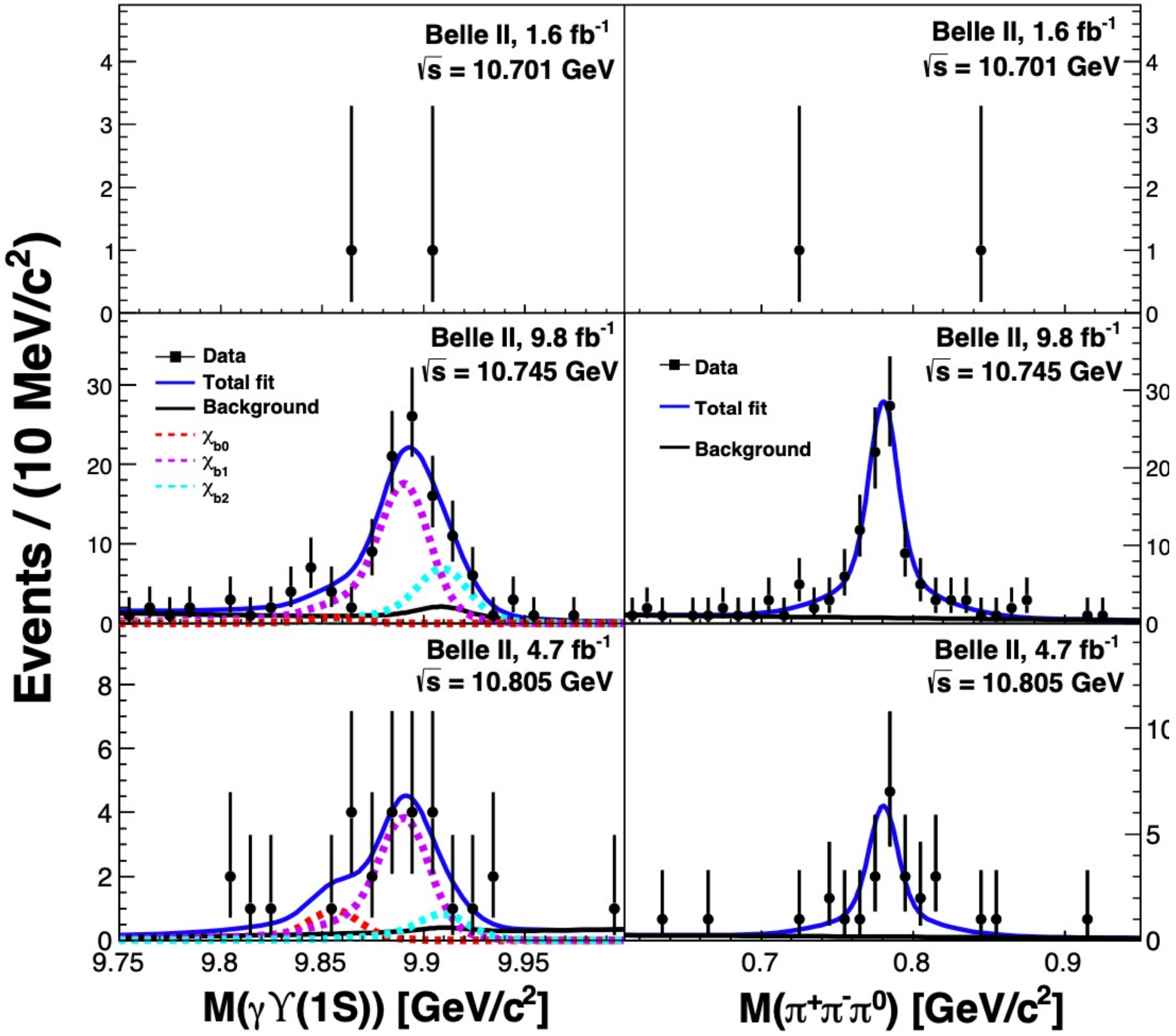
Mass distributions





- Red box contains 95% of signals

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



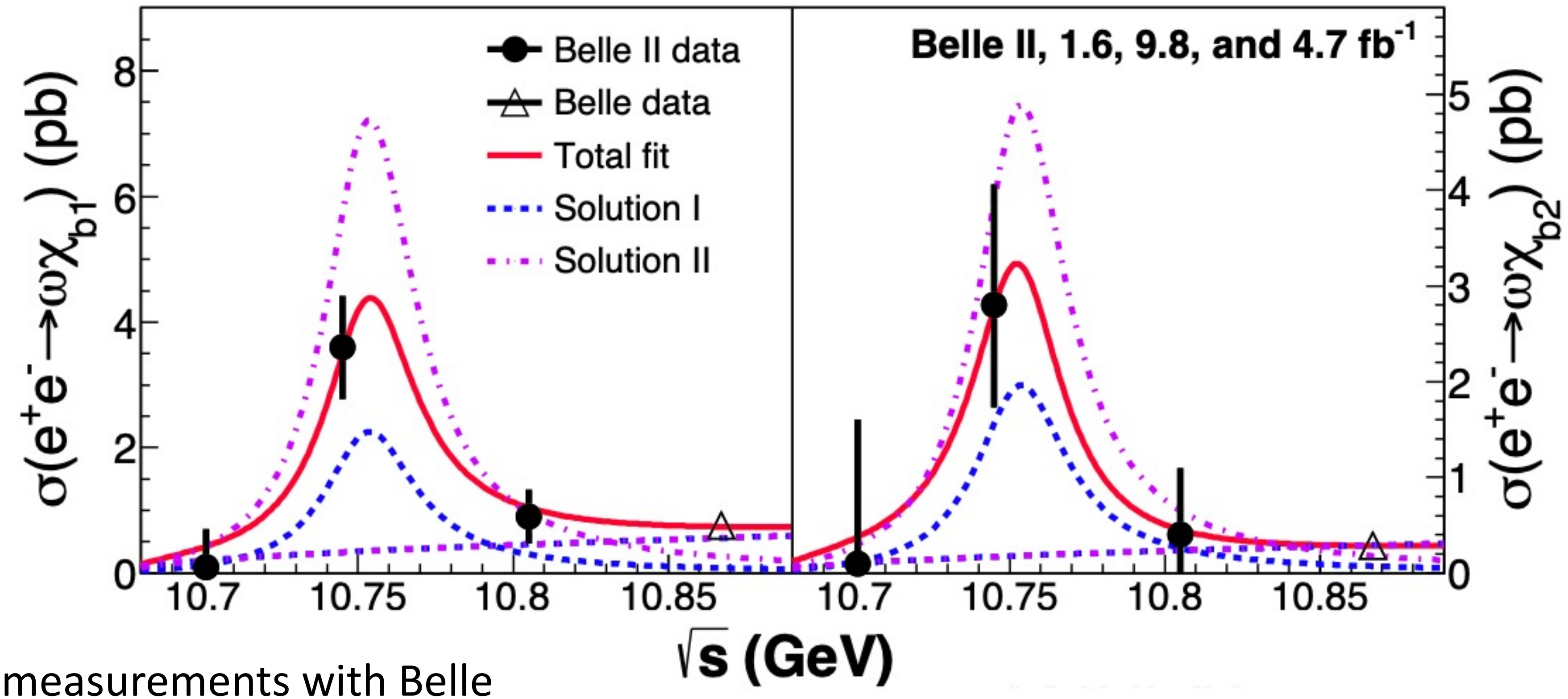
Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma_{Born}^{(UL)}$ (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 11.1σ and 4.5σ at $\sqrt{s}$ = 10.745 and 10.805 GeV.

Note that the $\sigma_{Born}(e^+e^- \to \omega\chi_{b1}/\omega\chi_{b2})$ is only (0.76±0.16)/(0.29±0.14) pb at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001(2014)].

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



Combine Belle II measurements with Belle measurement [PRL 113, 142001(2014)] to fit cross section with function:

$$\sigma_{e^+e^-\to\omega\chi_{b1}}(\sqrt{s}) = |\sqrt{PS_2(\sqrt{s})} + \mathrm{BW}(\sqrt{s})e^{i\phi}|^2,$$

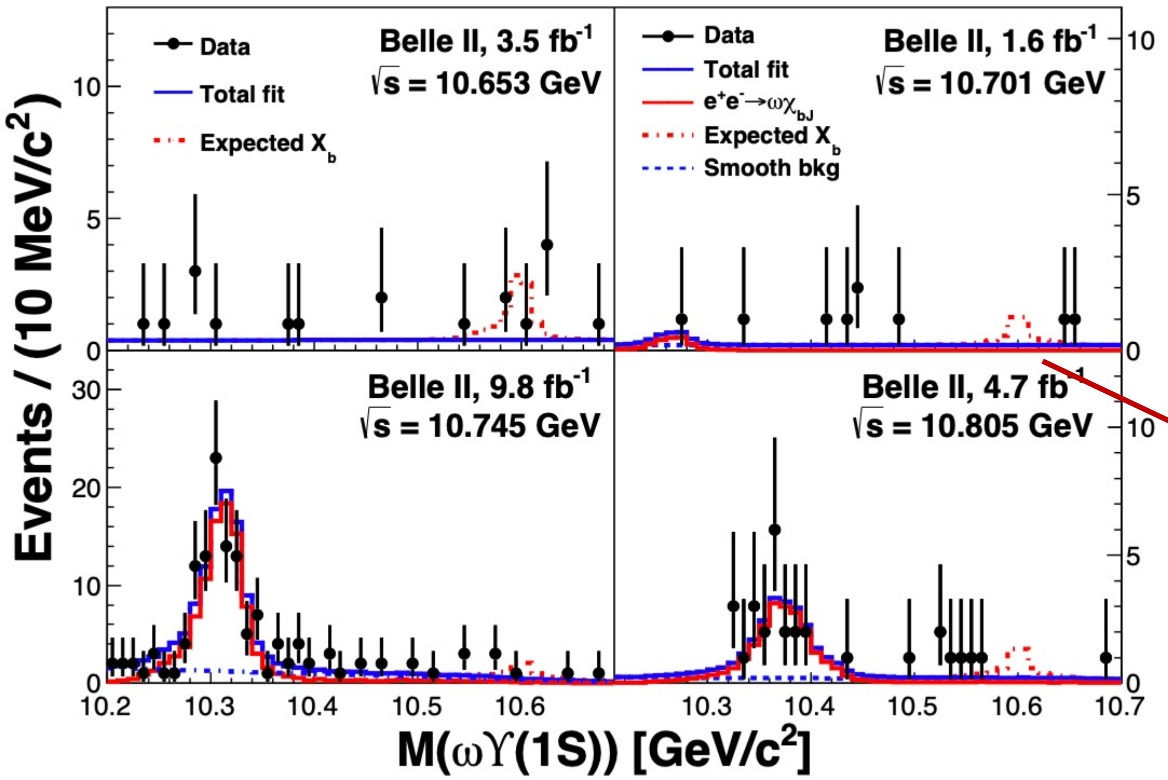
$$\mathrm{BW}(\sqrt{s}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 + iM\Gamma}\sqrt{\frac{PS_2(\sqrt{s})}{PS_2(M)}}$$

$\Gamma_{ee}\mathcal{B}_f$	**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

M and Γ of $\Upsilon(10753)$ are fixed according to Ref. [JHEP 10, 220 (2019)].

Search for X_b

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



- 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.

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	0.46	0.33	0.10	0.14
	$m(X_b) = (10.45, 10.65)$ GeV/c^2	(0.14, 0.55)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.37)

About $\Upsilon(10753)$:

- $\frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/b2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(1S,2S,3S))} \sim$ 2 - 5 for $\Upsilon(10753)$
- $\frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/b2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(1S,2S,3S))} \sim$ 0.2 for $\Upsilon(10860)$
- $\Upsilon(10753)$ and $\Upsilon(10860)$ have the same quantum numbers and are only 110 MeV/c^2 apart.

This analysis shows that the $e^+e^- \to \omega\chi_{bJ}$ process observed near $\Upsilon(10860)$ by Belle could be due to the tail of the $\Upsilon(10753)$. The large difference between the small value of the $\omega\chi_{bJ}$ to $\pi^+\pi^-\Upsilon(nS)$ production rate at the $\Upsilon(10860)$ and the value at the $\Upsilon(10753)$ may indicate different internal structures for these two states.

About $\Upsilon(10753)$:

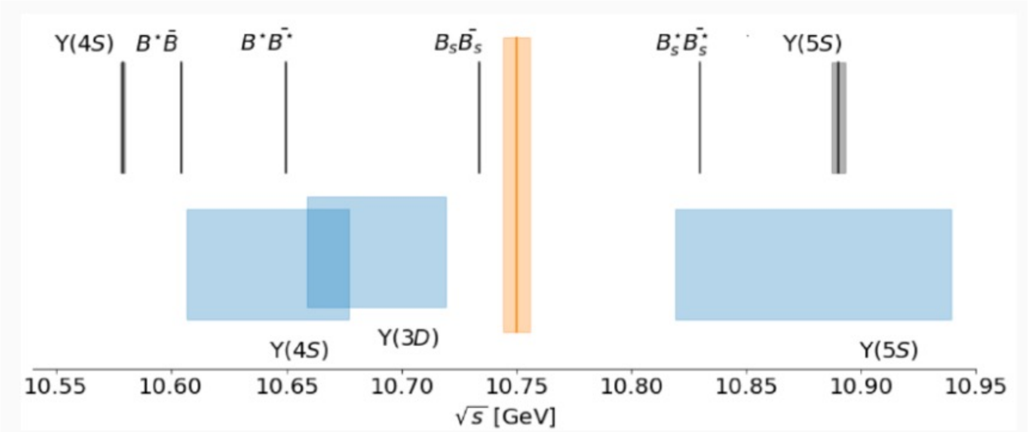
Our measurement:
$\sigma(e^+e^- \to \omega\chi_{b1})/\sigma(e^+e^- \to \omega\chi_{b2}) = 1.3 \pm 0.6$

➢ A pure D-wave bottomonium

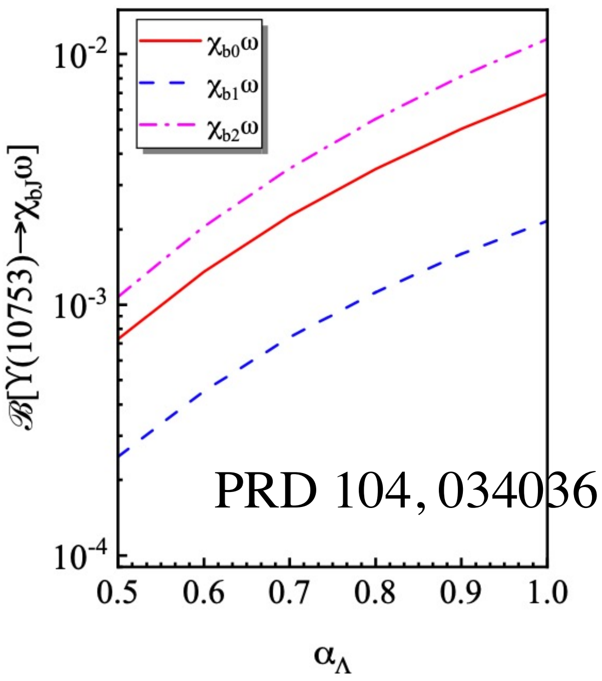
- From PLB 738, 172 (2014), for a pure D-wave bottomonium

$$\Gamma(\Upsilon(10753) \to \omega\chi_{b0}) : \Gamma(\Upsilon(10753) \to \omega\chi_{b1}) : \Gamma(\Upsilon(10753) \to \omega\chi_{b2}) = 20 : 15 : 1.$$

- Pure Υ(3D) interpretation contradicts theory: Godfrey and Moats, PRD 92, 054034 (2015)



➢ 4S - 3D mixing scheme



PRD 104, 034036 (2021)

- In the 4S - 3D mixing scheme for the $\Upsilon(10753)$,

$$\Gamma(\Upsilon(10753) \to \omega\chi_{b1}) : \Gamma(\Upsilon(10753) \to \omega\chi_{b2}) \sim 1 : 5$$

Belle II potential – 10.75 GeV

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

Channel
$e^+e^- \to B^{(*)}B^{(*)}$
$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$
$e^+e^- \to \gamma X_b$
$e^+e^- \to \eta\Upsilon(1S,2S)$
$e^+e^- \to \omega\eta_b(1S)$
$e^+e^- \to \pi^+\pi^-\Upsilon(1D)$
…

- 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 Bottomonium decays
- …

Summary

Belle II bottomonium program includes

- Early run near 10.75 GeV, Nov. 2021 (Done)
- Υ(3S), Υ(5S), Υ(6S), and scan above Υ(5S) in the future [PTEP 2019 (2019) 12, 123C01]

Based on early run data near $\sqrt{s}$ = 10.75 GeV

- New decay modes of $\Upsilon(10753) \to \omega\chi_{bJ}$ are observed for the first time.
- The value of $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1}/\omega\chi_{b2})$ is in the range 0.20–2.9/0.05–2.0 eV, which is consistent with $\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(nS))$ (n = 0, 1, or 2) [JHEP 10, 220(2019)]. But this is quite different from the $\Upsilon(10860)$, where the value of $\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \omega\chi_{b1}/\omega\chi_{b2})$ is much smaller.
- No evidence of a X_b signal is obtained with X_b masses between 10.45 and 10.65 GeV/c^2, and the upper limits at 90% C.L. are set.

Thanks for your attention!

Backup slides

Bottomonium(-like) prospects at Belle II

Run at $\Upsilon(6S)$ and $\Upsilon(5S)$ and high energy scan:

- Search for new missing bottomonia $\eta_b(3S)$, $h_b(3P)$, $\Upsilon(D)$, exotic states Y_b, Z_b, etc
- Improve precision of already known processes and states, e.g., Z_b
- Measure the effect of the coupled channel contribution
- Study $B^{(*)}\overline{B}^{(**)}$ and $B_s^{(*)}B_s^{(**)}$ threshold regions (challenging for Super-KEKB)

Run at $\Upsilon(3S)$ and $\Upsilon(2S)$:

- Search for missing $\pi\pi/\eta$ transitions in inclusive decays to constrain further models
- Search for new physics: LFV, LFU, light Higgs, …