Recent quarkonium results at Belle II

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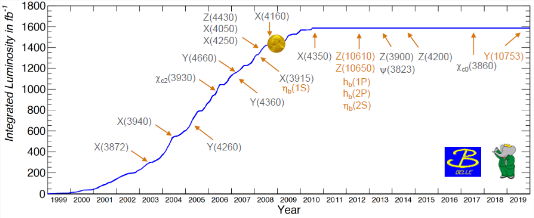
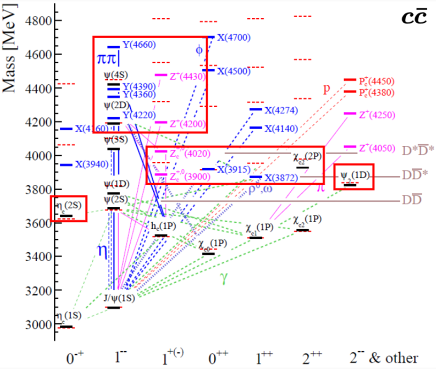
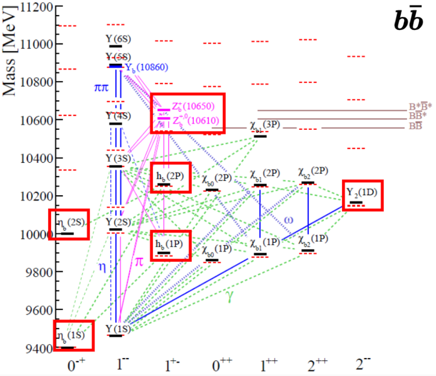
EU grant n.822070

Quarkonium(-like) mess

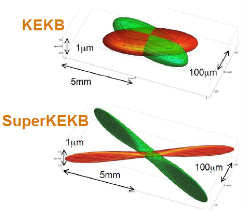
- Below $D\bar{D}/B\bar{B}$ thresholds $c\bar{c}$ and $b\bar{b}$ match QCD;
- Many exotic states observed in the past decade are hard to fit these spectra.







Belle II experiment overview

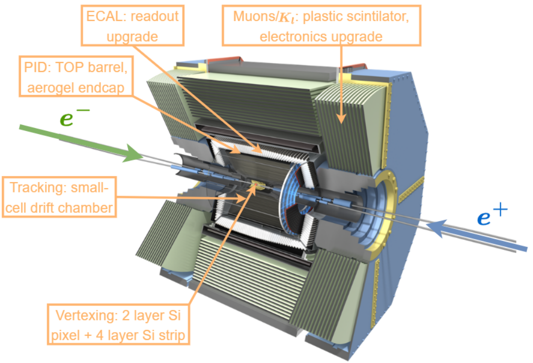


SuperKEKB:

- Asymmetric e^+e^- collider at KEK (Tsukuba, Japan);
- Energy adjustment: 3.5/8.0 GeV (Belle) $\rightarrow$ 7.0/4.0 GeV (Belle II);
- "Nano-beams" $\times$ current increase (x2) = x40 inst. luminosity increase;

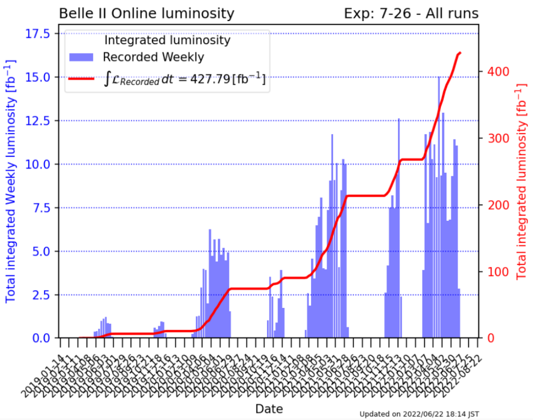
Belle II detector upgrade:

- Higher background:
  - Radiation damage;
  - Detector readout;
- Higher event rate ($\sim$ 30 kHz):
  - Trigger, DAQ, computing;
- Boost change:
  - Vertexing improvement;



Belle II timeline

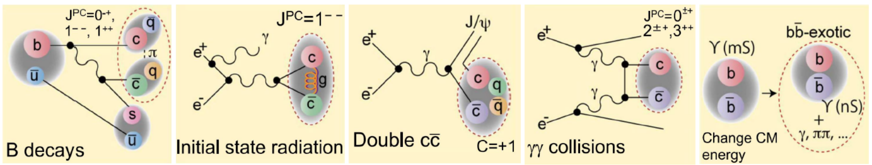
- 2016: "Phase 1":
  - Beam commissioning;
- 2017: Detector roll-in;
- 2018: "Phase 2":
  - Background study w. partial detector;
  - First collisions/data (28.04.2018);
- 2019: "Phase 3":
  - Nominal start of operations;
  - 2021: inst. lumin. record: $> 4.7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$;
  - 2021: Non $\Upsilon(4S)$ energy scan;
- 2022-2023: "Long Shutdown 1":
  - Detector/accelerator upgrades;



- 2023-2027: Resume operations, target: 5 ab^{-1};
- 2027+: "Long Shutdown 2" upgrade (?), continue up to 50 ab^{-1}.

Belle II quarkonium potential

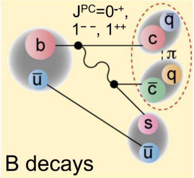
- Many flavor physics contributions, particularly in hadron spectroscopy;
- Advantages:
  - "Clean" environment;
  - Full event reconstruction, decays with neutral/soft particles;
  - Nominal $\sqrt{s} = 10.58$ GeV $= m(\Upsilon(4S))$, potential to reach 11 GeV;
  - Decay with neutrals $(\gamma, \pi^0, K_l, \nu)$ in final state;
  - Multiple production mechanisms;
  - Larger statistics $\rightarrow$ Complementary to LHC results;

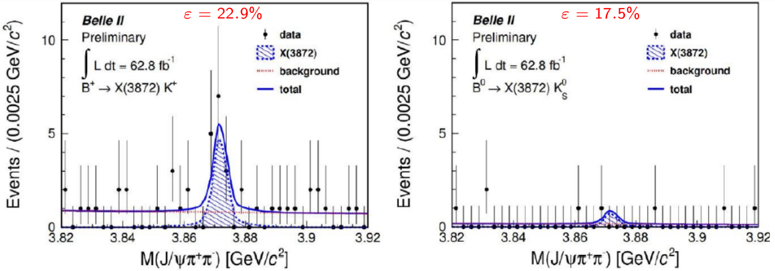


Charmonium(-like) studies at Belle II

Charmonium(-like) studies at Belle II: *B*-decays

- *B*-decays
  - $B \to KX_{c\bar{c}}$: CKM favored process → large branching fractions ($10^{-3} \sim 10^{-4}$);
  - Absolute $\mathcal{B}_f(B \to X(3872, 3915)K)$;
  - $X(3872)$ width measurement with $D^0\bar{D}^0\pi^0$;
  - Confirm Z_c states and search for neutral partners.





First observation of $X(3872)$ at Belle II: 14.4±4.6 events (4.6σ)

$^*\varepsilon(\psi(2S))$+=20% (w.r.t. Belle)

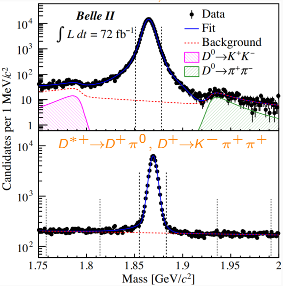
at 50 fb^{-1}

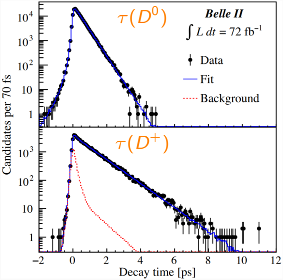
State	Production and decay	N
$X(3872)$	$B \to KX(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$	≈ 14400
$Y(4260)$	ISR, $Y(4260) \to J/\psi\pi^+\pi^-$	≈ 29600
$Z(4430)$	$B \to K^{\mp}Z(4430)$, $Z(4430) \to J/\psi\pi^{\pm}$	≈ 10200

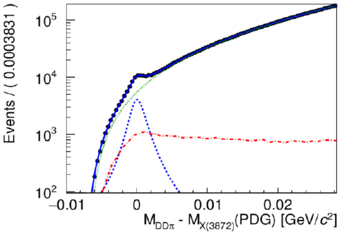
Charmonium(-like) studies at Belle II: $\Gamma(X(3872))$

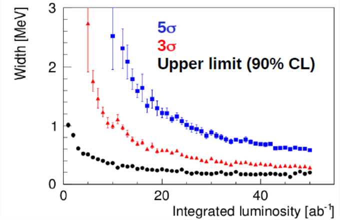
- Features:
  - Study of $X(3872)$ in $D^0\bar{D}^0\pi^0$ is a new approach;
  - Extremely small Q value gives an advantage;
- Possibilities:
  - (684 ± 8) keV mass resolution (vs. 1.93 ± 0.04 for $J\psi\pi\pi$)
  - Push $\Gamma^{UL}(X(3872))$ down to $\approx$280 keV (Note: Flatté fit $220^{+70+11-}_{-60-130}$);
  - Allows to decrease systematic uncertainty down to 110 keV;
  - possibility to combine $D^0\bar{D}^0\pi^0$ and $J/\psi\pi\pi$.
- Another idea: search for exotics at $D^*\bar{D}^*$ threshhold.

$D^{*+}\to D^0\pi^+$, $D^0\to K^-\pi^+$









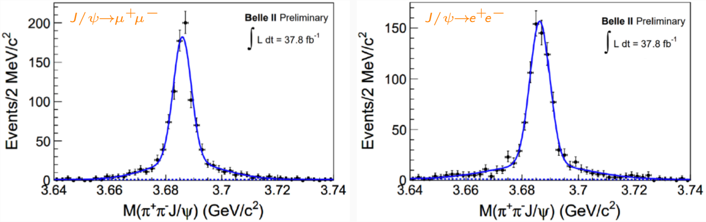
Mode	Q value (MeV)
$J/\psi\pi^+\pi^-$	495.65 ± 0.17
$D^0\bar{D}^0\pi^0$	7.05 ± 0.18
$D^0\bar{D}^{0*}$	0.01 ± 0.18

Phys Rev. Lett. 127 (2021) 211801

Further improvement is possible after PXD is fully functional

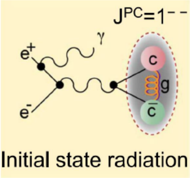
Charmonium(-like) studies at Belle II: other processes

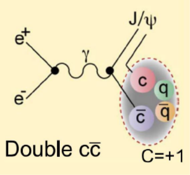
- Initial-state radiation (ISR):
  - Continuous mass range >4.7 GeV/c^2;
  - $Y \to c-$baryon pairs (Λ_c^+, Σ_c^-, $\Sigma_c^+\Sigma_c^-$), cs-meson pairs ($D_s D_{s2}(2573)$, $D_s D_{s0}^*(2317)$);
  - Search for Z_{cs} states decaying into $K^\pm J/\psi$, $D_s^- D^{*0}$+c.c.;
  - $Y(4260)$ rediscovery (expected 60 events per 100 fb^{-1}) + line shape;

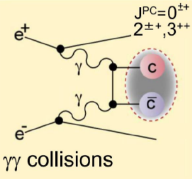


*clear observation of very clean ISR $\psi(2S)$ signals

- Two-photon process:
  - J^{PC} of $X(3915) \to \omega J/\psi$;
  - Confirm $X(4350) \to \phi J/\psi$;
- Double charmonium:
  - $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule;
  - J^{PC} of $X(3940)$.



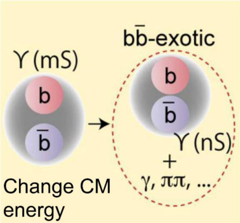


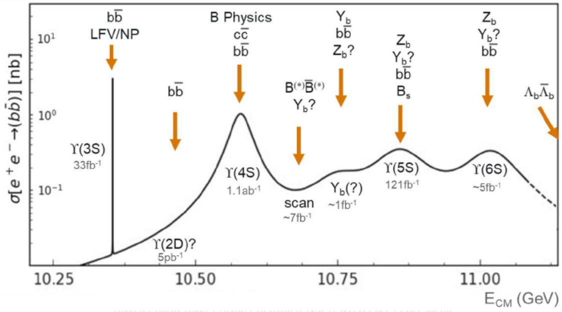


Bottomonium(-like) studies at Belle II

Bottomonium: life outside $\Upsilon(4S)$

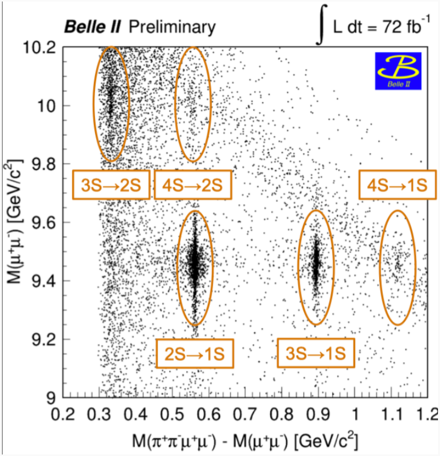
- B-factories' advantages for bottomonium research:
  - Able to adjust E_{CM} in 9.4-11.2 GeV region;
  - Pole-position for Υ, Y_b and Z_b states.
- B-factories legacy in bottomonium field:
  - BaBar $\Upsilon(3S)$: discovery of $\eta_b(1S)$
    arXiv:0809.1672v1 [hep-ex] 9 Sep 2008;
  - Belle $\Upsilon(5S)$: dicovery of $h_b(1P, 2P)$, $\eta_b(2S)$, $Z_b(10610, 10650)^{\pm}$
    PhysRevD.108.032001 (2012), PhysRevLett.109.232002 (2012), Europhys. Lett.96:11002, 2011;
  - Belle: $Y_b(10753)$ discovery;
    JHEP 06 (2019) 220





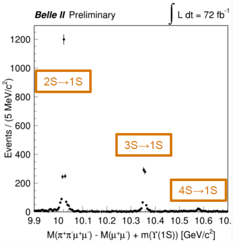
- Belle II data acquisition target:
  - Revisit $\Upsilon(5S)$ region;
  - Introduce $\Upsilon(6S)$ region.
- Principal ROI:
  - $\Upsilon(6S)$ vs. $\Upsilon(5S)$ in $\pi\pi\Upsilon$ and $\pi\pi\eta$ decays: is $\Upsilon(5S)$ a $b\bar{b}$ state?
  - Deeper study of 10.750 GeV/c^2 vicinity;
  - $c\bar{c}$ vs. $b\bar{b}$ spectrum discrepancy;

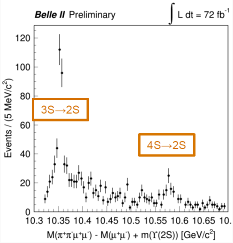
Bottomonium: Belle II early physics results



Prelude to energy scan analysis

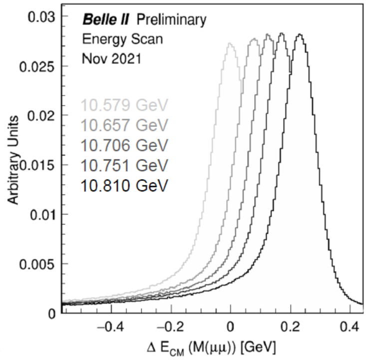
- ISR processes:
  - $\gamma_{ISR}\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$;
  - $\gamma_{ISR}\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S,2S)$;
- Direct transitions: $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S,2S)$;
- First-look results:
  - Improvement w.r.t. Belle;
  - The $3S \to 2S$ transition is seen;
  - $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$ Datitz analysis is ongoing;

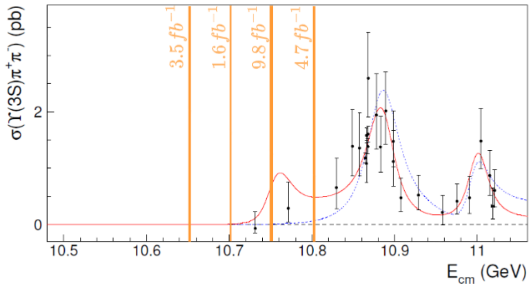


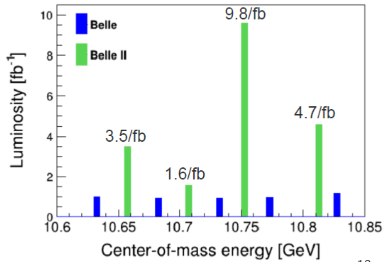


Belle II Energy Scan (Nov 2021)

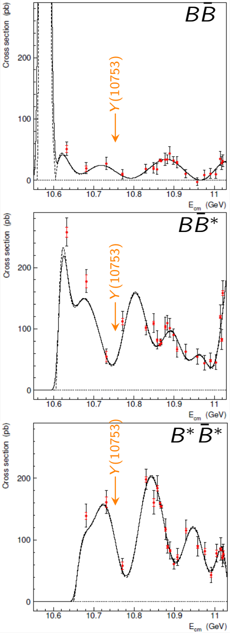
- Considerations:
  - Early physics at Belle II: fruitful field.
  - Major constraint: limited luminosity: $O(15fb^{-1})$.
  - Prospects: cover $\Upsilon(6S)$ region and beyond after detector upgrade.
- Status:
  - Energy scan operation was successful: x4 higher statistic w.r.t. Belle is accumulated.







Belle II potential: 10.75 GeV



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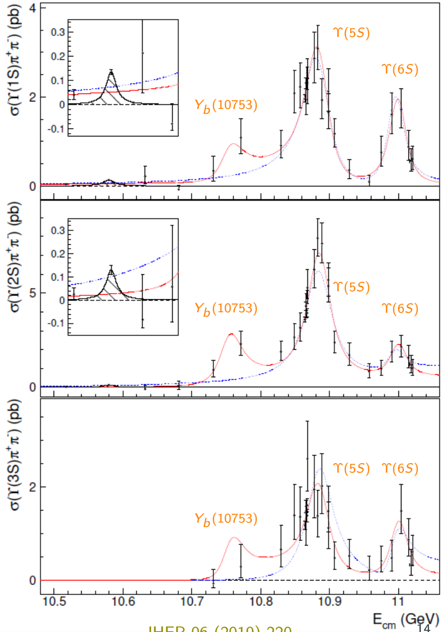
- Belle: 7 energy scan datasets (1 fb^{-1} each) below $\Upsilon(5S)$.
- New structure is observed in $\Upsilon(nS)\pi^+\pi^-$ system (n=1,2,3; $\Upsilon(nS) \to e^+e^-/\mu^+\mu^-$).
- Not seen in $B^{(*)}\bar{B}^{(*)}$ cross section.

Name	Properties [MeV]
$\Upsilon(10860)$	$M = 10885.3 \pm 1.5^{+2.2}_{-0.9}$ $\Gamma = 36.6^{+4.5+0.5}_{-3.9-1.1}$
$\Upsilon(11020)$	$M = 11020.3^{+4.0+1.0}_{-4.5-1.3}$ $\Gamma = 23.8^{+8.0+0.7}_{-6.8-1.8}$
New structure	$M = 10752.7 \pm 5.9^{+0.7}_{-1.1}$ $\Gamma = 35.5^{+17.6+3.9}_{-11.3-3.3}$



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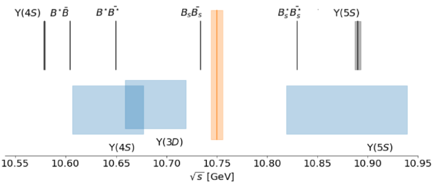
Why is $Y_b(10753)$ important?

- First observation (Belle, 2019) in $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ vs. E ($\sqrt{s} = 10.6 - 11.2$ GeV).
  R. Mizuk et al., J. High Energy Phys. 10, 220 (2019).
- Unclear nature
  - Pure $\Upsilon(3D)$ interpretation contradicts with theory.
    Godfrey, Moats, Phys. Rev. D 92 (2015) no.5, 054034.
  - Molecule? Too far from the threshold.



  - Tetraquark?
  - Hybrid?
  - ...
- Fast lane to today's aspects of XYZ puzzle in charmonium.

Conventional $b\bar{b}$ interpretation:

Bai, Li, Huang, Liu, Matsuki, Phys. Rev. D 105, 074007 (2022).
Li, Bai, Huang, Liu, Phys. Rev. D 104, 034036 (2021).
Li, Liu, Liu, Gui, Zhong, Eur. Phys. J. C 80, 59 (2020).
Chen, Zhang, He, Phys. Rev. D 101, 014020 (2020).
Giron and Lebed, Phys. Rev. D 102, 014036 (2020).
Kher, Chaturvedi, Devlani, Rai, Eur. Phys. J. Plus 137, 357 (2022).
Li, Bai, Liu, arXiv:2205.04049.
Liang, Ikeno, Oset, Phys. Lett. B 803, 135340 (2020).
Hüsken, Mitchell, Swanson, arXiv:2204.11915.
Beveren, Rupp, Prog. Part. Nucl. Phys. 117, 103845 (2021).
...

Tetraquark interpretation:

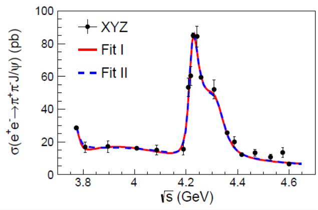
Ali, Maiani, Parkhomenko, Wang, Phys. Lett. B 802, 135217 (2020).
Bicudo, Cardoso, Müller, Wagner, Phys. Rev. D 103, 074507 (2021).
Bicudo, Cardoso, Müller, Wagner, arXiv:2205.11475.
Wang, Chin. Phys. C 43, 123102 (2019).
...

Hybrid interpretation:

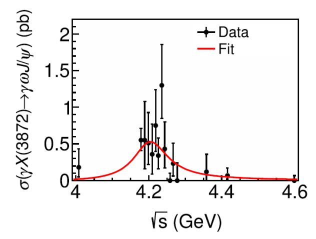
Castella, Passemar, Phys. Rev. D 104, 034019 (2021).
Brambilla, Eidelman, Hanhart, Nefediev, Shen, Thomas, Vairo, Yuan, Phys. Rept. 873, 1 (2020).
...

Motivation to start a new analysis over Belle II scan data

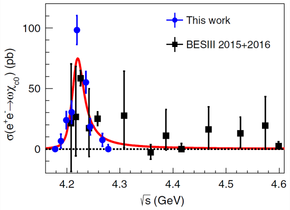
- Theoretical background:
  - $\mathcal{B}(Y(10753)) \to \omega\chi_{bJ} \quad 10^{-3}$ for $4S - 3D$ $b\bar{b}$ mixture.
    Li, Bai, Huang, Liu, Phys. Rev. D 104, 034036 (2021)
- X_b: $X(3872)$ conterpart candidate?
  Choi et al., Phys. Rev. Lett. 91, 262001 (2003)
  - The $\pi\pi J/\psi$ and $\pi\pi\Upsilon$ cross section spectrum similarity hints at similar nature.
  - $Y(4260)$ was observed by BESIII in $\gamma X(3872)$ and $\omega\chi_{c0}$ decays.
  - Should we expect $Y(10753)$ to decay into γX_b with $X_b \to \omega\Upsilon(1S)$? Worth checking!



PhysRevD 118, 092001 (2017)



PhysRevLett.122.232002



PhysRevD.99.091103

Belle II Energy Scan: first results

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

I. Adachi, L. Aggarwal, H. Ahmed, H. Aihara, N. Akopov, A. Aloisio, N. Anh Ky, T. Aushev, V. Aushev, H. Bae, P. Bambade, Sw. Banerjee, J. Baudot, M. Bauer, A. Beaubien, J. Becker, P. K. Behera, J. V. Bennett, E. Bernieri, F. U. Bernlochner, V. Bertacchi, M. Bertemes, E. Bertholet, M. Bessner, S. Bettarini, B. Bhuyan, F. Bianchi, T. Bilka, D. Biswas, D. Bodrov, A. Bolz, A. Bondar, J. Borah, A. Bozek, M. Bračko, P. Branchini, T. E. Browder, A. Budano, S. Bussino, M. Campajola, L. Cao, G. Casarosa, M.-C. Chang, P. Cheema, V. Chekelian, Y. Q. Chen, K. Chilikin, K. Chirapatpimol, H.-E. Cho, K. Cho, S.-J. Cho, S.-K. Choi, S. Choudhury, D. Cinabro, L. Corona, S. Cunliffe, S. Das, F. Dattola, E. De La Cruz-Burelo, S. A. De La Motte, G. De Nardo, M. De Nuccio, G. De Pietro, R. de Sangro, M. Destefanis, S. Dey, A. De Yta-Hernandez, R. Dhamija, A. Di Canto, F. Di Capua, Z. Doležal, I. Domínguez Jiménez, T. V. Dong, M. Dorigo, K. Dort, S. Dreyer, S. Dubey, G. Dujany, M. Eliachevitch,

...

(The Belle II Collaboration)

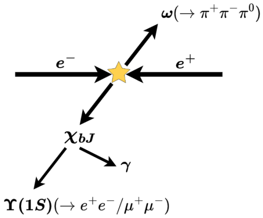
We study the processes $e^+e^- \to \omega\chi_{bJ}(1P)$ ($J = 0$, 1, or 2) using samples at center-of-mass energies $\sqrt{s} = 10.701$, 10.745, and 10.805 GeV, corresponding to 1.6, 9.8, and 4.7 fb^{-1} of integrated luminosity, respectively. These data were collected with the Belle II detector during a special run of the SuperKEKB collider above the $\Upsilon(4S)$ resonance. We report the first observation of $\omega\chi_{bJ}(1P)$ signals at $\sqrt{s} = 10.745$ GeV. By combining Belle II data with Belle results at $\sqrt{s} = 10.867$ GeV, we find energy dependencies of the Born cross sections for $e^+e^- \to \omega\chi_{b1,b2}(1P)$ to be consistent with the shape of the $\Upsilon(10753)$ state. Including data at $\sqrt{s} = 10.653$ GeV, we also search for the bottomonium equivalent of the $X(3872)$ state decaying into $\omega\Upsilon(1S)$. No significant signal is observed for masses between 10.45 and 10.65 GeV/c^2.

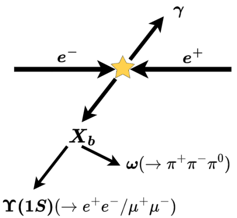
arXiv:2208.13189v1 [hep-ex] 28 Aug 2022

Analysis Overview

- $e^+e^- \to \omega\chi_{cJ}$ (σ_b)
  - Born cross section measurement (σ_b) at $\sqrt{s} = 10.701$, 10.745, 10.805 GeV.
  - Combining Belle results at $\sqrt{s} = 10.867$ GeV to study σ_b energy dependence.

    PhysRevLett.113.142001 (2014)
- $e^+e^- \to \gamma X_b$
  - Search for X_b signal at $\sqrt{s} = 10.653$, 10.701, 10.745, 10.805 GeV.
- Strategy
  - EvtGen: PHOKHARA and PHSP.
  - Geant4.
  - Offline analysis within Belle II framework.
- Events selection
  - Standard POCA and PID requirements are set charged tracks selection (90%+ eff.).
  - Bremsstrahlung and FSR suppression + $E(\gamma) > 50$ MeV.
  - Accurate π^0 combination.
  - χ^2-based BCS is applied.





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

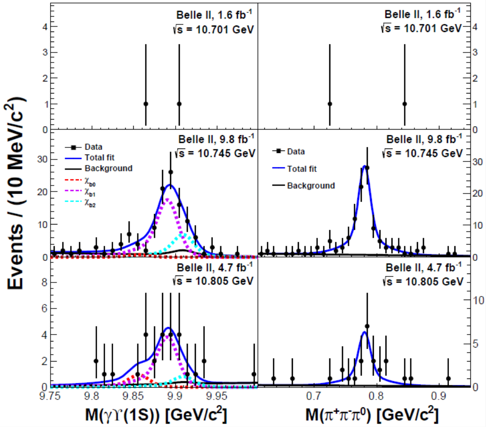
- 2D UML fit of $M(\gamma Y(1S))$ vs. $M(\pi^+\pi^-\pi^0)$ distribution.
- Model: signal (CB for χ_{bJ}, Voigt for ω) + peaking bkg. (same) + comb. bkg.

	Channel	$\sqrt{s}$ (GeV)	N^{sig}	σ_B (pb)
	$e^+e^- \to \omega\chi_{b0}$		$0.0^{+1.1}_{-0.0}$	< 16.6
	$e^+e^- \to \omega\chi_{b1}$	10.701	$0.0^{+2.1}_{-0.0}$	< 1.2
	$e^+e^- \to \omega\chi_{b2}$		$0.1^{+2.2}_{-0.1}$	< 2.5
	$e^+e^- \to \omega\chi_{b0}$		$3.0^{+5.5}_{-4.7}$	< 11.3
11σ	$e^+e^- \to \omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.5$
	$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.4$
	$e^+e^- \to \omega\chi_{b0}$		$3.6^{+3.8}_{-3.1}$	< 11.4
4.5σ	$e^+e^- \to \omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	< 1.7
	$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	< 1.6

Note:
$\sigma_B(\chi_{b1}) = (0.76 \pm 0.16)$ pb
$\sigma_B(\chi_{b2}) = (0.29 \pm 0.14)$ pb
at $\sqrt{s} = 10.867$ (Belle)

$$\frac{\mathcal{B}_f(Y(10753) \to \omega\chi_{b1})}{\mathcal{B}_f(Y(10753) \to \pi^+\pi^-\Upsilon(1S))} = 0.33 \pm 0.09 \pm 0.06$$

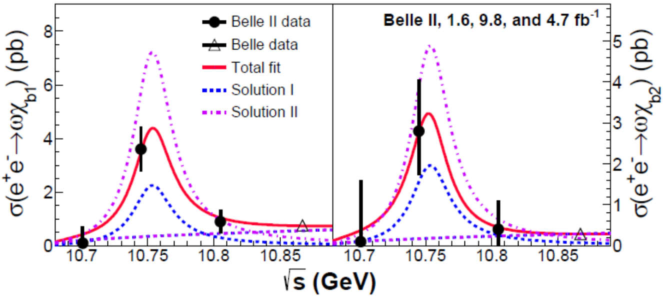
$$\frac{\mathcal{B}_f(\Upsilon(5S) \to \omega\chi_{b1})}{\mathcal{B}_f(\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S))} = 3.33 \pm 1.35 \pm 0.46$$



PhysRevLett.113.142001 (2014) arXiv:2208.13189 [hep-ex] 28 Aug 2022 arXiv:1905.05521 [hep-ex] 11 Oct 2019

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

- σ_B fit features:
  - Model: PHSP + BW*;
  - M and Γ of $Y(10753)$ are fixed to 10752.7 MeV and 35.5 MeV;
- σ_B fit result:
  - σ_B enhancement near 10.753 GeV;
  - No evident enhancement in the vicinity of $\Upsilon(5S)$;



- $\chi_{b1}/\chi_{b2} \sim 1$: agrees with HQET.

arXiv:hep-ph/9908366v1 16 Aug 1999

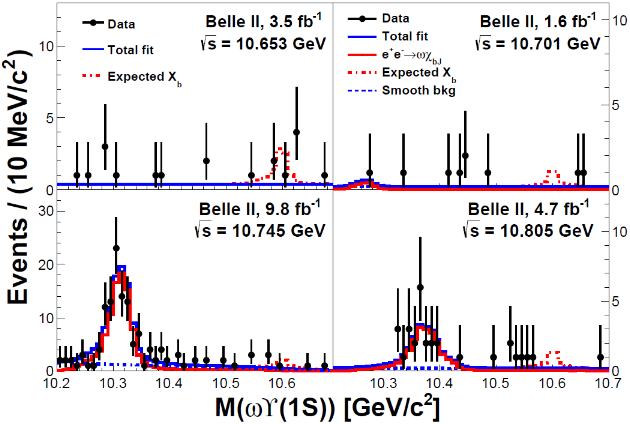
$$^{*}BW(\sqrt{s}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 - iM\Gamma}\sqrt{\frac{\Phi_1(\sqrt{s})}{\Phi_2(M)}}$$

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

Search for $X_b \to \omega\Upsilon(1S)$

- Search for resonances in $\omega\Upsilon(1S)$ in each energy scan.
- $\omega\chi_{bJ}$ reflection is accounted.
- No evidence for X_b signal.
- $^*\sigma^{UL}_{X_b}$ upper limit is set** for each E_{CM} and $M(X_b) \in [10.45, 10.65]$ GeV.

$\sqrt{s}$ (GeV)	M_{X_b} (GeV)	$\sigma^{UL}_{X_b}$
10.653	10.59	0.55
10.701	10.45	0.84
10.745	10.45	0.14
10.805	10.53	0.47



$^*\sigma^{UL}_{X_b} = \sigma^{UL}_B(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$

** at 90% Bayesian credibility

Summary

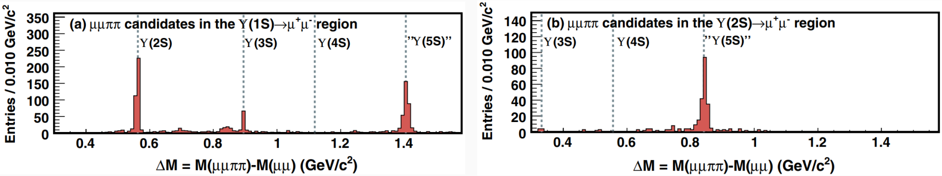
Charmonium(-like) studies at Belle II: from legacy prospects

- B-factories founded the XYZ studies, they are now complemented by other studies:
  - Many statistics-dominated B-decay modes covered by LHCb;
  - BES III energy scans extending range above 4.9 GeV;
- Still well-known for this legacy ($X(3872)$ is still the most cited paper) and essential for full understanding of new states;
- Key future contributions:
  - Models with neutrals (e.g. neutral Z partners, π^0 transitions/decays)
  - Unique double-charmonium ($e^+e^- \to c\bar{c}\,c\bar{c}$) and two-photon ($e^+e^- \to e^+e^-\ c\bar{c}$) production;
  - Statistics-dominated: results will come with the raise of integrated luminosity.

The future of Bottomonium at Belle II

- Open questions Belle II can give answers to:
  - α_s-suppressed $\Upsilon(nS)$ radiative transitions? (possible at Belle II only);
  - Y_b nature;
  - Z_b decomposition (only seen in $\Upsilon(5S)$ decays so far). Other molecular states?
  - $\Upsilon(5S)$ mystery;
- Long-term non-$\Upsilon(4S)$ possibilities:
  - Revisit $\Upsilon(6S)$ with 10x+ statistics;
  - LFV/spectroscopy in $\Upsilon(2S, 3S)$ decays;
  - Higher statistics scan of entire region and $\Upsilon(5S)$;
  - E_{CM} to $\Lambda_b\bar{\Lambda}_b$ (requires further SuperKEKB upgrades).

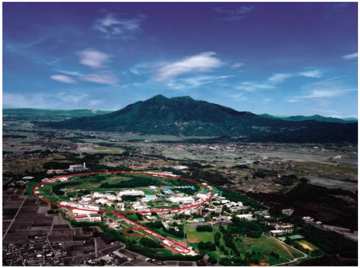
Golden Modes
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$
$B\overline{B}$ decomposition
$\pi^+\pi^-$ Dalitz
$Y_b \to \omega\eta_b(1S)$
$Y_b \to \omega\chi_{bJ}(1P)$
Silver Modes
$Y_b \to \pi^+\pi^- X$ (inclusive)
$Y_b \to \eta X$ (inclusive)
$Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$
$Y_b \to \Upsilon(1S)$ (inclusive)
Bronze Modes
$Y_b \to \gamma X_b$
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to \pi^0\pi^0 X$ (inclusive)
$Y_b \to \pi^0 X$ (incl. or excl.)
...



Belle Phys. Rev. Lett. 100, 112001 (2008)

Summary: Belle II take-off

- Huge experiment: 1100+ members, 123 institutions, 26 countries and regions;
- Run time is scheduled until 2031+;
- First major upgrade is ongoing;
- Next long-term data collection period is to be launched in the next year.



Thank you!