Pacific Northwest
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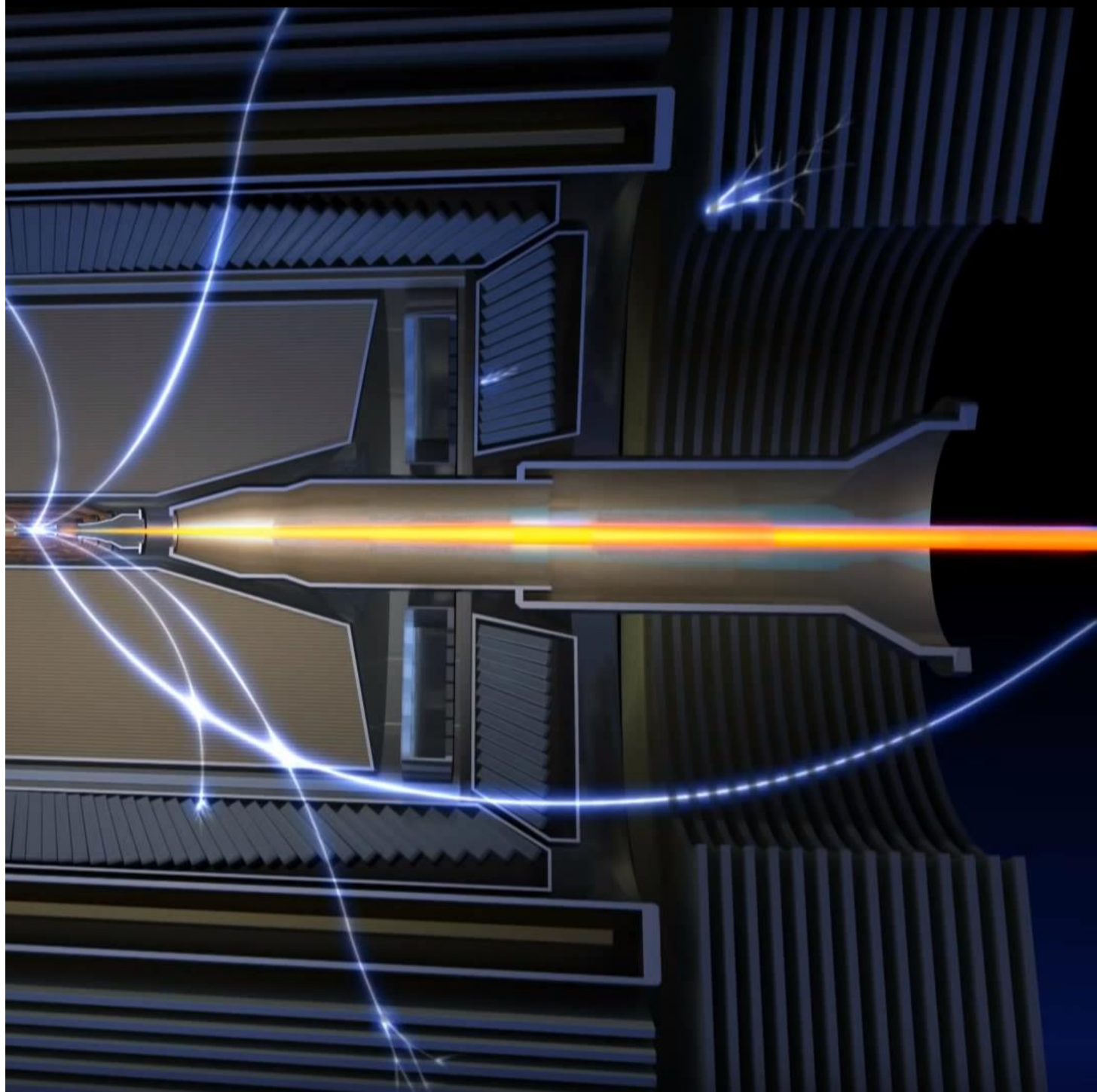
Energy Scan Results at Belle II

Sep 30, 2022

Bryan Fulsom (PNNL)

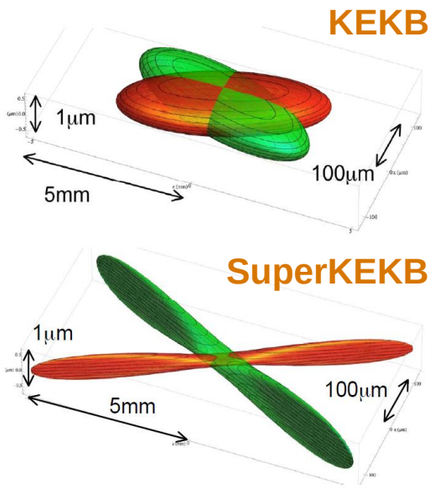
15th International Workshop on Heavy Quarkonium
GSI, Darmstadt, GERMANY



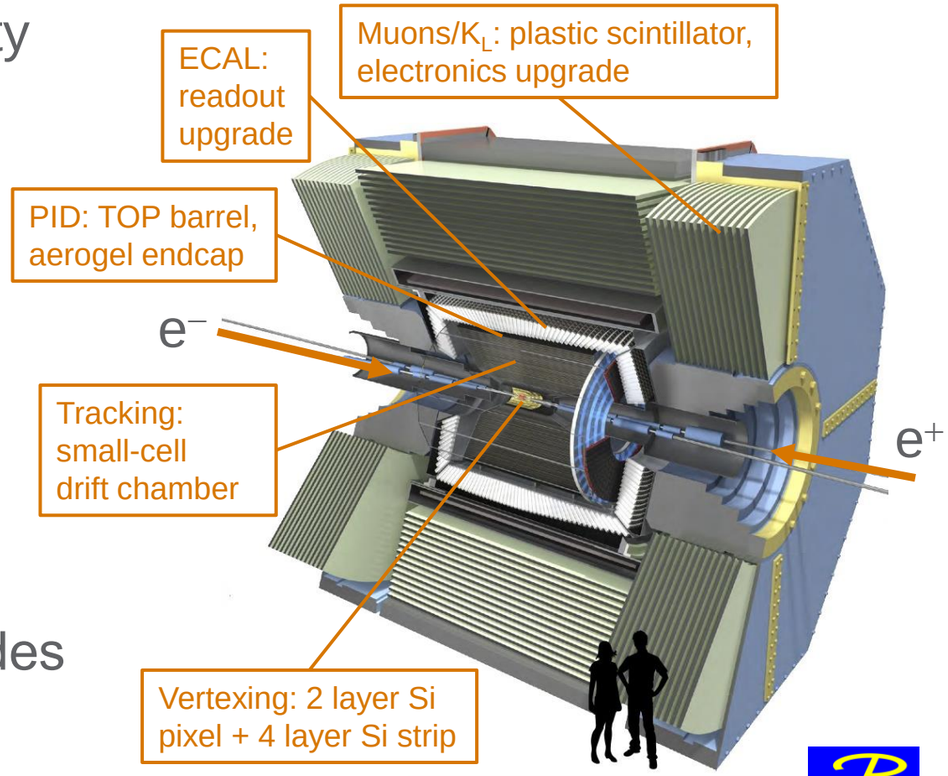
U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

SuperKEKB and Belle II



- SuperKEKB
  - Asymmetric e^+e^- (4/7 GeV) collider at KEK in Tsukuba, Japan
  - "Nano-beam" interaction point, current increase
  - Goal: 40x increase in inst. luminosity

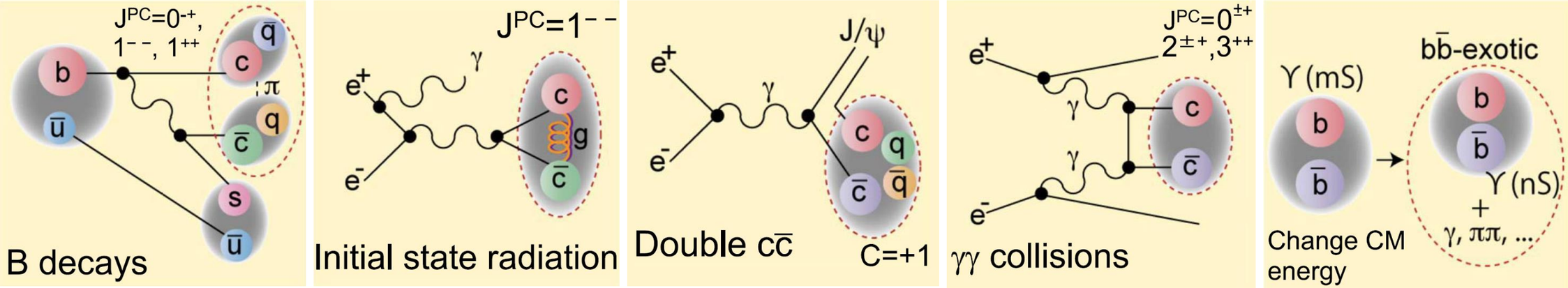


- Belle II Experiment
  - 1100+ members, 123 institutions, 26 countries
  - Significant detector upgrades
  - Integrated luminosity ~424 fb^{-1}
  - Peak luminosity record: >4.7x10^{34} $cm^{-2}s^{-1}$
  - Currently: "Long Shutdown 1" until 2023 for upgrades

arXiv:1011.0352 (2011)

Belle II Quarkonium Potential

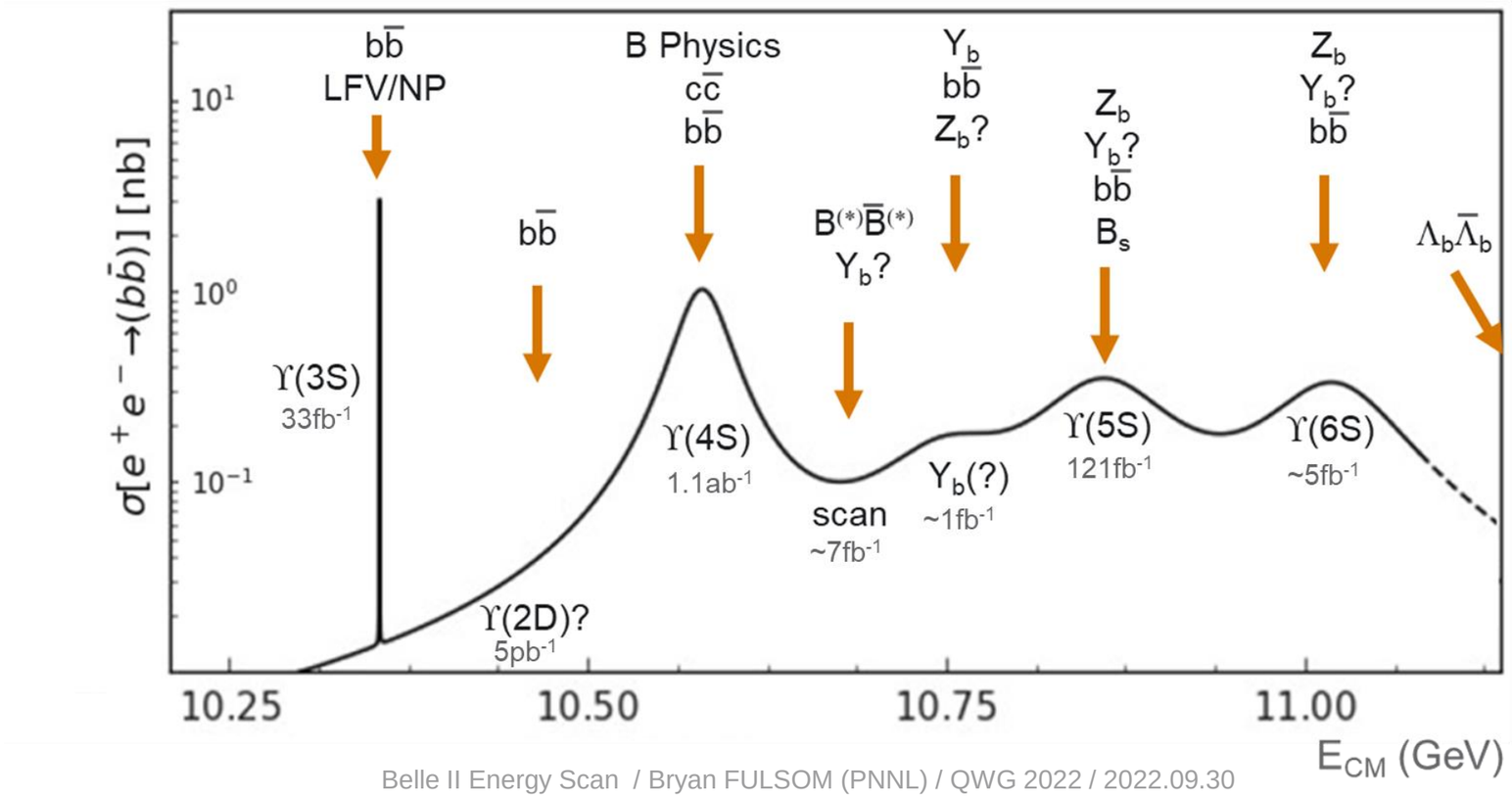
- Many flavor physics contributions, particularly in hadron spectroscopy
- Advantages
  - Full event reconstruction, decays with neutral/soft particles
  - Nominal $\sqrt{s}$ = 10.58 GeV = m(Υ(4S)), potential to reach ~11 GeV
  - Multiple production mechanisms

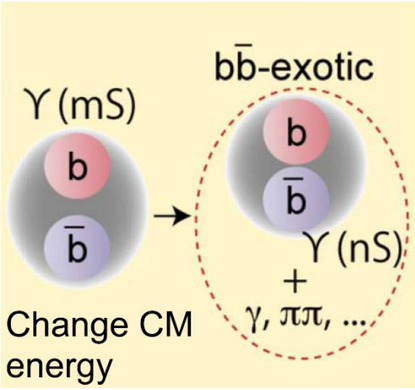


- Today's focus: above-Υ(4S) energy scan

Belle II Potential – Non-$\Upsilon(4S)$ Energies

- B-Factories extended their physics programs with non-$\Upsilon(4S)$ data
  - BaBar $\Upsilon(3S)$: discovery of $\eta_b(1S)$
  - Belle $\Upsilon(5S)$: discovery of $h_b(1P, 2P)$, $\eta_b(2S)$, $Z_b(10610, 10650)^{\pm}$
  - KEKB/Belle energy scan data: $Y_b(10753)$





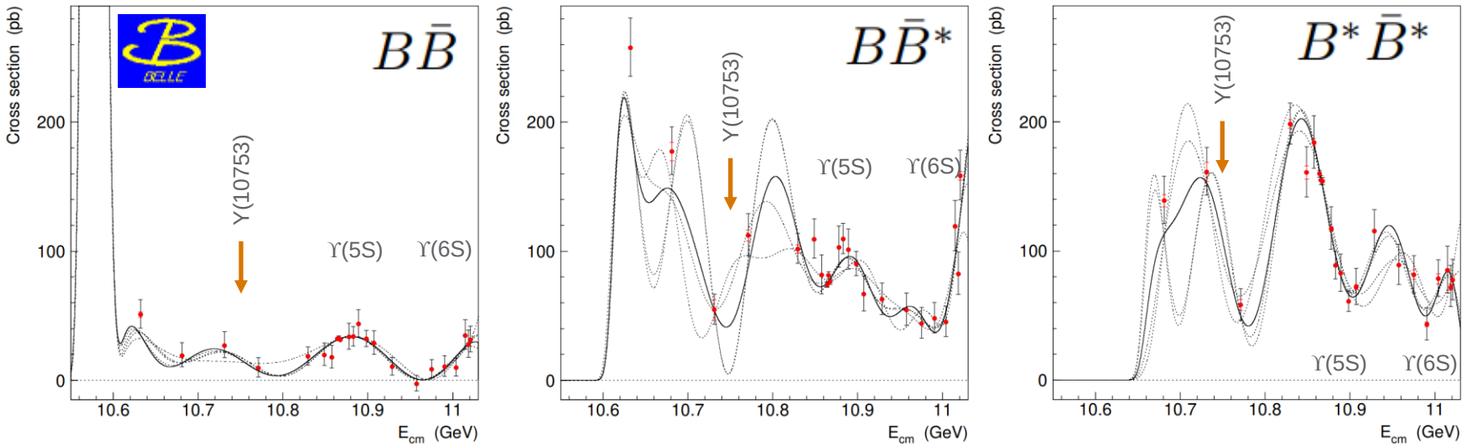
Belle II Potential – 10.75 GeV

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

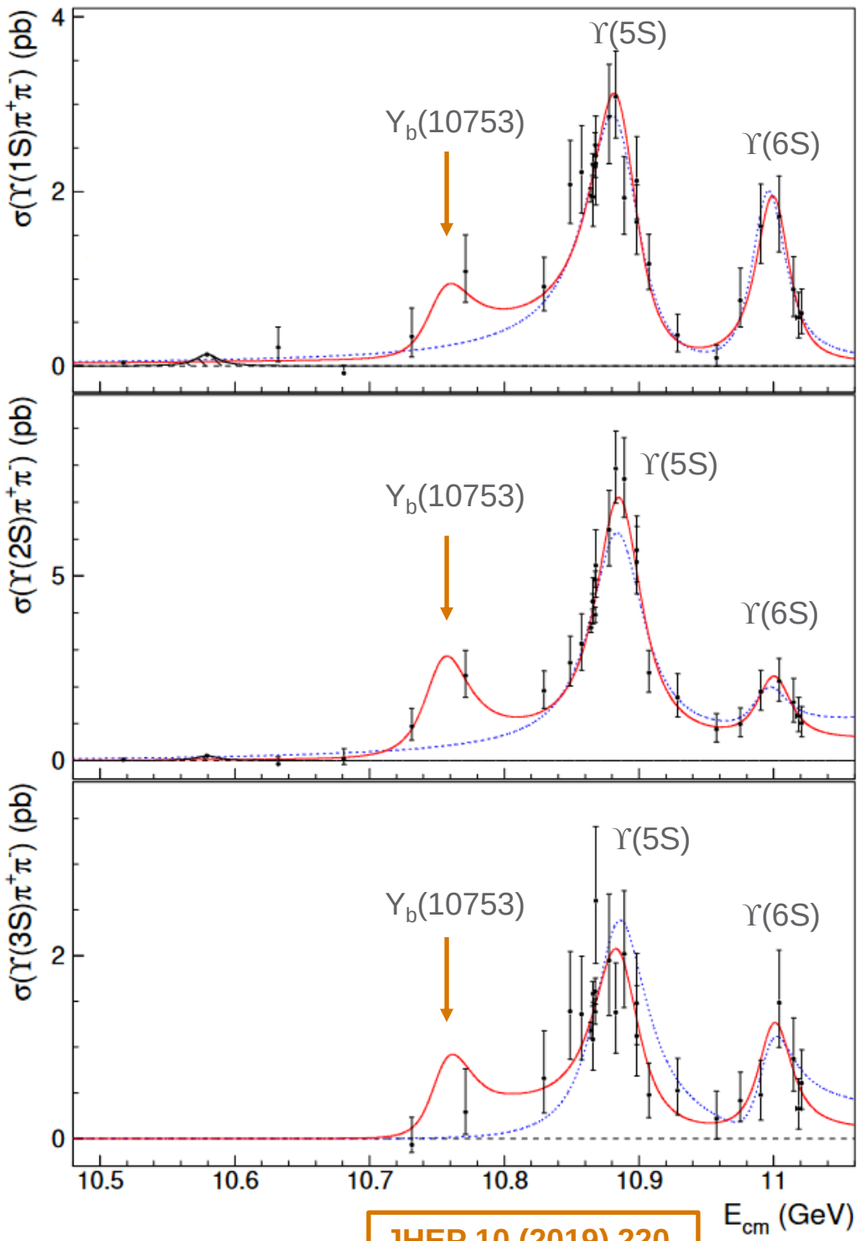
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$

- Varying $B\bar{B}$ cross sections

JHEP 06 (2021) 137



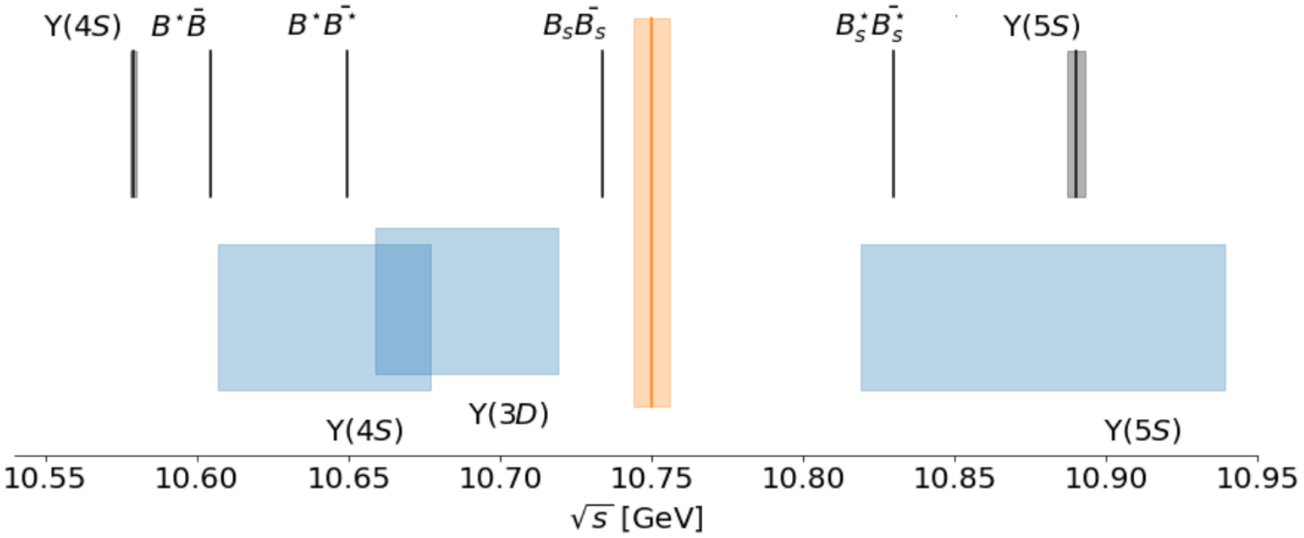
- Revisit this energy region with greater statistics



JHEP 10 (2019) 220

Why is the $Y_b(10753)$ important?

- Uncertain nature
  - Molecular interpretation? Does not coincide with a threshold...
  - No clear conventional $b\bar{b}$ candidate
  - Potential tetraquark?



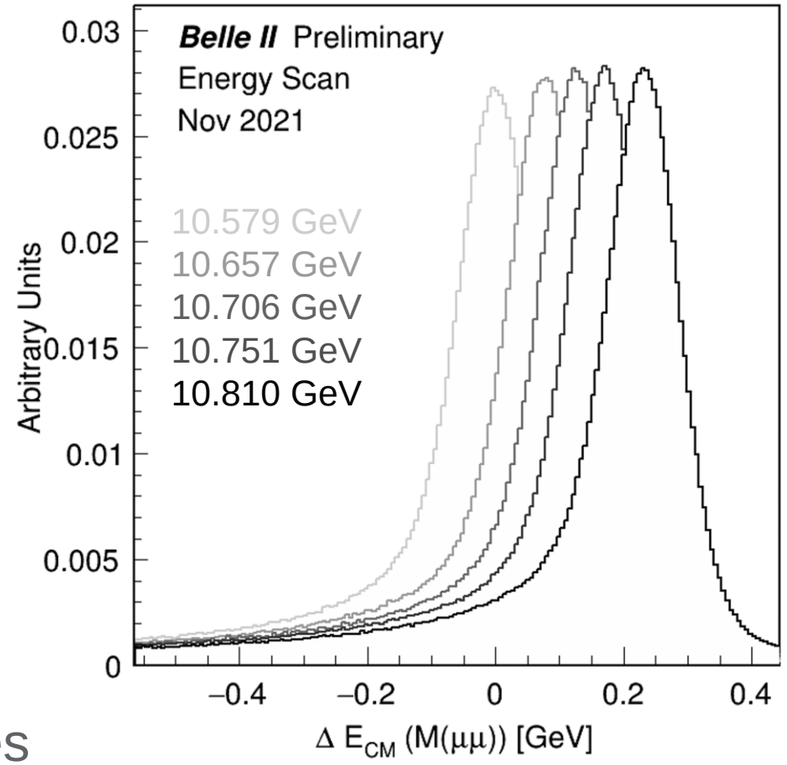
Conventional interpretations:
Chen, Zhang & He, PRD 101, 014020 (2020)
Giron & Lebed, PRD 102, 014036 (2020)
Li et al., EPJC 80, 59, (2020)
Li et al., PRD 104, 034036 (2021)
van Beveren & Oset, PPNP 117, 103845 (2021)
Bai et al., PRD 105, 074007 (2022)
Husken, Mitchell & Swanson, arXiv:2204.11915 (2022)
Kher et al., EPJ+ 137, 357 (2022)
Li, Bai & Liu, arXiv:2205.04049 (2022)
Liang, Ikeno & Oset, PLB 803, 135340 (2020)
…

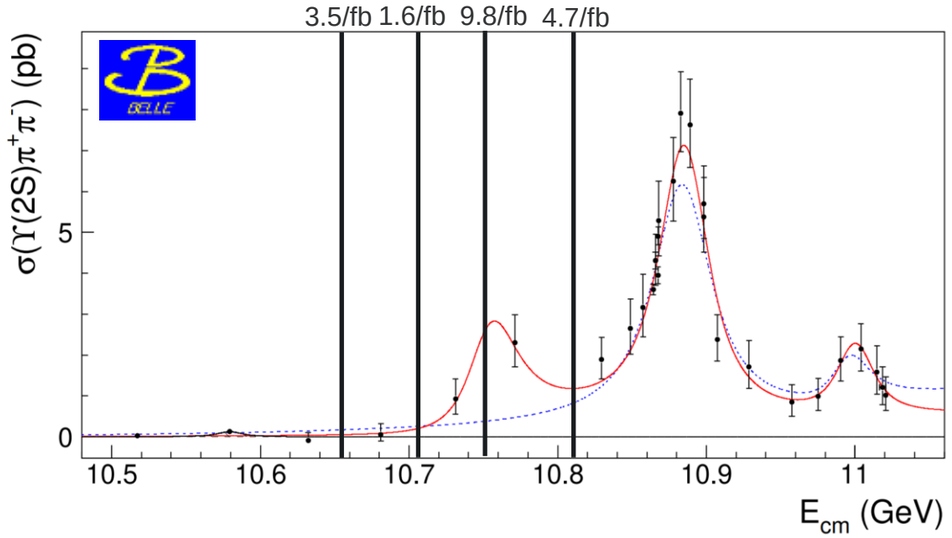
"Exotic" interpretations:
Wang, CPC 43, 123102 (2019)
Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
Bicudo, Cardoso & Wagner, PRD 103, 074507 (2020)
Castella & Passemar, PRD 104, 034019 (2021)
…

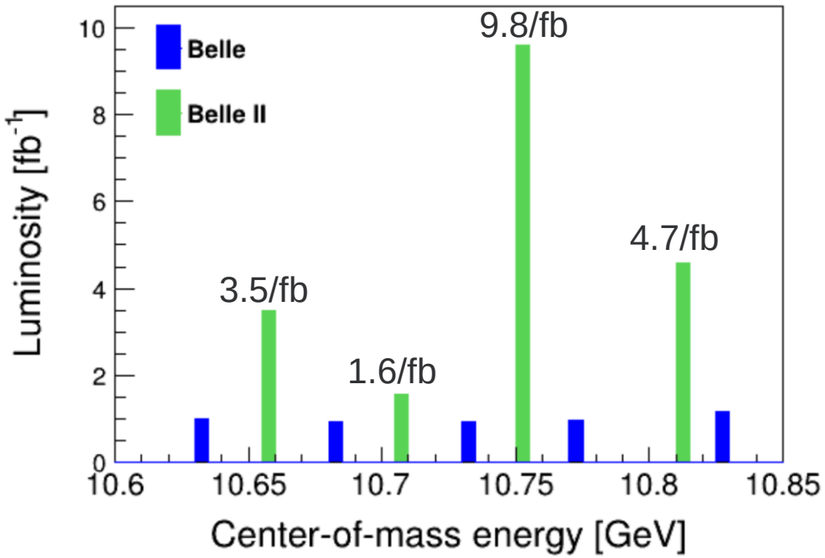
- Big picture: relationship to puzzles in XYZ/charmonium system

Belle II Energy Scan
Nov. 10-29, 2021 (JST)

- Considerations
  - Potential for early physics impact by Belle II
  - Limited luminosity requirement (O(15/fb))
  - Υ(6S) requires accelerator infrastructure upgrade
- Energy scan operation was successful
  - Unique high stat. points between previous Belle energies







Belle II Energy Scan – First Results

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

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, D. Epifanov, P. Feichtinger, T. Ferber, D. Ferlewicz, T. Fillinger, G. Finocchiaro, A. Fodor, F. Forti, B. G. Fulsom, ...

(The Belle II Collaboration)

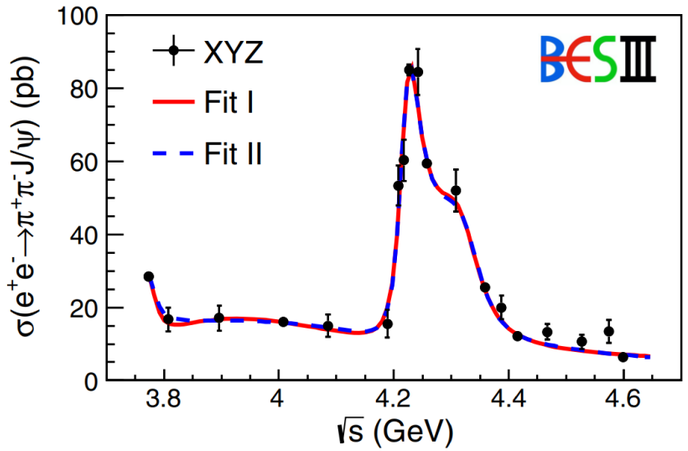
We study the processes $e^+e^- \to \omega\chi_{bJ}(1P)$ ($J = 0$, 1, or 2) using samples at center-of-mass energies $\sqrt{s} = 10.701$, 10.745, and 10.805 GeV, corresponding to 1.6, 9.8, and 4.7 fb^{-1} of integrated luminosity, respectively. These data were collected with the Belle II detector during 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.

Analysis Motivation

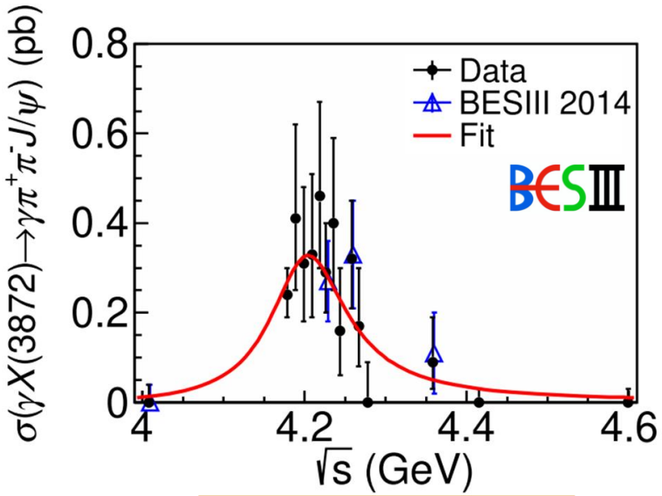
- Theoretical Predictions
  - $\mathcal{B}(\Upsilon(10753) \to \omega\chi_{bJ}) \sim 10^{-3}$ predicted for 4S-3D $b\bar{b}$ mixture

Bai et al., PRD 105, 074007 (2022)
Li, Bai & Liu, arXiv:2205.04049 (2022)

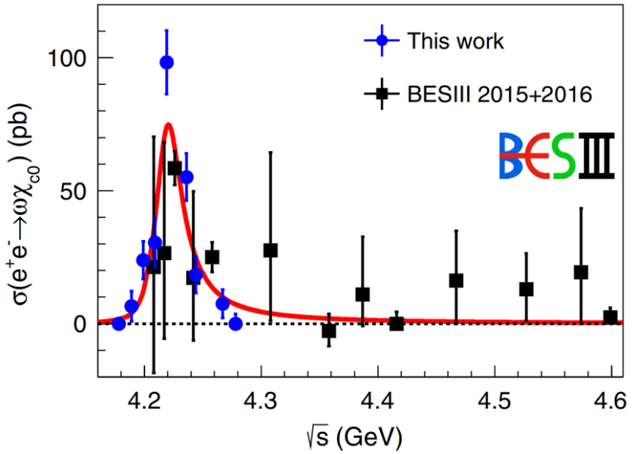
- X_b: bottomonium counterpart of X(3872)?
  - Peaks observed in $\pi\pi J/\psi$ and $\pi\pi\Upsilon$ cross section may suggest similar nature
  - $\Upsilon(4220) \to \gamma X(3872)$ and $\omega\chi_{c0}$ observed by BESIII
  - Implies $\Upsilon(10753)$ may decay to γX_b with $X_b \to \omega\Upsilon(1S)$?



PRL 118, 092001 (2017)

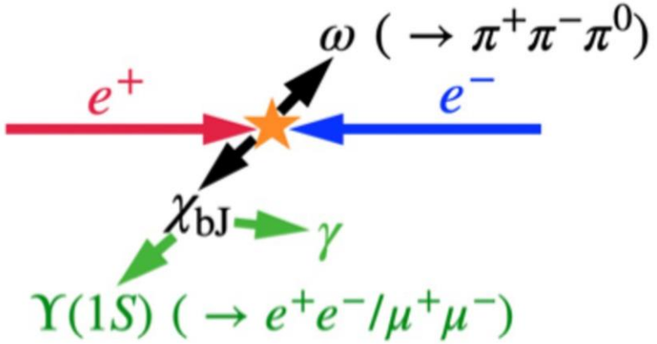


PRL 122, 232002 (2019)

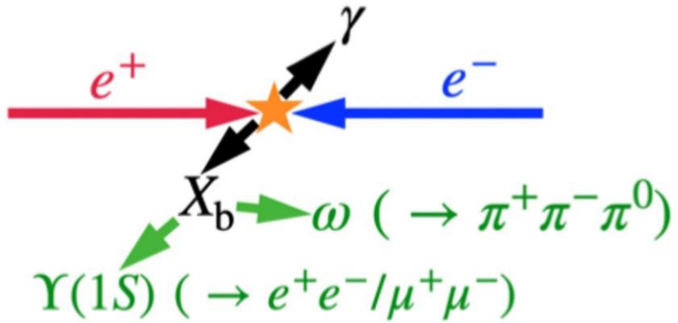


PRD 99, 091103 (2019)

Analysis Overview



- $e^+e^- \rightarrow \omega\chi_{bJ}$
  - Born cross (σ_B) section at $\sqrt{s}$ = 10.701, 10.745, 10.805 GeV
  - Energy dependence of σ_B by combining with Belle data at $\sqrt{s}$ = 10.867 GeV PRL 113, 142001 (2014)
- $e^+e^- \rightarrow \gamma X_b$
  - X_b search at $\sqrt{s}$ = 10.653, 10.701, 10.745, 10.805 GeV

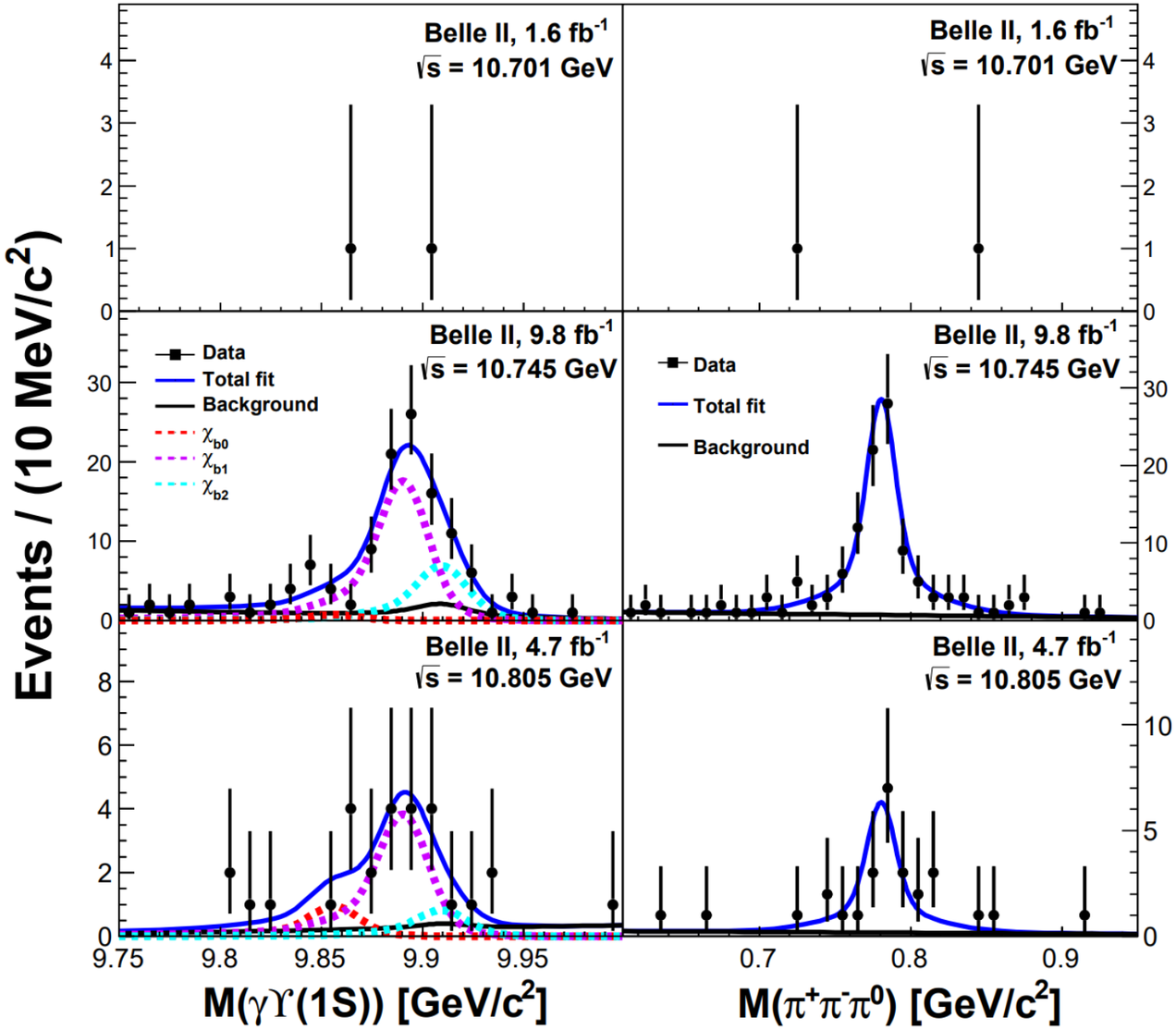


- Selection criteria
  - 4 or 5 charged particles
  - Standard PID (90+% eff. with <5% misID)
  - E_γ > 50 MeV (χ_{bJ} decay)
  - 105 < M($\gamma\gamma$) < 150 MeV/c^2
  - Constrained kinematic fit to $\gamma\pi^+\pi^-\pi^0(e^+e^-/\mu^+\mu^-)$
  - Best candidate based on fit quality

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

- 2D UML fit to M(γY(1S) and M($\pi^+\pi^-\pi^0$)

	Channel	$\sqrt{s}$ (GeV)	$N^{\rm sig}$	σ_B (pb)
	$e^+e^- \to \omega\chi_{b0}$	10.701	$0.0^{+1.1}_{-0.0}$	<16.6
	$e^+e^- \to \omega\chi_{b1}$		$0.0^{+2.1}_{-0.0}$	<1.2
	$e^+e^- \to \omega\chi_{b2}$		$0.1^{+2.2}_{-0.1}$	<2.5
	$e^+e^- \to \omega\chi_{b0}$	10.745	$3.0^{+5.5}_{-4.7}$	<11.3
11.5σ	$e^+e^- \to \omega\chi_{b1}$		$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.5$
	$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.4$
	$e^+e^- \to \omega\chi_{b0}$	10.805	$3.6^{+3.8}_{-3.1}$	<11.4
5.2σ	$e^+e^- \to \omega\chi_{b1}$		$15.0^{+6.8}_{-6.2}$	<1.7
	$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	<1.6



- Note @ $\sqrt{s}$ = 10.867 GeV

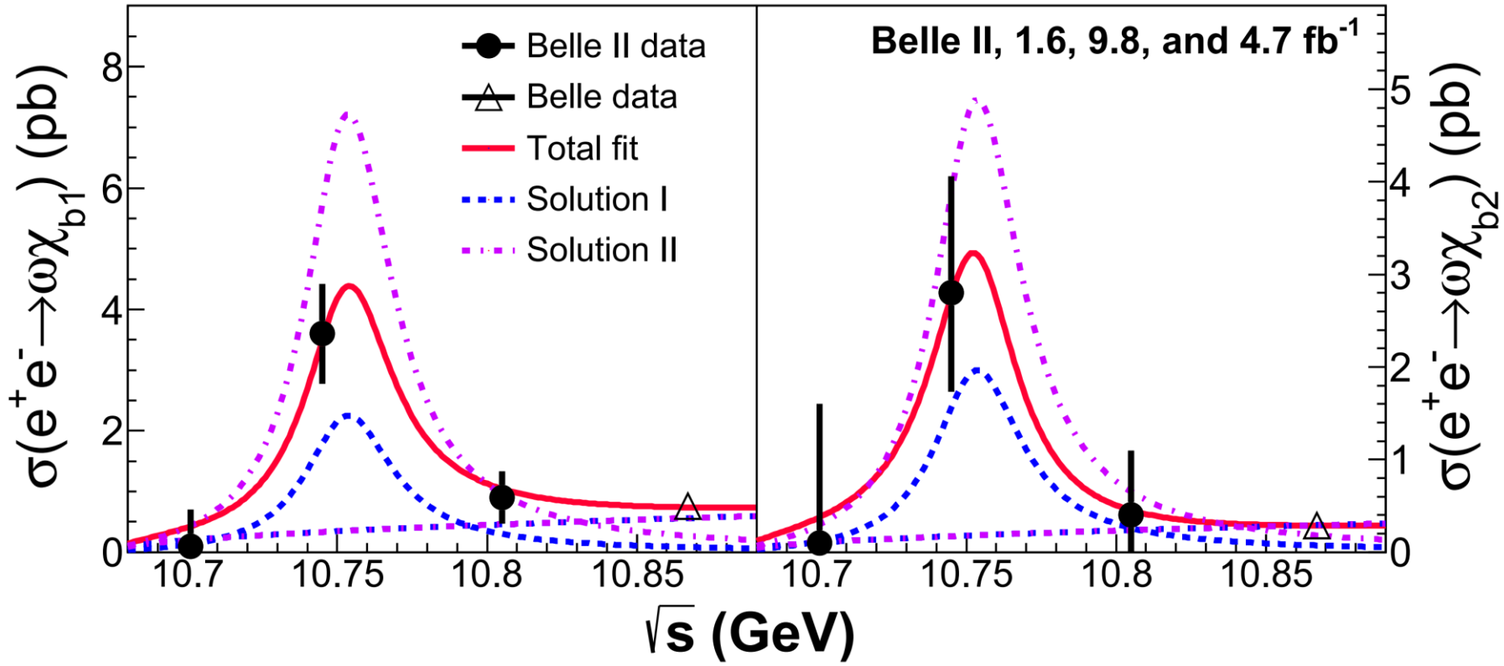
$\sigma_B(\chi_{b1},\chi_{b2})$ = (0.76±0.16, 0.29±0.14) pb

PRL 113, 142001 (2014)

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

- σ_B enhanced near Y(10753)
- No peak at Υ(5S)

- Cross section fit with sum of PHSP and BW
- Fix M, Γ of Y(10753)



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

- χ_{b1}/χ_{b2} ~1 agrees with HQET

hep-ph/9908366

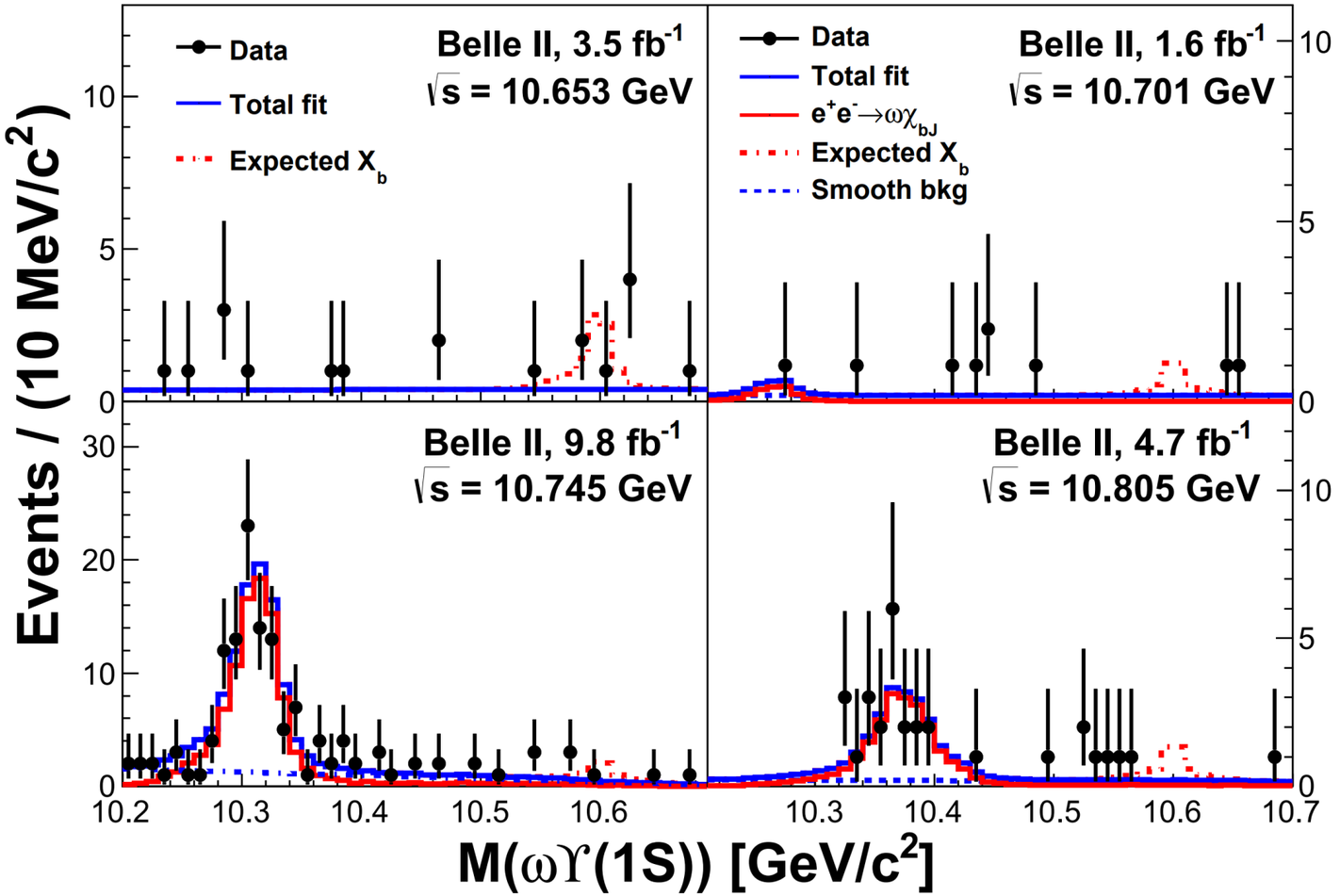
- $\omega\chi_{b1}/\pi\pi\Upsilon$(2S) ~1.5 at Y(10753) vs. 0.1 at Y(10860)

Search for X_b

- Search for enhancement in M($\omega\Upsilon$(1S)) at each CM energy
- Peaks due to $\omega\chi_{bJ}$ reflection
- No evidence for X_b signal

- Maximal upper bounds on $\sigma_B^{\rm UL}(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$

$\sqrt{s}$ (GeV)	M_{X_b} (GeV/c^2)	$\sigma^{\rm UL}_{X_b}$ (pb)
10.653	10.59	0.55
10.701	10.45	0.84
10.745	10.45	0.14
10.805	10.53	0.37



Belle II Energy Scan – Future Results

- Active analyses based on energy scan data
  - Quarkonium spectroscopy (conventional and exotic)
  - Hadronic and radiative transitions
  - Inclusive and exclusive final states
  - Precision study of vector bottomonium

- Future data at Υ(6S)
  - Accelerator upgrades during “Long Shutdown”
  - 11 GeV will be accessible
  - Revisit this region with 10x statistics?

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.)
...

Summary

- Belle II: next generation B-Factory
  - Major accelerator and detector upgrades
  - Data collection underway since 2019, will continue through this decade

- Quarkonium / “XYZs” are a main component of the physics program
  - Belle II is poised to continue the successes of Belle
  - Energy scan recently performed to understand features near 10.75 GeV
  - Success serves as motivation for other non-$\Upsilon(4S)$ data: $\Upsilon(6S)$ and beyond

- Several scan-data analyses underway, stay tuned for results

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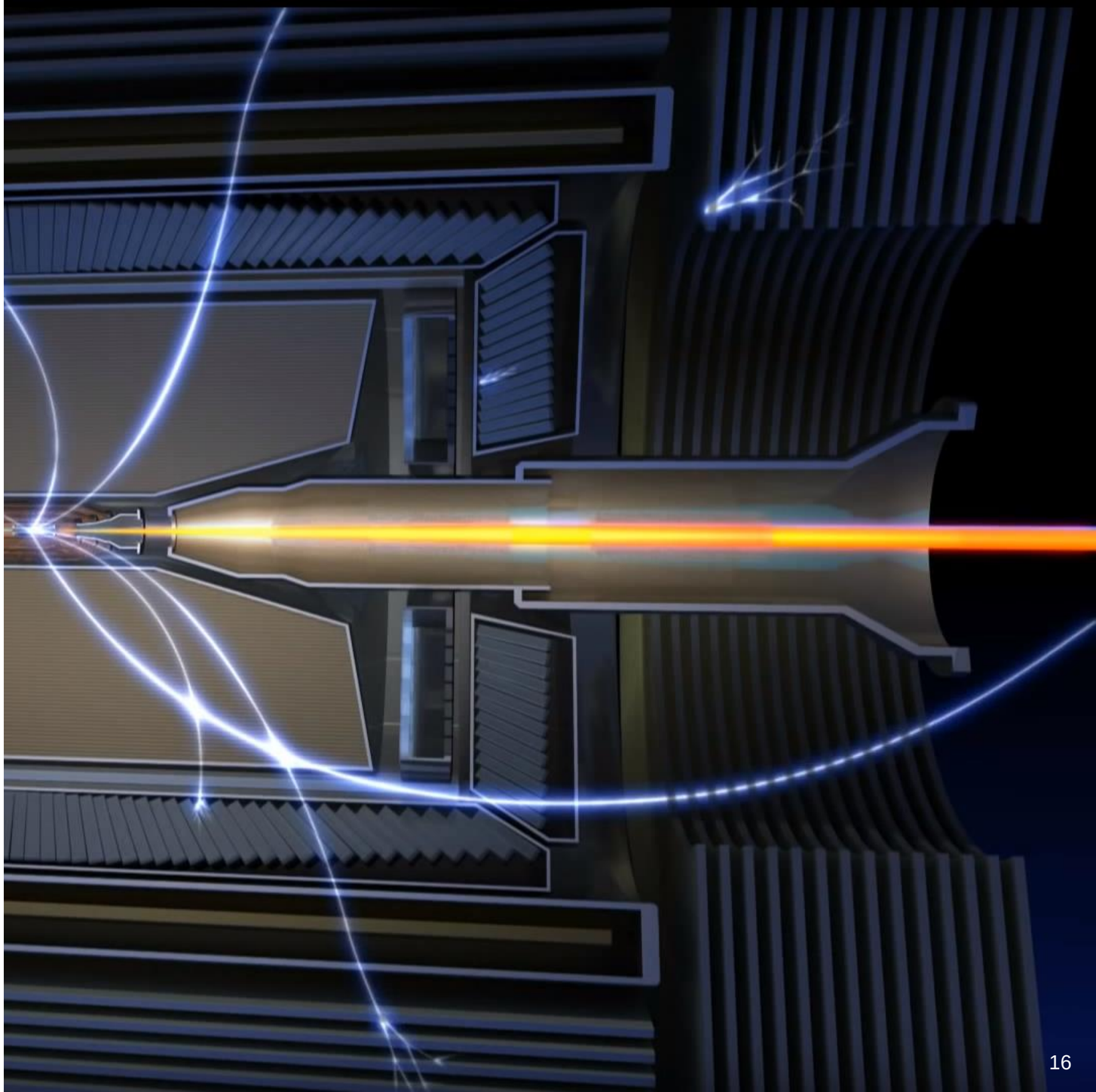
Thank you



Systematic Uncertainties

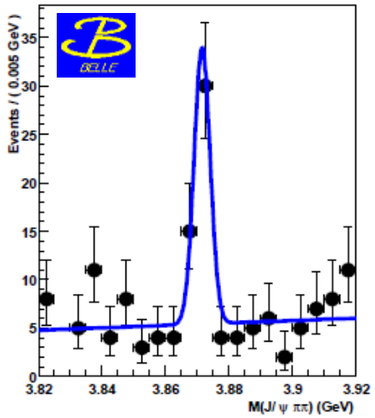
- Statistical uncertainty is a comparable factor
- Few large singular sources

Final states	$\omega\chi_{b0}/\omega\chi_{b1}/\omega\chi_{b2}$			γX_b			
$\sqrt{s}$ (GeV)	10.701	10.745	10.805	10.653	10.701	10.745	10.805
Detection efficiency	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Branching fractions	14.7/7.4/7.3	14.7/7.4/7.3	14.7/7.4/7.3	4.7	4.7	4.7	4.7
Radiative correction factor	2.0	5.1	13.7	0.2	0.4	0.5	0.7
Angular distribution	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Fit model	-	16.3/4.6/8.2	10.9/8.9/20.0	-	-	-	-
Trigger	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Beam energy	-	10.5/2.5/3.0	6.5/5.0/12.2	-	-	-	-
Luminosity	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total	16.6/10.6/10.6	25.9/12.7/14.5	24.9/20.2/29.1	8.7	8.7	8.7	8.8

B-Factories Legacy

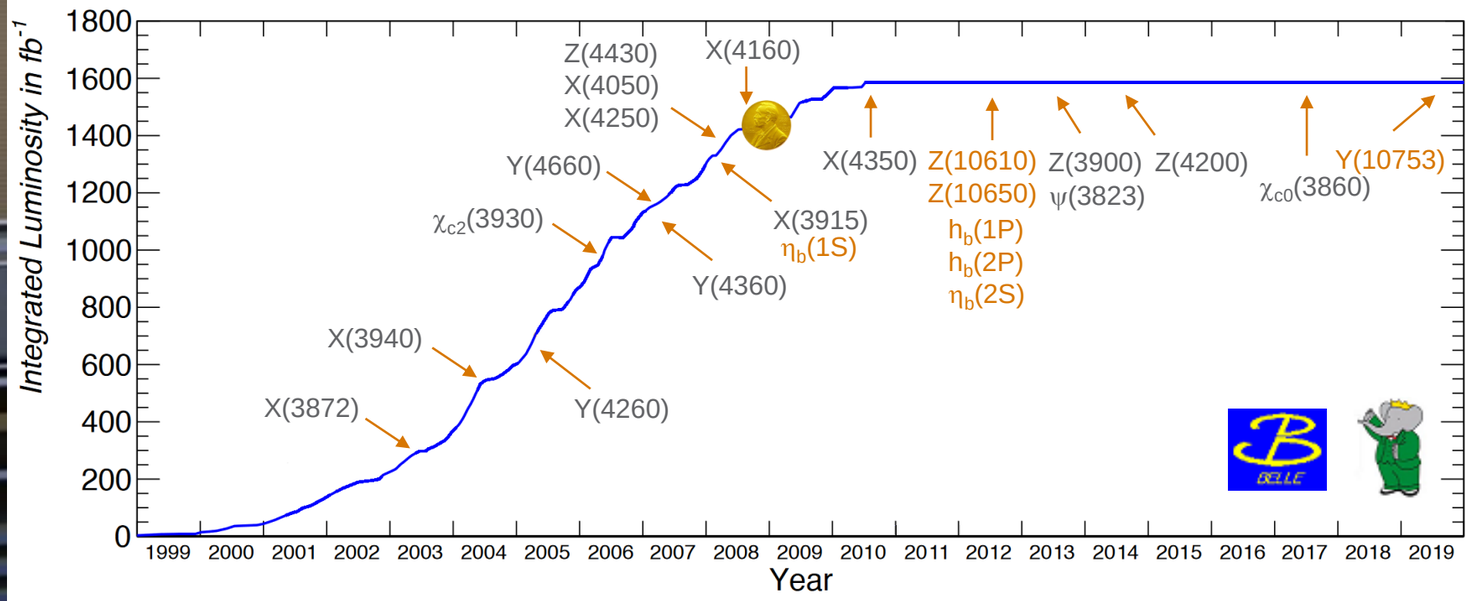
e.g.: "The Physics of the B Factories", EPJC 74, 3026 (2014)

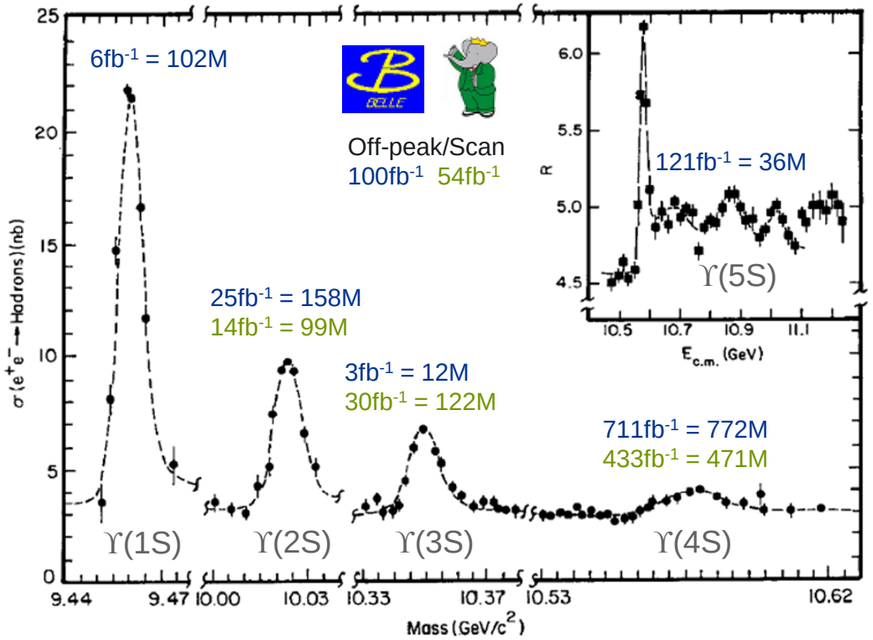
- 1999~2011 : BaBar (SLAC) & Belle (KEK)
- Flavor physics: CKM/UT, CPV in B decays
- Possible hints for NP in rare processes
- New particle discoveries: "XYZ" states



X(3872): Most cited Belle paper (~1900)

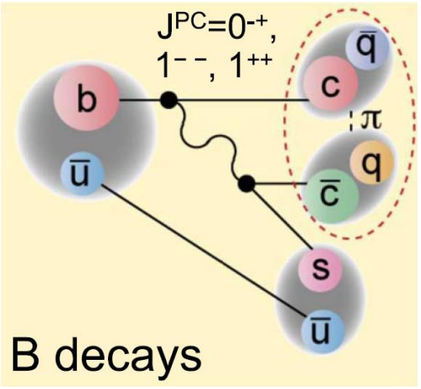
PRL 91, 262001 (2003)

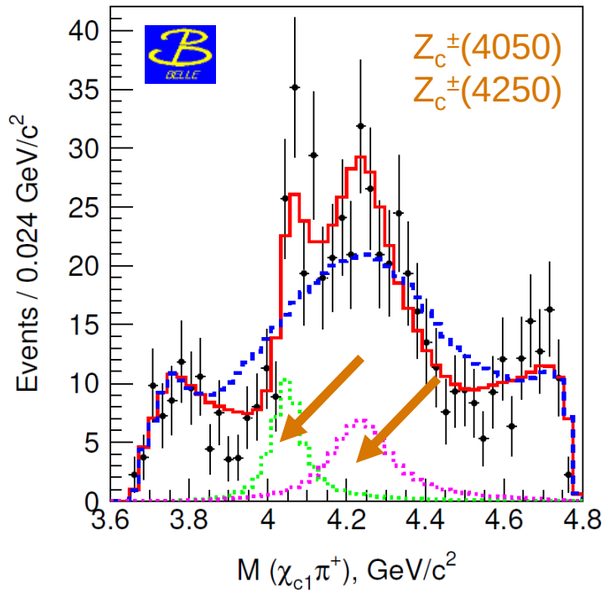




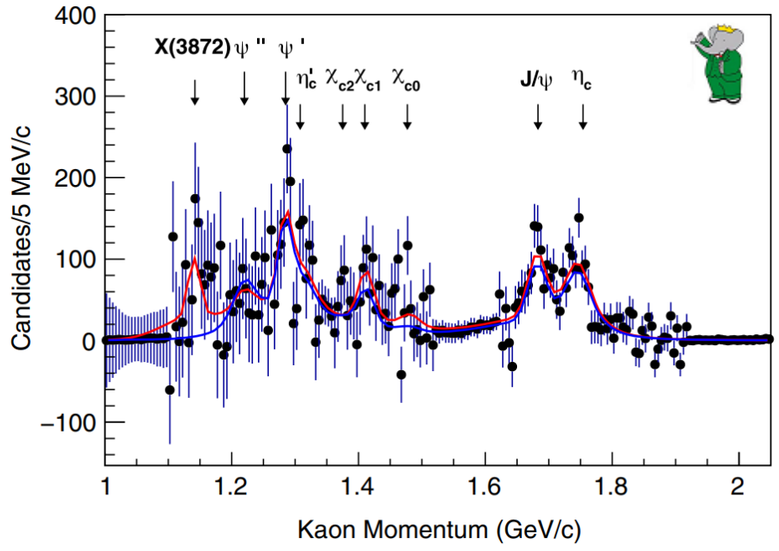
Belle II Potential – B Decay

- High-statistics continuation from B-Factories
- Competition from LHCb, advantages for modes with neutrals
  - Confirm Z_c states and search for neutral partners
  - Absolute branching fractions $B \to X(3872,3915)\, K$
  - $X(3872)$ width and lineshape measurement with $D^0\bar{D}^0\pi^0$

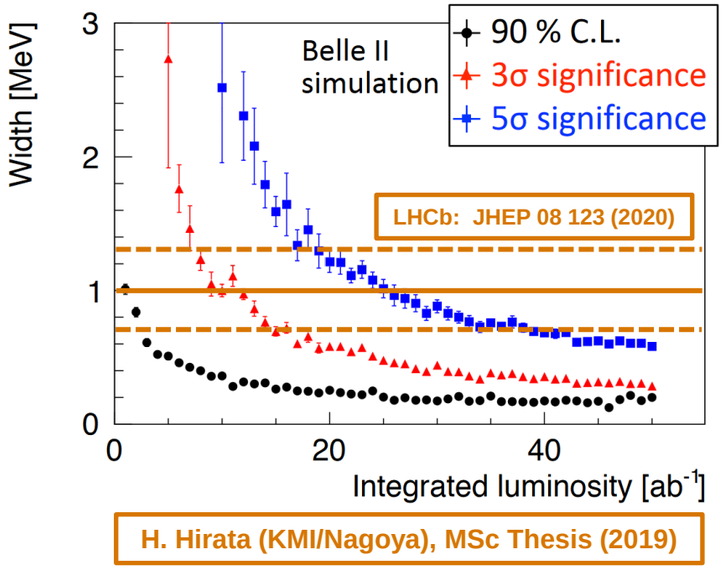




PRD 78, 072004 (2008)

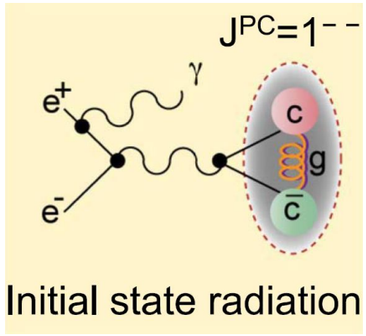


PRL 124, 152001 (2020)

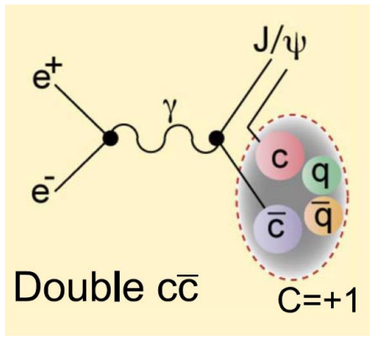


H. Hirata (KMI/Nagoya), MSc Thesis (2019)

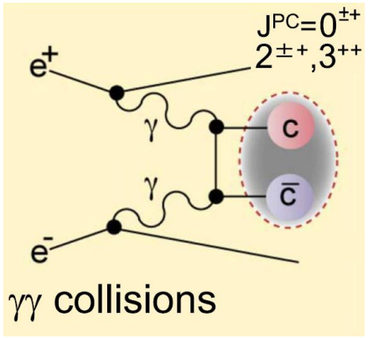
Belle II Potential – Other Processes



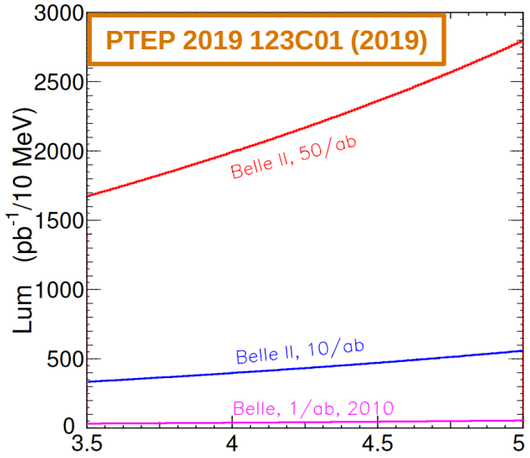
- ISR
  - Continuous mass range >4.9 GeV/c^2
  - Higher masses/channels (e.g. $\gamma_{ISR}\Sigma_c\bar{\Sigma}_c$)
  - Confirm Z_c states (e.g. $e^+e^- \rightarrow h_c\pi\pi$)

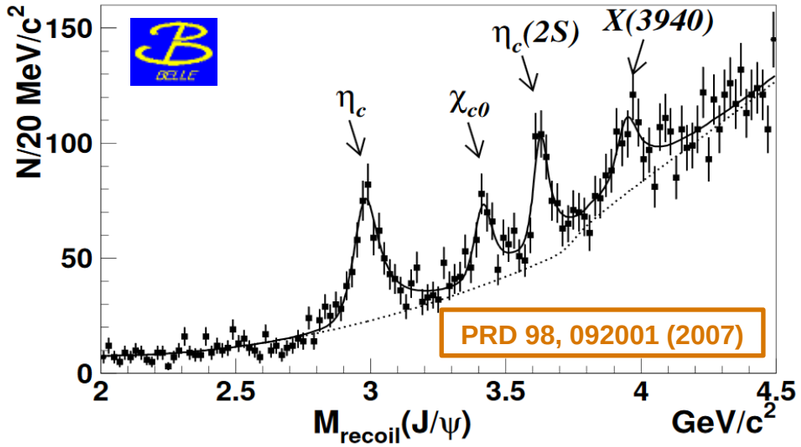


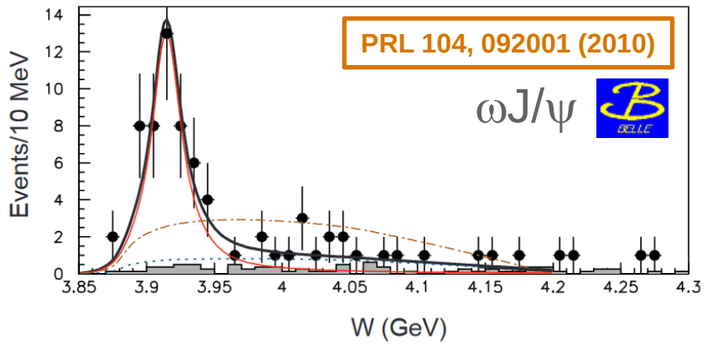
- Double-$c\bar{c}$
  - $e^+e^- \rightarrow (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
  - Discovery of X(3940, 4160)
  - Expand to other $c\bar{c}$, search for new states

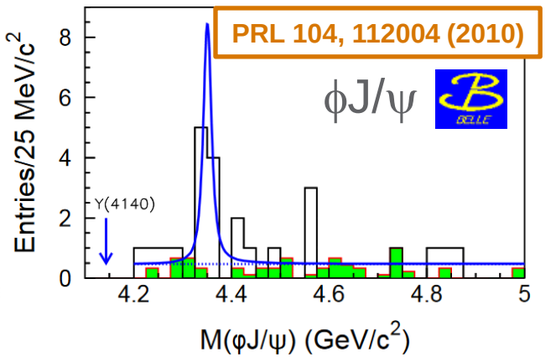


- Two-Photon
  - J^{PC} of X(3915)
  - Confirm $\phi J/\psi$ state?
  - $D^{(*)}\bar{D}^{(*)}$ final states



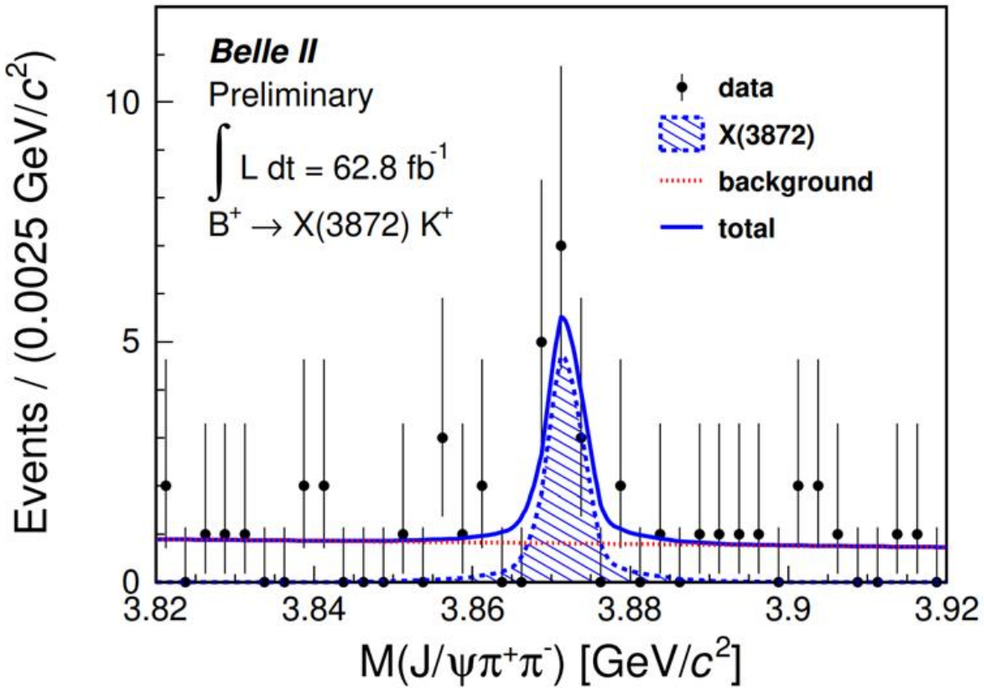






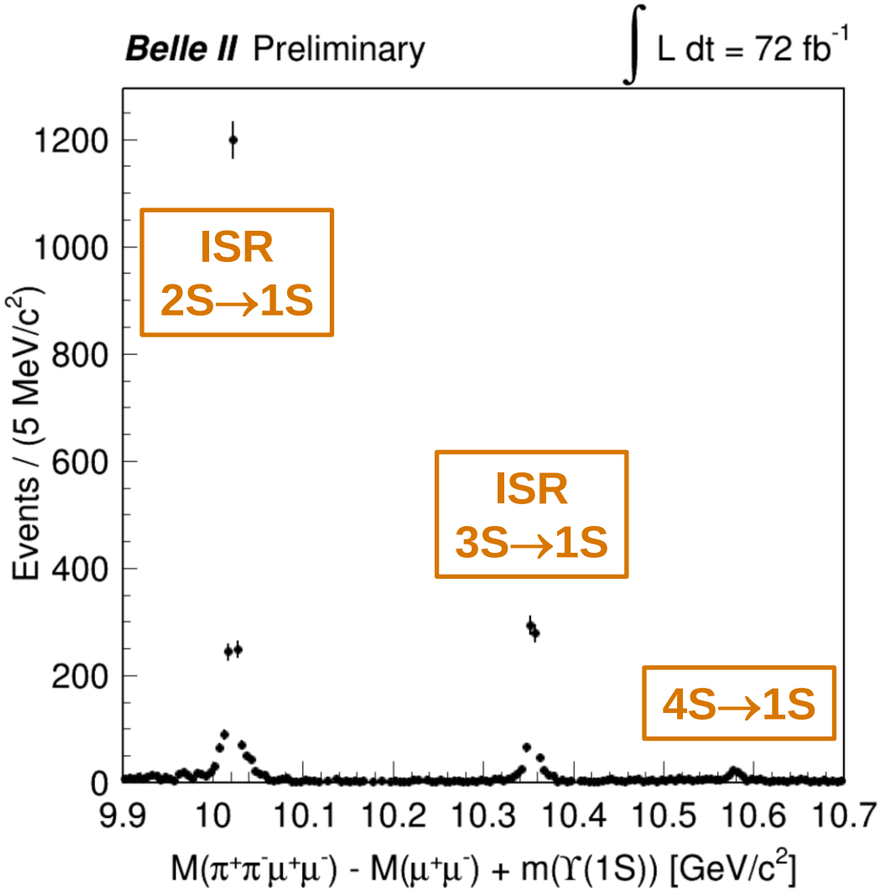
Other Belle II Quarkonium Progress

“Rediscovery” of the X(3872)



$\Upsilon(mS)\to\pi^+\pi^-\Upsilon(nS)$ decays in $\Upsilon(4S)$ data

prelude to $Y_b(10753)$ analysis



Belle II: Charmonium(-like) Future

- B-Factories started the XYZs…but do not hold a monopoly!
  - 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 (e.g., X(3872) still the most cited paper), and essential for full understanding of these new states

- Key future contributions
  - Modes 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 additional luminosity

Belle II: Bottomonium(-like) Future

- Belle II holds a special advantage
  - Able to exploit tunable beam energy in 9.4 – 11.2 GeV energy region
  - Main possibility to study Υ, Y_b, and Z_b states
  - Understanding of relationship between c- and b-sector spectroscopy

- Ability to run at non-Υ(4S) energies has been demonstrated
- Opens multiple possibilities
  - Revisit Υ(6S) with 10x+ statistics
  - LFV/spectroscopy in Υ(2S,3S) decays
  - Higher statistics scan of entire region and Υ(5S)
  - E_{CM} to $\Lambda_b\bar{\Lambda}_b$ (beyond requires SuperKEKB upgrades)