# Status and prospects of exotic hadrons at Belle II

Bruce Yabsley

University of Sydney

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# ABOUT THIS TALK

- $25 + 5$ minutes
- first talk of parallel session on first day
- substantial results slides are $\approx$ done
- need to add:
  - Belle II + dataset slide at start
  - some more $B\bar{B}$ details
  - summary
  - some more backup slides
- request advice on whether to add $P_{cs}(4459)^0$-at-Belle result at the 1–2 slide level — this result was changing at CWR1

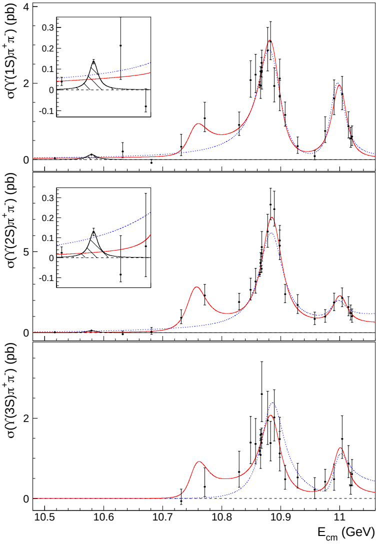
# Outline

1. **Belle II detector and datasets**
2. **Reminder: the $\Upsilon(10753)$**
3. **Using $\pi\pi\pi^0\gamma\Upsilon$ at four energies:**
   - Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$
   - Search for $X_b \to \omega\Upsilon(1S)$
4. **Using $\omega$ inclusive at $10745\,\mathrm{MeV}$:**
   - Search for $e^+e^- \to \omega\eta_b(1S)$ and $\omega\chi_{b0}(1P)$
5. **Using $B$-meson recon. at four energies + Belle energy scan:**
   - Measurement of energy dependence of $\sigma(e^+e^- \to B\bar{B},\, B\bar{B}^*,\, B^*\bar{B}^*)$
6. **Prospects**

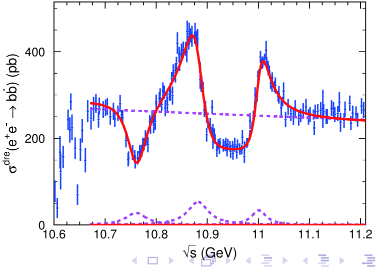
# Belle II detector and datasets

# Reminder: the $\Upsilon(10753)$

R. Mizuk et al. (Belle), JHEP 10 (2019), 220; DMWY, CPC 44 (2020) 083001




- a third peak in $\sigma(e^+e^- \to \Upsilon(nS)\pi\pi$
- *cf.* $\Upsilon(10860)$-&-$\Upsilon(11020)$-only fit
- Dong, Mo, Wang, and Yuan also see this in a fit to Belle & BaBar $\sigma(e^+e^- \to b\bar{b})$ data:
  - continuum amplitude
  - BWs for 10753, 10860, & 11020
  - interference is apparent

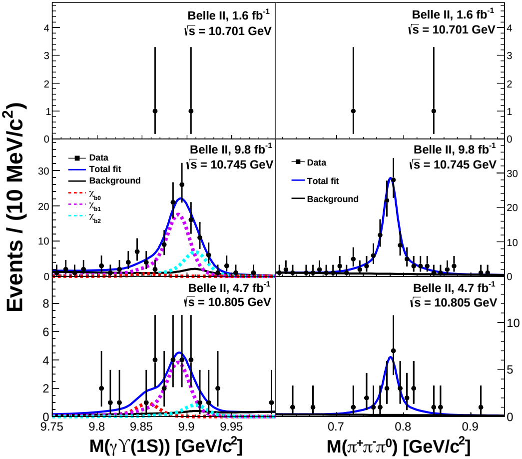


# Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ ...

I. Adachi et al. (Belle II), Phys. Rev. Lett. 130 (2023) 091902

$\sqrt{s} = 10653$ ($3.5\,\mathrm{fb}^{-1}$), 10701 ($1.6\,\mathrm{fb}^{-1}$), 10745 (9.9), $10805\,\mathrm{MeV}$ ($4.7\,\mathrm{fb}^{-1}$)

- mass-constrained fits to $\Upsilon(1S) \to \ell\ell$, $\omega \to \pi\pi\pi^0$
- $\chi_{bJ} \to \gamma\Upsilon$ photons $> 50\,\mathrm{MeV}$
- $\pi\pi\pi^0\gamma\Upsilon$ fit constrained to known $e^+e^-$ four-momentum
- 2D unbinned ML fit to $\gamma\Upsilon$ and $\pi\pi\pi^0$ masses $\longrightarrow$
- significant $\chi_{b1,b2}$ yields at 10745 and $10805\,\mathrm{MeV}$ (at 10745, $\chi_{b1}$ alone is $5.9\sigma$)
- upper limits at $10701\,\mathrm{MeV}$



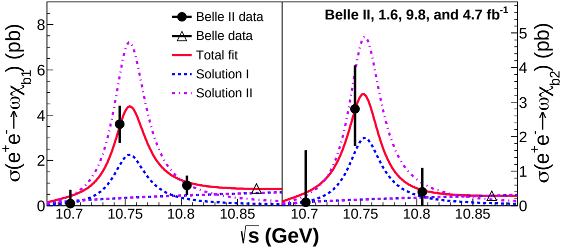

at $10745\,\mathrm{MeV}$: $\dfrac{\sigma_{\mathrm{Born}}(\omega\chi_{b1})}{\sigma_{\mathrm{Born}}(\omega\chi_{b2})} = 1.3 \pm 0.6$, *cf.* 15 for D-wave, 0.2 for 4S–3D mixed

# Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ ...

I. Adachi et al. (Belle II), Phys. Rev. Lett. 130 (2023) 091902

$E$-dep$^t$ fit includes $118\,\mathrm{fb}^{-1}$ Belle *PRL* **113** (2014) 142001 data at $10867\,\mathrm{MeV}$: note that $\omega\chi_{bJ}$ is *much* more prominent for $\Upsilon(10753)$ than for $\Upsilon(10860)$

- phase space & BW fixed to Belle 10753 params
- two distinct solutions w different relative phases
- alternative: tail of 10860 BW, and 10753 BW




$$\left|\sqrt{\Phi_2(\sqrt{s})} + \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 - iM\Gamma}\sqrt{\frac{\Phi_2(\sqrt{s})}{\Phi_2(M)}}e^{i\phi}\right|^2$$

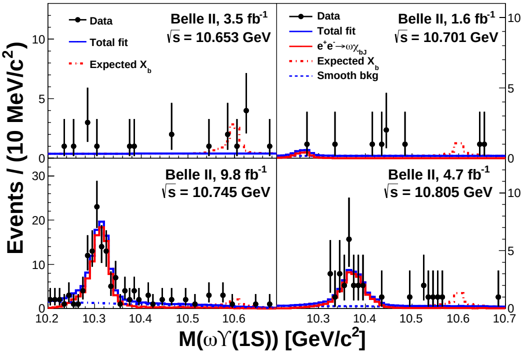
| | | | |
|---|---|---|---|
| $\Gamma_{ee}\mathcal{B}(\omega\chi_{b1,b2})$ | solution I: | $(0.63 \pm 0.39 \pm 0.20)\,\mathrm{eV}$ | $(0.53 \pm 0.46 \pm 0.15)\,\mathrm{eV}$ |
| | solution II: | $(2.01 \pm 0.38 \pm 0.76)\,\mathrm{eV}$ | $(1.32 \pm 0.44 \pm 0.55)\,\mathrm{eV}$ |
| | alternative: | $(1.24 \pm 0.56)\,\mathrm{eV}$ (stat.) | $(0.92 \pm 0.37)\,\mathrm{eV}$ (stat.) |

# ... and search for $X_b \to \omega\Upsilon(1S)$

I. Adachi et al. (Belle II), Phys. Rev. Lett. 130 (2023) 091902

The $\pi\pi\pi^0\gamma\Upsilon$ final state can also be used to search for $e^+e^- \to \gamma X_b$, in the isospin-allowed $X_b \to \omega\Upsilon$ decay mode:

- $700 < M(\pi\pi\pi^0) < 860\,\mathrm{MeV}$
- clear $\omega\chi_{bJ}$ reflections; shape taken from simulation
- linear smooth background
- upper limit yields for $M(X_b) \in [10450, 10650]\,\mathrm{MeV}$ obtained by counting
- (systematics in backup)



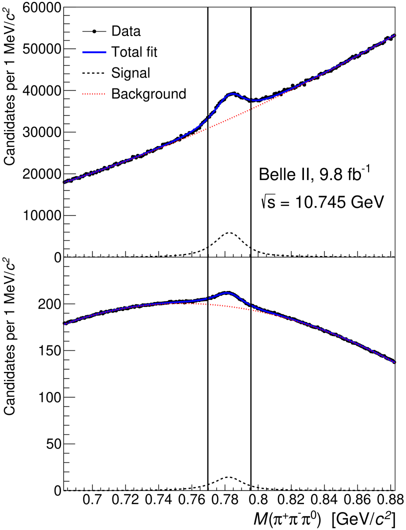

Limits on $\sigma(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon) \ni$ $(0.14\text{–}0.55)\,\mathrm{pb}$ $(0.25\text{–}0.84)\,\mathrm{pb}$ $(0.06\text{–}0.14)\,\mathrm{pb}$ $(0.08\text{–}0.37)\,\mathrm{pb}$

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

I. Adachi et al. (Belle II), Phys. Rev. D 109 (2024) 072013

Using the $9.8\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 10745\,\mathrm{MeV}$ data, near the $\Upsilon(10753)$ peak:

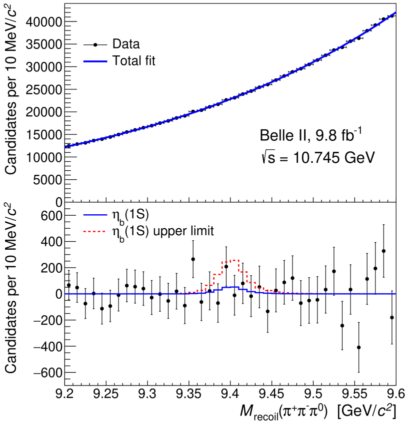
- photon $E > 50\,\mathrm{MeV}$ ($< 75\,\mathrm{MeV}$ in backward endcap)
- ECL cluster − $e^+e^-$ collision $|\Delta t| < 50\,\mathrm{ns}$ versus beam bkgd
- photon-like ECL clusters required: $E(3\times3)/E(5\times5-4\,\text{corners}) > 0.8$
- $p^*_{\pi^0} > 260\,(130)\,\mathrm{MeV}$ for $\eta_b$ $(\chi_{b0})$
- $|M(\pi\pi\pi^0) - m_\omega| < 13\,\mathrm{MeV}$
- symmetrised Dalitz $r < 0.84$ (0.82)
- use recoil mass $\sqrt{(\sqrt{s}-E_\omega)^2 - p_\omega^2}$: $M_{\text{recoil}} \in (9200, 9600)\,\mathrm{MeV}$ for $\eta_b$, $\in (9780, 9950)\,\mathrm{MeV}$ for $\chi_{b0}$

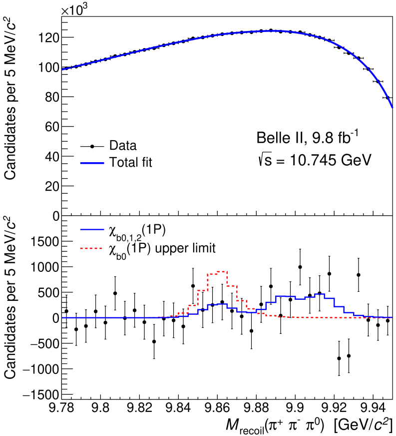


# Search for $e^+e^- \to \omega\eta_b(1S)$ and $\omega\chi_{b0}(1P)$

I. Adachi et al. (Belle II), Phys. Rev. D 109 (2024) 072013

$\chi^2$ fits to recoil mass, with signal shapes fixed to simulation:




bkgd: 3rd order Chebyshev

bkgd: 4th order Chebyshev × \sqrt

in the $\chi_{b0}$ fit, $\chi_{b1}/\chi_{b2}$ yields fixed to 1.4, total $\chi_{b1,b2}$ yield fixed to expectation

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

I. Adachi et al. (Belle II), Phys. Rev. D 109 (2024) 072013

TABLE II. Systematic uncertainties in the yields for the processes $e^+e^- \to \eta_b(1S)\omega$ and $e^+e^- \to \chi_{b0}(1P)\omega$ (in units of $10^3$).

| | $\eta_b(1S)\omega$ | $\chi_{b0}(1P)\omega$ |
|---|---|---|
| $\eta_b(1S)/\chi_{b0}(1P)$ mass | 0.05 | 0.08 |
| Collision-energy calibration | 0.02 | 0.19 |
| Cross-section shape | 0.01 | 0.13 |
| $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ yields | – | 0.27 |
| Background shape | 0.24 | 0.85 |
| Total | 0.25 | 0.92 |

TABLE III. Multiplicative systematic uncertainties for the measurement of the $e^+e^- \to \eta_b(1S)\omega$ and $e^+e^- \to \chi_{b0}(1P)\omega$ cross sections (in %).

| | $\eta_b(1S)\omega$ | $\chi_{b0}(1P)\omega$ |
|---|---|---|
| Track reconstruction efficiency | 1.6 | 2.4 |
| PID efficiency | 0.8 | 1.0 |
| $\pi^0$ reconstruction efficiency | 3.2 | 7.3 |
| $R_2$ efficiency | 10.0 | 10.0 |
| Luminosity | 0.6 | 0.6 |
| $\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)$ | 0.7 | 0.7 |
| Total multiplicative uncertainty | 10.7 | 12.7 |

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$\boldsymbol{\sigma_{\text{Born}}(e^+e^- \to \omega\eta_b(1S)) < 2.5\,\text{pb}}$, *cf.* 1–3 pb for observed $\pi\pi\Upsilon(nS)$ signals,

inconsistent with enhancement predicted for tetraquark $\Upsilon(10753)$

consistent with 0.2–0.4 $\times\ \pi\pi\Upsilon(nS)$ predicted for 4S–3D mixed

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$\boldsymbol{\sigma_{\text{Born}}(e^+e^- \to \omega\chi_{b0}) < 8.7\ (7.8)\,\text{pb}}$, *cf.* 3–4 pb for our $\omega\chi_{b1,b2}$ measurements

inconsistent with $Y(4230)$-like enhancement;

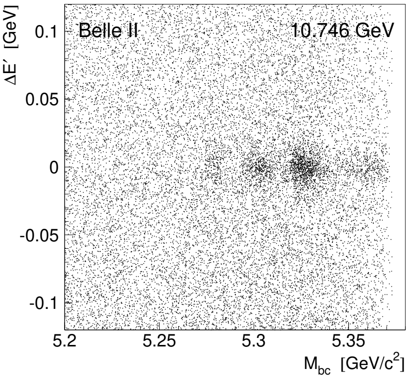
consistent with 4S–3D expectation of comparable rates

[the tighter limit is from combination with the (similar sensitivity) $\pi\pi\pi^0\gamma\Upsilon$ result]

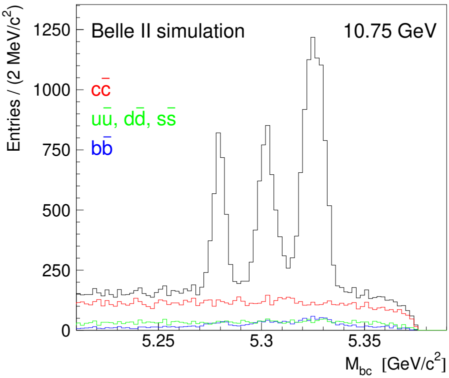
# Energy dependence of $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$

I. Adachi et al. (Belle II), arXiv:2405.18928 → JHEP

Multivariate algorithm to reconstruct $\pi^0$, $K^0_S$, ... then $D$, $D^*$, $J/\psi$, ... then $B$: the "Full Event Interpretation"; $\epsilon = (0.5802 \pm 0.0031 \pm 0.0116) \times 10^{-3}$ at the 4S




clear $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$ signals seen (this is 10.746 GeV data)



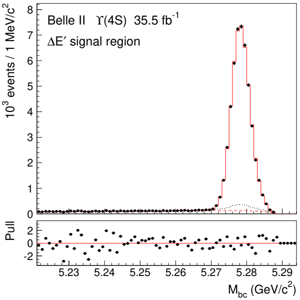

high purity; some $e^+e^- \to c\bar{c}$, small light-quark and broken $b\bar{b}$ background

# Energy dependence of $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$

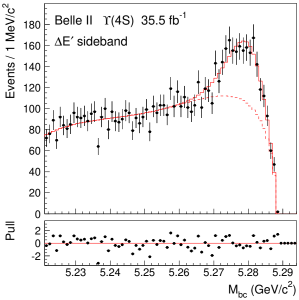
I. Adachi et al. (Belle II), arXiv:2405.18928 → JHEP

$\Upsilon(4S)$ data used to measure efficiency, and validate the fit function: includes

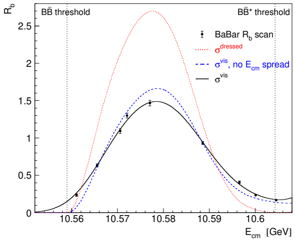
- energy spread of the colliding $e^+e^-$ beams
- initial state radiation (ISR)
- $B$-meson momentum resolution
- energy dependence of the production cross-section




$|\Delta E'| < 18\,\mathrm{MeV}$




$\Delta E'$ sideband: constrains bkgd, broken-signal shape




[BaBar PRL **102** (2009) 012001]

simultaneously fitted with $\Delta E'$ signal and sideband

# Energy dependence of $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$

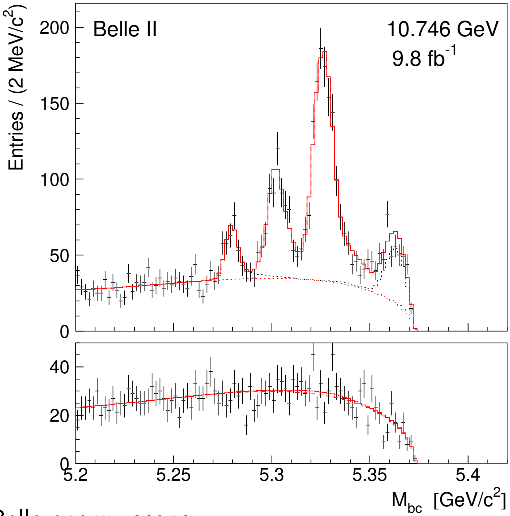
I. Adachi et al. (Belle II), arXiv:2405.18928 → JHEP

at 10804, **10746**, 10701, and 10653 $\mathrm{MeV}$, we use an iterative procedure for self-consistency:

- fit the $M_{bc}$ spectrum ($\Delta E'$ signal & sideband): note $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, & $\gamma_{ISR}\Upsilon(4S)$ peaks
- determine the cross-sections
- fit energy dependence of $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, and total $b\bar{b}$ cross-sections

— converges after 2 iterations

- $B^{(*)}\bar{B}^{(*)}$: include Belle results
- total $b\bar{b}$: combined BaBar & Belle energy scans



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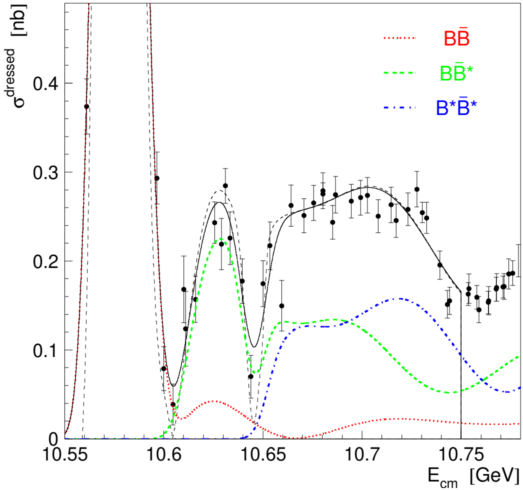
[in discussion and on slides, draw attention to rapid rise of $B^*\bar{B}^*$ cross-section from threshold]



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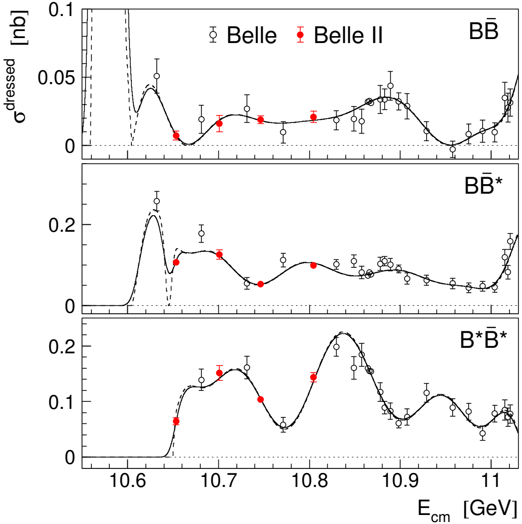

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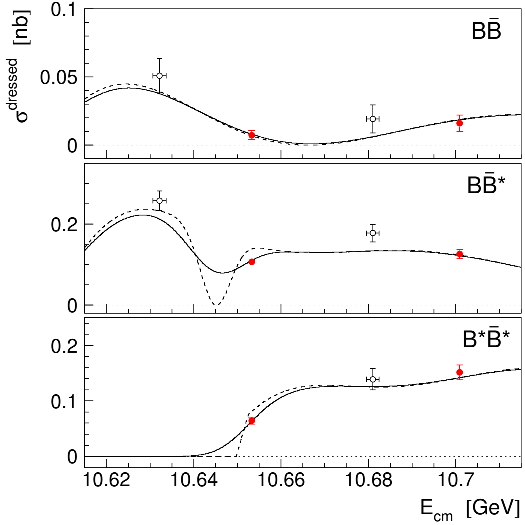

# Energy dependence of $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$

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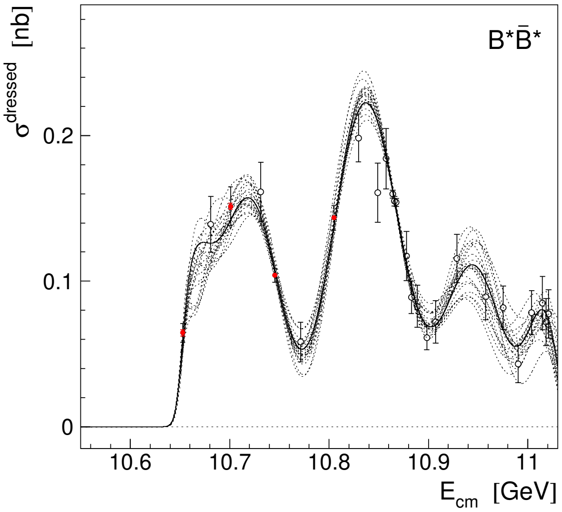
systematics example for $B^*\overline{B}^*$; others in backup



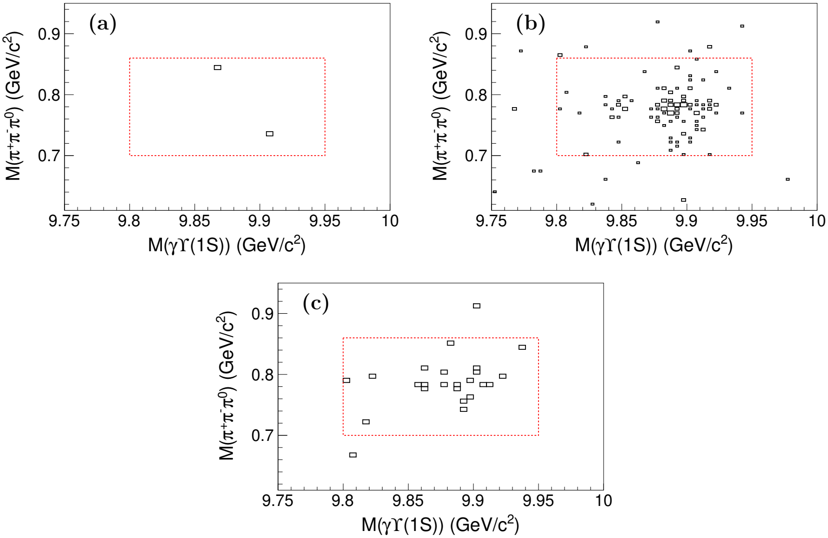
# Prospects

# Summary

# BACKUP SLIDES

# $e^+e^- \to \omega\chi_{bJ}(1P)$, and search for $X_b \to \omega\Upsilon(1S)$

I. Adachi et al. (Belle II), Phys. Rev. Lett. 130 (2023) 091902



# $e^+e^- \to \omega\chi_{bJ}(1P)$, and search for $X_b \to \omega\Upsilon(1S)$

I. Adachi et al. (Belle II), Phys. Rev. Lett. 130 (2023) 091902

TABLE I: Inputs and upper limits obtained for $X_b$ masses from 10.45 to 10.65 GeV/$c^2$ (at 90% Bayesian credibility) on the product of cross section times branching fraction $\sigma_B^{\mathrm{UL}}(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$ ($\sigma_{X_b}^{\mathrm{UL}}$) at $\sqrt{s}$ = 10.653, 10.701, 10.745, and 10.805 GeV. Since the upper limits depend on the test $X_b$ mass, only the least stringent bounds are reported for each collision energy.

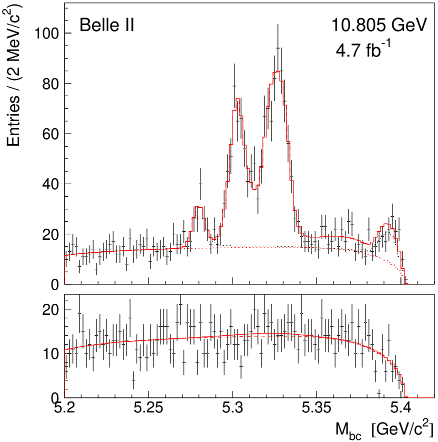
| $\sqrt{s}$ (GeV) | $M_{X_b}$ (GeV/$c^2$) | $N^{\mathrm{UL}}$ | $\varepsilon$ | $\lvert 1-\Pi \rvert^2$ | $1+\delta_{\mathrm{ISR}}$ | Syst (%) | $\sigma_{X_b}^{\mathrm{UL}}$ (pb) |
|---|---|---|---|---|---|---|---|
| 10.653 | 10.59 | 10.0 | 0.154 | 0.931 | 0.72 | 8.7 | 0.55 |
| 10.701 | 10.45 | 8.1 | 0.166 | 0.931 | 0.76 | 8.7 | 0.84 |
| 10.745 | 10.45 | 8.1 | 0.164 | 0.931 | 0.78 | 8.7 | 0.14 |
| 10.805 | 10.53 | 10.7 | 0.165 | 0.932 | 0.81 | 8.8 | 0.37 |

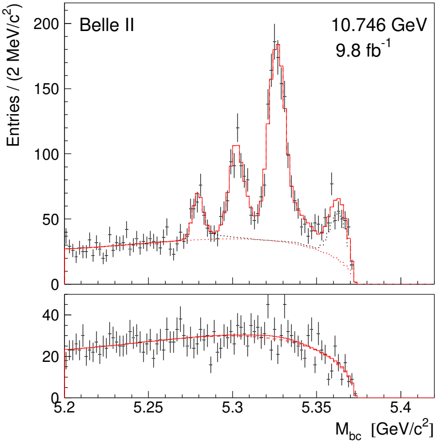
TABLE II: Fractional systematic uncertainties (%) in the measurements of $\sigma_B(e^+e^- \to \omega\chi_{bJ})$ and $\sigma_B(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$. Systematic uncertainties from detection efficiency, branching fractions, trigger, and luminosity are correlated between various energy points while other systematic uncertainties are uncorrelated.

| Final states | $\omega\chi_{b0}/\omega\chi_{b1}/\omega\chi_{b2}$ | | | $\gamma X_b$ | | | |
|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ (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 |

# Energy dependence of $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$

I. Adachi et al. (Belle II), arXiv:2405.18928 → JHEP



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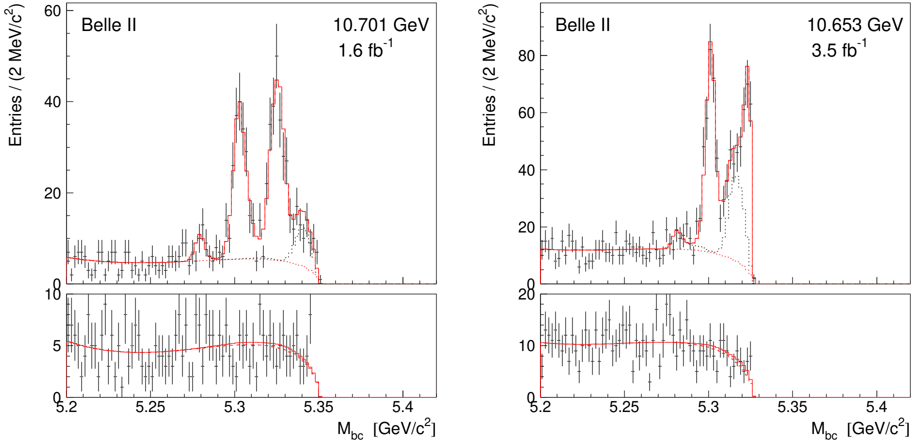

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