Status and prospects of exotic hadrons at Belle II

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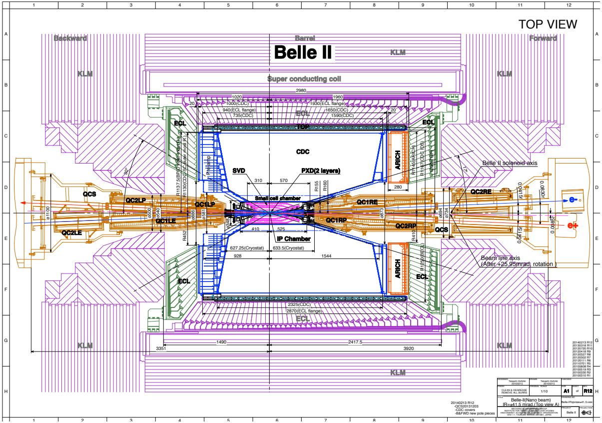
Outline

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

Belle II detector and datasets

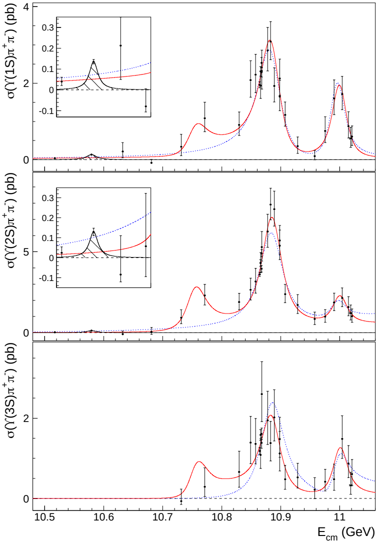
Belle II is an almost complete re-build of Belle, with various improvements: pixel Si layers close to beam, small-cell drift chamber, Cherenkov PID, calorimeter pulse-shape discrimination, (partial) scintillators in flux return

- exploit tens of ab^{-1} of data expected from SuperKEKB,
- mitigate higher backgrounds at $\mathcal{L} > 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- reached 4.5×10^{34} in recent running (close to 4.7 record)
- over $500\,\mathrm{fb}^{-1}$ now recorded, mostly $\Upsilon(4S) \to B\overline{B}$ plus some special running

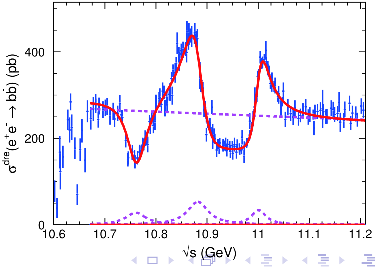


Reminder: the $\Upsilon(10753)$

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



Confirmation of the $\Upsilon(10753)$ signal ...

I. Adachi et al. (Belle II), arXiv:2401.12021v3 accepted by JHEP

dedicated SuperKEKB runs at 4 points near 10753, between the Belle points: $\sqrt{s} = 10653\ (3.5\,\mathrm{fb}^{-1})$, $10701\ (1.6\,\mathrm{fb}^{-1})$, $10745\ (9.9)$, $10805\,\mathrm{MeV}\ (4.7\,\mathrm{fb}^{-1})$

- $\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$ reconstruction; μID for one muon
- π^+, π^- reconstruction with p_T, muon veto, and γ-conversion veto on $\pi^+\pi^-$
- vertex fits to $\mu\mu$, $\pi\pi$, then $\pi\pi\mu\mu$; $p^*(\pi\pi\mu\mu) < 100\,\mathrm{MeV}$ to suppress bkgd
- $\Delta M = M(\pi\pi\mu\mu) - M(\mu\mu)$; fit $\Delta M \in (\Delta M_{\mathrm{nom}} - 100,\ \Delta M_{\mathrm{nom}} + 70)\,\mathrm{MeV}$
- iterative method:
  - weight simulated signal according to $e^+e^- \to \pi\pi\Upsilon(nS)$ lineshape
  - determine signal shape, efficiency (ϵ)
  - unbinned ML fit to ΔM to determine signal yield N_S
  - determine Born cross section $\sigma_{\mathrm{Born}} = \dfrac{N_S\,|1 - \Pi|^2}{\mathcal{L}\,\epsilon\,\mathcal{B}\,(1+\delta)}$
  - fit σ_{Born} for Belle II and Belle points with interfering Breit-Wigners for the $\Upsilon(10753)$, $\Upsilon(5S)$, and $\Upsilon(6S)$:

Confirmation of the $\Upsilon(10753)$ signal . . .

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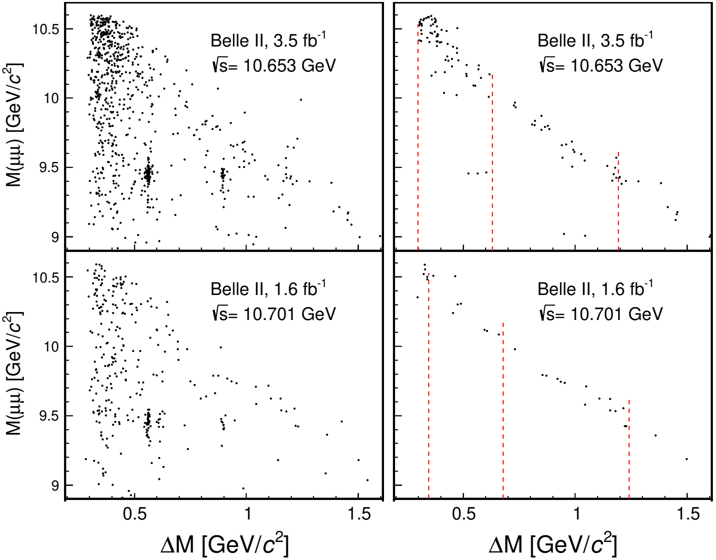

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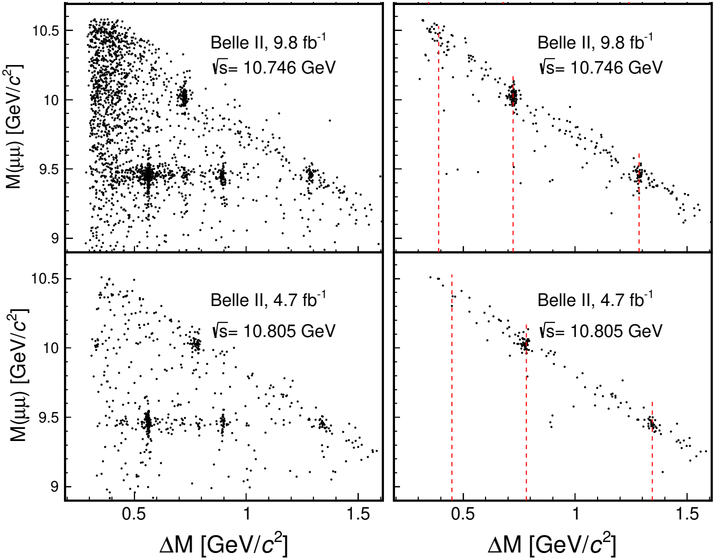

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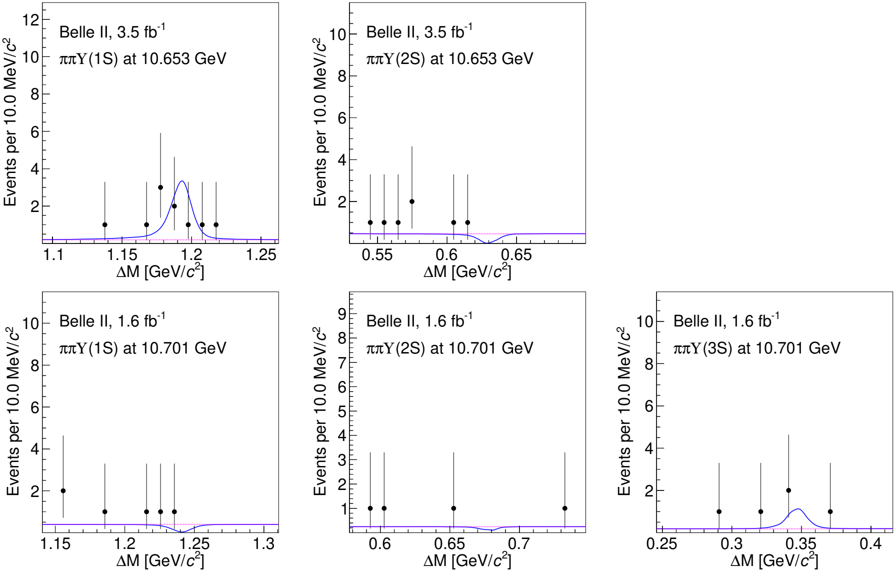

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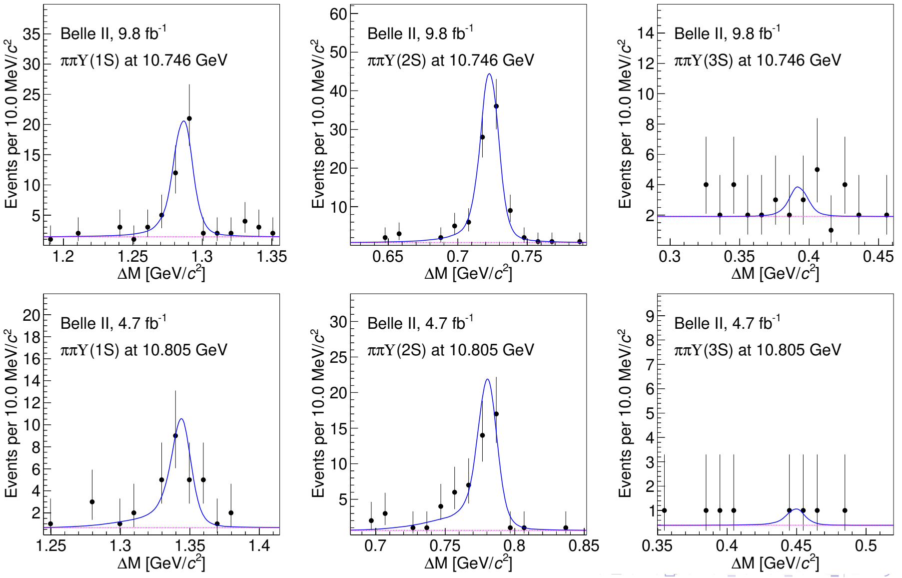

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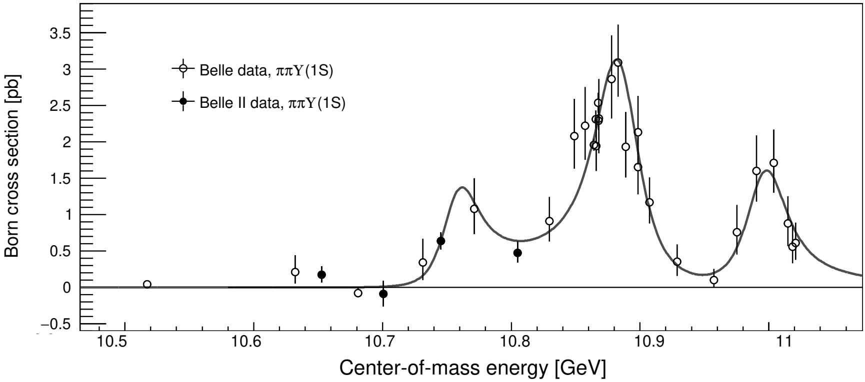

- significant $\Upsilon(10753)$ amplitude for $\pi\pi\Upsilon(1S, 2S)$; only 0.2σ for 3S
- $M = (10756.6 \pm 2.7 \pm 0.9)\,\mathrm{MeV}$, $\Gamma = (29.0 \pm 8.8 \pm 1.2)\,\mathrm{MeV}$
- $\Upsilon(5S)$, $\Upsilon(6S)$ parameters also recovered
- $\sigma(\pi\pi\Upsilon(3S))/\sigma(\pi\pi\Upsilon(2S))|_{\Upsilon(10753)} = 0.10^{+0.05}_{-0.04}$: low *cf.* 5S, 6S

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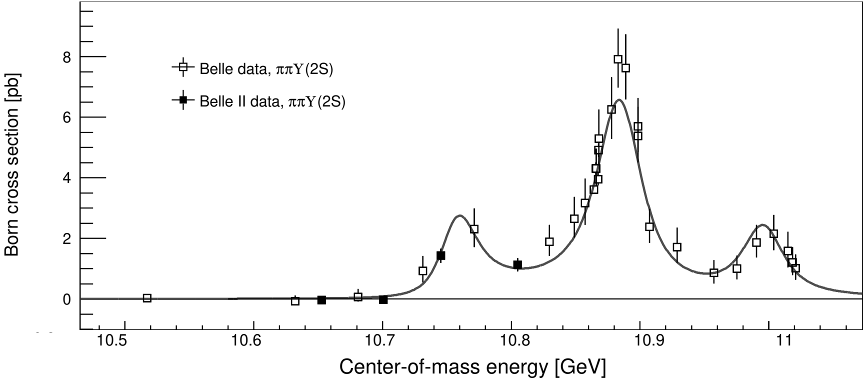

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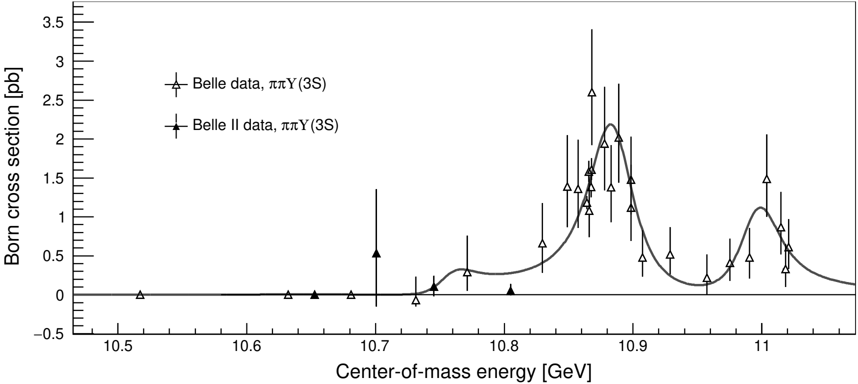

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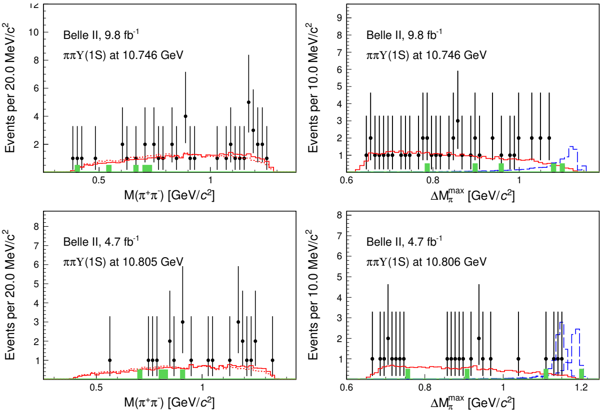
$M(\pi\pi)$ and the larger $\Delta M_\pi = M(\pi\mu\mu) - M(\mu\mu)$ are studied:

- $\pi\pi\Upsilon(1S)$ consistent w phase space



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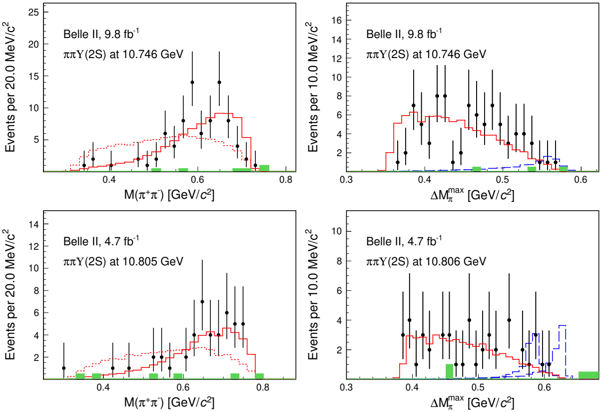
- $\pi\pi\Upsilon(2S)$ is not:

  CLEO-style fit to the $\pi\pi$ amplitude

  $\pi\pi\Upsilon(2S)$ decay is 2S $\to \pi\pi$ 1S-like



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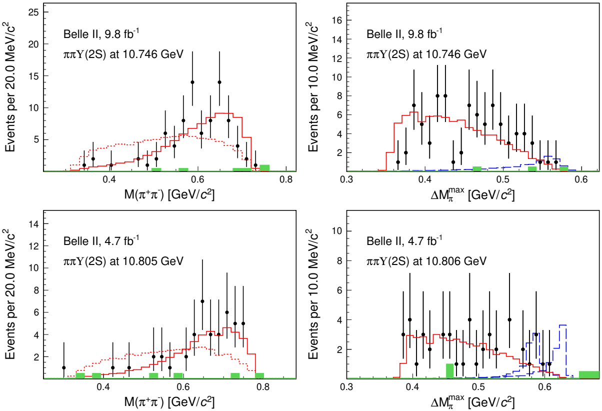
  $\pi\pi\Upsilon(2S)$ decay is 2S $\to \pi\pi$ 1S-like
- no Z_b signal is seen
- $\sigma_{\text{Born}} < 0.13,\ 0.14\,\text{pb}$ at $10746\,\text{MeV}$
- $\sigma_{\text{Born}} < 0.43,\ 0.35\,\text{pb}$ at $10805\,\text{MeV}$ for $e^+e^- \to \pi Z_b(\to \pi\Upsilon(1S, 2S))$

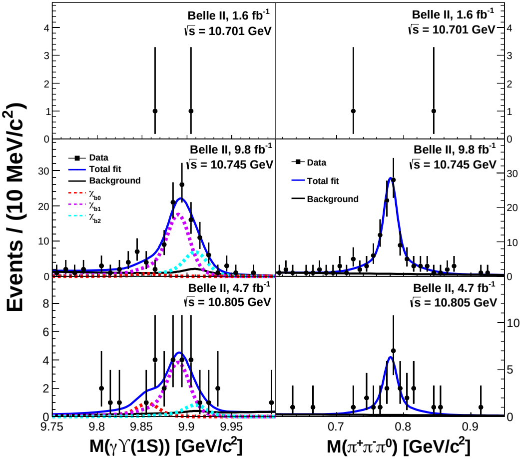


Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ ...

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 MeV (at 10745, χ_{b1} alone is 5.9σ)
- upper limits at 10701 MeV



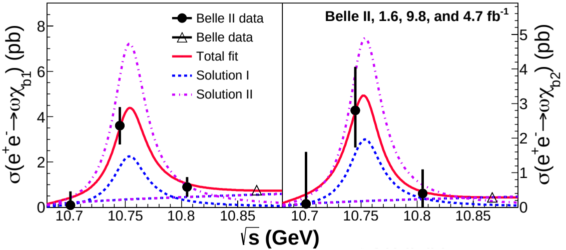
at 10745 MeV: $\dfrac{\sigma_{\mathrm{Born}}(\omega\chi_{b1})}{\sigma_{\mathrm{Born}}(\omega\chi_{b2})} = 1.3 \pm 0.6$, *cf.* 15 for D-wave, 0.2 for 4S–3D mixed

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 fb^{-1} Belle data** at 10867 MeV [*PRL* **113** (2014) 142001]; note that $\omega\chi_{bJ}$ is *much* more prominent for $\Upsilon(10753)$ than for $\Upsilon(10860)$

- 2-body phase space Φ_2 & 10753 BW (Belle params)
- two solutions:
  - constructive interference
  - destructive interference
- alternative: tail of 10860 BW, and 10753 BW



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

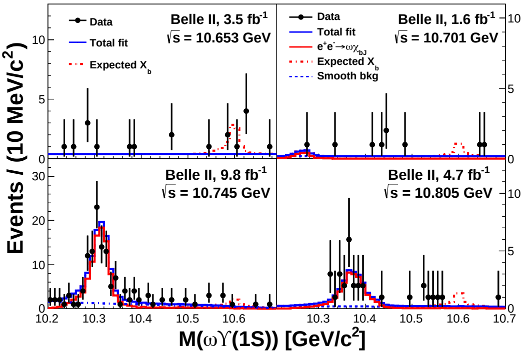
$\Gamma_{ee}\mathcal{B}(\omega\chi_{b1,b2})$	solution I:	$(0.63 \pm 0.39 \pm 0.20)\,\mathrm{eV}$	$(0.53 \pm 0.46 \pm 0.15)\,\mathrm{eV}$
	solution II:	$(2.01 \pm 0.38 \pm 0.76)\,\mathrm{eV}$	$(1.32 \pm 0.44 \pm 0.55)\,\mathrm{eV}$
	alternative:	$(1.24 \pm 0.56)\,\mathrm{eV}$ (stat.)	$(0.92 \pm 0.37)\,\mathrm{eV}$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

$(0.14\text{–}0.55)\,\mathrm{pb}$	$(0.25\text{–}0.84)\,\mathrm{pb}$
$(0.06\text{–}0.14)\,\mathrm{pb}$	$(0.08\text{–}0.37)\,\mathrm{pb}$

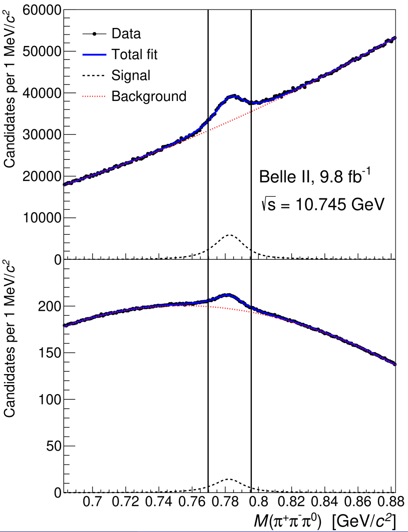
Search for $e^+e^- \to \omega\eta_b(1S)$ and $\omega\chi_{b0}(1P)$

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:

Reconstruct only the $\omega \to \pi\pi\pi^0$:

- 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: $E(3\times 3)/E(5\times 5 - 4\,\text{corners}) > 0.8$
- $p^*_{\pi^0} > 260\,(130)\,\mathrm{MeV}$ for η_b (χ_{b0})
- $|M(\pi\pi\pi^0) - m_\omega| < 13\,\mathrm{MeV}$
- symmetrised Dalitz $r < 0.84$ (0.82)
- use **recoil mass** $\sqrt{(\sqrt{s} - E_\omega)^2 - p_\omega^2}$:
  $M_\mathrm{recoil} \in (9200, 9600)\,\mathrm{MeV}$ for η_b,
  $\in (9780, 9950)\,\mathrm{MeV}$ for χ_{b0}



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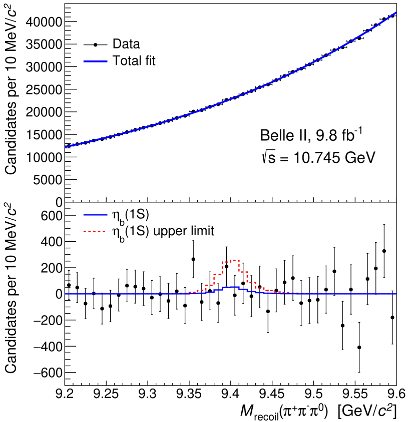
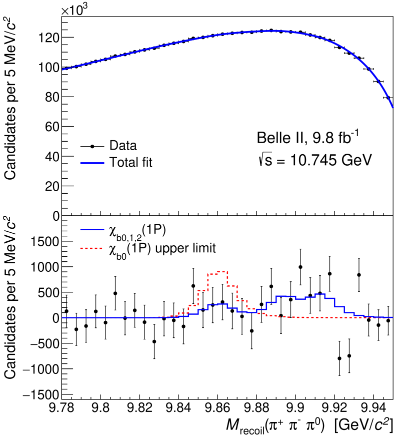
χ^2 fits to recoil mass, with signal shapes fixed to simulation:



bkgd: 3rd order Chebyshev



bkgd: 4th order Chebyshev $\times$ \sqrt

in the χ_{b0} fit, χ_{b1}/χ_{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
π^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

$\boldsymbol{\sigma_{\text{Born}}(e^+e^- \to \omega\eta_b(1S)) < 2.5\,\text{pb}}$, *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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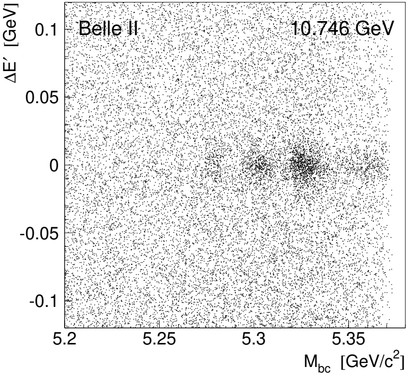
$\boldsymbol{\sigma_{\text{Born}}(e^+e^- \to \omega\chi_{b0}) < 8.7\ (7.8)\,\text{pb}}$, *cf.* 3–4 pb for our $\omega\chi_{b1,b2}$ measurements

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]

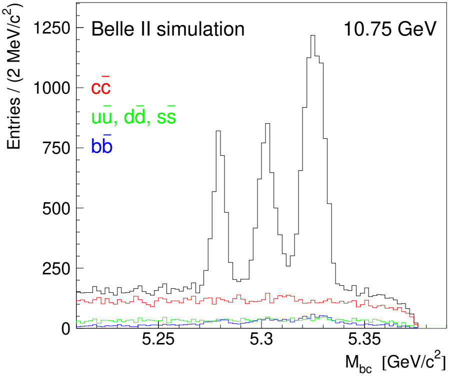
Energy dependence of $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$

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

Multivariate algorithm to reconstruct π^0, K^0_S, ... then D, D^*, J/ψ, ... 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)



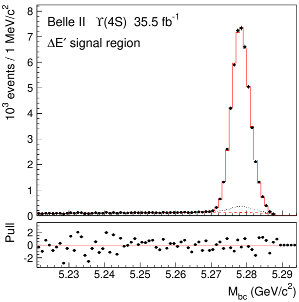
high purity; some $e^+e^- \to c\bar{c}$, small light-quark and broken $b\bar{b}$ background

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

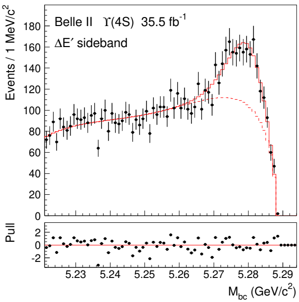
I. Adachi et al. (Belle II), arXiv:2405.18928 → JHEP

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

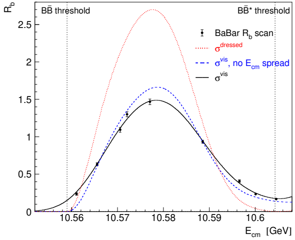
- energy spread of the colliding e^+e^- beams
- initial state radiation (ISR)
- B-meson momentum resolution
- energy dependence of the production cross-section



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



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



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

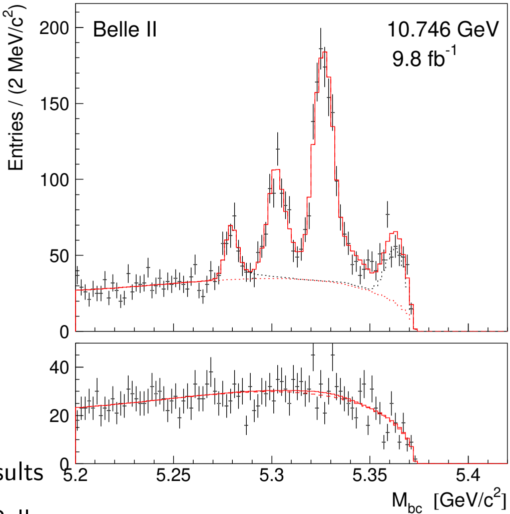
simultaneously fitted with $\Delta E'$ signal and sideband

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

at 10804, **10746**, 10701, and 10653 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

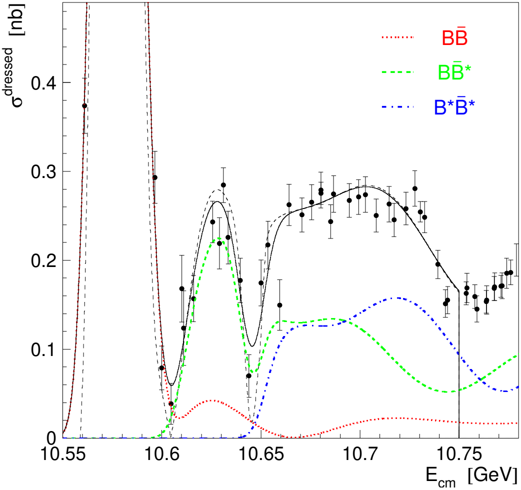


- $B^{(*)}\bar{B}^{(*)}$: also include Belle results
- total $b\bar{b}$: combined BaBar & Belle energy scans

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

- total cross section fitted up to $B\bar{B}^*\pi$ threshold with the sum of $B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$



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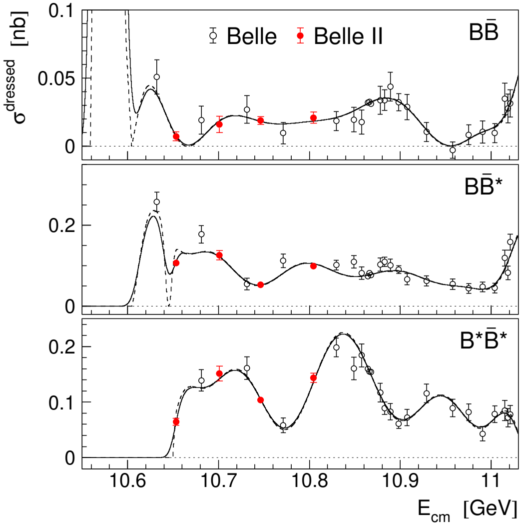
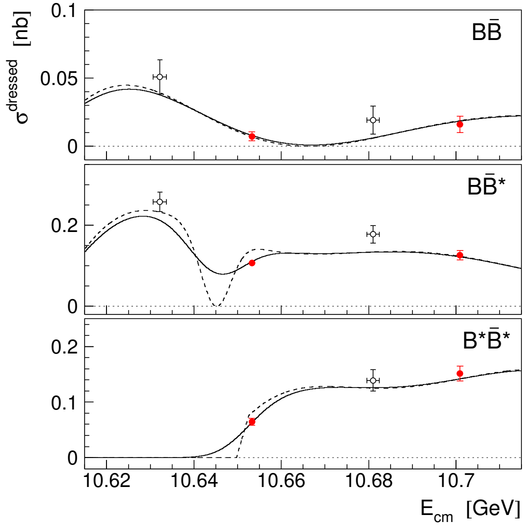
- total cross section fitted up to $B\bar{B}^*\pi$ threshold with the sum of $B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$
- individual cross-sections: Belle II *vs* Belle points
- by design: input to the next round of coupled-channel fits in and around $\Upsilon(10753)$



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

- total cross section fitted up to $B\bar{B}^*\pi$ threshold with the sum of $B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$
- individual cross-sections: Belle II *vs* Belle points
- by design: input to the next round of coupled-channel fits in and around $\Upsilon(10753)$
- **the surprise:** *very* rapid rise of the $B^*\bar{B}^*$ cross section *cf.* PS $\propto (\sqrt{s} - E_{\text{th}})^{3/2}$
    - suggests a $B^*\bar{B}^*$ state near the threshold
    - note also dip in $B\bar{B}^*$



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note high-order poly$^{\ell s}$ used as phenom$^{\ell}$ smooth x-sec shape

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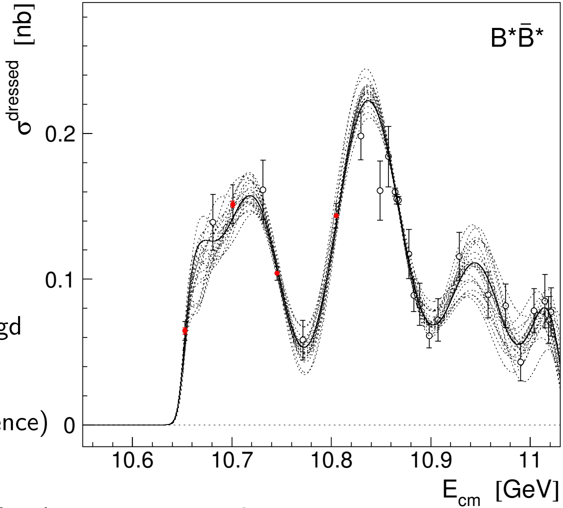
systematics:

- change poly$^{\ell}$ order
- many pseudoexperiment variants ($B^*\overline{B}^*$ shown)
- vary treatment of both broken signal & smooth bkgd



correlated systs:

- efficiency (value & dependence)
- luminosity
- masses → uncertainty on E_{cm}, but not cross sections

Summary and prospects

$\Upsilon(10753)$ results:

- $\Upsilon(10753) \to \pi\pi\Upsilon(1S, 2S)$ amplitude confirmed using new E points
- thorough $\sigma(e^+e^- \to B\bar{B},\ B\bar{B}^*,\ B^*\bar{B}^*)$ and $\sigma_{b\bar{b}}$ energy dependence fits
- signif. $\Upsilon(10753) \to \omega\chi_{b1,b2}$ amplitude; $\left.\frac{\sigma_{\text{Born}}(\omega\chi_{b1})}{\sigma_{\text{Born}}(\omega\chi_{b2})}\right|_{10745} = 1.3 \pm 0.6$; result disfavours a D-wave state
- $\omega\chi_{b0}$ limit disfavours a $Y(4230)$-like state; $\omega\eta_b$ limit disfavours tetraquark
- general consistency with 4S–3D mixed state so far

Other exotics:

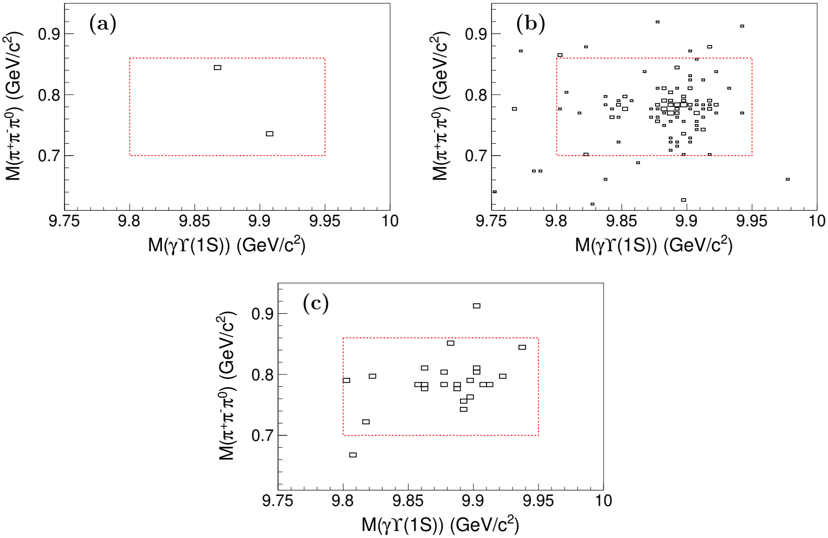
- σ_{Born} for $e^+e^- \to \pi Z_b(\to \pi\Upsilon(1S, 2S))$ is sub-pb for 10753
- $\sigma(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon)$ is sub-pb in the $\Upsilon(10753)$ region
- possible $B^*\bar{B}^*$ state near threshold based on rapid cross section rise

Large and growing $\boldsymbol{\Upsilon(4S) \to B\bar{B}}$ dataset ($>$ BaBar, $\frac{2}{3}$ Belle) with a raft of exotic hadron analyses underway (combined Belle $+$ Belle II also straightforward) — many more results in the near future

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^{UL}	ε	$\lvert 1-\Pi\rvert^2$	$1+\delta_{\mathrm{ISR}}$	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	$\omega\chi_{b0}/\omega\chi_{b1}/\omega\chi_{b2}$			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

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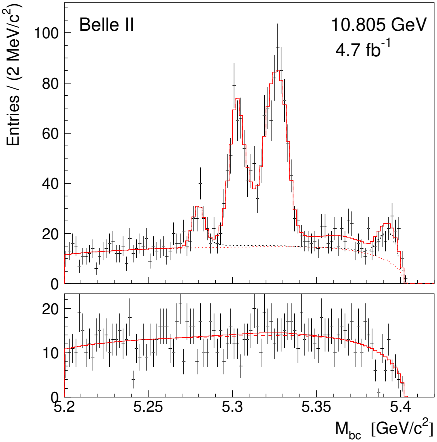

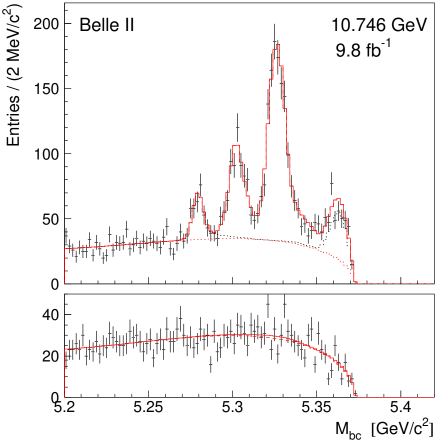

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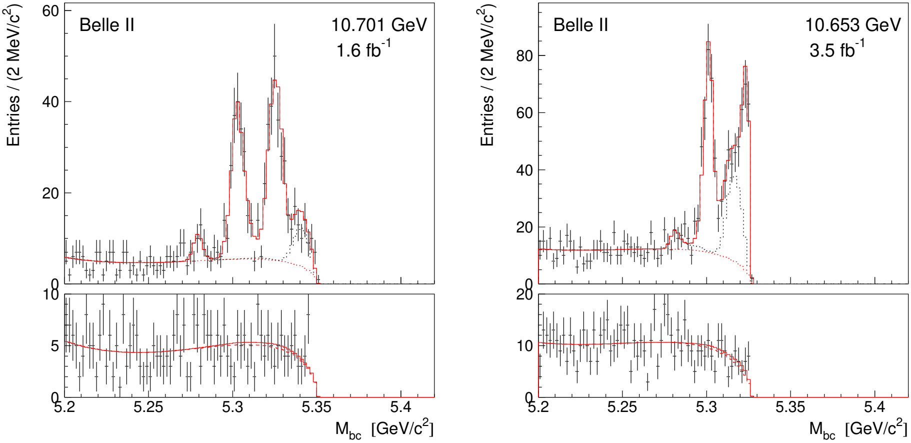

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