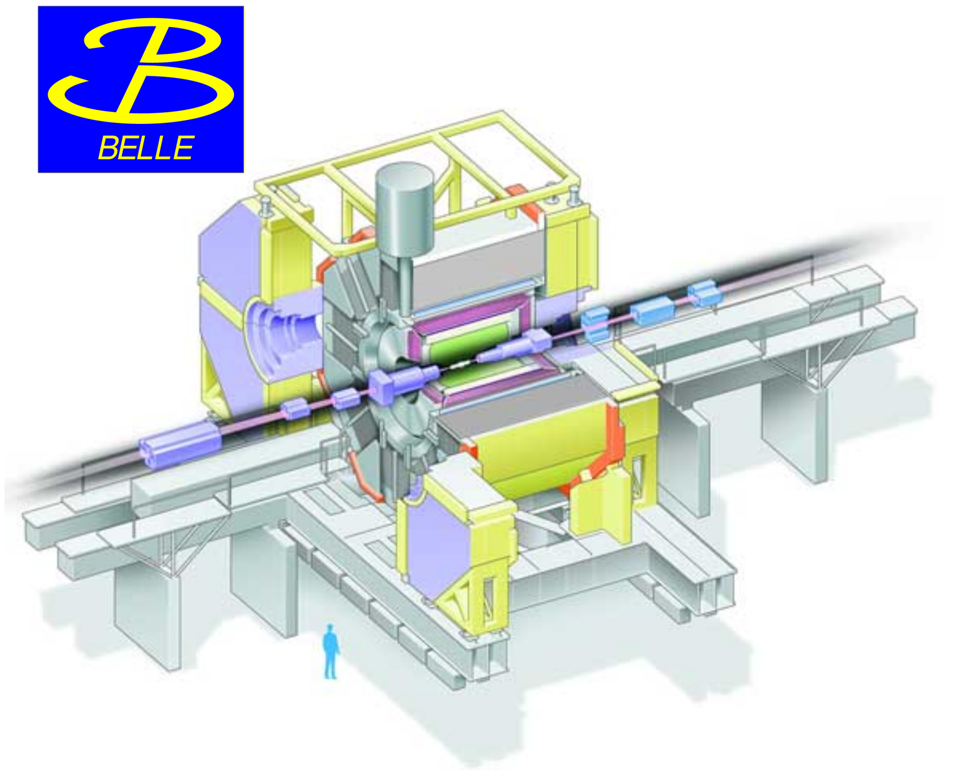
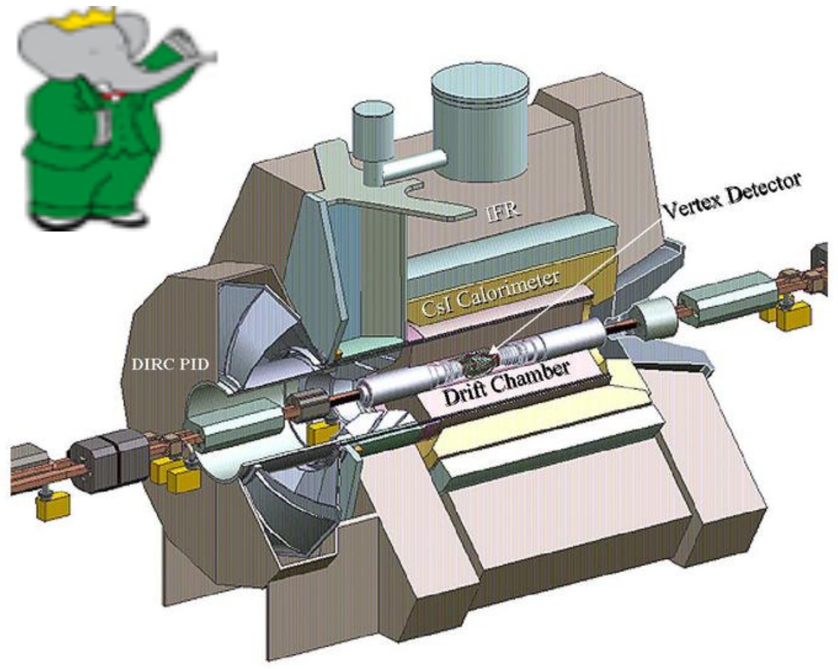
Studies of hadron spectroscopy at Belle and Belle II

Jake Bennett
The University of Mississippi
XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions - June 6, 2024

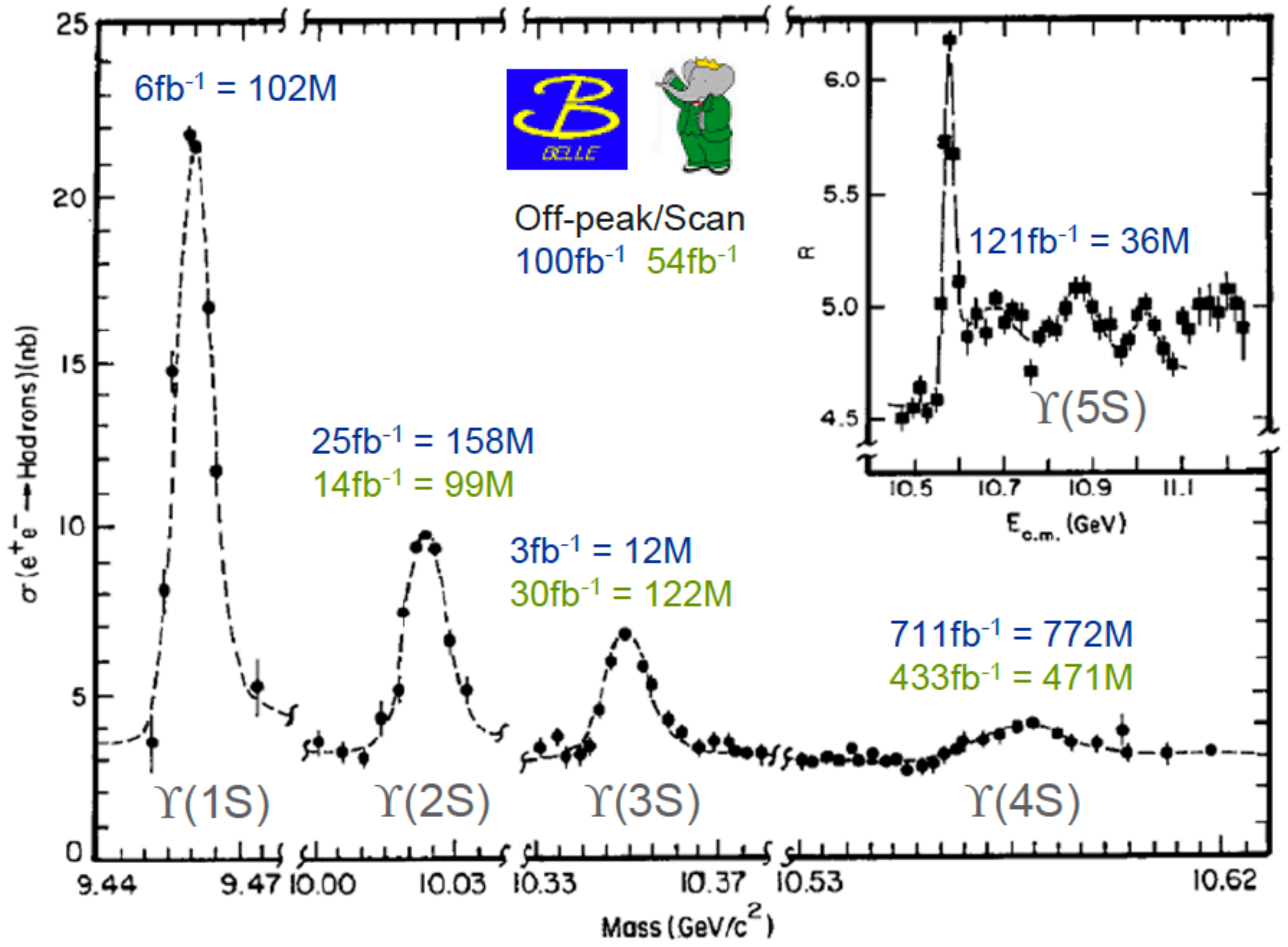
B factories

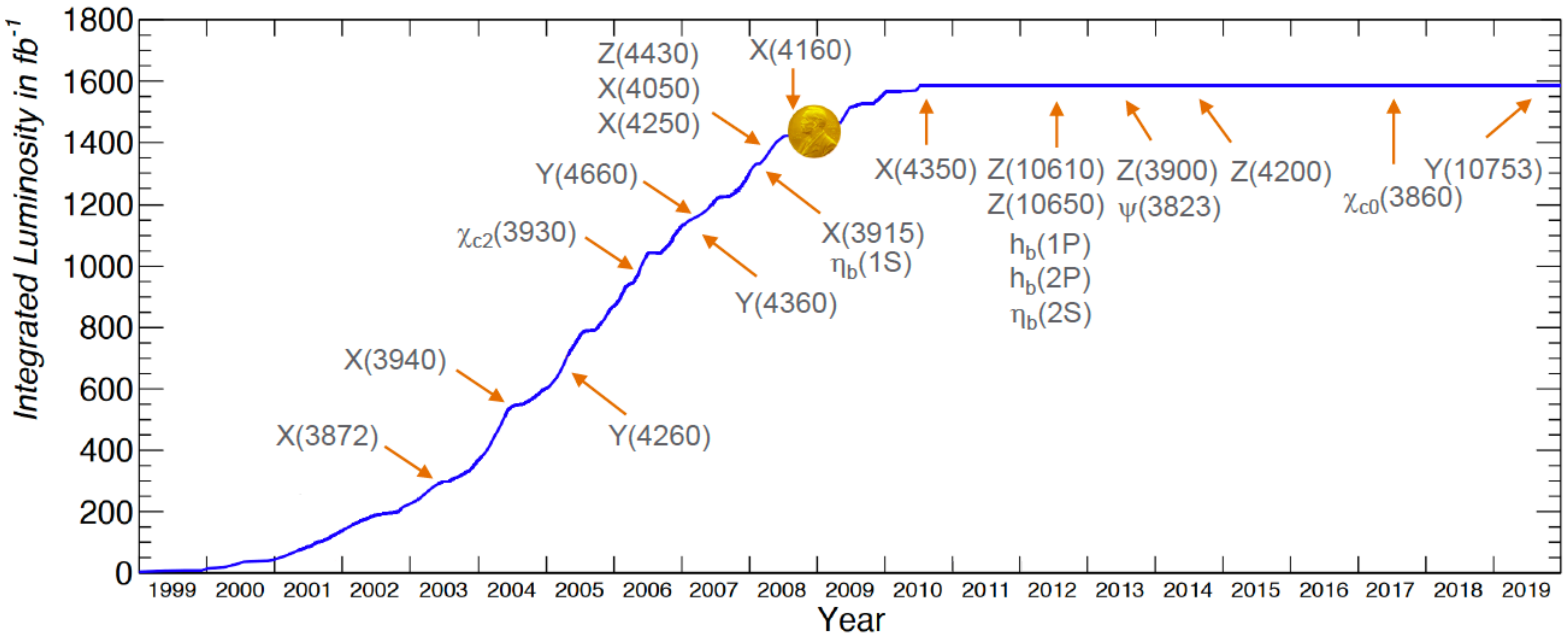




- Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)
  - Very successful physics programs with a total recorded sample over 1.5 ab^{-1} (1.25×10^9 $B\bar{B}$ pairs)
  - Flavor physics (CKM/UT, CPV), NP in rare processes, new particle discoveries

More details in "The Physics of the B Factories", EPJC 74, 3026 (2014)





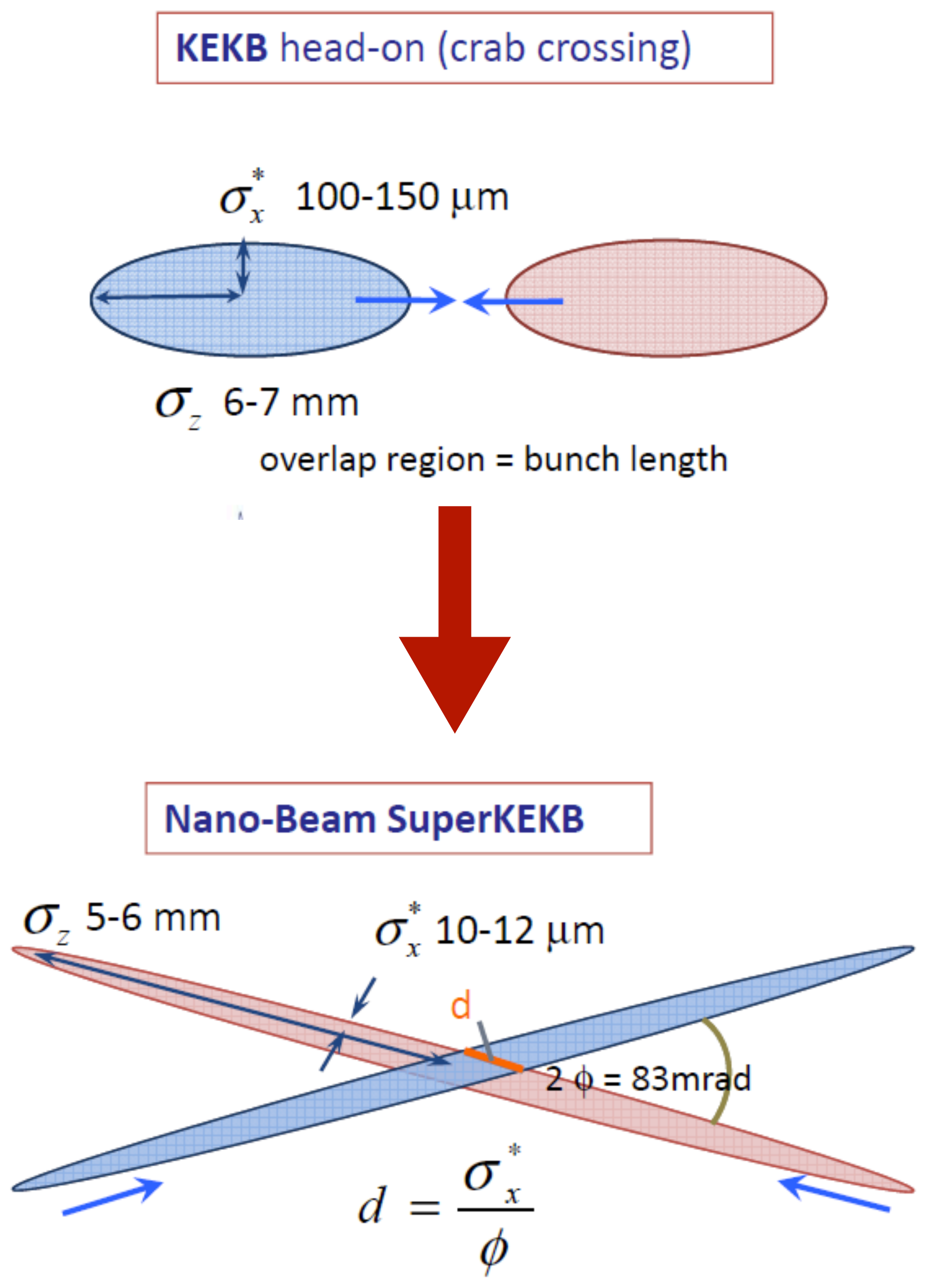
Even >10 years after data taking, still producing new results in hadron spectroscopy

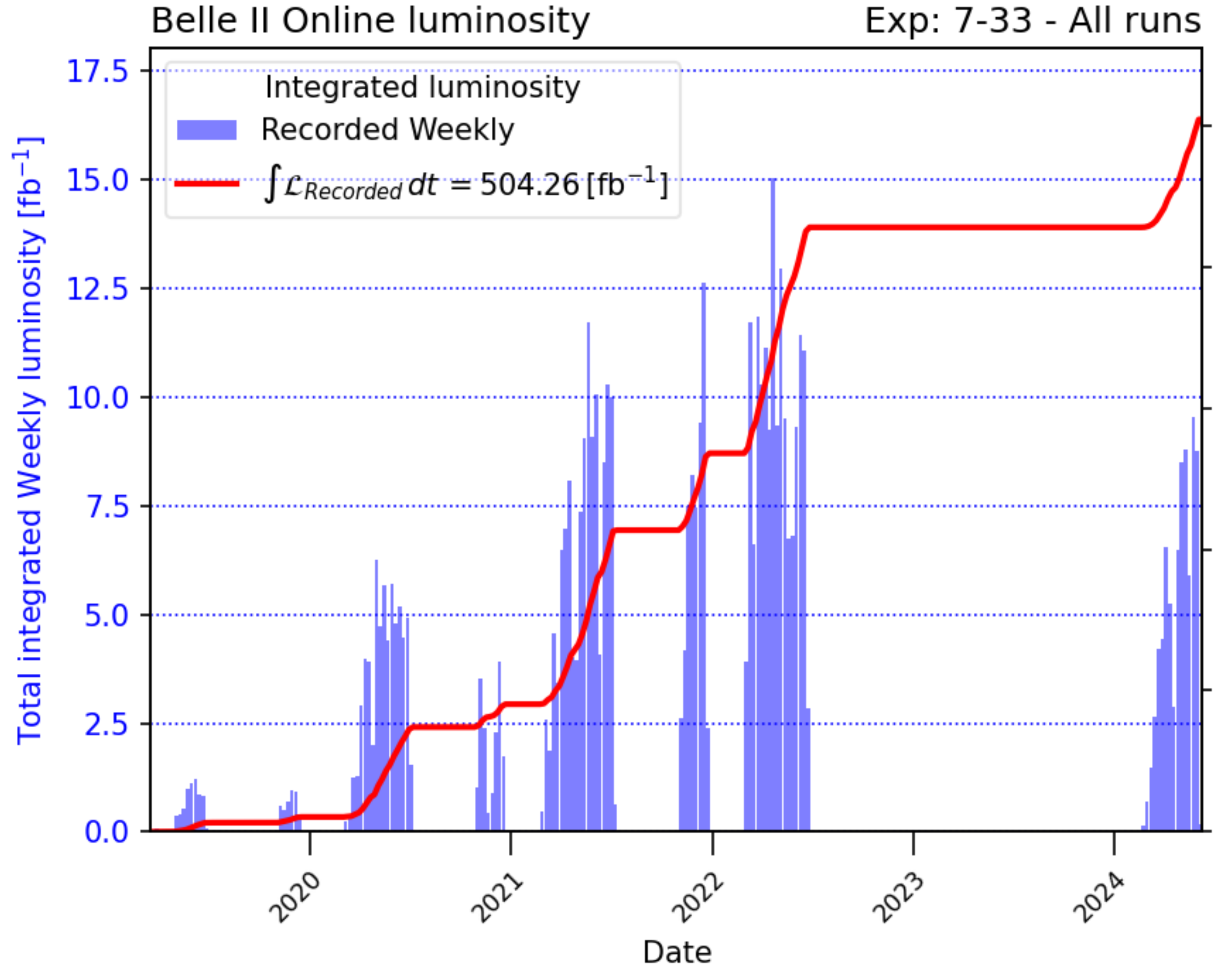
>350 papers published since Belle shutdown!

Belle II capabilities

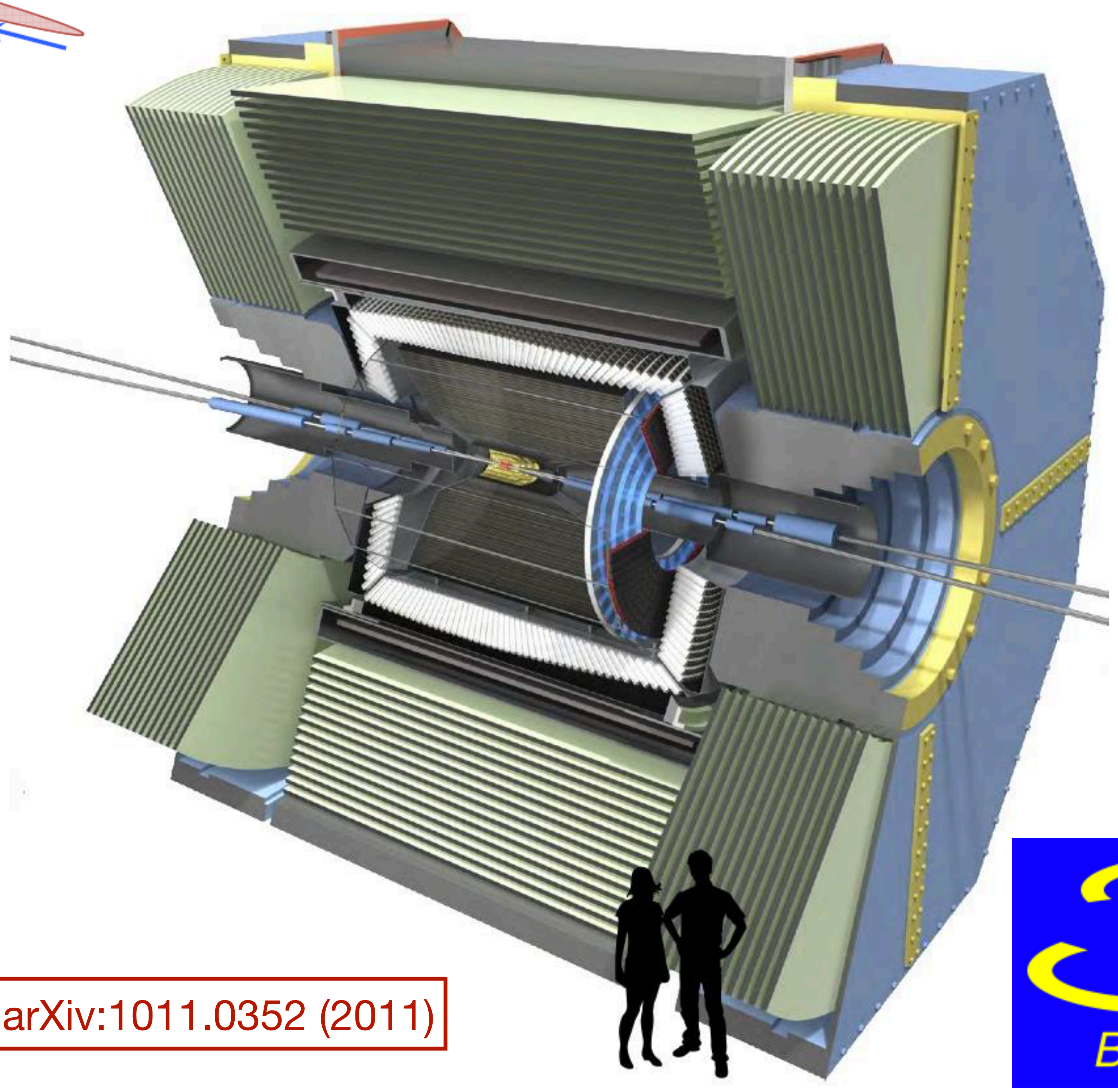
- Belle II is the next generation B-factory
  - Upgraded detector and accelerator
  - ~15-year program ongoing since 2019

- <u>Advantages for spectroscopy physics program</u>
  - World record instantaneous luminosity
    (aiming for 50x Belle integrated luminosity)
  - High resolution, hermetic detector, good PID capability
  - Efficient reconstruction of neutrals (π^0, η, …)
  - Reconstruct single resonance to explore recoiling system
    (e.g. $e^+e^- \to J/\psi\ X$)
  - Using tagged events (i.e. with a fully reconstructed partner B)
    to measure absolute branching fractions
  - Variety of production mechanisms accessible





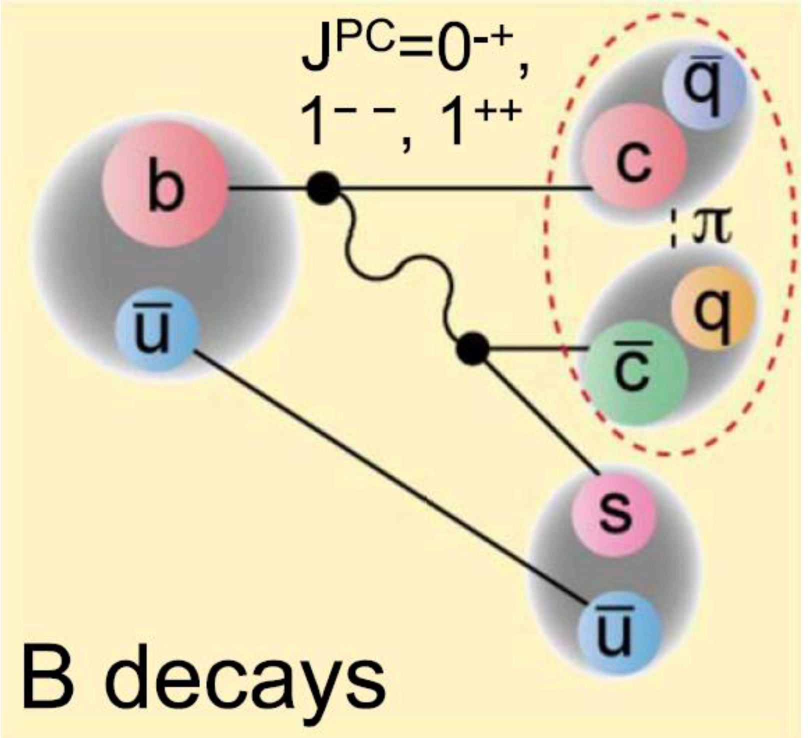
https://www.belle2.org/research/luminosity

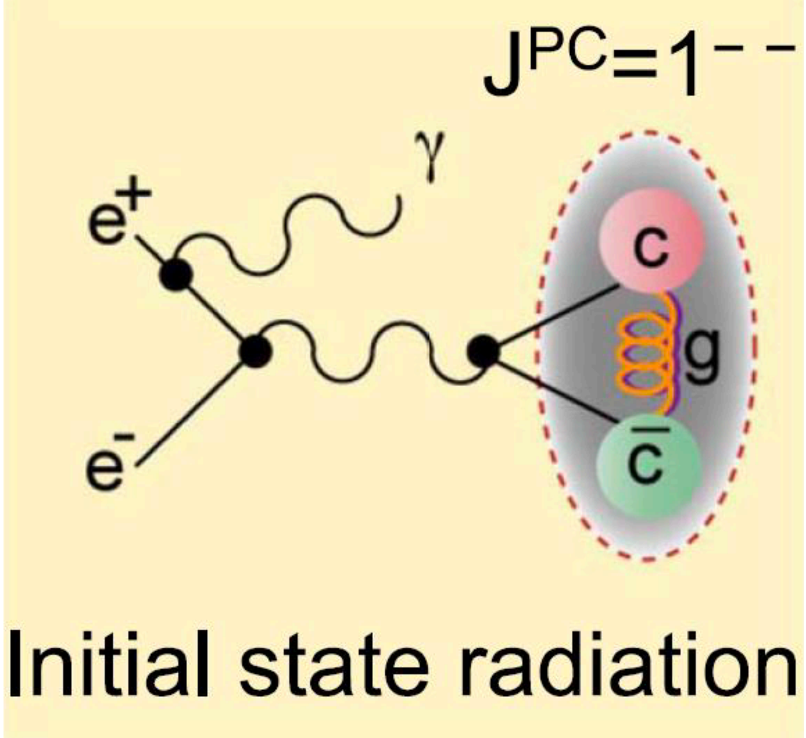


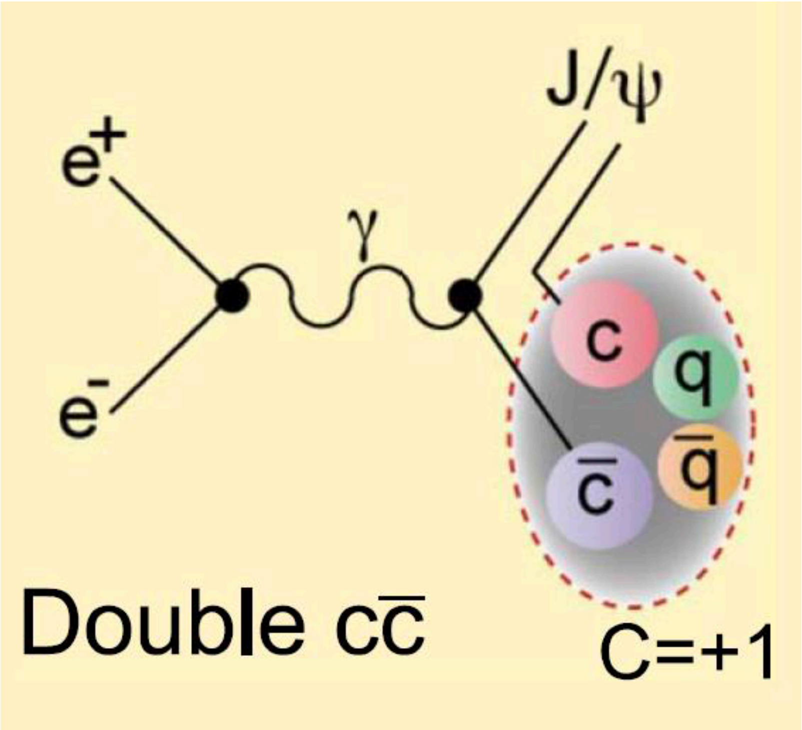
arXiv:1011.0352 (2011)

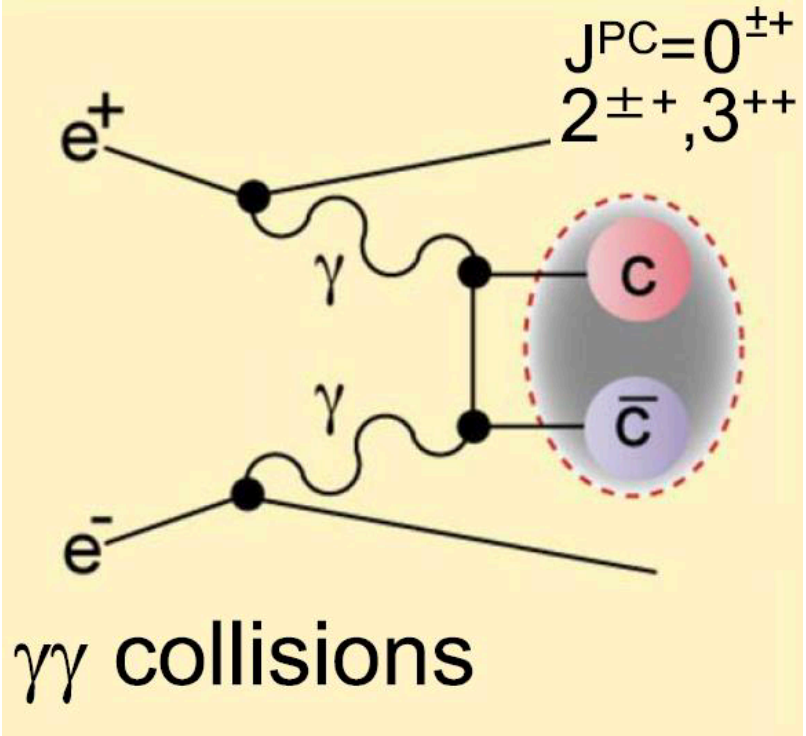
B-factory Datasets

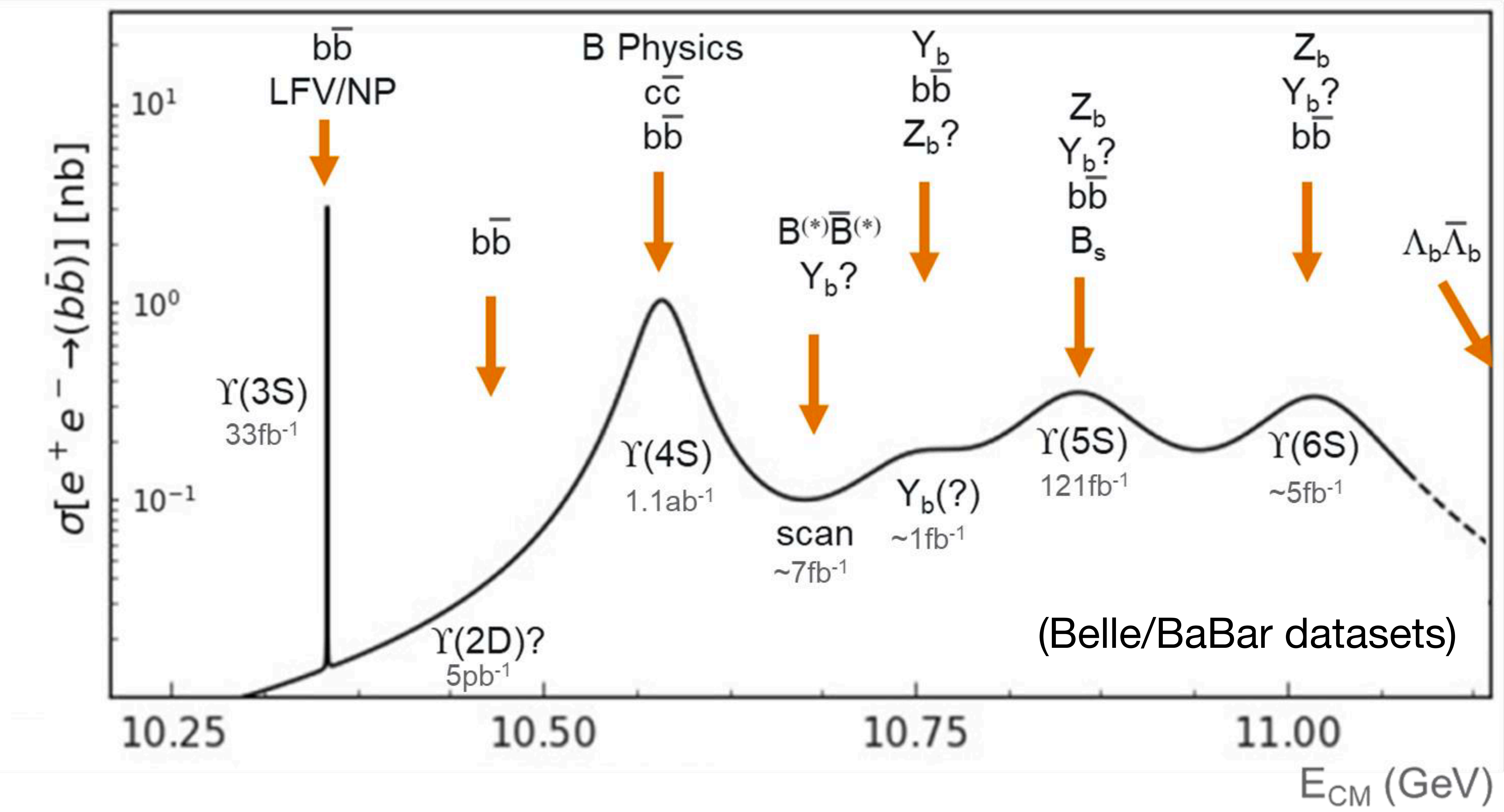
- Wide-ranging physics program including study of new XYZ states
- Many opportunities in unique production and decay modes
- Belle II: next generation B-factory building upon success of Belle







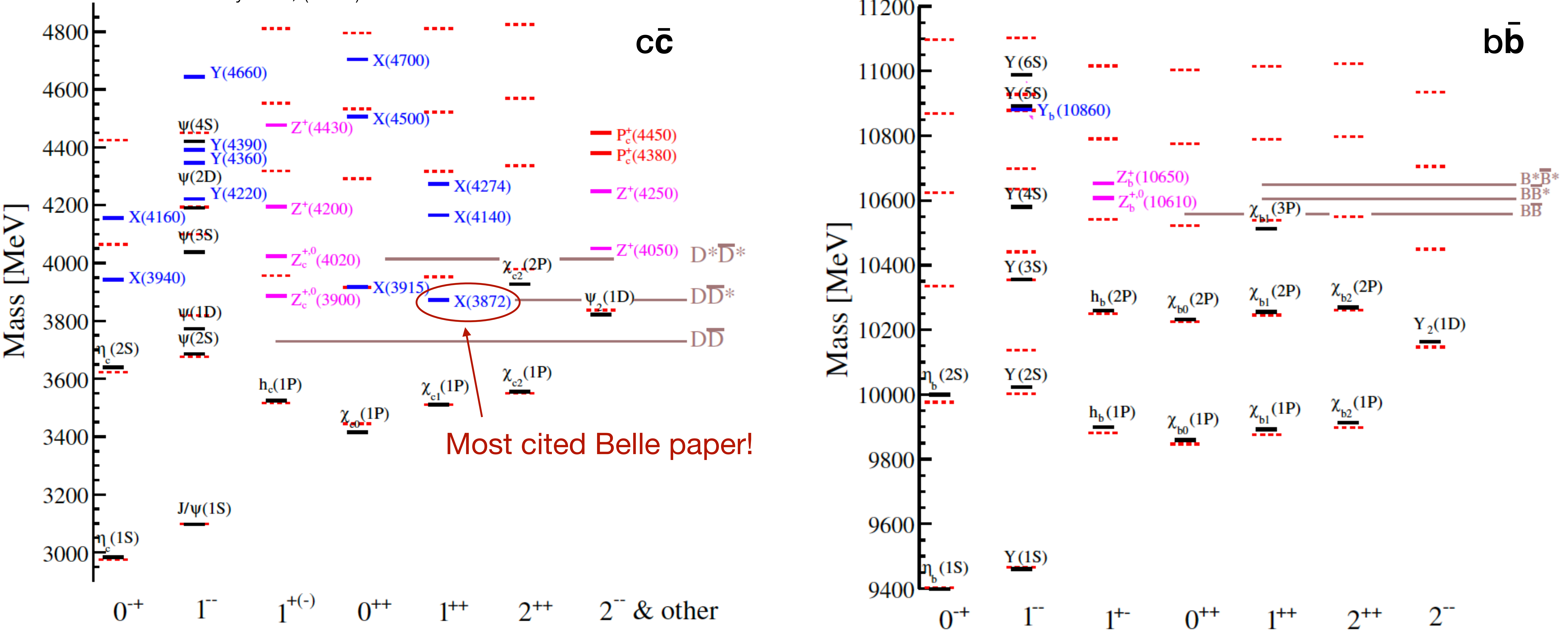




Quarkonium-like states, the XYZ zoo

red - expected states
black - charmonium states
blue/magenta - exotic candidates

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

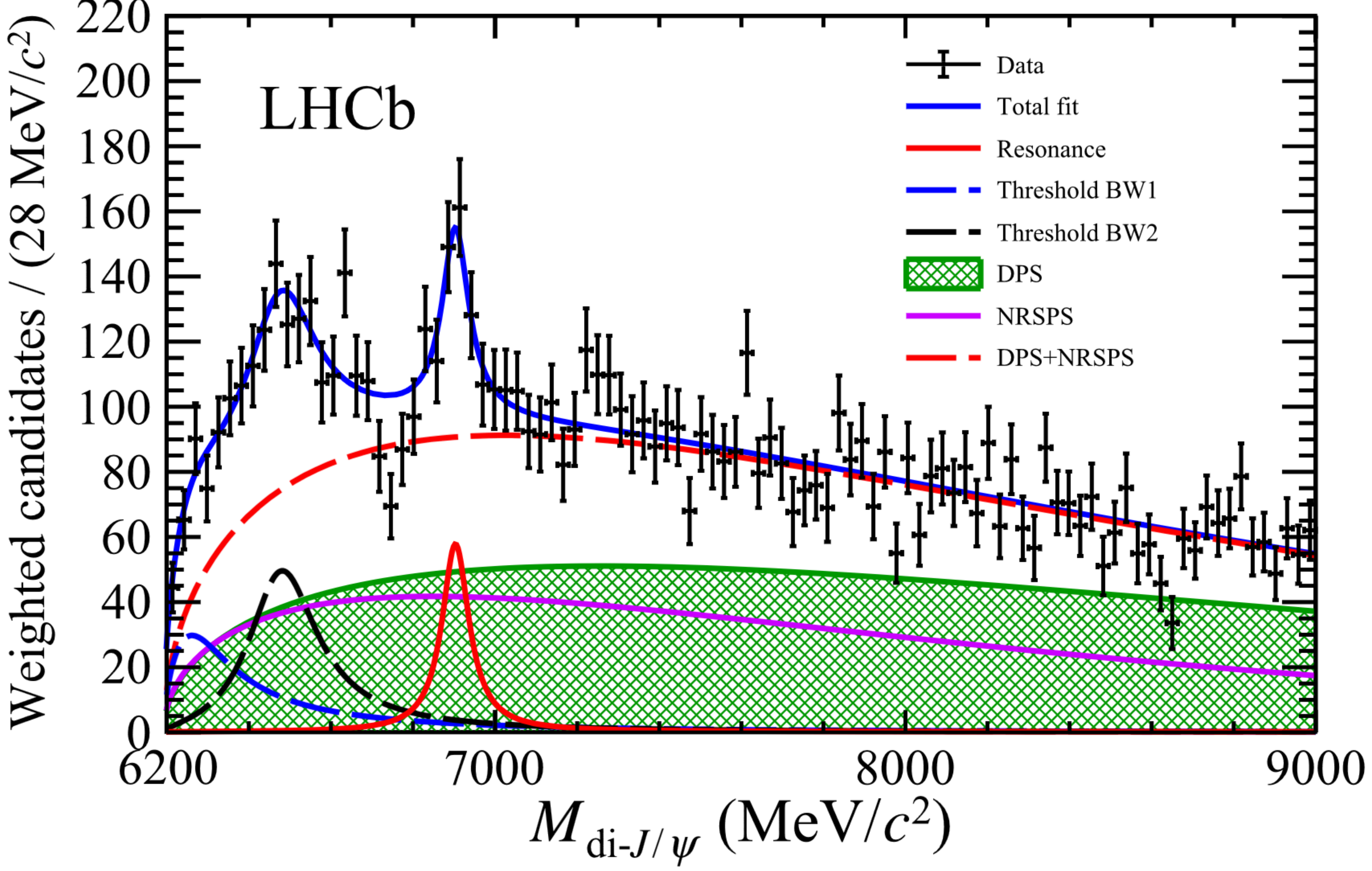


- Experimental clues for “exotic” states, especially near thresholds
- More data/studies provide better input, distinguishing characteristics for theoretical explanations

Search for a double-charmonium state with $\eta_c J/\psi$ at Belle

- Observation of enhancement in prompt double J/ψ production at the LHC
  - Interpreted as four-quark state ($cc\bar{c}\bar{c}$)
  - Potentially other nearby states (radially excited P-wave triplet?)
- Motivates search for additional states in double-charmonium

SciBull 65 (2020) 1983



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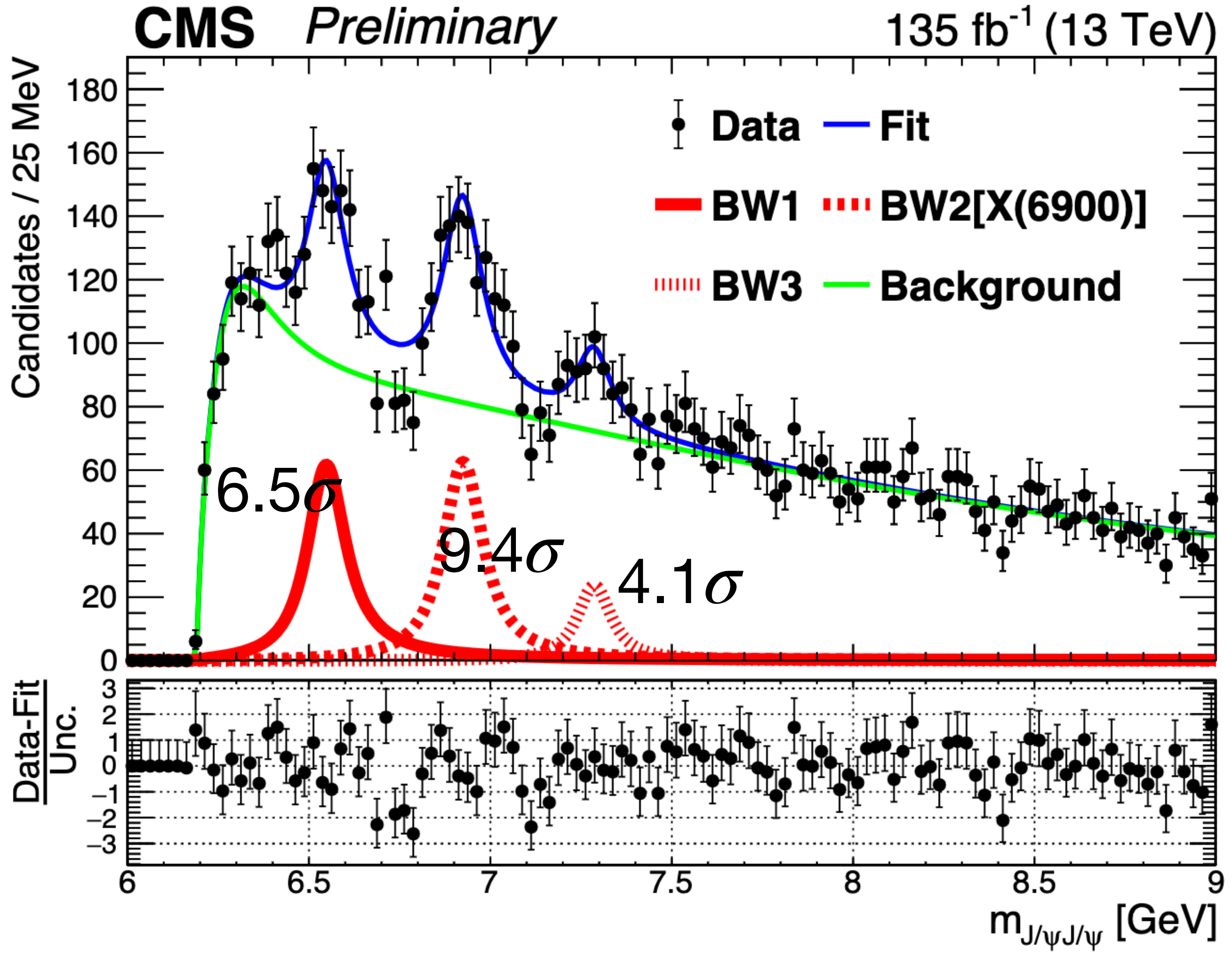
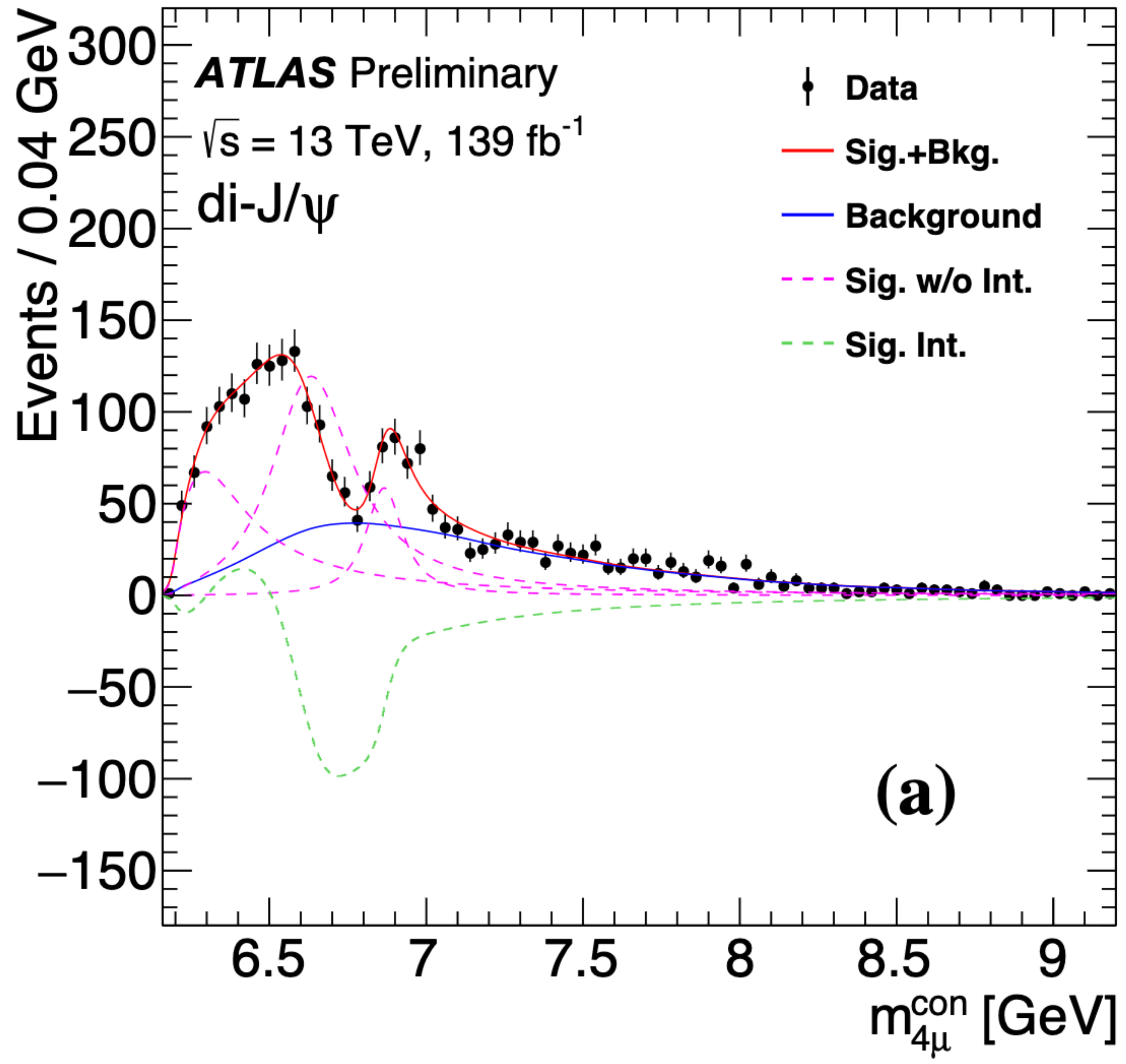


ATLAS-CONF-2022-040



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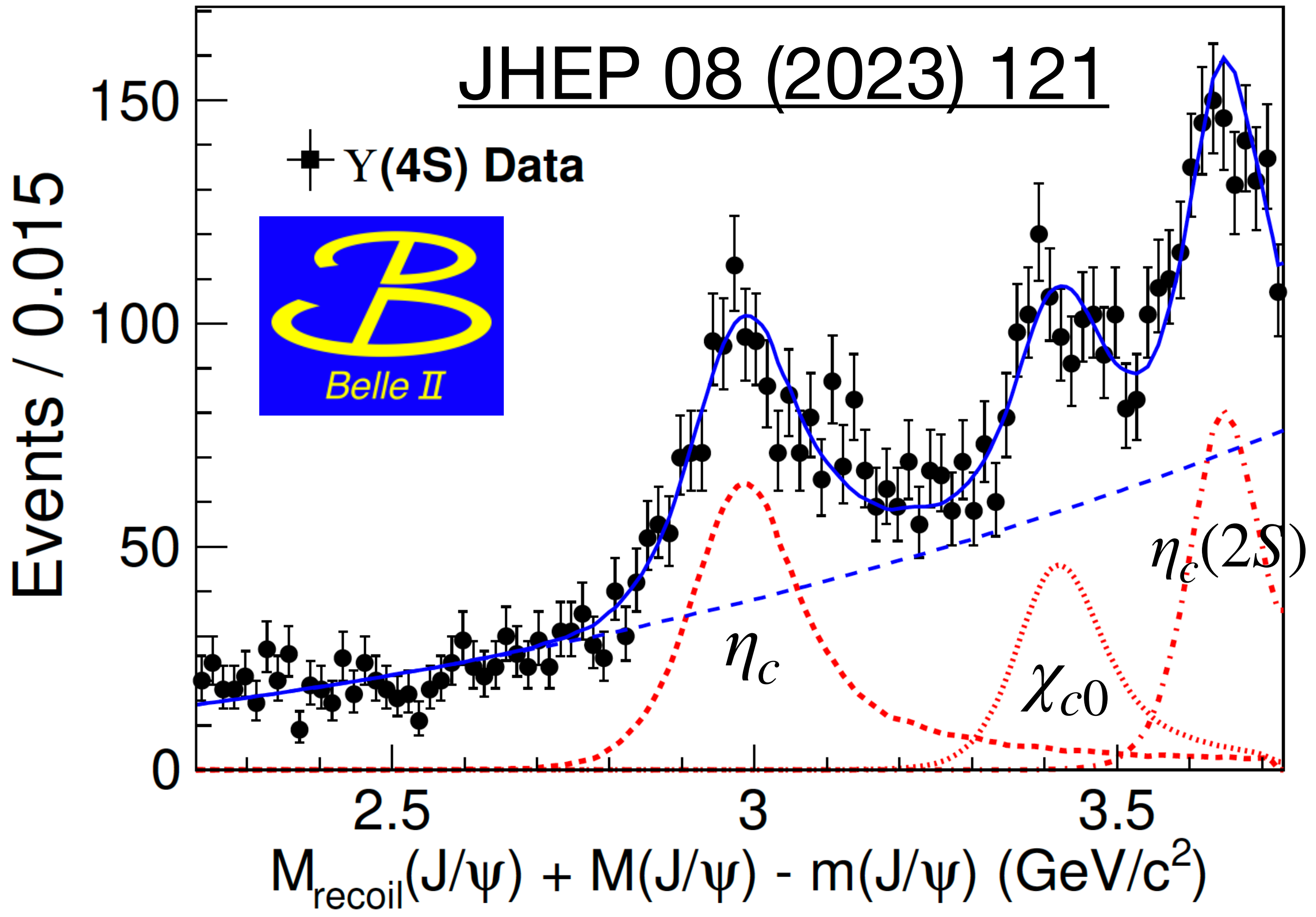

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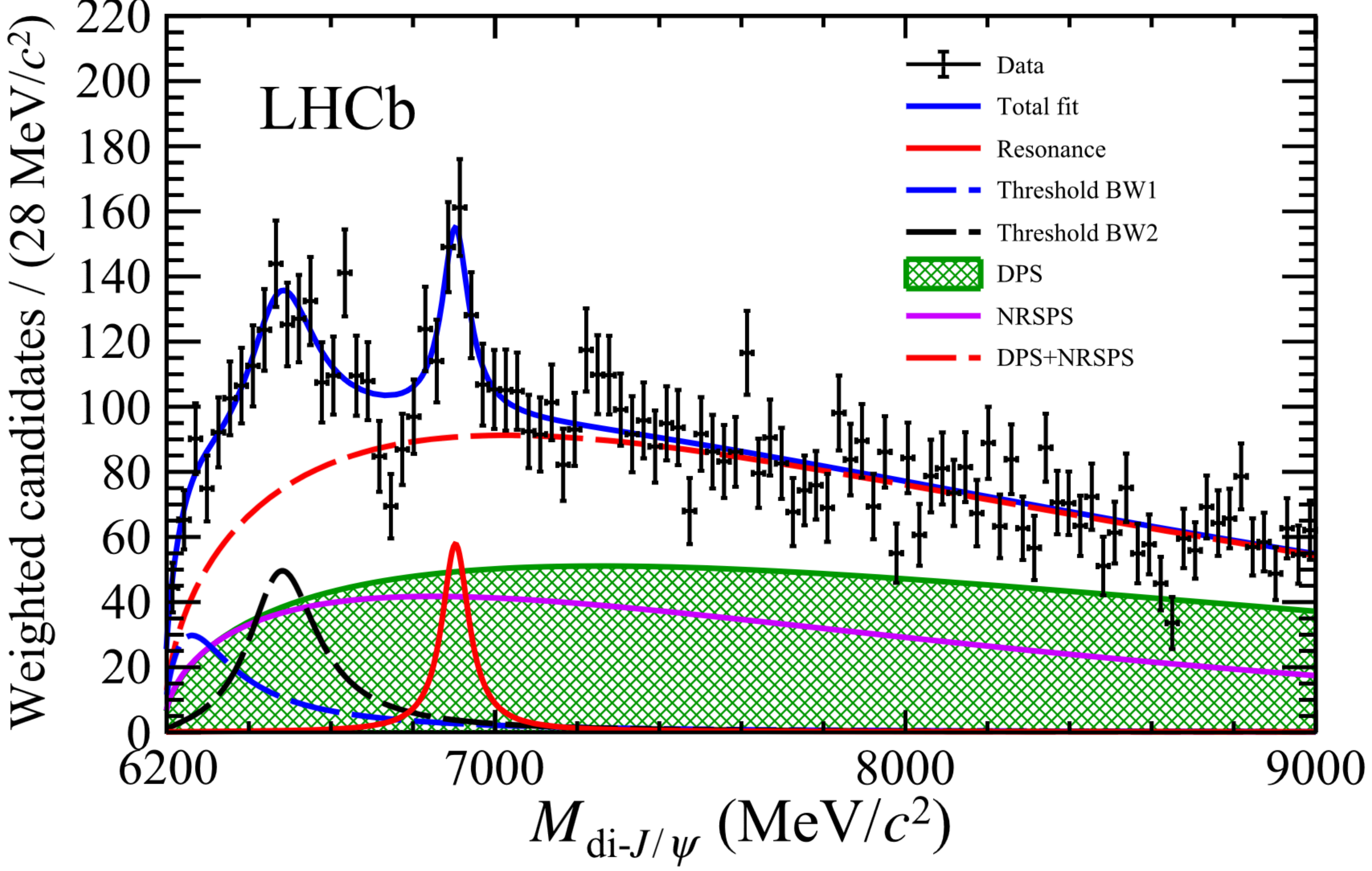

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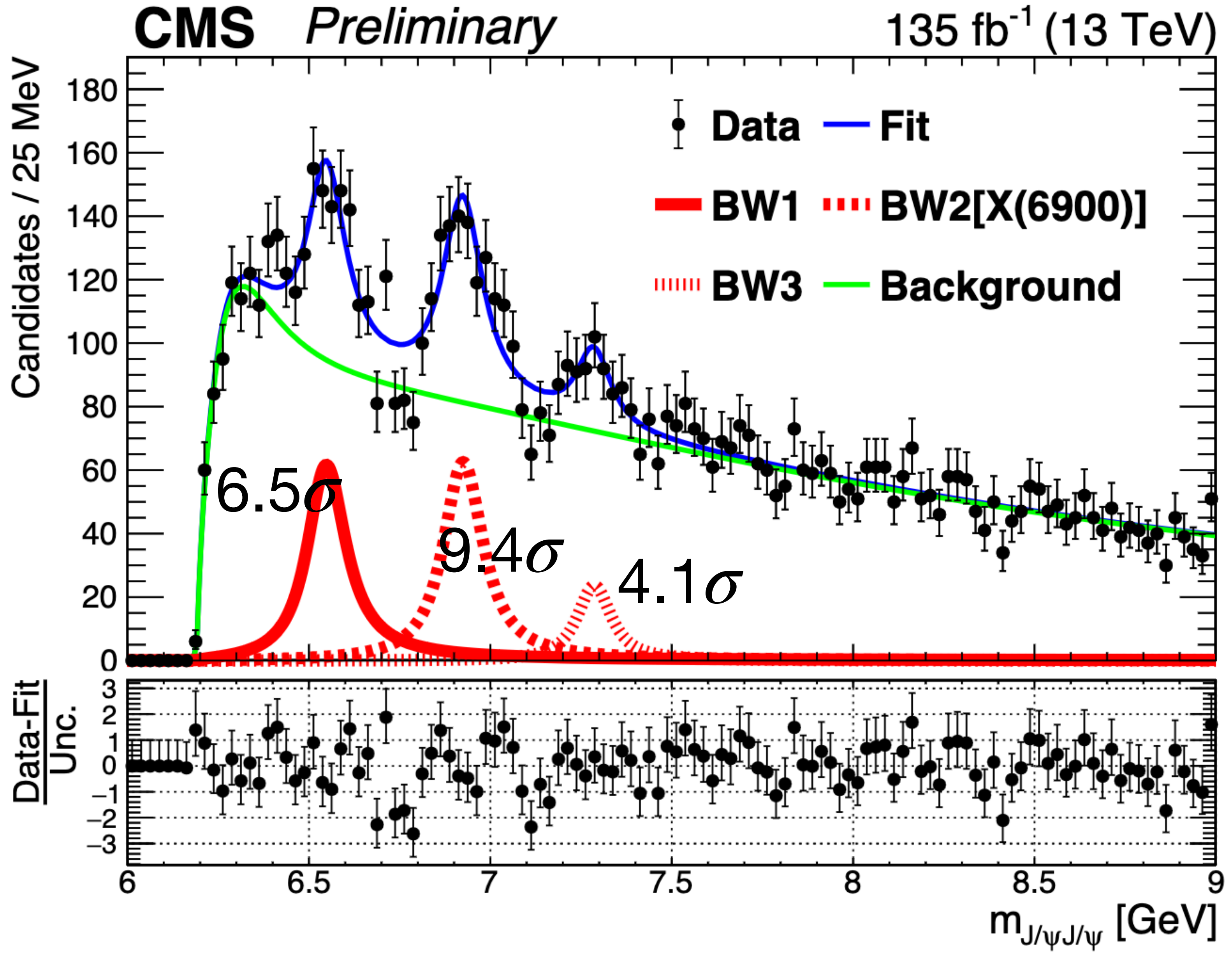

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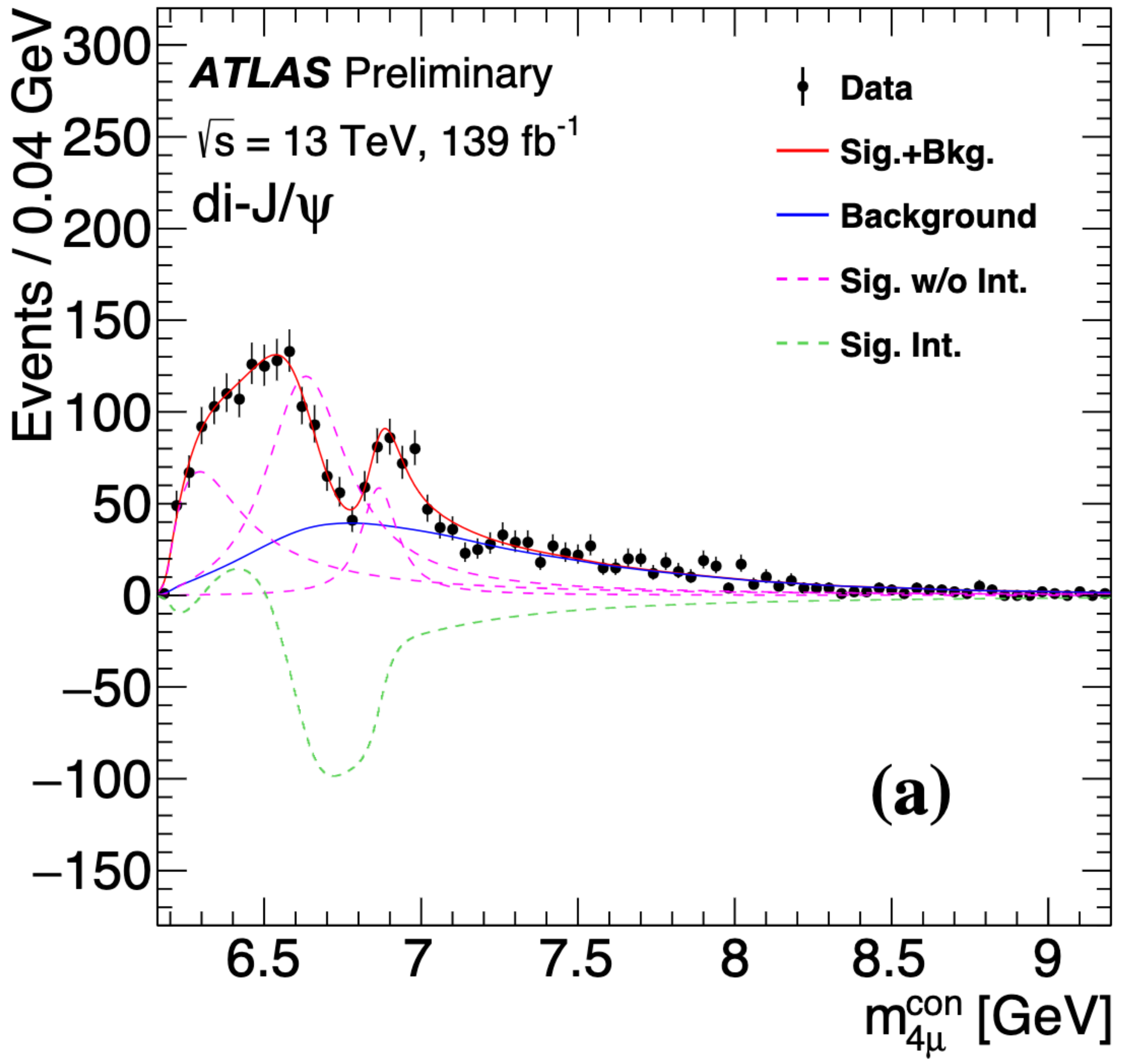
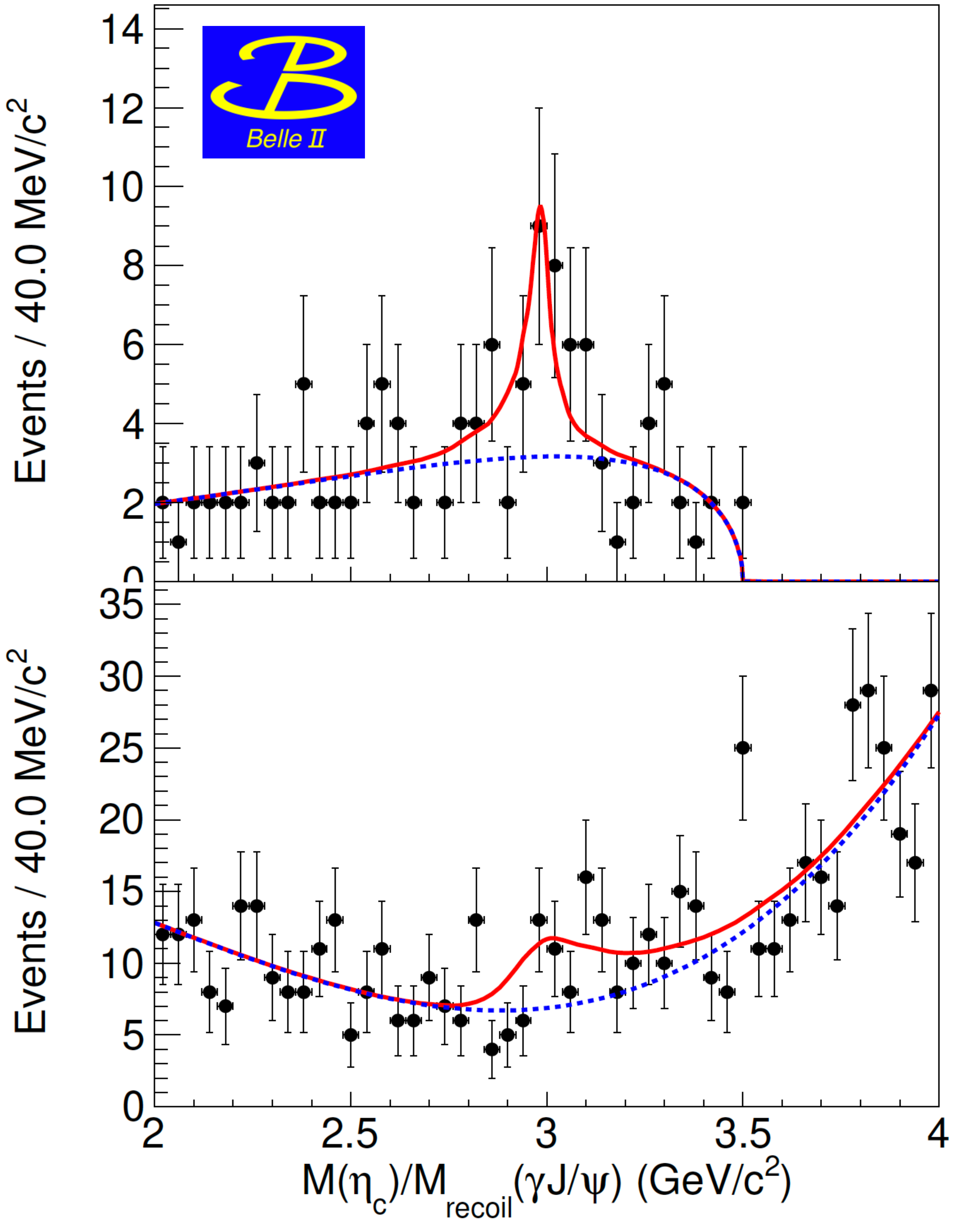
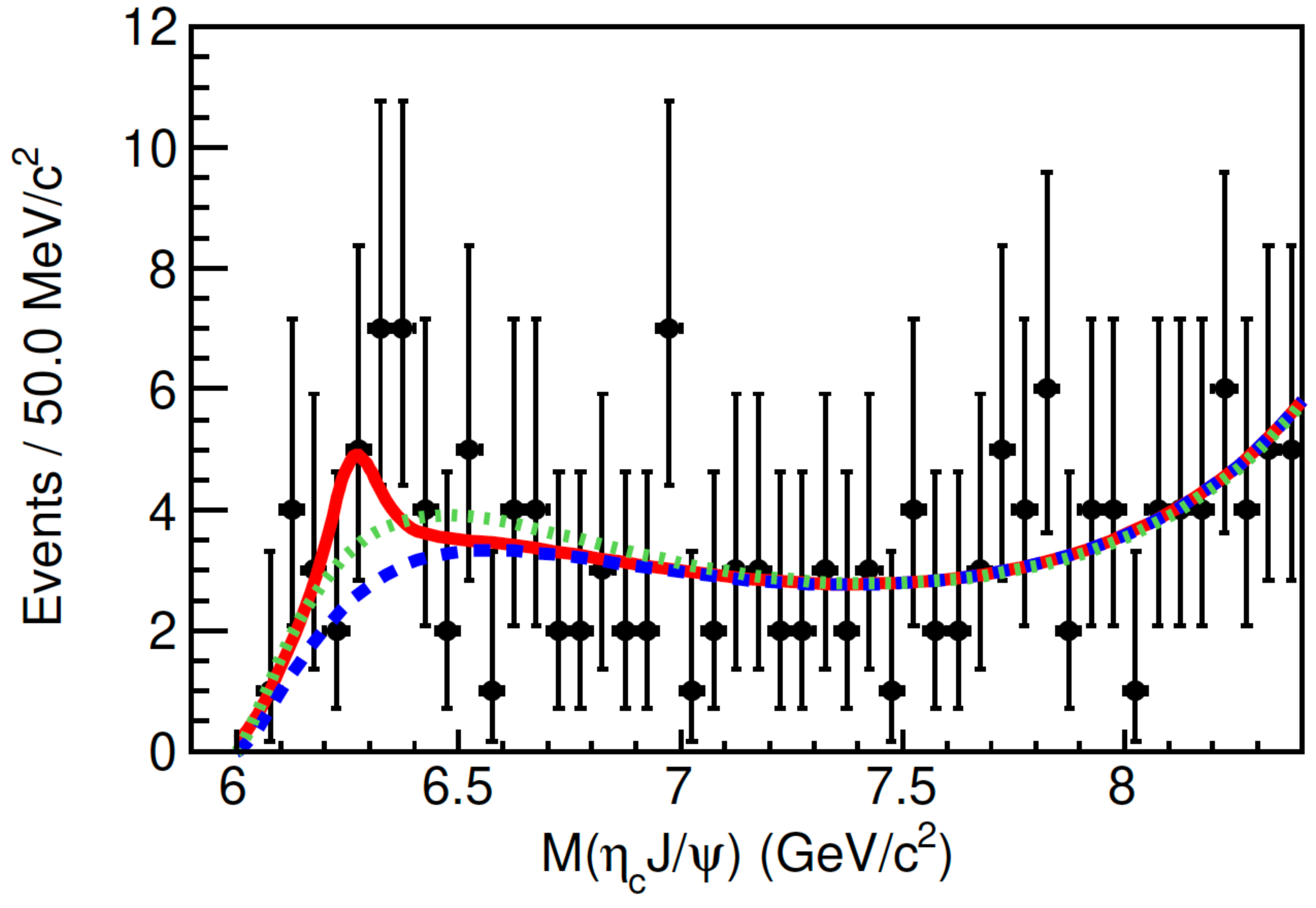


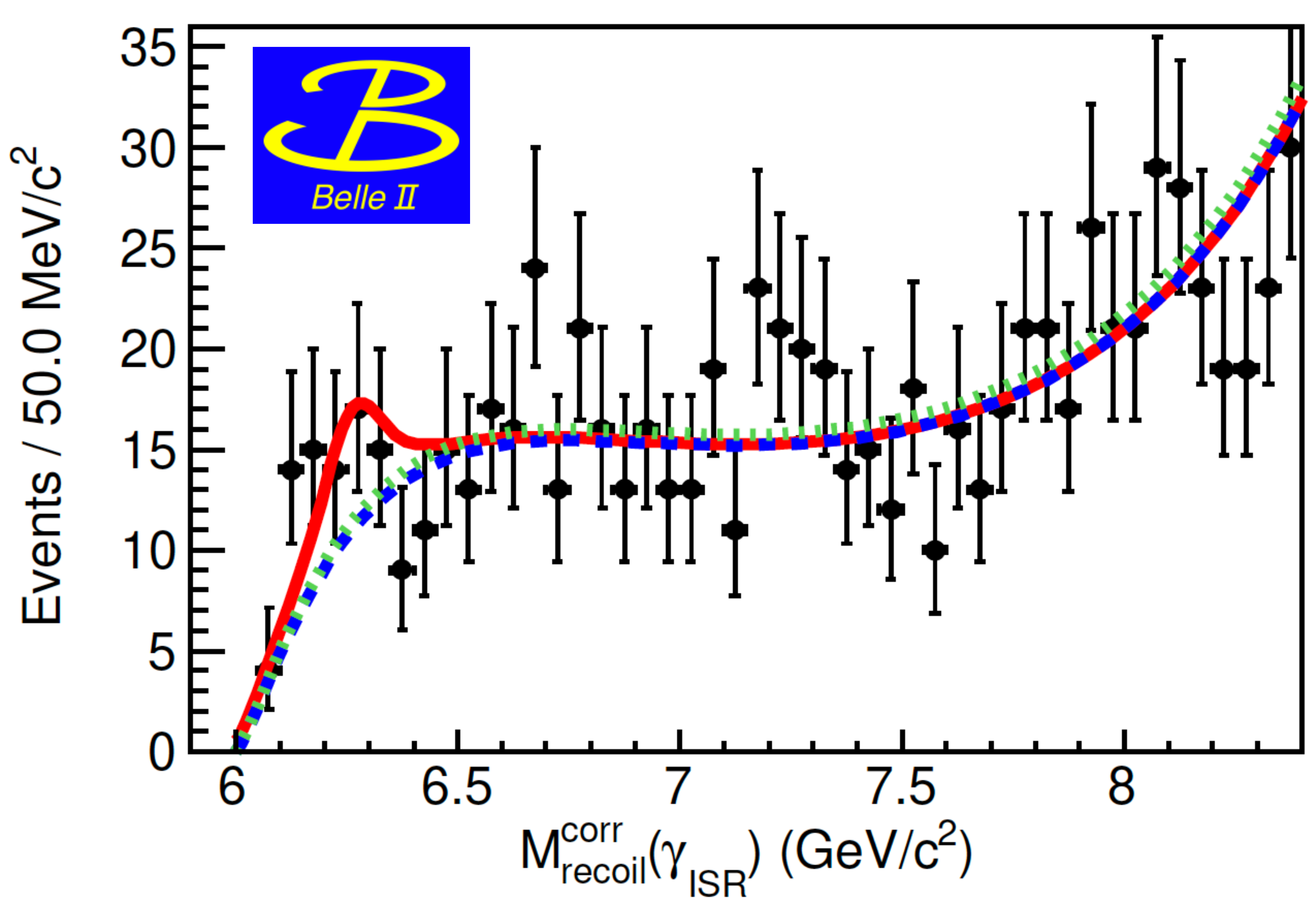
Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

- Simultaneous fit to exclusive ($\eta_c J/\psi$) and inclusive (γ_{ISR} recoil)
  - Remove events in common to avoid double counting
  - Significance for Breit-Wigner contribution is 2.1σ
- Simultaneous fit to η_c and $\gamma_{ISR} J/\psi$ mass spectra
  - Statistical significance for double charmonium production greater than 3.3σ
- Worth revisiting with higher statistics at Belle II

JHEP 08 (2023) 121



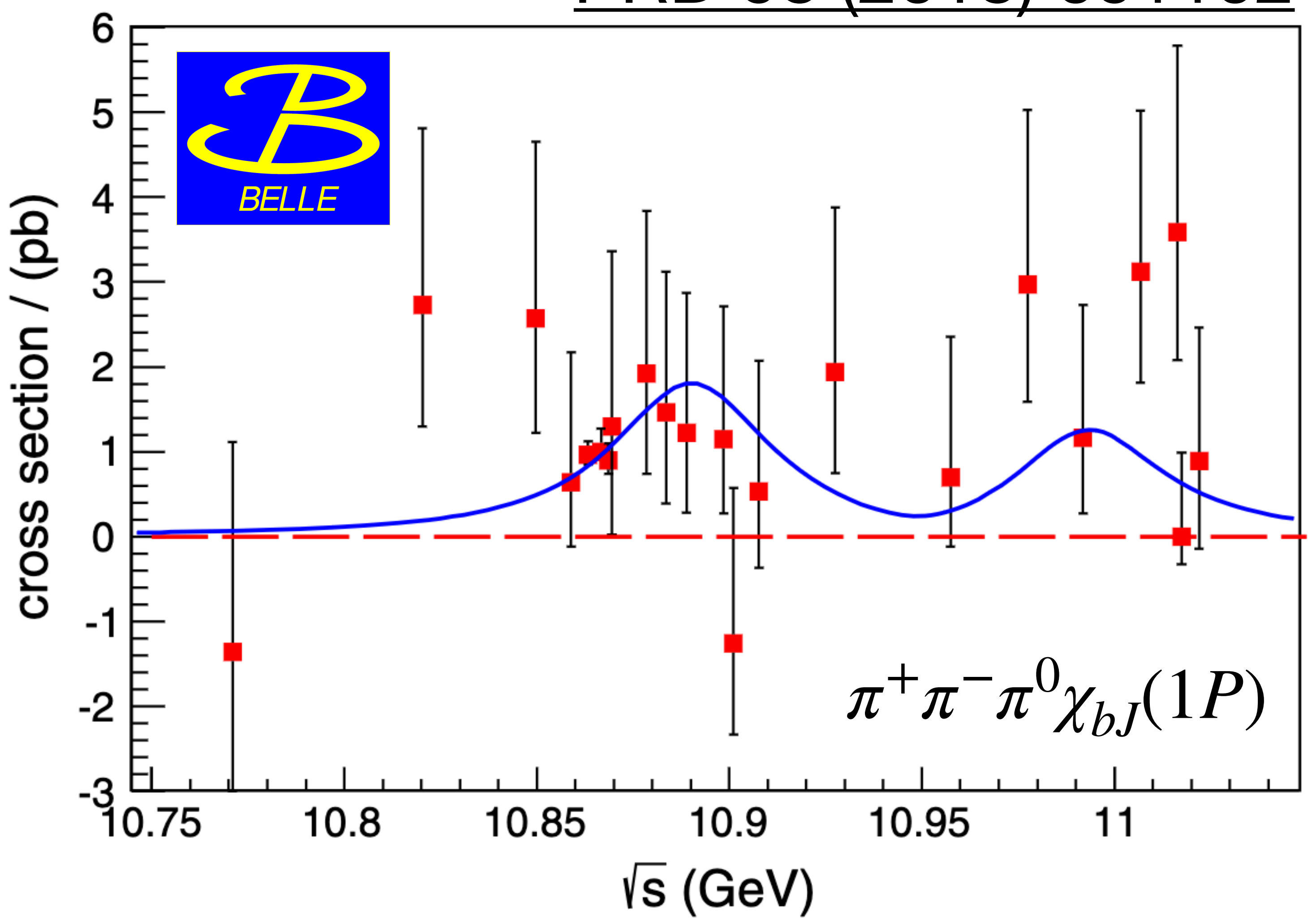




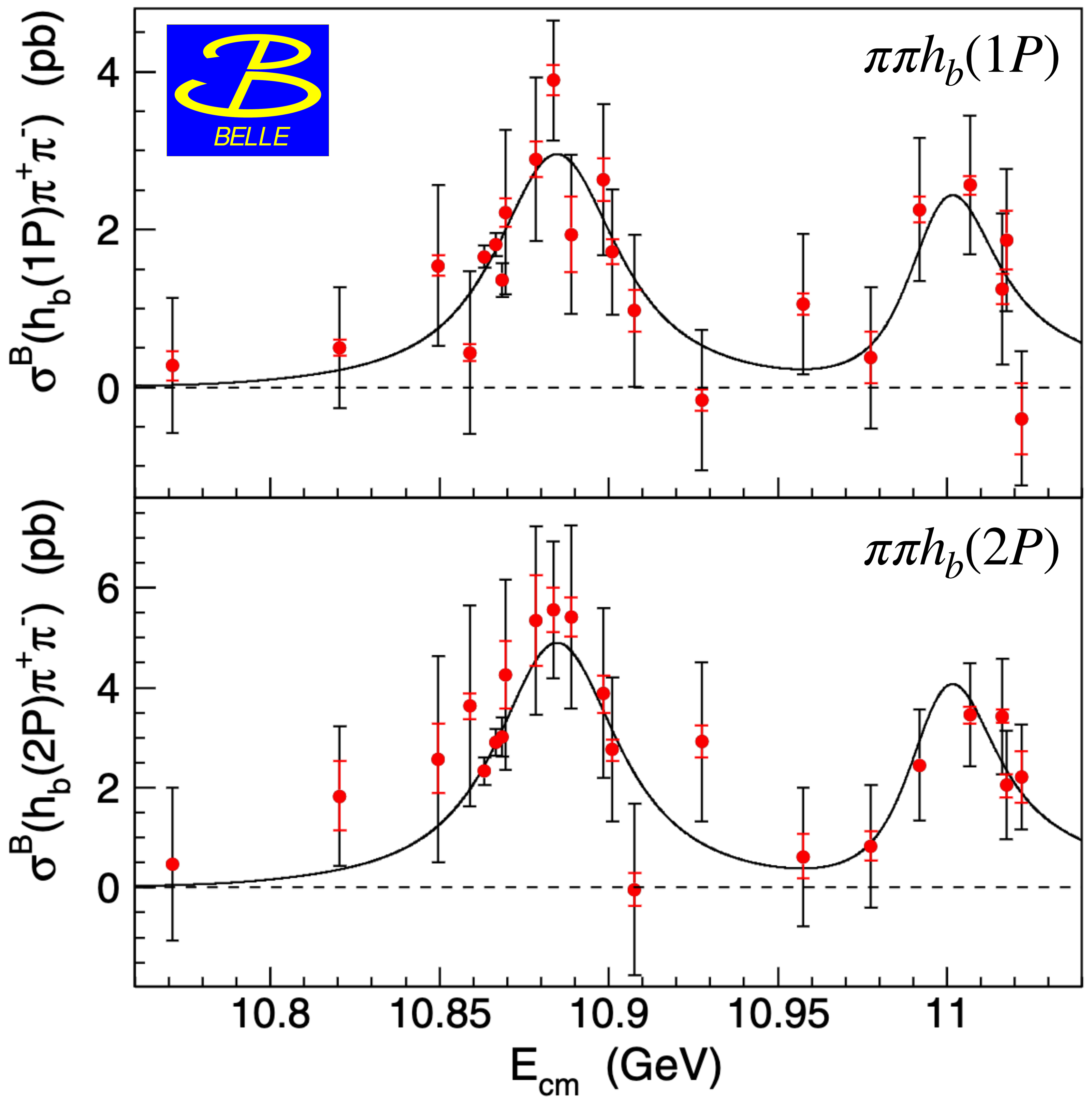
Nature of bottomonium states?

- Bottomonium states above $B\bar{B}$ threshold have unexpected behavior
  - Light hadron transitions to bottomonium enhanced
  - Some transitions strongly violate heavy quark spin symmetry
  - Potential admixture of $B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}$ ("dressed" by hadrons)?
  - Indication of nearby "exotic" states (e.g. tetraquarks, hadrobottomonia)

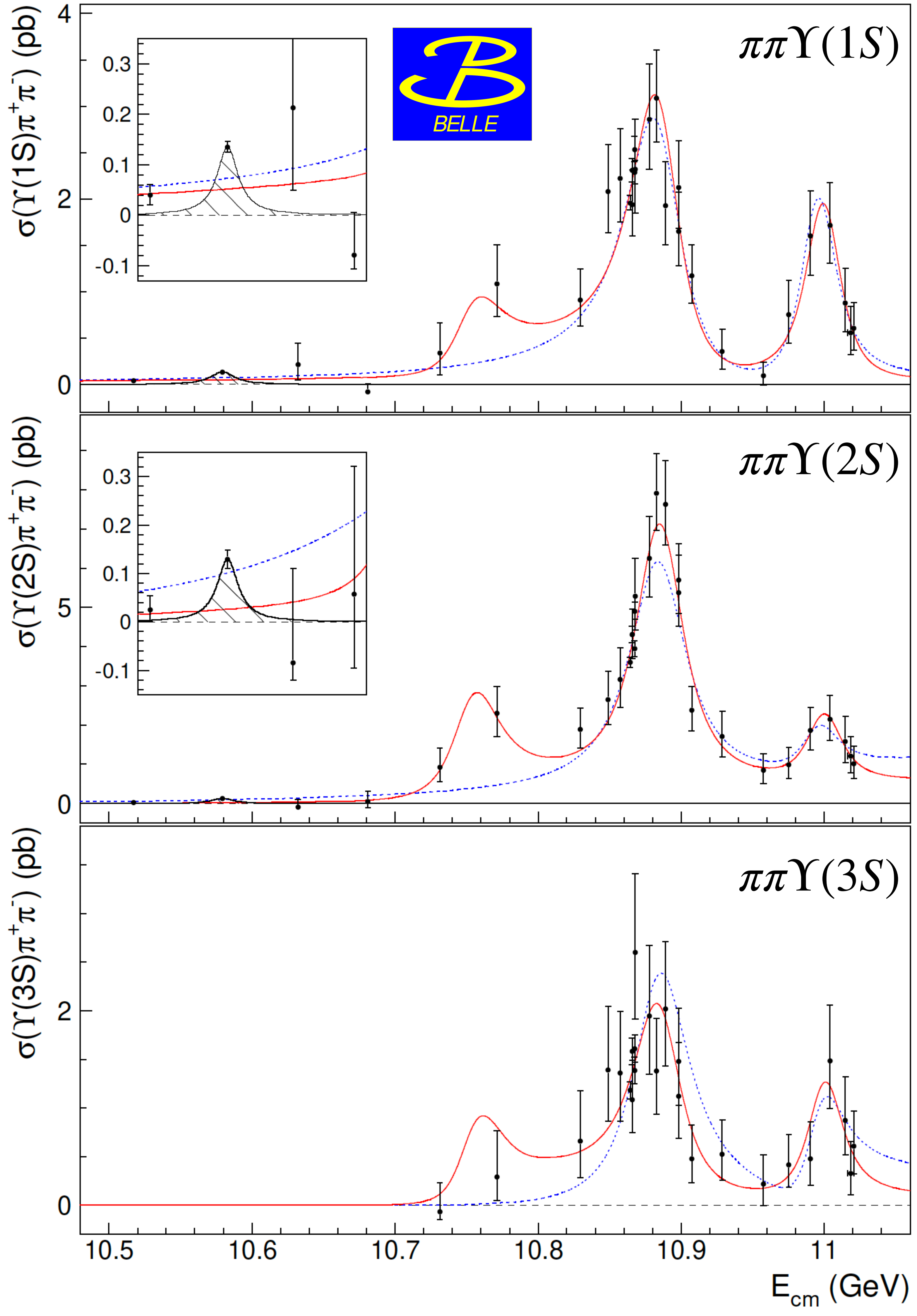
PRD 98 (2018) 091102



PRL 117 (2016) 142001



JHEP 10 (2019) 220

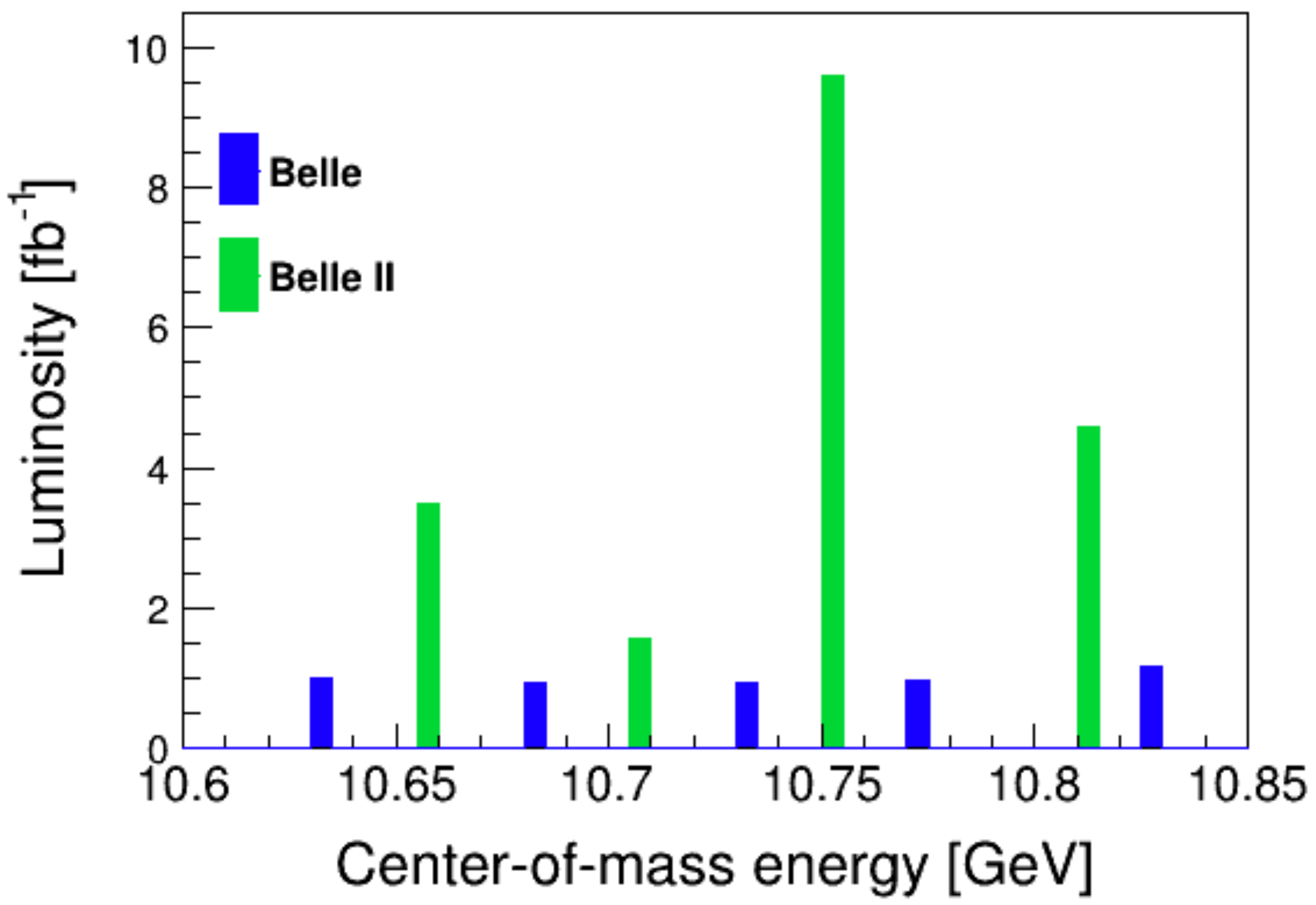


Unique opportunities at 10.75 GeV

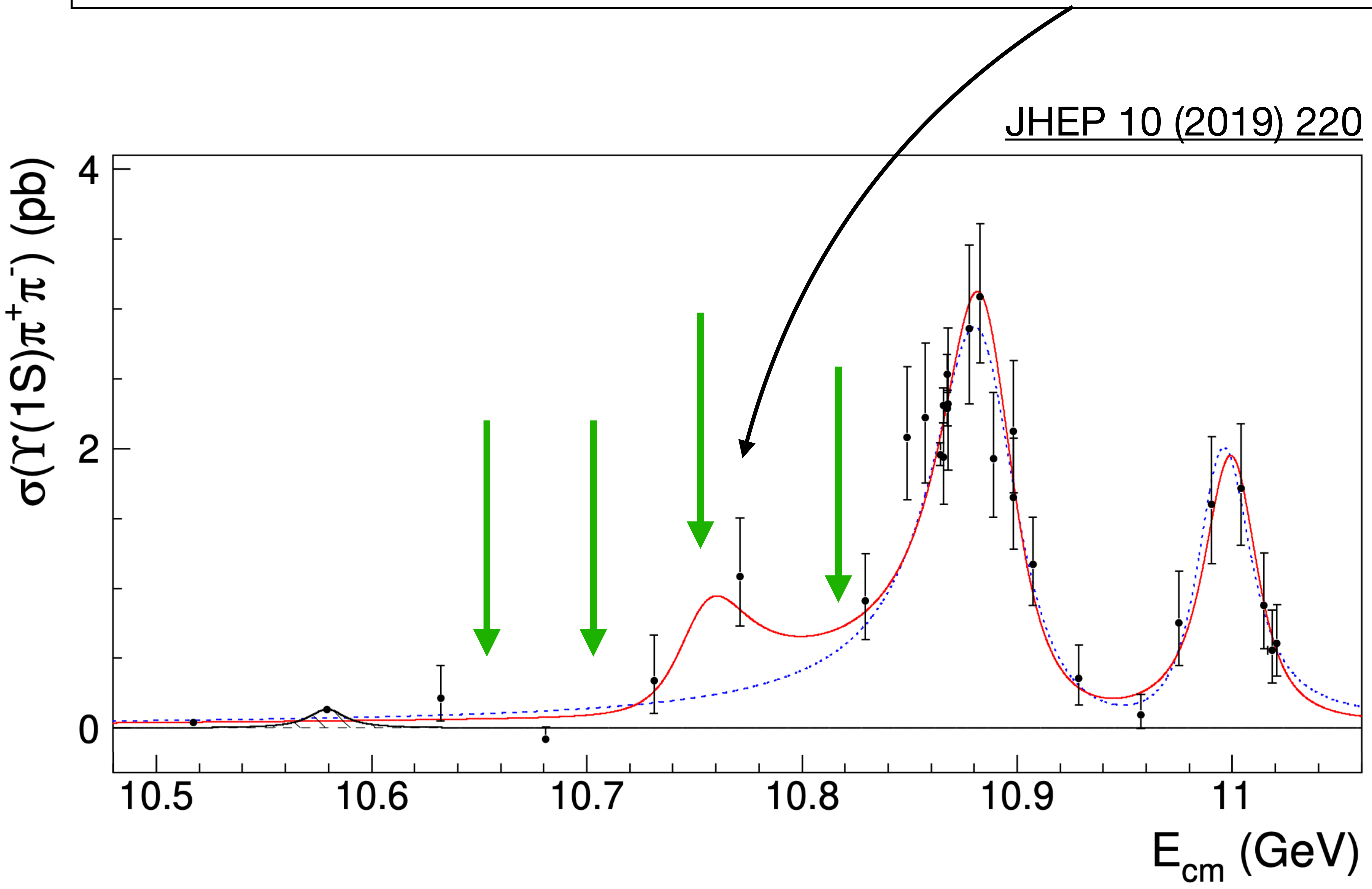
- Belle observed a structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
- Belle II dataset collected above the $\Upsilon(4S)$ in fall of 2021
  - Goal to characterize the $\Upsilon(10753)$ by studying golden channels (and others)

$\Upsilon(10753)$

	$\Upsilon(10860)$	$\Upsilon(11020)$	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 (2019) 220



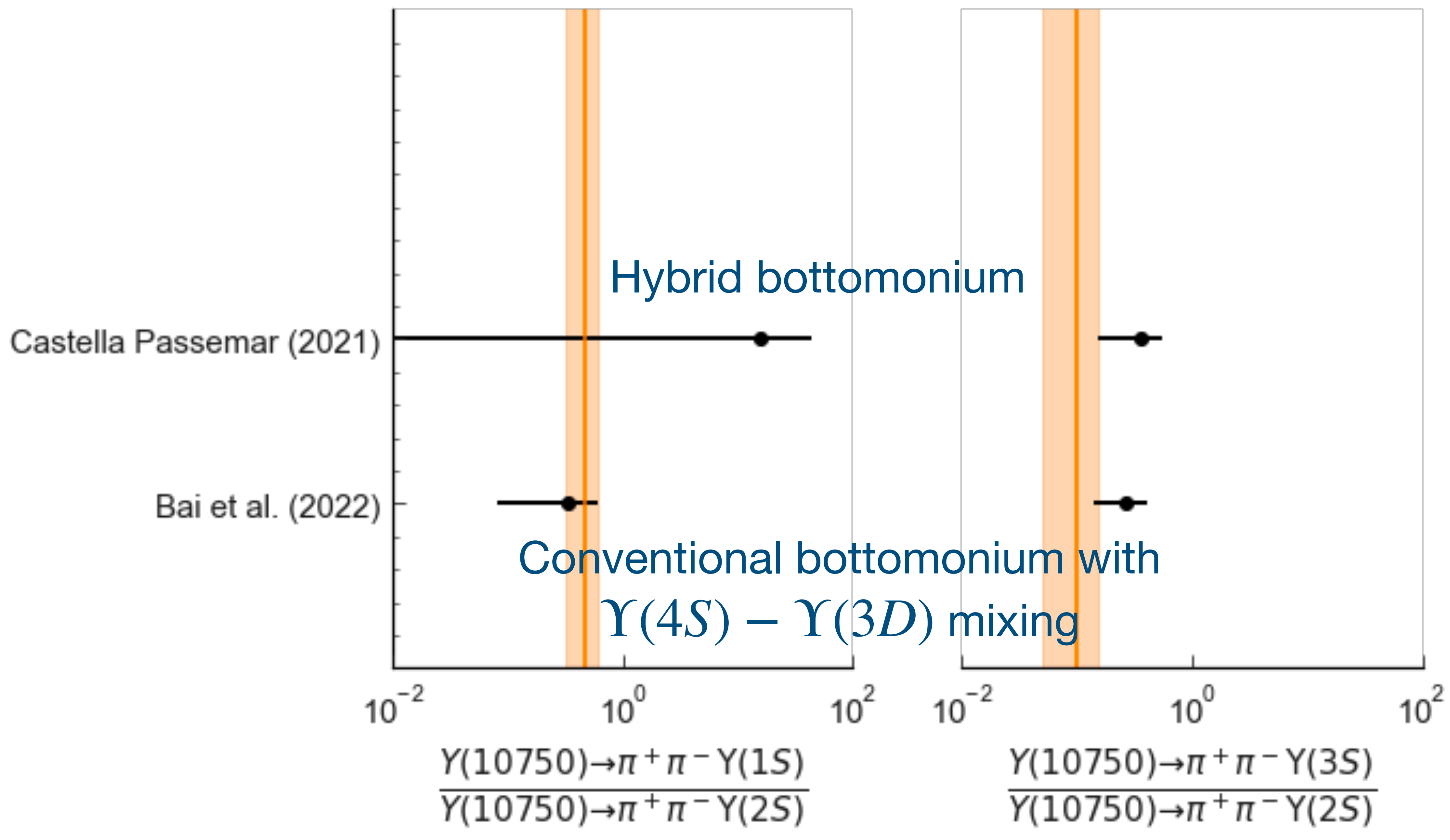
Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II

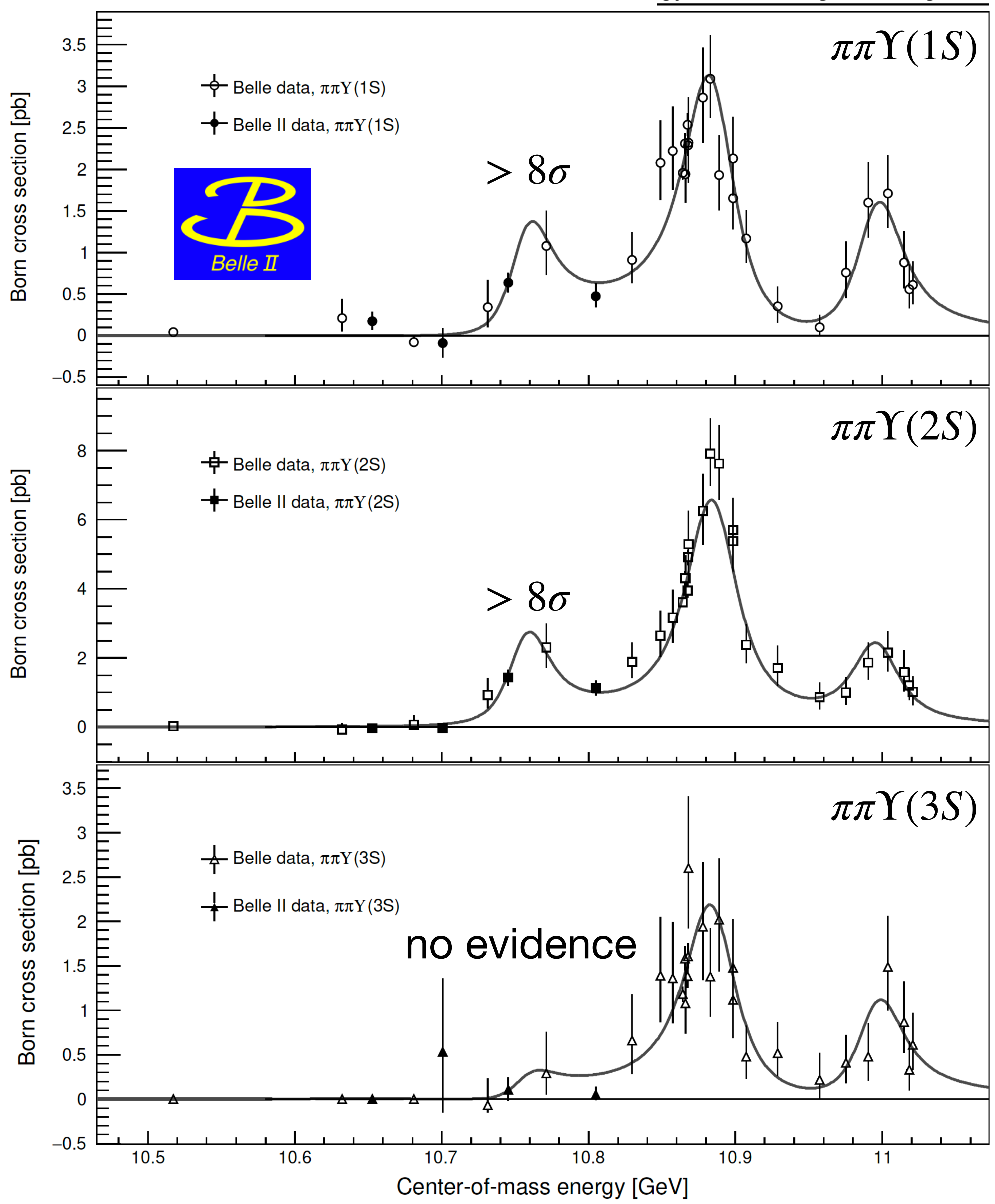
arXiv:2401.12021

- Confirm existence in discovery mode with much higher significance

	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$
Ratio	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$	$0.45^{+0.04}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.64^{+0.23}_{-0.13}$	$0.41^{+0.16}_{-0.12}$

Comparable ratios for $\pi^+\pi^-\Upsilon(1S)$





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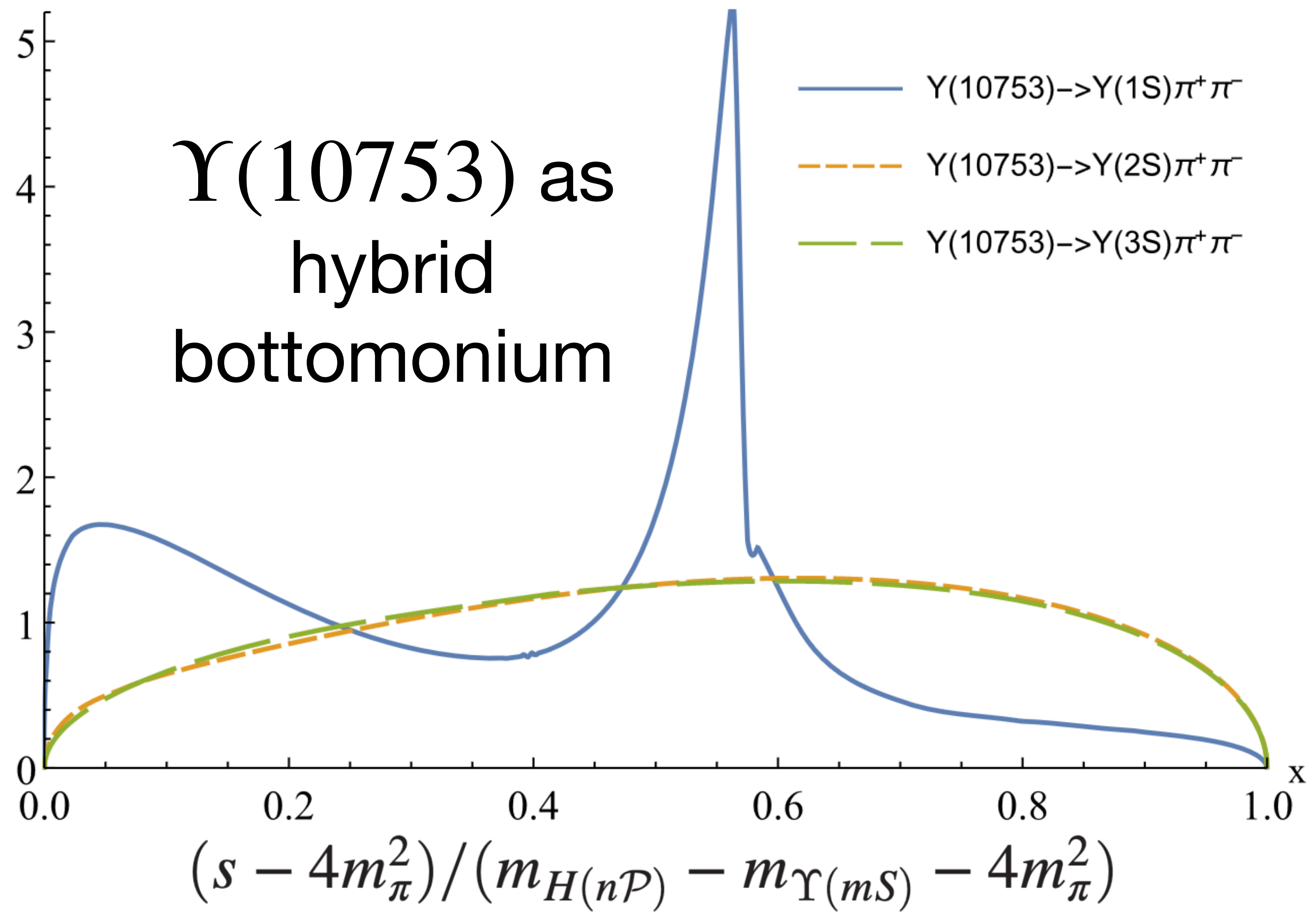
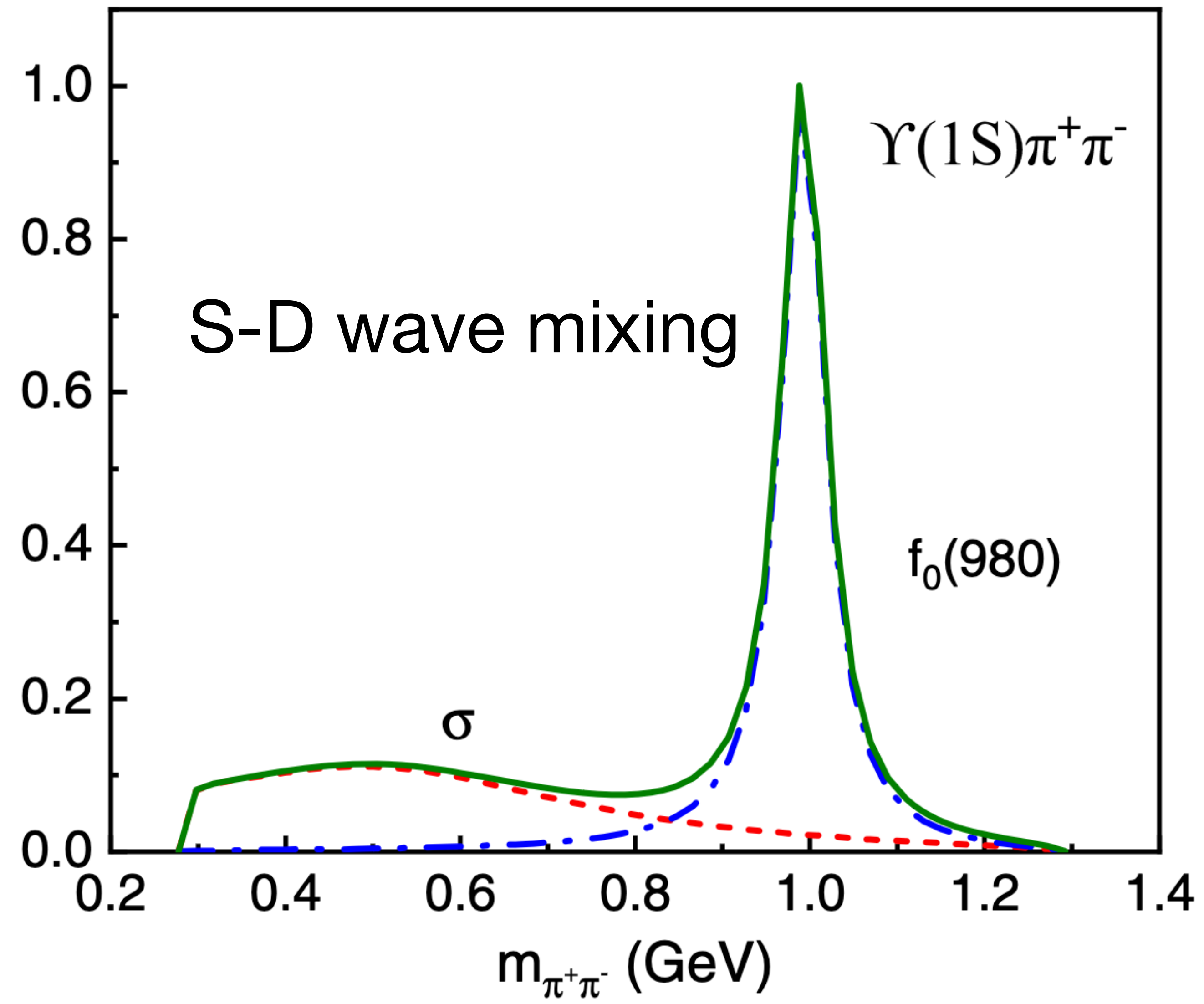
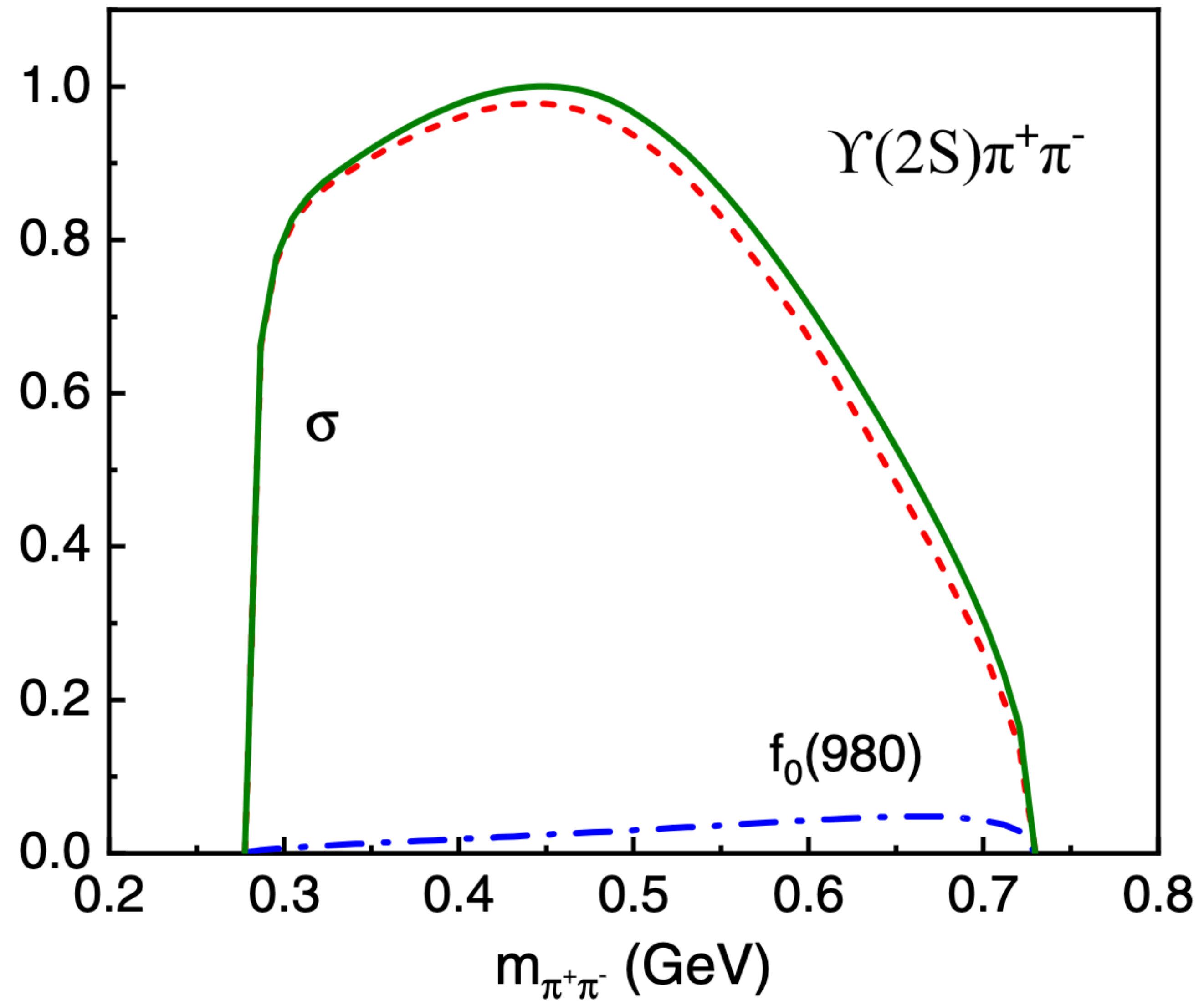
PRD 104 (2021) 034019





PRD 105 (2022) 074007



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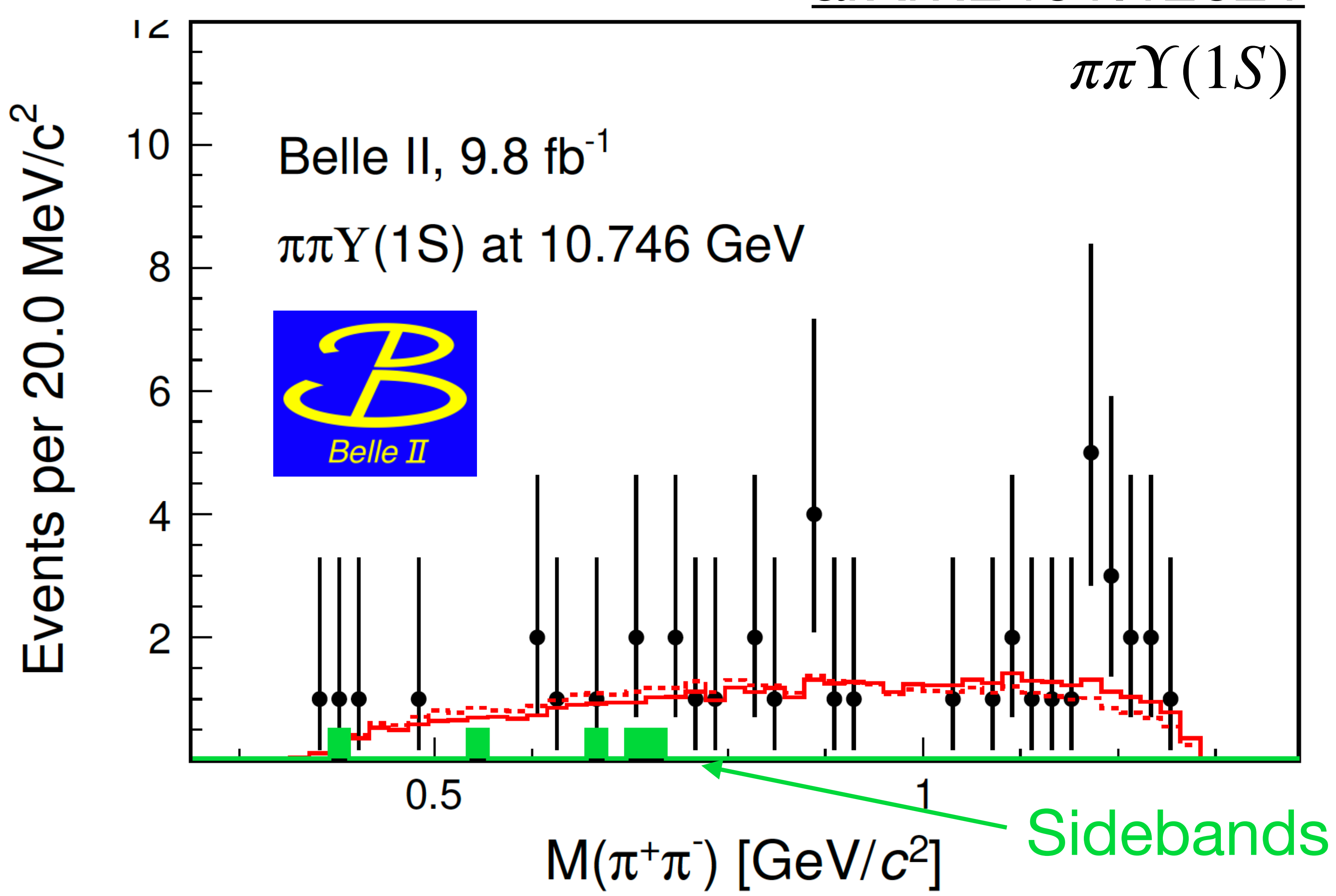
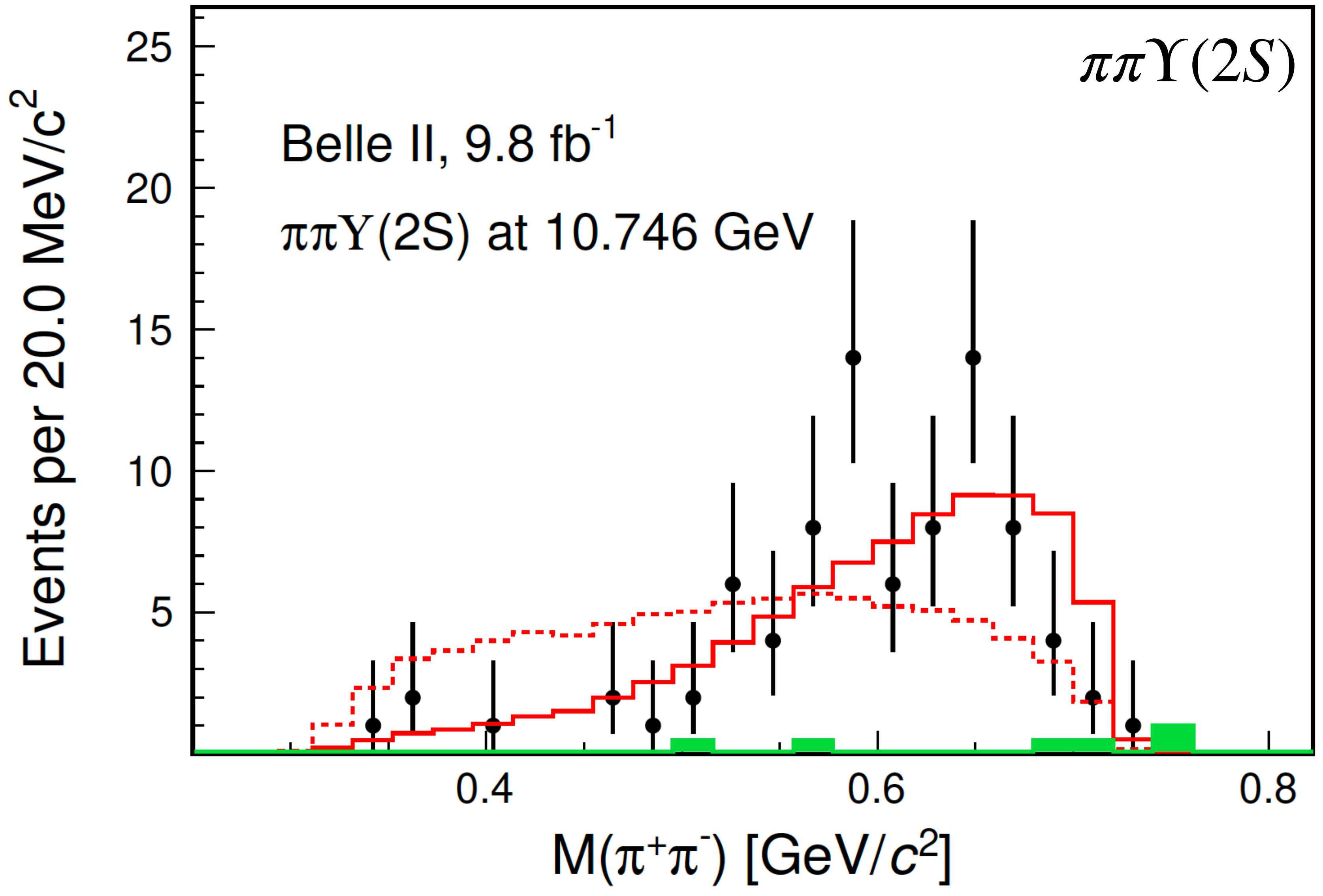




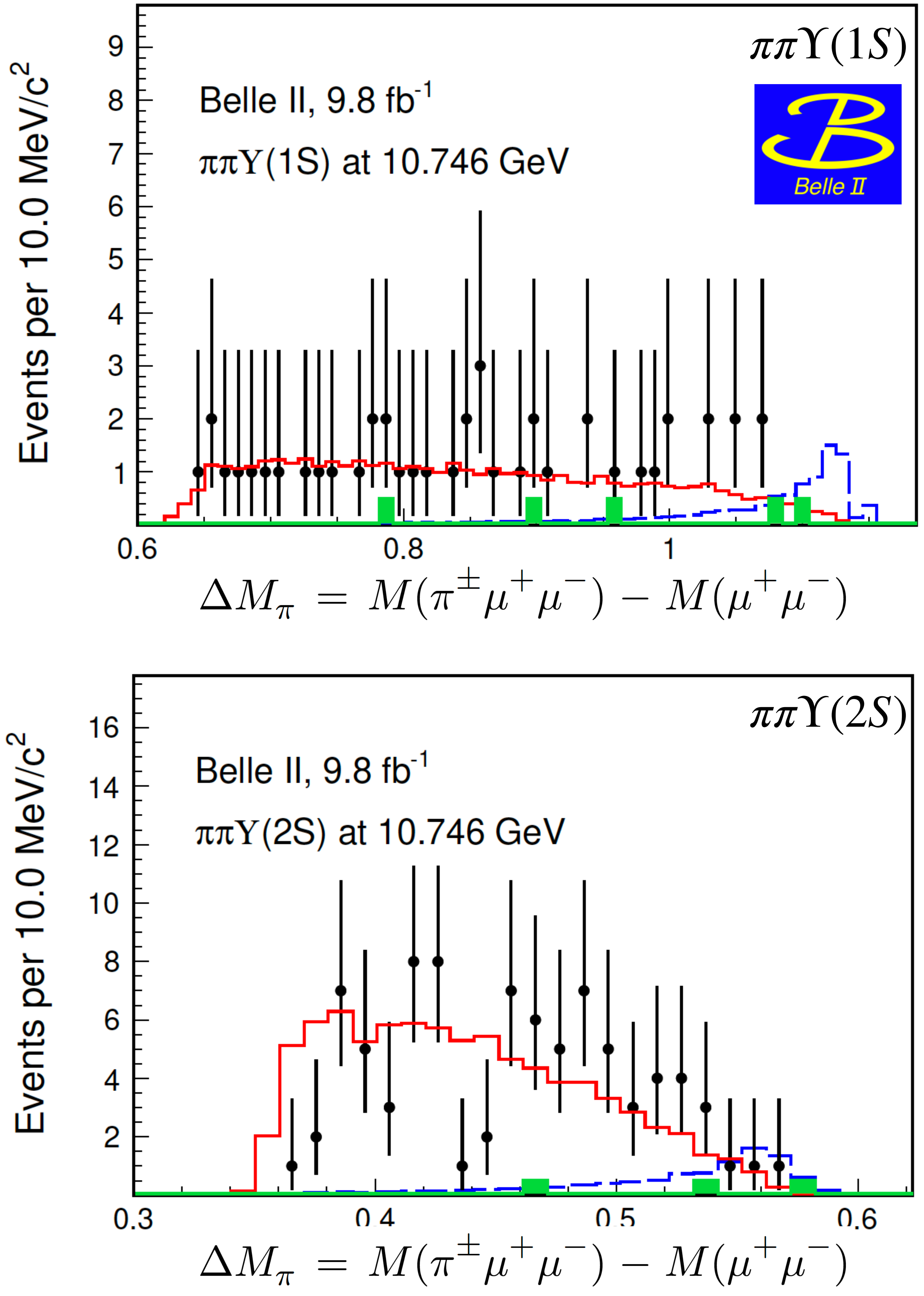
- Study di-pion spectrum
  - No evidence for $f_0(980)$ in $\pi^+\pi^-\Upsilon(1S)$ - disagrees with predictions
  - Di-pion mass spectrum in $\pi^+\pi^-\Upsilon(2S)$ similar to that in $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ - disagrees with S-D mixing prediction

Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II

arXiv:2401.12021

- Look for Z_b contributions in $M(\pi\Upsilon)$
  - No evidence for intermediate $Z_b(10610/10650)^{\pm}$

Mode	$N_{Z_{b1}}$	$N^{\rm UL}_{Z_{b1}}$	$\sigma_{Z_{b1}}$ (pb)	$\sigma^{\rm UL}_{Z_{b1}}$ (pb)	$N^{\rm UL}_{Z_{b2}}$	$N_{Z_{b2}}$	$\sigma_{Z_{b2}}$ (pb)	$\sigma^{\rm UL}_{Z_{b2}}$ (pb)
10.746 GeV								
$\pi\Upsilon(1S)$	$0.0^{+1.6}_{-0.0}$	< 4.9	$0.00^{+0.04}_{-0.00}$	< 0.13	–	–	–	
$\pi\Upsilon(2S)$	$5.8^{+5.9}_{-4.6}$	< 13.8	$0.06^{+0.06}_{-0.05}$	< 0.14	–	–	–	
10.805 GeV								
$\pi\Upsilon(1S)$	$2.5^{+2.4}_{-1.6}$	< 5.2	$0.21^{+0.20}_{-0.13}$	< 0.43	$0.0^{+0.7}_{-0.0}$	< 5.8	$0.00^{+0.03}_{-0.00}$	< 0.28
$\pi\Upsilon(2S)$	$5.2^{+3.8}_{-3.0}$	< 12.3	$0.15^{+0.11}_{-0.09}$	< 0.35	$0.0^{+0.8}_{-0.0}$	< 6.0	$0.00^{+0.04}_{-0.00}$	< 0.30



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

- $\Upsilon(10753)$ interpreted as conventional bottomonium, hybrid, tetraquark
  - Conventional quarkonium model (S-D mixing) give comparable predictions for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(1S)$ and $\omega\chi_{bJ}$

$$\mathcal{B}[\Upsilon(10753) \to \chi_{b0}\omega] = (0.73\text{–}6.94) \times 10^{-3}$$

$$\mathcal{B}[\Upsilon(10753) \to \chi_{b1}\omega] = (0.25\text{–}2.16) \times 10^{-3}$$

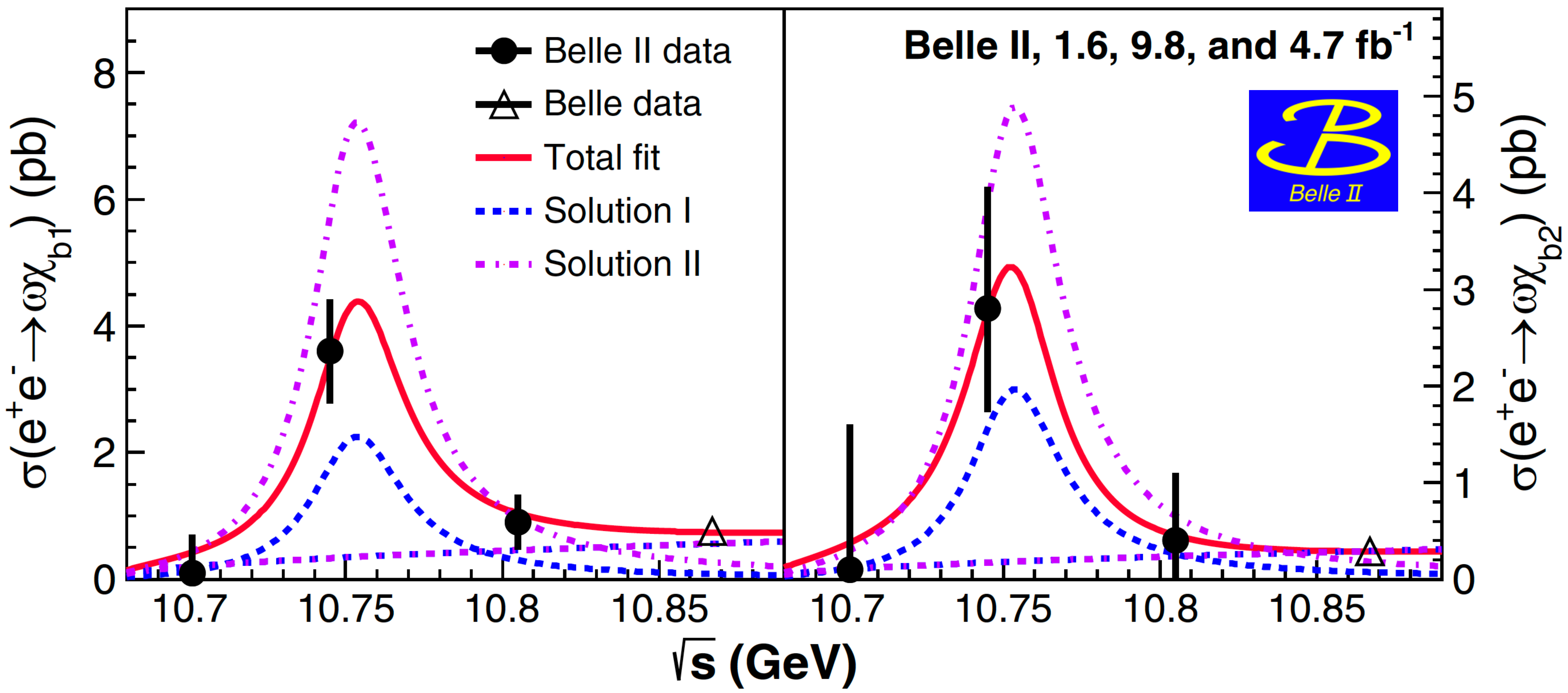
$$\mathcal{B}[\Upsilon(10753) \to \chi_{b2}\omega] = (1.08\text{–}11.5) \times 10^{-3}$$

$\omega\chi_{b1}$ predicted to be about 1/5 of $\omega\chi_{b2}$
[PRL 104 (2021) 034036]

$$\Gamma_{ee}B[\Upsilon(10753) \to \omega\chi_{b1}] = \begin{array}{l} 0.63\pm0.39\pm0.20 \text{ (con)} \\ 2.01\pm0.38\pm0.76 \text{ (des)} \end{array}$$

$$\Gamma_{ee}B[\Upsilon(10753) \to \omega\chi_{b2}] = \begin{array}{l} 0.53\pm0.46\pm0.15 \text{ (con)} \\ 1.32\pm0.44\pm0.55 \text{ (des)} \end{array}$$

PRL 130 (2023) 091902



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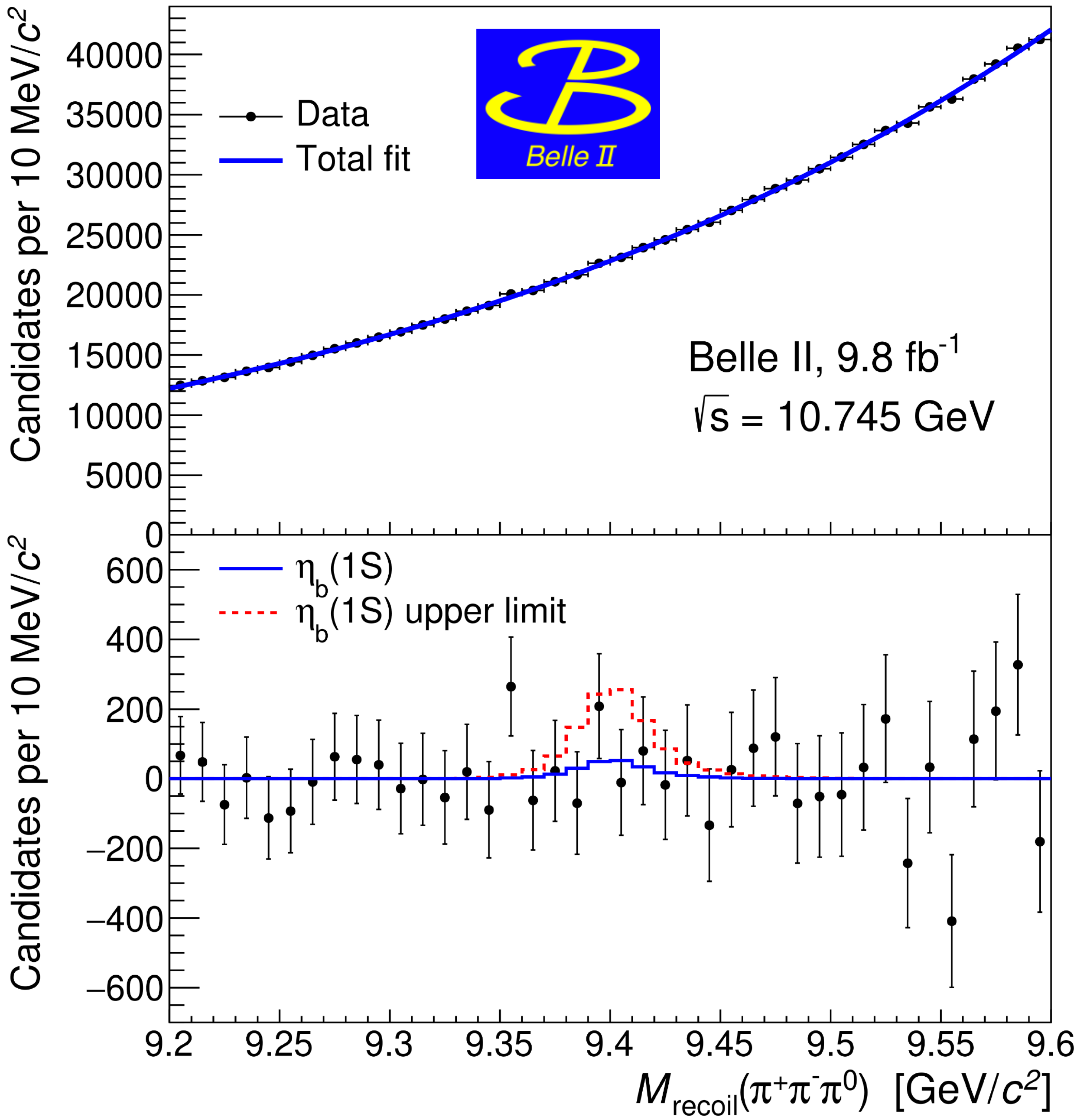
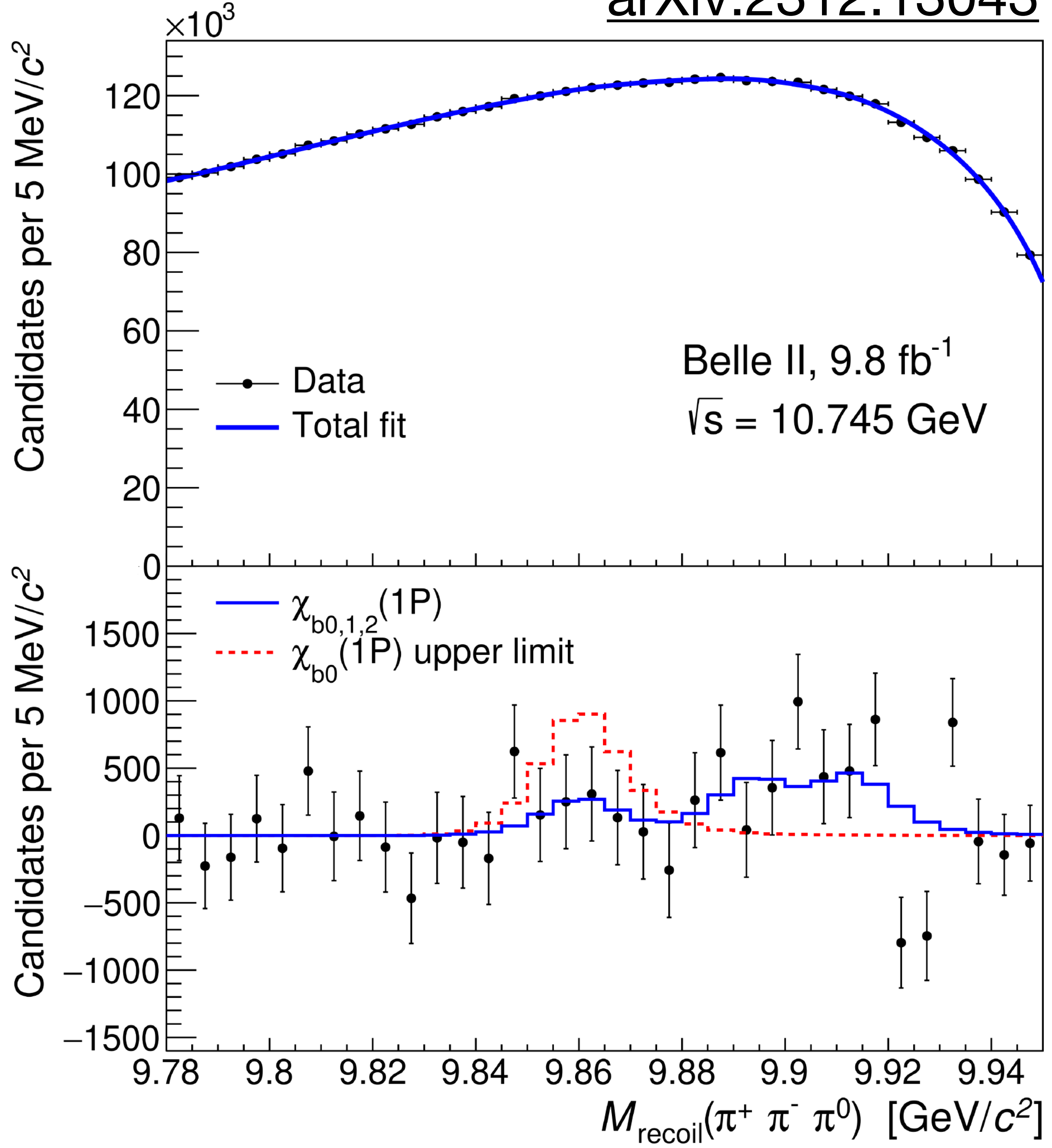
- Observed ratio $\sigma_B(e^+e^- \to \omega\chi_{b1})/\sigma_B(e^+e^- \to \omega\chi_{b2}) = 1.3 \pm 0.6$ contradicts expectations for pure D-wave state and ~1.8σ discrepancy with S-D mixing
- Large difference in $\omega\chi_{bJ}$ and $\pi^+\pi^-\Upsilon(1S)$ production rate at $\Upsilon(10753)$ and $\Upsilon(10860)$ may indicate different internal structure
- Observed $\Upsilon(10860) \to \omega\chi_{bJ}$ may simply be the tail of the $\Upsilon(10753)$

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

- No exclusive $\chi_{b0}(1P)$ channels with large branching ratio and efficiency, so study recoil against ω

arXiv:2312.13043

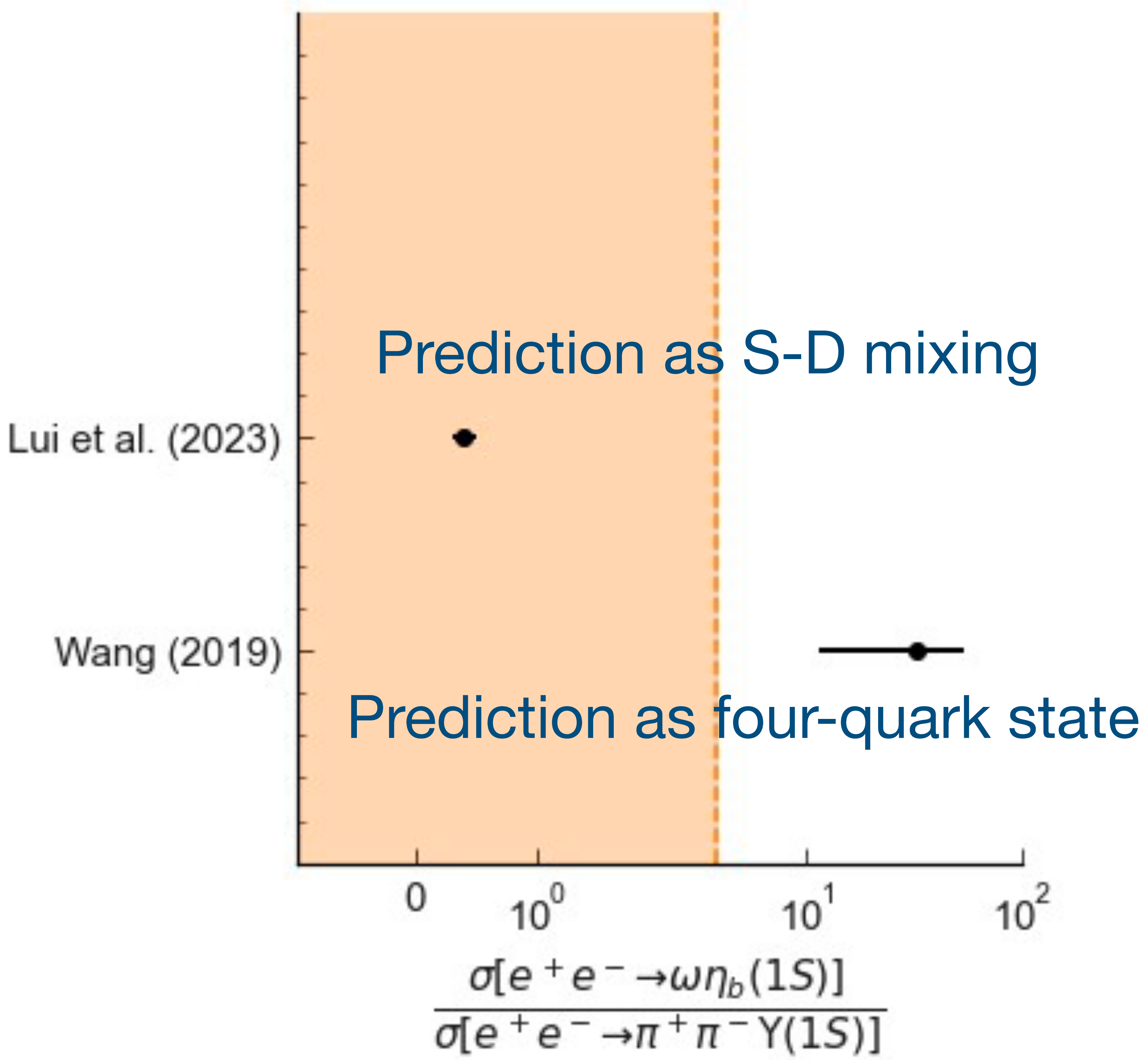




$$M_{\mathrm{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{\sqrt{s}-E_\omega}{c^2}\right)^2 - \left(\frac{p_\omega}{c}\right)^2}$$

$$\sigma_{\mathrm{B}}(e^+e^- \to \eta_b(1S)\omega) < 2.5\,\mathrm{pb}$$

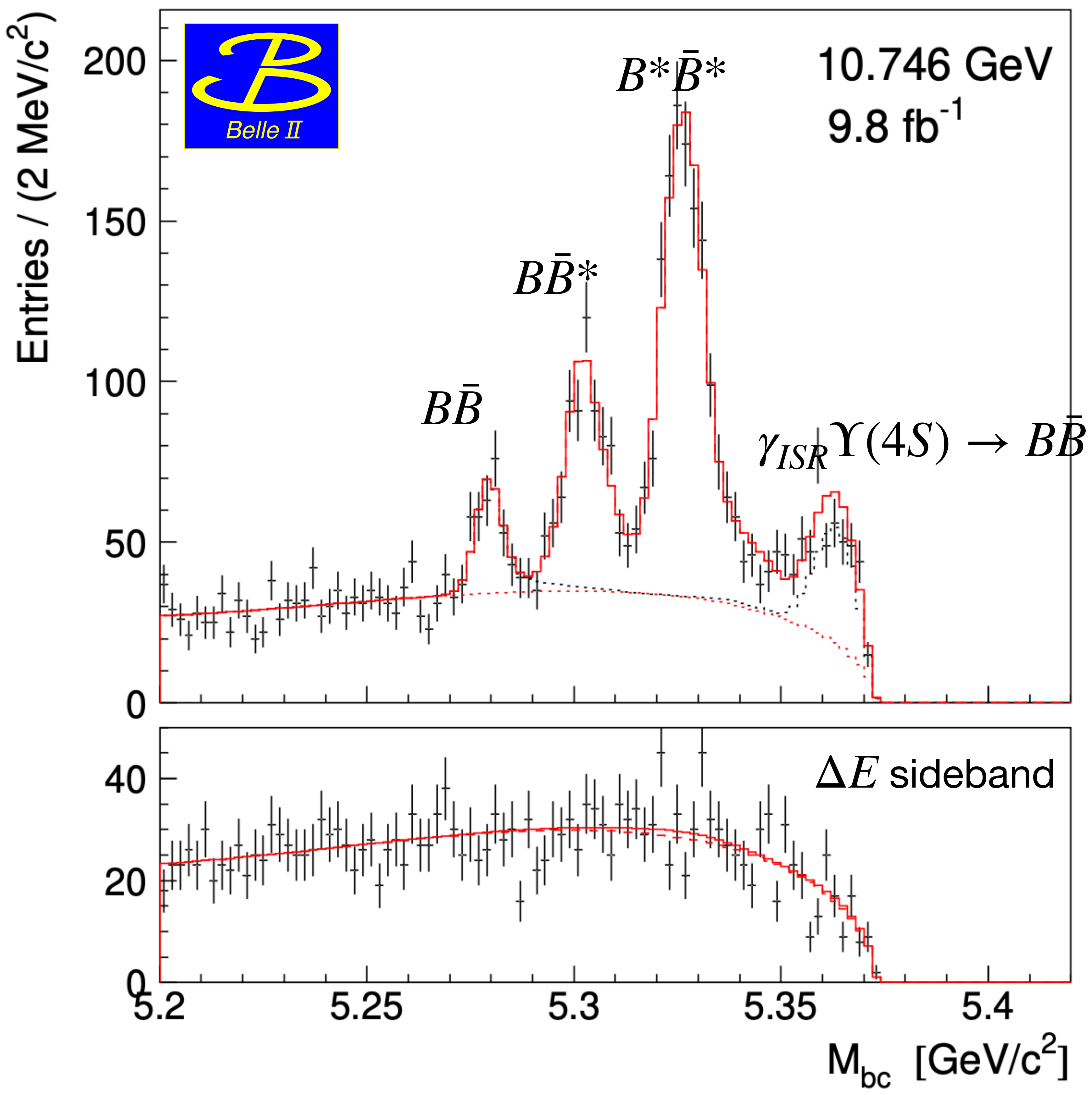
$$\sigma_{\mathrm{B}}(e^+e^- \to \chi_{b0}(1P)\omega) < 8.7\,\mathrm{pb}$$

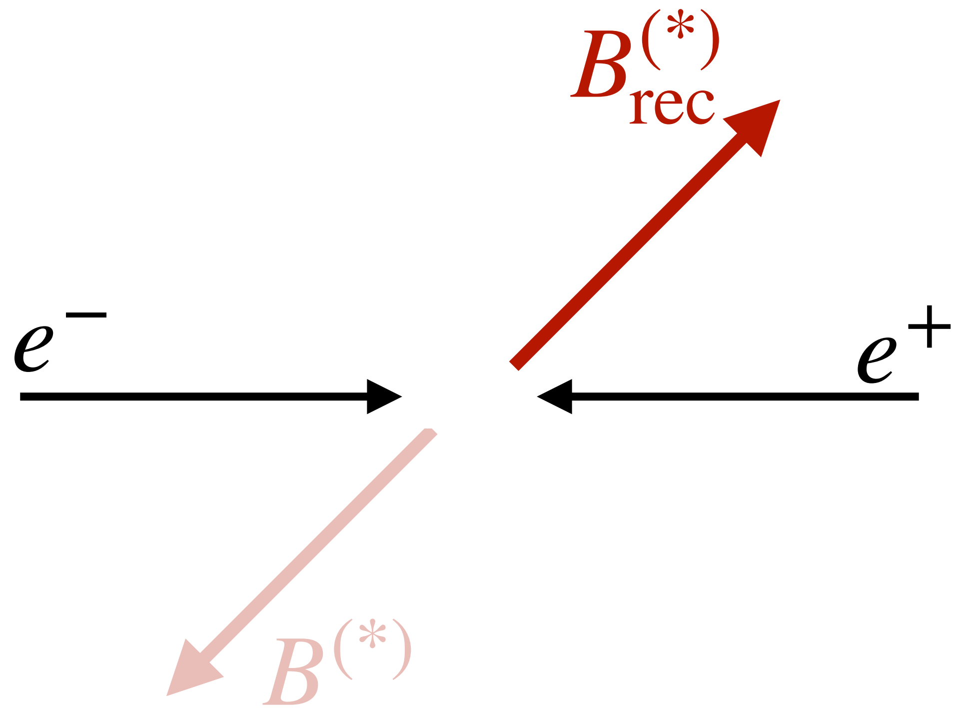


Energy dependence of $B\bar{B}$ cross sections at Belle II

- Semi-inclusive reconstruction: reconstruct one $B^{(*)}$ in 16 modes with $D^{(*)}_{(s)}$ or J/ψ

Belle II preliminary





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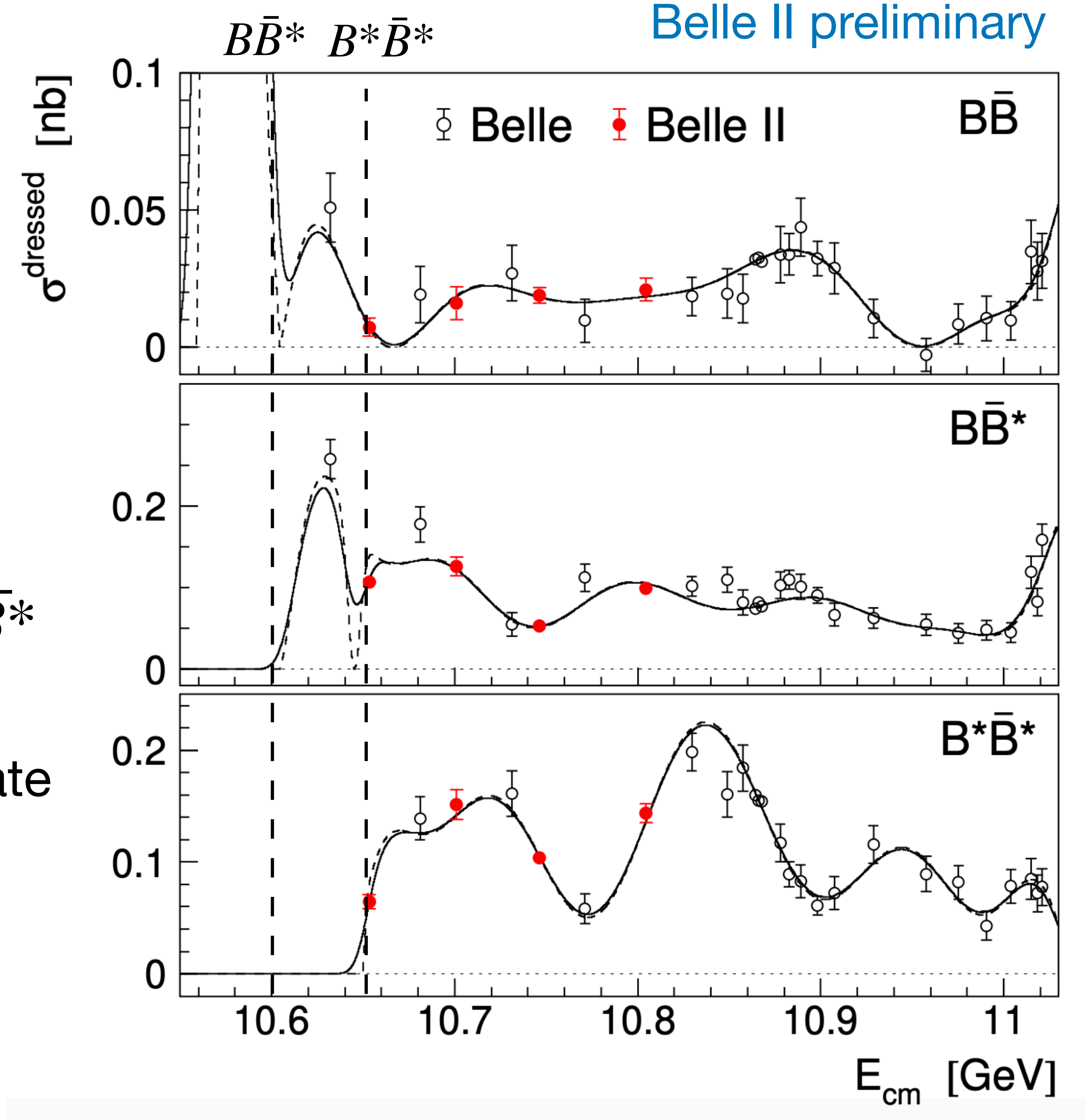
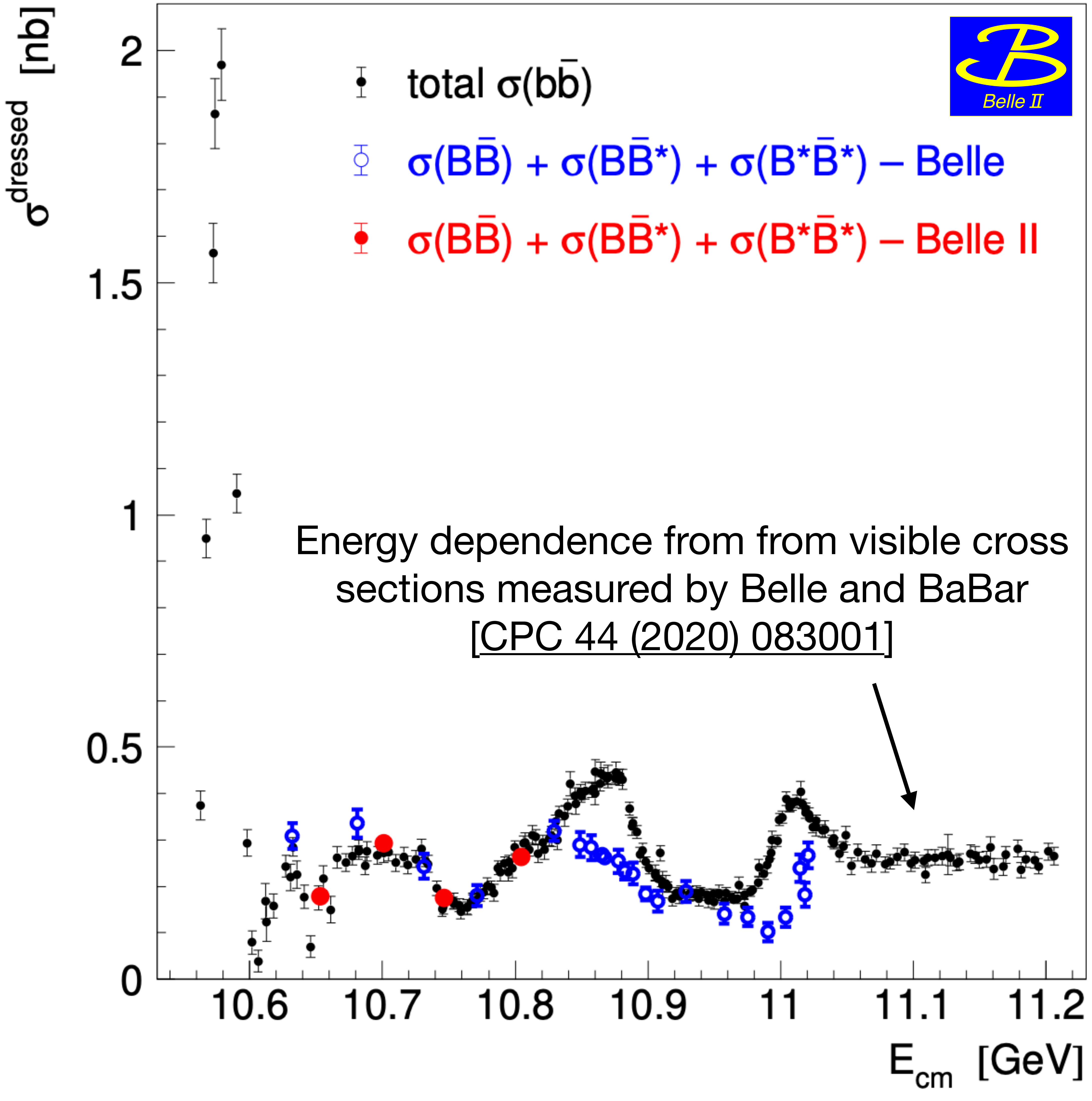
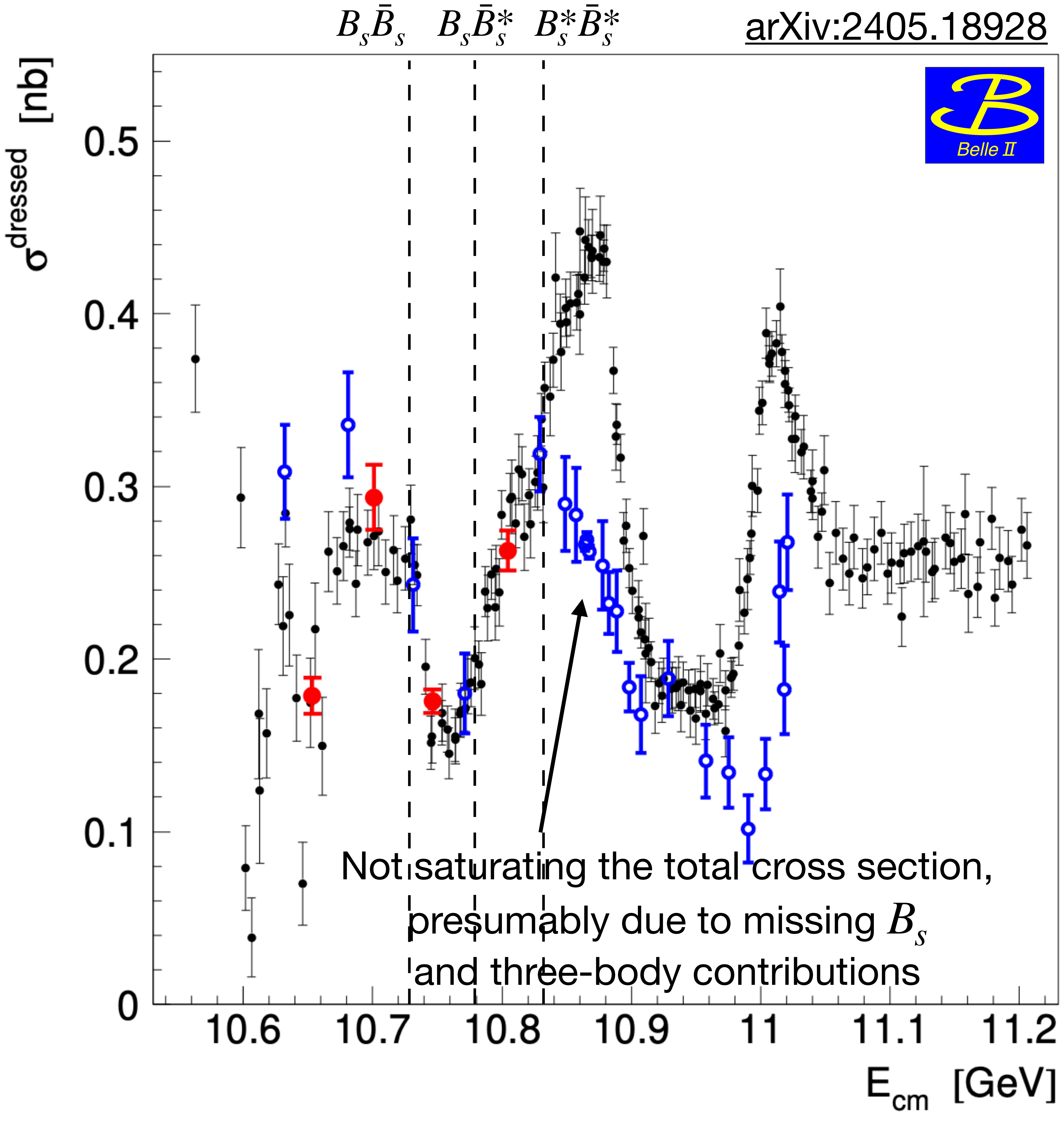


- Sharp rise in $B^*\bar{B}^*$, dip in $B\bar{B}^*$ near $B^*\bar{B}^*$ threshold
  - Indication of molecular state near threshold?
  - Similar phenomenon near $D^*\bar{D}^*$ threshold [MPLA 21, 2779 (2006)]

Energy dependence of $B\bar{B}$ cross sections at Belle II





Scan of $e^+e^- \to B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}X$ cross section

- Measure the fully-inclusive process $e^+e^- \to B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}X$ at various center-of-mass energies
  - Reconstruct $D_s^\pm$ as a proxy for B_s^0 and D^0 as a proxy for B

$$\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X) = 2\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X)\mathcal{B}(B_s^0 \to D_s^\pm X) + 2\,\sigma(e^+e^- \to B\bar{B}X)\mathcal{B}(B \to D_s^\pm X),$$

$$\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X) = 2\,\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X)\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) + 2\,\sigma(e^+e^- \to B\bar{B}X)\mathcal{B}(B \to D^0/\bar{D}^0 X).$$

  - Improves statistical precision over full reconstruction of $B_{(s)}$
  - Strong suppression of $B_s^{(*)}\bar{B}_s^{(*)}\pi^0$ (isospin) means $\sigma(e^+e^- \to B_s^0\bar{B}_s^0X) = \sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})$ up to $B_s^0\bar{B}_s^0\pi^0\pi^0$ threshold (11.004 GeV)
- Subtract continuum $e^+e^- \to D_{(s)}X$ using scaled momentum

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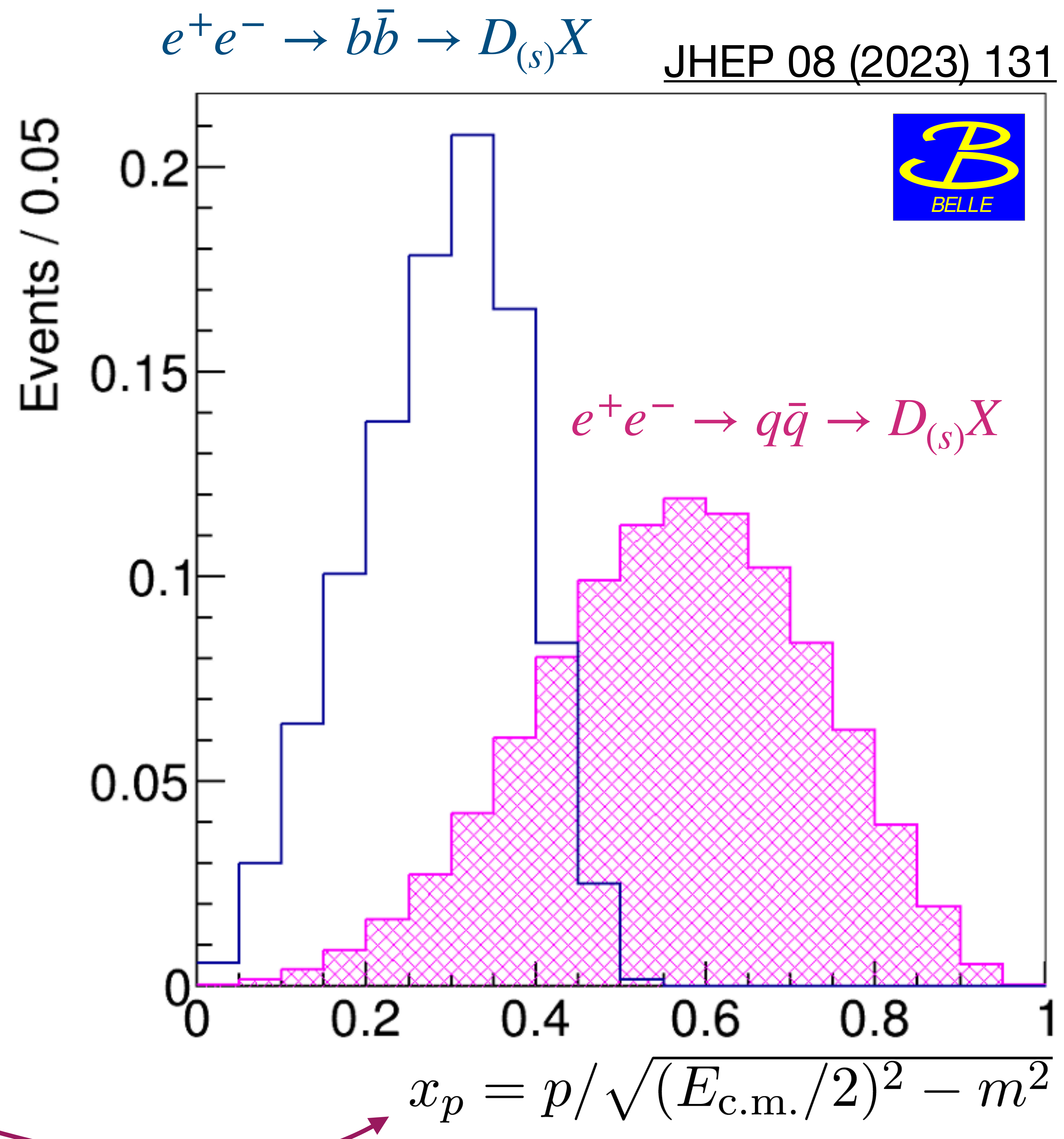

Scan of $e^+e^- \to B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}X$ cross section

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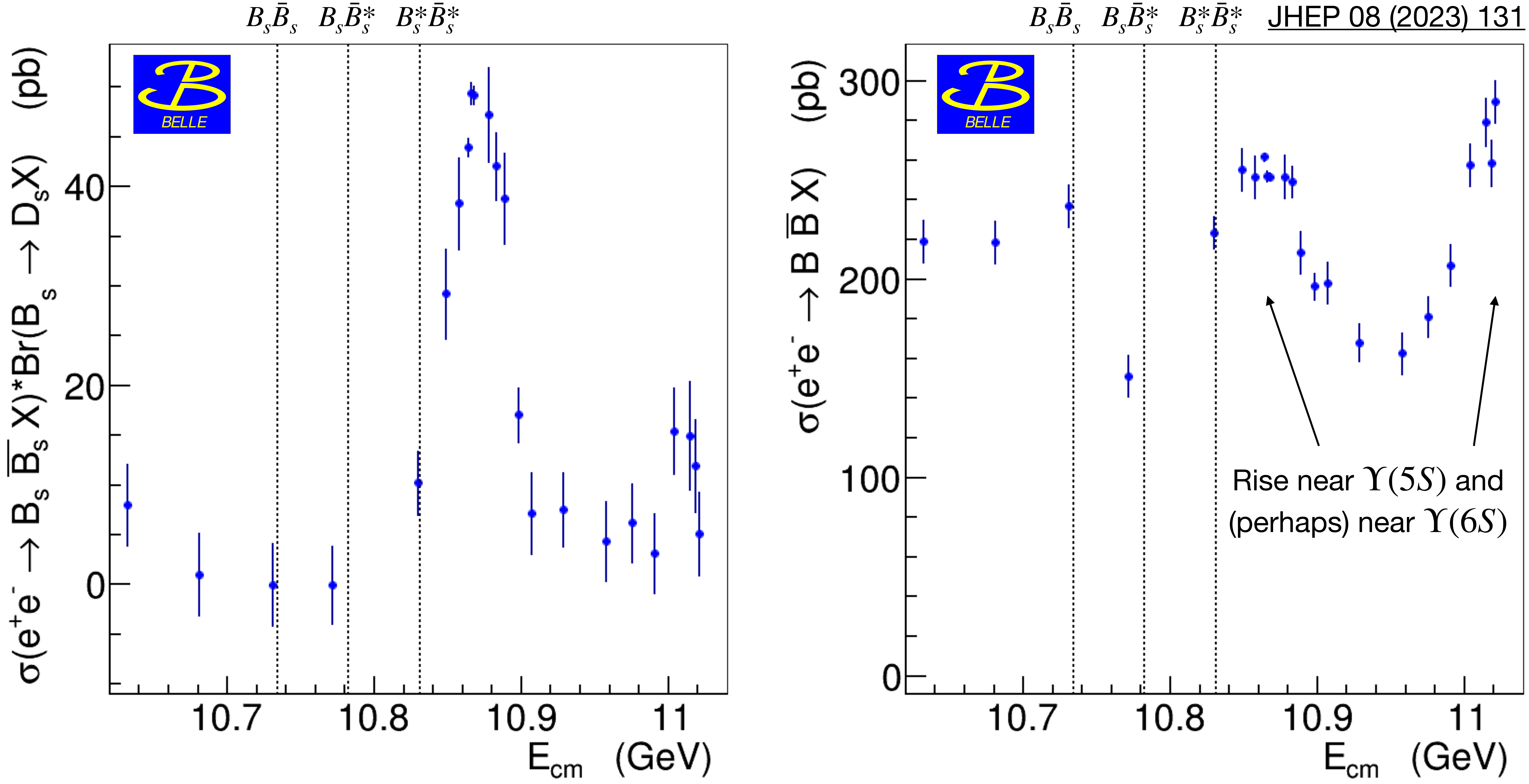
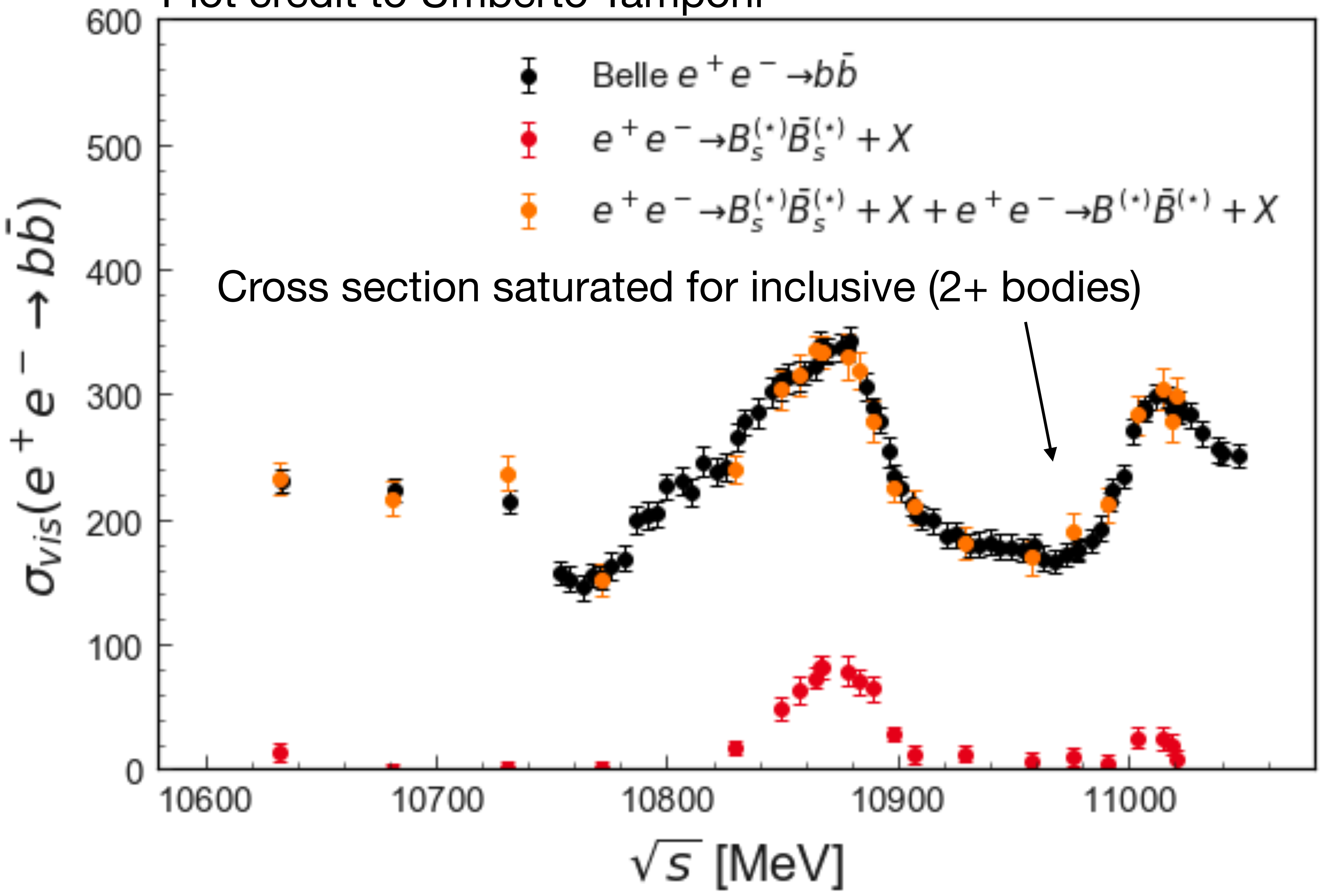
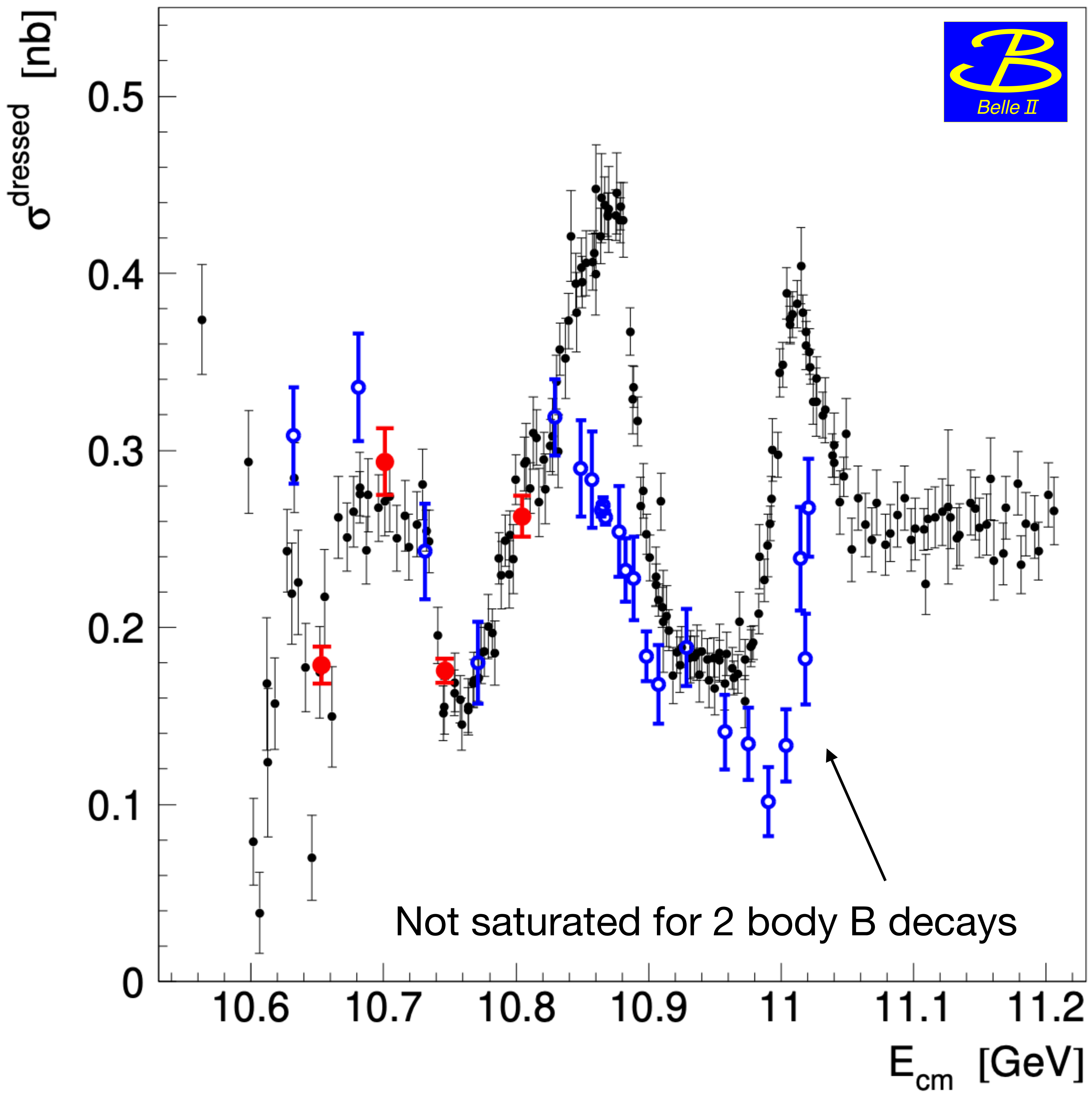


Scan of $e^+e^- \to B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}X$ cross section

Plot credit to Umberto Tamponi



arXiv:2405.18928

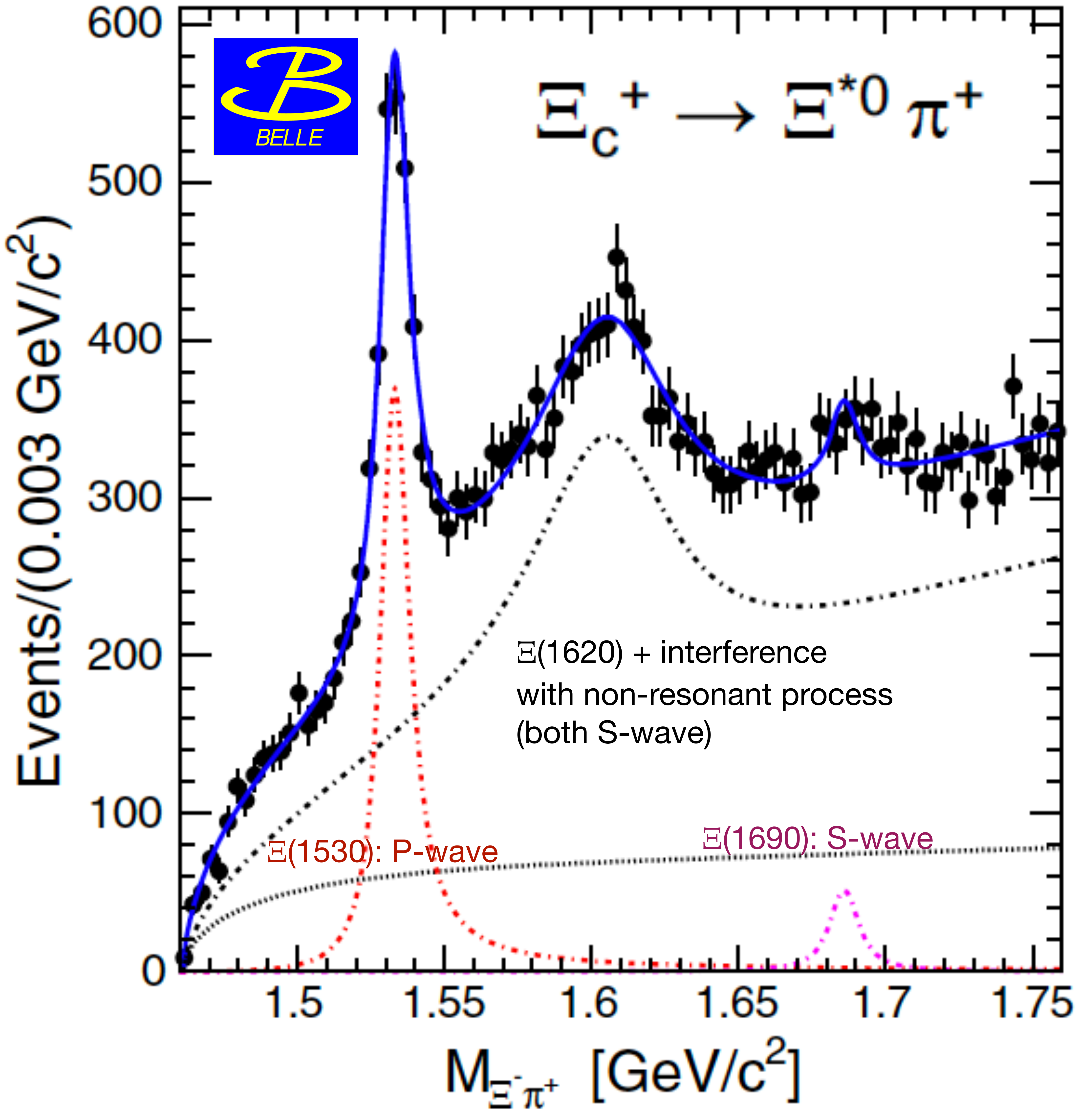


Prospects in baryon spectroscopy

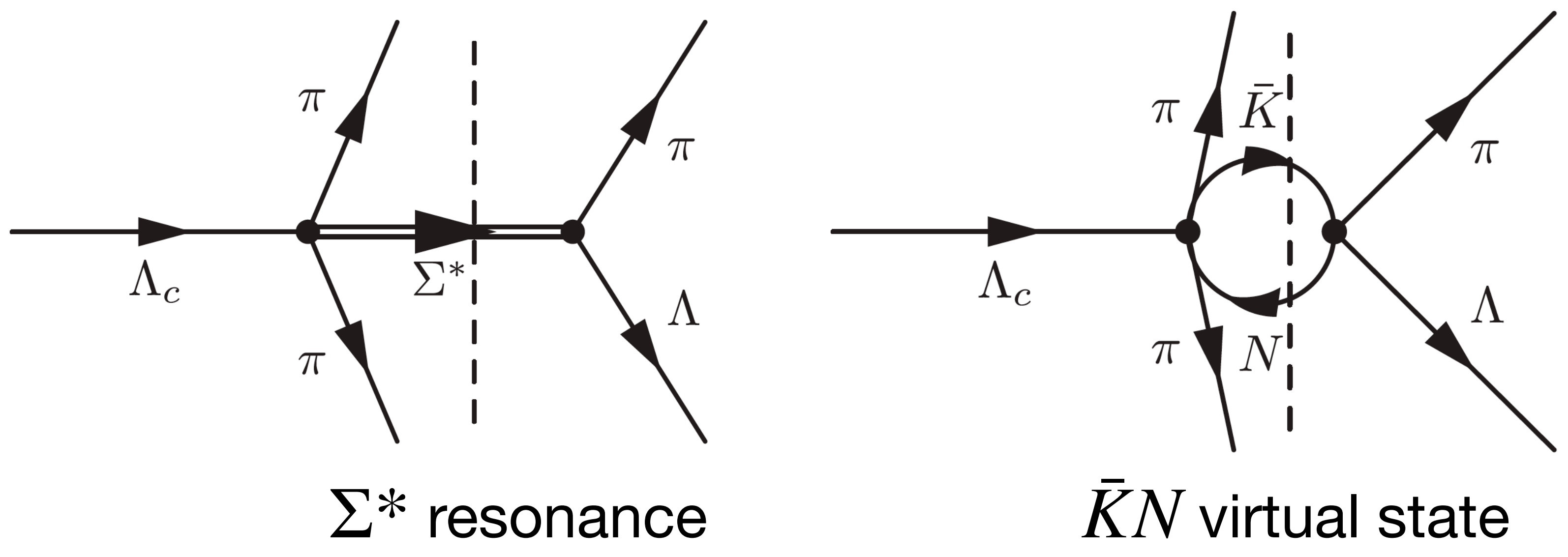
- Mesons get all the attention…
- Baryon spectrum is much more complicated than quarkonia but exotic candidates exist even in the first excited states
  - Notable examples include the Λ(1405) and N(1440)
- Excited spectrum not well understood
  - Many missing states
  - Multiple candidates for known states
  - Few quantum number determinations for baryons containing c or b quarks
- Belle still actively publishing

- Belle II can
  - measure quantum numbers for excited charmed baryons
  - search for excited baryons in charmed baryon decays
  - search for exotic candidate states

Belle PRL.122.072501 (2019)



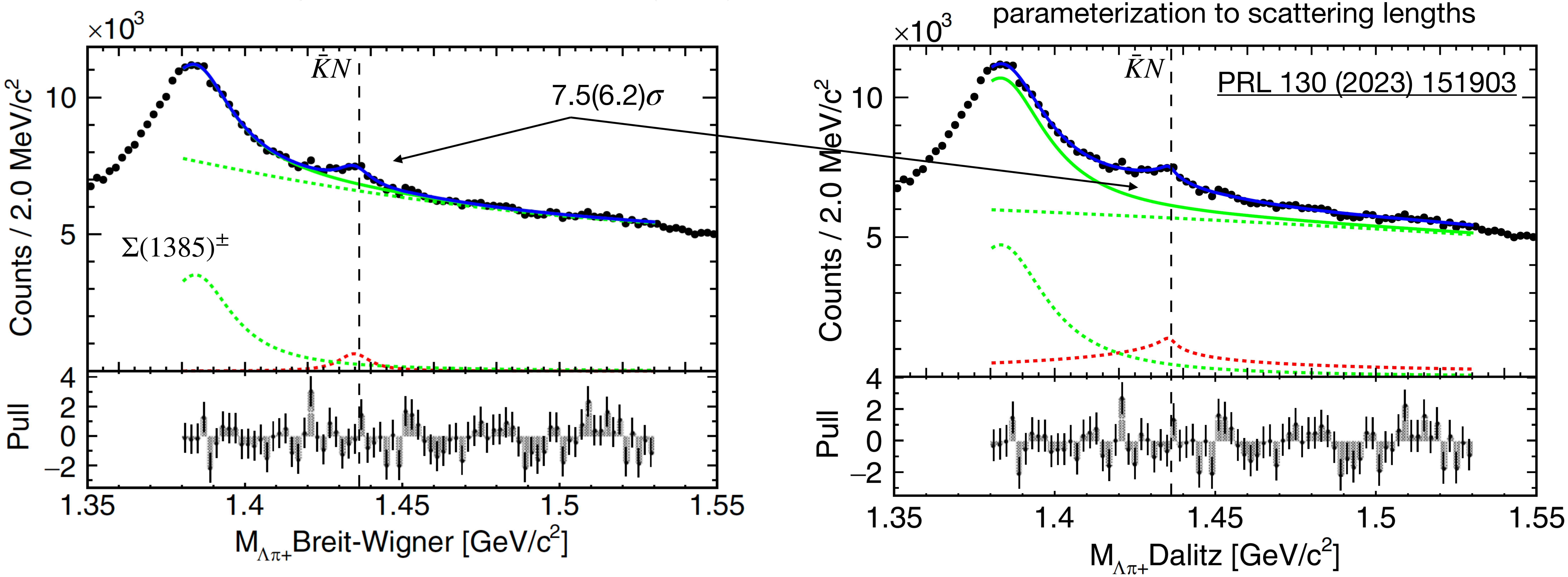
Study of $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$



- Charmed baryon decays have become a source for hyperon spectroscopy
- $\Lambda\pi$ spectrum in Λ_c decays similar to $\Lambda - \pi$ collider data to study I=1, S=-1 sector
- Besides $\Sigma(1385)^{\pm}$, no additional I=1 quark-model states expected near $\Lambda(1405)$

Model 1: Breit-Wigner, implies existence of $\Sigma(1435)$?

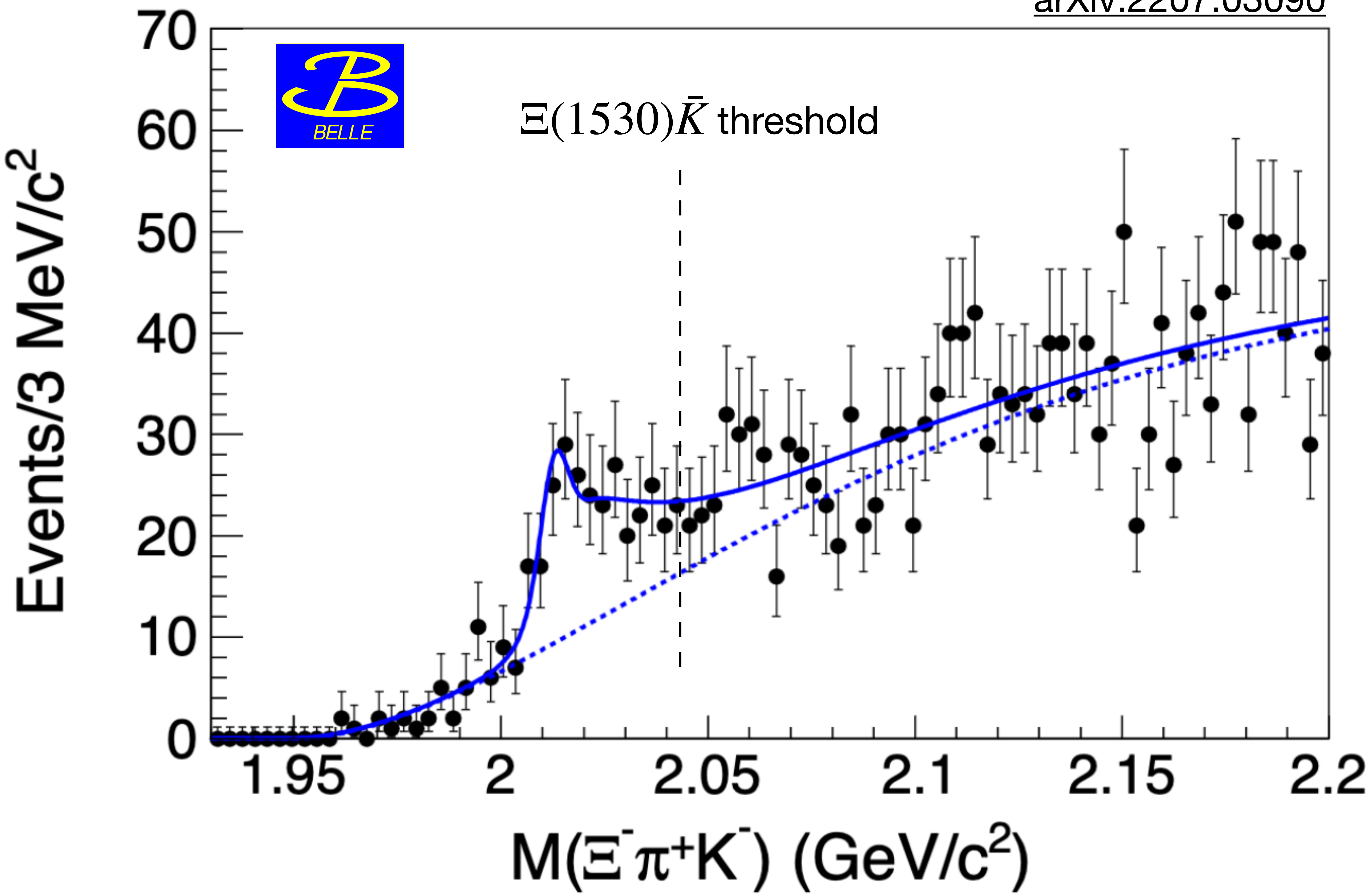
Model 2: Dalitz (cusp), relates Flatte parameterization to scattering lengths



Study of $\Omega(2012)^- \to \Xi(1530)\bar{K}$

- Limited experimental evidence for excited states like the $\Omega(2012)^-$
  - Can be interpreted as standard baryon or molecular state
  - Some suggestion that in the molecular picture decays to $\Xi\bar{K}$ and $\Xi(1530)\bar{K}$ should be similar

arXiv:2207.03090



$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = \frac{\mathcal{B}(\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K})}{\mathcal{B}(\Omega(2012)^- \to \Xi\bar{K})}$$

$$= 0.97 \pm 0.24 \pm 0.07$$

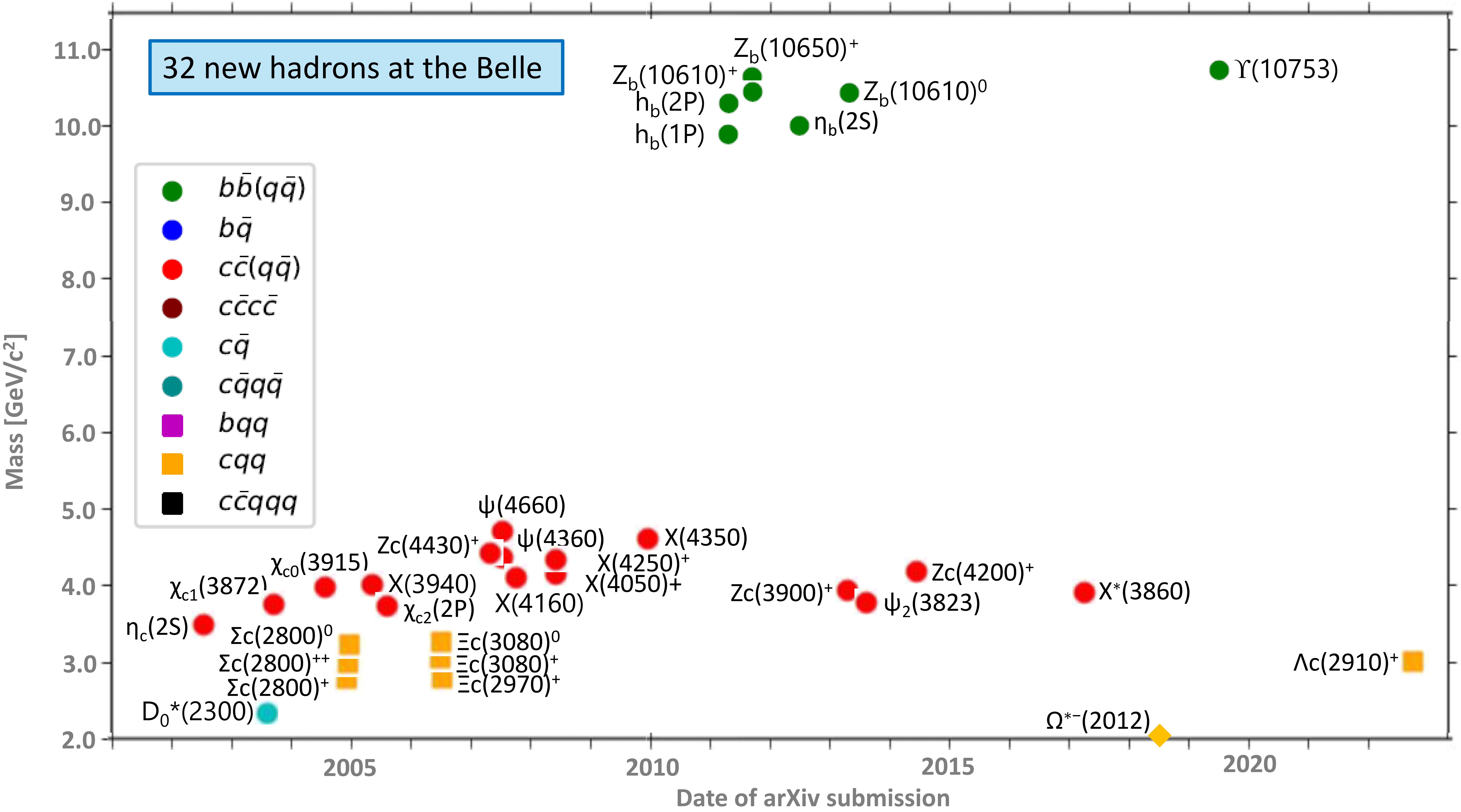
Summary and conclusions

- Continued studies of conventional and potentially exotic states at Belle and Belle II (with growing datasets)

- Much higher significance confirmation of the $\Upsilon(10753)$ by Belle II
  - No clear indication yet on its nature
  - Results in $\eta_b(1S)\omega$ consistent with S-D mixing, but not in $\chi_{bJ}(1P)\omega$
  - No enhancement in $\eta_b(1S)\omega$ as predicted by tetraquark model
  - Additional studies underway ($\pi\pi h_b(1P)$, $\eta h_b(1P)$, $\Upsilon(1S)$ inclusive, etc)

- Excellent environment for spectroscopy - not just quarkonia but hyperons too!
  - Further searches can include Ξ^* and Ω^* states
  - Spin-parity determinations
  - Collecting comprehensive details, since exotic states may be hidden

- Only 0.5% of target integrated luminosity collected so far - much more to come!



Plot credit: Alex Bondar