Heavy hadron spectroscopy studies at Belle and Belle II

COLLISIONS FROM PHI TO PSI 2026

JUNE 8 – 11, 2026

FEDERICO TESTA

ON BEHALF OF BELLE AND BELLE II

UNIVERSITÀ DI TORINO

BELLE

Belle II

INFN TORINO

Outline of the talk

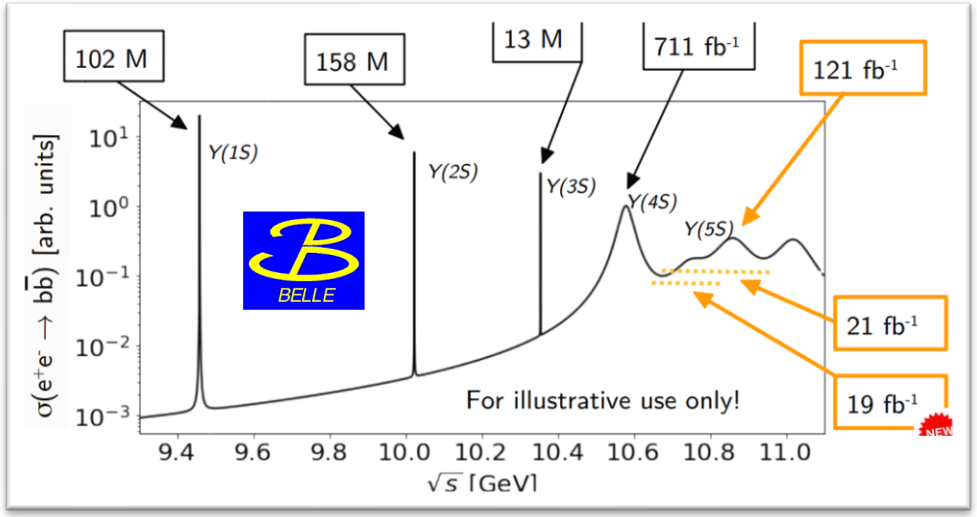
- Introduction:
  - SuperKEKB and Belle(II)
  - Heavy Hadron Spectroscopy: Quarkonium

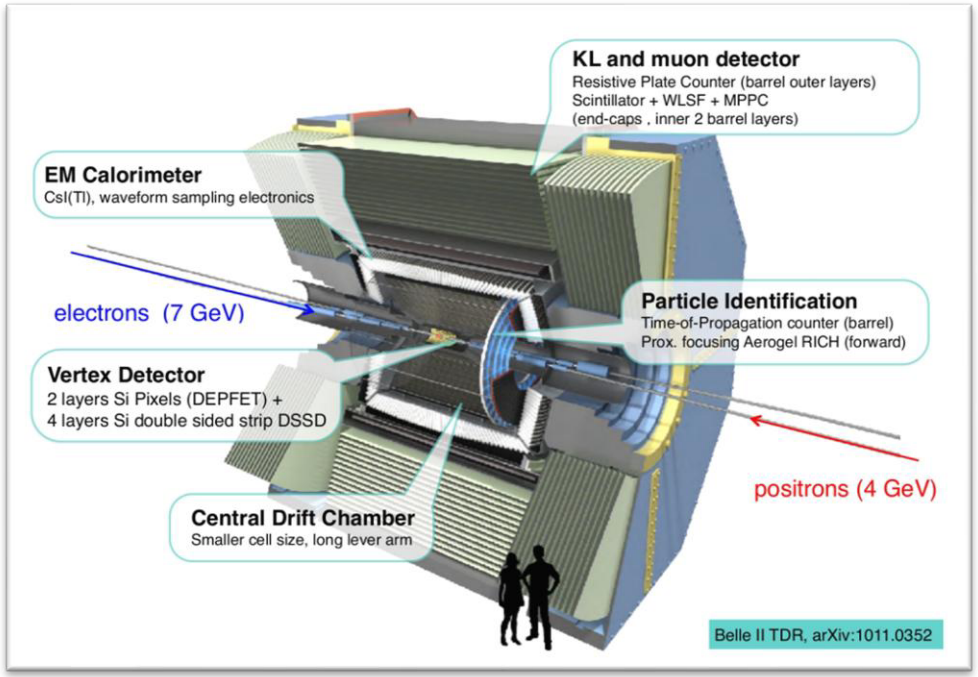
- Quarkonium at Belle and Belle II:
  - Study of $e^+e^- \to h^+h^- J/\psi\ (h = \pi, K, p)$ via ISR at Belle II; arXiv:2602:13569, accepted by PRD
  - Study of $e^+e^- \to \omega\, \chi_{bj}(1P)$ vs $(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\, \chi_{bj}(1P)$; *J. High Energ. Phys.* 2026, 101 (2026)
  - Cross section $e^+e^- \to \Upsilon(1,2S)\, \eta$ with Belle II scan; arXiv:2509.01917v2
  - Study of $e^+e^- \to \pi^+\pi^-\, \Upsilon_j(1D)$ with Belle II scan; arXiv:2602.19807
  - Search for $\Xi^0 p$, $\Omega^- p$ and $\Omega^- n$ dibaryons in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays at Belle; arXiv:2605.29778

SuperKEKB and Belle(II) experiments

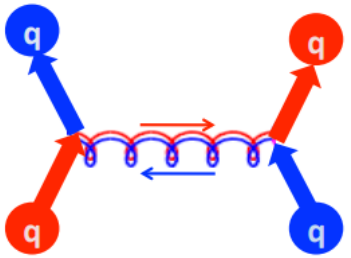
- SuperKEKB: asymmetric collider located in Tsukuba(JP)
  - NEW! Record of highest instantaneous luminosity 5.28 x 10^{34} ($cm^{-2}s^{-1}$)
  - Collision energy around $\Upsilon(4S)$ mass: $\sqrt{s}$ ~10.58 GeV
  - Copious production of B-mesons, charmed mesons and tau pair
  - Can perform energy scan to explore different regions

- Belle(II):
  - "Hermetic" experiment
  - Excellent vertex reconstruction, tracking and PID
  - Neutral reconstruction with ECL and KLM detector

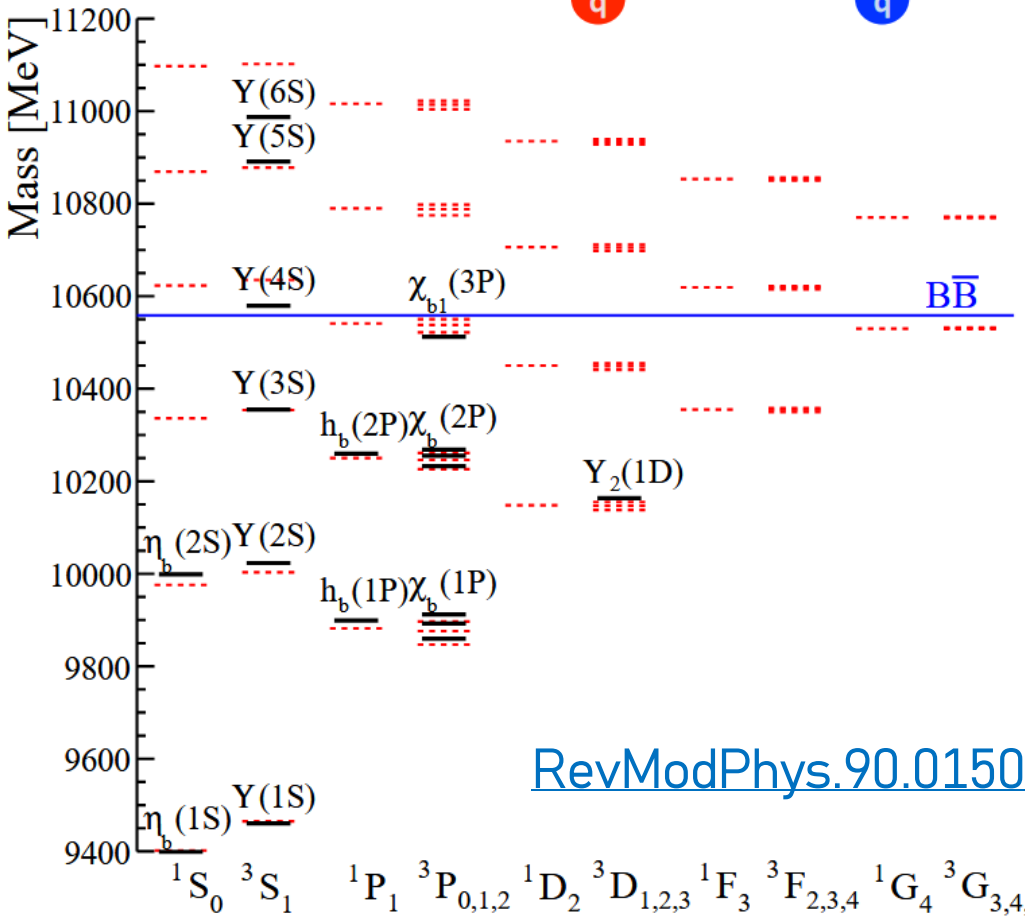




Heavy Hadron Spectroscopy: Quarkonium



- Quarkonium is the bound state of a heavy quark and antiquark ($Q\overline{Q}$)
- Ideal playground to test QCD at low energy between the perturbative and non perturbative regions: static potential model, NRQCD, lattice QCD…
- Starting from the $X(3872)$, many exotic states have been discovered, which require a different description from simple $Q\overline{Q}$ pair model
- In the heavy sector we can distinguish between exotic and conventional states by looking at their products from strong decay: low statistics and many thoretical models make these studies not so straightforward!



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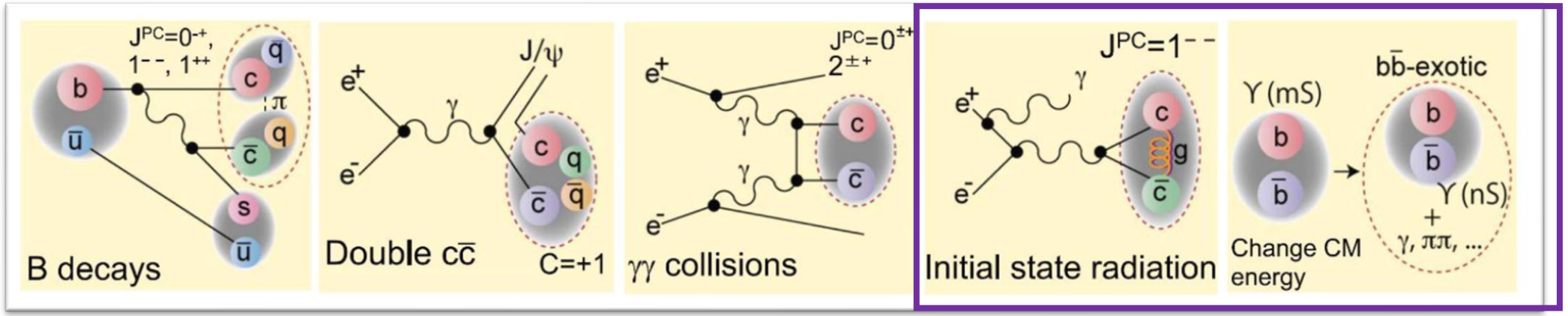
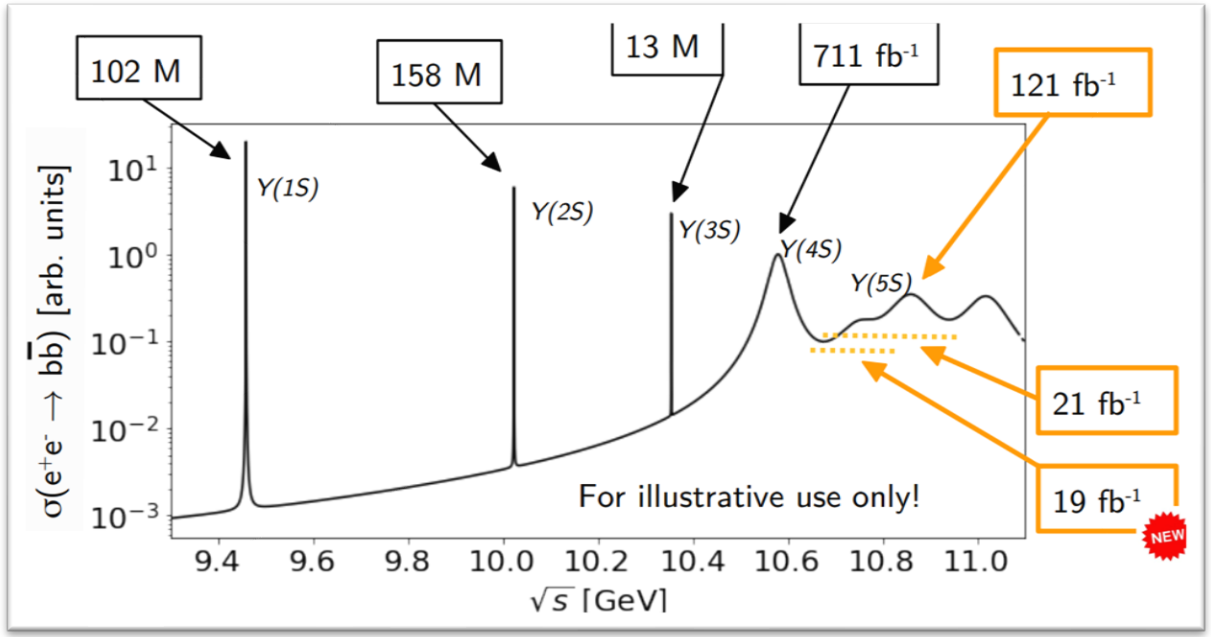
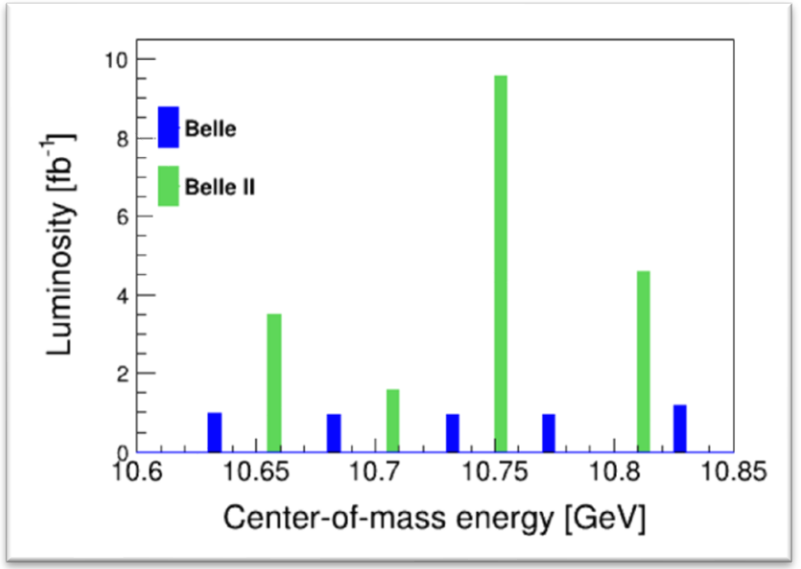
Quarkonium at Belle(II): production and dataset





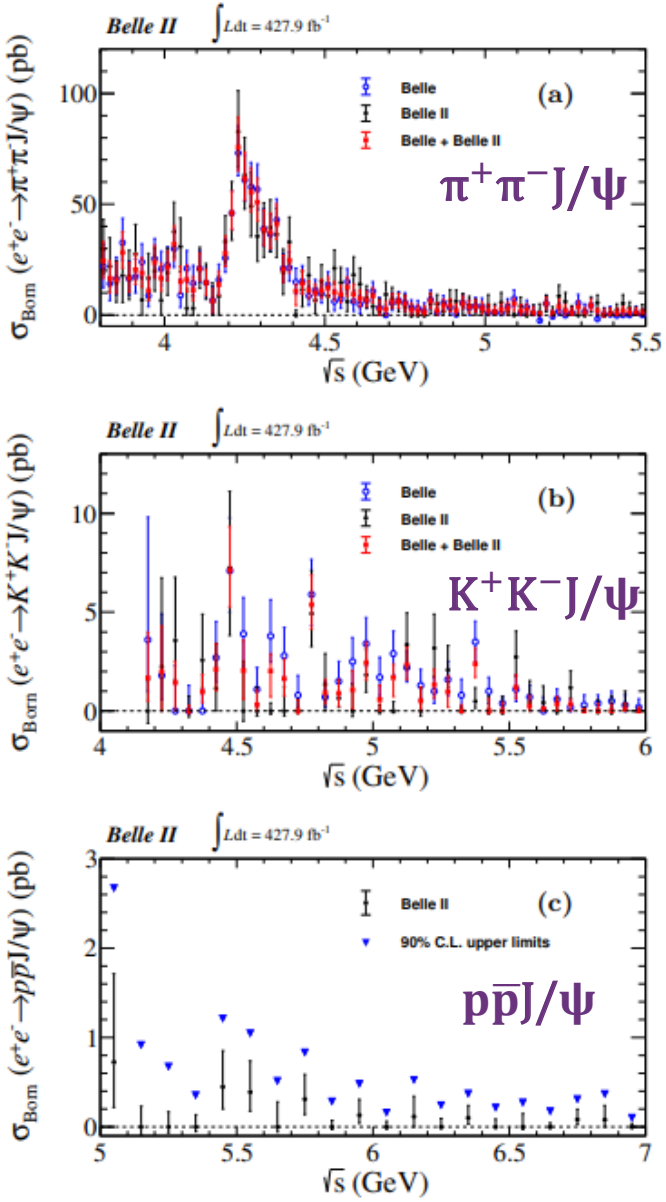


Study of $e^+e^- \to h^+h^- J/\psi$ ($h = \pi, K, p$) via ISR at Belle II

arXiv:2602:13569, accepted by PRD

Measure the cross section of $e^+e^- \to h^+h^- J/\psi$ ($h = \pi, K, p$) with the 427.9 fb^{-1} collected by Belle II

- The first initial-state radiation (ISR) study at Belle II
- Consistent results with previous measurements in $\pi^+\pi^- J/\psi$ and $K^+K^- J/\psi$
  - Excess in $\pi^+\pi^- J/\psi$ at 4.26 GeV/c compatible with the $Y(4230/4320)$ states observed by BABAR [1] and Belle [2]
- Useful input for global fits on the hidden charm cross sections
- First search in $p\bar{p}J/\psi$ channel with two baryons in the final states

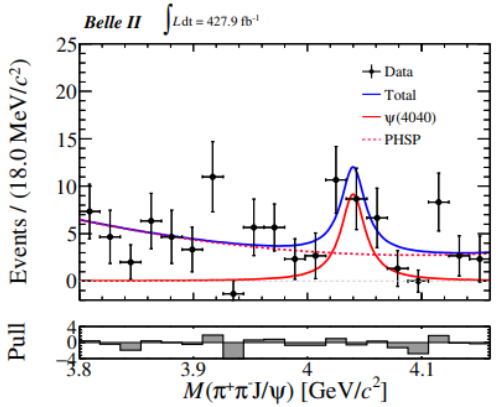


Study of $e^+e^- \to h^+h^- J/\psi$ ($h = \pi, K, p$) via ISR at Belle II

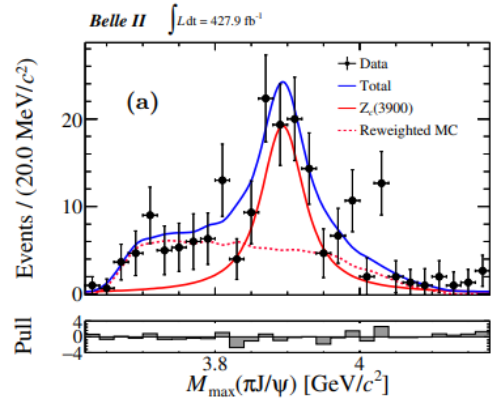
arXiv:2602:13569, accepted by PRD

Search for vector charmonium-like states in the $h^+h^- J/\psi$ systems, and for associated intermediate states in the $h^\pm J/\psi$ systems:

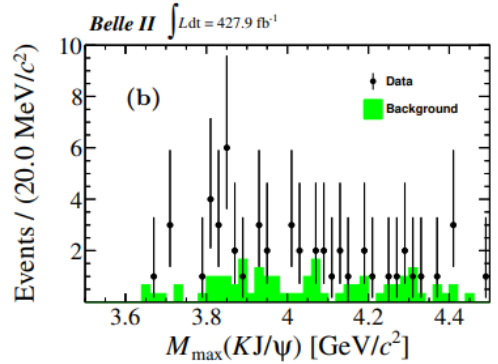
- A small excess near 4.1 GeV with a statistical significance of 2.0σ is found in $\pi^+\pi^- J/\psi$, may suggests the predicted $\psi(4040)$-like enhancement from the global coupled-channel analysis [3]
- A clear signal with a significance of 5.3σ for the $T_{c\bar{c}}(3900)^\pm$ in $\pi^\pm J/\psi$ is confirmed with (slightly) higher significance than Belle [4] (despite the lower statistic!)
- No obvious structure is found in other channels



$\pi^+\pi^- J/\psi$



$\pi^\pm J/\psi$



$K^+K^- J/\psi$

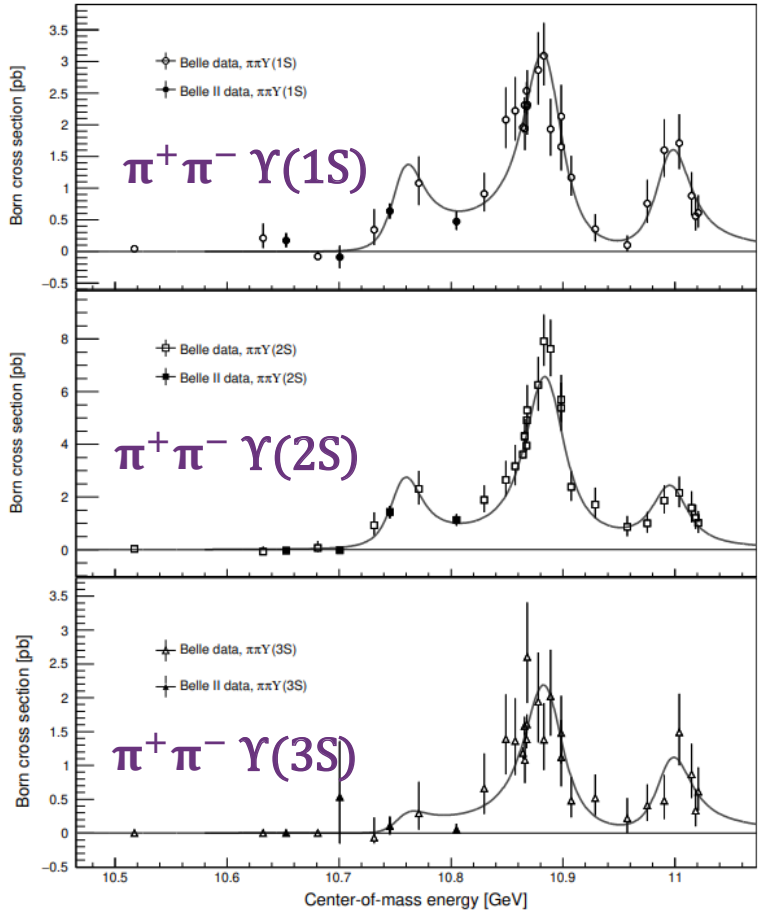
Exploring the $\Upsilon(10753)$

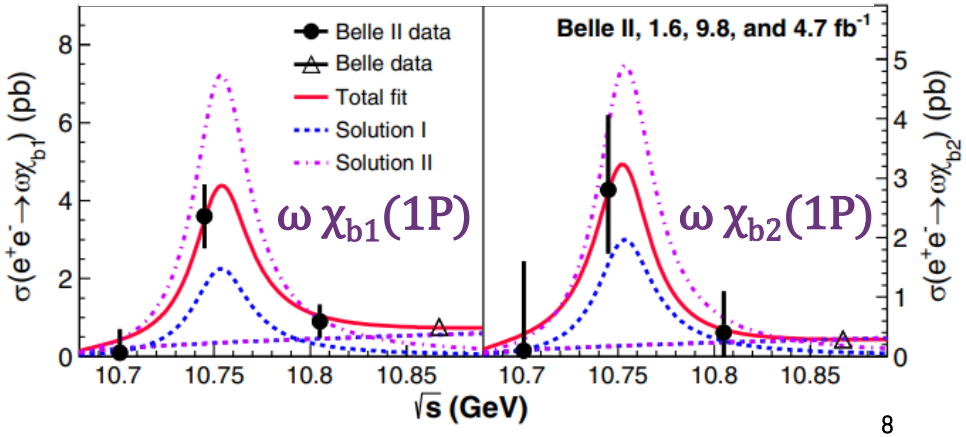
Discovered by Belle in $e^+e^- \to \pi^+\pi^- \Upsilon(1,2,3S)$ cross section:
Conventional bottomonium? Hybrid, tetraquark?

Larger statistics collected by Belle II to better understand the nature of the resonance:

- $e^+e^- \to \pi^+\pi^- \Upsilon(1,2,3S)$ JHEP 07, (2024)116
  - Confirmation of the resonance with higher significance

- $e^+e^- \to \omega\, \chi_{bj}(1P)$ PRL 130, 091902 (2023)
  - Similar process to $\Upsilon(4260) \to \omega\, \chi_{c0}(1P)$
  - Confirmation of the resonance in a different channel!
  - Can compare the results with a 4S-3D interpretation

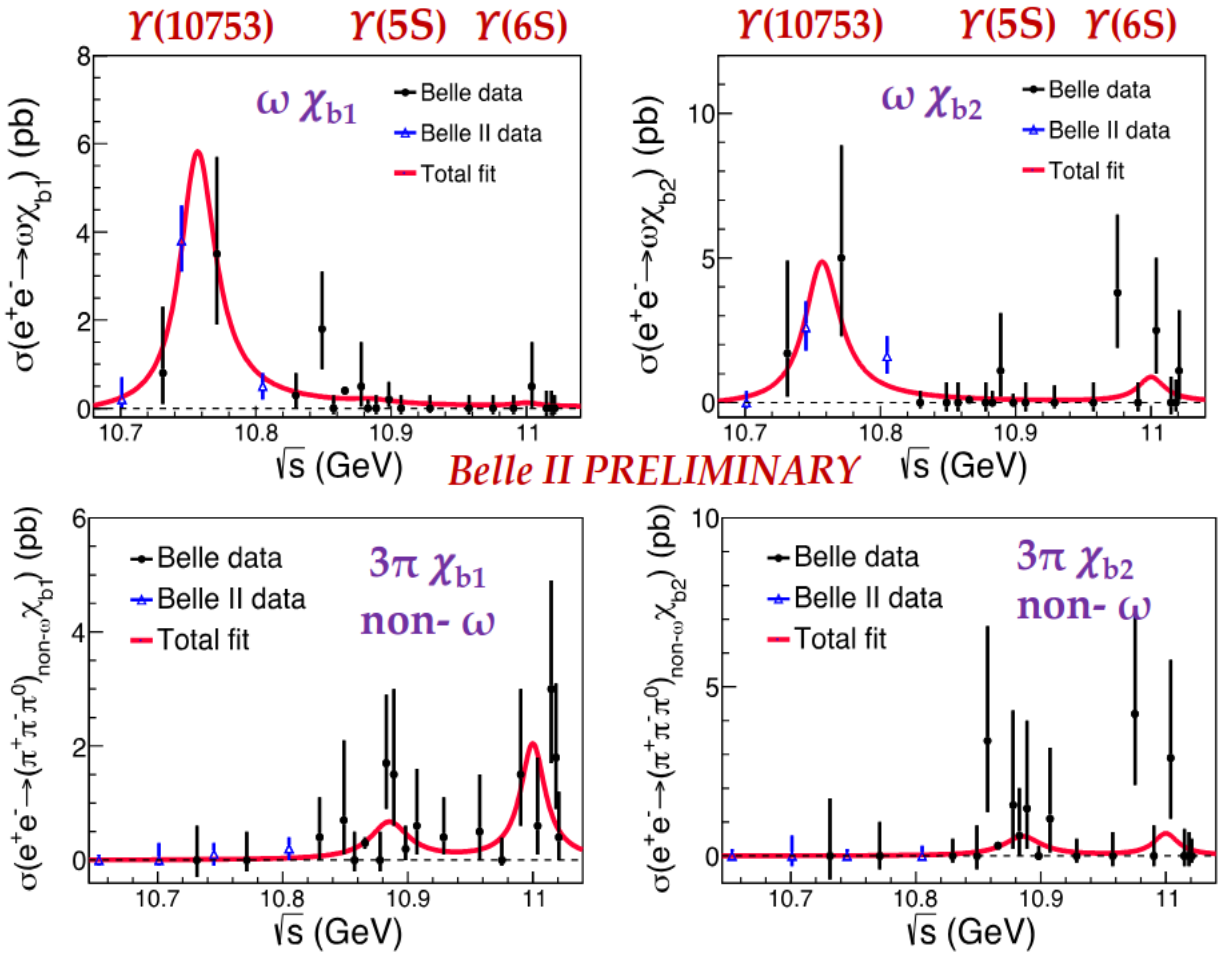




Study of $e^+e^- \to \omega\, \chi_{bj}(1P)$ vs $(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\, \chi_{bj}(1P)$

J. High Energ. Phys. 2026, 101 (2026)

- Belle II measured the $e^+e^- \to \omega\, \chi_{bj}(1P)$ cross section around the $\Upsilon(10753)$ finding some interesting results:
  - $\sigma(\omega\chi_{b1})/\sigma(\omega\chi_{b2})$ = 1.3 ± 0.6: 1.8σ with 4S-3D hypothesis from PRD 104 034036 (2021)
  - $\pi\pi\Upsilon(2S)/\omega\chi_{b2}$ cross section ratio at the $\Upsilon(10753)$ is around 0.9, which is around 30 times smaller than that at the $\Upsilon(5S)$
- Joint analysis with Belle dataset:
  - compare non resonant three pion production with $\Upsilon(5S)$ and $\Upsilon(6S)$
  - Different resonances display different preferences



Υ(10753)'s structure is significantly different from $\Upsilon(5/6S)$!

Observation of $e^+e^- \to \Upsilon(1,2S)\eta$ with Belle II scan

arXiv:2509.01917v2

Belle II

19.6 fb^{-1}

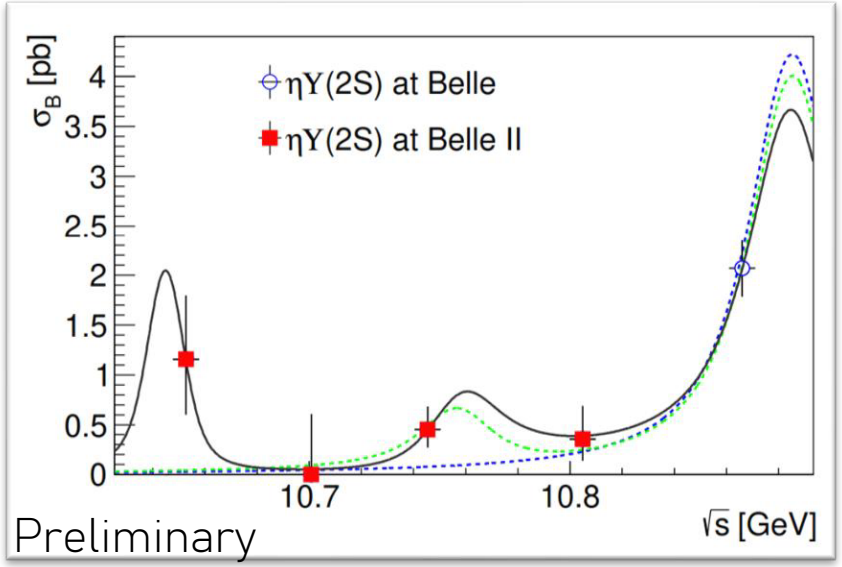
- Relative large branching fractions given the possibility of a 4S-3D mixing
- Look for the bottomium counterpart of the $\psi(4040) \to \eta J/\psi$ observed by Belle [5] close to the $D^*\bar{D}^*$ threshold)

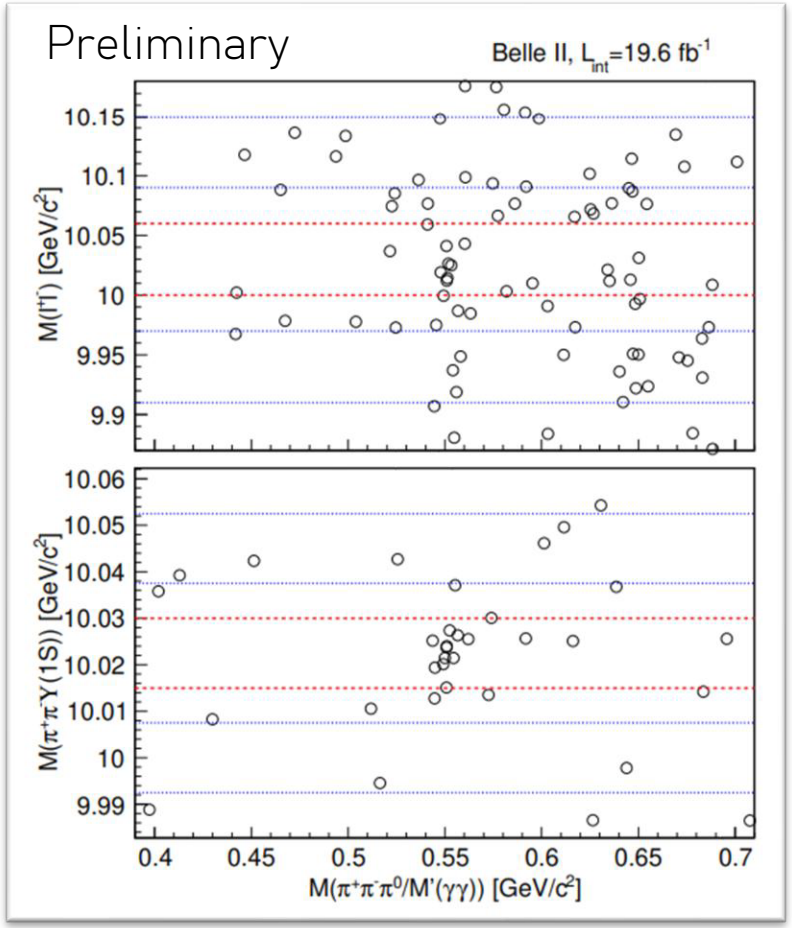
- Reconstruct full decay chain down to $\Upsilon(1S)$ or $\Upsilon(2S)$
  - Reconstruct $\eta \to \pi^+\pi^-\pi^0, \gamma\gamma$; 2D fit to M(η) and M($\Upsilon(1,2S)$)

- No sign of $\Upsilon(1S)$, evidence of $\Upsilon(2S)$

Hypothesis of signal due to tail from $\Upsilon(5S)$ or $\Upsilon(10753)$ is disfavored (3.5σ), with respect to a three-resonance model.

New state around 10.65 GeV/c²?
Need more data in the region!





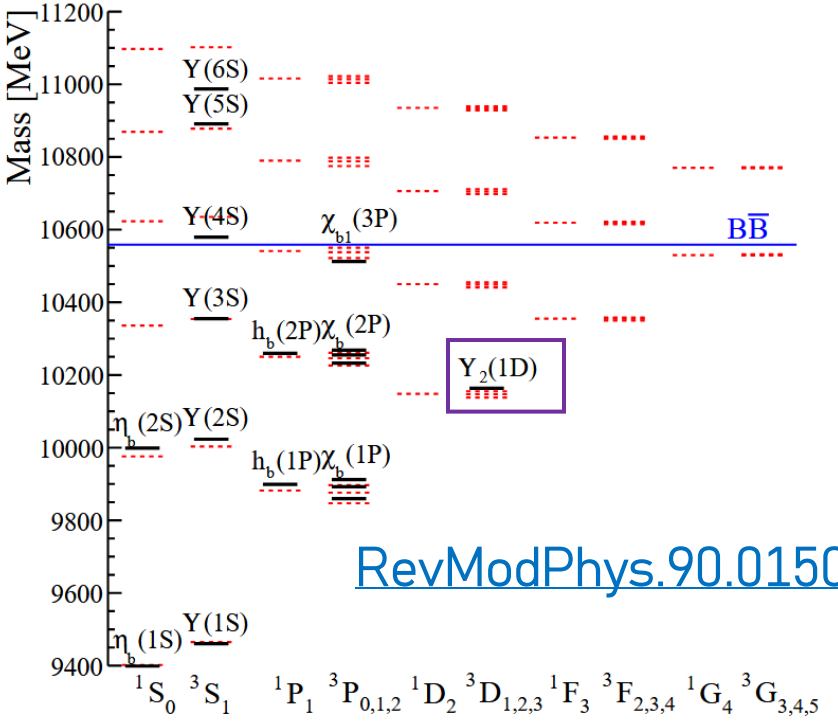
D wave states in bottomonium

- While being predicted by the potential model, D-wave states (L = 2) in the bottomonium spectrum are much less known with respect to the S and P wave (L = 0,1)

- The CLEO collaboration reported the first observation of $\Upsilon_j(1D)$ in the radiative decay $\Upsilon(3S) \to \gamma\gamma\, \Upsilon_j(1D)$ [6], favoring a J = 2 assignment, confirmed by BaBar [7]
- Low significance excess found by Belle in the $\Upsilon(5S) \to \pi^+\pi^-\, \Upsilon_j(1D)$ in $\Upsilon(5S) \to \pi^+\pi^-\, X$ [8]

- Exploring the $\Upsilon_j(1D)$ states in decays from other resonances could give insights on the production mechanism and transitions in the bottomonium spectrum:

Use Belle II scan to search for $e^+e^- \to \pi^+\pi^-\, \Upsilon_j(1D)$ at the Υ(10753)



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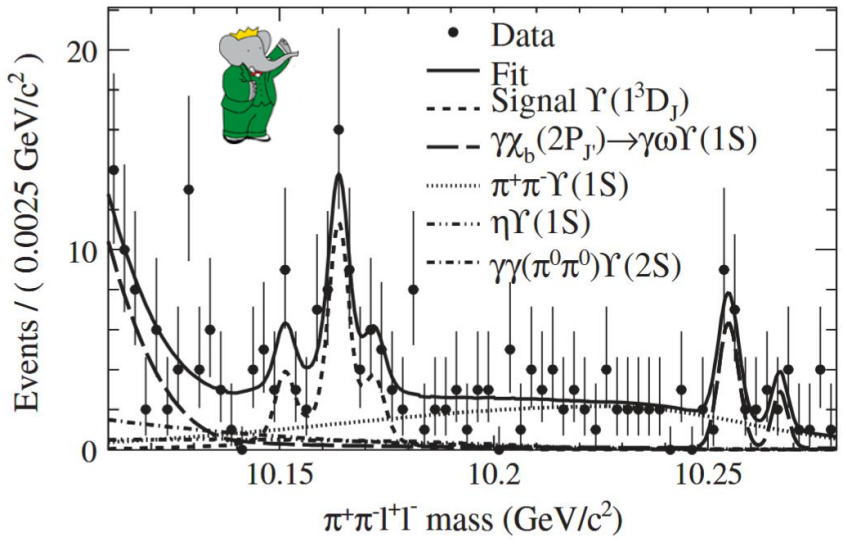
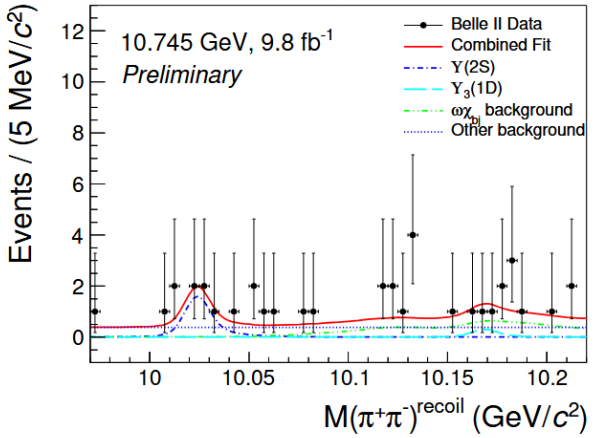


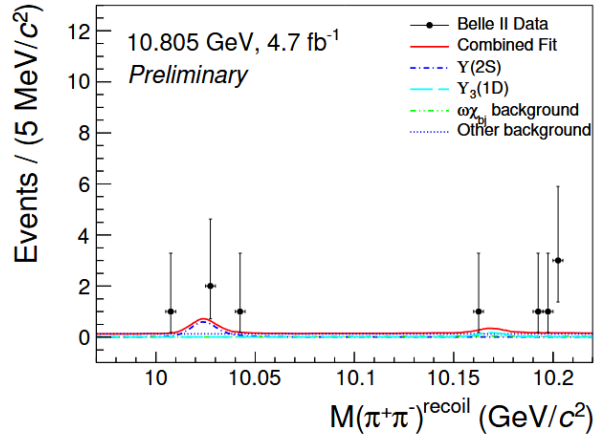
Phys. Rev. D 82 (2010)

Study of $e^+e^- \to \pi^+\pi^- \Upsilon_j(1D)$ at Belle II arXiv:2602.19807

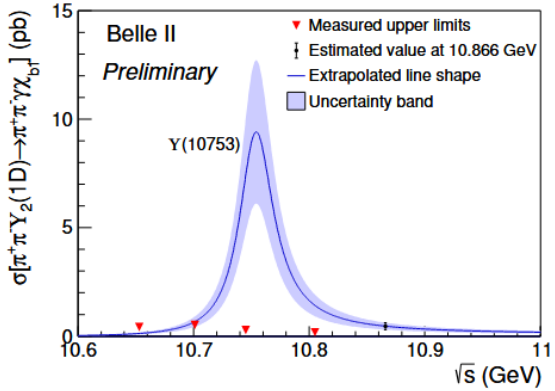
Belle II
19.6 fb^{-1}

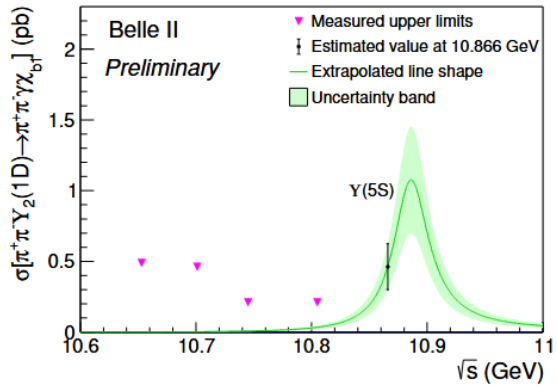
- Study the $e^+e^- \to \pi^+\pi^- \Upsilon_j(1D)$ cross section with the 19.6 fb^{-1} collected by Belle II around the $\Upsilon(10753)$
- To maximise sensitivity, we focus on the modes:
  - $e^+e^- \to \pi^+\pi^- \Upsilon_2(1D)\ [\to \gamma\chi_{b1}]$
  - $e^+e^- \to \pi^+\pi^- \Upsilon_3(1D)\ [\to \gamma\chi_{b2}]$
- Retrieve signal with a fit on the recoil mass of the di-pion:
  - Account for $e^+e^- \to \pi^+\pi^- \Upsilon(2S)$ and $e^+e^- \to \omega\, \chi_{bj}(1P)$ contributions
- No signal is observed → UL at 90% CL: compatible with the cross section extrapolated from the Belle analysis of $\Upsilon(5S) \to \pi^+\pi^- X$





$$M(\pi^+\pi^-)^{\text{recoil}} \equiv \sqrt{(P_{e^+e^-} - P_{\pi^+} - P_{\pi^-})^2}$$





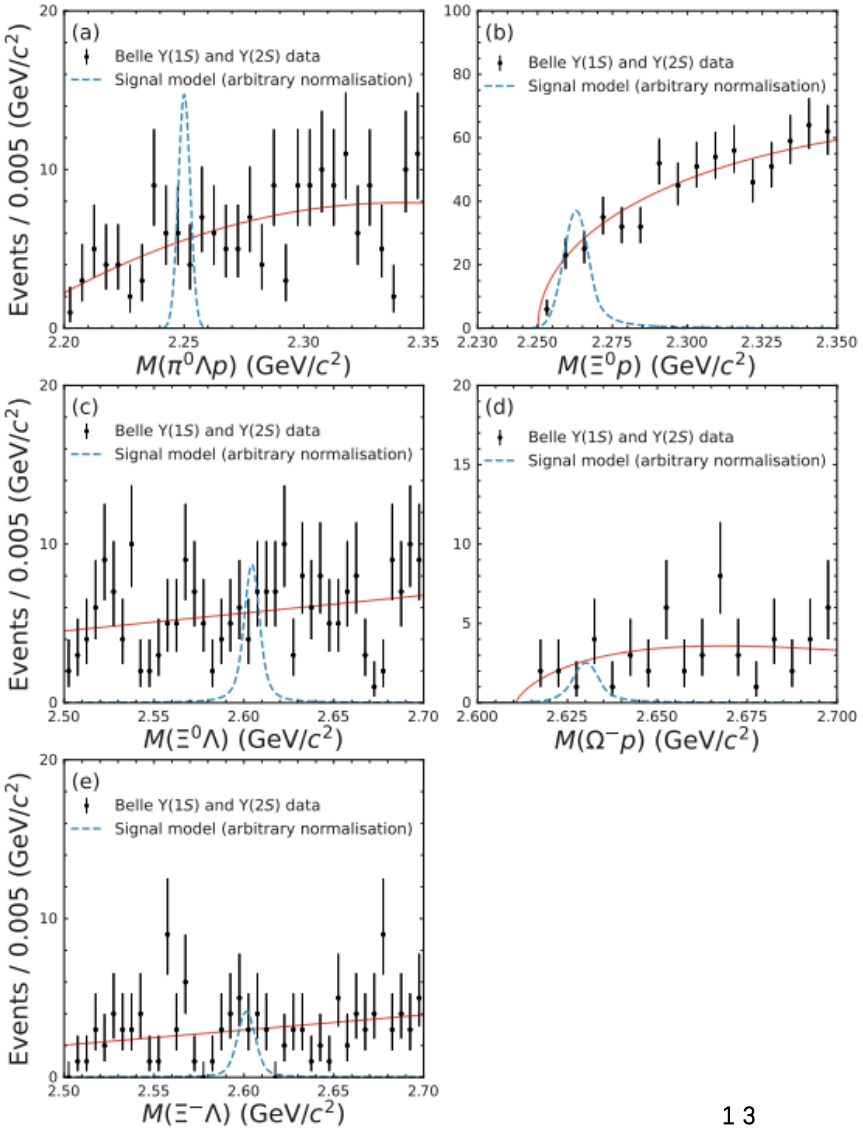
Search for Ξ^0p, Ω^-p and Ω^-n dibaryons in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays at Belle

arXiv:2605.29778

- Multi-strange baryon-baryon interactions remain largely unconstrained
- Indications of attractive ΞN and ΩN interactions motivate searches for weakly bound states

- Look or $\Upsilon(S) \to \Xi^0$p, Ω^-p and Ω^-n using samples of 102M $\Upsilon(1S)$ and 158M $\Upsilon(1S)$ collected by Belle
- Reconstruct the dibaryons with different topologies for the bound/unbound state hypothesis

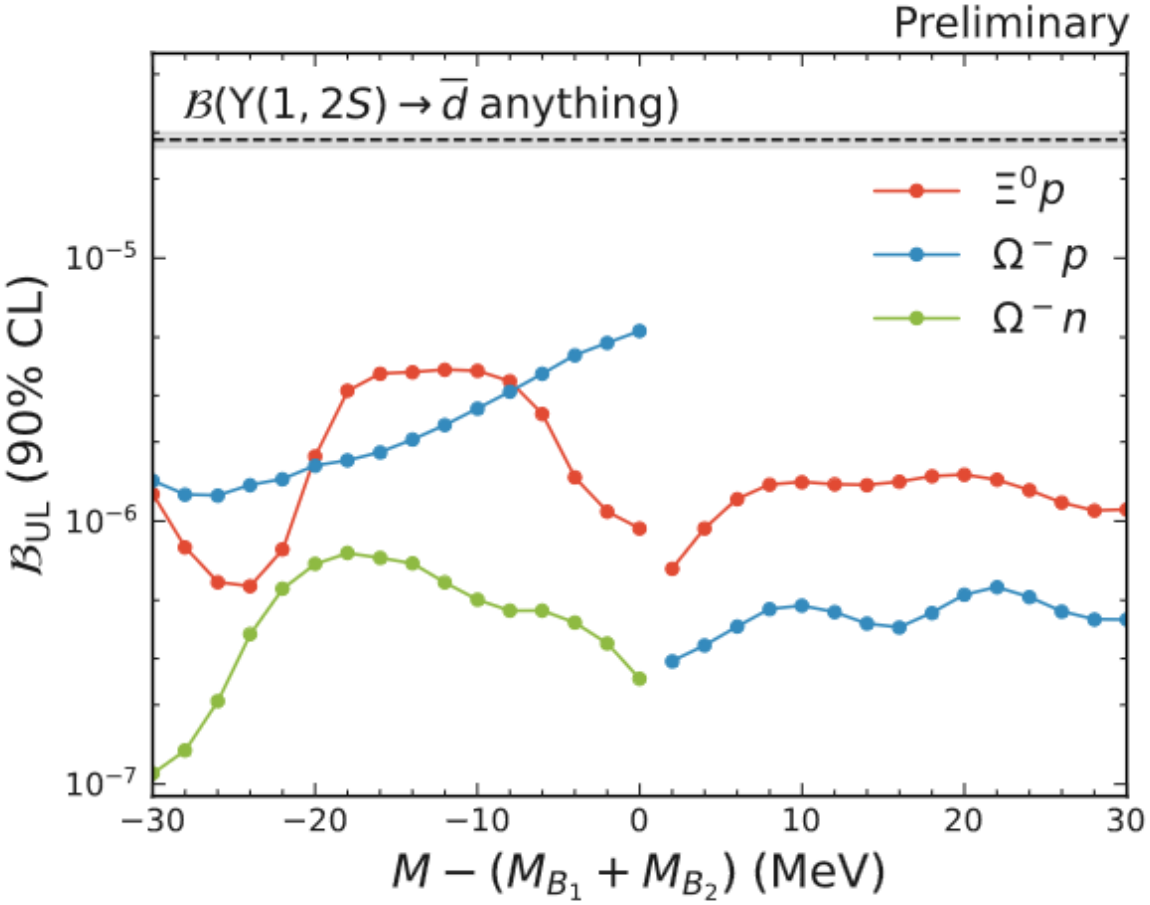
	Hypothesis	**Topologies**
$\Xi^0 p$	Bound	$\pi^0 \Lambda p$
$\Xi^0 p$	Unbound	$\Xi^0 p$
$\Omega^- p$	Bound	$\Xi^0 \Lambda$
$\Omega^- p$	Unbound	$\Omega^- p$
$\Omega^- n$	Unbound	$\Xi^- \Lambda$



Search for $\Xi^0 p$, $\Omega^- p$ and $\Omega^- n$ dibaryons in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays at Belle

arXiv:2605.29778

- Compute 90% UL on the BR scanning the binding energy from -30 to 30 MeV
- New experimental constraints on the formation of multi-strange dibaryons in gluon-rich bottomonium decays.
- Complement existing searches in hadronic, nuclear, and heavy ion environments.



Summary

- Study of $e^+e^- \to h^+h^- J/\psi\ (h = \pi, K, p)$ via ISR at Belle II; arXiv:2602:13569
  - First ISR study in Belle II, 5.3σ observation of $T_{c\bar{c}}(3900)^{\pm}$ in $\pi^{\pm}J/\psi$, 2.0σ enhancement in $\pi^+\pi^-J/\psi$ compatible with $\psi(4040)$

- Study of $e^+e^- \to \omega\, \chi_{bj}(1P)$ vs $(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\, \chi_{bj}(1P)$; *J. High Energ. Phys.* 2026, 101 (2026)
  - $\Upsilon(10753) \to \pi^+\pi^-\pi^0\, \chi_{bj}(1P)$ decay proceeds only through the resonant- ω channel, confirming a different internal structure from the $\Upsilon(5S)$ and $\Upsilon(6S)$

- Cross section $e^+e^- \to \Upsilon(1,2S)\, \eta$ with Belle II scan; arXiv:2509.01917v2
  - Three-resonance model well describes the data, hinting towards a resonant state at the $B^*\bar{B}^*$ threshold

- Study of $e^+e^- \to \pi^+\pi^- \Upsilon_j(1D)$ with Belle II scan; arXiv:2602.19807
  - No signal is observed, upper limits consistent with the extrapolated cross section for $\Upsilon(5S) \to \pi^+\pi^- \Upsilon_j(1D)$

- Search for $\Xi^0 p$, $\Omega^- p$ and $\Omega^- n$ dibaryons in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays at Belle; arXiv:2605.29778
  - New experimental constraints on the formation of multi-strange dibaryons in bottomonium decays.

Thanks for your attention!

Backup

Heavy hadron spectroscopy: not just quarkonium

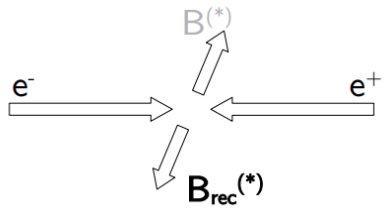
Measurement of the mass difference $m(B^0) - m(B^+)$ and energy dependence of the cross-section ratio $\sigma(e^+e^- \to B^0\overline{B}^0)/\sigma(e^+e^- \to B^+B^-)$ by Belle and Belle II

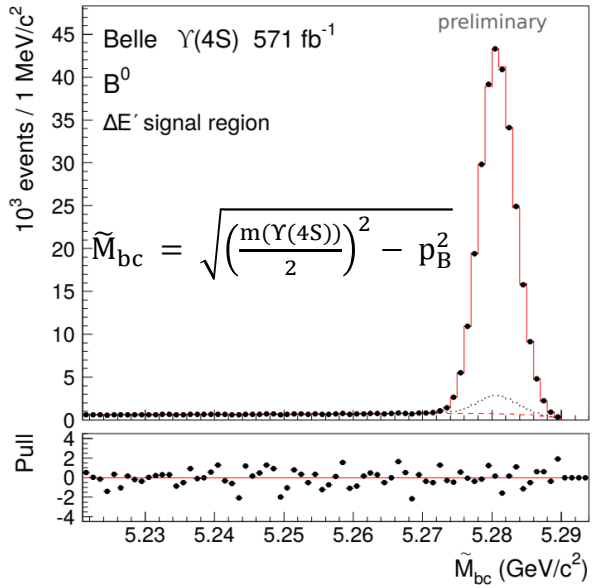
Belle	Belle II
572 fb^{-1}	365 fb^{-1}

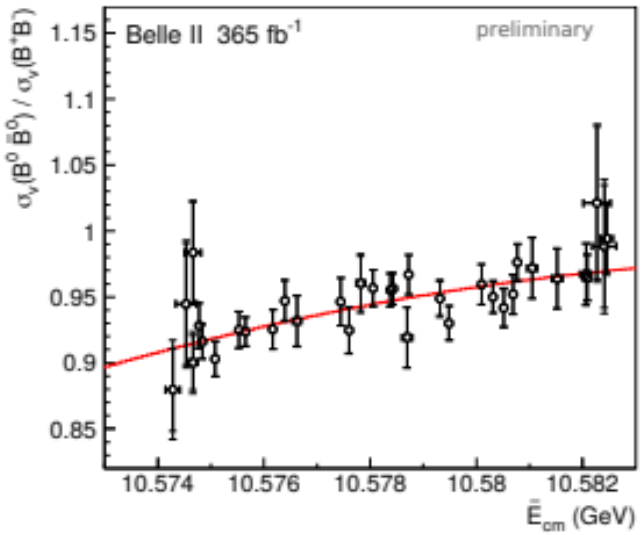
Measurement of the mass difference $m(B^0) - m(B^+)$ and energy dependence of the cross-section ratio $R = \sigma(e^+e^- \to B^0\bar{B}^0)/\sigma(e^+e^- \to B^+B^-)$ by Belle + Belle II

arXiv:2511.15926v1

- $\Delta M = (m(B^0) - m(B^+))$: isospin-violating effect due to mass difference between u and d quarks and electromagnetic interaction between the b quark and light quarks
- Combined Belle (571fb^{-1}) + Belle II (365 fb^{-1}) data samples
- Key component of the analysis is the fit function on $\widetilde{M}_{bc}$
- Fit function takes into account e^+e^- energy spread, ISR, energy dependence of $B^0\bar{B}^0$ or B^+B^- cross sections, and momentum resolution.
- Measure R(E_{cm}) using variation of E_{cm} and then include the result into the combined fit.







Combined fit to extract ΔM arXiv:2511.15926v1

Belle	Belle II
983 fb^{-1}	428 fb^{-1}

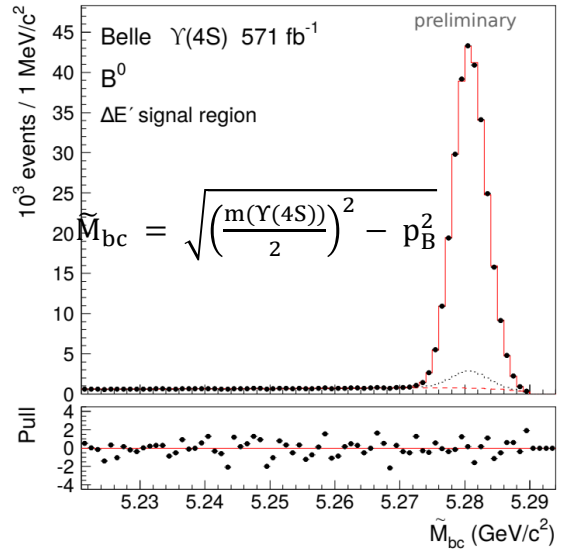
- Key component of the analysis is the fit function on M_{bc}
- Fit function takes into account e+ e− energy spread, ISR, energy dependence of $\mathbf{B^0\bar{B}^0}$ or $\mathbf{B^+B^-}$ cross sections, momentum resolution.
- Measure R(E_{cm}) using variation of Ecm and then include the result into the combined fit.

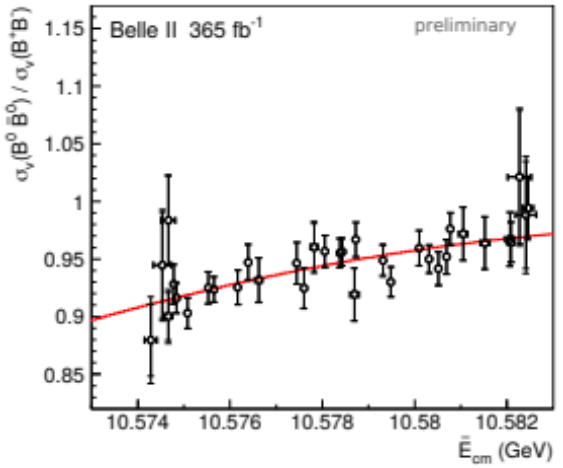
1 2

$$[\sum_i w_i\, G(E_{\rm cm};\ E_{\rm cm0} + \Delta E^{(i)}_{\rm cm},\ \sigma_{E_{\rm cm}})] \otimes f_{\rm ISR} \times \sigma(e^+e^- \to B^+B^-)$$

3 4

$$\longmapsto f(p_{B^+}),\ \otimes f_{\rm resolution} \longmapsto f(\tilde{M}_{\rm bc}),$$



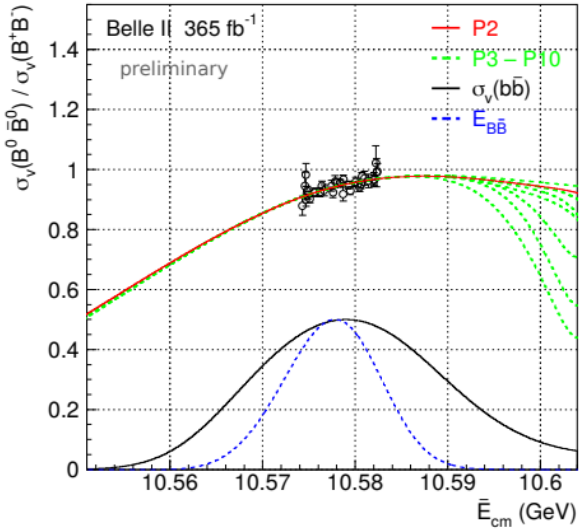


1. Invariant mass distribution of the virtual photon produced in the e^+e^- annihilation
2. Distribution of the B-meson pair energy
3. Change variable to B^+ momentum, taking into account non linear effect close to the kinematic boundary (p_B = 0)
4. Change to the M_{bc} variables

Belle	Belle II
572 fb^{-1}	365 fb^{-1}

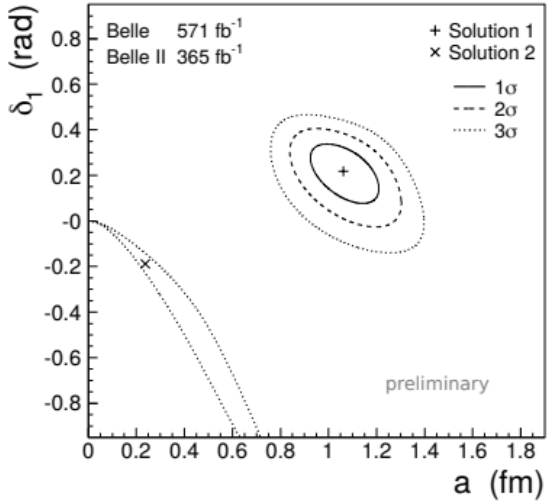
Results and phenomenological analysis arXiv:2511.15926v1

- $\Delta M = 0.495 \pm 0.024 \pm 0.005$ MeV:
  - Twice more precise than BABAR: $\Delta M = 0.33 \pm 0.05 \pm 0.03$ MeV
  - 3σ away from BABAR: discrepancy understood
    - PHSP excluded at 10σ



- Combined fit sensitive to $R(E_{cm})$ on a wider energy range

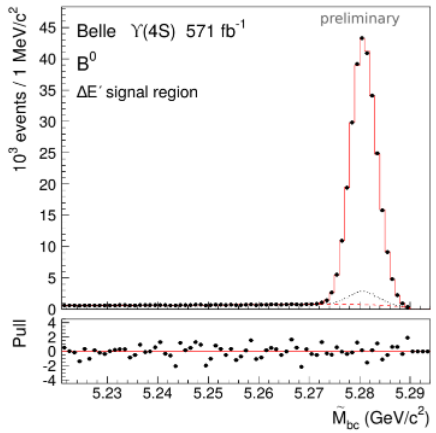
- Phenomenological analysis on $R(E_{cm})$ to describe the isovector potential with two parameters:
  - a = radius of the interaction region
  - δ^1 = scattering phase in the isovector $B\overline{B}$ channel



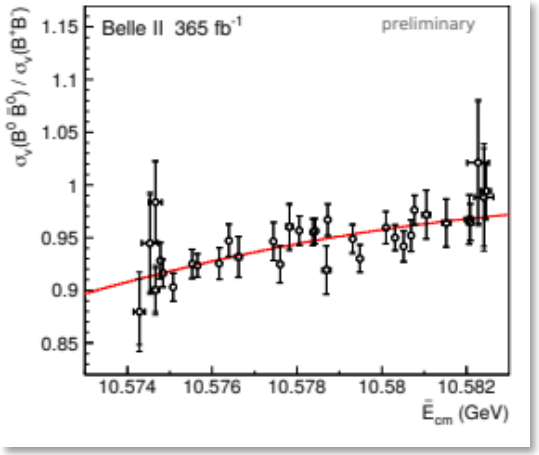
- Result suggests attractive potential (2σ)

Combined fit to extract ΔM

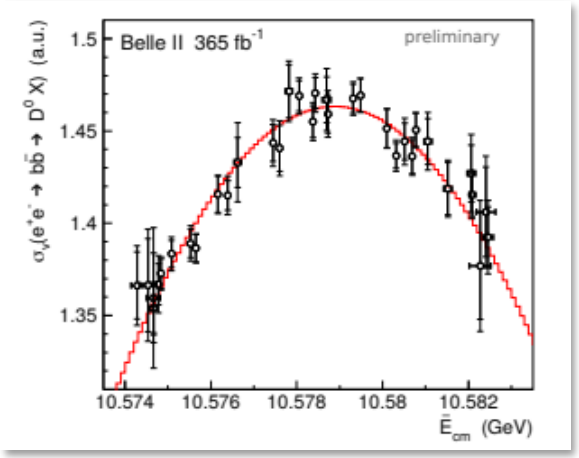
$$\tilde{M}_{bc} = \sqrt{\left(\frac{m(\Upsilon(4S))}{2}\right)^2 - p_B^2}$$



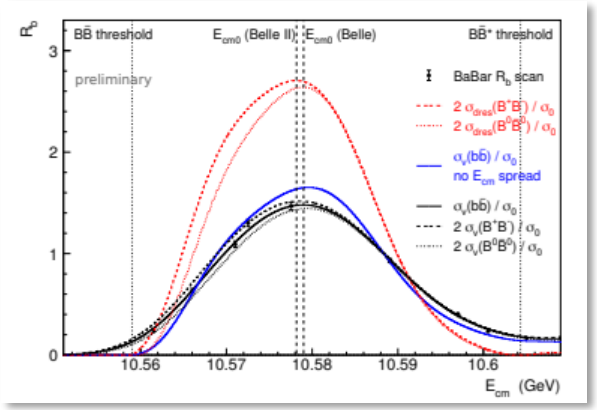
$$\frac{\sigma(B^0\bar{B}^0)}{\sigma(B^+B^-)}$$



$$\sigma_v(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0X)$$



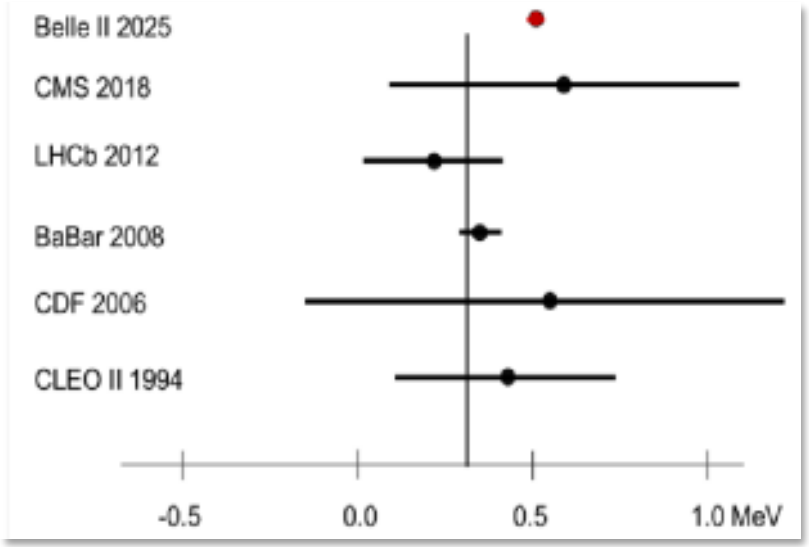
$$R_b = \frac{\sigma_v(e^+e^- \to b\bar{b})}{\sigma_0}$$



Belle(II):
$\Delta M = 0.495 \pm 0.024 \pm 0.005$ MeV
PHSP excluded at 10

Twice more precise than BaBar
Discrepancy understood

Paper accepted by JHEP



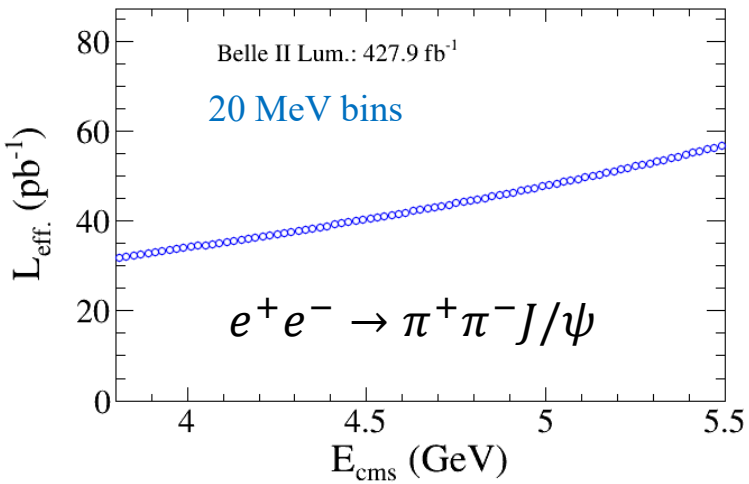
Study of $e^+e^- \to h^+h^- J/\psi$ $(h = \pi, K, p)$ via initial-state radiation at Belle II

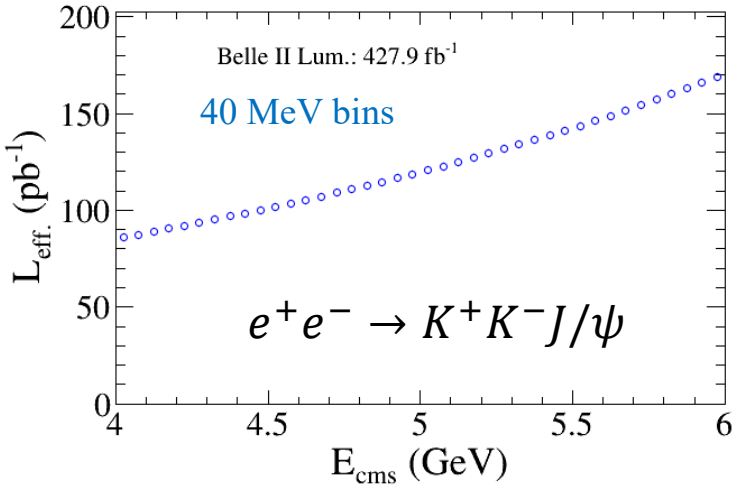
- The Born cross section at each energy bin is calculated by

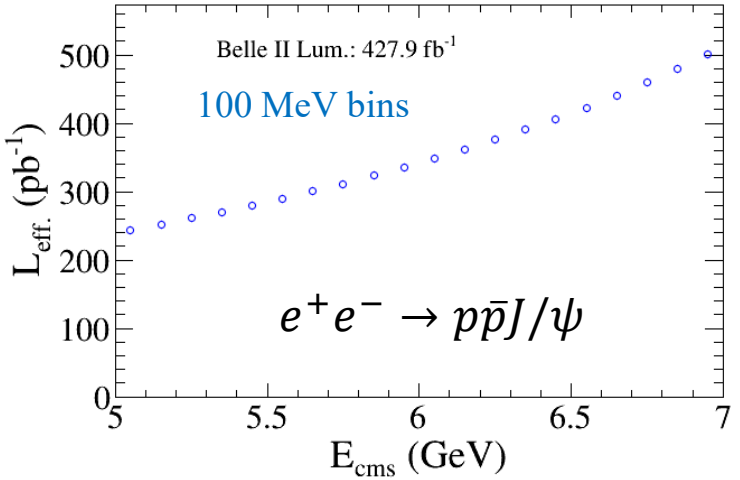
$$\sigma_i = \frac{N_i^{sig}}{\mathcal{L}_i \cdot \varepsilon \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

- The effective ISR luminosity ($\mathcal{L}_i$) obtained from the QED calculation

Sov. J. Nucl. Phys ***41****, 466 (1985)*
CPC ***44****, 083001 (2022)*







Can be used to estimate the ISR luminosity of Belle II with 50 ab-1;

Study of $e^+e^- \to h^+h^- J/\psi$ $(h = \pi, K, p)$ via initial-state radiation at Belle II

*PRD **86**, 051102 (2012)*
*PRL **110**, 252002 (2013)*
*PRD **89**, 072015 (2014)*
*PRD **106**, 072001 (2022)*
*CPC **46**, 111002 (2022)*
*PRL **131**, 211902 (2023)*

- Comparison among other experiments
- Good consistency between our results and previous measurements