# Status of Exotic Hadron Studies at SuperKEKB/Belle II

KMI 2026

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November 10, 2026

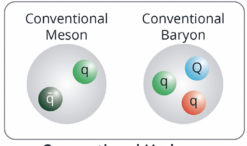
# Introduction

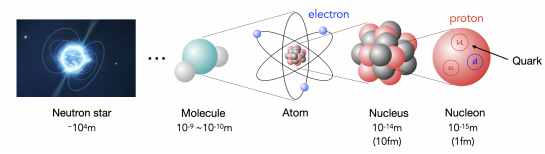
**Hierarchical structure of matter**

- $q$ and $g$ are confined and cannot be observed as isolated particles.
- Nucleons are the most common hadrons
- QCD plays a key role in matter, from the microscopic to the macroscopic scale.

**What is hadon?**

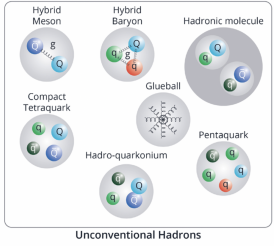
- Composite subatomic particle; Made up with $qqq$ (baryon) or $q\bar{q}$ (meson).
- Confinement $\rightarrow$ color singlet




**What are Exotic hadrons?**

- Beyond $qqq$ or $q\bar{q}$ configurations.




[NUPECC, LRP 2024]

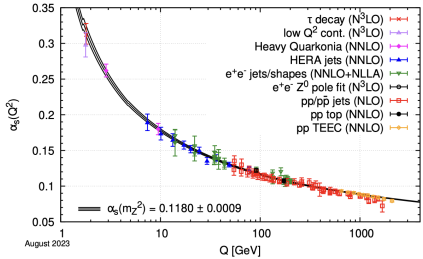
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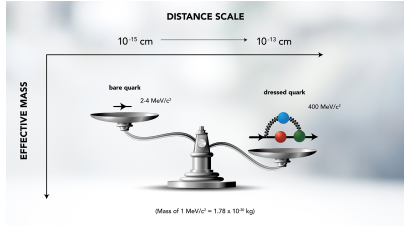
**QCD in a Nutshell**

- Fundamental theory of the strong interaction.
- Describes interactions between quarks and gluons.
- QCD Lagrangian is written, but solving QCD is challenging.
- Non-perturbative QCD is essential for understanding hadron physics.

**What is non-perturbative aspect of QCD?**

- Color confinement and the emergence of hadron masses.
- **Rich variety of hadrons (hundreds of states!)**




[PDG2024, Jefferson Lab illustration/Shannon West]

# Introduction

**Why Heavy Quarks?**

- $m_Q \gg \Lambda_{\mathrm{QCD}} \sim 200$ MeV.
- Heavy quarkonia can be treated non-relativistically.
- Their spectra are well described by potential models.

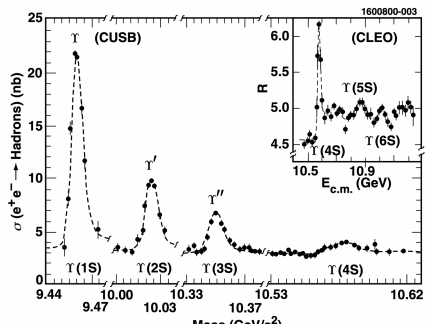
**What is Bottomonium?**

- A bound state of a bottom quark and an antibottom quark ($b\bar{b}$).
- Examples: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$.

**Why Bottomonium?**

- Non-relativistic approximation works better than for charmonium.
- Predictions from Born–Oppenheimer EFT can be tested experimentally.
- Less explored than charmonium (see following slide).

| Quark | Mass [GeV/$c^2$] |
|---|---|
| Charm ($c$) | 1.27 |
| Bottom ($b$) | 4.18 |

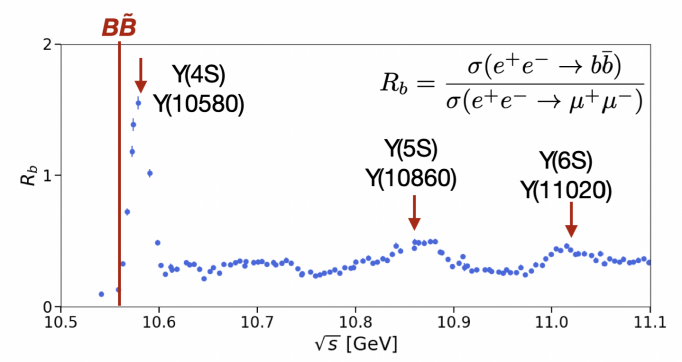



[Phys.Rev.D 110 (2024) 9, 094040, CLEO]

Our goal is to understand how the strong interaction gives rise to the rich variety of hadrons.

# Bottomonium above the $B\bar{B}$ threshold

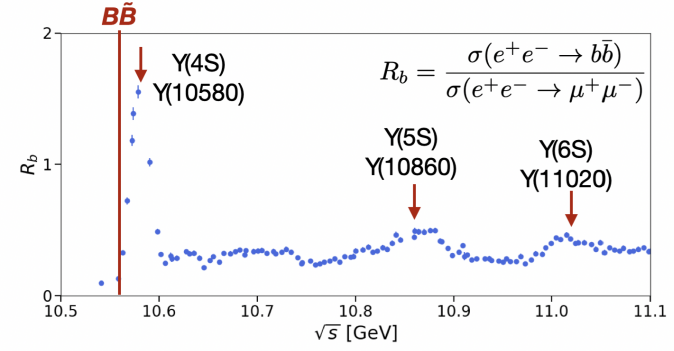
- Around 2008, three $b\bar{b}$ states are known: $\Upsilon(4S)$, $\Upsilon(5S)$, $\Upsilon(6S)$
  - Unlike lower-bottomonia, they exhibit anomalous decay patterns.
    $\rightarrow$ Suggesting that they may not be pure $b\bar{b}$?

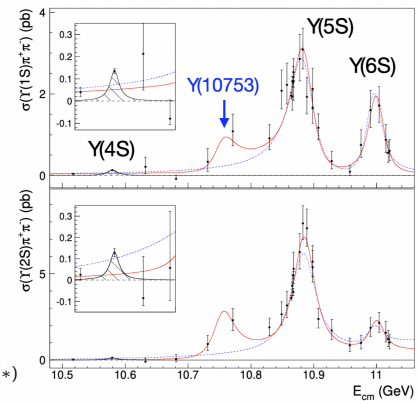



[BaBar, PRL 102 (2009) 012001, Belle, JHEP10, 220 (2019)]

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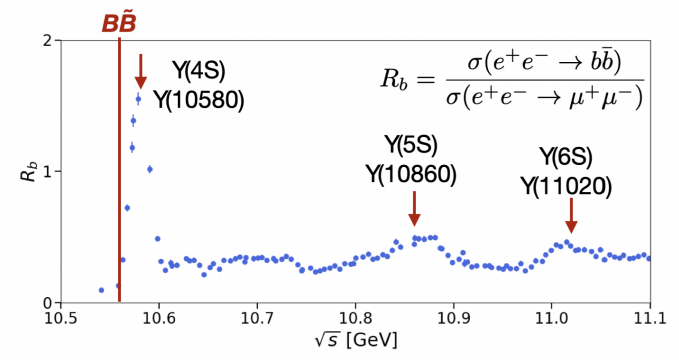



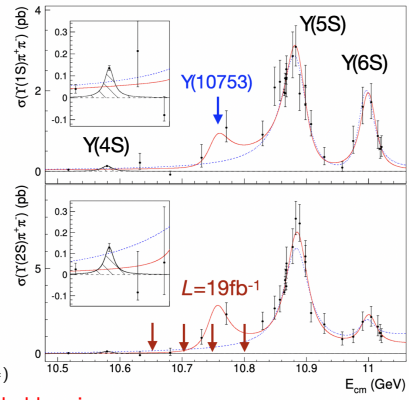

- 2019, Belle observed a new state $\Upsilon(10753)$
  - Interpretations: mixture of D-wave and S-wave states with $B^{(*)}\bar{B}^{(*)}$

[BaBar, PRL 102 (2009) 012001, Belle, JHEP10, 220 (2019)]

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- 2019, Belle observed a new state $\Upsilon(10753)$
  - Interpretations: mixture of D-wave and S-wave states with $B^{(*)}\bar{B}^{(*)}$
    → Motivation to further investigate $\Upsilon(10753)$ and the $B^*\bar{B}^*$ threshold region.

[BaBar, PRL 102 (2009) 012001, Belle, JHEP10, 220 (2019)]

# Why Belle II at SuperKEKB?

**Experiments Worldwide**

- Belle and BaBar: Data taking completed.
- BESIII@BEPCII (China): $e^+e^-$ collider in the charm region.
- LHC experiments (LHCb, ATLAS, CMS, ALICE):
  Heavy-flavor and exotic hadron studies in hadron collisions.
- Belle II/SuperKEKB: The only operating B factory.

**Advantages of $e^+e^-$ collisions**

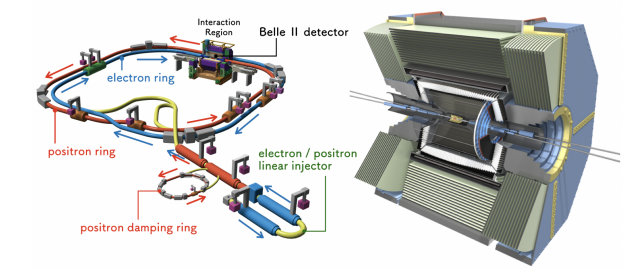
- Clean collision environment with relatively low QCD backgrounds.
- Collision energy can be varied to scan the bottomonium region.
- Direct access to vector states ($J^{PC} = 1^{--}$).

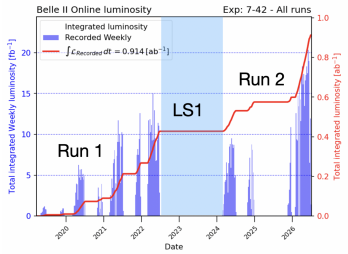
**Belle II offers a unique opportunity for energy-scan measurements in the bottomonium region.**




[CERN, A. Del Rosso (2017)]

# SuperKEKB/Belle II

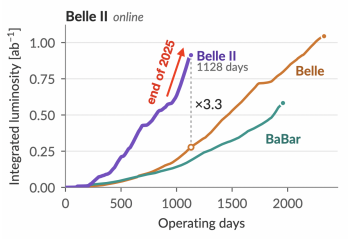



- SuperKEKB: Asymmetric $e^+e^-$ collider using nanobeam scheme.
- Belle II: General purpose detector for charged and neutral particles. Primarily operates at the $\Upsilon(4S)$ resonance, with dedicated energy-scan campaigns.

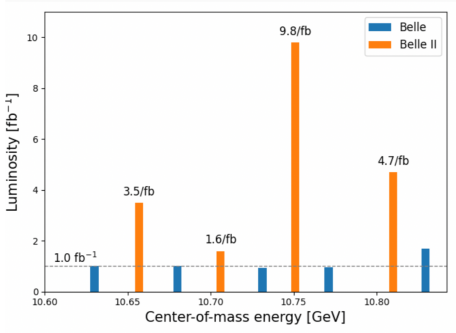
**Operation in Run2**

- Run 2 started in early 2024, stable since end of 2025.
- SuperKEKB achieved luminosity record: $5.28\times10^{34}$ cm$^{-2}$ s$^{-1}$
- Belle II collected total integrated luminosity 941 fb$^{-1}$



# Energy scan at Belle II

In November 2021, Belle II performed energy scan: 4 points, $L = 19\,\mathrm{fb}^{-1}$ (5× Belle).
Goal: study $\Upsilon(10753)$ and $B^{(*)}\bar{B}^{(*)}$ threshold region.

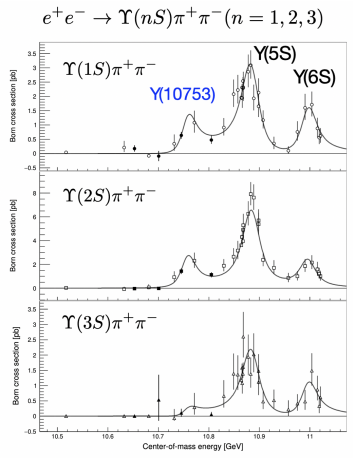



**Belle**

- Energy scans from 10.63 to 11.02 GeV: 22 points, $\sim 1\,\mathrm{fb}^{-1}$ per point.
- $\Upsilon(5S)$ region: $L = 121\,\mathrm{fb}^{-1}$.

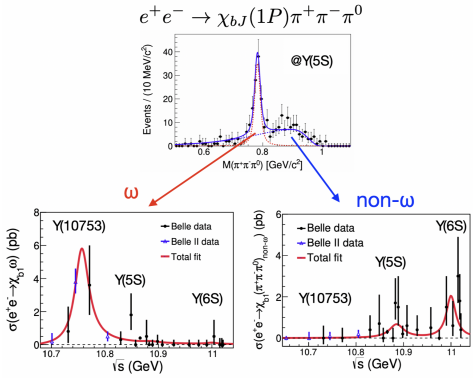
# Higlights from Belle II energy scan

1. Confirmation of $\Upsilon(10753)$ at Belle II




$m = 10756.6 \pm 2.7 \pm 0.9$ MeV/$c^2$
$\Gamma = 29.0 \pm 8.8 \pm 1.2$ MeV

2. Different decay patterns of $\Upsilon(10753)$ and $\Upsilon(5S, 6S)$



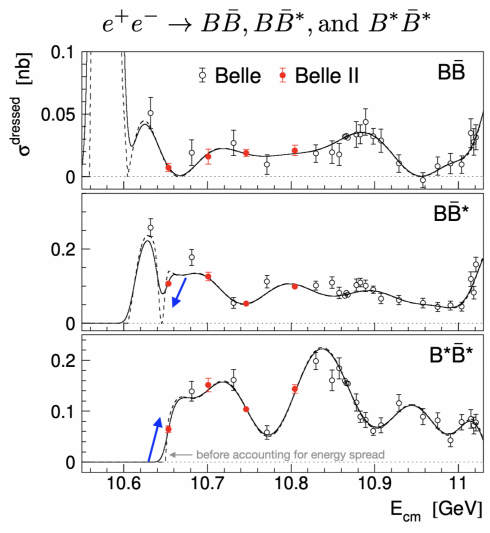

- Despite their small masses differences and identical quantum numbers ⇒ their internal structure may differ.

[Belle II JHEP 07, 116 (2024), Belle and Belle II, JHEP04(2026)101]

# Higlights from Belle II energy scan

- 3 Possible bound states near the $B^{(*)}\bar{B}^{(*)}$ thresholds
- $B^{(*)}\bar{B}^{(*)}$ dominates total $b\bar{b}$ cross section in this energy region
- Hadronic molecular states may emerge near $B^{(*)}\bar{B}^{(*)}$ thresholds.
- Rapid increase in $B^*\bar{B}^*$
  $\rightarrow$ Intriguing because $P$-wave production is suppressed near threshold ($\sigma \propto p^3$).
  $\rightarrow$ indication of molecular state?
- Pheno analysis confirms $\Upsilon(10650)$

  Salnikov,Bondar,Milstein NPA 1041,122764 (2024).




[Belle and Belle II, JHEP 10, 114 (2024)]

# Publications from the Quarkonium Working Group I

1. 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
   PRL 130, 091902 (2023)
2. Search for the $e^+e^- \to \eta_b(1S)\omega$ and $e^+e^- \to \chi_{b0}\omega$ processes at $\sqrt{s} = 10.745$ GeV
   PRD 109, 072013 (2024)
3. Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II
   JHEP 07, 116 (2024)
4. Measurement of the energy dependence of the $e^+e^- \to B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$ cross sections at Belle II
   JHEP 10, 114 (2024)
5. Measurement of the inclusive branching fractions for $B_s^0$ decays into $D$ mesons via hadronic tagging
   JHEP 04 2025, 114 (2025)
6. Evidence for $P_{c\bar{c}s}(4459)^0$ in $\Upsilon(1S, 2S)$ inclusive decays at Belle
   PRL 135, 041901 (2025)
7. Search for $e^+e^- \to \gamma\chi_{bJ}$ (J = 0, 1, 2) at $\sqrt{s}$ near 10.746 GeV at Belle II
   PRD 113, 052009 (2026)
8. Observation of $e^+e^- \to \eta\Upsilon(2S)$ and search for $e^+e^- \to \eta\Upsilon(1S)$, $\gamma X_b$ at $\sqrt{s}$ near 10.75 GeV
   arxiv:2509.01917
9. Improved measurement of Born cross sections for $\chi_{bJ}\,\omega$ and $\chi_{bJ}\,(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$ ($J$ = 0, 1, 2) at Belle (II)
   JHEP 04, 101 (2026)

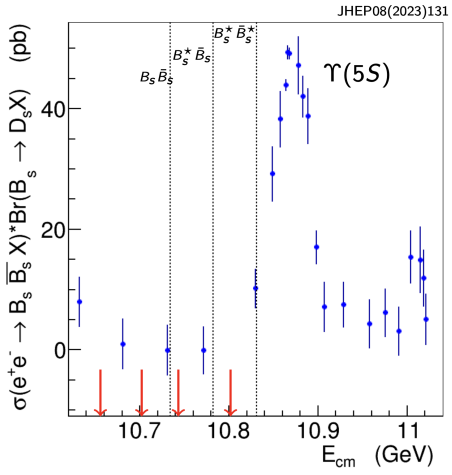
# Publications from the Quarkonium Working Group II

1. First measurement of the masses of the $\Upsilon_1(1D)$ and $\Upsilon_3(1D)$ states and the energy dependence of the cross sections for $e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$
   PRL 137, 191901 (2026)
2. Measurements of the mass difference $m(B^0) - m(B^+)$ and the energy dependence of the cross-section ratio $\sigma(e^+e^- \to B^0\bar{B}^0)/\sigma(e^+e^- \to B^+B^-)$ at Belle and Belle II
   arxiv:2511.15926
3. First evidence of $X(3872) \to \pi^0\chi_{c0}(1P)$ and search for $X(3915) \to \pi^0\chi_{c1}(1P)$
   arXiv:2606.24578
4. Study of $e^+e^- \to h^+h^- J/\psi$ ($h = \pi, K, p$) via initial-state radiation at Belle II
   PRD 113, 112010 (2026)
5. Searches for charged-lepton flavor violation in $\chi_{bJ}(1P)$ decays
   PRL 137, 071803 (2026)
6. Study of $e^+e^- \to \pi^+\pi^-\Upsilon(1D)$ at Belle II
   JHEP 06, 278 (2026)

# Ongoing analysis: $\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})$ measurement

**Motivation**

- Two Belle II scan points are above $B_s\bar{B}_s$ threshold.
- Are there bumps close to $B_s^{(\star)}\bar{B}_s^{(\star)}$ thresholds?
  $\to$ $B_s^{(\star)}\bar{B}_s^{(\star)}$ molecular states?
- $B_s^{(\star)}\bar{B}_s^{(\star)}$ is the second-largest contribution to the $b\bar{b}$ cross section
- Belle measured at an energy very close to the $B_s\bar{B}_s$ threshold.




Blue points: Belle data; red arrows: Belle II scan points; dashed line: $B_s^*\bar{B}_s^*$ threshold.

# Method for measuring $\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})$

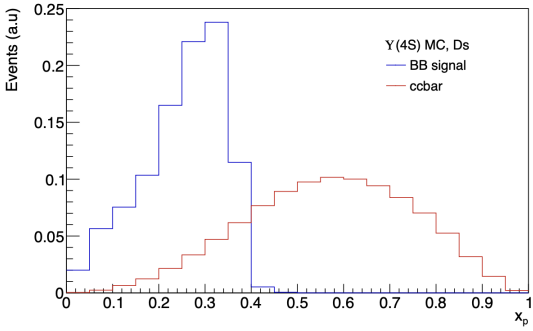
Extract the $B_s^{(*)}\bar{B}_s^{(*)}$ cross section from inclusive $D_s$ and $D^0$ production, using branching fractions as external inputs.

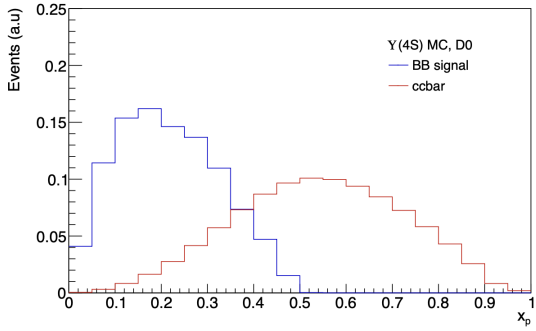
$$\begin{aligned}\sigma(e^+e^- \to b\bar{b} \to D_s^{\pm}X) = {} & 2\,\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})\mathcal{B}(B_s^0 \to D_s^{\pm}X) \\ & + 2\,\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi))\mathcal{B}(B \to D_s^{\pm}X)\end{aligned}$$

$$\begin{aligned}\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0X) = {} & 2\,\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})\mathcal{B}(B_s^0 \to D^0/\bar{D}^0X) \\ & + 2\,\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi))\mathcal{B}(B \to D^0/\bar{D}^0X)\end{aligned}$$

- Measure inclusive $D_s^{\pm}$ and $D^0/\bar{D}^0$ cross sections from $b\bar{b}$ events.
- Branching fractions are taken from PDG.
- Factor of 2 accounts for pair production.
- Solve the two equations for $B_s^{(*)}\bar{B}_s^{(*)}$ and $B^{(*)}\bar{B}^{(*)}(\pi)$ production cross sections.

# How to measure $\sigma(e^+e^- \to b\bar{b} \to D_{(s)}X)$




- Subtract $e^+e^- \to c\bar{c} \to D_{(s)}X$ contribution
- Use normalized momentum for subtraction:

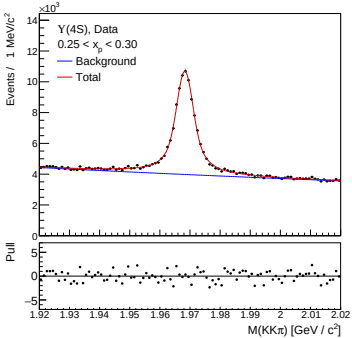
$$x_p = p/\sqrt{(E_{\mathrm{cm}}/2) - m^2}$$

- The shape of $c\bar{c}$ can be determined using data collected below $B\bar{B}$ threshold

# Measurement of $D_s$ yields in $x_p$ bins

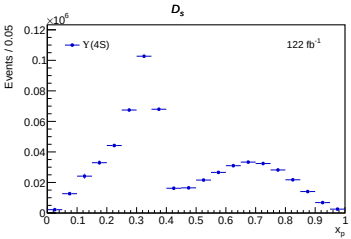
**1. Signal extraction**

Fit the $K^+K^-\pi^+$ invariant-mass distribution in each $x_p$ bin.



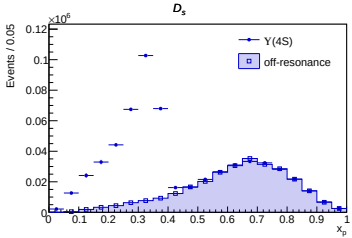

**2. Raw yields vs. $x_p$**

Obtain the $x_p$ dependence of the extracted $D_s$ yields.

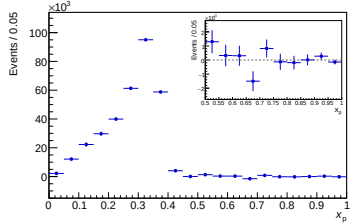



Repeat the analysis for off-resonance data and overlay the normalized yields.

**3. Continuum normalization**



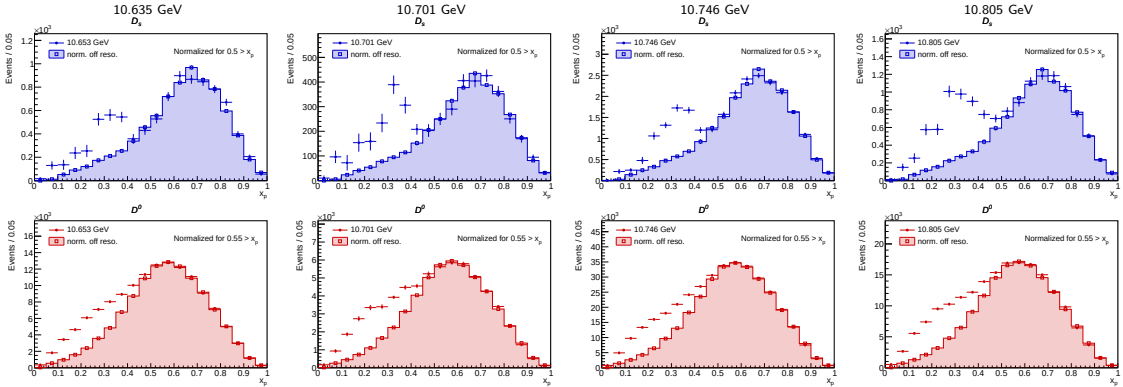

**4. After subtraction**




After steps 1–4, apply corrections to obtain the cross sections.
Use the same procedure to obtain the $D^0$ cross section.
Validate the method with $\Upsilon(4S)$ data, then apply it to the energy scan data.

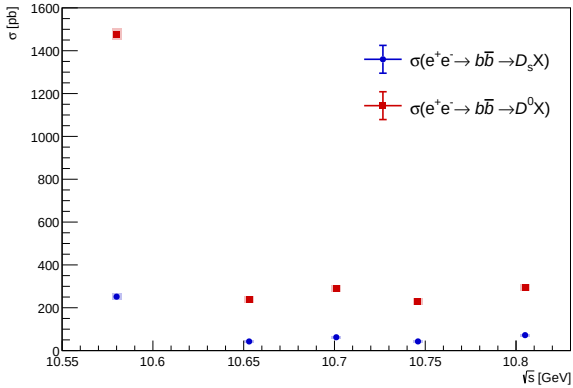
# Inclusive $D_{(s)}$ cross sections in the energy-scan data

- Repeat analysis for energy scan data. Fix signal parameters from $\Upsilon(4S)$ fits.

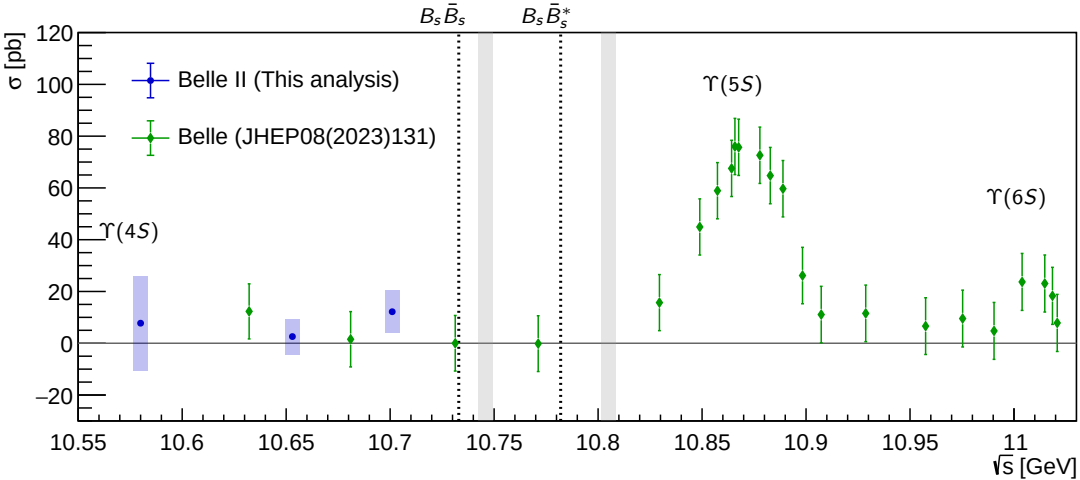


# Inclusive $D_{(s)}$ cross sections

- Measured inclusive $D_s$ and $D^0$ cross sections at the $\Upsilon(4S)$ and at the energy scan points.
- Next, solve the system of equations to extract the $B_s^{(*)}\bar{B}_s^{(*)}X$ cross section.



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




- Below the $B_s\bar{B}_s$ production threshold, $\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}X)$ is consistent with zero.
- Gray bands indicate the two blinded energy points.

# Summary

- The bottomonium region above the $B\bar{B}$ threshold remains relatively unexplored and offers a good opportunity to test BOEFT predictions.
- SuperKEKB/Belle II is ideally suited to exploring this region through energy scans across resonances and production thresholds.
- Belle II scanned this energy region to study the $\Upsilon(10753)$ and $B^*\bar{B}^*$ production.
- The $\Upsilon(10753)$ shows intriguing decay patterns, and possible molecular states near the $B^*\bar{B}^*$ thresholds.
- Ongoing analysis of the energy dependence of the $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}X$ cross section.