Recent quarkonium results at Belle II

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(on behalf of the
Belle II Collaboration)

Belle II

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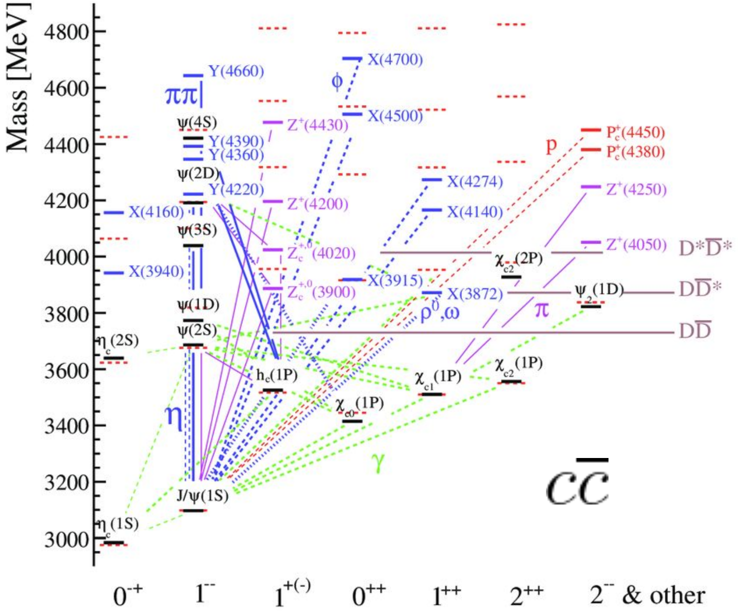
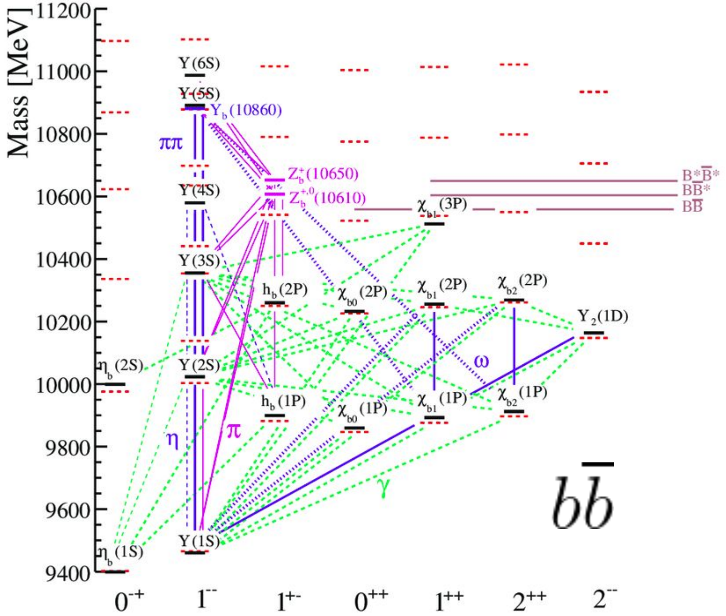
Heavy quarkonia

Non-relativistic heavy quarks ⇒ multi-scale system

$$m \gg mv \gg mv^2$$

mv < 1 GeV ⇒ low energy ⇒ **nonperturbative** QCD





Exotic hadrons

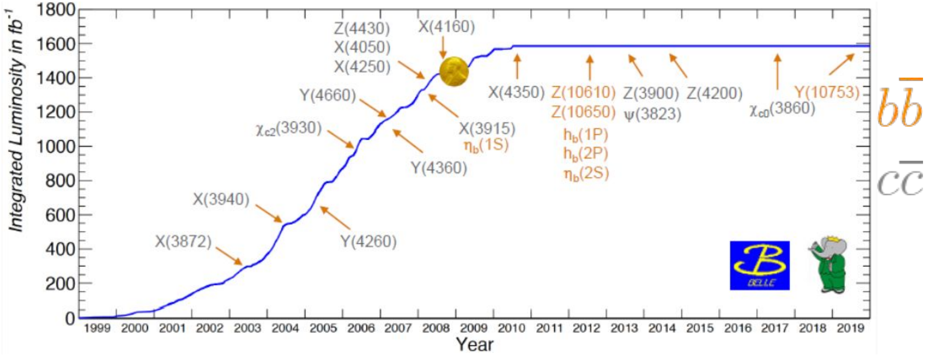
XYZ states:

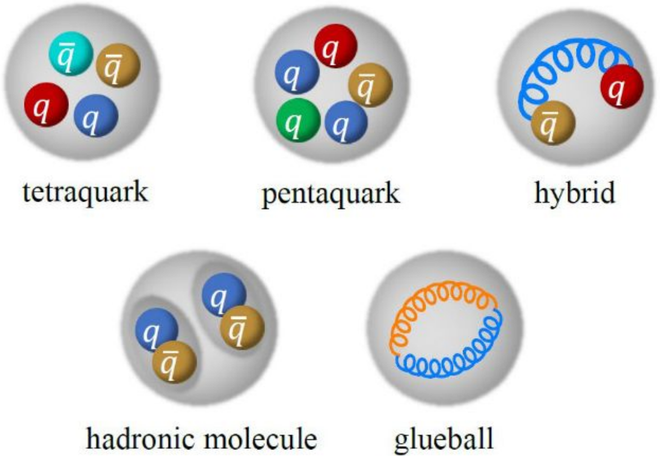
- ➢ lots of them in charmonium
- ➢ bottomonium analogues: Y_b, Z_b, Z'_b

what are they?

⇔

which partons compose them?
which is the color arrangement?





or kinematic effects:
thresholds, cusps

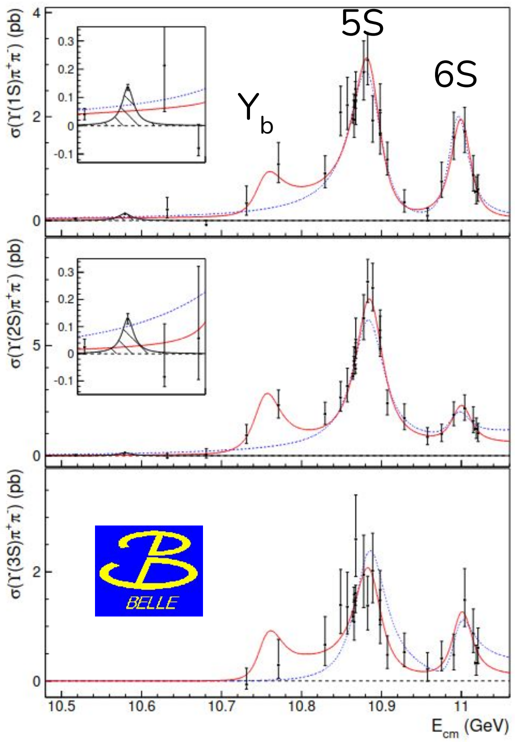
The Belle legacy

Belle@KEKB (**B-factory**) → optimized for

$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$

However

- Y(5S): discovery of h_b(1,2P), η_b(2S), Z_b(10610,10650) [PR D91 072003, PRL 109 232002]
  - exotic states and anomalous ππ transition widths
- Energy scan data: **Y(10753)** aka **Y_b**
  - rise in hadronic transition cross sections (**resonance**)



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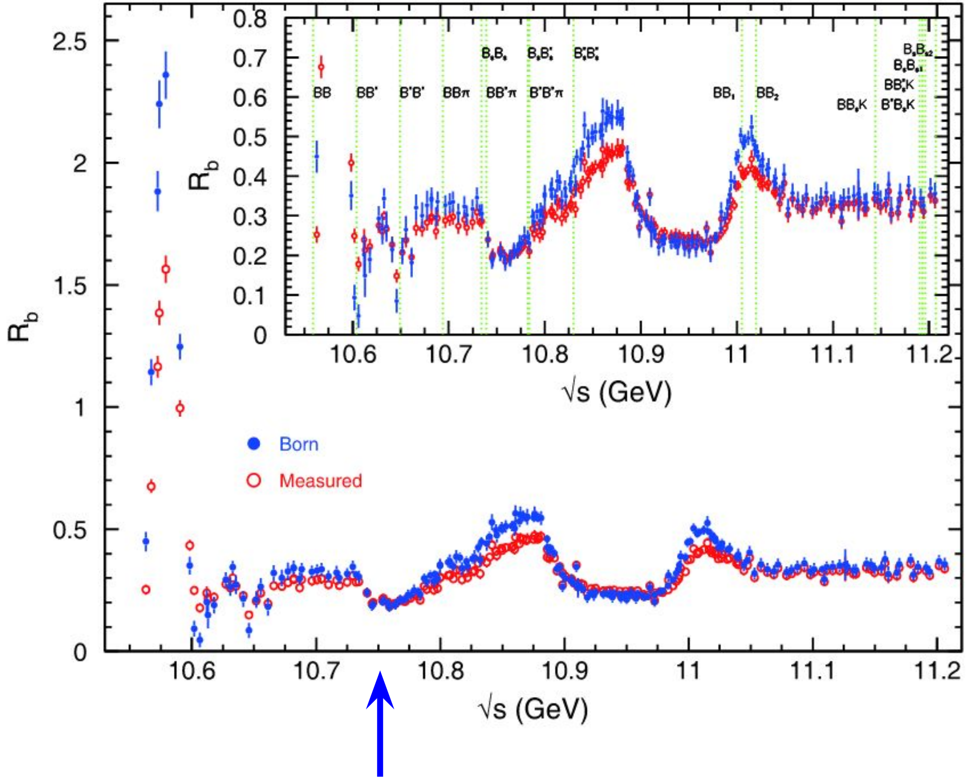
Y(10753): why it's important



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

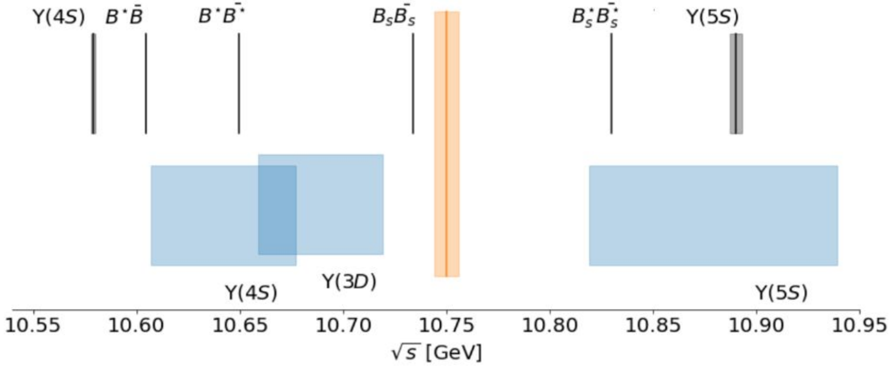
Dip likely caused by **interference** between BW and smooth component

[Chin. Phys. C 44 (2020) 8, 083001]

Y(10753): why it's important

Uncertain nature:

- No clear conventional $b\bar{b}$ candidate
- Y(4S)-Y(3D) mixing?
- Molecule?
- Tetraquark?



10.75 GeV ~ Z_b(10610)π threshold

Conventional interpretations:

Chen, Zhang & He, PRD 101, 014020 (2020)
Giron & Lebed, PRD 102, 014036 (2020)
Li et al., EPJC 80, 59, (2020)
Li et al., PRD 104, 034036 (2021)
van Beveren & Oset, PPNP 117, 103845 (2021)
Bai et al., PRD 105, 074007 (2022)
Husken, Mitchell & Swanson, arXiv:2204.11915 (2022)
Kher et al., EPJ+ 137, 357 (2022)
Li, Bai & Liu, arXiv:2205.04049 (2022)
Liang, Ikeno & Oset, PLB 803, 135340 (2020)
...

Exotic interpretations:

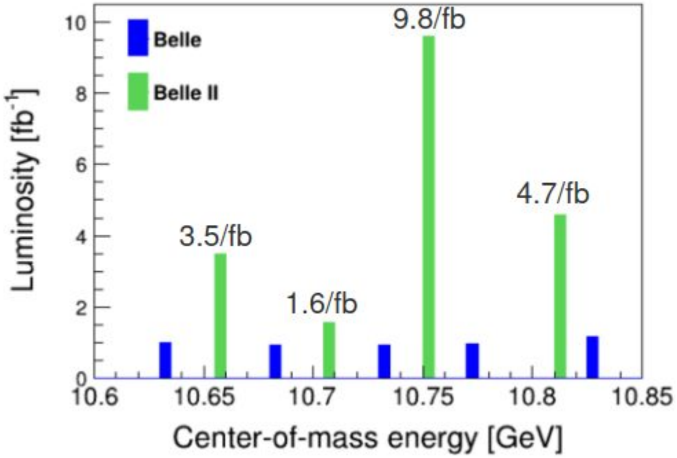
Wang, CPC 43, 123102 (2019)
Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
Bicudo, Cardoso & Wagner, PRD 103, 074507 (2020)
Castella & Passemar, PRD 104, 034019 (2021)
...

Above Υ(4S): Nov. 2021 energy scan

Analyses at Υ(10753): limited luminosity requirement (~O(15 fb^{-1}))

The scan was successful: **19 fb^{-1}** collected at four E_{cm} points (between Belle's)

Belle: ~1 fb^{-1} per point



What are we doing with these data?

Observation of $e^+e^- \rightarrow \omega\chi_{bJ}(1P)$ and Search for $X_b \rightarrow \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

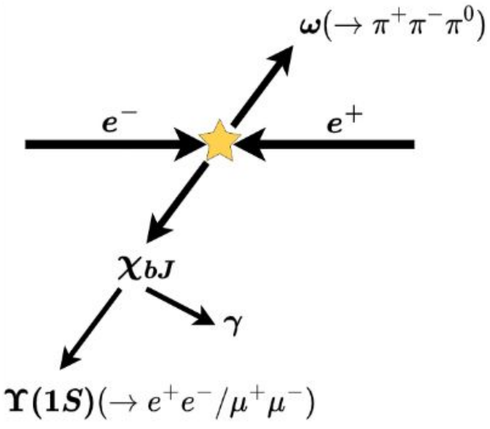
PRL 130 091902 (2023)

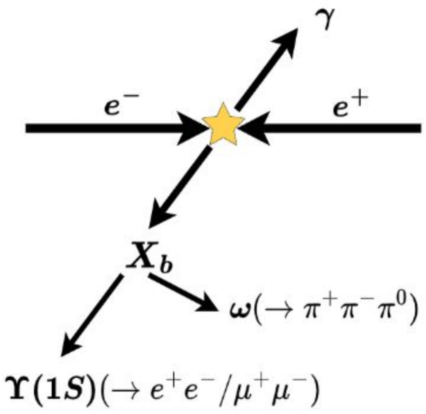
Motivation

Predictions for the 4S-3D mixing
[PR D104 034036 (2021)] :

BR comparable with $Y_b \to \pi^+\pi^- Y(nS)$

$$\frac{\mathcal{B}(\omega\chi_{b1})}{\mathcal{B}(\omega\chi_{b2})} \sim \frac{1}{5}$$





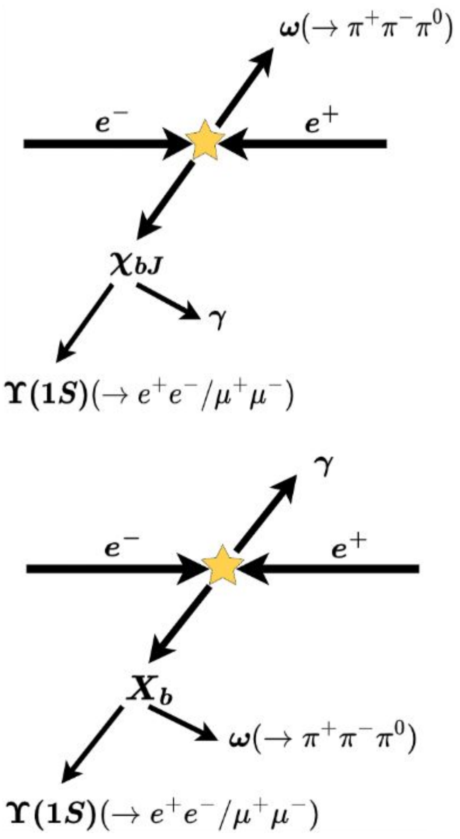
Same final state

X_b predicted by molecular and tetraquark models

Analog of X(3872)

Production: analogous to
$e^+e^- \to Y(4220) \to \gamma X(3872) \to \gamma\omega\, J/\psi$

Event selection



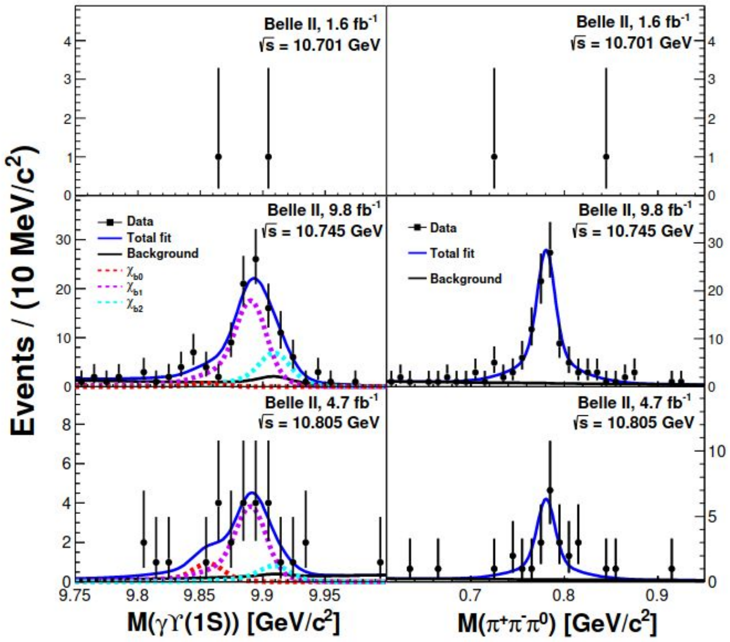
Same for the 2 channels

- 4 – 5 charged tracks
- standard Belle II PID (90 – 95% eff.)
- E(γ) > 50 MeV
- 105 < M(γγ) < 150 MeV/c^2 (90% eff.)
- bremsstrahlung and FSR correction
- 4C kinematic fit
- best candidate selection based on fit χ^2

$\Upsilon(10753)\to\omega\chi_{bJ}(1P)$: fit to signal yields

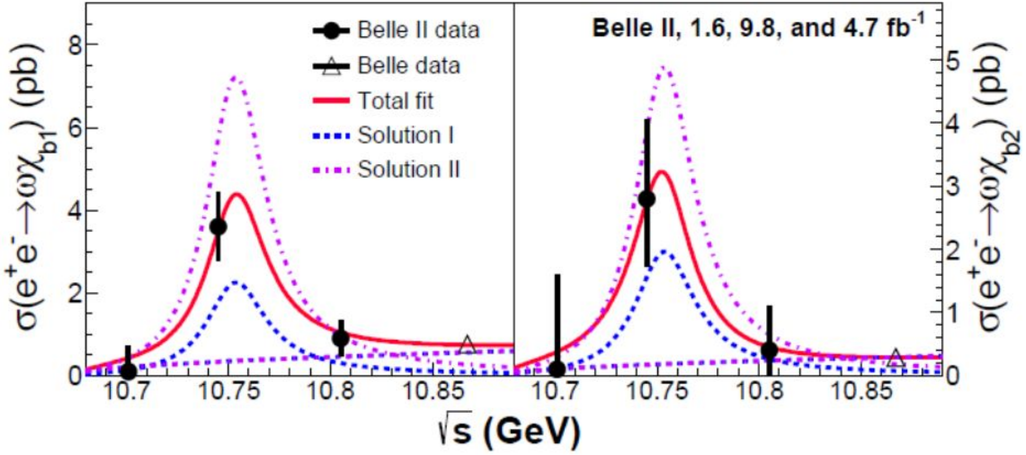
2D fit to $M(\gamma\Upsilon(1S))$ vs $M(\pi^+\pi^-\pi^0)$
Model:
- signal (CB for χ_{bJ}, Voigt for ω) +
- peaking bkg (same) +
- comb. bkg

Channel	$\sqrt{s}$ (GeV)	N_{sig}	σ^B (pb)
$e^+e^-\to\omega\chi_{b0}$		$0.0^{+1.1}_{-0.0}$	<16.6
$e^+e^-\to\omega\chi_{b1}$	10.701	$0.0^{+2.1}_{-0.0}$	<1.2
$e^+e^-\to\omega\chi_{b2}$		$0.1^{+2.2}_{-0.1}$	<2.5
$e^+e^-\to\omega\chi_{b0}$		$3.0^{+5.5}_{-4.7}$	<11.3
$e^+e^-\to\omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6\pm0.7\pm0.5$
$e^+e^-\to\omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0}\pm0.4$
$e^+e^-\to\omega\chi_{b0}$		$3.6^{+3.8}_{-3.1}$	<11.4
$e^+e^-\to\omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	<1.7
$e^+e^-\to\omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	<1.6



Peaks on $\chi_{b1,2}(1P)$ | Peaks on ω

$\Upsilon(10753)\to\omega\chi_{bJ}(1P)$: fit to σ^B



Triangle in plot: Belle result

Now we can see that the **peak is at 10.75 GeV**

No clear peak at 10.860 GeV (aka Υ(5S))

Fixed parameters:

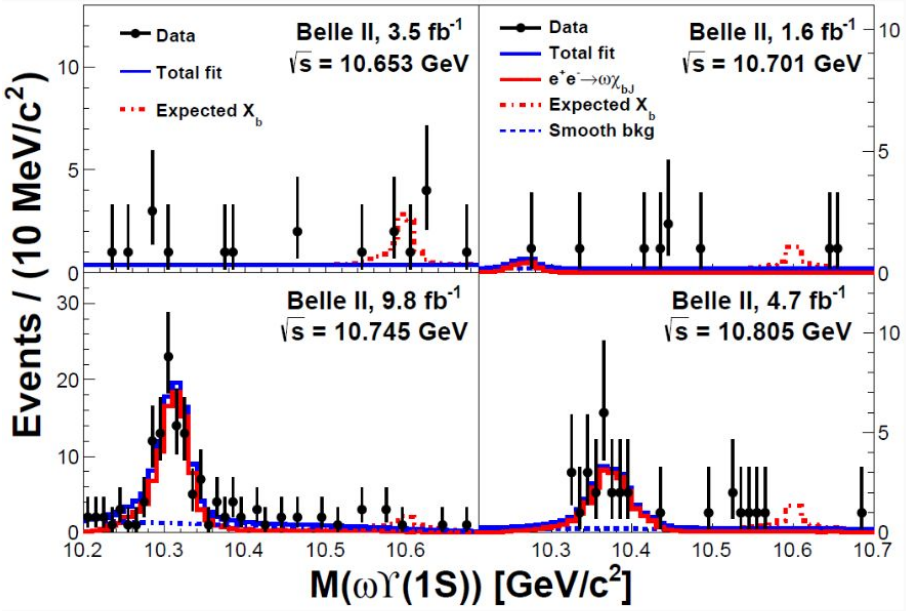
- ➢ mass = 10752.7 MeV
- ➢ width = 35.5 MeV

Search for $X_b \to \omega \Upsilon(1S)$

- Search for resonances in $M(\omega \Upsilon(1S))$
- Reflection from $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$
- No evidence for X_b signal

⇒ Upper limit to σ_{Xb}

$\sqrt{s}$ (GeV)	M_{X_b} (GeV)	$\sigma^{UL}_{X_b}$ (pb)
10.653	10.59	0.55
10.701	10.45	0.84
10.745	10.45	0.14
10.805	10.53	0.47



Measurement of the energy dependence of the $e^+e^- \to B\overline{B},\, B\overline{B}^*, B^*\overline{B}^*$ cross sections

Motivation

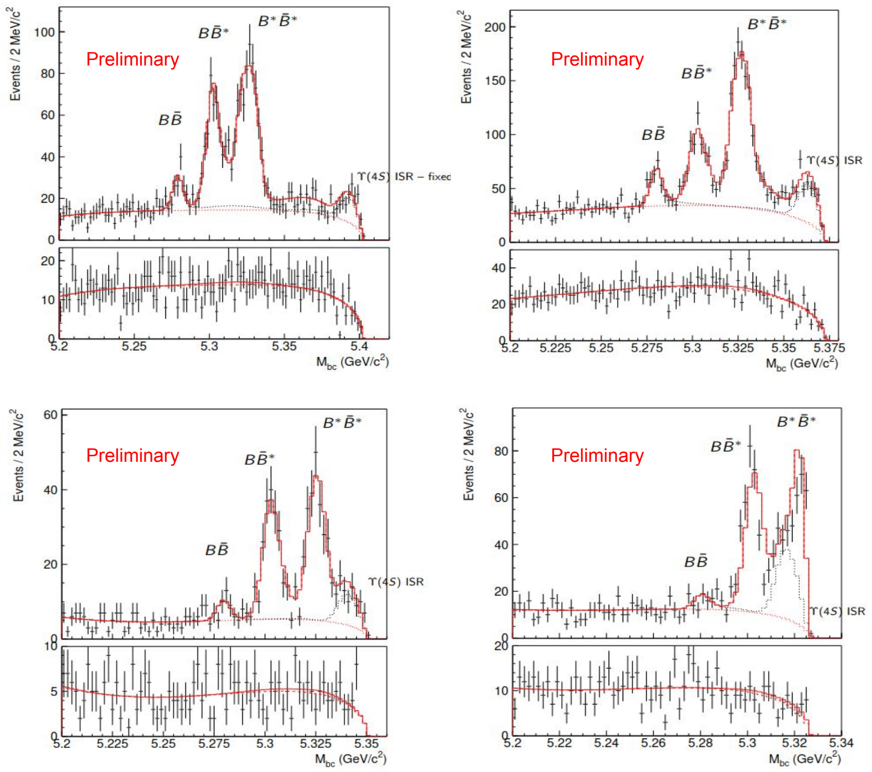
All $b\bar{b}$ above $B\overline{B}$ threshold exhibit anomalous properties

Broad Belle II program to measure exclusive cross sections

Method:

- ➢ fully reconstruct one B in had decays
- ➢ identify signals with M_{bc}
- ➢ combine with Belle measurement [JHEP 06, 137 (2021)]

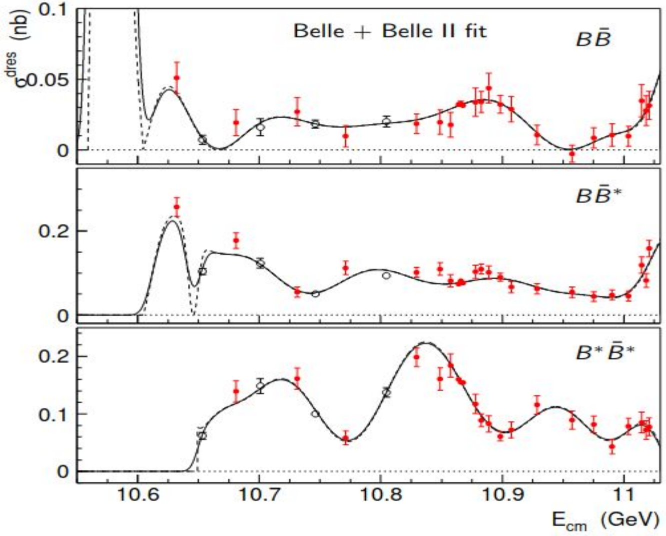
$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$

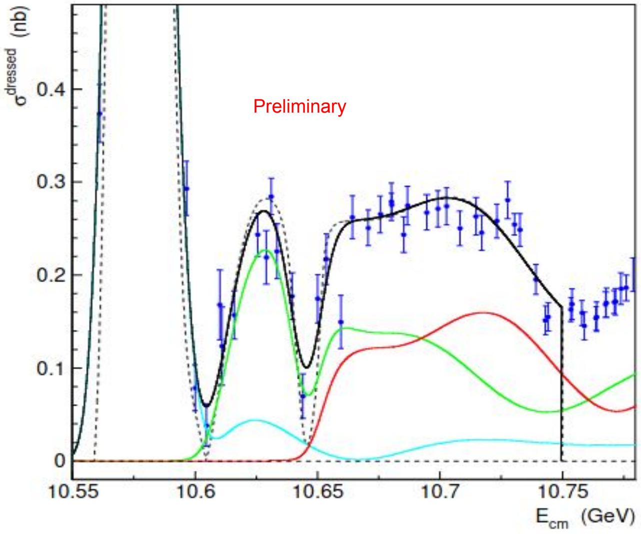


Fit to cross section vs E_{cm}

Fits to both exclusive and total σ

Preliminary





Belle II Belle

Y(10753) scan @Belle II: the future

Golden Modes
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$
$B\overline{B}$ decomposition
$\pi^+\pi^-$ Dalitz
$Y_b \to \omega\eta_b(1S)$
$Y_b \to \omega\chi_{bJ}(1P)$
Silver Modes
$Y_b \to \pi^+\pi^- X$ (inclusive)
$Y_b \to \eta X$ (inclusive)
$Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$
$Y_b \to \Upsilon(1S)$ (inclusive)
Bronze Modes
$Y_b \to \gamma X_b$
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to \pi^0\pi^0 X$ (inclusive)
$Y_b \to \pi^0 X$ (incl. or excl.)
...

- Reconstruction of hadronic/EM transitions
- Branching ratio measurement
- Cross sections vs. E_{cm} measurement
- Precise decomposition of the R_b ratio
- Systematic exploration of threshold regions
- Search for new exotic states

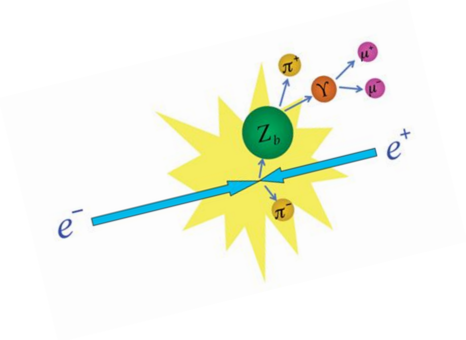
Summary

We are at the beginning of a rich quarkonium physics program

Belle II collected unique data near $E_{cm} \sim 10.75$ GeV

- ➢ Unique quarkonium production at SuperKEKB
- ➢ Resonant transition $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$ observed for the 1st time
- ➢ No evidence for X_b
- ➢ Preliminary results on $\sigma(e^+e^- \to b\bar{b})$ vs E_{cm}

Many ongoing analyses on 4S and scan data!



BACKUP

The Belle legacy

Belle@KEKB (**B-factory**) → optimized for

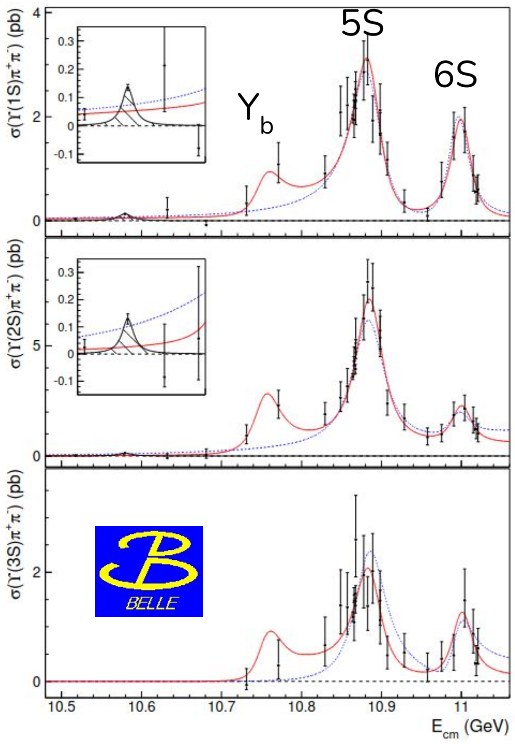
$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$

However

- Υ(5S): discovery of h_b(1,2P), η_b(2S), Z_b(10610,10650) [PR D91 072003, PRL 109 232002]
    - exotic states and anomalous ππ transition widths

Process	Partial width
$\Upsilon(10860) \to \Upsilon(3S)\pi^+\pi^-$	$(0.59 \pm 0.04 \pm 0.09)\ MeV$
$\Upsilon(10860) \to \Upsilon(2S)\pi^+\pi^-$	$(0.85 \pm 0.07 \pm 0.09)\ MeV$
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	$(0.52^{+0.20}_{-0.17} \pm 0.10)\ MeV$
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	$(8.9 \pm 0.8) \times 10^{-4}\ MeV$

- Energy scan data: **Υ(10753)** aka **$Υ_b$**
    - rise in hadronic transition cross sections (**resonance**)



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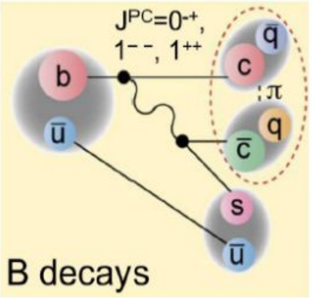
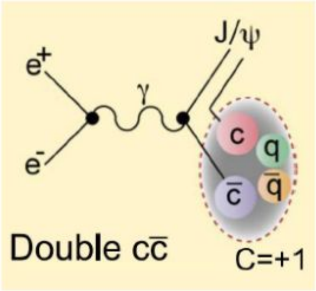
Charmonium(-like) prospects



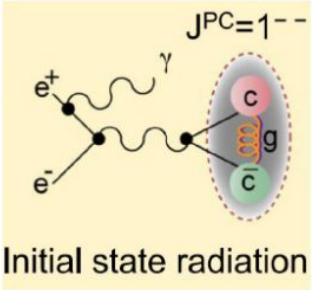
$\mathcal{B}[B \to X(3872, 3915)K]$

$X(3872) \to D^0\overline{D^0}\pi^0$



J^{PC} of $X(3915) \to \omega J/\psi$

Confirm $X(4350) \to \phi J/\psi$

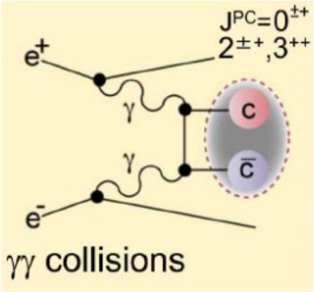


$\Lambda_c^+\Sigma_c^+$, $\Sigma_c^+\Sigma_c^-$

$D_s D_{s2}(2573)$

$D_s D_{s0}^*(2317)$

$Z_{cs}^\pm \to K^\pm J/\psi$



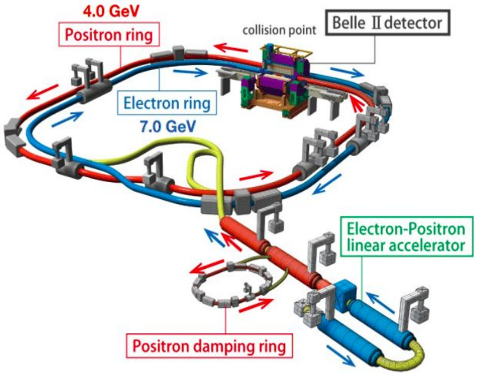
$e^+e^- \to (c\bar{c})_{J=0}(c\bar{c})_{J=1}$

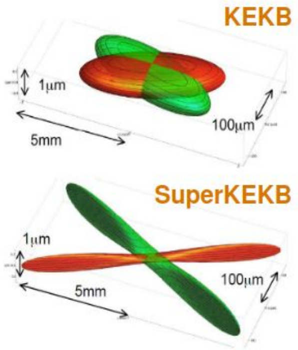
J^{PC} of $X(3940)$

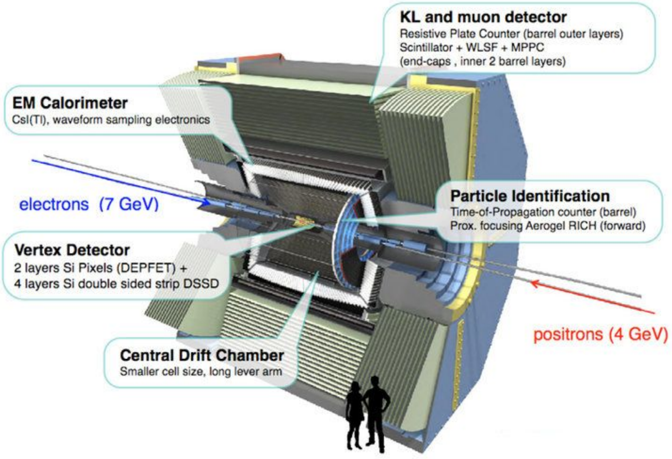
Belle II @ SuperKEKB

SuperKEKB:

- ➢ Asymmetric e+e- collider in Tsukuba, JP
- ➢ Nano-beam interaction point
  - ○ $\mathcal{L} = 4.7 \times 10^{34}$ cm^{-2}s^{-1} (record), L = 424 fb^{-1}
- ➢ Tunable E_{cm} around Υ(4S) mass





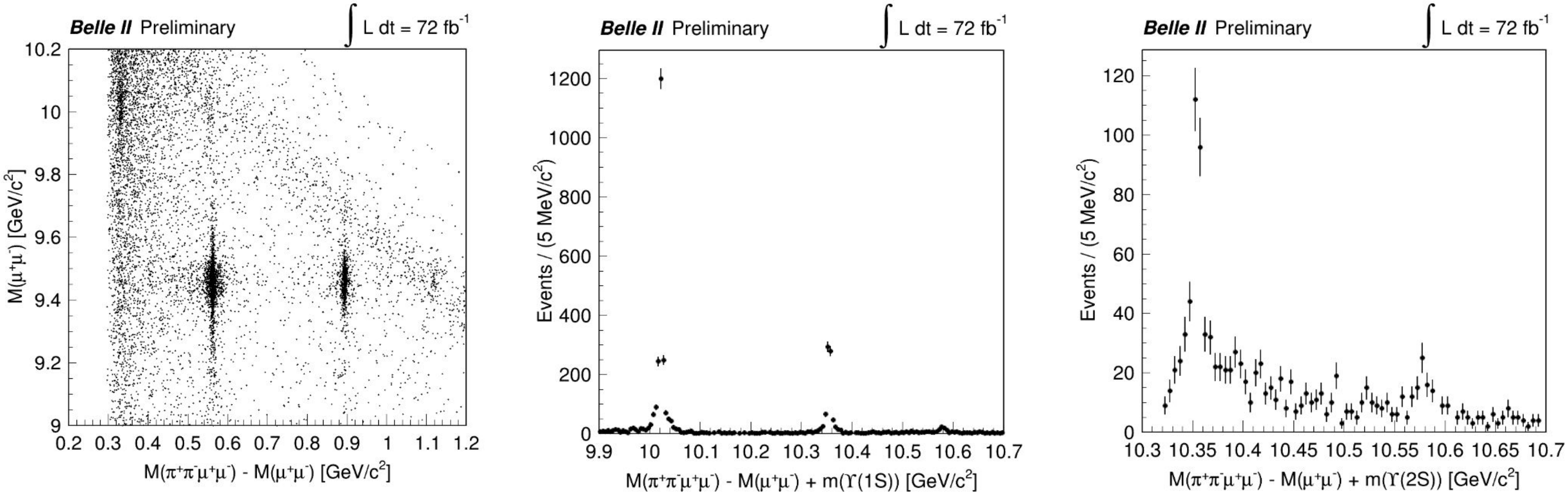


Belle II detector:

- ➢ ~4π magnetic spectrometer with optimal vertexing, tracking, PID, calorimetry capabilities

$e^+e^- \to \pi^+\pi^-\Upsilon(pS)$ $[\to l^+l^-]$

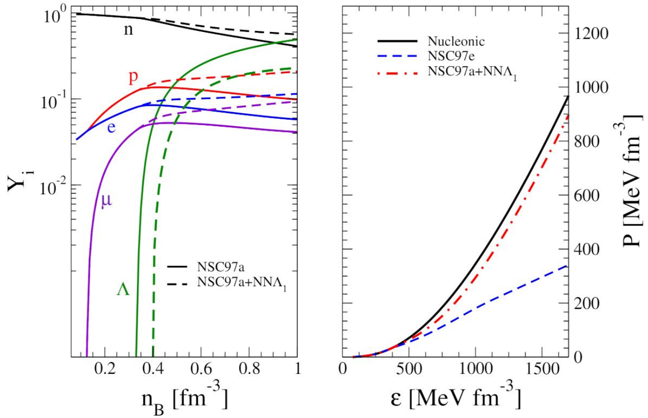
Analyzed data: on and off-resonance 4S + above 4S scan
Main backgrounds: low mult., QED processes



Femtoscopy studies (Belle II + Belle)

Subject of my PhD thesis

Λ dynamics in neutron stars should affect the EoS, based on Λ-Λ (Λ-N) interaction (attractive / repulsive?)



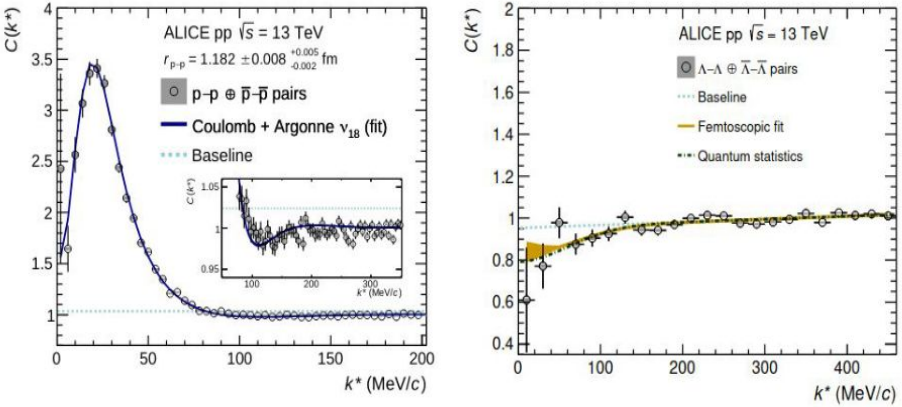
Universe 2021, 7, 408

- ➢ $e^+e^- \to q\bar{q} \to \Lambda\Lambda X$
- ➢ $e^+e^- \to \Upsilon(nS) \to ggg \to \Lambda\Lambda X$

Dynamic correlations between Λ's

⇒ constraints on interaction models

⇒ constraints on neutron star EoS



PLB 797, 134822 (2019)

Femtoscopy studies (Belle II + Belle)

Two-particle dynamic correlations bring information about

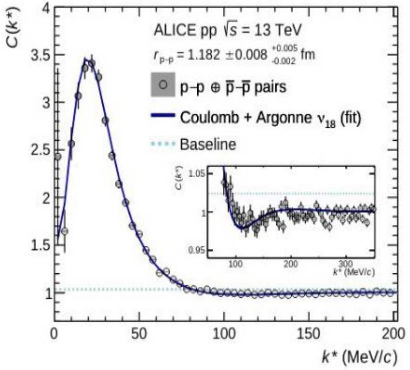
- ➢ interactions between them
- ➢ geometry of the emitting source

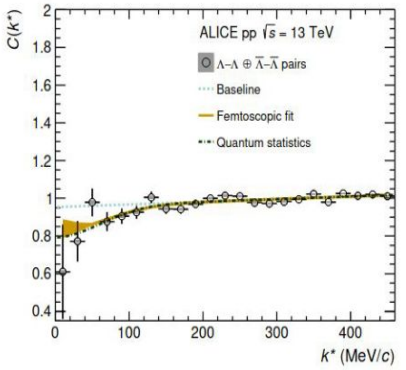
Λ-Λ interactions using femtoscopy:

- ➢ mixed event technique: method already used at ALICE
- ➢ we have a cleaner experimental environment

Applications: neutron star EoS, nuclear force, H-dibaryon, ...

$$C(k^*) \propto \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$



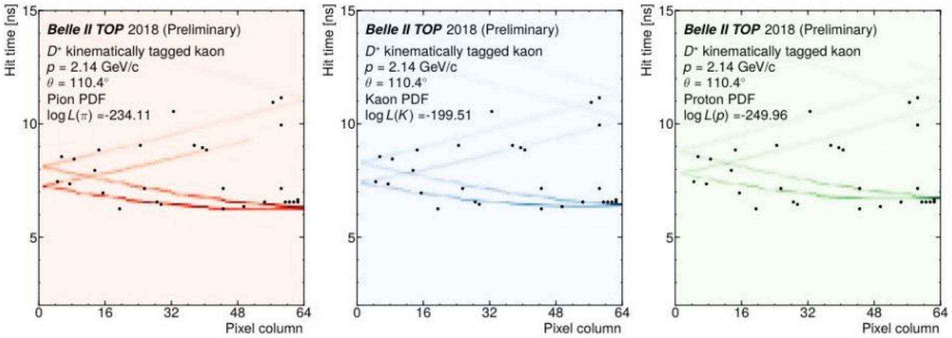


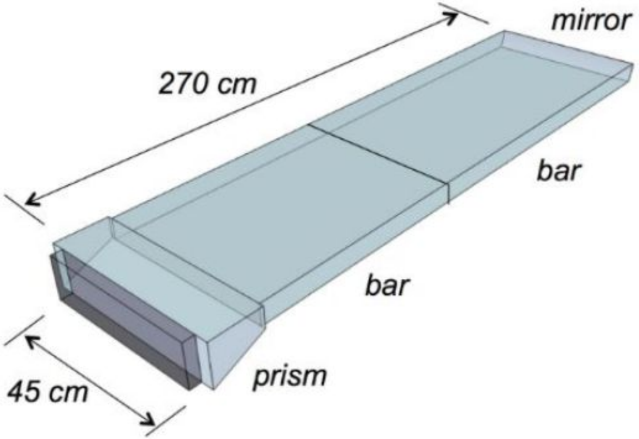
PID with the TOP detector

Key improvement in PID w.r.t. Belle

TOP = DIRC in the time domain

- ➢ Cherenkov light trapped and propagated to the readout in bar of fused silica
- ➢ Cherenkov angle measured by the time of propagation





The running α_s

At low Q (< 1 GeV), $\alpha_S \sim 1$

⇒ Perturbation theory doesn't work

(**Non-perturbative** QCD)

- lots of effective theories
- unknown couplings and/or mechanisms

⇒ Large theor. uncertainties

How can we help?