Charm and quarkonium at Belle and Belle II

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Moriond QCD

La Thuile, March 30th / April 6th, 2025

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- Introduction
  - Belle and Belle II
- Charm
  - BF of charmed baryons
  - A_{CP} in $D^0 \rightarrow K_S K_S$
- Quarkonium
  - Energy dependence of $\sigma(e^+e^- \rightarrow \omega X_{bJ} (1P))$

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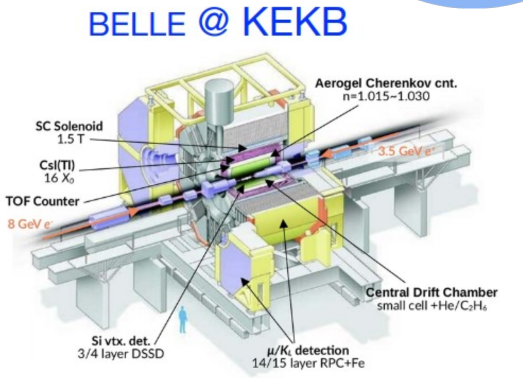
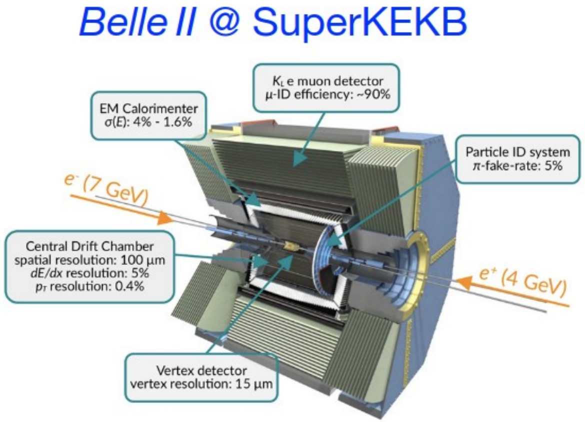
Belle and Belle II Experiments

- Belle and Belle II collect(ed) data at asymmetric e^+e^- colliders at or near the Υ(4S) resonance
  - KEKB (1999-2010), peak lumi = 2×10^{34} cm^{-2} s^{-1}, L_{int} = 1/ab
  - SuperKEKB, peak lumi = 5.1×10^{34} cm^{-2} s^{-1}
    Run1 (2019-2022), L_{int} = 0.42/ab
    Run2 (2024 – present), L_{int} = 0.15/ab



- Belle & Belle II are now synergic experiments
  - Belle data can be analysed with the Belle II software
  - Common review procedures in place
  - Especially important for analyses where large statistics is crucial to improve the precision



Belle II: physics potential

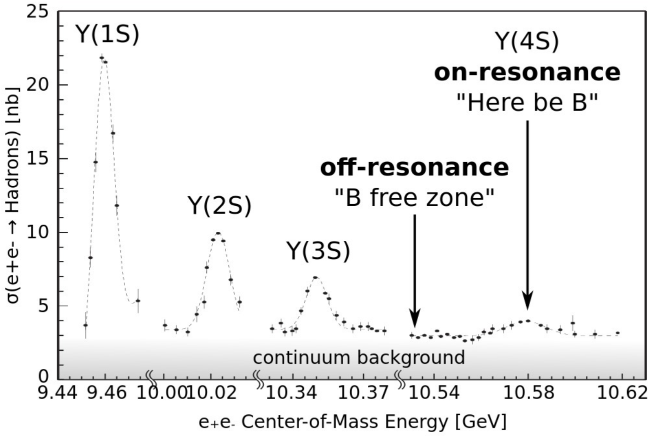
Belle II operates mainly at $\sqrt{s}$ = 10.58 GeV:

- $\sigma(e^+e^- \to b\bar{b}) \sim 1.1$ nb
  $L_{peak} = 2.7\ 10^{34} cm^{-2}\ s^{-1} \to 30\ B\bar{B}$/s

- $\sigma(e^+e^- \to \tau\tau) \sim 0.9$ nb

- $\sigma(e^+e^- \to c\bar{c}) \sim 1.3$ nb

→ *B* & τ & *c* factory



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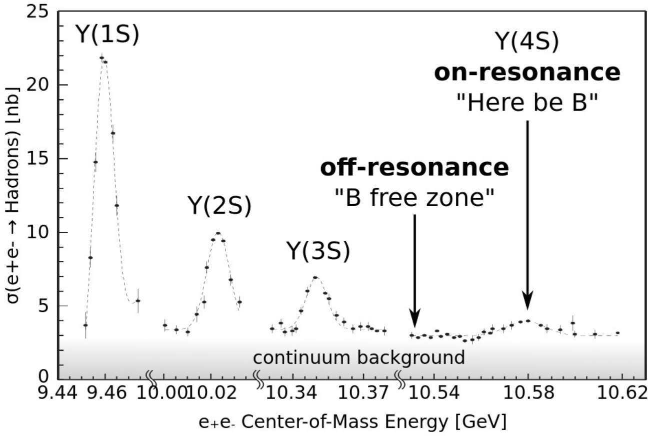
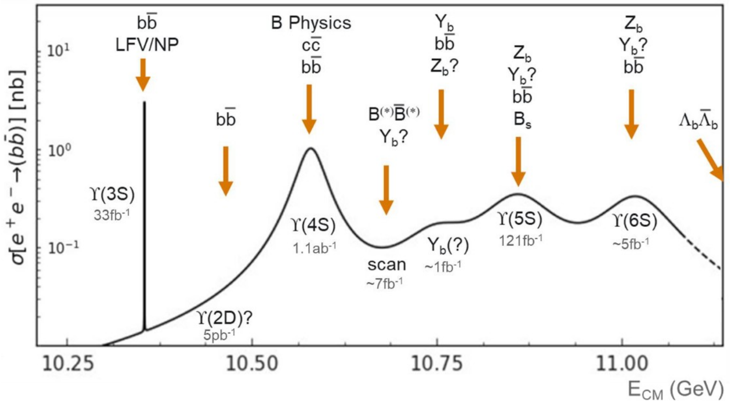


B-Factories can extend their physics programs with non-Υ(4S) data

- Belle II: 2019 unique energy scan at ~10.75 GeV



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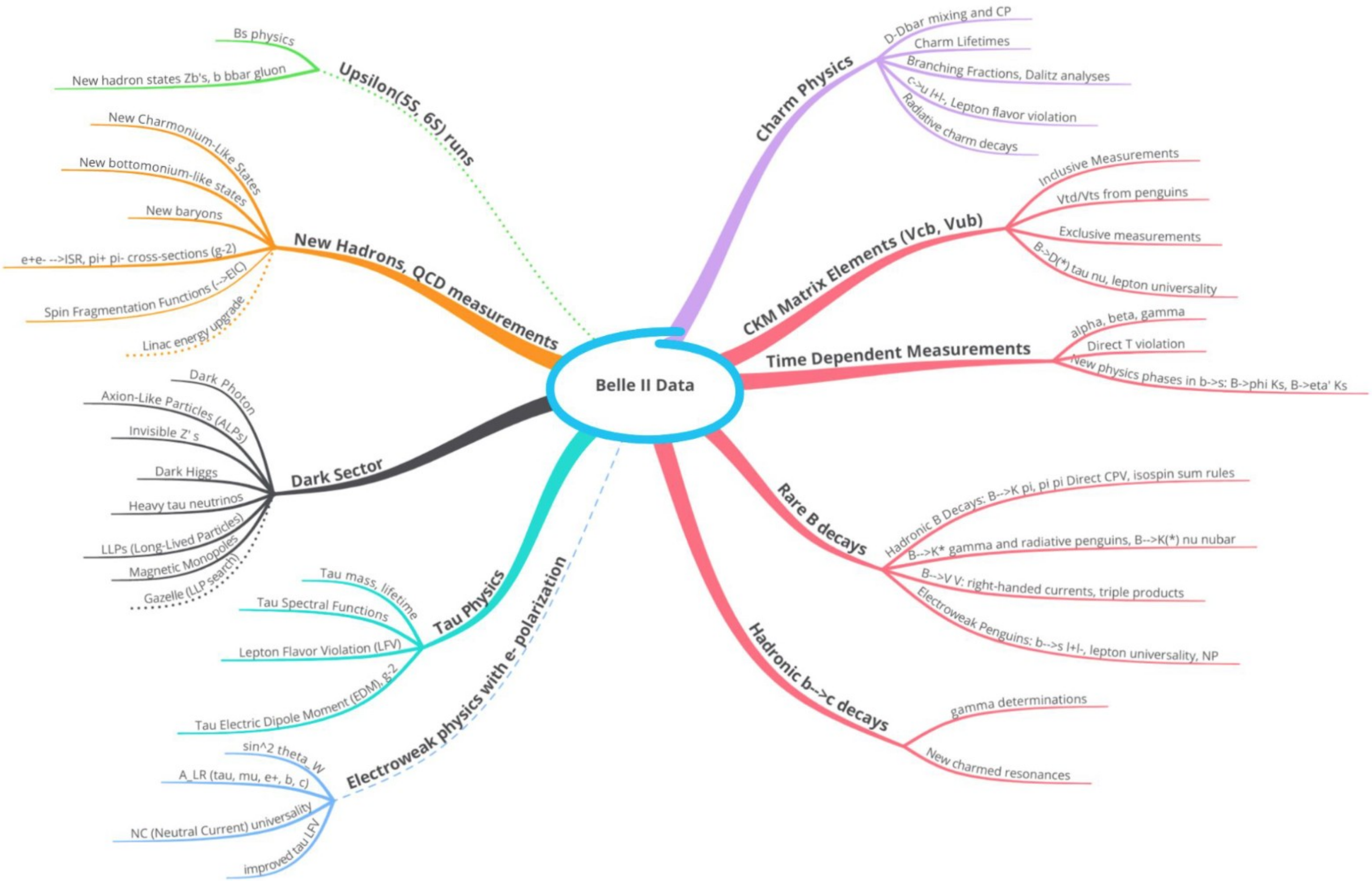
Belle II: physics program

[See: BIITIP, Snowmass Whitepaper]



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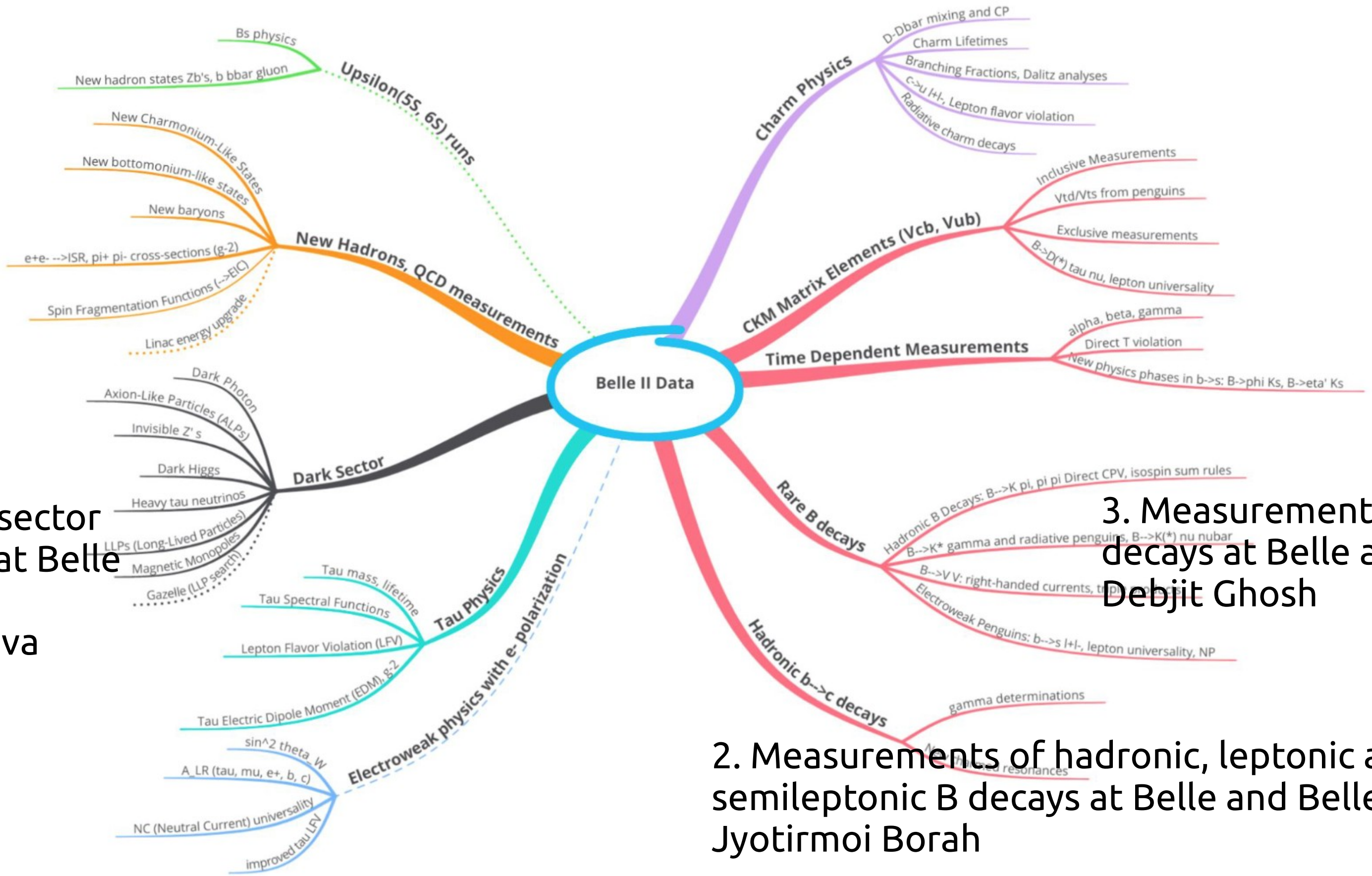

4. Tau and dark sector measurements at Belle and Belle II
Zuzana Gruberova

3. Measurements of rare B decays at Belle and Belle II
Debjit Ghosh

2. Measurements of hadronic, leptonic and semileptonic B decays at Belle and Belle II
Jyotirmoi Borah

Charm

Charm physics at B-Factories

Two ways of producing charm at B-Factories:

- One or more charmed hadrons produced in B decays
- Two charmed hadrons produced from continuum, along with fragmentation particles

Ample physics program

- Baryons: conflicting or missing predictions for BF and lifetimes, results to verify models
  Today: Ξ_c^+ branching fractions, $\Lambda^+_c \to p K_S \pi$ BF
- Mesons: precise measurement in Cabibbo-suppressed decays, where non-SM physics can contribute at a detectible level
  Most interesting probes: CPV measurements, expect low values ($O(10^{-3})$) in charm sector
  Today: A_{CP} in $D^0 \to K_S K_S$

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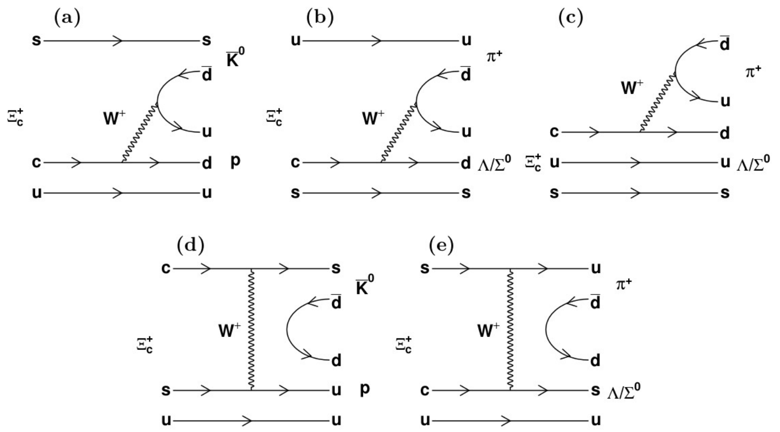
Ξ_c^+ branching fractions

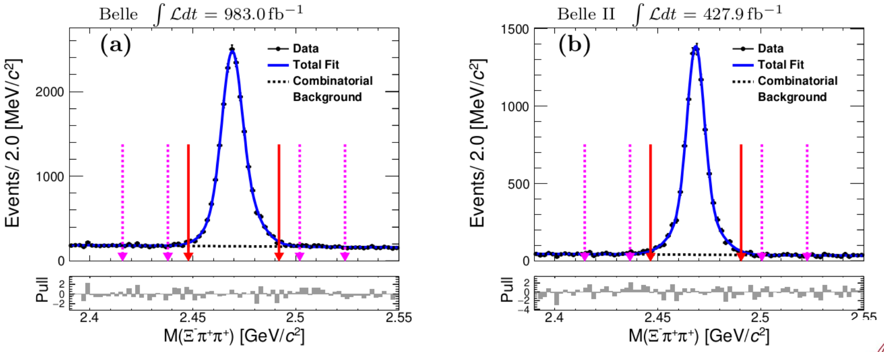
Ξ^+_c decay channels: (many) not yet measured

Currently many predictions
→ need measurement to rule out some of them

Reconstruct
- (CF) $\Xi^+_c \to \Sigma^+ K_S$, $\Xi^+_c \to \Xi^0 \pi^+$
- (SCS) $\Xi^+_c \to \Xi^0 K$, $\Xi^+_c \to p K_S$, $\Xi^+_c \to \Lambda \pi$, $\Xi^+_c \to \Sigma\, \pi$

Analysis strategy:
- From π, K and p reconstruct intermediate baryons Λ, Σ, Ξ, then optimize selection ranges on each invariant mass
- Measure signal yields fitting the invariant mass, extract branching fractions using $\Xi^+_c \to \Xi^- \pi^+ \pi^+$ as normalization mode



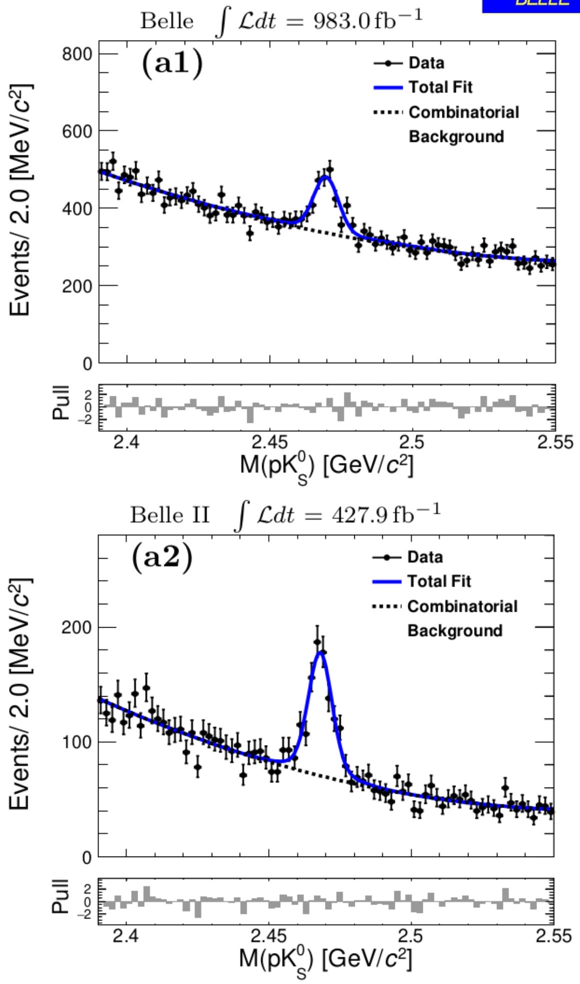


Ξ_c^+ branching fractions

First or most precise measurements!

	Belle	Belle II	Combined
$\frac{\mathcal{B}(\Xi_c^+\to pK_S^0)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$	$(2.36\pm0.27\pm0.08)\%$	$(2.56\pm0.19\pm0.11)\%$	$(2.47\pm0.16\pm0.07)\%$
$\frac{\mathcal{B}(\Xi_c^+\to\Lambda\pi^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$	$(1.72\pm0.29\pm0.11)\%$	$(1.47\pm0.16\pm0.09)\%$	$(1.56\pm0.14\pm0.09)\%$
$\frac{\mathcal{B}(\Xi_c^+\to\Sigma^0\pi^+)}{\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)}$	$(3.97\pm0.42\pm0.23)\%$	$(4.26\pm0.33\pm0.24)\%$	$(4.13\pm0.26\pm0.22)\%$

Mode	Belle	Belle II	Combined
$\mathcal{B}(\Xi_c^+\to\Sigma^+K_S^0)/\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)$	$0.062\pm0.009\pm0.004$	$0.067\pm0.012\pm0.005$	$0.064\pm0.007\pm0.003$
$\mathcal{B}(\Xi_c^+\to\Xi^0\pi^+)/\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)$	$0.232\pm0.014\pm0.013$	$0.234\pm0.010\pm0.014$	$0.233\pm0.008\pm0.010$
$\mathcal{B}(\Xi_c^+\to\Xi^0K^+)/\mathcal{B}(\Xi_c^+\to\Xi^-\pi^+\pi^+)$	$0.015\pm0.003\pm0.001$	$0.017\pm0.003\pm0.001$	$0.016\pm0.002\pm0.001$
$\mathcal{B}(\Xi_c^+\to\Xi^0K^+)/\mathcal{B}(\Xi_c^+\to\Xi^0\pi^+)$	$0.064\pm0.015\pm0.005$	$0.073\pm0.015\pm0.006$	$0.068\pm0.011\pm0.004$



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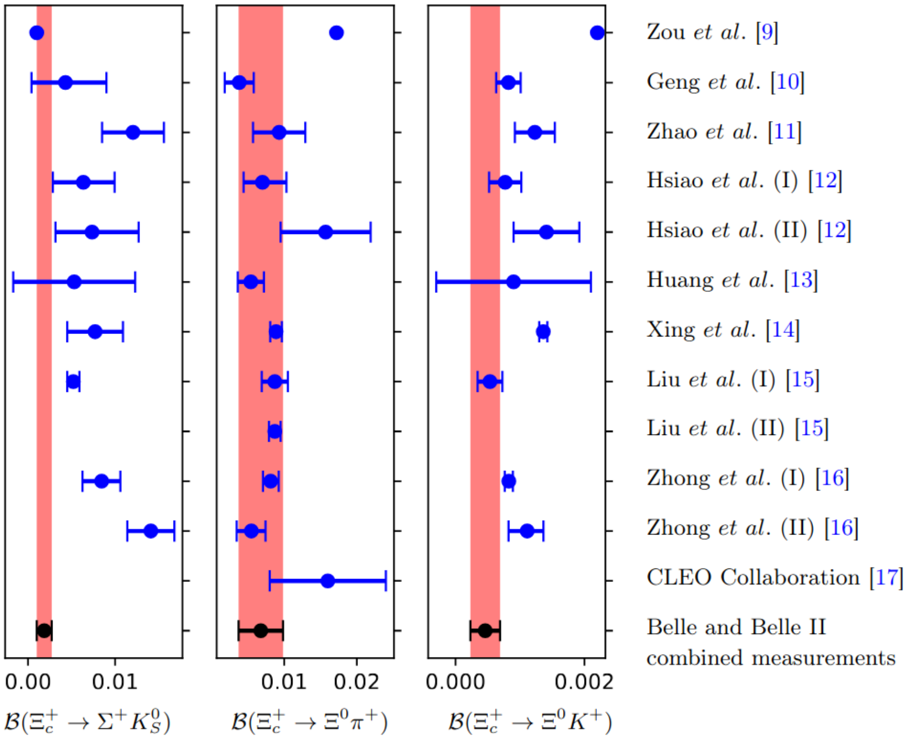
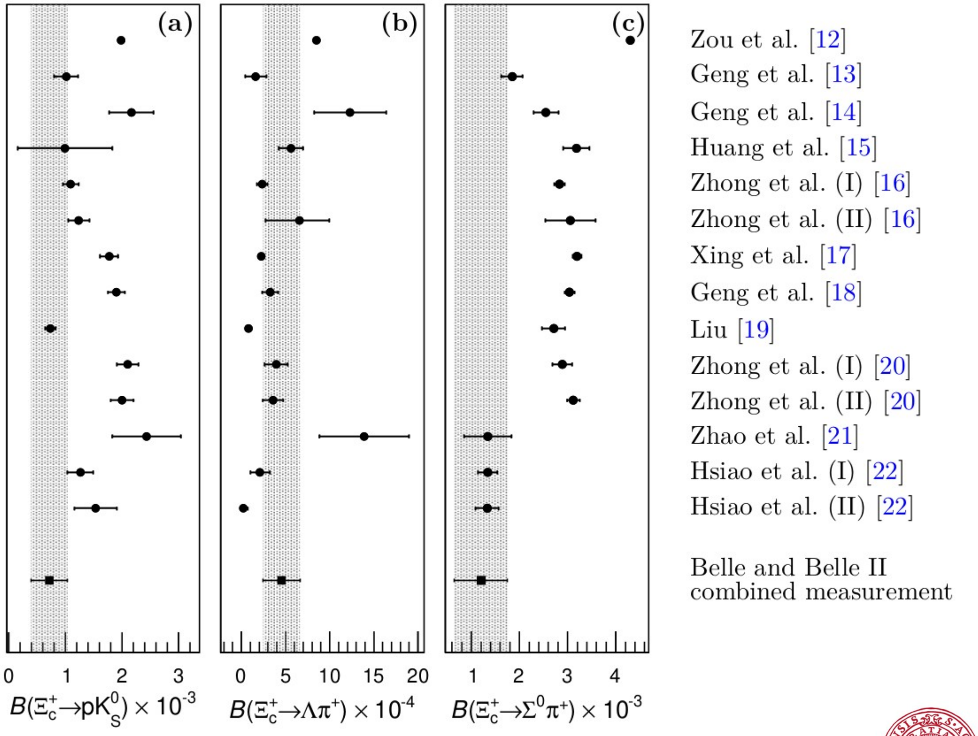
Ξ_c^+ branching fractions

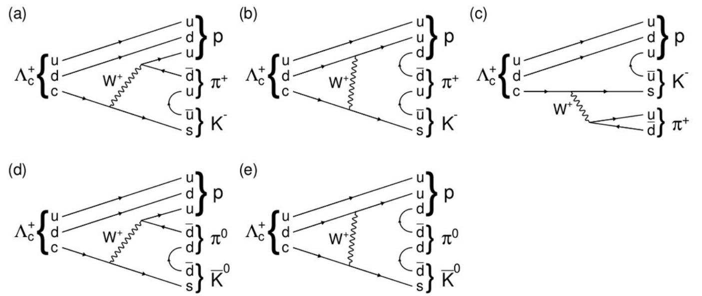
First or most precise measurements!





BF of $\Lambda^+_c \to p K_S \pi^0$

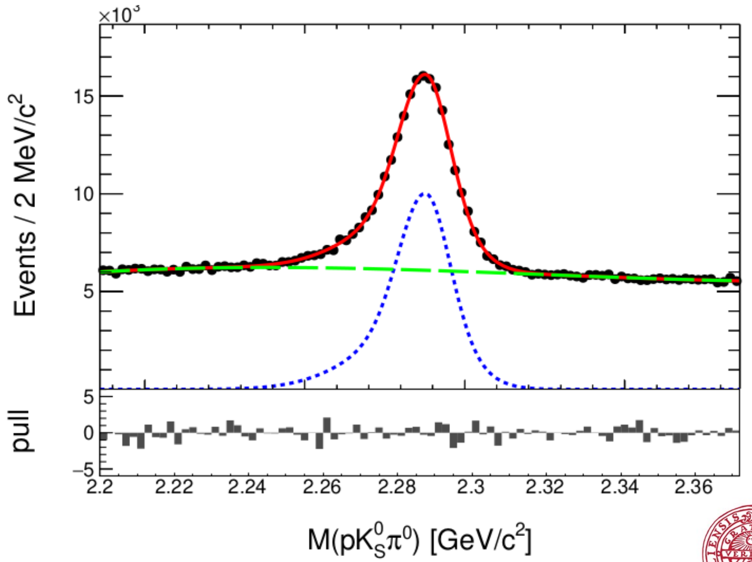
Nonleptonic weak decays of Λ^+_c:
unique testing ground for understanding
$c \to s$ transition and final-state interactions



- Precise measurement of the relative BF for $\Lambda^+_c \to p K_S \pi^0$

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.339 \pm 0.002 \pm 0.009,$$

$$\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0) = (2.12 \pm 0.01 \pm 0.05 \pm 0.10)\%,$$



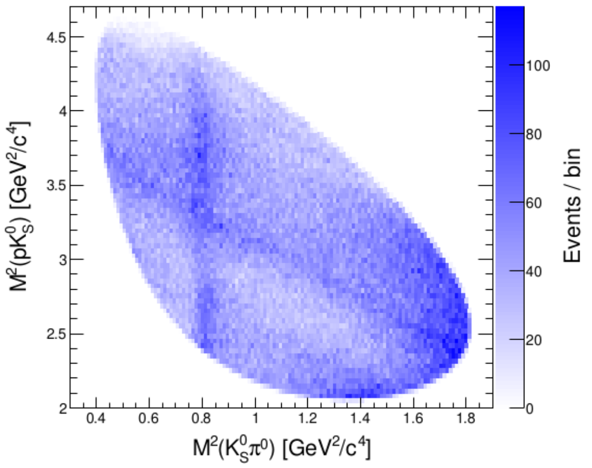
BF of $\Lambda^+_c \to p\, K_S\, \pi^0$

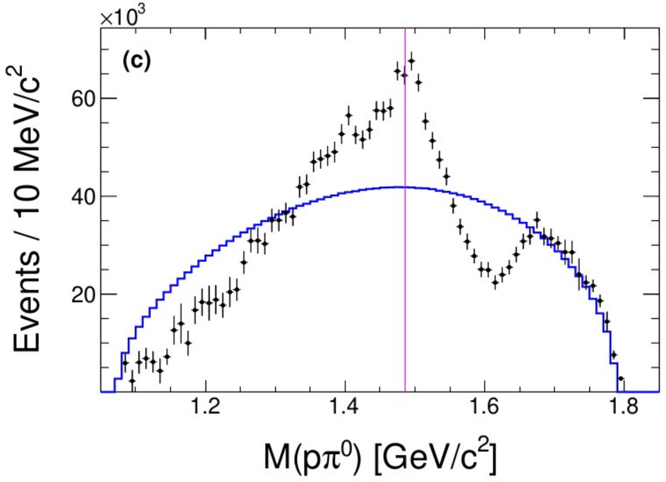
Nonleptonic weak decays of Λ^+_c:
unique testing ground for understanding
$c \to s$ transition and final-state interactions

- Precise measurement of the relative BF for $\Lambda^+_c \to p\, K_S\, \pi^0$

- First investigation of intermediate resonances:
  Observation of a peaking structure in the $p\pi^0$ system near the $p\eta$ threshold

→ Further amplitude analysis required to understand the contributions of intermediate resonances and to estimate the non-resonant contribution





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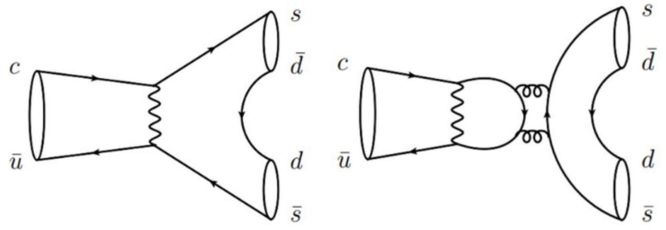
A_{CP} in $D^0 \to K_S K_S$

$D^0 \to K_S K_S$: Singly Cabibbo-suppressed decays
- Involves the interference between $c \to u s \bar{s}$ and $c \to u d \bar{d}$
- Expect A_{CP}~1% [PRD 92, 054036]

→ Larger values would indicate non-SM physics



World average value of the A_{CP} symmetry is limited by statistics

A_{CP} ($D^0 \to K_S K_S$) = (-1.9 ± 1.0)%

$$A_{CP} \equiv \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$$

$A_{CP}(D^0 \to K_S^0 K_S^0) = -0.02 \pm 1.53(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.17\ (\text{cont. mode})$ Belle [PRL 119, 171801 (2017)]

$A_{CP}(D^0 \to K_S^0 K_S^0) = -3.1 \pm 1.2(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.2\ (\text{cont. mode})$ LHCb [PRD 104, L031102 (2021)]

There are nuisance asymmetries induced by production and detection mechanisms

Take $D^0 \to K^+K^-$ as control channel to calibrate A_{CP}

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A_{CP} in $D^0 \to K_S K_S$: D^*-tagged D^0

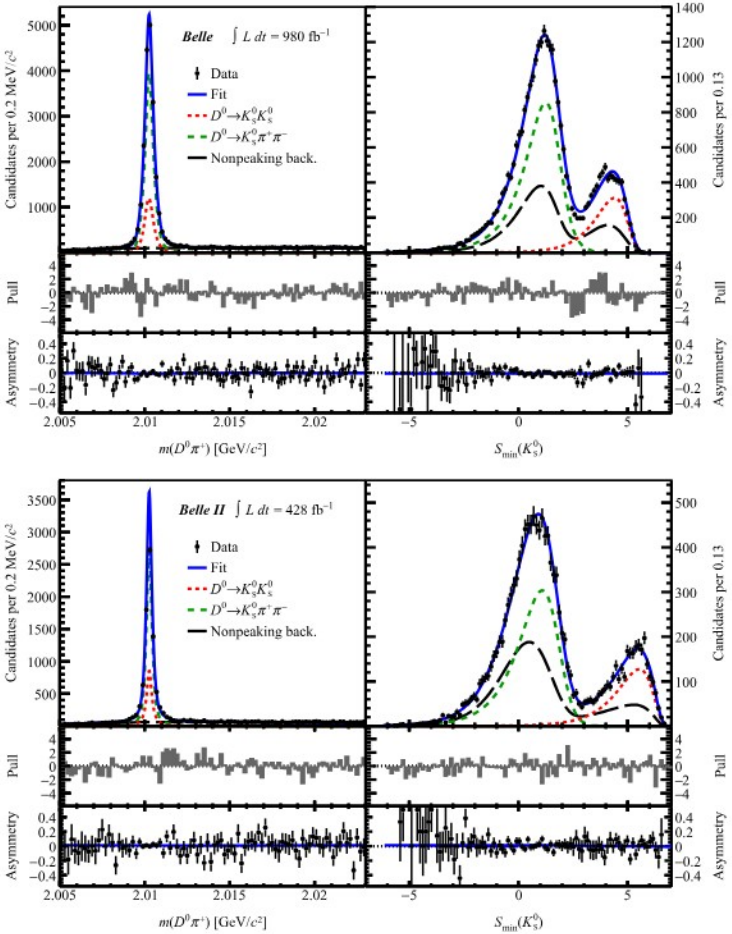
Reconstruct $D^{*+} \to \pi^+ D^0 (\to K_S K_S)$
• Main background: same-final-state $D^0 \to K_S \pi^+\pi^-$ decays

Separate with K_S flight distance signifcance L/σ:
$S_{min} = \log[\min(L1/\sigma1, L2/\sigma2)]$

Fit Δm and S_{min}, subtract detection asymmetries using $D^0 \to K^+K^-$ decays

Combine Belle and Belle II data:

$$A_{CP} = (-1.4 \pm 1.3 \pm 0.1)\,\%$$

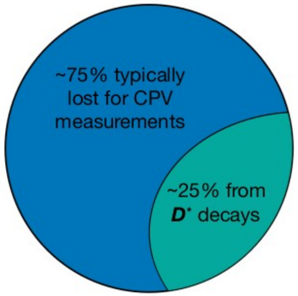


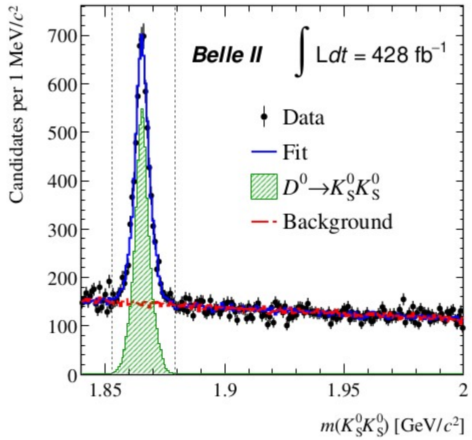
A_{CP} in $D^0 \to K_S K_S$: Charm-flavor-tag D^0

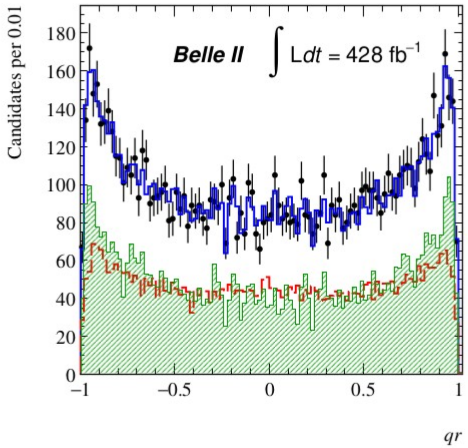
Charm favor tagger [PRD107,112010] : novel method to tag flavor of D^0 meson from other collision products ($K^{\pm}/\mu$ from other charm hadron) → new CFT-tag independent sample

Larger bkg wrt D^*-tag: train BDT with kinematic information, then cut on BDT output and S_{min}

Fit $m(K_S K_S)$ and product of tagged flavor q and tag quality r
Calibrate r with data to correct any detection asymmetry







Method	A_{CP} [%]
D^*-tag [PRD 111, 012015]	$-1.4 \pm 1.3 \pm 0.1$
CFT-tag	$1.3 \pm 2.0 \pm 0.3$
Combination	$\mathbf{-0.6 \pm 1.1 \pm 0.1}$

World's best determination

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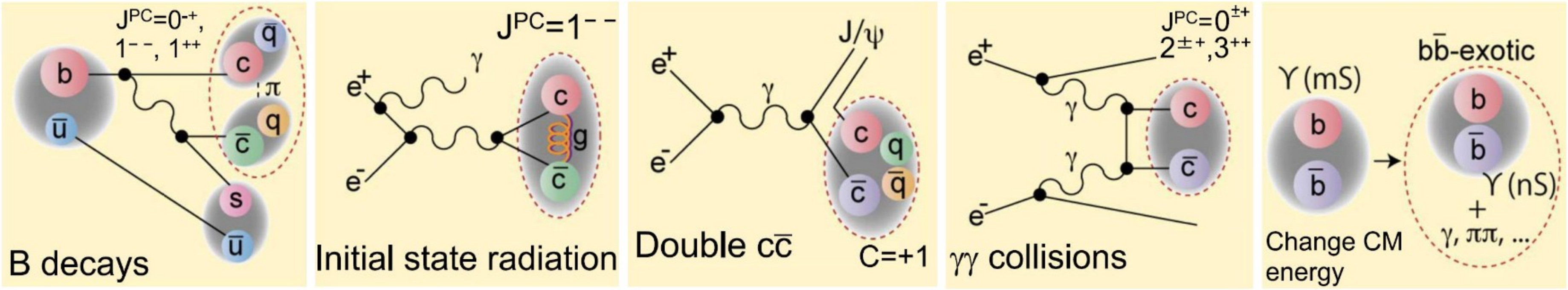
Quarkonium

Quarkonium physics at B-Factories

- Multiple production mechanisms



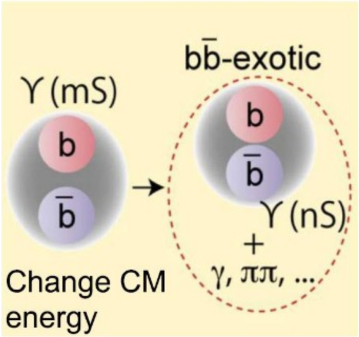
- Full event reconstruction, decays with neutral/soft particles
- Nominal $\sqrt{s}$ = 10.58 GeV = m(ϒ(4S)), potential to reach ~11 GeV

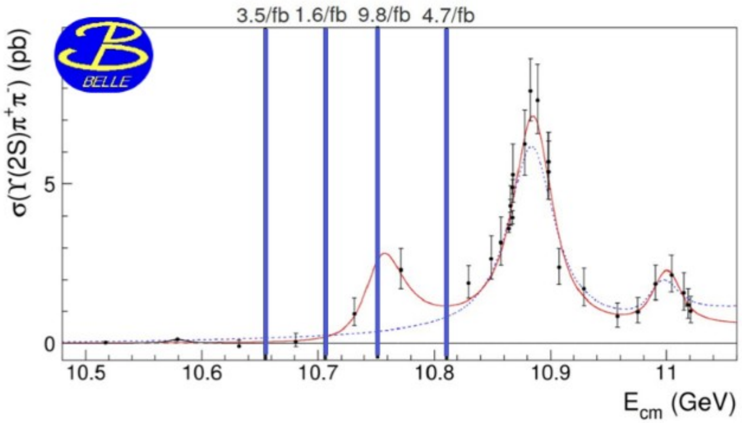
Quarkonium: above Υ(4S) energy scan

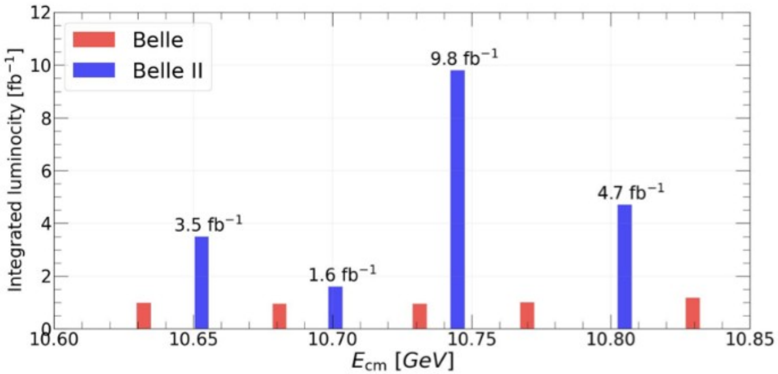
Today's focus: Energy dependence of $\sigma(e^+e^- \rightarrow \omega X_{bJ}(1P))$
- above Υ(4S) energy scan

Nov 2021: Belle II collected 19 fb^{-1} of unique data at energies above Υ(4S)
→ 4 energy scan points around 10.75 GeV in this region

Main motivation
- Confirm and study the Υ(10753)
- Improve the precision of exclusive cross-section below the Υ(5S)







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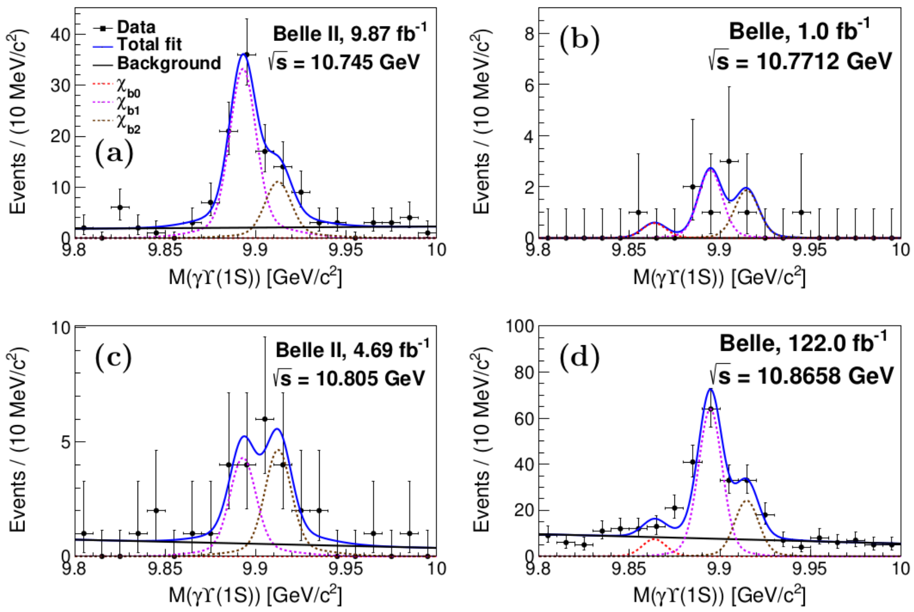
Energy dependence of σ($e^+e^- \rightarrow \omega \chi_{bJ}$ (1P))

$$\frac{B(\Upsilon(10753) \rightarrow \omega \chi_{b1})}{B(\Upsilon(10753) \rightarrow \omega \chi_{b2})}$$ predictions:

- Pure Υ(3D) state: **~15**
  PLB 738, 172 (2014)

- 4S-3D mixed state: **~0.2**
  PRD 104, 034036 (2021)



Data: Belle + Belle II scan data (10.73-11.02 GeV)

- Full reconstruction of $e^+e^- \rightarrow \omega \chi_{bJ}$ (1P),
  $\omega \rightarrow \pi^+\pi^-\pi^0$, χ_{bJ} (1P) $\rightarrow \gamma\Upsilon(1S)$, $\Upsilon(1S) \rightarrow l^+l^-$ (l=e, μ)

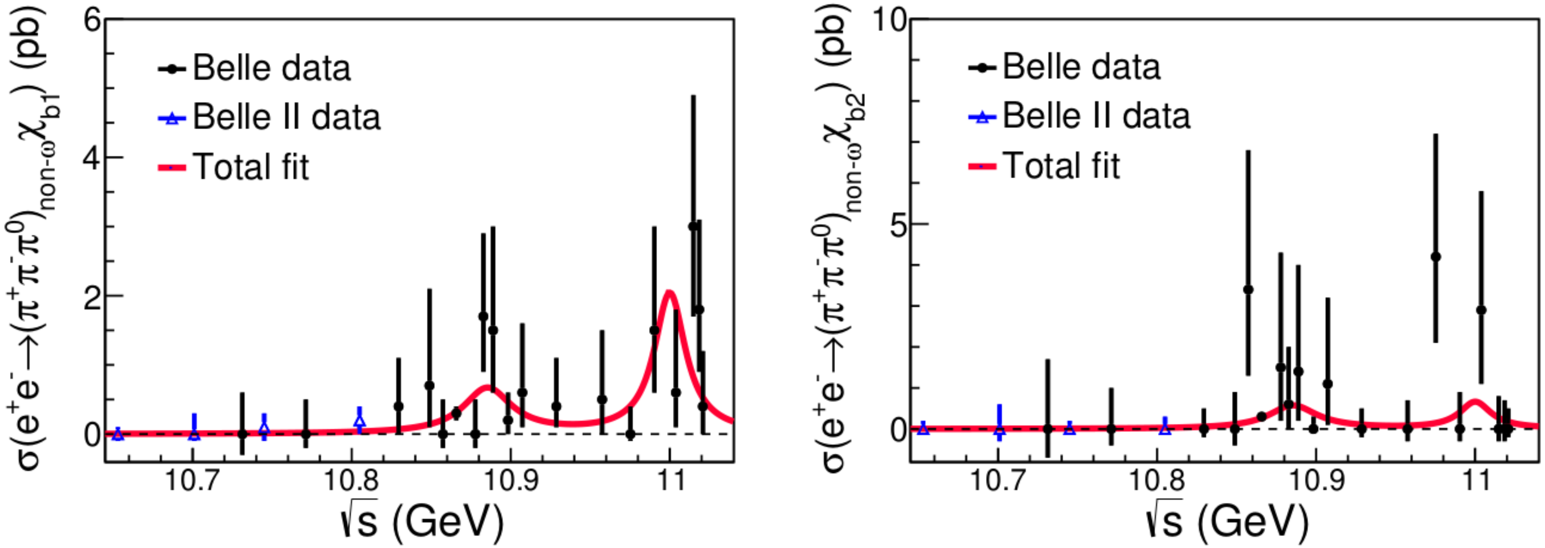
- Search for $e^+e^- \rightarrow (\pi^+\pi^-\pi^0)_{non-\omega} \chi_{bJ}$ (1P),
  same final state

Energy dependence of σ($e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\,\chi_{bJ}$ (1P))

$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to (\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b1})$	$(0.00 \pm 0.05 \pm 0.02)$ eV (<0.08 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to (\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b2})$	$(0.00 \pm 0.03 \pm 0.02)$ eV (<0.07 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to (\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b1})$	$(0.26 \pm 0.08 \pm 0.12)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to (\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b2})$	$(0.17 \pm 0.05 \pm 0.04)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to (\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b1})$	$(0.48 \pm 0.19 \pm 0.18)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to (\pi^+\pi^-\pi^0)_{\rm non-\omega}\chi_{b2})$	$(0.14 \pm 0.12 \pm 0.10)$ eV

- Decays of Y(5S) and Y(6S) into $(\pi^+\pi^-\pi^0)_{non\text{-}\omega}\,\chi_{bJ}$ (1P)

→ Possible explanation: cascade decay of Y(10860, 11020) → $Z_b\pi \to \chi_{bJ}\,\rho\pi$



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Energy dependence of $\sigma(e^+e^- \to \omega\chi_{bJ}(1P))$

$M(\Upsilon(10753))$	$(10756.1 \pm 3.4 \pm 2.7)$ MeV/c^2
$\Gamma(\Upsilon(10753))$	$(32.2 \pm 11.3 \pm 14.9)$ MeV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$	$(1.46 \pm 0.25 \pm 0.17)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$	$(1.29 \pm 0.38 \pm 0.30)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \omega\chi_{b1})$	$(0.02 \pm 0.04 \pm 0.04)$ eV ($<$0.09 eV)
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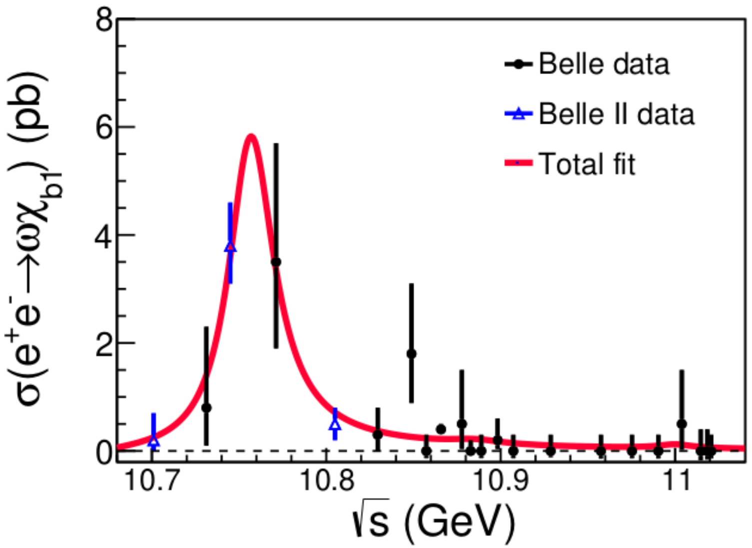
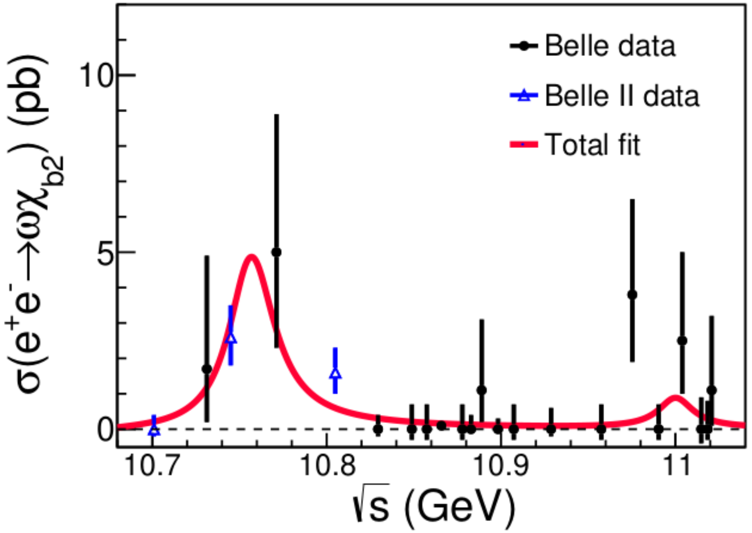
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b1})$	$(0.01 \pm 0.02 \pm 0.03)$ eV ($<$0.07 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b2})$	$(0.17 \pm 0.16 \pm 0.05)$ eV ($<$0.43 eV)

$$M = 10756.1 \pm 3.4 \pm 2.7 \text{ MeV}$$
$$\Gamma = 32.2 \pm 11.3 \pm 14.9 \text{ MeV}$$

- Mass and width consistent with $e^+e^- \to Y(nS)\,\pi\,\pi$





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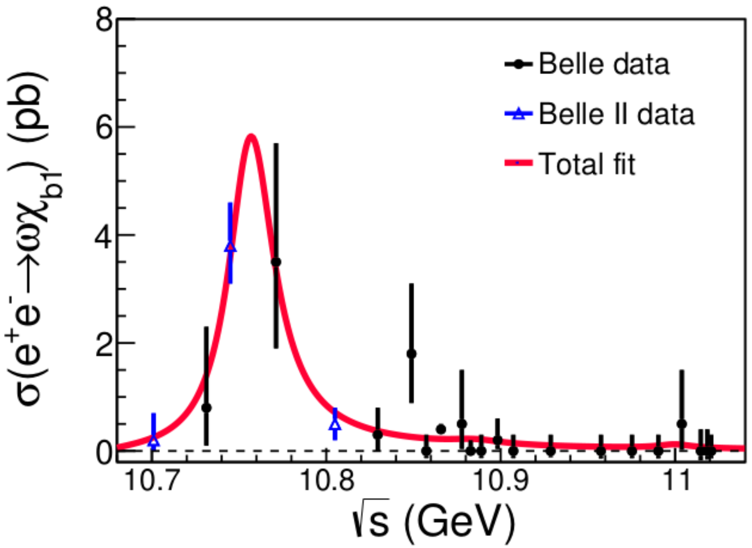
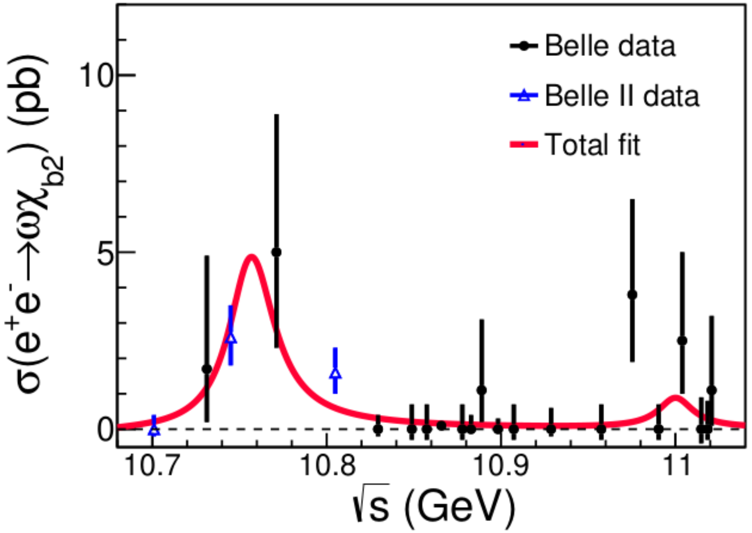
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b1})$	$(0.01 \pm 0.02 \pm 0.03)$ eV ($<$0.07 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b2})$	$(0.17 \pm 0.16 \pm 0.05)$ eV ($<$0.43 eV)

$$\left.\frac{\sigma(e^+e^- \to \omega\chi_{b1})}{\sigma(e^+e^- \to \omega\chi_{b2})}\right|_{\Upsilon(10753)} = 1.5 \pm 0.6$$

- Does not support pure 3D, 2.2σ discrepancy from S-D mixing



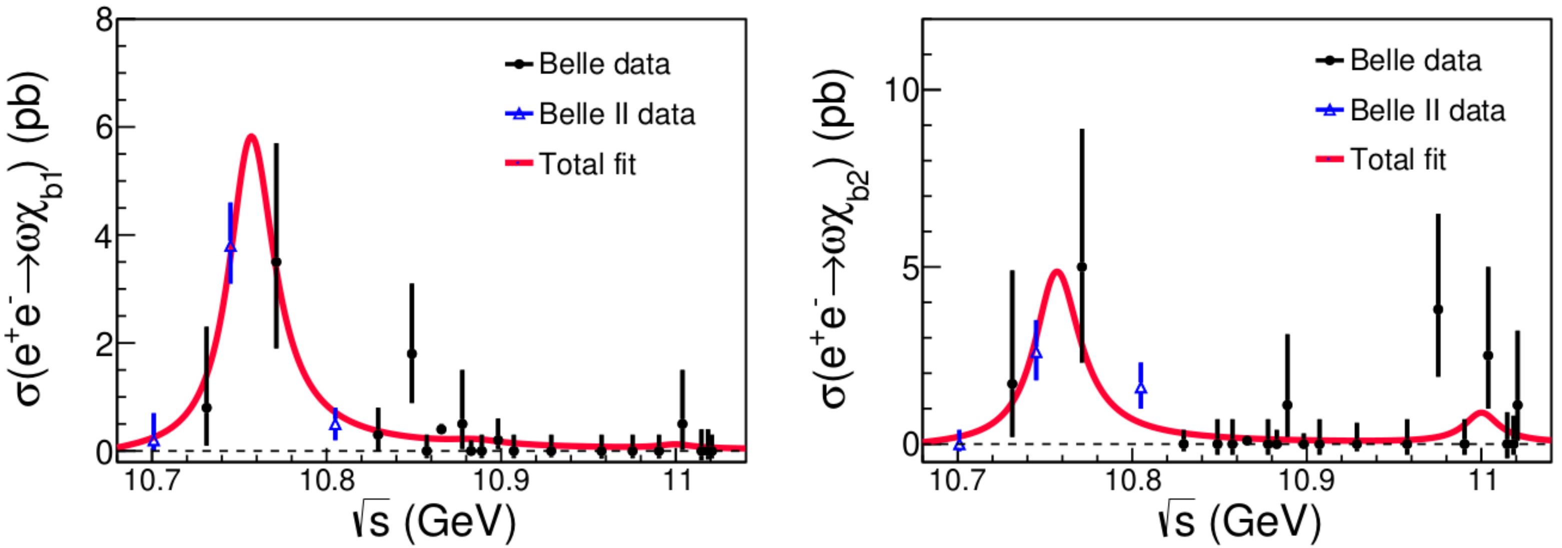


Energy dependence of σ($e^+e^- \to \omega\chi_{bJ}$ (1P))

$M(\Upsilon(10753))$	$(10756.1 \pm 3.4 \pm 2.7)$ MeV$/c^2$
$\Gamma(\Upsilon(10753))$	$(32.2 \pm 11.3 \pm 14.9)$ MeV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$	$(1.46 \pm 0.25 \pm 0.17)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$	$(1.29 \pm 0.38 \pm 0.30)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \omega\chi_{b1})$	$(0.02 \pm 0.04 \pm 0.04)$ eV (<0.09 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \omega\chi_{b2})$	$(0.00 \pm 0.04 \pm 0.02)$ eV (<0.07 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b1})$	$(0.01 \pm 0.02 \pm 0.03)$ eV (<0.07 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b2})$	$(0.17 \pm 0.16 \pm 0.05)$ eV (<0.43 eV)

$$\frac{\Gamma(\Upsilon(nS)\pi^+\pi^-)}{\Gamma(\omega\chi_{bJ})} = \begin{cases} < 0.9 \; at \; \Upsilon(10753) \\ > 28.1 \; at \; \Upsilon(5S) \end{cases}$$

- Different structure?



Summary

The Belle II physics program has strong potential both in charm and bottomonium physics

- charm physics: baryon decays, CPV measurements, ..
- quarkonium: unique potential above Υ(4S)

Today showed:

- First observation and best measurement of Ξ_c^+ branching fractions
- $\Lambda^+_c \to p K_S \pi$ BF measurement and first investigation of intermediate resonances
- World's best measurements of A_{CP} in $D^0 \to K_S K_S$
- Energy dependence of $\sigma(e^+e^- \to \omega X_{bJ}(1P))$

Only 1% of target lumi collected so far

- Run2 ongoing, with record-breaking instantaneous luminosity, with the goal of further testing the Standard Model