Knut and Alice Wallenberg Foundation

Charm and quarkonium at Belle and Belle II

Bianca Scavino (she/her)

on behalf of the Belle II collaboration

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Belle II

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Rencontres de Moriond since 1966

Moriond QCD

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

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Introduction

- Belle and Belle II

Charm

- A_{CP} in $D^0 \to \pi^0\pi^0$ NEW!
- A_{CP} in $D^0 \to K_S K_S$ NEW!
- Ξ_c^+ branching fraction NEW!

Quarkonium

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

Moriond QCD

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

Belle and Belle II Experiments

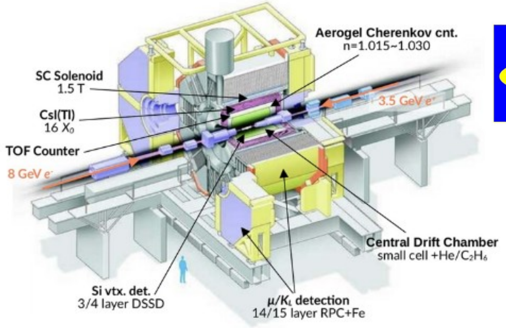
Belle and Belle II collect(ed) data at asymmetric e^+e^- colliders at or near the Υ(4S) resonance

- KEKB (1999-2010), peak lumi = $2\text{x}10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, L_{int} = 1/ab
- SuperKEKB, peak lumi = $5.1\text{x}10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
  Run1 (2019-2022), L_{int} = 0.42/ab
  Run2 (2024 – present), L_{int} = 0.15/ab

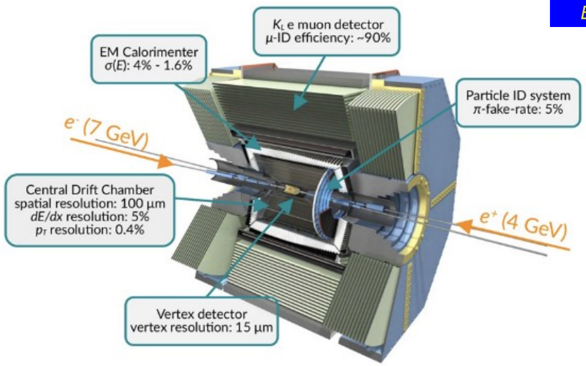
Belle & Belle II are now synergic experiments

- Belle data can be analyzed with the Belle II software
- Analyses with combined data samples
  → Common review procedures in place

BELLE @ KEKB



Belle II @ SuperKEKB



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Belle II: Physics Potential

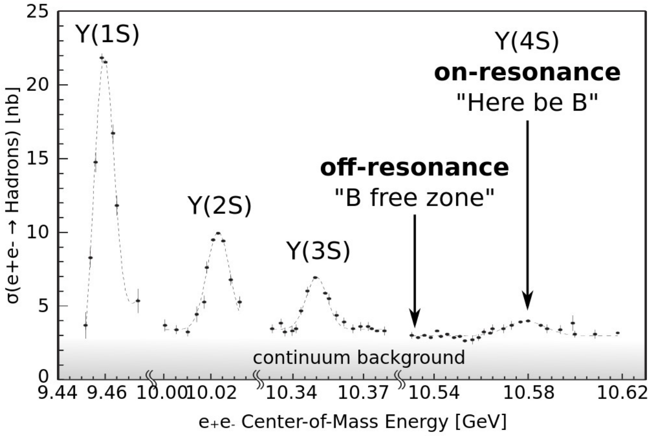
Belle II operates mainly at $\sqrt{s}$ = 10.58 GeV:

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

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

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

→ *B* & τ & *c* factory



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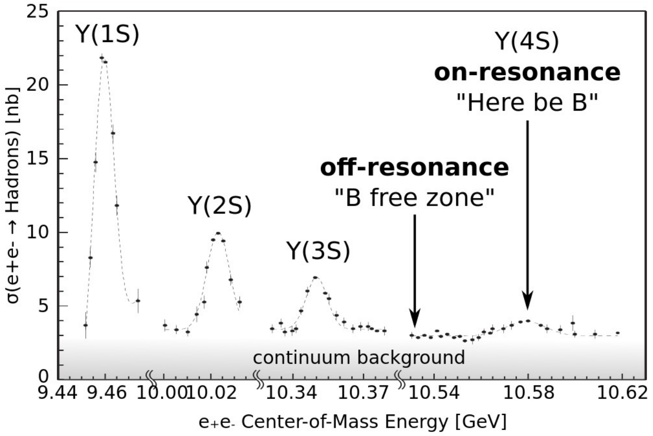
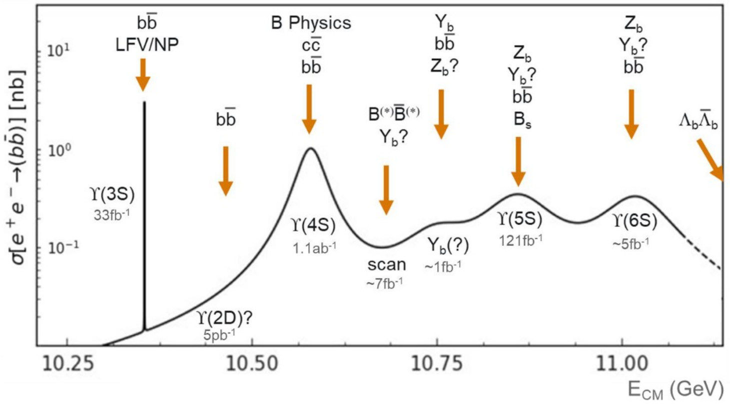


B-Factories can extend their physics programs with non-Υ(4S) data

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



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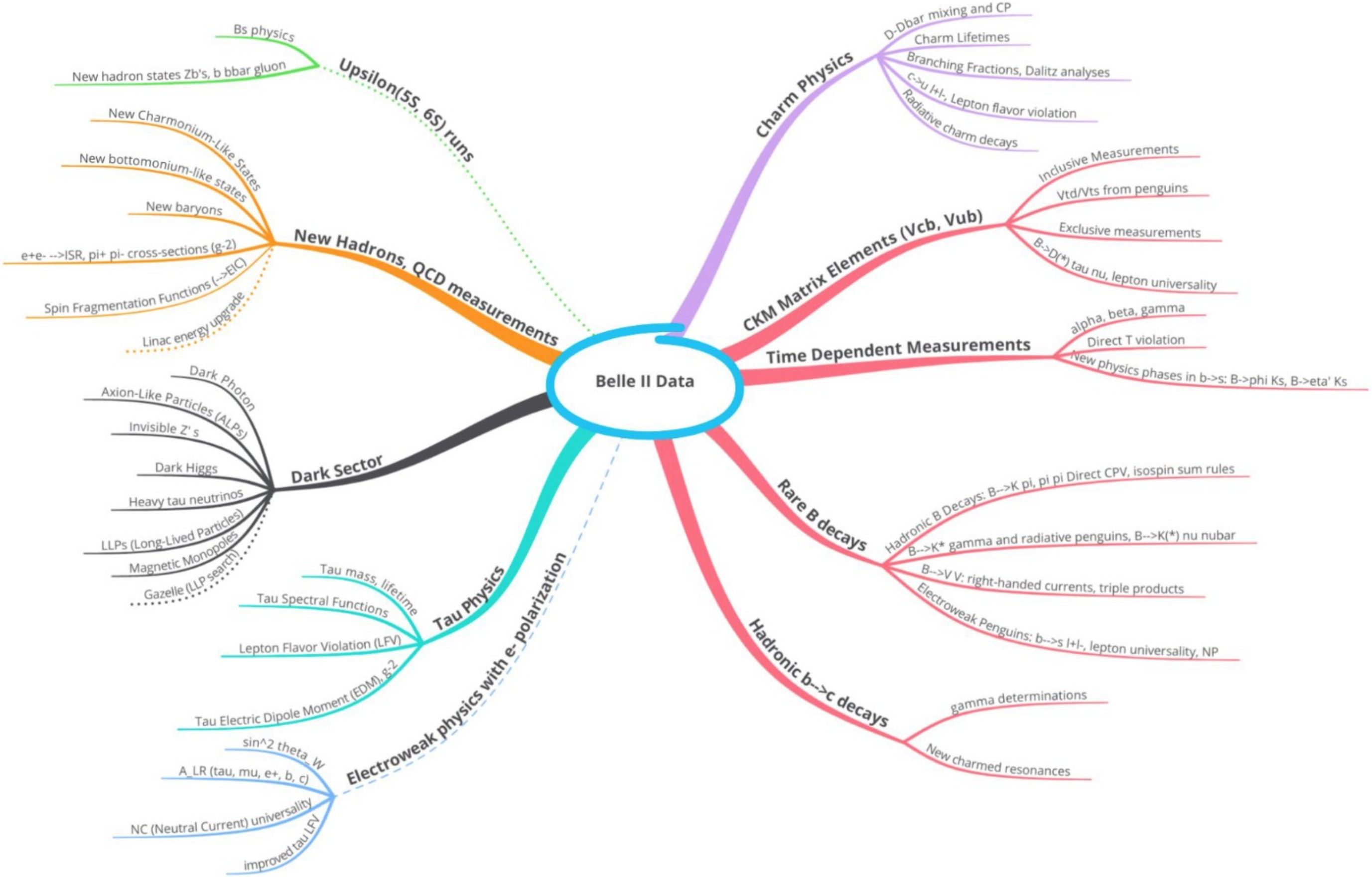
Belle II: Physics Program

[See: BIITIP, Snowmass Whitepaper]



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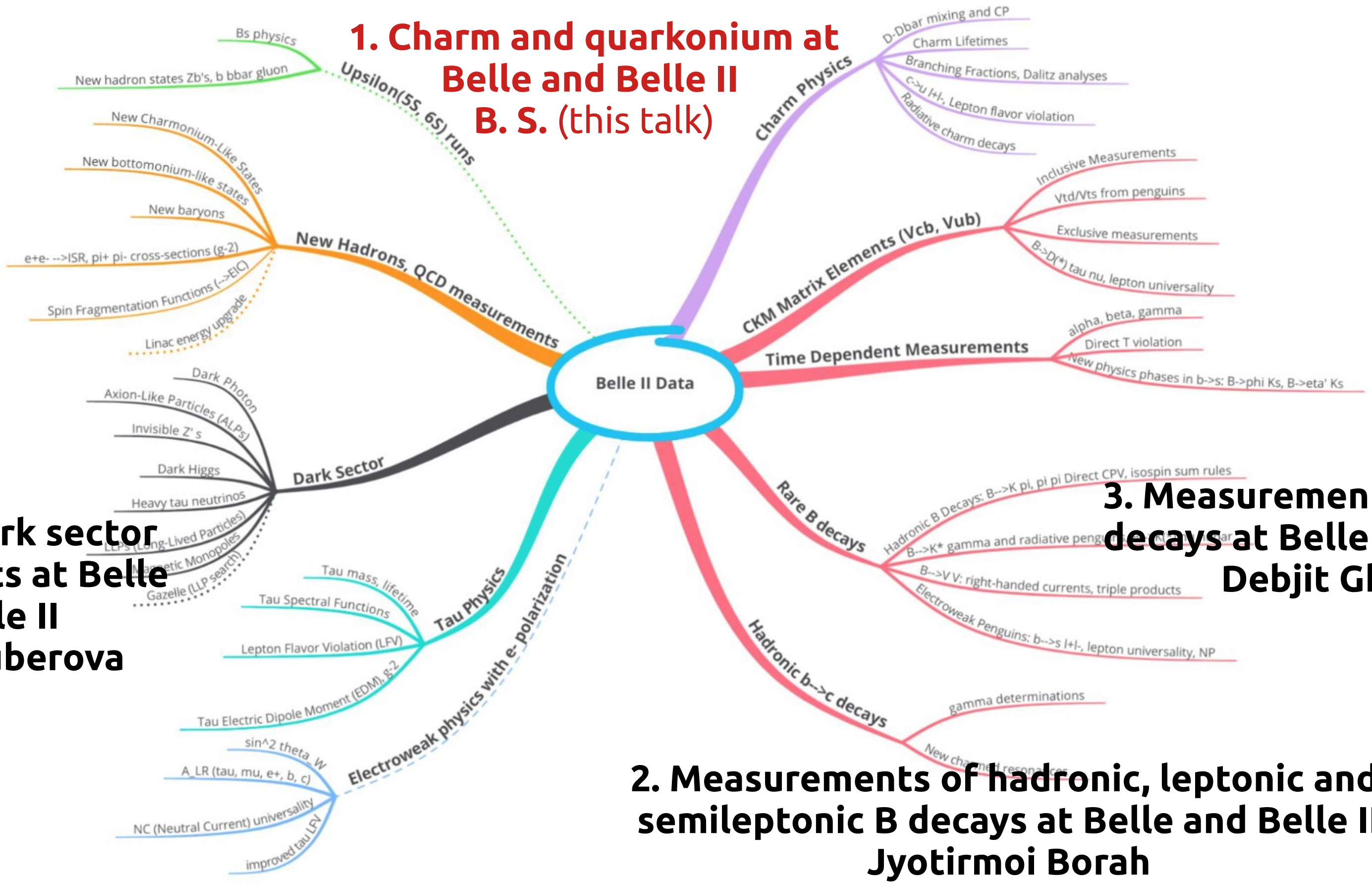
Belle II: Physics Program

[See: BIITIP, Snowmass Whitepaper]

1. Charm and quarkonium at Belle and Belle II
B. S. (this talk)



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

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

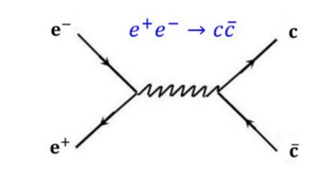
2. Measurements of hadronic, leptonic and semileptonic B decays at Belle and Belle II
Jyotirmoi Borah

Charm

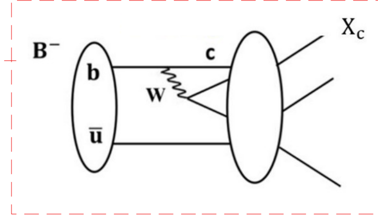
Charm physics at B-Factories

Two ways of producing charm at B-Factories

- Two charmed hadrons produced from continuum



- One or more charmed hadrons produced in B decays



Rich physics program

- Mesons: Precise measurement in Cabibbo-suppressed decays, non-SM physics can contribute at a detectible level
  Most interesting probes: CPV measurements
  expect low values in charm sector ($O(10^{-3})$)

NEW!
Today
- A_{CP} in $D^0 \to \pi^0\pi^0$
- A_{CP} in $D^0 \to K_S K_S$

- Baryons: Conflicting or missing predictions for BF and lifetimes
  → results to verify models

NEW!
Today
- Ξ_c^+ branching fraction

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

NEW!

Currently limiting precision on isospin-related $D \to \pi\pi$ sum rule

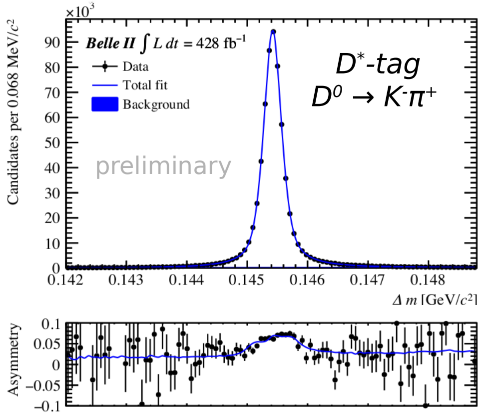
$$R = \frac{A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)} + \frac{A_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)}$$

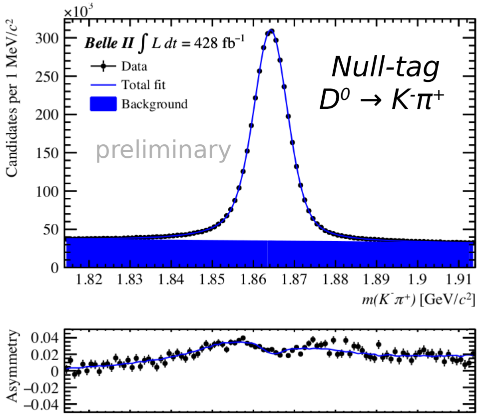
- Expected R ~ 0 in SM
- Measured $(0.9 \pm 3.1) \times 10^{-3}$

Strategy:

- Measure observed asymmetry in $D \to \pi^0\pi^0$ channel
- Correct instrumental effects subtracting asymmetries measured in $D \to K^-\pi^+$

Control channels





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

NEW!

Reconstruct $D^{*+} \to \pi^+ D^0 (\to \pi^0 \pi^0)$
4 ɣ final state, large background

Train BDT to suppress background w/ information on
ɣ kinematics and calorimeter clusters

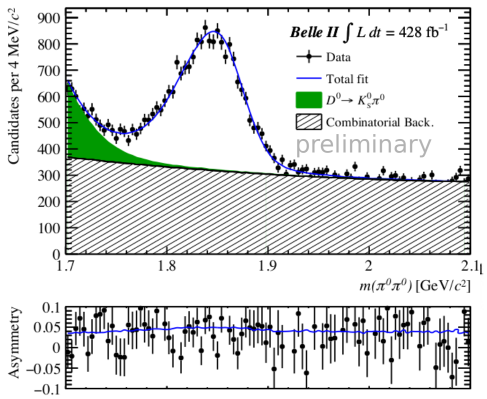
- Fit D^{*+}-D^0 mass difference (Δm) and $m(\pi\pi)$
  in forward and backward calorimeter regions

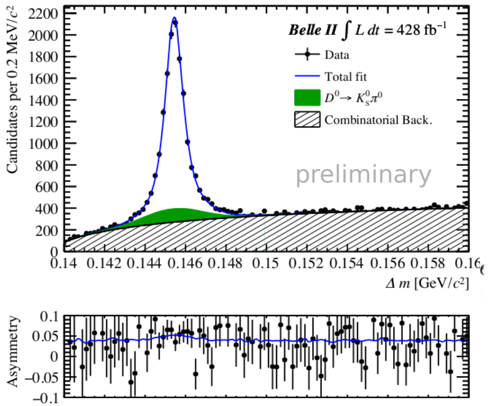
- Subtract detection asymmetries with D^*-tag and
  null-tagged $D^0 \to K^- \pi^+$

$$A_{CP} = (0.30 \pm 0.72 \pm 0.20)\ \%$$

$$R = (1.5 \pm 2.5) \times 10^{-3}$$

20% improvement in sum-rule precision





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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 interference between $c \to us\bar{s}$ and $c \to ud\bar{d}$
- Expect A_{CP}~1% **PRD 92, 054036**

→ Larger values would indicate non-SM physics

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

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

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

BELLE: $A_{CP}(D^0 \to K_S K_S) = -0.02 \pm 1.53(stat) \pm 0.02(sys) \pm 0.17$ (cont.mode) **PRL 119, 171801 (2017)**

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

Nuisance asymmetries induced by production and detection mechanisms

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

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:

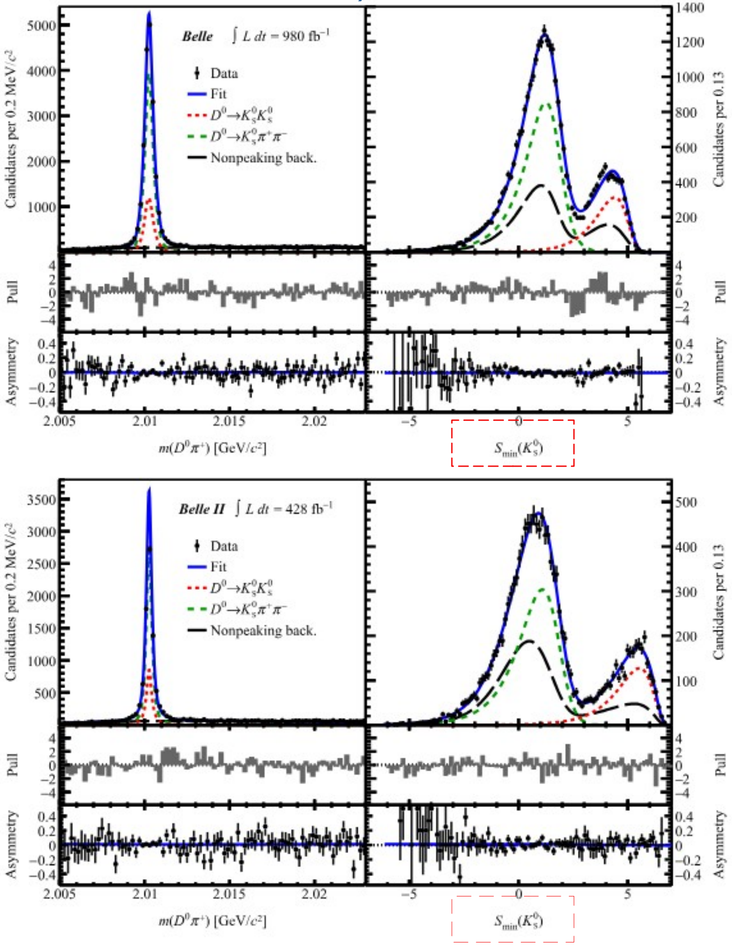
$$S_{min} = \log[\ \min(L1/\sigma1, L2/\sigma2)\ ]$$

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

Combine Belle and Belle II data:

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

PRD 111, 012015



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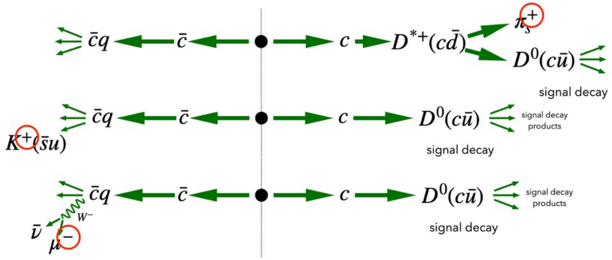
A_{CP} in $D^0 \to K_S K_S$: Charm-flavor-tag D^0

NEW!

Charm favor tagger: novel method to tag flavor of D^0 meson from other collision products

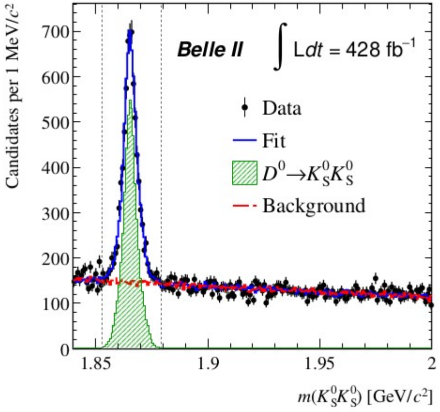
PRD107, 112010

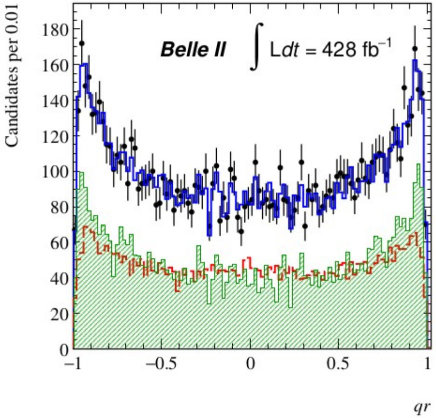


→ new CFT-tag independent sample

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

Fit $m(K_S K_S)$ and q (tagged flavor) x r (tag quality)
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	$\mathbf{-0.6 \pm 1.1 \pm 0.1}$

Worlds' best determination

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Ξ_c^+ branching fractions

JHEP03(2025)061
arXiv:2503.17643

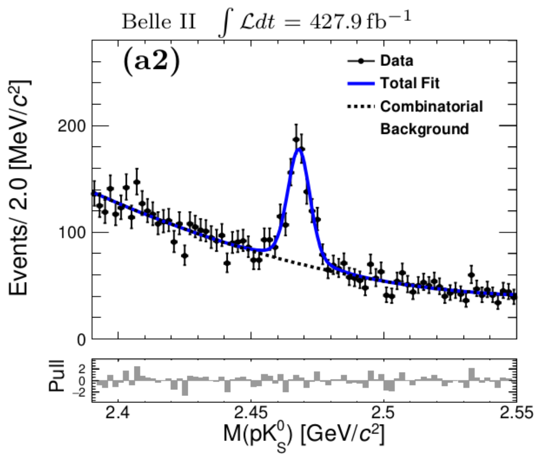
NEW!

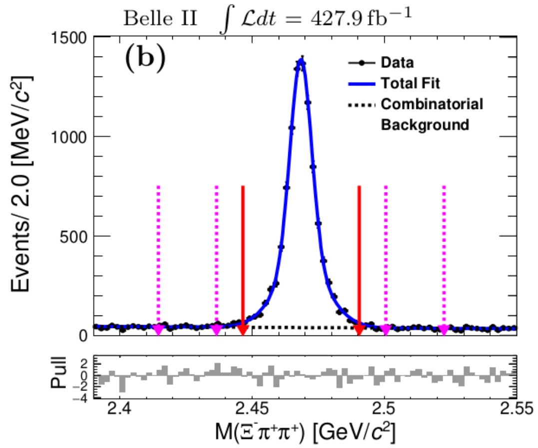
Ξ^+_c decay channels: (many) not yet measured

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) $\Xi^+_c \to \Xi^0 K$, $\Xi^+_c \to pK_S$, $\Xi^+_c \to \Lambda\pi$, $\Xi^+_c \to \Sigma\,\pi$

Analysis strategy:
- Reconstruct intermediate baryons Λ, Σ, Ξ, optimize selection ranges on each invariant mass
- Signal yields: fitting the invariant mass
- Branching fractions: $\Xi^+_c \to \Xi^- \pi^+\pi^+$ as normalization mode





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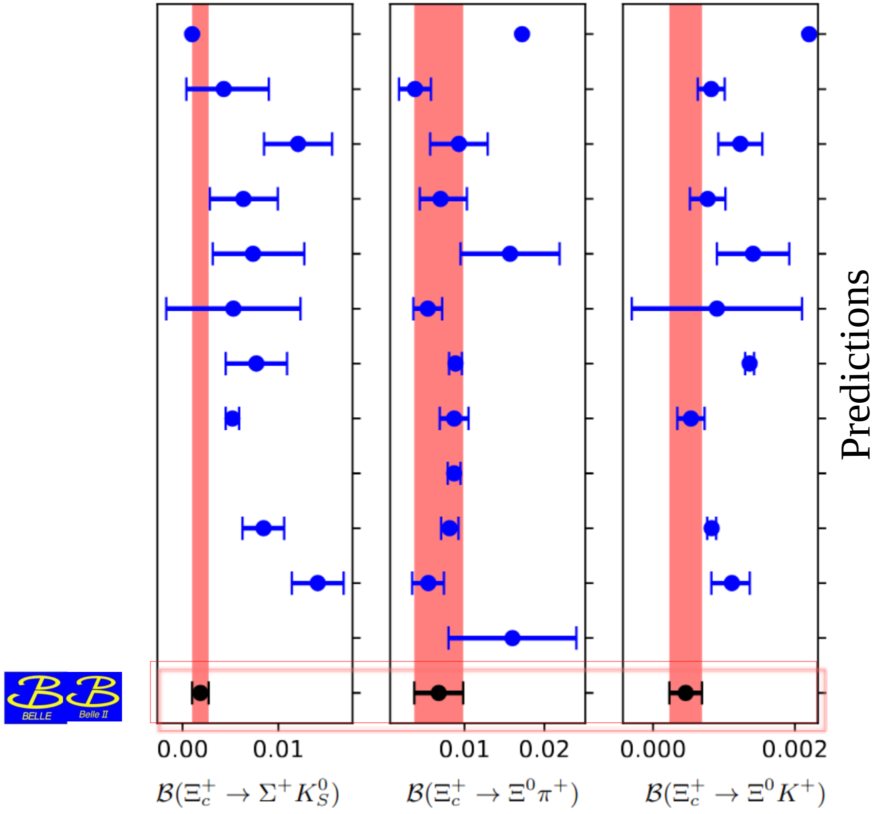
Ξ_c^+ branching fractions

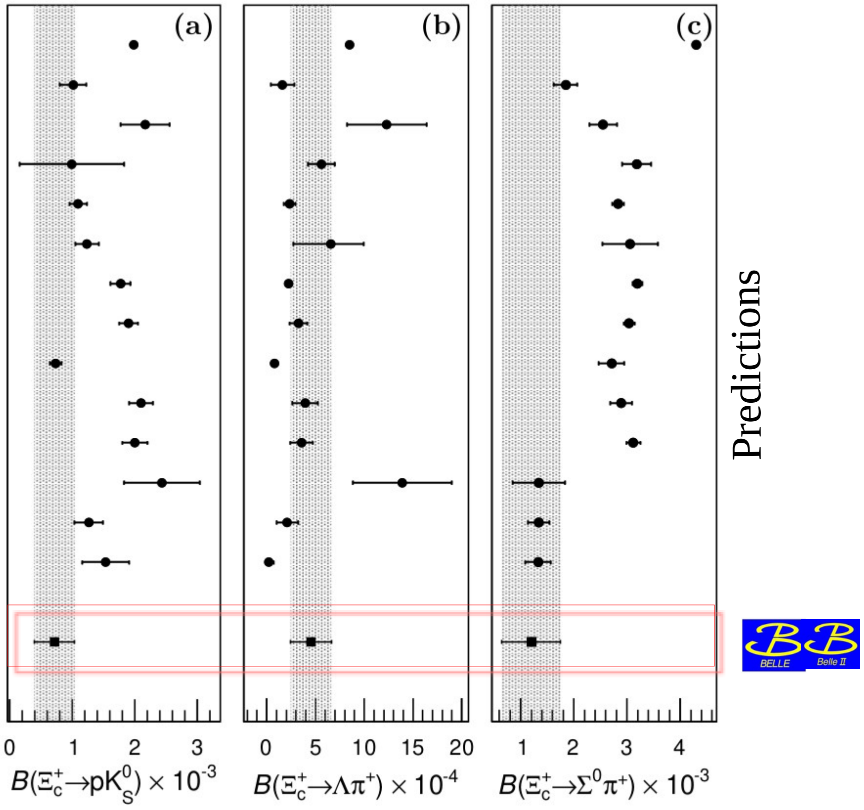
NEW!

First or most precise measurements!

arXiv:2503.17643



JHEP03(2025)061



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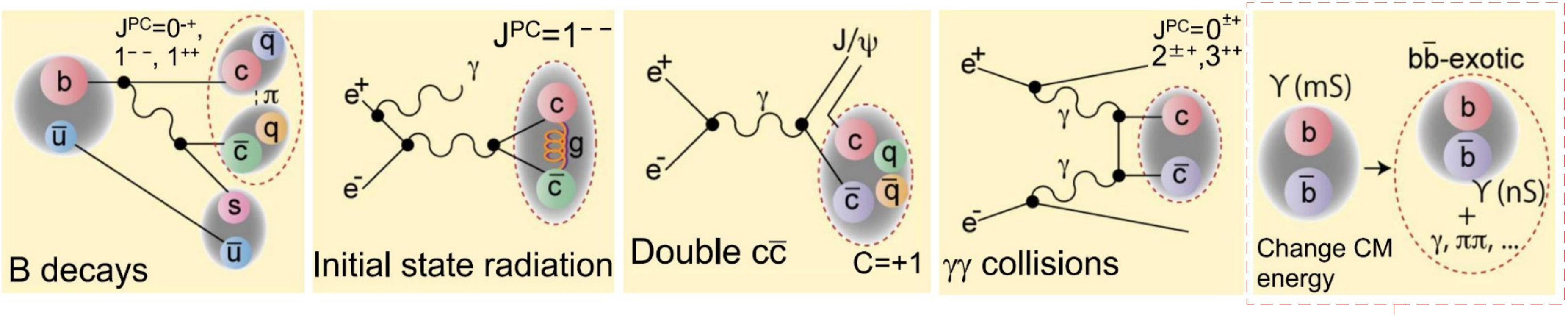
Quarkonium

Quarkonium physics at B-Factories

- Multiple production mechanisms



- Nominal √s = 10.58 GeV = m(Υ(4S)), potential to reach ~11 GeV

- Full event reconstruction, decays with neutral/soft particles

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Quarkonium: above Υ(4S) energy scan

Above Υ(4S) energy scan (Nov 2021)

- Belle II collected 19 fb^{-1} of unique data

→ 4 energy scan points around 10.75 GeV

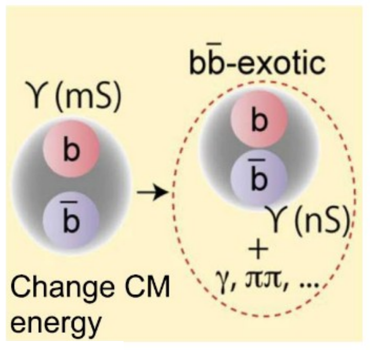
Main motivation

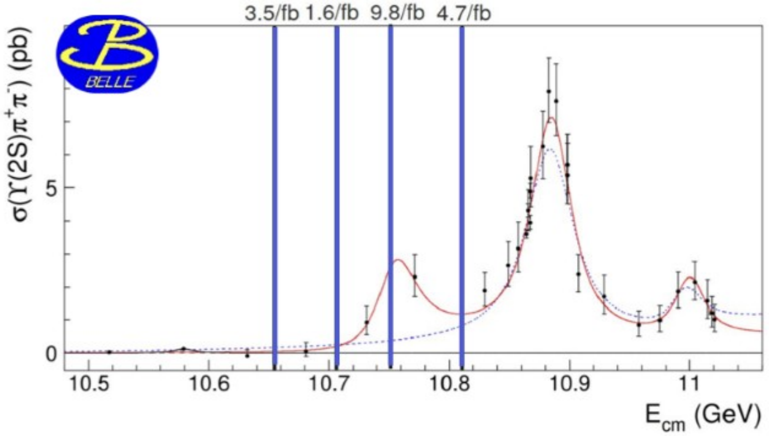
- Confirm and study the Υ(10753)
- Improve the precision of exclusive cross-section below the Υ(5S)

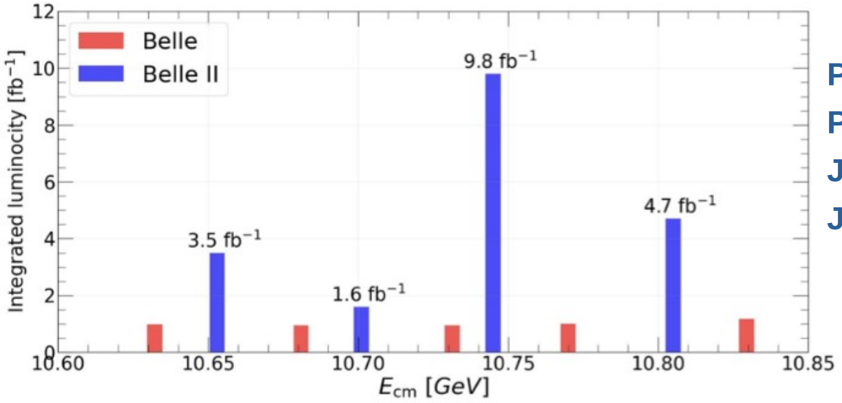
NEW!

Today

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







PRL 130, 091902 (2023)
PRD 109, 072013 (2014)
JHEP 07, 116 (2024)
JHEP 10, 114 (2024)

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

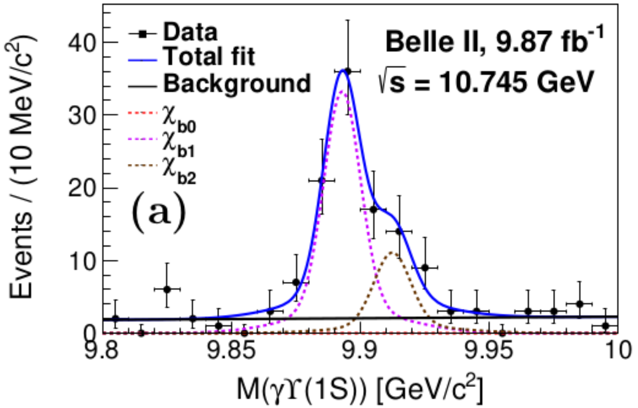
NEW!

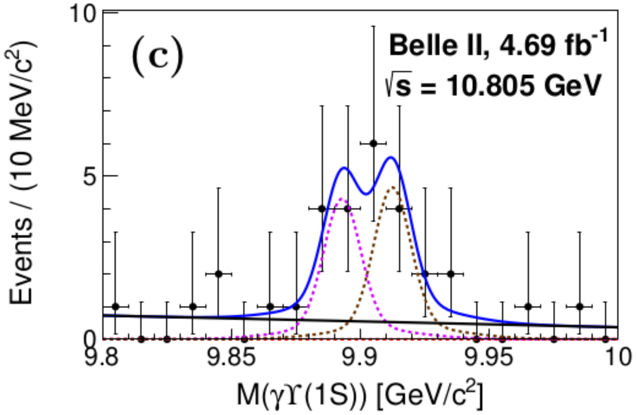
$$\frac{\sigma(\Upsilon(10753) \to \omega X_{b1})}{\sigma(\Upsilon(10753) \to \omega X_{b2})}$$ Predictions:

- Pure Υ(3D) state: **~15** **PLB 738, 172 (2014)**
- 4S-3D mixed state: **~0.2** **PRD 104, 034036 (2021)**

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

- Full reconstruction of $e^+e^- \to \omega X_{bJ}$ (1P),
  $\omega \to \pi^+\pi^-\pi^0$, X_{bJ} (1P) $\to \gamma\Upsilon(1S)$, $\Upsilon(1S) \to l^+l^-$ (l=e, μ)
- Search for $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega} X_{bJ}$ (1P), same final state





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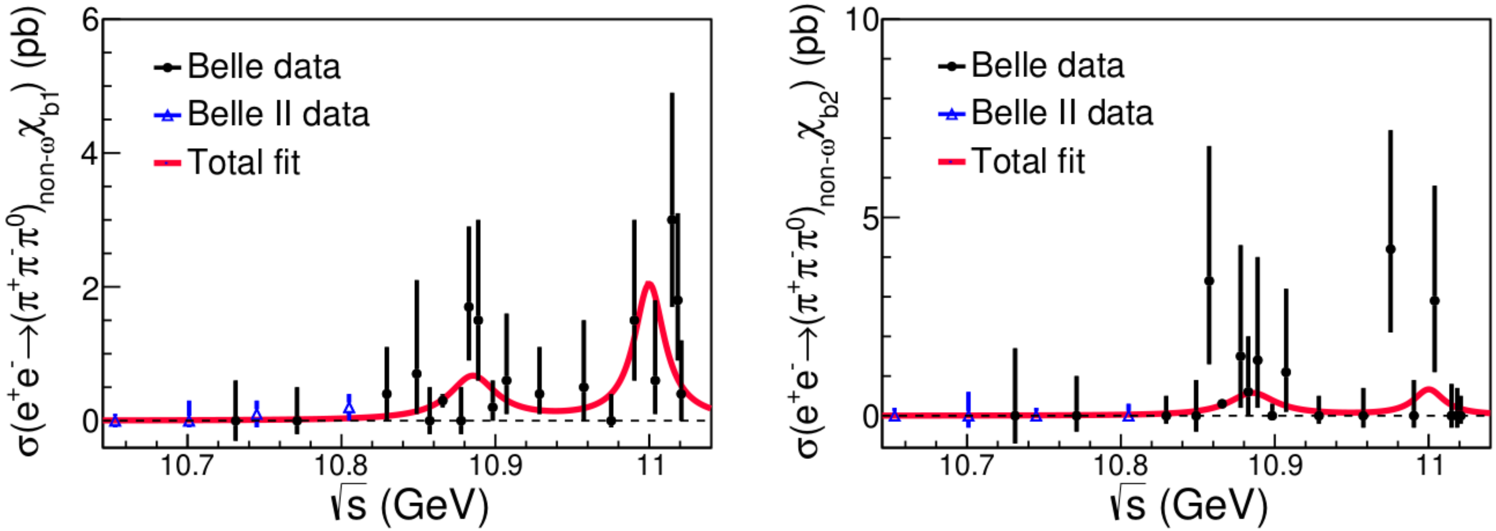
Energy dependence of σ($e^+e^- \rightarrow (\pi^+\pi^-\pi^0)_{non-\omega} \chi_{bJ}(1P)$)

NEW!

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

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



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

NEW!

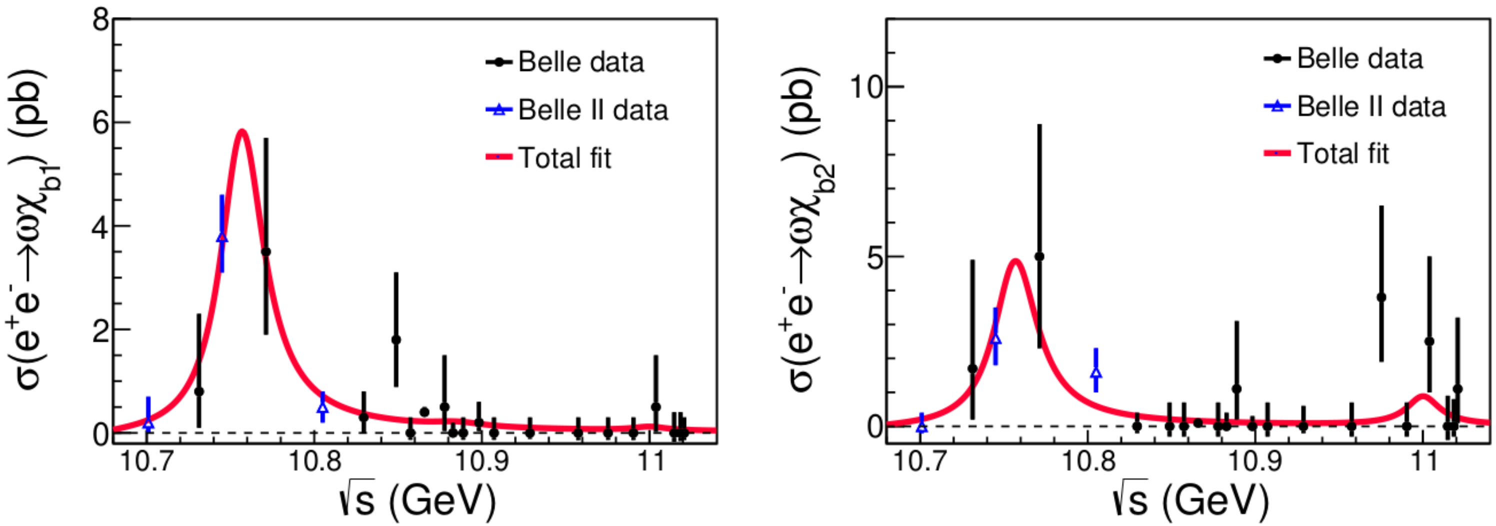
- Mass and width consistent with $e^+e^- \to Y(nS)\,\pi\pi$

M = 10756.1 ± 3.4 ± 2.7 MeV

Γ = 32.2 ± 11.3 ± 14.9 MeV

- $\dfrac{\sigma(Y(10753) \to \omega X_{b1})}{\sigma(Y(10753) \to \omega X_{b2})}$ = 1.5 ± 0.6 → no support 3D, 2.2σ discrepancy from S-D mixing

- $\dfrac{\Gamma(Y(nS)\,\pi^+\pi^-)}{\Gamma(\omega X_{bj})} = \begin{cases} < 0.9 \text{ at } Y(10753) \\ > 28.1 \text{ at } Y(5S) \end{cases}$ → Different structure?



Summary

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

- Charm physics: CPV measurements, baryon decays, ..
- Quarkonium: unique potential above Y(4S)

Today showed:

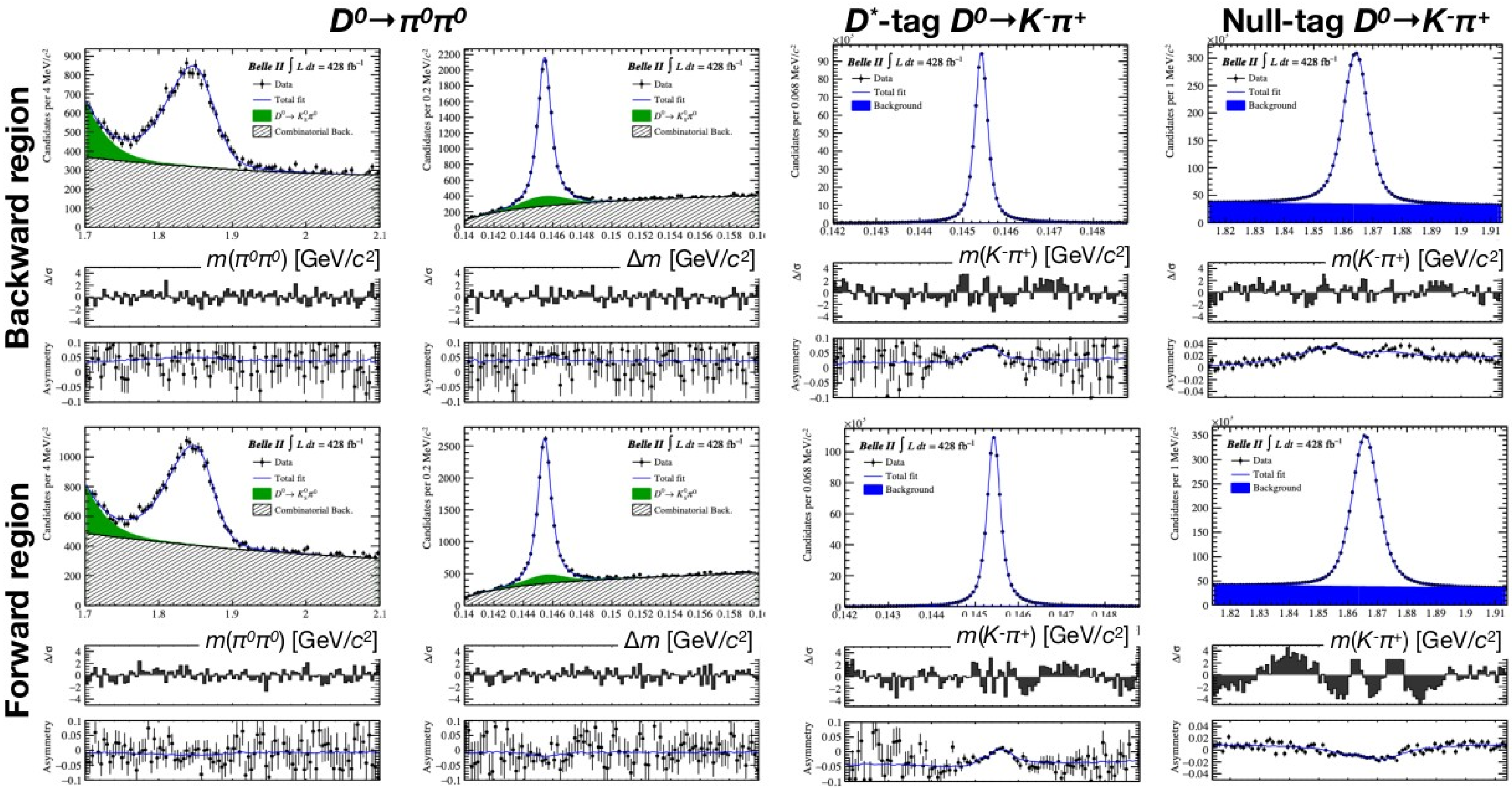
- NEW! First observation and best measurement of Ξ_c^+ branching fractions
- NEW! World's best measurements of A_{CP} in $D^0 \to \pi^0 \pi^0$ (final state unique for Belle II)
- NEW! World's best measurements of A_{CP} in $D^0 \to K_S K_S$
- NEW! Energy dependence of $\sigma(e^+e^- \to \omega X_{bJ} (1P))$

Only 1% of target luminosity collected so far

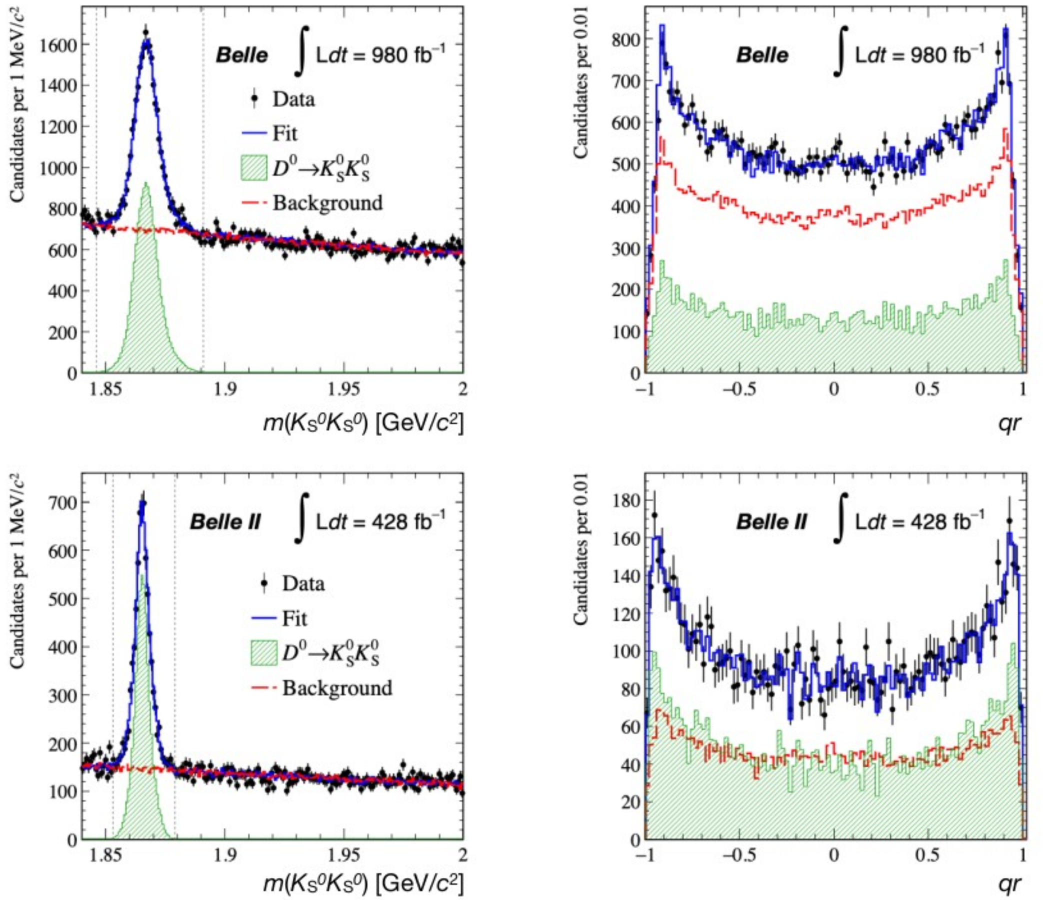
- Run2 ongoing, with record-breaking instantaneous luminosity
- Rich and extensive physics program, goal of further testing the Standard Model

BACKUP

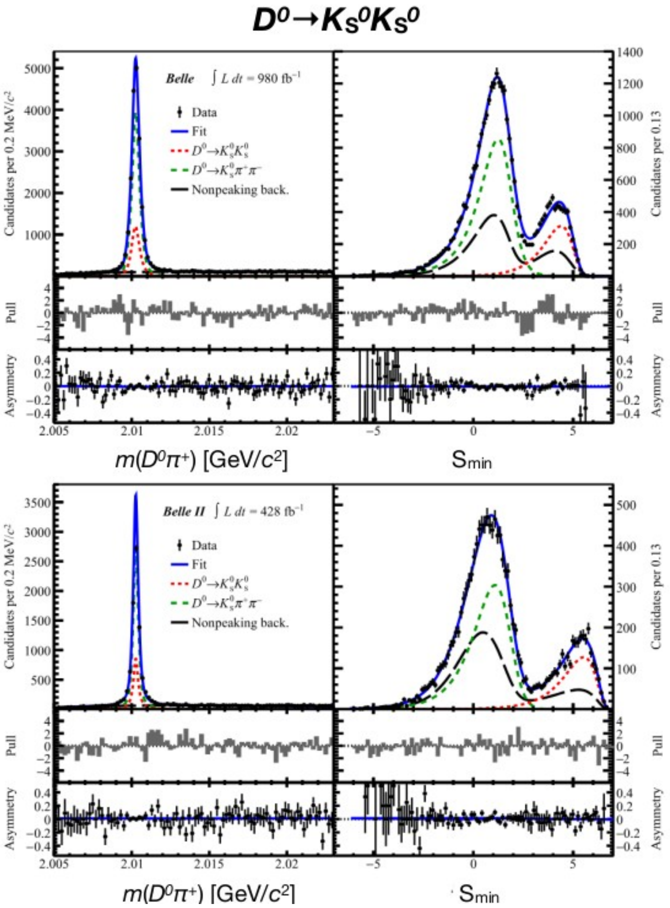
$D^0 \to \pi^0\pi^0$, Full set of fits

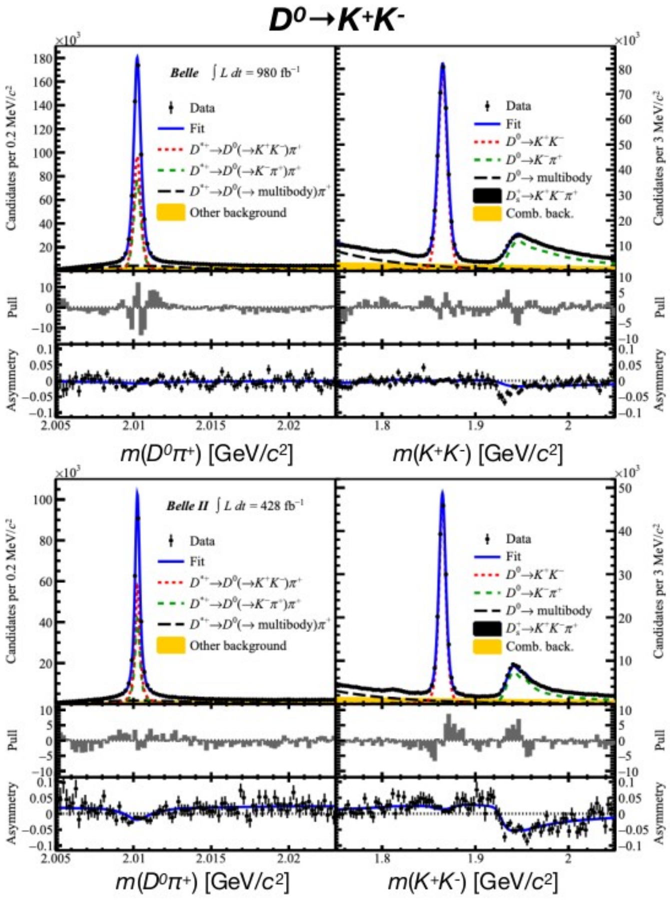


CFT-tag $D^0 \to K_S K_S$, Full set of fits



D*-tag $D^0 \to K_S K_S$, Full set of fits





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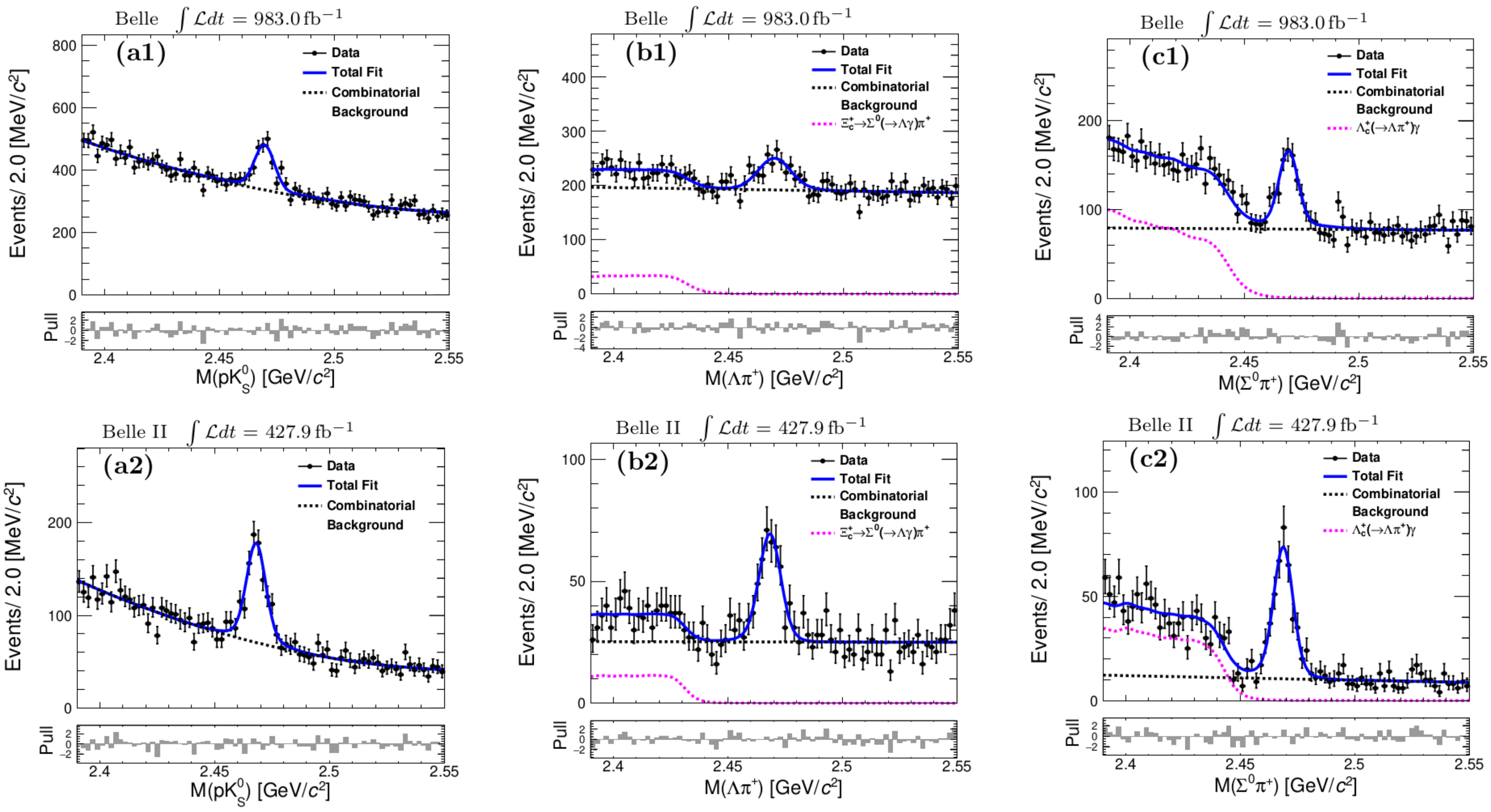
Ξ_c^+ invariant mass fits



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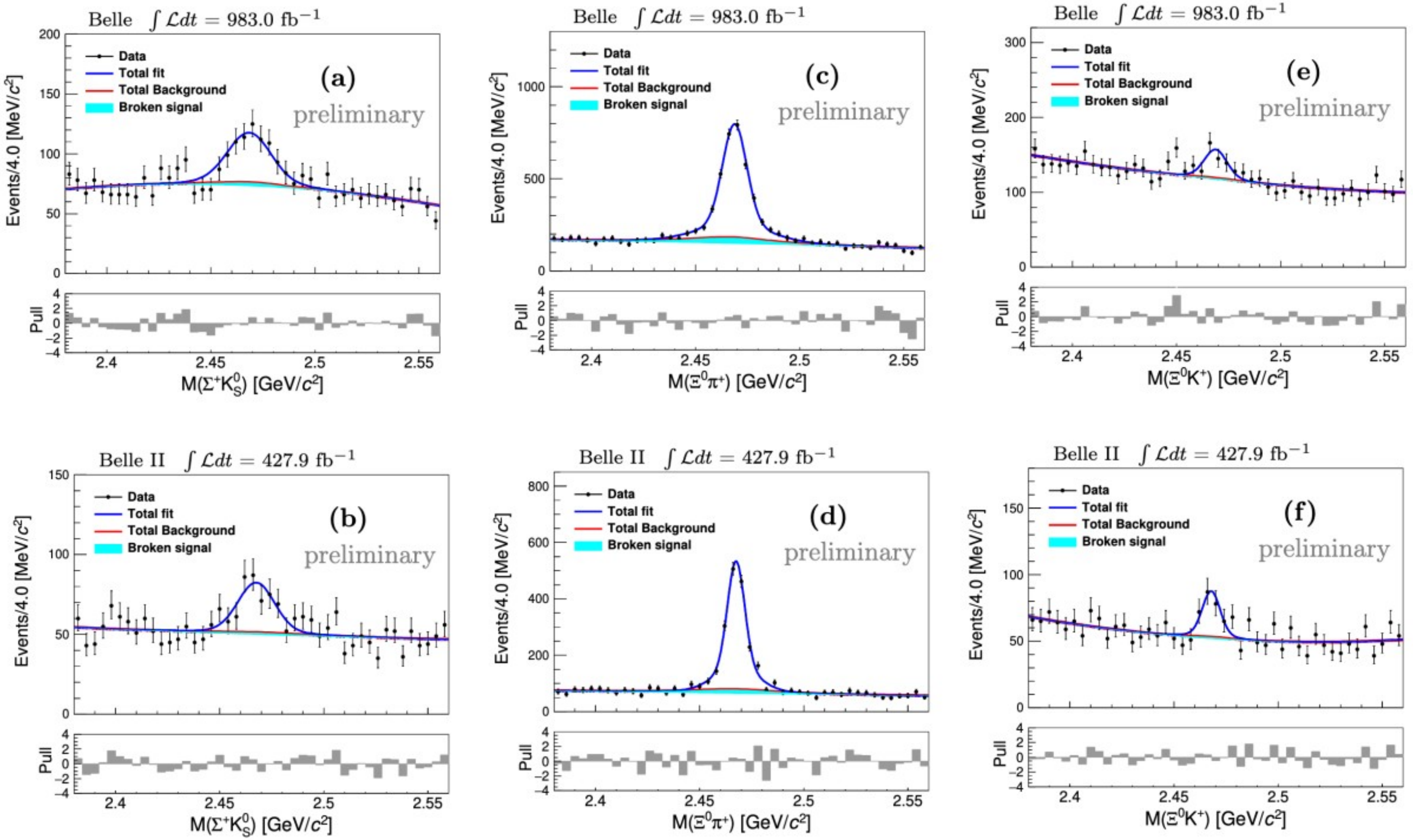
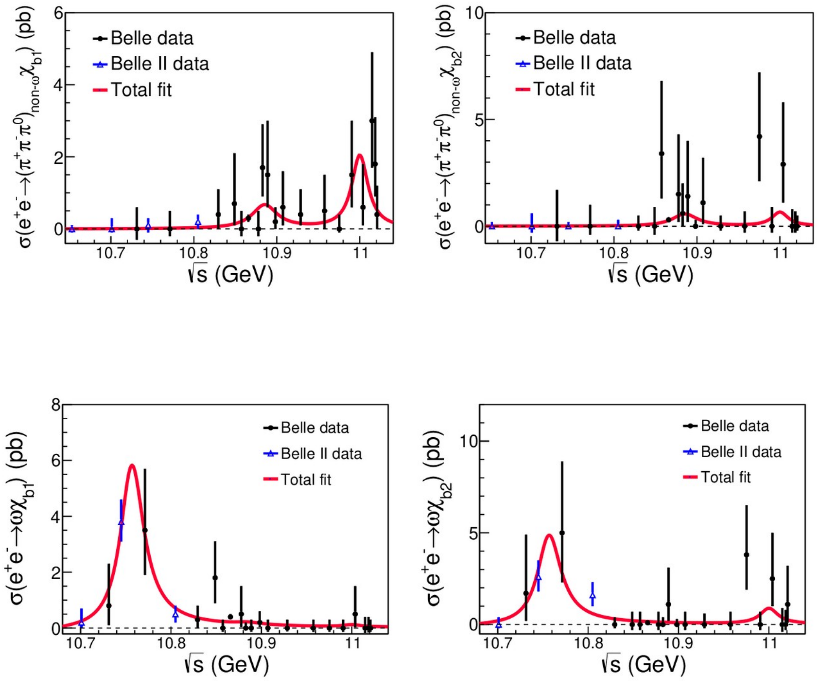
Ξ_c^+ invariant mass fits



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

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

$M(\Upsilon(10753))$	$(10756.1 \pm 3.4 \pm 2.7)$ 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)



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