Overview of the Belle II experiment

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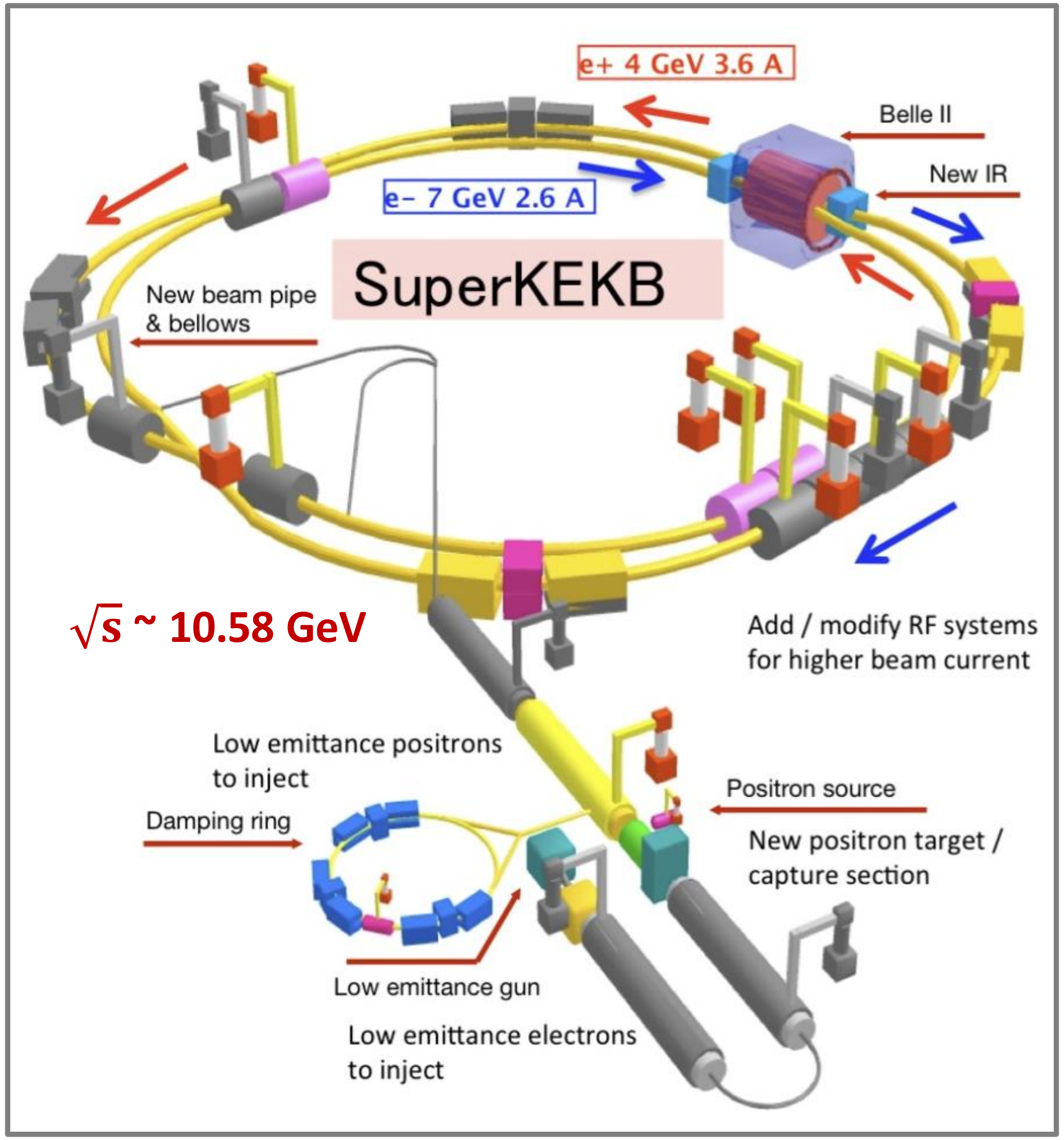
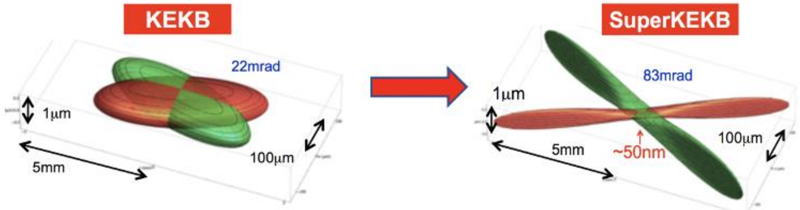
SuperKEKB and Belle II



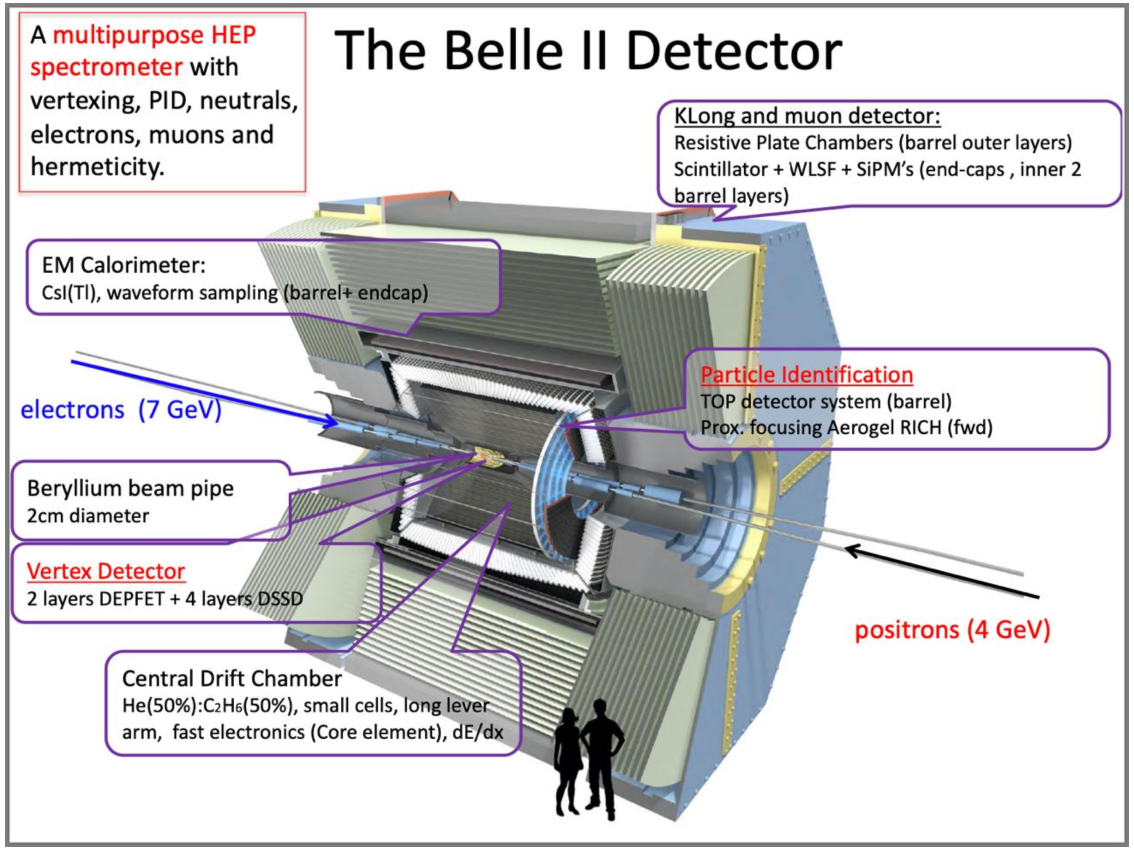
$\sqrt{s}$ ~ 10.58 GeV



Nano-beam design:

Beam squeezing: ×20 smaller; Beam current: ×2 larger

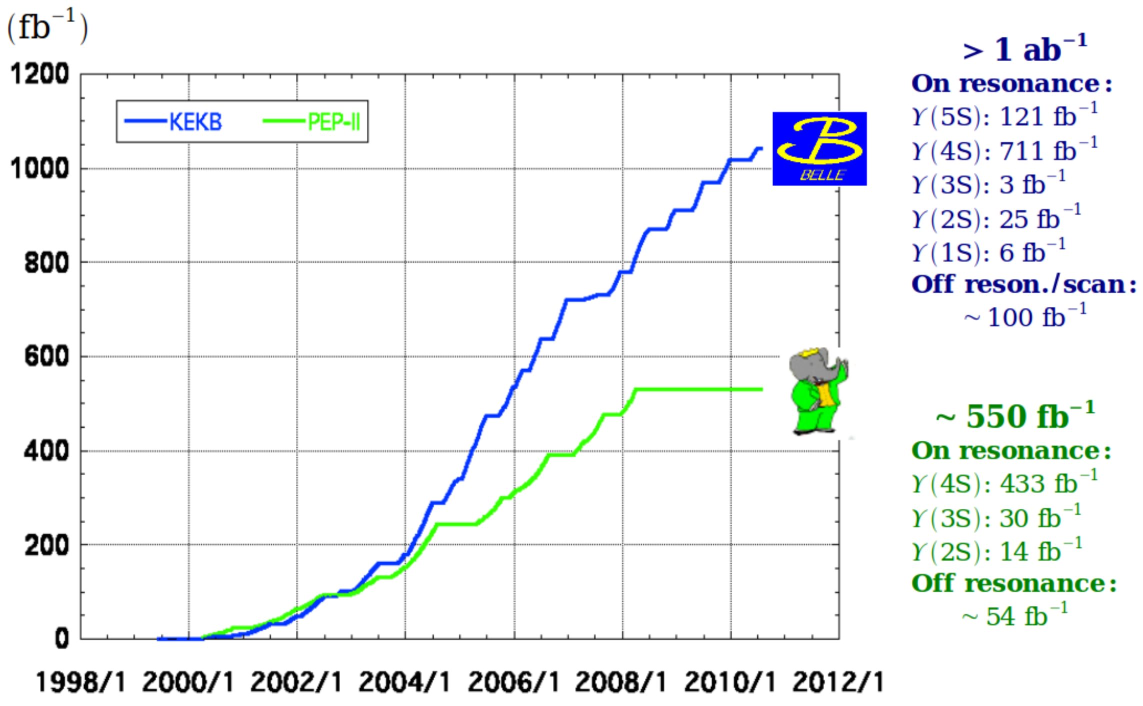
Target peak luminosity: KEKB×30



Belle and Belle II Datasets

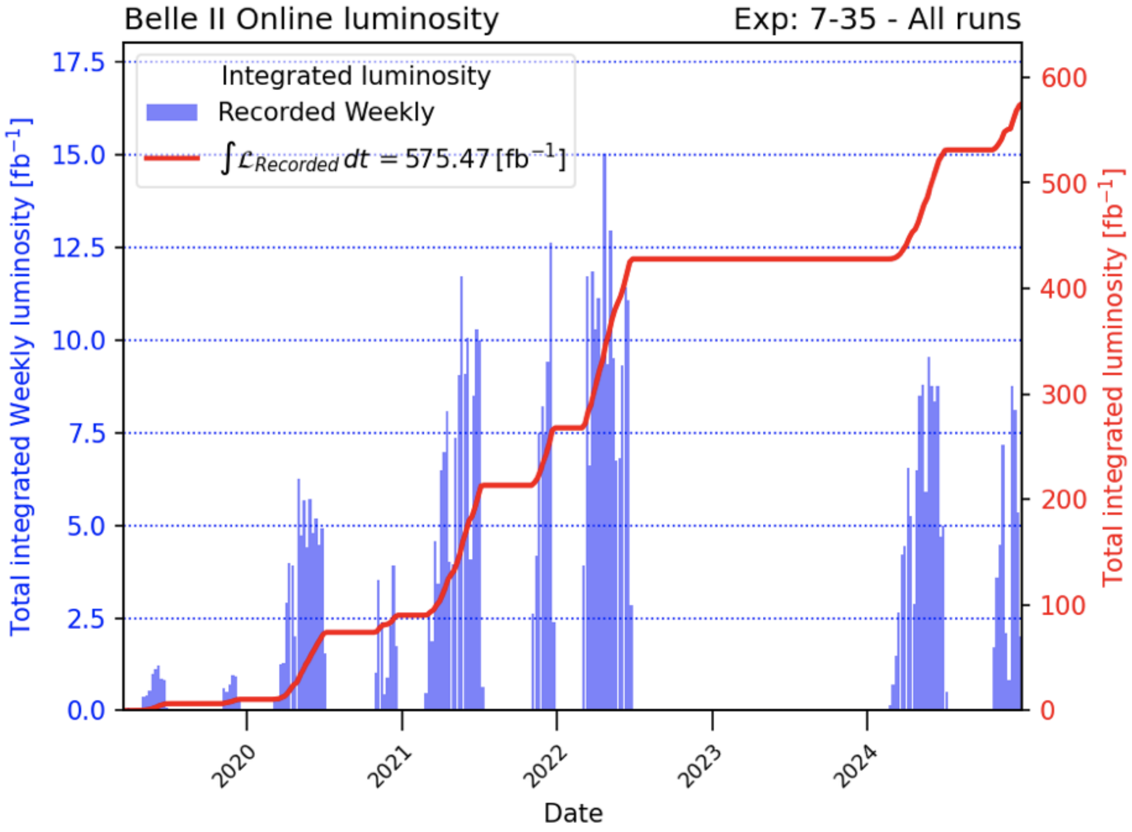
- **Belle (1999 - 2012)**
- **Belle II RUN-I (2019 - 2023)**
- **Belle II RUN-II (2014 - 2025)**

Integrated luminosity of B factories



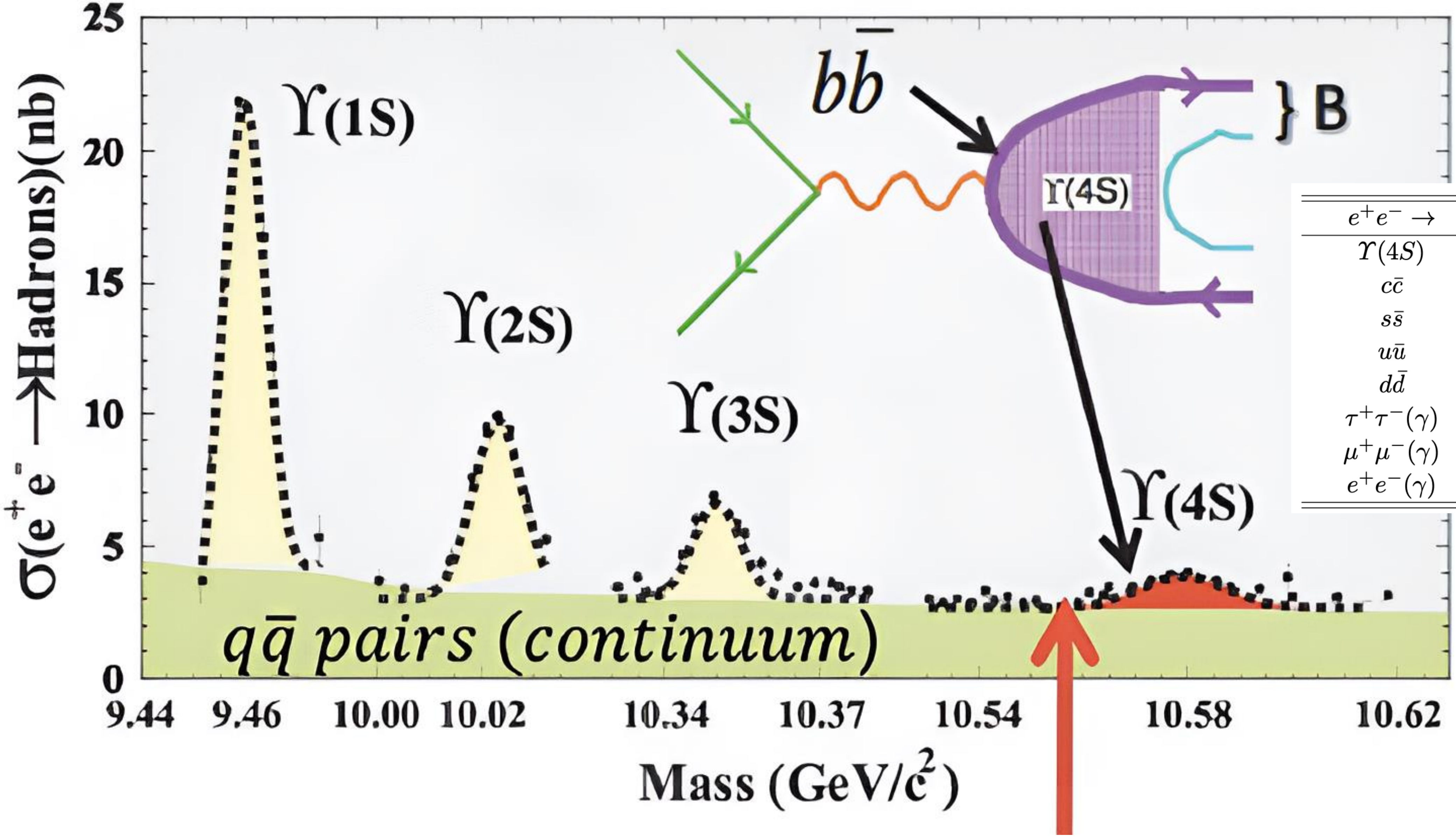
In December 2024

WORLD RECORD: $5.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Most data at or near the $\Upsilon(4S)$ resonance, and 19.6 fb^{-1} near $\Upsilon(10753)$.

Belle II physics



$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

Belle II physics

The Belle II Physics Book: [PTEP 2019 (2019) 12, 123C01]

Charm physics

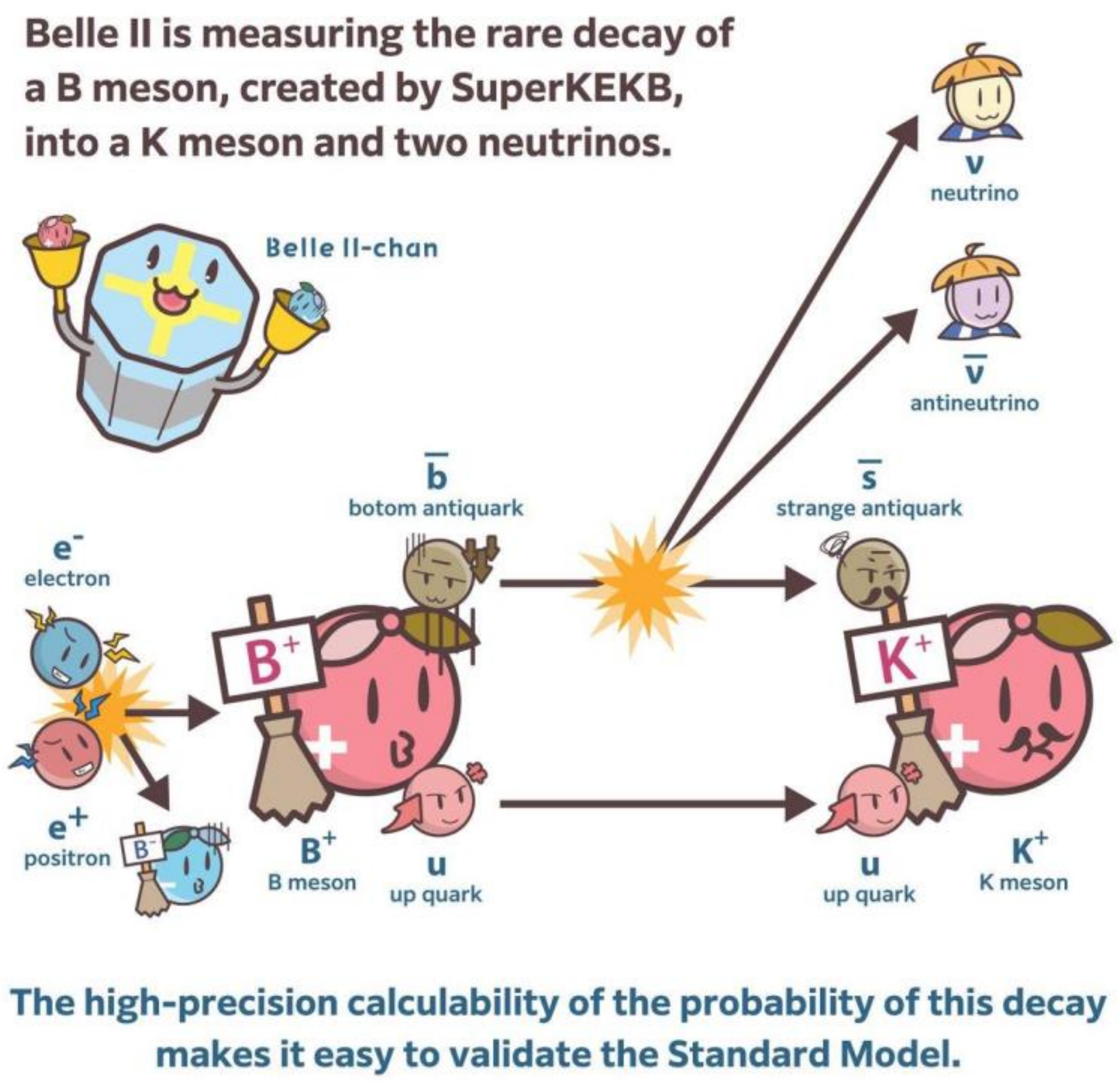
$\Upsilon(10753)$ study and pentaquark

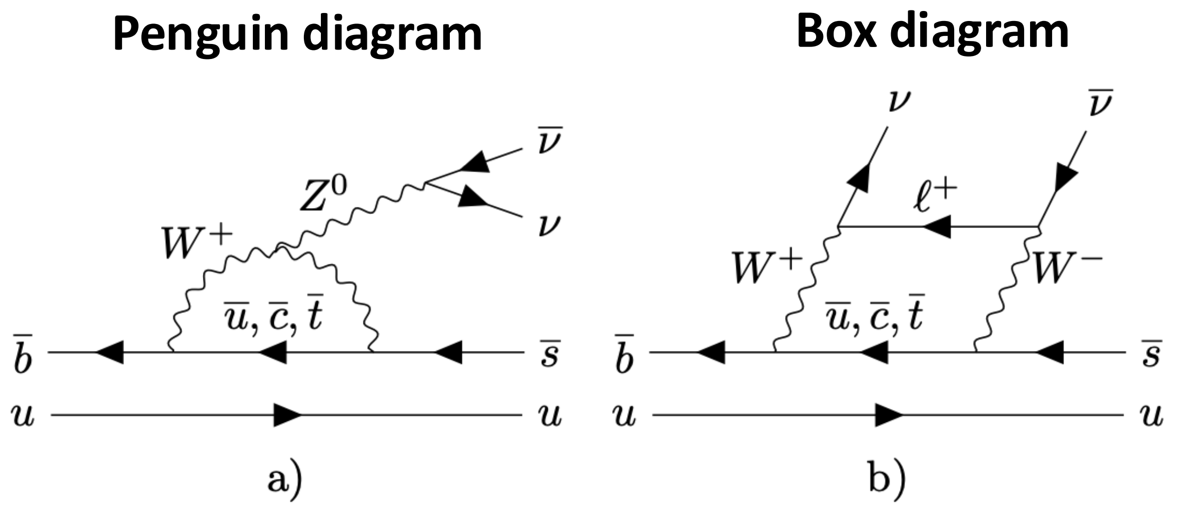
B rare decays

τ physics

rare B decays

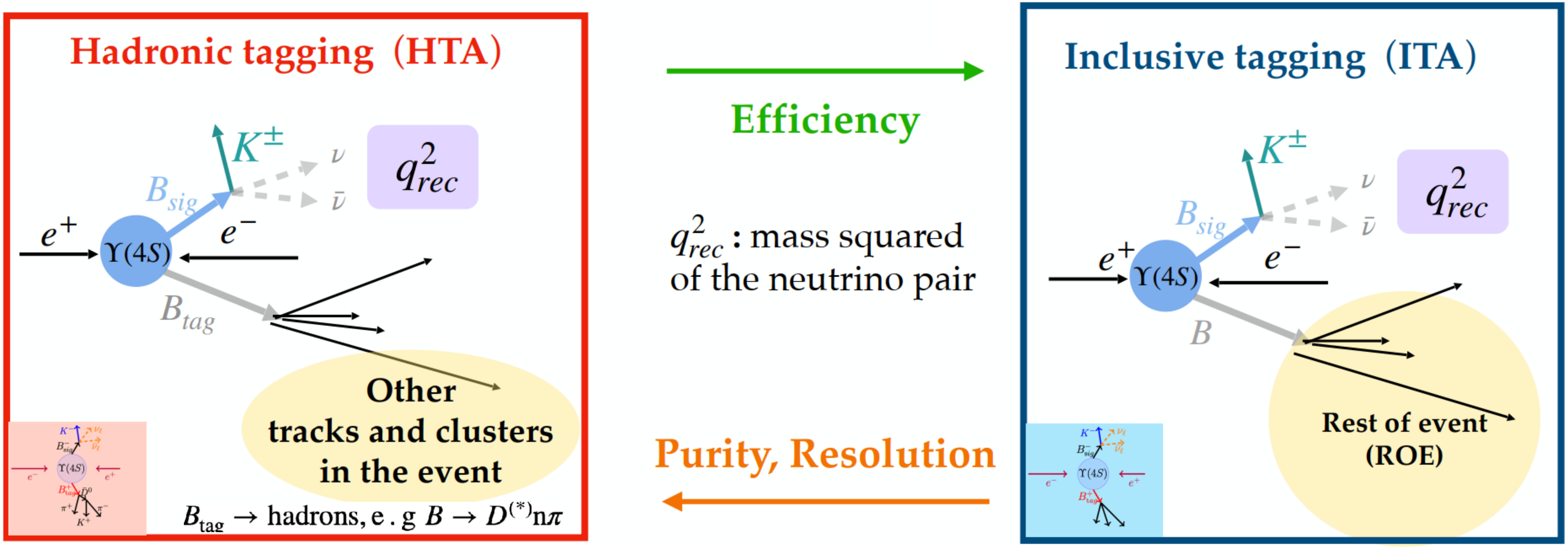
$B \to K\nu\bar{\nu}$





- The process is known with high accuracy in the SM: $\mathcal{B}(\mathrm{B} \to \mathrm{K}\nu\bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}$ [PRD 107, 014511 (2023)]
- Extensions beyond SM may lead to significant rate increase.
- Very challenging experimentally, not yet observed

Two ways of tagging



- *New technique* from Belle II with inclusive ROE (Rest of Event) tagging ($\times$ 10−20 efficiency, but large backgrounds)
- Add some ML/AI (boosted decision trees or BDTs) to help suppress the large backgrounds.

First evidence for $B \to K\nu\bar{\nu}$

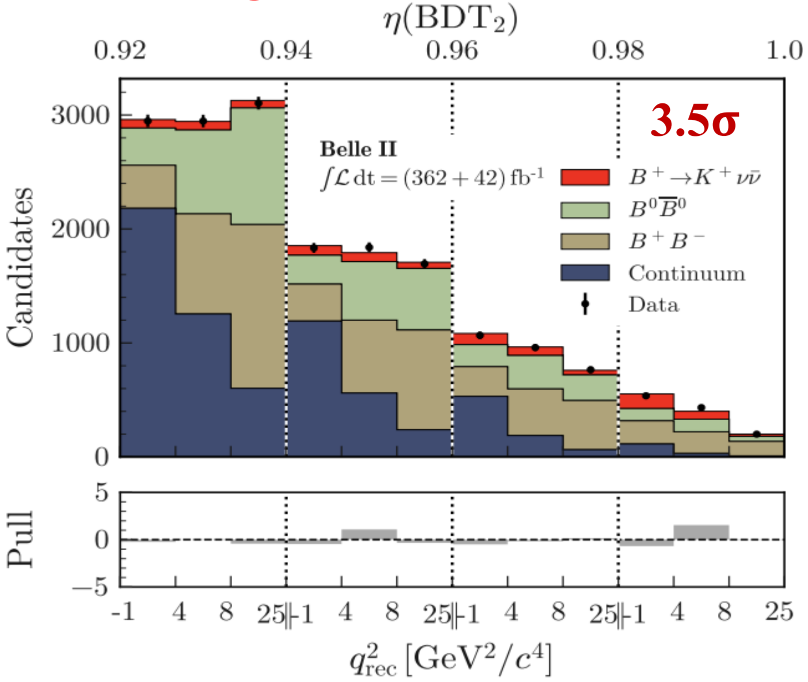
[PRD 109, 112006 (2024)]

- Extract signal from maximum likelihood fit
  - Inclusive tag: in bins of $q^2_{\rm rec}$ and $\eta(\mathrm{BDT}_2)$
  - Hadronic tag: in bins of $\eta(\mathrm{BDT_h})$

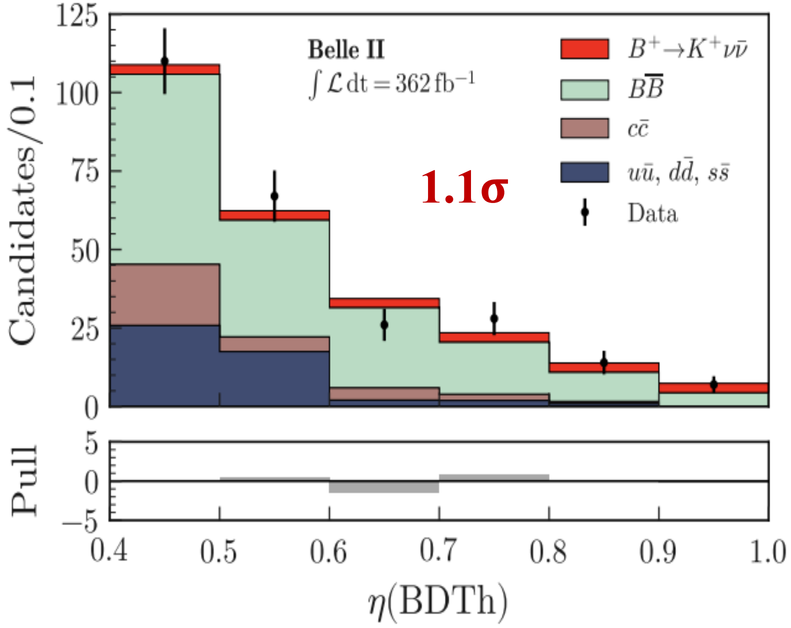
$\mathcal{B}(\mathrm{B} \to \mathrm{K}\nu\bar{\nu}) = (2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-5}$ **(inclusive tag)**

$\mathcal{B}(\mathrm{B} \to \mathrm{K}\nu\bar{\nu}) = (1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})) \times 10^{-5}$ **(hadronic tag)**

Inclusive tag



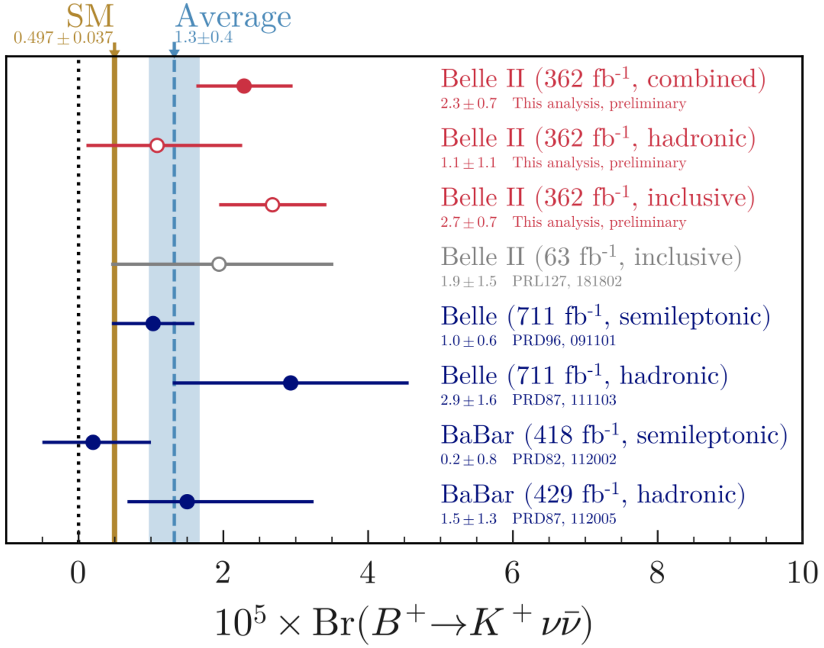
Hadronic tag



Combination and comparisons with other measurements:

$\mathcal{B}(\mathrm{B} \to \mathrm{K}\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$

Significance: 3.5σ

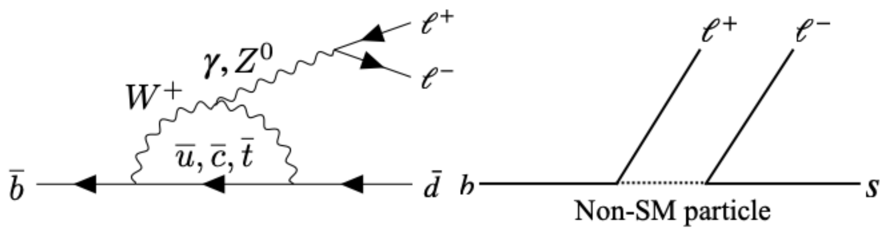


The signal is **2.7σ** above the SM expectation.

Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$

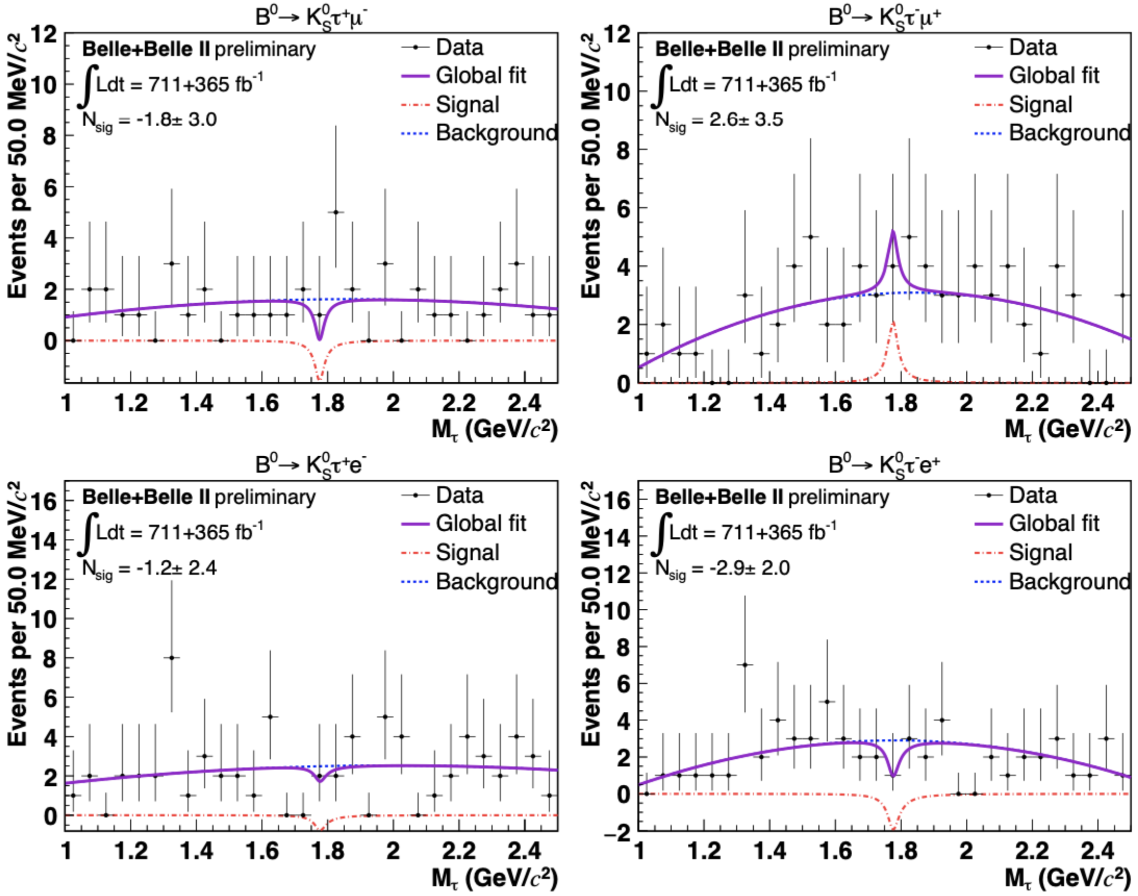
[arXiv: 2412.16470]

- Flavor changing neutral current processes are forbidden in SM at tree level.
- NP models that accommodate the b → cτℓ anomalies predict an enhancement of several orders of magnitude with τ.
- Never searched for before
- High K_S^0 purity (>98%)
- Search in 1-prong τ decays: $\tau^+ \to \ell^+ \nu\bar{\nu}, \pi^+\nu, \rho^+\nu$
- Fit recoil τ mass (M_τ) for signal extraction



$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

at 90% CL



First search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ decays

Search for $B^0 \to K^{*0}\tau^{\pm}\ell^{\mp}$

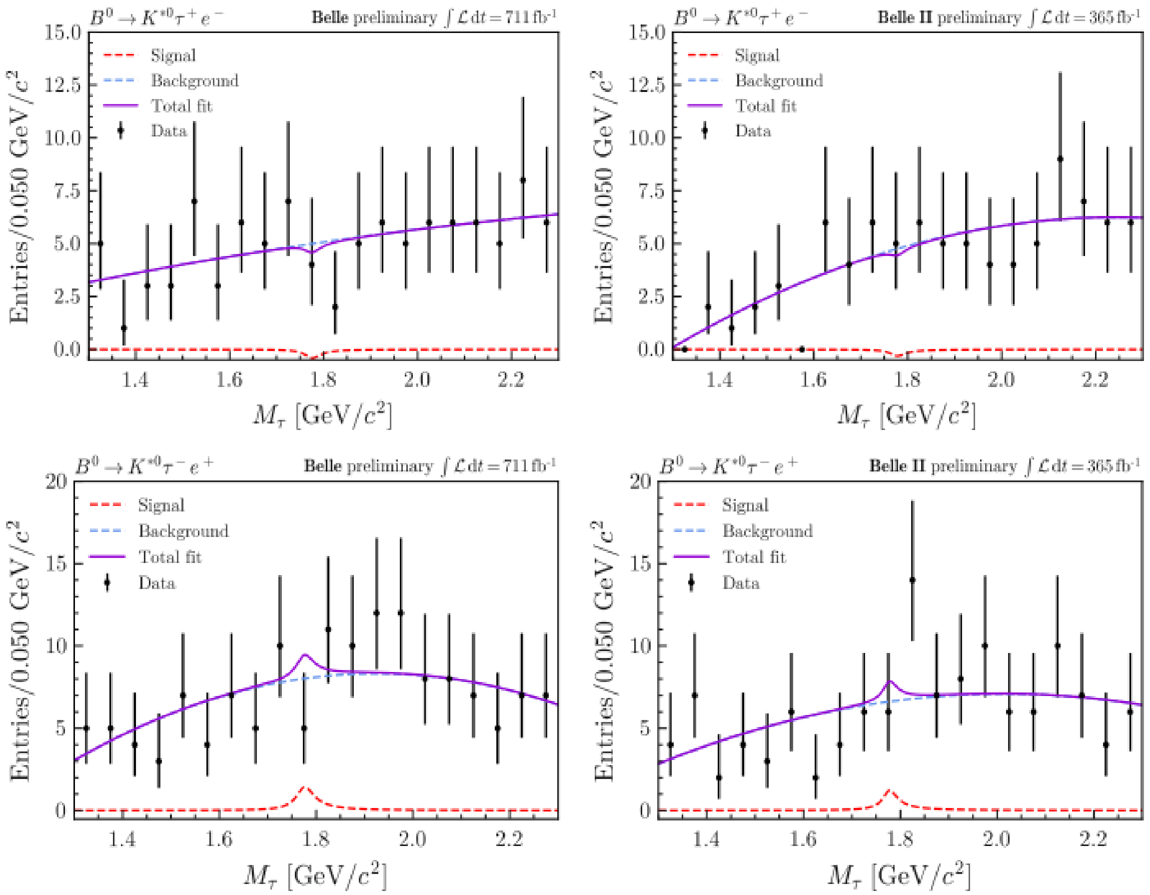
[arXiv: 2505.08418]

- World best limit in by LHCb [JHEP 06 (2023) 143]:
  $\mathcal{B}^{\mathrm{UL}}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$
  $\mathcal{B}^{\mathrm{UL}}(B^0 \to K^{*0}\tau^-\mu^+) < 0.8 \times 10^{-5}$
- No search for $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$ yet.
- Require one track t_τ from τ decay for background rejection
- Suppress background with classifier using m($K^*\ell$), m($K^{*0}t_\tau$), residual tracks and clusters properties, K^{*0} vertex fit, event topology, etc.

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 3.9 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 5.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+e^-) < 2.7 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-e^+) < 5.6 \times 10^{-5}$$

at 90% CL

Simultaneous fit recoil τ mass ($\mathbf{M_\tau}$) in Belle and Belle II data sets:

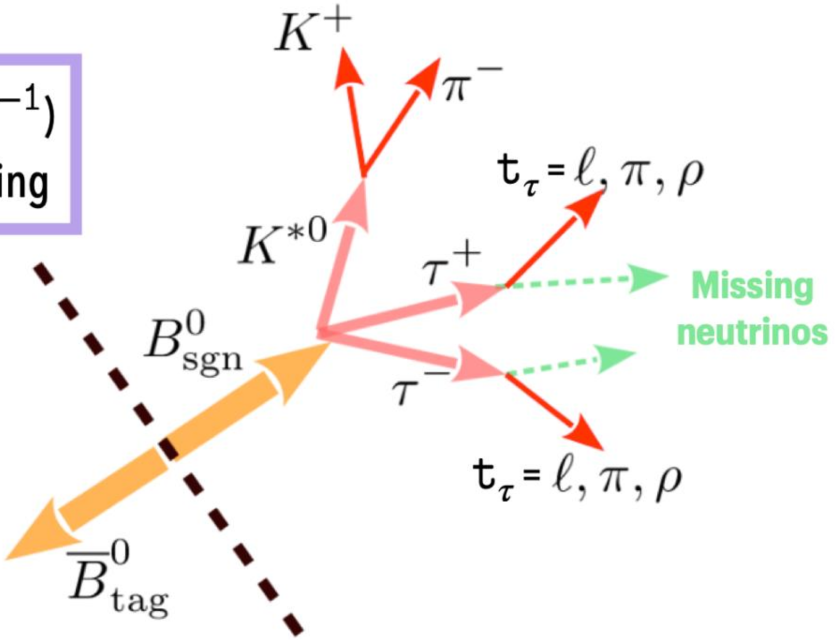


Search for $B^0 \to K^{*0}\tau^+\tau^-$

[arXiv: 2504.10042]

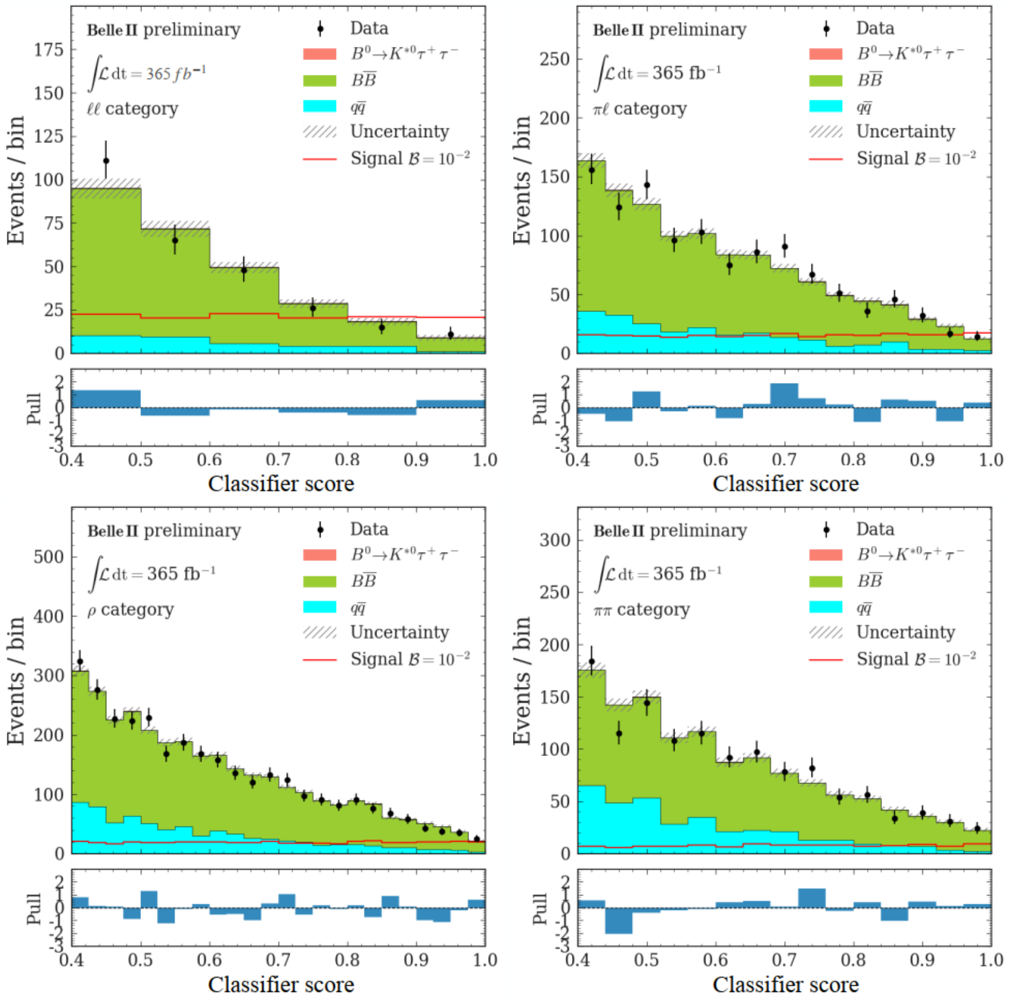
- Non-SM particles, explaining recent anomalies, would enhance BF upto $\mathcal{O}(10^3)$ due to presence of two τs
- Main challenge: no signal peaking kinematic observable due to multiple undetected neutrinos
- Relies on missing energy information and residual calorimeter energy; Belle II is ideally suited

Belle II (364 fb^{-1})
hadronic B-tagging



Combinations of sub-track from τ lead to 4 categories: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX

BDT is trained using missing energy, extra cluster energy in EM calorimeter, $M(K^{*0}t_\tau)$, q^2,etc



$\mathscr{B}^{\rm UL} = 1.8 \times 10^{-3}$ at 90% confidence level

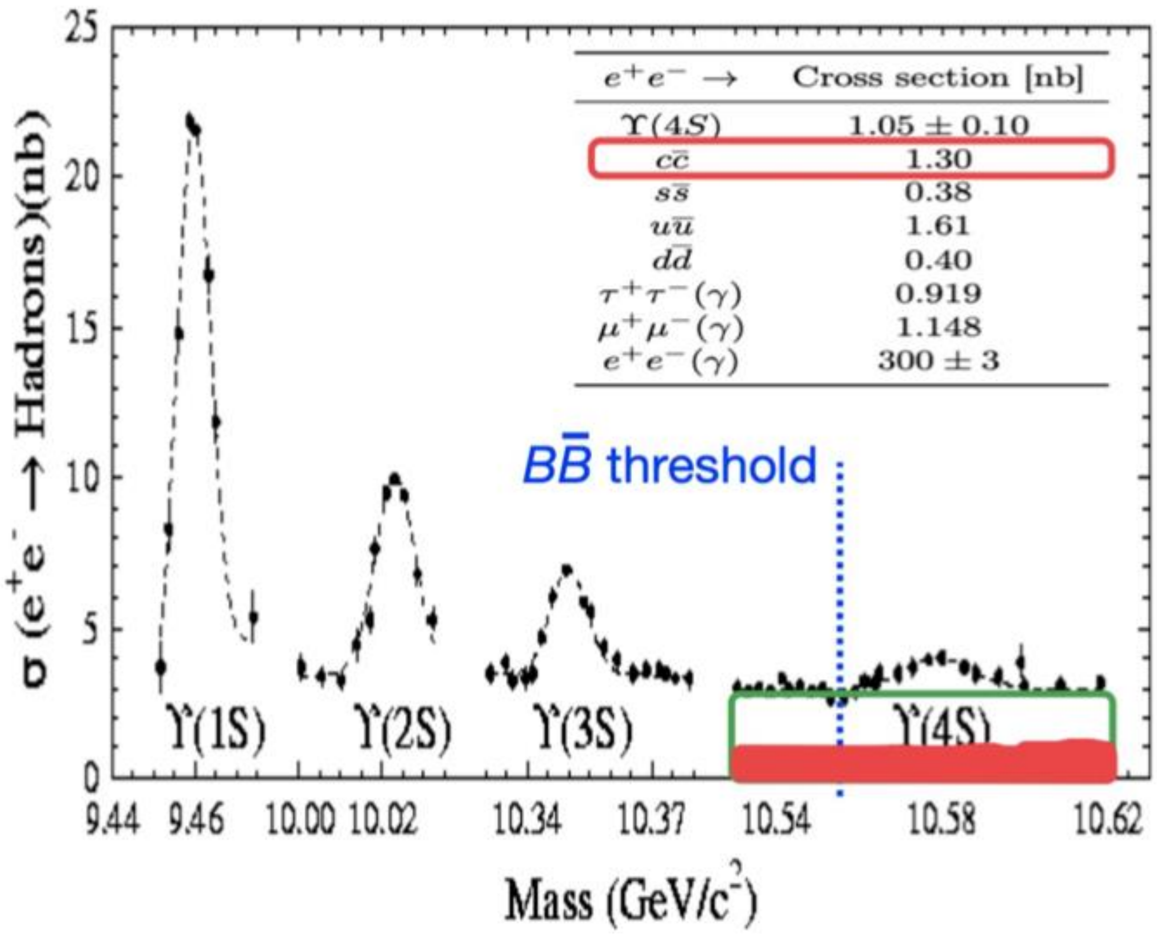
Twice better with only half sample wrt Belle!
Better tagging + more categories + BDT classifer...

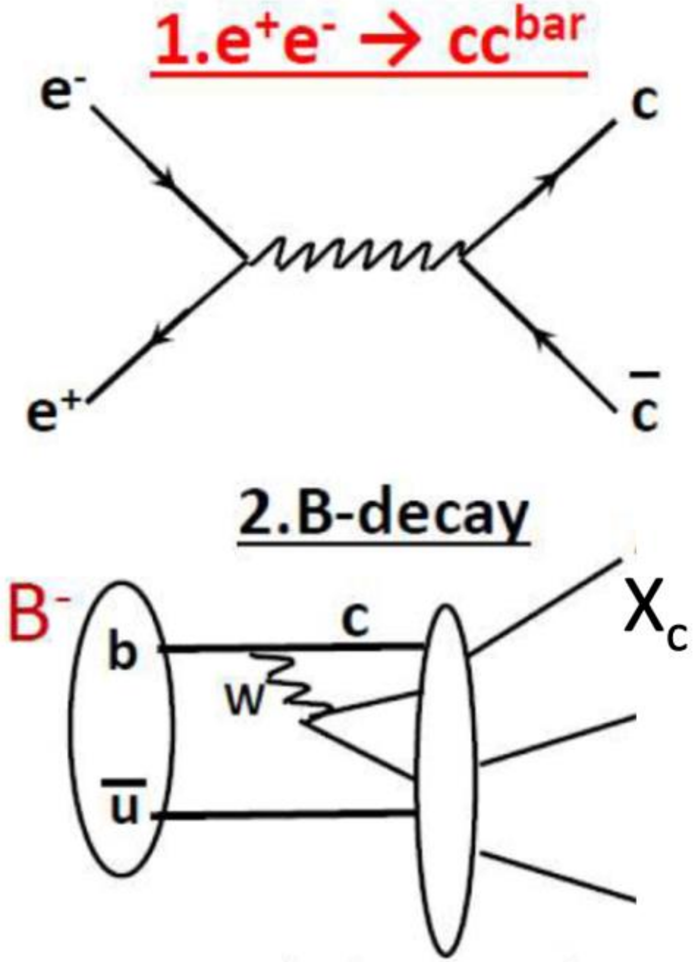
The most stringent limit on the $B^0 \to K^{*0}\tau^+\tau^-$ decay

Charm

Charm production at Belle II

- At Belle II, e^+e^- mainly collide at 10.58 GeV to make $\Upsilon(4S)$ resonance mainly decaying into $B\bar{B}$.
- Meanwhile, **continuum processes $e^+e^- \to q\bar{q}$ (q = u, d, s, c) have large cross sections**.
- Two ways to produce charm samples: **1) $e^+e^- \to c\bar{c}$, and 2) B → charm decays**.





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

- The following sum-rule for CPV in $D \to \pi\pi$ decays; it helps to determine the source of CPV:

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

  - if R $\neq$ 0, CPV from ΔI = 1/2 amplitude; if R = 0 and at least one $A_{CP}^{\mathrm{dir}} \neq 0$, CPV from a beyond-SM ΔI = 3/2 amplitude.
  - The $\mathcal{B}$'s and τ have been well-measured (by BESIII/Belle II/etc.)
  - $A_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$: precise; first evidence of direct CPV in a specific D decay (by LHCb)

- Raw asymmetry of $D^0 \to \pi^0\pi^0$ from the $D^{*+} \to D^0\pi_s^+$ sample:

$$\boxed{A_{\mathrm{raw}}(D^0 \to \pi^0\pi^0) = A_{CP}(D^0 \to \pi^0\pi^0) + A_{\mathrm{prod}}^{D^{*+}} + A_{\varepsilon}^{\pi_s}}$$

  - $A_{\mathrm{prod}}^{D^{*+}}$ (the forward-backward asymmetric production of D^{*+} mesons in $e^+e^- \to c\bar{c}$ events): being an odd function of $\cos\theta^*$, i.e. the cosine of the charmed-meson polar angle in e^+e^- c.m.s
  - $A_{\varepsilon}^{\pi_s}$ (charge asymmetries in the detection efficiency of positive and negative soft pions): using tagged and untagged $D^0 \to K^-\pi^+$ samples.

- Time-integrated CP asymmetry: $\boxed{A_{CP}(D^0 \to \pi^0\pi^0) = A_{\mathrm{avg}}^{\pi^0\pi^0} - A_{\mathrm{avg}}^{K\pi} + A_{\mathrm{avg}}^{K\pi,\mathrm{untag}}}$

  - Here, $A_{\mathrm{avg}}^{f} = (A^f(\cos\theta^* < 0) + A^f(\cos\theta^* > 0))/2$, where f = $\pi^0\pi^0$, $K\pi$, untag.

A_{CP} in $D^{+} \rightarrow \pi^0\pi^0$

[arXiv: 2505.02912]

- Utilizing data split in the forward and backward bins: N^{sig} = 14100$\pm$130 and 11550$\pm$110.

- Result at Belle II (428 fb^{-1})
  $A_{CP}(D^0 \rightarrow \pi^0\pi^0)$ = (+0.30$\pm$0.72$\pm$0.20)%

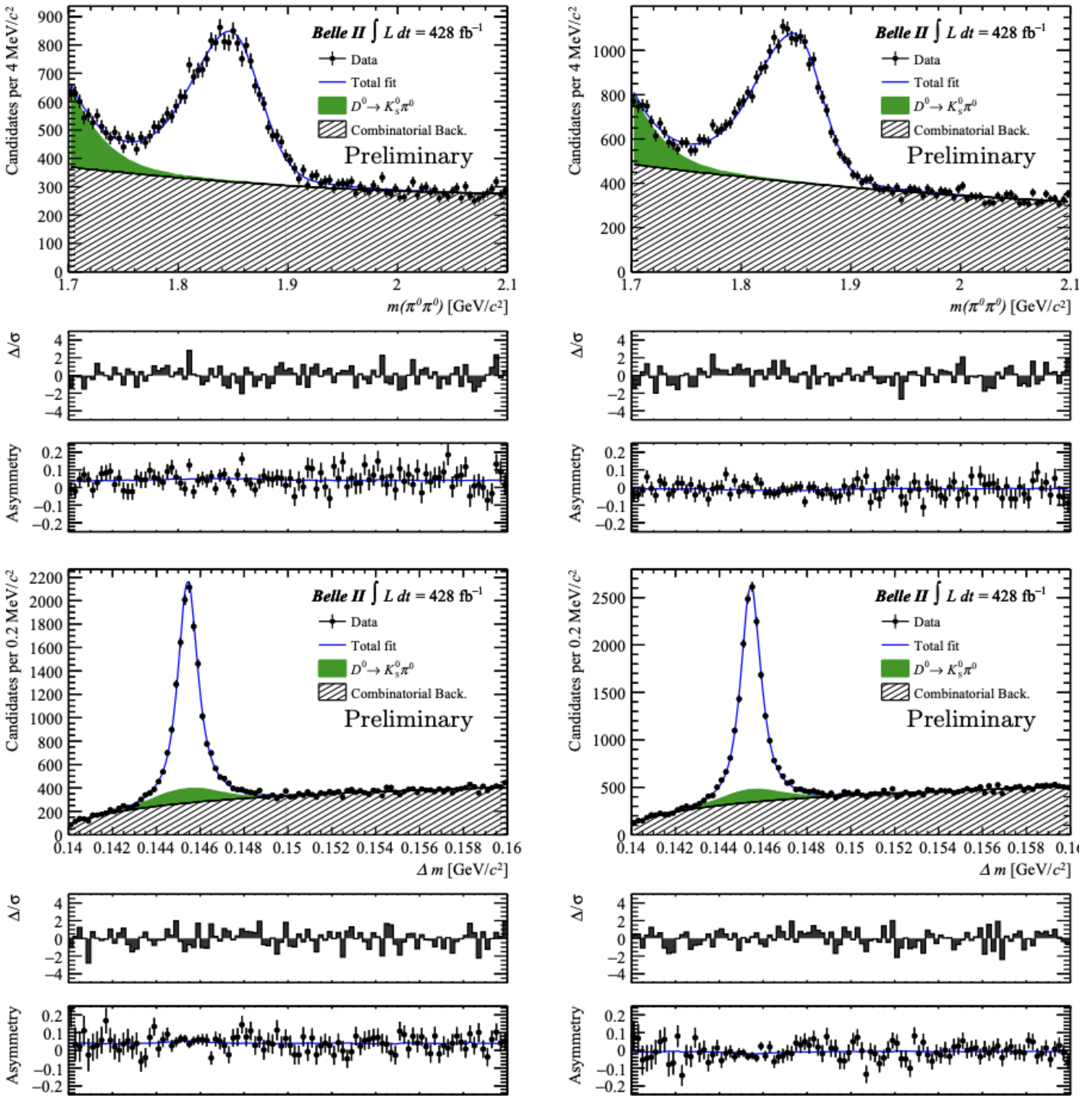
  Consistent with CP symmetry;
  vs. Belle (980 fb^{-1}): (−0.03$\pm$0.64$\pm$0.10)% [PRL 112, 211601 (2014)]

  15% less precision than Belle; improved precision per luminosity.

- Using our result, $A_{CP}^{\pi^+\pi^-}$ and ΔY from LHCb, W.A. $A_{CP}^{\pi^+\pi^0}$ and $\mathcal{B}$'s, and $\tau(D^{0,+})$, we have ***R* = (1.5$\pm$2.5)$\times$ 10^{-3}**.

  precision of the sum rule: improved by ~ 20% w.r.t current HFLAV result [PRD 107, 052008 (2023)].

$\cos\theta^*(D^{*+}) < 0$ | $\cos\theta^*(D^{*+}) > 0$



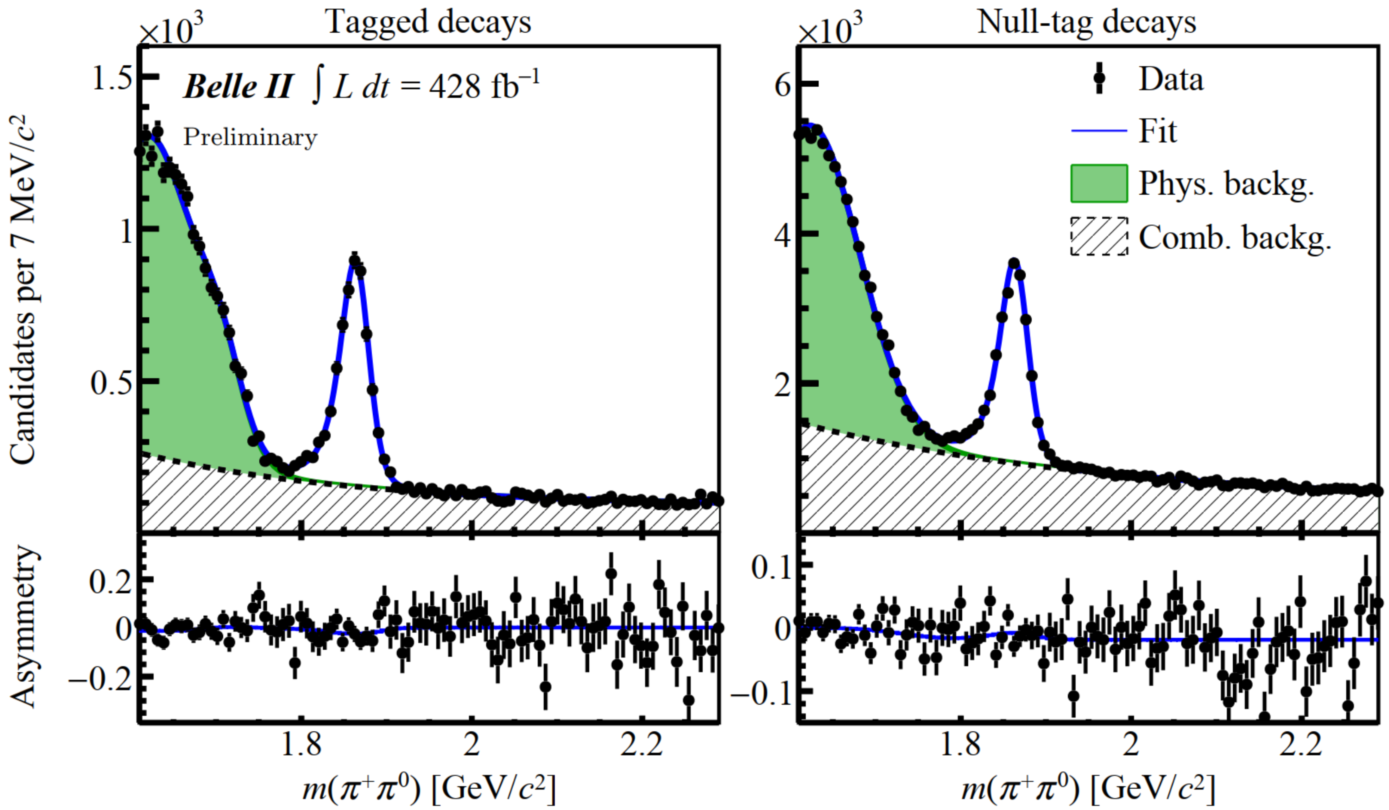
A_{CP} in $D^+ \to \pi^+\pi^0$

[arXiv: 2506.07879]

- Utilizing a sample of $e^+e^- \to c\bar{c}$ data collected by Belle II (with high momentum requirement)
- Using $D^+ \to K_S^0\pi^+$ to eliminate common asymmetry sources: $A^D_{\rm prod}$ and $A^{\pi^+}_{\varepsilon}$, thus CP asymmetry of interest:

$$\boxed{A_{CP}^{\pi^+\pi^0} = A_{\rm raw}^{\pi^+\pi^0} - A_{\rm raw}^{K_S^0\pi^+} + A^{\overline{K}^0}}$$

- Combined $A_{CP}^{\rm tag}$ and $A_{CP}^{\rm null}$ at Belle II (428 fb^{-1}):
  $A_{CP}(D^+ \to \pi^+\pi^0) = (-1.8 \pm 0.9 \pm 0.1)\%$
  (most precise)
- Precision 30% improved w.r.t Belle (921 fb^{-1}):
  $(+2.31 \pm 1.24 \pm 0.23)\%$
  [PRD 97, 011101 (2018)]
- Better purity achieved through an improved event selection



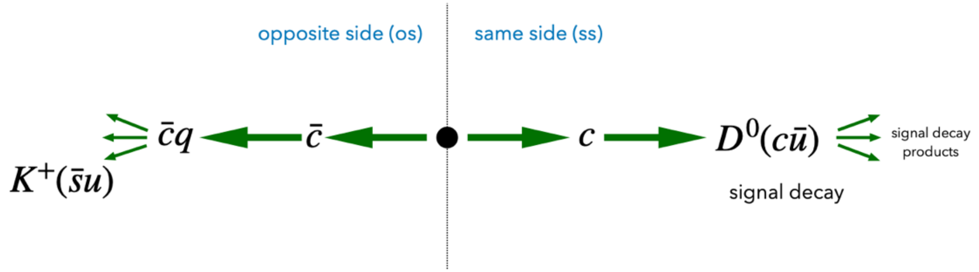
$N_{\rm sig}^{\rm tag} = 5\,130 \pm 110$ $\quad N_{\rm sig}^{\rm null} = 18\,510 \pm 240$

$A_{CP}^{\rm tag} = (-3.9 \pm 1.8 \pm 0.2)\%$ $\quad A_{CP}^{\rm null} = (-1.1 \pm 1.0 \pm 0.1)\%$

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

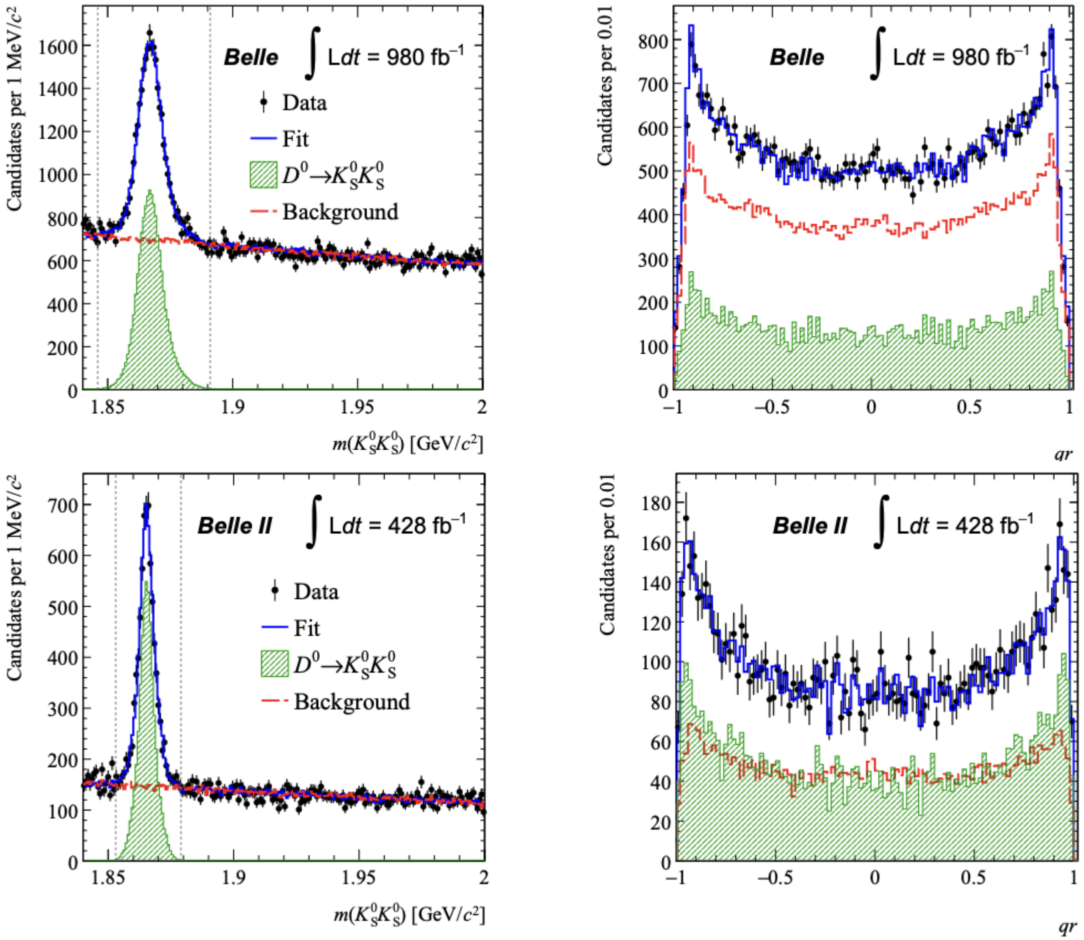
Charm-flavor-tag (CFT) D^0: exploits the correlation between the flavor of a D^0 meson and the electric charges of particles reconstructed in the rest of the $e^+e^- \to c\bar{c}$ event [PRD 107, 112010 (2023)].

CFT-tag



Double the size of sample compered to D^*-tag

Fit $m(K_S^0 K_S^0)$ and product of tagged flavor q and tag quality r:



[PRD 111, 012015 (2025)]

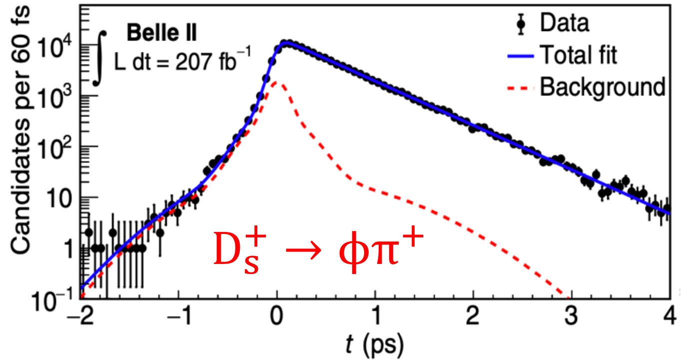
- An independent sample from Belle and Belle II:
  $A_{CP}^{B1}(D^0 \to K_S^0 K_S^0) = (+2.5 \pm 2.7 \pm 0.4)\%$
  $A_{CP}^{B2}(D^0 \to K_S^0 K_S^0) = (-0.1 \pm 3.0 \pm 0.3)\%$
- Combined $A_{CP} = (+1.3 \pm 2.0 \pm 0.2)\%$

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	$\mathbf{-0.6 \pm 1.1 \pm 0.1}$

Most precise!

Charm Meson and Charmed Baryon Lifetimes

[PRL 131, 171803 (2023)]

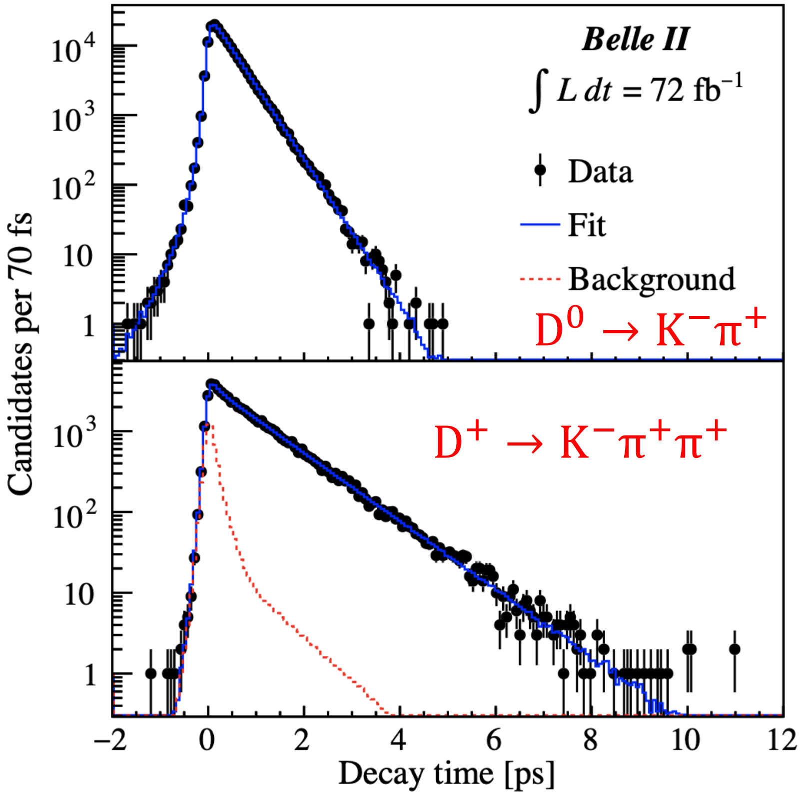


- PDF Model:

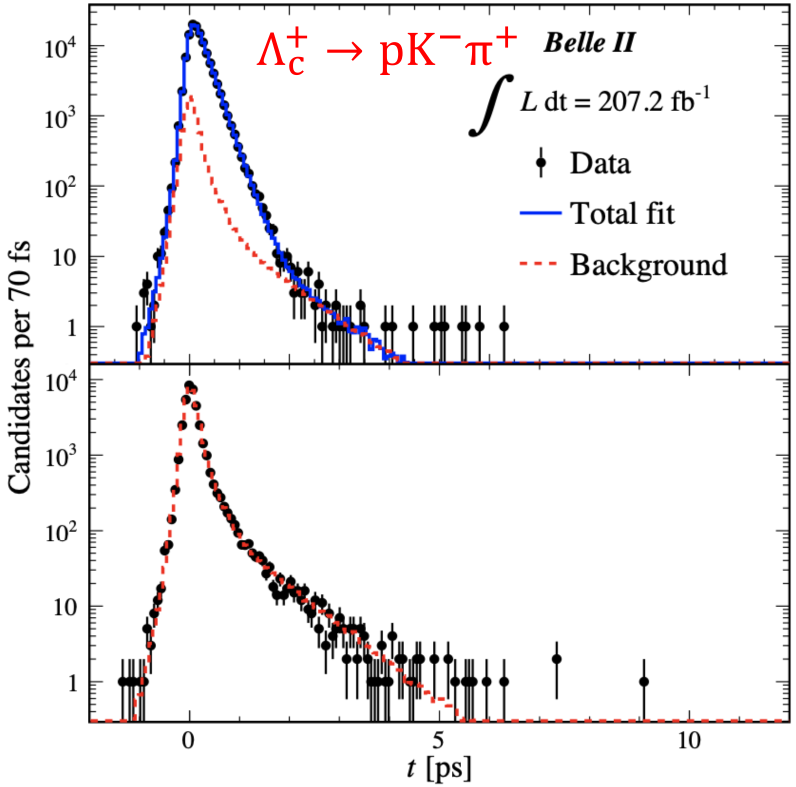
$$\mathrm{PDF}(t,\sigma_t) = (1-\mathrm{f_b})\int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t-t_{\mathrm{true}}\,|\,b, s\sigma_t)\,dt_{\mathrm{true}}\,\mathrm{PDF_{sig}}(\sigma_t) + \mathrm{f_b}\,\mathrm{PDF_{bkg}}(t,\sigma_t)$$

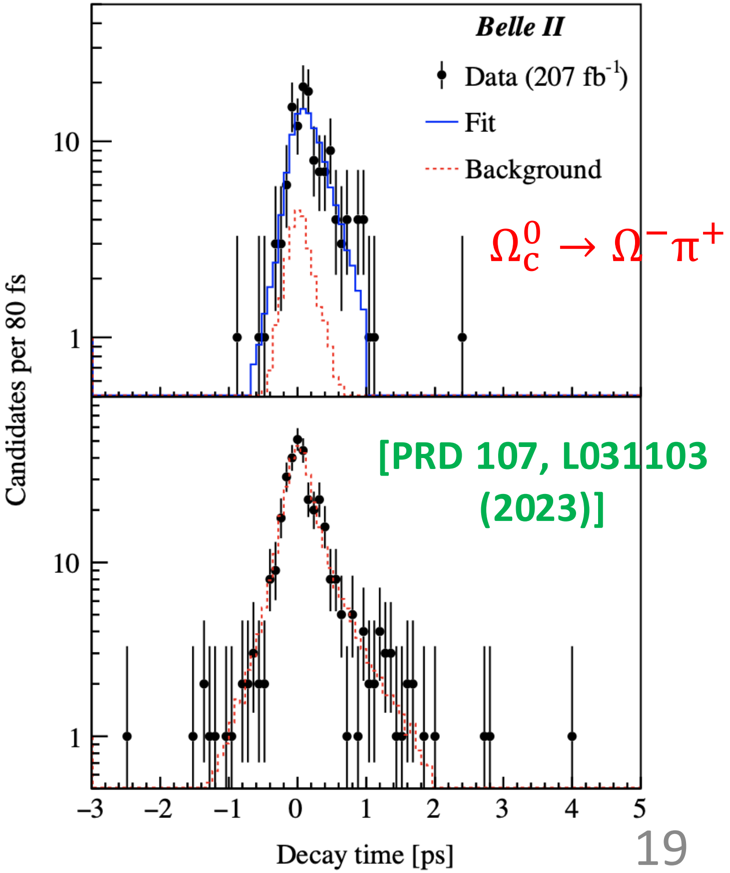
t: decay-time; σ_t: decay-time uncertainty

[PRL 127, 211801 (2021)]

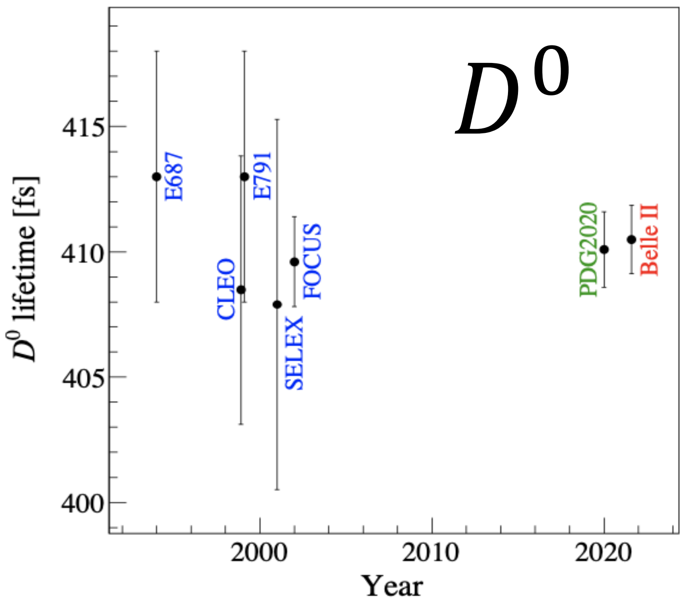


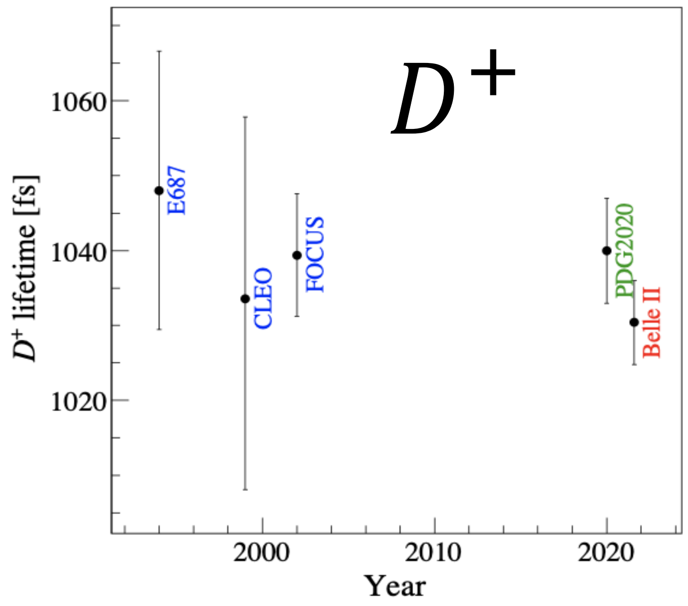
[PRL 130, 071802 (2023)]

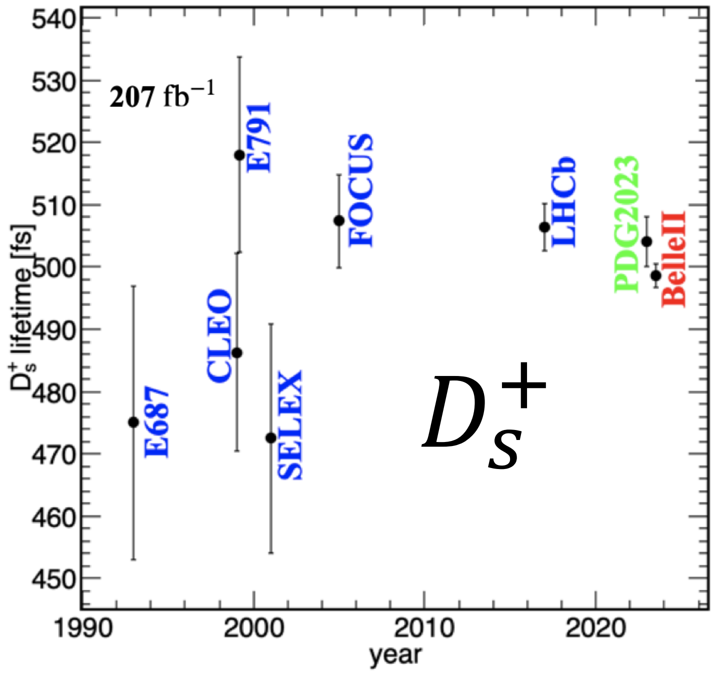


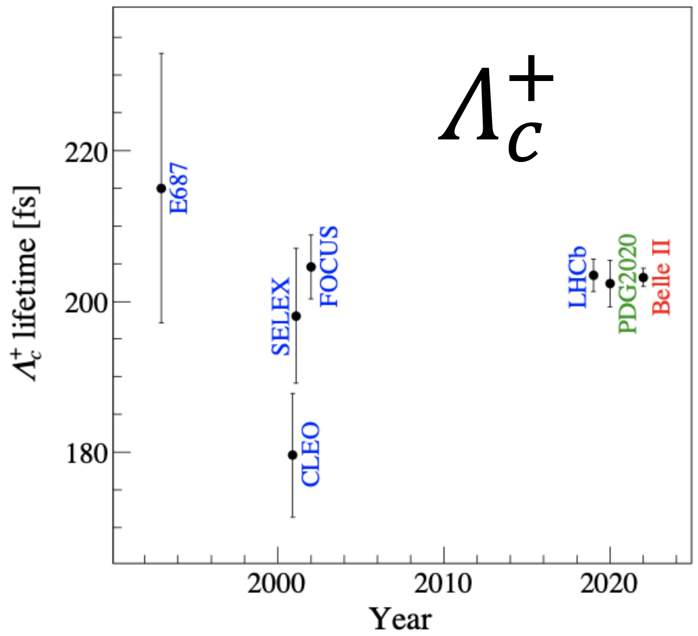


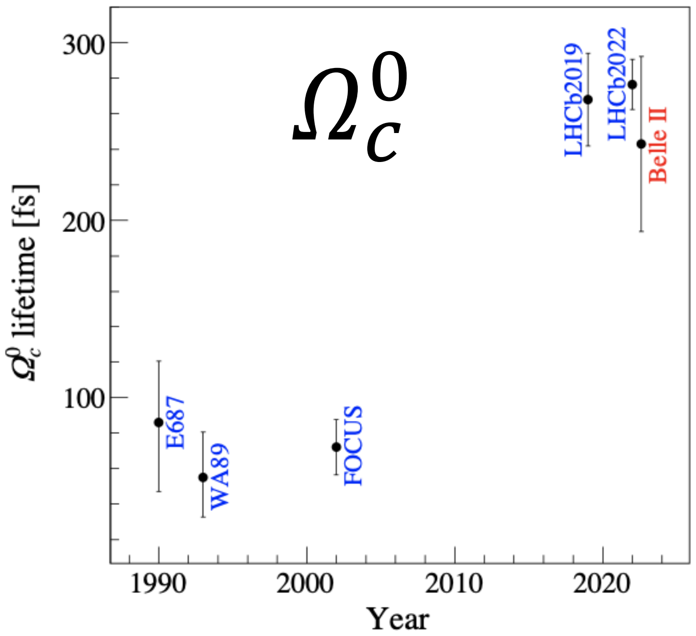
Charm Meson and Charmed Baryon Lifetimes









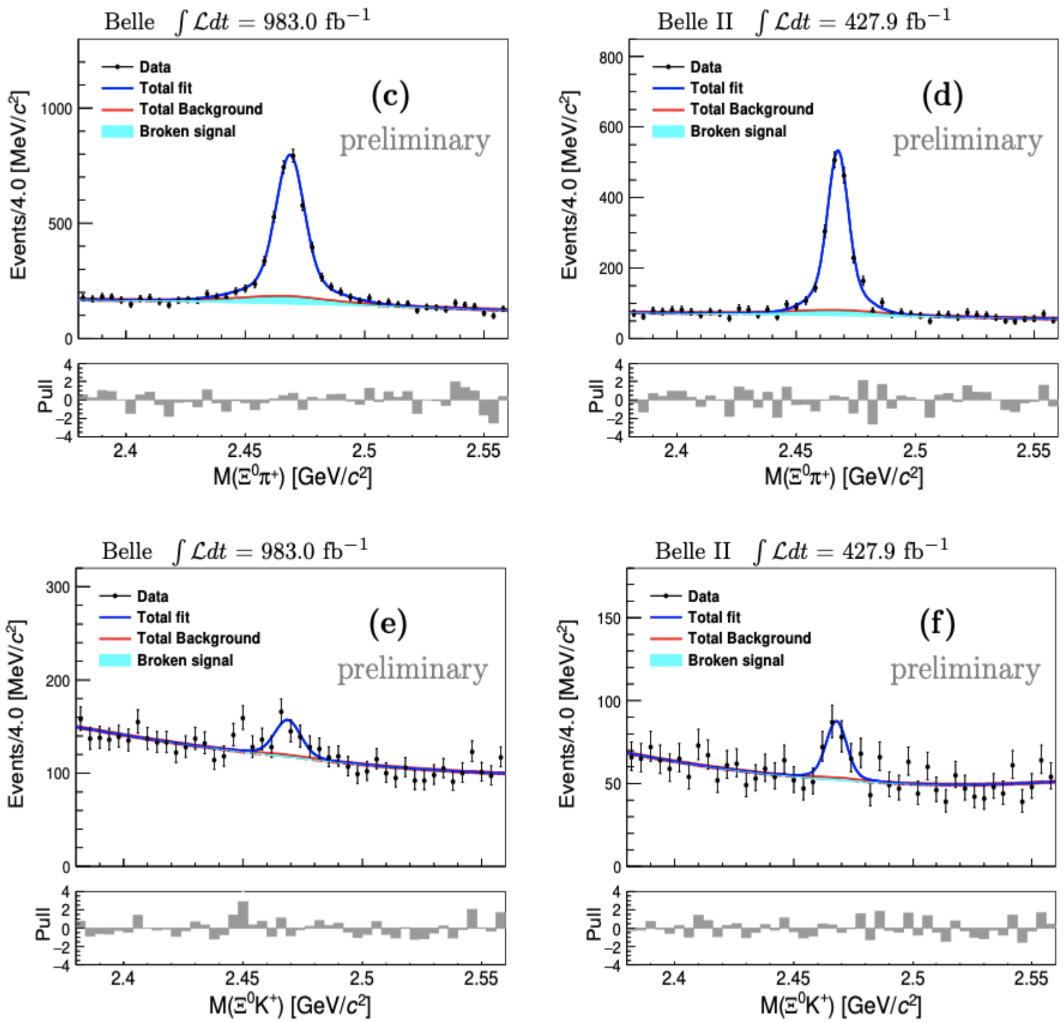


- *Most precise measurements of D^0, D^+, Λ_c^+, and D_s^+ lifetimes to date.*
- *The lifetime of Ω_c^0 consistent the measurement from LHCb.*

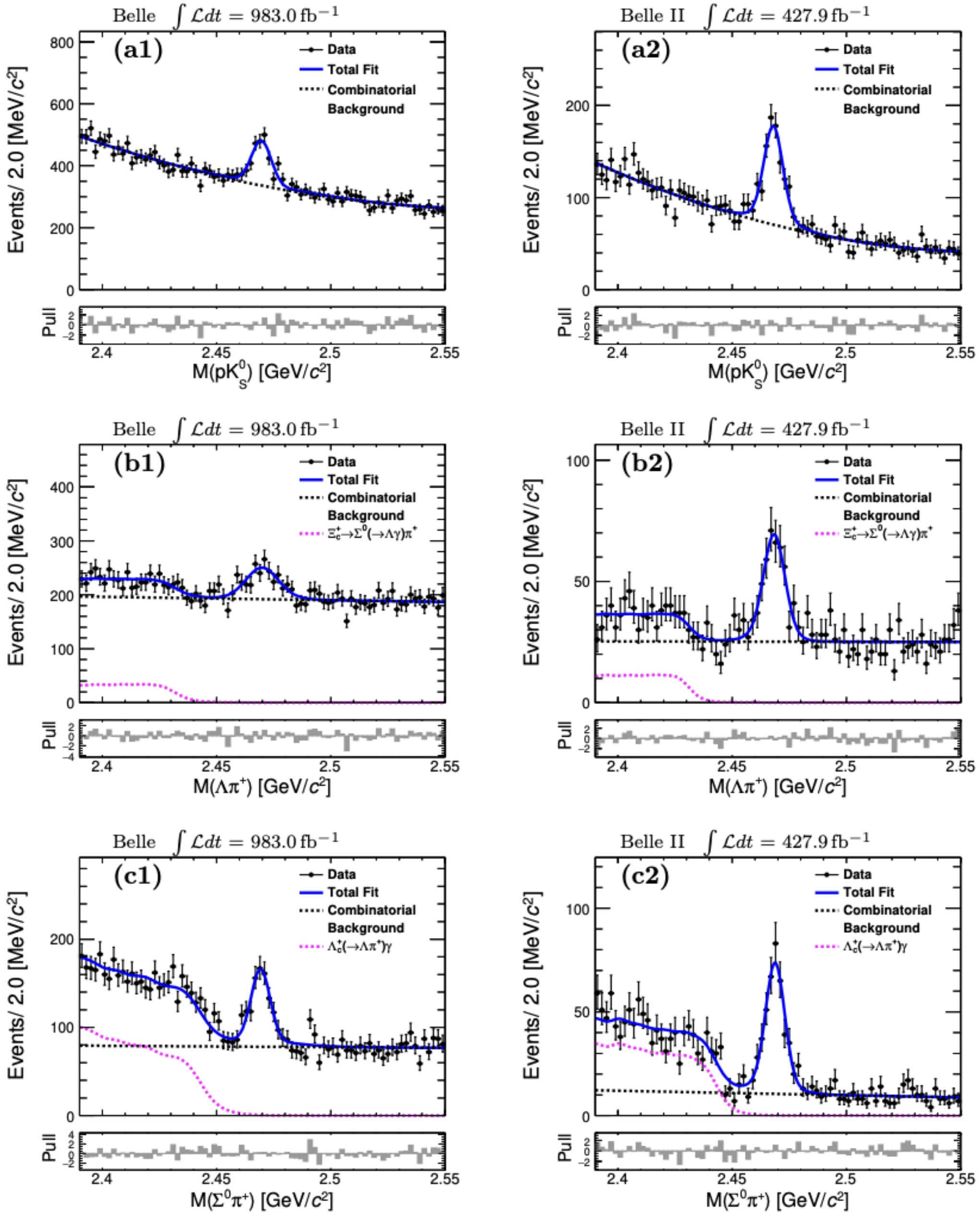
Ξ_c^+ branching fractions

Reconstruct:

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



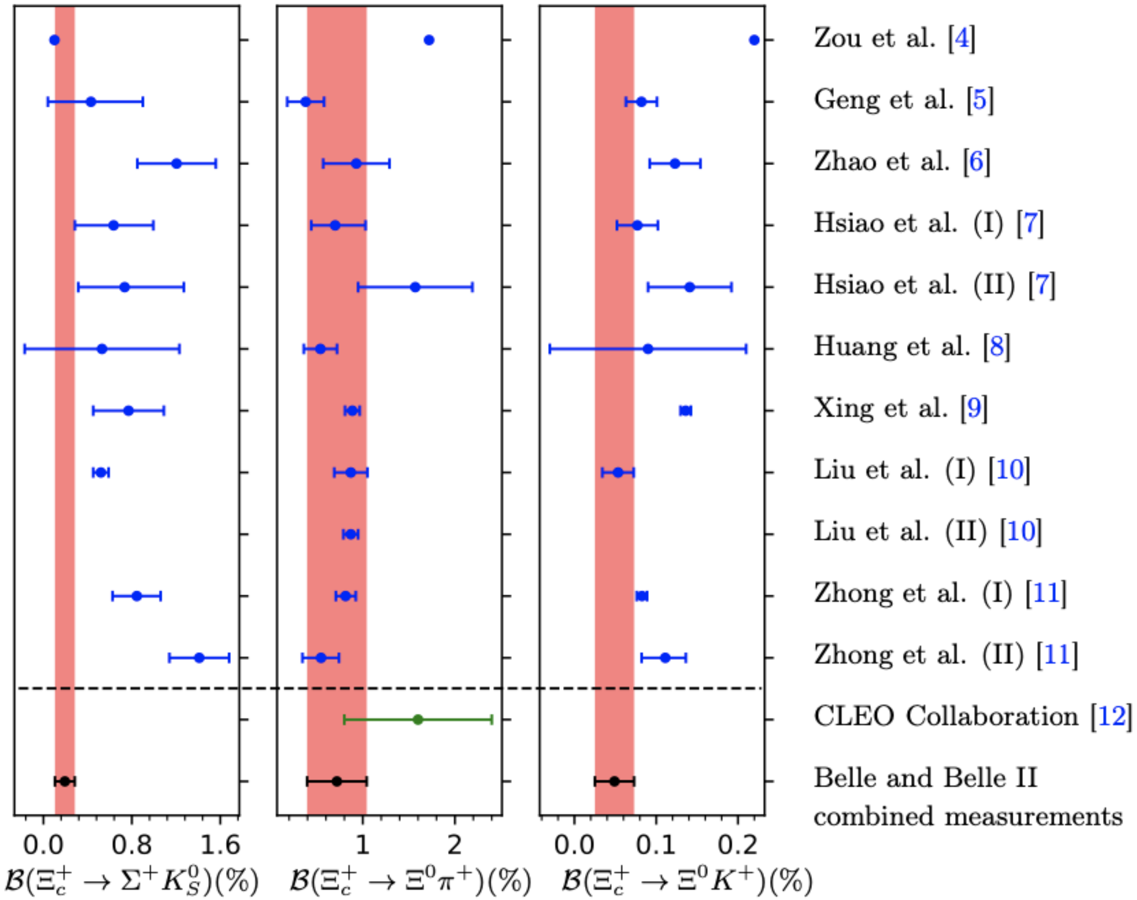
$e^+e^- \to \Xi_c^+ +$ anything



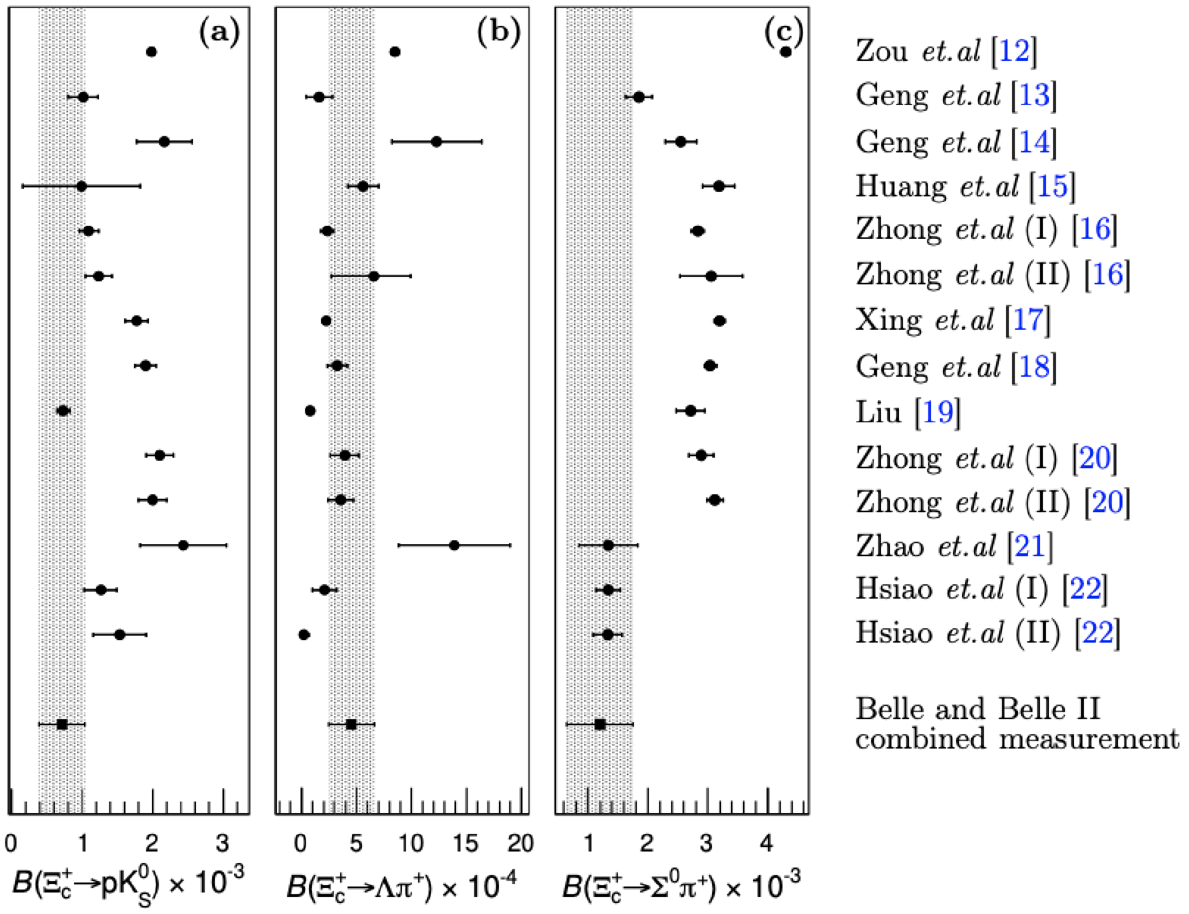
Ξ_c^+ branching fractions

First or most precise measurements!

[arVix: 2503.17643]



- In hadronic weak decays of charmed baryons, nonfactorizable contributions play an essential role and cannot be neglected.
- Various approaches describe the nonfactorizable effects: the covariant confined quark model, the pole model (Pole), current algebra (CA), and, $SU(3)_F$ flavor symmetry.



[JHEP 03 (2025) 061]

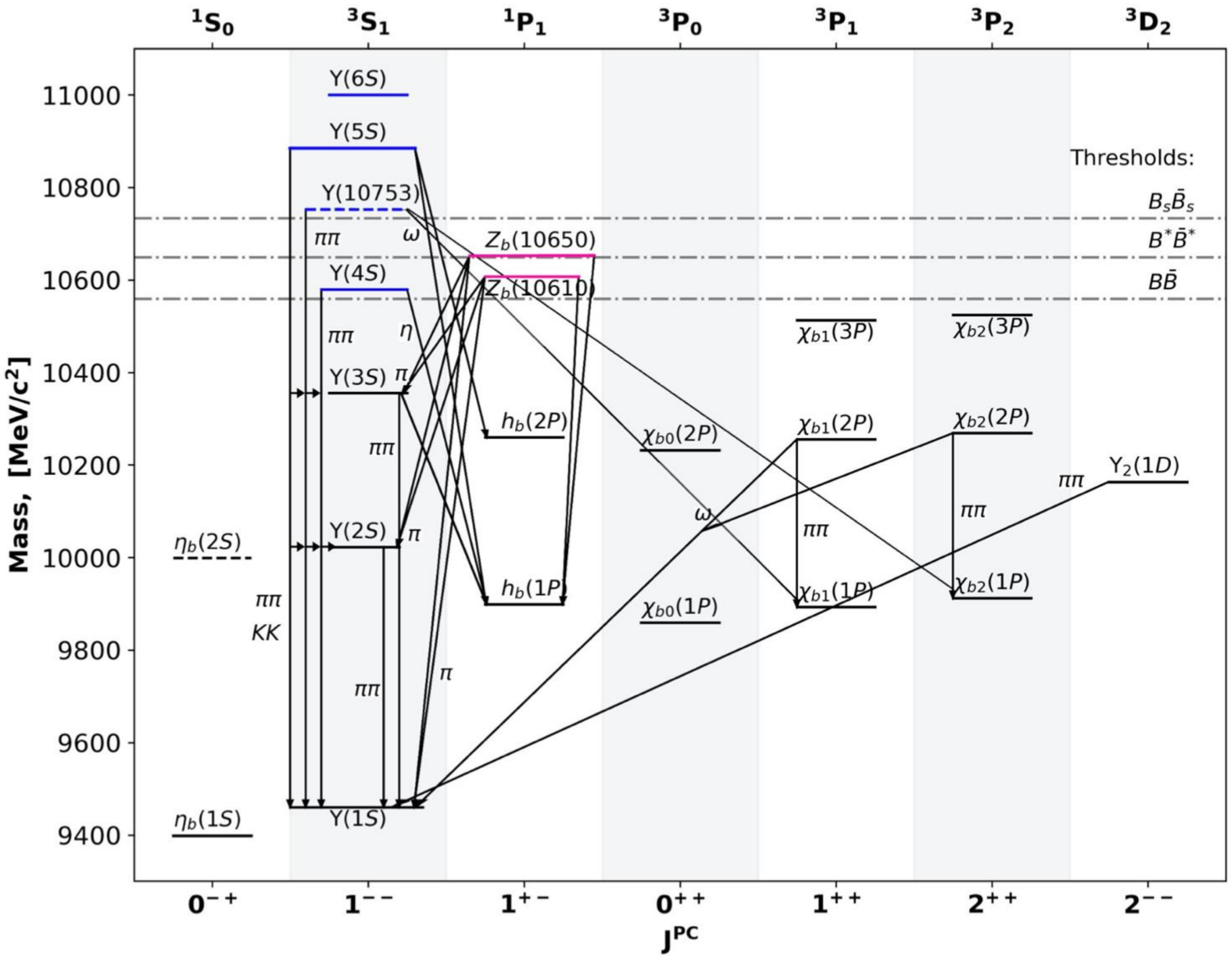
quarkoium

Bottomonium

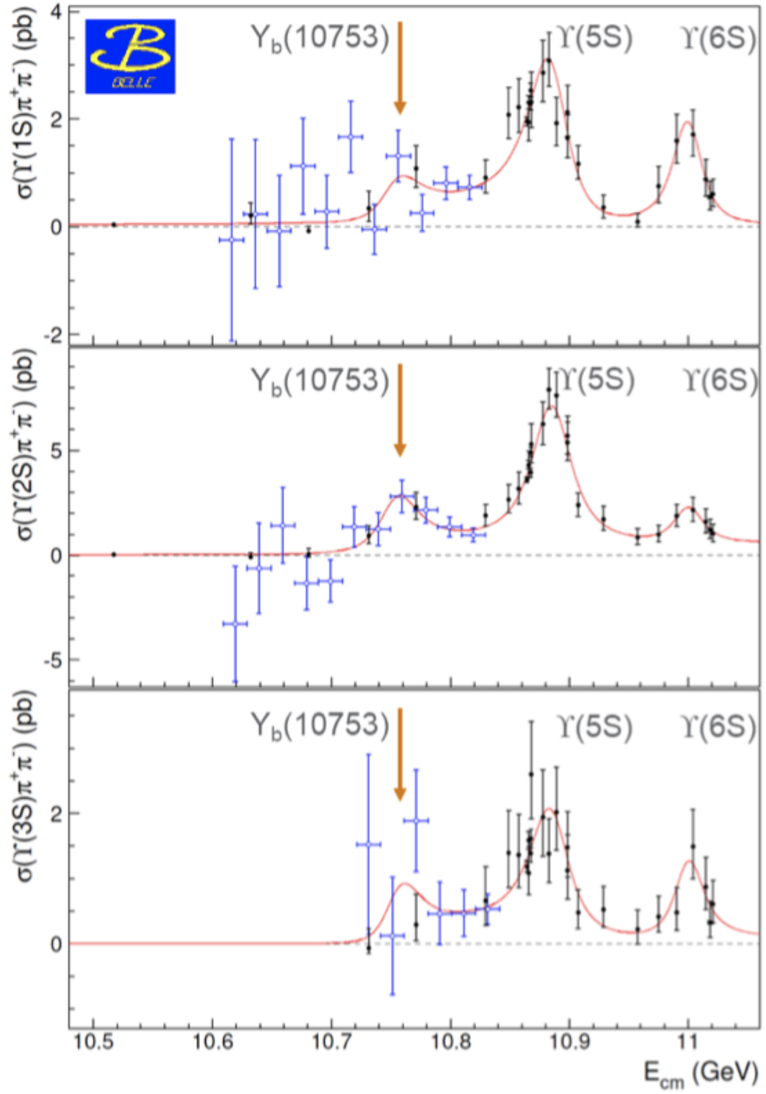
Conventional bottomonium (pure $b\bar{b}$ states)

Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)

Exotic charged states (Z_b^+)

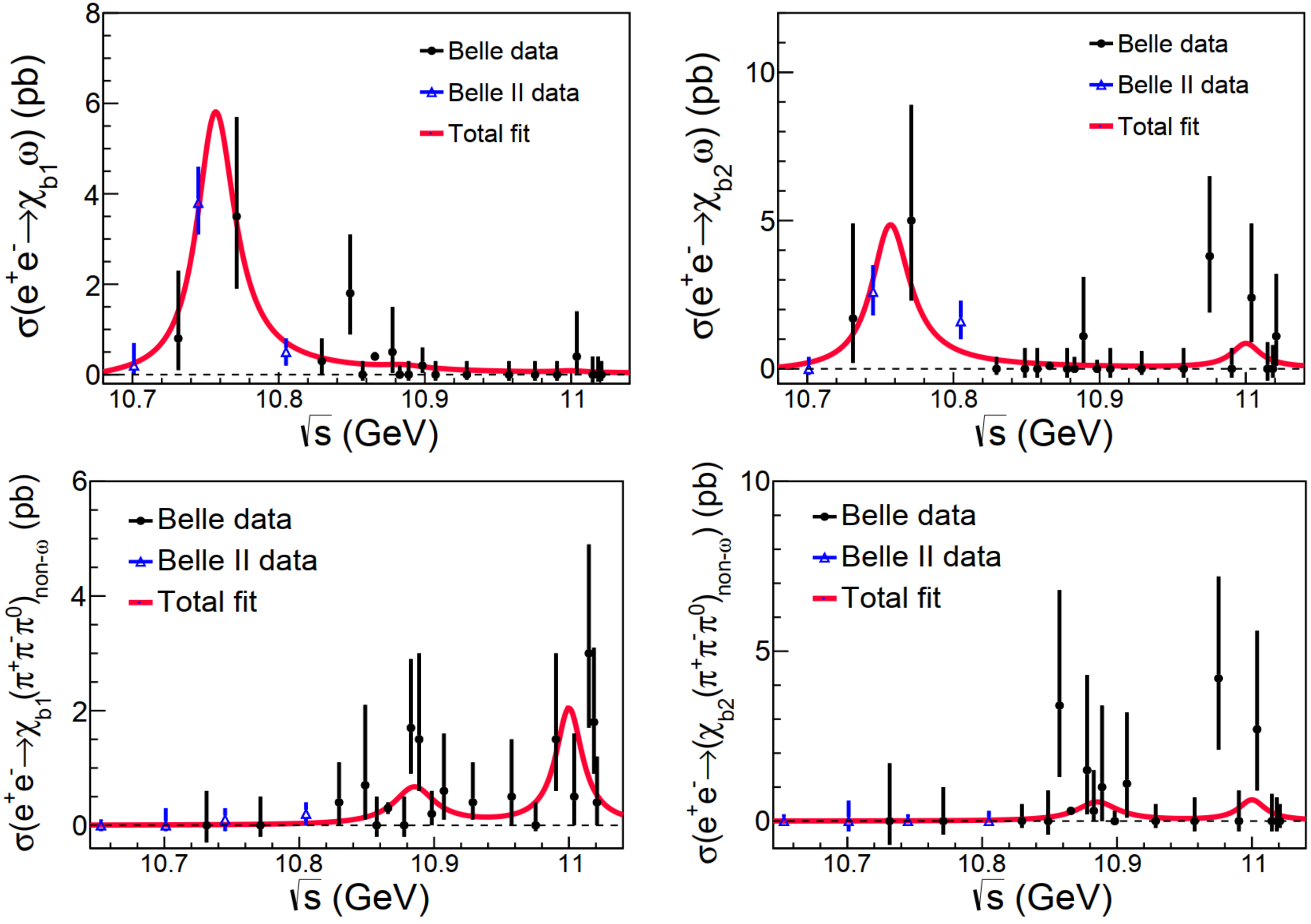


The Υ(10753) was first discovered in $\pi^+\pi^-\Upsilon(nS)$ final states using scan data by Belle [JHEP 10, 220 (2019)].



Recently, Belle II collected **19 fb^{-1} of unique data around $\sqrt{s} \sim$ 10.75 GeV** to study the nature of the Υ(10753).

$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ at Belle and Belle II



[Preliminary results]

$\Upsilon(10753)$ mass	(10756.1 ± 4.3) MeV/c^2
$\Upsilon(10753)$ width	(32.2 ± 18.7) MeV

- The mass and width are consistent with those from $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ measuremnt [JHEP 07, 116 (2024)].

$$\frac{\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)}$$

1.5 at $\sqrt{s}\sim$ 10.75 GeV **0.15 at $\sqrt{s}\sim$ 10.867 GeV**

This may indicate the difference in the internal structures of $\Upsilon(10753)$ and $\Upsilon(10860)$.

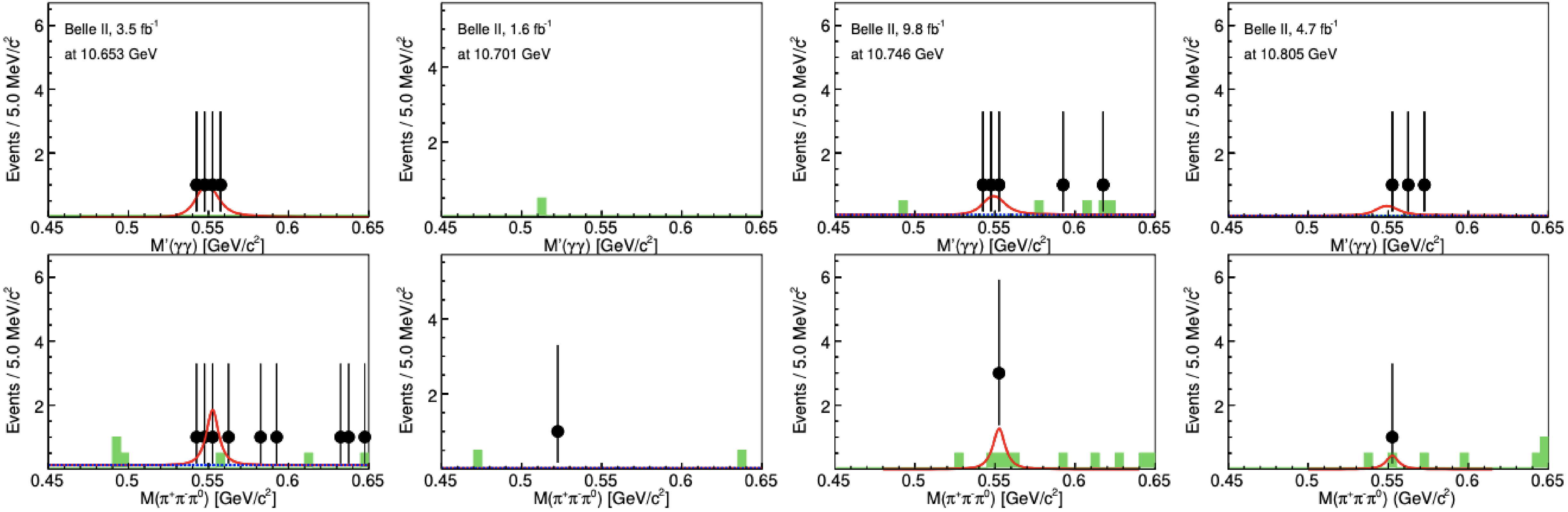
- The $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(10860,11020) \to Z_b\pi \to \chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].

$e^+e^- \rightarrow \eta\Upsilon(2S)$ at $\sqrt{s} \sim 10.75$ GeV

$\eta \rightarrow \gamma\gamma, \Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \rightarrow \ell^+\ell^-$
$\eta \rightarrow \pi^+\pi^-\pi^0, \Upsilon(2S) \rightarrow \ell^+\ell^-$

[Preliminary results]

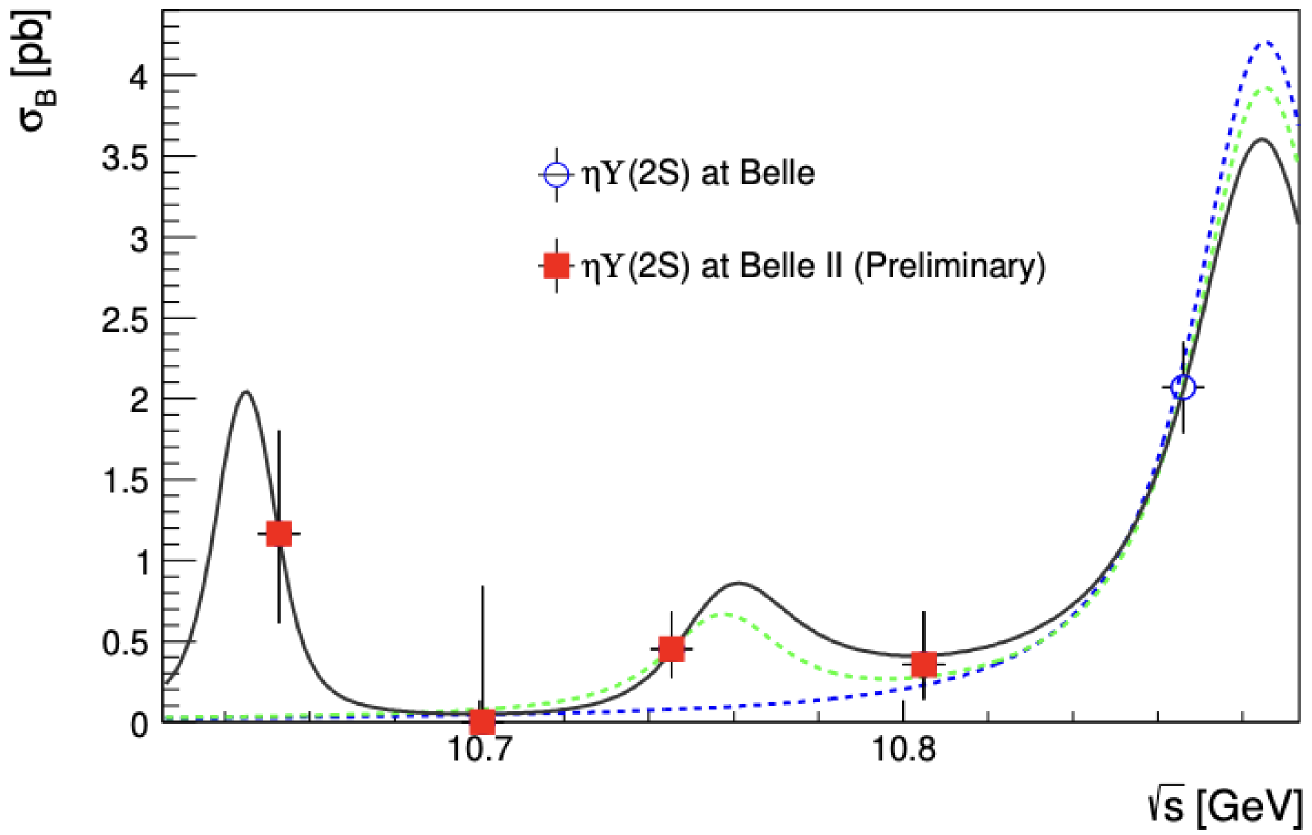
After requiring $\Upsilon(2S)$ signal region, simultaneous fit to $M(\gamma\gamma)$ and $M(\pi^+\pi^-\pi^0)$ for each energy point.



- Combining all of the energy points, the signal yields for $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ are $6.0^{+1.7}_{-1.5}$ and $11.5^{+3.3}_{-2.8}$.
- **The statistical significance is 6.4σ for $e^+e^- \rightarrow \eta\Upsilon(2S)$ at $\sqrt{s} \sim 10.75$ GeV.**

$e^+e^- \to \eta\Upsilon(2S)$ at $\sqrt{s} \sim 10.75$ GeV

[Preliminary results]



The Born cross section of $e^+e^- \to \eta\Upsilon(2S)$ around $B^*\bar{B}^*$ mass is relatively large.

Fit the with 3 different hypotheses:

H_1: only $\Upsilon(5S)$ [blue curve]

H_2: $\Upsilon(10753)$ + $\Upsilon(5S)$ [Green curve]

H_3: $B^*\bar{B}^*$ bound state + $\Upsilon(10753)$ + $\Upsilon(5S)$ [Black curve], the default fit.

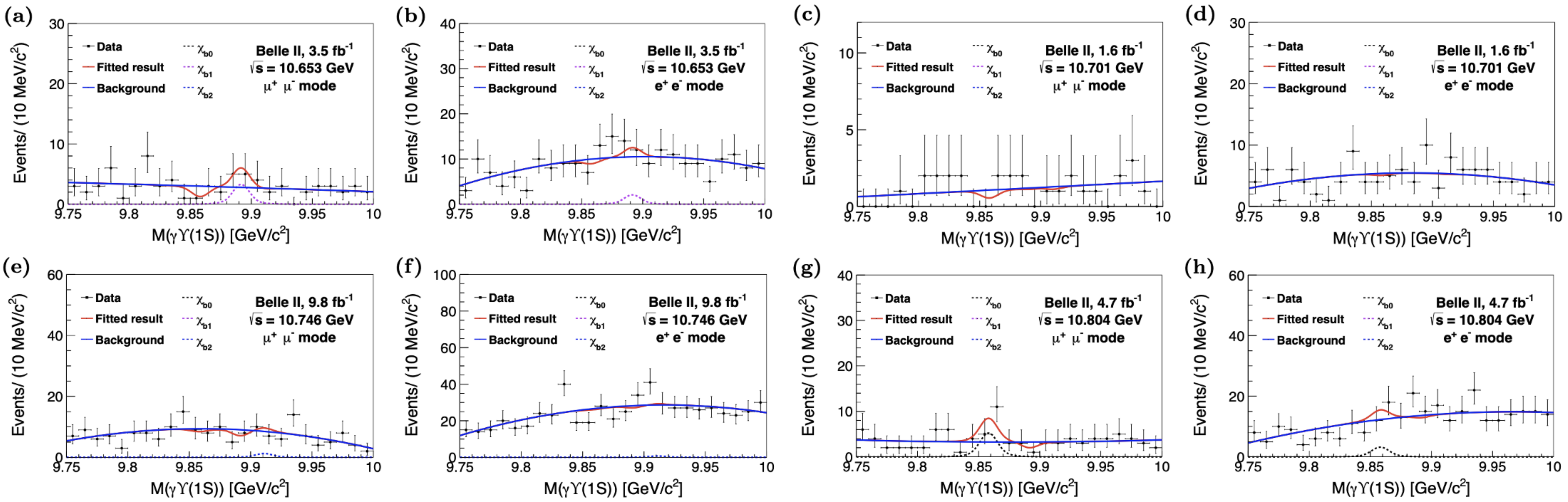
The masses and widths of $B^*\bar{B}^*$ bound state, $\Upsilon(10753)$, and $\Upsilon(5S)$ are fixed [JHEP 10 (2024) 114].

The statistical significance of $B^*\bar{B}^*$ bound state is larger than 3.2σ [H_3 comapred to H_1 or H_3 comapred to H_2].

$e^+e^- \to \gamma\chi_{bJ}$ $(J = 0, 1, 2)$

[Preliminary results]

The simultaneous fitted results to $M(\gamma\Upsilon(1S))$ distributions from data samples in e^+e^- and $\mu^+\mu^-$ modes.

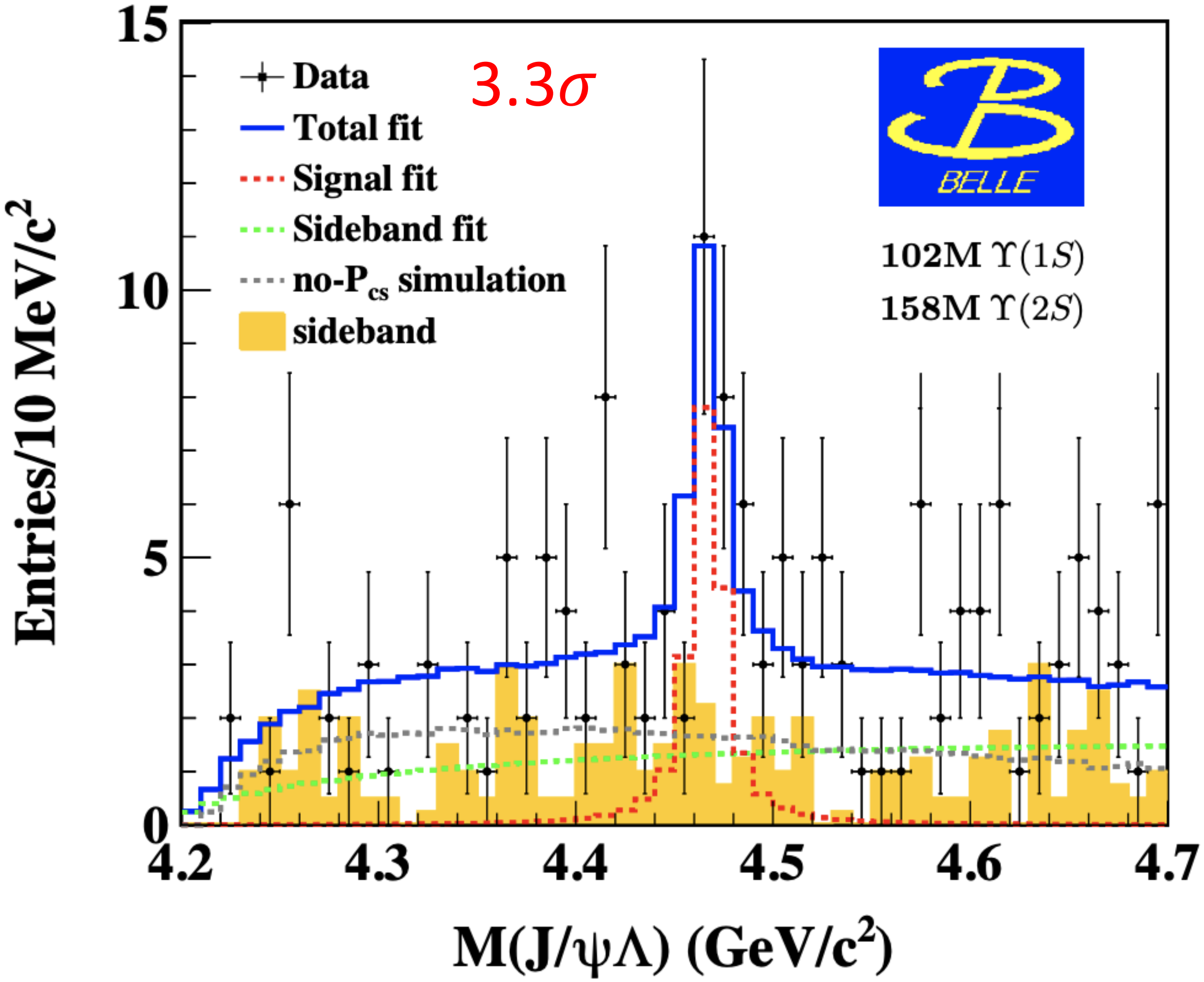


- No clear signal of $e^+e^- \to \gamma\chi_{bJ}$ can be seen.
- $\sigma^{UL}_{Born}(e^+e^- \to \gamma\chi_{b1})$ at $\sqrt{s}$ = 10.746 GeV is 0.25 pb ($\mathcal{B}^{UL}_{Born}(e^+e^- \to \gamma\chi_{b1}) \sim 10^{-4}$).

- If the Y(10753) consists of a significant D-wave component, the branching fraction for $\Upsilon(10753) \to \gamma\chi_{bJ}$ can reach 10^{-2} [PRD 92, 054034 (2015), EPJC 78, 915 (2018)].
- Our measurement indicates that **the D-wave component in the Y(10753) cannot be large**.

Evidence of $P_{c\bar{c}s}(4459)$ at Belle

[arXiv:2502.09951]



- OZI suppressed decays of $\Upsilon(1S)$ and $\Upsilon(2S)$ rich in gluons:
  - enhanced baryon production
  - Pentaquarks?
- Select inclusive $\Upsilon(1S, 2S) \to J/\psi\Lambda + X$ decays, then search for $P_{c\bar{c}s} \to J/\psi\Lambda$ in $M(J/\psi\Lambda)$
- 4.0σ local significance with free mass and width
- 3.3σ significance with the Gaussian constraints from LHCb measurement [Sci. Bull. 66, 1278 (2021)]

$$-2\ln\mathcal{L} + \frac{(m-m_0)^2}{\sigma_{m_0}^2} + \frac{(\Gamma-\Gamma_0)^2}{\sigma_{\Gamma_0}^2}$$

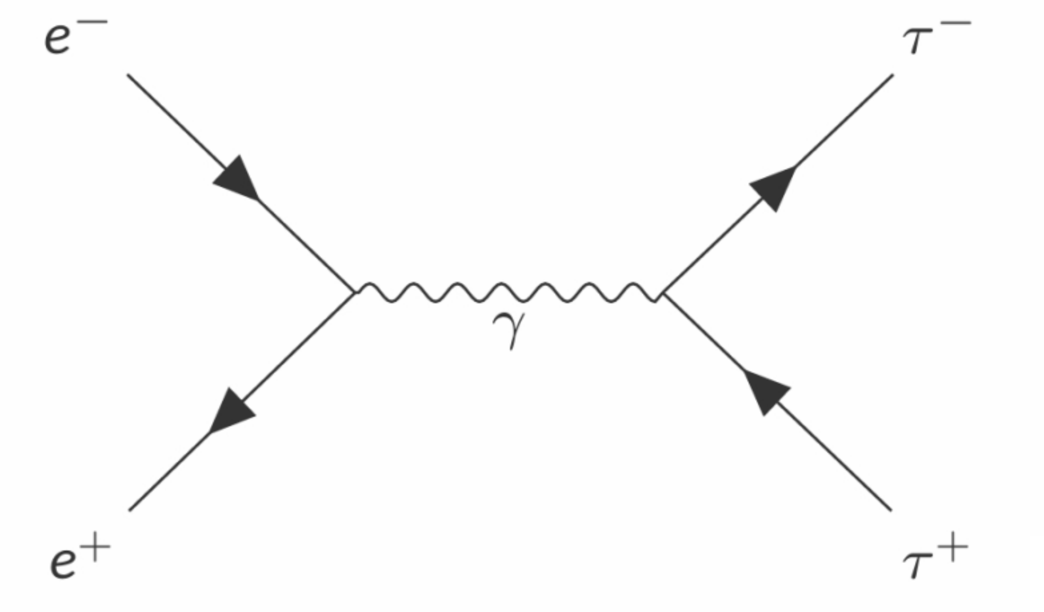
Tau

τ physics

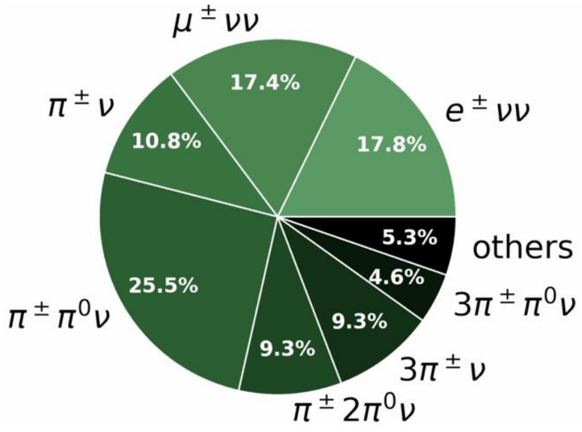
≫ τ mass and lifetime, lepton flavor/number violation, CKM unitarity, CP violation, ...

SuperKEKB as a ***τ factory***

- e^+e^- collider produce τ lepton pairs at high rate

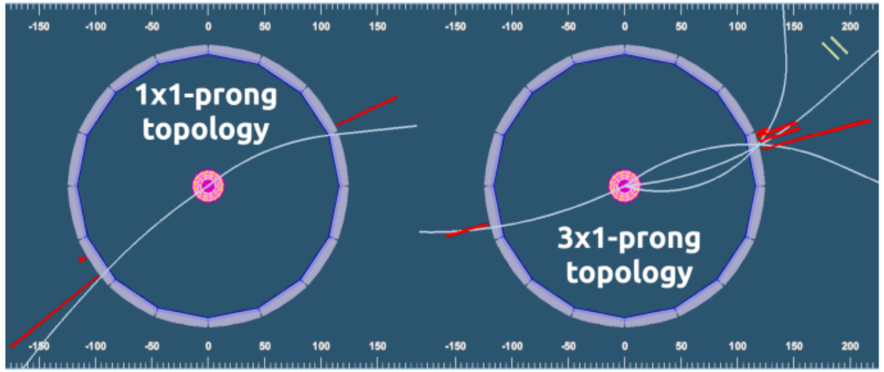


$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\,nb$$
$$\sigma(e^+e^- \to B\bar{B}) = 1.05\,nb$$



τ decay modes

Advantages at Belle II:
- ✓ High luminosity
- ✓ Good vertexing and tracking capabilities
- ✓ Good trigger system and particle ID

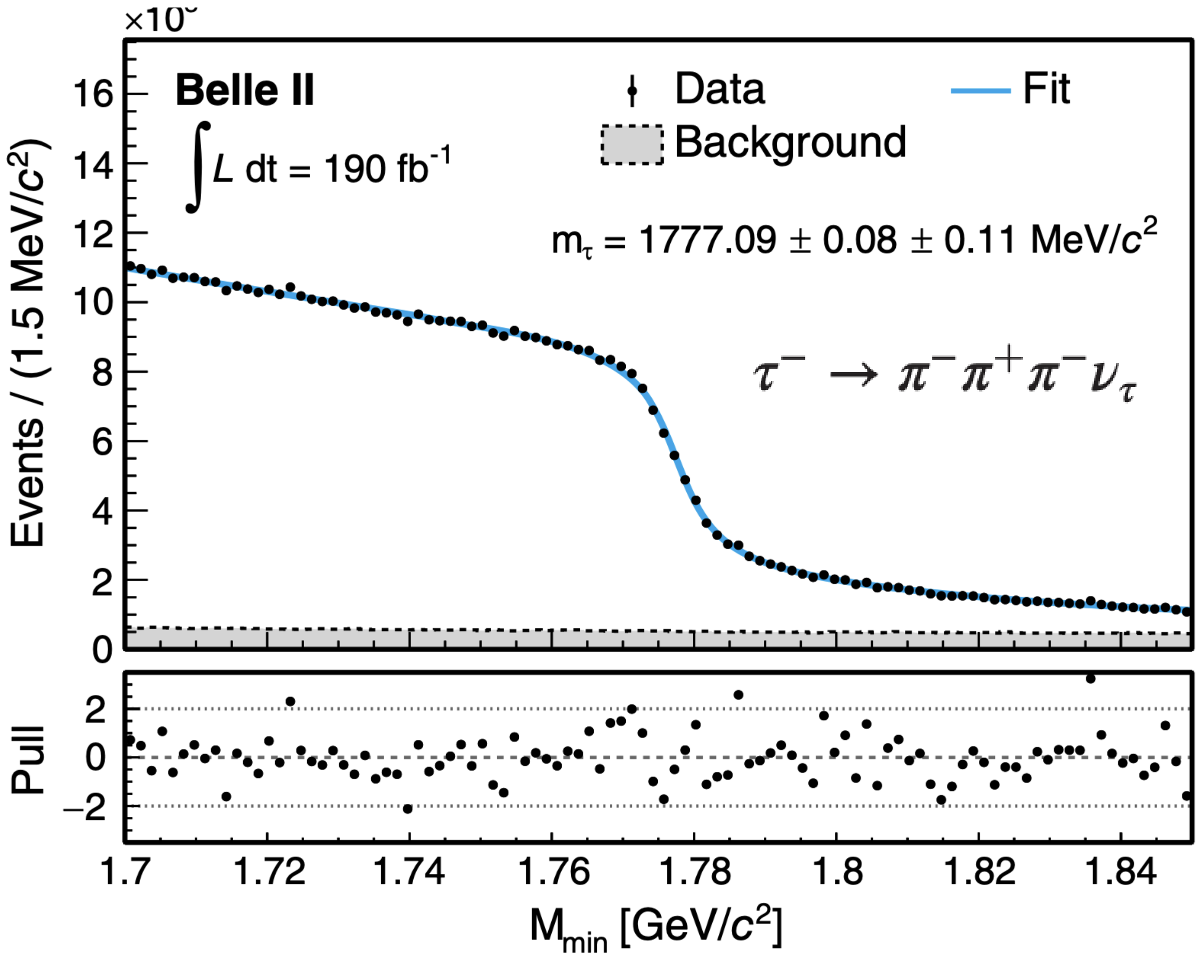


Taupair events are produced back-to-back and each tau is reconstructed via 1 or 3 charged tracks.

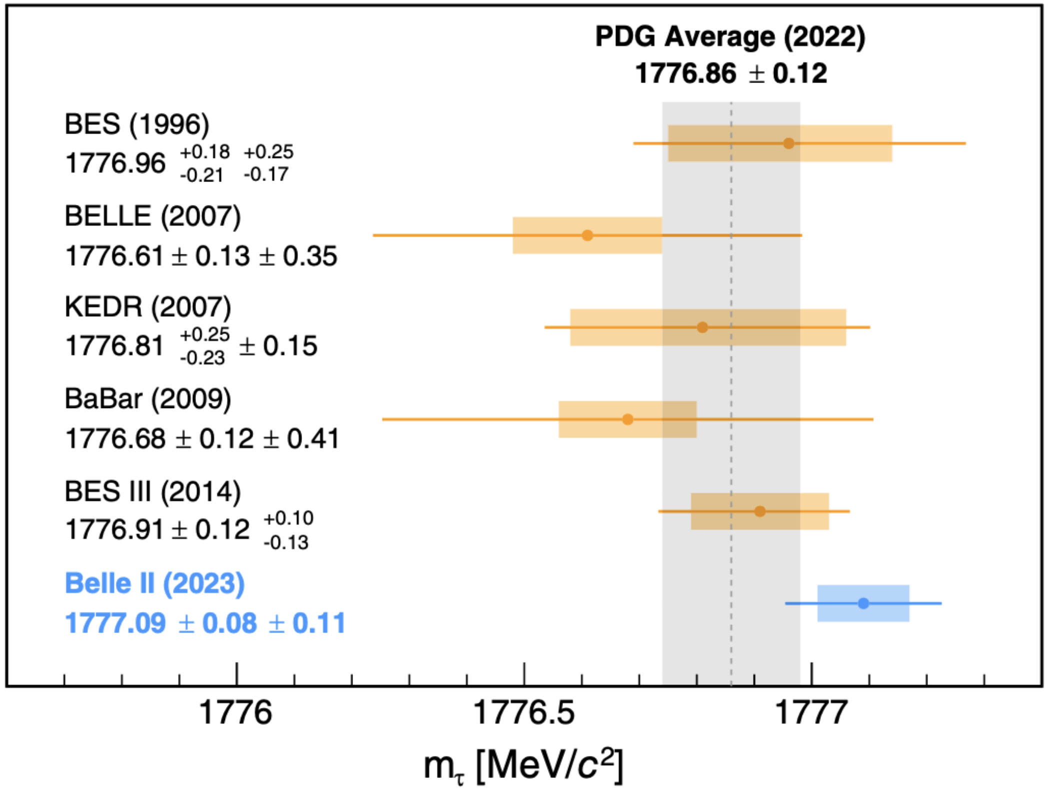
τ mass

M(τ) = (1777.09±0.08±0.11) MeV/c²
Most precise to date.

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$



Systematic uncertainty (0.11), dominant by beam-energy correction and charged-particle momentum correction. **[PRD 108, 032006 (2023)]**



Fit the distribution with a Heaviside step function:

$$F(M_{\min}) = 1 - P_3 \arctan\left(\frac{M_{\min} - \boxed{P_1}}{P_2}\right) + P_4(M_{\min} - P_1) + P_5(M_{\min} - P_1)^2$$

τ mass

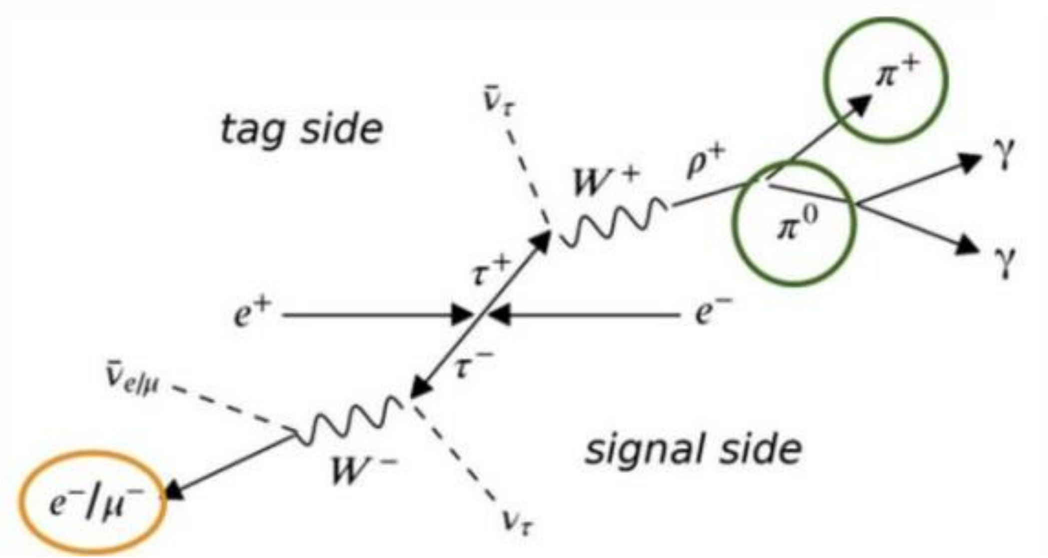
Lepton-flavor universality in τ physics

[JHEP 08 (2024) 205]

$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}.$$

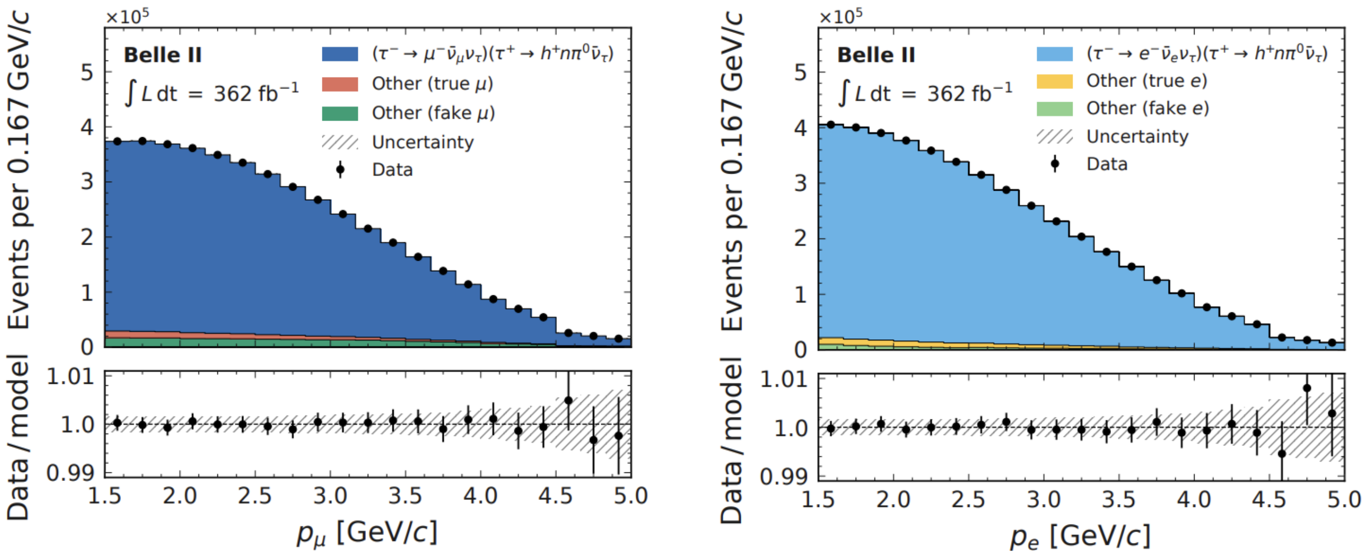
$$\left|\frac{g_\mu}{g_e}\right| \equiv 1 \text{ in SM}$$

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$



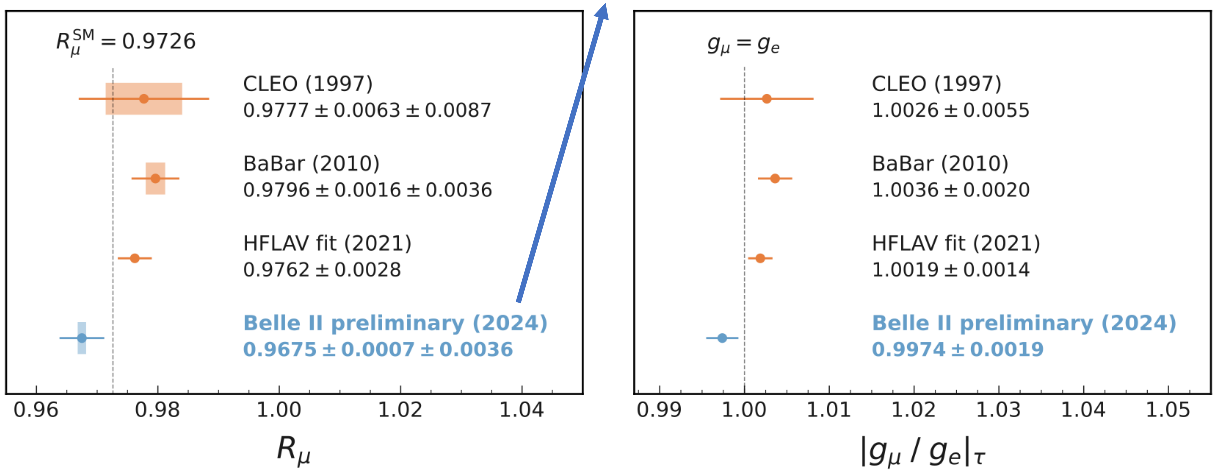
Neural Network for background suppression
94% purity with 9.6% signal efficiency

Extract $\mathcal{R}_\mu$ by fitting the lepton momentum [1.5, 5] GeV/c:



❑ Results:

Most precise to date



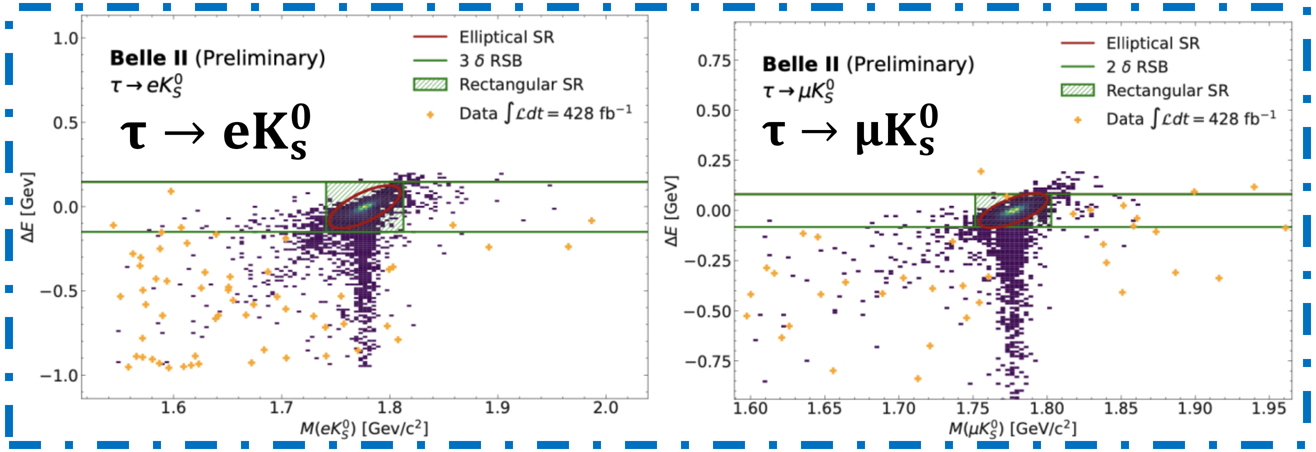
Lepton-flavor/number violation in τ physics

[arXiv:2504.15745]

Lepton flavour violation is only allowed by:
- **Neutrino oscillations** $\mathcal{O}(10^{-55})$

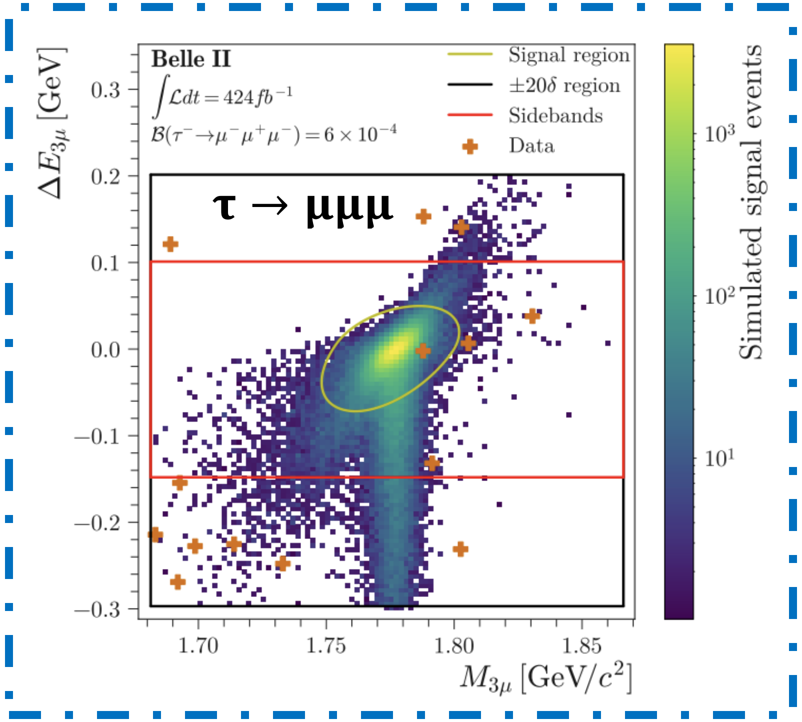
far beyond current experimental sensitivities
- **New Physics models** $\mathcal{O}(10^{-8})$

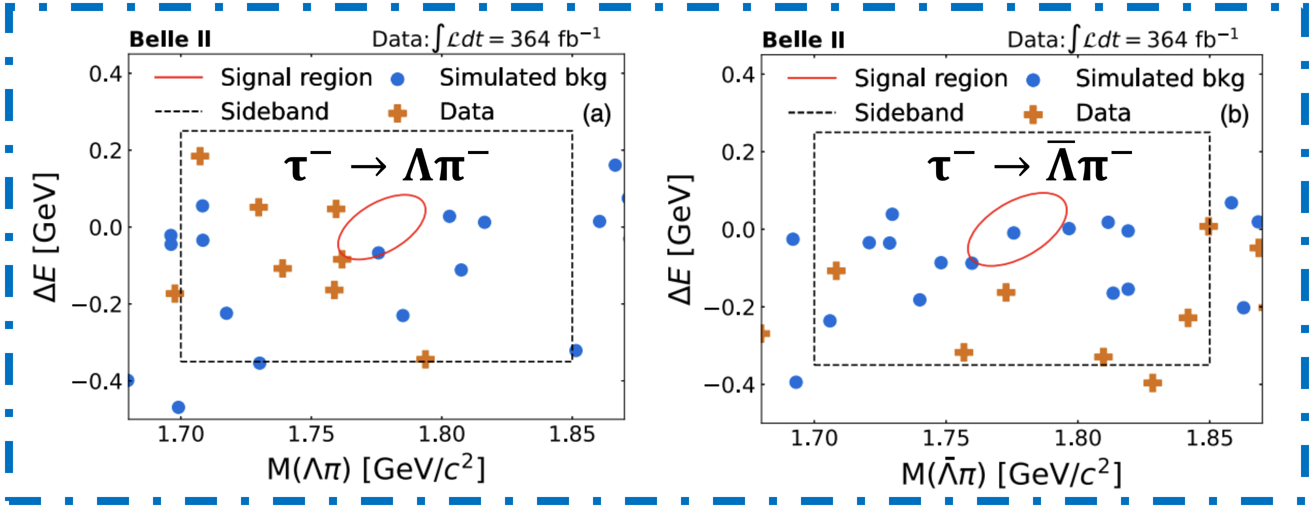
e.g. Leptoquarks for $\tau^- \to \ell^- V^0$ deals with $R(K^{*0})$ anomalies



[JHEP 09 (2024) 062]

[PRD 110, 112003 (2024)]





$$\Delta E_{3\mu} = E_\tau^* - \sqrt{s}/2$$

$\mathcal{B}^{\mathrm{UL}}(\tau \to e(\mu)K_S^0) < 0.8(1.2) \times 10^{-8}$	The most stringent constraints
$\mathcal{B}^{\mathrm{UL}}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$	Less data, more restrictive than Belle
$\mathcal{B}^{\mathrm{UL}}(\tau^- \to \Lambda\pi^-(\bar{\Lambda}\pi^-)) < 4.7(4.3) \times 10^{-8}$	The most stringent constraints

Summary

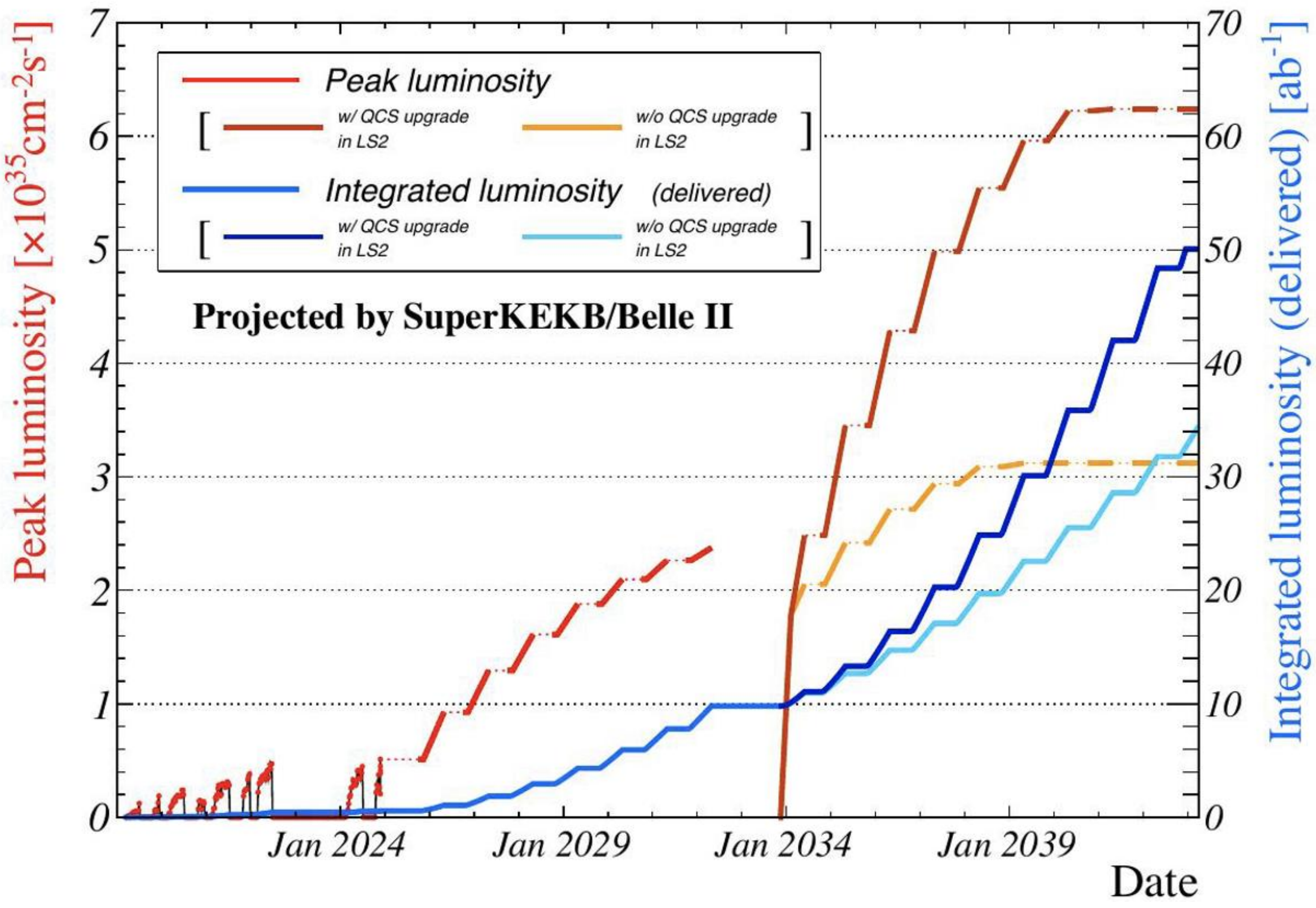
- Belle II and Belle hold a unique data sample. A number of interesting measurement has been already performed in different fields, such as
  - Provide a unique environment to study modes with missing energy: $\mathrm{B} \to \mathrm{K}\nu\bar{\nu}$, $\mathrm{B}^0 \to \mathrm{K}_S^0\tau^{\pm}\ell^{\mp}$, $\mathrm{B}^0 \to \mathrm{K}^{*0}\tau^{\pm}\ell^{\mp}$,$\mathrm{B}^0 \to \mathrm{K}^{*0}\tau^{+}\tau^{-}$
  - World's best determinations for A_{CP} in $\mathrm{D}^{0,+} \to \pi^{0,+}\pi^0$ and $\mathrm{D}^0 \to \mathrm{K}_S^0\mathrm{K}_S^0$, most precise measurements of D^0, D^+, Λ_c^+, and D_s^+ lifetimes to date, and first or most precise measurements for some charmed baryon decays
  - Properties study of $\Upsilon(10753)$, unique in Belle II
  - τ factory! Precise property measurements and search for NP

- Only 1% of target luminosity collected so far. Stay tuned for more exciting results from Belle II.

Thanks for your attention!

Backup slides

Data-taking plan at Belle II



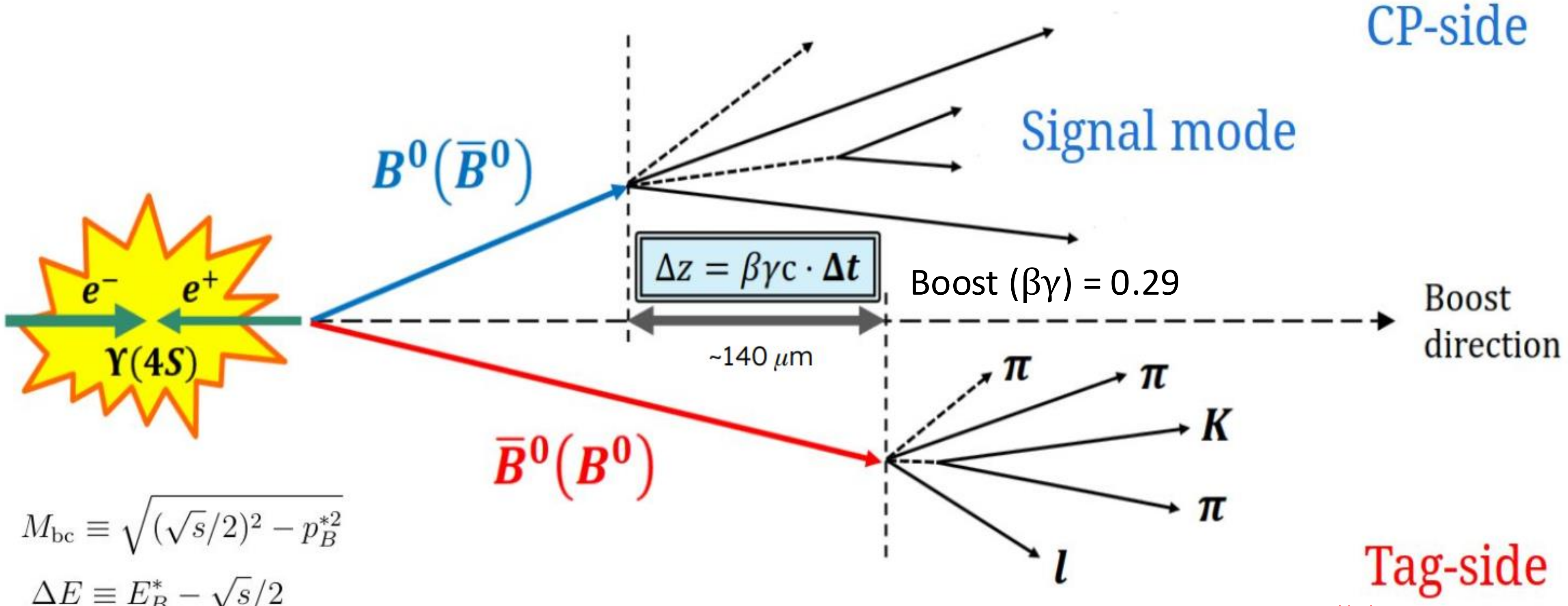
- Until 2026, about 1 ab^{-1} data, comparable to Belle
- Until 2029, about 4 ab^{-1} data.

Hadronic, leptonic, and semi-leptonic B decays

Strategy for CP measurements

$B\overline{B}$-pair entanglement → B-meson flavour is opposite to its pair at time of decay, then oscillates in time.

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$



$$M_{bc} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$$

$$\Delta E \equiv E_B^* - \sqrt{s}/2$$

All results today involve hadronic tagging, except for $R(D^{(*+)})$ and $B \to K\nu\bar{\nu}$.

$B^0 \to \rho^+\rho^-$

[arXiv: 2412.19624]

Goal: Branching fraction ($\mathcal{B}$), polarisation (f_L), CP asymmetry (S and C), ϕ_2 measurement

This decay gives stringent constraints of ϕ_2 due to small contribution from loop amplitude (b→d).

Probability distribution

Mixing-induced CPV param.

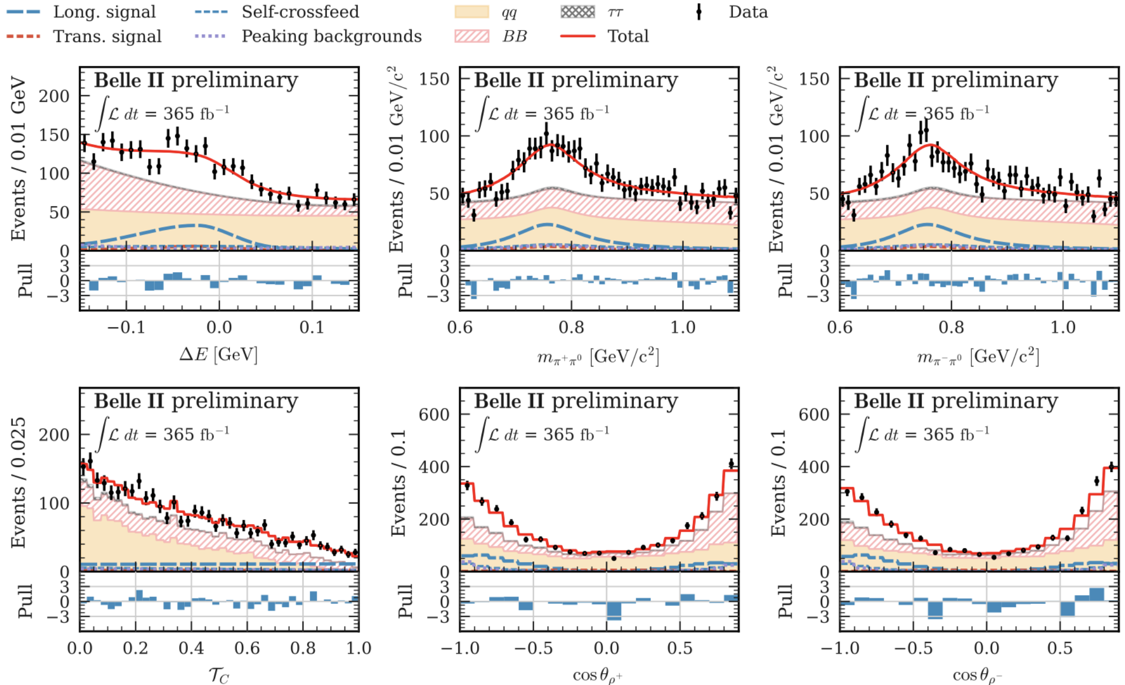
$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q\big[S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\big]\Big\},$$

Direct CPV param.

Helicity angle distribution

Longitudinal polarisation fraction

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_{\rho^+}\,d\cos\theta_{\rho^-}} = \frac{9}{4}\Big[\frac{1}{4}(1-f_L)\sin^2\theta_{\rho^+}\sin^2\theta_{\rho^-} + f_L\cos^2\theta_{\rho^+}\cos^2\theta_{\rho^-}\Big],$$



Extend ML fit to 6 obs: ΔE, $m_{\pi^\pm\pi^0}$, $\mathcal{T}_c$, and $\cos\theta_{\rho^+}$ to **extract $\mathcal{B}$ and f_L**

Results (Preliminary)

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.88^{+0.23}_{-0.22}{}^{+0.29}_{-0.27}) \times 10^{-5}$$

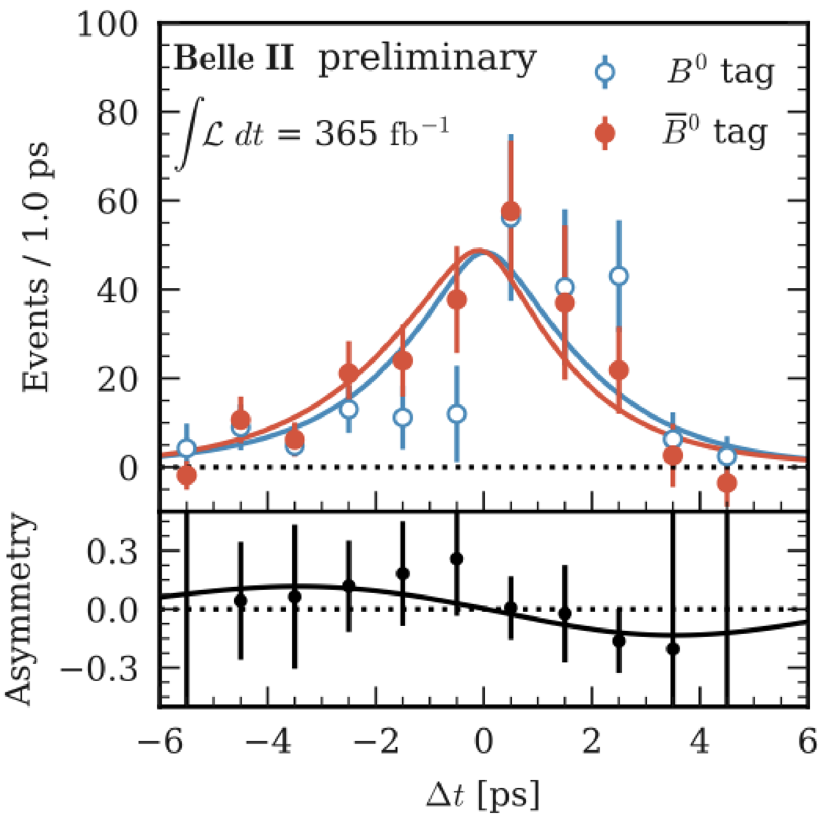
$$f_L = 0.921^{+0.024}_{-0.025}{}^{+0.017}_{-0.015}$$

$B^0 \to \rho^+\rho^-$

[arXiv: 2412.19624]

$$\frac{1}{\sqrt{2}}A_{+-} + A_{00} = A_{+0}$$
$$\frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00} = \bar{A}_{-0}$$

Extend ML fit to Δt to extract *S* and *C:*



$S = -0.26 \pm 0.19 \pm 0.08$

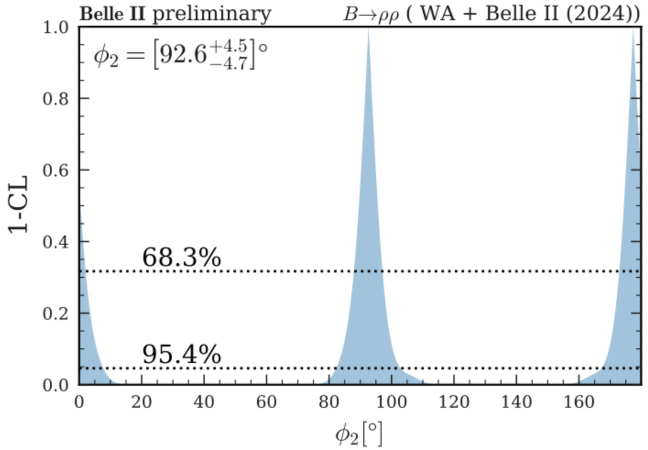
$C = -0.02 \pm 0.12 \pm 0.05$

Constraining ϕ_2

- Perform isospin analysis based on the amplitude of longitudinally polarized $B \to \rho^i\rho^j$, Aij
- Constrain using this measurement + World Averages (BaBar, Belle, and LHCb)

$$\phi_2 = (\ 91.5\ ^{+4.8}_{-5.2}\ )^\circ$$

Dominated by systematics from *S*



Second solution of ϕ_2 excluded by ϕ_1 and ϕ_3 measurements

Good agreement with previous BaBar (2007) and Belle (2016) with equivalent BaBar and ~50% of Belle equivalent luminosity !

Search for $B^+ \to \tau^+ \nu_\tau$

[arXiv: 2502.04885]

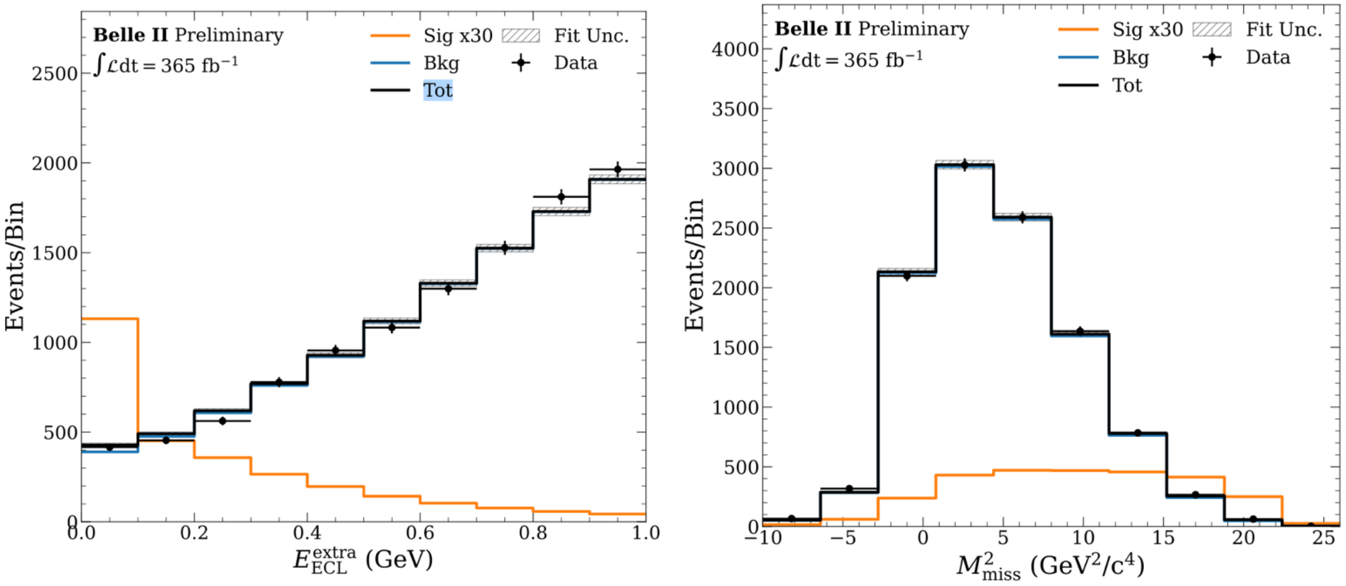
- **Precise BF value is important to check consistency with SM predictions / constrain new physics**

$$\mathcal{B}(B \to \tau\nu) > \mathcal{B}(B \to \mu\nu) > \mathcal{B}(B \to e\nu)$$

- **Potential modes to precisely measure $|V_{ub}|$**
- **Challenging (particularly, τ mode) due to undetected neutrinos in the final state**

Validate simulations/efficiency/modelling using control channels $\mathbf{B \to X\ell\nu}$, $\mathbf{B \to D^{(*)}\pi}$, and $\mathbf{B \to D^{*0}\ell\nu_\ell}$, then

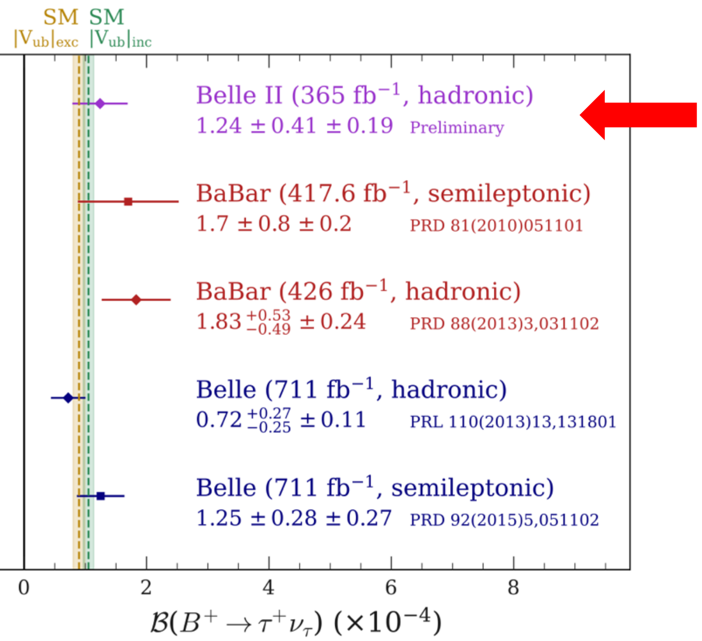
Simultaneous **binned** ML 2D fit to $M^2_{\text{miss}}, E^{\text{extra}}_{\text{ECL}}$



Results (Preliminary)

3σ significance

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.24 \pm 0.41 \pm 0.19) \times 10^{-4}$$



$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

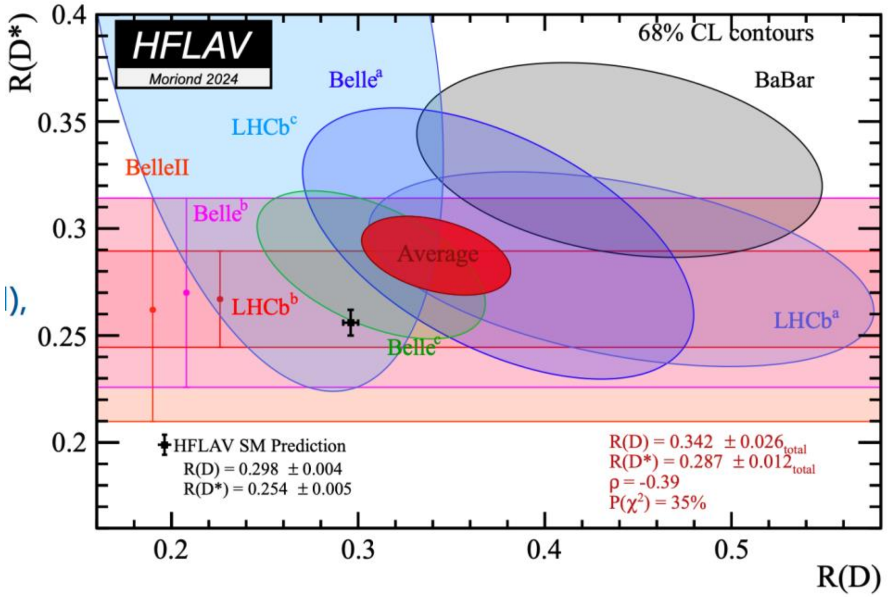
$$\mathcal{R}(D^{(*)+}) = \frac{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

- In SM, the W boson couples equally to $\tau, \mu, e \Longrightarrow$ **Lepton-Flavor Universality (LFU)**
- **Ratio measuremnts** provide strigent LFU tests: branching fractions, angular asymmetry, etc.
  - Normalization ($|\mathrm{V}_{\mathrm{xb}}|$) cancels
  - Part of theoretical, experimental uncertainties cancels

Goal: $\mathcal{R}(D^+)$ and $\mathcal{R}(D^{*+})$ measurement using semi-leptonic tagged approach (First results)

Reconstruction:

- Use semi-leptonic FEI to reconstruct the $\mathrm{B}_{\mathrm{tag}}$
- $\mathrm{B}_{\mathrm{sig}}$ is reconstructed from $\mathrm{D}^{(*)}$, leptons, and leptonic τ decays



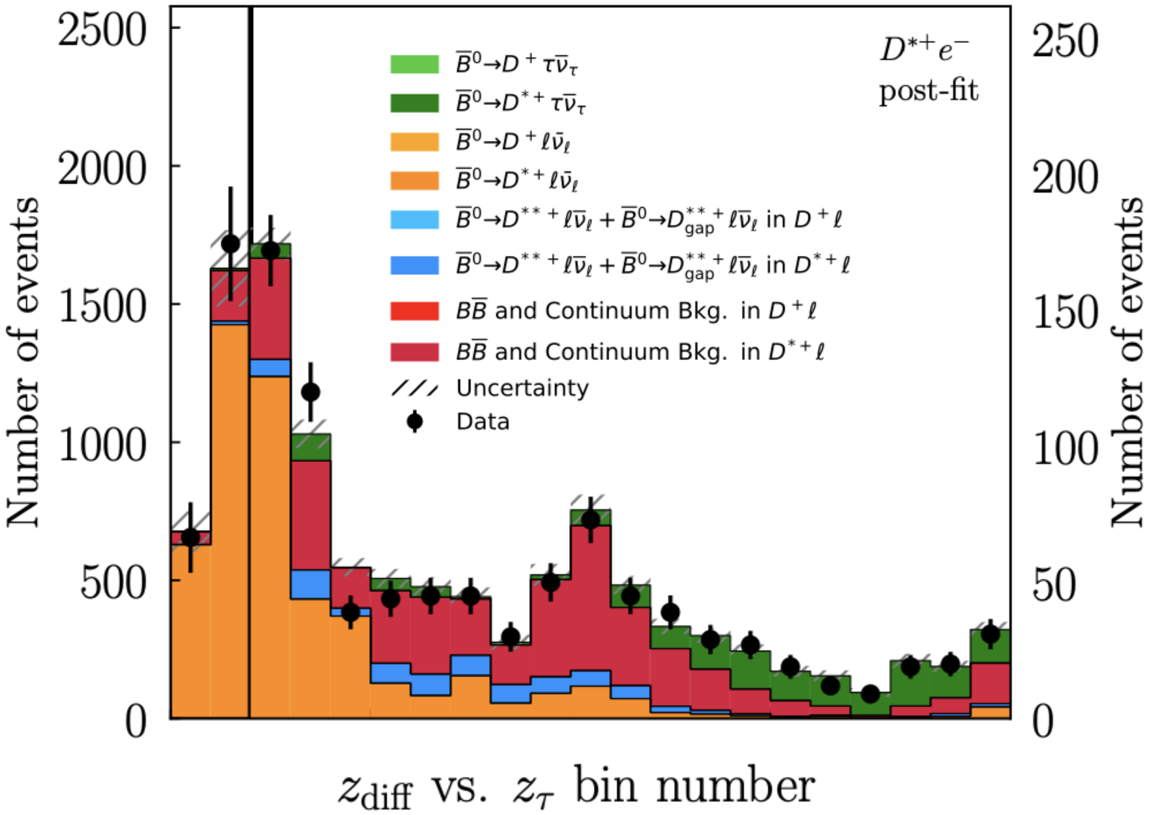
Combined deviation from SM stands at 3.3σ

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

[arXiv: 2504.11220]

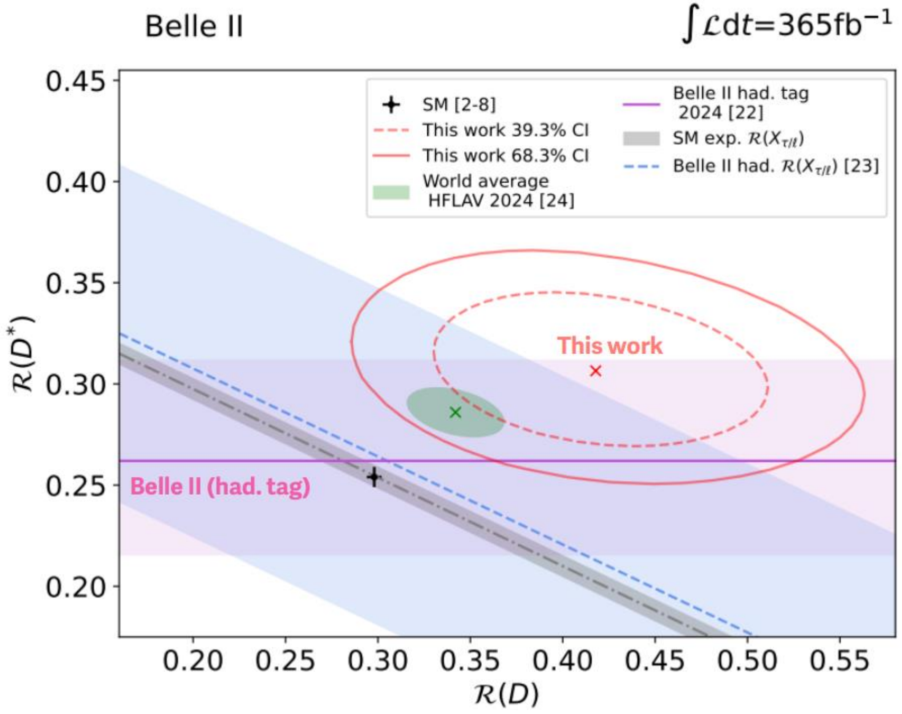
Signal extraction

- 2D binned log-likelihood fit to z_τ and $z_{\mathrm{diff}} = z_\ell - z_{\mathrm{bkg}}$
- The three classification scores are denoted as z_τ, z_ℓ, and z_{bkg} for semitauonic, semileptonic, and background events, respectively.
- Input BDT variables: angular, momenta of ℓ and $D^{(*)}$, and E_{ECL} extra.



Results (Preliminary)

$$\mathcal{R}(D^+) = 0.418 \pm 0.074\ (\mathrm{stat}) \pm 0.051\ (\mathrm{syst})$$
$$\mathcal{R}(D^{*+}) = 0.306 \pm 0.034\ (\mathrm{stat}) \pm 0.018\ (\mathrm{syst})$$

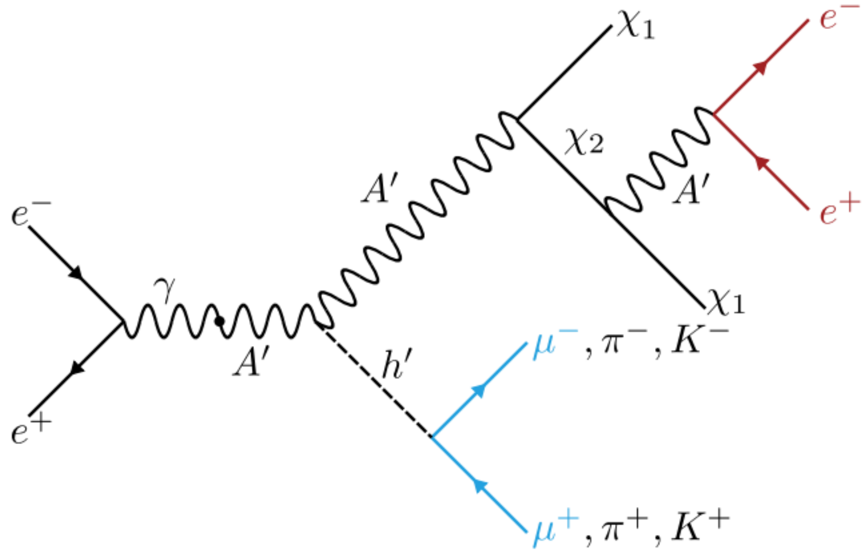


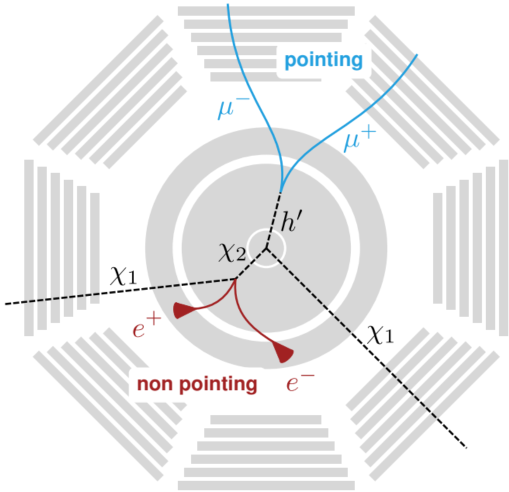
- Results are compatible with SM within 1.7σ

A dark Higgs boson in association with inelastic dark matter

[Preliminary results]

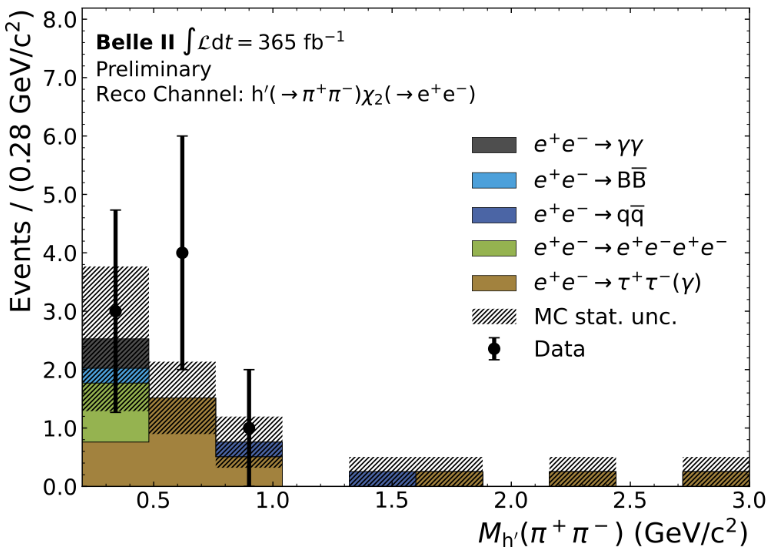
Dark photon A′, dark Higgs h′, and two dark matter states χ_1, χ_2



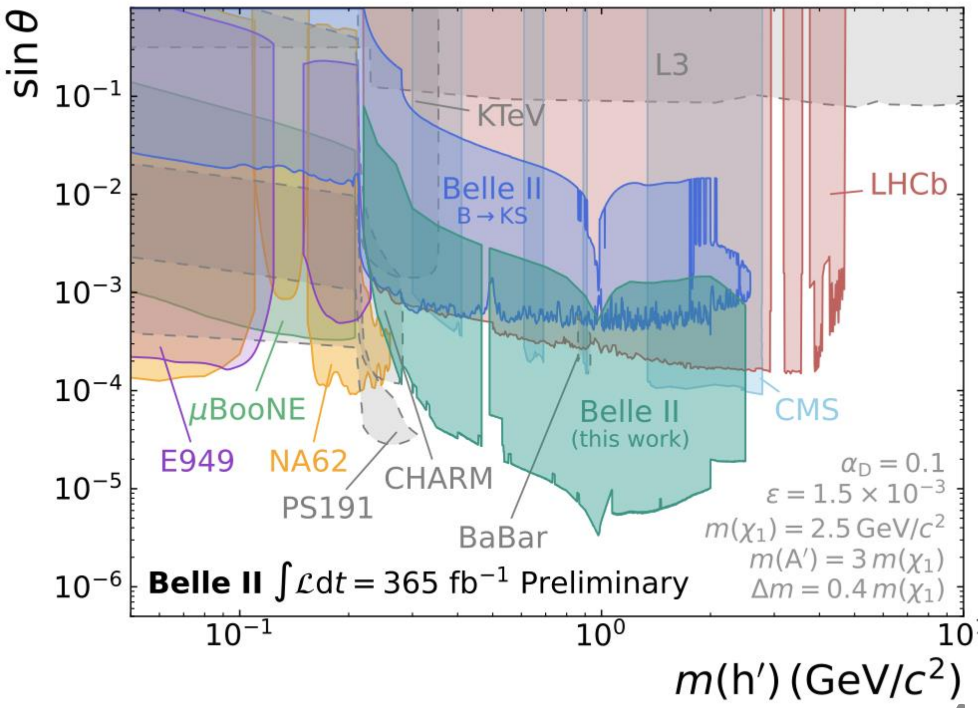


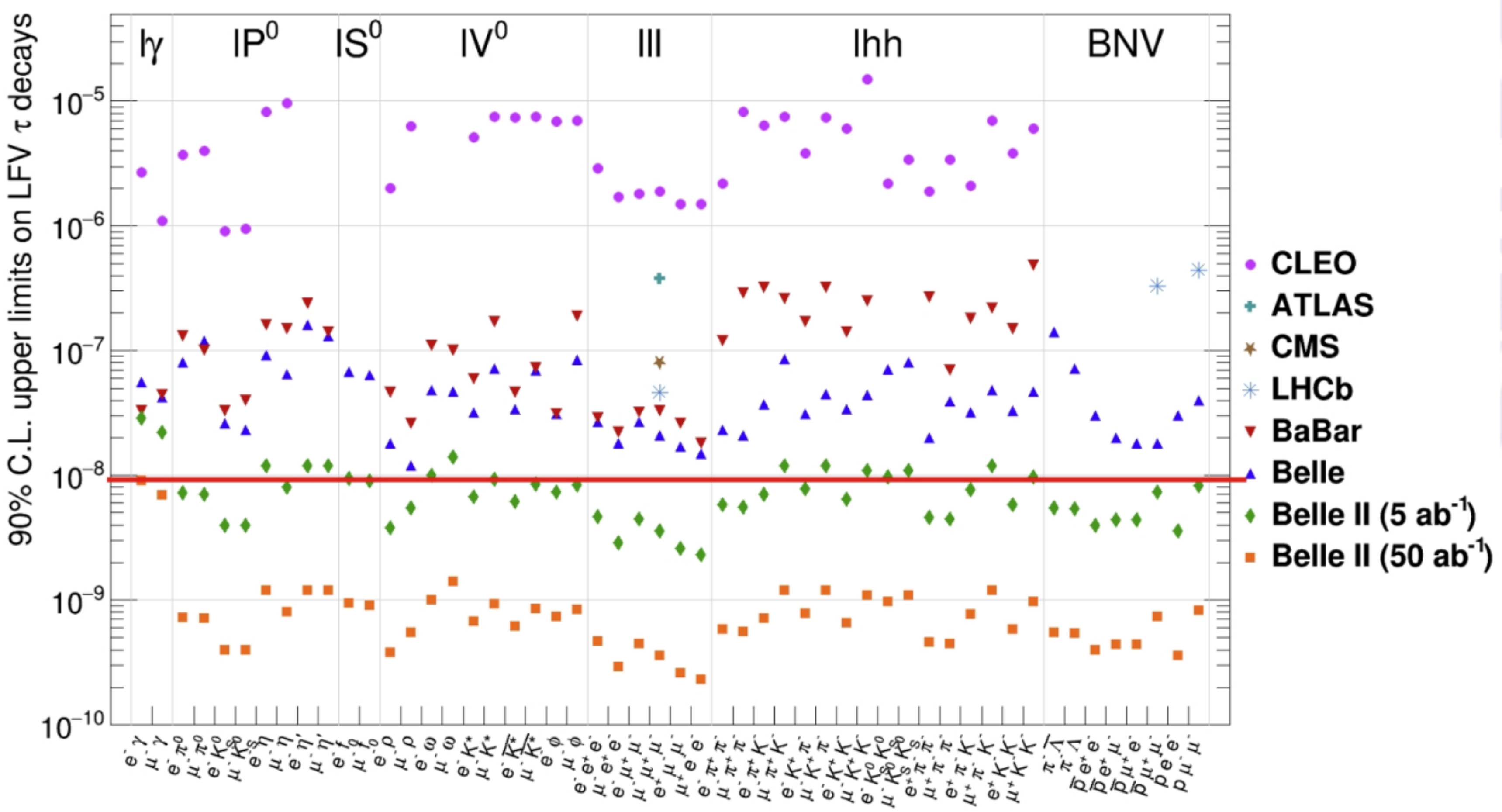
Looking for simultaneous production of A′ and h′

- 4 tracks in the final state
- 2 forming a pointing dispaced vertex
- mising energy



- cut-and-count strategy in $M_{h'}$ (x^+x^-) distributions
- No signicant excess found
- 8 events observed consistent with expected background
- Convert UL at 90% C.L. of $\sigma(e^+e^- \to \chi_1\chi_2 h') \times \mathcal{B}(\chi_2 \to \chi_1 e^+e^-) \times \mathcal{B}(h' \to x^+x^-)$ to mixing angle θ

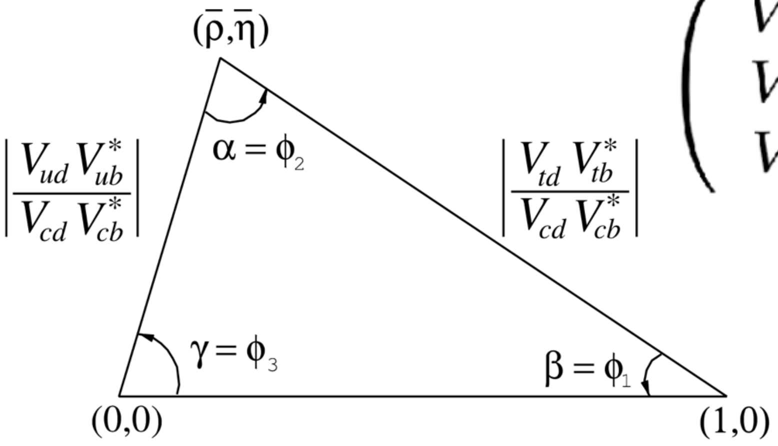



90% C.L. upper limits on LFV τ decays
lγ
lP0
lS0
lV0
lll
lhh
BNV
CLEO
ATLAS
CMS
LHCb
BaBar
Belle
Belle II (5 ab-1)
Belle II (50 ab-1)

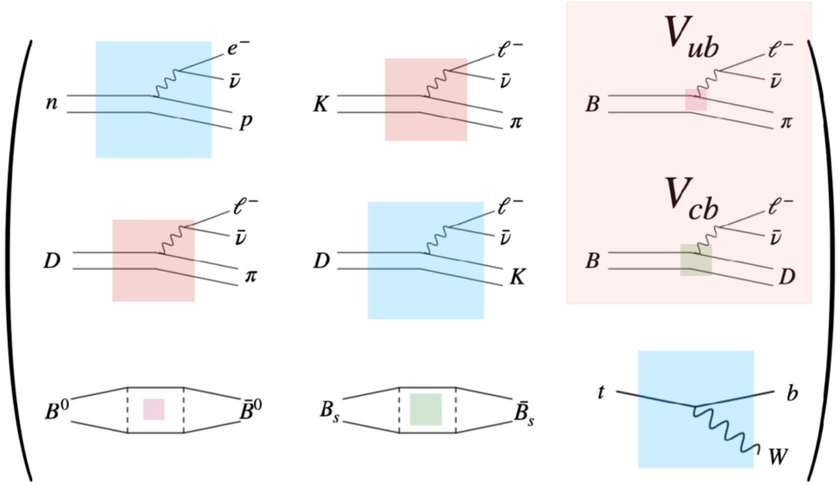
CKM matrix element

Belle II important task:

Constrain CKM unitarity triangle & test SM



$$\begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

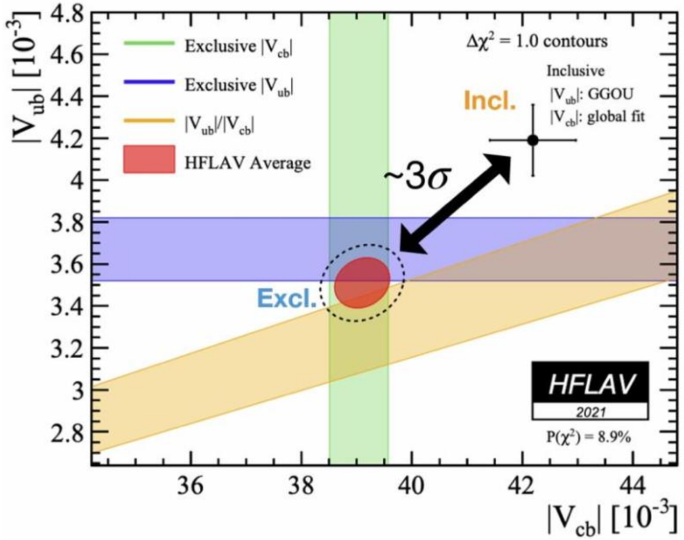


Exclusive: $B\to\pi l\nu, B\to\rho l\nu, B\to D^{(*)}l\nu, etc$

$\frac{dB}{dq^2}\propto|V_{xb}|^2\times|FF(q^2)|^2$ Form factor from LCSR, LQCD

Inclusive: $B\to X_u l\nu, B\to X_c l\nu$

$\mathcal{B}\propto|V_{xb}|^2\times\left[\Gamma(b\to q l\bar{\nu}_l)+\frac{1}{m_b}+\alpha_s+\cdots\right]$ From OPE



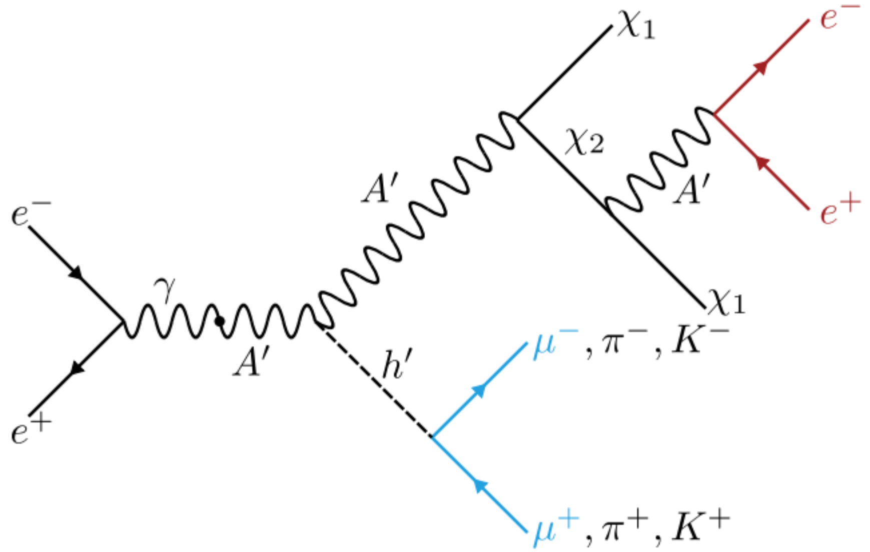
Several measurements carried out by Belle and Belle II:

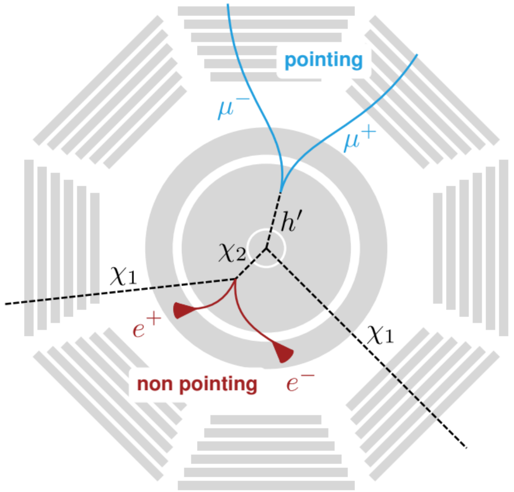
$\lvert V_{cb}\rvert$	- Angular coefficients of $B\to D^*l\nu$ **Belle: PRL 133, 131801 (2024)**
$\lvert V_{ub}\rvert$	- $\lvert V_{ub}\rvert$ from $B\to(\pi,\rho)l\nu$ simultaneous analysis New from Belle II - Simultaneous inclusive and exclusive $\lvert V_{ub}\rvert$ **Belle: PRL 131, 211801 (2023)**
$\frac{\lvert V_{ub}\rvert}{\lvert V_{cb}\rvert}$	- Ratio of inclusive $b\to c$ and $b\to u$ decays **Belle: arXiv: 2311.00458**

A dark Higgs boson in association with inelastic dark matter

[Preliminary results]

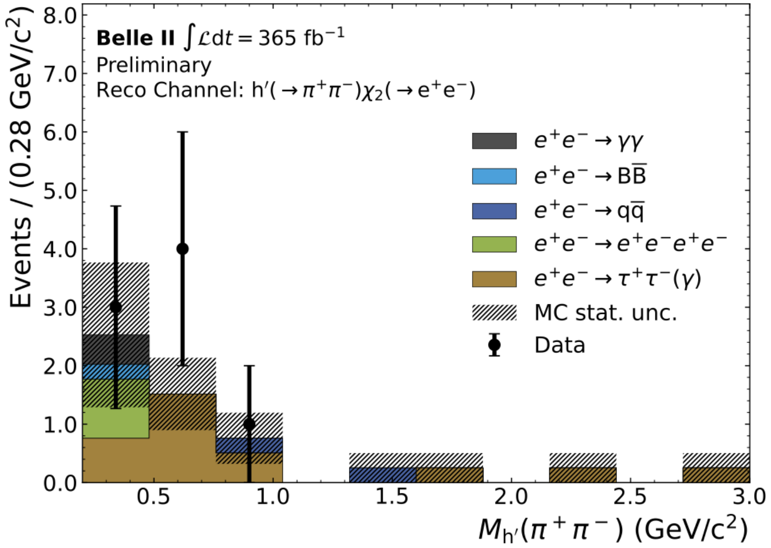
Dark photon A′, dark Higgs h′, and two dark matter states χ_1, χ_2





Looking for simultaneous production of A′ and h′

- 4 tracks in the final state
- 2 forming a pointing dispaced vertex
- mising energy



- cut-and-count strategy in $M_{h'}$ (x^+x^-) distributions
- No signicant excess found
- 8 events observed consistent with expected background
- Convert UL at 90% C.L. of $\sigma(e^+e^- \to \chi_1\chi_2 h') \times \mathcal{B}(\chi_2 \to \chi_1 e^+e^-) \times \mathcal{B}(h' \to x^+x^-)$ to mixing angle θ