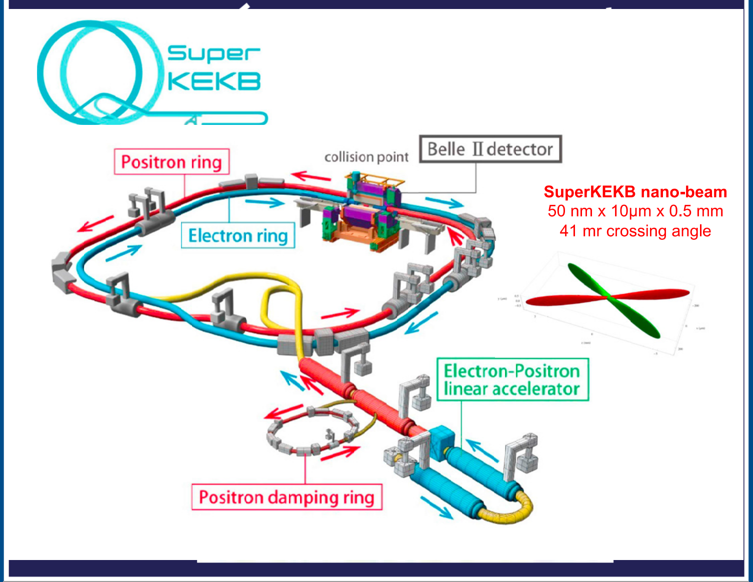
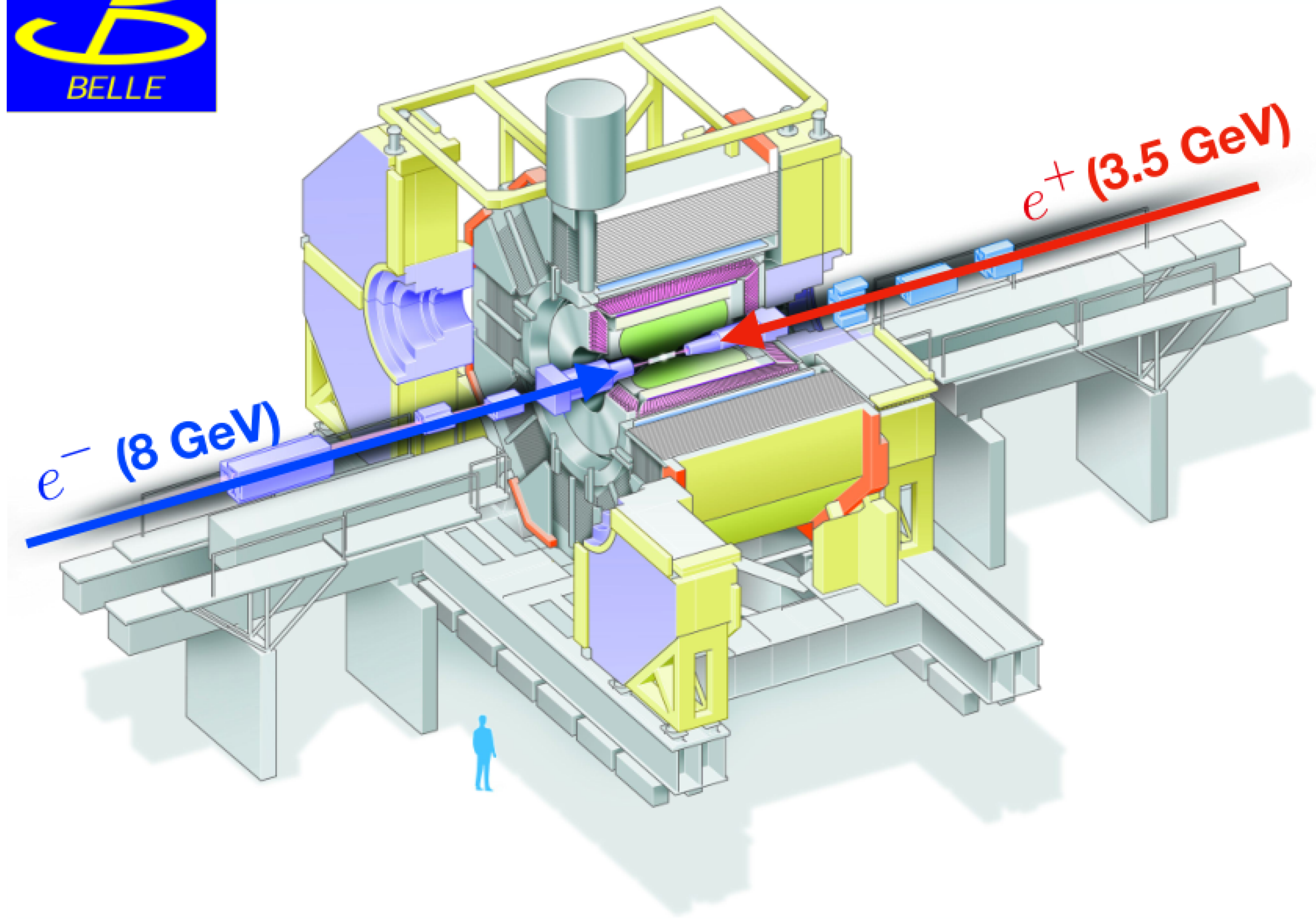
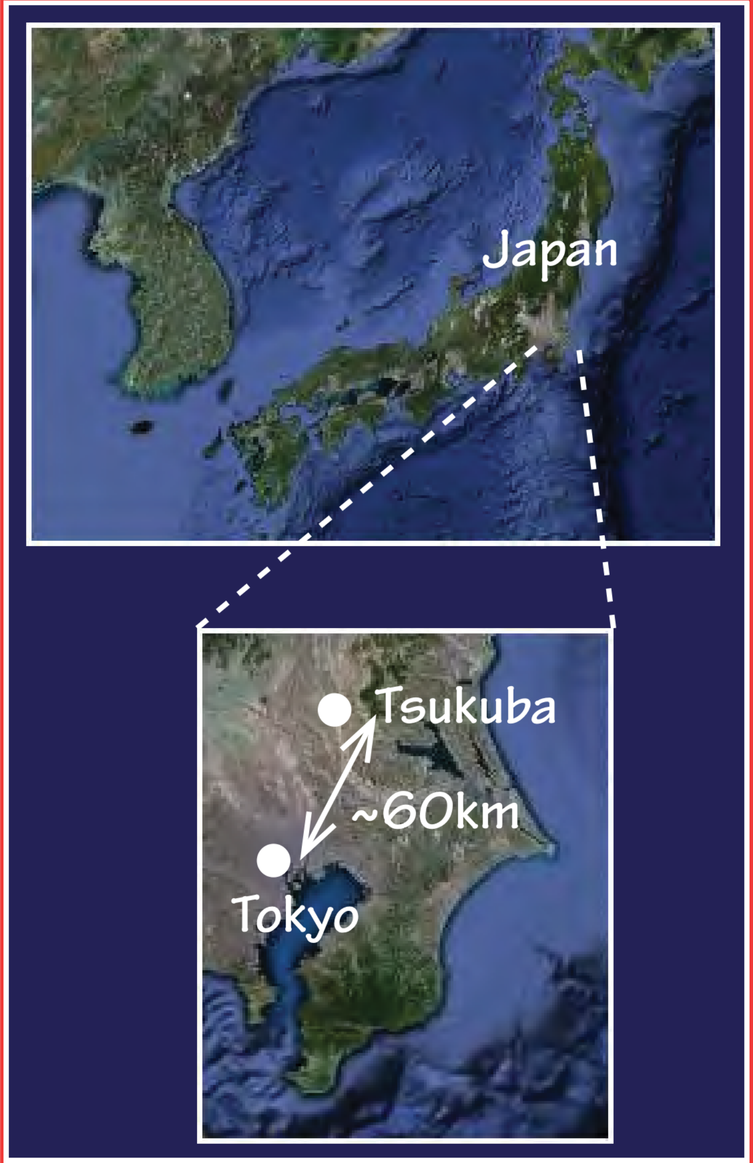
Measurements of τ decays at Belle and Belle II

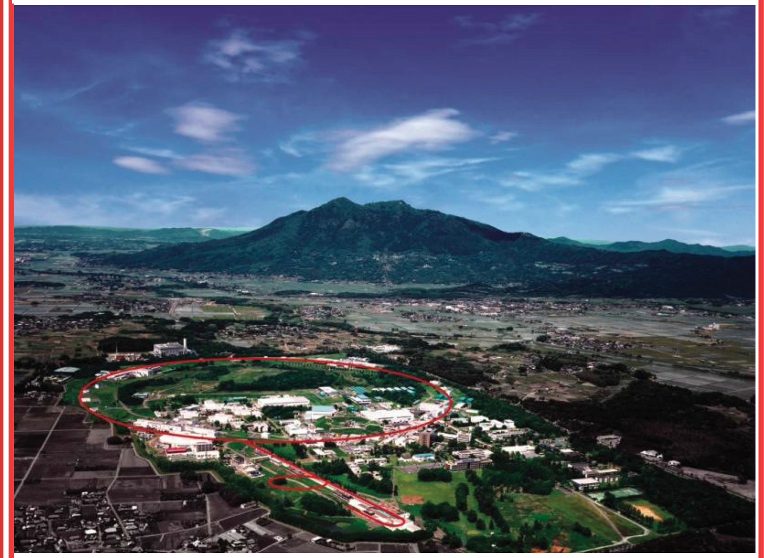


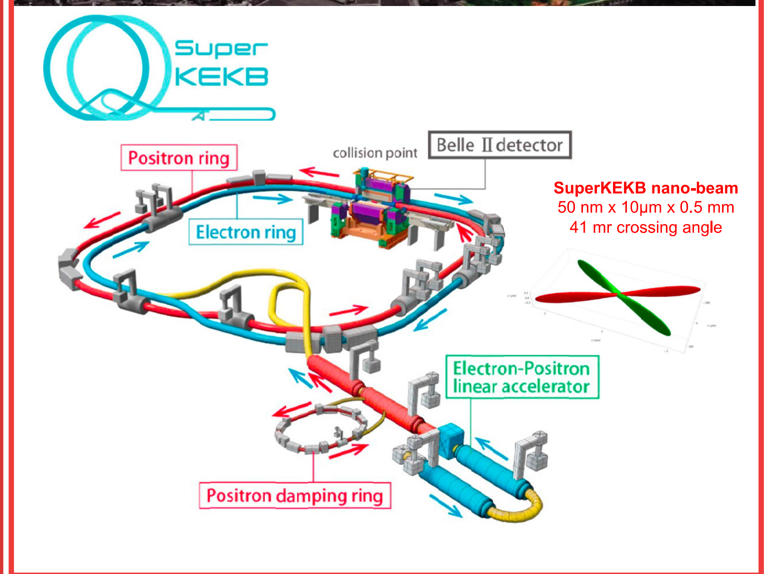
Vladimir Savinov (University of Pittsburgh), on behalf of the Belle and Belle II Collaborations

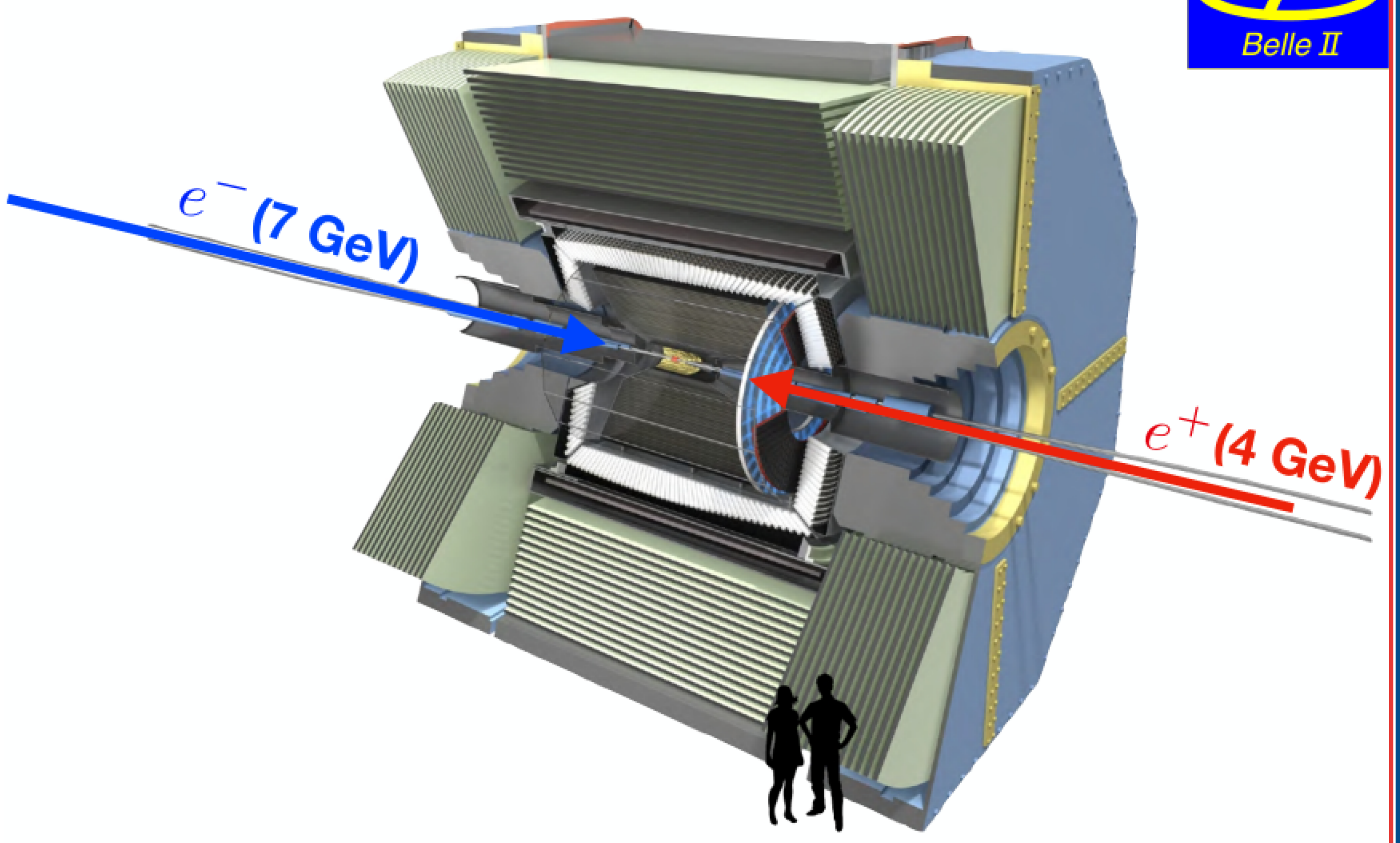


- Operated from 1999 to 2010.
- Asymmetric e^+ (3.5 GeV) - e^- (8 GeV) collider.
- Collected total of 1 ab^{-1} of data.
- Collected 711 fb^{-1} at $\Upsilon(4S)$ resonance.





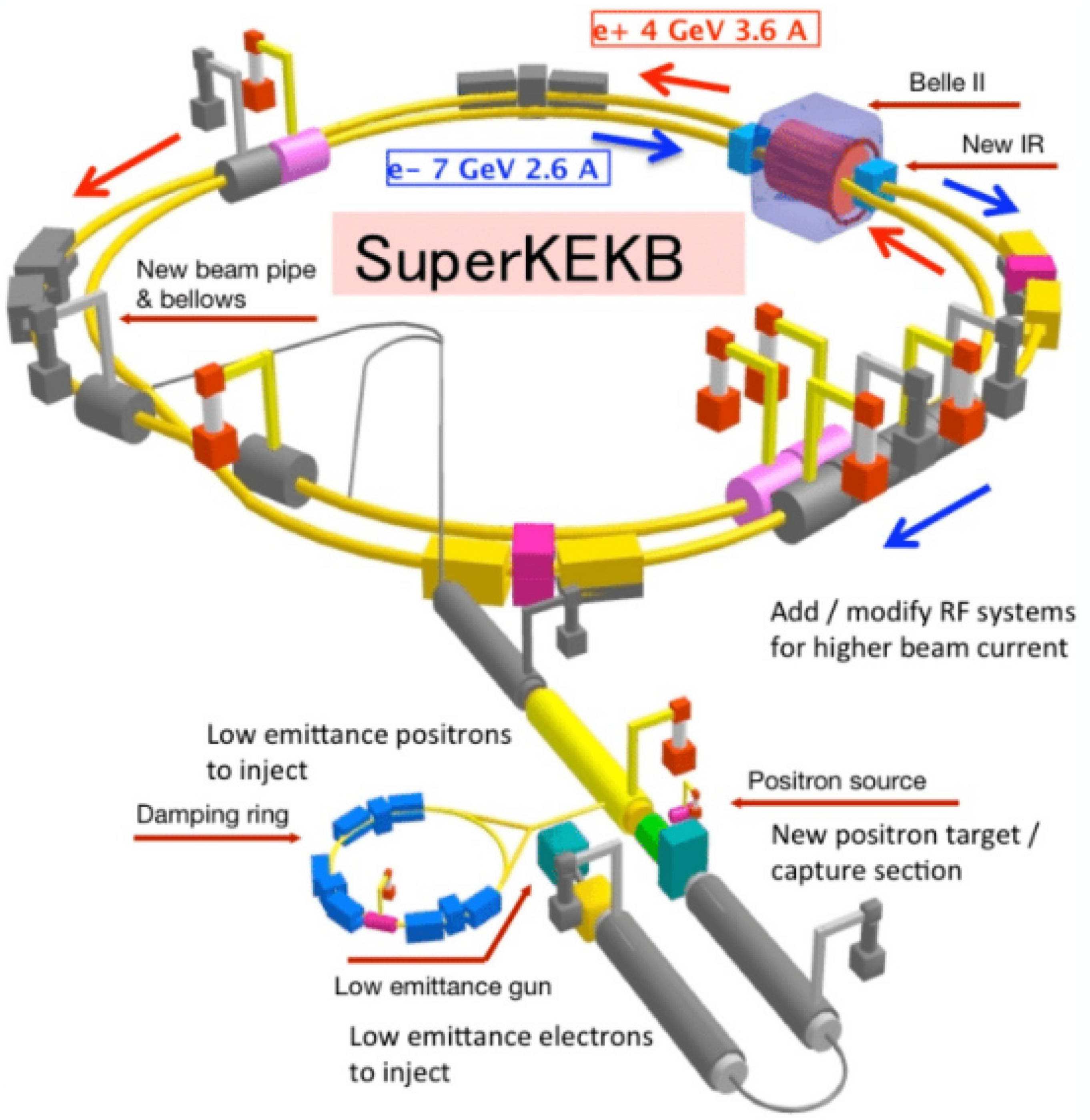




- Asymmetric e^+ (4 GeV) - e^- (7 GeV) collider.
- Recorded 531 fb^{-1} of data: equivalent to BaBar and 1/2 of Belle dataset.
- Run I data at $\Upsilon(4S)$ resonance: 365 fb^{-1}
- Run II started February 2024.
- **Aims to collect many-ab^{-1} of data!**

SuperKEKB goal instantaneous luminosity: $\mathscr{L}_{\text{Belle II}} = 6 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$ ($\mathscr{L}_{\text{Belle}} = 2.11 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$)

(record luminosity achieved by SuperKEKB in Dec. 2024: $5.1 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)

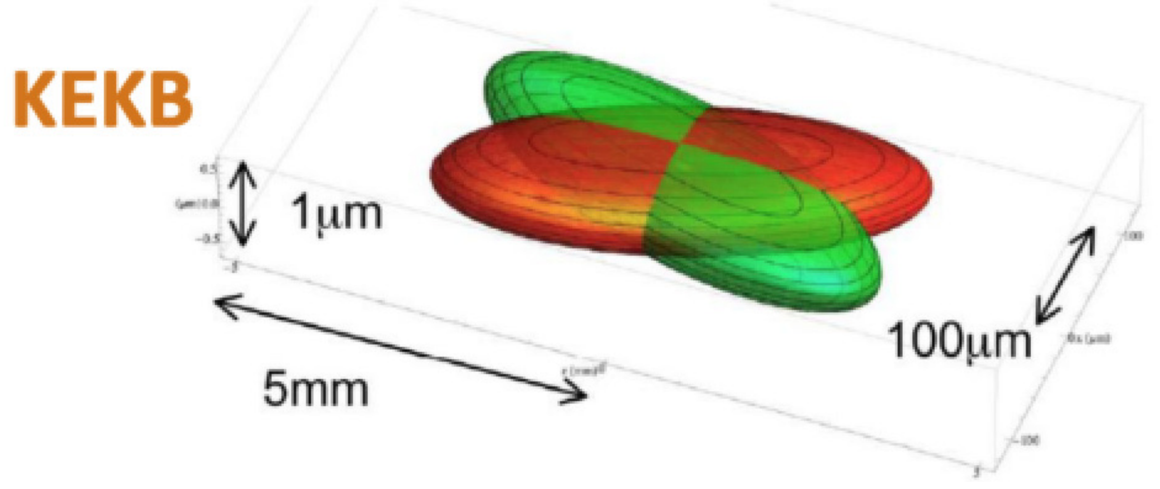


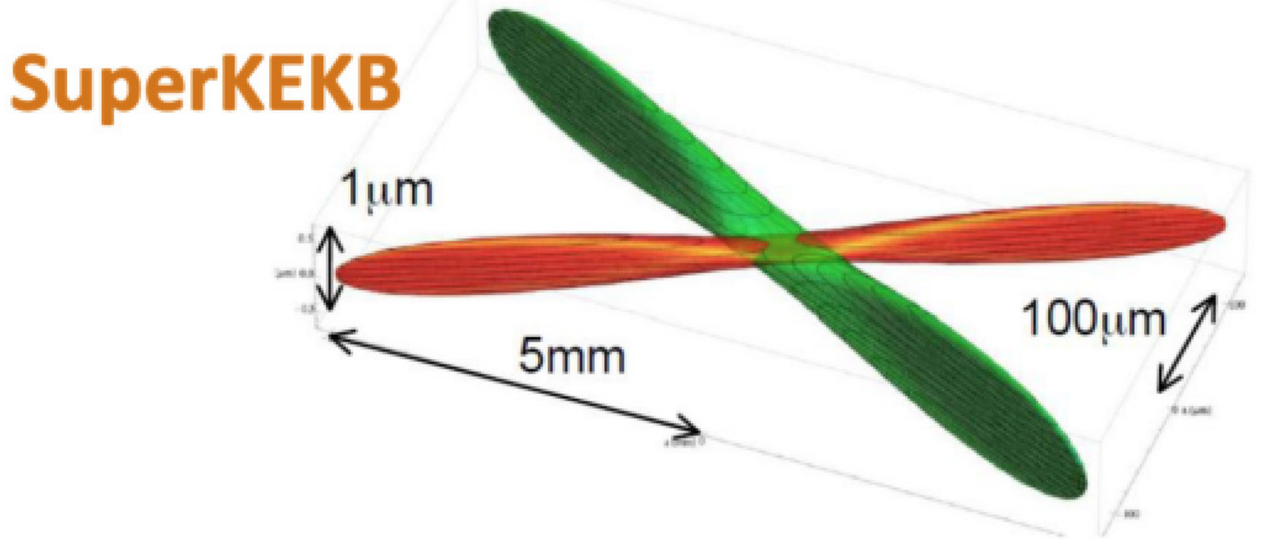
How to increase luminosity:

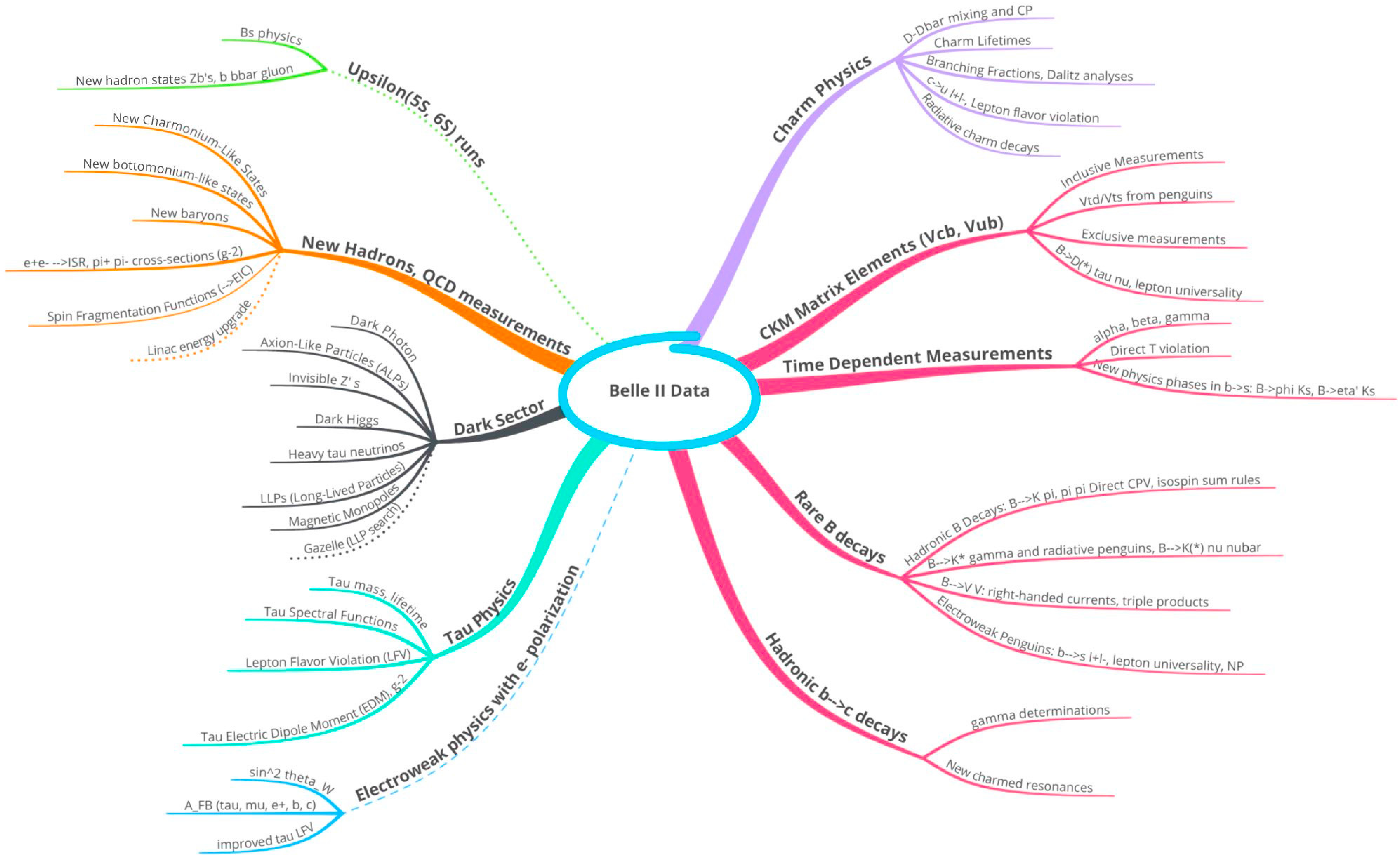
$$L = \frac{\gamma_{\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

- Lorentz factor: $\gamma_{\pm}$
- Beam size: σ_y^*/σ_x^*
- Beam current x 1.5: $I_{\pm}$
- Beam-beam parameter: $\zeta_{\pm y}$
- Vertical β function x 1/20: β_y^*
- Geometric factors: R_L/R_y

Nano-beam scheme: Squeeze vertical beam spot size down to ≈ 50 nm using superconducting focusing magnets.



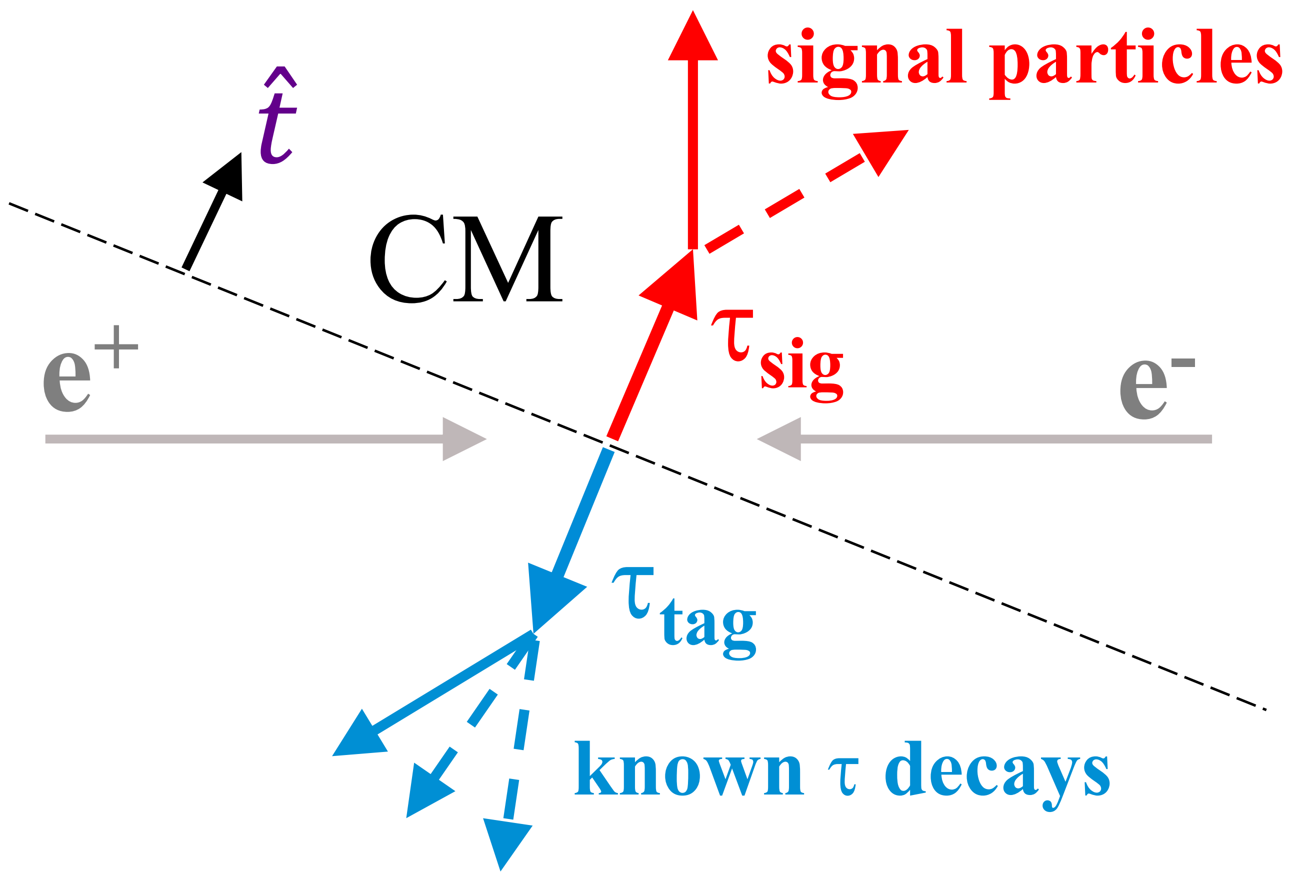


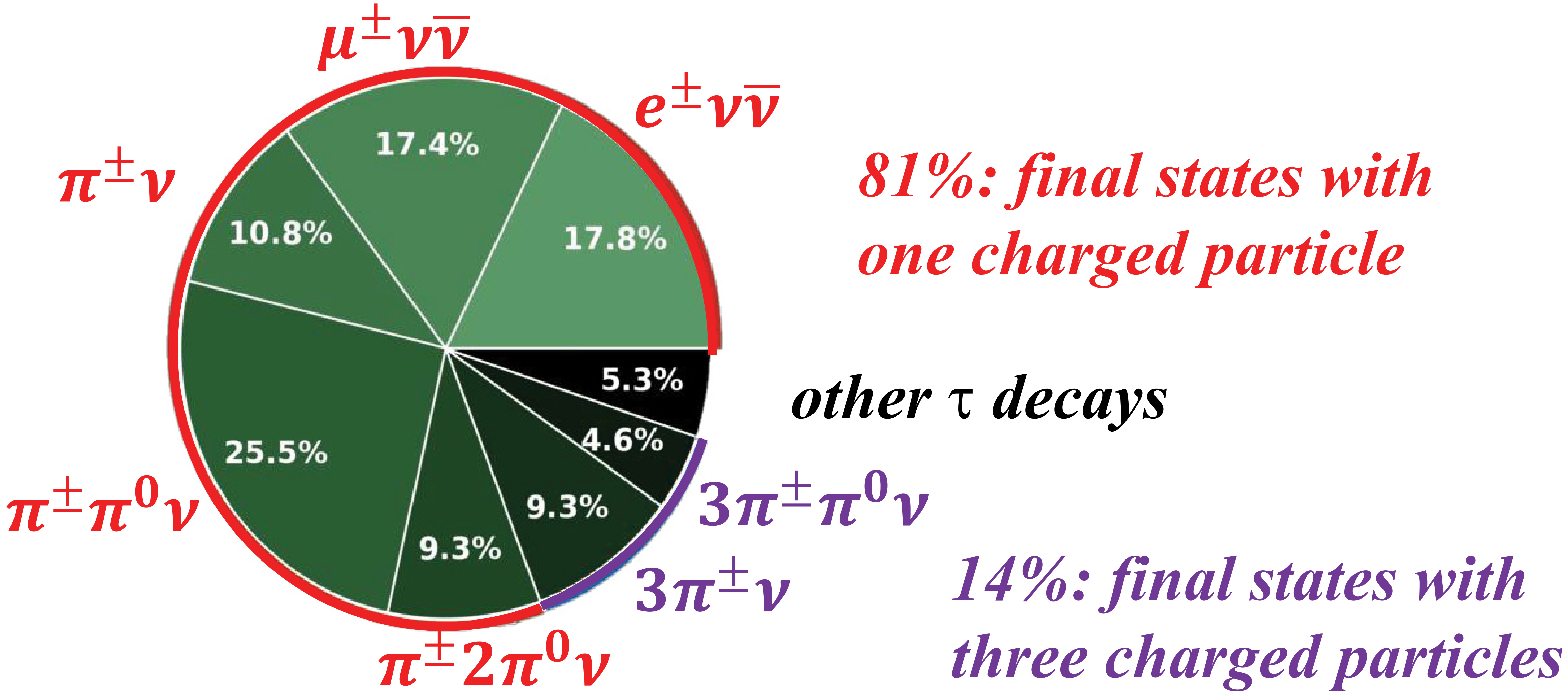

Belle II Data
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e+e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
A_FB (tau, mu, e+, b, c)
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances

Topology of τ pairs Production and Relevant Numerology

The thrust vector $\hat{t}$ maximizes the thrust value T and is used as an approximation for the direction of τ momentum:

$$T = \max_{\hat{t}} \left\{ \frac{\sum_i |p_i^{cm} \cdot \hat{t}|}{\sum_i |p_i^{cm}|} \right\}$$





$$\sigma\left(e^+e^- \to \Upsilon(4S)\right) = 1.05\, nb$$

$$\sigma\left(e^+e^- \to \tau^+\tau^-\right) = 0.92\, nb$$

Belle: 900M τ pairs (1 ab^{-1})

Belle II: 400M τ pairs (0.4 ab^{-1})

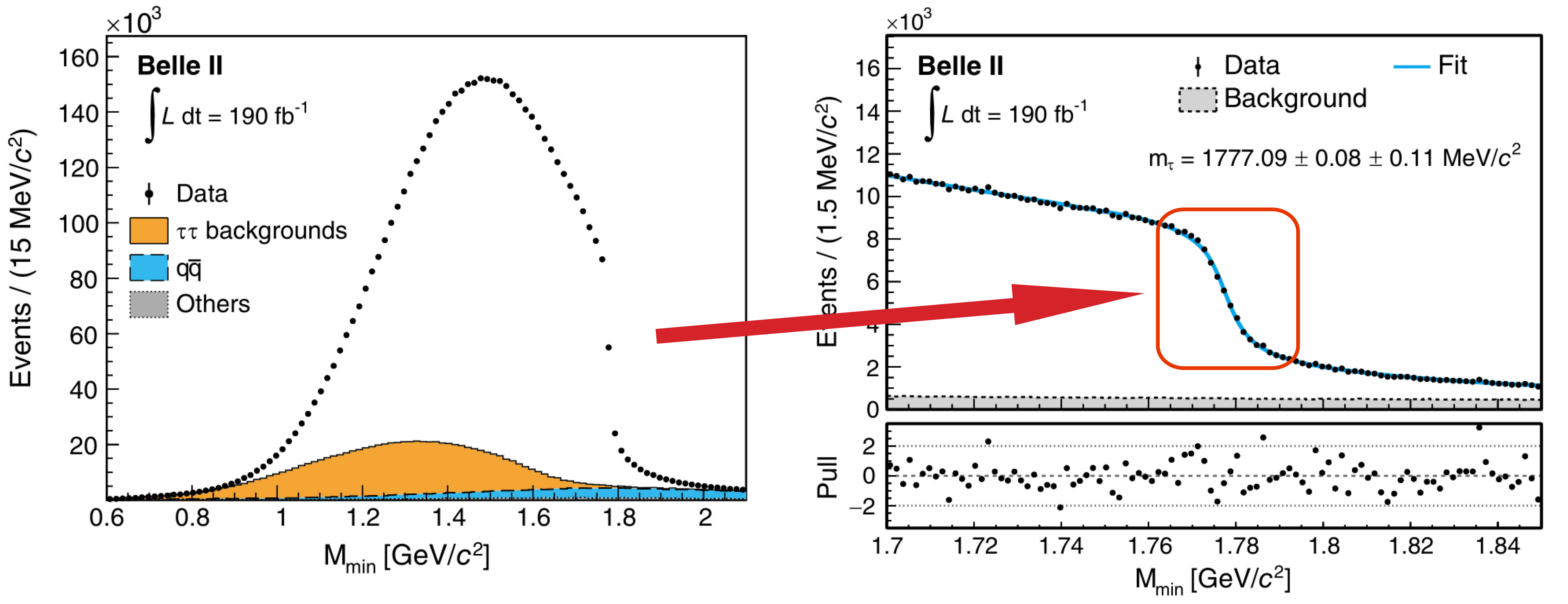
(run 1, till 2022)

Measurement of the τ-lepton mass with the Belle II experiment

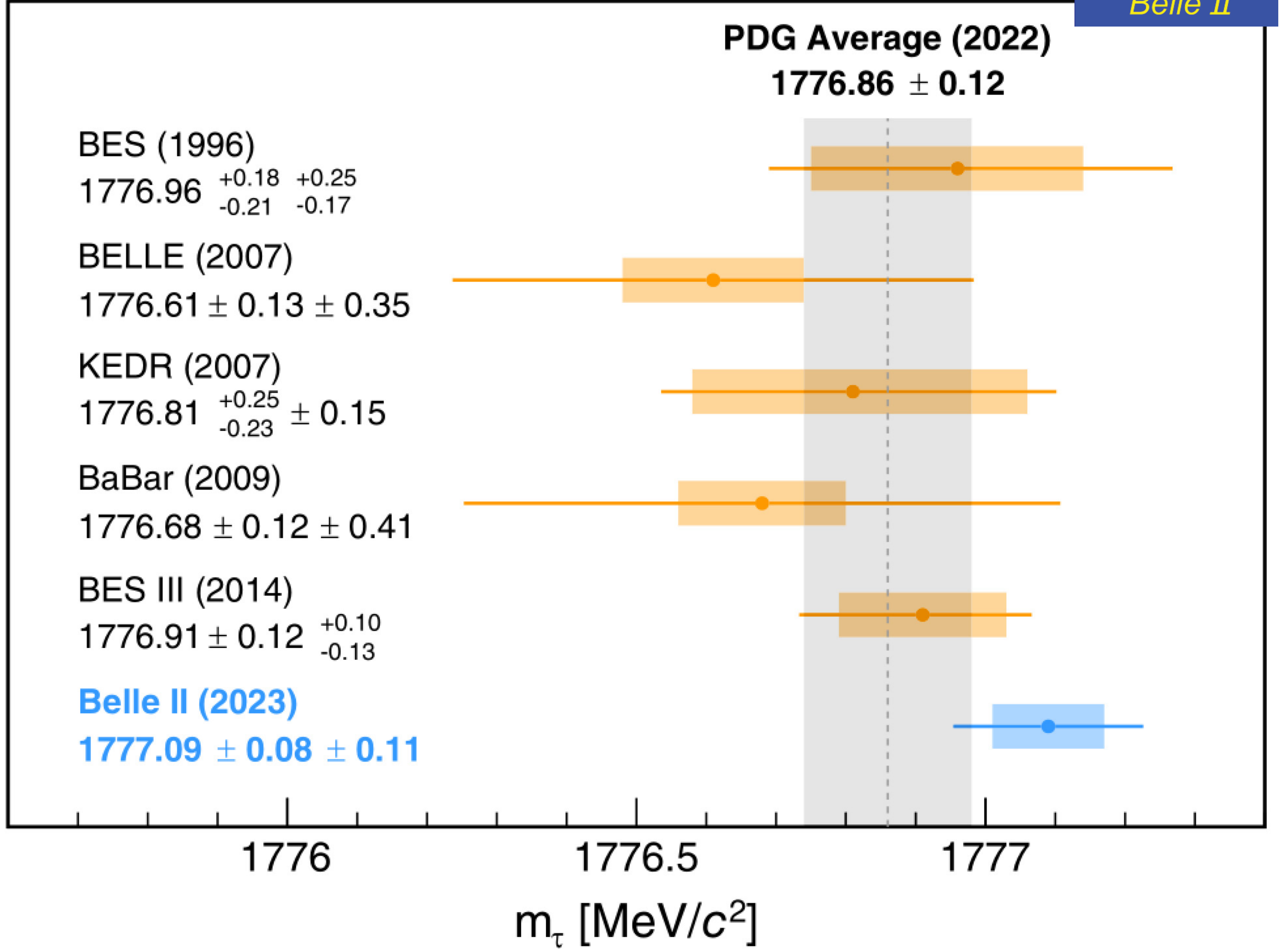
PHYSICAL REVIEW D **108,** 032006 (2023)

- Fundamental physics parameter measurement
- Signal channel: $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}\nu_{\tau}$
- Tag side: $\tau \rightarrow e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi^{\pm}\nu,\ \pi^{\pm}\pi^{0}\nu$
  (ε = 2.3%, purity 90%)
- The pseudomass M_{min} has a threshold at m_{τ}

$$M_{min} = \sqrt{M_{3\pi}^{2} + 2\left(\frac{\sqrt{s}}{2} - E_{3\pi}^{*}\right)\left(E_{3\pi}^{*} - p_{3\pi}^{*}\right)} < m_{\tau}$$



190 fb^{-1}, 175M τ pairs



Belle II result:

$$m_{\tau} = 1777.09 \pm 0.08 \pm 0.11\ \text{MeV/c}^{2}$$

(most precise measurement to date)

Test of light-lepton universality in τ decays

JHEP 08 (2024) 205

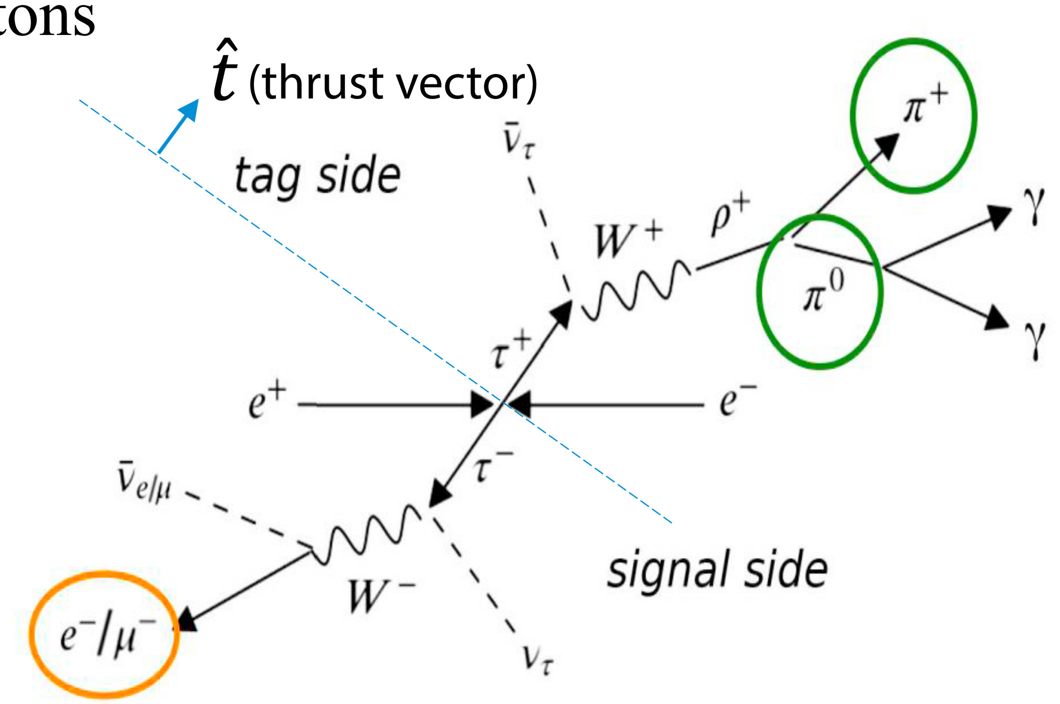
362 fb^{-1}, 333M τ pairs

- Test the W couplings strength to the three generation leptons
- Signal channel: $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu}$
- Tag side: $\tau \to \pi n\pi^0\nu$ (n=1,2) ($\pi\pi^0$ peaking at ρ mass) (ε = 9.6%, purity 94%)
- Results: $R_\mu = \frac{\mathcal{B}(\tau\to\mu\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau\to e\bar{\nu}_e\nu_\tau)} = 0.9675 \pm 0.0007 \pm 0.0036$

$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} = 0.9974 \pm 0.0019,\ \text{where}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

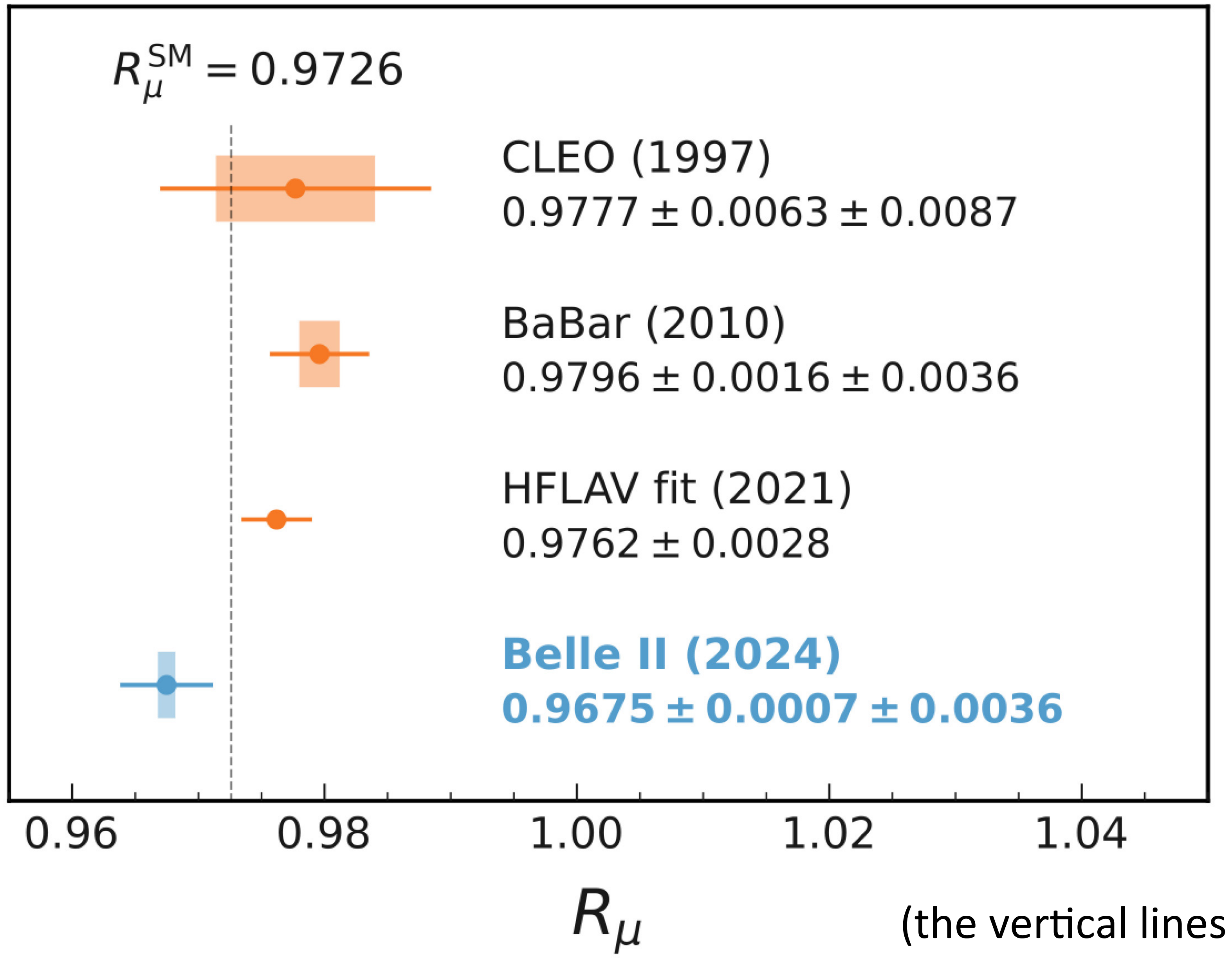
Y.-S. Tsai, *Decay correlations of heavy leptons in* $e^+ + e^- \to l^+ + l^-$ *Phys.Rev.D* 4 (1971) 2821, *Phys.Rev.D* 13 (1976) 771 (erratum)

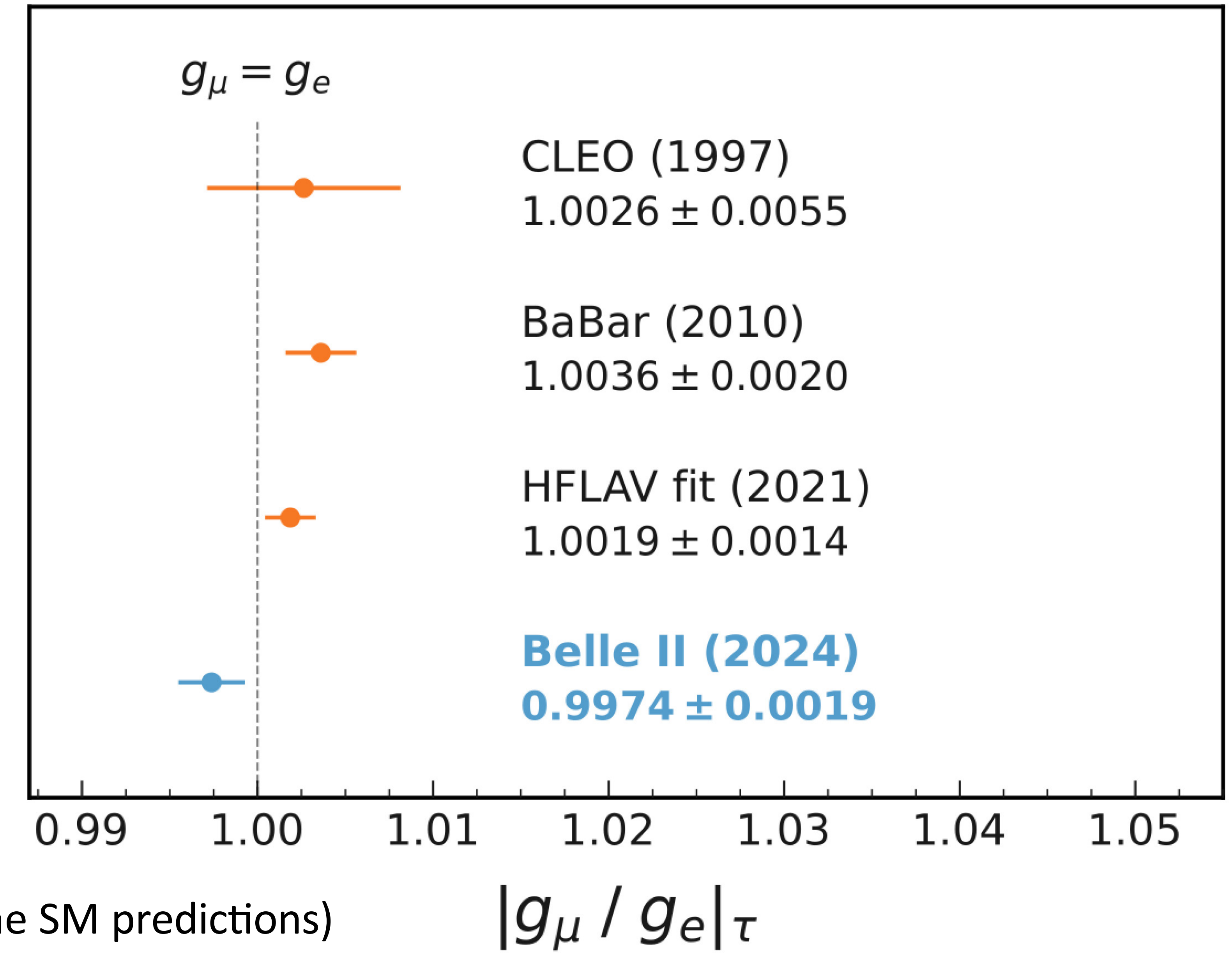


Belle II

Belle II's is the most precise measurement to date, very relevant for the muon g-2 results interpretation, see, e.g.,

Giacomo Cacciapaglia, Corentin Cot, Francesco Sannino, "Naturalness of lepton non-universality and muon g-2", Physics Letters B 825 (2022) 136864





(the vertical lines show the SM predictions)

Search for lepton-flavor-violating τ decays into a lepton and a vector meson using the full Belle data sample

$\tau \to \ell V^0$ $(\ell = e, \mu)$

JHEP 06 (2023) 118

980 fb^{-1}, 905M τ pairs

BELLE

- 980 fb^{-1} Belle data
- Signal: $\ell = e, \mu$ and $V^0 = \rho^0, \phi, \omega, K^{*0}, and\ \bar{K}^{*0}$
- One- and three-prong tags used: $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi^\pm n\pi^0\nu(n = 0,1,2),\ \pi^\pm\pi^\mp\pi^\pm\nu$
- 10 upper limits are set at 90% C.L. (8 of these are most precise to date)

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}_{\rm obs}$ $(\times 10^{-8})$
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7

$\tau \to \mu\mu\mu$

JHEP 09 (2024) 062

- Inclusive tagging using all the rest information for the tag side ($\varepsilon = 20.4\%$)
- 1 event observed with 0.7 expected background

  $\mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$ @90% CL

Belle II

424 fb^{-1}
389M τ pairs

$\tau \to \ell K_s^0$ ($\ell = e, \mu$)

JHEP (submitted to)

- Tag side: $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi^{\pm}\nu$ ($\varepsilon \sim 10.2\%$)
- No significant excess above expected background.

  $\mathcal{B}(\tau \to eK_s^0) < 0.8 \times 10^{-8}$ @90% CL

  $\mathcal{B}(\tau \to \mu K_s^0) < 1.2 \times 10^{-8}$ @90% CL

BELLE
Belle II

980 fb^{-1} + 428 fb^{-1}
1.3B τ pairs

Search for the baryon number and lepton number violating decays $\tau^- \to \Lambda\pi^-$ and $\tau^- \to \bar{\Lambda}\pi^-$ at Belle II

PHYSICAL REVIEW D **110**, 112003 (2024)

$\tau^- \to (\Lambda/\bar{\Lambda})\pi^-$

- Baryon and Lepton numbers are violated, but $|\Delta(B-L)| = 2, 0$ (allowed in some models)
- Tag side: $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi^\pm\nu, \pi^\pm\pi^0\nu$
  ($\varepsilon = 9.5\%/9.9\%$ for $\tau^- \to (\Lambda/\bar{\Lambda})\pi^-$)

$$\Delta E = E(\Lambda\pi) - \sqrt{s}/2$$

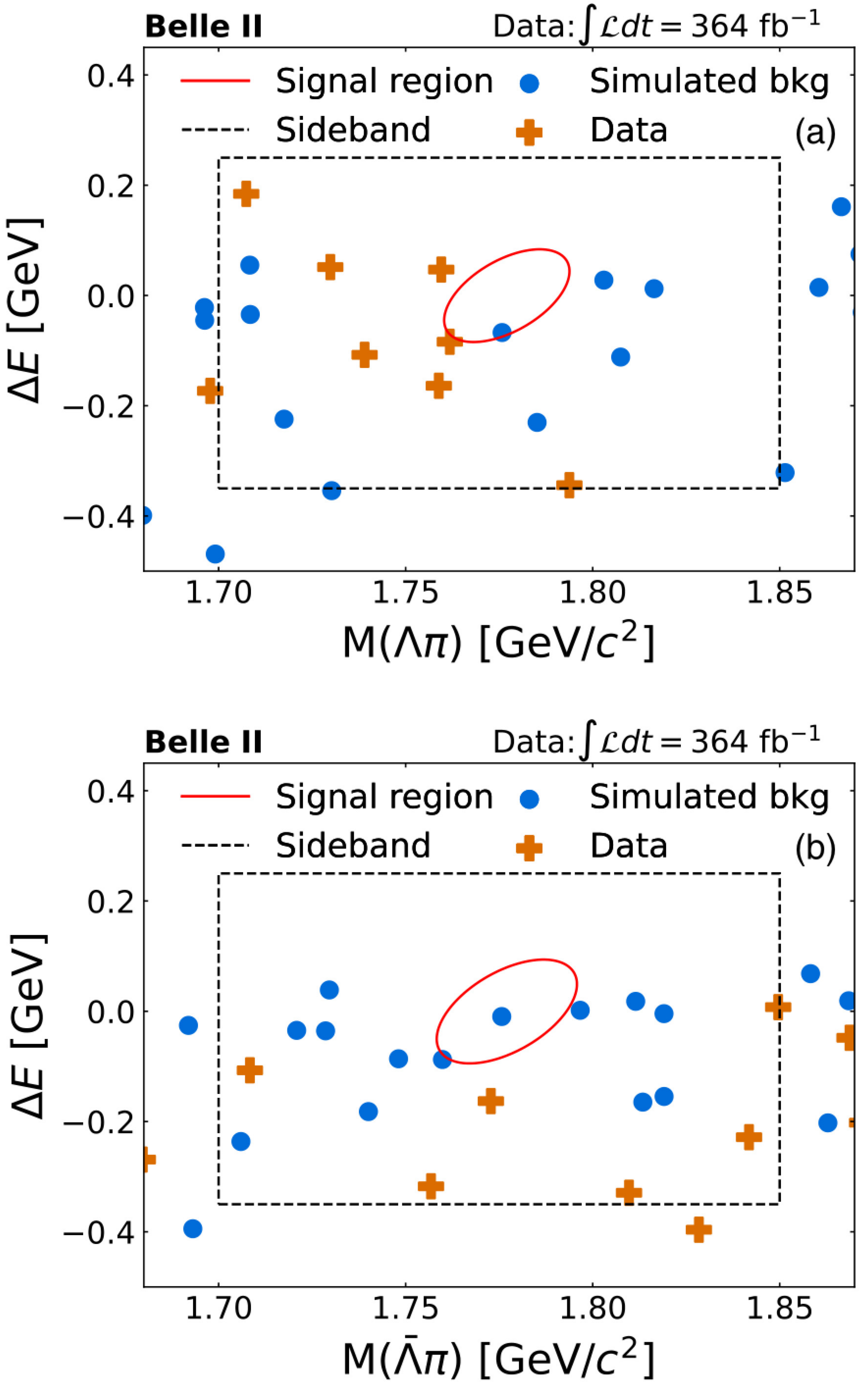
- No events observed while expecting 1.0/0.5 background events for $\tau^- \to (\Lambda/\bar{\Lambda})\pi^-$

$$\mathcal{B}(\tau^- \to \Lambda\pi^-) = \frac{N_{\text{sig}}}{2\varepsilon_{\text{sig}}\mathcal{L}\sigma_{\tau\tau}\mathcal{B}(\Lambda \to p\pi^-)}$$

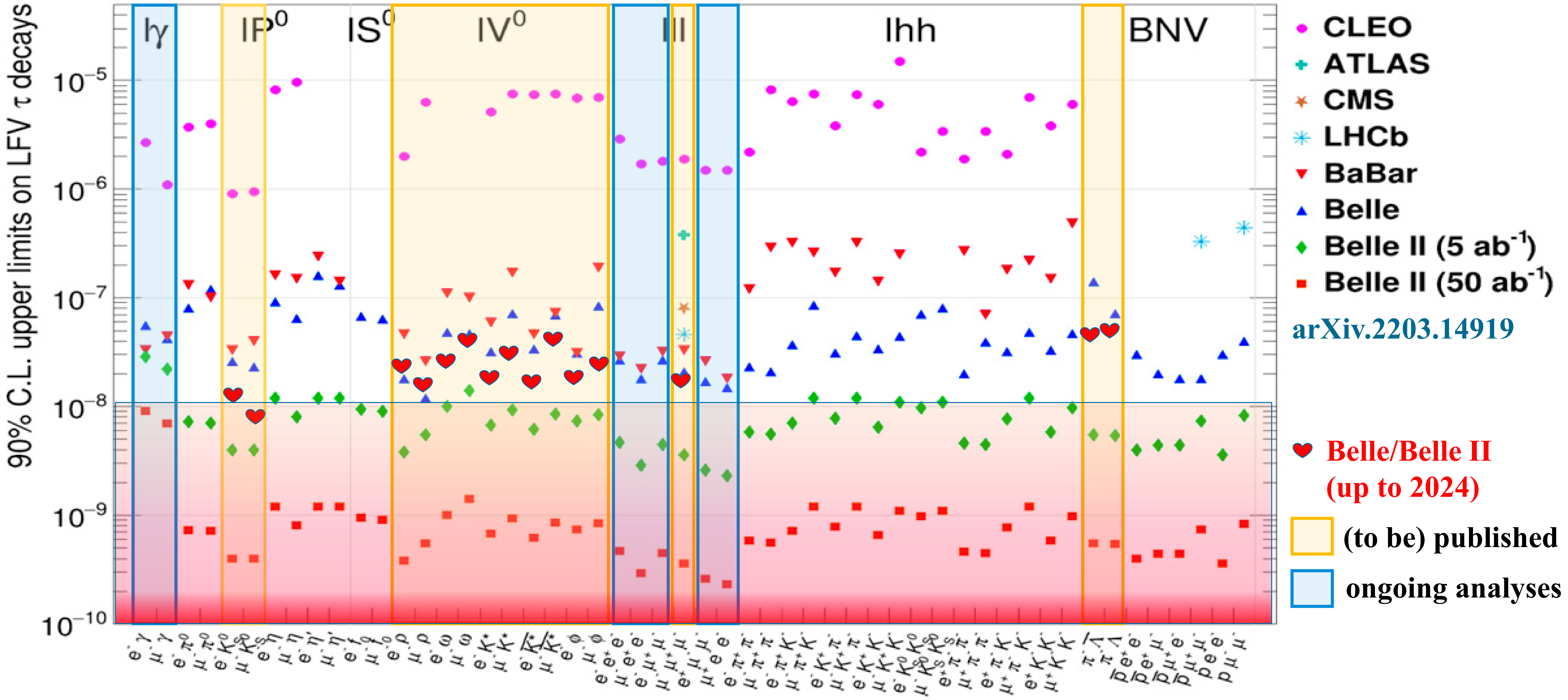
364 fb^{-1}, 334M τ pairs

$$\mathcal{B}(\tau^- \to \Lambda\pi^-) < 4.7 \times 10^{-8} \text{ @90\% CL}$$
$$\mathcal{B}(\tau^- \to \bar{\Lambda}\pi^-) < 4.3 \times 10^{-8} \text{ @90\% CL}$$

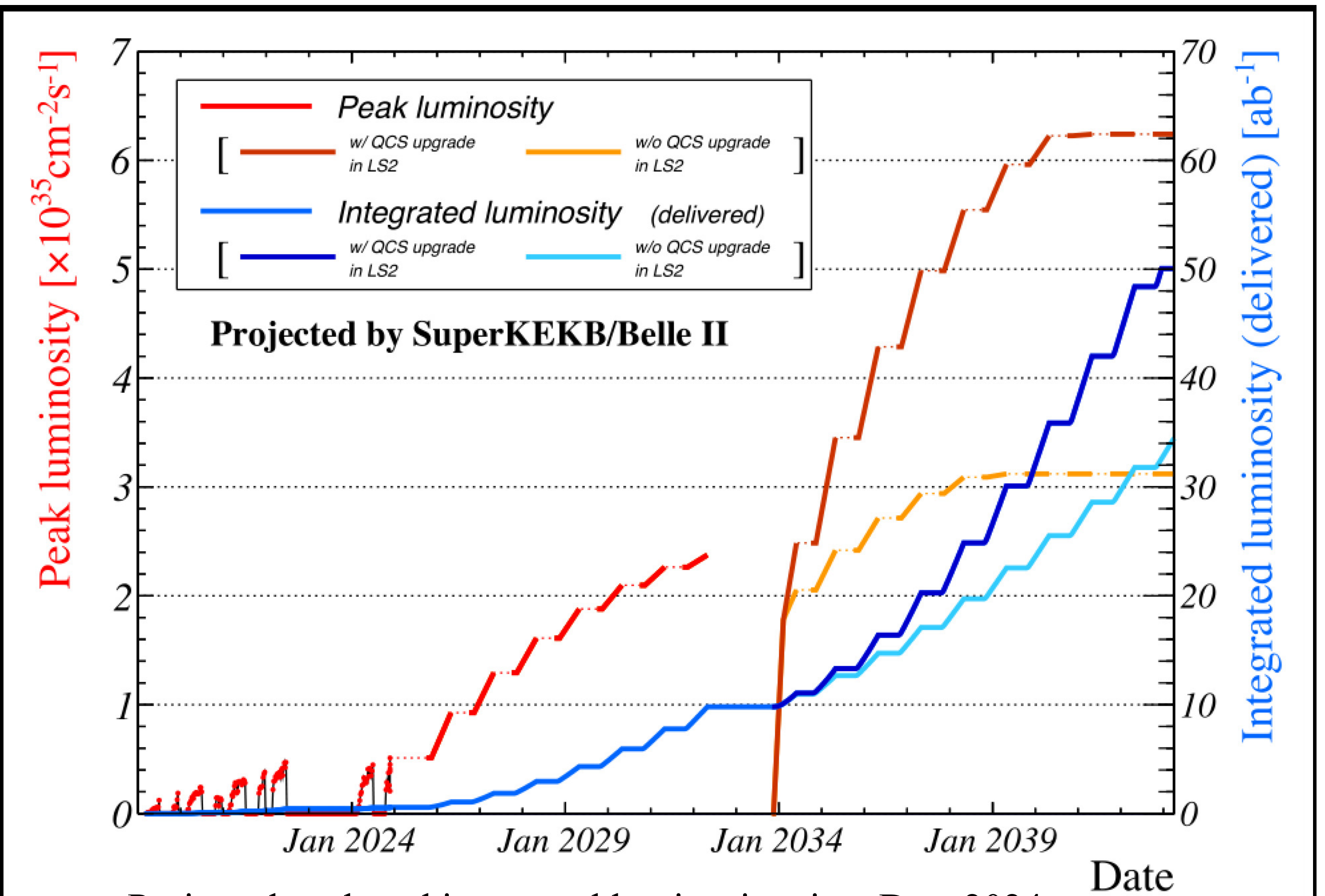
Belle II



Summary of Searches for LFV, LNV and BNV at Belle / Belle II



Concluding Remarks



Projected peak and integrated luminosity circa Dec. 2024

Performed precision measurement of τ-lepton mass

Reported a stringent test of lepton universality in τ decays

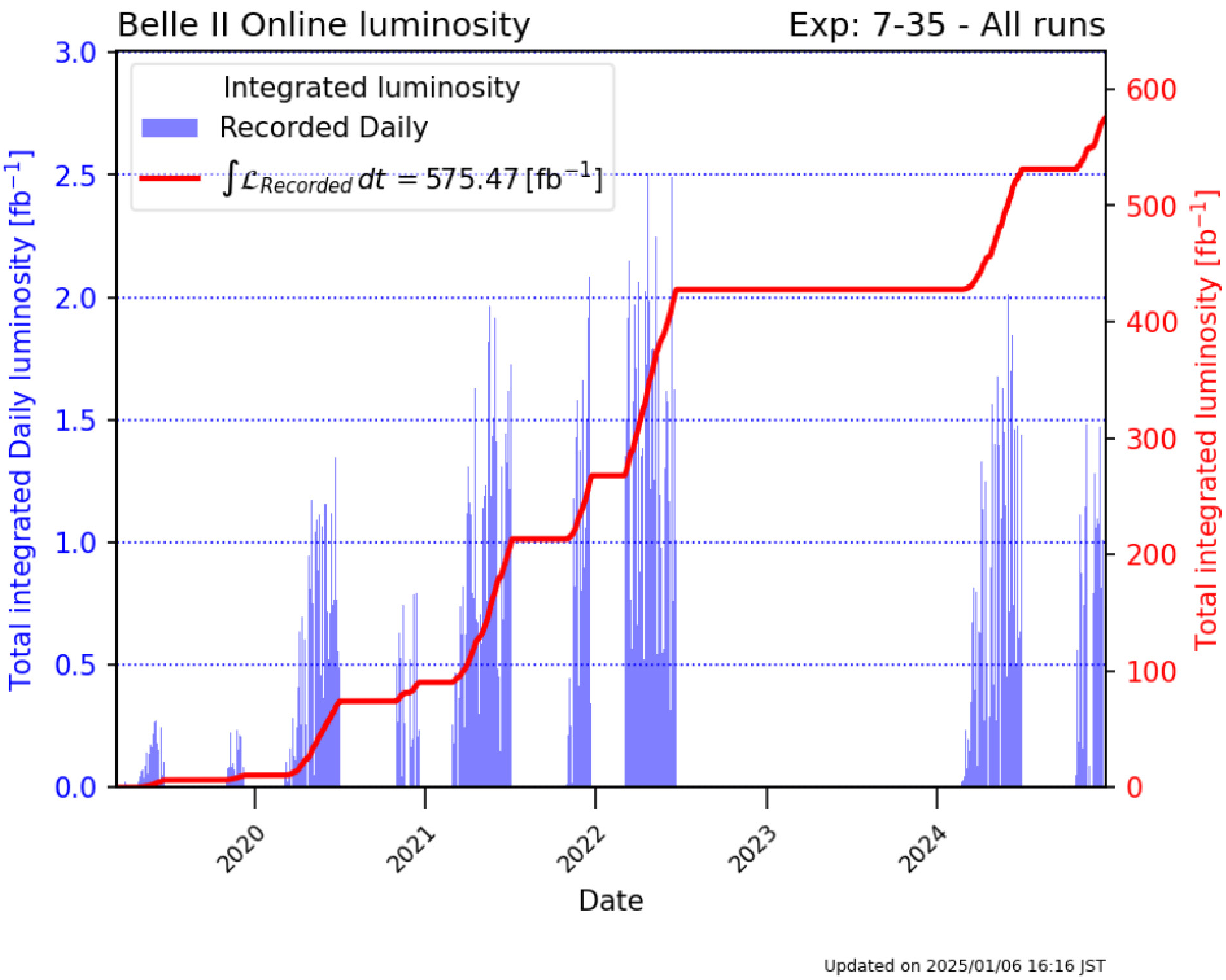
Shared new exciting results from searches for LFV, LNV and BNV

Where does it take us?

In the SM, conservation of lepton and baryon numbers is accidental, such processes are either forbidden or are predicted at below 10^{-50} level.

Various models of New Physics predict the rates in the range already being probed by Belle II - and with more statistics we will do even better.

Dec. 25, 2024 / SuperKEKB Control Room: Instantaneous Luminosity Record!



Belle II Online luminosity
Exp: 7-35 - All runs
Integrated luminosity
Recorded Daily
$\int \mathcal{L}_{Recorded}\, dt = 575.47\ [fb^{-1}]$
Total integrated Daily luminosity [fb^{-1}]
Total integrated luminosity [fb^{-1}]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
600
500
400
300
200
100
0
2020
2021
2022
2023
2024
Date
Updated on 2025/01/06 16:16 JST