Unveiling New Physics with Tau Leptons: Innovative Approaches at Belle II

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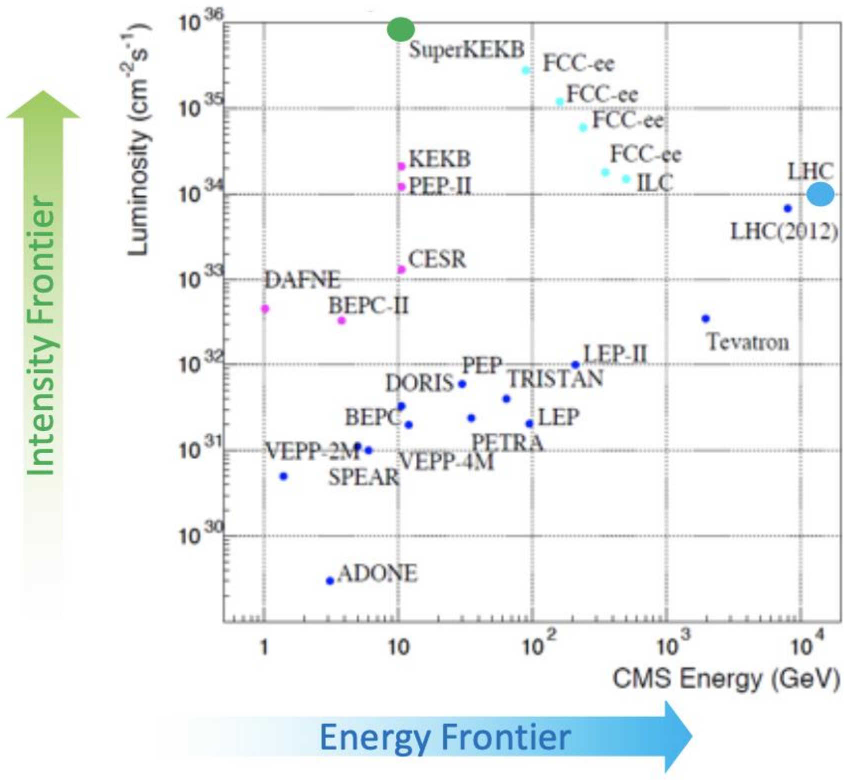
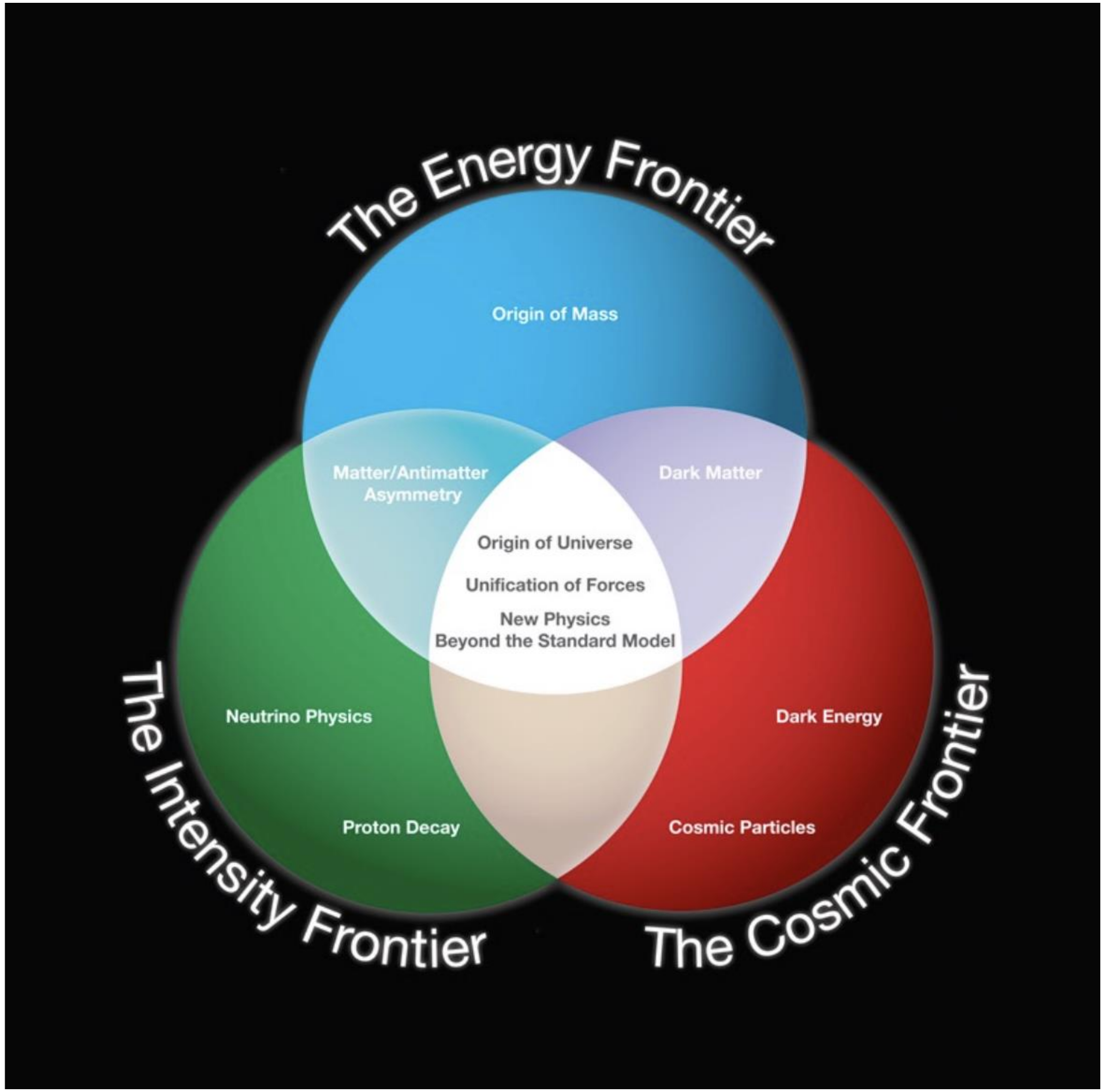
CINVESTAV

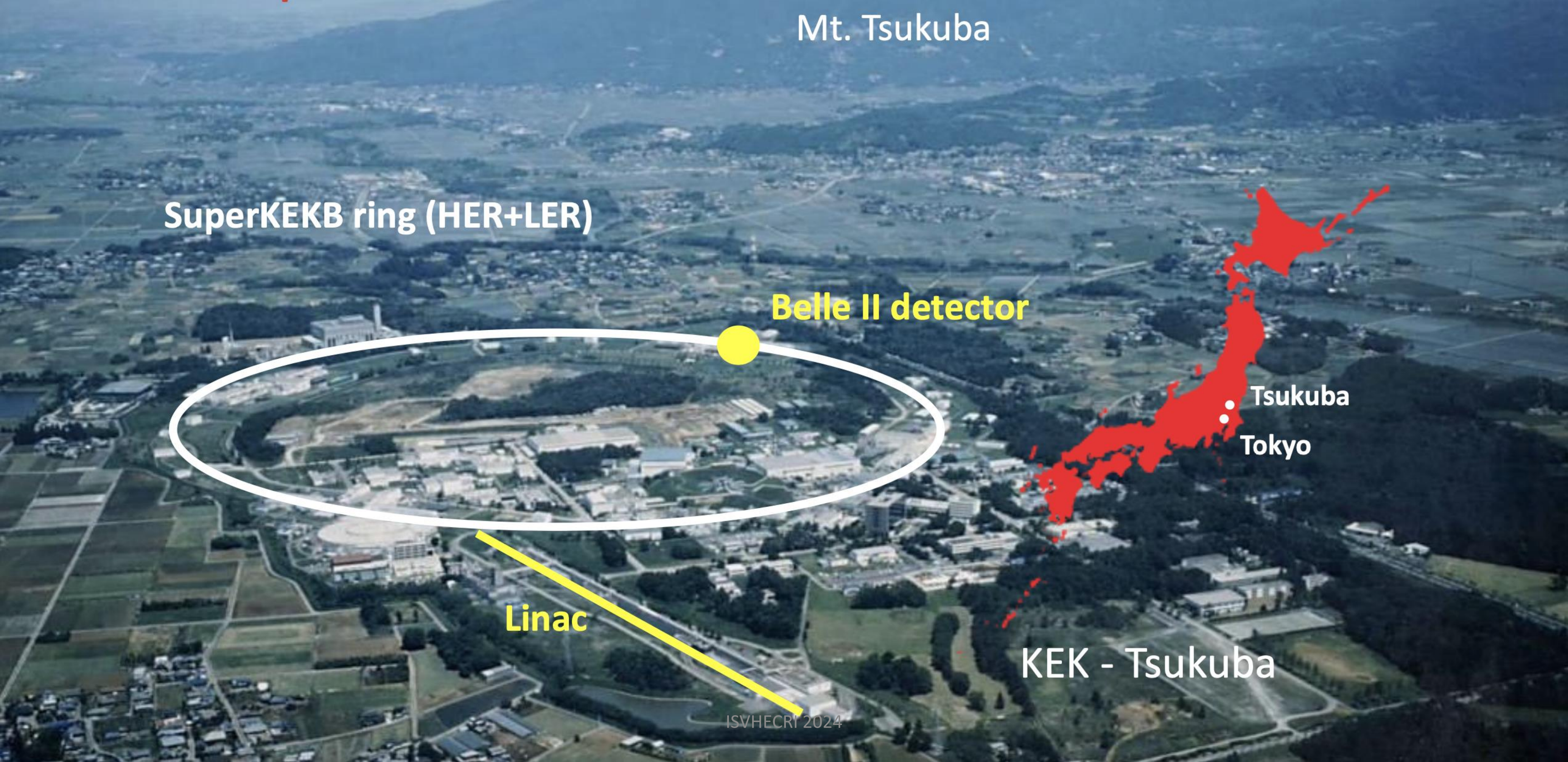


- The **Intensity Frontier**: Search for rare new phenomena using *medium-energy high-luminosity* machines

Belle II



The SuperKEKB Accelerator



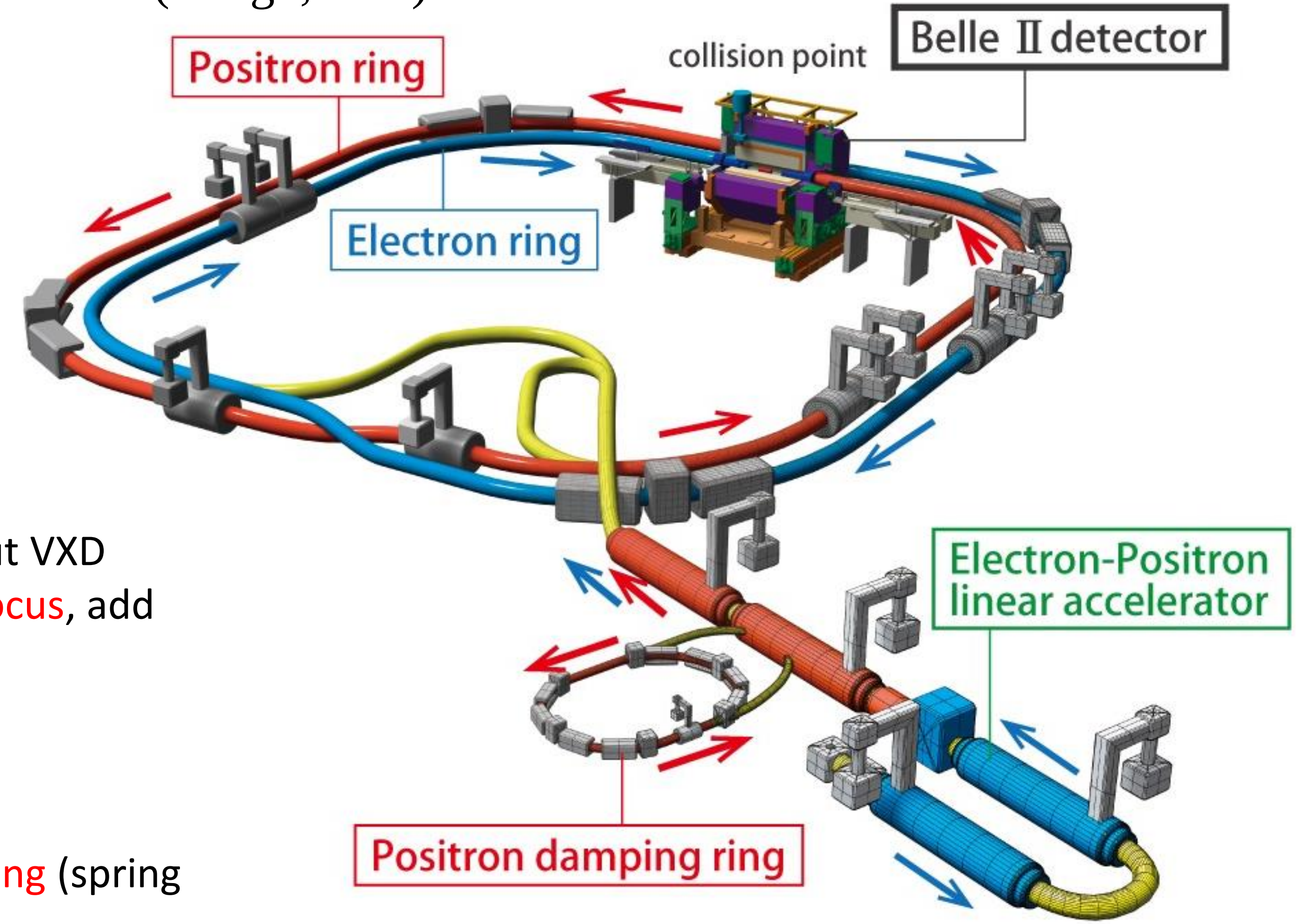
SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (pp)). Operates on the Upsilon(4S) resonance with 7 GeV(e-) on 4 GeV(e+) beams.

Phase 1:
Background, Optics Commissioning
Feb-June 2016.
Brand new
3 km positron ring.

Phase 2: Pilot run without VXD
Superconducting Final Focus, add positron damping ring,
First Collisions (0.5 fb^{-1}).
April 27-July 17, 2018

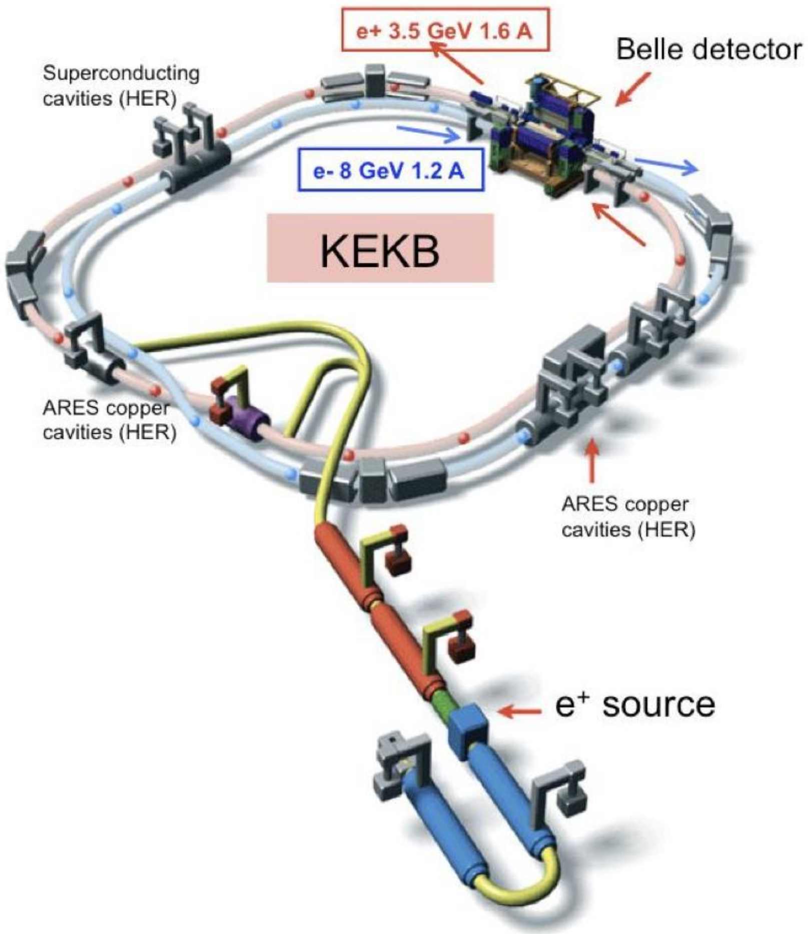
Phase 3: → Physics running (spring 2019 to present).
Have integrated 213 fb^{-1} so far.

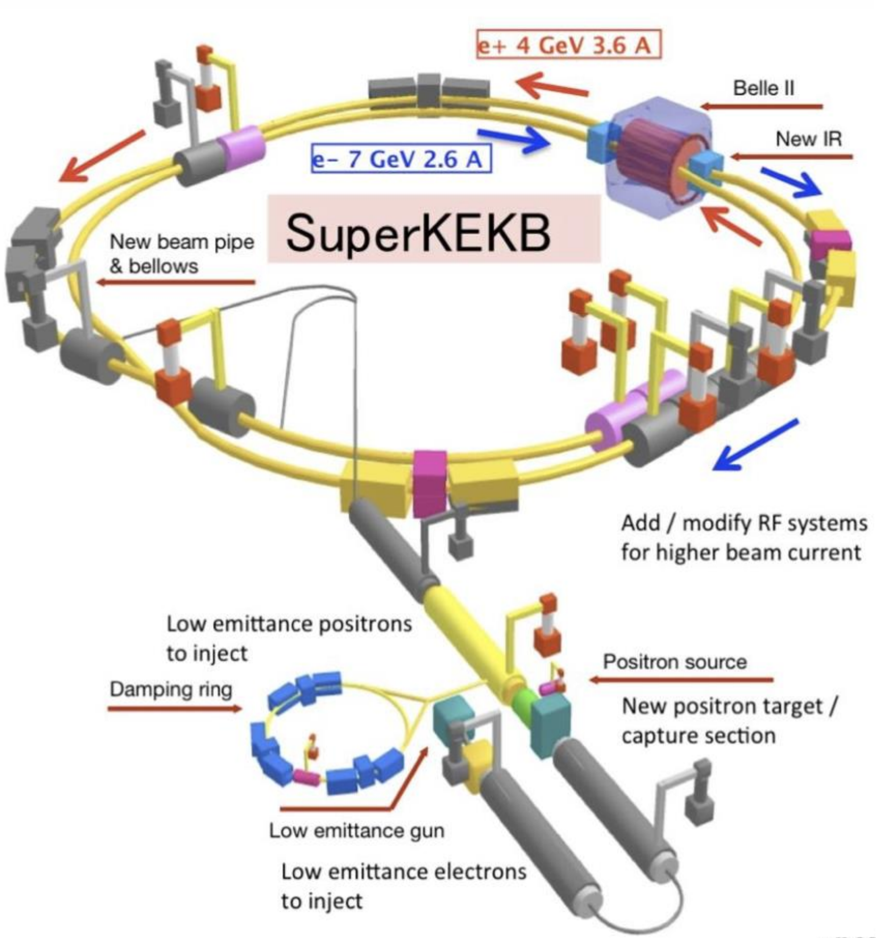
L(design,2020) = 6.5 x $10^{35}/cm^2/sec$

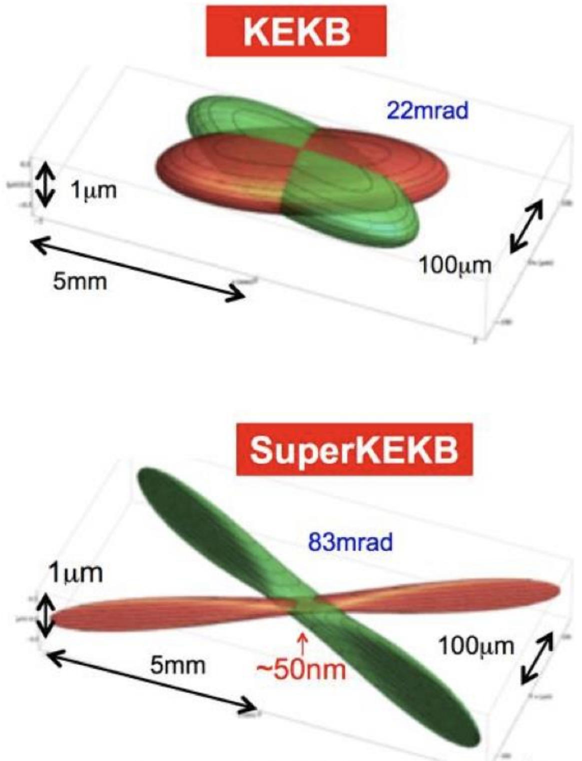


Accelerator innovations: nano-beams and crab waist optics (*rather than large beam currents*)

From KEKB to SuperKEKB







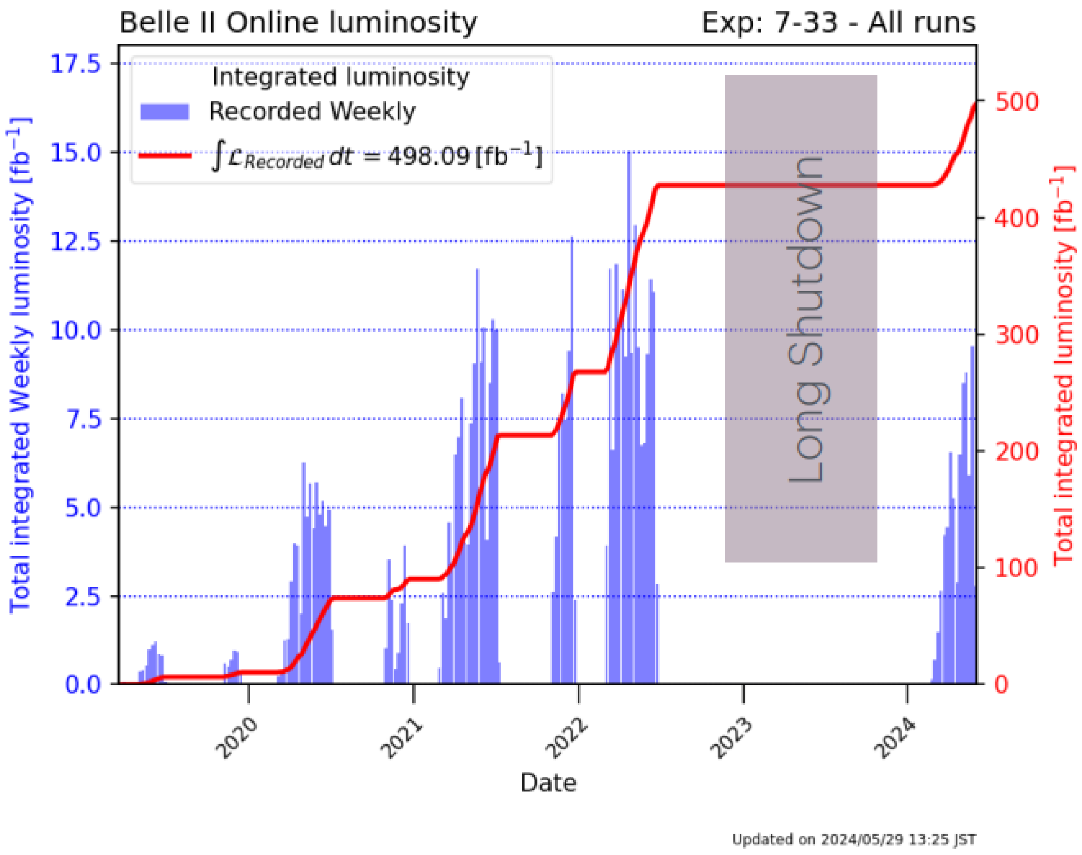
$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

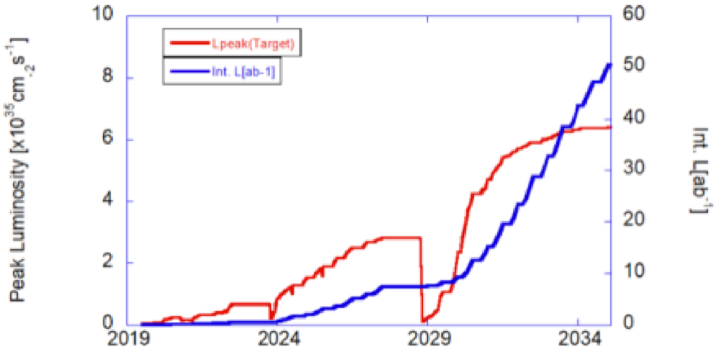
$$\mathcal{L}_{\rm II}^{\rm peak} \approx 30 \times \mathcal{L}_{\rm I}^{\rm peak}$$

$$\int^{\rm goal} \mathcal{L}_{\rm II}\, dt = 50\ {\rm ab}^{-1} \approx 50 \int \mathcal{L}_{\rm I}\, dt$$

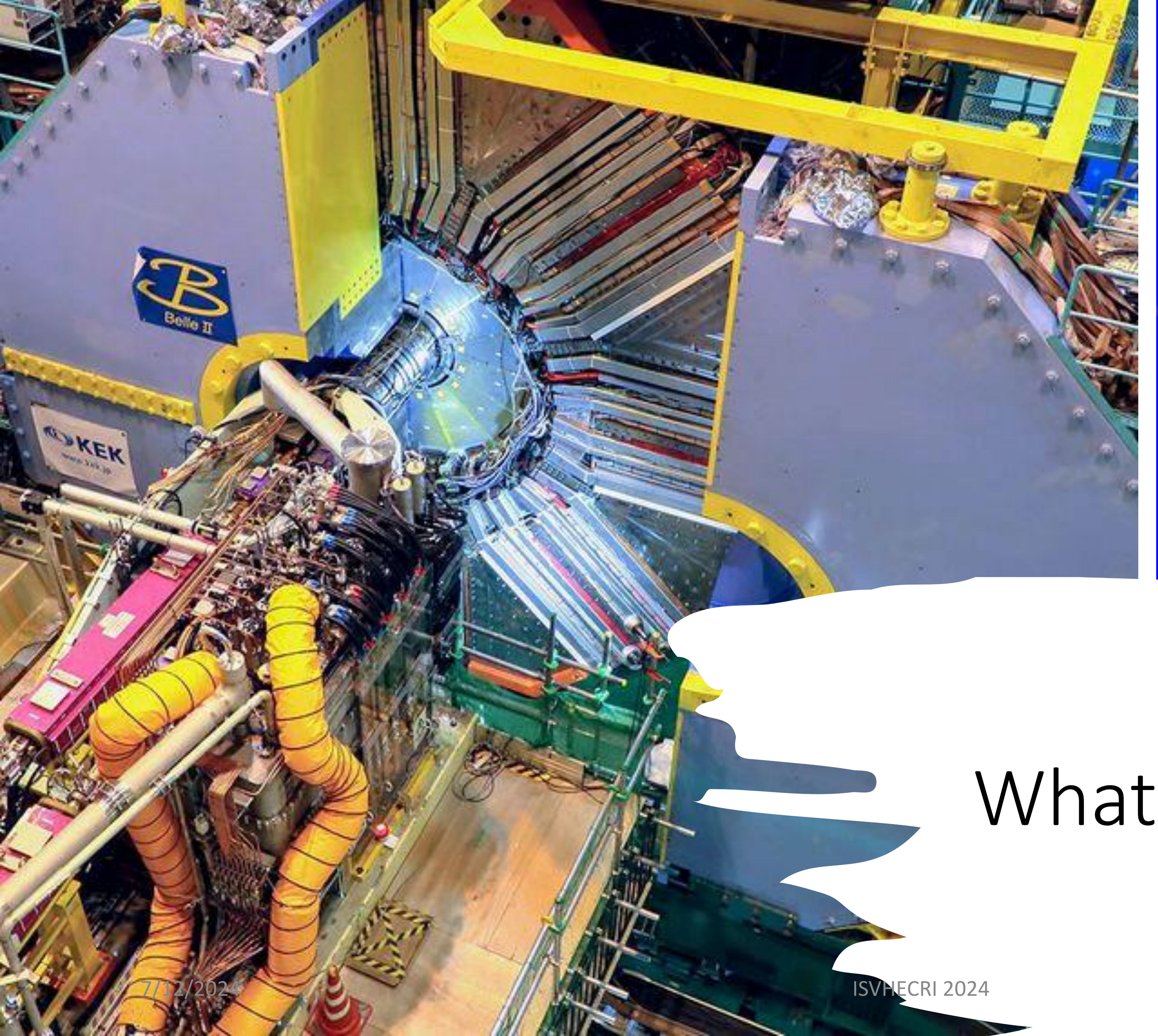
- **moderately increased beam currents**
- **Squeeze beams @IP by ~1/20**

Luminosity



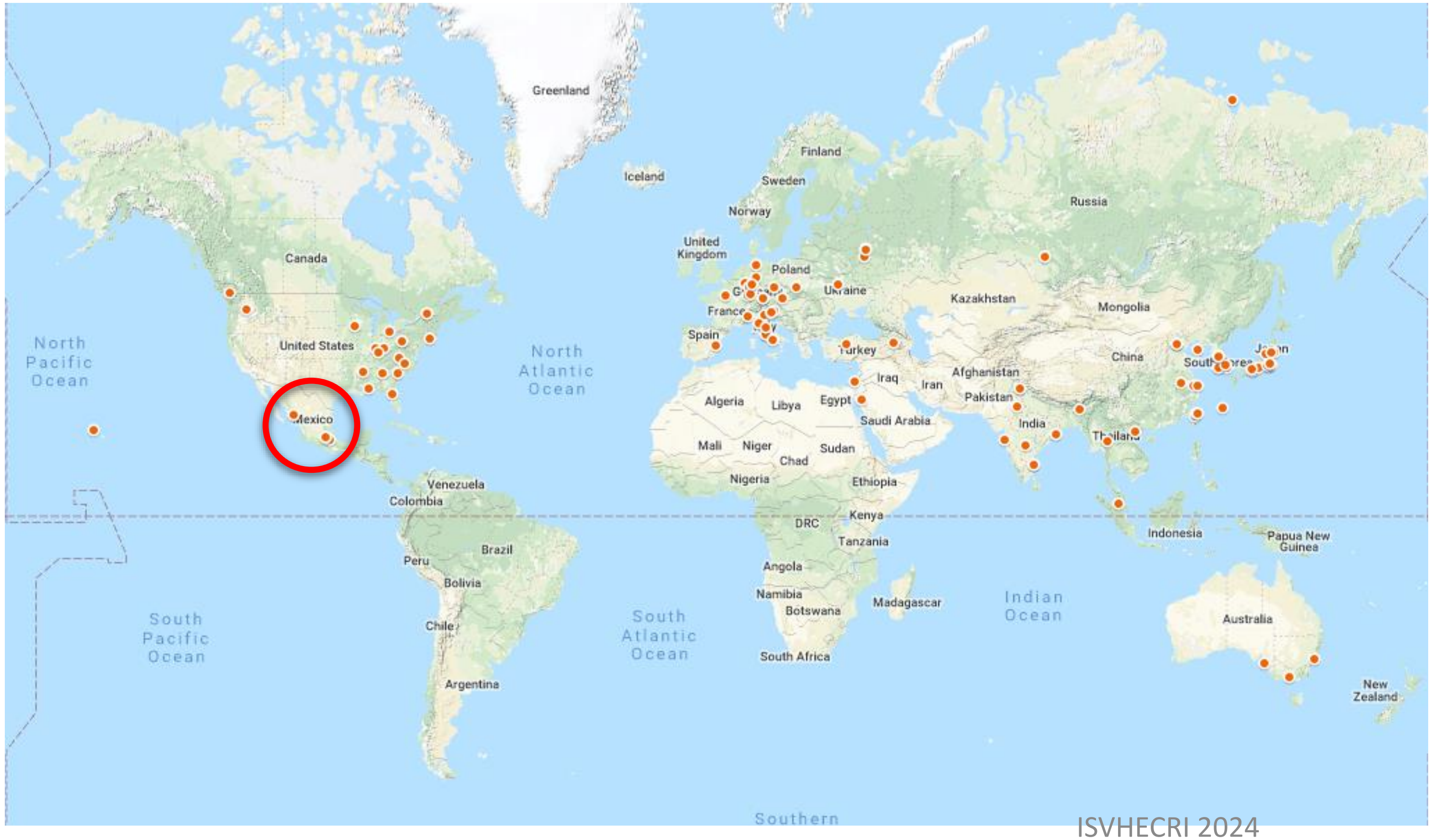


- Design integrated luminosity 50 ab^{-1}
- Regular data-taking since April 2019
- At present, we are taking data
- Current integrated luminosity 498 fb^{-1}



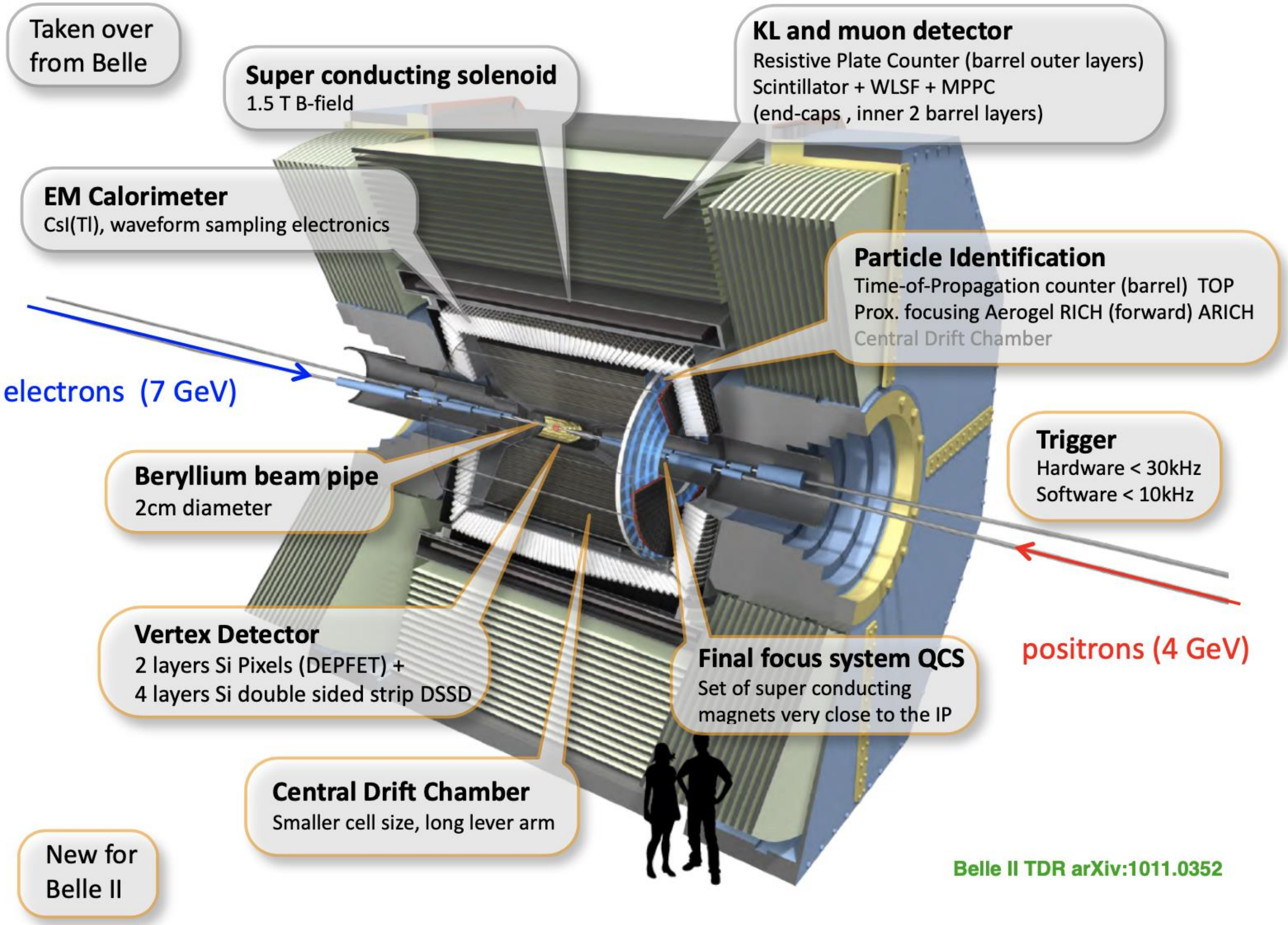
What is Belle II?

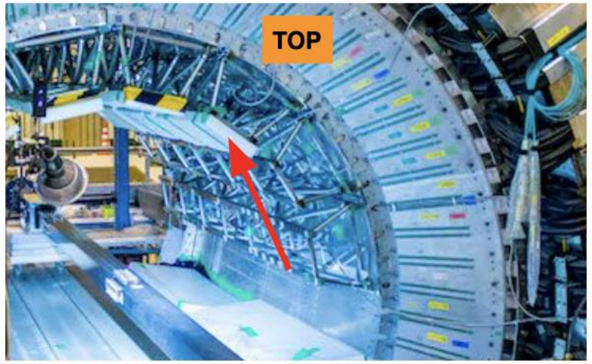
Belle II is an international collaboration

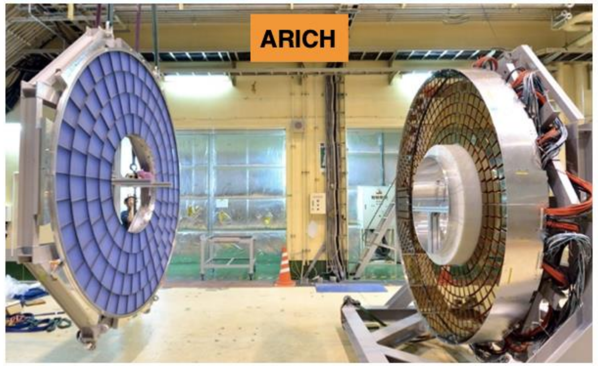


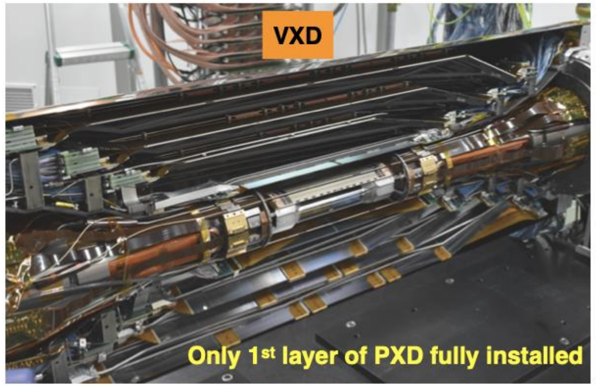
- Belle II detectors is based in Japan in the SuperKEKB collider
- Belle II now has grown to 1000+ researchers from 26 countries
- Around 330 are students
- Mexico joined Belle II in July 2013
- First collisions in 2018.

Belle II Detector









Physics at Belle II

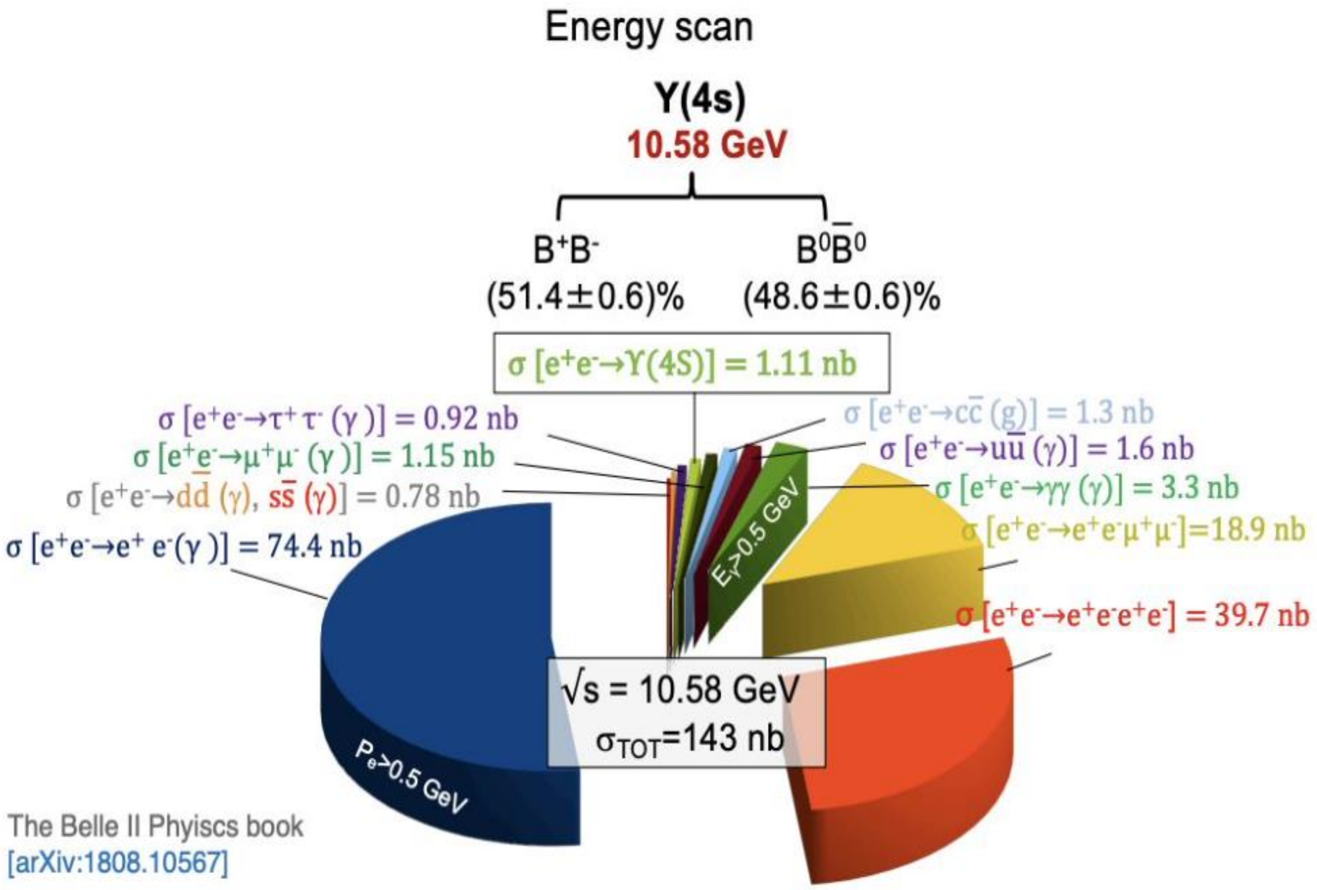
- Not *just* a B-factory!
  - τ, c, and b pairs have similar cross sections at $\sqrt{s}$ = 10.58 GeV

$\sigma(e^+e^- \rightarrow \Upsilon(4S)) = 1.11$ nb

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

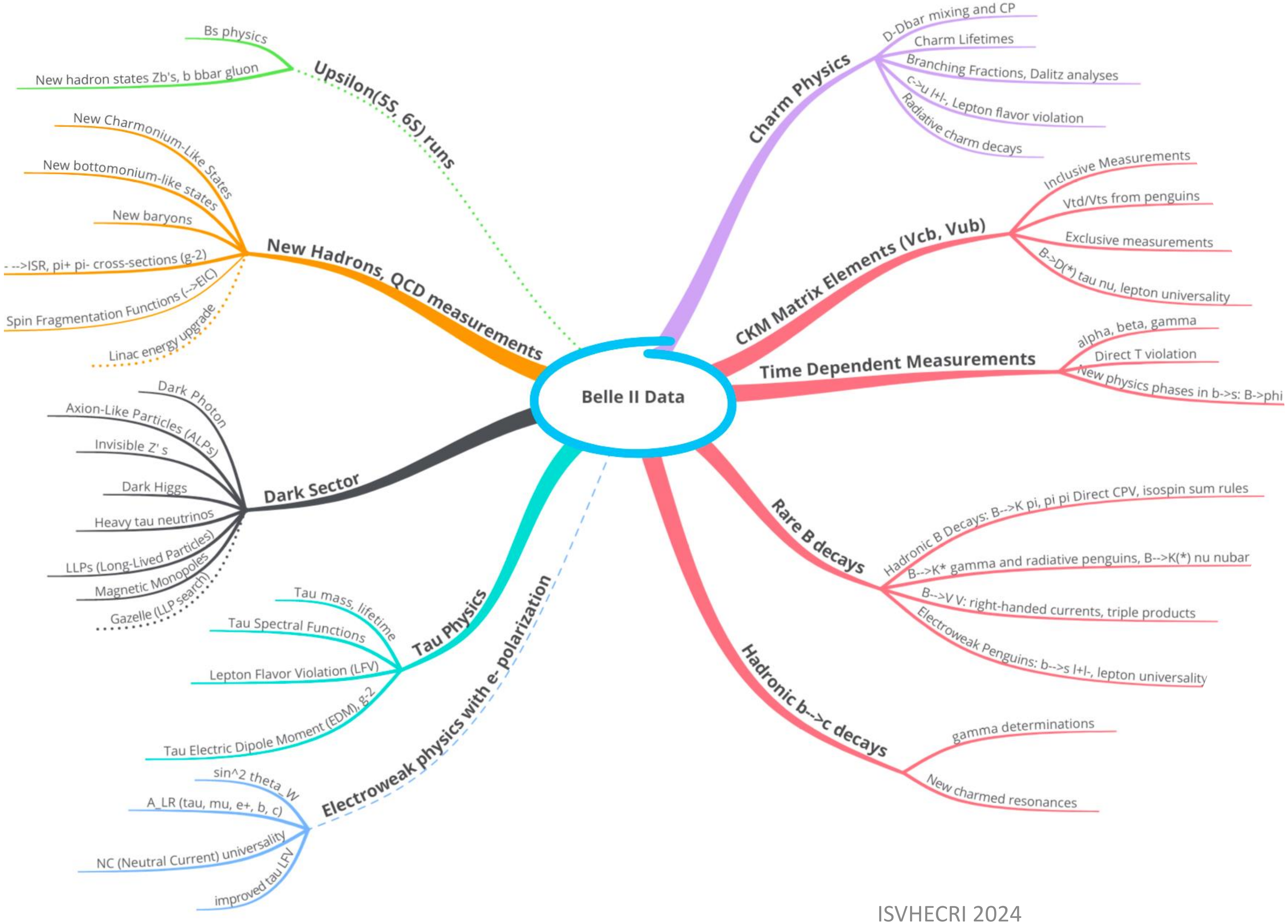
$\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92$ nb

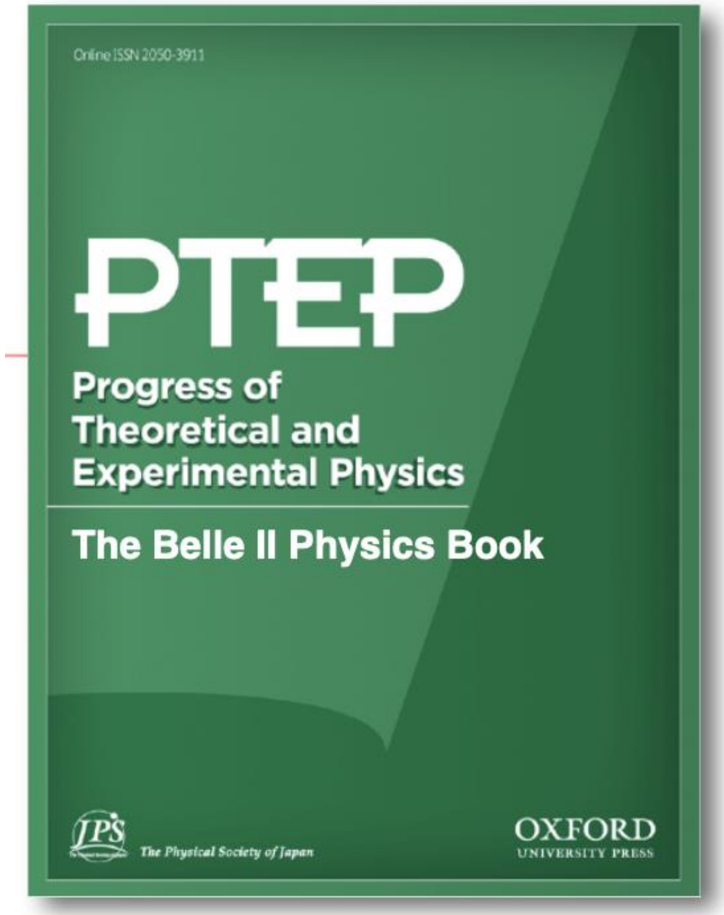
- Wide physics program
  - precision measurements of time-dependent CPV and CKM parameters
  - searches for lepton flavor universality/number violations
  - dark-sector searches
  - and many more



The Belle II Phyiscs book
[arXiv:1808.10567]

Belle II Physics mind map

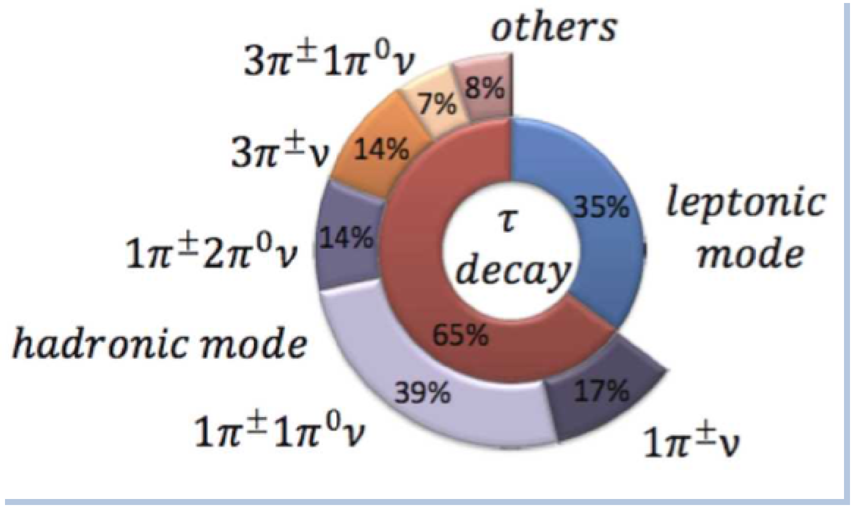




Prog. Theor. Exp. Phys. 2019, 123C01
arXiv:1808.10567

τ -Physics at Belle II

- Why τ ***physics***?
  - Large production cs:
    $\sigma(e^+e^- \to \tau^+\tau^-)$ = 0.9 nb (τ –factory)
  - The τ is the only lepton massive enough to decay into hadrons:
    - Leptonic decays: BR ~ 35%
    - Hadronic decays: BR ~ 65%

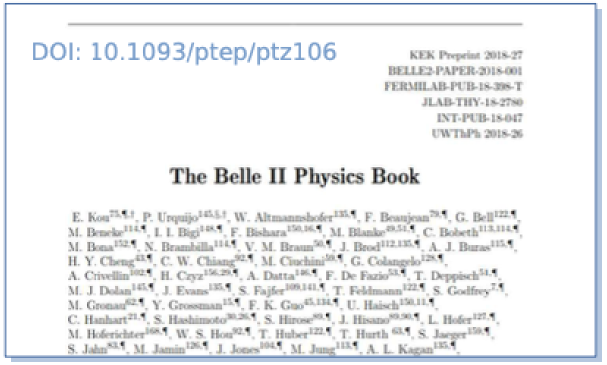


- τ **physics** program
  Rich program of precision SM measurements and new physics searches @ Belle II

Several physics analyses @ Belle II:

- Precision SM measurements / Indirect NP searches (deviations from the SM)
  - Mass
  - Lifetime
  - Lepton universality in $\tau \to l\nu\nu$ decays
  - τ EDM and MDM
  - $\tau \to ee e\nu\nu$
  - CP violation $\tau \to K_s\pi\nu$

- Direct NP searches (forbidden / strongly suppressed decays)
  - $\tau \to l\,\alpha$
  - $\tau \to l\,\phi$
  - $\tau \to l\,\gamma$
  - $\tau \to \mu\mu\mu$
  - $\tau \to l\pi^0$
  - $\tau \to lhh$


DOI: 10.1093/ptep/ptz106

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

https://www.belle2.org/

Dark sector searches Belle and Belle II

Vector portal Dark Photons, Z' bosons

- $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible (Invisible: neutrino , dark matter)(Belle II : PRL 130.231801)
- $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$(Belle II : arXiv 2306.12294)
- $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$(Belle II : arXiv 2403.02841)

Pseudo-scalar portal Axion Like Particles (ALPs)

- $e^+e^- \to \gamma a, a \to \gamma\gamma$(Belle II : PRL 125.161806)
- $\tau \to l\alpha, \alpha$ invisible(Belle II : PRL 130.181803)

Scalar portal Dark Higgs / Scalars

- $e^+e^- \to \tau^+\tau^- l^+ l^-$(Belle : PRD 109.032002)
- $e^+e^- \to \mu^+\mu^-$ + invisible h'(Belle II : PRL 130.071804)

Neutrino portal Sterile neutrinos

- $\tau \to \pi N(\to \mu^+\mu^-\nu_\tau)$(Belle : arXiv 2402.02580)

τ lepton mass

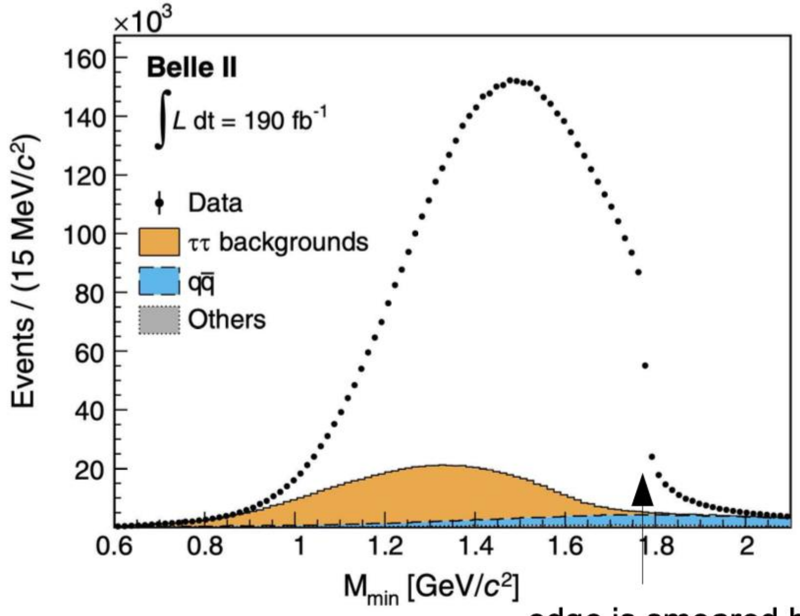
Mass of the τ lepton is a fundamental SM parameter

- Use kinematic edge of $M_{\min}$ distribution in $\tau \to 3\pi\nu$ decays

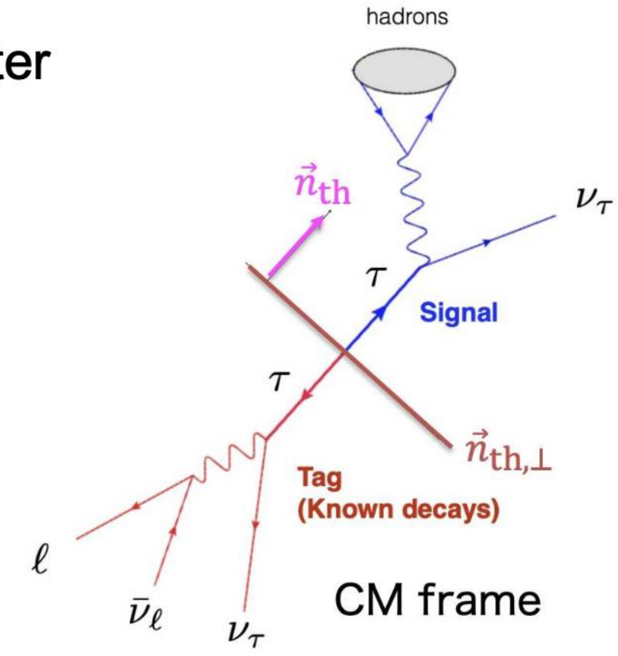
Pseudomass endpoint method:

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

- Assumes neutrino is collinear with 3π direction, and utilizes beam energy constraint



edge is smeared by detector effects and ISR



$\tau^+\tau^-$ pairs are produced at Belle II in $e^+e^- \to \tau^+\tau^-$ with relatively high boost

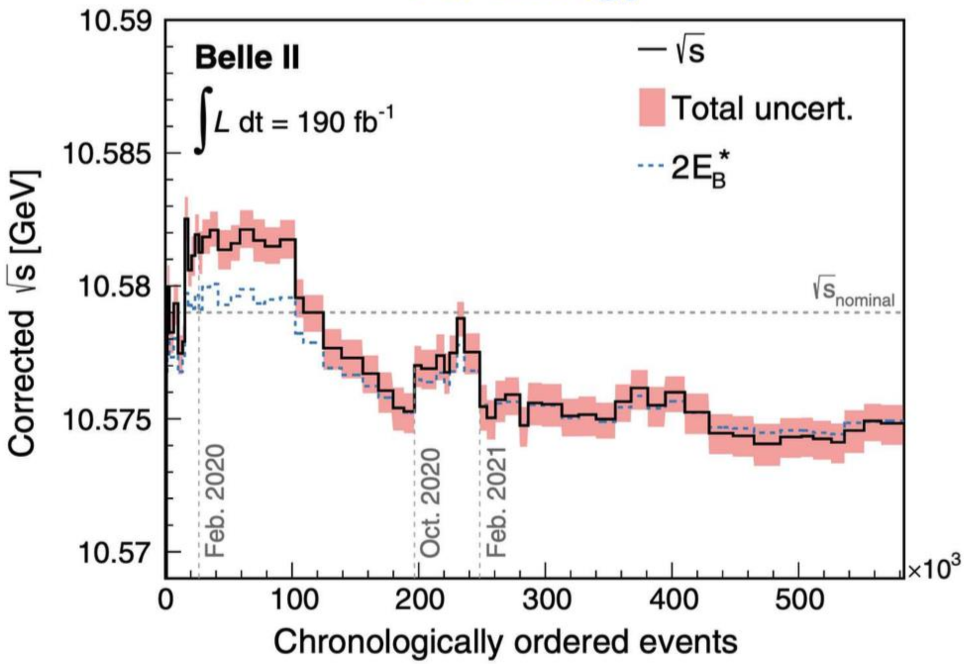
- "Jetty" topology, with the decay daughters from the two taus cleanly separated into two "hemispheres"
- "Tag and probe" to cleanly and inclusively select τ signal candidate sample

τ lepton mass

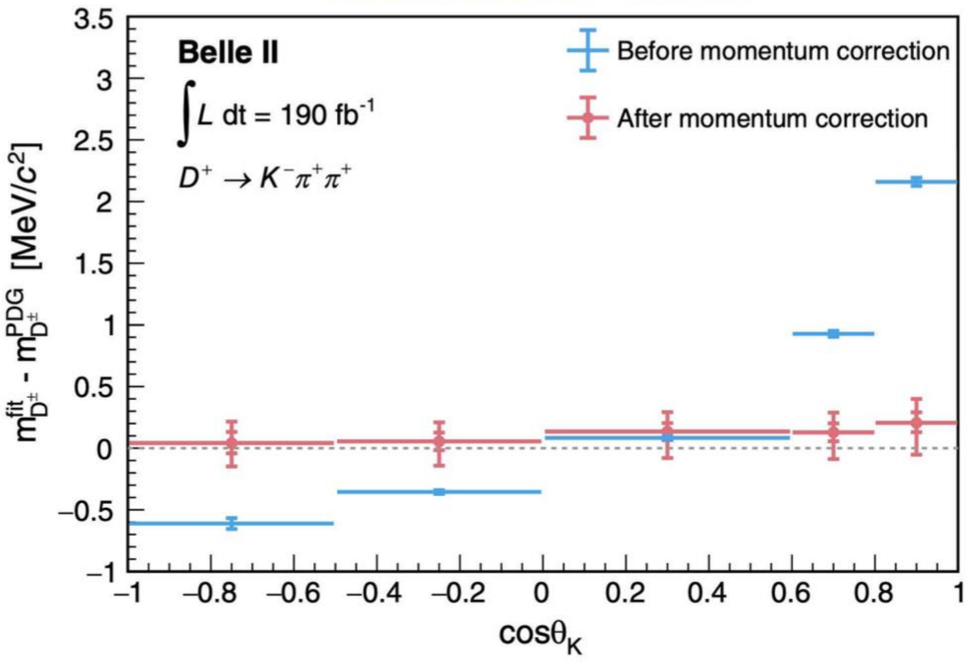
Critical to control beam energy and track momentum scale calibrations

- Beam energy calibrated using B meson hadronic decays
- Momentum scale sensitive to magnetic field imperfections, detector material etc. Extract scale factors for K and π using $D^{*+} \to D^0 \; (\to K^-\pi^+) \; \pi^+$ from data

CM Energy



Measured D^+ mass

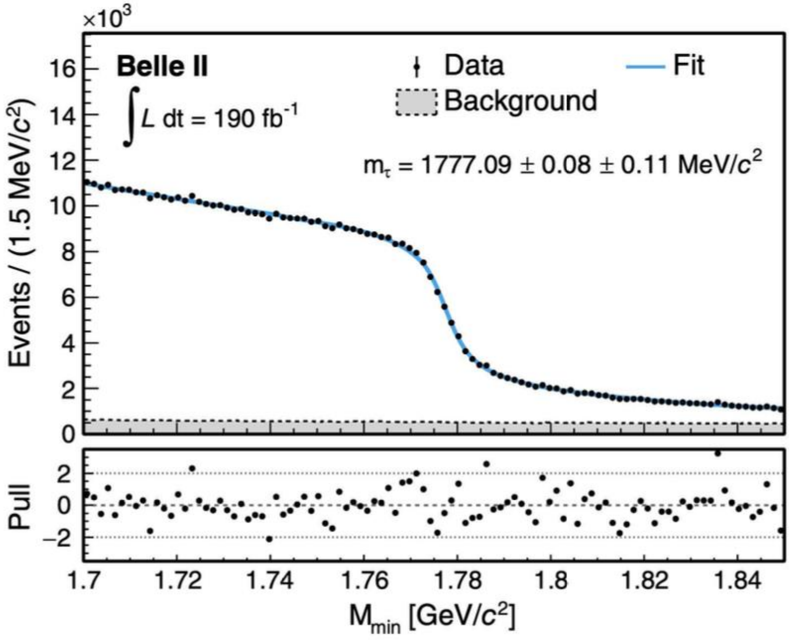


τ lepton mass

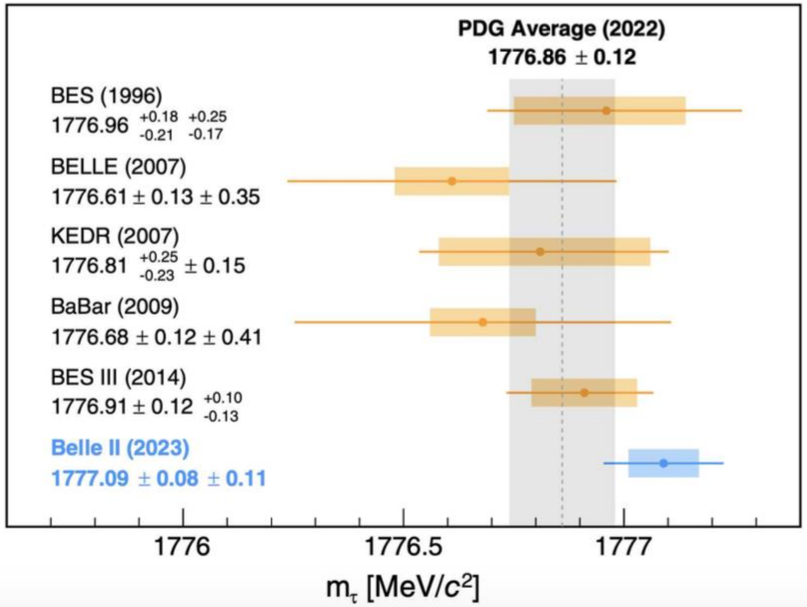
Mass determined from unbinned maximum likelihood fit to an empirical endpoint function:

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

Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11



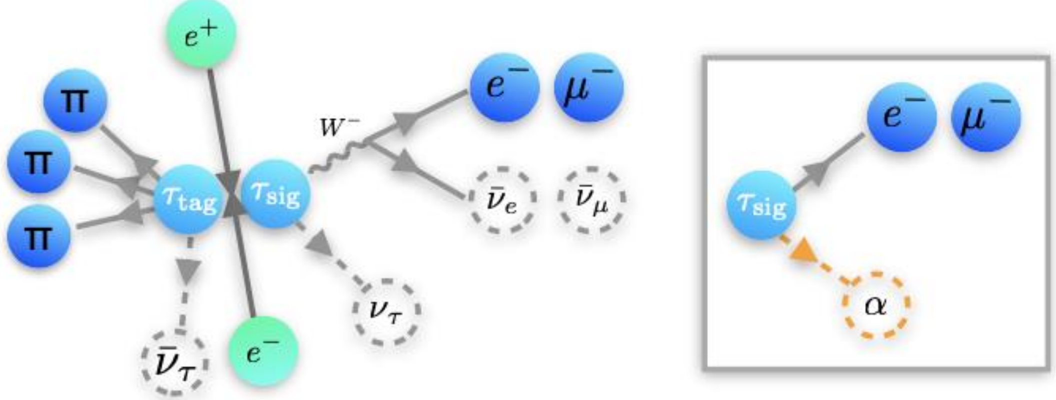
- Most precise experimental determination to date!

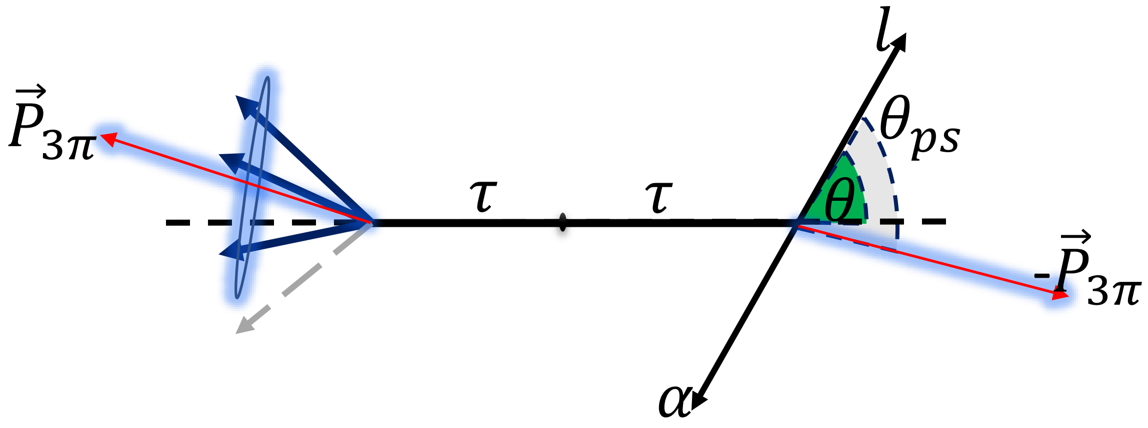


Phys.Rev.D 108 (2023) 3, 032006
arXiv:2305.19116 [hep-ex]

Search for LFV $\tau \to l + \alpha(invisible)$

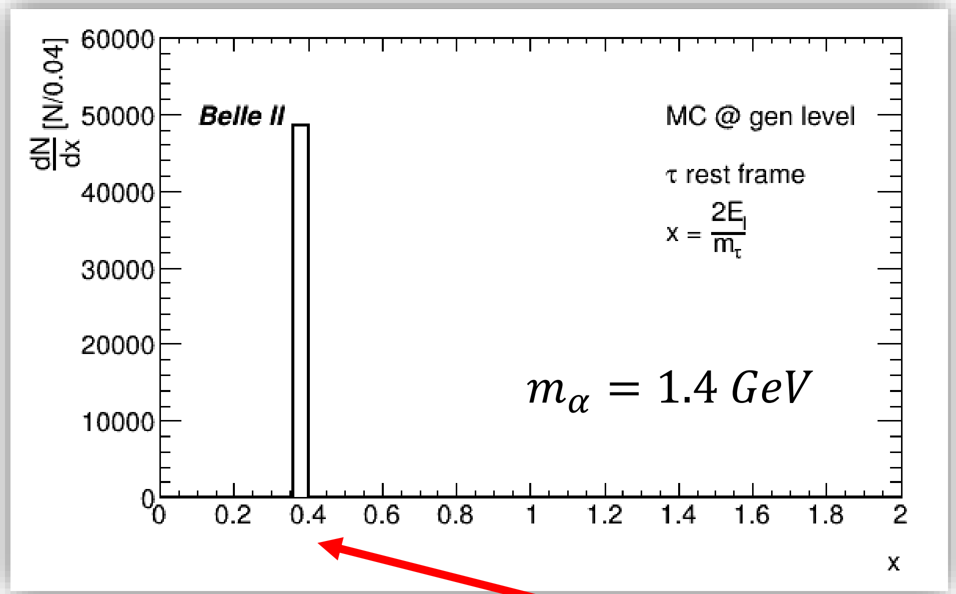
- LFV process not present in the SM but appears in several NP models.
- Search for a two-body decay spectrum:
  - Signal is a monochromatic peak in the tau rest frame
  - The tau rest frame not accessible due to the missing neutrino.
- Approximate tau rest frame by:
  - $E_\tau \approx \frac{E_{cm}}{2}$
  - Direction of the τ given by the opposite to the 3π direction.
  - This is called the tau pseudo-rest frame.
- Search over irreducible background of $\tau \to l\nu\nu$

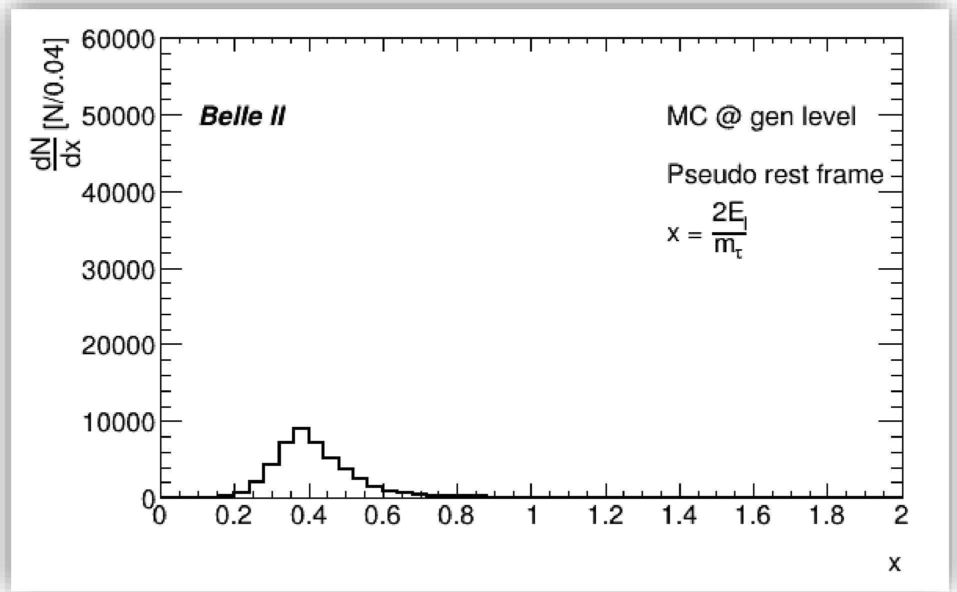




The effect of the pseudo-rest frame

2-body decay case

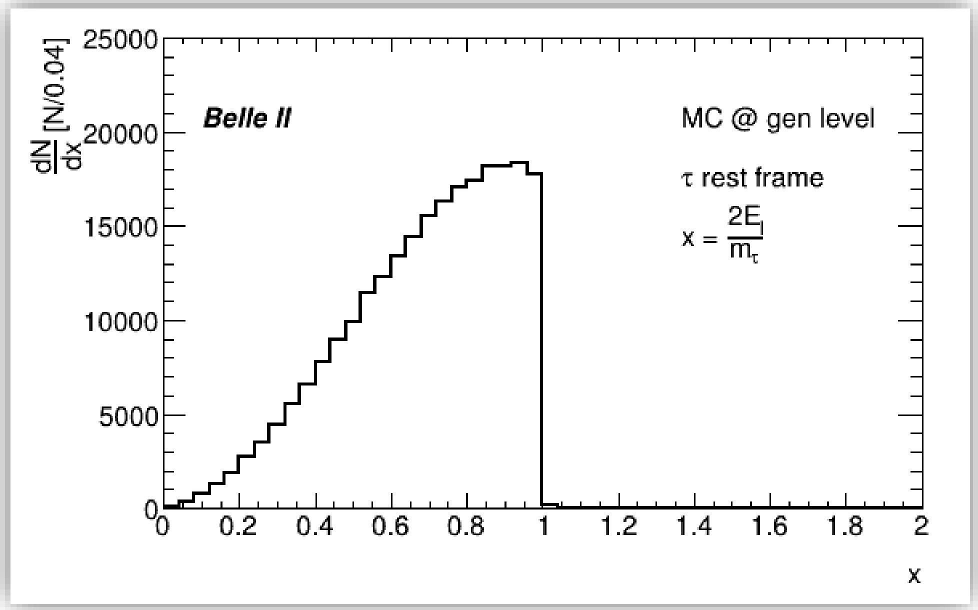


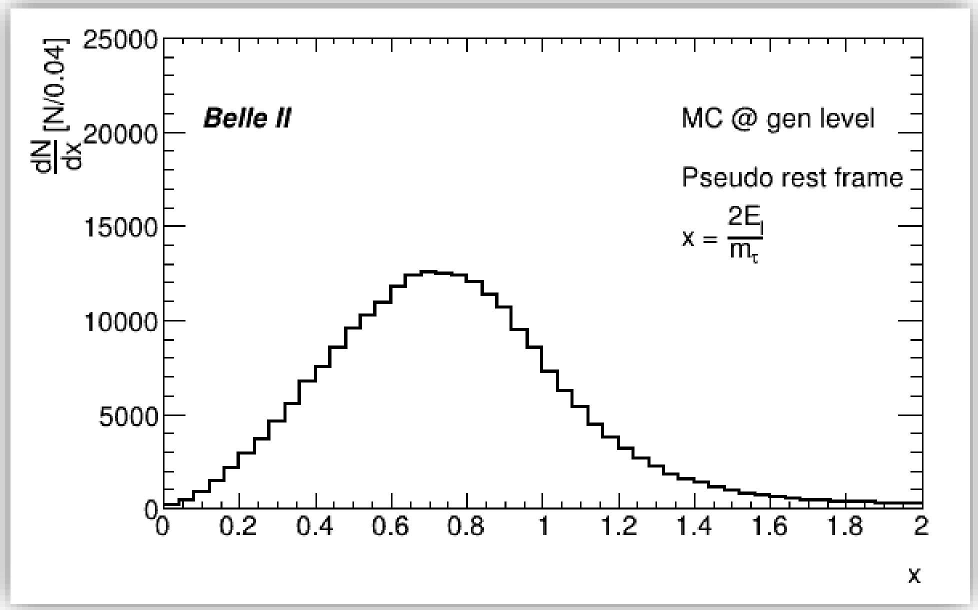


$$x = \frac{2E_l}{m_\tau}$$

$$x_m = 1 + \frac{m_l^2}{m_\tau^2} - \frac{m_\alpha^2}{m_\tau^2}$$

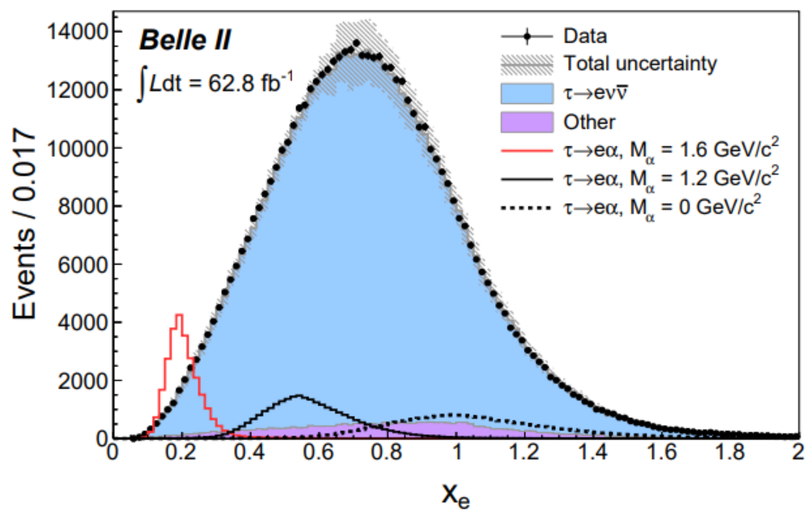
The effect of the pseudo-rest frame

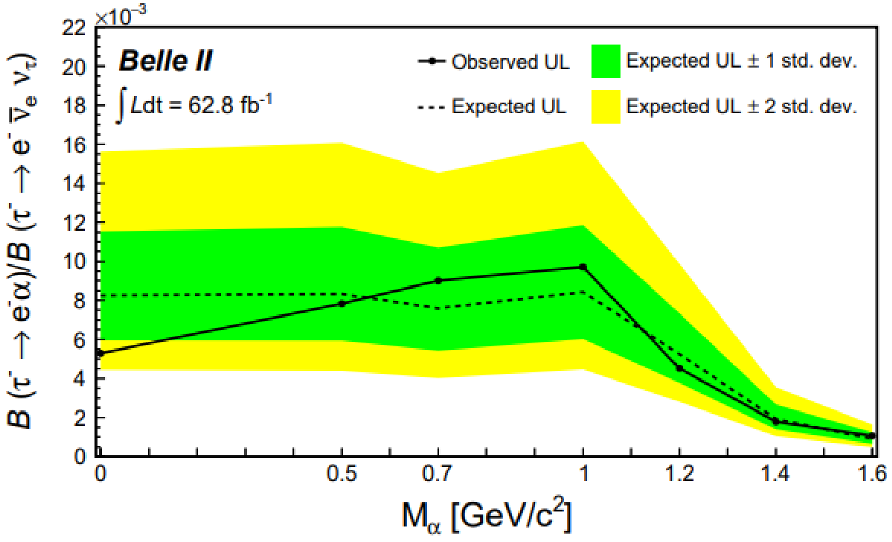


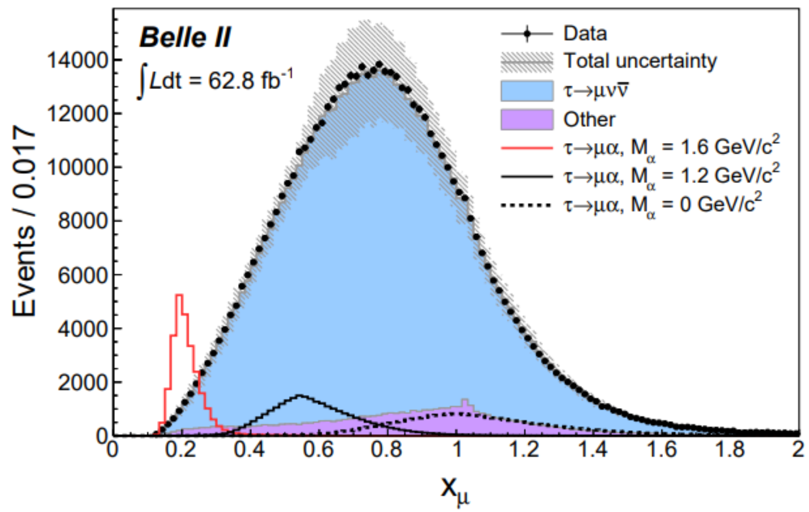


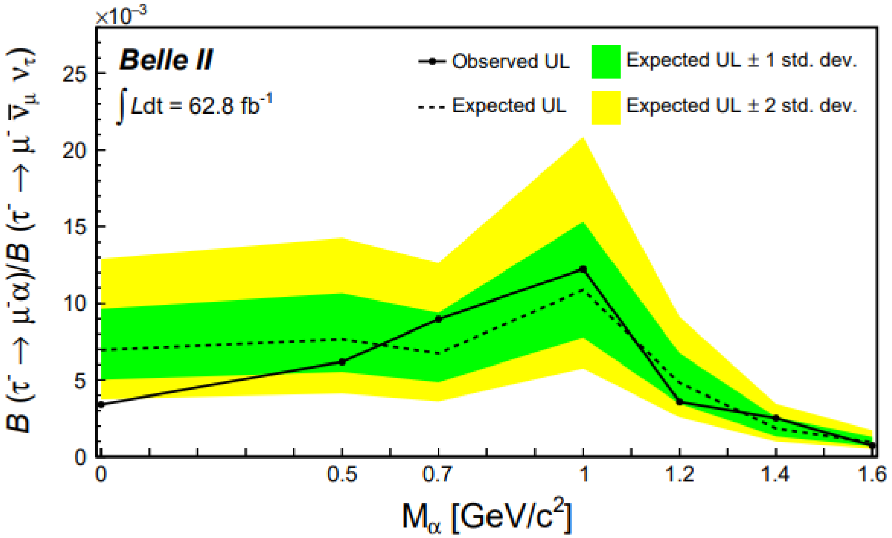
3-body decay case ($\tau \rightarrow l\bar{\nu}_l\nu_\tau$)

Search for LFV $\tau \rightarrow l + \alpha(invisible)$









Could we do better?
Let us try to use all kinematic information

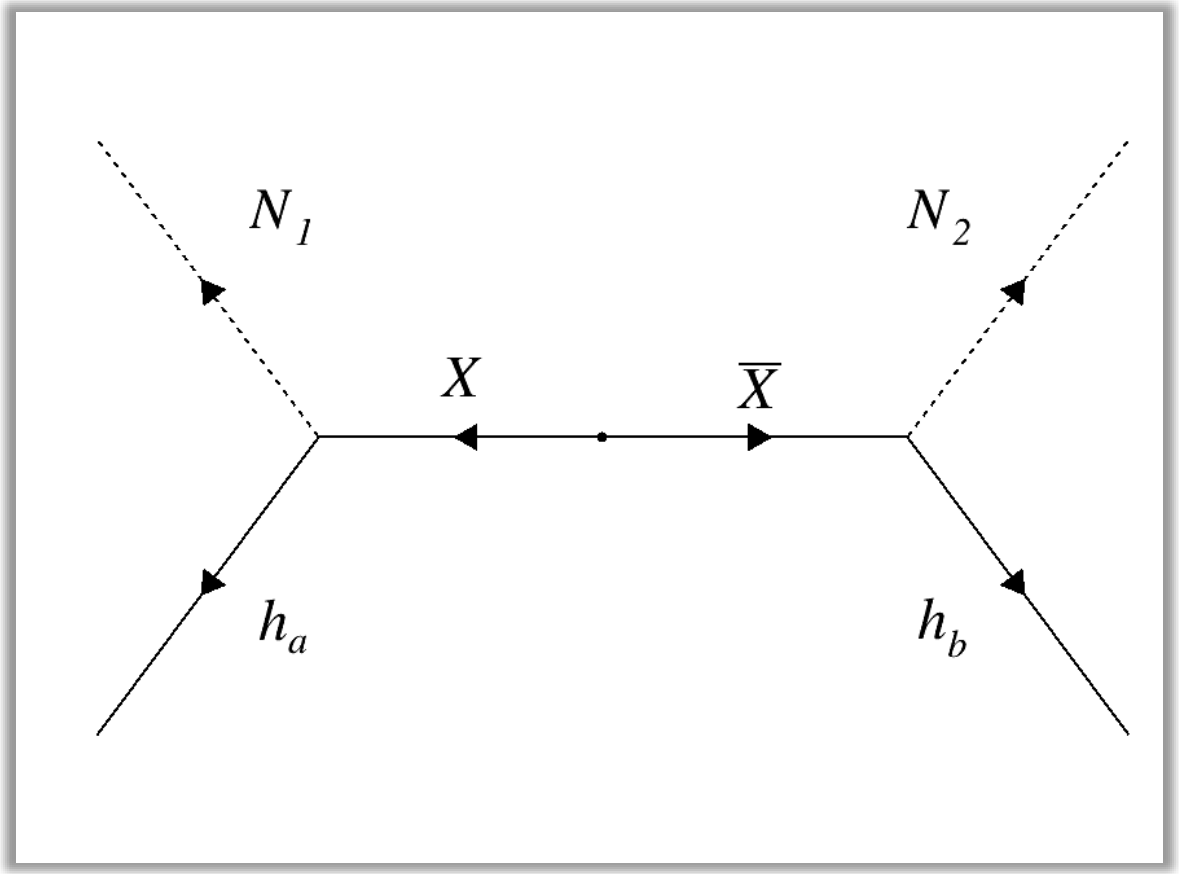
- Particles h are visible particles
- Particles N are invisible particles
- Particle X is the mother particle

$$q^{\mu} = p_a^{\mu} + p_b^{\mu} + p_1^{\mu} + p_2^{\mu}, \quad \mu = 0,1,2,3,$$

$$p_1^2 = m_1^2,$$

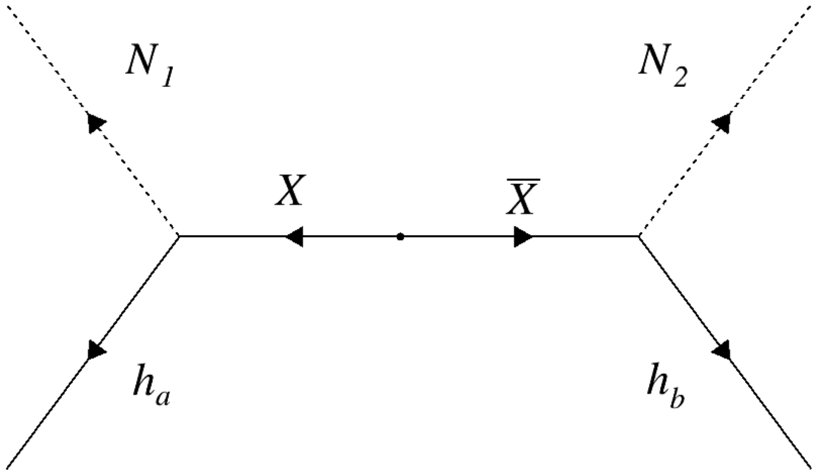
$$p_2^2 = m_2^2,$$

$$(p_a + p_1)^2 = (p_b + p_2)^2 = m_X^2,$$



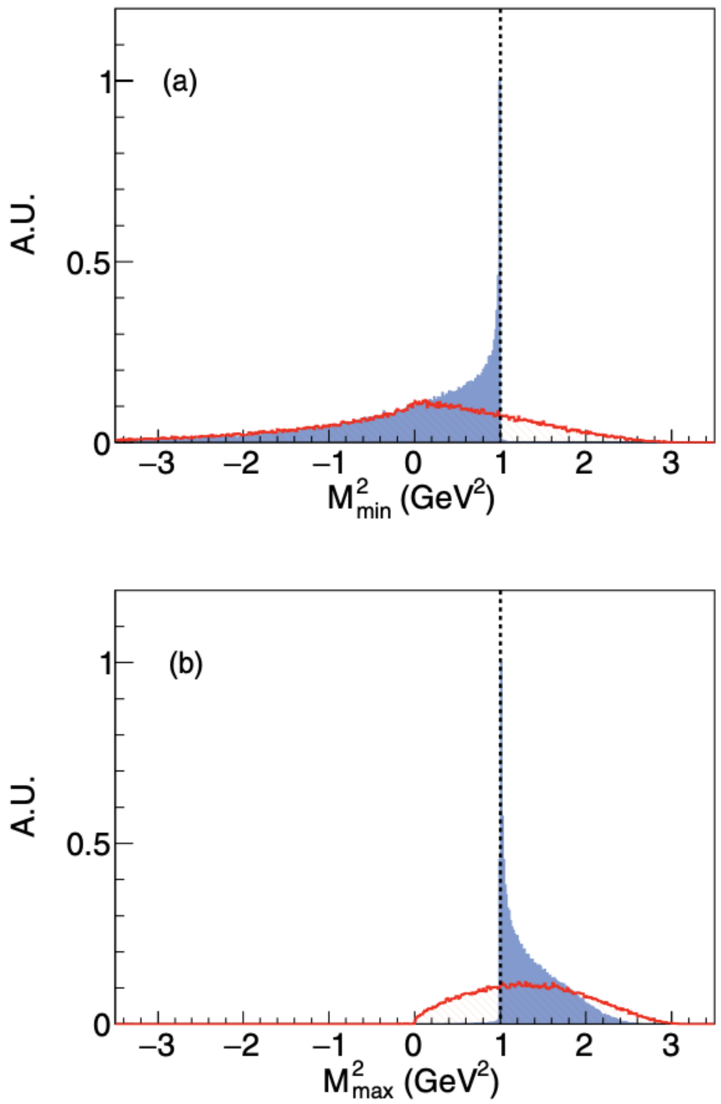
Kinematics endpoints

- A, B, C, and D coefficients depends on observed information.
- $\frac{\mu_i}{\sqrt{s}}$ are the normalized masses to the cms energy



$$
\begin{aligned}
& A_1(\mu_X^2-\mu_1^2)^2+A_2(\mu_X^2-\mu_2^2)^2 \\
& +A_3(\mu_X^2-\mu_1^2)(\mu_X^2-\mu_2^2) \\
& +B_1(\mu_X^2-\mu_1^2)+B_2(\mu_X^2-\mu_2^2) \\
& +C_1\mu_1^2+D_1\leq 0,
\end{aligned}
$$

$\tau \rightarrow e + \alpha$



- Blue is signal with α mass equal to 1 GeV
- Red is 3-body decays

$$A_0(\mu_\alpha^2)^2 + B_0\mu_\alpha^2 + C_0 \leq 0,$$

$$M^2_{\rm min} \leq m^2_\alpha \leq M^2_{\rm max},$$

where

$$M^2_{\rm min} = (\sqrt{s})^2\left(\frac{-B_0 - \sqrt{B_0^2 - 4A_0C_0}}{2A_0}\right),$$

$$M^2_{\rm max} = (\sqrt{s})^2\left(\frac{-B_0 + \sqrt{B_0^2 - 4A_0C_0}}{2A_0}\right).$$

In fact, we can do better

PHYSICAL REVIEW D 102, 115001 (2020)

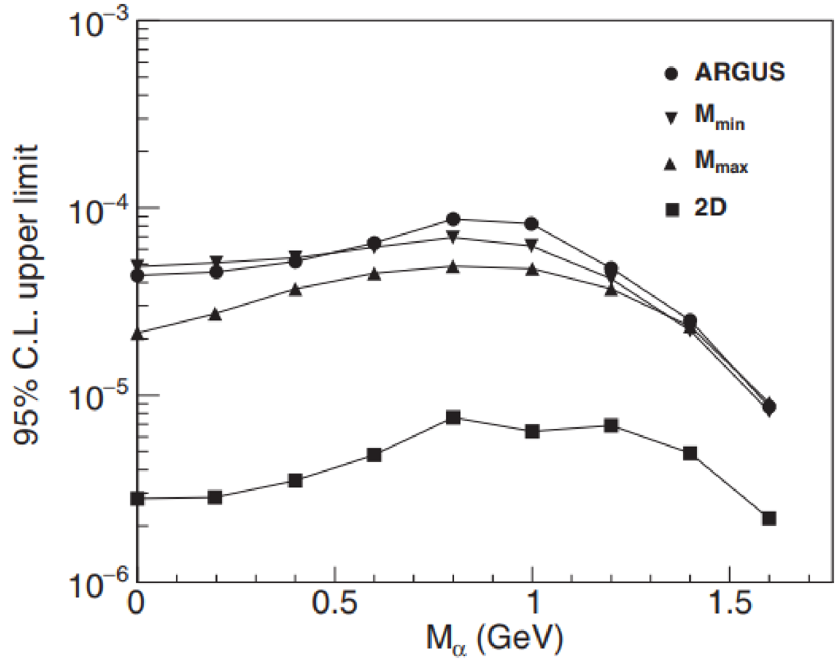


FIG. 4. 95% C.L. upper limits on the relative branching ratio $\mathrm{Br}(\tau \to e\alpha)/\mathrm{Br}(\tau \to e\bar{\nu}_e\nu_\tau)$ for an integrated luminosity of 50 ab^{-1} for tau pairs in 3×1 prong decays.

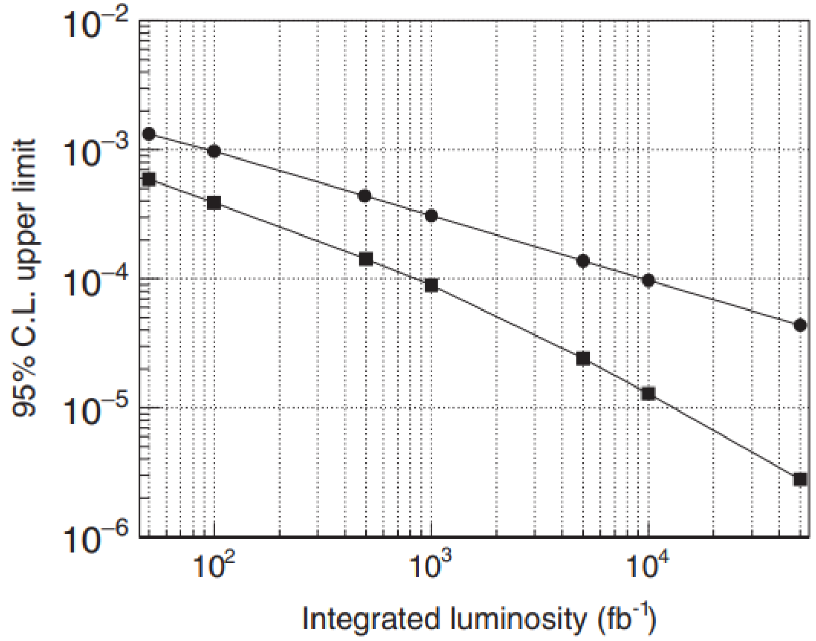


FIG. 5. 95% C.L. upper limits on the relative branching fraction $\mathrm{Br}(\tau \to e\alpha)/\mathrm{Br}(\tau \to e\bar{\nu}_e\nu_\tau)$ as a function of the integrated luminosity for tau pairs in 3×1 prong decays. Black circle (squared) points are for ARGUS (2D) method. The upper limit are for $m_\alpha = 0$.

Remarks:

- For the search of a new boson in LFV $\tau \rightarrow l + \alpha$, we can improve for zero mass of the new boson up to 15 times better upper limit, which in a simple scaling is like requiring 225 more data.
- The method can be applied to 1x1 topology as well.
- Not presented here, but this can be applied to measure the tau mass, providing more events in the endpoint than the pseudo-mass endpoint.