Measurements of Michel parameters and tests of lepton universality in τ decays at Belle and Belle II

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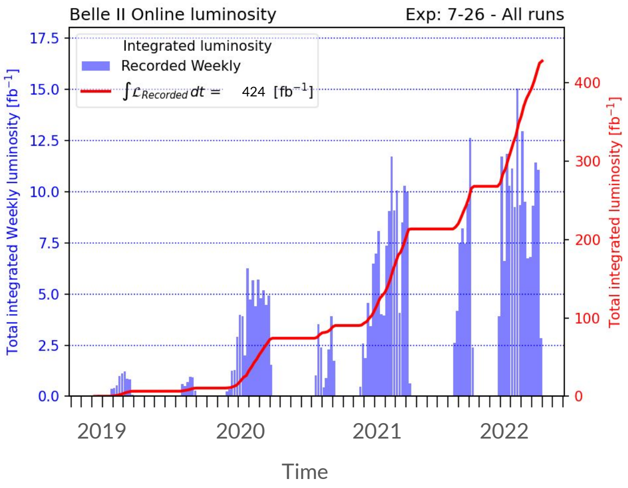
τ physics at B factories

- Belle/Belle II are general purpose detectors: B and D physics, quarkonium, τ-physics, dark sector, …
- colliding electrons and positrons around $\sqrt{s} \approx 10.58$ GeV/c²

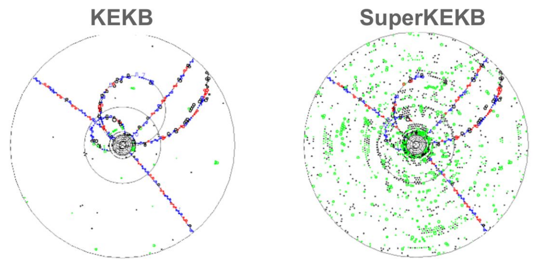
$$\sigma\left(e^+e^- \rightarrow \Upsilon(4S)\right) = 1.05\text{nb}$$
$$\sigma\left(e^+e^- \rightarrow \tau^+\tau^-\right) = 0.919\text{nb}$$

  - Belle: 988 fb^{-1} → **~908 million** τ pairs
  - Belle II: 424 fb^{-1} → **~390 million** τ pairs
- clean collision environment
- large solid angle coverage (> 90%)
  - well known missing mass and energy
- good track reconstruction, particle identification



KEKB → SuperKEKB accelerator

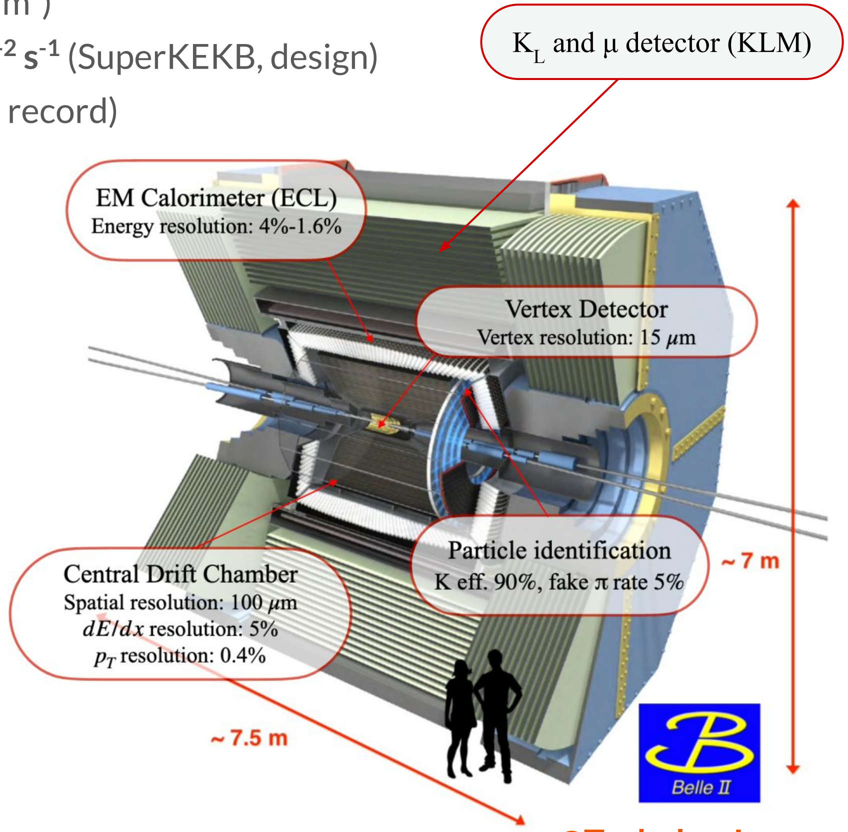
- 2x beam currents, 50 nm vertical beam spot size (“nano beam”)
- peak luminosity 2.1×10^{34} (KEKB, achieved) → **6.0×10^{35} cm^{-2} s^{-1}** (SuperKEKB, design)
- so far SuperKEKB achieved 4.7×10^{34} cm^{-2}s^{-1} (current world record)



challenge: increased beam backgrounds and trigger rates

Belle → Belle II detector

- new 2-layer Pixel Detector with first layer at 1.4cm
- 4-layer Silicon Vertex Detector with larger acceptance
- Central Drift Chamber with larger outer radius
- improved particle ID (K/π separation)
- improved trigger, and faster electronics in general



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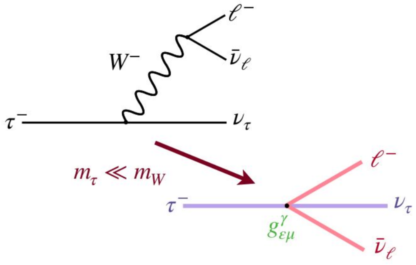
» arXiv:1011.0352 (Technical Design Report)

Michel parameters in leptonic decays

- Michel parameters (MP) of a lepton decay are bilinear combinations of coupling constants arising in the most general expression for the decay matrix element



$$= \frac{4G_F}{\sqrt{2}} \sum_{\substack{N=S,V,T \\ i,j=L,R}} g_{ij}^{N} \left[\overline{u}_i(\ell)\Gamma^N v_n(\nu_\ell)\right]\left[\overline{u}_m(\nu_\tau)\Gamma_N u_j(\tau)\right]$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = i\left(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right)/2\sqrt{2}$$

Scalar Vector Tensor

- MP describe the Lorentz structure of the charged current in the theory of weak interaction and can be used to test the SM (only nonzero term in SM is $g_{LL}^{V} = 1$)
- deviations can be caused by anomalous coupling with the W-boson, new gauge or charged Higgs bosons, presence of massive neutrinos [1]

» [1] JHEP 2022 (2022) 117

Measurement of Michel parameters at Belle

$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \frac{m_\tau}{4\pi^3} W_{\ell\tau}^4 G_F^2 \sqrt{x^2 - x_0^2}\,\Big(F_{IS}(x) \pm F_{AS}(x) P_\tau \cos\theta + F_{T_1}(x) P_\tau \sin\theta\zeta_1 + F_{T_2}(x) P_\tau \sin\theta\zeta_2 + (\pm F_{IP}(x) + F_{AP}(x) P_\tau \cos\theta)\zeta_3\Big)$$

parametric functions	MPs	
$F_{IS}(x)$:	ρ, η	daughter lepton polarisation insensitive
$F_{AS}(x)$:	$\xi, \xi\delta$	
$F_{IP}(x)$:	$\xi', \xi, \xi\delta$	daughter lepton polarisation sensitive

$$W_{\ell\tau} = \max E_\ell = \frac{m_\tau^2 + m_\ell^2}{2m_\tau},\ x = \frac{E_\ell}{\max E_\ell},\ x_0 = \frac{m_\ell}{\max E_\ell},\ P_\tau = |\boldsymbol{P}_\tau|$$

	$\mu^- \to e^-\nu_\mu\overline{\nu}_e$	$\tau^- \to e^-\nu_\tau\overline{\nu}_e$	$\tau^- \to \mu^-\nu_\tau\overline{\nu}_\mu$	SM
ρ	0.74979 ± 0.00026	0.747 ± 0.010	0.763 ± 0.020	0.75
η	0.057 ± 0.034	–	0.094 ± 0.073	0
ξ	$1.0009^{+0.0016}_{-0.0007}$	0.994 ± 0.040	1.030 ± 0.059	1
$\xi\delta$	$0.7511^{+0.0012}_{-0.0006}$	0.734 ± 0.028	0.778 ± 0.037	0.75
ξ'	1.00 ± 0.04	–	0.22 ± 1.03	1
ξ''	0.98 ± 0.04	–	–	1

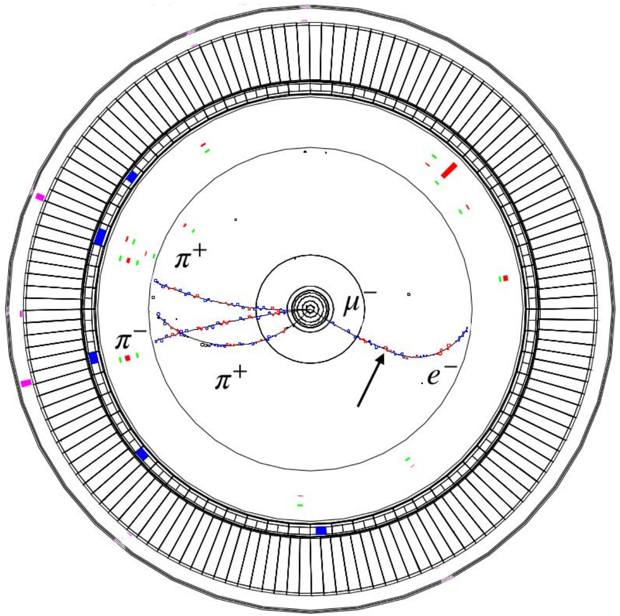
Michel parameters and their most accurate determinations [4]

- ongoing analysis for ϱ, η, ξ and $\xi\delta$ in τ decays [1]
  - ➢ statistical uncertainty of the order of 10^{-3}
    systematics around 10^{-2}
- measurement of MPs $\bar{\eta}$ and $\xi\kappa$ in radiative leptonic τ-decays [2]
- first direct measurement of ξ' in $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ [3]

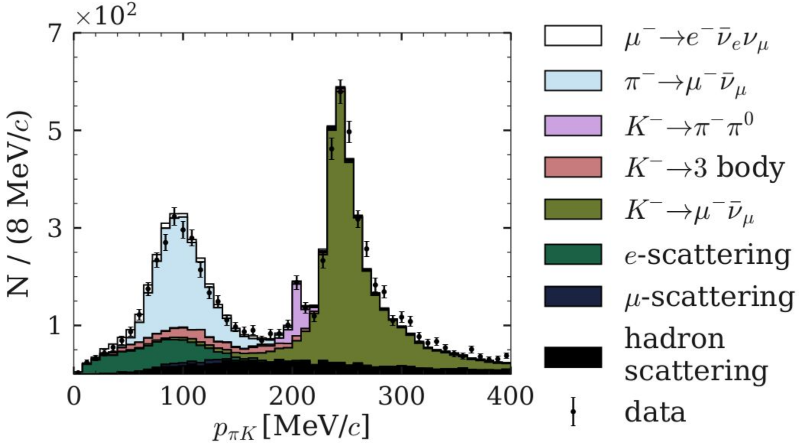
» [1] Nucl.Part.Phys.Proc. 287-288 (2017)
» [2] PTEP 2018 (2018) 2, 023C01
» [3] Phys.Rev.Lett. 131 (2023) 021801
» [4] PTEP 2022 (2022) 083C01

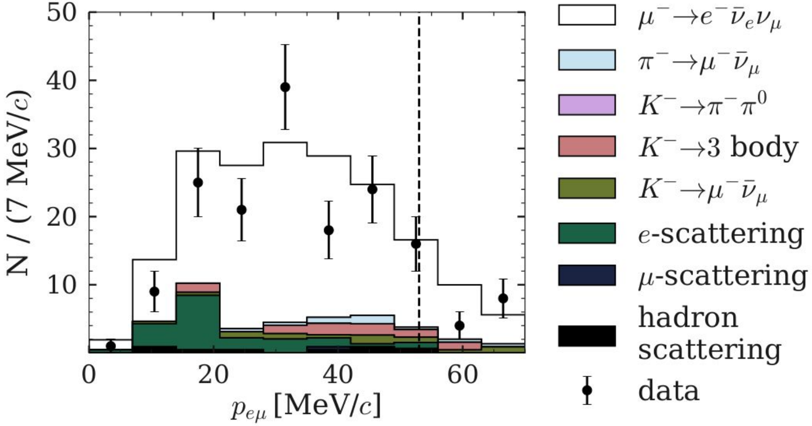
First measurement of the Michel parameter ξ′ in the $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decay at Belle

- method uses muon decay-in-flight
- searching for kinks inside the tracking detector
- the information about muon spin can be inferred from the daughter electron direction in the muon rest frame due to P-violation in the decay
- using the full Belle data sample of 988 fb^{-1}



Kink candidates

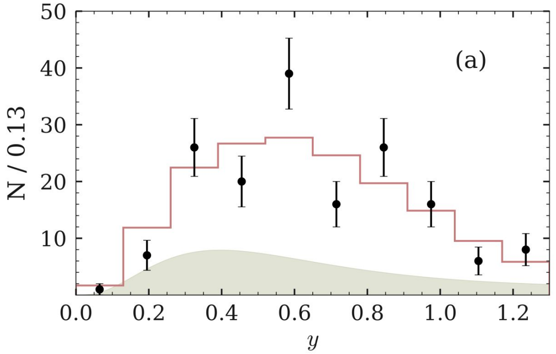




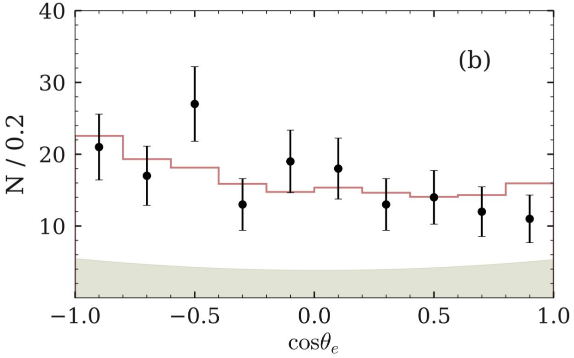
- daughter particle momentum in the rest frame of the mother particle
  - using mass hypothesis "K → π"
- main background sources are two body decays of K and π

- BDT is used to suppress background by 50 times with the signal efficiency $\varepsilon_{sig} \approx 80$ %

Result



$e^{\pm}$ energy in $\mu^{\pm}$ rest frame divided by $m_{\mu}/2$



angle of electron emission direction in the muon rest frame

- 2D unbinned likelihood fit using y and $\cos\theta_e$
- histogram is signal, filled area is the background function
- the measured value is **ξ' = 0.22 ± 0.94 (stat) ± 0.42 (syst)** [1, 2]
  - total uncertainty is 1.03

- Belle II (with 50 ab^{-1}) can improve the statistical uncertainty up to $\sigma_{\xi'} \approx 7 \times 10^{-3}$ [3]
  - enlarged drift chamber, special kink reconstruction algorithm, higher integrated luminosity
  - GNN-based tracking algorithm for displaced tracks [4]
  - systematics can be controlled at the same level with various data samples with kinks

» [1] Phys.Rev.Lett. 131 (2023) 021801
» [2] Phys.Rev.D 108 (2023) 012003
» [3] JHEP 10 (2022) 035
» [4] Reuter et al, CHEP 2023 (Poster)

Lepton universality tests at Belle II

- in the SM the electroweak gauge bosons have the same coupling to all generations of leptons
- precise test of μ-e universality by measuring

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma)\right)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \qquad [1]$$

- ratio of leptonic branching fractions

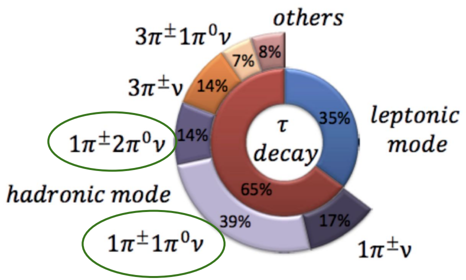
$$R_\mu \equiv \frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma)\right)} \stackrel{\text{SM}}{=} 0.9726$$

is sensitive to new physics if it violates

- ➢ lepton flavour [2]
- ➢ lepton universality in weak charged-currents

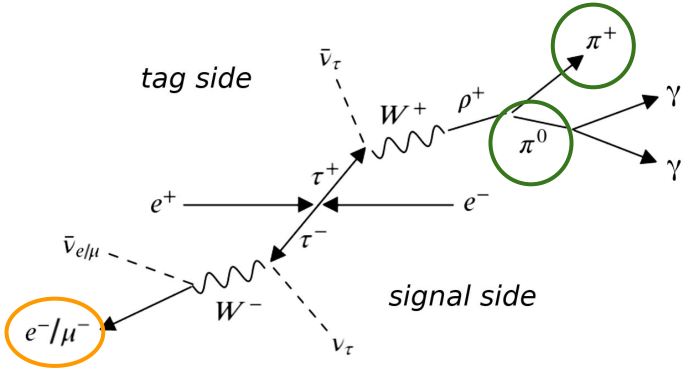
» [1] Phys.Rev.Lett. 61 (1988) 1815
» [2] Phys. Lett. B 762 (2016) 389-398

Event topology



using 1-prong decays with one charged hadron and at least one π^0 on the tag side

- large BF (~35%), low backgrounds, high trigger efficiency
- Signal side selection
  - ➢ 1 track: particle ID requirement (μ or e)
- Tag side selection
  - ➢ 1 track: $E_{cluster}$ / p < 0.8
  - ➢ $N(\pi^0)_{tag} > 0$



Dataset

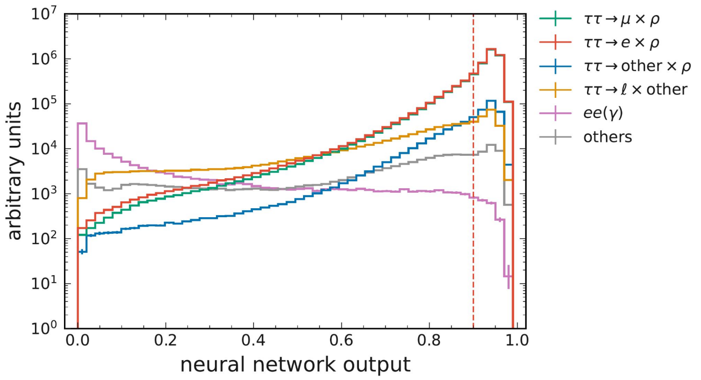
- on-resonance sample corresponding to 362 fb^{-1} (2019 - 2022)

Event selection

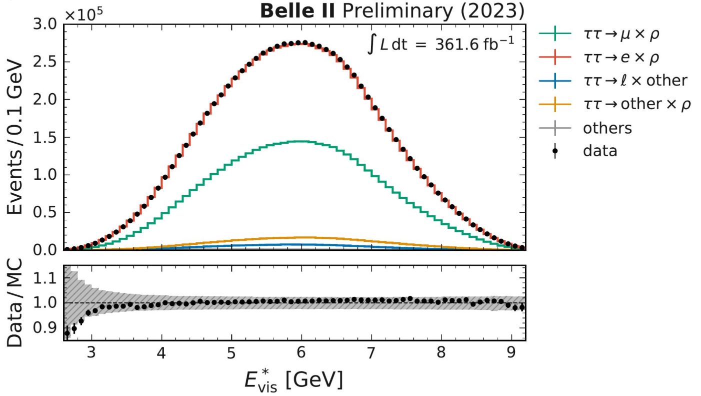
- background suppression with rectangular cuts + neural network
- exactly same selection is used for e and μ sample

  - thrust value
  - thrust axis θ
  - total visible energy (CMS)
  - missing momentum: $p_{T,}$ θ (CMS)
  - tag side: p, θ, M (CMS)

analysis cut



- restrict analysis to region least sensitive to particle ID systematics
  - $0.82 < \theta_{lepton} < 2.13$ (barrel of muon detector)
  - 1.5 GeV $< p_{lepton} < 5.0$ GeV



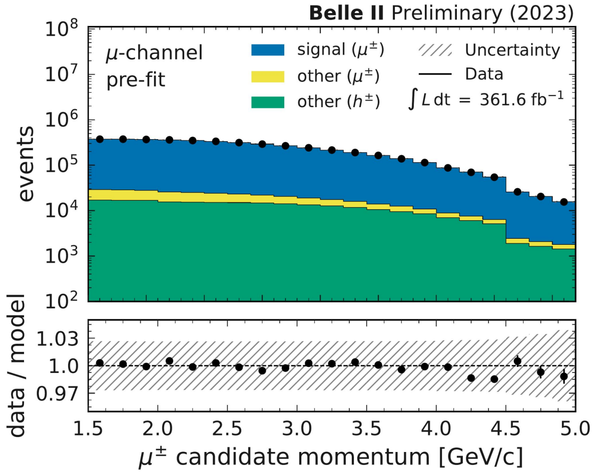
- 94% purity @ 9.6% signal efficiency for combined e+μ sample

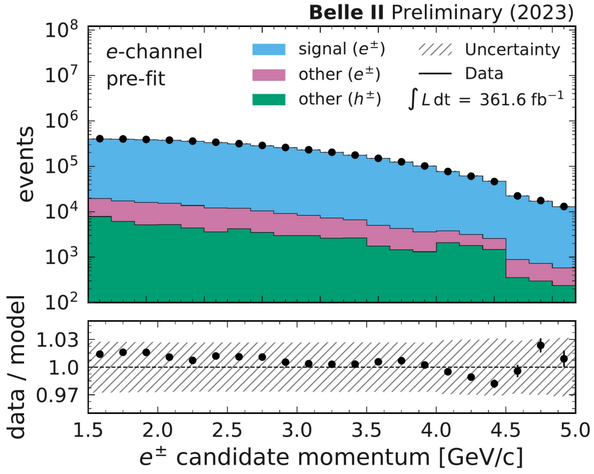
  - $e^+e^- \to \tau^+\tau^-$ ($\pi^\pm$ faking $\mu^\pm/e^\pm$): ~3.3%
  - $e^+e^- \to \tau^+\tau^-$ (wrong tag): ~2.3%
  - $e^+e^- \to e^+e^-\tau^+\tau^-$: 0.2%

main backgrounds

R_μ extraction

- measure R_μ with a *binned maximum likelihood* fit using the *pyhf* library [1]
- 21 bins defined over lepton momentum from 1.5 to 5 GeV
- systematics are included with (constrained) nuisance parameters that modify the templates
- 3 templates for μ and e channel
  - signal decays
  - background with correct lepton on the signal side
  - background with misidentified particle on the signal side





» [1] JOSS 6 (2021) 2823

Systematics

Particle identification (leading) **(0.32%)**

- correction factors and uncertainties derived from calibration channels
  - eff.: $J/\psi \to \ell^+\ell^-$, $e^+e^- \to e^+e^-\ell^+\ell^-$ and $e^+e^- \to \ell^+\ell^-(\gamma)$
    - e/μ eff.: 99.7% / 93.9%
  - fakes: $K_S^0 \to \pi^+\pi^-$ and $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$
    - $\pi \to e/\mu$: 0.9% / 3.1%

Trigger (sub-leading) **(0.10%)**

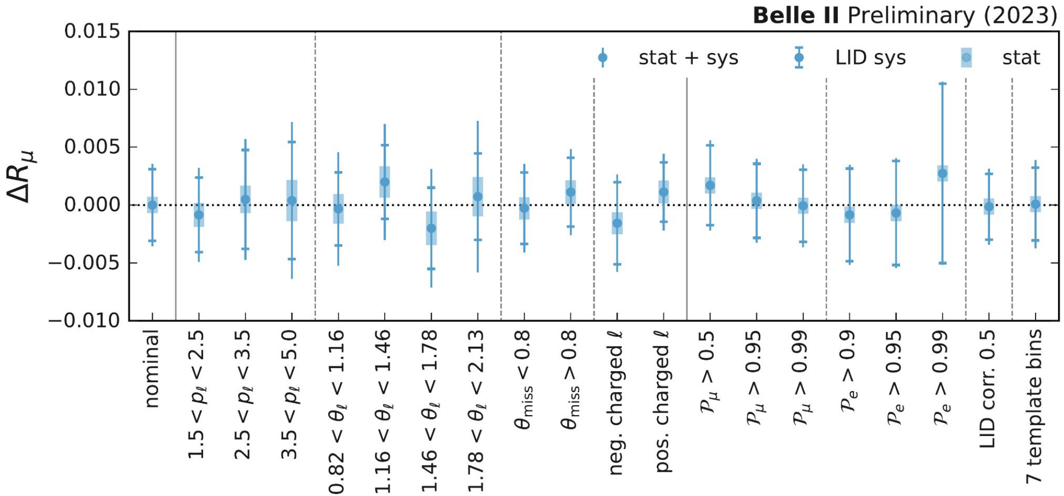
- used triggers are based on EM calorimeter information, targeting low multiplicity events
  - most important: E_{ECL}>1 GeV trigger
- correction factor for MC obtained directly from data
  - ε=99.8% for $\tau^-\to e^-\bar{\nu}_e\nu_\tau$ and ε=96.6% for $\tau^-\to\mu^-\bar{\nu}_\mu\nu_\tau$

Source	Uncertainty [%]
Charged-particle identification:	
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Trigger	0.10
Imperfections of the simulation:	
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Size of the samples	
Simulated samples	0.06
Luminosity	0.01
Charged-particle reconstruction:	
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Total	0.37

relative systematic uncertainties of R_μ

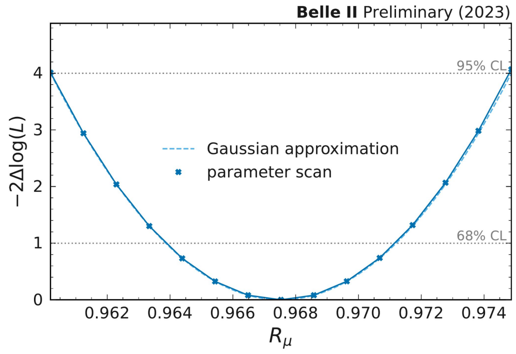
Stability of the result

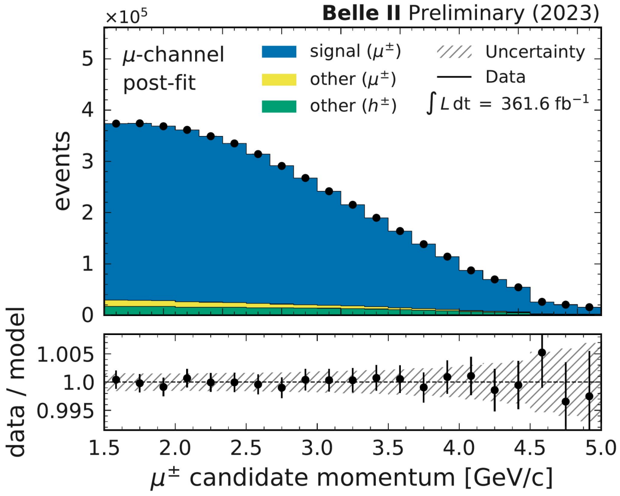
- checked for consistency of the result before unblinding
- sub-regions for different kinematic variables (momentum, polar angle, missing momentum, charge), data-taking periods as well as different requirements for particle-identification
- good agreement between the measured values

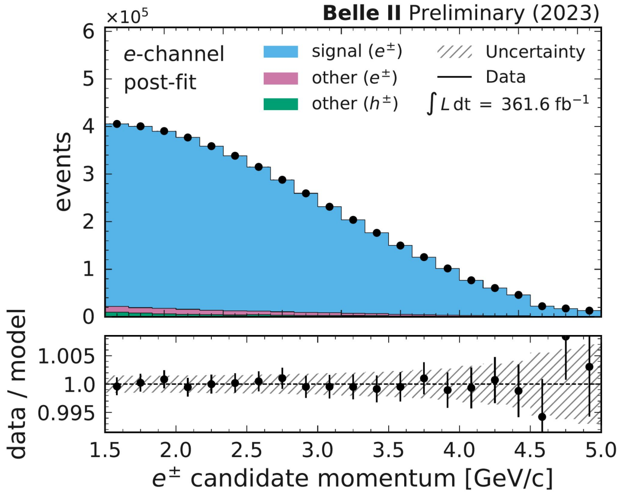


Result

- we measure R_μ **= 0.9675 ± 0.0037**
  - statistical uncertainty 0.0007
  - systematic uncertainty 0.0036
- consistent with SM expectation at the level of 1.4 sigma



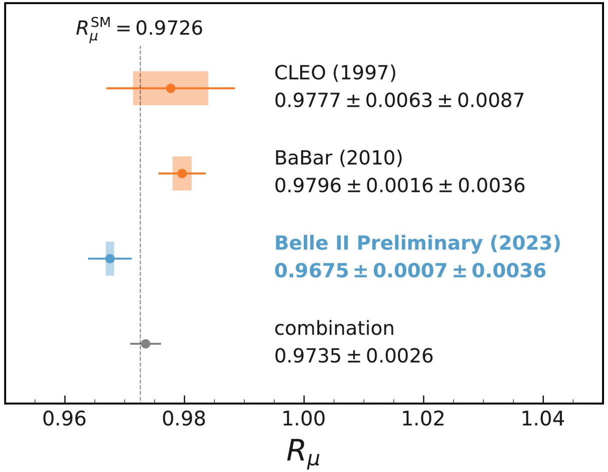


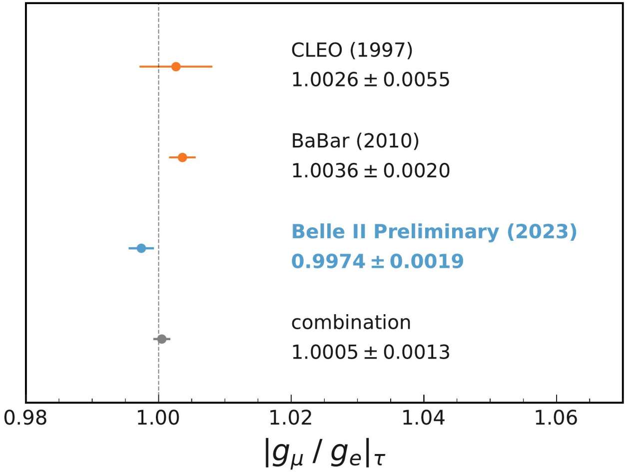


Result

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

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



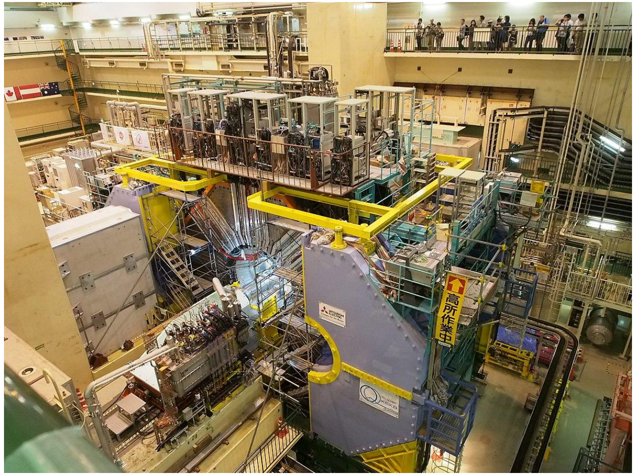


- most precise test of μ-e universality in τ decays from a single measurement
    - determination of $(g_\mu/g_e)_\tau$ from global fit to tau BFs: 1.0019 ± 0.0014 [1]
- combination of CLEO, BaBar and Belle II (assuming indep. systematics) yields $(g_\mu/g_e)_\tau$ = 1.0005 ± 0.0013

» [1] HFLAV, Phys.Rev.D 107 (2023) 052008

Summary

- Belle data (988 fb^{-1}) is still being actively analysed
  - first measurement of the Michel parameter ξ' using a novel method
- Belle II recorded 424 fb^{-1} so far, resuming data taking soon
- new results for test of μ-e universality
  - world's best determination from single measurement
  - similar systematics as BaBar measurement
- more (τ) physics to come from Belle/Belle II



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Radiative and five-body leptonic τ decays

- Radiative and five-body leptonic τ-decays provide information about Michel parameters that describe daughter lepton polarization in $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$
- Their understanding is also crucial for LFV studies as they are main background

Radiative leptonic τ-decay

$$\frac{d\Gamma(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma)}{dE_\ell \, d\Omega_\ell \, dE_\gamma \, d\Omega_\gamma} = \left(A_0 + \bar{\eta} A_1\right) + \left(\vec{B}_0 + \xi\kappa \vec{B}_1\right) \cdot \vec{S}_\tau$$

$$\xi\kappa = -1/4(\xi + \xi') + 2/3\xi\delta$$
$$\bar{\eta} = 4/3\rho - 1/4\xi'' - 3/4$$

Belle collaboration measured $\xi\kappa(e) = -0.4 \pm 1.2$, $\xi\kappa(\mu) = 0.8 \pm 0.6$, and $\bar{\eta}(\mu) = -1.3 \pm 1.7$ ($\mathscr{L} = 711$ fb^{-1}) PTEP 2018 (2018) 2, 023C01

Five-body leptonic τ-decay

Belle estimations for $\mathscr{L} = 700$ fb^{-1}

Mode	SM Br	Measured	Expected N	Systematics
$\tau^- \to e^- e^+ e^- \bar{\nu}_e \nu_\tau$	$4.21(1) \times 10^{-5}$	$(1.8 \pm 1.5) \times 10^{-5}$	$1300\,(r_s = 47\%)$	$(6-12)\,\%$
$\tau^- \to \mu^- e^+ e^- \bar{\nu}_e \nu_\tau$	$1.984(4) \times 10^{-5}$	$< 3.2 \times 10^{-5}\,(90\%)$	$430\,(r_s = 50\%)$	$(8-13)\,\%$
$\tau^- \to e^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau$	$1.247(1) \times 10^{-7}$	NM	$8\,(r_s = 37\%)$	$(36-72)\,\%$
$\tau^- \to \mu^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau$	$1.183(1) \times 10^{-7}$	NM	$4\,(r_s = 16\%)$	$(36-72)\,\%$

JHEP 04 (2016) 185   J.Phys.Conf.Ser. 912 (2017) 1

Belle II can repeat with better precision!

τ lepton polarization at Belle II

- The beams at Belle II are not polarized, so average τ lepton polarization is zero. Nevertheless, spins of τ leptons are correlated in $e^+e^- \to \tau^+\tau^-$:

$$\frac{d\sigma(e^+e^-(w^-) \to \tau_{\text{sig}}(\vec{s}_{\text{sig}})\tau_{\text{tag}}(\vec{s}_{\text{tag}}))}{d\Omega_\tau} = \frac{\alpha^2\beta}{64E^2}\left[A_0 + D_{ij}(\vec{s}_{\text{sig}})_i(\vec{s}_{\text{tag}})_j\right]$$

$$A_0 = 1 + \cos^2\theta_\tau + \frac{\sin^2\theta_\tau}{\gamma^2} \qquad D_{ij} = \begin{pmatrix} \left(1+\frac{1}{\gamma^2}\right)\sin^2\theta_\tau & 0 & \frac{1}{\gamma}\sin 2\theta_\tau \\ 0 & -\beta^2\sin^2\theta_\tau & 0 \\ \frac{1}{\gamma}\sin 2\theta_\tau & 0 & 1+\cos^2\theta_\tau - \frac{\sin^2\theta_\tau}{\gamma^2} \end{pmatrix}$$

- One can use tagging τ lepton as a spin analyzer with the decay mode $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$. This mode has the largest branching fraction (around $25\ \%$), and it is also well-studied

Leptonic differential decay width parametric functions definition

$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$F_{AS}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 3 - \frac{x_0^2}{2}\right)\right]$$

$$F_{IP}(x) = \frac{1}{54}\sqrt{x^2 - x_0^2}\left[-9\xi'\left(2x - 3 + \frac{x_0^2}{2}\right) + 4\xi\left(\delta - \frac{3}{4}\right)\left(4x - 3 - \frac{x_0^2}{2}\right)\right]$$

$$F_{AP}(x) = \frac{1}{6}\left[\xi''\left(2x^2 - x - x_0^2\right) + 4\left(\rho - \frac{3}{4}\right)\left(4x^2 - 3x - x_0^2\right) + 2\eta'' x_0(1-x)\right]$$

$$F_{T_1}(x) = -\frac{1}{12}\left[2\left(\xi'' + 12\left(\rho - \frac{3}{4}\right)\right)(1-x)x_0 + 3\eta(x^2 - x_0^2) + \eta''(3x^2 - 4x + x_0^2)\right]$$

$$F_{T_2}(x) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left(3\frac{\alpha'}{A}(1-x) + \frac{\beta'}{A}(2 - x_0^2)\right)$$

MP parameters through coupling constants

$$\rho = \frac{3}{4} - \frac{3}{4}\left[\left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right) + \Re\left\{g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR}\right\}\right]$$

$$\eta = \frac{1}{2}\Re\left\{g^V_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right) + g^V_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right) + \left(g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right)\right\}$$

$$\xi = 4\Re\left\{g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL}\right\} + \left(|g^V_{LL}|^2 - |g^V_{RR}|^2\right) + 3\left(|g^V_{LR}|^2 - |g^V_{RL}|^2\right)$$
$$+5\left(|g^T_{LR}|^2 - |g^T_{RL}|^2\right) + \frac{1}{4}\left(|g^S_{LL}|^2 - |g^S_{RR}|^2 + |g^S_{RL}|^2 - |g^S_{LR}|^2\right)$$

$$\xi\delta = \frac{3}{16}\left(|g^S_{LL}|^2 - |g^S_{RR}|^2 + |g^S_{RL}|^2 - |g^S_{LR}|^2\right) + \frac{3}{4}\left(|g^V_{LL}|^2 - |g^V_{RR}|^2 - |g^T_{LR}|^2\right.$$
$$\left. + |g^T_{RL}|^2 + \Re\left\{g^S_{LR}g^{T*}_{LR} - g^S_{RL}g^{T*}_{RL}\right\}\right)$$

MP parameters through coupling constants (2)

$$\xi' = -\Big[3\left(|g^T_{RL}|^2 - |g^T_{LR}|^2\right) + \left(|g^V_{RR}|^2 + |g^V_{RL}|^2 - |g^V_{LR}|^2 - |g^V_{LL}|^2\right) + \frac{1}{4}\left(|g^S_{RR}|^2 + |g^S_{RL}|^2 - |g^S_{LR}|^2 - |g^S_{LL}|^2\right)\Big]$$

$$\xi'' = 1 - \frac{1}{2}\left(|g^S_{RL}|^2 + |g^S_{LR}|^2\right) + 2\left(|g^V_{RL}|^2 + |g^V_{LR}|^2 + |g^T_{RL}|^2 + |g^T_{LR}|^2\right) + 4\Re\left\{g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR}\right\}$$

$$\eta'' = \frac{1}{2}\Re\left\{3g^V_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right) + 3g^V_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right) - \left(g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right)\right\}$$

$$\frac{\alpha'}{A} = \frac{1}{2}\Im\left\{g^V_{LR}\left(g^{S*}_{RL} + 6g^{T*}_{RL}\right) - g^V_{RL}\left(g^{S*}_{LR} + 6g^{T*}_{LR}\right)\right\}$$

$$\frac{\beta'}{A} = \frac{1}{4}\Im\left\{g^V_{RR}g^{S*}_{LL} - g^V_{LL}g^{S*}_{RR}\right\}$$

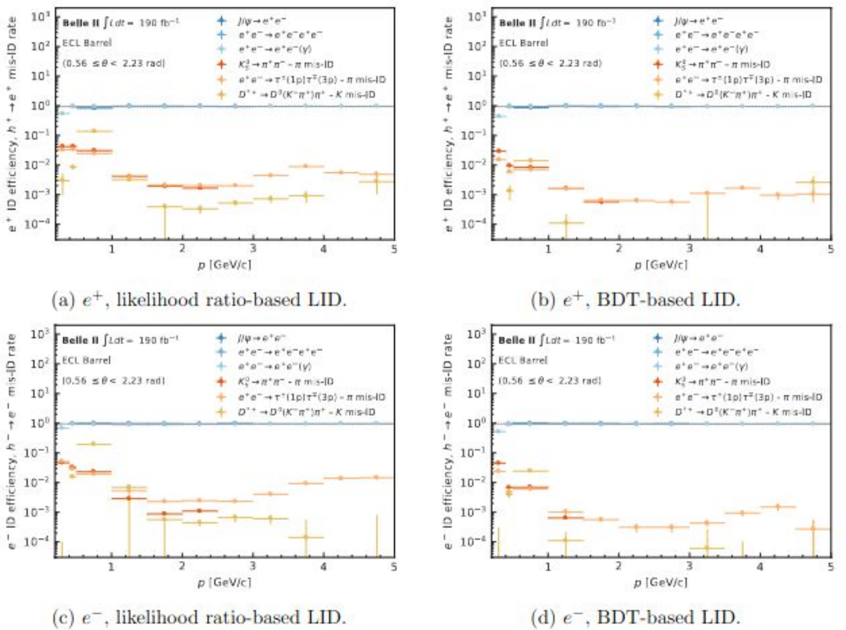

FIG. 26: Electron identification performance in data: efficiencies and pion, kaon mis-identification probabilities from the various channels are shown as a function of p_{lab} in the ECL barrel region. Results for the likelihood ratio-based lepton ID are on the left, and for the BDT-based lepton ID are on the right. The top row shows the results for positively charged tracks, and the bottom row for negatively charged tracks. The selection criteria for the lepton ID variables are tuned in MC to achieve 95% electron identification efficiency, uniform across the bins shown.

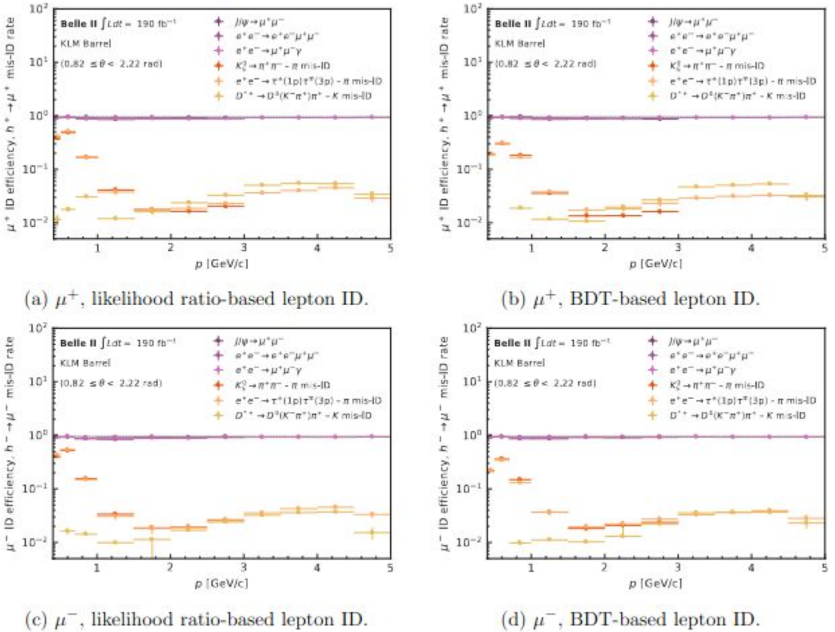

FIG. 27: Muon identification performance in data: efficiencies and pion, kaon mis-identification probabilities from the various channels are shown as a function of p_{lab} in the ECL barrel region. Results for the likelihood ratio-based lepton ID are on the left, and for the BDT-based lepton ID are on the right. The top row shows the results for positively charged tracks, and the bottom row for negatively charged tracks. The selection criteria for the lepton ID variables are tuned in MC to achieve 95% muon identification efficiency, uniform across the bins shown.

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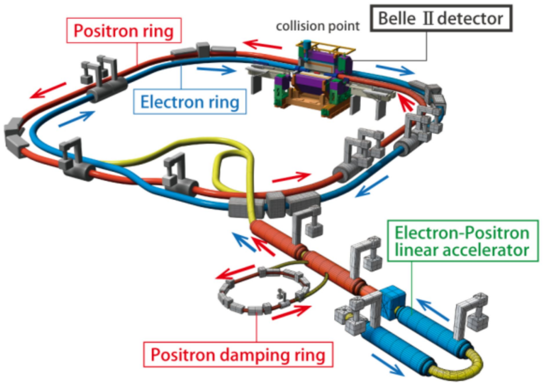
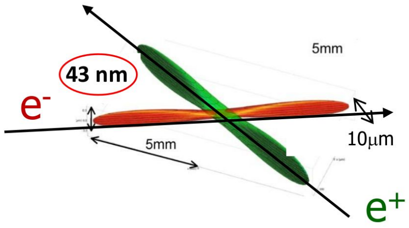
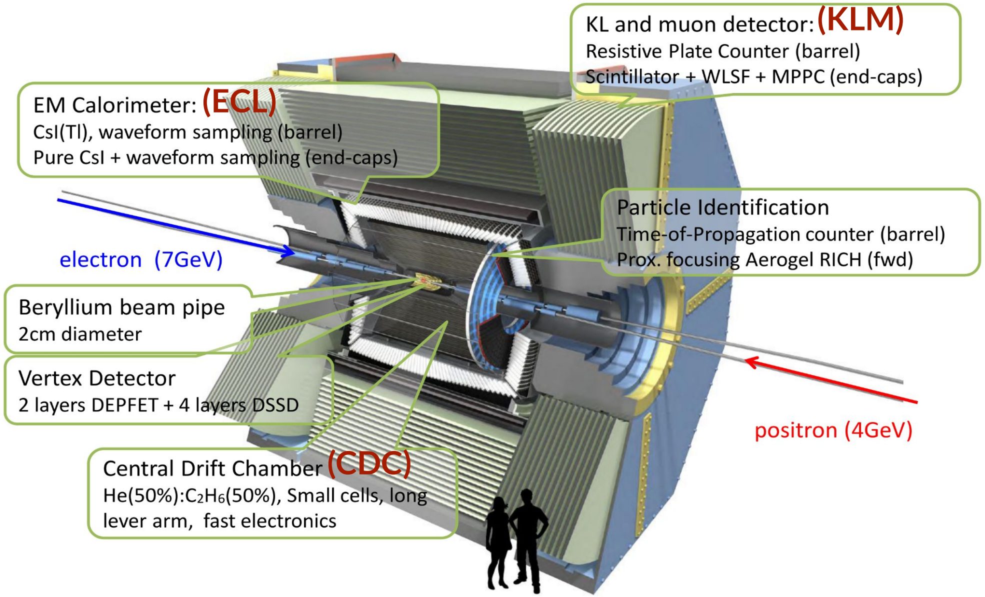


SuperKEKB accelerator @Tsukuba, Japan



$$V_{thrust} \overset{max}{=} \frac{\sum_i |\vec{p}_i^{\,\mathrm{CM}} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i^{\,\mathrm{CM}}|}$$

Belle II detector



» [arXiv:1011.0352 (Technical Design Report)]