Measurements of Michel parameters and tests of lepton universality in $\tau$ 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/c$^2$

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

○ Belle: 988 fb$^{-1}$ → $\sim 908$ million τ pairs
○ Belle II: 424 fb$^{-1}$ → $\sim 390$ 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 $2.1 \times 10^{34}$ (KEKB, achieved) → $6.0 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ (SuperKEKB, design)
- so far SuperKEKB achieved $4.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (current world record)

**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

Challenge: increased beam backgrounds and trigger rates

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:

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

- 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 \( g_{\ell\ell}^V = 1 \))

- deviations can be caused by anomalous coupling with the W-boson, new gauge or charged Higgs bosons, presence of massive neutrinos [1]

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

Scalar \hspace{1cm} Vector \hspace{1cm} Tensor

Measurement of Michel parameters at Belle

\[
\frac{d^2\Gamma}{dx\,d\cos\theta} = \frac{m_\tau^2}{4\pi^3} W_{\ell\tau}^4 G_F^2 \sqrt{x^2 - x_0^2} \left( F_{IS}(x) \pm F_{AS}(x) P_\tau \cos\theta + F_{T1}(x) P_\tau \sin\theta \xi_1 \right. \\
+ \left. F_{T2}(x) P_\tau \sin\theta \xi_2 + (\pm F_{IP}(x) + F_{AP}(x) P_\tau \cos\theta) \xi_3 \right)
\]

\[ W_{\ell\tau} = \max E_\ell = \frac{m_\ell^2 + m_\tau^2}{2m_\tau}, \quad x = \frac{E_\ell}{\max E_\ell}, \quad x_0 = \frac{m_\ell}{\max E_\ell}, \quad P_\tau = |P_\tau| \]

- ongoing analysis for $\rho, \eta, \xi$ and $\xi \delta$ in $\tau$ 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 $\tau$-decays [2]

- first direct measurement of $\xi'$ in $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ [3]


| Michel parameters and their most accurate determinations [4] |
|---------------------------|---------------------------|---------------------------|---------------------------|
| $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ | $\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$ | $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$ | SM |
| $\rho$ | 0.74979 ± 0.00026 | 0.747 ± 0.010 | 0.763 ± 0.020 | 0.75 |
| $\eta$ | 0.057 ± 0.034 | - | 0.094 ± 0.073 | 0 |
| $\xi$ | 1.0009$_{-0.0007}^{+0.0016}$ | 0.994 ± 0.040 | 1.030 ± 0.059 | 1 |
| $\xi \delta$ | 0.7511$_{-0.0006}^{+0.0012}$ | 0.734 ± 0.028 | 0.778 ± 0.037 | 0.75 |
| $\xi'$ | 1.00 ± 0.04 | - | 0.22 ± 1.03 | 1 |
| $\xi''$ | 0.98 ± 0.04 | - | - | 1 |

- [4] PTEP 2022 (2022) 083C01
First measurement of the Michel parameter $\xi'$ in the $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ 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 \( K \rightarrow \pi \)
- main background sources are two body decays of \( K \) and \( \pi \)
- BDT is used to suppress background by 50 times with the signal efficiency \( \varepsilon_{\text{sig}} \approx 80\% \)
Result

- 2D unbinned likelihood fit using $y$ and $\cos\theta_e$
- histogram is signal, filled area is the background function
- the measured value is $\xi' = 0.22 \pm 0.94 \text{ (stat)} \pm 0.42 \text{ (syst)}$ [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

» [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 $\mu$-e universality by measuring

$$
\left( \frac{g_\mu}{g_e} \right)_\tau = \sqrt{ \frac{B(\tau^- \to \nu_{\tau} \mu^- \bar{\nu}_\mu(\gamma))}{B(\tau^- \to \nu_{\tau} e^- \bar{\nu}_e(\gamma))} \frac{f(m_e^2/m_\mu^2)}{f(m_\mu^2/m_\tau^2)} } \\
\text{sensitivity to new physics if it violates}
$$

- ratio of leptonic branching fractions

$$
R_\mu \equiv \frac{B(\tau^- \to \nu_{\tau} \mu^- \bar{\nu}_\mu(\gamma))}{B(\tau^- \to \nu_{\tau} e^- \bar{\nu}_e(\gamma))} \overset{\text{SM}}{=} 0.9726
$$

is sensitive to new physics if it violates

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

\[ f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \] \[ \text{[1]} \]
Event topology

using 1-prong decays with one charged hadron and at least one \( \pi^0 \) on the tag side

- large BF (\( \sim 35\% \)), low backgrounds, high trigger efficiency

- **Signal side selection**
  - 1 track: particle ID requirement (\( \mu \) or e)

- **Tag side selection**
  - 1 track: \( E_{\text{cluster}} / p < 0.8 \)
  - \( N(\pi^0)_{\text{tag}} > 0 \)

**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 \( \mu \) sample
  - thrust value
  - thrust axis \( \theta \)
  - total visible energy (CMS)
  - missing momentum: \( p_T, \theta \) (CMS)
  - tag side: \( p, \theta, M \) (CMS)
- restrict analysis to region least sensitive to particle ID systematics
  - \( 0.82 < \theta_{\text{lepton}} < 2.13 \) (barrel of muon detector)
  - \( 1.5 \text{ GeV} < p_{\text{lepton}} < 5.0 \text{ GeV} \)
- 94% purity @ 9.6% signal efficiency for combined e+\( \mu \) sample
  - \( e^+e^- \rightarrow \tau^+\tau^- \) (\( \pi^\pm \) faking \( \mu^\pm/e^\pm \)): \( \sim 3.3\% \)
  - \( e^+e^- \rightarrow \tau^+\tau^- \) (wrong tag): \( \sim 2.3\% \)
  - \( e^+e^- \rightarrow e^+e^-\tau^+\tau^- \): 0.2%
$R_\mu$ extraction

- measure $R_\mu$ 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 $\mu$ 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.: $J/\psi \rightarrow \ell^+\ell^-$, $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$ and $e^+e^- \rightarrow \ell^+\ell^- (\gamma)$
    - $e/\mu$ eff.: 99.7% / 93.9%
  - fakes: $K_S^0 \rightarrow \pi^+\pi^-$ and $\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu_\tau$
    - $\pi \rightarrow e/\mu$: 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
  - $\epsilon = 99.8\%$ for $\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$ and $\epsilon = 96.6\%$ for $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged-particle identification:</td>
<td></td>
</tr>
<tr>
<td>Electron identification</td>
<td>0.22</td>
</tr>
<tr>
<td>Muon misidentification</td>
<td>0.19</td>
</tr>
<tr>
<td>Electron misidentification</td>
<td>0.12</td>
</tr>
<tr>
<td>Muon identification</td>
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</tr>
<tr>
<td>Trigger</td>
<td>0.10</td>
</tr>
<tr>
<td>Imperfections of the simulation:</td>
<td></td>
</tr>
<tr>
<td>Modelling of FSR</td>
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</tr>
<tr>
<td>Normalisation of individual processes</td>
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<tr>
<td>Modelling of the momentum distribution</td>
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</tr>
<tr>
<td>Tag side modelling</td>
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<tr>
<td>$\pi^0$ efficiency</td>
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<tr>
<td>Modelling of ISR</td>
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<tr>
<td>Photon efficiency</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Photon energy</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Size of the samples</td>
<td></td>
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<tr>
<td>Simulated samples</td>
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</tr>
<tr>
<td>Luminosity</td>
<td>0.01</td>
</tr>
<tr>
<td>Charged-particle reconstruction:</td>
<td></td>
</tr>
<tr>
<td>Particle decay-in-flight</td>
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</tr>
<tr>
<td>Tracking efficiency</td>
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</tr>
<tr>
<td>Detector misalignment</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Momentum correction</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Total</td>
<td>0.37</td>
</tr>
</tbody>
</table>

relative systematic uncertainties of $R_\mu$
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 $R_\mu = 0.9675 \pm 0.0037$
  - statistical uncertainty 0.0007
  - systematic uncertainty 0.0036
- consistent with SM expectation at the level of 1.4 sigma
**Result**

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

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

Summary

- Belle data (988 fb$^{-1}$) is still being actively analysed
  - first measurement of the Michel parameter $\xi'$ using a novel method
- Belle II recorded 424 fb$^{-1}$ so far, resuming data taking soon
- new results for test of $\mu$-e universality
  - world’s best determination from single measurement
  - similar systematics as BaBar measurement
- more ($\tau$) physics to come from Belle/Belle II
backup slides
Radiative and five-body leptonic $\tau$ decays

- Radiative and five-body leptonic $\tau$-decays provide information about Michel parameters that describe daughter lepton polarization in $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_{\tau}$

- Their understanding is also crucial for LFV studies as they are main background

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

Belle collaboration measured $\xi \kappa(\ell) = -0.4 \pm 1.2$, $\xi \kappa(\mu) = 0.8 \pm 0.6$, and $\bar{\eta}(\mu) = -1.3 \pm 1.7$ ($\mathcal{L} = 711 \text{ fb}^{-1}$)

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>SM Br</th>
<th>Measured</th>
<th>Expected N</th>
<th>Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow e^- e^+ e^- \bar{\nu}<em>e \nu</em>{\tau}$</td>
<td>$(4.21 \pm 1.5) \times 10^{-5}$</td>
<td>$(1.8 \pm 1.5) \times 10^{-5}$</td>
<td>$1300 (r_s = 47%)$</td>
<td>$(6 - 12)%$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- e^+ \mu^- \bar{\nu}<em>e \nu</em>{\tau}$</td>
<td>$(1.984(4) \times 10^{-5})$</td>
<td>$&lt;3.2 \times 10^{-5}$</td>
<td>$430 (r_s = 50%)$</td>
<td>$(8 - 13)%$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^- \mu^+ \mu^- \bar{\nu}<em>e \nu</em>{\tau}$</td>
<td>$(1.247(1) \times 10^{-7})$</td>
<td>NM</td>
<td>8 ($r_s = 37%)$</td>
<td>$(36 - 72)%$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \mu^+ \mu^- \bar{\nu}<em>e \nu</em>{\tau}$</td>
<td>$(1.183(1) \times 10^{-7})$</td>
<td>NM</td>
<td>4 ($r_s = 16%)$</td>
<td>$(36 - 72)%$</td>
</tr>
</tbody>
</table>

Denis Bodrov

Tau physics program at Belle II
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 \( e^+e^- \rightarrow \tau^+\tau^- \):

\[
\frac{d\sigma(e^+e^-\rightarrow \tau^\pm\tau^-)}{d\Omega_{\tau}} = \frac{\alpha^2\beta}{64E^2} \left[ A_0 + D_\beta(\vec{s}_{\text{sig}})(\vec{s}_{\text{tag}}) \right]
\]

\[
A_0 = 1 + \cos^2 \theta_\tau + \frac{\sin^2 \theta_\tau}{\gamma^2}, \quad D_\beta = \begin{pmatrix}
\left(1 + \frac{1}{\gamma^2}\right) \sin^2 \theta_\tau & 0 & \frac{1}{\gamma} \sin 2\theta_\tau \\
0 & -\beta^2 \sin^2 \theta_\tau & 0 \\
\frac{1}{\gamma} \sin 2\theta_\tau & 0 & 1 + \cos^2 \theta_\tau \frac{\sin^2 \theta_\tau}{\gamma^2}
\end{pmatrix}
\]

- One can use tagging τ lepton as a spin analyzer with the decay mode \( \tau^+ \rightarrow \pi^+\pi^0\nu_\tau \). This mode has the largest branching fraction (around 25% ), and it is also well-studied.
Leptonic differential decay width
parametric functions definition

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

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

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

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

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

\[ F_{T_2}(x) = \frac{1}{3} \sqrt{x^2 - x_0^2} \left( \frac{3}{A} \alpha' (1-x) + \frac{\beta'}{A} (2-x^2) \right) \]
\[
\rho = \frac{3}{4} - \frac{3}{4} \left[ \left( |g_{RL}^V|^2 + |g_{LR}^V|^2 \right) + 2 \left( |g_{LR}^T|^2 + |g_{RL}^T|^2 \right) + \Re \left\{ g_{RL}^S g_{RL}^{T \ast} + g_{LR}^S g_{LR}^{T \ast} \right\} \right] \\
\eta = \frac{1}{2} \Re \left\{ g_{RL}^V \left( g_{LR}^{S \ast} + 6g_{LR}^{T \ast} \right) + g_{LR}^V \left( g_{RL}^{S \ast} + 6g_{RL}^{T \ast} \right) + \left( g_{RR}^S g_{LL}^{T \ast} + g_{LL}^S g_{RR}^{T \ast} \right) \right\} \\
\xi = 4 \Re \left\{ g_{LR}^S g_{LR}^{T \ast} - g_{RL}^S g_{RL}^{T \ast} \right\} + \left( |g_{LL}^V|^2 - |g_{RR}^V|^2 \right) + 3 \left( |g_{LR}^V|^2 - |g_{RL}^V|^2 \right) \\
+ 5 \left( |g_{LR}^T|^2 - |g_{RL}^T|^2 \right) + \frac{1}{4} \left( |g_{LL}^S|^2 - |g_{RR}^S|^2 + |g_{RL}^S|^2 - |g_{LR}^S|^2 \right) \\
\xi \delta = \frac{3}{16} \left( |g_{LL}^S|^2 - |g_{RR}^S|^2 + |g_{RL}^S|^2 - |g_{LR}^S|^2 \right) + \frac{3}{4} \left( |g_{LL}^V|^2 - |g_{RR}^V|^2 - |g_{LR}^V|^2 \right) \\
+ |g_{RL}^T|^2 + \Re \left\{ g_{LR}^S g_{RL}^{T \ast} - g_{RL}^S g_{RL}^{T \ast} \right\} 
\]
\[ \xi' = -\left[ 3 \left( |g_{RL}^T|^2 - |g_{LR}^T|^2 \right) + \left( |g_{RR}^V|^2 + |g_{RL}^V|^2 - |g_{LR}^V|^2 - |g_{LL}^V|^2 \right) \right. \\
\left. + \frac{1}{4} \left( |g_{RR}^S|^2 + |g_{RL}^S|^2 - |g_{LR}^S|^2 - |g_{LL}^S|^2 \right) \right] \]

\[ \xi'' = 1 - \frac{1}{2} \left( |g_{RL}^S|^2 + |g_{LR}^S|^2 \right) + 2 \left( |g_{RL}^V|^2 + |g_{LR}^V|^2 + |g_{RL}^T|^2 + |g_{LR}^T|^2 \right) \\
+ 4 \Re \left\{ g_{RL}^S g_{RL}^T \bar{g}_{LR}^S \bar{g}_{LR}^T \right\} \]

\[ \eta'' = \frac{1}{2} \Re \left\{ 3g_{RL}^V (g_{LR}^S + 6g_{LR}^T) + 3g_{LR}^T (g_{RL}^S + 6g_{RL}^T) - (g_{RR}^V g_{LL}^S + g_{LL}^V g_{RR}^S) \right\} \]

\[ \alpha' = \frac{1}{2} \Im \left\{ g_{LR}^V (g_{RL}^S + 6g_{RL}^T) - g_{RL}^S (g_{LR}^S + 6g_{LR}^T) \right\} \]

\[ \beta' = \frac{1}{4} \Im \left\{ g_{RR}^V g_{LL}^S - g_{LL}^V g_{RR}^S \right\} \]
FIG. 26: Electron identification performance in data: efficiencies and pion, kaon mis-identification probabilities from the various channels are shown as a function of $p_{\text{lab}}$ 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 $p_{\text{lab}}$ 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.
SuperKEKB accelerator @Tsukuba, Japan

Belle II detector

KL and muon detector (KLM)
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter (ECL)
- CsI(Tl), waveform sampling (barrel)
- Pure CsI + waveform sampling (end-caps)

Particle Identification
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (fwd)

Central Drift Chamber (CDC)
- He(50%):C₂H₆(50%), Small cells, long lever arm, fast electronics

Vertex Detector
- 2 layers DEPFET + 4 layers DSSD

Beryllium beam pipe
- 2cm diameter

Electron (7GeV)

Positron (4GeV)

\[ V_{\text{thrust}} = \max \sum_i |\vec{p}_i^{\text{CM}} \cdot \hat{n}_{\text{thrust}}| \]

\[ \sum_i |\vec{p}_i^{\text{CM}}| \]