Overview of worldwide efforts in the search for charged lepton flavour violation
(with special emphasis on muon based searches)

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Paul Scherrer Institute, Switzerland
Content

• Introduction:
  • Charged Lepton flavour motivation
  • The role of low energy physics, precision measurements and its complementary counter part at high energy colliders
  • Overview of current experimental activities based muon-beams, B-Factories, hadron productions and LHC experiments
    • MEGII @PSI, Mu3e @PSI, Mu2e @Fermilab, COMET @JPARC
    • BelleII@SuperKEKB (ref. CLEO, BABAR and BELLE)
    • BESIII@BEPCII
    • LHCb, ATLAS, CMS and NA62 @ CERN
The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory

- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale
Charged lepton flavour violation
Charged lepton flavour violation

• Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)
Neural lepton flavour violation

\[ \Delta N_i \neq 0 \text{ with } i = 1,2,3 \]
Charged lepton flavour violation

• Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)
  Neutral lepton flavour violation

\[ \Delta N_i \neq 0 \quad \text{with } i = 1,2,3 \]

• Charged lepton flavour violation: NOT yet observed
cLFV searches: Many channels

- A wide field of research
  - LVF decays of leptons
  - Muon-to-electron conversion
  - LVF in meson decays
cLFV search landscape

- **Muons** (~250)
  - MEG, PSI
  - MEGII, PSI
  - Mu3e, PSI
  - DeeMee, J-PARC
  - MuSiC, Osaka
  - Mu2e, FNAL
  - COMET, J-PARC
  - PROJECT X, FNAL
  - PRIME, J-PARC

- **Kaons** (~100)
  - NA48, CERN
  - NA62, CERN
  - KOTO, J-PARC

- **Taus** (~250)
  - BABAR, PEPII
  - BELLE/BELLE II, KEKB/SuperKEKB

- **cLFV @ LHC** (~250)
  - ATLAS, CERN
  - CMS, CERN
  - LHCb, CERN

- **J/ψ @ BEPCII** (~100)
  - BESIII, Beijing

Rough estimate of numbers of researchers, in total ~ 850 (with some overlap)
Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

\[ B(\mu^+ \rightarrow e^+\gamma) \approx 10^{-54} \]

too small to access experimentally

BSM

\[ B(\mu^+ \rightarrow e^+\gamma) \gg 10^{-54} \]

an experimental evidence:

a clear signature of New Physics NP

(SM background FREE)

Current upper limits on \( B_i \)

SM

0 \( \rightarrow \) 10\(^{-50} \)

New Physics

10\(^{-13} \) \( \rightarrow \) 10\(^{-10} \)

\[ B_i = \frac{\Gamma_i}{\Gamma_{tot}} \]
Charged lepton flavour violation search: Motivation

\[ \mu^+ \rightarrow e^+e^+e^- \]

New particles

Current upper limits on \( B_i \)

\[ B_i = \frac{\Gamma_i}{\Gamma_{tot}} \]

SM

New Physics

\[ \begin{array}{cccc}
0 & 10^{-50} & 10^{-40} & 10^{-30} & 10^{-20} & 10^{-13} & 10^{-10} & 10^0 \\
\end{array} \]
Charged lepton flavour violation search: Motivation

\[ \mu^+ \rightarrow e^+ e^+ e^- \]

Current upper limits on \( B_i \)

\[ B_i = \frac{\Gamma_i}{\Gamma_{tot}} \]

New Physics
Charged lepton flavour violation search: Motivation

\[ \mu^- N \rightarrow e^- N \]

Current upper limits on \( B_i \)

\[ B_i = \frac{\Gamma_i}{\Gamma_{tot}} \]

New particles

New Physics
Charged lepton flavour violation search: Motivation

**Current upper limits on** $B_i$

$B_i = \frac{\Gamma_i}{\Gamma_{tot}}$

0  $10^{-50}$  $10^{-40}$  $10^{-30}$  $10^{-20}$  $10^{-13}$  $10^{-10}$  $10^0$

**SM**

**New Physics**

**New particles**
Charged lepton flavour violation search: Motivation

Current upper limits on $B_i$:

$B_i = \frac{\Gamma_i}{\Gamma_{tot}}$

New Physics

New particles
Complementary to “Energy Frontier”

Energy frontier

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} O^{(d)} \]

Unveil new physics

Probe energy scale otherwise otherwise unreachable

\( E > 1000 \text{ TeV} \)
cLFV searches with muons: Status and prospects

<table>
<thead>
<tr>
<th>Process</th>
<th>Current upper limit</th>
<th>Future sensitivity</th>
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<tbody>
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<td>$\mu \to e\gamma$</td>
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<td>$7.0 \times 10^{-13}$</td>
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Cosmic rays
Stopped $\pi$
Beams
cLFV searches with muons: Status and prospects

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![Graph showing cLFV search results]
cLFV searches with muons: Status and prospects

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In the near future O(5-10) years: Impressive sensitivity
cLFV searches with muons: Status and prospects

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- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV.
Due to the extremely-low accessible branching ratios, muon cLFV can strongly constrain new physics models and scales.

**Model independent lagrangian**

\[
\begin{align*}
\frac{m_\mu}{(\kappa + 1)\Lambda^2} \times & \quad + \quad \frac{\kappa}{(\kappa + 1)\Lambda^2} \times \\
\text{dipole term} & \quad \text{contact term}
\end{align*}
\]

- $\mu \rightarrow e\gamma$
- $\mu \rightarrow eee$
- $\mu N \rightarrow eN$
cLFV searches with muons: Status and prospects

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- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV.
Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world’s highest beam intensities

DC or Pulsed?

- DC beam for coincidence experiments
  - $\mu \rightarrow e \gamma$, $\mu \rightarrow e e e$

- Pulse beam for non-coincidence experiments
  - $\mu$-e conversion

@ PSI

$\approx 20 \, \text{ns}$

@ JPARC, FERMILAB

$1-2 \, \mu$s
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  - $\mu$-e conversion

@ PSI

\[ I_{beam} \sim 10^8 - 10^{10} \mu/s \]

\sim 20 \text{ ns}

@ JPARC, FERMILAB

\[ I_{beam} \sim 10^{11} \mu/s \]

\[ 1-2 \mu s \]

Muon Decay In Orbit

nuclear muon capture
The world’s most intense continuous muon beam

• PSI delivers the most intense continuous low momentum muon beam in the world (Intensity Frontiers)

• MEG/MEG II/Mu3e beam requirements:
  • Intensity $O(10^8 \, \text{muon/s})$, low momentum $p = 29 \, \text{MeV/c}$
  • Small straggling and good identification of the decay region

• $\tau$ ideal probe for NP w. r. t. $\mu$
  • Smaller GIM suppression
  • Stronger coupling
  • Many decays

• $\mu$ most sensitive probe
  • Huge statistics

590 MeV proton ring cyclotron

1.4 MW

PSI landscape
MEG: Signature, experimental setup and result

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $\text{BR}(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables $(E_g, E_e, t_{eg}, \vartheta_{eg}, \phi_{eg})$ to characterize $\mu \rightarrow e \gamma$ events

Full data sample: 2009-2013
Best fitted branching ratio at 90% C.L.:

$$\mathcal{B}(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}$$
The MEGII experiment

New electronics: Wavedream

~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam

Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

35 ps resolution w/ multiple hits

Full available stopped beam intensity $7 \times 10^7$

Liquid xenon photon detector (LXe)

COBRA superconducting magnet

Radiative decay counter (RDC)

Cylindrical drift chamber (CDCH)

Pixelated timing counter (pTC)

Muon stopping target

Background rejection

Single volume He:iC$_4$H$_{10}$
Where we will be

$\sim 6 \times 10^{-14}$

MEG

MEGII
Where we are: Pre-engineering run ongoing

- All sub-detector installed
Where we are: Pre-engineering run ongoing
Mu3e: The $\mu^+ \rightarrow e^+ e^+ e^-$ search

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (Phase I) up to down $\sim 10^{-16}$ (Phase II). Previous upper limit $\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment.
- Observables ($E_e$, $t_e$, vertex) to characterize $\mu \rightarrow eee$ events.

**Signature**

- $\Delta t_{eee} = 0$
- $\Sigma p_e = 0$
- $\Sigma E_e = m_\mu$

**Background**
The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet
Homogeneous field 1T

Tile detector
70 ps resolution w/ single hit

Fibre hodoscope
< 500 ps resolution w/ multi hits
thickness: < 0.3% X₀

MIDAS DAQ and Slow Control
Run, history, alarms, HV etc.

Mupix detector

Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X₀

Muon Beam and target
Full available beam intensity O(10⁸)
The Mu3e experiment: R&D completed. Prototyping phase

- Mupix detector
- Tile detector: 70 ps resolution w/ single hit
- Fibre hodoscope: < 500 ps resolution w/ multi hits, thickness: < 0.3% X₀
- Superconducting solenoid Magnet
- Homogeneous field 1T
- MIDAS DAQ and Slow Control: Run, history, alarms, HV etc.
- Mupix detector: Tracking, integrate sensor and readout in the same device: 50 um thick, 1 layer: ~ 0.1% X₀
- Muon Beam and target: Full available beam intensity O(10⁸)
The MEGII and Mu3e experimental area: Pictures

- Beam: Delivered $8 \times 10^7$ muon/s via the CMBL
- Infrastructure ready

Overview piE5 area

Mu3e control room
Mu3e Phase I sensitivity

- Different signal BR
- Combinatorial Bkg
- Irreducible Bkg
- Additional suppression due to Timing detectors
Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world’s highest beam intensities

**DC or Pulsed?**

- DC beam for coincidence experiments
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- Pulse beam for non-coincidence experiments
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@ PSI
$I_{\text{beam}} \sim 10^8 - 10^{10} \mu/s$

@ JPARC, FERMILAB
$I_{\text{beam}} \sim 10^{11} \mu/s$

Muon Decay In Orbit

Nuclear muon capture
μ⁻ N → e⁻ N experiments

- Signal of mu-e conversion is single mono-energetic electron

\[ R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)} \]

- Background: Any event at the endpoint energy can mimic the signal

---

Free muon decay

\[ E_e = m_\mu c^2 - (\text{B.E.})_{1S} - E_{\text{recoil}} \]

\[ E_e = m_\mu c^2 - (\text{B.E.})_{1S} - E_{\text{recoil}} = 104.96 \text{ MeV} \]

\[ E_e(\text{max}) = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV} \]

Conversion electron energy

OIO shape
\( \mu^- N \rightarrow e^- N \) experiments

- Signal of mu-e conversion is single mono-energetic electron

\[
R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}
\]

- Background: Any event at the endpoint energy can mimic the signal

@ the endpoint

\( \frac{R(DIO)}{R(\text{stopped-}\mu)} \approx 39\% \)
The two giants campus delivering astonishing intense pulsed muon beams

Fermilab

- **Booster** provides 8 GeV protons to the **Recycler**
- **Recycler** stacks protons into 4 bunches
- **Delivery Ring** takes 1 out of every 4 bunches from the **Recycler**
- **Mu2e** slow extracts protons every 1695 ns

JPARC

- **Bunched** 8 GeV protons extracted from the Main Ring and delivered to the pion target production inside a capture solenoid
- **Muons** are charge and momentum selected using curved superconducting solenoids
\( \mu^- N \rightarrow e^- N \) experiments

- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! \( O(10^{18}) \)
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Use timing to reject beam backgrounds (extinction factor \( 10^{-10} \))
  - Pulsed proton beam 1.7 \( \mu \)s between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays

![Data acquisition gate and Selection Window diagram]
The Mu2e experiment

- Three superconducting solenoids: Production, Transport and Detector solenoids
- Muons stop in thin aluminum foils
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID
- Scintillators for the Veto

Talk: S. Di Falco

\[ B_z = 4.5T \quad 2.5T \quad 2.0T \quad 1.0T \]
The Mu2e experiment

- **Proton absorber:**
  - made of high-density polyethylene
  - designed in order to reduce proton flux on the tracker and minimize energy loss

- **Tracker:**
  - ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
  - Expected momentum resolution < 200 keV/c

- **Targets:**
  - 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (864 ns) that matches nicely the need of prompt separation in the Mu2e beam structure.

- **Calorimeter:**
  - 2 disks composed of undoped CsI crystals

- **Muon beam stop:**
  - made of several cylinders of different materials: stainless steel and polyethylene
The Mu2e experiment: Status

- **2021:** Detector and Beamline commissioning; **2022-2024:** Data taking
  - **Tracker:**
  - **Beamline and solenoids**
  - **Calorimeter:**
  - **Muon beam stob:**
  - **Cosmic Ray Veto**
The COMET experiment

- Stage phase approach: Phase I and Phase II

COMET phase I

- Cylindrical detector for CLFV measurement

COMET phase II

- Phase-II prototype for background characterisation
The COMET experiment: Status

- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]

COMET phase I

Trigger scintillators + Cerenkov detector

Trigger/DAQ/Analysis: in very good shape
Muon cLFV searches: Present and Future

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- Submitted inputs to the European Strategy Committee
DC and Pulsed muon beams - present and future

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Beam Line</th>
<th>DC rate (μ/sec)</th>
<th>Pulsed rate (μ/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI (CH) (590 MeV, 1.3 MW)</td>
<td>μE4, πE5</td>
<td>2 ÷ 4 × 10^8 (μ⁺)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HiMB at EH</td>
<td>O(10^{10}) (μ⁺) (&gt;2018)</td>
<td></td>
</tr>
<tr>
<td>J-PARC (Japan) (3 GeV, 210 kW)</td>
<td>MUSE D-Line</td>
<td>3 × 10^7 (μ⁺)</td>
<td>6.4 × 10^7 (μ⁺)</td>
</tr>
<tr>
<td></td>
<td>MUSE U-Line</td>
<td>1 × 10^{11} (μ⁻) (2020)</td>
<td></td>
</tr>
<tr>
<td>FNAL (USA) (8 GeV, 25 kW)</td>
<td>Mu2e</td>
<td>5 × 10^{10} (μ⁻) (2020)</td>
<td></td>
</tr>
<tr>
<td>TRIUMF (Canada) (500 MeV, 75 kW)</td>
<td>M13, M15, M20</td>
<td>1.8 ÷ 2 × 10^6 (μ⁺)</td>
<td></td>
</tr>
<tr>
<td>RAL-ISIS (UK) (800 MeV, 160 kW)</td>
<td>EC/RIKEN-RAL</td>
<td>7 × 10^4 (μ⁻)</td>
<td>6 × 10^5 (μ⁺)</td>
</tr>
<tr>
<td>KEK (Tskuba, Japan) (500 MeV, 25 kW)</td>
<td>Dai Omega</td>
<td>4 × 10^5 (μ⁺) (2020)</td>
<td></td>
</tr>
<tr>
<td>RCNP (Osaka, Japan) (400 MeV, 400 W)</td>
<td>MuSIC</td>
<td>10^4 (μ⁻) ÷ 10^5 (μ⁺)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10^2 (μ⁻) ÷ 10^8 (μ⁺) (&gt;2018)</td>
<td></td>
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<tr>
<td>JINR (Dubna, Russia) (660 MeV, 1.6 kW)</td>
<td>Phasotron</td>
<td>10^5 (μ⁺)</td>
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<tr>
<td>RISP (Korea) (600 MeV, 0.6 MW)</td>
<td>RAON</td>
<td>2 × 10^8 (μ⁺) (&gt;2020)</td>
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<tr>
<td>CSNS (China) (1.6 6eV, 4 kW)</td>
<td>HEPEA</td>
<td>1 × 10^8 (μ⁺) (&gt;2020)</td>
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The High intensity Muon Beam (HiMB) project at PSI

- **Aim:** $O(10^{10} \text{ muon/s})$; Surface (positive) muon beam ($p = 28 \text{ MeV/c}$); DC beam
- **Time schedule:** $O(2025)$
- **Put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**
DC and Pulsed muon beams - present and future
cLFV searches at B-factories

• B-factory are τ-factory at the same time
  • A lot of studies can be done:
    • tau physics: tau decays from tau pair production
    • b => ll's: LFV in B decays
tau-based cLFV searches

- B-factory are τ-factory at the same time
- Present and future prospects


~2 orders of magnitude lower (final statistics)
tau-based cLFV searches

- B-factory are $\tau$-factory at the same time
- Present and future prospects

\[ \text{~10}^{-2} \text{ (final statistics BELLE II)} \]
BELLE: A $\tau$-factory

- Belle, being an $e^+ e^-$ B-factory experiment, is a $\tau$-factory experiment at the same time.

- With nearly 1 billion $\tau^+ \tau^-$ sample, Belle has obtained the most stringent upper limits in most of the $\tau$ LFV, LNV and BNV decays, with 90% UL of $O(10^{-8})$.

<table>
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<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}$</th>
<th>$\sigma_{syst}$ (%)</th>
<th>$N_{obs}$</th>
<th>$s_{90}$</th>
<th>$B$ ($10^{-8}$)</th>
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<tr>
<td>$\tau^- \to \mu^-\pi^+\pi^-$</td>
<td>5.83</td>
<td>0.63 ± 0.23</td>
<td>5.7</td>
<td>0</td>
<td>1.87</td>
<td>2.1</td>
</tr>
<tr>
<td>$\tau^- \to \mu^+\pi^-\pi^-$</td>
<td>6.55</td>
<td>0.33 ± 0.16</td>
<td>5.6</td>
<td>1</td>
<td>4.01</td>
<td>3.9</td>
</tr>
<tr>
<td>$\tau^- \to e^-\pi^+\pi^-$</td>
<td>5.45</td>
<td>0.55 ± 0.23</td>
<td>5.7</td>
<td>0</td>
<td>1.94</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^- \to e^+\pi^-\pi^-$</td>
<td>6.56</td>
<td>0.37 ± 0.19</td>
<td>5.5</td>
<td>0</td>
<td>2.10</td>
<td>2.0</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-K^+K^-$</td>
<td>2.85</td>
<td>0.51 ± 0.19</td>
<td>6.1</td>
<td>0</td>
<td>1.97</td>
<td>4.4</td>
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<tr>
<td>$\tau^- \to \mu^+K^-K^-$</td>
<td>2.98</td>
<td>0.25 ± 0.13</td>
<td>6.2</td>
<td>0</td>
<td>2.21</td>
<td>4.7</td>
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<tr>
<td>$\tau^- \to e^-K^+K^-$</td>
<td>4.29</td>
<td>0.17 ± 0.10</td>
<td>6.7</td>
<td>0</td>
<td>2.29</td>
<td>3.4</td>
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<tr>
<td>$\tau^- \to e^+K^-K^-$</td>
<td>4.64</td>
<td>0.06 ± 0.06</td>
<td>6.5</td>
<td>0</td>
<td>2.39</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-\pi^+K^-$</td>
<td>2.72</td>
<td>0.72 ± 0.28</td>
<td>6.2</td>
<td>1</td>
<td>3.65</td>
<td>8.6</td>
</tr>
<tr>
<td>$\tau^- \to e^-\pi^+K^-$</td>
<td>3.97</td>
<td>0.18 ± 0.13</td>
<td>6.4</td>
<td>0</td>
<td>2.27</td>
<td>3.7</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-K^+\pi^-$</td>
<td>2.62</td>
<td>0.64 ± 0.23</td>
<td>5.7</td>
<td>0</td>
<td>1.86</td>
<td>4.5</td>
</tr>
<tr>
<td>$\tau^- \to e^-K^+\pi^-$</td>
<td>4.07</td>
<td>0.55 ± 0.31</td>
<td>6.2</td>
<td>0</td>
<td>1.97</td>
<td>3.1</td>
</tr>
<tr>
<td>$\tau^- \to \mu^+K^-\pi^-$</td>
<td>2.55</td>
<td>0.56 ± 0.21</td>
<td>6.1</td>
<td>0</td>
<td>1.93</td>
<td>4.8</td>
</tr>
<tr>
<td>$\tau^- \to e^+K^-\pi^-$</td>
<td>4.00</td>
<td>0.46 ± 0.21</td>
<td>6.2</td>
<td>0</td>
<td>2.03</td>
<td>3.2</td>
</tr>
</tbody>
</table>
The incoming future: Belle II

- With ~50 billion $\tau^+ \tau^-$ events expected in the upgraded Belle II experiment, B-physics searches will be greatly improved: LFUV involving B decays to $\tau$ [R(D), R(D*)]; LFUV, LFV involving EW penguin B decays [R(K), R(K*) for LFUV, $B \rightarrow K(*) \tau$, $K(*) e \mu$ etc. for LFV].
- For very clean modes (e.g. $\tau^+ \rightarrow e^+e^-\mu^+$), CLFV upper limits are expected to improve linearly with luminosity: They will be very powerful probes for new physics beyond the SM.
- First $\tau$ LFV sensitivity study:

<table>
<thead>
<tr>
<th>Belle (535 fb$^{-1}$)</th>
<th>Belle II (1 ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ (cm$^2$/s)</td>
<td>$2.11 \times 10^{34}$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{signal}}$</td>
<td>5.09%</td>
</tr>
<tr>
<td>$n_{\text{BG}}$</td>
<td>10</td>
</tr>
<tr>
<td>$B^{90}_{\tau \rightarrow \mu \gamma}$</td>
<td>$4.5 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Belle II (50 ab$^{-1}$)

**a naive extrapolation by luminosity**

$5.5 \times 10^{-10}$
Belle II

**EM Calorimeter:**
CsI(Tl), waveform sampling

**Beryllium beam pipe:**
2cm diameter

**Vertex Detector:**
2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber:**
He(50%):C₃H₆(50%), Small cells, long lever arm, fast electronics

**K_L and muon detector:**
Resistive Plate Counter (barrel outer layers), Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

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

**Electron (7GeV):**

**Positron (4GeV):**
Signal and backgrounds

- Major backgrounds differ among LFV channels

**LFV Signal**
- Neutrino(s) in tag side
- Particle ID
- Mass of mesons

**SM ττ**
- Neutrinos in both sides
- Missing energy in signal side

**2photon process**
- \( f = \text{leptons, quarks} \)

**q̅q**
- Many tracks

**radiative Bhabha**
BELLE II: Status

- Very reach physics potentiality (arXiv 1808.10567)
- Final goal: 40x KEKB Luminosity

All the details are in “The Belle II Physics Book” E. Kou, P. Urquijo et al.,

KEKB peak luminosity We are here Belle int. luminosity

B→η’Ks new CP
Confirm B→D*τν new physics
Resolve |V_{ub}| puzzle

τ LFV discovery
α,γ < 2°

WR in B→ργ
B→Kνν SM discovery
B→Kee LFUV new physics

ee→A'(χχ)γ
precision for (g-2)_μ

ee→ππ(γ) discovery
B→μν discovery
LVF K* \( l^+ l^- \) decays: Belle updated results

- Belle opened world best constraints of the LVF k* ll modes @ 90% C.L.
- Belle II will aim at an improved sensitivity of \( O(10^{-8}) \)

\[
\begin{align*}
\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) & < 1.2 \times 10^{-7} \\
\mathcal{B}(B^0 \rightarrow K^{*0} \mu^- \mu^+) & < 1.6 \times 10^{-7} \\
\mathcal{B}(B^0 \rightarrow K^{-0} \mu^+ \mu^-) & < 1.8 \times 10^{-7}
\end{align*}
\]

\textbf{arXiv:1807.03267}
Violations in $D^0 \rightarrow \text{hh’ll’}$: Babar updated results

- Updated analysis from the Babar experiment: arXiv 1905.00608v1
- Lepton flavour violating (LFV) and lepton number violating (LNV) processes
- No signal but improvements wrt the previous limits

### Lepton flavour violating (LFV)

$$\pi^+ \pi^- e^+ e^- \mu^- \mu^+ \quad K^- \pi^+ e^+ e^- \mu^- \mu^+ \quad K^- K^+ e^+ e^- \mu^- \mu^+$$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N_{\text{sig}}$ (candidates)</th>
<th>$\epsilon_{\text{sig}}$ (%)</th>
<th>$\mathcal{B}$ ($\times 10^{-7}$)</th>
<th>$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^- e^+ e^+$</td>
<td>$0.22 \pm 3.15 \pm 0.54$</td>
<td>4.38</td>
<td>$0.27 \pm 3.90 \pm 0.67$</td>
<td>9.1</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \mu^+ \mu^+$</td>
<td>$6.69 \pm 4.88 \pm 0.80$</td>
<td>4.91</td>
<td>$7.40 \pm 5.40 \pm 0.91$</td>
<td>15.2</td>
</tr>
<tr>
<td>$\pi^+ \pi^- e^+ \mu^+$</td>
<td>$12.42 \pm 5.30 \pm 1.45$</td>
<td>4.38</td>
<td>$15.4 \pm 6.59 \pm 1.85$</td>
<td>30.6</td>
</tr>
<tr>
<td>$\pi^+ \pi^+ e^- \mu^+$</td>
<td>$1.37 \pm 6.15 \pm 1.28$</td>
<td>4.79</td>
<td>$1.55 \pm 6.97 \pm 1.45$</td>
<td>17.1</td>
</tr>
<tr>
<td>$K^- \pi^+ e^+ e^+$</td>
<td>$-0.23 \pm 0.97 \pm 1.28$</td>
<td>3.19</td>
<td>$-0.38 \pm 1.60 \pm 2.11$</td>
<td>5.0</td>
</tr>
<tr>
<td>$K^- \pi^- \mu^+ \mu^+$</td>
<td>$-0.03 \pm 2.10 \pm 0.40$</td>
<td>3.30</td>
<td>$-0.05 \pm 3.34 \pm 0.64$</td>
<td>5.3</td>
</tr>
<tr>
<td>$K^- \pi^+ e^- e^+$</td>
<td>$3.87 \pm 3.96 \pm 2.36$</td>
<td>3.48</td>
<td>$5.84 \pm 5.97 \pm 3.56$</td>
<td>21.0</td>
</tr>
<tr>
<td>$K^- \pi^+ e^+ \mu^+$</td>
<td>$2.52 \pm 4.60 \pm 1.35$</td>
<td>3.65</td>
<td>$3.62 \pm 6.61 \pm 1.95$</td>
<td>19.0</td>
</tr>
<tr>
<td>$K^- K^- e^+ e^+$</td>
<td>$0.30 \pm 1.08 \pm 0.41$</td>
<td>3.25</td>
<td>$0.43 \pm 1.54 \pm 0.58$</td>
<td>3.4</td>
</tr>
<tr>
<td>$K^- K^- \mu^+ \mu^+$</td>
<td>$-1.09 \pm 1.29 \pm 0.42$</td>
<td>6.21</td>
<td>$-0.81 \pm 0.96 \pm 0.32$</td>
<td>1.0</td>
</tr>
<tr>
<td>$K^- K^- e^+ \mu^+$</td>
<td>$1.93 \pm 1.92 \pm 0.83$</td>
<td>4.63</td>
<td>$1.93 \pm 1.93 \pm 0.84$</td>
<td>5.8</td>
</tr>
<tr>
<td>$K^- K^+ e^+ \mu^+$</td>
<td>$4.09 \pm 3.00 \pm 1.59$</td>
<td>4.83</td>
<td>$3.93 \pm 2.89 \pm 1.45$</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Previous best limit ($\times 10^{-7}$):
- $1120$
- $290$
- $790$
- $150$
- $2060$
- $3900$
- $2180$
- $5330$
- $1520$
- $950$
- $570$
- $1800$
The BESIII experiment at BEPCII in Beijing is designed to provide a comprehensive world-class physics program in the charm threshold region.

Beam energy: 1-2.3 GeV  
Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$  
Optimum energy: 1.89 GeV  
Energy spread: $5.16 \times 10^{-4}$  
No. of bunches: 93  
Bunch length: 1.5 cm  
Total current: 0.91 A  
SR mode: 0.25A @ 2.5 GeV
cLFV via $J/\psi \rightarrow e\mu$ at BESIII

- With the world largest $e^+ e^-$ annihilation $J/\psi$ data including more than 225 million $J/\psi$ events, the BESIII collaboration got the leading upper limit on $J/\psi \rightarrow e\mu$ decay.

- Event topology: two opposite, back-to-back, charged tracks, no obvious extra EMC showers. Most of the backgrounds are from $J/\psi \rightarrow e^+ e^-$, $J/\psi \rightarrow \mu^+ \mu^-$, $J/\psi \rightarrow \pi^+ \pi^-$, $J/\psi \rightarrow K^+ K^-$, $e^+ e^- \rightarrow e^+ e^- (\gamma)$ and $e^+ e^- \rightarrow \mu^+ \mu^- (\gamma)$.

- Better sensitivities on $J/\psi \rightarrow e\tau$ and $J/\psi \rightarrow \mu\tau$ based on 1300 million $J/\psi$ events are coming soon.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BESII upper limit</th>
<th>BESIII upper limit</th>
<th>Other experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow e\mu$</td>
<td>$1.1 \times 10^{-6}$ (58M)</td>
<td>$1.6 \times 10^{-7}$ (225M)</td>
<td>-</td>
</tr>
<tr>
<td>$J/\psi \rightarrow e\tau$</td>
<td>$8.3 \times 10^{-6}$ (58M)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \mu\tau$</td>
<td>$2.0 \times 10^{-6}$ (58M)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
cLFV most recent results with LHCb
cLFV most recent results with LHCb

- $B^0_{(s)} \rightarrow e\mu$ JHEP 03 (2018) 043
- $B^0_{(s)} \rightarrow \tau\mu$ arXiv:1905.06614 (PRL)
- $h^0 \rightarrow \tau\mu$ EPJ C78 (2018) 1008

**Pair of tracks with**
- good secondary vertex
- clearly separated from primary vertex (15x uncertainty)

**B-candidate**
- transverse momentum $> 0.5$ GeV/c
- originating from primary vertex
- invariant mass window $[4900 - 5850]$ MeV/c²

**Normalization**
- $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow J/\psi K^+$
cLFV most recent results with LHCb

\[ B(\bar{B}^0 \to e\mu) < 1.0(1.3) \times 10^{-9} \]
\[ B(\bar{B}_s^0 \to e\mu) < 5.4(6.3) \times 10^{-9} \]

2–3x improvement over previous result

\[ B(\bar{B}^0 \to \tau\mu) < 1.2(1.4) \times 10^{-5} \]
\[ B(\bar{B}_s^0 \to \tau\mu) < 3.4(4.2) \times 10^{-5} \]

\[ B^0 : \text{2x improvement} \quad \text{over previous result} \]
\[ B_s^0 : \text{first measurement} \]
LHCb: cLFV in charm

- CLFV searches in $D^0 \rightarrow e^+ \mu^-$
- If only upper limits are set: Strong constraints on RPV SUSY models for improved $O(10^{-7})$ and parameter space in some lepton-quarks models for $O(10^{-8})$
- New upper limit set (previous upper limit from Belle: $\text{BR} (D^0 \rightarrow e^+ \mu^-) < 2.6 \times 10^{-7} @ 90\% \text{ C.L.}$)

$\text{BR}(D^0 \rightarrow e^+ \mu^-) < 1.3 \times 10^{-8}$ at 90\% C.L.
LFV prospects with hadrons

credits: G.Onderwater
Take away message

- **LHCb**: study flavour physics with all three lepton generations
- With LHC Run-I data LHCb sharpened limits for many LFV (LNV, BNV) channels
- No significant deviations from SM seen
- Demonstrated sensitive BSM searches @ hadron collider
- Many additional channels available
- Lots of additional data to be analyzed from Run-II (just completed) & expected from Run-III
ATLAS&CMS

- CLFV in $\tau \rightarrow \mu\mu\mu$
- soon be competitive with limits set by LEP and other facilities such as Belle

ATLAS: $\text{BR}(\tau \rightarrow \mu\mu\mu) < 3.8 \times 10^{-7}$ @ 95% CL
CMS: $\text{BR}(\tau \rightarrow \mu\mu\mu) < 8.8 \times 10^{-8}$ @ 90% CL

PDG: $\text{BR}(\tau \rightarrow \mu\mu\mu) < 2.1 \times 10^{-8}$ @ 95% CL (BELLE)
< $3.3 \times 10^{-8}$ @ 95% CL (BABAR)
< $4.6 \times 10^{-8}$ @ 95% CL (LHCb)
ATLAS&CMS

- $Z \rightarrow e \mu$ suppressed in the SM (BR < 4 $10^{-60}$)
- Clear signature for new physics ($e^+ \mu^-$ or $e^- \mu^+$): Search for $Z$ mass resonance

ATLAS: BR (Z -> e $\mu$) < 7.5 $10^{-7}$ CMS: BR (Z -> e $\mu$) < 7.3 $10^{-7}$
ATLAS&CMS

- H -> \mu \tau/e \tau searches
- Main backgrounds are the Z-> \tau \tau, W=jets, ttbar and QCD production

Observed (expected) limits at 95% CL

ATLAS: BR (H -> \mu \tau) < 0.28 (0.37+0.14-0.10) %
BR(H -> e\tau) < 0.47 (0.34+-0.13-0.10) %

CMS: BR (H -> \mu \tau) < 0.25(0.25) %
BR(H -> e\tau) < 0.61 (0.37) %
ATLAS

- LVF top decays: First direct search
- Couplings with cLFV top quark less unconstrained: within the sensitivity of the LHC

$\text{BR}(t \rightarrow l'l'q) < 1.86 \times 10^{-5}$ at 95% CL
$\text{BR}(t \rightarrow e\mu q) < 6.6 \times 10^{-6}$ at 95% CL
Take away message

- **ATLAS & CMS** have diverse and expanding program of direct and indirect cLFV searches
- Intriguing hints of new physics in B meson decays have renewed interest
- No evidence or discovery of LFV processes so far **but there is still room with the full run2 (2016+ 2017+ 2018) datasets**
NA62: LFV/LNV $K^+ \rightarrow \pi^- l^+ l^+$

- $K^+ \rightarrow \pi^- l^+ l^+$: $\Delta L = 2$ and $\Delta L_\mu = 2$ or $\Delta L_e = 2$ ($l = \mu / e$) via Majorana neutrinos $U$ [PL B491 (2000) 285-290, JHEP 0905 (2009) 030]

- **Experimental status**
  - $\text{BR}(K^+ \rightarrow \pi^- e^+ e^+)$: $6.4 \times 10^{-10}$ at 90% CL [BNL E865, PRL 85 (2000) 2877]
  - $\text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+)$ < $8.6 \times 10^{-11}$ at 90% CL [NA48, PL B769 (2017) 67]
K^+ \rightarrow \pi^- e^+ e^+ / \pi^- \mu^+ \mu^+ 

- Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

BR(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10} at 90\% CL  
BR(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} at 90\% CL
Future prospects

Upper Limits set with 80% of the 2017 NA62 data set:

- $\text{BR}(K^+ \rightarrow \pi^-e^+e^+) < 2.2 \times 10^{-10}$ at 90% CL
- $\text{BR}(K^+ \rightarrow \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ at 90% CL

Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

Competitive SES achieved with 2017 data for:

- $K^+ \rightarrow \pi^-\mu^+e^+$ [LNV] & $K^+ \rightarrow \pi^+\mu^-e^+$ [LFV]
  \[\text{SES} \sim 5 \times 10^{-11}\] (factor $\sim 5$ improvement on BNL-E865)

- $K^+ \rightarrow e^-\nu\mu^+\mu^+$ [LFV]
  \[\text{SES} \sim 5 \times 10^{-11}\] (first search for this mode)

- $K^+ \rightarrow \mu^-ve^+e^+$ [LFV]
  \[\text{SES} \sim 1 \times 10^{-10}\] (factor 100 improvement on PDG)

Analysis in progress
Final remarks: Low energy prospects

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- **muon-cLFV remains one of the most exciting place where to search for new physics**
- **Strong support from the European Strategy Committee**
Final remarks: Precision measurements at B-factories

- Flavour physics provide an extremely rich landscape of measurements opening windows on New Physics
- High luminosity e+e- colliders offer a pristine and well defined environment
- Existing data sets (Babar and Belle) are still providing new results
- BESIII is providing more measurements at the tau/charm energy
- BelleII just started looking forward to more luminosity
Final remarks: LHC & low energy

7 Conclusions

From the comprehensive case study in this work, we see that precision measurements and the LHC study are indeed complementary. Which experiment gives the best reach depends on both the quark flavour and the lepton pair in the operator. For light quarks $u$, $d$ and $s$, precision measurements clearly outperform the LHC irrespective of the charged lepton flavour. However, the LHC becomes competitive for heavier quarks, $c$ and $b$, and there is an interesting interplay between the two approaches to obtain limits on LFV operators with two quarks and two leptons. Operators with $e\mu$ are still highly constrained by precision measurements, particularly $\mu-e$ conversion in nuclei, but the LHC competes for LFV operators with right-handed $\tau$ leptons and can set limits independent of the phase of the Wilson coefficient. We set a lower limit of 600–800 GeV on the cutoff scale of all these operators.

“A Case Study of the Sensitivity to LFV Operators with Precision Measurements and the LHC”, Cai & Schmidt, JHEP02(2016)176
# cLFV best upper limits

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper limit</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \to e^+ \gamma$</td>
<td>$4.2 \times 10^{-13}$</td>
<td>Eur. Phy. J. c 76 (2016) 434</td>
<td>MEG</td>
</tr>
<tr>
<td>$\mu^+ \to e^+ e^+ e^-$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>Nucl. Phy. B299 (1988) 1</td>
<td>SINDRUM</td>
</tr>
<tr>
<td>$\mu^- N \to e^- N$</td>
<td>$7.0 \times 10^{-13}$</td>
<td>Eur. Phy. J. c 47 (2006) 337</td>
<td>SINDRUM II</td>
</tr>
<tr>
<td>$\tau \to e \gamma$</td>
<td>$3.3 \times 10^{-8}$</td>
<td>PRL 104 (2010) 021802</td>
<td>Babar</td>
</tr>
<tr>
<td>$\tau \to \mu \gamma$</td>
<td>$4.4 \times 10^{-8}$</td>
<td>PRL 104 (2010) 021802</td>
<td>Babar</td>
</tr>
<tr>
<td>$\tau \to e^- e^+ e^-$</td>
<td>$2.7 \times 10^{-8}$</td>
<td>Phy. Let. B 687 (2010) 139</td>
<td>Belle</td>
</tr>
<tr>
<td>$\tau \to \mu^- \mu^+ \mu^-$</td>
<td>$2.1 \times 10^{-8}$</td>
<td>Phy. Let. B 687 (2010) 139</td>
<td>Belle</td>
</tr>
<tr>
<td>$\tau \to \mu^+ e^- e^-$</td>
<td>$1.5 \times 10^{-8}$</td>
<td>Phy. Let. B 687 (2010) 139</td>
<td>Belle</td>
</tr>
<tr>
<td>$B_0 \to e \mu$</td>
<td>$1.0 \times 10^{-9}$</td>
<td>JHEP 03 (2018) 043</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B_0 \to \tau \mu$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>arXiv:1905.06614 (PRL)</td>
<td>LHCb</td>
</tr>
<tr>
<td>$Z \to \mu e$</td>
<td>$7.5 \times 10^{-7}$</td>
<td>Phy. Rev. D 90 (2014) 072010</td>
<td>Atlas</td>
</tr>
<tr>
<td>$Z \to \mu e$</td>
<td>$7.3 \times 10^{-7}$</td>
<td>CMS PAS EXO-13-005</td>
<td>CMS</td>
</tr>
<tr>
<td>$H \to \tau \mu$</td>
<td>$0.25 \times 10^{-2}$</td>
<td>JHEP 06 (2018) 001</td>
<td>CMS (*)</td>
</tr>
<tr>
<td>$H \to \tau e$</td>
<td>$0.47 \times 10^{-2}$</td>
<td>ATLAS-CONF-2019-013</td>
<td>ATLAS (*)</td>
</tr>
<tr>
<td>$K_L \to \mu e$</td>
<td>$4.7 \times 10^{-12}$</td>
<td>PRL 81 (1998) 5734</td>
<td>BNL</td>
</tr>
</tbody>
</table>

* $\mathcal{B}(H \to \mu e) < O(10^{-8})$ from $\mu \to e \gamma$
Conclusions

• Thanks a lot for your attention

• Credits: all cLFV community
Back-up
The High intensity Muon Beam (HiMB) project at PSI

• Aim: $O(10^{10}$ muon/s); Surface (positive) muon beam ($p = 28$ MeV/c); DC beam

• Strategy:
  • Target optimization
  • Beam line optimization

• Time schedule: $O(2025)$
The High intensity Muon Beam (HiMB) project at PSI

- Back to standard target to exploit possible improvements towards high intensity beams:

  - **Target geometry and alternate materials**
    - Search for high pion yield materials -> higher muon yield

\[
\text{relative } \mu^+ \text{ yield } \propto \pi^+ \text{ stop density } \cdot \mu^+ \text{ Range } \cdot \text{length}
\]

\[
\propto n \cdot \sigma \pi^+ \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_c (6/12)_c}{\rho_x (Z/A)_x}
\]

\[
\propto \frac{1}{Z^{1/3}} \cdot \frac{1}{Z} \cdot \frac{1}{Z}
\]

\[
\propto \frac{1}{Z^{2/3}}
\]
The High intensity Muon Beam (HiMB) project at PSI

- Back to standard target to exploit possible improvements towards high intensity beams:
  - **Target geometry and alternate materials**
    - Search for high pion yield materials -> higher muon yield

- 50% of muon beam intensity gain, would correspond to effectively raising the proton beam power at PSI by 650 kW, equivalent to a beam power of almost 2 MW without the additional complications such as increased energy and radiation deposition into the target and its surroundings.
The High intensity Muon Beam (HiMB) project at PSI

- **Aim:** $O(10^{10}$ muon/s); Surface (positive) muon beam ($p = 28$ MeV/c); DC beam
- **Time schedule:** $O(2025)$
- Put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**

![Diagram of beam line with labels and numbers for beam intensities and efficiencies.]
Slanted target: Prototype test this year

- Expect 30-60% enhancement
- Measurements foreseen in three directions in 2019
- Aim: $O(10^8 \text{ muon/s})$; Surface (positive) muon beam ($p = 28 \text{ MeV/c}$); DC beam

**Conventional muon beamline**

- **Proton beam**
  - Ex. J-Parc MUSE
  - 1000 kW proton beam
  - 20mm graphite target
- **Graphite target**
  - Proton beam loss $\sim 5\%$
- **Capture magnet**
  - Bend ($\pi$ selection)
- **Decay volume**
  - Bend ($\mu$ selection)
- **Muon**
  - To neutron facility

- Thin target ($\sim 20\text{mm}$)
- Small solid angle
- Separate pion and muon momentum selection
  (obtain highly polarized muon beam)
MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Aim: \( \mathcal{O}(10^8 \text{ muon/s}) \); Surface (positive) muon beam (\( p = 28 \text{ MeV/c} \)); DC beam

**Conventional muon beamline**

- Proton beam
- Graphite target
- Capture magnet
- Proton beam loss \( \sim 5\% \)
- To neutron facility

**MuSIC beamline**

- Muon
- Proton beam
- Transport solenoid
- Capture solenoid
- Collect \( \pi / \mu \) with 3.5T solenoidal field
- To dump

**Thin target (\( \sim 20\text{mmt} \))**

**Small solid angle**

**Separate pion and muon momentum selection (obtain highly polarized muon beam)**

**Ex. J-Parc MUSE**
- 1000 kW proton beam
- 20mmt graphite target

**Ex. MuSIC**
- 0.4 kW proton beam
- 200 mmt graphite target

**Thick target (200mmt)**

**Large solid angle, good collection efficiency**

**No muon spin selection (no selection of pion / muon momentum)**
MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- proton beam energy is only 100 MeV above pion production threshold (~2mπ)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)
MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Multi-purpose facility. Beam line commissioning

Succeed in observing surface muons (~28 MeV/c)

Target position tuned for surface muon

\[ \sim 3 \times 10^4 \text{ surface } \mu^+ / \text{s} @ 28 \text{ MeV/c} \]

with 1 mA proton beam

Inflight-decay muons

Typical observed asymmetry spectra

\[ \alpha \cos(\gamma_t B t + \delta_0) \]

\[ \gamma_t : \text{Larmor frequency} \]

\[ p = 28 \text{ MeV/c} \]

\[ p = 60 \text{ MeV/c} \]

Status:

- Start experiments with negative and positive muons
- Muon capture and X-ray elemental analysis are in progress
- DC \( \mu \)SR study (still in commissioning for user experiments)
Muon golden channels with the Feynman’s eyes

Current upper limits on $\mathcal{B}_i$

$\mathcal{B}_i = \frac{\Gamma_i}{\Gamma_{tot}}$

SM

0 $10^{-50}$ $10^{-40}$ $10^{-30}$ $10^{-20}$ $10^{-13}$ $10^{-10}$ $10^{0}$

New Physics
cLFV searches with muons: Status and prospects

In the near future impressive sensitivities:

<table>
<thead>
<tr>
<th>Current upper limit</th>
<th>Future sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$4.2 \times 10^{-13}$</td>
</tr>
<tr>
<td>$\mu \to eee$</td>
<td>$1.0 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu N \to eN'$</td>
<td>$7.0 \times 10^{-13}$</td>
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Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV
\( \mu^- N \rightarrow e^- N \) experiments

- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! \( O(10^{18}) \)
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Use timing to reject beam backgrounds (extinction factor \( 10^{-10} \))
  - Pulsed proton beam 1.7 \( \mu \)s between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays
The COMET experiment

- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]

**Pion Capture Section**
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet

**COMET phase I**

**Detector Section**
A detector to search for muon-to-electron conversion processes.

**Pion-Decay and Muon-Transport Section**
A section to collect muons from decay of pions under a solenoidal magnetic field.

5m
The COMET experiment: Status

- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]

**COMET phase I**

- **Cylindrical Drift Chamber:** Ready

- **Pion Capture Section:**
  A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet

- **Detector Section:**
  A detector to search for muon-to-electron conversion processes.

- **Trigger scintillators + Cerenkov detector:** Ready

- **Trigger/DAQ/Analysis:** in very good shape
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

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<td>few $\times 10^{-17}$</td>
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- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV
The world’s most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas
The MEGII (and Mu3e) beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - Intensity $O(10^8 \text{ muon/s})$, low momentum $p = 28 \text{ MeV/c}$
  - Small straggling and good identification of the decay region
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered $8 \times 10^7 \text{ muon/s}$ during 2016 test beam

The Mu3e CMBL

The MEGII BL
More and selected pulsed muons in three steps

1. Pion production in magnetic field

2. Pion/muon collection using gradient magnetic filed

3. Beam transport with curved solenoid magnets
More and selected pulsed muons in three steps

- 1. Pion production in magnetic field
- 2. Pion/muon collection using gradient magnetic filed
- 3. Beam transport with curved solenoid magnets
ATLAS

- CLFV double charged Higgs decays (H++/H --); possible also LNV
- 3.2 fb−1 [2015] + 10.7 fb−1 [2016] data set
CMS

- Lepton flavour violating Higgs decays: $H \rightarrow e \tau$ and $H \rightarrow \mu \tau$. Four final states ($e \tau, e \tau h, \mu \tau, \mu \tau h$)
- Derive limit on BR and Yukawa couplings

2016 data set up to 35.9 fb-1 at $\sqrt{s} = 13$ TeV

Boosted decision tree and cut based analysis

$$\text{BR}(H \rightarrow e\tau) < 0.61\% \text{ at } 95\% \text{ C.L.}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$$
CMS

- Lepton flavour violating Higgs decays: $H \rightarrow e \tau$ and $H \rightarrow \mu \tau$. Four final states ($e\tau$, $e\tau_h$, $\mu\tau$, $\mu\tau_h$)
- Derive limit on BR and Yukawa couplings

2016 data set up to 35.9 fb-1 at $\sqrt{s} = 13$ TeV

Boosted decision tree and cut based analysis

$$\text{BR}(H \rightarrow \mu\tau) < 0.25\%$$

at 95 % C.L.

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$$
Feynman diagrams
Signature and background vs beam characteristics

**Kinematics**
- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

**Background**
- Accidental background

**Kinematics**
- Quasi 2-body decay
- Monoenergetic $e^-$
- Single particle detected

**Background**
- Decay in orbit
- Antiprotons, pions

**Kinematics**
- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

**Background**
- Radiative decay
- Accidental background