Charged Lepton Flavor Violation Experiments

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Outline

• (Charged) Lepton Flavour in the Standard Model
• Observables towards new physics
• The “classical searches”
  • $\mu \rightarrow e\gamma$
  • $\mu \rightarrow 3e$
  • $\mu N \rightarrow eN$
• Status and perspectives
Flavor in the SM

• Unlike the quark sector, lepton flavor transitions are forbidden in the SM due to the vanishing neutrino masses
• Charged current interaction with the W field

\[ J^\mu = \bar{d}_L^i \gamma_\mu U^d_L \, \bar{u}_L^j u_L^j + \bar{e}_L^i \gamma_\mu U^e_L \, \bar{\nu}_L^j \nu_L \]

V_{\text{CKM}}

• In the SM lepton flavor transition are forbidden
• Nevertheless neutrino oscillations were observed
  - Flavor transitions in the (neutral) lepton sector
  - vSM
charged Lepton Flavor Violation

- cLFV decays in the SM is radiatively induced by neutrino masses and mixings at a negligible level

\[ \Gamma(\mu \rightarrow e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left( \frac{\alpha}{2\pi} \right) \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2_{23}}{M_W^2} \right) \]

\[ \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left( \frac{3\alpha}{32\pi} \right) \left( \frac{\Delta m^2_{23} s_{13} c_{13} s_{23}}{M_W^2} \right)^2 \]

relative probability \( \sim 10^{-54} \)

- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)

- Clear evidence for physics beyond the SM
  - background-free
- Restrict parameter space of SM extensions
Many processes

- LFV is related to "new" lepton-lepton couplings and effective operators

\[
\frac{1}{\Lambda} \ell_i \sigma_{\mu\nu} \ell_j F^{\mu\nu} \quad \frac{1}{\Lambda^2} \ell_i \gamma_\mu \ell_j (\bar{q}_k \gamma^\mu q_m + \bar{\ell}_k \gamma^\mu \ell_m)
\]

- A wide field of research
  - LFV decays
  - Anomalous magnetic moment for the \( \mu, \tau \)
  - Muon-to-electron conversion
  - (LFV in B-meson decays)
Processes are correlated

- Model-dependent correlations

Barbieri et al., Nucl. Phys B445 (1995) 225
...
Connections

- Collider physics
  - it is Super Symmetry + Grand Unification that predicts new particles in the loop.
  - alternate search for \((E/M_{\text{SUSY}})^N\) suppressed effects

- neutrino oscillations
  - mixing matrix in charged sector can be proportional to
    - PMNS
    - CKM

- muon \(g-2\)
  - \(a_\mu\) is the “diagonal” term
  - \(\mu\to e\gamma\) diagram is the “off-diagonal”

- SUPER Flavor factory
  - Investigates LFV in the \(\tau\to\mu, e \gamma\) decays

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  - $\text{PMNS}$
  - $\text{CKM}$

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  - $a_\mu$ is the “diagonal” term
  - $\mu \rightarrow e \gamma$ diagram is the “off-diagonal”

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  - Investigates LFV in the $\tau \rightarrow \mu, e \gamma$ decays

Barbieri et al., Nucl. Phys B445 (1995) 225
The CLFV wheel

\[ \alpha \left( \frac{Z \alpha}{\pi} \right) \]

\[ \mu \rightarrow e\gamma \]

\[ \mu \rightarrow eee \]

\[ \mu \rightarrow eN \rightarrow eN \]

\[ \tau \rightarrow e\gamma \]

\[ \tau \rightarrow \mu\gamma \]

\[ (g - 2) \mu \]

\[ B_{\mu e\gamma} \sim 10^{-12} \sim \left( \frac{\Delta a_\mu}{10^{-9}} \right)^2 \]

\[ \propto \left( \frac{m_\tau}{m_\mu} \right)^{2/4} \]

\[ \propto \left[ \Delta a_\mu \right]^2 \]

\[ \propto \left( \frac{\alpha_{e.m.}}{\alpha} \right) \]

\[ \propto \tan^2 \beta \]

Common Models
Present limits

SINDRUM
$B(\mu Ti \rightarrow e Ti) < 4.3 \times 10^{-12}$
$B(\mu Au \rightarrow e Au) < 7 \times 10^{-13}$
$\mu \rightarrow e e e$
$1 \times 10^{-12}$
$1988$

MEG@PSI
$\mu \rightarrow e \gamma$
$2.4 \times 10^{-12}$
$\tau \rightarrow \mu \gamma$
$\tau \rightarrow e \gamma$
$(g - 2)_{\mu} \times \tan^2 \beta$

BNL E821
$3.3 \div 4.5 \times 10^{-8}$
$a_{\mu}^{\exp} - a_{\mu}^{SM} = (296 \pm 81) \times 10^{-11}$

SINDRUM II
$\mu \rightarrow e \gamma$
$2.4 \times 10^{-12}$
running
$\tau \rightarrow \mu \gamma$
$\tau \rightarrow e \gamma$

2010
B-factories

2006

2004
a hint for NP?

2006

2013

1988

2013
# Experimental effort

<table>
<thead>
<tr>
<th></th>
<th><strong>Dedicated experiment</strong></th>
<th><strong>Multi-purpose experiment</strong></th>
</tr>
</thead>
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<tr>
<td><strong>Exotic Searches</strong></td>
<td>$\mu \rightarrow e\gamma$</td>
<td>$\tau \rightarrow \mu\gamma$</td>
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<td>$\mu^- N \rightarrow e^- N$</td>
<td>$K^0_L \rightarrow \mu e$</td>
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<td><strong>New Physics if seen</strong></td>
<td><strong>Experiment limited</strong></td>
<td>$Z' \rightarrow e\mu$</td>
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<td></td>
<td></td>
<td>$\tau \rightarrow 3\ell$</td>
</tr>
<tr>
<td><strong>BSM physics</strong></td>
<td>$e, \mu, n$ edm</td>
<td>$B \rightarrow \mu\mu$</td>
</tr>
<tr>
<td></td>
<td>$(g-2)_\mu$</td>
<td>$b \rightarrow s\gamma$</td>
</tr>
<tr>
<td></td>
<td>$(g-2)_e$</td>
<td>$\tau \rightarrow ev\nu$</td>
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<td>$\pi^+(K^+) \rightarrow e^+\nu$</td>
<td>$\tau \rightarrow \mu\nu\nu$</td>
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$\mu \rightarrow eee$  
$\mu^- N \rightarrow e^- N$ | $\tau \rightarrow \mu\gamma$  
$\tau \rightarrow e\gamma$  
$K_L^0 \rightarrow \mu e$  
$Z' \rightarrow e\mu$  
$\tau \rightarrow 3\ell$ |
| Experiment limited |                      |                         |

| BSM physics NP if deviations from SM Theory limited | $e, \mu, n \text{ edm}$  
$(g - 2)_\mu$  
$(g - 2)_e$  
$\pi^+(K^+) \rightarrow e^+\nu$  
$\pi^+(K^+) \rightarrow \mu^+\nu$  
$K_L^0 \rightarrow \pi^0\nu\nu$ | $B \rightarrow \mu\mu$  
$K^+ \rightarrow \pi^+\nu\nu$ |

I will concentrate on the “classical” searches
65 years of searches

- Each improvement linked to beam and detector technology
- Trade-off between sub-detectors to achieve the best “sensitivity”
Complementarity

- Capability of different measurements to discriminate between models

\[ \frac{m_\mu}{(1 + \kappa) \Lambda^2} + \frac{\kappa}{(1 + \kappa) \Lambda^2} \]
“Classical” searches

- Widespread in the world
- MEG
- Mu3e
- Mu2e - Deeme - Comet Phase I - II
Kinematics

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

- 2-body decay
- Monoenergetic \( e^+, \gamma \)
- Back-to-back

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

- Quasi 2-body decay
- Monoenergetic \( e^- \)
- Single particle detected

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

- 3-body decay
- Invariant mass constraint
- \( \Sigma p_i = 0 \)
Background

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
- $\sum p_i = 0$

Background
- Radiative decay
- Accidental background
Beam requirements

Kinematics
- 2-body decay
- Monoenergetic e
- Back-to-back

Background
- Accidental background

Continuous Beam
- Quasi 2-body decay
- Monoenergetic e
- Single particle detected

Background
- Decay in orbit
- Antiprotons, pions

Pulsed Beam
- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

Background
- Radiative decay
- Accidental background

Kinematics
- $\mu^+ \rightarrow e^+\gamma$
- $\mu^- N \rightarrow e^- N$
- $\mu^+ \rightarrow e^+ e^- e^+$

Continuous Beam
- $\mu^+ \rightarrow e^+\gamma$
- $\mu^- N \rightarrow e^- N$
- $\mu^+ \rightarrow e^+ e^- e^+$
**µ→eγ signal and background**

"Signal"

**µ→eγ**

µ⁺ → e⁺γ

- **E_e = E_γ = 52.8 MeV**
- **θ_eγ = 180°**
- **t_eγ ≈ 0**

"RMD"

**µ → eννγ**

µ⁺ → e⁺γ

- Event:
  - eN → eNγ
  - e⁺e⁻ → γγ

\[ E_e = E_γ = 52.8 \text{ MeV} \]

\[ \theta_eγ = 180° \]

\[ t_eγ \approx 0 \]

"Accidental"

**µ → eνν**

- **B_{prompt} ≈ 0.1 × B_{acc}**
- **B_{acc} ≈ R_µ \Delta E_e \Delta E_γ^2 \Delta θ^2 \Delta t**

The accidental background is dominant and it is determined by the experimental resolutions.
MEG experimental method

- **μ**: stopped beam of $3 \times 10^7 \mu$ /sec in a 205 $\mu$m polyethylene target
  - PSI πE5 beam line: 29 MeV $\mu^+$
- **e^+** detection
  - Magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum
  - Plastic counters for timing
- **γ** detection
  - Liquid Xenon detector based on the scintillation light
    - Fast: 4 / 22 / 45 ns
    - High LY: $\approx 0.8 \times$ NaI
    - Short $X_0$: 2.77 cm
Some detector pictures

LXe detector

DC system

Beam Line

TC with fibers exposed
Calibration & Monitoring

Proton Accelerator

Li(p,γ)Be
LiF target at COBRA center
17.6MeV γ
~daily calib.
also for initial setup

Detected

Alpha on wires

PMT QE & Att. L
Cold GXe
LXe

Mott e⁺ scattering

Cosmic ray alignment

μ radiative decay

γ

π⁺ + p → π⁰ + n
π⁰ → γγ (55MeV, 83MeV)
π⁺ + p → γ + n (129MeV)
LH₂ target

Detector Calibration

Cosmic ray alignment

Nickel γ Generator

Lower beam intensity < 10⁷
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

NaI

Cosmic ray alignment

9 MeV Nickel -line

LXe side

Beam

LXe side

Pneumatic actuator

MEG target

[Diagram of beam alignment and target setup]
Calibration & Monitoring

Proton Accelerator

Li(p,γ)Be
LIF target at COBRA center
17.6 MeV γ
~daily calib.

Alpha on wires

Laser

Relative timing calib.

Nickel Generator

9 MeV

NaI

Source (Cf) transferred by comp air → on/off

Is necessary to reduce pile-ups
A few days ~ 1 week to get enough statistics

Laser

 Illuminate Xe from the back

LiF target at COBRA center

LH2 target

µ radiative decay

0 → 0

0 + p → 0 + n (55 MeV, 83 MeV)

0 + p + n (129 MeV)

RMS < 0.2%

Energy scale (a.u.)

Number of events

Detector

Mott e+ scattering

Cosmic ray alignment

Calibration & Monitoring
• **2009+2010** analysis: BR(µ→eγ)< $2.4 \times 10^{-12}$ @ 90%C.L.

• **2011** data
  - Doubled the **statistics**
    - Improved trigger and reconstruction **efficiency**
  - **Hardware modification**
    - BGO for calibration
    - Laser tracker system for drift chamber alignment

• **2009-2011 Analysis** improvements
  - **Reconstruction** improvements
    - γ-ray pileup unfolding
    - e⁺ waveform FFT noise reduction + revised track fitter

• **2012** in progress
2009-2011 fit result

- **Blind-box analysis strategy**
  - off-time sideband
  - off angle sideband

- **Three independent analyses**
  - different pdf implementation
  - Fit or input $N_{\text{RMD}}, N_{\text{BG}}$
  - Different statistical treatment (Freq. or Bayes)

- **Use of the sidebands**
  - our main background comes from accidental coincidences
  - RMD can be studied in the low $E_\gamma$ sideband

\[ N_{\text{sig}} = -0.4^{+4.8}_{-1.9} \]
\[ N_{\text{acc}} = 2413.6 \pm 37 \]
\[ N_{\text{RMD}} = 167.5 \pm 24 \]
Combined 2009 + 2010

- 90% C.L. Feldman-Cousins upper limit
  - $8 \times 10^{-13}$ expected for no signal (sensitivity)

\[
\frac{\Gamma(\mu^+ \rightarrow e^+\gamma)}{\Gamma(\mu^+ \rightarrow e^+\nu\bar{\nu})} \leq 5.7 \times 10^{-13}
\]

PRL 17 May 2013
20 times better than previous limit!
Present & Future

• We have just started the 2013 data-taking (last year)

• MEG is expected to saturate its sensitivity with this year’s run

• In the meanwhile an upgrade was presented and accepted by PSI laboratory

1. Increasing $\mu^+-$stop on target
2. Reducing target thickness to minimize e+ MS & brehmsstrahlung
3. Replacing the e+ tracker reducing its radiation length and improving its granularity and resolutions
4. Improving the timing counter granularity for better timing and reconstruction
5. Improving the positron tracking-timing integration by measuring the e+ trajectory up to the TC interface
6. Extending the $\gamma$-ray detector acceptance
7. Improving the $\gamma$-ray energy and position resolution for shallow events
8. Integrating splitter, trigger and DAQ maintaining a high bandwidth
**MEG$^{UP}$ sensitivity**

- Ultimate sensitivity at the few $\times 10^{-14}$ level
- Engineering run 2015
- Data taking 2016-2018

A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det]
Mu3e at PSI

• Search for $\mu \rightarrow e^+ e^- e^-$
  - $10^{-15}$ sensitivity in phase I
  - $10^{-16}$ sensitivity in phase II
• Project approved in January 2013
  - Double cone target
  - HV-MAPS ultra thin silicon detectors
  - Scintillating fibers timing counter
HIMB at PSI

- Muon rates in excess of $10^{10}/s$ in acceptance
- $2 \cdot 10^9/s$ needed for $\mu \rightarrow eee$ at $10^{-16}$
- Not before 2017
\[ \mu N \rightarrow e N \]

- Coherent muon capture on nucleus (Al is the candidate)
- Single **mono-energetic electron**
  - \( E_e = m\mu - B\mu - \text{recoil} \)
- Only **one particle** in final state
  - No (accidental) background limited
  - Unlike \( \mu \rightarrow e\gamma \) and \( \mu \rightarrow 3e \) there is no experimental “wall” until conversion rates \( O(10^{-18}) \)
  - It is anticipated that will provide the **ultimate sensitivity** to CLFV
- Background comes from
  - \( \mu \) decay-in-orbit (DIO)
  - Radiative muon capture
    - bkg n and \( \gamma \)-rays are produced
  - Beam related background (\( \pi \) and e contaminations)
    - high purity environment
    - curved solenoid (Dzhilkibaev and Lobashev, 1989)
    - pulsed beam with challenging extinction

\[ (E\mu - E_e)^5 \]
\(~10^{-17}\) of the spectrum within the last MeV
$\mu N \rightarrow e N$ experiments: mu2e

- Mu2e @ FNAL and COMET @ J-PARC are quite similar in the outline

- p-beam hits a target
- solenoid collects $\pi^-$ and let them decay to $\mu^-$
- $\mu^-$ are transported to the capture target
- A pulsed beam allows a time window for events ⇒ needs high extinction

Starts in 2020
Data in 2022
SES ~ $2 \times 10^{-17}$
COMET: phase II

- COMET @ J-PARC has some differences

- **S-shape** instead of **C-shape**

- Detector has an extra curved magnet acting as an electron spectrometer

- Proton beam

- Production Target

- Pions

- Muons

- Capture target

- Transport

- Starts in 2020
  Data in 2022
  SES ~ $2 \times 10^{-17}$
COMET: phase I

- COMET @ J-PARC has some differences

Starts in 2016
Data in 2017
SES \( \sim 3 \times 10^{-15} \)

target will be placed at the center of the detector (à la Mu2e)

Phase-I Detector
- A cylindrical drift chamber (CDC) for the \( \mu \)-e conversion search
- A prototype ECAL and straw tube tracker for the background studies
In the meanwhile: DeeMe

- DeeMe at J-PARC aims at searching for $\mu N \rightarrow eN$ with a $10^{-14}$ sensitivity
- production target and conversion target are the same
- rotating silicon carbide target
- physics data taking planned to start in 2015

\[
p \rightarrow \pi \rightarrow \mu \rightarrow e
\]
Summary

- **CLFV activities** in the World
- Complements *flavor* physics from the lepton sector
- **MEG** improved the limit on $\mu \rightarrow e \gamma$
  - $5.7 \times 10^{-13} @ 90\% \text{ C.L.}$
  - Further improvement expected
- **MEG^\text{UP}**
  - Down to $6 \times 10^{-14}$
- **Mu3e** @ PSI
  - *Staged* approach waiting for a HIMB
  - $<10^{-16}$ level
- **Mu2e, DeeMe** and **COMET**
  - Intensive R&D for the realization of the experiments
  - **Staged setup** to test part of the techniques
  - $10^{-17}$ level
  - Towards $10^{-18}$ with future muon campuses (Project-X and PRISM/PRIME)
- **Complementarity** with $\tau$, meson and exotic CLFV
The future: stay tuned!

E. C. Dukes, TAU2010
End of slides
Prospects for $\tau$ LFV at Belle II

- Belle II will collect $\sim 10^{11}$ $\tau$-leptons (50/ab)
- Sensitivity depends on the background level
  - $\tau \rightarrow 3\ell$ still clean even at Belle II
  - For $\tau \rightarrow \mu \gamma$ better understanding of backgrounds, signal resolution and intelligent selections are needed
Summary Belle $\tau$ LFV results

48 modes searched for, U.L.s around $\sim 10^{-8}$
Super $\theta^+\theta^-$ factory sensitivity directly confronts New Physics models of CLFV

<table>
<thead>
<tr>
<th>Mode</th>
<th>BABAR ($\times 10^{-8}$)</th>
<th>Belle ($\times 10^{-8}$)</th>
<th>SuperB ($\times 10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^\pm \rightarrow e^\pm \gamma$</td>
<td>3.3</td>
<td>12</td>
<td>0.3</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm \gamma$</td>
<td>4.4</td>
<td>4.5</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm \mu^+\mu^-$</td>
<td>3.3</td>
<td>2.1</td>
<td>0.08</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow e^\pm e^+e^-$</td>
<td>2.9</td>
<td>2.7</td>
<td>0.02</td>
</tr>
</tbody>
</table>
### Summary of results in LFV searches

<table>
<thead>
<tr>
<th>channel</th>
<th>limit</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(B^- \rightarrow \pi^+ e^- e^-)$</td>
<td>$&lt; 2.3 \times 10^{-8}$</td>
<td>@90 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow K^+ e^- e^-)$</td>
<td>$&lt; 3.0 \times 10^{-8}$</td>
<td>@90 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow K^{*-} e^- e^-)$</td>
<td>$&lt; 2.8 \times 10^{-6}$</td>
<td>@90 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow \rho^+ e^- e^-)$</td>
<td>$&lt; 2.6 \times 10^{-6}$</td>
<td>@90 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow D^+ e^- e^-)$</td>
<td>$&lt; 2.6 \times 10^{-6}$</td>
<td>@90 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow D^+ e^- \mu^-)$</td>
<td>$&lt; 1.8 \times 10^{-6}$</td>
<td>@90 % CL</td>
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<tr>
<td>$B(B^- \rightarrow \pi^+ \mu^- \mu^-)$</td>
<td>$&lt; 1.3 \times 10^{-8}$</td>
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</tr>
<tr>
<td>$B(B^- \rightarrow K^+ \mu^- \mu^-)$</td>
<td>$&lt; 5.4 \times 10^{-7}$</td>
<td>@95 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow D^+ \mu^- \mu^-)$</td>
<td>$&lt; 6.9 \times 10^{-7}$</td>
<td>@95 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow D^{*+} \mu^- \mu^-)$</td>
<td>$&lt; 2.4 \times 10^{-6}$</td>
<td>@95 % CL</td>
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<tr>
<td>$B(B^- \rightarrow D_s^+ \mu^- \mu^-)$</td>
<td>$&lt; 5.8 \times 10^{-7}$</td>
<td>@95 % CL</td>
</tr>
<tr>
<td>$B(B^- \rightarrow D^0 \pi^- \mu^- \mu^-)$</td>
<td>$&lt; 1.5 \times 10^{-6}$</td>
<td>@95 % CL</td>
</tr>
</tbody>
</table>

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*BaBar, Phys. Rev. D 85, 071103 (2012)*
*CLEO, Phys. Rev. D 65, 111102 (2002)*
*Belle, Phys. Rev. D 84, 071106(R), (2011)*
*LHCb, Phys. Rev. D 85,112004 (2012)*
μZ → eZ

But also neutrinoless nuclear capture μZ → eZ...

Only one particle in final state: no accidental background issue. Background scales only linearly with beam rate → very big chance to explore extremely low BR...

Background coming from:
• μ decay in orbit
• radiative μ capture

Beam related background:
• π and e contaminations

Looking for single monoenergetic electron: \( E_e \sim E_\mu - B_\mu \) (recoil energy negligible)

improving detector resolutions

high purity environment:
• curved solenoid with gradient field
• pulsed beam with challenging extinction time
Current limit by SINDRUM II:
- BR($\mu$Ti→eTi)< 4.3×10^{-12}
- BR($\mu$Au→eAu)< 7×10^{-13}

Beam intensity: 3×10^{7} $\mu$/s (@PSI)

Energy of emitted electrons is measured with a cylindrical magnetic spectrometer: drift chamber and scintillators/Cerenkov hodoscope.

SINDRUM II parameters:
- beam intensity: 3×10^{7} $\mu$/s
- $\mu$ momentum: 53 MeV/c
- magnetic field: 0.33T
- acceptance: 7%
- momentum res.: 2% FWHM
- S.E.S 3.3×10^{-13}

$\mu^Z$→e$^Z$ status

$\mu^N$→e$^N$ status
<table>
<thead>
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<th>Mu2e</th>
<th>COMET</th>
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</table>
| **Proton Beam** | 8 GeV, 8kW  
    bunch-bunch spacing 1.69 µsec  
    rebunching  
    Extinction: < 10\(^{-10}\) | 8 GeV, 50kW  
    bunch-bunch spacing 1.18-1.76 µsec  
    empty buckets  
    Extinction: < 10\(^{-9}\) |
| **Muon Transport** | S-shape solenoid | C-shape solenoid |
| **Detector** | Straight Solenoid w/gradient field  
    Tracker and Calorimeter | C-shape solenoid with gradient field  
    Tracker & calorimeter |
| **Sensitivity** | SES: 2 \times 10^{-17}  
    90% CL U.L.: 6 \times 10^{-17} | SES: 2.6 \times 10^{-17}  
    90% CL U.L.: 6 \times 10^{-17} |
Aiming for a $10^{-18}$ search with an extreme high intensity ($10^{11} \div 10^{12} \mu/s$) beam with \( \mu \) storage ring.

Fixed-field alternating gradient synchrotron perform conversion from original short-pulse beam with high momentum spread (30%) into a long pulse beam with narrow momentum spread (3%).
Key elements to MEG$^{UP}$

1. Increasing $\mu^+$–stop on target

2. Reducing target thickness to minimize $e^+$ MS & brehmsstrahlung

3. Replacing the $e^+$ tracker reducing its radiation length and improving its granularity and resolutions

4. Improving the timing counter granularity for better timing and reconstruction

5. Improving the positron tracking-timing integration by measuring the $e^+$ trajectory up to the TC interface

6. Extending the $\gamma$–ray detector acceptance

7. Improving the $\gamma$-ray energy and position resolution for shallow events

8. Integrating splitter, trigger and DAQ maintaining a high bandwidth
CLFV Programs