Charged Lepton Flavor and Dipole Moments

K.Kirch, ETH Zurich – PSI Villigen, CH
Setting the scene

Conservation of lepton flavor is a mystery

- Besides quark mixing, we have neutrino mixing
- Why wouldn’t we expect charged lepton mixing?
- Theories beyond SM naturally provide LFV
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  - To explain the observed BAU
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Non-SM precision physics, finite observables
- Some uniquely sensitive areas
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Search for charged LFV, e.g. $\mu \rightarrow e \gamma$

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Search for charged LFV
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Non-SM CP violation seems necessary
- To explain BAU
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Search for CPV
- e.g. measure EDMs, $e$, $n$, $\mu$, …

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- Why don't we expect charged lepton mixing?
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Non-SM CP violation seems necessary
- To explain
  - Search for CPV
  - e.g. measure EDMs, e, n, μ, ...

Non-SM precision physics, finite observables
- Some uniquely
  - e.g. measure MDMs, e, μ, ...
Setting the scene

- Not clear what new non-SM physics will be
  - Search for LFV in all accessible channels
  - Some are more promising than others
  - But who knows? → need all to disentangle physics

- Not clear what new non-SM physics will be
  - Search for CPV in all accessible channels
  - In particular, search for EDMs in many systems

- Not clear what new non-SM physics will be
  - Measure with ultimate precision where theory can accurately calculate
This talk …

- … can’t cover all cLFV searches like, e.g. $K_L \to \mu e$, … (or other decays of $\pi, K, D, B, W, Z, H$)
- … only touches on important $\tau$ decays (dominated by Belle, LHCb entering, future: Belle-II and LHCb upgrade)
- … has LFV searches with muons (@PSI, FNAL, J-PARC)
- … has muon g-2 (@BNL, FNAL, J-PARC) but only mentions electron g-2
- … has EDM searches (many systems @many places)
(g-2)\(\mu\)

\(\tau \rightarrow \mu \gamma \rightarrow e\gamma\)

\(\mu \rightarrow e\gamma\)

\(\tau \rightarrow \mu \mu \mu \rightarrow eee\)

\(\mu \rightarrow eee\)

\(\pi^0 \rightarrow \mu e\)

\(\mu \rightarrow e\) e.g. Al

\((g-2)\)\(\mu\)

\(\mu \rightarrow e\gamma\)

\(d_\mu\)

\(d_n\)

\(d_{Hg}\)

\(d_{YbF}\)

\(d_e\)

\(d_p, d_d\)

\(d_{Xe, Ra, ...}\)

\(d_{Tl, Fr, ...}\)
The image shows a diagram of different branches of physics, including:

- Particle Physics
- Nuclear Physics
- Atomic Physics
- Molecular Physics

Within each branch, specific processes and particles are highlighted. For example, in Particle Physics, processes such as $\tau \rightarrow \mu \gamma \rightarrow e\gamma$ and $\mu \rightarrow e\gamma$ are mentioned. In Nuclear Physics, processes like $\pi^0 \rightarrow \mu e$ and $\mu \rightarrow eee$ are shown. In Atomic Physics, $\mu \rightarrow e$ and $\mu \rightarrow e e e$ are highlighted. In Molecular Physics, $e.g. Al$ and $d_{YbF}$ are mentioned.

The diagram also lists specific particles such as $d_{\mu}$, $d_n$, $d_{Hg}$, and $d_{YbF}$, along with other elements like $d_e$, $d_p, d_d$, $d_{Xe, Ra, ...}$, and $d_{Tl, Fr, ...}$.

The content suggests a discussion on the properties and transitions of these particles and their implications in each respective field of physics.
Particle Physics
Nuclear Physics
Atomic Physics
Molecular Physics

Need many experimental techniques

$\tau \rightarrow \mu \gamma$
$\mu \rightarrow e \gamma$
$\tau \rightarrow \mu \mu \mu$
$\mu \rightarrow eee$
$\pi^0 \rightarrow \mu e$
e.g. Al

(g-2)$_\mu$

$\mu \rightarrow e \gamma$
$\tau \rightarrow \mu \gamma$
$\mu \rightarrow eee$
$\pi^0 \rightarrow \mu e$
e.g. Al

(g-2)$_e$

$\mu \rightarrow e \gamma$
$\tau \rightarrow \mu \gamma$
$\mu \rightarrow eee$
$\pi^0 \rightarrow \mu e$
e.g. Al

(g-2)$_\mu$

$d_\mu$
$d_n$
$d_{Hg}$
$d_{YbF}$
$d_e$
$d_p, d_d$
$d_{Xe, Ra, ...}$
$d_{Ti, Fr, ...}$
## General concept: constrain effective operator coefficients

**Table 1** Bounds on CP- or flavor violating effective operators, expressed as upper limits on their dimensionless coefficients $\epsilon$, scaled to the strength of weak interactions. For more details, in particular the overall normalization convention for the effective operators, see Sect. 3.1.2

<table>
<thead>
<tr>
<th>Observable</th>
<th>Operator</th>
<th>Limit on $\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$EDM</td>
<td>$\overline{e}<em>L \sigma^{\mu\nu} \gamma_5 e_R F</em>{\mu\nu}$</td>
<td>$\leq 2.1 \times 10^{-12}$</td>
</tr>
<tr>
<td>$B(\mu \to e\gamma)$</td>
<td>$\overline{\mu} \sigma^{\mu\nu} e F_{\mu\nu}$</td>
<td>$\leq 3.4 \times 10^{-12}$</td>
</tr>
<tr>
<td>$B(\tau \to \mu\gamma)$</td>
<td>$\overline{\tau} \sigma^{\mu\nu} \mu F_{\mu\nu}$</td>
<td>$\leq 8.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B(K_L^0 \to \mu^\pm e^{\mp})$</td>
<td>$(\overline{\mu} \gamma^\mu P_L e)(\overline{s} \gamma^\mu P_L d)$</td>
<td>$\leq 2.9 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

From:
Raidal, van der Schaaf et al.,
Flavor physics of leptons and dipole moments,
Flavor violating Higgs decays

\[ |Y_{\mu e}| \]

To illustrate complementarity

From:
Harnik, Kopp, Zupan
arXiv:1209.1397
Flavor violating Higgs decays

From: Harnik, Kopp, Zupan
arXiv:1209.1397
One slide on kaons

High NP mass scales accessible for tree-level contributions

Example: $K_L \rightarrow \mu^+e^-$

Dimensional argument:

$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left( \frac{g_X}{g_W} \cdot \frac{M_W}{M_X} \right)^4$$

For $g_X \approx g_W$ and $\mathcal{B} \sim 10^{-12}$,

$M_X \sim 100 \text{ TeV}$

To illustrate the mass reach

See also: European Strategy for PP – unique mass reach also in other rare decays, cLFV and EDMs
Reminder: cLFV is small in SM

- Only known LFV so far: neutrino mixing
- Suppressed by \((\delta m_\nu/m_W)^4\) and thus smaller than \(10^{-50}\)
  \(\rightarrow\) SM not observable
- Plenty of room for new physics

Expect from SM:
\[ \text{BR}(\mu-e\gamma) < 10^{-50} \]
Experimentally so far:
\[ < 5.7 \times 10^{-13} \]
Reminder: EDM are small in SM

Leptons: 4\textsuperscript{th} order electro-weak

Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

F. Hoogeveen:  

Expect from SM, approximately:

\[ d_e \leq 10^{-38} \text{ e-cm} \]
\[ d_\mu \leq 10^{-36} \text{ e-cm} \]
\[ d_\tau \leq 10^{-35} \text{ e-cm} \]

Experimentally so far:

\[ d_e < 1 \times 10^{-27} \text{ e-cm} \]
\[ d_\mu < 2 \times 10^{-19} \text{ e-cm} \]
\[ d_\tau < 3 \times 10^{-17} \text{ e-cm} \]
Reminder: EDM are small in SM

Neutron, Proton, ..

Expect from SM: 
\[ d_n < 10^{-30} \text{ e\,cm} \]

Experimentally so far: 
\[ < 2.9 \times 10^{-26} \text{ e\,cm} \]

\[ d_n \sim 10^{-32} - 10^{-34} \text{ e\,cm} \]

[Khriplovich & Zhitnitsky ‘86]
Caveat:
The strong CP problem

$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + \frac{g^2}{32\pi^2} \theta_{QCD} \bar{G}G$$

$$d_n \approx 10^{-16} \text{ e cm} \cdot \theta_{QCD}$$

$$\theta_{QCD} \lesssim 10^{-10}$$

Why is $\theta_{QCD}$ so small?
Reminder: $g-2$ is calculable in SM
(with remarkable precision)

\[
\begin{align*}
\text{QED:} & \quad \gamma \rightarrow \mu^+ \mu^- \gamma \\
& + \gamma \rightarrow e^+ e^- \gamma \\
& + \text{higher order terms} \\
& 11,658,470.57(29) \times 10^{-10} \\
\text{Had:} & \quad \gamma \rightarrow h \mu^+ \mu^- \\
& + \mu^+ \mu^- \rightarrow h \gamma \\
& + \text{higher order terms} \\
& 692.4(6.2) \times 10^{-10} \\
& -10.1(6) \times 10^{-10} \\
& 12(4.0) \times 10^{-10} \\
\text{Weak:} & \quad \gamma \rightarrow W^+ \nu W^- \\
& + 38.9 \\
& \gamma \rightarrow Z \mu^+ \mu^- \\
& -19.4 \\
& \gamma \rightarrow H \mu^+ \mu^- \\
& < 0.1 \\
& \text{1st + 2nd Order Weak} = 15.1(4) \times 10^{-10}
\end{align*}
\]
well known

- International effort continues on the Standard-Model theory value
  - more $e^+e^-$ data for lowest order hadronic contribution (using a dispersion relation)
  - Lattice calculations are underway for both contributions
  - Two photon program at Frascati and BES to help with H-LBL

- Present difference is between 3 and 4 $\sigma$

significant work ongoing
The present best limits on LFV come from PSI muon experiments

$$\mu^+ \rightarrow e^+ee$$
BR $< 1 \times 10^{-12}$
SINDRUM 1988

$$\mu^- + \text{Au} \rightarrow e^- + \text{Au}$$
BR $< 7 \times 10^{-13}$
SINDRUM II 2006

$$\mu^+ \rightarrow e^+ + \gamma$$
BR $< 5.7 \times 10^{-13}$
MEG 2013

[90 % C.L.]
cLFV Searches: Current Situation

The present best limits on LFV come from PSI muon experiments

\[ \mu^+ \rightarrow e^+ee \]
BR < $1 \times 10^{-12}$
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\[ \mu^- + \text{Au} \rightarrow e^- + \text{Au} \]
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\[ \mu^+ \rightarrow e^+ + \gamma \]
BR < $5.7 \times 10^{-13}$
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[90 % C.L.]
Summary Belle $\tau$ LFV results

48 modes searched for, U.L.s around $\sim 10^{-8}$

Schwanda, Lecce, 2013
Belle-II and LHCb upgrade

Activity directly confronts New Physics models of CLFV

Hitlin, Lecce, 2013
Complementarity in muon cLFV

\[ \mu \rightarrow e + \text{jet} \]

\[ B(\mu \rightarrow eee) = 10^{-16} \]

\[ B(\mu \rightarrow e\gamma) = 10^{-14} \]

\[ B(\mu \rightarrow e\gamma) = 10^{-13} \]

\[ B(\mu \rightarrow \text{conv in } ^{27} \text{Al}) = 10^{-18} \]

\[ 10^{000} \text{ TeV} \]

\[ 1000 \text{ TeV} \]

\[ \text{EXCLUDED (90\% CL)} \]

\[ \kappa \]

\[ \text{de Gouvea, Vogel} \]

\[ \text{arXiv:1303.4097} \]
The MEG experiment at PSI ($\mu \rightarrow e \gamma$ decay search at rest)

New results! $< 5.7 \times 10^{-13}$ (90% CL)

End of data taking: September this year
The MEG UPgrade project (approved)

New positron Drift Chamber

New positron Timing counter

Smaller photosensors for the photon detector

Further: improved electronics and full exploitation of the PSI muon beam intensity

MEG upgrade aiming at $< 5 \times 10^{-14}$ sensitivity

Courtesy: A. Baldini
Mu3e Experiment at PSI

Experiment:

- Search for LFV decay: $\mu \rightarrow eee$
- Single event sensitivity better than $10^{-16}$
- Muon rate >$10^9$ per second
- 100 electron tracks within 50ns

Detector Requirements:

- good momentum resolution ($B=1$ T)
- good vertex resolution ($\rightarrow$ accidentals)
- good timing resolution ($\rightarrow$ accidentals)


Courtesy: A. Schoening
Mu3e Experiment at PSI

Mu3e Schedule:
> 2012 prototyping
> 2014 construction
> 2015 first measurements (phase I)
> 2017 full experimental setup (phase II)

Mu3e Phase 2 sensitivity:

- Phase 2 requires installation of the proposed HiMB (High Intensity Muon Beamline) at PSI to provide muon rates $> 2 \cdot 10^9$ per second

Courtesy: A. Schoening
Mu2e at FNAL

- **Charged Lepton Flavor Violation:** Search for $\mu N \rightarrow eN$ at $6 \times 10^{-17}$
  - Quarks and neutrinos violate flavor: why don’t the charged leptons?
  - Uniquely sensitive to both SUSY and non-SUSY new physics
  - Complements LHC and probes mass scales to $10^4$ TeV/c^2
  - A powerful discriminator among models

- **Prototyping of Detector and Tests of Superconducting Cable Underway**

- **Civil Construction** to start late 2014

- **Physics data-taking** to start early 2020 for 2-3 years

Courtesy: R. Bernstein
Mu2e Signal Sensitivity

Full G4 detector simulation, background overlay, reconstruction

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-proton capture</td>
<td>0.1 ± 0.06</td>
</tr>
<tr>
<td>Radiative π⁻ capture</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>Beam electrons</td>
<td>0.001 ± 0.001</td>
</tr>
<tr>
<td>μ decay in orbit</td>
<td>0.2 ± 0.06</td>
</tr>
<tr>
<td>Cosmic ray induced</td>
<td>0.025 ± 0.025</td>
</tr>
<tr>
<td>μ decay in flight</td>
<td>0.01 ± 0.005</td>
</tr>
<tr>
<td>Total</td>
<td>0.4 ± 0.1</td>
</tr>
</tbody>
</table>

\[ R_{\mu e} \text{ SES} = 2 \times 10^{-17} \]

Courtesy: R. Bernstein
COMET \((l < 10^{-14}; ll < 10^{-16})\)

Search for muon to electron conversion
Adopted staging approach
Phase-I: \(< 10^{-14}\)
Phase-II: \(< 10^{-16}\)
Budget for phase-I is approved!! to start the measurement in 2016.

DeeMe \((Br < 10^{-14})\)

Search for muon to electron conversion
Share H-Line at MLF with g-2/EDM
Partially funds from TRIUMF

J-PARC

Courtesy: N. Saito
Resonant Laser Ionization of Muonium ($\sim 10^6 \int \pm \text{ s}$)

Surface muon beam (28 MeV/c, $4 \times 10^8 /\text{s}$)  
Muonium Production (300 K $\sim 25 \text{ meV}$)

Super Precision Magnetic Field (3T, ~1ppm local precision)

66 cm diameter

Simulated “Wiggle Plot” for This Experiment

$P_{\mu^+} = 100\%$, $N_{e^+} = 1.5 \times 10^{12}$  
$\Delta \omega_a / \omega_a = 0.1 \text{ ppm}$

Courtesy: N. Saito
FNAL muon g-2 status

• Superconducting coils are now in Illinois, will arrive at Fermilab on Friday 26/7
• Building under construction
• Half the steel is at Fermilab

http://muon-g-2.fnal.gov/bigmove/

Unloading the barge in Lemont Illinois
Timeline

• Building completed 1/2014
• Remaining steel will arrive just after the building is complete
• Re-assembly will take between 12-18 months
• Ring together and powered early 2015
  – magnet shimming expected to take 6 to 12 months
• Beamline construction begins in 2015
• **Data collection 2016**
EDM Searches: Current Situation

- neutron  \( d_n < 2.9 \times 10^{-26} \text{ e cm} \)  PRL97(2006)131801
- Hg-199  \( d_{\text{Hg}} < 3.1 \times 10^{-29} \text{ e cm} \)  PRL102(2009)101601
  \( \rightarrow d_p < 8 \times 10^{-25} \text{ e cm}^* \)
- Xe-129  \( d_{\text{Xe}} < 6 \times 10^{-27} \text{ e cm} \)  PRL86(2001)22
- Tl-205  \( d_{\text{Tl}} < 9 \times 10^{-25} \text{ e cm} \)  PRL88(2002)071805
  \( \rightarrow d_e < 1.6 \times 10^{-27} \text{ e cm}^* \)
- YbF  \( d_e < 1.05 \times 10^{-27} \text{ e cm}^* \)  Nature473(2011)493
- muon  \( d_\mu < 1.8 \times 10^{-19} \text{ e cm} \)  PRD80(2009)052008

* using the '1-miracle assumption', i.e. no cancelations with other CP-odd effects.

Only for one fundamental fermion, the muon, a direct EDM-limits exist.

Many people consider the neutron almost fundamental -- so we may perhaps count two direct basic EDM limits.

Pospelov, Ritz, Ann. Phys. 318(2005)119 for \( M_{\text{SUSY}} = 500 \text{GeV}, \tan \beta = 3 \)
Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
  ~200

- Molecules
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma
  ~50

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale
  ~10

- Ions-Muons
  - @BNL
  - @FZJ
  - @FNAL
  - @J-PARC
  ~200

- Atoms
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto
  ~100

• Rough estimate of numbers of researchers, in total ~500 (with some overlap)
In conclusion: experiments with unique reach

- cLFV with taus will be boosted with Belle-II and LHCb upgrade \( \rightarrow 10^{-9} \)
- cLFV with muons will see a major step forward in the next years @PSI, J-PARC, FNAL \( \rightarrow 5 \times 10^{-14}, 10^{-16}, 10^{-14} \ldots 18 \)
- muon g-2 will be improved @FNAL, J-PARC (need experiment and theory) \( \rightarrow 0.1 \text{ ppm} \)
- many EDM experiments around the world hold promise for improved sensitivities \( \rightarrow n < 5 \times 10^{-28} \text{ ecm}, e < 10^{-28} \text{ ecm}, H g < 5 \times 10^{-30} \text{ ecm}, p < 5 \times 10^{-29} \text{ ecm} \ldots \)

Need more work on consistent theoretical framework for relevant and more global comparisons of HE and LE
Backup
Origin of EDMs

- Origin of EDMs
- QCD
- TeV
- Fundamental CP-odd phases
- $d_\mu$
- $d_e$
- $C_{qe}, C_{qq}$
- $\theta, d_q, d_q, w$
- $g_{\pi NN}$
- Neutron & proton EDMs
- EDMs of nuclei and ions (deuteron, etc.)
- EDMs of paramagnetic atoms & molecules
  - Ti, Cs, YbF, PbO, ThO, HfF, WC
- EDMs of diamagnetic atoms
  - Hg, Xe, Ra, Rn
- Solid state EDM effects
  - GdIG, GdYIG, (EU, Ba)TiO$_3$

Adapted from:
Complex composite systems have constituents and interactions

Paramagnetic atoms

\[ d_{\text{para}}(d_e) \sim 10 \alpha^2 Z^3 d_e \rightarrow d_{\text{Tl}} = -585d_e - 43 \text{ GeV} \times e \frac{C_s^{\text{singlet}}}{\alpha} \]

Paramagnetic molecules

additional enhancement from large internal electric fields of order 10 GV/cm or more, influenced by molecular level structure

Diamagnetic atoms

\[ d_{\text{dia}} \sim 10Z^2 \left( \frac{R_N}{R_A} \right)^2 \tilde{d}_q \]

\[ d_{\text{Hg}} = 7 \times 10^{-3} e (\tilde{d}_u - \tilde{d}_d) + 10^{-2} d_e + \mathcal{O}(C_S, C_{qq}) \]

enhancement factors possible due to atomic state mixing and nuclear deformation.
## International context (nEDMs)

<table>
<thead>
<tr>
<th>Project</th>
<th>Goal (en e.cm)</th>
<th>Result expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>nEDM@PSI</td>
<td>$\sim 5 \times 10^{-27}$</td>
<td>2014</td>
</tr>
<tr>
<td>n2EDM@PSI</td>
<td>$\sim 5 \times 10^{-28}$</td>
<td>2014, 2020</td>
</tr>
<tr>
<td>PNPI@ILL</td>
<td>$\sim 1 \times 10^{-26}$</td>
<td>2014</td>
</tr>
<tr>
<td>CryoEDM@ILL</td>
<td>$\sim 3 \times 10^{-27}$</td>
<td>2016</td>
</tr>
<tr>
<td>nEDM@SNS</td>
<td>$\sim 3 \times 10^{-28}$</td>
<td>2020</td>
</tr>
<tr>
<td>nEDM@TRIUMF</td>
<td>$\sim 3 \times 10^{-27}$</td>
<td>2017, 2020</td>
</tr>
<tr>
<td>nEDM@TUM</td>
<td>$\sim 5 \times 10^{-28}$</td>
<td>2018</td>
</tr>
</tbody>
</table>
The SUSY CP problem
(for neutron and electron!)

\[ d_n \approx 10^{-23} \, e \, cm \left( \frac{300 \, \text{GeV}/c^2}{M_{\text{SUSY}}} \right)^2 \sin \phi_{\text{SUSY}} \]

Why is \( \phi_{\text{SUSY}} \) so small?

(this is testing \( M \) already to 10TeV and you may also ask: why are the masses so huge?)

Pospelov, Ritz, Ann. Phys. 318(2005)119 for \( M_{\text{SUSY}} = 500 \text{GeV} \), \( \tan \beta = 3 \)
Complementarity with high energy:
Electroweak baryogenesis in MSSM

Cirigliano, Li, Profumo, Ramsey-Musolf

could eventually become completely excluded by LHC plus next generation nEDM

see: JHEP 1001:002,2010
# Muon cLFV: Status

<table>
<thead>
<tr>
<th>Mode</th>
<th>Upper limit (90% C.L.)</th>
<th>Year</th>
<th>Exp./Lab.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \to e^+\gamma$</td>
<td>$5.7 \times 10^{-13}$</td>
<td>2013</td>
<td>MEG / PSI</td>
</tr>
<tr>
<td>$\mu^+ \to e^+e^+e^-$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>1988</td>
<td>SINDRUM I / PSI</td>
</tr>
<tr>
<td>$\mu^+e^- \leftrightarrow \mu^-e^+$</td>
<td>$8.3 \times 10^{-11}$</td>
<td>1999</td>
<td>PSI</td>
</tr>
<tr>
<td>$\mu^-Ti \to e^-Ti$</td>
<td>$6.1 \times 10^{-13}$</td>
<td>1998</td>
<td>SINDRUM II / PSI</td>
</tr>
<tr>
<td>$\mu^-Ti \to e^+Ca^*$</td>
<td>$3.6 \times 10^{-11}$</td>
<td>1998</td>
<td>SINDRUM II / PSI</td>
</tr>
<tr>
<td>$\mu^-Pb \to e^-Pb$</td>
<td>$4.6 \times 10^{-11}$</td>
<td>1996</td>
<td>SINDRUM II / PSI</td>
</tr>
<tr>
<td>$\mu^-Au \to e^-Au$</td>
<td>$7 \times 10^{-13}$</td>
<td>2006</td>
<td>SINDRUM II / PSI</td>
</tr>
</tbody>
</table>

Adapted from:
Raidal, van der Schaaf et al.,
Flavor physics of leptons and dipole moments,
Model Comparison ($\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$)

Effective charge LFV Lagrangian ("toy" model) (Kuno and Okada)

\[ L = \frac{m_\mu}{\Lambda^2 (1 + \kappa)} H_{\text{dipole}} + \frac{\kappa}{\Lambda^2 (1 + \kappa)} J_{\sigma}^{e\mu} J_{\sigma,ee} \]

\[ \Lambda = \text{effective mass scale} \]
\[ \kappa = \text{"parameter" of toy model} \]

\[ \frac{BR(\mu^+ \rightarrow e^+ e^- e^+)}{BR(\mu^+ \rightarrow e^+ \gamma)} \sim 0.006 \]
μ→e Conversion

- ‘Dipole’ terms
  - i.e. SUSY
  - Also mediates μ→eγ
- ‘Contact’ terms
  - Direct coupling between quarks and leptons
  - Only accessible by μN→eN
- Effective Lagrangian
  - contact κ, mass scale Λ

\[ L = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}R\sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma^\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L \]

R. Bernstein
Table 4  Bounds at 90% CL on selected lepton flavor violating decays of pseudoscalar mesons

<table>
<thead>
<tr>
<th>Channel</th>
<th>Upper limit</th>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow \mu^+e^-$</td>
<td>$3.59 \times 10^{-10}$</td>
<td>KTeV</td>
<td>75</td>
</tr>
<tr>
<td>$\rho \rightarrow \mu^+e^-$</td>
<td>$6 \times 10^{-6}$</td>
<td>Saturne SPES2</td>
<td>76</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^0 \mu^+e^-$</td>
<td>$7.56 \times 10^{-11}$</td>
<td>KTeV</td>
<td>75</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow 2\pi^0 \mu^+e^-$</td>
<td>$1.64 \times 10^{-10}$</td>
<td>KTeV</td>
<td>75</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \mu^+e^-$</td>
<td>$4.7 \times 10^{-12}$</td>
<td>BNL E871</td>
<td>74</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^+e^-$</td>
<td>$1.3 \times 10^{-11}$</td>
<td>BNL E865, E777</td>
<td>73</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+\mu^+e^-$</td>
<td>$3.4 \times 10^{-5}$</td>
<td>Fermilab E791</td>
<td>77</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+\mu^+e^-$</td>
<td>$6.8 \times 10^{-5}$</td>
<td>Fermilab E791</td>
<td>77</td>
</tr>
<tr>
<td>$D^0 \rightarrow \mu^+e^-$</td>
<td>$8.1 \times 10^{-7}$</td>
<td>BaBar</td>
<td>78</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\mu^+e^-$</td>
<td>$6.1 \times 10^{-4}$</td>
<td>Fermilab E791</td>
<td>77</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+\mu^+e^-$</td>
<td>$6.3 \times 10^{-4}$</td>
<td>Fermilab E791</td>
<td>77</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+e^-$</td>
<td>$9.2 \times 10^{-8}$</td>
<td>BaBar (347 fb$^{-1}$)</td>
<td>79</td>
</tr>
<tr>
<td>$B^0 \rightarrow \tau^+e^-$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>CLEO (9.2 fb$^{-1}$)</td>
<td>80</td>
</tr>
<tr>
<td>$B^0 \rightarrow \tau^+\mu^-$</td>
<td>$3.8 \times 10^{-5}$</td>
<td>CLEO (9.2 fb$^{-1}$)</td>
<td>80</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+e^+\mu^+$</td>
<td>$9.1 \times 10^{-8}$</td>
<td>BaBar (208 fb$^{-1}$)</td>
<td>81</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+e^+\tau^+$</td>
<td>$7.7 \times 10^{-5}$</td>
<td>BaBar (348 fb$^{-1}$)</td>
<td>82</td>
</tr>
<tr>
<td>$B_{s}^0 \rightarrow e^+\mu^+$</td>
<td>$6.1 \times 10^{-6}$</td>
<td>CDF (102 pb$^{-1}$)</td>
<td>83</td>
</tr>
</tbody>
</table>
Searching for $\mu \rightarrow e\gamma$:

MEG collaboration

$< 5.7 \times 10^{-13}$ (90% CL)

PRL110(2013)201801

MEG upgrade aiming at $< 5 \times 10^{-14}$ sensitivity
Impact on NP Models
MEG
Detector performance and Data sample

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resolution (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Energy (%)</td>
<td>1.7 (depth &gt; 2 cm), 2.4</td>
</tr>
<tr>
<td>Gamma Timing (psec)</td>
<td>67</td>
</tr>
<tr>
<td>Gamma Position (mm)</td>
<td>5 (u, v), 6 (w)</td>
</tr>
<tr>
<td>Gamma Efficiency (%)</td>
<td>63</td>
</tr>
<tr>
<td>Positron Momentum (KeV)</td>
<td>305 (core = 85%)</td>
</tr>
<tr>
<td>Positron Timing (psec)</td>
<td>108</td>
</tr>
<tr>
<td>Positron Angles (mrad)</td>
<td>7.5 (Φ), 10.6 (θ)</td>
</tr>
<tr>
<td>Positron Efficiency (%)</td>
<td>40</td>
</tr>
<tr>
<td>Gamma-Positron Timing (psec)</td>
<td>127</td>
</tr>
<tr>
<td>Muon decay point (mm)</td>
<td>1.9 (z), 1.3 (y)</td>
</tr>
</tbody>
</table>

Data statistics

<table>
<thead>
<tr>
<th>Year</th>
<th>Normalization-factor/10^12</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>1</td>
</tr>
<tr>
<td>2009</td>
<td>2</td>
</tr>
<tr>
<td>2010</td>
<td>3</td>
</tr>
<tr>
<td>2011</td>
<td>4</td>
</tr>
<tr>
<td>2012</td>
<td>5</td>
</tr>
<tr>
<td>2013</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>μ stopped (10^14)</th>
<th>Sensitivity (10^-12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009+10</td>
<td>1.75x10^{14}</td>
<td>1.3x10^{-12}</td>
</tr>
<tr>
<td>2011</td>
<td>1.85x10^{14}</td>
<td>1.1x10^{-12}</td>
</tr>
<tr>
<td>2009+10+11</td>
<td>3.60x10^{14}</td>
<td>7.7x10^{-13}</td>
</tr>
</tbody>
</table>

This result
Searching for $\mu \rightarrow eee$:

**Mu3e collaboration**

search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity $\sim 10^{-16}$ (PeV scale) using the most intense DC muon beam ($p \sim 28$ MeV/c) in the world

→ observe $\sim 10^{17}$ $\mu$ decays (over a reasonable time scale)

rate $\sim 2 \times 10^9$ $\mu$ decays / sec

→ build a detector capable of measuring $2 \times 10^9$ $\mu$ decays / sec

Staged approach:

first measurement 2015-17 aiming at $10^{-15}$
Mu3e Baseline Design

search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity $\sim 10^{-16}$ (PeV scale) using the most intense DC muon beam ($p \sim 28 \text{ MeV}/c$) in the world → observe $\sim 10^{17} \mu$ decays (over a reasonable time scale) rate $\sim 2 \times 10^9 \mu$ decays / sec → build a detector capable of measuring $2 \times 10^9 \mu$ decays / sec

Mu3e Baseline Design

- 200 M HV-MAPS (Si pixels w/ embedded ampli.) channels
- $\sim 10^k$ ToF channels (SciFi and Tiles)

acceptance $\sim 70\%$ for $\mu \rightarrow eee$ decay (3 tracks!)

Phase I

surface $\mu$
$p \sim 28 \text{ MeV}/c$
Backgrounds

irreducible backgrounds: accidental backgrounds

signal

\[ \sum_i p_i = 0 \]
\[ \sum_i E_i = m_\mu \]
\[ \Delta t_{\text{tracks}} \sim 0 \]

irreducible backgrounds

accidental backgrounds

\[ \text{BR}(\mu \rightarrow \text{eee} \nu \nu) = 3.4 \times 10^{-5} \]

to suppress backgrounds

precise kinematics (p and E_{\text{TOT}} resolution):
\[ \Delta m_\mu < 0.5 \text{ MeV/c}^2 \]
precise timing (ToF): \[ \Delta t \sim 100 \text{ ps} \]
precise vertexing: \[ \Delta x \sim 0.1 \text{ mm} \]
Staged Approach

Phase IA
rate $\leq 10^7 \mu / s$

only central pixel

Phase IB
rate $\sim 10^8 \mu / s$

+ inner recurl sta.
+ time of flight

Phase II
rate $\sim 10^9 \mu / s$

+ outer recurl sta.
Next Generation Facilities & cLFV experiments

J-PARC JP

J-PARC cLFV $\mu \rightarrow e$ Conversion (Pulsed!)
Staged Expt:
(i) COMET (2019-2020) \(10^{11} \mu/s\)
(ii) PRIME/PRISM (>2020) \(10^{11-12} \mu/s\)

FNAL USA

FNAL cLFV $\mu \rightarrow e$ Conversion (Pulsed!)
Staged Expt:
(i) Mu2e (2019-2020) \(5 \cdot 10^{10} \mu/s\)
(ii) Project X Mu2e (>2022) \(2 \cdot 10^{12} \mu/s\)

HiMB@PSI

PSI cLFV $\mu \rightarrow e \gamma \mu \rightarrow 3e$ (DC)
Staged Expt:
(i) Mu3e I (2014-2017) \(\pi E 5 \Rightarrow 2 \cdot 10^8 \mu^+ /s\)
(ii) Mu3e II (>2017) SINO >10^{10} \mu^+ /s
PSI 2013

3rd Workshop on the Physics of Fundamental Symmetries and Interactions at low energies and the precision frontier

September 9–12, 2013
Paul Scherrer Institut, Switzerland

www.psi.ch/psi2013

Topics:
- Low energy precision tests of the Standard Model
- Fundamental physics with e, μ, n, p, nuclei, atoms
- Searches for symmetry violations
- Searches for new forces
- Precision measurements of fundamental constants
- Searches for permanent electric dipole moments
- Exotic atoms and molecules
- Precision magnetometry
- Advanced muon and ultracold neutron sources
- Advanced detector technologies

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