Observations on Lepton Flavor Violation Experiments

Doug Bryman

1st Conference on Charged Lepton Flavor Violation
Lecce 2013
15-16\textsuperscript{th} Century Explorations into Unknown Waters

Christoforo Colombo – 1492 search for East Indies…

Discovered

Amerigo Vespucci – 1499 search for Asia …

Discovered

Ponce de Leon – 1513 search for the Fountain of Youth …

Discovered

D. Bryman   CLFV, Lecce, Italy
21st Century Explorations Into Unknown Waters

- High energy
- Dark matter
- Dark energy
- Charged lepton flavor violation, EDMs, and CP violation

Vague but well motivated ideas of what to look for --- really searching in the dark....

Here be dragons.

The 1265 Psalter world map.
1st Conference on Charged Lepton Flavor Violation
Conference Summary

Day 1+ Theory:
Grossman, Theory of charged leptons
Lavignac, CLFV Model Constraints from MEG, BELLE/BaBar and LHCb
Redi, Lepton Violation in non-SUSY
Mannel, Possibilities with Angular Distribution and Polarization
Shadmi, Model Constraints from CLFV at Muons and Taus
Paradisi, Interrelationships among g-2, EDMs and CLFV
Hambye, Lepton flavor violation in low-energy see-saw models
Czarnecki, Calculations of Radiative Backgrounds
Vicente, Charged Lepton Flavor Violation beyond minimal SUSY

Conclusion:
No tail, no definite theory, but if you find it, we’ll make one!

D. Bryman  CLFV, Lecce, Italy
Standard Model: A great story … but definitely not the whole story…

- **Cosmological issues**: inflation, dark matter, dark energy, matter anti-matter asymmetry…
- **Theoretical issues**: gravity (CC), neutrino mass, *flavor*, hierarchy problem, strong CP, ….
The Flavor Puzzle
Experiments ahead of theory

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>e</td>
</tr>
<tr>
<td>c</td>
<td>μ</td>
</tr>
<tr>
<td>t</td>
<td>τ</td>
</tr>
<tr>
<td>d</td>
<td>ν&lt;sub&gt;e&lt;/sub&gt;</td>
</tr>
<tr>
<td>s</td>
<td>ν&lt;sub&gt;μ&lt;/sub&gt;</td>
</tr>
<tr>
<td>b</td>
<td>ν&lt;sub&gt;τ&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

- Weak states ≠ mass states
- Quark, lepton flavors not conserved

Unexplained observations (no theory of flavor):
- Three (“identical”) generations
- Huge mass differences between and within the generations
- Universality of interactions
- CP violation
- Symmetry between lepton and quark sectors (GUT, scale?)
### Exotic Searches

New physics if seen. Experiments limit how far we can go.

- $\mu \rightarrow e\gamma, 3e$
- $\tau \rightarrow e\gamma, \mu\gamma$
- $\mu^- N \rightarrow e^- N$
- $K_L^0 \rightarrow \mu e$

<table>
<thead>
<tr>
<th>$\beta\beta_{0\nu}$</th>
<th>Lepton Number Violation</th>
</tr>
</thead>
</table>

### BSM Physics

New physics if deviations from well-calculated SM predictions occur. Theory limits how far we can go.

- $e, \mu, n \ldots edm$
- $(g - 2)_\mu$
- $\pi^+(K^+) \rightarrow e^+\nu$, $\pi^+(K^+) \rightarrow \mu^+\nu$
- $\tau^+ \rightarrow e^+\nu\nu$, $\tau^+ \rightarrow \mu^+\nu\nu$

Universality

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$
- $B \rightarrow \mu\mu, b \rightarrow s\gamma, \ldots$

### Lepton Flavor Violation

- $e^-, \mu^- 

### Lepton Number Violation

- $\beta\beta_{0\nu}$
Example: Universality Tests Sensitive to high mass scales

$$R_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu+\pi \rightarrow e\gamma)}{\Gamma(\pi \rightarrow \mu\nu+\pi \rightarrow \mu\nu\gamma)}$$

(a) \hspace{2cm} (b) \hspace{2cm} (c)

1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m_H^2}{m_e(m_d+m_u)} \sim \left(\frac{1\text{TeV}}{\Lambda_{eP}}\right)^2 \times 10^3$

0.05% Measurement $R_{e/\mu} \rightarrow \Lambda_{eP} > 1000$ TeV

Charged Higgs mass $m_{H^\pm} \sim 200$ TeV probed.

Non-standard Higgs couplings

D. Bryman, CLFV, Lecce, Italy

| $g_{\mu}/g_e$ |
|---|---|
| 0.9970 ± 0.0100 | (LEP EW WG $W \rightarrow \mu \bar{\nu}_\mu/(W \rightarrow e \bar{\nu}_e)$) |
| 1.0010 ± 0.0025 | (FlaviaNet $K \rightarrow \pi \mu \bar{\nu}_\mu/(K \rightarrow \pi e \bar{\nu}_e)$) |
| 0.9980 ± 0.0025 | (NA62, KLOE $K \rightarrow \mu \bar{\nu}_\mu/(K \rightarrow e \bar{\nu}_e)$) |
| 1.0017 ± 0.0015 | (TRIUMF, PSI $\pi \rightarrow \mu \bar{\nu}_\mu/(\pi \rightarrow e \bar{\nu}_e)$) |
| 1.0018 ± 0.0014 | (HFAG Fit $\tau \rightarrow \mu \bar{\nu}_\mu \bar{\nu}_\mu/(\tau \rightarrow e \bar{\nu}_e \bar{\nu}_e)$) |
At low energy, BSM physics is described by local operators; LFV and dipole moments probe strengths of different operators and their flavor structures.

**Effective Operators** for CP-violating EDMs and LFV processes:

\[
\bar{l}_i \sigma^{\mu\nu} \gamma_5 l_j F_{\mu\nu}^{em} \quad l_i \sigma^{\mu\nu} l_j F_{\mu\nu}^{em} \quad \bar{l}_i \Gamma^a l_j \bar{q}_k \Gamma^a q_l \quad \bar{l}_i \Gamma^a l_j \bar{l}_k \Gamma^a l_l
\]

with dimensionless coefficients \( \epsilon \sim \frac{M_W^2}{M_{NP}^2} \frac{g_{NP}^2}{g_W^2} \delta_{CPV} \delta_{mix} \)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Operator</th>
<th>Limit on ( \epsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>eEDM</td>
<td>( \bar{e} \sigma^{\mu\nu} \gamma_5 e R F_{\mu\nu} )</td>
<td>( \leq 1.1 \times 10^{-3} )</td>
</tr>
<tr>
<td>B(( \mu \rightarrow e\gamma ))</td>
<td>( \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} )</td>
<td>( \leq 1.4 \times 10^{-4} )</td>
</tr>
<tr>
<td>B(( \tau \rightarrow \mu\gamma ))</td>
<td>( \bar{\tau} \sigma^{\mu\nu} \mu F_{\mu\nu} )</td>
<td>( \leq 2.2 \times 10^{-2} )</td>
</tr>
<tr>
<td>B(( K_L^0 \rightarrow \mu^\pm e^\mp ))</td>
<td>( (\bar{\mu} \gamma^\mu P_L e)(\bar{\sigma} \gamma^\mu P_L d) )</td>
<td>( \leq 2.9 \times 10^{-7} )</td>
</tr>
</tbody>
</table>

Lepton Flavor Violation

Neutrino oscillations → lepton family numbers not conserved

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

**SM**

\[
\text{BR}(\mu^- \rightarrow e^- \gamma)_{\text{SM}} \propto \frac{m_{\nu}\nu}{m_W} \approx 10^{-54}
\]

**SUSY**

\[
\text{BR}(\mu^- \rightarrow e^- \gamma)_{\text{SUSY}} \approx 10^{-5} \frac{\Delta m_{\tilde{\nu}}^2}{m_{\tilde{\nu}}^2} \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^4 \tan^2 \beta \approx 10^{-13}
\]

- Observation means new physics.
- Some SUSY models predict \( \text{BR}(\mu \rightarrow e \gamma) \) near the experimental limit (always!). CLFV may also be observable at the LHC (Shadmi).

Sensitivity to new physics \( \sim \frac{1}{M_H^4} \) with \( M_H \sim 1 - 100 \text{ TeV} \)

D. Bryman CLFV, Lecce, Italy
\( \mu \rightarrow e\gamma \) and \( \mu \rightarrow e \) Conversion Test Different Operators

Target-dependence of \( \mu \rightarrow e \) rate

Theory uncertainties cancel in ratios
Model discriminating power by Measuring different processes.

Two operators:

\[ \mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa + 1) \Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa + 1) \Lambda^2} \bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f \]

\( \kappa \) controls relative strength of dipole vs vector operator

There may also be important connections between models for CLFV, g-2, and neutrino mass generation e.g. via Seesaw types I, II, III..

Paradisi, Hambye
Flavor Physics Testing COMPOSITE HIGGS MODELS

Elementary → Composite

$\mu e$ Conversion vs $\mu \rightarrow e\gamma$

Randall Sundrum Model
Warped extra dimensions

$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ vs $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Some parameters are not viable anymore.

Large parameter space open.

D. Bryman  CLFV, Lecce, Italy
1st Conference on Charged Lepton Flavor Violation
Conference Summary

Day 2-3 Experiments
Sawada, MEG: Status and Upgrades
Berger, Mu->3e
Brown, Mu2e
Edmonds, COMET Stage 1 and 2
Natori, DeeMe
Goudzovski, Kaon System: Rare Decay Experiments
Hitlin, CLFV at BaBar
Schawanda, CLFV at BELLE and BELLE-II
Liu, CLFV at ATLAS
Lusito, CLFV at CMS
Khanji, Charged Lepton Flavor Violation at LHCb
Tschirhart, Future Facilities

Summary:

"Hope springs eternal"
but
"Wishing does not make a poor man rich."

(Arabian Proverb)
History of Some Rare Decay Experiments

Lepton Flavor Violation

From Marciano, Mori, Roney 2010

Hincks, Pontecorvo

D.B. Thesis

$\mu \rightarrow e\gamma$ 1977

TRIUMF TPC (1987)

KEK Belle

PSI Sindrum II (2006)

PSI MEG (2013)

Future: Many new experiments coming.

D. Bryman  CLFV, Lecce, Italy

90% CL
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Present limit</th>
<th>Future Possibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \rightarrow e^+\gamma$</td>
<td>$&lt; 5.7 \times 10^{-13}$</td>
<td>$6 \times 10^{-14}$ (PSI)</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+e^+e^-$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
<td>$10^{-16}$ (PSI)</td>
</tr>
<tr>
<td>$\mu^- Ti \rightarrow e^- Ti$</td>
<td>$&lt; 4.6 \times 10^{-12}$</td>
<td>$10^{-14} \rightarrow 10^{-16}$</td>
</tr>
<tr>
<td>$\mu^- Au \rightarrow e^- Au$</td>
<td>$&lt; 7 \times 10^{-13}$</td>
<td>(Fermilab, JPARC)</td>
</tr>
<tr>
<td>$\mu^+e^- \rightarrow \mu^-e^+$</td>
<td>$&lt; 8.3 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow e\gamma$</td>
<td>$&lt; 1.1 \times 10^{-7}$</td>
<td>$&lt; 10^{-9}$ (KEK Belle II)</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\gamma$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
<td>~10^{-9} LHCb</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$</td>
<td>$&lt; 2.1 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow eee$</td>
<td>$&lt; 3.6 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \mu e$</td>
<td>$&lt; 8.6 \times 10^{-9}$</td>
<td>$10^{-11}$ NA62</td>
</tr>
<tr>
<td>$K^0L \rightarrow \mu e$</td>
<td>$&lt; 4.7 \times 10^{-12}$</td>
<td>Project X (?)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^+e^-$</td>
<td>$&lt; 2.1 \times 10^{-10}$</td>
<td>$10^{-12}$ NA62</td>
</tr>
<tr>
<td>$K^0L \rightarrow \pi^0\mu^+e^-$</td>
<td>$&lt; 3.1 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$Z^0 \rightarrow \mu e$</td>
<td>$&lt; 1.7 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$Z^0 \rightarrow te$</td>
<td>$&lt; 9.8 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$Z^0 \rightarrow \tau\mu$</td>
<td>$&lt; 1.2 \times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

D. Bryman  CLFV, Lecce, Italy
LFV $\tau$ Decays
Joining the LFV Club

B(τ⁻ → μ⁺μ⁻μ⁻) < 8.3(10.2) × 10⁻⁸ at 90% (95%) CL
B(τ⁻ → pμ⁺μ⁻) < 4.6(5.9) × 10⁻⁷ at 90% (95%) CL
B(τ⁻ → pμ⁻μ⁻) < 5.4(6.9) × 10⁻⁷ at 90% (95%) CL

B(D⁺ → π⁻μ⁺μ⁺) < 2.2(2.5) × 10⁻⁸ at 90% (95%) CL
B(Dₛ → π⁻μ⁺μ⁺) < 1.2(1.4) × 10⁻⁷ at 90% (95%) CL

B(B⁻ → D⁺μ⁻μ⁻) < 6.9 × 10⁻⁷ at 95% CL
B(B⁻ → D⁺μ⁻μ⁻) < 2.4 × 10⁻⁶ at 95% CL
B(B⁻ → π⁺μ⁻μ⁻) < 1.3 × 10⁻⁸ at 95% CL
B(B⁻ → D⁺μ⁻μ⁻) < 5.8 × 10⁻⁷ at 95% CL
B(B⁻ → D⁰π⁺μ⁻μ⁻) < 1.5 × 10⁻⁶ at 95% CL

B. Khanji, LHCb (Milano-Bicocca, INFN)

LHCb

B. Khanji, LHCb (Milano-Bicocca, INFN)
## Cautionary Tales

<table>
<thead>
<tr>
<th>LFV Experiments</th>
<th>Limit Reached</th>
<th>Goal; (Result/Goal)</th>
<th>“Comments”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Badertscher et al. 1982 $\mu\rightarrow e$</td>
<td>$7 \times 10^{-11}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIUMF TPC Ahmad et al. 1987 $\mu\rightarrow e$</td>
<td>$4.6 \times 10^{-12}$</td>
<td>$2 \times 10^{-12}$ (2)</td>
<td>Data collection took 5x as long as originally guessed (1 month!)</td>
</tr>
<tr>
<td>SINDRUM II Bertl et al. 2006 $\mu\rightarrow e$</td>
<td>$7 \times 10^{-13}$ Au</td>
<td>“10$^{-14}$” (1987)-$3 \times 10^{-14}$ (1993) “engineering” Ti (&gt;60)</td>
<td>Flux lower by 10; pion suppression device didn’t work; unanticipated high electron bkg.; shorter running.</td>
</tr>
<tr>
<td>MEGA Ahmed et al. 2002 $\mu\rightarrow e\gamma$</td>
<td>$1.2 \times 10^{-11}$</td>
<td>0.9-$4 \times 10^{-13}$ “engineering” (133-35)</td>
<td>Death by a thousand blows to acceptance</td>
</tr>
</tbody>
</table>
Case Study I: MEGA at LAMPF

\[ B = \left( \frac{R_\mu}{d} \Delta t \right) \left( \frac{\Delta E_e}{m_\mu/2} \right) \left( \frac{\Delta E_\gamma}{15m_\mu/2} \right)^2 \left( \frac{\Delta \theta}{2} \right)^2 f(\theta_\gamma) \eta_{\text{IBV}}. \]

TABLE VII. The contributions to the signal sensitivity of the MEGA experiment at the design stage and after a complete analysis of the data.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Designed</th>
<th>Achieved</th>
<th>Degradation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{e\gamma} ) (90% C.L.)</td>
<td>( \leq 2.3 )</td>
<td>( \leq 5.1 )</td>
<td>2.2</td>
</tr>
<tr>
<td>( \Omega/4\pi )</td>
<td>0.42</td>
<td>0.31</td>
<td>1.4</td>
</tr>
<tr>
<td>( \epsilon_e )</td>
<td>0.95</td>
<td>0.53</td>
<td>1.8</td>
</tr>
<tr>
<td>( \epsilon_\gamma )</td>
<td>0.051</td>
<td>0.024</td>
<td>2.1</td>
</tr>
<tr>
<td>( N_s )</td>
<td>( 3.6 \times 10^{14} )</td>
<td>( 1.2 \times 10^{14} )</td>
<td>3.0</td>
</tr>
<tr>
<td>Total factor</td>
<td></td>
<td></td>
<td>34.9</td>
</tr>
</tbody>
</table>

TABLE VIII. The contributions to the background sensitivity of the MEGA experiment at the design stage and after a complete analysis of the data.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Designed</th>
<th>Achieved</th>
<th>Degradation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_\mu ) (MHz)</td>
<td>30.0</td>
<td>15.0</td>
<td>0.5</td>
</tr>
<tr>
<td>( t_{e\gamma} ) (ns)</td>
<td>0.8</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>( E_e ) (MeV)</td>
<td>0.25</td>
<td>0.54</td>
<td>1.5</td>
</tr>
<tr>
<td>( E_\gamma ) (MeV)</td>
<td>1.7</td>
<td>1.730</td>
<td>1.6</td>
</tr>
<tr>
<td>( \theta_{e\gamma} ) (deg)</td>
<td>1.0</td>
<td>1.9</td>
<td>3.6</td>
</tr>
<tr>
<td>( \theta_\gamma ) (deg)</td>
<td>10.0</td>
<td>10.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( \eta_{\text{IBV}} )</td>
<td>0.2</td>
<td>1.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Total factor</td>
<td></td>
<td></td>
<td>43.3</td>
</tr>
</tbody>
</table>
Case study II: SINDRUM II PSI

- Proposed $10^8$ stops; (muE1) beam was only $10^7$
- Designed “PMC” to kill pions; simulated; swamped unexpectedly by electrons; solenoid took years longer to obtain.
- Eventually went to very low momentum (50 MeV/c) killing pions by range; pion background persisted.
- Final result obtained in a couple of months; group had dispersed….” could have done better”….
Remarks: How to lose a factor 10 (100...) in a LFV experiment?

Tension between needing high rates and high sensitivities.

• Optimistic resolutions – excessive rates or beam contamination?
• Optimistic acceptances – extra losses due to cuts?
• Missing background sources e.g. due to high energy production or multiple low probability events ...
• Cosmic rays and other effects?
• Fill in your own....
Dedicated detector with asymmetric coverage ($\Omega_{\text{MEG}}/4\pi = 11\%$):

1. Liquid Xenon photon calorimeter with excellent position, time and energy resolutions
2. Low-mass positron spectrometer with gradient B-field for fast positron sweep out
3. Stable, well monitored & calibrated detector (arsenal of calibration & monitoring tools)
4. High performance DAQ system (multi-GHz waveform digitization of nearly all 3k channels)
• Proposal (1999): goal \(<2\times10^{-14}\) (2.2\times10^7 \text{ s})
• 2013 Result: \(<5.7\times10^{-13}\)
• New goal (~2020): \(<6\times10^{-14}\)

- 3x10^7 \mu/\text{sec, 100\% duty factor}
- LXe for efficient \(\gamma\) detection
- Solenoidal magnetic spectrometer
MEG  Current result (2013)  
B <5.7 x 10^{-13}  (90\% c.l.)  
(Additional data to be analyzed)

signal PDF contours at 1, 1.64 and 2 sigma

Data 2009-2011  
D. Bryman    CLFV, Lecce, Italy
$\mu \rightarrow 3e$ at PSI: Goal $<10^{-16}$

Mu3e proposal

Phase I uses MEG beamline to provide $\sim 10^8 \mu^+/s$ to get to $10^{-15}$

Phase II assumes construction of new high intensity beam at PSI spallation neutron source to reach $10^{-16}$

50$\mu$m Monolithic active pixel (MAP) detectors

D. Bryman   CLFV, Lecce, Italy
Figure 17.2: Reconstructed mass resolution for signal events in the phase IA configuration.

Figure 17.9: Internal conversion background (colours) and signal (black dots) in the acoplanar momentum - reconstructed mass plane for the phase IA detector configuration.

<table>
<thead>
<tr>
<th></th>
<th>Phase IA</th>
<th>Phase IB</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Backgrounds:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Michel</td>
<td>0</td>
<td>&lt; 2.5 \times 10^{-18}</td>
<td>5 \times 10^{-18}</td>
</tr>
<tr>
<td>$\mu \rightarrow eee\nu$</td>
<td>1 \times 10^{-16}</td>
<td>1 \times 10^{-17}</td>
<td>1 \times 10^{-17}</td>
</tr>
<tr>
<td>$\mu \rightarrow eee\nu$ and accidental Michel</td>
<td>0</td>
<td>&lt; 2.5 \times 10^{-21}</td>
<td>7.5 \times 10^{-18}</td>
</tr>
<tr>
<td>Total Background</td>
<td>1 \times 10^{-16}</td>
<td>1 \times 10^{-17}</td>
<td>2.3 \times 10^{-17}</td>
</tr>
<tr>
<td><strong>Signal:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Track reconstruction and selection efficiency</td>
<td>26%</td>
<td>39%</td>
<td>38%</td>
</tr>
<tr>
<td>Kinematic cut ($2\sigma$)</td>
<td>95%</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Vertex efficiency ($2.5\sigma)^2$</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td>Timing efficiency ($2\sigma)^2$</td>
<td>-</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>24%</td>
<td>33%</td>
<td>32%</td>
</tr>
<tr>
<td><strong>Sensitivity:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single event sensitivity</td>
<td>4 \times 10^{-16}</td>
<td>3 \times 10^{-17}</td>
<td>7 \times 10^{-17}</td>
</tr>
<tr>
<td>Muons on target rate (Hz)</td>
<td>2 \times 10^7</td>
<td>1 \times 10^8</td>
<td>2 \times 10^9</td>
</tr>
<tr>
<td>Running days to reach 1 \times 10^{-15}</td>
<td>2600</td>
<td>350</td>
<td>18</td>
</tr>
<tr>
<td>Running days to reach 1 \times 10^{-16}</td>
<td>-</td>
<td>3500</td>
<td>180</td>
</tr>
<tr>
<td>Running days to reach single event sensitivity</td>
<td>6500</td>
<td>11700</td>
<td>260</td>
</tr>
</tbody>
</table>
• Singles experiment allows ultra-high beam rates.
• Intrinsic background (decay-in-orbit) known and calculable. Czarnecki et al.

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

Radiative corrections under study.
• High resolution detector feasible.
• Proposed improvements $> 10^4$
DeeMe\textsuperscript{(P41)}

- Process: $\mu^{-} + (A,Z) \rightarrow e^{-} + (A,Z)$
  - A single mono-energetic electron
    - $105$ MeV
    - Delayed: $\sim 1 \mu$S
- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_{e} > 102.5$ MeV (BR: $10^{-14}$)
    - $E_{e} > 103.5$ MeV (BR: $10^{-16}$)
  - Beam Pion Capture
    - $\pi^{+} (A,Z) \rightarrow (A,Z-1)^{*} \rightarrow \gamma + (A,Z-1)$
    - $\gamma \rightarrow e^{+} e^{-}$
- Prompt timing

- Low Energy main part: suppressed by the beamline.
- High Energy tail: Magnet Spectrometer ($\Delta p < 0.3\%$)
- Main pulse: Kicker to reduce the detector rate.
- After-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{AP} < 10^{-17}$. 

D. Bryman  CLFV, Lecce, Italy
Sensitivity and Backgrounds

- Signal Sensitivity
  - S.E.S.: $2 \times 10^{-14}$ (1 MW, $2 \times 10^7$ sec)
- Backgrounds
  - $R_{AP} < 9 \times 10^{-18}$
  - Detector live-time Duty = 1/20000

<table>
<thead>
<tr>
<th>Background</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIO Background</td>
<td>0.09</td>
</tr>
<tr>
<td>After-Proton Background</td>
<td>&lt; 0.027 (&lt;0.05 90% CL)</td>
</tr>
<tr>
<td>Cosmic-Muon Induced Electron BG</td>
<td>&lt; 0.018 (MC stat. limited)</td>
</tr>
<tr>
<td>Cosmic-Muon Induced Muon BG</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>
| Radiative Muon Capture BG                 | < 0.0009
\[ \mu^- N \rightarrow e^- N \text{ at } 10^{-16} \]


Moscow Meson Factory***

D. Bryman    CLFV, Lecce, Italy
BNL MECO → Mu2E

\[ \mu \rightarrow e \] Conversion at Fermilab

Mu2e Muon Beam:
Three Solenoids and Gradient

\[ 4.6T \rightarrow \text{B-field gradient} \rightarrow 1T \]

PS  2.5T  TS  2T  DS  1T

- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

Muon Momentum
\~ 50 MeV/c:
muons range out in stopping foils

R. Bernstein, FNAL

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Detector Solenoid

octagonal tracker surrounding central region:

radius of helix proportional to momentum,

\[ p = qBR \]

low momentum particles and almost all DIO background passes down center

Al foil stopping target

signal events pass through tracker and produce hits, then stop in calorimeter
Backgrounds

- For $R_{\mu e} = 10^{-15}$
  - ~40 events / 0.41 bkg
  (LHC SUSY?)

- For $R_{\mu e} = 10^{-16}$
  - ~4 events / 0.41 bkg

<table>
<thead>
<tr>
<th>Background</th>
<th>Size</th>
<th>Uncertainty</th>
<th>Source of Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon Decay-In Orbit</td>
<td>0.22</td>
<td>±0.06</td>
<td>Acceptance and Energy Loss Modeling</td>
</tr>
<tr>
<td>Antiproton RPC</td>
<td>0.10</td>
<td>+0.05</td>
<td>Cross-Section and Acceptance</td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td>0.05</td>
<td>±0.05</td>
<td>Statistics of Sample</td>
</tr>
<tr>
<td>Radiative Pion Capture</td>
<td>0.03</td>
<td>+0.007</td>
<td>Acceptance and Reconstruction</td>
</tr>
<tr>
<td>Muon Decay-in-Flight</td>
<td>0.01</td>
<td>+0.003</td>
<td>Cross-Section, Acceptance and Modeling</td>
</tr>
<tr>
<td>Pion Decay-in-Flight</td>
<td>0.003</td>
<td>+0.0015</td>
<td>same</td>
</tr>
<tr>
<td>Beam Electrons</td>
<td>0.0006</td>
<td>+0.0003</td>
<td>same</td>
</tr>
<tr>
<td>Radiative Muon Capture</td>
<td>&lt; 2 x 10^{-6}</td>
<td>—</td>
<td>Calculation</td>
</tr>
<tr>
<td>Sum</td>
<td>0.41</td>
<td>+0.08</td>
<td>Added in Quadrature</td>
</tr>
</tbody>
</table>

Numbers are changing at 10% level as experiment matures

R. Bernstein, FNAL

24 Mu2e IF Workshop 25 April 2013
COMET at JPARC

$\mu^- N \rightarrow e^- N$ at $10^{-16}$
Comet Phase I Goal

s.e.s. $3 \times 10^{-15}$

Engineering runs >2016

D. Bryman  CLFV, Lecce, Italy
COMET Phase I: Background Studies

COMET Detector for Background measurements

- Proton Extinction
- Particle content, rates, especially pbars
- Others?
Useful Advanced Measurements for $\mu$-e Conversion Experiments

- Extinction rate
- Particle fluxes ($e, \mu, \pi, K, \bar{p}$...) at detector (Comet phase I)
- $p$ and $n$ rates from $\mu$ Capture (in the works at PSI)
- Cosmic rays – could be done in a test setup?
- Radiative pion capture $\rightarrow 100$MeV electrons?
- $P$ bar background rate $\rightarrow 100$MeV electrons?
- ...

General questions for high sensitivity $\mu$-e Conversion Experiments

- What are the uncertainties and risk factors in the background, acceptance estimates?
- How are the backgrounds to be measured during the experiment?
- How is a blind analysis to be done?
- What would make a believable signal?
LFV in Kaon Decays: NA62

Triggering on lepton pairs

NA62 three-track decay rate upstream CHOD: $F_{3\text{track}} = 640 \text{ kHz}$

→ Too high to collect all three-track decays (as NA48/2 did)

Available L0 trigger primitives:

- $Q_N$: at least $N$ hodoscope quadrants;
- $LKR_N(x)$: at least $N$ LKr clusters with energy $E > x$ GeV;
- $MUV_N$: hits in at least $N$ MUV3 pads.

Possible L0 triggers for LFV searches:

- ee pair: $Q_2 \times LKR_2(15)$
- $\mu e$ pair: $Q_2 \times LKR_1(15) \times MUV_1$
- $\mu \mu$ pair: $Q_2 \times MUV_2$

Total lepton pair L0 rate (dominated by $K^+ \rightarrow \pi^+\pi^+\pi^-$): $F = \text{few} \times 10 \text{ kHz}$

→ Charge-blind lepton pair collection is feasible

S.E.S

$10^{-12}$
\[ \tau \rightarrow \mu, \tau \rightarrow e, \mu \rightarrow e \] Rates are Model Dependent!

Third generation effects could dominate.

**Charged lepton flavor violation**

- Charged lepton flavor violation can be large in SUSY GUTs
- The LFV branching fractions are very sensitive to the details of the Yukawa couplings and the mass scale of heavy neutrinos $\nu_R$

\[
A \rightarrow \ell_i \rightarrow \ell_j \gamma = \\
\alpha [Y_{\ell_i}^\dagger Y_{\ell_j}]_{ij} + \beta [Y_{\widetilde{U}}^\dagger Y_{D}]_{ij}
\]

**PMNS mixing**
- dominant if $M_R > 10^{12}$ GeV

**CKM mixing**
- dominant if $M_R < 10^{12}$ GeV

\[ \mathcal{B}(\tau \rightarrow \mu \gamma) : \mathcal{B}(\tau \rightarrow e \gamma) : \mathcal{B}(\mu \rightarrow e \gamma) \]

\[ [500-10] : 1:1 \quad 10^4 : 500 : 1 \]

**SU(5) $\oplus \nu_2$ (non-degenerate)**

**Correlations between $\mathcal{B}(\mu \rightarrow e \gamma)$ and $\mathcal{B}(\tau \rightarrow \mu \gamma)$, $\mathcal{B}(\tau \rightarrow e \gamma)$ in an SU(5) model with right-handed neutrinos, with different structures for the neutrino Yukawa couplings (I and II)**
Polarized $\tau$s can probe the chiral structure of LFV

- Should $\tau \rightarrow lll$ events be observed, it is possible to study the Lorentz structure of the coupling using the Dalitz plot.

Flipping the helicity of the polarized electron beam allows us to determine the chiral structure of dimension 6 four fermion lepton flavor-violating interactions.

Belle II Sensitivity to LFV

<table>
<thead>
<tr>
<th>DECAY CHANNEL</th>
<th>BELLE LIMIT</th>
<th>BABAR LIMIT</th>
<th>BELLE II PROJ. (5 ab(^{-1}))</th>
<th>BELLE II PROJ. (50 ab(^{-1}))</th>
<th>SUPERB PROJ. (75 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau \to \mu \gamma)</td>
<td>4.5 \cdot 10^8 [26]</td>
<td>4.4 \cdot 10^8 [27]</td>
<td>1.0 \cdot 10^9 [42,43]</td>
<td>3 \cdot 10^9 [42,43]</td>
<td>1.8 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to e \gamma)</td>
<td>12 \cdot 10^8 [26]</td>
<td>3.3 \cdot 10^8 [27]</td>
<td>3 \cdot 10^9 [42,43]</td>
<td>1 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to \mu \mu \mu)</td>
<td>2.1 \cdot 10^8 [34]</td>
<td>3.3 \cdot 10^8 [28]</td>
<td>5 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [42,43]</td>
<td>4 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to e e e)</td>
<td>2.7 \cdot 10^8 [34]</td>
<td>2.9 \cdot 10^8 [28]</td>
<td>5 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [42,43]</td>
<td>6 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to \mu \eta)</td>
<td>2.3 \cdot 10^8 [25]</td>
<td>15 \cdot 10^8 [33]</td>
<td>5 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to e \eta)</td>
<td>4.4 \cdot 10^8 [25]</td>
<td>16 \cdot 10^8 [33]</td>
<td>5 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to \mu K_S^0)</td>
<td>2.3 \cdot 10^8 [35]</td>
<td>4.0 \cdot 10^8 [31]</td>
<td>5 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [96]</td>
</tr>
<tr>
<td>(\tau \to e K_S^0)</td>
<td>2.6 \cdot 10^8 [35]</td>
<td>3.3 \cdot 10^8 [31]</td>
<td>5 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [42,43]</td>
<td>2 \cdot 10^9 [96]</td>
</tr>
</tbody>
</table>

Table 3.3: Measured and projected limits on selected lepton flavour violating \(\tau\) decays (90\% C.L.).

\(^1\) The SuperB projections assumed a polarized electron beam; they also assumed that all backgrounds except initial state radiation can be suppressed to the desired level. The SuperB project was canceled in November 2012.

LHCb is now also a player.
LFV topics at ATLAS

- SUSY $\tilde{\nu}$, to $e\mu/\tau\mu/\mu\tau$ search
  - 7TeV 35pb$^{-1}$, publication on PRL: Phys. Rev. Lett. 106, 251801
  - 7TeV 1fb$^{-1}$, publication on EPJC: EPJC Vol.71, 12(2011)1809
  - 7TeV 5fb$^{-1}$, publication on PLB: PLB 29354
- $Z'\rightarrow e\mu$ search
  - 7TeV 35pb$^{-1}$, published together with $\tilde{\nu}$ on PRL
  - 7TeV 1fb$^{-1}$, published together with $\tilde{\nu}$ on EPJC
- stop $\rightarrow e\mu$ continuum search
- $(\geq)4$-lepton search
  - 7TeV, 5fb$^{-1}$, published on JHEP: JHEP (2012) 124
- $\mu+$displaced vertex
CMS Searches

Outline

1 Motivation
   - Physics motivations
   - The CMS detector

2 Narrow resonances
   - Search for narrow resonances in dilepton mass spectra

3 Heavy neutrinos
   - Search for heavy lepton partners of neutrinos in pp collisions at $\sqrt{s} = 7$ TeV, in the context of the Type III seesaw mechanism.
   - Search for heavy Majorana neutrinos in $\mu^+\mu^+$+jets and $e^+e^+$+jets in pp collisions at $\sqrt{s} = 7$ TeV.
   - Heavy neutrino and right-handed W of the left-right symmetric model.

4 Leptonic-RPV SUSY searches
   - Search for RPV supersymmetry with three or more leptons and b-tags
   - Search for stop in R-parity-violating supersymmetry with three or more leptons and b-tags

Experimental strategy

Heavy Majorana Neutrino
# Project X Staging Plan

<table>
<thead>
<tr>
<th></th>
<th>Present complex with PIP*</th>
<th>Stage 1 Project X 1 GeV CW Linac</th>
<th>Stage 2 Project X 3 GeV CW Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 GeV Muon</td>
<td>20 kW</td>
<td>0 – 20 kW</td>
<td>0 – 20 kW</td>
</tr>
<tr>
<td>1 GeV Muon</td>
<td>None</td>
<td>80 kW</td>
<td>none</td>
</tr>
<tr>
<td>3 GeV Muon</td>
<td>None</td>
<td>None</td>
<td>1000 kW</td>
</tr>
<tr>
<td>Kaon Program</td>
<td>0 – 30 kW</td>
<td>0 – 75 kW</td>
<td>1100 kW</td>
</tr>
</tbody>
</table>

* PIP = Proton Improvement Plan

---

*Image of a map showing the layout of Project X Staging Plan*
Example of an Experimental Program at Fermilab Project X

<table>
<thead>
<tr>
<th></th>
<th>Present complex with PIP*</th>
<th>Stage 1 Project X 1 GeV CW Linac</th>
<th>Stage 2 Project X 3 Gev CW Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mu2e</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>g-2</td>
<td>X</td>
<td>X (1 GeV into Booster)</td>
<td></td>
</tr>
<tr>
<td>$\mu \rightarrow e\gamma$</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$\mu \rightarrow 3e$</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \pi^0\nu\bar{\nu}$</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>EDM</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

* PIP = Proton Improvement Plan

D. Bryman    CLFV, Lecce, Italy
Concluding Observations

• Charged lepton flavor violation experiments are powerful searches for new physics at high mass scales
• CLFV remains popular in most BSM theories but target sensitivities are obscure and gains in mass scale \( (\text{Br} \sim 1/M^4) \) are slow
• Big gains in experimental sensitivity are in the works
• Worthwhile to keep at it until BSM physics becomes clearer or experimental capabilities wane (or experiments become too expensive)