(Charged) Lepton Physics @ High Intensity Frontier

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Acknowledgements

- Robert Bernstein
- Doug Glenzinsky
- David Hertzog
- Peter Raimond Kettle
- Yoshi Kuno-san
- Angela Papa
- Lee Roberts

→ thanks for sending me lots of material for this presentation

Note: all limits are quoted for 90% CL
Physics with Charged Leptons

Test of SM

\[ \gamma, W, Z \]

- electrical charge
- dipole moments
- (magnetic, electric, weak)

Beyond the SM

\[ \gamma, W, Z, X \]

- lepton number violation
- lepton flavor violation
- direct CP-violation

→ theoretical predictions are very precise (in contrast to quark physics)

Precision! Precision! Precision!
Physics with Charged Leptons

Test of SM

- $\gamma, W, Z$

Beyond the SM

- $\gamma, W, Z, X$

- lepton number violation
- lepton flavor violation
- direct CP-violation

- electrical charge
- dipole moments
  - (magnetic, electric, weak)

→ theoretical predictions are very precise (in contrast to quark physics)
Flavor Changing Neutral Currents

from Kuno-san

Quark (suppressed)

\[ |A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2 \text{Re}(A_{SM}\varepsilon_{NP}) + |\varepsilon_{N}|^2 \]

\[ \propto \frac{1}{\Lambda^2} \]

subject to SM uncertainties!

Lepton (forbidden)

\[ |A_{SM} + \varepsilon_{NP}|^2 \sim |A_{SM}|^2 + 2 \text{Re}(A_{SM}\varepsilon_{NP}) + |\varepsilon_{N}|^2 \]

\[ \propto \frac{1}{\Lambda^4} \]

sensitivity to highest scales!

... stronger decoupling in leptonic sector!

→ very small but clean signals

→ tested scales much larger than the EW scale

\[ \Lambda \gg 246 \text{ GeV} \]
History of LFV Decay experiments

Feinberg, Kabir, Weinberg (1959)
from non-observation of 
\[ \mu \rightarrow e \gamma \]
lepton flavour must be conserved!
→ no FCNC in lepton sector
Discovery of Neutrino Oscillations

neutrino oscillations $\rightarrow$ FCNC
charged lepton flavour violation (cLFV) on macroscopic scale!

→ Nobel prize 2015: B.McDonald, T.Kajita
History of LFV Decay experiments

How large is cLFV in the lab from lepton mixing?
FCNC + Fermion Mass Pattern

- FCNC in SM quark sector $\sim 10^{-10}$
- FCNC in SM lepton sector $\ll 10^{-50}$

SM diagram:

$$BR(l_j \rightarrow l_k \gamma) \propto \left| \sum_i V_{ij} V_{jk}^* \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \sim \left( \frac{\Delta m_{\nu_{jk}}^2}{M_W^2} \right)^2$$

→ Charged LFV is THE signature for new physics!
History of LFV Decay experiments

new generation of LFV experiments
LFV Muon Decays in the SM

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

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

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

SM: LFV loops

Branching ratios suppressed by

\[ \propto \frac{\left(\Delta m^2_{\nu}\right)^2}{m_W^4} \approx 10^{-50} \]
LFV Muon Decays from SUSY Loops

\[
\begin{align*}
\mu^+ &\rightarrow e^+\gamma \\
\mu^- N &\rightarrow e^- N \\
\mu^+ &\rightarrow e^+e^+e^-
\end{align*}
\]

SUSY loops

enhanced by coherent conversion in nucleus field for \(Q^2(\gamma^*)\sim 0\)

suppressed by extra vertex with respect to \(\mu^+ \rightarrow e^+\gamma\)
LFV Muon Decays: Experimental Situation

$\mu^+ \rightarrow e^+ \gamma$

$\mu^+ \rightarrow e^+ e^+ e^-$

$\mu^- N \rightarrow e^- N$

MEG (PSI)

$B(\mu^+ \rightarrow e^+ \gamma) \leq 5.7 \cdot 10^{-13}$ (2013)

SINDRUM II (PSI)

$B(\mu Au \rightarrow e Au) \leq 7 \cdot 10^{-13}$ (2006)

SINDRUM (PSI)

$B(\mu^+ \rightarrow e^+ e^+ e^-) \leq 10^{-12}$ (1988)

being upgraded
Signal:
- mono-energetic $e, \gamma$
- back-to-back
- in time

Background:
- accidentals

---

Signal:
- mono-energetic $e$
- $E_e = m_\mu$

Background:
- large nuclear recoils (DIO)
- pion decays

---

Signal:
- $\Sigma p = 0$
- $\Sigma E_i = m_\mu$
- common vertex
- in time

Background:
- radiative decay with internal conversion
- accidentals (Bhabha)
LFV Muon Decays from SUSY Loops

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

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

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

Most BSM models (e.g. SUSY) induce naturally LFV
LFV Tree Diagrams

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

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

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

\[ \mu \rightarrow e \]

not allowed

e.g. Leptoquarks

\[ \mu \rightarrow e \]

e.g. Leptoquarks

extra Z', LFV Higgs, etc.

Additional BSM tree diagrams for \( \mu N \rightarrow eN \) and \( \mu N \rightarrow eee \)
Lepton Flavor Violating Decay: $\mu^+ \rightarrow e^+ e^+ e^-$

- Supersymmetry
- Little Higgs Models
- Seesaw Models
- GUT models (Leptoquarks)
- many other models

- Higgs Triplet Model
- New Heavy Vector bosons ($Z'$)
- Extra Dimensions (KK towers)

Exotic Physics

loop diagrams

tree diagram
### Complementarity of LFV Processes


<table>
<thead>
<tr>
<th>ratio</th>
<th>LHT</th>
<th>MSSM (dipole)</th>
<th>MSSM (Higgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{Br(\mu^-\rightarrow e^-e^+e^-)}{Br(\mu\rightarrow e\gamma)}$</td>
<td>0.02...1</td>
<td>$\sim 6 \cdot 10^{-3}$</td>
<td>$\sim 6 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-e^+e^-)}{Br(\tau\rightarrow e\gamma)}$</td>
<td>0.04...0.4</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow \mu^-\mu^+\mu^-)}{Br(\tau\rightarrow \mu\gamma)}$</td>
<td>0.04...0.4</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.06...0.1</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-\mu^+\mu^-)}{Br(\tau\rightarrow e\gamma)}$</td>
<td>0.04...0.3</td>
<td>$\sim 2 \cdot 10^{-3}$</td>
<td>0.02...0.04</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow \mu^-e^+e^-)}{Br(\tau\rightarrow \mu\gamma)}$</td>
<td>0.04...0.3</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
<td>$\sim 1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow e^-e^+e^-)}{Br(\tau^-\rightarrow e^-\mu^+\mu^-)}$</td>
<td>0.8...2.0</td>
<td>$\sim 5$</td>
<td>0.3...0.5</td>
</tr>
<tr>
<td>$\frac{Br(\tau^-\rightarrow \mu^-\mu^+\mu^-)}{Br(\tau^-\rightarrow \mu^-e^+e^-)}$</td>
<td>0.7...1.6</td>
<td>$\sim 0.2$</td>
<td>5...10</td>
</tr>
<tr>
<td>$\frac{R(\mu Ti\rightarrow e Ti)}{Br(\mu\rightarrow e\gamma)}$</td>
<td>$10^{-3} \ldots 10^{2}$</td>
<td>$\sim 5 \cdot 10^{-3}$</td>
<td>0.08...0.15</td>
</tr>
</tbody>
</table>

Table 3: Comparison of various ratios of branching ratios in the LHT model ($f = 1\text{ TeV}$) and in the MSSM without $[92,93]$ and with $[96,97]$ significant Higgs contributions.
Model Independent Comparison (Tensor vs Tree)

μ → eee

Effective cLFV Lagrangian:

\[ L = \frac{m_\mu}{\Lambda^2 (1 + \kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1 + \kappa)} J^{e\mu}_v J^{\nu, ee}_v \]

\( \kappa \) = parameter

\( \Lambda \) = common effective mass scale

\[
\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \sim 0.006
\]

\[
\frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} = \infty
\]
Model Independent Comparison (Tensor vs Tree)

\[ \mu \rightarrow eee \]

\[ \kappa \rightarrow 0 \]

\[ \frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} \approx 0.006 \]

\[ \frac{B(\mu^+ \rightarrow e^+e^+e^-)}{B(\mu^+ \rightarrow e^+\gamma)} = \infty \]

\[ \mu e e e \text{ contact IA} \]
Model Independent Comparison (Tensor vs Tree)

$\mu \to e$ conversion

$\kappa \to 0$

$\kappa \to \infty$

→ LFV processes are highly complementary!
### Some CLFV Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Limit</th>
<th>Next Generation exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \eta$</td>
<td>BR &lt; 6.5 E-8</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>BR &lt; 6.8 E-8</td>
<td>$10^{-9} - 10^{-10}$ (Belle II)</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \mu \mu$</td>
<td>BR &lt; 3.2 E-8</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow \text{eee}$</td>
<td>BR &lt; 3.6 E-8</td>
<td></td>
</tr>
<tr>
<td>$K_L \rightarrow e\mu$</td>
<td>BR &lt; 4.7 E-12</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+e^-\mu^+$</td>
<td>BR &lt; 1.3 E-11</td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow e\mu$</td>
<td>BR &lt; 7.8 E-8</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+e\mu$</td>
<td>BR &lt; 9.1 E-8</td>
<td></td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+\gamma$</td>
<td>BR &lt; 5.7 E-13</td>
<td>10^{-14} (MEG)</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+e^+e^-$</td>
<td>BR &lt; 1.0 E-12</td>
<td>10^{-16} (PSI)</td>
</tr>
<tr>
<td>$\mu N \rightarrow eN$</td>
<td>$R_{\mu e} &lt; 7.0$ E-13</td>
<td>10^{-17} (Mu2e, COMET)</td>
</tr>
</tbody>
</table>

- **Most promising CLFV measurements use $\mu$**
Discovery Potential of New Physics


<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>δLL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 - \bar{D}^0$</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>?</td>
</tr>
<tr>
<td>$\epsilon_K$</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$S_{\psi\phi}$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$S_{\phi K_S}$</td>
<td>★★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{\text{CP}}(B \to X_s \gamma)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{\tau, s}(B \to K^* \mu^+ \mu^-)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★</td>
<td>?</td>
</tr>
<tr>
<td>$A_9(B \to K^* \mu^+ \mu^-)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$B \to K^{(*)}\nu\bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\nu\bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$K_L \to \pi^0\nu\bar{\nu}$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$\mu \to e\gamma$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$\mu + N \to e + N$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$d_n$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
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<td>★★★★</td>
</tr>
<tr>
<td>$d_e$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>$(g - 2)_\mu$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★</td>
</tr>
</tbody>
</table>

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★★ signals large effects, ★★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

lepton flavor violation
What is Muon to Electron Conversion?

1s state in a muonic atom

Neutrino-less muon nuclear capture

\[ \mu^- + (A,Z) \rightarrow e^- + (A,Z) \]

Event Signature:
- a single mono-energetic electron of 105 MeV

Backgrounds:
1. physics backgrounds
   - ex. muon decay in orbit (DIO)
2. beam-related backgrounds
   - ex. radiative pion capture, muon decay in flight,
3. cosmic rays, false tracking

Muon decay in orbit

\[ \mu^- \rightarrow e^- \nu \bar{\nu} \]

Nuclear muon capture

\[ \mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z - 1) \]
Sensitivity Goals COMET

2018/19: $R_{e\mu} < 10^{-15}$

2021: $R_{e\mu} < \sim 10^{-17}$

**COMET Phase-I**

- Protons
- Production Target
- Pions
- Muons
- Stopping Target

**COMET Phase-II**

- Protons
- Production Target
- Pions
- Muons
- Detector Section
  - A detector to search for muon-to-electron conversion processes.
- Stopping Target
- Pion-Capture Section
  - A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet.
- Pion-Decay and Muon-Transport Section
  - A section to collect muons from decay of pions under a solenoidal magnetic field.

(from Kuno-san)
COMET Beam Timing

The measurement window opens about 700 sec after the beam prompt.

For aluminum, a lifetime of a muonic atom is about 0.8 μsec.
CDC Wire Stringing Completed!

CDC

Completed on Nov. 24th, 2015, about 20,000 wires in 122 working days (about 6 months).
Curved Solenoids for Muon Transport Completed!

from Kuno-san
Mu2e vs. COMET

<table>
<thead>
<tr>
<th></th>
<th>Mu2e</th>
<th>COMET</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon beam line</td>
<td>2x 90° bends (opposite direction)</td>
<td>2x 90° bend (same direction)</td>
</tr>
<tr>
<td>electron</td>
<td>straight solenoid</td>
<td>curved solenoid</td>
</tr>
<tr>
<td>spectrometer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dipole Coils
COMET curved solenoids have dipole coils on top of the solenoids, to keep muons with momentum of interest in the bending plane.
Mu2e Experiment at Fermilab

Mu2e Experiment at Fermilab

pulsed muons beam with $\sim 10^{20}$ protons on target

$R_{e\mu} < \sim 10^{-17}$
Mu2e Experiment at Fermilab

- Detector acceptance only for high momentum tracks (filter)
- Precise momentum determination using straw tube tracker
- Background from recoils
- Other BG: cosmics, pions, etc.
Mu2e Momentum Resolution

simulated!

core width = 115 keV/c
high tail slope = 179 keV/c
high tail fraction = 2.9%

$P_{\text{reco}} - P_{\text{tru}}$ (MeV/c)
• Inner 38 cm is purposefully un-instrumented
  – Blind to beam flash
  – Blind to >99% of DIO spectrum
A signal electron, together with all the other “stuff” occurring simultaneously, integrated over 500-1695 ns window
Construction Photos

- **July 2015**
  - Concrete floor being poured

- **August, 2015**
  - Walls formed

- **September, 2015**
  - Lower level walls completed

• Steady progress being made
MEG Experiment
MEG Experiment @ PSI: Search for $\mu \rightarrow e \gamma$

Proton cyclotron:
$I_p = 2.4 \text{ mA}$
@ 590 MeV

World-highest intensity beam!

PiE5 beamline: MEG experiment
MEG Experiment @ PSI: Search for $\mu \rightarrow e \gamma$

- Search for back-back monochromatic positron-photon pair
- coincident in time
- background: accidentals

signal

$\mu^+ \rightarrow e^+ \nu \nu \gamma$, $e^+e^- \rightarrow \gamma \gamma$ etc
MEG Experiment @ PSI: Search for $\mu \to e \gamma$

- Limit from MEG 2008-2011: $B(\mu \to e \gamma) < 5.7 \cdot 10^{-13}$ (exp. $7.7 \cdot 10^{-13}$)
- Data from 2012 still being analysed

- Main limitation is detector resolution which determines the accidental BG and maximum beam intensity
  → upgrade of detector 2013-2015
MEG II Upgrade @ PSI: Search for $\mu \rightarrow e \gamma$

- Twice the number of photomultipliers
- New homogeneous drift chamber

Upgrade will allow to run at much higher muon rates ($7 \cdot 10^7$ muons/s)

- Expected post-upgrade sensitivity: $B(\mu \rightarrow e \gamma) < 5 \cdot 10^{-14}$
LXe detector: modifications in lateral faces & finer photon sensors at entrance face

12 x 12 mm$^2$ SiPM sensitive to LXe scintillation light.

Expected a factor 2 better resolution in position and almost a factor 2 in energy.

Present detector: 2-inch PMTS

Upgraded detector: 12 x 12 mm$^2$ SiPM

improved $\rightarrow E_{\gamma}$ resolution
MU3E Experiment
Search for $\mu^+ \rightarrow e^+e^+e^-$ at the Paul Scherrer Institute

project approved in Jan 2013

PSI provides high intensity DC muon beam of $E_{\text{kin}} = 29$ MeV

Aiming for a sensitivity of

$\text{BR}(\mu \rightarrow e e e) < 10^{-15}$ (phase I)

requires: $\rightarrow 10^8$ muons/s

$\text{BR}(\mu \rightarrow e e e) < 10^{-16}$ (phase II)

$\rightarrow >10^9$ muons/s
Mu3e Collaboration

- DPNC Geneva University
- Physics Institute, University Heidelberg
- Kichhoff Institute, University Heidelberg
- IPE @ KIT, Karlsruhe
- Institute for Nuclear Physics, Mainz
- Paul Scherrer Institute
- Physics Institute, University Zurich
- Institute for Particle Physics, ETH Zurich
- University of Liverpool
PSI Facility for Mu3e

Phase I (2016+): \( \sim 10^8 \) muons/s

Phase II (?): \( > 10^9 \) muons/s

proton cyclotron

\[ I_p = 2.4 \text{ mA} \]

@ 590 MeV

world-highest intensity beam!
Compact Muon Beamline (Phase I)

MEG and Mu3e share the same beamline

- muon rates of up to $10^8$/s achieved in past
- $\mathcal{B}(\mu^+ \rightarrow e^+e^+e^-) \sim 2 \cdot 10^{-15}$ (90%CL) after three years running
mockup for Mu3e solenoid
Mu3e Backgrounds

**Irreducible BG:** radiative decay with internal conversion

\[
\sum_i E_i = m_\mu \\
\sum_i \vec{p}_i = 0
\]

\[B(\mu^+ \rightarrow e^+e^+e^-\nu\nu) = 3.4 \cdot 10^{-5}\]
**Backgrounds**

**Irreducible BG:** radiative decay with internal conversion

\[ B(\mu^+ \rightarrow e^+e^+e^-\nu\nu) = 3.4 \cdot 10^{-5} \]

\[ e^- + e^- + e^- + \nu \rightarrow \nu \nu \text{missing energy from two neutrinos} \]

Steeply falling!

R.M. Djilkibaev, R.V. Konoplich
PRD79 (2009)

Very good momentum +
Total energy resolution required!
Accidental Backgrounds

- **Overlays** of two ordinary $\mu^+$ decays with a (fake) electron ($e^-$)
- Electrons from: Bhabha scattering, photon conversion, mis-reconstruction

Need excellent:
- Vertex resolution
- Timing resolution
- Kinematic reconstruction
Mu3e Baseline Design

Long cylinder → spectrometer concept

➢ low material budget is key issue as multiple scattering dominates!
Tracking Design Considerations

\[ \frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega} \]

(linearised)

precision requires large lever arm!

\[ \rightarrow \text{large bending angle } \Omega \]
Pixel Detector + Helium Gas Cooling

He gas cooling concept
→ temperatures 20-50 °C

Phase I design

~15 cm

based on HV-MAPS technology

He gas cooling simulation

50 µm
Mu3e Status and Plans

- Magnet will be delivered by end 2016
- Detector construction will start in 2017
- Phase I data taking will start in 2018

- Phase II: requires design and approval of High Intensity Muon Beam Line → HiMB not before 2020
Tests of the Standard Model with Dipole Moments
Electric and Magnetic Dipole Moments

Hamiltonian: \( H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \)

- magnetic dipole moment: \( \vec{\mu} = g \mu_B \vec{J} \)
- electric dipole moment (EDM): \( \vec{d} = \eta \left( \frac{q \vec{J}}{2m} \right) \)

CPT transformation properties:

<table>
<thead>
<tr>
<th></th>
<th>( \mu / d )</th>
<th>B</th>
<th>E</th>
<th>( \mu \cdot B )</th>
<th>( d \cdot E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>T</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

EDMs violate P and T invariance

helicity flip → massive particles

forbidden in SM → new physics
G-2 Experiments

Magnetic moment of fermions:

\[ \mu = g \mu_B J \]
\[ \mu_B = \frac{e \hbar}{2m} \]
\[ g = \text{Landé factor} \]

Anomalous magnetic moment from radiative corrections:

\[ a = (g - 2)/2 \]

Precision experiments for electrons and muons:

\[ a(e) = 11596521.8073(28) \times 10^{-10} \]  
Hanneke et al.

\[ a(e)_{\text{theor}} = 11596521.7760(520) \times 10^{-10} \]  
BNL measurement

\[ a(\mu) = 11659208.9 \pm 5.4 \pm 3.3 \times 10^{-10} \]

\[ a(\mu)_{\text{theor}} = 11659182.8 \pm 4.9 \times 10^{-10} \]

> 3.5 sigma discrepancy
Dipole Moments and Lepton Masses

Sensitivity to new physics (NP):

$$\delta a_1(\text{NP}) \propto \frac{m_l^2}{M_{NP}^2}$$

Muon/Electron sensitivity: $\sim 42000!$
Tau/Muon sensitivity: $\sim 280$

$\rightarrow$ heavy leptons have higher sensitivity to g-2
Electric versus Magnetic Dipole Moments

Sensitivity to new physics (NP):

\[ d_l(NP) = a_l(NP) \frac{e}{2 m_l} \tan \phi_l^{NP} \]

Light lepton EDMs are less disfavored:
→ EDM is sensitive to new physics if phase not too small

In general:
→ EDM and G-2 are complementary tests of the SM
Electric Dipole Moment (EDM)

- Electric dipole moments violate P and T invariance!
- Sensitive to new physics!

Lepton EDM limits (PDG):

<table>
<thead>
<tr>
<th></th>
<th>Exp. Limit [e cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_e$</td>
<td>$&lt; 0.87 \times 10^{-28}$ (CL 90%)</td>
</tr>
<tr>
<td>$d_\mu$</td>
<td>(-0.1 to 0.9) $\times 10^{-19}$</td>
</tr>
<tr>
<td>Re($d_\tau$)</td>
<td>(-0.22 to 0.45) $\times 10^{-16}$</td>
</tr>
<tr>
<td>Im($d_\tau$)</td>
<td>(-0.25 to 0.008) $\times 10^{-16}$</td>
</tr>
</tbody>
</table>

*** New strong limit from Baron et al. (2014)
Muon EDM Searches and Predictions

proposals:

theory:

- model-independent relation to exp. g-2 anomaly with $\theta_{CP} \approx 1$

- cubic
- quadratic
- linear

- inferred limits from $d_m < 1.1 \times 10^{-17}$ e cm
  - (lepton mass scaling, Babu, Barr, Dorsner [2001])

- FV SUSY
  - (Feng, Matchev, Shadmi [2001])

- LR SUSY + See-Saw
  - (Babu, Dutta, Mohapatra [2000])

- SM: $< 10^{-38}$

- PSI
- JPARC

year
Muon g-2 Spin Precision Experiment

Advantages of muon g-2:

- g-2 is a clean electroweak variable with precise theoretical prediction
- recent progress on hadronic corrections
  (→ input from: e^+e^- → hadrons, g-2 electron)

Hadronic Vacuum Polarisation

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Uncertainty</th>
<th>δa_μ/μ_μ (ppb)</th>
<th>δa_μ/μ_μ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED</td>
<td>0.08</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Weak</td>
<td>1</td>
<td>8.6</td>
<td>8.6</td>
</tr>
<tr>
<td>Had-HO</td>
<td>0.7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>HVP (e.g., Ref [4])</td>
<td>42</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>HLbL</td>
<td>26</td>
<td>223</td>
<td>223</td>
</tr>
<tr>
<td>Net theory</td>
<td>49</td>
<td>420</td>
<td>420</td>
</tr>
</tbody>
</table>
Summary of $e^+e^- \rightarrow \text{hadrons}$ data

→ input for non-perturbative calculationns of hadronic corrections
Measurement of g-2 Spin Precision

Cyclotron frequency:
\[ \omega_c = \frac{eB}{m_\mu \gamma} \]

Spin rotation frequency:
\[ \omega_s = \frac{eB}{m_\mu \gamma} + a_\mu \frac{eB}{m_\mu} \]

Spin precession frequency:
\[ \omega_a = a_\mu \frac{eB}{m_\mu} \]

Extra electric fields (focusing):
\[ \vec{\omega}_a = \frac{e}{m_\mu} \left( a_\mu \vec{B} - \left[ a_\mu - \frac{1}{\gamma^2 - 1} \right] \vec{v} \times \vec{E} \right) \]

cancellation if: \( a_\mu = \frac{1}{\gamma^2 - 1} \) \( \Rightarrow \gamma = 29.3 \) \( \Rightarrow E_{\text{magic}} = \gamma m_\mu = 3.098 \text{ GeV} \)

“magic energy” concept exploited by BNL and former CERN experiments
Muon Storage Ring at BNL

Concept exploits only electric quadrupole fields for muon focusing!
Muon Injection at BNL

Protons from AGS

Pions p=3.1 GeV

Target

Polarized Muons

Inflector

Injection Point

π⁺ → μ⁺ν_μ

In Pion Rest Frame

π⁺

ν_μ

μ⁺

spin momentum

“Forward” Decay Muons are highly polarized

Fig. 5. Decay of $\mu^+$ and detection of the emitted $e^+$ (PMT = Photomultiplier).
Time Dependent Muon Decay Rate

→ ratio of muon precession frequency to proton cyclotron frequency
Uncertainties of BNL g-2 Experiment

\[ a_{\mu}^{\text{Exp}} = \frac{g_e \omega_a m_\mu \mu_p}{2 \bar{\omega}_p m_e \mu_e} \]

\text{g-2 measurement:}

\begin{table}
\begin{tabular}{|l|c|c|}
\hline
Quantity & Uncertainty & $\delta a_{\mu}/a_{\mu}$ \\
& $\times 10^{-11}$ & (ppb) \\
\hline
Total $\omega_a$ Statistical & 53 & 458 \\
Final $\omega_a$ Systematic & 24 & 210 \\
Final $\bar{\omega}_p$ Systematic & 20 & 170 \\
CODATA $m_\mu/m_e$ & 2.6 & 22 \\
CODATA $\mu_p/\mu_e$ & 0.35 & 3 \\
Electron $g$ factor, $g_e$ & 0.000035 & 0.0003 \\
Final E821 & 63 & 540 \\
\hline
\end{tabular}
\end{table}

statistics was main limitation

table from D.Hertzog
Summary Plot $g\mu -2$ Experiments


status 2009
The New G-2 Experiment at FNAL

21 x more statistics is needed!
“The Big Move” BNL → FNAL

BNL Muon Storage Ring transported to FNAL
→ essentially everything is rebuild except muon-storage ring
The New FNAL E989 Experiment

New segmented PbF$_2$ Cherenkov crystals with SiPM readout for calorimetry

Field Shimming on the way to improve magnetic field quality

Goal: reduction of exp. uncertainties by factor 4 wrt former BNL experiment

from D. Hertzog
Muon Electric Dipole Moment (mEDM)

Spin precession experiments are also used to derive limits on electric dipole moments:

\[
\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{\beta} \times \vec{B} + \vec{E}}{c} \right) \right]
\]

- current limits on mEDM obtained at BNL E821
- Alternative experiments proposed e.g. at
  - JPARC (no electric fields)
  - PSI (frozen spin technique → cancellation of spin precision)
JPARC g-2/mEDM Experiment

Concept:

- no electric fields for focusing → instead weak magnetic focusing

\[
\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]
\]

- can run at any (low) muon energy (no magic energy requirement)

→ JPARC working point: \( E_\mu = 300 \text{ MeV} \)
→ small magnet!
New Muon g-2/EDM experiment at J-PARC with Ultra-Cold muon Beam

from B. Shwartz (Phi to Psi 2015)

\[ \Delta(g-2) = 0.1 \text{ ppm} \]
\[ \text{EDM} \sim 10^{-21} \text{ e} \cdot \text{cm} \]
Table 1.2: Specification of the storage field.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field strength</td>
<td>3 T</td>
</tr>
<tr>
<td>Field uniformity locally</td>
<td>≤ 1 ppm</td>
</tr>
<tr>
<td>Field uniformity integral</td>
<td>&lt; 0.1 ppm</td>
</tr>
<tr>
<td>Uniform region radius</td>
<td>33.3 ± 1.5 cm</td>
</tr>
<tr>
<td>Uniform region height</td>
<td>± 5.0 cm</td>
</tr>
</tbody>
</table>
Muon-EDM JPARC-E24

Super conductive solenoid magnet

tunnel

homogeneous solenoidal field

Silicon strip detectors

from B. Shwartz
(Phi to Psi 2015)
A typical simulated event of muon decay ($p = 200$)
Summary of g-2 Projects


<table>
<thead>
<tr>
<th>Quantity</th>
<th>Uncertainty $\times 10^{-11}$</th>
<th>$\delta a_\mu / a_\mu$ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net theory</td>
<td>49</td>
<td>420</td>
</tr>
<tr>
<td>Final E821</td>
<td>63</td>
<td>540</td>
</tr>
<tr>
<td>Goal Fermilab E989</td>
<td>16</td>
<td>140</td>
</tr>
<tr>
<td>Goal J-PARC E24</td>
<td>47</td>
<td>400</td>
</tr>
</tbody>
</table>

→ important to have two experiments!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fermilab E989</th>
<th>J-PARC E24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical goal</td>
<td>100 ppb</td>
<td>400 ppb</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.45 T</td>
<td>3.0 T</td>
</tr>
<tr>
<td>Radius</td>
<td>711 cm</td>
<td>33.3 cm</td>
</tr>
<tr>
<td>Cyclotron period</td>
<td>149.1 ns</td>
<td>7.4 ns</td>
</tr>
<tr>
<td>Precession frequency, $\omega_a$</td>
<td>1.43 MHz</td>
<td>2.96 MHz</td>
</tr>
<tr>
<td>Lifetime, $\gamma\tau_\mu$</td>
<td>64.4 $\mu$s</td>
<td>6.6 $\mu$s</td>
</tr>
<tr>
<td>Typical asymmetry, $A$</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>0.97</td>
<td>0.50</td>
</tr>
<tr>
<td>Events in final fit</td>
<td>$1.5 \times 10^{11}$</td>
<td>$8.1 \times 10^{11}$</td>
</tr>
</tbody>
</table>
Opportunities for Tau-Lepton Physics

Motivation:
- In many models NP couples \( \sim m_{\text{lepton}} \) or \( (m_{\text{lepton}})^2 \)

Experiments:
- LHCb at LHC (running)
- Belle2 at KEKb (in preparation)
- Supertau-Charm Factory at Novosibirsk
- ILD at International Linear Collider (ILC)

Interesting Measurements:
- Tau lepton flavor violation (LFV)
- Tau electric dipole moments (EDM)
- Tau magnetic dipole moments (g-2)

→ would be an extra talk
Supertau-Charm Factory at Novosibirsk

- $e^+e^-$ machine at 2-5 GeV
- Conceptual Design Report 2011
- $L=10^{35}$ cm$^{-2}$s$^{-1}$ with Crab Waist Concept
- polarised beams
- about $10^{10}$ tau-pairs per year at $s^{1/2} = 4.2$ GeV
  → ideal for tau-LFV searches
- no funding for tunnel yet

Accelerator Complex

Detector Concept

Crab Waist Concept

Figure 3.1: Universal magnetic detector: 1 – vertex detector; 2 – drift chamber; 3 – identification system based on FAIRICH; 4 – calorimeter; 5 – superconducting coil; 6 – yoke with a muon system.
New Technologies

Performance boost of low energy experiments high intensity frontier due to advances in:

- accelerator technologies and beam preparation
- detector technologies
- readout technologies

Two examples
- HV-MAPS
- Ultracold Muons
Ultracold Muons (MuCool Experiment@PSI)

Muon cooling: longitudinal compression

Yu Bao,¹ Aldo Antognini,²,* Wilhelm Bertl,¹ Malte Hildebrandt,¹ Kim Siang Khaw,² Klaus Kirch,¹,² Angela Papa,¹ Claude Petitjean,¹ Florian M. Piegsa,² Stefan Ritt,¹ Kamil Sedlak,¹ Alexey Stoykov,¹ and David Taququ¹

¹Paul Scherrer Institute, 5232 Villigen–PSI, Switzerland.
²Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland.

Idea:
cool muons firstly in cold helium and secondly in room-temperature helium to produce compact ultracold muons

Possible applications:
• MuSR experiments
• Muonium spectroscopy
• Muonium oscillations
• muon g-2
• muon EDM
High Voltage-Monolithic Active Pixel Sensors (HV-MAPS)

transistor logic embedded in N-well ("smart diode array")

- sensor and readout electronics in same chip
- **active sensors** → hit finding + digitisation + serial readout
- can be "thinned" down to ~50 µm (~ 0.0005 X₀)
- low production costs (standard HV-CMOS process)
- Mu3e experiment:
  → layer thickness ~1/30 of standard hybrid detectors (ATLAS/CMS)

→ interesting technology for high rate experiments @ low energy

I. Peric, P. Fischer et al., NIM A 582 (2007) 876