Rare Decay Experiments

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Outline

• Why Rare Decay Experiments?
• Which Rare Decays?
• Examples of the Rare Decay Experiments
• How to do Rare Decay Experiments?
• Beam for Rare Decay Experiment
• Summary
Why Rare Decay Experiments?
Standard Model

The Standard Model can explain most of the experimental results. However, there are many undetermined parameters and issues.
The Standard Model is considered to be incomplete. New Physics is needed.
Three Frontiers of Particle Physics
To explore new physics...
Three Frontiers of Particle Physics

To explore new physics...

The Intensity Frontier
use intense beams to observe rare processes and study the particle properties to probe physics beyond the SM.
Three Frontiers of Particle Physics

- **The Intensity Frontier**: use intense beams to observe rare processes and study the particle properties to probe physics beyond the Standard Model (SM).

- **Rare Decays**: To explore new physics...

- **The Energy Frontier**: Origin of Mass, Matter/Anti-matter Asymmetry, Unification of Forces, Origin of Universe

- **The Cosmic Frontier**: Dark Matter, Neutrino Physics, Dark Energy, Proton Decay

- **Beyond the Standard Model**: Dark Matter, Neutrino Physics, Proton Decay
Symmetry Breaking and Frontiers
Symmetry Breaking and Frontiers

Electroweak Symmetry Breaking

\[ SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM} \]

\[ \sim O(100 \text{ GeV}) \]

- The LHC will directly address this.

Energy Frontier
Symmetry Breaking and Frontiers

Electroweak Symmetry Breaking

\[ SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM} \]

\[ \sim O(100 \text{ GeV}) \]

• The LHC will directly address this.

Energy Frontier

Flavor Symmetry Breaking

• Which interaction distinguishes generations.

\[ \sim \text{Higher energy scale (GUT?)} \]

• Flavor physics in quark and lepton sectors.

Intensity Frontier
Energy (GeV)

Inverse of Force Strength

U(1) Electromagnetic Force
SU(2) Weak Force
SU(3) Strong Force

Measured Data

Standard Model
SUSY Model
GUT $\left(1/\alpha_{\text{GUT}}\right)$

$10^{16}$ GeV
History of the Universe

- **Electroweak Epoch**
  - Higgs particles
  - Supersymmetry

- **Unification Epoch**
  - Grand unification of fundamental forces
  - Origin of Neutrino mass (RH neutrino)
  - Leptogenesis (baryogenesis)

- **Quantum Gravity Epoch**
  - Superstrings

- **Time Scale**
  - 10^13 sec
  - 10^2 sec
  - 10^{-10} sec
  - 10^{-34} sec

- **Energy Scale**
  - 10^{-9} GeV
  - 10^{-3} GeV
  - 10^3 GeV
  - 10^{16} GeV
  - 10^{19} GeV
**History of the Universe**

- **Quantum Gravity Epoch**: $10^{-34}$ sec, $10^{16}$ GeV
  - Superstrings

- **Unification Epoch**: $10^{-10}$ sec, $10^{3}$ GeV
  - Grand unification of fundamental forces
  - Origin of Neutrino mass (RH neutrino)
  - Leptogenesis (baryogenesis)

- **Electroweak Epoch**: $10^{-2}$ sec, $10^{-3}$ GeV
  - Higgs particles
  - Supersymmetry

- **Big Bang**: $10^{13}$ sec, $10^{-9}$ GeV
This energy scale cannot be directly reached by accelerators.

Electroweak Epoch
- Higgs particles
- Supersymmetry

Unification Epoch
- Grand unification of fundamental forces
- Origin of Neutrino mass (RH neutrino)
- Leptogenesis (baryogenesis)

Quantum Gravity Epoch
- Superstrings
The Intensity Frontier is.....
The Intensity Frontier is.....

The energy scale reached by the intensity frontier could be very high through quantum radiative corrections (renormalization group equation = RGE).

Quantum Corrections

Effects are small.

\[ \Delta E \sim \frac{\hbar}{2\Delta t} \]

Uncertainty principle
The Intensity Frontier is.....

The energy scale reached by the intensity frontier could be very high through quantum radiative corrections (renormalization group equation = RGE).

Quantum Corrections

Effects are small.

$\Delta E \sim \frac{\hbar}{2\Delta t}$

Uncertainty principle

Rare Decays
Sensitivity to High Energy-scale Physics
Exercise (1) :
Sensitivity to High Energy-scale Physics

Exercise (1):

Take an example of rare decay of $\mu \rightarrow e\gamma$ ($\text{Br} < 10^{-11}$)

$$\mathcal{L}_{\text{LFV}} = y \frac{e m_\mu}{\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \text{h.c.} + \cdots$$

$$\text{BR}(\mu \rightarrow e\gamma) = y^2 \frac{3(4\pi)^3 \alpha}{G_F \Lambda^4} \quad \Lambda : \text{new physics scale}$$
Sensitivity to High Energy-scale Physics

Exercise (1):

Take an example of rare decay of $\mu \rightarrow e\gamma$ ($\text{Br} < 10^{-11}$)

$$\mathcal{L}_{\text{LFV}} = y \frac{e m_\mu}{\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \text{h.c.} + \cdots$$

$$\text{BR}(\mu \rightarrow e\gamma) = y^2 \frac{3(4\pi)^3 \alpha}{G_F^2 \Lambda^4}$$  \(\Lambda\) : new physics scale

For tree diagrams,

$$\text{BR}(\mu \rightarrow e\gamma) = 1 \times 10^{-11} \times \left(\frac{400\text{TeV}}{\Lambda}\right)^4 \left(\frac{y}{1}\right)^2$$

> sensitive to energy scale higher than 400 TeV
Sensitivity to High Energy-scale Physics
Exercise (2) :
Sensitivity to High Energy-scale Physics

Exercise (2):

\[ y = \frac{g^2}{16\pi^2} \theta_{\mu e} \]

For loop diagrams,

\[ \text{BR}(\mu \to e\gamma) = 1 \times 10^{-11} \times \left( \frac{2 \text{TeV}}{\Lambda} \right)^4 \left( \frac{\theta_{\mu e}}{10^{-2}} \right)^2 \]

> sensitive to TeV energy scale with reasonable mixing
Sensitivity to High Energy-scale Physics

Exercise (2):

For loop diagrams,

$$\text{BR}(\mu \rightarrow e\gamma) = 1 \times 10^{-11} \times \left( \frac{2\text{TeV}}{\Lambda} \right)^4 \left( \frac{\theta_{\mu e}}{10^{-2}} \right)^2$$

$$y = \frac{g^2}{16\pi^2} \theta_{\mu e}$$

> sensitive to TeV energy scale with reasonable mixing

example diagram for SUSY (~TeV)

Physics at about $10^{16}$ GeV

SUSY-GUT model

SUSY neutrino seesaw model

slepton mixing (from RGE)

example:

- large extra dimension
- SUSY: new physics scale

Is the LFV searches sensitive to TeV scale physics?

For loop diagrams, > sensitive to TeV energy scale with reasonable mixing
Which Rare Decays?
Guideline for Choosing Processes.....
Guideline for Choosing Processes.....

Contributions from new physics must be small.
Guideline for Choosing Processes.....

Contributions from new physics must be small.

Process

SM
Standard Model Contribution

New Physics Contribution

NP

SM contribution is dominant.
Guideline for Choosing Processes.....

Contributions from new physics must be small.

SM contribution is dominant.

SM contribution is highly suppressed.

SM contribution is forbidden.
Flavor Changing Neutral Current (FCNC)

a process that is highly suppressed or forbidden in the SM.

FCNC in Quark Sector

\[ B \to X_s \gamma \]
\[ K^+ \to \pi^+ \nu \bar{\nu} \]
\[ K_L \to \pi^0 \nu \bar{\nu} \quad \text{CPV} \]

\[ B_{\text{SM}}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.2 \pm 0.8) \times 10^{-11} \]
\[ B_{\text{SM}}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (2.8 \pm 0.4) \times 10^{-11} \]

The SM contributions are highly suppressed and are known within the uncertainty of a few \%.
Flavor Changing Neutral Current (FCNC)

A process that is highly suppressed or forbidden in the SM.

**FCNC in Lepton Sector**

\[ \mu \rightarrow e\gamma \]

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

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

**charged lepton flavor violation (cLFV)**

\[ B_{SM}(\mu \rightarrow e\gamma) \sim O(10^{-52}) \]

The SM contributions are forbidden for cLFV.
Example: SUSY Prediction for $\mu$-$e$ conversion (charged lepton flavor violation)

$B(\mu Ti \rightarrow e Ti) \times 10^{12}$ vs $M_{1/2}$ (GeV)

Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139

experimental bound $BR \sim 10^{-12}$

$10^6$

experiment projection $BR \sim 10^{-18}$
### Rating of DNA of New Physics (a la Prof. Dr. A. Buras)

#### Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models

<table>
<thead>
<tr>
<th>Observable</th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>δLL</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
</tr>
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<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>$S_{\delta K}$</td>
<td>★★★★</td>
<td>★★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{CP} (B \to X_s \gamma)$</td>
<td>★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{7,8} (B \to K^* \mu^+ \mu^-)$</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>
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<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>
<td>★</td>
<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.
Examples of Rare Decay Experiments
**K^+ → π^+νν**: E787/E949 at BNL (1988 - 2008)

### Special Features of Measuring \( K^+ → π^+νν \)

**Bayesian Measure**

\[ B_{SM}(K^+ → π^+νν) = (8.5 \pm 0.7) \times 10^{-11} \]

- Experimentally weak signature with background processes exceeding signal by \( >10^{10} \)

- Determine everything possible about the \( K^+ \) and \( π^+ \)
  - \( π^+/μ^+ \) particle ID better than \( 10^6 \) (\( π^+ → μ^+ → e^+ \))

- Eliminate events with extra charged particles or **photons**
  - \( π^0 \) inefficiency \( < 10^{-6} \)

- Suppress backgrounds well below the expected signal (S/N~10)
  - Predict backgrounds *from data*: dual independent cuts
  - Use “Blind analysis” techniques
  - Test predictions with outside-the-signal-region measurements

- Evaluate candidate events with S/N function
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ : E787/E949 at BNL (1988 - 2008)
$K^+ \rightarrow \pi^+ \nu \nu$:
Observation of $K^+ \rightarrow \pi^+ \nu \nu$ Events

E787/E949: 7 events observed

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$

Standard Model:

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$
K^+\rightarrow\pi^+\nu\nu: NA62 at CERN SPS

CERN NA-62 first generation decay-in-flight experiment.

75 GeV

- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 40-50 events/yr at SM
- Under construction; start >2013

- cherenkov
- Si trackers
- straw chambers
- RICH detector
- liquid Kr calorimeter
- muon veto

\[ \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu2})} \]
\[ K^+ \rightarrow \pi^+ \nu \nu \]:
NA62 at CERN SPS talks at TIPP2011

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
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</thead>
<tbody>
<tr>
<td>[59]</td>
<td>The Large Angle Photon Veto System for the NA62 Experiment at CERN: PALLADINO, Vito</td>
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<td>[369]</td>
<td>The TDCpix readout ASIC: a 75 ps resolution timing front-end for the Gigatracker of the NA62 experiment: Dr. AGLIERI RINELLA, Gianluca</td>
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<td>[9]</td>
<td>THE NA62 RICH DETECTOR: PEPE, Monica</td>
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<td>[55]</td>
<td>Results from the NA62 Gigatracker prototype: a low-mass and sub-ns time resolution silicon pixel detector: Dr. FIORINI, Massimiliano</td>
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<td>[108]</td>
<td>GPUs for fast triggering in NA62 experiment: LAMANNA, Gianluca MARCO, Sozzi</td>
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<td>[135]</td>
<td>NA62 spectrometer: a low mass straw tracker: SERGI, Antonino</td>
</tr>
<tr>
<td>[389]</td>
<td>The CHarged ANTIcounter for the NA62 experiment at CERN: Dr. SARACINO, Giulio</td>
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</tbody>
</table>
$K_L \to \pi^0\nu\nu$:

K0TO (E16) at J-PARC

K0TO: use improved KEK E391a ($<2.6 \times 10^{-8}$) detector

- Improved J-PARC Beam line
- (Eventually) higher power
- Aim: 2.8 events (S/B~1) at SM
- Under construction; start >2011

- CsI carolimeter
- photon veto
$K_L \rightarrow \pi^0 \nu \nu$

K0TO (E16) at J-PARC talks at TIPP 2011

[132] The Data Acquisition System for the K0TO Detector TECCHIO, Monica
What is $\mu \rightarrow e\gamma$?

**Event Signature**
- $E_e = m_\mu/2$, $E_\gamma = m_\mu/2$ ($=52.8$ MeV)
- angle $\theta_{\mu e}=180$ degrees (back-to-back)
- time coincidence

**Backgrounds**
- prompt physics backgrounds
  - radiative muon decay $\mu \rightarrow e\nu\nu\gamma$ when two neutrinos carry very small energies.
- accidental backgrounds
  - positron in $\mu \rightarrow e\nu\nu$
  - photon in $\mu \rightarrow e\nu\nu\gamma$ or photon from $e^+e^-$ annihilation in flight.
The MEG Experiment

International Collaboration (~65 collaborators)

LXe Gamma-Ray Detector

Muon Beam

COBRA SC Magnet

Drift Chambers

Timing Counter

2010 preliminary $<1.5 \times 10^{-11}$ from 2 month-data in 2009 (sensitivity: $6.1 \times 10^{-12}$) Final goal is $2 \times 10^{-13}$
We opened the blind box on 06/July/2010

* Contours of the PDFs (1σ, 1.64σ & 2σ) are shown

* Same events in two plots are numbered correspondingly, by decreasing ranking in terms of relative signal likelihood (S(R+B))

Smoking from MEG 2010 Results (preliminary)
μ→eγ :
MEG at PSI talks at TIPP 2011

[287] Liquid xenon gamma-ray calorimeter for the MEG experiment :
Dr. IWAMOTO, Toshiyuki
Muon to Electron Conversion

1s state in a muonic atom

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

Muon decay in orbit

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

Nuclear muon capture

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

\( \mu^- - B_\mu \sim 105 MeV \)

Signal is a single mono-energetic electron

Lepton flavors change by one unit.
µ-e conversion: Mu2e at Fermilab

\[ B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17} \]
\[ B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.) \]

- Reincarnation of MECO at BNL.
- Antiproton buncher and accumulator rings are used to produce a pulsed proton beam.
- Approved in 2009, and CD0 in 2009.
µ-e Conversion :
Mu2e at FNAL talks at TIPP 2011

[127] R Effort for Plastic Scintillator Based Cosmic Ray Veto System for the Mu2e : Dr. OKSUZIAN, Yuri
**µ-e conversion:**
**COMET (E21) at J-PARC**

- 8 GeV proton beam
- 5T pion capture solenoid
- 3T muon transport (curved solenoids)
- Muon stopping target
- Electron transport
- Electron tracker and calorimeter

**Experimental Goal of COMET**

\[
B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}
\]
\[
B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)
\]

- $10^{11}$ muon stops/sec for 56 kW proton beam power.
- C-shape muon beam line and C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.
How to Do Rare Decay Experiments?
Important Considerations in Experiment Design
Important Considerations in Experiment Design

1. Redundancy
Important Considerations in Experiment Design

1. Redundancy

2. Redundancy
Important Considerations in Experiment Design

1. Redundancy
2. Redundancy
3. Redundancy
Important Considerations in Experiment Design

1. Redundancy

Redundancy only gives confidence to discriminate signals from backgrounds.

2. Redundancy

Ambiguous hits, accidental hits, dead channels, reconstruction of ghost tracks.

3. Redundancy
Example: E787/E949

measure **momentum, energy, range** of pions, and pion decay by wave-form digitizers
Considerations for Detectors (1)

To improve signal sensitivity, the number of parent particles (i.e. beam intensity) has to be increased.

1. **High rate capability**

example: rate for $\mu$-e conversion experiments

With $10^{11}$/s stops, the rate of straw chambers is about 6 MHz per wire at prompt, and 180 kHz per wire after 700 nsec (measurement window).
Considerations for Detectors (2)

Accidental Backgrounds

example. accidental backgrounds for \( \mu \rightarrow e\gamma \)

\[
\text{Accidental Background} \propto \left( R_\mu \right)^2 \times \Delta E_e \times \left( \Delta E_\gamma \right)^2 \times \Delta t_{e\gamma} \times \left( \Delta \theta_{e\gamma} \right)^2
\]

<table>
<thead>
<tr>
<th>Place</th>
<th>Year</th>
<th>( \Delta E_e )</th>
<th>( \Delta E_\gamma )</th>
<th>( \Delta t_{e\gamma} )</th>
<th>( \Delta \theta_{e\gamma} )</th>
<th>Upper limit</th>
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<tr>
<td>TRIUMF</td>
<td>1977</td>
<td>10%</td>
<td>8.7%</td>
<td>6.7ns</td>
<td>–</td>
<td>( &lt; 3.6 \times 10^{-9} )</td>
</tr>
<tr>
<td>SIN</td>
<td>1980</td>
<td>8.7%</td>
<td>9.3%</td>
<td>1.4ns</td>
<td>–</td>
<td>( &lt; 1.0 \times 10^{-9} )</td>
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<tr>
<td>LANL</td>
<td>1982</td>
<td>8.8%</td>
<td>8%</td>
<td>1.9ns</td>
<td>37mrad</td>
<td>( &lt; 1.7 \times 10^{-10} )</td>
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<tr>
<td>LANL</td>
<td>1988</td>
<td>8%</td>
<td>8%</td>
<td>1.8ns</td>
<td>87mrad</td>
<td>( &lt; 4.9 \times 10^{-11} )</td>
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<tr>
<td>LANL</td>
<td>1999</td>
<td>1.2%</td>
<td>4.5%</td>
<td>1.6ns</td>
<td>15mrad</td>
<td>( &lt; 1.2 \times 10^{-11} )</td>
</tr>
<tr>
<td>PSI (MEG)</td>
<td>2007</td>
<td>0.9%</td>
<td>5%</td>
<td>0.1 ns</td>
<td>23mrad</td>
<td>( &lt; 10^{-13} )</td>
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Improvements of detector resolutions are critical.
### MEG Detector Resolutions

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>PRELIMINARY</th>
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</thead>
<tbody>
<tr>
<td><strong>γ Energy σE_{γ} (%)</strong></td>
<td>2.0 (depth&gt;2cm)</td>
<td>2.1 (depth&gt;2cm)</td>
</tr>
<tr>
<td><strong>γ Timing σt_{γ} (ps)</strong></td>
<td>80</td>
<td>&gt;67</td>
</tr>
<tr>
<td><strong>γ Position σx_{γ} (mm)</strong></td>
<td>5/6</td>
<td>5/6</td>
</tr>
<tr>
<td><strong>γ Efficiency ε_{γ} (%)</strong></td>
<td>63</td>
<td>58</td>
</tr>
<tr>
<td><strong>e^+ Mom. σp_e (%)</strong></td>
<td>1.6</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>e^+ Timing σt_e (ps)</strong></td>
<td>&lt;125</td>
<td>&lt;125</td>
</tr>
<tr>
<td><strong>e^+ Angle σθ_e (mrad)</strong></td>
<td>10(φ)/18(θ)</td>
<td>7.4(φ)/11.2(θ)</td>
</tr>
<tr>
<td><strong>e^+ Efficiency ε_e (%)</strong></td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td><strong>γ-e^+ Relative Timing</strong></td>
<td>148</td>
<td>142</td>
</tr>
<tr>
<td><strong>μ^+ decay vertex (mm)</strong></td>
<td>3.2/4.5</td>
<td>2.3/2.8</td>
</tr>
<tr>
<td><strong>Trigger Efficiency (%)</strong></td>
<td>66</td>
<td>84</td>
</tr>
<tr>
<td><strong>μ^+ Stopping Rate (Hz)</strong></td>
<td>3×10^7</td>
<td><strong>2.8×10^7</strong></td>
</tr>
<tr>
<td><strong>DAQ Time (days)</strong></td>
<td>48</td>
<td>35</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>1.3×10^{-11}</td>
<td><strong>coming soon</strong></td>
</tr>
<tr>
<td><strong>BR Upper Limit</strong></td>
<td>2.8×10^{-11}</td>
<td><strong>coming soon</strong></td>
</tr>
</tbody>
</table>

Because of accidental backgrounds, the full PSI beam of 10^8/s intensity cannot be taken yet.
To avoid accidental backgrounds at all, try....

a single particle measurement, such as $\mu$-e conversion ($\mu^-N \rightarrow e^-N$)
Considerations in Detectors (3)

In rare decay experiments using muon and kaon decay at rest, decay products are all in low energy of \( O(10-100 \text{ MeV}) \).

3 Low energy detection

Trackers should be low-mass and be placed in vacuum.

thin chamber for MEG

thin straw chambers in vacuum for COMET and Mu2e
Considerations in Detectors (3)

3 Low energy detection

Photon detector should have high light yields.

Liquid Xenon scintillation detector at MEG
- 800 litter volume
- 846 PMT readout
- Energy resolution:
  - 2% at 52.8 MeV
- Position resolution:
  - 5-6mm at 52.8 MeV
- Timing resolution:
  - 70 ps at 52.8 MeV
Wave form recording with high sampling rates is needed.

Example:
switched capacitor arrays (SCA) called DRS (Domino Ring Sample) developed at PSI for MEG

DRS4
9 Giga-samples per second
depth 1024-8192
signal to noise : 11 bits

example : E787/E949 500 MHz
wave-form digitizers
Beams for Rare Decay Experiments
Increase of Secondary Beam Intensity....
Increase of Secondary Beam Intensity....

1. Increase proton intensity

A number of secondaries is proportional to proton beam power.
Increase of Secondary Beam Intensity....

1. Increase proton intensity

A number of secondaries is proportional to proton beam power.

PSI:
beam power ~ 1.2 MW

J-PARC:
goal beam power ~ 0.75 MW
After Tevatron shutdown

Project X

Neutrino physics
Muon physics
Kaon physics
Nuclear physics

“simultaneously”
After Tevatron shutdown

**Project X**

Neutrino physics
Muon physics
Kaon physics
Nuclear physics

“simultaneously”

3 MW@3 GeV total for muon, kaon and nuclear, simultaneously

2 MW@120 GeV for neutrinos

3 GeV, 1 mA CW proton (H⁻) linac

3-8 GeV pulsed proton linac

2 MW at ~3 GeV, flexible time structure and pulse intensities

Rare Decay programs with MW beam x100 improvements

Remove Accelerators from Cockroft–Walton though Booster and Booster neutrino.
After Tevatron shutdown, Project X focuses on Neutrino physics, Muon physics, Kaon physics, and Nuclear physics, all simultaneously.

**2 MW at ~3 GeV**
- For neutrinos
- 3 GeV, 1 mA CW proton (H⁻) linac
- Multiple programs with MW beam, x100 improvements

**3-8 GeV pulsed proton linac**
- 3 MW@3 GeV total for muon, kaon, and nuclear

**Rare Decay programs**
- Aim to start in 2019

**2 MW (60-120 GeV)**
- 1300 km

**3-8 GeV pulsed proton linac**
- 2 MW at ~3 GeV
- Flexible time structure and pulse intensities
Increase of Secondary Beam Intensity.....
Increase of Secondary Beam Intensity.....

2. Increase collection efficiency of secondaries
Increase of Secondary Beam Intensity.....

2 Increase collection efficiency of secondaries

ex. a muon beam line for \(\mu\)-e conversion experiments

The pion production target is surrounded by superconducting solenoid magnets of a high magnetic field.

For 50 kW beam power, \(10^{11}/\text{sec}\), (in contrast to \(10^8\)/sec for 1.2 MW)
Increase of Secondary Beam Intensity.....

2. Increase collection efficiency of secondaries

ex. a muon beam line for $\mu$-e conversion experiments

The pion production target is surrounded by superconducting solenoid magnets of a high magnetic field. For 50 kW beam power, $10^{11}$/sec, (in contrast to $10^8$/sec for 1.2 MW) improvement of muon yield of about 10,000
Increase of Secondary Beam Intensity....
Increase of Secondary Beam Intensity.....

development of highly intense muon source
Increase of Secondary Beam Intensity..... development of highly intense muon source
Increase of Secondary Beam Intensity....

development of highly intense muon source

Neutrino Factory

Energy frontier Muon Collider - 2~4 TeV
“MuSIC Project”
at Osaka University
“MuSIC Project” at Osaka University

Cyclotron, Osaka University, 1µA, 400 MeV (400W)
“MuSIC Project” at Osaka University

Cyclotron, Osaka University, 1µA, 400 MeV (400W)
“MuSIC Project” at Osaka University

Cyclotron, Osaka University, 1µA, 400 MeV (400W)

Beam test in February, 2011

Muon Life in Cu : run170

| Entries | 26752 |
| Mean    | 1.302e+04 |
| RMS     | 9265 |
| $\chi^2/\text{ndf}$ | 167.6 / 146 |
| Prob    | 0.1068 |
| $N_0$   | 344.3 ± 14.2 |
| $\tau$  | 2191 ± 107.3 |
| const   | 150 ± 1.2 |

about $10^9$/s for 400 W protons
“MuSIC Project” at Osaka University

Cyclotron, Osaka University
1µA, 400 MeV (400W)

Highest Muon Yield in the World

Muon Life in Cu : run170
Beam test in February, 2011
about 10^9 /s for 400 W protons
Spin-off from MuSIC

A Eco Muon Source
Summary
Summary

• Rare decay experiments, as one of the intensity frontier, would be of compelling importance, in particular, their sensitivity to high energy-scale physics.
• Charged lepton flavor violation (cLFV) and quark FCNC would be the best choice for rare decay experiments.
• There are several rare decay experiments on-going and being prepared.
• Technology breakthrough on detectors as well as beams are being developed.
• We hope that these searches would make great discovery.