Probing New Physics with Muon Beams

Mark Lancaster
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“As you undoubtedly know, theoretical physics – what with the haunting ghosts of neutrinos, the Copenhagen conviction,

**against all evidence,**

**that cosmic rays are protons**

Born’s absolutely unquantizable field theory, the divergence difficulties with the positron and the utter impossibility of making a rigorous calculation at all

– is in a hell of a way”

June 1934
The problem
Late 1920s developed a theory: the “Birth Cry of Atoms”
- Religion inspired fusion model forming atoms that also emitted photons.
- Primary cosmic rays were photons of discrete energies

With a dodgy theory and dubious fits to the ionisation data of cosmic rays – he claimed he could explain all the data!

Millikan ignored warnings from Oppenheimer and got his PhD student to make more measurements to prove “The Birth Cry”
Milikan ignored the fact that if primary cosmic rays were not photons then there would be a “lattitude effect” due to the earth’s magnetic field.

Millkan failed to measure the “lattitude effect” Compton did and the two Nobel Prize winners had several public spats.

Millikan and Anderson continued to ignore QM and believed $e^-$ and $e^+$ existed in the nucleus and were knocked out by the “Birth-Cry” cosmic ray photons.

They rejected the Dirac theory of “pair creation” since more $e^-$ were observed than $e^+$

It was in the Cavendish (Blackett, Rossi, Occhialini) where $e^-e^+$ pair-creation coincidence measurements were made and which vindicated Dirac.

Soon after Anderson distanced himself from Millikan and continued his work solo...
Two types of particle seen

Showering particles believed to be electrons but only after a lot of theoretical work by Bethe, Heitler, Oppenheimer, Carlsson in developing QED of $e^+e^-$ pair creation
Red and Blue Electrons!

But no tweaks to the theory could explain why $e^-$ would be penetrating.

For a time the theorists toyed with the idea of the cosmic-ray particles being protons.

They then rejected that in favour of a model of “red” and “blue” electrons: one type showering and one type penetrating!

These rather embarrassing conjectures were quickly swept under the theorist’s carpet when the experimentalists started measuring masses and charges of the penetrating particles.
Chronology

1935 : Yukawa proposes a “mesotron” to explain the finite range of the nuclear force. A particle with mass between $e^-$ and $p$.

March 1937 : Anderson, Neddermeyer (CalTech)
\[\pm \text{particles with mass between } e \text{ and } p\]

April 1937 : Street, Stevenson (Harvard)
\[\text{mass } (+) = (130 \pm 30) \text{ } m_e\]

August 1937 : Nishina, Takeuchi, Ichimiya (Tokyo)
\[\text{mass}(+) = (220 \pm 40) \text{ } m_e\]

June 1938 : Anderson, Neddermeyer
\[\text{mass } (+) \sim 240 \times m_e\]

Jan 1939 : Nishina, Takeuchi, Ichimiya
\[\text{mass}(-) = (170 \pm 10) \text{ } m_e; \text{mass}(+) = (180 \pm 20) \text{ } m_e\]

Everybody goes off to Los Alamos to build a bomb
The 1947 Consensus : Muon and Pion

After the war it was still believed that what had been observed was Yukawa’s mesotron.

1947 : Conversi, Pancini and Piccioni showed that interactions of the negative mesotron with the nucleus were not “strong” but “weak”.

1947 : Weisskopf, Teller and Fermi noted that the decay time of mesotrons in matter was $10^{12}$ longer than for the “Yukaka mesotron”.

The negative mesotron was then given the symbol : $\mu$.

1947 : Lattes, Muirhead, Occhialini and Powell find $\mu^-$ arise from decay products of another cosmic ray mesotron that they give the symbol $\pi$.

It was finally realised the $\mu$ wasn’t a meson but the name “mu-meson” persisted for many years with “muon” only being widely adopted in the 1960s.

Yukawa’s mesotron was christened the pi-meson and latterly the pion.
Who ordered that?

Rabi: instrumental in setting up CERN.

One of first CERN experiments was Lederman’s “g-2” using the 600 MeV accelerator.
Muon was “discovered” by 3 sets of experimentalists and cogent interpretation wouldn’t have been possible without the theory input.

Arguably the Japanese had the most incisive measurement.

The data and its interpretation took 15 years to be accepted.

Solution – no Nobel Prize for the Muon Discovery!

- Keep the Japanese happy: Yukawa (1949) gets a prize for the pion theory
- Keep the USA happy: Anderson already got the prize for $e^+$ (1936) and gets the credit for the muon but not a second prize
- Keep the Brits happy: Powell (1950) for the experimental discovery of the pion and Blackett (1948) for cloud chamber.
- Italians not happy….

CDF, D0, ATLAS, CMS, Englert, Guralnik, Hagen, Higgs, Kibble, ....
Title: Science is measurement: muons, money and the Nobel Prize  
Author: Jeffrey David Turk  
Address: Scientific Research Centre of the Slovenian Academy of Sciences and Arts, Chemin des Deux Maisons 67/28, 1200 Brussels, Belgium  
Abstract: This article investigates the difference in measurement methods between contemporary particle physics and economics. The book Measurement in Economics: A Handbook, (Boumans, 2007), is used to present the current state of measurement technique in economics. These views are compared with the measurement of the anomalous magnetic moment of the muon. Particle physics is realist in measurement while economics is not. The reality check on theory that measurement provides in particle physics is conspicuously absent in economics. However, the nature of the social world precludes the use of the same measurement approach.

“Particle Physics is realist in measurement while economics is not”
Was the muon an unstable heavy electron?

Pontecorvo (Dec 1947)

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

Liverpool 1959.
Physics is in a “hell of a way”

Need new physics to:

1. Give mass to W/Z and neutrino and explain why $m_\nu/m_t = 10^{-12}$

2. Give significant CP violation to explain matter anti-matter asymmetry but also to explain why there is zero CP in QCD: axion !!!

3. Explain dark matter

4. Develop a quantum theory of gravity

One hopes the LHC will help explain some of this but ......
1. Neutrino oscillations : > 5σ
2. \((g-2)\) of muon : 3.6σ
3. D0 like-sign dimuon asymmetry : 3.9σ
4. DAMA/COGENT/CRESST : 10 GeV dark matter
5. CDF/D0 top asymmetry : 2.4σ (was 3.4σ)
6. LHCb/CDF CP violation in D mesons : 3.8σ
7. CDF W+dijets : 4.1σ
8. OPERA ...
9. ......
Experimentalist’s View

0.1 TeV: Higgs?  
1 TeV

WW scattering?  
5 TeV

50 TeV
SCALE OF NEW PHYSICS

EWK SYMMETRY BREAKING

TWEAKED

FLAVOUR SYMMETRY BREAKING

TWEAKED

NATURAL...

NATURAL...

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QMUL Seminar: Mar 2012: p15
We need measurements on several fronts!
Probing $\mu$ Flavour Violation – why?

What is the nature of new physics between the TeV-scale & the GUT-scale?

What role do leptons play in the mechanism generating the Universe’s baryon asymmetry?
Motivation

SEESAW MECHANISM

100 GeV TO GUT SCALE
HEAVY MAJORANA $\nu$

LIGHT $\nu$

LEPTON ASYMMETRY

Decay

Sphaleron Interactions

BARYON ASYMMETRY

0$\nu\beta\beta$ EXPERIMENTS
cLFV EXPTS

$\nu$ OSCILLATION EXPTS

Need all 3 types of experiment

LHC has limited input into this

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Motivation

\[ \gamma_1 = 3\pi/8, \gamma_2 = \pi/2 \]

\[ \eta_B \geq 6.2 \times 10^{-10} \]

\[ \delta m_\kappa = 0.25 \]

\[ B_{\mu e}^{(48\text{Ti})} = 10^{-16} \]

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

\[ 10^{-12} \]

\[ 10^{-11} \]

\[ 10^{-10} \]

\[ 10^{-9} \]

\[ \kappa_1, \kappa_2, \gamma_1, \gamma_2 \text{ symmetry breaking parameters} \]

arXiV:1012.1834
Why Muon LFV?

1. SM is $O(10^{-50})$

Observation IS new physics

$$O \left( \frac{m_\nu}{M_W} \right)^4$$

No SM theory systematic
Why Muon LFV ?

2. BSM predictions are $O(10^{-10} - 10^{-20})$

We know lepton # is not sacrosanct ($\nu$ oscillations)

How far we can probe is determined by technology

Recent advances in accelerator, s/c magnets and detectors mean $O(10^4)$ improvement in reach is readily achievable.
Why Muon LFV?

3. Complementary to & probes scales > LHC

Region to be probed by MEG in next 1-4 years

# LFV events at 100/fb LHC

\[
\sin^2(\theta_{13})
\]

\[
B(\mu\to e\gamma)
\]

\[
\Delta m_{\odot}^2 > 0
\]

\[
\Delta m_{\odot}^2 < 0
\]

arXiv:1012.1834

arXiv:1011.1404

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QMUL Seminar: Mar 2012: p22
Flavor Physics Observables

4. Sensitivity to widest variety of BSM 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>
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<td>$B \to K^{(*)} \nu \bar{\nu}$</td>
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<td>$(g-2)_\mu$</td>
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Different SUSY and non-SUSY BSM models.

Large effects ★★★
Visible but small ★★
No sizeable effect ★
Where are we now?

Limits improved $O(10^{10})$ for three muon LFV processes over 50 years

and $\Delta L=2$ decays of muonic ($\mu^+e^-$) atoms have placed limits on $G_F'$
Where are we now?

The present $e\gamma$ limit is the most incisive measurements since typically in BSM models:

$$R(\mu N \rightarrow eN)/R(\mu \rightarrow e\gamma) \sim O(\alpha_{\text{EM}})$$

& similarly for $\mu \rightarrow 3e$

So present MEG/PSI limit is $\sim 10$ beyond the two SINDRUM/PSI limits.
Where are we now?

Present MEG $\mu \rightarrow e\gamma$
converted to eN and $\tau \rightarrow \mu\gamma$

limits shown by -----, -----,

In effect the MEG limit surpasses
the eN limits by $O(100)$ and the
tau limits by $O(1000)$
Muons vs Taus

SPS 1a
\[ m_{N1} = 10^{10} \text{ GeV}, \quad m_{N2} = 10^{11} \text{ GeV} \]
\[ m_{\nu_1} = 10^{-5} \text{ eV} \]
\[ 0 \leq |\theta_1| \leq \pi/4 \]
\[ 0 \leq |\theta_2| \leq \pi/4 \]
\[ \theta_3 = 0 \]

MEG
MEG 2010
MEG 2011
MEG 2015 ?

Daya Bay = 9°

hep-ph/0610439
Where do we want to be?

Measurements of all 3 \( \mu \) processes (\& \( \tau \)) with commensurate sensitivity.
- \( \mu N \rightarrow e N \) \& \( \mu \rightarrow 3e \) : need \( O(100) \) improvement to eclipse present \( \mu \rightarrow e \gamma \) (MEG).

4\(^{th}\) gen. model.

B (\( \mu \rightarrow e e e \))

\( \text{PSI Limit} \)
Ideally need $\mu \rightarrow 3e$ at $10^{-16}$ and beyond

Generic Lagrangian with BSM dipole (low $\kappa$) and BSM 4-fermion (high $\kappa$) interactions at scale $\Lambda$

$$\frac{1}{\Lambda^2} \approx \frac{g^2 \theta_{e\mu}}{M_{\text{SUSY}}^2}$$

Note scale is $O(1000)$ TeV ...

Need $\mu N \rightarrow e N$ at $10^{-16}$ and beyond

$\Lambda$ (TeV)

$B(\mu \rightarrow e\text{ conv in }^{48}\text{Ti}) > 10^{-18}$

$B(\mu \rightarrow e\gamma) > 10^{-14}$

$B(\mu \rightarrow e\gamma) > 10^{-13}$

$M_N = 10^{14}$ GeV
$
\tan \beta = 60
$

$\mu > 0$

$\mu < 0$

$M_H(SUSY)$

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Process Ratios are Model Dependent

e.g. In “Littlest Higgs model” with T-parity (LHT): \( \frac{R(\mu N \rightarrow eN)}{R(\mu e \rightarrow e\gamma)} \sim 1 \)

Process Ratios are Model Dependent

\[ BR(\mu \to \text{e}e) \]

\[ BR(\mu \to \text{e}\gamma) \]

LHT Model
We also want to measure Z dependence.

- Measure all 3 muon LFV processes (and $\tau$)
- Need to get to $O(10^{-16})$ & beyond in $\mu N \rightarrow eN$ & $\mu \rightarrow 3e$ (improve by $10^4$) and push $\mu \rightarrow e\gamma$ beyond $10^{-13}$
- Measure $\mu N \rightarrow eN$ with Al and higher-Z targets.

Can this be done with any current detector/facility?
Can This Be Done With Existing Facilities?

The only complete and fully-funded facility/detector is MEG@PSI **but**:

- to significantly improve on $\mu \rightarrow 3e$ and $\mu \rightarrow e\gamma$ needs advances in detector technology and more muons (at high duty factor) than PSI presently produces.

- to improve on $\mu N \rightarrow eN$ requires a new methodology/technology than was previously used at PSI (SINDRUM II).

To understand what facilities we need it is instructive to consider the current state of the art i.e. MEG @ PSI
For The Theorists

Proton Beam

Production Target

π

Muonic Atom Formed and Decays

µ

Stopping Target aka THE TARGET

Detector

µ

Apply symmetries, translations, rotations, .....
Current State of The Art

PSI (Zurich/Switzerland) Facility

$3 \times 10^7$ “stopped” $\mu^+$/sec

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MEG present limit on $\mu \rightarrow e \gamma$ is $2.4 \times 10^{-12}$. It is aiming to get to $1 \times 10^{-13}$.

\[ E_\gamma = E_{e^+} = 52.8 \text{ MeV} \]
\[ \theta_{\gamma e} = 180^0 \]
\[ \gamma \text{ and } e^+ \text{ in time} \]
MEG Experiment

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QMUL Seminar : Mar 2012 : p39
MEG Experiment

Run 59731 Event 1212
$E_\gamma = 52.25$ MeV
$E_{e^+} = 52.84$ MeV
$\Delta \theta_{e^+\gamma} = 178.8$ degrees
$\Delta T_{e\gamma} = 26.8$ ps

Liquid Xe calorimeter

Drift Chamber

Timing Chamber
MEG Sensitivity Determined By

- **# of stopped muons**: accelerator driven (2010 : $2.3 \times 10^7$/s)
  - Need high duty cycle. PSI is DC : 100% duty cycle.

- **Resolution** in $e^+$ and photon energy and angle, time between them

---

2010 MEG data
Accidental background goes as $N(\mu)^2$

Increasing intensity for more statistics needs *reduction in resolutions*

\[
N_{\text{BG}} = \left( \frac{R_\mu}{D} \right)^2 \Delta t_{e\gamma} \Delta E_e (\Delta E_\gamma)^2 (\Delta \Theta_{e\gamma})^2
\]

$R_\mu$: Muon stop rate

$D$: Duty Cycle
2010 data only

Expected limit = $2.2 \times 10^{-12}$

Observed limit = $1.7 \times 10^{-12}$

$\mu$ on Target $\times 10^{12}$

2009+2010 limit = $2.4 \times 10^{-12}$

2010 Resolutions/Efficiencies

2012 limit $\sim 7 \times 10^{-13}$
Assume $10^7$ sec running per year for 2013-2016.

- **2012**: $5 \times 10^{-13}$ (-20% resn.)
  - 3 x $10^7 \mu/s$

- **2016**: $1 \times 10^{-13}$
  - -50% resn.
  - 4 years @ 6 x $10^7 \mu/s$

- **2016**: $1 \times 10^{-13}$
  - -20% resn.
  - PSI @ 2 x $10^8 \mu/s$

PSI already providing ~ $10^8$/sec.

MEG will increase its e⁺ detection efficiency + some detector improvements.

~ $10^{-13}$ achievable.
Beyond MEG to $10^{-14}$

To go below $10^{-13}$ using the “MEG method” i.e. tracker ($e^+$) + calorimeter ($\gamma$) method requires:

Significant improvements in detector resolutions $O(50\%)$ (at high rates...)

Stopped muon rate $\approx 10^9/s$ (DC)
(MEG now @ $3 \times 10^7/s$)

4 year run
Resolutions

Improved resolutions need to be achieved in high pile-up environment (acceptance)

<table>
<thead>
<tr>
<th>Exp. (Δ = FWHM)</th>
<th>$\Delta t_{\gamma\gamma}$</th>
<th>$\Delta E_{\gamma\gamma}$</th>
<th>$\Delta \Theta_{\gamma\gamma}$</th>
<th>$\Delta E_e$</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEG</td>
<td>290 ps</td>
<td>4.5%-5.6% (core)</td>
<td>52 mrad</td>
<td>1.4% (core)</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Other Methodology

- $E_\gamma$, $\Theta_{e\gamma}$ resolution and pile-up are limiting factors particularly at high $\mu$ intensities

- Another option to achieve reduced sensitivity is to have a “track-only” analysis.

Conversion point and event vertex defined by precision tracking.
Optimise material thickness to optimise rate reduction vs resolution degradation.

MEGA (LANL:1990s) used this approach & achieved

$\Delta \theta_{e\gamma} = 33 \text{ mrad vs } 52 \text{ mrad in MEG and}$

$\Delta E_\gamma = 1.7 - 3\% \text{ vs } 4.5 - 5.6\% \text{ (MEG)}.$

The 50% improvement in key resolutions is possible if one can cope with high rates. MEGA could not and had a v. low acceptance (0.4%).
Ultimate $\mu \rightarrow e\gamma$ : Requirements

**Facility**
- DC muons @ > $10^9$/sec. PSI now at $10^8$ with plan to $10^9$ and possibly $2 \times 10^{10}$
- Pulsed muons @ $10^{12}$/sec – but with $10\tau_\mu$ gap so can reduce accidental bgrd. by waiting for radiative decays to subside in a measurement window.

**Detector**
High resoln. (0.5(e) – 1.0(\gamma) MeV [FWHM]) tracking detector with high resilience to pile-up

**Other**
Online Track Trigger (without calorimeter) or triggerless operating at $O(100$ Gbit/s) e.g GPU farm.

**Possible Reach**
$10^{-14}$ *(factor of 250 improvement vs MEG(2011))*

These requirements share much with the next generation $\mu \rightarrow 3e$
One of the options under discussion:

Spallation target as a muon source?
- Larger energy range of $\pi$ production exploited
- Stopping volume substantially larger
- Higher $Z$
- Target window: surface muon source

First (very rough) estimate:
- 300 x more $\mu^+$
- $\sim 3 \times 10^{10} \mu^+/s$

Very preliminary! Under study

Klaus Kirch ICFA Oct 2011

$\mu E5 \sim 10^9$

$SINQ \sim 10^{10}$

P.-R. Kettle, M. Wohlmuther, work in progress
Current state of the art is 1988 with limit @ $10^{-12}$

Given MEG results (@ $10^{-13}$) this only begins to get interesting at $10^{-14}$ (e.g. LHT models) BUT ideally would like to get to $10^{-16}$
Same issues as $\mu \rightarrow e\gamma$
- accidental/pile-up backgrounds: $(R_{\mu}/D)^2$ – so DC beam required.

Two $\mu^+$ decays and fake $e^-$ (Bhaba scattering, $\gamma$ conversion)

- irreducible background: $R_{\mu}$

As with $\mu \rightarrow e\gamma$ the solution is resolution, resolution, resolution...

Dominant

$BR = 3 \times 10^{-5}$

Issue as go to $\nu$, high rates
Experimental signature

- 2 +ve tracks, one –ve
- common vertex and event time

\[ \sum_i p_i = 0, \quad \sum_i E_i = m_\mu \]
Limit achievable vs cut on $m_\mu - E_{TOT}$

Need resolution on $\Sigma E$ to 1.5 MeV to reach $10^{-16}$

And for this to be achieved in high rate environment

Accidental background depends on tracking resolution at high muon rates. Seems tracking OK down to $10^{-17}$ even at $10^{10}$ muon stops.

**Limiting factor is the irreducible radiative background**

![Graph showing BR versus $\sigma_E$ (MeV)](image)

- **Two $\mu \rightarrow e\nu\nu$ and one wrong signed track**
- **freq x $\sigma_{Time} = 0.1$**
- **100 decays for muon rate @ $10^9$/sec**

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Future $\mu \rightarrow eee$ experiments

Two proposals to go beyond current $10^{-12}$ limit

- MUSIC @ Osaka : $10^{-15}$ from $3 \times 10^8 \mu/s$ at 400W ($E_p = 392$ MeV)
  - budget request presently being considered

- mu3e @ PSI : $< 10^{-16}$ from $> 10^9 \mu/s$ at 1.4 MW ($E_p = 530$ MeV)
  - LOI to be submitted early 2012
Utilising prototype pion production environment for COMET
MUSIC (eee) @ Osaka

Three commissioning runs in 2010/11 with reduced beam I (6pA [2.4mW]) with Cu and Mg targets for muon beam

Due to pion capture solenoid. Muon yield per W of beam power is $\sim O(1000)$ PSI.

Detector design still evolving but expecting to use TPC since heavy ion experiments have shown these can be used in high rate environment ($10^8$ tracks/sec).

If funded physics run in 2016.
Aiming to achieve sensitivity $O(100)$ beyond MUSIC
- simple detector to get to $10^{-15}$ in existing ($\sim$ few $10^8 \mu s$) PSI/MEG beam line: 2014/15
- PSI beamline upgrade ($> 10^9 \mu s$ e.g. using backward muons from the SINQ beamline) to get to $10^{-16}$: after 2016/17

Scintillating Fibers for precision timing

Hollow double cone target

Very thin silicon sensors for precision momentum and vertexing
### mu3e @ PSI

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<th>Technology</th>
<th>Thickness</th>
<th>Speed</th>
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<td>260 μm</td>
<td>25 ns</td>
<td>extra RO chip</td>
</tr>
<tr>
<td>DEPFET (Belle II)</td>
<td>50 μm</td>
<td>slow (frames)</td>
<td>extra RO chip</td>
</tr>
<tr>
<td>MAPS</td>
<td>50 μm</td>
<td>slow (diffusion)</td>
<td>fully integrated</td>
</tr>
<tr>
<td>HV-MAPS</td>
<td>&gt; 30 μm</td>
<td>O(100 ns)</td>
<td>fully integrated</td>
</tr>
</tbody>
</table>

- HV-MAPS Si pixel offers reduced multiple scattering resolution
- Pixels: 80 x 80 μm; zero suppressed data @ 800 Mbit/sec with 10 MHz clock
- Low power consumption (150 mW/cm²)

With 40 μm thick sensors hope to achieve $\sigma(\theta)_{\text{MS}} = 5$ mrad (c.f. SINDRUM-I: 28 mrad)
Fiber tracker: $\sigma(t) = 100 \text{ ps readout with SiPM}$ (SINDRUM-I: 800 ps)

Vertex Resolution: 120-150 $\mu$m.
$\sigma(p): 0.45-0.65 \text{ MeV}$

cf SINDRUM-1
Vertex: 1mm
$\sigma(p): 2.5 \text{ MeV}$
mu3e @ PSI

Designs still evolving but Si pixel (HV-MAPS) and fibers for timing provide excellent resolution.

Looks like can better the irreducible background to below $10^{-16}$
Ultimate $\mu \rightarrow eee$

Given ultimate $\mu \rightarrow e\gamma$ is likely track-based then similar design

**Facility**
- DC muons @ (> $10^9$/sec.
- Pulsed muons @ $10^{12}$/sec – but with $10\tau_\mu$ gap so can reduce accidental bgrd.
  by waiting for irreducible decays to subside in a measurement window.

**Detector**
High resoln tracking detector with high resilience to pile-up ($\Sigma E_i$ at < 0.5 MeV)
Timing resolution better than $\sigma \sim 100$ ps.

**Possible Reach**

$10^{-15}$ (short term MUSIC/mu3e), $10^{-16}$ (mu3e), $10^{-17-18}$ (ultimate ?)

*May be possible to modify next generation $\mu \rightarrow eee$ to incorporate $\mu \rightarrow e\gamma$*
Muon to Electron Conversion

Processes considered so far suffer, at the highest rates, from accidental backgrounds that scale as $R(\mu)^2$

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

The “conversion process” has a simple one particle signature. $E_e \sim m_\mu$

($\gg E_e$ from free muon decay).

Arguably best route to highest sensitivity at high muon rates.
μN→eN Backgrounds

Three pertinent backgrounds

1. Decay in orbit (DIO) of stopped muon. In atom gives electrons beyond the free-muon 53 MeV end-point.

\[ \text{O}(10^{-17}) \text{ within 1 MeV of conversion signal.} \]

\[ \text{Czarnecki et al, arXiv:1111.4237} \]

Controlled by detector resolution AND energy loss prior to detector.

Need FWHM < 1 MeV
μN→eN Backgrounds

2. Radiative Pion Capture (RPC)

\[ \pi^- N \rightarrow \gamma N^* \quad \text{and} \quad \gamma \rightarrow e^+ e^- \]
\[ \pi^- N \rightarrow e^+ e^- N \]

External conversion
Internal conversion

Suppress by reducing # pions on target: wait, stop them, veto them
- beamline and accelerator are the constraint.
3. Instrumental Backgrounds / Devil-In-The-Detail Issues

- Cosmics that radiate electrons in muon stopping-target region

- Muons captured by nucleus result in
  - low energy neutrons that can stop in cosmic ray veto scintillator, produce gamma and veto event.
  - protons (heavily ionising) that can “deaden” a detector region.

- .....
Muon to Electron Conversion

Current best measurement (SINDRUM-II @ PSI) used 8mm of CH$_2$ to reduce pion (RPC) contamination to 1 in $10^9$ π reaching target

**Limit**: $7 \times 10^{-13}$ (Gold target).
Beyond SINDRUM: $\mu N \rightarrow eN$

No complete detector or facility to go beyond the $7 \times 10^{-13}$ SINDRUM limit
Recall to be commensurate with MEG ($10^{-13}$ limit) likely needs $O(10^{-15})$

Three proposals

- **DeeMe** at J-PARC : $5 \times 10^{-14}$ in 2015 to $10^{-14}$ in 2019/20.
  - KEK Muon PAC has granted stage-1 approval
  - JPARC PAC recognises scientific merit and is encouraging further R&D
  - significant synergy with JPARC g-2, particularly new H- beamline.

- **COMET** at J-PARC : $6 \times 10^{-17}$ in 2019/20.
  - JPARC stage-1 (of 2 stage) approval based on 2009 CDR.
  - TDR in 2012.

- **mu2e** at FNAL : $6 \times 10^{-17}$ in 2019/20.
  - DOE CD-0 approval granted in 2009.
  - CD-1 in 2012.
Challenges

Going beyond SINDRUM requires

- Rate of stopped muons to be $\sim O(5 \times 10^{10})/s$

- High resolution ($< 1$ MeV) e- momentum measurement to control DIO.

- Control of energy loss/straggling in stopping target

- Mechanism to reduce # pions at target and veto prompt backgrounds.

All proposed experiments use pulsed beam & only “measure” after prompt background subsided
Challenges : Proton Extinction / ”After protons”

Require that between proton pulses there are no rogue proton pulses that could produce a “prompt” background e.g. RPC in the timing window.

AC dipole/collimator system kicks out the out-of-time particles
Challenges: Stopped Muon Yield

High field Pion capture solenoid that reverses forward $\pi$ to low $p$ backward $\pi$

Increases yield by $O(1000)$ - method successfully demonstrated at MUSIC in Osaka in 2010

Transport solenoids that select low $p$ ($< 50$ MeV) muons and reject high $p$ particles before the stopping target.
Challenges: High Rates in Detector

mu2e simulated backgrounds
Challenges: Resolution and Energy Loss

Point of electron creation distributed in time (beam $\Delta t$) and distance.

Muons distributed in energy affecting stopping probability/point.

Electrons must pass through adjacent target material.

Tracker
DeeMe @ JPARC : $O(10^{-14})$

Simpler experiment than COMET/mu2e
DeeMe @ JPARC : $O(10^{-14})$

3 GeV “fast extracted” beam (cf ~ 8 GeV at COMET/mu2e)
Production & stopping target are combined: “surface muons” → μ-atom in target
Spectrometer selects only ~ 105 MeV particles.
Prompt background reduced by delay and fast kicker magnet.

Requirement of extinction is : $O(10^{-17})$

25Hz rep rate, 300 ns fall time, 385 G
Reduce prompt burst (50 M particles) by factor of 1000.
DeeMe @ JPARC : O(10^{-14})

In 2015 : JPARC RCS will provide 1MW @ 3 GeV.

Existing low acceptance (D) beamline and graphite target : 90% BR @ 7\times10^{-13}
New high acceptance (H) beamline and SiC target : 90% BR @ 5\times10^{-14} for 2\times10^7 s run

Particle yield (e^{+/-} from \( \mu \)) has already been measured using gated-PMT and agrees well with simulation : 5\times10^9 \( \mu \)/s/MW (x2 for SiC).
Due to limited momentum acceptance of beamline, DeeMe aims to measure DIO and high-p prompt background in situ.

\[ \sigma(p) < 0.5 \text{ MeV (wire chambers)} \]

1st extinction measurements performed: no signal recorded from $10^{20}$ p (258 hrs)
COMET/Mu2e : 6x10^{-17}

Design sensitivity is > 1000 MEG (10^{-13}) limit, so x10 with $\alpha_{EM}$

COMET : $10^{18}$ $\mu$/yr (CDR) with lower acceptance & requirement of dedicated running vs Mu2e $4.5 \times 10^{17}$ $\mu$/yr (CD0) and concurrent Nova running
Previous extinctions have been at $10^{-3}$ level. Require $>10^{-9}$

MC simulation (MARS): $10^{-12}$ achievable with momentum-scraping + AC dipole
$\sigma(p) \sim 0.13 \text{ MeV}$

Straw Tracker (X-Y View)

this side contributes background from lower ene
Conversion @ $10^{-15}$

Conversion E without any energy loss

40 signal
0.18 background
Using 56 kW ($10^{11}$ μ/sec) slow extracted 7.1 GeV (KE) from JPARC Main Ring. Unlike Mu2E requires dedicated beam without neutrino (T2K) running.

Observed muons at rate $O(1000)$ x PSI per W of beam power.
COMET: Irradiation Tests

Pion production solenoid is 1.3m diameter 5T solenoid subject to to $10^{21}$ n/m$^2$

- Neutron irradiation tests of Superconductor and Al stabiliser at Kyoto nuclear reactor using $10^{20}$ n/m$^2$
- Resistance increased by $\sim 2.5\mu\Omega$
- $\frac{1}{2}$ day thermal cycling returns resistance to pre-radiated value
Extinction level of \((5.4 \pm 0.6) \times 10^{-7}\) measured at secondary J-PARC beam line and \(O(10^{-7})\) at abort line

And additional \(O(10^{-6})\) from double kick injection into MR

Bunched slow extraction using ESS to dedicated target/secondary beamline
Beyond COMET/Mu2E

Strategy depends somewhat on whether signal is seen or not.

**If signal is seen**
- run with high-Z target to elucidate the underlying physics

**If no signal seen**
- push sensitivity down to $O(10^{-18})$

$10^{-18}$ and beyond is difficult with current methodology/detectors since DIO & RPC backgrounds dominate.

**Requires:**
- reduction in # pions at target by $O(100)$
- better event localisation (t,pos) at target
- reduced E-loss in target (now $\sim 1$ MeV)
Beyond COMET/Mu2E : High Z Run

Which High-Z
Gold has best discrimination against BSM models but short $\tau$ is problematic
- Prompt beam-flash : $O(100 \text{ ns})$
- Delay $O(200 \text{ ns})$ still has huge RPC bgrd.

![Graph showing pion decay times]
- 200 ns delay for Gold : $10^5 \pi/\text{sec}$ at target!
- 700 ns for Al

Ti = 338 ns
Au = 72 ns
Al = 864 ns

Need facility that can provide beams pulses with configurable time gap and small $\Delta t$.

Ti is best bet for higher-Z study
Beyond COMET/Mu2E : $O(10^{-18})$

Need facility providing $O(100)$ more muons ie ~ $O(10^{20}/yr$ [$10^{13}/s$]) compared to COMET/Mu2e AND significant changes to experiment/beamlines to beat down backgrounds.

**J-PARC**
- Will provide 56 kW @ 7.1 GeV (KE) to COMET
- In 2020 MR capable of 300 kW @ 7.1 GeV [ 1.7 MW @ 3 GeV from RCS ]

**FNAL (Project-X)**
- In 2022 : 2.9 MW @ 3 GeV or 190 kW @ 8 GeV
- Variable beam time-structure within few μs period

Muon yield depends linearly on $E_p$
Run (CW pulses) at 3 GeV (no pbars)
Cylindrical rotating graphite target (1 MW)
Yield into transport solenoid ~ 0.003 μ/p @ 3 GeV

Initial PX studies

![Graph showing μ- from carbon target](image)
Two key requirements of next-generation-facilities in addition to muon yield are:

- production of $\mu$ with low KE (ie $p < 20$ MeV) & beam to have a small momentum and time spread.

  *This maximises stopping, ensures stopping is localised such that a single stopping foil could be used which reduces $dE/dx$ of signal-electrons considerably.*

- a large extinction of pions of $O(10^{-14})$ e.g. by having 90m of decay beamline.

*Ideas to achieving this include “beam cooling” / FFAGs but difficult to balance yield with low-p requirement.*
Low duty cycle scheme unlike e.g. Project-X
Use initial beam with short pulses (10 ns) and use phase rotation to achieve narrow momentum spread at Liouville’s expense of longer (220 ns pulse)

Reduce p-spread: 20% to 2% in 6 turns (~1.5 μs).

Pions extinguished below $10^{-20}$ in 6 turns
Phase Rotation demonstrated with FFAG at Osaka using α-particles
Many issues being worked on:
- injection and extraction (80 ns rise time kicker magnets)
- beamline matching

PRIME is detector concept – employs “Guggenheim” electron ($p \sim 105$ MeV) transport solenoid
**Project-X : Cooling**

Much synergy with work on muon collider and many cooling ideas being discussed.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Muon collider</th>
<th>P-X Muon beam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Protons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>8 GeV</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Beam power</td>
<td>4 MW</td>
<td>1 MW</td>
</tr>
<tr>
<td>Bunches/second</td>
<td>15</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Duty factor</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>3 nsec</td>
<td>20 psec</td>
</tr>
<tr>
<td><strong>Muons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>muon/proton ratio</td>
<td>0.1</td>
<td>~0.001</td>
</tr>
<tr>
<td>required cooling</td>
<td>extreme</td>
<td>moderate</td>
</tr>
</tbody>
</table>
PX – Dipole + Wedge

Momentum Dependent HCC

Matching Section

Proton Beam (8 GeV)

Wedge (Cu)

Dipole

Mark Lancaster: New Physics With Muons
Muonium

\[ \mu^+ \rightarrow \mu^- \text{ transition a la } K^0 \rightarrow \bar{K}^0 \]

V-A new physics: coupling \( G_{\text{MuMu}} \)

World’s best limit yet again from PSI: MACS experiment (1999)

\[ G_{\text{MuMu}} < 3 \times 10^{-3} G_F \text{ (Probability of spon. transition } < 8.2 \times 10^{-11} ) \]

Relatively easy (better resolution detector) to improve this by \( O(100) \)
Where are we now / timescales?

<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Status</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>MEG @ PSI</td>
<td>1.0E-12</td>
<td>1.0E-13</td>
</tr>
<tr>
<td>2012</td>
<td>COMET @ J-PARC</td>
<td>APPROVAL</td>
<td>PHASE-I CONSTRUCTION</td>
</tr>
<tr>
<td>2014</td>
<td>COMET @ J-PARC</td>
<td>1.0E-14</td>
<td>PHYSICS</td>
</tr>
<tr>
<td>2016</td>
<td>Mu2e @ FNAL</td>
<td>APPROVAL</td>
<td>CONSTRUCTION</td>
</tr>
<tr>
<td>2016</td>
<td>Mu3e @ PSI</td>
<td>APPROVAL</td>
<td>CONSTRUCTION</td>
</tr>
<tr>
<td>2018</td>
<td>PROJECT-X @ FNAL</td>
<td>APPROVAL</td>
<td>CONSTRUCTION</td>
</tr>
<tr>
<td>2019</td>
<td>g-2 @ FNAL</td>
<td>APPROVAL</td>
<td>CONSTRUCTION</td>
</tr>
<tr>
<td>2019</td>
<td>g-2 @ J-PARC</td>
<td>APPROVAL</td>
<td>PHYSICS</td>
</tr>
<tr>
<td>2020</td>
<td>EDM @ PSI</td>
<td>PHYSICS</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>EDM at J-PARC</td>
<td>PHYSICS</td>
<td></td>
</tr>
</tbody>
</table>

PHASE-1 APPROVED!
COMET Phase-I

Much of the work has been done by students.

- 107 collaborators
- 25 institutes
- 11 countries

UCL : 5, Imperial : 6 and v. recently Manchester : 5, Oxford : 1

Mark Lancaster : New Physics With Muons

QMUL Seminar : Mar 2012 : 96
COMET Phase-I

Phase-1
$30M: beamline
$15M: detector/DAQ etc

Phase-2
$45M

COMET Beam Dump
COMET Experimental Area
Main Beam Line Controller
Primary Proton Beam

Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting magnet

Detector Section
A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.

Mark Lancaster: New Physics With Muons
Cylindrical detector (AMY solenoid) has higher acceptance but poorer resolution compared to transverse/phase-II detector.
COMET Phase-I: Transverse Detector

**Pros**
Can also be used for background studies
Same as final detector

**Cons**
Poorer acceptance
COMET Phase-I: Aims

Current Mu2e/COMET sensitivity estimates of BR < $10^{-16}$ extrapolate current background knowledge over 4 orders of magnitude...

1. Demonstrate that beam extinction of $10^{-9}$ can be achieved

2. Measure in-situ backgrounds: neutrons, anti-p, nuclear capture products and so refine/optimise the simulation.

3. Test final/prototype detectors

4. Measure conversion process with sensitivity x100 that of SINDRUM-II ie go below $10^{-14}$: physics-wise comparable to the MEG (2013) limit.
Preliminary Phase-I Studies

Muon beam dispersion after 90 degrees

Momentum range broader than phase-II COMET but can also accommodate measurements with $\mu^+$

Much optimisation remains to be done
## Flavour Violation Summary

<table>
<thead>
<tr>
<th>Process</th>
<th>Limit Now</th>
<th>Limit 5-10 yr</th>
<th>Ultimate</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \rightarrow e\gamma$</td>
<td>$2.4 \times 10^{-12}$</td>
<td>$1 \times 10^{-13}$</td>
<td>$1 \times 10^{-14}$</td>
<td>O($10^{10}$) DC $\mu$/sec Excellent tracking, timing</td>
</tr>
<tr>
<td></td>
<td>PSI/MEG (2011)</td>
<td>PSI/MEG</td>
<td>PSI/Mu3e FNAL/PX</td>
<td></td>
</tr>
<tr>
<td>$\mu \rightarrow eee$</td>
<td>$1 \times 10^{-12}$</td>
<td>$1 \times 10^{-16}$</td>
<td>$1 \times 10^{-17}$</td>
<td>O($10^{10}$) DC $\mu$/sec Excellent tracking, timing</td>
</tr>
<tr>
<td></td>
<td>PSI/SIN-I (1988)</td>
<td>PSI/Mu3e OSAKA/MUSIC</td>
<td>PSI/Mu3e FNAL/PX</td>
<td></td>
</tr>
<tr>
<td>$\mu N \rightarrow eN$</td>
<td>$7 \times 10^{-13}$</td>
<td>$6 \times 10^{-17}$</td>
<td>$1 \times 10^{-18}$</td>
<td>O($10^{13}$) Pulsed $\mu$/sec Excellent tracking</td>
</tr>
<tr>
<td></td>
<td>PSI/SIN-II (2006)</td>
<td>FNAL/Mu2e J-PARC/COMET</td>
<td>J-PARC/PRISM FNAL/PX</td>
<td>Variable bunch timing $\pi$ extinction, cooled muons</td>
</tr>
</tbody>
</table>

Long term – how to achieve high muon yields at low $p$ with small $\Delta p$ and $\Delta t$. 

Mark Lancaster : New Physics With Muons
Muon Dipole Moments

Deviation from precisely known SM value

- Magnetic Dipole Moment / “g-2” ~ 0.002 but predicted in SM to 0.42ppm
- Present experimental uncertainty: $\Delta(a_\mu) = 0.54$ ppm

Measure non zero value where SM value ~ 0

- Electric Dipole Moment / EDM
  - Present limit ($10^{-19}$) is poor compared to other EDMs. SM value ~ $10^{-36}$

Lepton flavour violating interactions.

- Present limits $10^{-11-12}$. SM ~ $10^{-50}$
Muon Magnetic Moment ("g-2")

\[ g_\mu^{\text{exp}} = 2.00233184178(126) \]

2 331 694 36 (0)

* QED calculation for electron now out to 10th order (12672 diagrams)
Muon Magnetic Moment ("g-2")

\[ g^\text{exp}_\mu = 2.00233184178 \pm 0.000126 \]

\[ \frac{\alpha}{2\pi} = 0.00232 \]

Hadronic

\[ \lambda_{\text{sens}} \propto \left( \frac{m_\mu}{m_e} \right)^2 \approx 40,000 \]

* Hadronic corrections for the electron g-2 don't show up until the 12th decimal
Muon Magnetic Moment ("g-2")

\[ g_\mu^{\text{exp}} = 2.00233184178 \pm 0.00126 \]

2 331 694 36 (0)
138 60 (98)
3 08 (4)

\[ \frac{\alpha}{2\pi} = 0.00232 \]
Muon Magnetic Dipole Moment (“g-2”)

\[ a_{\mu}^{\text{exp}} = 116\,592\,089 \pm 63 \times 10^{-11} \]

\[ a_{\mu}^{\text{thy}} = 116\,591\,802 \pm 49 \times 10^{-11} \]

\[ a_{\mu}^{\text{exp}} - a_{\mu}^{\text{thy}} = 287 \pm 80 \times 10^{-11} \]

\[ a_{\mu} = \frac{g - 2}{2} \]
Muon Magnetic Dipole Moment ("g-2")

\[ a_\mu^{\text{exp}} - a_\mu^{\text{thy}} = 287 (80) \times 10^{-11} \]

\[ a_\mu^{\text{LOHVP}} = 6903 (42) \times 10^{-11} \]

\[ a_\mu^{\text{HLBL}} = 105 (26) \times 10^{-11} \]
Muon Magnetic Dipole Moment ("g-2")

Systematic?

<table>
<thead>
<tr>
<th></th>
<th>2001 [ppm]</th>
<th>2000 [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Syst Error</td>
<td>0.27</td>
<td>0.39</td>
</tr>
<tr>
<td>Statistical Error</td>
<td>0.66</td>
<td>0.62</td>
</tr>
<tr>
<td>Total Error</td>
<td>0.71</td>
<td>0.73</td>
</tr>
</tbody>
</table>

BNL experiment ended stat-limited

Final result combined of $\mu^+$ and $\mu^-$ with different systematics
- Opposite B-field polarity
- Different E-field
- Lower losses

No trials factor in g-2
New FNAL experiment will re-use BNL magnets but with x20 stats and reduced systematics.

Aiming for x4 improvement in $a_\mu$ uncertainty to be 0.1ppm ($16 \times 10^{-11}$) measurement

Expecting theory uncertainty to reduce from $49 \times 10^{-11}$ to $30 \times 10^{-11}$ such that present $\sim 3.6 \sigma$ discrepancy could become $\sim 7.5 \sigma$
FNAL Muon g-2

Mark Lancaster: New Physics With Muons

QMUL Seminar: Mar 2012: p112
average over muons

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

\[ \gamma_{\text{magic}} = 29.3 \]

Or

1. No vertical E focussing E field and v. small vertical beam divergence \((\Delta p_T/p_T = 10^{-5})\)
2. \(\beta \sim 0\) by using ultra cold muons
3. Very large and uniform B (using MRI magnets)
J-PARC Muon g-2

**g-2 project @ J-PARC!**

- 3 GeV proton beam (333 μA)
- Graphite target (20 mm)
- Surface muon beam (28 MeV/c, 4x10^8/s)
- Muonium Production (300 K ~ 25 meV)
- Silicon Tracker
- Super Precision Magnetic Field (3T, ~1ppm local precision)
- Resonant Laser Ionization of Muonium (∼10^6 μ^+/s)
- Muon LINAC (300 MeV/c)

**New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam**

Mark Lancaster: New Physics With Muons

QMUL Seminar: Mar 2012: p114
J-PARC Muon g-2

Requires advances in “muonium” production
- target materials e.g. nano-structured SiO$_2$
- lasers (pulsed 100 $\mu$J VUV) to ionise muonium (x100)

Technique also being pursued at PSI for EDM measurement.

Muons from 2100K to 300K
J-PARC Muon g-2

Upcoming laser ionization test at RAL

An area of fruitful cross-disciplinary collaboration both within HEP
e.g. SiLC readout, BELLE sensors and outside : material scientists, laser chemists etc
Clearly Pros and Cons of two approaches:

Cold muons: no pion contamination, no coherent betatron oscillations
  BUT: \( \pi^+ \) only and as yet unproven method
“Hot” muons: proven technology, utilising existing accelerator etc

<table>
<thead>
<tr>
<th></th>
<th>BNL-E821</th>
<th>Fermilab</th>
<th>This Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum</td>
<td>3.09 GeV/c</td>
<td>0.3 GeV/c</td>
<td></td>
</tr>
<tr>
<td>( \gamma )</td>
<td>29.3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Storage field</td>
<td>( B = 1.45 ) T</td>
<td>( B = 3.0 ) T</td>
<td></td>
</tr>
<tr>
<td>Focusing field</td>
<td>Electric Quad.</td>
<td>none/very weak</td>
<td></td>
</tr>
<tr>
<td># of detected ( e^+ )</td>
<td>( 5.0 \times 10^9 )</td>
<td>( 1.8 \times 10^{11} )</td>
<td>( 1.5 \times 10^{12} )</td>
</tr>
<tr>
<td># of detected ( e^- )</td>
<td>( 3.6 \times 10^9 )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Statistical precision</td>
<td>0.46 ppm</td>
<td>0.1 ppm</td>
<td>0.1 ppm</td>
</tr>
</tbody>
</table>
Muon EDM

Expect muon EDM below $10^{-22}$ and likely below $10^{-24}$ (SM = 0)

Present limit (BNL) is $1.8 \times 10^{-19}$.

FNAL (g-2) should reach $10^{-21}$ looking at vertical angle, $90^0$ out of phase with g-2 modulation

Muon unique since 2nd generation & it’s a single particle measurement unlike e/n EDM.

Mark Lancaster : New Physics With Muons
Muon EDM beyond $10^{-21}$: Frozen Spin

Judicious choice of $E$ and $B$ to cancel magnetic moment contribution

$$\tilde{\omega} = \frac{e}{m} \left[ a\vec{B} + \left( a - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right]$$

**magnetic moment anomaly**

**EDM**

$$E = \frac{aB\beta}{1 - (1 + a)\beta^2} \approx aB\beta\gamma^2$$

$$S_y = \frac{2(1 + a)}{\hbar a \gamma^2} \int E\,dt$$

$S_x$, $S_y$, $S_z$
Muon EDM beyond $10^{-21}$: Frozen Spin

PSI proposal (hep-ex/0606034v3)
Summary

There is life outside the LHC!

Precision muons: well defined 10+ year programme with cross-disciplinary appeal

- Next generation $(g-2)$ will reach 0.1ppm level and would move BNL $3\sigma$ to $7.5\sigma$

- Muon EDMs will reach sensitivity @ $10^{-24}$ level

- Lepton flavour violation limits will improve by 100-10,000 in next 2-8 years particularly with mu$^2$e/COMET.

Provide a clean and complementary probe of BSM physics and particularly at high energy scales with a connection to leptogenesis.

Measurements are not limited by theory but technical innovation.

As an experimentalist this is a wonderful place to be and in which the next generation can receive hands-on and analysis skills.
UK Contributions

So far only to COMET

COMET, mu2e and FNAL g-2 are all welcoming UK collaborators

Chance to get in on the ground floor and lead a project

g-2 perfect thesis topic

We need more people!
THE END

BACKUP
We also want to measure Z dependence

Ratio of conversion to $e\gamma$ also Z dependent.

Process Ratios are Model Dependent

\[ \frac{\text{BR}(\mu \rightarrow e\gamma) \times 10^{11}}{\text{BR}(\mu \rightarrow eN)} \times 10^{14} \]

Little Higgs Model

F. del Aguila et. al: JHEP 1103 (2011)

50 TeV scale
Z Dependence of Muonic Atoms

**Capture:** $\mu_{A,Z} \rightarrow e^{-} + \nu_{\mu} A, Z - 1$

**DIO:** $\mu N \rightarrow e^{-} \nu_{\mu} N$

Endpoint Energy (MeV) vs. Z

Free muon ($\tau = 2,197$ ns)

C, Al ($\tau = 864$ ns)

Ti, Cu

Stopped Muon Lifetime (s) vs. Z
COMET Extinction

“Double Kicking” injection into the MR

1st measurements show $O(10^{-6})$ additional extinction can be achieved
Graded Fields

Detector Solenoid

Pion Capture Solenoid

Magnetic Fields in COMET (in Tesla)
MUSIC Plan (Budget Permitting)

- 2014: Matching & injection
- 2012-2013: Transport solenoid
- 2015-2016: Muon FFAG storage ring
- 2009: Pion capture solenoid Complete and operated
J-PARC Timeline

Operational Plan for JFY2012 and JFY2013

Case-2 New Method

Case-1 Old method

Earthquake

Construction of 400 MeV Linac

New Funding for 3 years

200 kW

145 kW Earthquake Stop

Normal Summer

Summer 400MeV RFQ, IonS.

Summer 400MeV RFQ, IonS.

Goal of 1.7MW (fast) 0.3MW (slow) by 2020

Nagamiya-san, July 2011

Mark Lancaster: New Physics With Muons

QMUL Seminar: Mar 2012: 131
J-PARC H-Line (DeeMe)

Muon Physics at H-Line

3 GeV proton beam at 25 Hz

Large Acceptance Beamline

Mu HFS
Precision measurement of Hyper-Fine Structure of Muonium
- Synergy with g-2/EDM (magnet, detector)
- Provide lambda for g-2

DeMee
Experiment to search for mu-e conversion in the primary target

g-2/EDM
Measure spin precession precisely
Parallel to Magnetic Field → g-2
Orthogonal to Mag. Field → EDM

Mark Lancaster : New Physics With Muons

QMUL Seminar : Mar 2012 : 132
Muonium

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

\( M \rightarrow \bar{M} \) transition a la \( K^0 \rightarrow \bar{K}^0 \)

V-A new physics: coupling \( G_{\text{MuMu}} \)

World’s best limit yet again from PSI: MACS experiment (1999)

\[ G_{\text{MuMu}} < 3 \times 10^{-3} G_F \text{ (Probability of spon. transition} < 8.2 \times 10^{-11}) \]
Muonium

Signature: e- from \( \mu^- \) decay and 13.5 eV e+

In time and from common-vertex

Similar issues/backgrounds as \( \mu \rightarrow eee \)

- Radiative: \( \mu^+ \rightarrow e^+e^+e^-\nu\nu \)
- Accidental overlap: \( \mu^+ \) decay and Bhabha e+ scattering giving e-.
Muonium : Improving Limits

Same experiment but with better detector : **O(100) improvement.**

Improved timing resolution : MACS FWHM was 3.3 ns, cg MEG ~ 300 ps.
Improved electron E measurement : MACS achieved 27 MeV, cf MEG ~ 0.7 MeV

**Further improvements**
- pulsed muon source & delay measurement to suppress radiative decay background

**Form muonium in a tungsten foil**
- detect the positron
- detect muon via \( W \rightarrow ^{184}Ta \) and characteristic \((\beta,\gamma,\gamma)\) \(^{184}Ta\) decay

**BUT** this requires no extraneous \( \mu^- \) e.g. from cosmics and more pertinently the \( \mu^+ \) beam needs to be \( \mu^- \) free at the \( O(10^{-14}) \) level.
Requires : FFAG, Helical cooling to achieve such a beam purity.
cLFV in Muonic Atoms

In high-Z muonic atom: $e^-$ attracted to nucleus and hence $\mu^-$
And cLFV decay:

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

is $(Z-1)^3$ enhanced (offset somewhat by increased nuclear capture)

MEG/SINDRUM-I limits mean expected BR < $10^{-19}$

Requires $O(10^{20})$ stopped $\mu$ ie 100 x Mu2e/COMET.

Next generation experiment.
PX Muons

\[ \text{Yield} \]

\[ p_{\text{cm}} \text{ in MeV/c} \]

\[ \times 10^{-3} \]

1 \text{ mm cylinder}
5 \text{ mm cylinder}
Muons vs Tau

![Graph showing the changing right-handed $\nu_\mu$ mass](image)

- Right-handed $\nu_\tau$ mass: $10^{15}$ GeV
- $10^{14}$ GeV
- $10^{13}$ GeV
- $10^{12}$ GeV

Br(\tau \rightarrow \mu \gamma): $10^{-8}$ to $10^{-10}$

Br(\mu \rightarrow e \gamma): $10^{-12}$ to $10^{-14}$

Parameters:
- $U_{e3} = 0.01$
- $m_0 = 100$ GeV
- $m_1/2 = 200$ GeV
- $\tan \beta = 10$
Recent improvement by factor of 10 in muon lifetime and hence $G_F$

\[
\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + \delta q)
\]

\[
\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} (1 + \delta r)
\]

2.5 $\sigma$ below previous PDG

MULAN (@ PSI) : $10^{12}$ muons
PRL. 106, 041803 (2011)
$G_F$ now know to 1ppm
Theory $\sim$ 0.2 ppm
g-2 Timeline

Mark Lancaster: New Physics With Muons
Muon Moments

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\vec{\mu} = g \frac{e\hbar}{2m} \hat{\sigma}$$

$$\vec{d} = \eta \frac{e\hbar}{2m} \hat{\sigma}$$

$$g = 2(a + 1)$$

$$\eta = 0$$

\(g-2\) : has SM (strong, weak, EM) contributions and potentially BSM
\(\eta = 0\) : any deviation from this is CP-violating new physics.