Imperial College London

Searching Beyond the Standard Model...

(Gazing at Charged Leptons)

Yoshi Uchida

UK HEP Forum: The “Spice of Flavour”

28 November 2018

Today

- Studies of charged lepton decays
- The Standard Model and the impact of lepton flavour
- Beyond the Standard Model
- Present-day/near-future CLFV searches
- Further into the future....
- A few thoughts?

1947

Nuclear Capture of Mesons and the Meson Decay

B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada

June 21, 1947

...Returning to the actual decay of the meson, an experiment suggests itself which might answer the following question: Is the electron emitted by the meson with a mean life of about 2.2 microseconds accompanied by a photon of about 50 Mev? This experiment is being attempted at the present time, since it is felt that the available analysis[10] of the soft component in equilibrium with its primary meson component is probably insufficient to decide definitely whether the meson decays into either an electron plus neutral particle(s) or electron plus photon.

1947

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. Hincks and B. Pontecorvo
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada

December 9, 1947

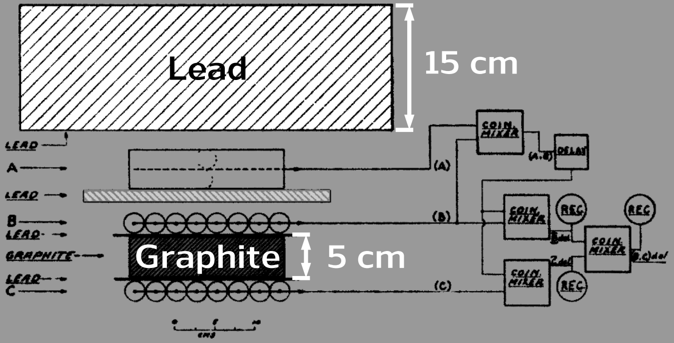


FIGURE 1 - ARRANGEMENT OF APPARATUS

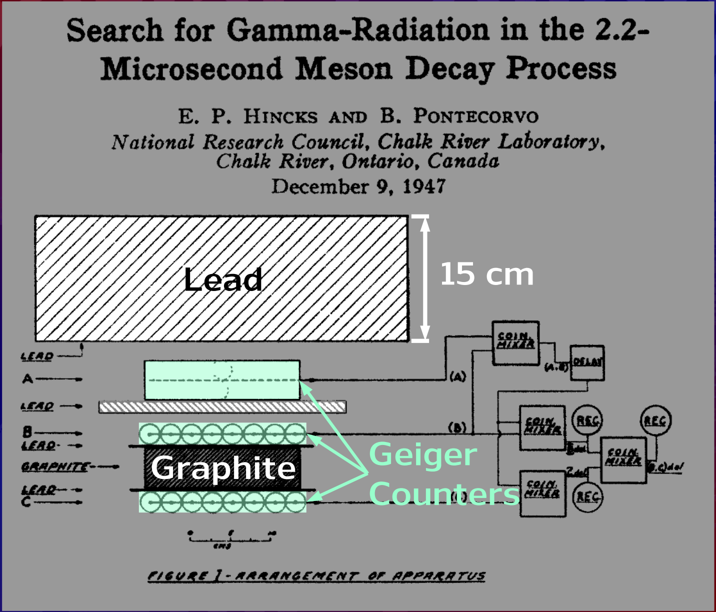
also similar investigations by Sard and Althaus [1948]

1947

Studies of fundamental properties of muon decay

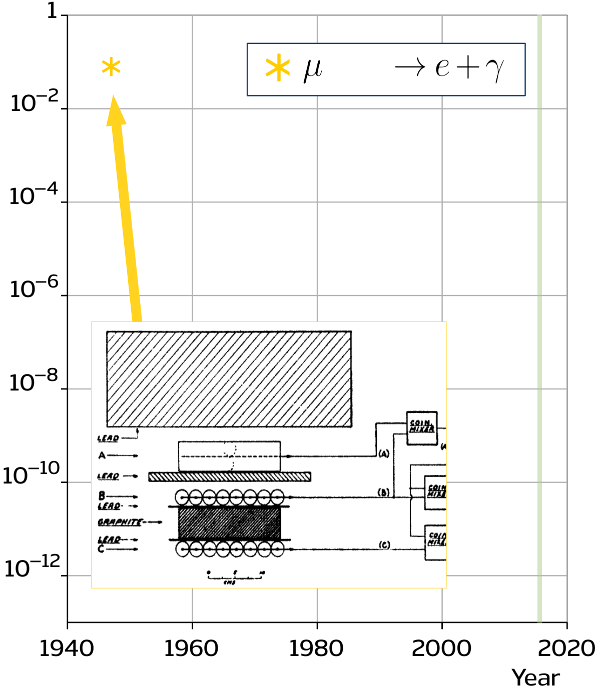
using $O(1000)$ cosmic events

decay into how many particles, and which ones



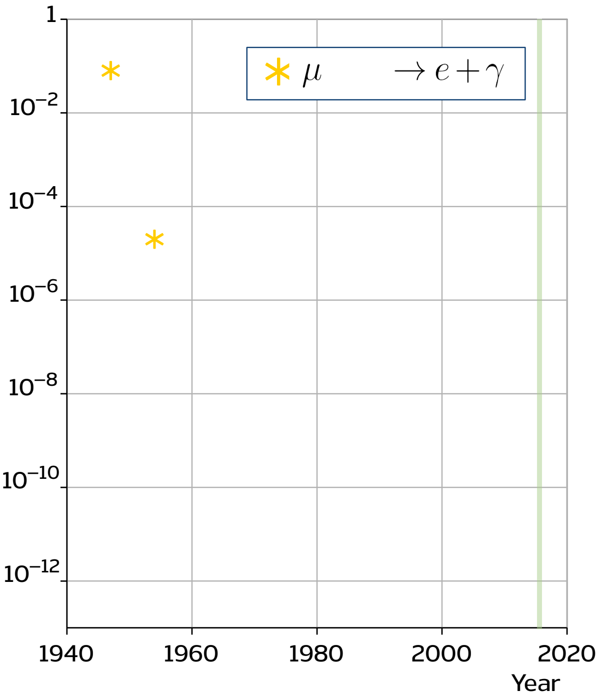
Demonstrated $\mu \to e + \gamma$ is not a major component of μ-decay

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

Charged Lepton Flavour Violation



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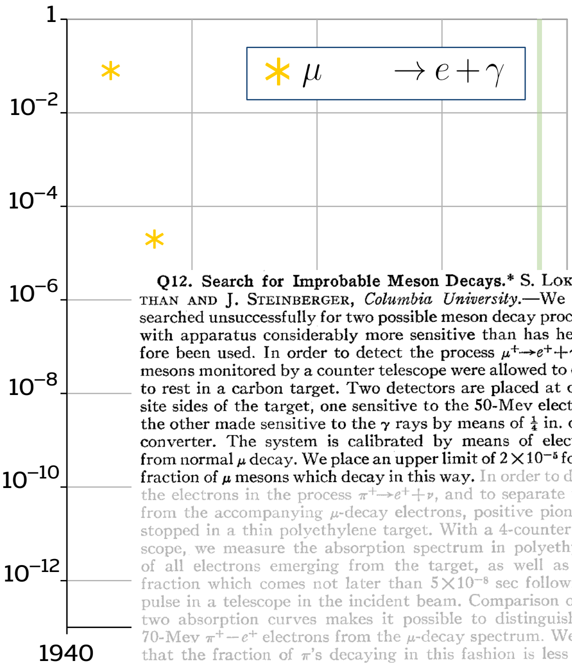
Charged Lepton Flavour Violation

Minutes of the 1954 APS Thanksgiving Meeting

90% C.L. upper limit on branching ratios



Q12. Search for Improbable Meson Decays.* S. Lokanathan and J. Steinberger, *Columbia University.*—We have searched unsuccessfully for two possible meson decay processes with apparatus considerably more sensitive than has heretofore been used. In order to detect the process $\mu^+ \rightarrow e^+ + \gamma$, π^+ mesons monitored by a counter telescope were allowed to come to rest in a carbon target. Two detectors are placed at opposite sides of the target, one sensitive to the 50-Mev electrons, the other made sensitive to the γ rays by means of $\frac{1}{4}$ in. of Pb converter. The system is calibrated by means of electrons from normal μ decay. We place an upper limit of 2×10^{-5} for the fraction of μ mesons which decay in this way. In order to detect the electrons in the process $\pi^+ \rightarrow e^+ + \nu$, and to separate them from the accompanying μ-decay electrons, positive pions are stopped in a thin polyethylene target. With a 4-counter telescope, we measure the absorption spectrum in polyethylene of all electrons emerging from the target, as well as that fraction which comes not later than 5×10^{-8} sec following a pulse in a telescope in the incident beam. Comparison of the two absorption curves makes it possible to distinguish the 70-Mev $\pi^+ - e^+$ electrons from the μ-decay spectrum. We find that the fraction of π's decaying in this fashion is less than 5×10^{-5}.

* This work was performed under the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

Charged Lepton Flavour Violation

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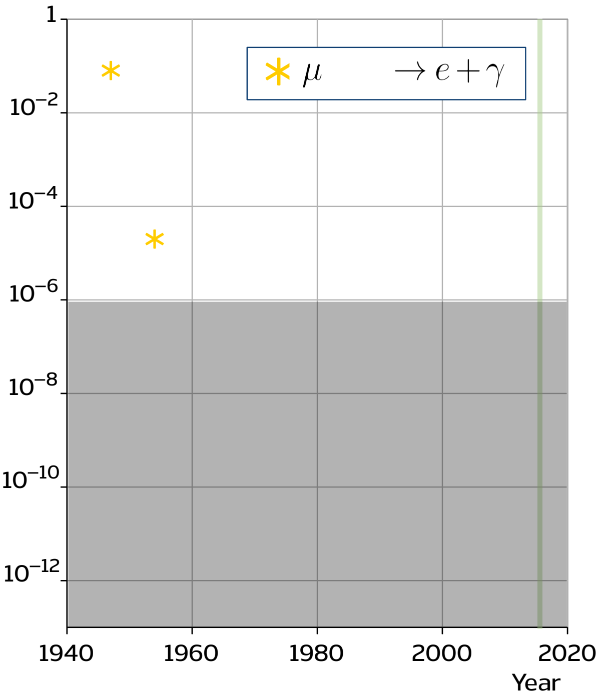


1959

ELECTROMAGNETIC TRANSITIONS BETWEEN μ MESON AND ELECTRON*

S. Weinberg†
Columbia University, New York, New York

G. Feinberg‡
Brookhaven National Laboratory, Upton, New York

(Received June 15, 1959)

The existence of the ordinary μ decay, $\mu \to e + \nu + \bar{\nu}$, seems to prove that the muon and electron do not differ in any quantum numbers.[1] It follows that weak electromagnetic transitions between muons and electrons could occur, if there is a mechanism to produce them. For example, one such mechanism would exist **if the μ decay** was not caused by a direct $\bar{\mu}e\bar{\nu}\nu$ Fermi interaction but instead **involved a virtual charged boson**. This particular possibility seems ruled out, since **the predicted[2] rate for $\mu \to e + \gamma$ would be considerably greater than the upper limit set by recent experiments.[3,4]** The purpose of this note is to discuss phenomenologically (without attachment to any specific mechanism) other kinds of electromagnetic transitions between muon and electron that may be possible even if $\mu \to e + \gamma$ is somehow suppressed.

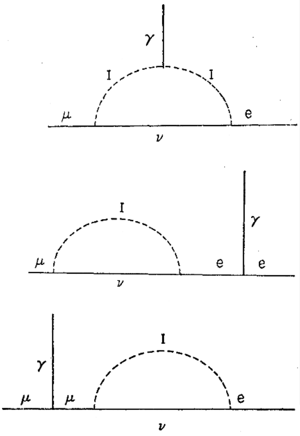


FIG. 1. Feynman diagrams for $\mu \to e + \gamma$ through an intermediate boson. I labels the intermediate boson field.

Feinberg, 1958

1961

LAW OF CONSERVATION OF MUONS*

G. Feinberg†
Department of Physics, Columbia University, New York, New York

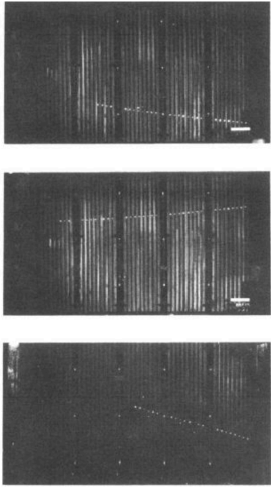
S. Weinberg
Department of Physics, University of California, Berkeley, California
(Received February 8, 1961)

The apparent absence of muon-electron transitions without neutrinos, such as $\mu \rightarrow e+\gamma$, $\mu \rightarrow 3e$, and $\mu^- + p \rightarrow e^- + p$, leads one to suspect that there is a new conservation law forbidding them. Calculations[1] of the rate of such processes, assuming no such law exists, have indicated that it is hard to understand their absence in an intermediate boson theory of weak interactions....

If we assume that μ^--e^- transitions are forbidden by a selection rule, the nature of the selection rule remains an open question. It has been suggested[3] that an additive quantum number exists which is always conserved, and which[4] is +1 for μ^- and zero for e^-. In order to make this consistent with known weak interactions, it is necessary to assume that there are two neutrinos, which are distinguished by their value of this quantum number. The conservation law forbids all reactions in which any nonzero number of muons change into electrons, without neutrinos.

also Salam, Nishijima, Schwinger and others

1962: The Second Neutrino Flavour



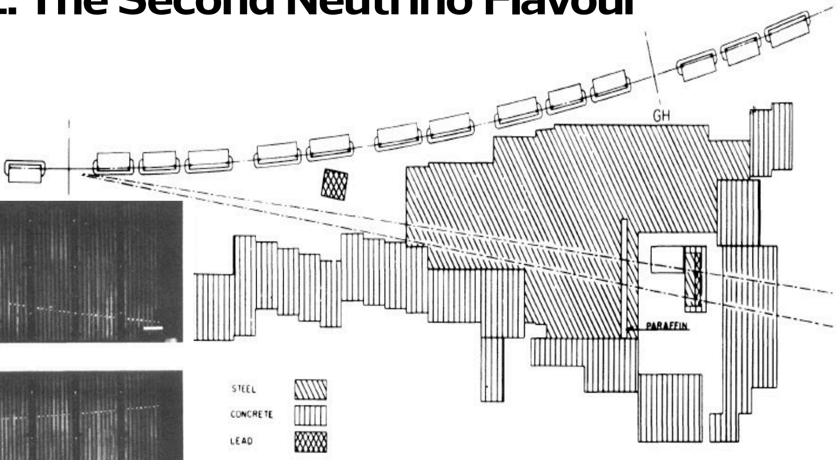


FIG. 1. Plan view of AGS neutrino experiment.

Discovery of muon neutrinos at Brookhaven
(Lederman, Schwartz, Steinberger)

Lepton Flavour Conservation to $O(10^{-6})$

- Severe constraint on models of the weak interaction
- New conservation laws
- Forced lepton flavour conservation to be written into SM

1955

Conservation of electric charge is a consequence of gauge invariance and a massless gauge boson

Similar arguments for particle number conservation lead to a repulsion between the conserved particles

Gauge invariance cannot explain "heavy particle" number (baryon number, lepton number etc) conservation

Phys. Rev. 98, 5 (1955)

Conservation of Heavy Particles and Generalized Gauge Transformations

T. D. Lee, *Columbia University, New York, New York*

and

C. N. Yang, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 2, 1955)

The possibility of a heavy-particle gauge transformation is discussed.

If we take the conservation of heavy particles to mean invariance under the transformation

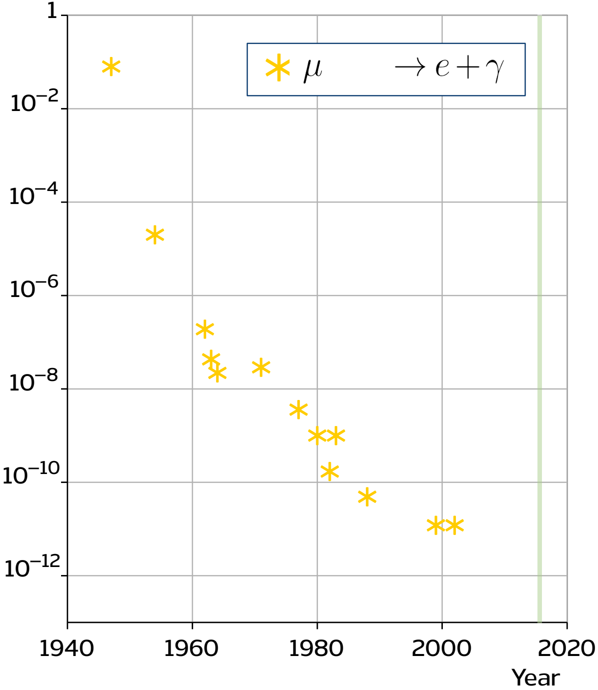
$$\psi_N \to e^{i\alpha}\psi_N, \quad \psi_P \to e^{i\alpha}\psi_P, \qquad (1)$$

Such a gauge transformation is formally completely identical with the electromagnetic gauge transformation. Invariance under such a transformation therefore necessitates the existence of a neutral vector massless field coupled to all heavy particles. A nucleon would have a "heavy-particle charge" of $+\eta$ in such a field and an antinucleon would have a "heavy-particle charge" of $-\eta$. The force between two massive bodies therefore would contain a contribution from the Coulomb-like repulsion between such "heavy-particle charges." The total force including the gravitational attraction is:

$$\text{Force} = -G(M_1M_2/R^2) + \eta^2(A_1A_2/R^2). \qquad (2)$$

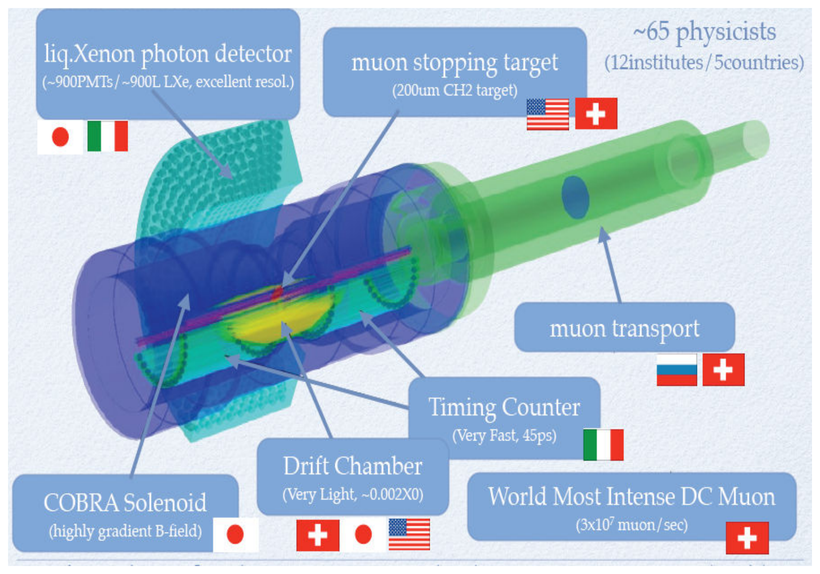
Here M_1, M_2, A_1, and A_2 are the inertia masses and mass numbers of the two bodies.

Charged Lepton Flavour Violation



90% C.L.
upper limit on
branching ratios

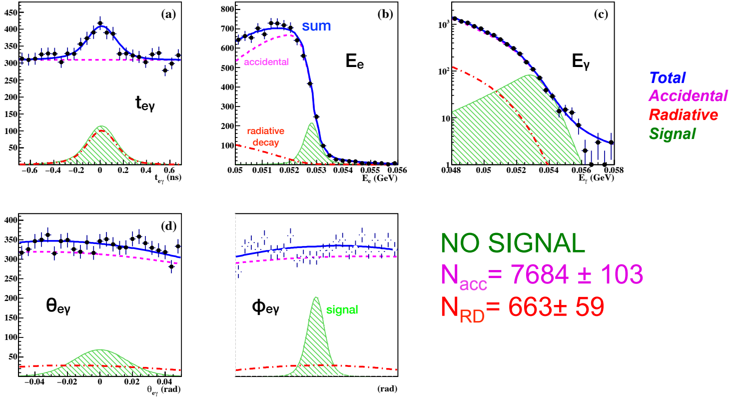
MEG Experiment at PSI



Cecilia Voena, CLFV 2016, Charlottesville

MEG Experiment at PSI

The best fitted likelihood function (projection) is shown
"Signal" is magnified for illustrative purposes



NO SIGNAL
N_{acc}= 7684 ± 103
N_{RD}= 663± 59

Cecilia Voena, CLFV 2016, Charlottesville

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MEG Experiment at PSI

- New constraint on the $\mu \rightarrow e\gamma$ decay set by the MEG experiment with its final dataset: 7.5×10^{14} stopped μ^+

BR ($\mu \rightarrow e\gamma$) < 4.3×10^{-13} at 90% C.L.

submitted to EPJC

- MEG-II detector is in the construction phase
  - same design of MEG but better resolution

- By the end of a decade sensitivity pushed to $\sim 4 \times 10^{-14}$

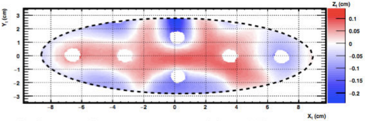
- Ultimate $\mu^+ \rightarrow e^+\gamma$?
  - PSI HiMB Project: $\sim 1.3 \times 10^{10}$ μ/s seems possible..
  - Need to fight accidental background (photon conversion?)

Cecilia Voena, CLFV 2016, Charlottesville

MEG Experiment at PSI

- Non planar, non negligible target deformation observed
  - taken into account in the likelihhod analysis
  - 13% worse sensitivity

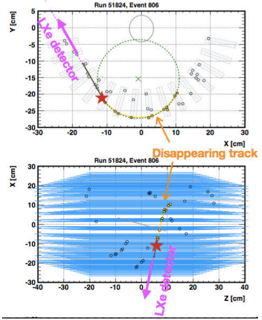
Comparison 2009-2011 vs last publication ok



deformation measured by 3D scanner

- Photons from e+ annihilations inside DC were identified & removed
  - background rejection~2%
  - signal inefficiency~1%

- Revised the algorithm to recover missing first turn of positron in the DC
  - Signal efficiency improved by 4%



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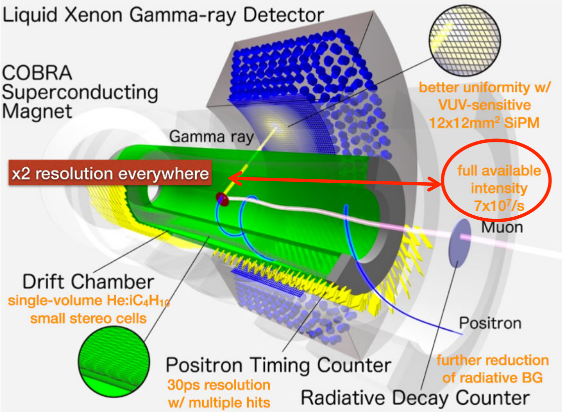
Cecilia Voena, CLFV 2016, Charlottesville

MEG Experiment at PSI

- Extending the search of μ→eγ is complementary to New Physics searches at the high energy frontier

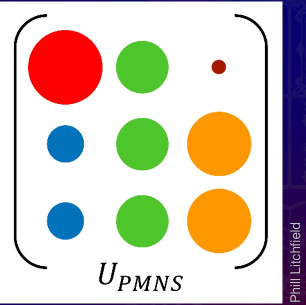


optimized to enhance sensitivity (accidental background prop. to I^2_{μ})

Cecilia Voena, CLFV 2016, Charlottesville

Neutrinos and Charged Lepton Flavour Violation

- Lepton Flavour: Perfectly Conserved in the SM
  - Charged lepton masses (Yukawa couplings) can be used to label all leptons
- but....
- SM is not correct
- Neutrinos have masses and they differ
- **Leads to another way of labelling leptons**



- Conversion matrix between the two bases (not very diagonal!)

Neutrino masses: BSM physics which ignores $\ell^{\pm}$ mass basis
$\Rightarrow$ no reason that further New Physics would respect it either

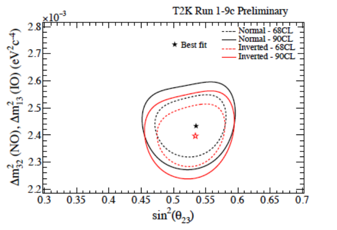
Neutrinos Oscillate

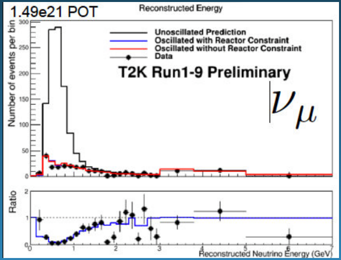
SUMMER 2018 RESULTS: θ_{23} AND ΔM^2_{32} MEASUREMENT

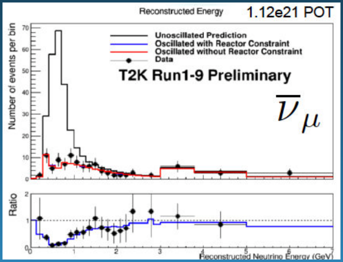
Parameter fit with reactor constraint

Consistent with maximal mixing (θ=45°)

	NH (Δm^2_{32}>0)	IH (Δm^2_{32}<0)
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2_{32}\rvert$ (10^{-3} eV^2/c^4)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$



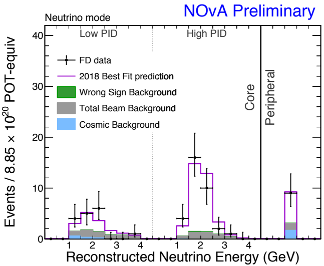




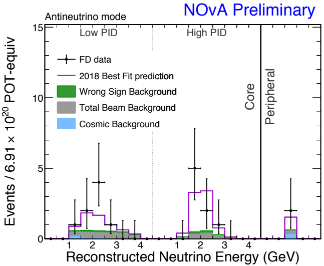
Neutrinos Oscillate

ν_e Appearance

- Observe 58 ν_e candidates
  - ➢ background 15



- Observe 18 $\bar{\nu}_e$ candidates
  - ➢ background 5.3



>4σ electron antineutrino appearance signal
A world first!

University of Sussex

Jeff Hartnell, HEP Forum Nov. '18 21

FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

LAUREATES

Breakthrough Prize

The 2016 Breakthrough Prize in Fundamental Physics was awarded to five experiments investigating neutrino oscillation.

Kam-Biu Luk and the Daya Bay Collaboration

Yifang Wang and the Daya Bay Collaboration

Koichiro Nishikawa and the K2K and T2K Collaboration

Atsuto Suzuki and the KamLAND Collaboration

Arthur B. McDonald and the SNO Collaboration

Takaaki Kajita and the Super K Collaboration

Yoichiro Suzuki and the Super K Collaboration

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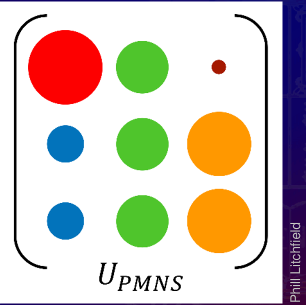

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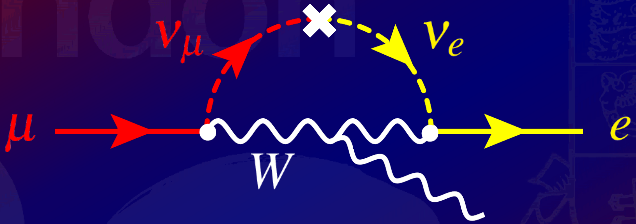
Charged Lepton Flavour Violation

- **Beyond-the-Standard Model Physics** can cause CLFV
  - e.g. **introduction of non-zero neutrino mass**



- but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{\ell} V^*_{\mu\ell} V_{e\ell} \frac{\Delta m^2_{\nu_\ell}}{m^2_W} \right|^2$$

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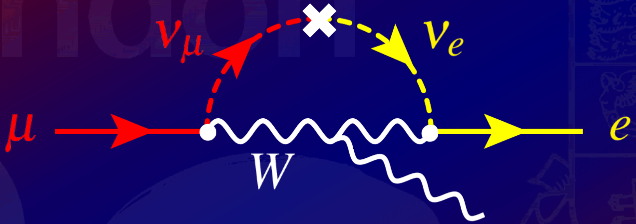

- but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) \sim 10^{-54} \times \frac{\sin^2 2\theta_{13}}{0.15}$$

Charged Lepton Flavour Violation

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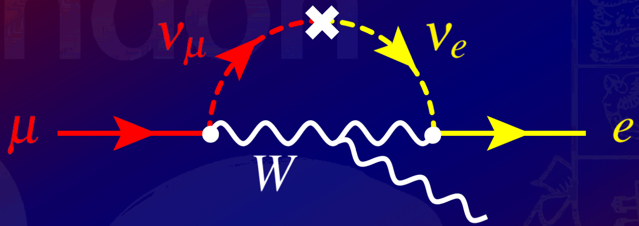
  - e.g. **introduction of non-zero neutrino mass**

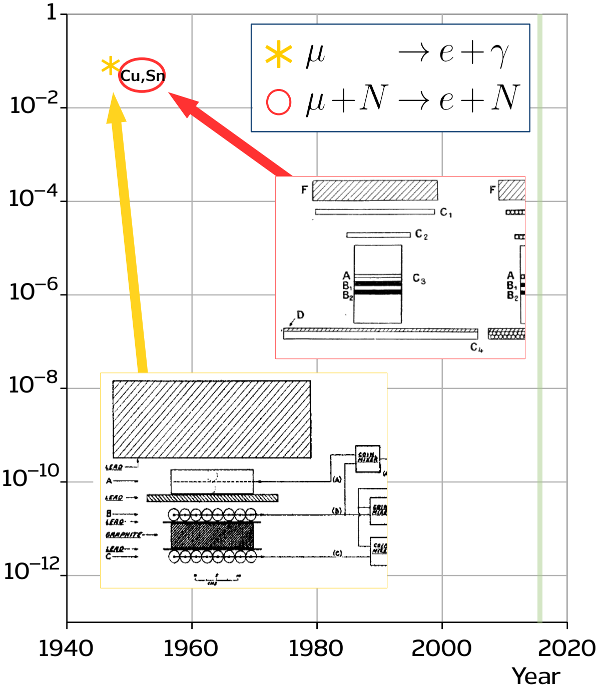


- but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) \sim 10^{-54} \quad \left(\sim \frac{m_\mu}{30 m_\oplus}\right)$$

- if CLFV seen, **unambiguous new physics discovery**
- for other models, CLFV signal can be much larger

Charged Lepton Flavour Violation



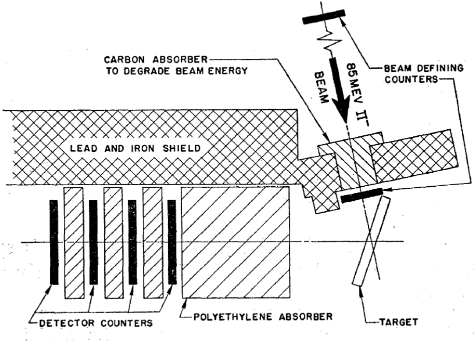
90% C.L.
upper limit on
branching ratios

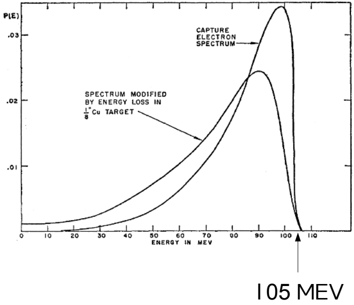
1955

Electrons from Muon Capture*

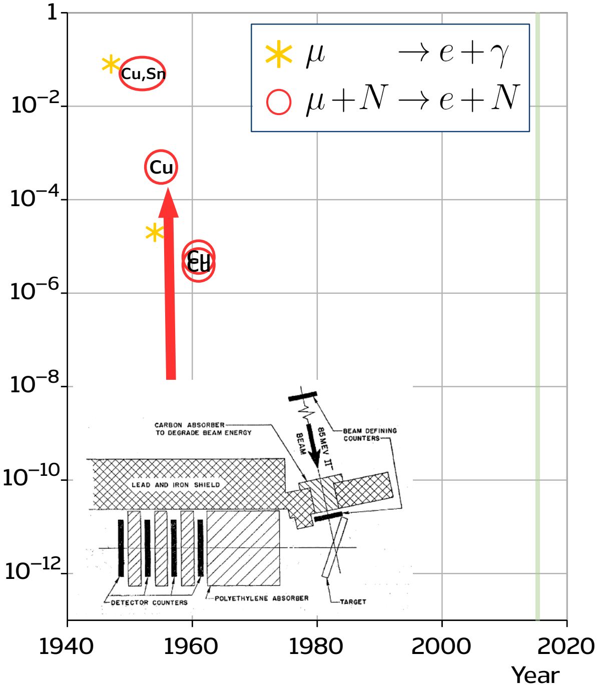
J. STEINBERGER AND HARRY B. WOLFE
Columbia University, New York, New York
(Received August 31, 1955)

We have searched for the process $\mu^- + p \rightarrow p + e^-$ or $\mu^- + n \rightarrow n + e^-$ for μ mesons stopped in a Cu target. Scintillation counters were employed to detect the electrons from the process. No counts attributable to the electrons were obtained and we place an upper limit of $\sim 5 \times 10^{-4}$ for the relative rate of this process to that for the usual nuclear capture reaction.



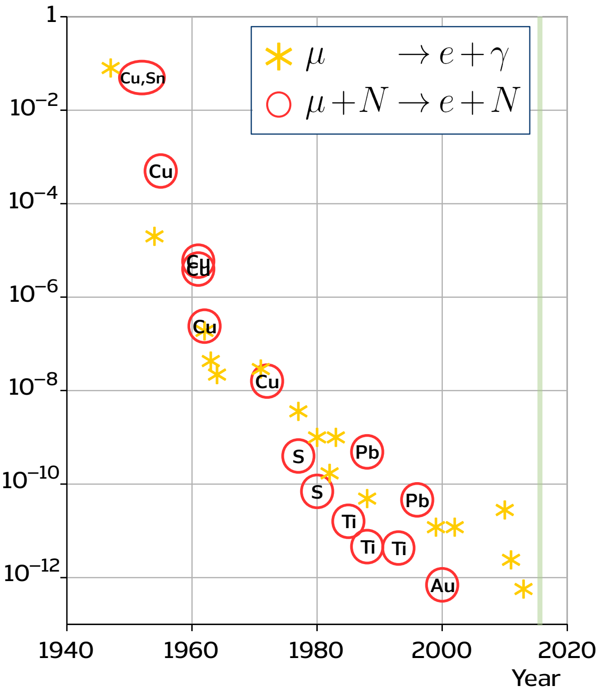


Charged Lepton Flavour Violation



90% C.L. upper limit on branching ratios

Charged Lepton Flavour Violation



90% C.L. upper limit on branching ratios

Muon-to-Electron Conversion

- Search for the process

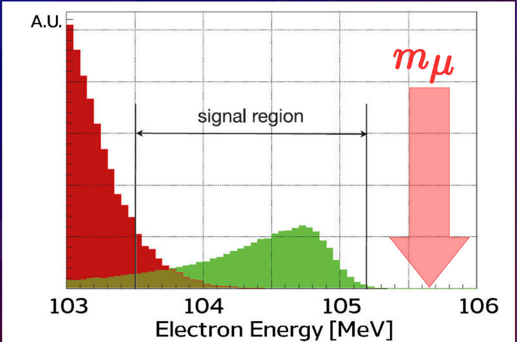
$$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$$

muonic atom — mono-energetic electron ($E_e \leq$ 105 MeV)

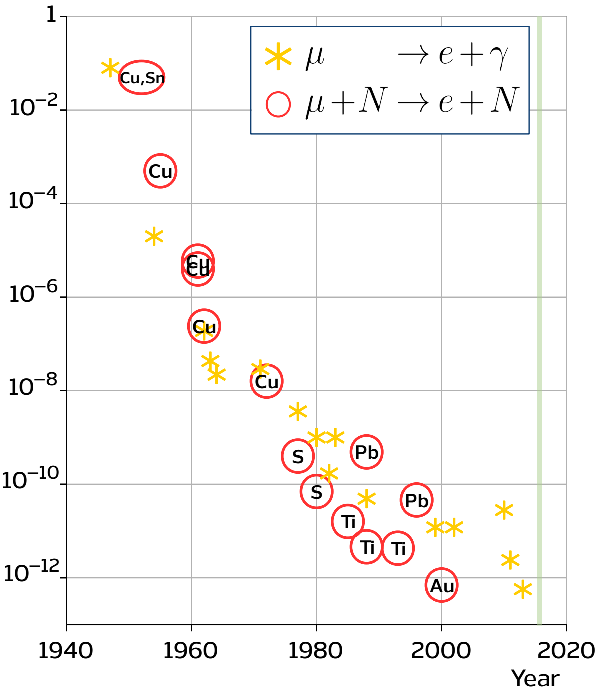
- Time available after formation of muonic atom: up to about **1 microsecond (Z-dependent)**

- $E_e = m_\mu - E_{\mathrm{bind}} - E_{\mathrm{recoil}}$

- **observed signal is smeared because** of detector effects



Charged Lepton Flavour Violation



90% C.L.
upper limit on
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"MELC" proposal from 1980s

Search for Lepton-Flavor-Violating Rare Muon Processes

R. M. Djilkibaev* and V. M. Lobashev**

Institute for Nuclear Research, Russian Academy of Sciences, pr. Shestidesyatiletiya Oktyabrya 7a, Moscow, 117312 Russia

Received March 26, 2010; in final form, July 12, 2010

Abstract—A new approach to seeking three lepton-flavor-violating rare muon processes ($\mu \to e$ conversion, $\mu \to e + \gamma$, and $\mu \to 3e$) on the basis of a single experimental facility is proposed. This approach makes it possible to improve the sensitivity level of relevant experiments by factors of 10^5, 600, and 300 for, respectively, the first, the second, and the third of the above processes in relation to the existing experimental level. The approach is based on employing a pulsed proton beam and on combining a muon source and the detector part of the facility into a unified magnetic system featuring a nonuniform field. A new detector design involving separate units and making it possible to study all three muonic processes at a single facility that admits a simple rearrangement of the detectors used is discussed.

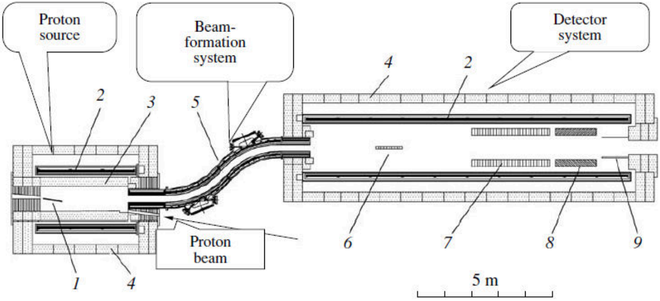
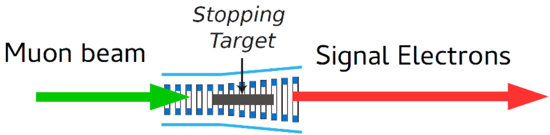
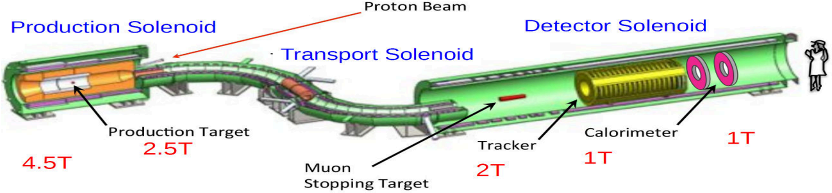


Fig. 1. Central horizontal cut of the MELC facility: (*1*) proton target, (*2*) superconductor solenoid, (*3*) shield of the solenoid, (*4*) steel yoke, (*5*) transport solenoid and collimator, (*6*) detector target, (*7*) coordinate detector, (*8*) calorimeter, and (*9*) detector shield and beam trap.



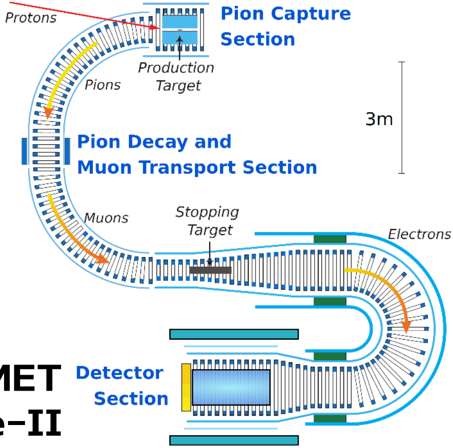
Muon beam
Stopping
Target
Signal Electrons

Mu2E



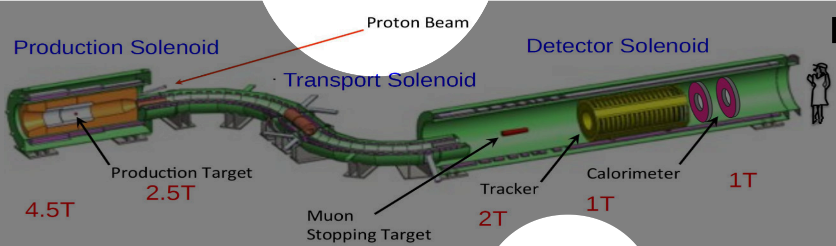
Experimental Layouts

Mu2e is truer to the original MELC design

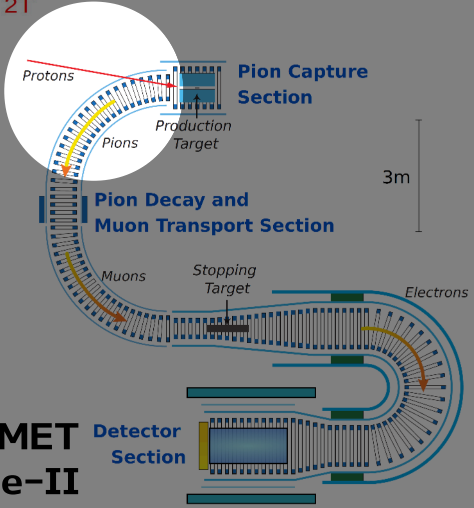


COMET Phase-II

Mu2E



Experimental Layouts

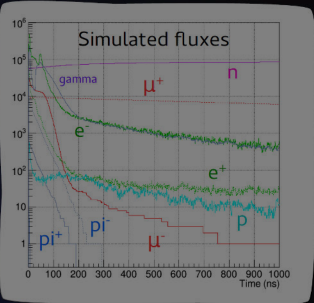


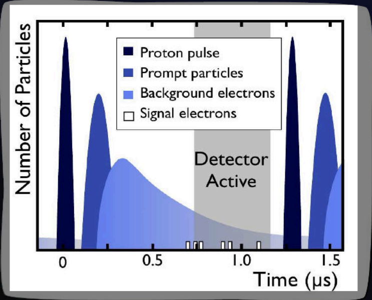
COMET Phase-II

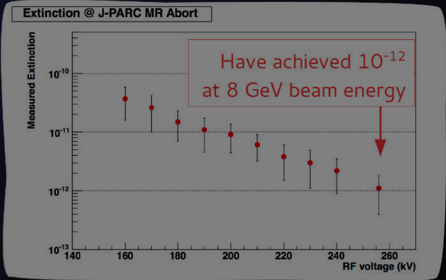
Proton Beam: Timing

- Pulsed beam removes beam-related backgrounds
- Need pulse timing > muon lifetime in aluminium
  - Muon lifetime on Aluminium: 864 ns
- As few protons between pulses as possible:
  - Extinction factor:

$$\text{Extinction} = \frac{N(\text{Protons between pulse})}{N(\text{Protons in bunch})}$$







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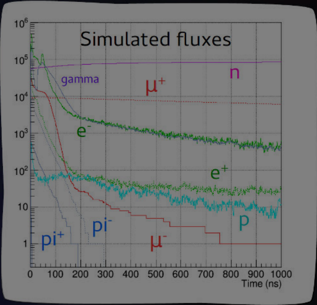
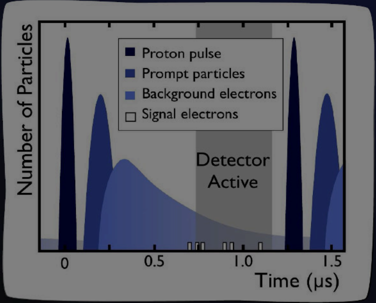
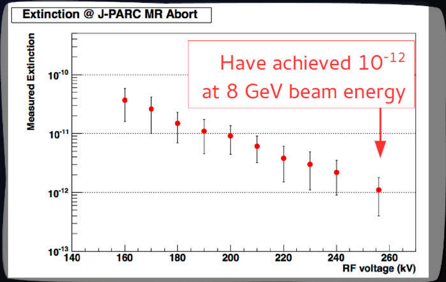
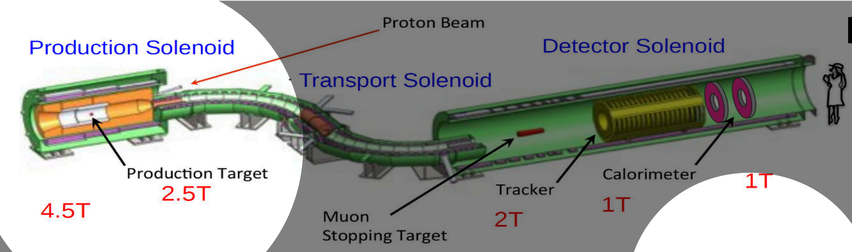




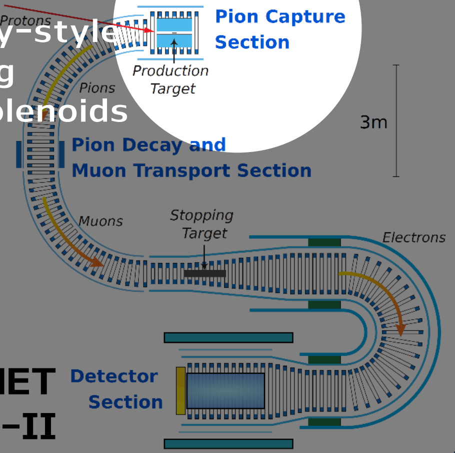




Mu2E

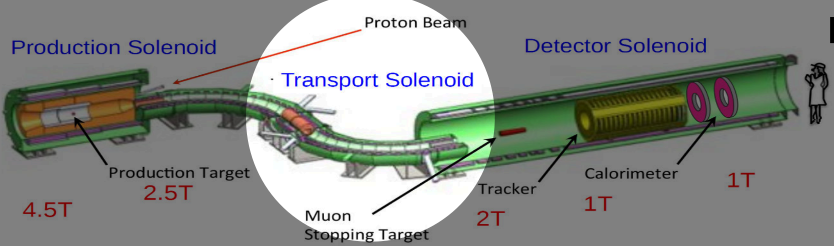
Neutrino Factory-style
Superconducting
Pion-Capture Solenoids

Experimental Layouts

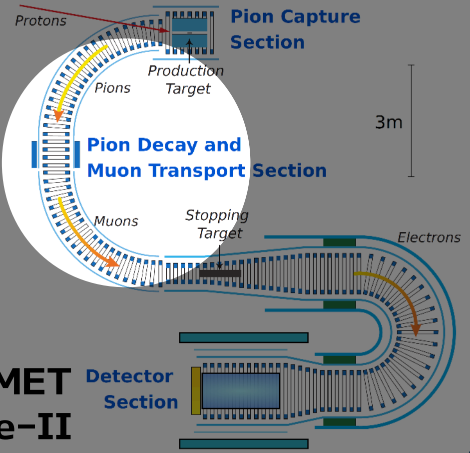


COMET
Phase-II

Mu2E



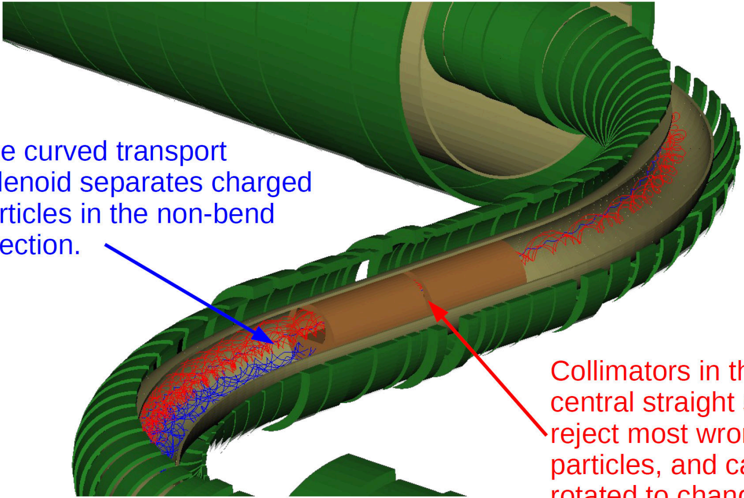
Experimental Layouts



COMET Phase-II

The transport solenoid sign selects charged particles

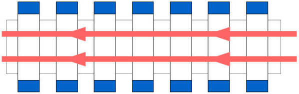
Mu2e: Kevin Lynch



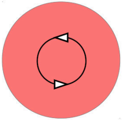
The curved transport solenoid separates charged particles in the non-bend direction.

Collimators in the central straight section reject most wrong sign particles, and can be rotated to change sign for calibration runs.

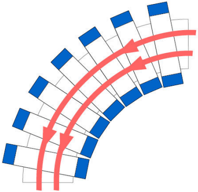
Muon Beam: Bent Solenoid Drifts



- Uniform B field
- Linear field lines



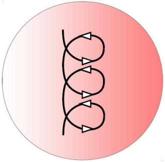
Circular motion about field lines



- Radial gradient in magnetic field
- Cylindrical field lines

$$D \propto \frac{1}{qB}\left(\frac{p_l^2 + \frac{1}{2}p_t^2}{p_l}\right)$$

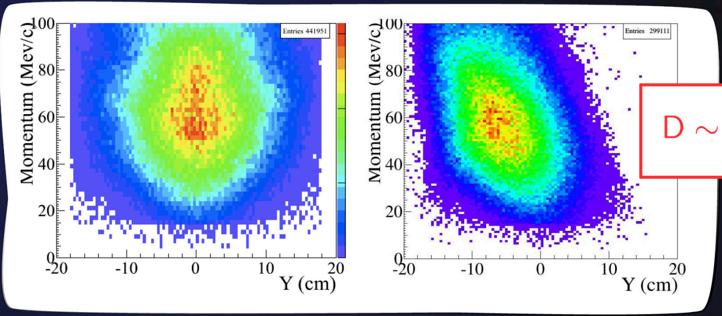
$$\propto \frac{1}{qB}\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$



Circular motion about a drifting centre.

MUSIC Facility at Osaka

Muon Beam: Bent Solenoid Drifts



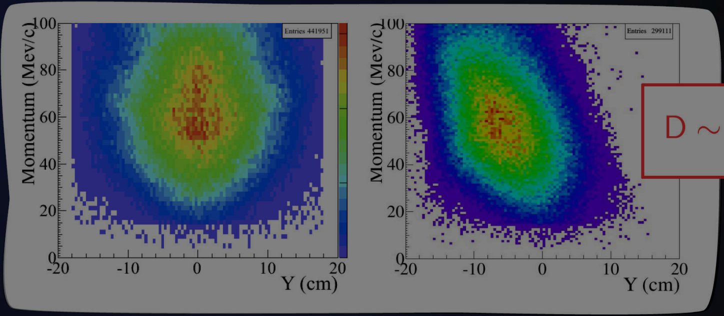
At entrance to bent solenoid — After 90° of bent solenoid

$$D \sim \frac{p}{q}$$

- Drift due to bent solenoid: position and momentum correlated
- Vertical dipole field applied
  - Tuned to maintain nominal momentum on axis
- Collimators select for charge and momentum

See talk by Yang Ye on Thursday

Muon Beam: Bent Solenoid Drifts



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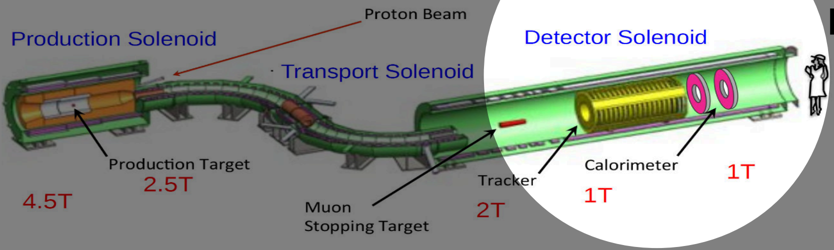
- Drift due to bent solenoid: position and momentum correlated
- Vertical dipole field applied
  - Tuned to maintain nominal momentum on axis
- Collimators select for charge and momentum

Different design choice to Mu2e

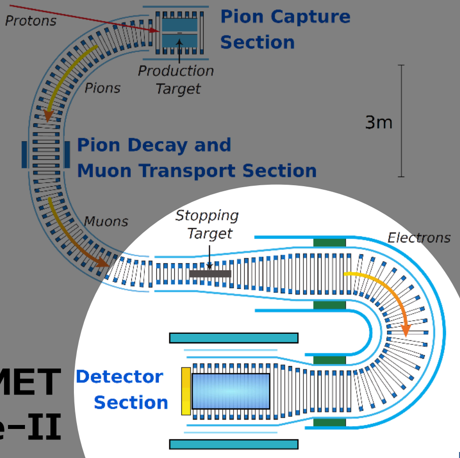
See talk by Yang Ye on Thursday

Experimental Layouts

Mu2E

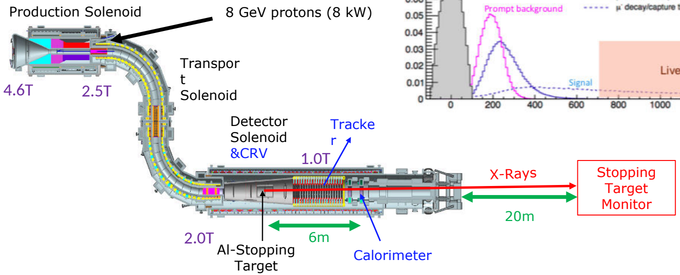


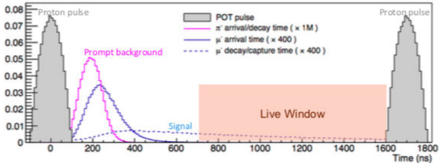
COMET Phase-II



Mu2e Experiment

Full-budget ($274M) DOE approved in July 2016.





Extinction better than 10^{-10}

Mu2e
Status

Beamline into Mu2e building already completed.

Most of the accelerator modifications done since also needed by g-2

Can run simultaneously with NOVA

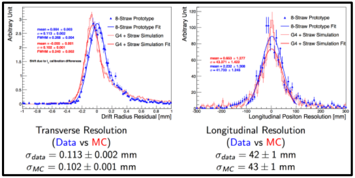
Mu2e
Status

Mass Production of solenoids & detectors underway

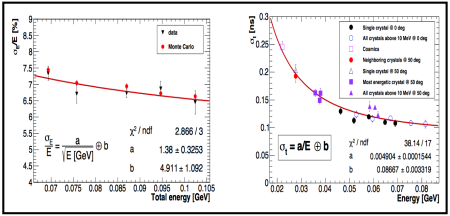
Mu2e
Status

Detectors performing as expected in testbeams

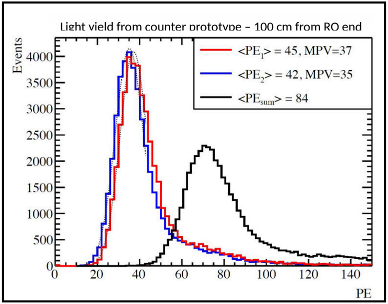
Tracker



Calorimeter



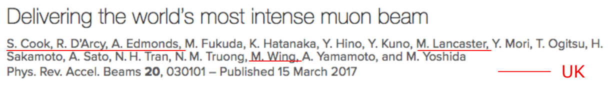
Cosmic veto



Mu2e

Status

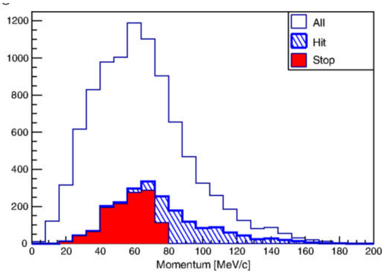
Muon yields now confirmed in independent beam study


Delivering the world's most intense muon beam

S. Cook, R. D'Arcy, A. Edmonds, M. Fukuda, K. Hatanaka, Y. Hino, Y. Kuno, M. Lancaster, Y. Mori, T. Ogitsu, H. Sakamoto, A. Sato, N. H. Tran, N. M. Truong, M. Wing, A. Yamamoto, and M. Yoshida

Phys. Rev. Accel. Beams **20**, 030101 – Published 15 March 2017

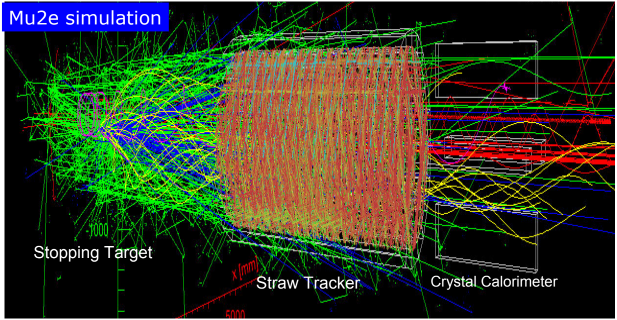
UK



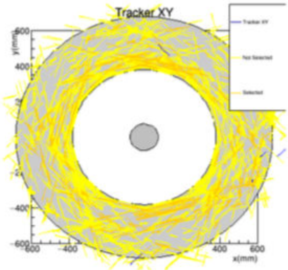
Mu2e
Status

10^{10} muons stopped in Al stopping target per second

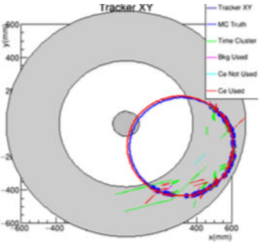
Occupancy is 1% in a 50 ns (drift time) window



Mu2e
Status



1 μs selection window after beam flash

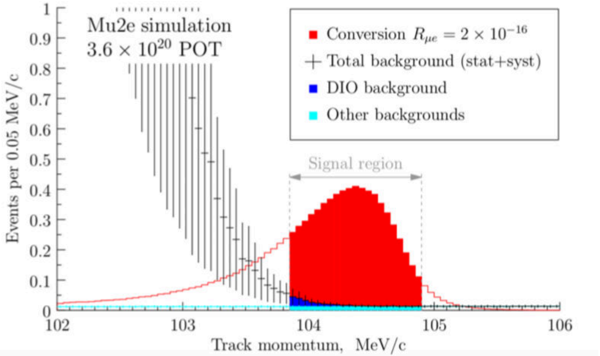


Hits selected by track finder within ± 50 ns selection window around potential track

Mu2e

Status

Mu2e sensitivity



- Discovery reach (5σ) : $R_{\mu e} \geq 2x10^{-16}$
- Exclusion power (90% CL) : $R_{\mu e} \geq 7x10^{-17}$

Mu2e Schedule

- Full scale solenoid & detector construction has started
- Solenoid and detector installation in 2019-2020
- Initial commissioning in 2021
- First physics running in 2022

- At full intensity
  - Reach Sindrum-II sensitivity in 100 min
  - x10 in 17 hours running
  - x100 in 7 days running
  - x10000 in 700 days running

Mu2e Collaboration (Liverpool, Manchester, RAL-TD, UCL)

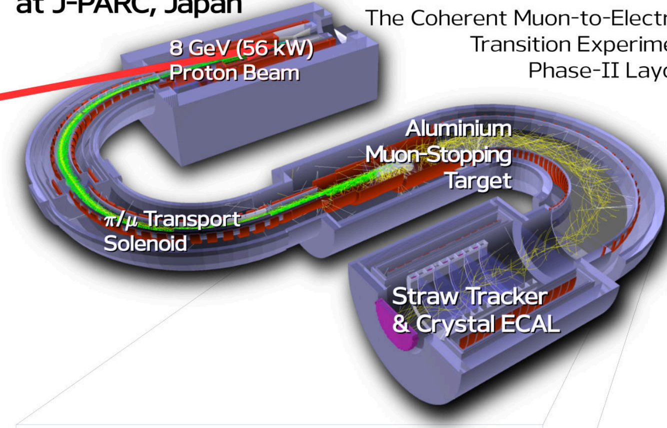
Over 200 Scientists from 37 Institutions

Argonne National Laboratory, Boston University, University of California Berkeley, University of California Davis, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University/Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University

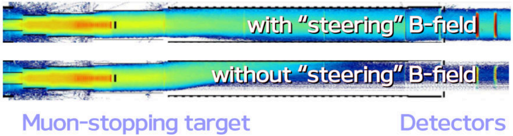
The COMET Experiment

Muon-to-electron conversion experiment at J-PARC, Japan

The Coherent Muon-to-Electron
Transition Experiment
Phase-II Layout



Signal electron density along curved beam line



<u>Curved solenoids with vertical B-fields:</u>
steerable **momentum-and-charge selection** for muons and signal electrons

<u>56 kW proton beam:</u>
Seven times the muon production rate of Mu2e

Fully physics study by Ben Krikler (PhD Thesis, 2016)

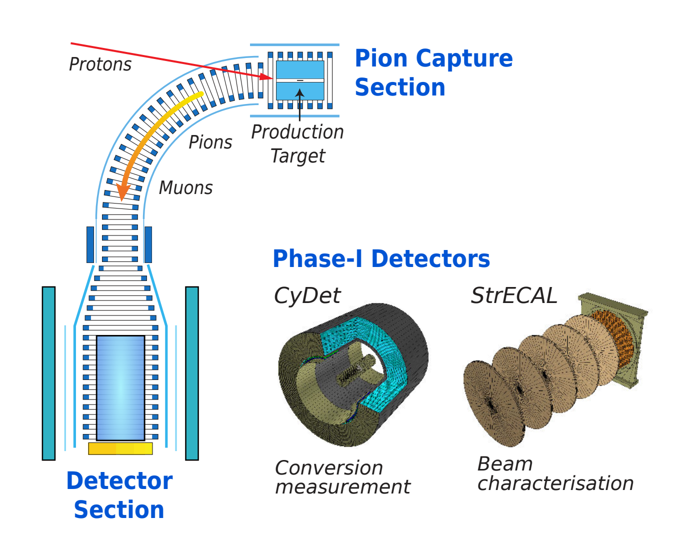
COMET Phase-II Sensitivity

- Curved solenoids with “steering” B-fields and high-power beam (56 kW) allow for large acceptances and good background rejection, cosmic ray performance and systematics studies
- Potential for improved performance
- Full Phase-II sensitivity study (2016, B. Krikler PhD thesis) gave detailed breakdown of backgrounds and pointed out areas of potential improvement
- Significant further work carried out across collaboration
- Several areas of improvement identified; sensitivity and data-collection rate

Sensitivity reach expectation for COMET Phase-II is now approximately $\times 10$ previous design, to allow it to reach a single-event sensitivity on the order of 2×10^{-18} in 3×10^{7} seconds of data-taking

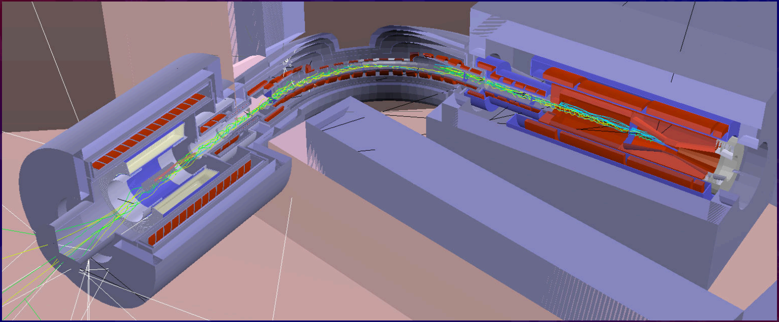
The COMET Experiment

Phase-I, under construction



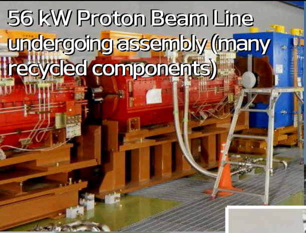
The COMET Experiment

Phase-I, under construction

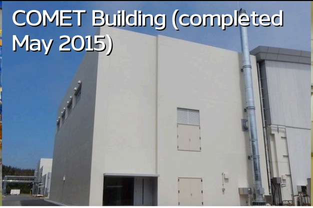


- Phase-I will improve the current sensitivity by two orders of magnitude

COMET Status (I)



56 kW Proton Beam Line undergoing assembly (many recycled components)



COMET Building (completed May 2015)

Phase-II experimental Hall (completed March 2015)

Diamond Beam Monitor prototype

Phase-I π / μ Transport Solenoid (also for Phase-II; delivered March 2015)

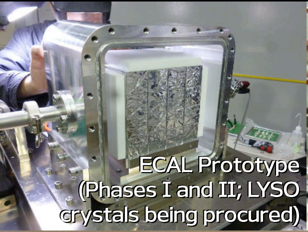
Undergoing testing in close cooperation with Toshiba

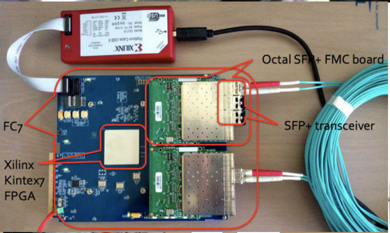
Phase-I and II Detector Solenoid (completed March 2016)

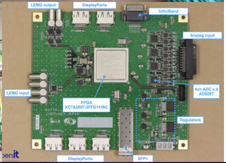
Proton Beam Target prototype

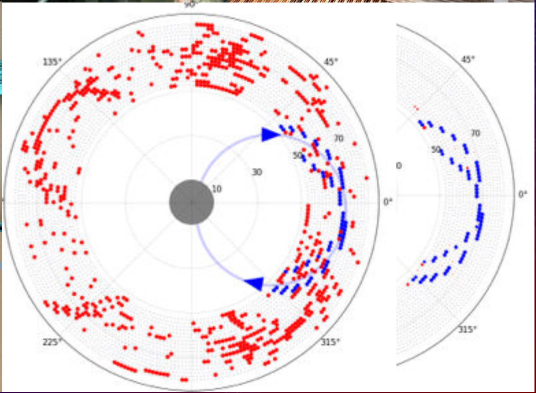
Cylindrical Drift Chamber (main Phase-I detector; completed June 2016, FE electronics also ready)

COMET Status (II)









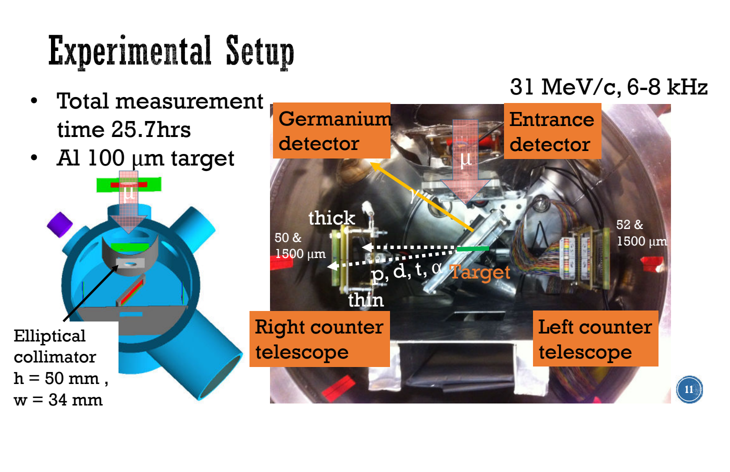
COMET Status

Over 150 collaborators from 34 institutions in 17 countries:

- Detectors, electronics, hardware and software currently under construction or being tested
- Proton beam to arrive at upstream point of COMET by end of JFY 2019 (March 2020)
- Beam studies (intensity and quality, radiation, extinction etc.) to start then
- Detector systems to have been full tested (including cosmic ray tests) by that time, ready for integration

AlCap for SM Muonic Atom Measurements

COMET/Mu2e joint experiment



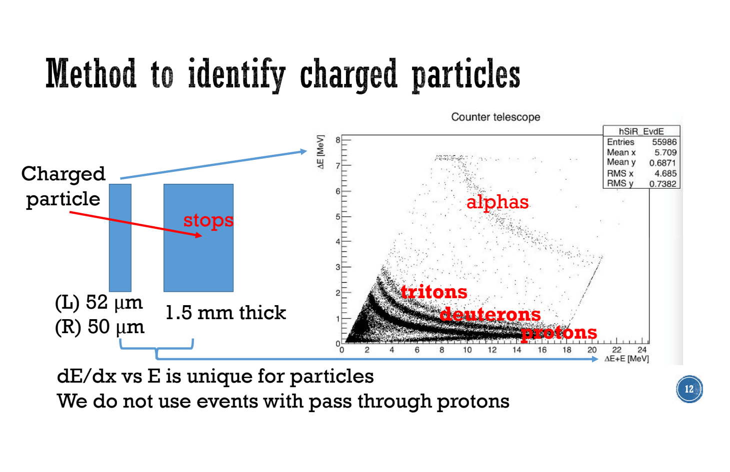
Mark Wong, PhD Thesis 2017, Osaka

2017, M. Wong, PhD Thesis

Inputs from AlCap being used in current COMET/Mu2e simulations

AlCap for SM Muonic Atom Measurements

COMET/Mu2e joint experiment



Mark Wong, PhD Thesis 2017, Osaka

2017, M. Wong, PhD Thesis

Inputs from AlCap being used in current COMET/Mu2e simulations

AlCap for SM Muonic Atom Measurements

COMET/Mu2e joint experiment

Conclusions

- 2p-1s and 3p-1s photon peaks used for muon normalization
- Energy de-convoluted to obtain true charged particle emission energies
- Emission rates after nuclear muon capture in Al
  - proton as $2.69 \pm 0.06(\text{stat.}) \pm 0.20(\text{syst.})\%$
  - deuterons as $1.79 \pm 0.05(\text{stat.}) \pm 0.14(\text{syst.})\ \%$
  - tritons $0.41 \pm 0.02(\text{stat.}) \pm 0.03(\text{syst.})\%$
- Proton (Deuteron) rates would be 3.31% (2.29%) if the spectrum shape holds.
- Possibility of muon normalization using protons detected by the COMET Phase-I tracking detector

44

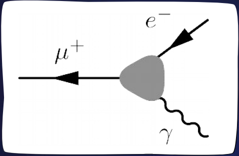
Mark Wong, PhD Thesis 2017, Osaka

2017, M. Wong, PhD Thesis

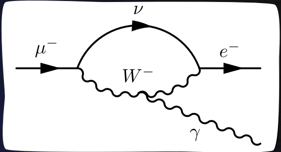
Inputs from AlCap being used in current COMET/Mu2e simulations

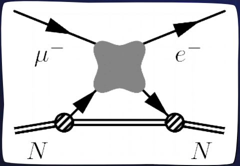
Muonic CLFV Channels

Forbidden Muon Decay Searches

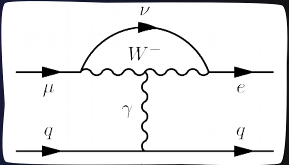


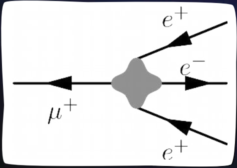
"Mu E Gamma"



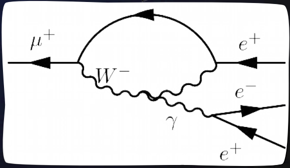


"Mu E Conversion"

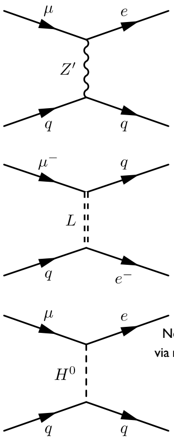




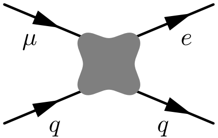
"Mu to 3 E"



Mu-e conversion: Beyond the Standard Model



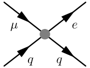
- Predicted in many Beyond the Standard Model theories
- Rate is model dependent but only constrained by direct CLFV searches



Current limits: $\mathcal{R} < \mathcal{O}(10^{-14})$

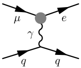
New physics couples to quarks via new heavy exchange particle

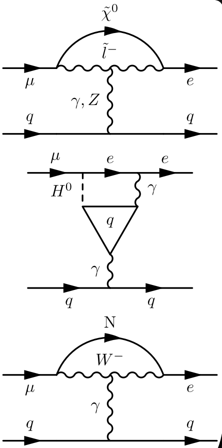
4-Fermi Contact term



New physics couples to quarks via a photon:

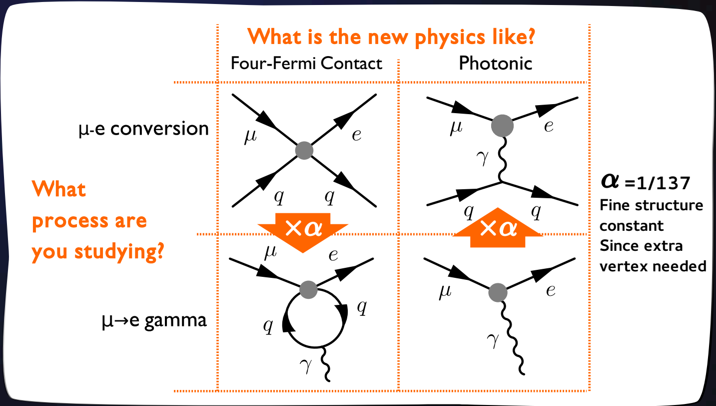
Photonic term





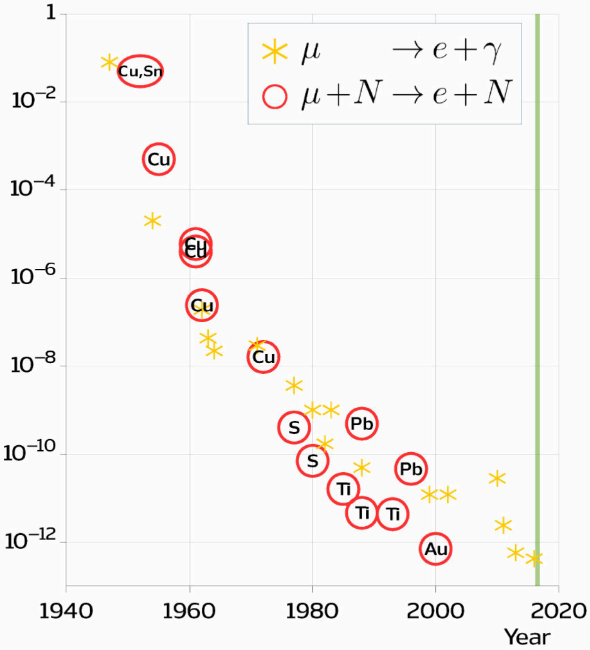
Muonic CLFV Channels

μ→e gamma vs μ-e conversion



- Relative sensitivity in μ-e conversion and μ-e gamma is very model dependent
- Highly complementary searches between μ→e gamma and mu-e conversion

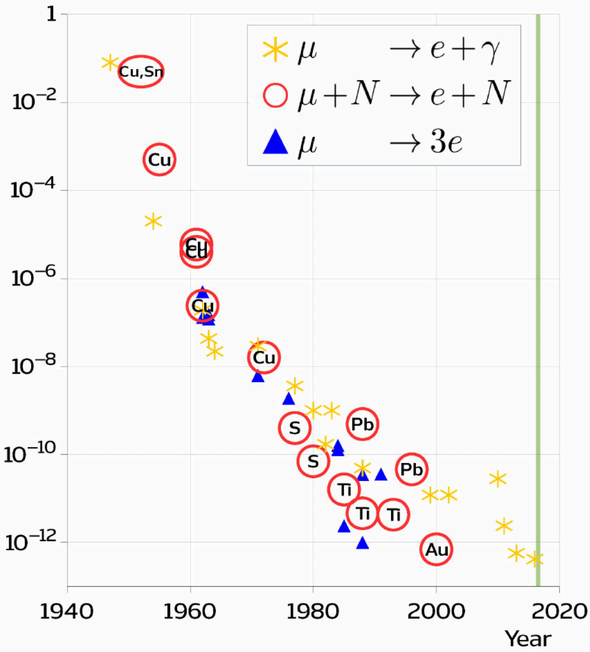
Charged Lepton Flavour Violation in Muons



90% C.L.
upper limit on
branching ratios

Charged Lepton Flavour Violation in Muons

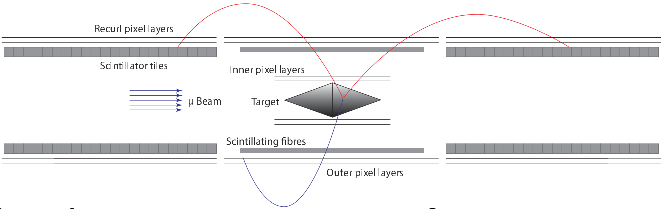
- Previous $\mu \to 3e$ results were in 1998



90% C.L. upper limit on branching ratios

Mu3e at PSI

Mu3e in a Nutshell



- Search for cLFV in $\mu \to eee$
- Observe $\mathcal{O}(10^{15})$ to $\mathcal{O}(10^{16})$ muons
- Precise tracking of e^+/e^-
- High geometric and momentum acceptance ($p_T > 10\,\text{MeV}$)
- Online reconstruction of all tracks
- Filtering of $\mu \to eee$ candidates

- Current limit:
  $BR < 1.0 \cdot 10^{-12}$ at 90 % CL
  (SINDRUM 1988)
  What can Mu3e achieve?

- What else can we look for with so many muon decays?

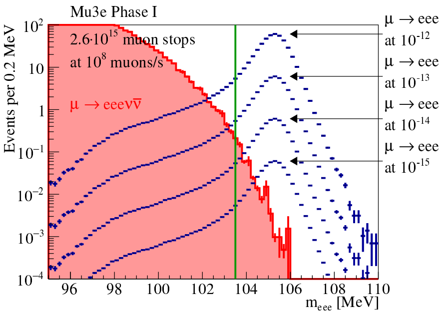
Mu3e at PSI

Sensitivity to μ → eee in Phase I

Reconstructed μ → eee events (signal and background)

- Long tracks only
- Cuts on $\Delta t_{e_i e_j}$, χ^2_{vertex}, $d_{\text{vertex-target}}$, $|\sum \vec{p}_e|$, m_{eee}
- Background-free with $2.6 \cdot 10^{15}$ stopped μ
- Signal efficiency 17 %

⇒ BR ≥ $5.2 \cdot 10^{-15}$ at 90 % CL

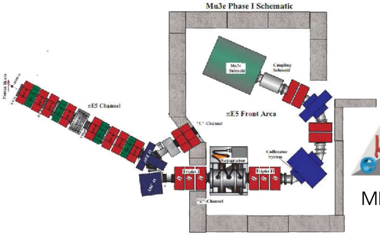


Mu3e at PSI

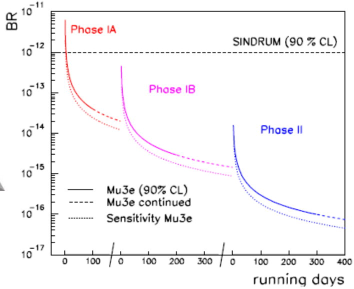
mu3e Schedule

Phase 1A and 1B (2019-2021): Br($\mu \rightarrow eee$) < 10^{-15}

- Approved (2013) and funded. PSI πE5 beam, shared with MEG.
- 10^8 μ/s on target for mu3e demonstrated.



MEG



Phase 2 (2021): Br($\mu \rightarrow eee$) <10^{-16} (10^4 improvement wrt SINDRUM)

HiMB beam at PSI → 10^9 μ/s on target for mu3e

Development work focussed on improving muon yield from "E-target" using solenoids to capture muons

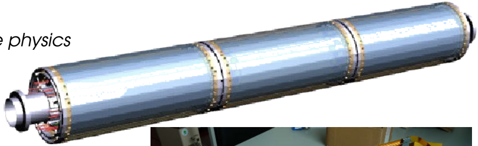
Gavin Hesketh

Mu3e at PSI

MuPix outer pixel layers for Phase 1

1.1 m^2 HV-MAPS pixel tracker

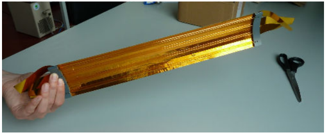
- *first HV-CMOS tracker in particle physics*



Material budget critical:

- 50 μm HV-MAPS
- 25 μm support
- 25 μm flex-print
- 12 μm aluminium traces
- 10 μm adhesive
- gaseous helium cooling

→ 0.1% X_0 per tracking layer



UK Deliverables (Bristol, Liverpool, Oxford, UCL)

- Commission assembly tooling & procedures (Aug 2017)
- Participate in final pre-production towards MuPix chip (start production Summer 2018)
- Tooling for chip-to-ladder assembly, ladder prototype production.
- Assembly of all Phase 1A outer tracker (Spring 2019).
  & Phase 1B recurl layers (Spring 2020).
- Design and deliver clock and control system for time-slice based daq (Spring 2019)

Gavin Hesketh

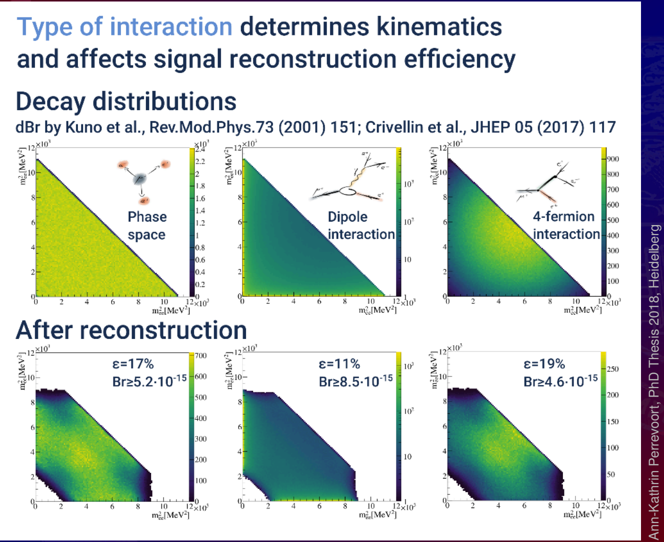
Beyond the next generation

With the next generation of experiments

- One of the experiments may see a signal
  - opens up a new era of study
  - complementary information from different CLFV channels
  - further detailed measurements within each channel
- Can continue to improve sensitivities
- Simultaneously study more “exotic” processes
  - including lepton *number*-violation

Kinematics of $\mu^+ \to e^+e^+e^-$

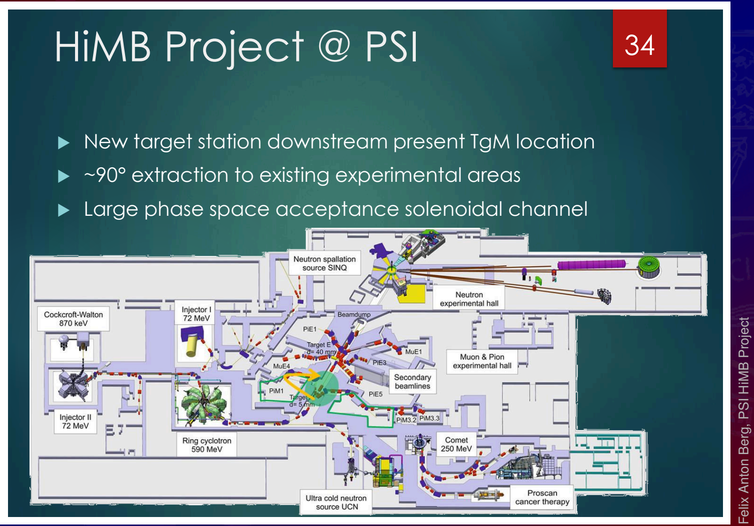
Disentangling the BSM Physics



2018, A-K Perrevoort PhD Thesis

PSI Beam Upgrade

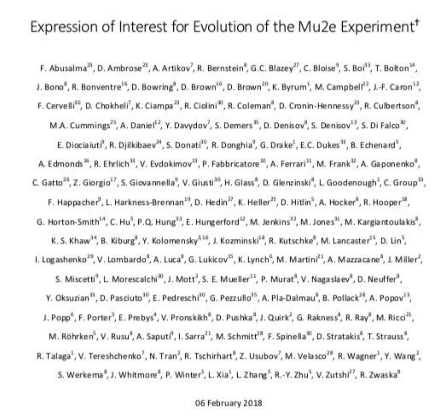
For MEG and Mu3e and other PSI experiments



Aiming for $O(10^{10})$ μ^+ per second (almost a factor 100 improvement)

Mu2e-II

- In event of a signal, Mu2e-II would give ×10 stats and running with Aluminium, Titanium and Gold targets would give sensitivity to BSM interaction type
- In absence of signal improve sensitivity by ×10
- "utilize the increased proton intensity provided by the Fermilab PIP-II upgrade"
- 800 MeV, 100 kW (Mu2e-I is 8 kW)
- arXiv:1802.02599



Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14],
J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12],
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S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Z–Dependence of Muon–to–Electron Conversion

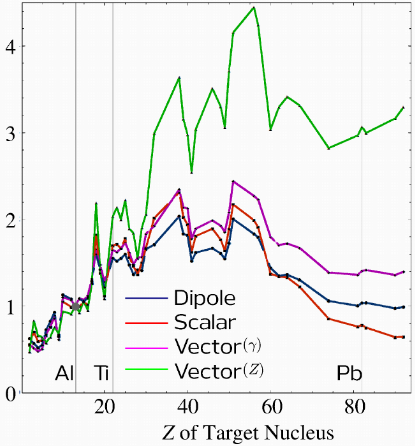
Disentangling the BSM Physics

Z–Dependence of Muon–to–Electron Conversion

- differs according to type of New Physics interaction

Relative dependences of the muon-to-electron conversion branching ratio on the target nucleus

For different nuclei, different
size of nucleus,
radius of orbit,
u- and d-quark composition



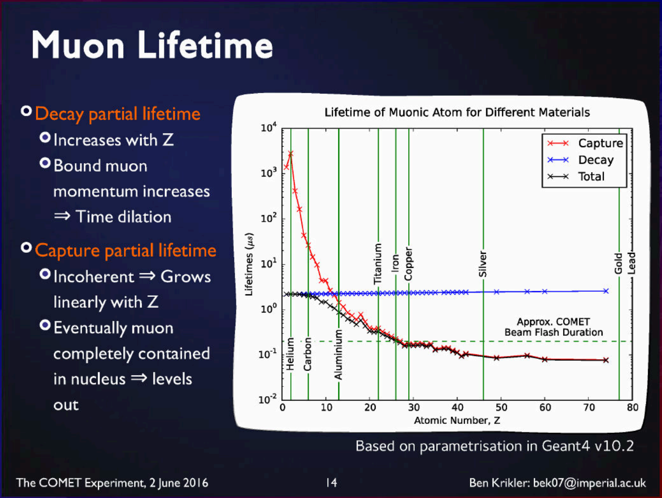
I. Cirigliano et al., Phys. Rev. D 80, 013002 (2009)

Z-Dependence of Muon-to-Electron Conversion

Disentangling the BSM Physics

Z-dependence of the bound muon lifetime

- Competing effects on bound muon lifetime
- Becomes very short above, say, Titanium or Iron

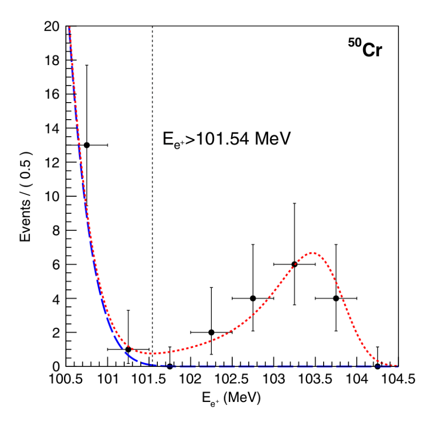


Ben Krikler

Other Observables

In addition to searching for the golden channels of CLFV, other possibilities can be pursued including some which violate Lepton Number

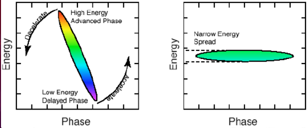
- $\mu^- \to e^+$ **in a muonic atom**
- $\mu^- + e^- \to e^- + e^-$ in a muonic atom
- $\mu^+ \to e^+ + X$ (X single neutral particle)
- $\mu^+ \to 5e$
- muonium to antimuonium
- ...



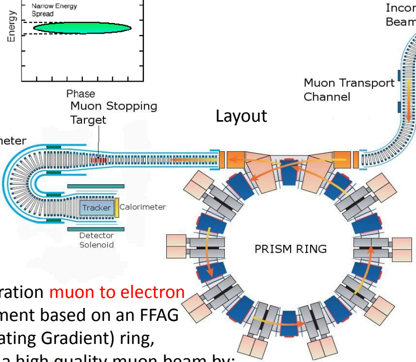
Phys. Rev. D 96, 075027

PRISM FFAG Muon-to-Electron Conversion

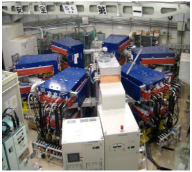
PRISM - Phase Rotated Intense Slow Muon beam



Phase Rotation



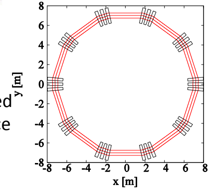
Test ring in Osaka



PRISM:

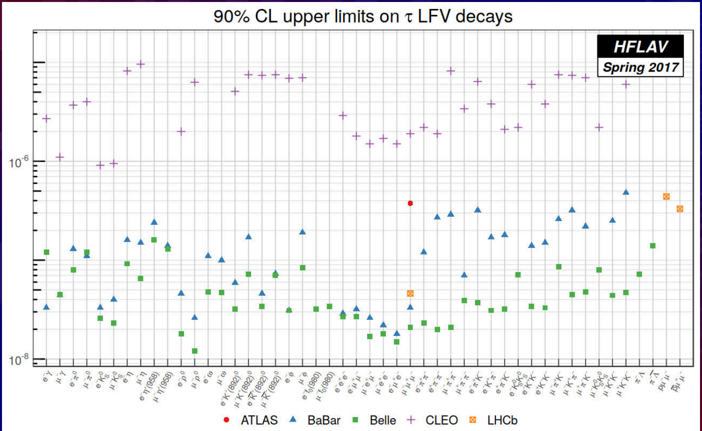
- It is the next generation muon to electron conversion experiment based on an FFAG (Fixed Field Alternating Gradient) ring,
- It allows to create a high quality muon beam by:
  - reducing the muon beam energy spread by RF phase rotation,
  - purifying the muon beam in the storage ring.
- It will have single event sensitivity – 3×10^{-19}
- Design details are being addressed by the Task Force led by Jaroslaw Pasternak (contact him for more details).

Alternative ring designed by Task Force



Other CLFV Searches

- τ CLFV at colliders
  - Absolute numerical limits restricted by tau production rates, but valuable because of model dependencies on m_ℓ.



- Also $H \to \mu\tau$, $Z \to \mu e$ etc., at GPDs, and searches in Kaon decays.

Other CLFV Searches

- τ CLFV at colliders
  - Absolute numerical limits restricted by tau production rates, but valuable because of model dependencies on m_ℓ.

Searches for LF/LN violating decays at NA62

- Lepton number violating decays
  - $K^+ \to \pi^-\mu^+\mu^+$ $(BR < 1.1\times10^{-9})$ NA48/2@CERN [PLB 697 (2011) 107]
  - $K^+ \to \pi^-\mu^+e^+$ $(BR < 5.0\times10^{-10})$
  - $K^+ \to \pi^-e^+e^+$ $(BR < 6.4\times10^{-10})$
- Lepton flavour violating decays
  - $K^+ \to \pi^+\mu^-e^+$ $(BR < 5.2\times10^{-10})$

  } BNL E865 [PRL 85 (2000) 2877]
  - $K^+ \to \pi^+\mu^+e^-$ $(BR < 1.3\times10^{-11})$ BNL E777/E865 [PRD 72 (2005) 012005]
  - $K^+ \to \pi^+\pi^0,\ \pi^0 \to \mu^\pm e^\mp$ $(BR < 3.6\times10^{-10})$ kTeV@FNAL [PRL 100 (2008) 131803]
  - $K^+ \to \mu^-\nu e^+e^+$ $(BR < 2.1\times10^{-8})$ Geneva-Saclay [PL 62B (1976) 485]
- $\Delta S = \Delta Q$ violating modes
  - $K^+ \to \pi^+\pi^+\mu^-\overline{\nu_\mu}$ $(BR < 3.0\times10^{-6})$ LRL [PR 139 (1965) B1600]
  - $K^+ \to \pi^+\pi^+e^-\overline{\nu_e}$ $(BR < 1.3\times10^{-8})$ Geneva-Saclay [PL 60B (1976) 393]

- NA62 is able to improve on most of these modes
  - Single event sensitivity $\sim 10^{-11}$

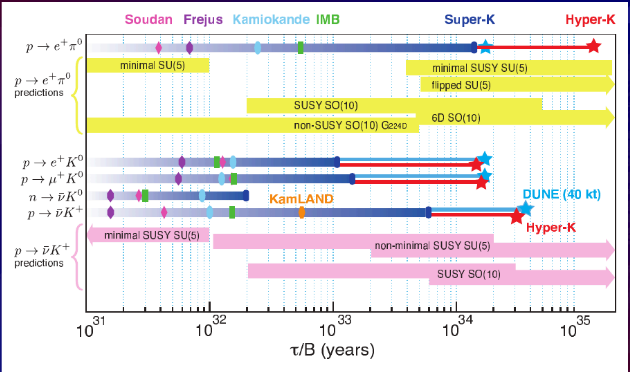
17/08/2018 11

- Also $H \to \mu\tau$, $Z \to \mu e$ etc., at GPDs, and searches in Kaon decays.

Physics Reach of Experiments

Graphical representations of physics reach of experiments (even if somewhat over-simplified) can be useful....

- Proton decay
- EDMs
- CLFV
  - Perhaps an area which can be improved



DUNE CDR

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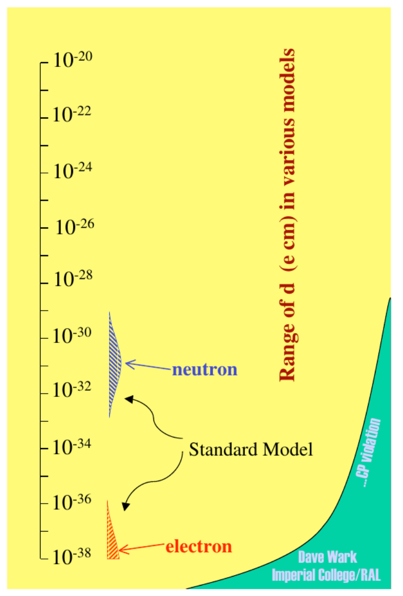

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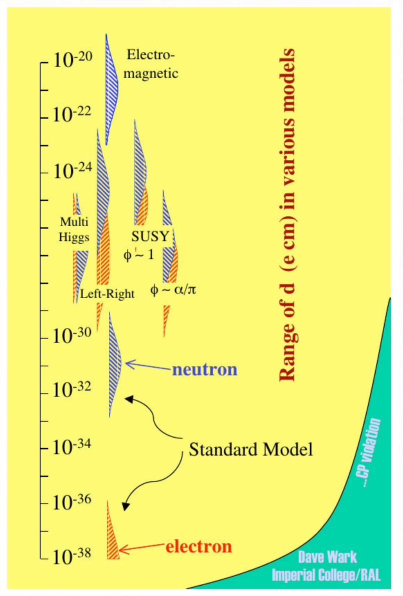

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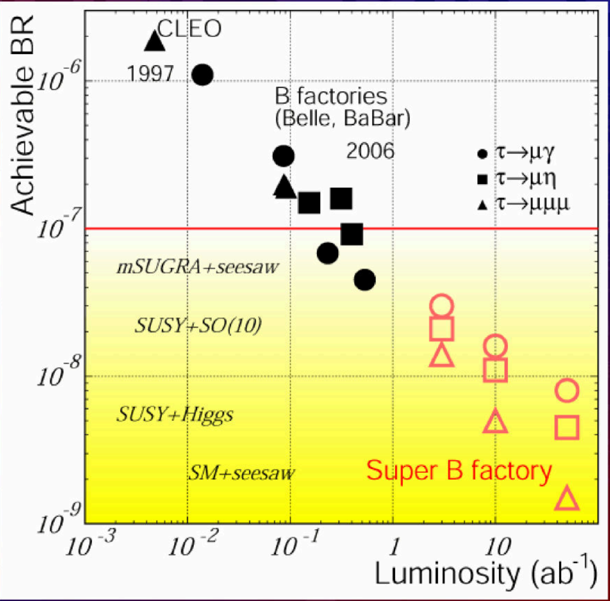

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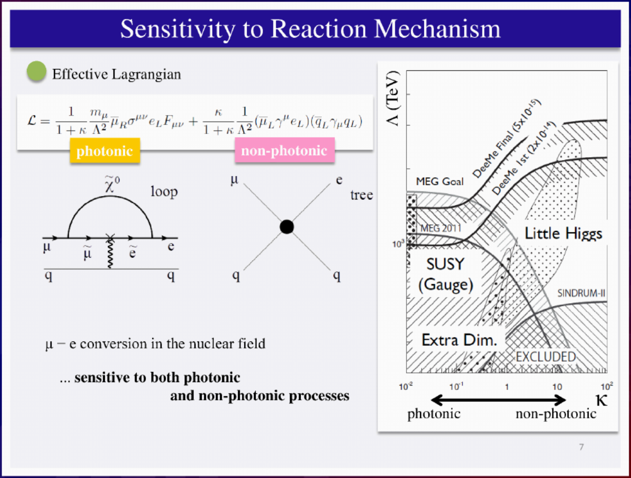

Yohei Nakatsugawa

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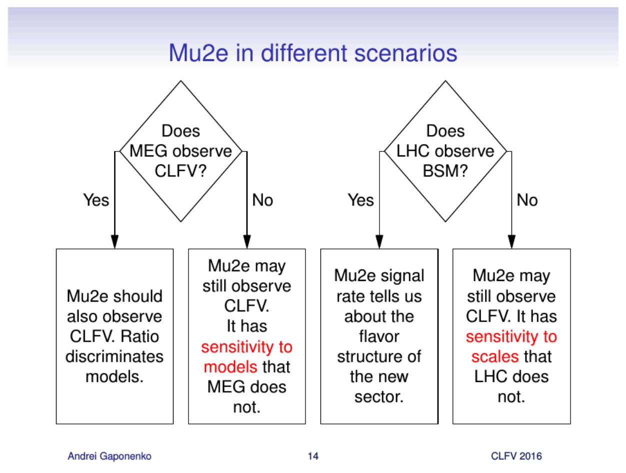

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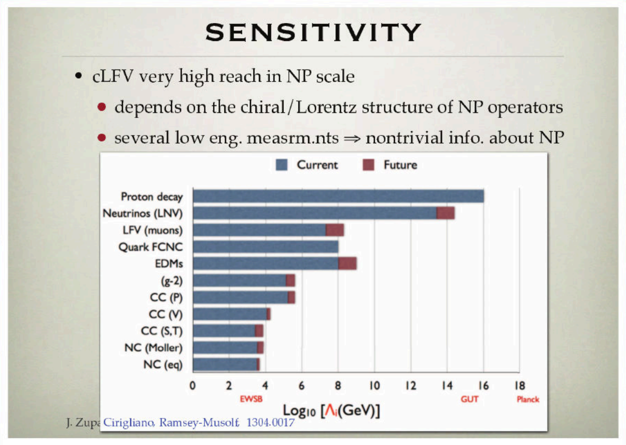

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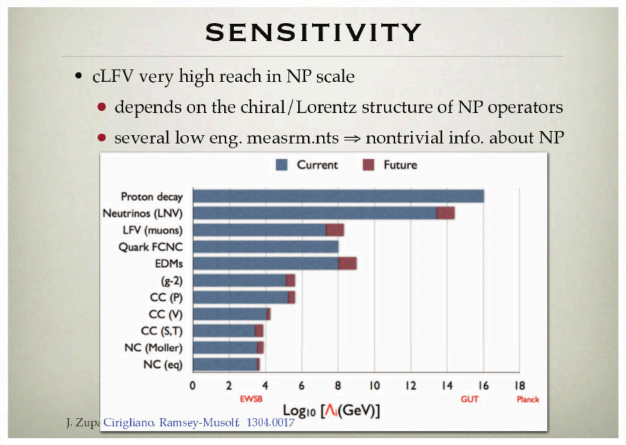


Conclusions

Charged Lepton Flavour Physics is a highly active field, worldwide and in the UK

- experimental conservation of flavour helped shape the SM
- flavour is completely conserved in the SM, but only “accidentally”
- CLFV measurement highly sensitive to deviations from SM
- zero theoretical SM backgrounds
- complementary to the LHC
- near-future experiments to probe further by orders of magnitude
- many techniques, improvements
- a discovery would trigger a succession of complementary and informative measurements
  - remember: neutrinos used to be a “niche” area....
  - also: muon $g-2$....

Thanks to: MEG, Mu2e, Mu3e, M. Lancaster, G. Hesketh, B. Krikler, P. Litchfield and others

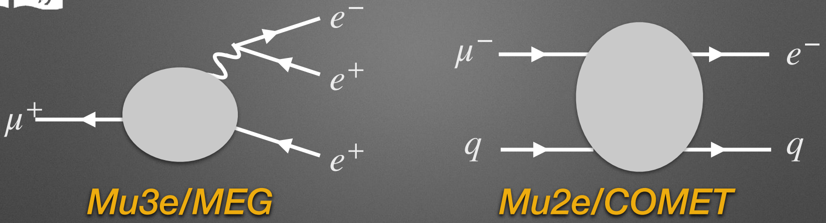
Lepton Flavour Violation
PPAP July 2018

Joel Goldstein
University of Bristol

Introduction

- Dedicated charged LFV experiments
  1. Mu2e
  2. Mu3e
  3. COMET
     - *(MEG has no UK involvement)*
  4. Future
- Thanks for input from Yoshi, Joost and Mark

Background



- LFV already established in the neutrino sector
- Resulting effects in charged lepton decays *Br* << 10^{-50}
- Existing limits ~ 10^{-12}
- Sensitive to multi-TeV scale new physics
  - SUSY, leptoquarks, dark matter…

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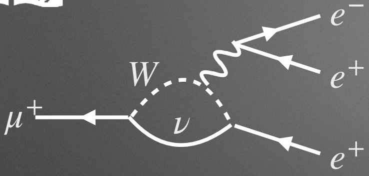
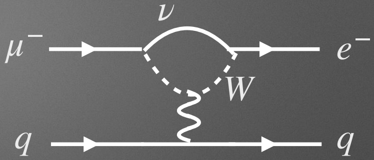


Mu3e/MEG



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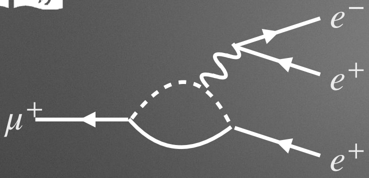

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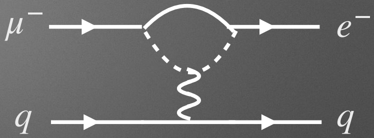

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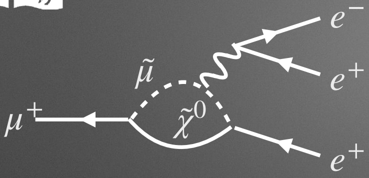

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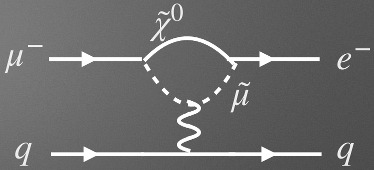

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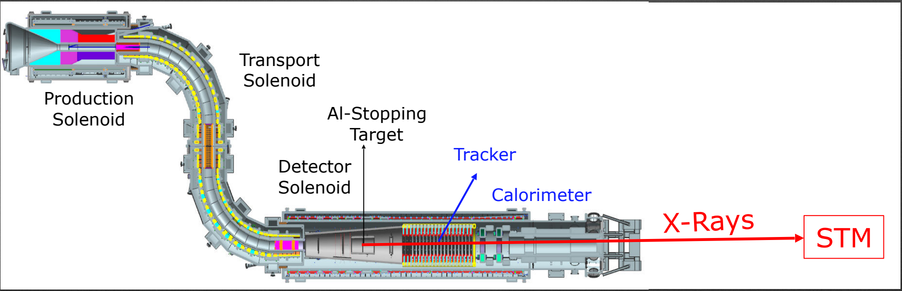
- Resulting effects in charged lepton decays *Br* << 10^{-50}
- Existing limits ~ 10^{-12}
- Sensitive to multi-TeV scale new physics
  - SUSY, leptoquarks, dark matter…

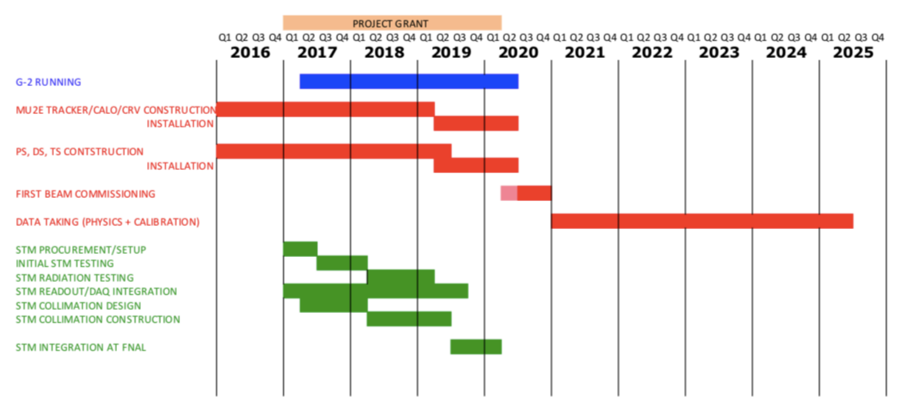
Mu2e - Status

- DOE approved in July 2016
- UK providing the Stopping Target Monitor (STM)
- STFC-TD to provide the proton target *(DOE Funded)*

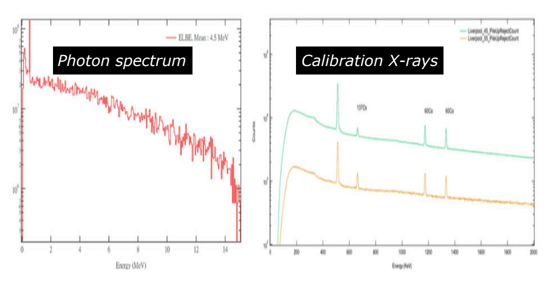


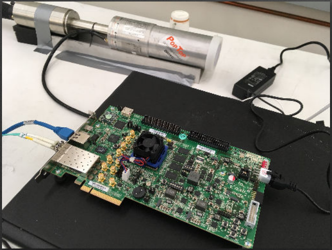
Mu2e - Plans

- First beam in 2020/21; concluding 2025.



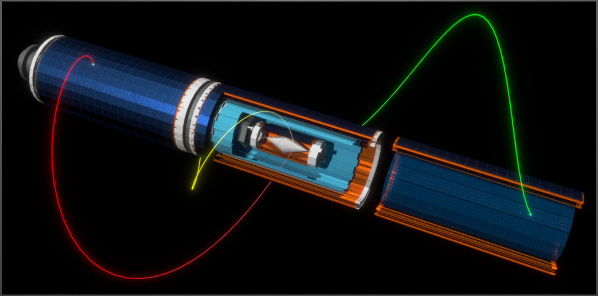
Mu2e UK





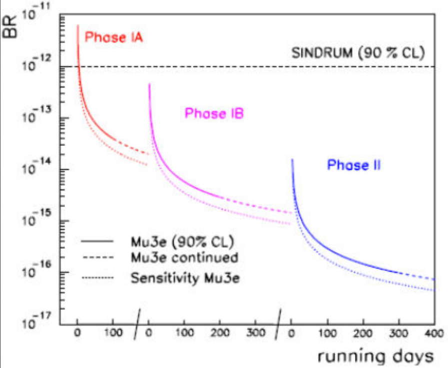
- Prototype STM irradiated at HZDR.
  - No degradation in resolution
  - 100 Hz signal (60 kHz photon bkgnd)
- DAQ/readout tests at FNAL

Mu3e - Status



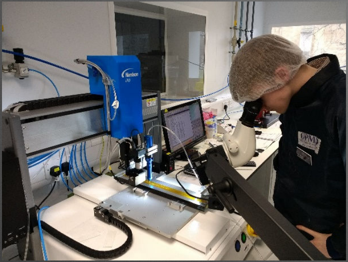
- Approved by PSI in 2013
- UK responsible for outer pixel layers
  - HV CMOS Mupix sensor
- Also clock and timing

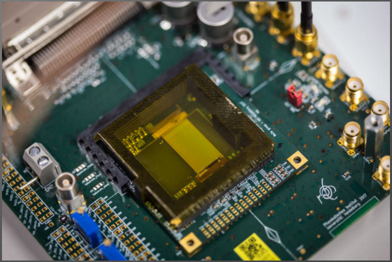
Mu3e - Plans



- Commissioning late 2019
- Physics operation in 2020
- Recurl stations added 2021
- Phase-II ~2024:
  - Upgraded beam line
  - Increased acceptance
  - Possible e-gamma option

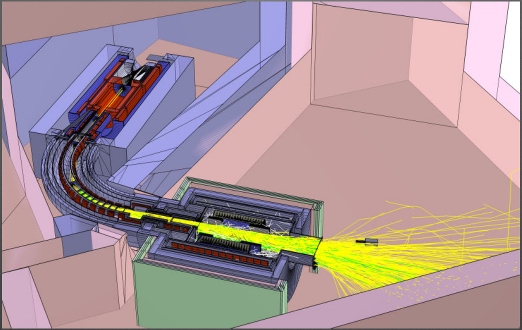
Mu3e UK





- Deliver complete pixel outer tracker by 2020
- Participate in installation and commissioning 2019-21
- Operations and exploitation 2020-2024
- *Natural for UK to build Mu3e-II pixel extension*

COMET - Status



- Phase-I detector systems approaching completion
- UK designed DAQ/fast control
- UK leading software and analysis

COMET - Plans

- Protons to COMET by end 2019
- Phase-II construction in parallel to operations
  - 100x increase in sensitivity
- Growing international collaboration
  - 16+ countries, 40+institutions

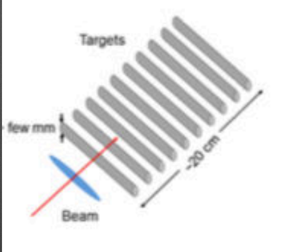
Funding

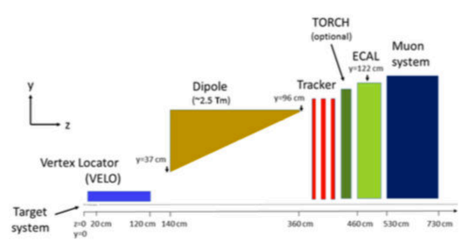
- Phase I construction:
  - Support from CG
  - Mu2e and Mu3e supported by STFC project funding
  - *Construction of all three experiments fully funded*
- Operations
  - Bid for common fund/engineer, travel and RA support in CG
- Phase-II less certain (UK, international)
  - Mu3e-II pixel extension PPRP bid, …??

Future

- **Mu2e Phase II**
  - Presented to FNAL PAC yesterday
  - Timescale ~2030, 10x sensitivity
  - Change targets to allow model discrimination
- **COMET - PRISM**
  - FFAG baseline lattice established, larger acceptance (UK)
  - 100x improvement in sensitivity
- **TauFV**
- **Future “combined facility”…?!?**
- **UK charged lepton “medium” Big Idea proposal**

TauFV





- Dedicated search for $(D_s \to)\,\tau \to 3\mu$
- Sensitivity $\sim 10^{-10}$
- Installed at SPS BDF
  - Parasitic to SHiP

Fit in ES

- Smaller, cheaper and faster experiments
- Clear discovery potential
  - No SM backgrounds
- Complimentary to energy frontier
- Maintain breadth and diversity
- Train next generations