LFV and g-2 experiments with muons

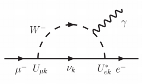
F. Kapusta

LPNHE Paris

The future of the intensity frontier
GdR-Inf Workshop
CERN
2 february 2018

Physics Motivation : Beyond the Standard Model with muons

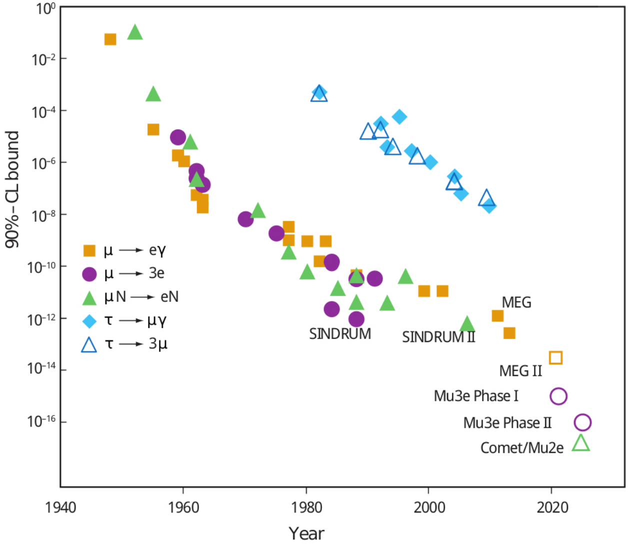
- LF is not conserved from neutrino oscillations.
- cLFV in the SM ($+m_\nu$) is negligibly small.



B. Pontecorvo (1947) : $\mu = e^*$
Cheng and Li ('77,'80) Petcov('77).
$BR(\mu \to e\gamma) \simeq O(10^{-54})$.

- Search for rare processes or measure fundamental quantities like g-2
- Direct search (Energy Frontier) LHC, ILC : higher energy for heavier new particle(s).
$$|A_{SM} + \varepsilon_{NP}|^2 \simeq |A_{SM}|^2 + 2Re(A_{SM}\varepsilon_{NP})$$
- Indirect search (Intensity Frontier): "slight" difference from SM prediction.
$$|A_{SM} + \varepsilon_{NP}|^2 \simeq |\varepsilon_{NP}|^2 \Rightarrow \text{Rate} \simeq \frac{1}{\Lambda^4}$$
- Probe the PeV scale with cLFV.

Past and future



Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]

from Ann-Kathrin Perrevoort NuFACT2017

Experimental consequences

Rare decays searches require :

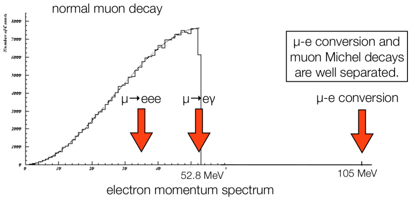
- Detectors with very good resolution and excellent background rejection.
- Background includes physical background, beam-related backgrounds, accidentals, cosmic rays and false tracking.
- As good as possible simulation and tracking are mandatory

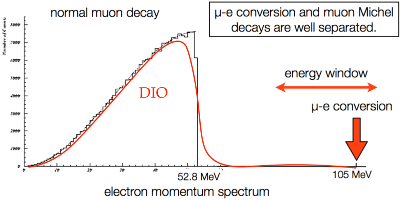
Comparison between $\mu \to e\gamma$ and $\mu - e$ conversion :

	background	challenge	beam intensity
$\mu \to e\gamma$	accidentals	detector resolution	limited
$\mu - e$ conversion	beam	beam background	no limitation

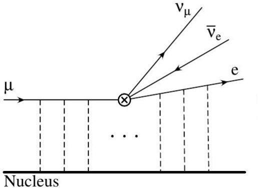
- High intensity pulsed muon beams require strict proton beam extinction between pulses.
- Discussions on limits on BR or SES between experiments.

Signal and Intrinsic Background

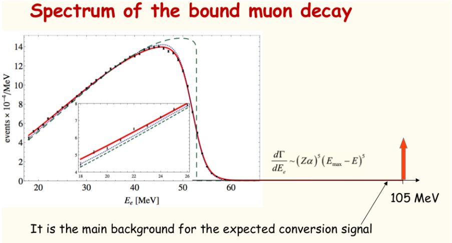




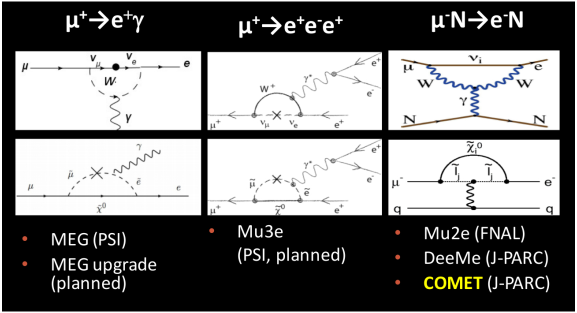
- DIO : decay in the field of a nucleus.



- TWIST (2009), A. Czarnecki et al. (2014). Included in GEANT4.



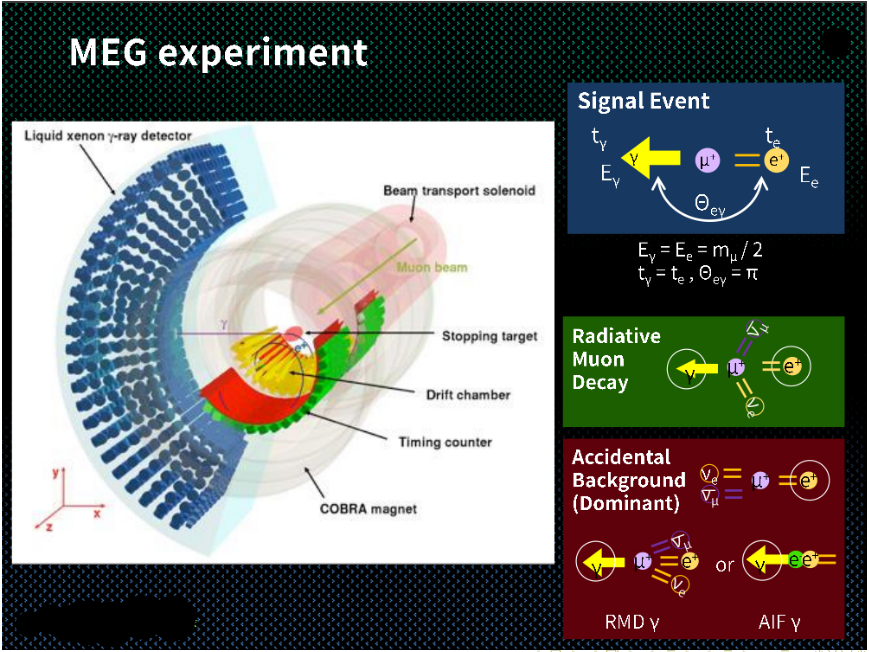
Current bounds and future sensitivities



Process	Experiment	Limit
BR($\mu^+ \to e^+\gamma$)	MEG('13)	4.2 10^{-13}
	MEG-II($\geq$ '20) at PSI	4 10^{-14}
BR($\mu^+ \to eee$)	SINDRUM('88)	10^{-12}
	Mu3e Phase I($\geq$ '20) at PSI	2 10^{-15}
R($\mu \to e$:Au)	SINDRUM-II('06)	7 10^{-3}
R($\mu \to e$:Al)	COMET-PhaseI($\simeq$ '20)	3 10^{-15}
	COMET-PhaseII($>$'20)	3 10^{-17}
	Mu2e($\geq$ '20)	7.5 10^{-17}
R($\mu \to e$:Ti)	PRISM($>$ '20)	O(10^{-18})

PSI vs J-PARC : $10^8 \mu/s$ vs $10^{11} \mu/s$

MEG : coincidences and reconstructed mass

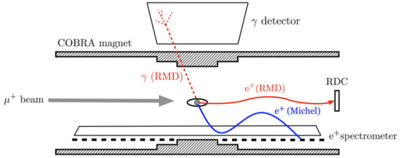


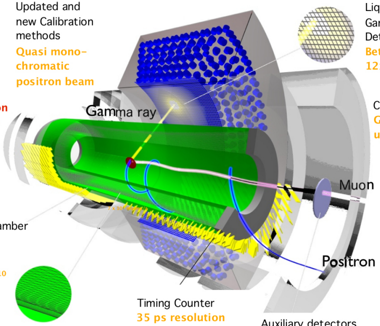
MEGII

Improve all resolutions : energy, momentum and timing.

$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$

Momentum resolution
Energy resolution
Relative timing resolution
Relative angular resolution





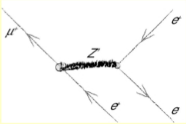
from Angela Papa NuFACT2016

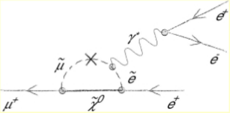
The Mu3e Experiment

- Search for LFV decay: **μ → eee**
- Single event sensitivity of

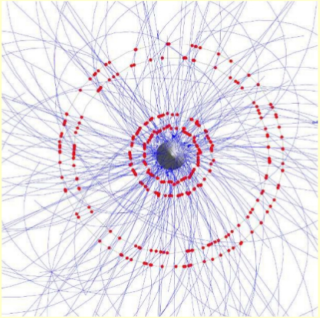
  10^{-15} Phase I

  $<10^{-16}$ Phase II
- Muon rate **10^8** **($>10^9$)** per second
- O(10) (O(100)) tracks within 50ns
- Sensitive to New Physics:



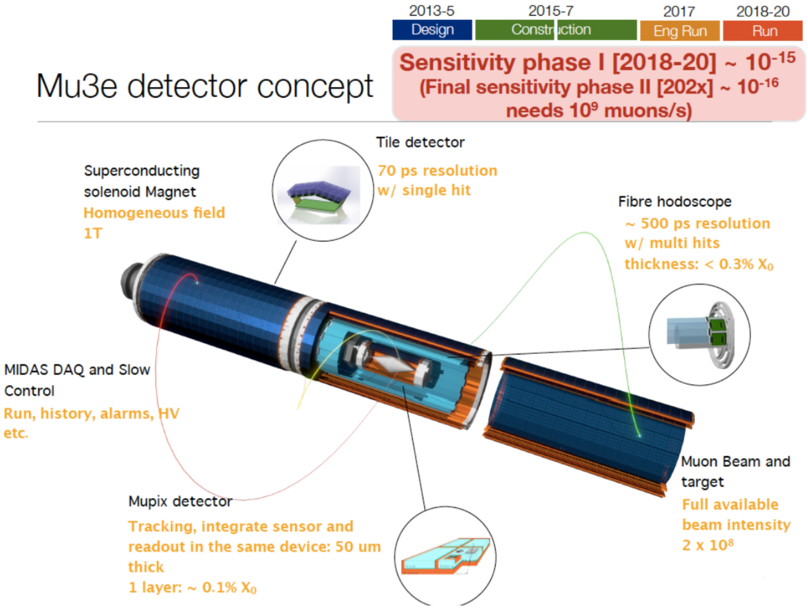


Discussed in Research Proposal:
→ arXiv:1301.6113



All silicon tracker
based on
HV-MAPS technology

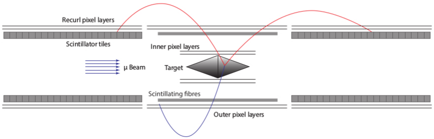
Mu3e Concept

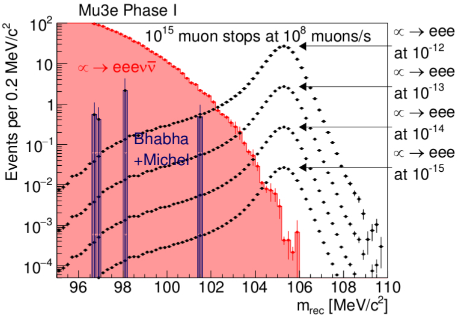


from Angela Papa NuFACT2016

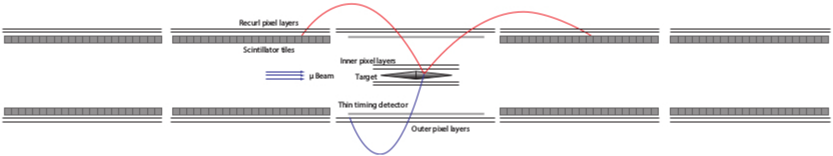
Mu3e from Phase I to Phase II

- A detector with good vertex and time resolution.
- Pixels and Scintillating Fibers.
- Low material budget for low momemtum electrons.



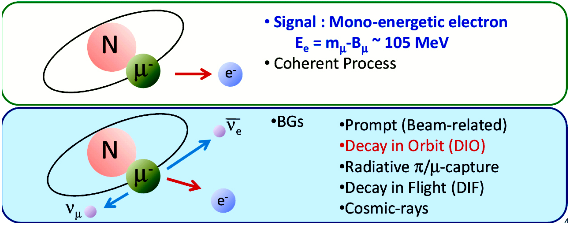


- Increase acceptance for recurlers
- Smaller beam profile

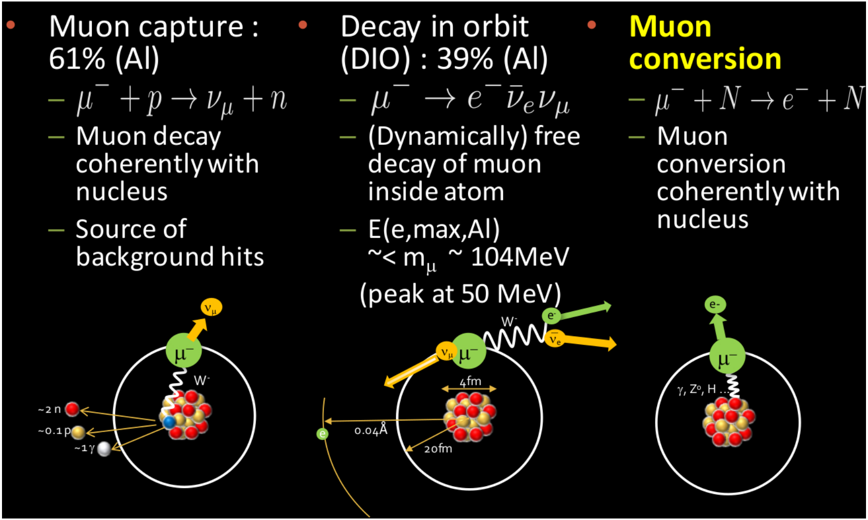


μ-e conversion

- Coherent process: unchanged nucleus.
- Signal : mono-energetic electron $E_e = m_\mu - B_\mu - E_{recoil}$
- $m_e \ll m_\mu$, $B_\mu = m_\mu \frac{1}{2} Z^2 \alpha^2$ and $E_{recoil} = m_\mu \frac{m_\mu}{2M}$
- For aluminum used by COMET : $E_e = 104.9$ MeV.
- Define a conversion rate $BR = \frac{\Gamma(conversion\ \mu - e)}{\Gamma(capture\ de\ \mu)}$
- Current limit for SINDRUM-II at 90% CL on gold : $BR < 7.\ 10^{-13}$
- COMET Single-Event-Sensitivity Phase-I $\leq 3\ 10^{-15}$ and Phase-II $\leq 3\ 10^{-17}$



Backgrounds and signal



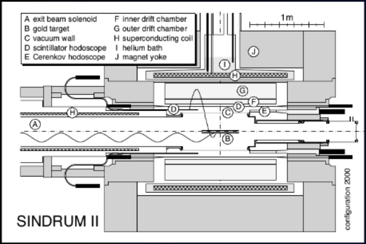
from Myeongjae Lee NuFACT2017

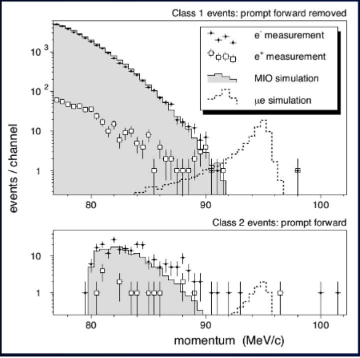
SINDRUM

SINDRUM-II (PSI)

Published Results (2004)

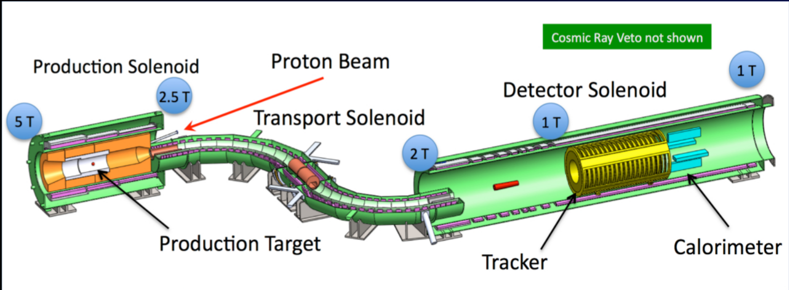
$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$





PSI muon beam intensity ~ 10^{7-8}/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

μ-e conversion : Mu2e at Fermilab



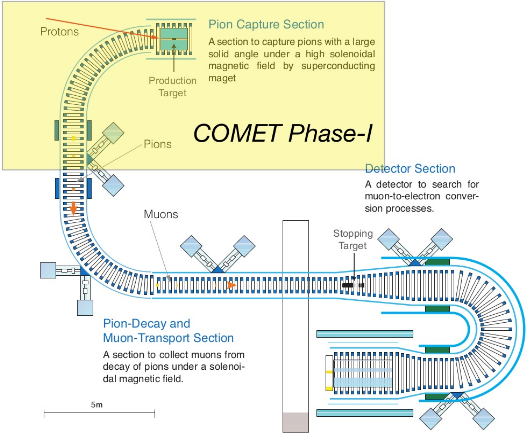
$$B(\mu^- + Al \rightarrow e^- + Al) = 5 \times 10^{-17} \quad \text{(S.E.)}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16} \quad (90\%\text{C.L.})$$

- Reincarnation of MECO at BNL.
- Antiproton buncher ring is used to produce a pulsed proton beam.
- Approved in 2009, and CD0 in 2009, and CD1 in 2011.
- Data taking starts in about 2019.

COMET

$\mu \to e$ conversion

- Staging approach : Phase I to achieve 10^{-14} sensitivity and then Phase II

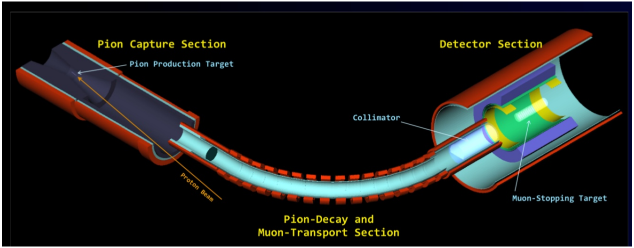


- 8 GeV, pulsed proton beam to produce high-intensity muon beam
- COMET building finished and Muon Transport Solenoid installed

COMET (E21)

COMET Phase I (2016)

- Beam background study and achieve S.E.S. $\simeq 3.10^{-15}$ with 8 GeV - 3.2 kW proton beam, $\sim$ 3 months DAQ

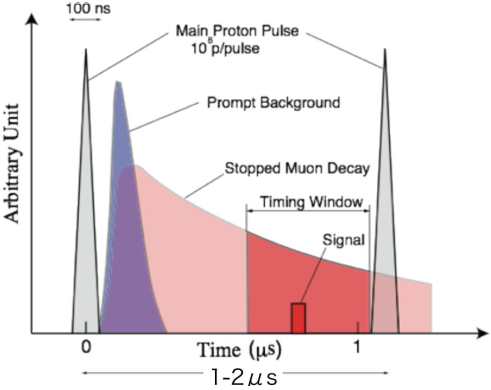


COMET Phase II (2020)

- 8 GeV - 56 kW proton beam , $\sim$ 1 year DAQ to achieve the COMET final goal of S.E.S $\simeq 3.10^{-17}$

COMET

- $\mu \to e$ conversion signal identified with an energetic electron of 105MeV emitted from a muonic atom with delayed timing.



COMET Sensitivity

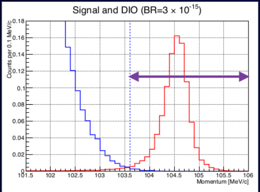
Signal Sensitivity for COMET Phase-I with CyDet

Osaka University

Signal Acceptance

Table 28: *Breakdown of the $\mu^- N \to e^- N$ conversion signal acceptance.*

Event selection	Value	Comments
Geometrical acceptance	0.37	
Track quality cuts	0.66	
Momentum selection	0.93	103.6 MeV/c < P_e <106.0 MeV/c
Timing window	0.3	700 ns < t < 1100 ns
Trigger efficiency	0.8	
DAQ efficiency	0.8	
Track reconstruction efficiency	0.8	
Total	0.043	



Signal Sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

- $f_{cap} = 0.6$
- $A_e = 0.043$
- $N_\mu = 1.23\text{x}10^{16}$ muons

$$B(\mu^- + Al \to e^- + Al) = 3.1 \times 10^{-15}$$

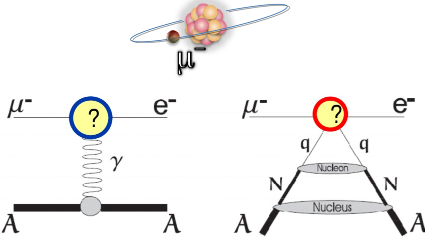
$$B(\mu^- + Al \to e^- + Al) < 7 \times 10^{-15} \quad (90\% C.L.)$$

Muon intensity

about 0.00052 muons stopped/proton

With 0.4 μA, a running time of about 110 days is needed.

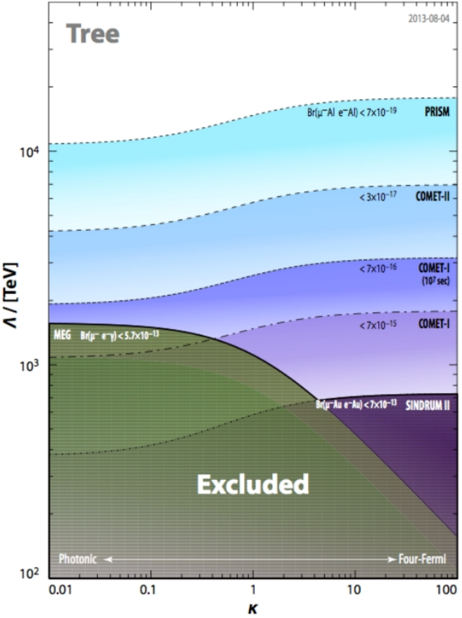
Exclusion diagrams



Dipole and 4-fermion couplings

$\mu^- N \rightarrow e^- N$ low energy effective lagrangian

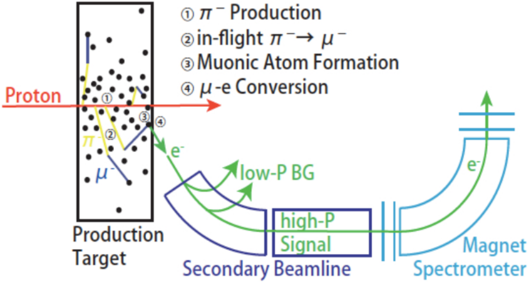
$$\mathcal{L} = \frac{1}{1+\kappa} \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L \mathcal{F}_{\mu\nu}$$
$$+$$
$$\frac{\kappa}{1+\kappa} \frac{1}{\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{q}_L \gamma_\mu q_L) + h.c.$$



DeeMe


3GeV RCS
Rapid Cycling
Synchrotron
DeeMe
30GeV MR
Main Ring
COMET


DeeMe


① π^- Production
② in-flight $\pi^- \to \mu^-$
③ Muonic Atom Formation
④ μ-e Conversion
Proton
π^-
μ^-
e^-
low-P BG
high-P
Signal
e^-
Magnet
Spectrometer
Production
Target
Secondary Beamline

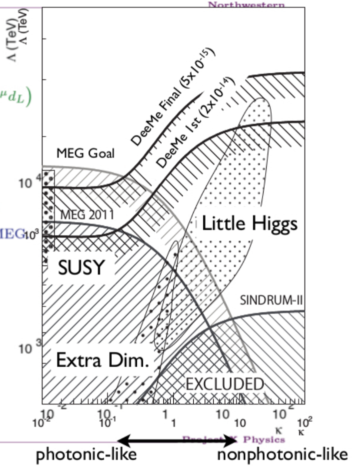
μ→eγ vs. μ-e conversion

André de Gouvêa — Northwestern

Model Independent Analysis

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

- $\mu \to e$-conv at 10^{-17} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- We don't think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$-conv "only" way forward after MEG.
- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 1000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.



g-2 experiments

New g-2 at FERMILAB

PARTICLE PHYSICS

Muon's magnetism could point to new physics

After a hiatus of nearly 20 years, experimental scrutiny of fleeting particle resumes

By **Adrian Cho**

Next week, physicists will pick up an old quest for new physics. A team of 190 researchers at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, will begin measuring to exquisite precision the magnetism of a fleeting particle called the muon. They hope to firm up tantalizing hints from an earlier incarnation of the experiment, which suggested that the particle is ever so slightly more magnetic than predicted by the prevailing standard model of particle physics. That would give researchers something they have desired for decades: proof of physics beyond the standard model.

"Physics could use a little shot of love from nature right now," says David Hertzog, a physicist at the University of Washington in Seattle and co-spokesperson for the experiment, which is known as Muon g-2 (pronounced "gee minus two"). Physicists are feeling increasingly stymied because the world's biggest atom smasher, the Large Hadron Collider (LHC) near Geneva, Switzerland, has yet to blast out particles beyond those in the standard model. However, g-2 could provide indirect evidence of particles too heavy to be produced by the LHC.

The muon is a heavier, unstable cousin of the electron. Because it is charged, it will circle in a magnetic field. Each muon is also magnetized like a miniature bar magnet. Place a muon in a magnetic field perpendicular to the orientation of its magnetization, and its magnetic polarity will turn, or precess, just like a twirling compass needle.

At first glance, theory predicts that in a magnetic field a muon's magnetism should precess at the same rate as the particle itself circulates, so that if it starts out polarized in the direction it's flying, it will remain locked that way throughout its orbit. Thanks to quantum uncertainty, however, the muon continually emits and reabsorbs other particles. That haze of particles popping in and out of existence increases the muon's magnetism and make it precess slightly faster than it circulates.

Because the muon can emit and reabsorb any particle, its magnetism tallies all possible particles—even new ones too massive for the LHC to make. Other charged particles could also sample this unseen zoo, says Aida El-Khadra, a theorist at the University of Illinois in Urbana. But, she adds, "The muon hits the sweet spot of being light enough to be long-lived and heavy enough to be sensitive to new physics."

From 1997 to 2001, researchers on the original g-2 experiment at Brookhaven National Laboratory in Upton, New York, tested this promise by shooting the particles by the thousands into a ring-shaped vacuum chamber 45 meters in diameter, sandwiched between superconducting magnets. Over hundreds of microseconds, the positively charged muons decay into positrons, which tend to be spat out in the direction of the muons' polarization. Physicists can track the muons' precession by watching for positrons with detectors lining the edge of the ring.

The g-2 team first reported a slight excess in the muon's magnetism in 2001. That result quickly faded as theorists found a simple math mistake in the standard model prediction (*Science*, 21 December 2001, p. 2449). Still, by the time the team reported on the last of its Brookhaven data in 2004, the discrepancy had re-emerged. Since then, the result has grown, as theorists improved their standard model calculations. They had struggled to account for the process in which the muon emits and reabsorbs particles called hadrons, says Michel Davier, a theorist at the University of Paris-South in Orsay, France. By using data from electron-positron colliders, he says, the theorists managed to reduce this largest uncertainty.

Physicists measure the strength of signals in multiples of the experimental uncertainty, σ, and the discrepancy now stands at 3.5 σ—short of the 5 σ needed to claim a discovery, but interesting enough to warrant trying again.

In 2013, the g-2 team lugged the experiment on a 5000-kilometer odyssey from Brookhaven to Fermilab, taking the ring by barge around the U.S. eastern seaboard and up the Mississippi River (*Science*, 14 June 2013, p. 1277). Since then, they have made the magnetic field three times more uniform, and at Fermilab, they can generate far purer muon beams. "It's really a whole new experiment," says Lee Roberts, a g-2 physicist at Boston University. "Everything is better."

Over 3 years, the team aims to collect 21 times more data than during its time at Brookhaven, Roberts says. By next year, Hertzog says, the team hopes to have enough data for a first result, which could push the discrepancy above 5 σ.

Will the muon end up being a portal to new physics? JoAnne Hewett, a theorist at SLAC National Accelerator Laboratory in Menlo Park, California, hesitates to wager. "In my physics lifetime, every 3-σ deviation from the standard model has gone away," she says. "If it weren't for that baggage, I'd be cautiously optimistic." ■

The magnetism of muons is measured as the short-lived particles circulate in a 700-ton ring.

PHOTO: FERMILAB

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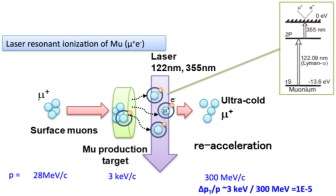
g-2 at J-PARC

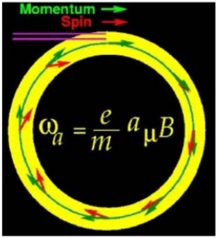
μ^+ beam intensity achievement.



g-2 measurements

- Spin precession in a uniform B-field

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



- Two alternative methods
  - Magic momentum : BNL E821 and FNAL E989
    - Eliminate the 2nd term by setting p=3.09 GeV/c (γ=29.3)
    - Can use E-field for beam focusing

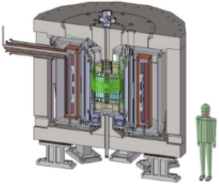
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

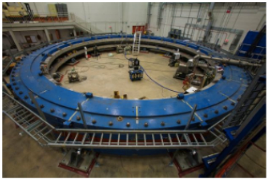
  - Zero E-field : J-PARC E34
    - Separation of a_μ and η_μ
    - A new technology is necessary.
      - Muon beam w/o E-focusing

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

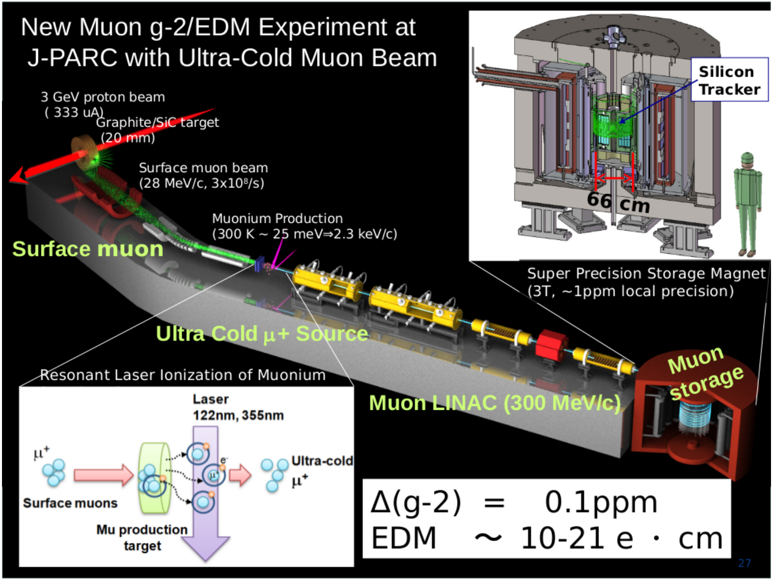
⇨ Ultra-cold muon beam

The new Muon g-2 experiments: A comparison

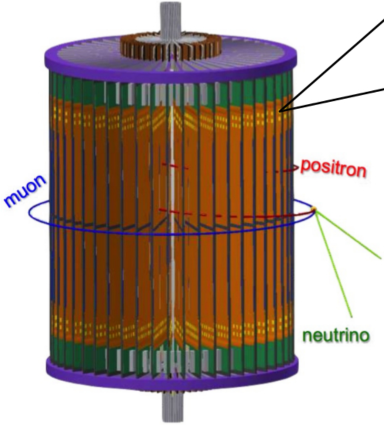


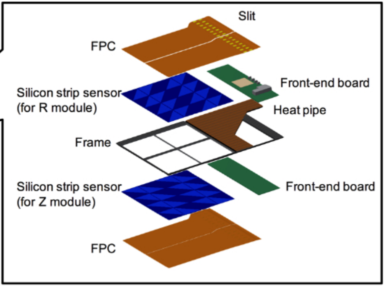


	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/C)
Polarization	P_{max} = 50%	$P \approx$ 97%
Magnet	MRI-like solenoid ($r_{storage}$ = 33cm)	Storage ring (7m radius)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Electron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	400 ppb	140 ppb

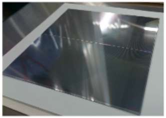

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam
3 GeV proton beam (333 uA)
Graphite/SiC target (20 mm)
Surface muon beam (28 MeV/c, 3x10^8/s)
Muonium Production (300 K ~ 25 meV⇒2.3 keV/c)
Surface muon
Ultra Cold μ+ Source
Resonant Laser Ionization of Muonium
Laser 122nm, 355nm
μ^+
Surface muons
Mu production target
e-
Ultra-cold μ^+
Muon LINAC (300 MeV/c)
Silicon Tracker
66 cm
Super Precision Storage Magnet (3T, ~1ppm local precision)
Muon storage
Δ(g-2) = 0.1ppm
EDM ~ 10-21 e · cm
27

Positron tracking detector

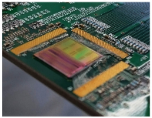




Components design optimized for the g-2/EDM



Silicon strip sensor

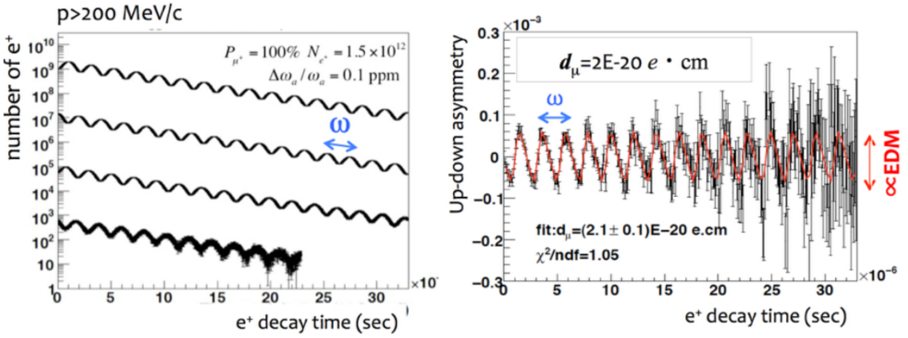


Frontend ASIC

Partial funding available to complete ~1/3 of the system

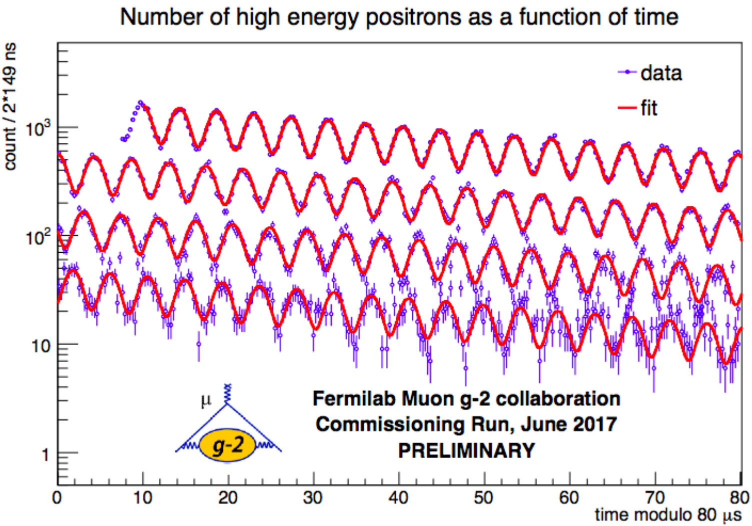
g-2/EDM expected measurement

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

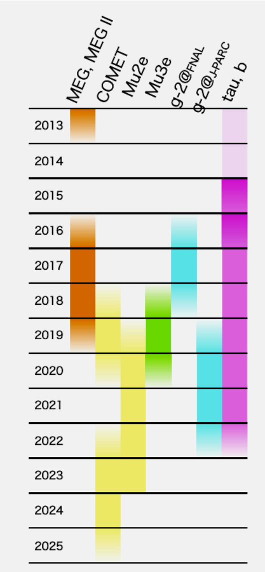


- Separation of g-2 and EDM.
- SImultaneous measurement.

New g-2 at FERMILAB



Welcome to COMET (and g-2/EDM) with a tentative schedule from Satoshi Mihara



Conclusions

- An interesting period of expected new results.
- Either discovery or new limits,
  it will impinge on the high energy physics strategy.
- But still a lot of work to keep pushing the limits.