Status and Prospects of $(g-2)_\mu$ measurements

g-2/EDM/LFV

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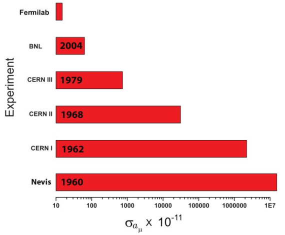
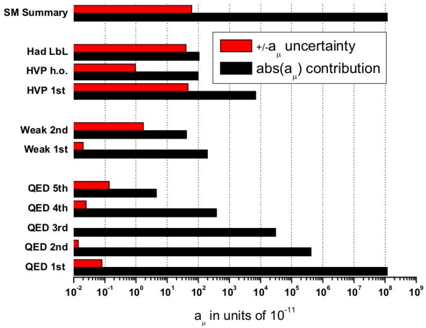
Outline

- 1957: Garwin, Lederman, Weinrich at Nevis
  $g_\mu = 2.00 \pm 0.10$
- 1965: CERN I
  $a_\mu = 0.001162(5) \pm 4300$ppm
  sensitive to 2^{nd} order
- 1968: Second CERN experiment
  $a_\mu = 0.00116616(31) \pm 270$ppm
  Sensitive to 3^{rd} order QED and light-by-light scattering
- 1979: Third CERN Experiment
  $a_\mu = 0.001165924(8.5) \pm 7$ppm
  Sensitive to hadronic vacuum polarization
- 1984: Brookhaven E821
  QED was calculated to fourth order
  First publication in 1999





Introduction

- Measurement of a_e at Harvard has reached an astonishing precision of 0.24 ppb.

$$a_e(\mathrm{HV}) = 1\ 159\ 652\ 180.73\ (0.28)\ \times 10^{-12}\quad [0.24\mathrm{ppb}].$$

Hanneke,Fogwell,Gabrielse, PRL 100, 120801 (2008).
Hanneke,Fogwell Hoogerheide, Gabrielse, PRA 83, 052122 (2011).

- Measurement of a_μ at BNL achieved the precision of 0.5 ppm.

$$a_\mu(\mathrm{BNL}) = 116\ 592\ 089\ (63)\ \times 10^{-11}\quad [0.5\mathrm{ppm}].$$

Bennett et al., PRL 92, 161802 (2004).
Roberts, Chinese Phys. C 34, 741 (2010).

- They provide the most stringent tests of QED and Standard Model.

- Collecting all contributions we obtain

$$a_\mu(\mathrm{SM}) = 116\,591\,840\ (59) \times 10^{-11},$$

and

$$a_\mu(\exp) - a_\mu(\mathrm{SM}) = 249\ (87) \times 10^{-11},$$

where the uncertainty of "theory" comes mostly from hadronic terms.

- Theory and experiment seem to disagree by $\sim$ 3 s.d.
- Is this indication of new physics beyond S. M. or something else ?

- In terms of new values of $A_1^{(8)}$ and $A_1^{(10)}$ we find

$$\alpha^{-1}(a_e) = 137.035\,999\,166\,8\,(62)(46)(19)(331) \quad [0.25\ ppb],$$

where 62, 46, 19, 331 are uncertainties of 8th-order, 10th-order, hadronic and electroweak terms, and a_e(exp).

- This is to be compared with the value of $\alpha^{-1}(Rb)$,

$$\alpha^{-1}(Rb) = 137.035\,999\,049\,(90) \qquad [0.66\ ppb],$$

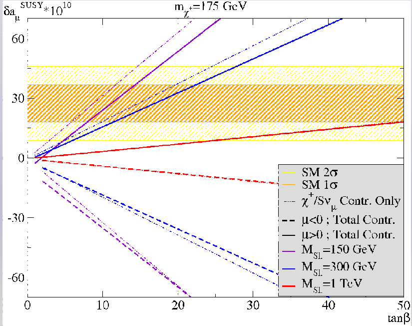
calculated from the measurements of h/m_{Rb}, Rydberg constant, and m_{Rb}/m_e.

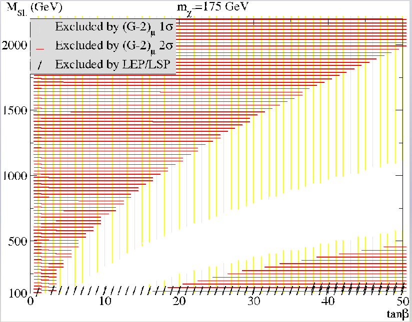
Bouchendira et al., PRL 106, 080801 (2011).

- They are about 1.3 s.d. apart.

- To conclude, the jelly-built structure still looks good at the precision exceeding 1 part in 10^9.
- If disagreement is detected at the next level of precision it might indicate that breakdown of SM comes, not necessarily from high energy region, but from an entirely unexpected direction.
- Unfortunately such an event may not be detectable until α is measured by some independent method with precision comparable to that of $\alpha(a_e)$.
- Until then, $\alpha(a_e)$ serves as the yardstick by which validity of other types of measurements and their theories is examined.

Constraints on the MSSM parameter space





- Chargino/Slepton loop tends to be dominant;
- Effect $\propto Y_\mu \propto \tan\beta$;
- $\mu > 0$ required;
- Light binos can also have significant effect.

Conclusion: The 3σ deviation can be reproduced provided SUSY particles are sufficiently light / $\tan\beta$ is large.

Consequences of a ~ 125 GeV Higgs?

In a Constrained Model

CMSSM/NUHM: Universality conditions at the GUT scale for the SUSY-breaking terms.

- $(G-2)_\mu$: light SUSY particles;
- $m_H \sim 125$ GeV: heavy SUSY particles;

  ⇒ Tensions…

  [Buchmuller et al., 2011]

Model	Minimum χ^2/d.o.f.	Fit Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM						
pre-Higgs	28.8/22	15%	780	450	−1110	41
$M_h \simeq 125$ GeV, $(g-2)_\mu$	30.6/23	13%	1800	1080	860	48
$M_h \simeq 125$ GeV, no $(g-2)_\mu$	21.0/22	52%	2000	1050	430	46
$M_h \simeq 119$ GeV	28.8/23	19%	780	450	−1110	41
NUHM1						
pre-Higgs	26.9/21	17%	730	150	−910	41
$M_h \simeq 125$ GeV, $(g-2)_\mu$	29.7/22	13%	830	290	660	33
$M_h \simeq 125$ GeV, no $(g-2)_\mu$	20.6/21	48%	2000	1400	2560	47
$M_h \simeq 119$ GeV	26.9/22	22%	730	150	−910	41

Table 1

Comparison of the best-fit points found in the CMSSM and NUHM1 pre-Higgs [3] and for the two potential LHC Higgs mass measurements discussed in the text: $M_h \simeq 119$ and 125 GeV. In the latter case, we also quote results if the $(g-2)_\mu$ constraint is dropped.

In the general case

- $(G-2)_\mu$: essentially sensitive to 2nd generation sleptons $(\tilde{\nu}_\mu, \tilde{\mu})$;
- Higgs mass: essentially sensitive to 3rd generation squarks $(\tilde{T}, \tilde{B})$;

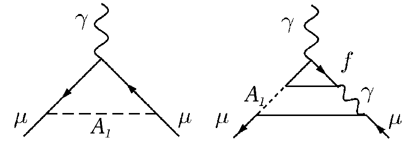
⇒ Both constraints are no longer mutually exclusive.

Specific NMSSM Contributions: Light Pseudoscalar

Light Pseudoscalars in the NMSSM:

- Higgs Effects negligible in the SM and the MSSM: $m_H \geq 115\,\text{GeV} \quad \Rightarrow \quad a_\mu^H \leq 5.10^{-14}$;
- NMSSM: Pseudoscalars A_1 can be very light ($\sim$ a few GeV) without violating LEP constraints;
- B-constraints ($B_s \to \mu^+\mu^-$, $B \to X_s\mu^+\mu^-$, $\Upsilon \to \gamma\tau^+\tau^-, \ldots$) can be avoided too.

Light Pseudoscalars can lead to a non-negligible effect on a_μ, specific to the NMSSM.



Light Pseudoscalar contribution to a_μ [*Krawczyk (2002), Gunion et al. (2006)*]

- 1-loop contribution negative / 2-loop contribution positive;
- When $m_{A_1} \geq 3\,GeV$, 2-loop contribution dominates;
- Proportional to $\tan^2\beta$;
- Proportional to A_1 coupling to the Standard sector (doublet component).

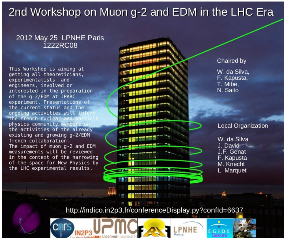
Conclusion

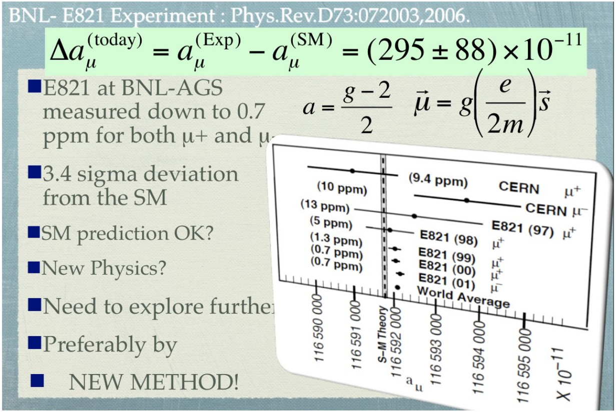
- Hint for Physics beyond the SM in $(G-2)_\mu$ favours New Physics close to the EW scale.
- Interestingly, SUSY-inspired models seem able to generate an effect of the correct order of magnitude…

  … provided sufficiently-light SUSY particles / $\tan\beta$-enhancement.

  $\Rightarrow$ *Significant constraints on their parameter spaces!*
- New effects beyond MSSM can be relevant.

From N. Saito
2nd Workshop on Muon g-2 and EDM in the LHC Era





Magic vs “New Magic”

- **Complimentary!**

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

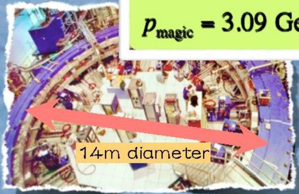
BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

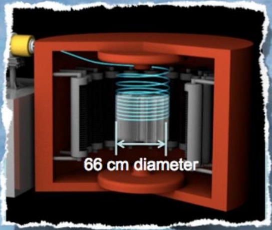
$$p_{\text{magic}} = 3.09\ \text{GeV/c}$$



J-PARC Approach

$$\vec{E} = 0$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$



$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

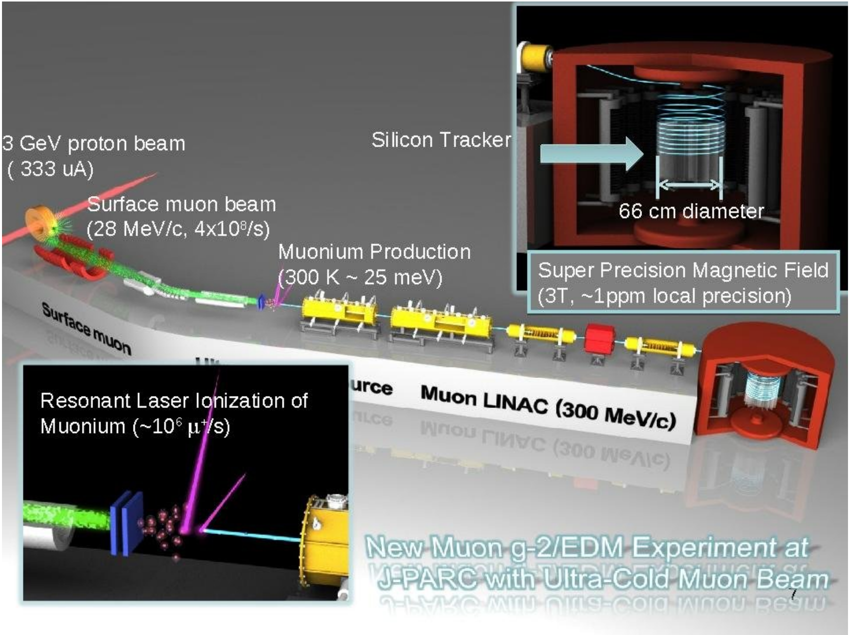
Both
FERMILAB New g-2 Experiment (submitted to the DOE Office of HEP 5 april 2010)
and
J-PARC g-2/EDM (LOI submitted at the 8^{th} PAC 17-19 july 2009)
intend to start physics run around 2016

	BNL-E821	FNAL-E989	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Polarization	100%		$>$ 90%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		very-weak magnetic
Cyclotron period	149 ns		7.4 ns
Anomalous spin precession period	4.37 μs		2.11 μs
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	–	–
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

JPARC Calendar

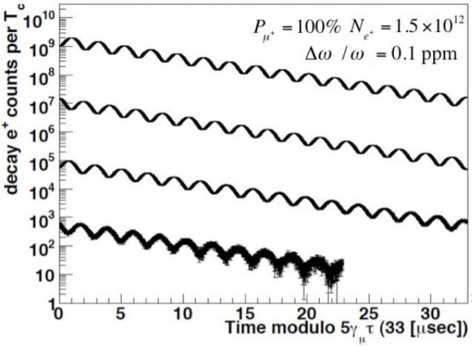
27 november 2009: Proto-Collaboration Meeting
15-17 january 2010: Proposed at the 9th PAC
Received strong encouragement and support for further R&D
8-9 june 2010: 1st CM
16-18 july 2010: Updates presented at the 10th PAC
PAC asked more detailed schedule with a set of milestones
9-10 december 2010: 2nd CM
14-16 january 2011: Response submitted at the 11th PAC
29-30 june 2011: 3rd CM
8-10 july 2011: Status Report at the 12th PAC
7 september 2011: Mini-CM
10-12 november 2011: 4th CM
13-15 january 2012: CDR presented at the 13th PAC
Stage-1 recommended to IPNS Director
15-17 march 2012: Muon at MLF at the 14th PAC
13-15 july 2012: Status Report at the 15th PAC
21 september 2012:
Stage1 Status granted P34 $\rightarrow$ E34

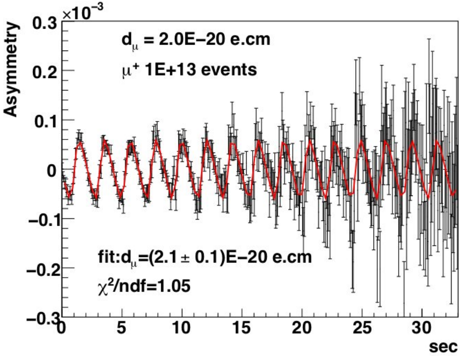
JPARC μ^+ beamline



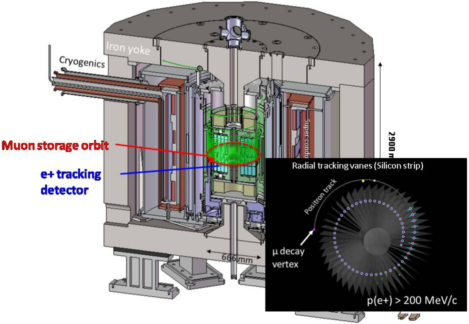
$$N_e(t) = \frac{N_e^{cut}}{\gamma\tau} exp(-\frac{t}{\gamma\tau})[1 - A\cos(\omega_a t)]\Delta t$$
$$\frac{\Delta\omega_a}{\omega_a} \propto \frac{1}{A\sqrt{N_e^{cut}}\gamma B}$$

$$\vec{\omega_a} = -\frac{e}{m}[a_\mu \vec{B} + \frac{\eta}{2}(\vec{\beta} x \vec{B})]$$
$$\vec{d_\mu} = \eta \frac{e}{2m_\mu c}\vec{s}$$





Muon storage magnet and detector



Requirements

- Tracking e+ from muon decay (p = 200-300 MeV/c)
- Trackback vertex resolution σ_r = 1mm for the focusing field n=3x10^{-5}
- No contamination in B-field (< 1ppm) and E-field (<10mV/cm) in the muon storage region.
- Efficient and stable over ~5 lifetime (33μs)
  - Notes
    - Instantaneous rate changes by two orders of magnitude.
    - Flipping spin of muon will cancel rate effect in the leading order.

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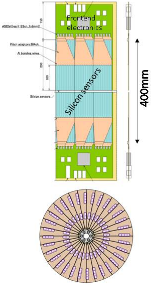
Silicon strip tracker

Detector module



Item	Specifications
Fiducial volume	240mm (radial) x 400 mm (axial)
Number of vane	48 (subject for optimization)
Sensor technology	Double- or single-sided Silicon strip sensor
Strip	axial-strip : 188μm pitch, 72mm long , 384 ch radial-strip: 255μm pitch, 98mm long, 384 ch
Sensor dimension	74 mm x 98 mm x 0.32mm
Number of sensor	576 (12 sensors per vane)
Number of channel	442,368 ch
Time measurement	Period : 33μs, Sampling time : 5ns

4

detector development team

- KEK
  - Osamu Sasaki
  - Manobu Tanaka
  - Masahiro Ikeno
  - Tomohisa Uchida
  - Takashi Kohriki
  - Naohito Saito
  - Tsutomu Mibe
  - Kazuki Ueno
- Univ. of Tokyo
  - Takuya Kakurai
  - Shoichiro Nishimura
- Rikkyo Univ.
  - Jiro Murata
  - Haruna Murakami
  - Tomomi Sakuda
  - Sachi Ozaki
- JAXA
  - Hirokazu Ikeda
- Kyoto-U
  - Yoshihisa Iwashita
- LPHNE Paris
  - Frédéric Kapusta
  - Wilfrid da Silva
  - Jean-François Genat
  - Jaques David
- CC-IN2P3 Lyon
  - Yonny Cardenas

9

1-3 november 2012 CM6 News

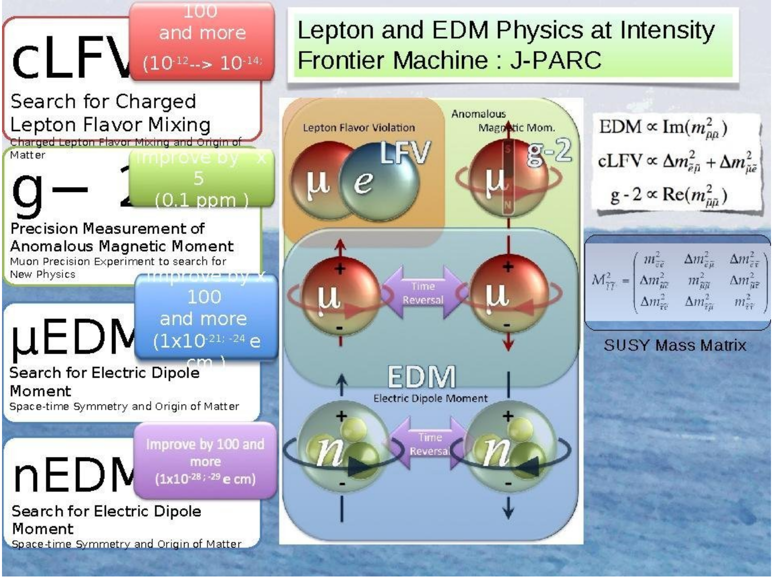
Post-CDR Milestones

- Demonstration of UCM Production : $10^6 \mu^+$/sec or $>$ 1% conversion efficiency
- Muon acceleration test: RFQ and IH
- Prototyping Precision Magnet: Control local precision < 1 ppm
- Injection and Kicker: With low-E electron
- High-rate tracker Verify the time response up to $>$ 1MHz /strip

Organizational Changes

- KEK
  - Prof. Atsuto Suzuki will continue as DG
  - Prof. Nobu Toge (our collaborator) appointed as an Executive Board Member
- KEK-IPNS
  - New Director : Prof. Masa Yamauchi
    - COMET-phase 1 to be realized
    - Continue R&D of g-2/EDM for realization
  - g-2/EDM group and LFV group merged together as Muon Group for the mission stated above
- J-PARC Center
  - New Director : Dr. Yujiro Ikeda
  - New deputy directors
    - Takashi Kato for JAEA side
    - Naohito Saito for KEK side

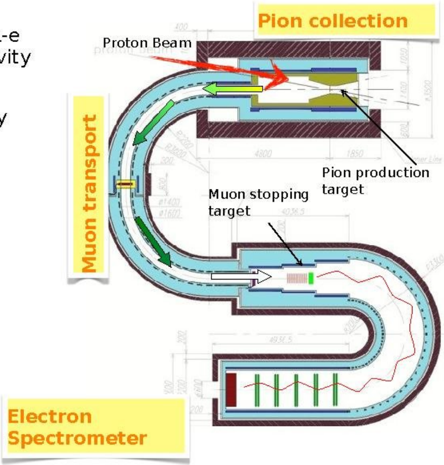
And a talk by T. Kinoshita
2^{nd} of november 2012
"Tenth-Order QED Calculation of Lepton Anomalous Magnetic Moments"


100
and more
(10^{-12}--> 10^{-14})
cLFV
Search for Charged
Lepton Flavor Mixing
Charged Lepton Flavor Mixing and Origin of Matter
Improve by x 5
(0.1 ppm)
g-2
Precision Measurement of
Anomalous Magnetic Moment
Muon Precision Experiment to search for New Physics
Improve by x 100
and more
($1\times10^{-21;-24}$ e cm)
μEDM
Search for Electric Dipole Moment
Space-time Symmetry and Origin of Matter
Improve by 100 and more
($1\times10^{-28;-29}$ e cm)
nEDM
Search for Electric Dipole Moment
Space-time Symmetry and Origin of Matter
Lepton and EDM Physics at Intensity Frontier Machine : J-PARC
Lepton Flavor Violation
LFV
Anomalous Magnetic Mom.
g-2
Time Reversal
EDM
Electric Dipole Moment
Time Reversal
$\mathrm{EDM} \propto \mathrm{Im}(m^2_{\tilde{\mu}\tilde{\mu}})$
$\mathrm{cLFV} \propto \Delta m^2_{\tilde{e}\tilde{\mu}} + \Delta m^2_{\tilde{\mu}\tilde{e}}$
$g-2 \propto \mathrm{Re}(m^2_{\tilde{\mu}\tilde{\mu}})$
$M^2_{\tilde{l}\tilde{l}} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$
SUSY Mass Matrix

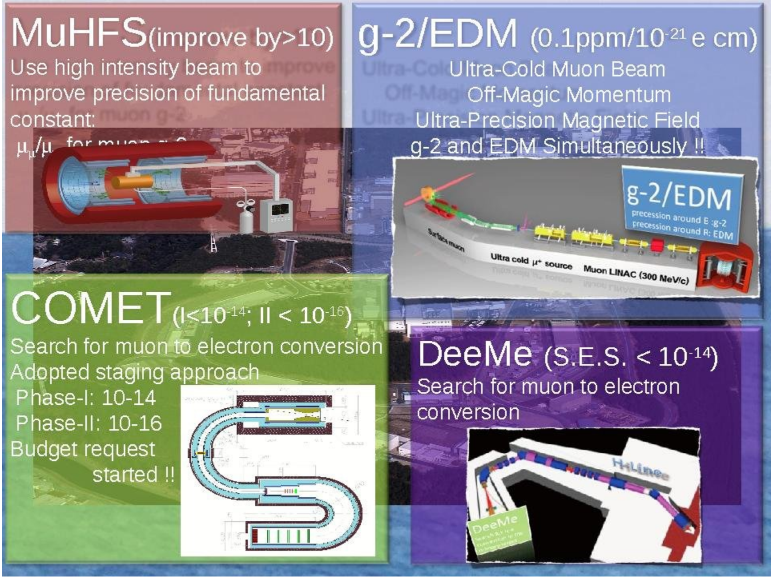
COMET mu-e conversion search wit ultra-high sensitivity

- Search for LFV process, μ-e conversion with a sensitivity of 10^{-16}
- Utilize J-PARC Hi- Intensity proton beam
- 8GeV, 7μA
- Innovative apparatus
- Pion collection
- Muon Transport
- Electron Spectrometer

Staging Approach
phase-I : ~1e-14
phase-II : ~1e-16



JPARC g-2/EDM/LFV Activities



"Muon Group"(g-2/EDM and LFV) from the french side

- French participation for the g-2/EDM CDR : 2011-2012.
- Workshop in Paris, 25 may 2012.
- Paris Group : 2 physicists , 2 electronicians
- COMET with UCL and IC british colleagues
- A subtopic of the GDR Terascale for precision measurements : g-2/EDM/LFV.
- You are welcome to join the Muon Group Collaboration both Exp and Th.