Precision Muon Physics at J-PARC

2016 Joint Workshop of FKPPL and TYL/FJPPL
May 18 2016, KIAS, Seoul, Korea
Soohyung Lee (CAPP/IBS)

on behalf of FKPPL muonists†

† This word doesn’t exist, so don’t open you dictionary.

Toward the New Physics

- Higgs boson was a missing piece of puzzle named SM
  - However, it was not the end of the story (..and our mission)
- Dark matter, matter-dominated universe, gravity, neutrino masses → **demands for NP**
- Precision muon physics can be a breakthrough to NP
  - Discrepancy between experiments and SM prediction → **muon g-2**
  - Suspicions to elementary particles → **muon electric dipole moment**
  - Forbidden/rare processes in SM → **charged lepton flavor violation (cLFV)**

"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

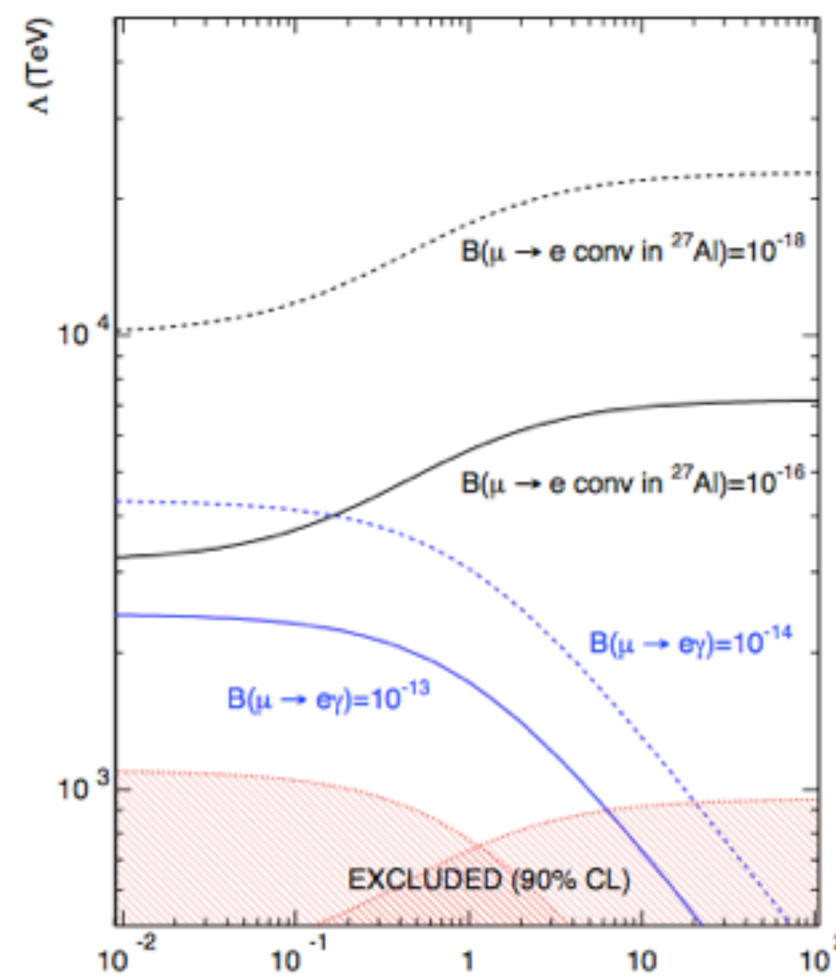
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

W. Altmanshofer *et al.*, Nucl. Phys. **B 830**, 17 (2010)

μ→e Conversion

- Flavor changing in charged lepton has never been observed
  - Br(μ→eγ) < O(10^{-54}) in SM (only possibility for a "free" muon)
  - Interaction with nuclei (**μN→eN**) gives more possibilities
    - μN→eN is more sensitive to some models, so if we observe it, it will allow us to discriminate the models
  - Energy scale probed is PeV level!
    - Complimentary with LHC-like searches

http://www.particlebites.com



A. Gouvea and P. Vogel, arXiv:1303.4097

Muon g-2/EDM

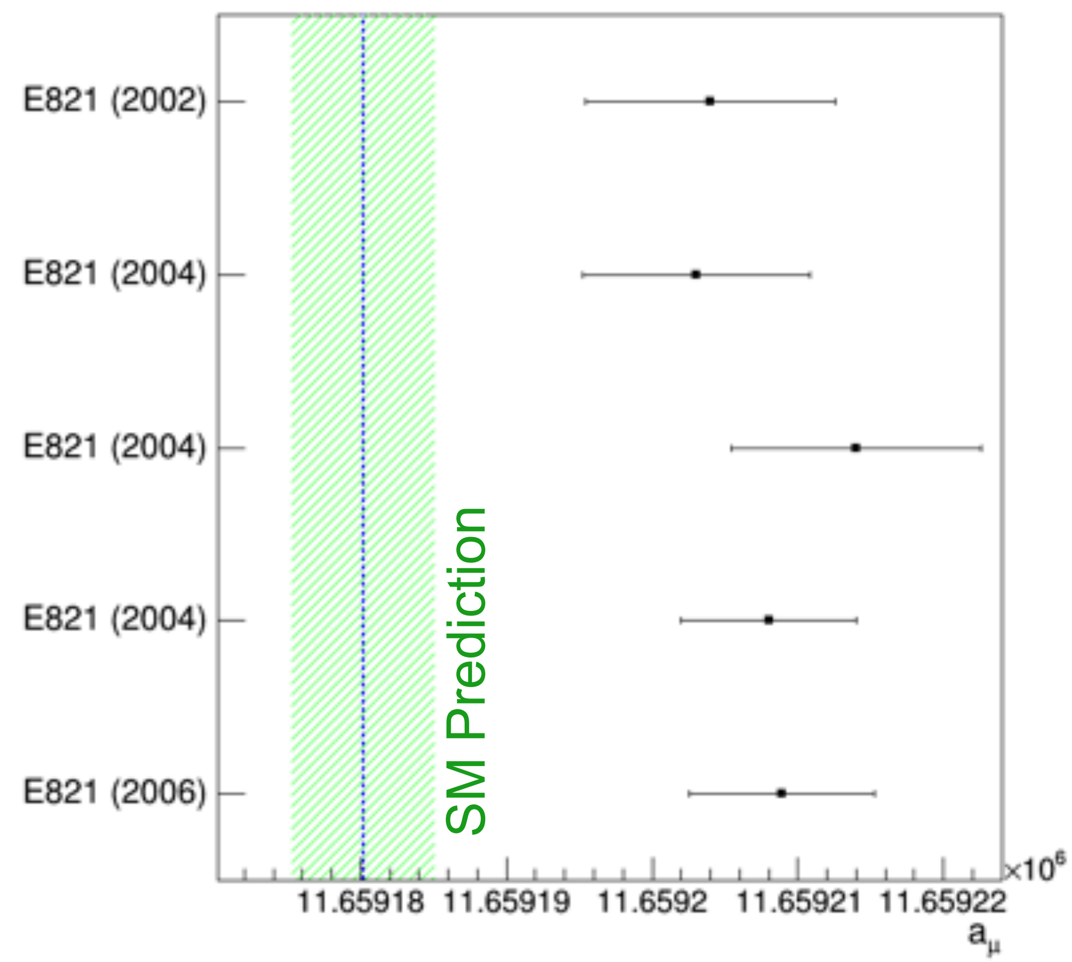
- SM predicts muon anomalous magnetic moment:

$$a_\mu^{SM} = (116\ 591\ 802 \pm 49) \times 10^{-11}$$

- Latest result from E821 at BNL:

$$a_\mu^{E821} = (116\ 592\ 089 \pm 63) \times 10^{-11}$$

  - Experimental result is ~3.5σ away from SM



- Muon electric dipole moment:
  - SM: ~2×10^{-38} e·cm
  - E821 (2009): (-0.1±**0.9**)×10^{-19} e·cm
  - No clue of existence yet

- Precision measurement will be a new breakthrough to NP!

For a brief introduction, see http://www.youtube.com/watch?v=UckuqHDB08I

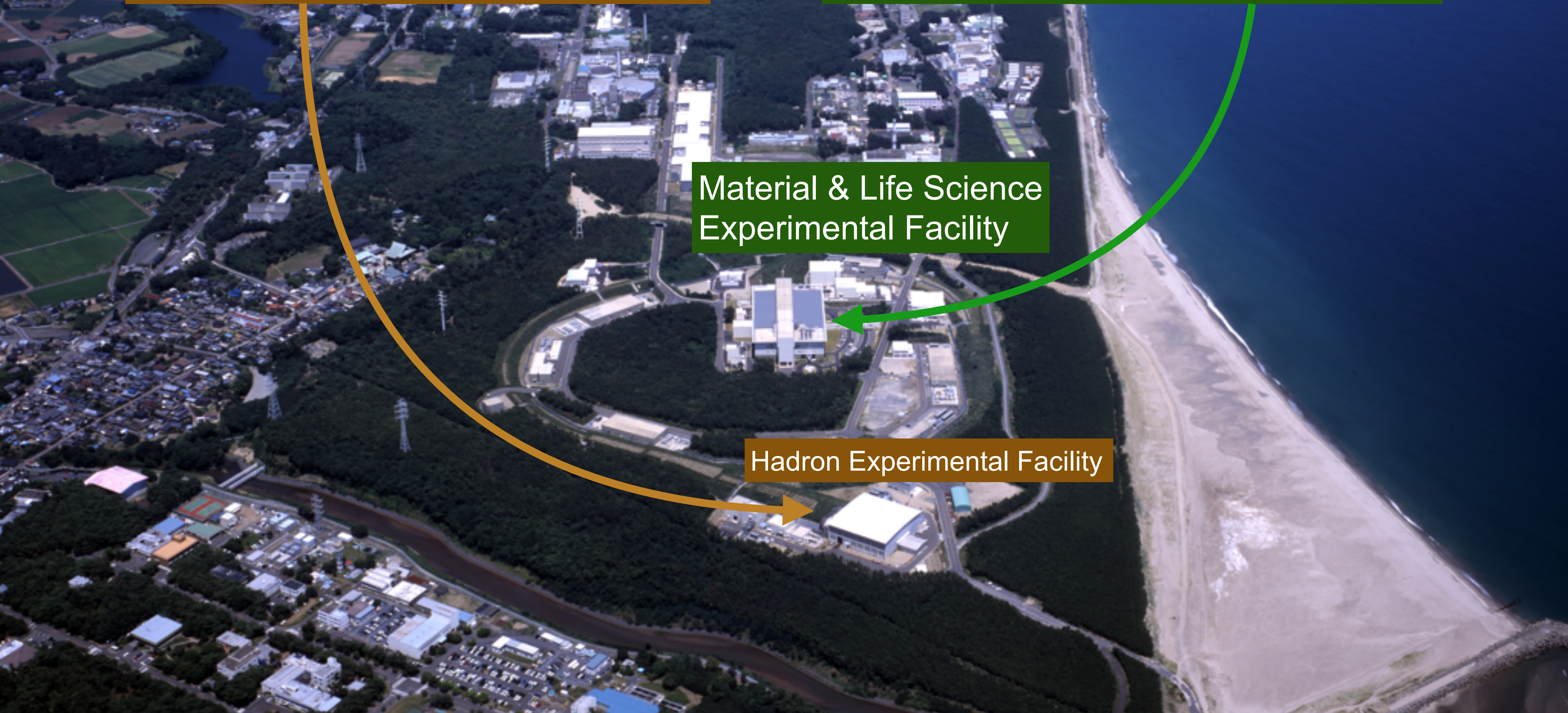
Precision Muon Physics at J-PARC

COMET

Searching for charged Lepton Flavor Violation (cLFV) from $\mu^- \rightarrow e^-$ conversion

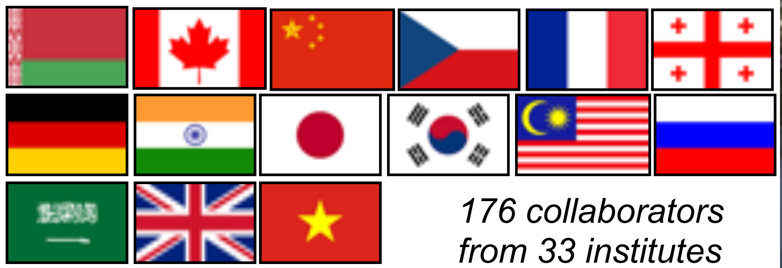
Muon g-2/EDM

Precision measurements of anomalous magnetic and electric dipole moment of muon

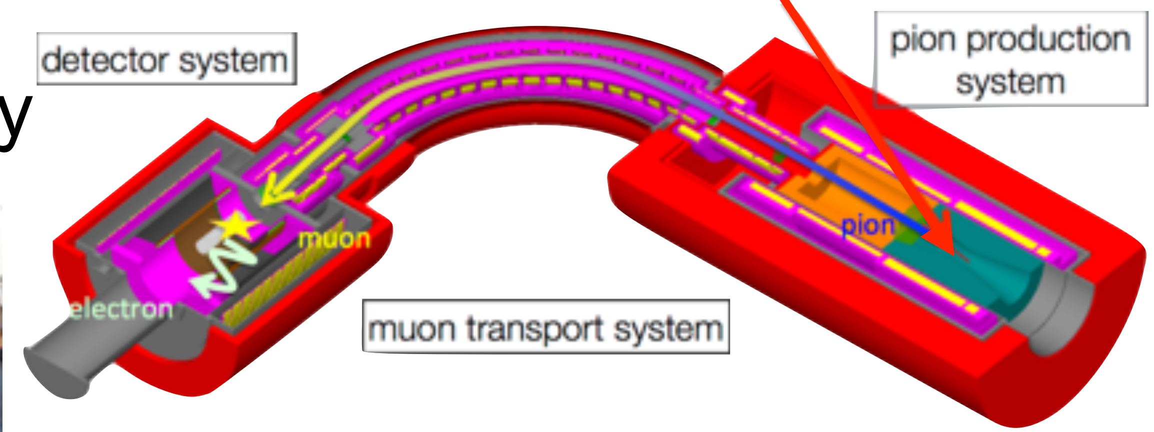


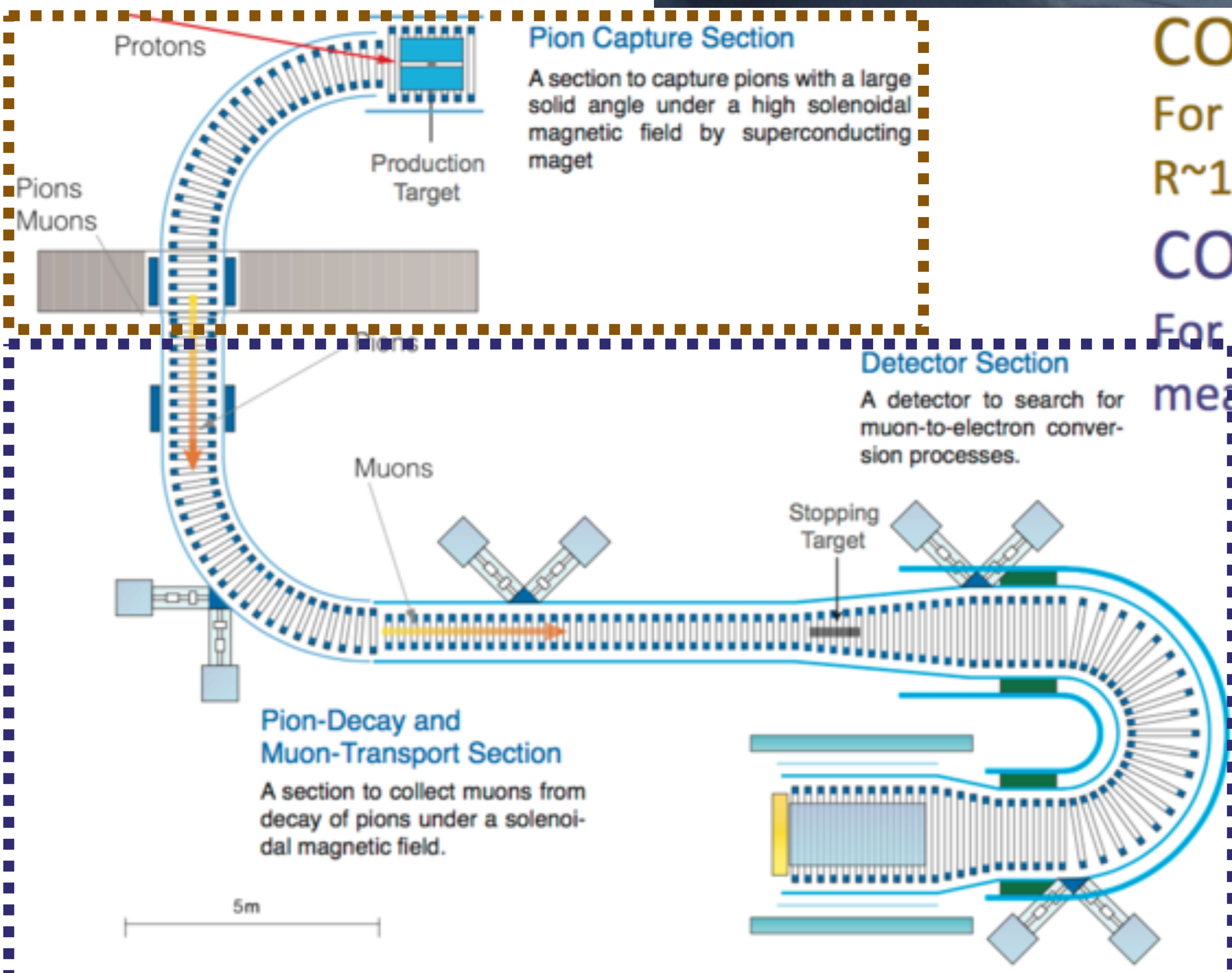
COMET

- @ J-PARC Hadron Experimental Facility



176 collaborators from 33 institutes





COMET-Phase-I

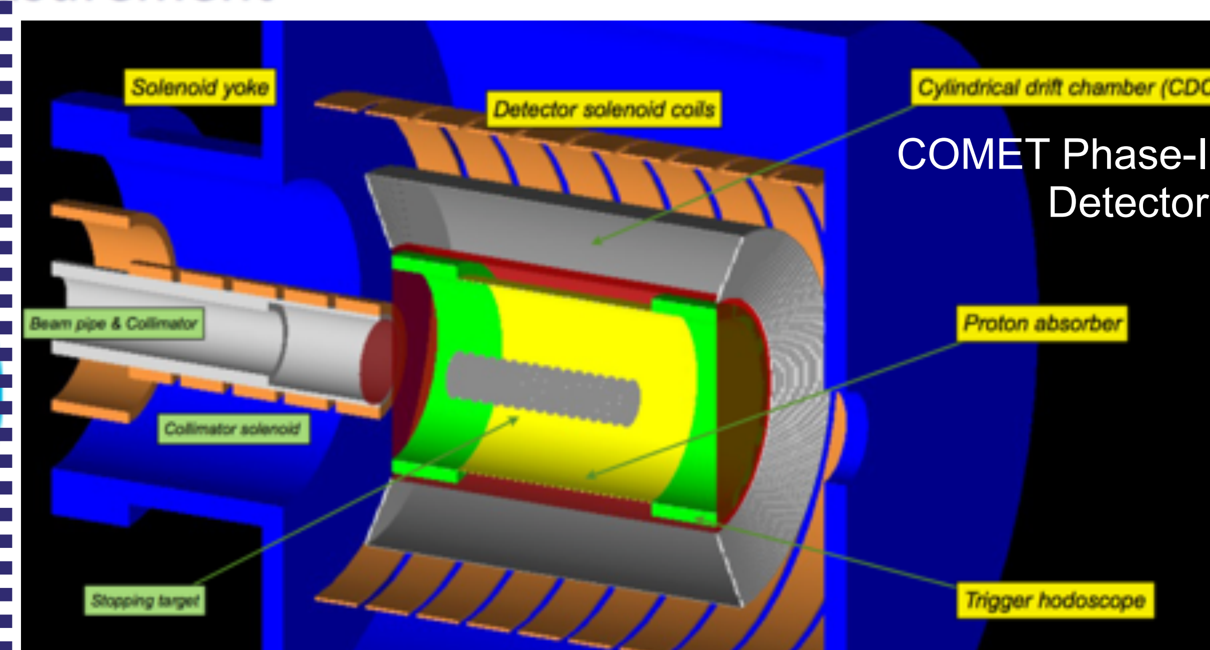
For BG measurement, R~10^{-15} muon conversion

Commissioning in 2018

COMET Phase-II

For R~10^{-17} muon conversion measurement

Commissioning in 2021



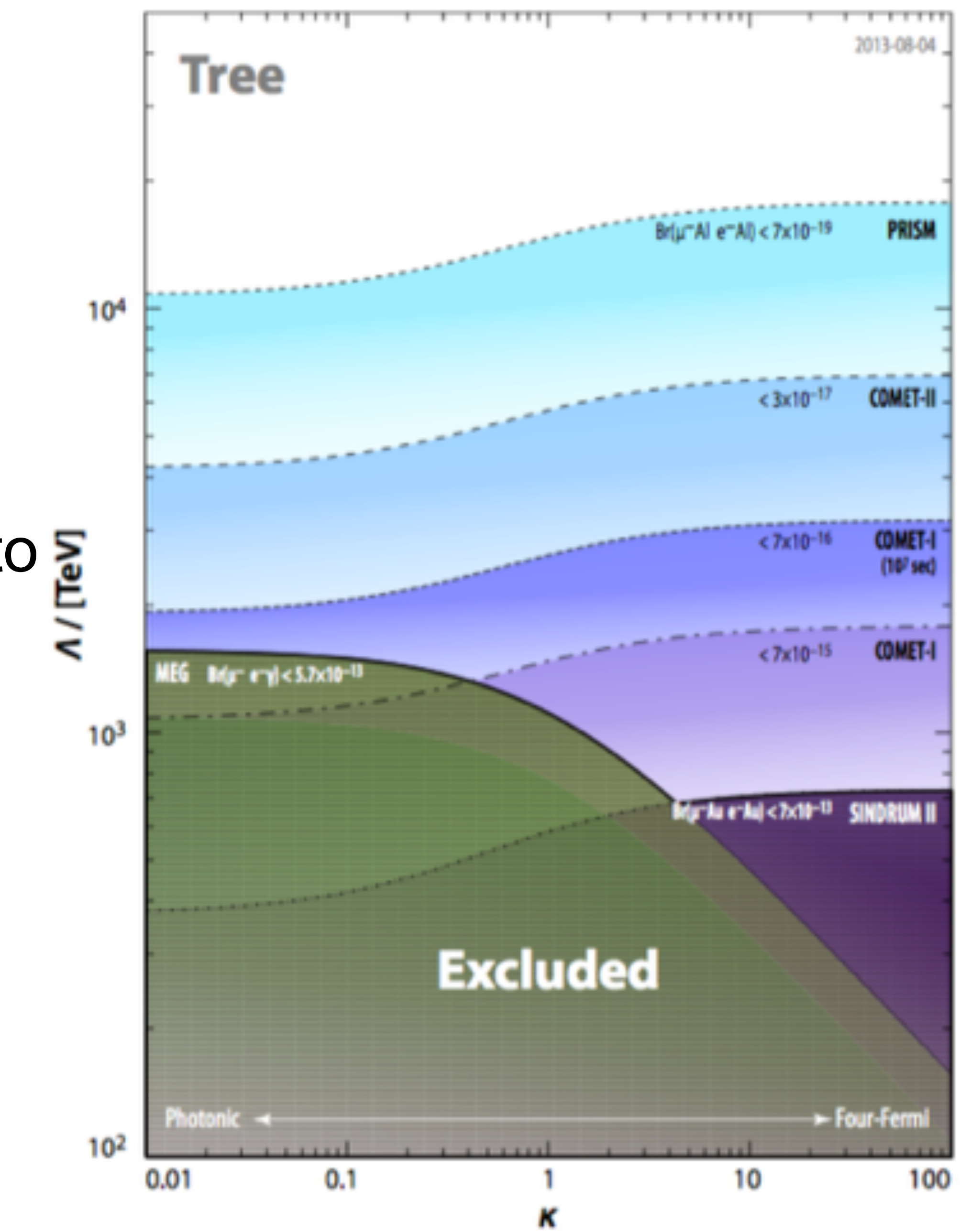
COMET

- COMET Phase-I (Data taking is planned to be 2018)
  - Target single event sensitivity: **$B(\mu^- N \rightarrow e^- N) < 3.5\times10^{-15}$**
  - Main goals are:
    - Backgrounds studies for Phase-II
    - Achieve the sensitivity $O(10^{-15})$ (100 times better than SINDRUM II)

- COMET Phase-II (Data taking is planned to be 2021)
  - Target single event sensitivity: **$B(\mu^- N \rightarrow e^- N) < 3\times10^{-17}$**

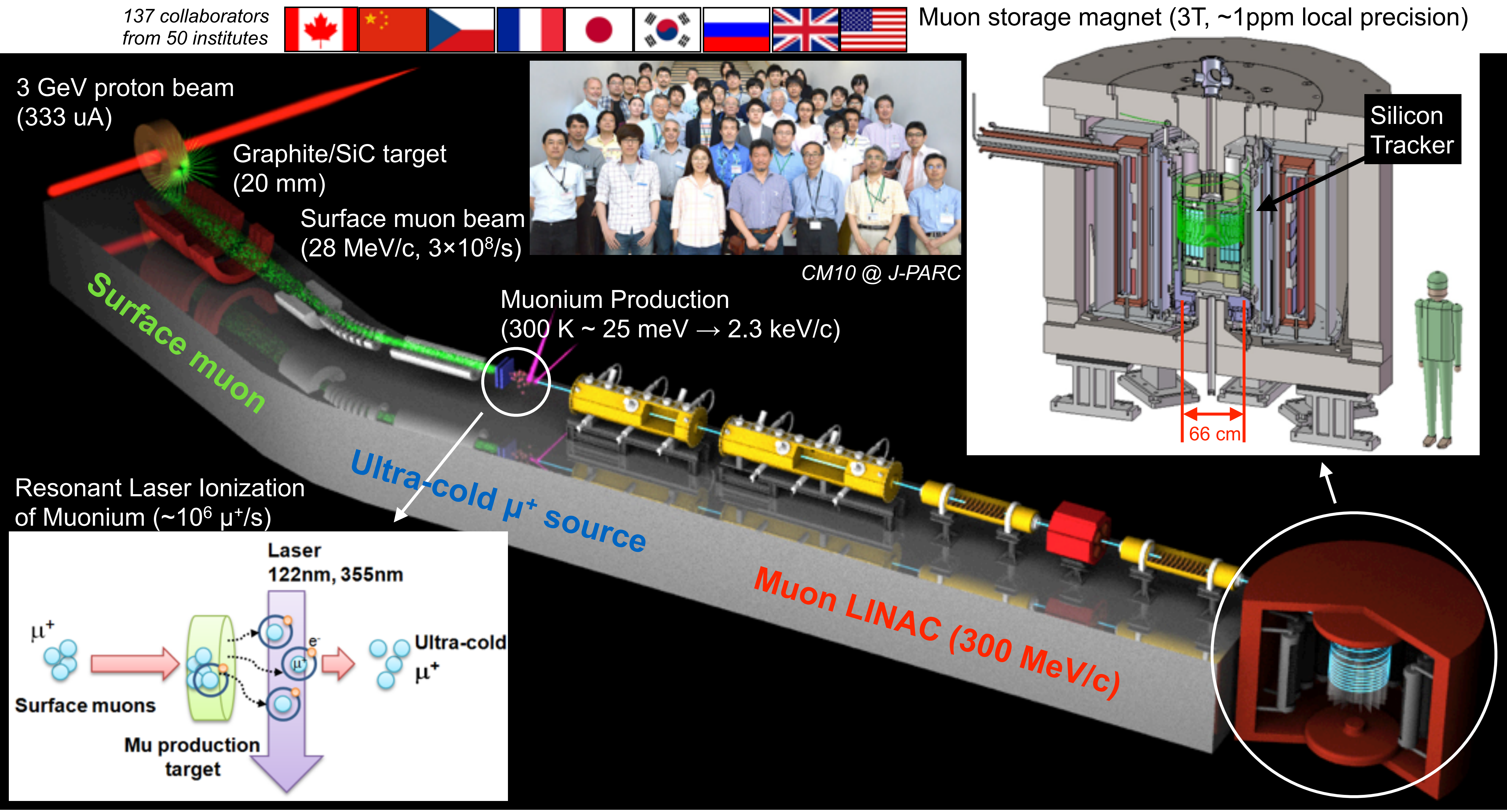
Finding a needle in a trillion (10^{12}) haystacks!

R. Akhmetshin et al., COMET Phase-I TDR



Muon g-2/EDM Experiment

- @ J-PARC Material and Life Science Facility (MLF)

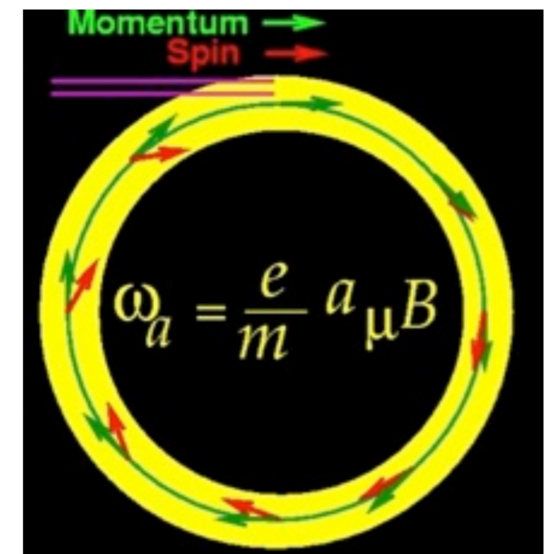


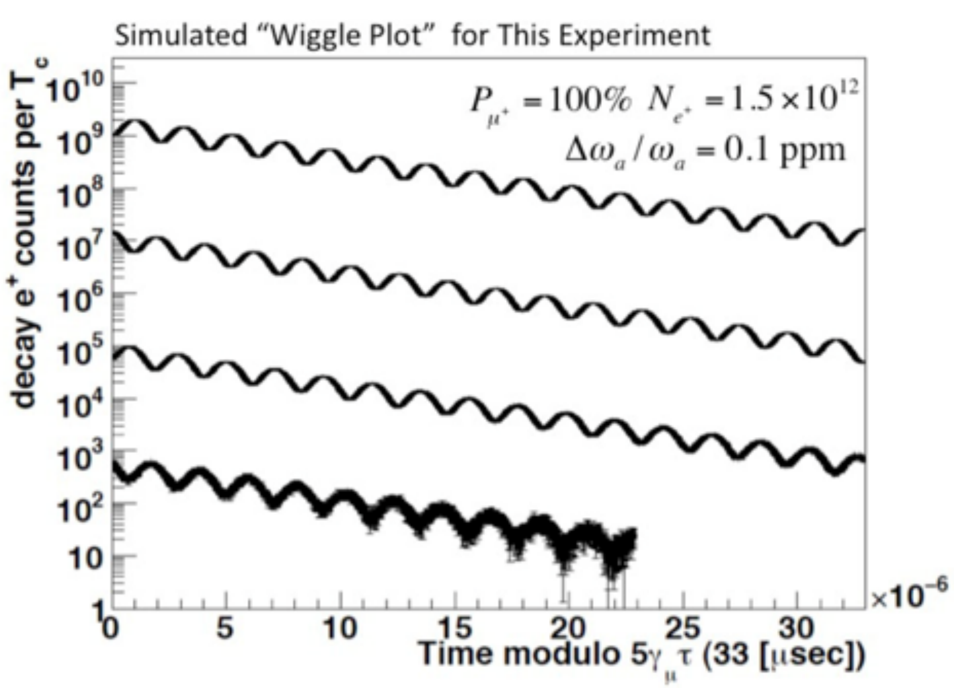
Muon g-2/EDM Experiment

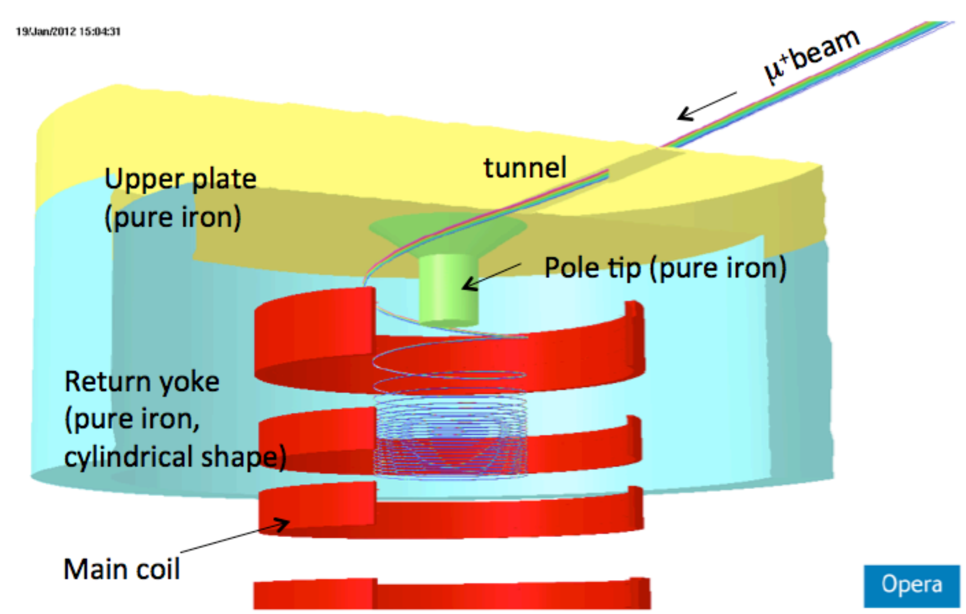
- T-BMT equation governs the spin precession of muons
  - In the experiment, we put E=0, and it gets much simpler

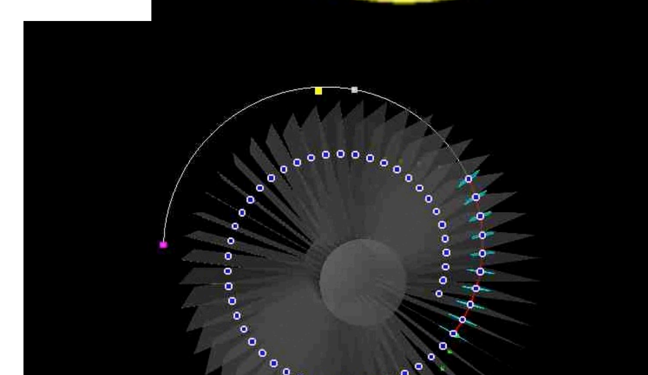
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

  - Spin will precess as the polarized muon orbits
  - The spin precession makes changes of detected positrons which comes from the muon decay ($\mu^+ \rightarrow e^+ \nu_e$)








Simulated muon decay (p = 200 MeV/c)

Muon g-2/EDM Experiment

- Goals of statistical sensitivity:
  - a_μ: 0.47 ppm (50% polarization) / 0.14 ppm (100% polarization)
  - EDM: $O(10^{-21})$ e·cm
  - Approach is very different from FNAL, but the same sensitivity goal

Table 1.1: *Comparison of the previous experiment BNL-E821, FNAL-E989, and this experiment.*

	BNL-E821	FNAL-E989	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Polarization	100%		50% → 100%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		very-weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
# of detected e^+	5.0×10^9	1.8×10^{11}	$8.7\times10^{11} \rightarrow 1.5\times10^{12}$
# of detected e^-	3.6×10^9	–	–
Statistical precision (a_μ)	0.46 ppm	0.14 ppm	0.37 ppm → 0.14 ppm
Statistical precision (EDM)	0.9×10^{-19} $e\cdot$cm	10^{-21} $e\cdot$cm	10^{-21} $e\cdot$cm

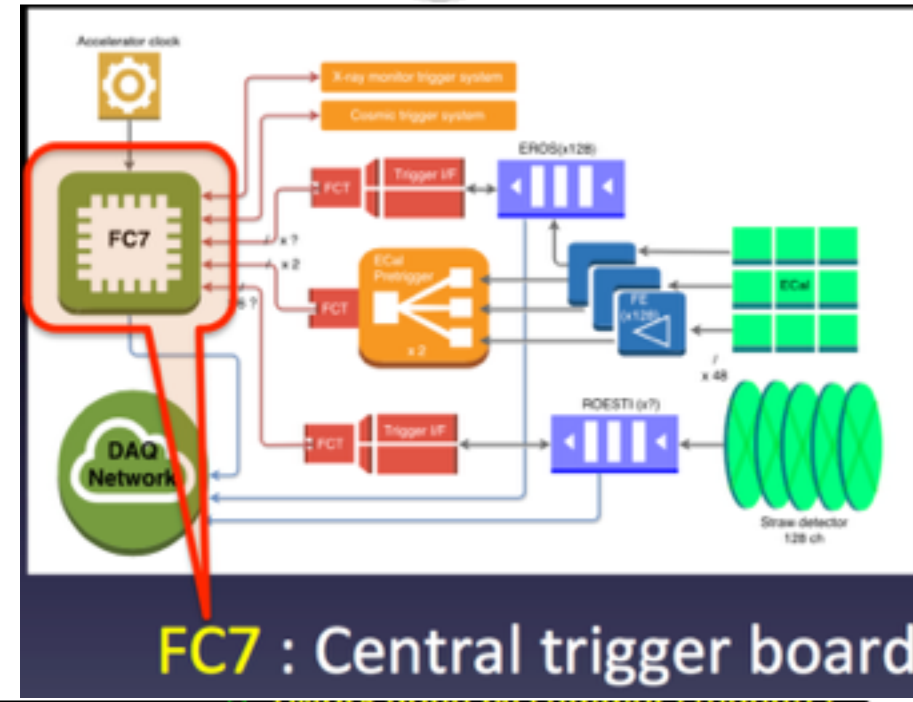
Muon g-2/EDM experiment TDR

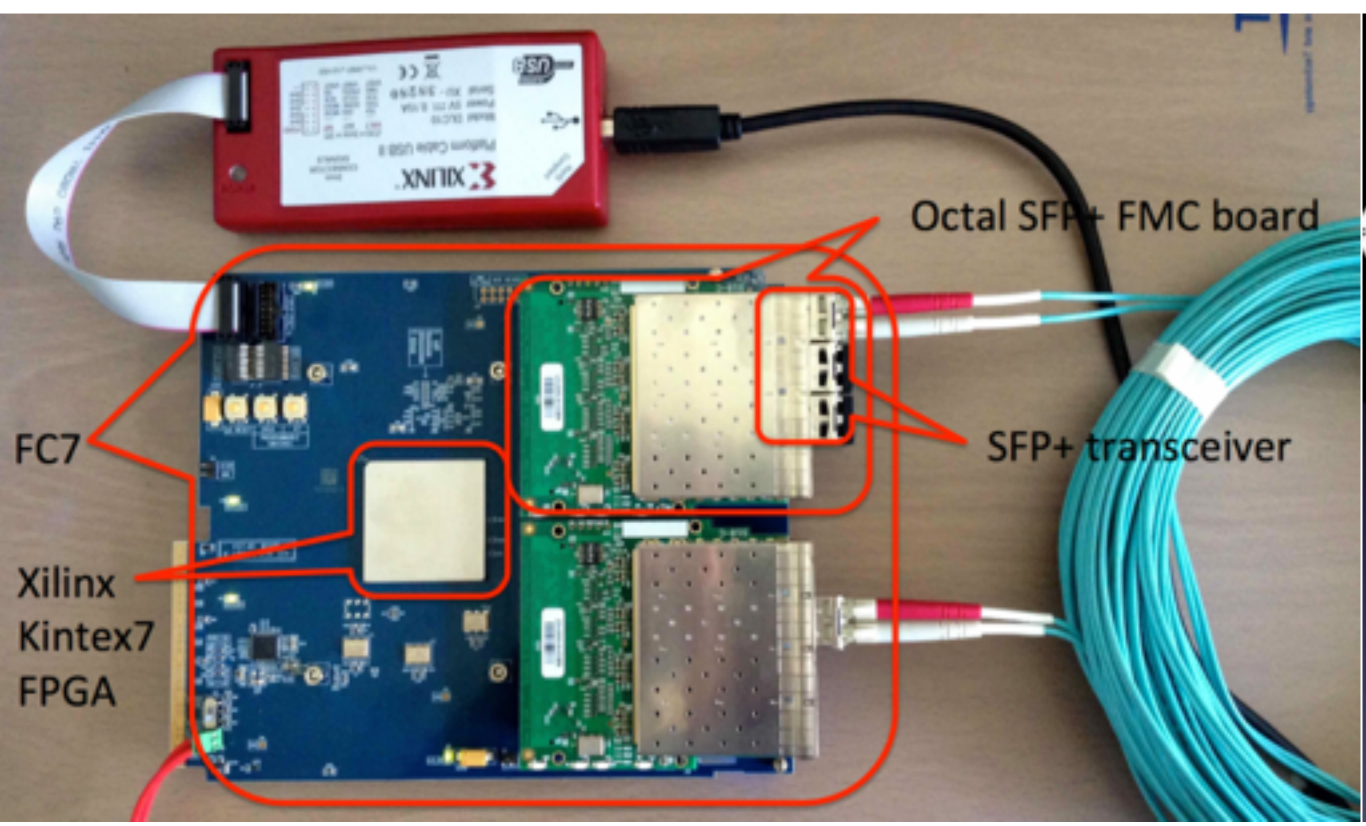
Korean Group Contributions

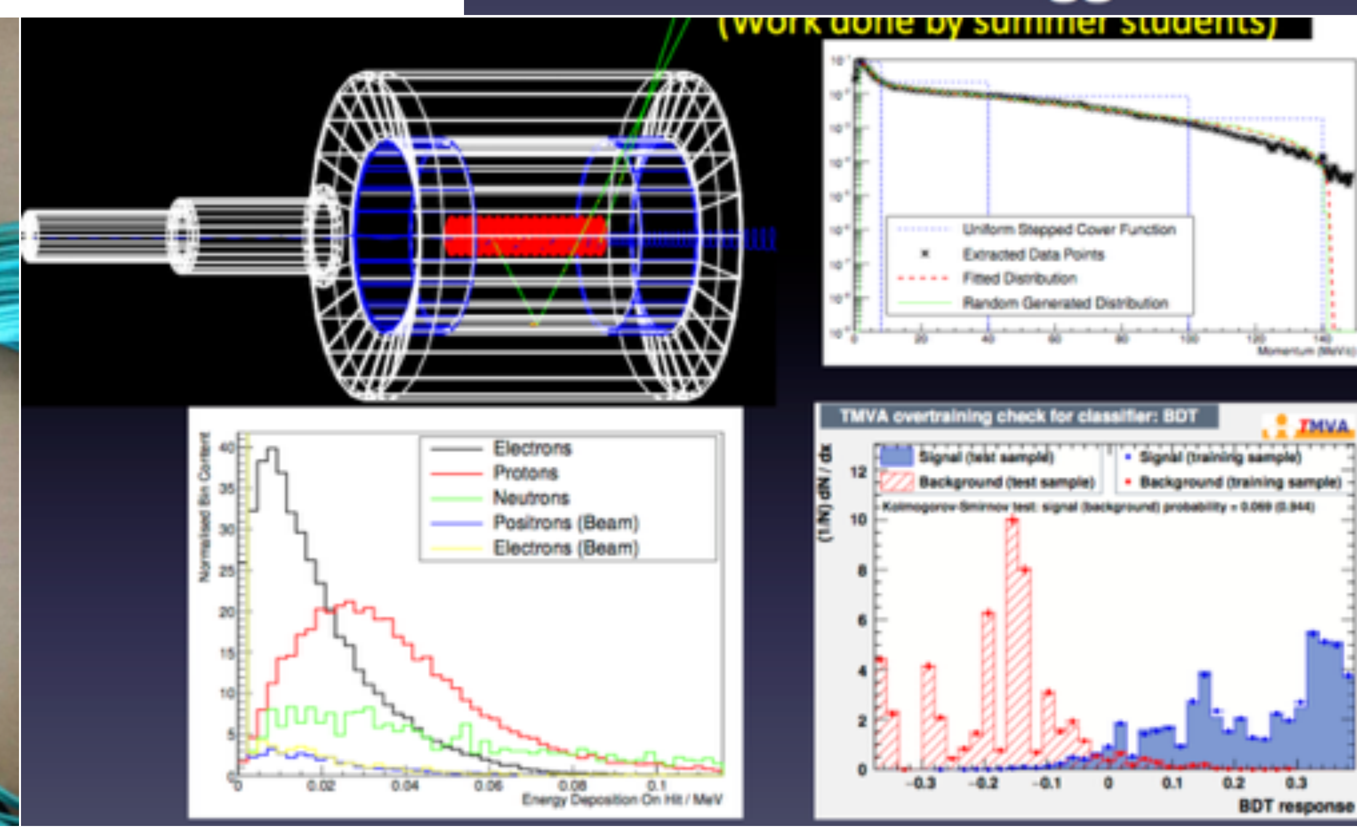
- **COMET**
  - **Center for Axion and Precision Physics Research, Institute for Basic Science (CAPP/IBS)**
    - Trigger R&D (Myeongjae Lee)
- **Muon g-2/EDM**
  - **Korea University (KU)**
    - DC-DC converter, High-energy beam profile monitor R&D (Eunil Won, Woodo Lee)
  - **Seoul National University (SNU)**
    - Low-energy beam profile monitor (Seonho Choi, Bongho Kim)
  - **Korea Advanced Institute of Science and Technology (KAIST)**
    - Electric field monitor R&D (Jhinhwan Lee)
  - **CAPP/IBS**
    - Non-destructive beam profile monitor R&D (Selcuk Haciomeroglu)
    - Precision beam tracking and systematics study (Yannis Semertzidis, Soohyung Lee)

COMET: CAPP/IBS

- Trigger R&D
  - Leading COMET trigger subproject, and responsible to central trigger system R&D
  - Primitive trigger system made and tested
  - More hardware R&D and simulation studies are underway



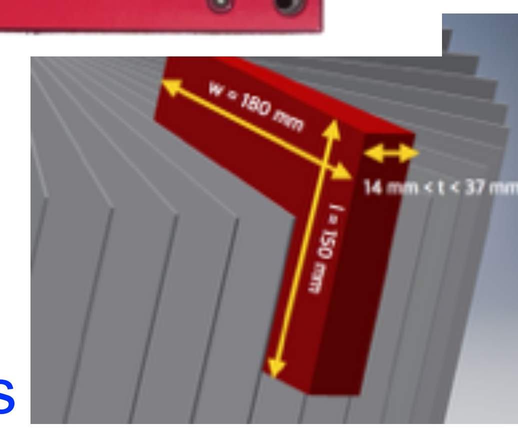




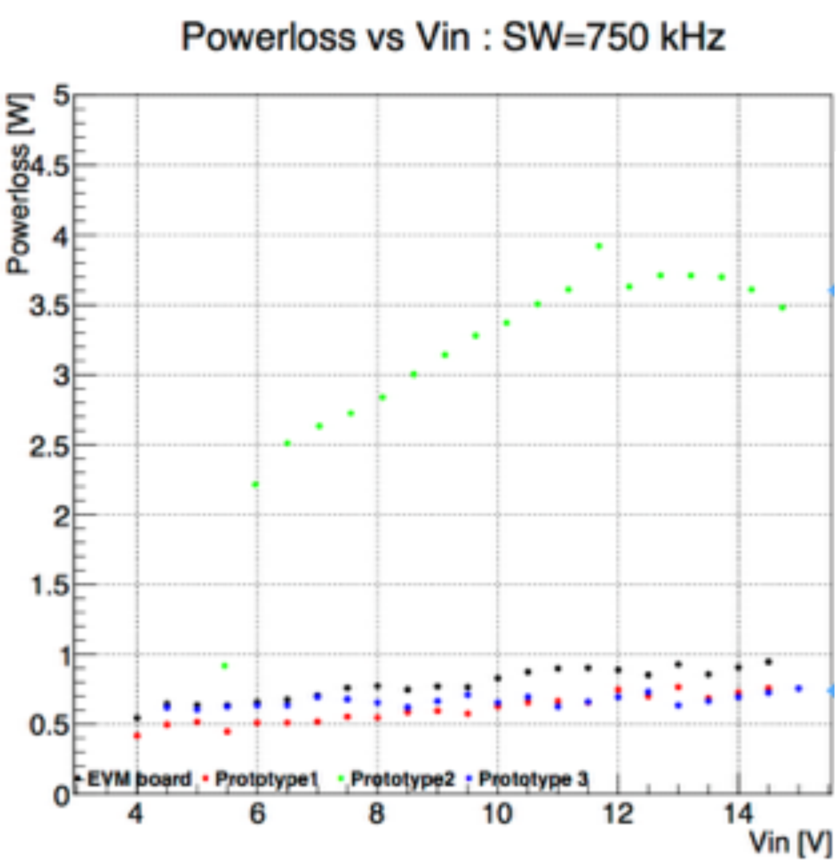
Myeongjae Lee

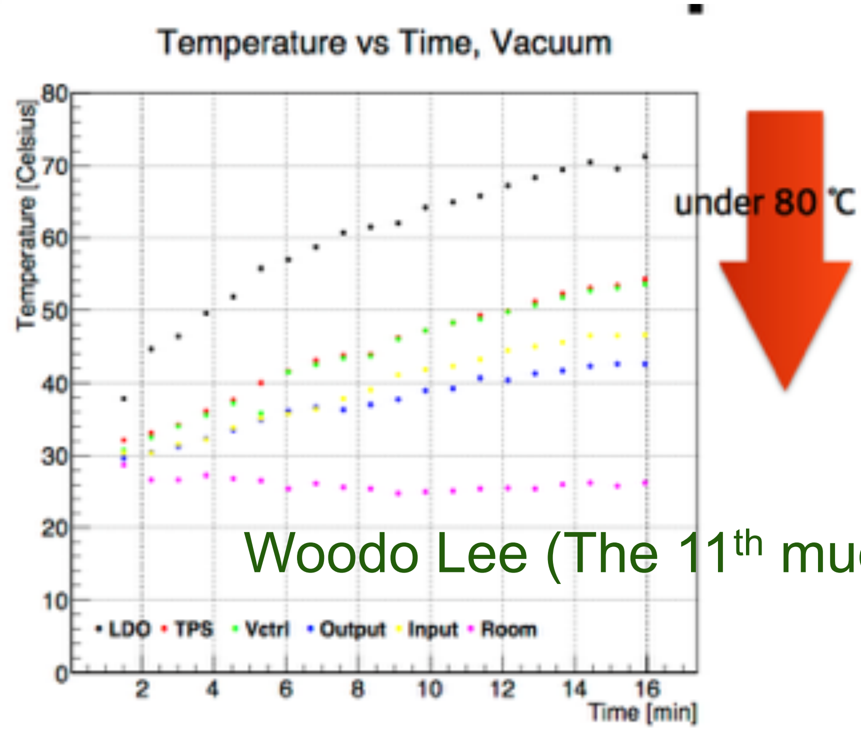
Muon g-2/EDM: KU

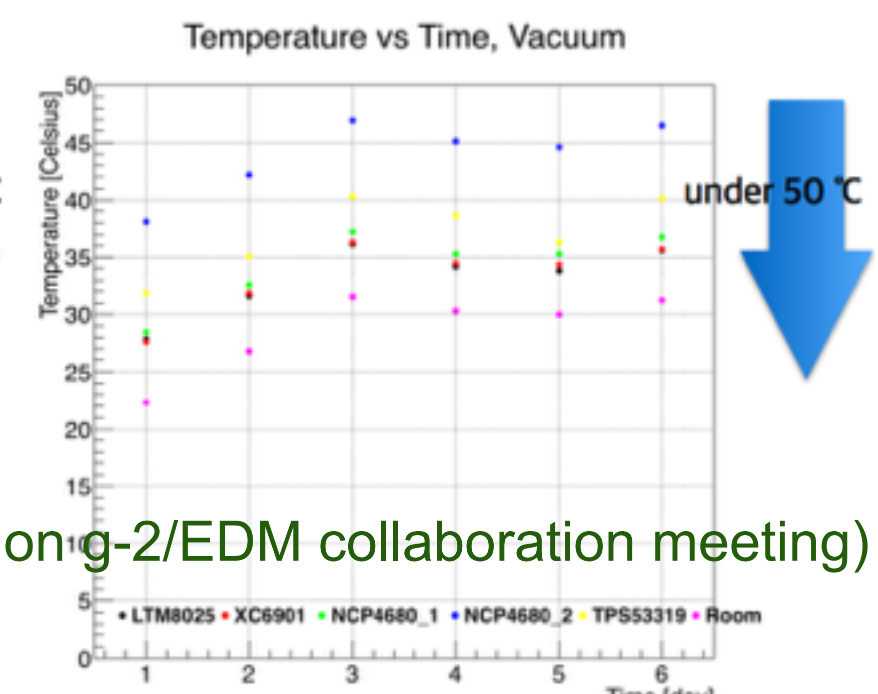
- DC-DC converter
  - Provides a various DC power to components in the storage magnet
  - Should not produce significant electric and magnetic fields (E ≪ 10 mV/cm, B ≪ 0.3 μT)
  - 3rd prototype is out, and 4th prototype is on the way
  - Functionality and other properties are measured



On every vanes, i.e., 48 converters





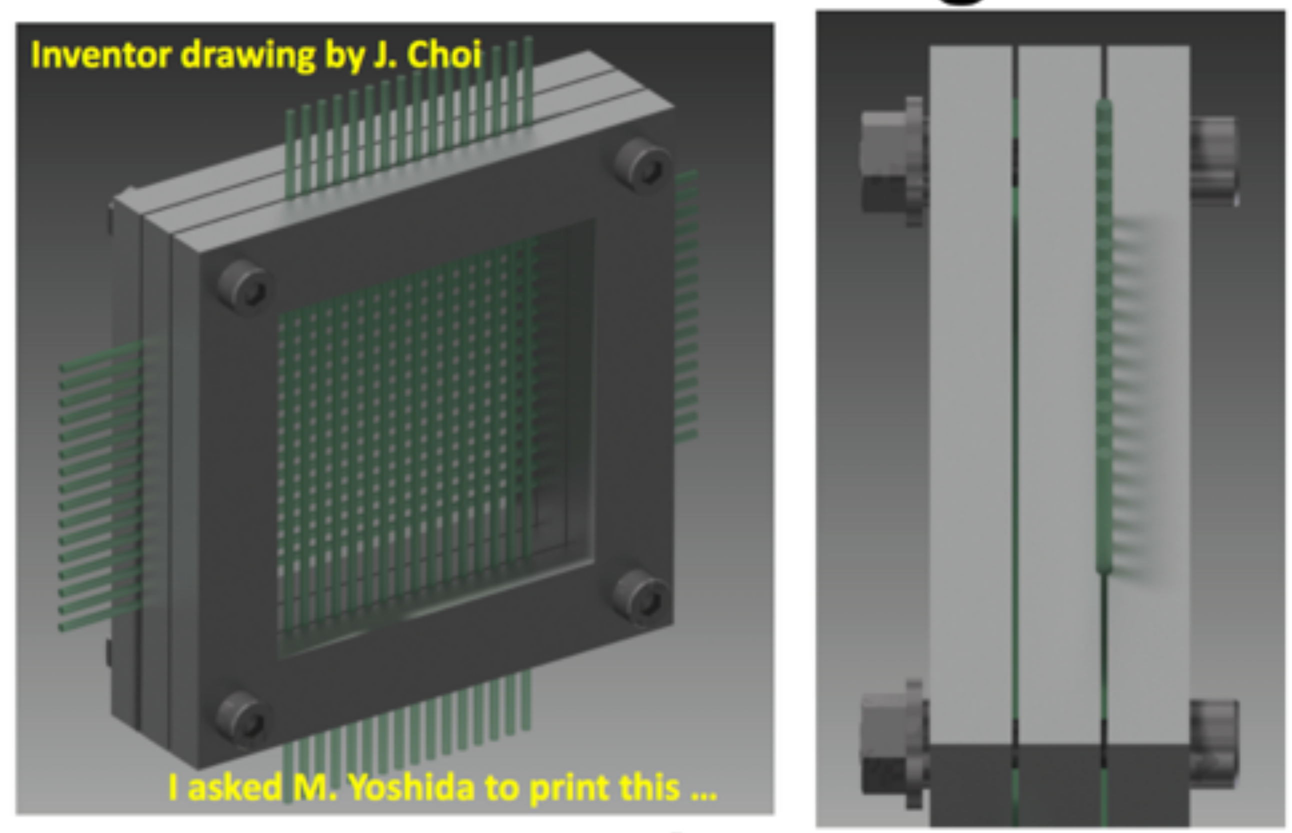


Woodo Lee (The 11th muon g-2/EDM collaboration meeting)

Muon g-2/EDM: KU

- High-energy muon beam profile monitor
  - O(10) monitors in high energy muon beam line for beam diagnosis
  - Based on scintillating fiber
  - Design and estimation done

CAD drawing



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CAPP/IBS and Korea Univ. Dept. of Physics, Euni

An estimate (summary)

- **Momentum of μ^+ = 300 MeV/c**

- PDG says for $p(\mu^+)$ = 300 MeV/c, stopping power =~ 2 MeV cm^2/g
- Multi-cladding fiber density: 1.05 g/cm^3 (Kuraray fibers)

  # energy loss per mm = 0.21 MeV/mm
- photon yield: 8,000 photons/MeV (Saint-gobin)
- Attenuation of fibre: 3 m and we assume 0.5 m in total for our readout
- MPPC PDE = fill factor x QE x avalanche probability = 20%

  # of photo-electrons to MPPC

  = 8,000 x 0.2 (MeV/mm) x 1 (mm) x exp(-0.5/3) x 0.2 = 270 photo-electrons

  (wavelength mismatch btw MPPC and fibre not included)

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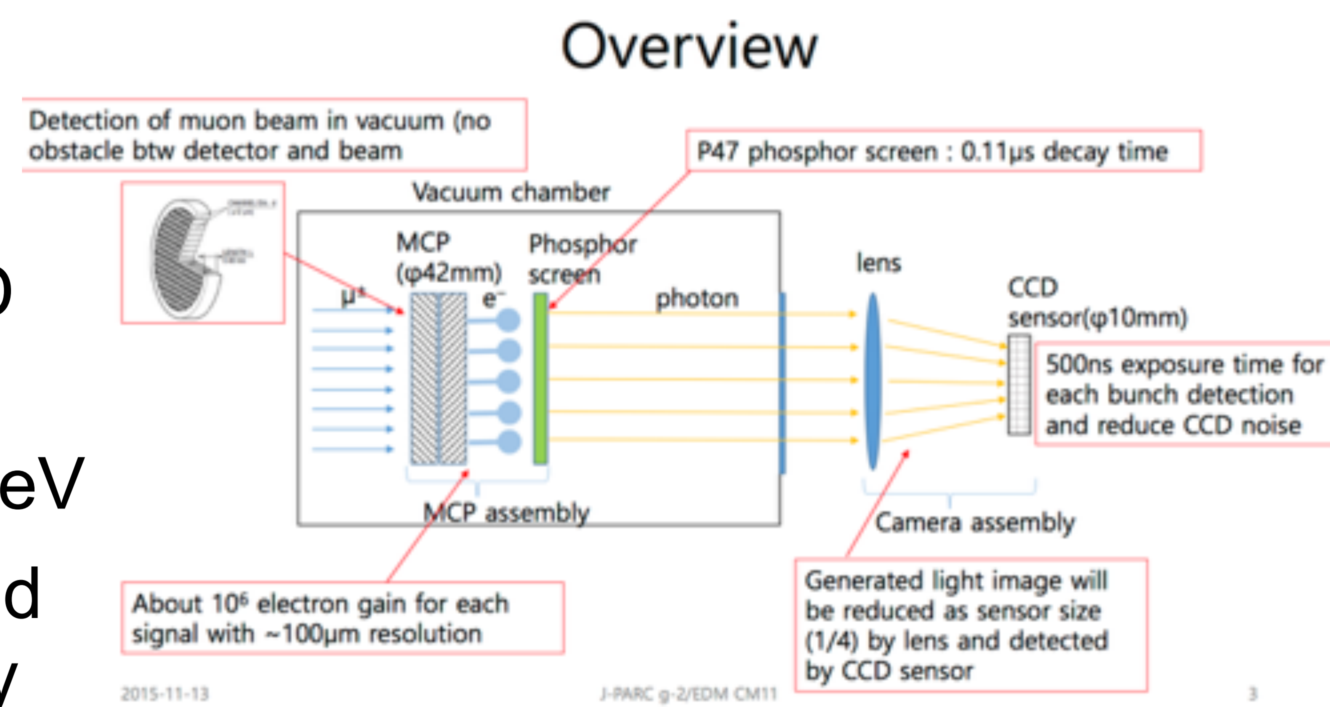
CAPP/IBS and Korea Univ. Dept. of Physics, Eunil Won

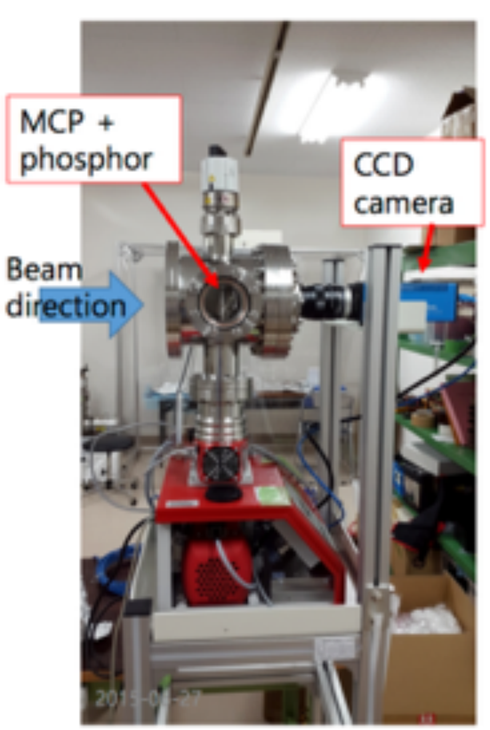
Eunil Won (The 10th muon g-2/EDM collaboration meeting)

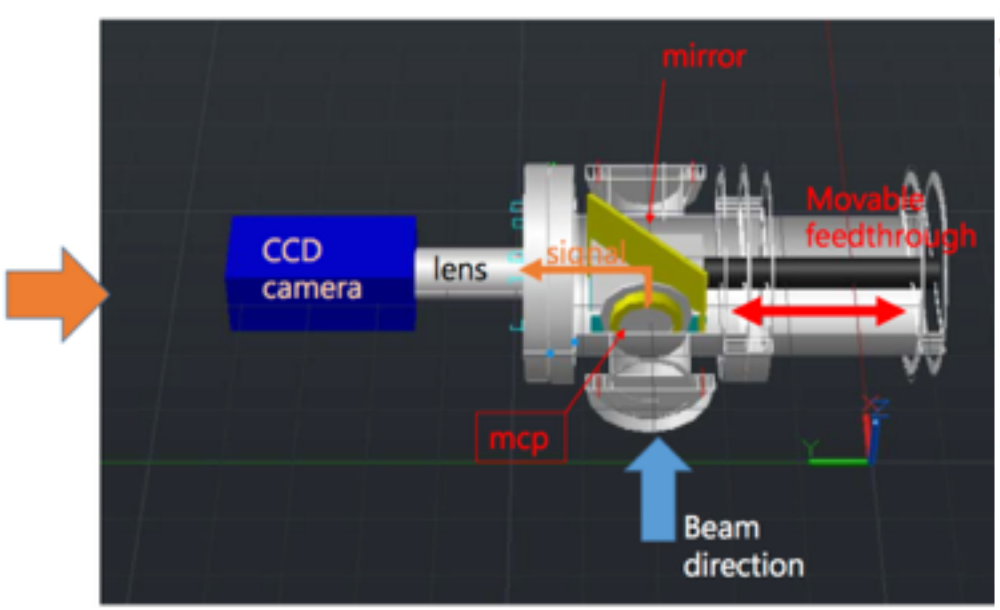
Muon g-2/EDM: SNU

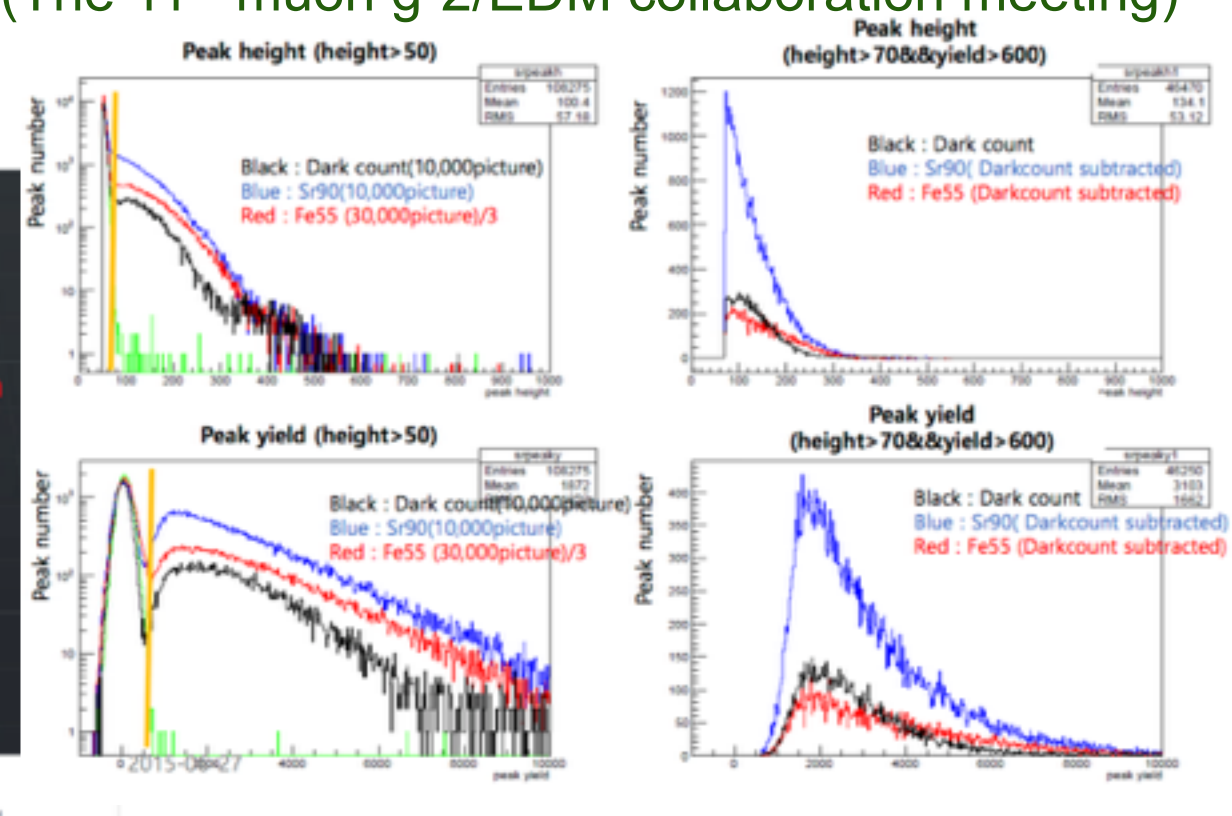
- Low-energy muon beam profile monitor
  - Based on MCP/phosphor and CCD sensor
  - O(10^5) muon detection up to 1.2 MeV
  - Preliminary beam line test done and more beam line tests are underway



Bongho Kim (The 11th muon g-2/EDM collaboration meeting)







Muon g-2/EDM: KAIST

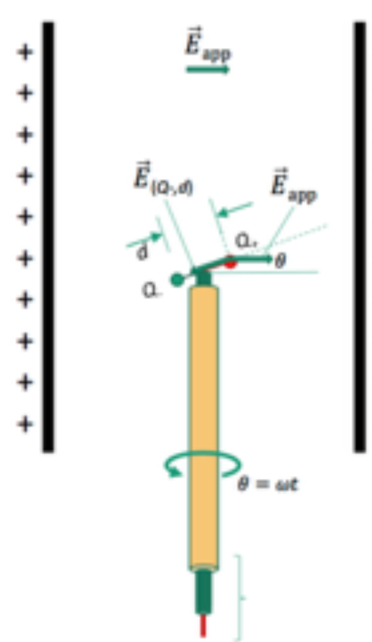
- Electric Field Monitor
  - The experiment assumes E=0 in the storage magnet, but it's hard to achieve it, so we need measure the small E field precisely
  - Based on a dipole antenna for the high sensitivity measurements
  - Preliminary design done and more details are underway

Basic concept

Here is a suggestion to use precision electrometers and a lock-in amplifier to fully electronically measure the induced charges in the dipole antenna rotating in the field, enabling the measurement of E-field-induced charges equivalent to less than 10 electrons and E-field as low as 0.1 mV/m.

Jhinhwan Lee (The 11th muon g-2/EDM collaboration meeting)

$$Q_- = -Q_0\cos(\omega t) \qquad Q_0 = d^2E_{app}/k$$
$$Q_+ = Q_0\cos(\omega t)$$



The electric field by Q_- and the applied electric field should have zero net electric field component along the dipole antenna direction at Q_+ at equilibrium.
(Otherwise more charge will accumulate at Q_+ or Q_+ will be drifted toward Q_-.):

$$E_{app}\cos\theta + E(Q_-, d) = 0$$
$$E_{app}\cos\theta + \frac{kQ_-}{d^2} = 0$$
$$Q_- = -k^{-1}d^2E_{app}\cos\theta = -Q_+$$

At $\theta = 0, E_{app} = 1\text{V/m}, \text{d} = 10^{-2}\text{ m}, k = 9\times10^9\text{ Nm}^2/\text{C}^2$, the induced charge is $Q_0 = Q_+ = -Q_- = 1.1\times10^{-14}\text{C}$.
If we rotate the dipole antenna at a frequency ω ($\theta = \omega t$), the currents into the antenna poles are:

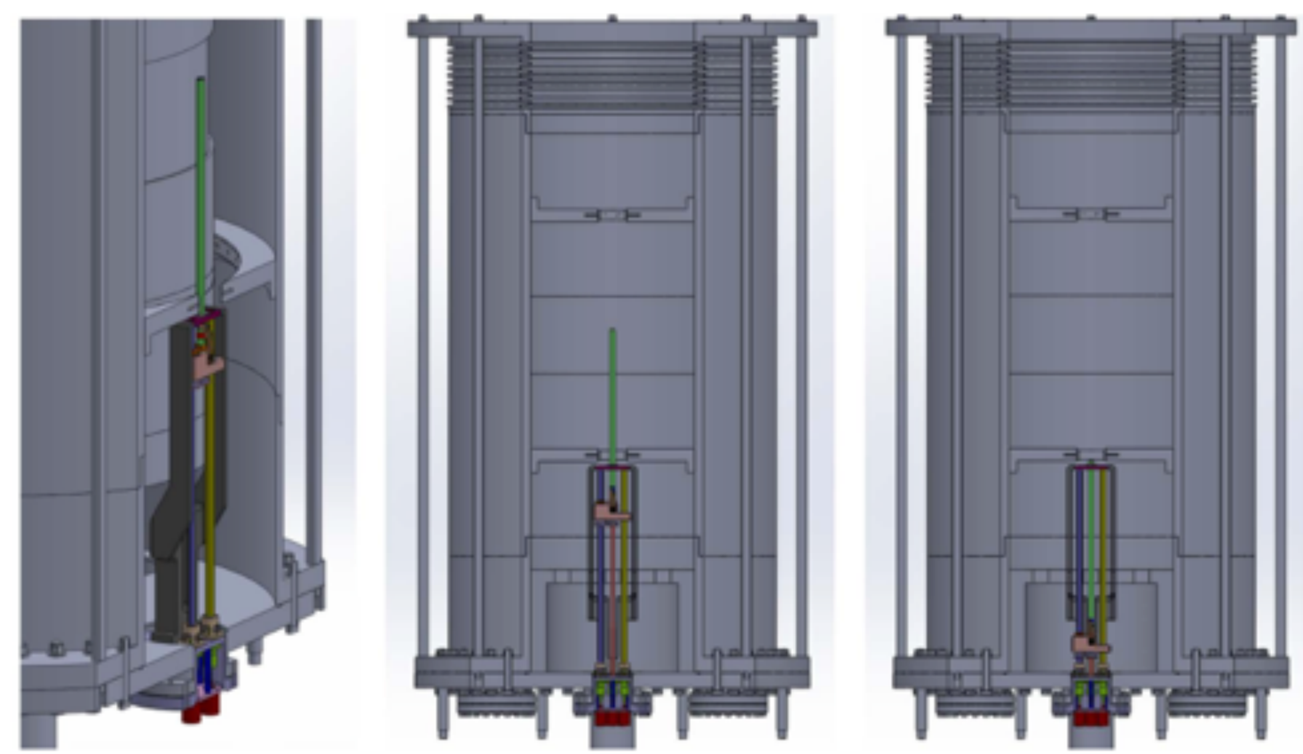
$$I_- = \frac{dQ_-}{dt} = \omega Q_0\sin(\omega t)$$
$$I_+ = \frac{dQ_+}{dt} = -\omega Q_0\sin(\omega t)$$

At f=10 rev/s, the peak current for both poles is:

$$I_{peak} = \omega Q_0 = \frac{2\pi f d^2 E_{app}}{k} = 6.6\times10^{-13}\text{A} = 0.66\text{ pA}$$

The 11th g-2/EDM collaboration meeting

Jhinhwan Lee, IBS CAPP / KAIST Physics

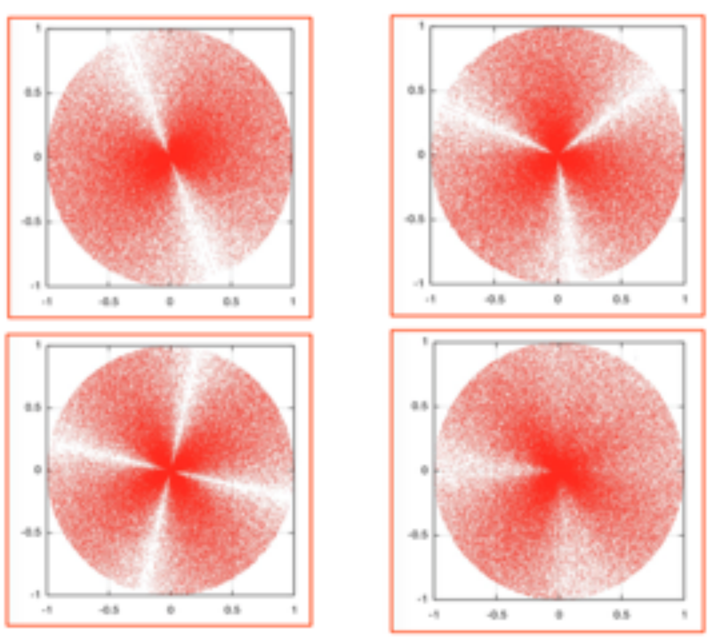


Muon g-2/EDM: CAPP/IBS

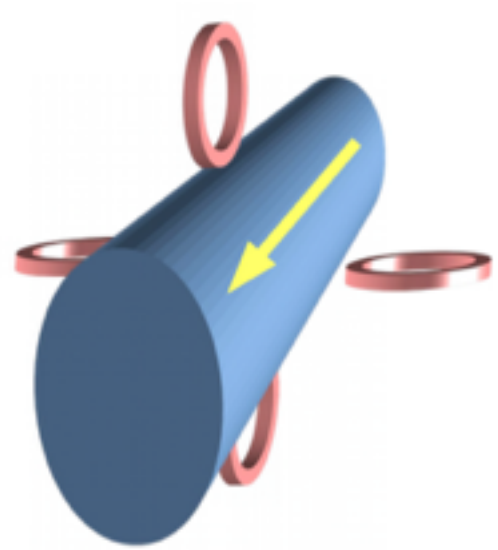
- Non-destructive muon beam profile monitor
  - Measures beam position based on induced currents by beam
  - Several options are being considered (Rogowski coil, SQUID, …)
  - Simulation studies and prototyping are in progress

Selcuk Haciomeroglu (The 11th muon g-2/EDM collaboration meeting)

Beam profile



S. Haciomeroglu, CM11



B-field measurement with pickup loop

Pulse with g-2 beam shape

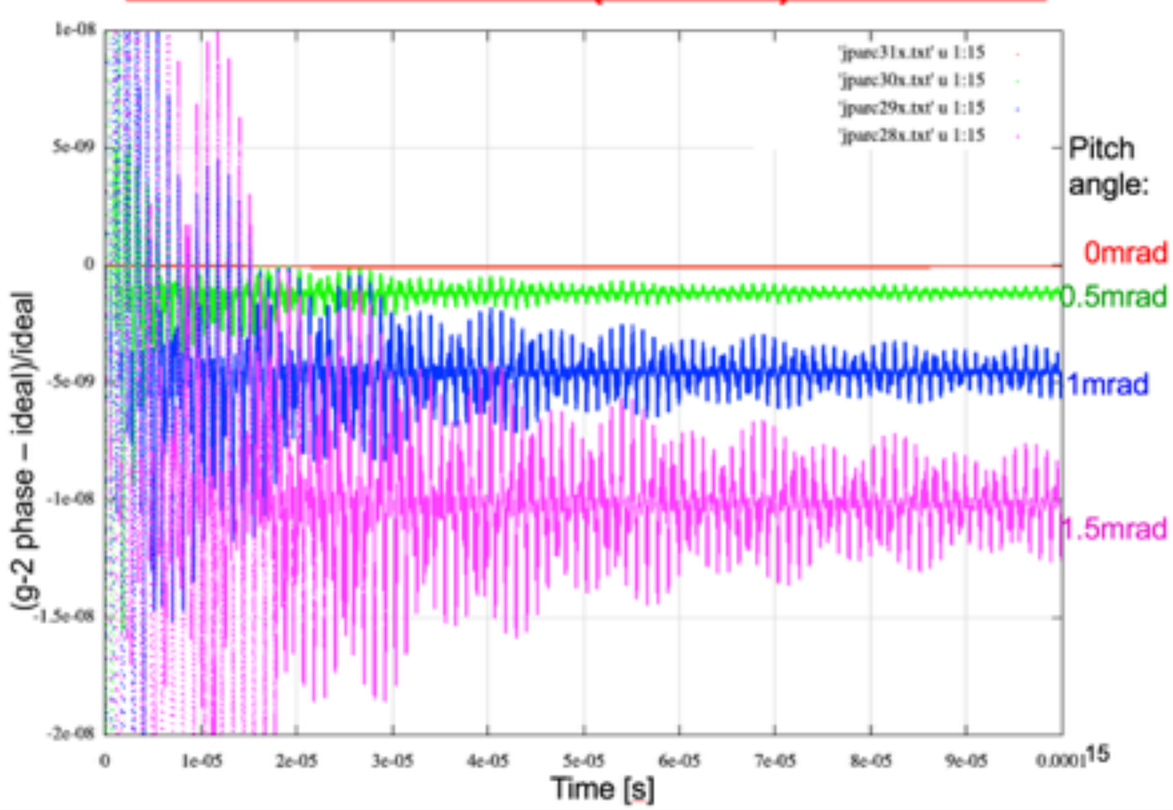
Current passes through the wire and the B-field is picked up by the loop

S. Haciomeroglu, CM11

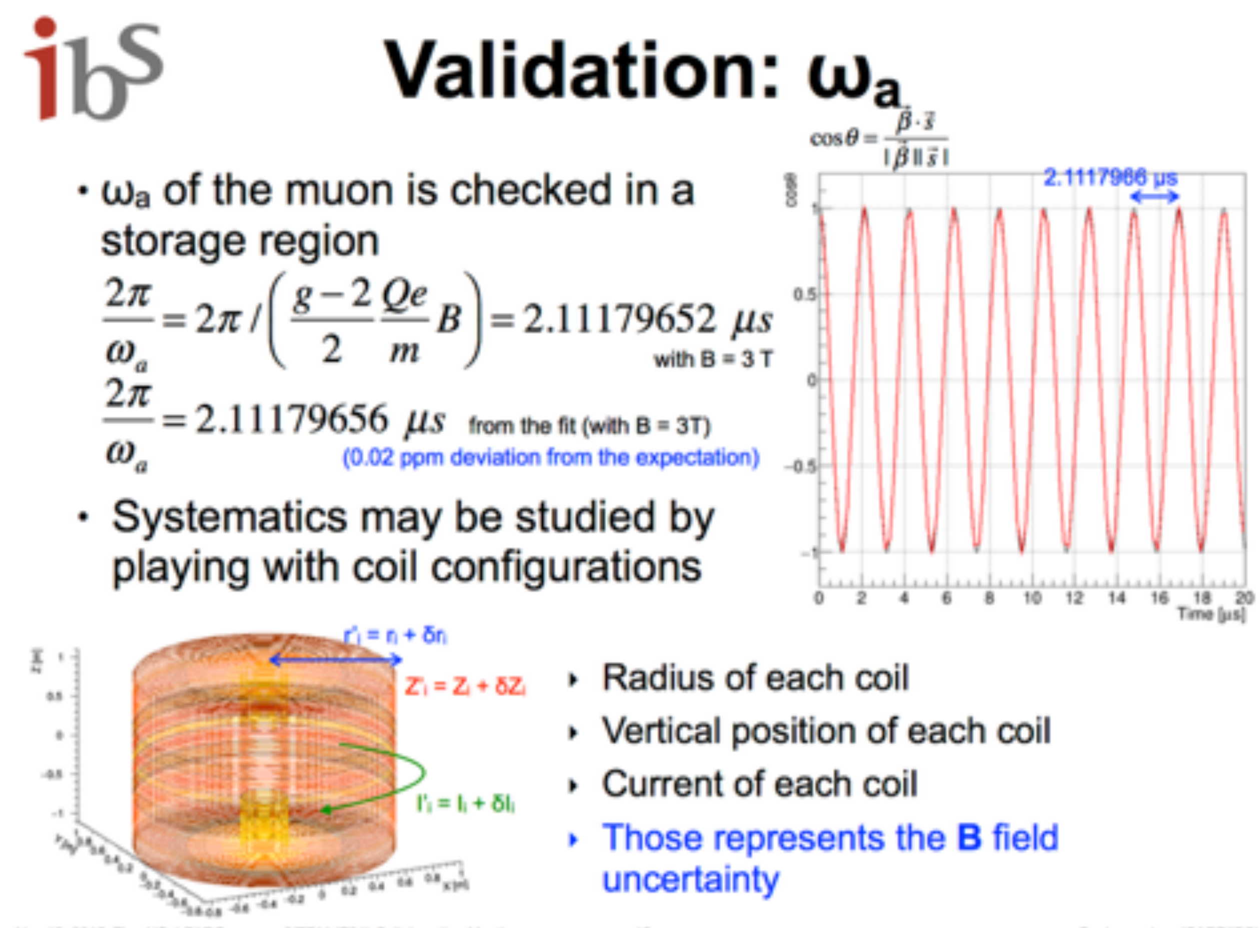
Muon g-2/EDM: CAPP/IBS

- Precision beam tracking and systematics study
  - Many new techniques in the experiment, so systematics study is crucial
  - Precision beam tracking is necessary to understand the beam behavior
  - Primitive simulation in a storage region done and realistic one is in progress

J-PARC case (NEW), n=10^{-4}



Yannis K. Semertzidis
(The 8th muon g-2/EDM collaboration meeting)



Soohyung Lee
(The 11th muon g-2/EDM collaboration meeting)

FKPPL Contributions

- Our French colleagues are involved in development of a software framework for COMET (ICEDUST), and it can be extended for muon g-2/EDM as well
  - No concrete plan for the software framework for muon g-2/EDM experiment yet
  - Korean group is working on electronics and triggers, therefore, the synergy of collaboration will be great
  - The collaboration of FKPPL for muon g-2/EDM is being established - FKPPL project application submitted
  - We are expecting great efforts from this project!

Summary

- Frontier experiments in muon precision measurement is being developed in J-PARC
  - They will be breakthroughs to the New Physics
- Korean group contributes to both experiments actively
  - Covers hardware developments, simulations, and systematics studies
- French group is developing a software framework for COMET
  - FKPPL muonists† would like to make it for muon g-2/EDM as well

† Again, this word doesn't exist, so don't open you dictionary.