New Measurements of
Muon g-2 and EDM with Ultra-Cold Muon Beam at J-PARC

October, 6-7, 2011, DESY

Naohito SAITO

(KEK)

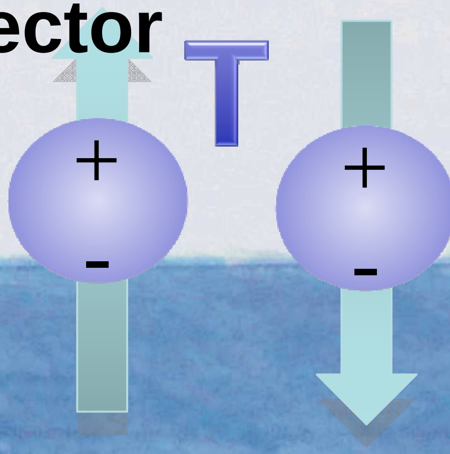
Collaboration (today's snap shot)

- 85 members (was 77 …still evolving)
- M. Aoki, P. Bakule, B. Bassalleck, G. Beer, A. Deshpande, S. Eidelman, D. E. Fields, M. Finger, M. Finger Jr., Y. Fujirawa, Y. Fukao, S. Hirota * , H. Iinuma, M. Ikegami, N. Hayashizaki, K. Ishida, M. Iwasaki, R. Kadono, T. Kakurai, T. Kamitani, Y. Kamiya, S. Kanda, N. Kawamura, S. Komamiya, K. Koseki, T. Kohriki, Y. Kuno, A. Luccio, O. Luchev, M. Maki, G. Marshall, M. Masuzawa, Y. Matsuda, T. Matsuzaki, T. Mibe, K. Midorikawa, S. Mihara, Y.Miyake, J. Murata, W.M. Morse, R. Muto, K. Nagamine, T. Naito, H. Nakayama, M. Naruki, H. Nishiguchi, M. Nio, D. Nomura, H. Noumi, T. Ogawa, T. Ogitsu, K. Ohishi, K. Oide, A. Olin, N. Saito, N.F. Saito, Y. Sakemi, K. Sasaki, O. Sasaki, A. Sato, A. Savoy-Navarro, Y. Semeritzidis, Yu. Shatunov, K. Shimomura, B. Shwartz, P. Strasser, R. Sugahara, M. Sugano, K. Tanaka, K. Tanaka, N. Terunuma, N. Toge, D. Tomono, E. Torikai, T.Toshito, A. Toyoda, K. Tsukada, K. Ueno, V. Vrba, S. Wada, A. Yamamoto, K. Yokoya, K. Yokoyama, Ma. Yoshida, M. H. Yoshida, and K. Yoshimura
- 19 Institutions
- Academy of Science, BNL, BINP, CRNS-APC, UC Riverside, Charles U., KEK, NIRS, UNM, Osaka U., RCNP, STFC RAL, RIKEN, Rikkyo U., SUNYSB, CRC Tohoku, U. Tokyo, TITech, TRIUMF, U. Victoria
- 7 countries
- Czech, USA, Russia, Japan, UK, Canada, France

Particle Dipole Moments

- **Magnetic and Electric Dipole Moments are related to Spin of the Particle: axial vector**

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}$$



$$a = \frac{g-2}{2}$$

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

MDM (Magnetic Dipole Moment)
Contains contributions from ALL PHYSICS!
- EW, QCD, and New Physics
⇒ precision test of the SM
⇒ the most precise determination of α_{EM} from electron g-2 (0.37 ppb)

EDM (Electric Dipole Moment)
If EDM nonzero, T is violated
⇒ CP violation in the lepton sector (under CPT)
⇒ leptogenesis?
⇒ Baryon Asymmetry in the Universe

Muon magnetic moment

- **Magnetic moment and spin can be related as**

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

$\vec{\mu}$: magnetic moment
$\vec{s}$: spin
g: gyromagnetic ratio

- **Dirac equation predicts g=2** ⇨ a=0

$$\mu = (1+a)\left(\frac{e\hbar}{2m}\right) \qquad a = \frac{g-2}{2}$$

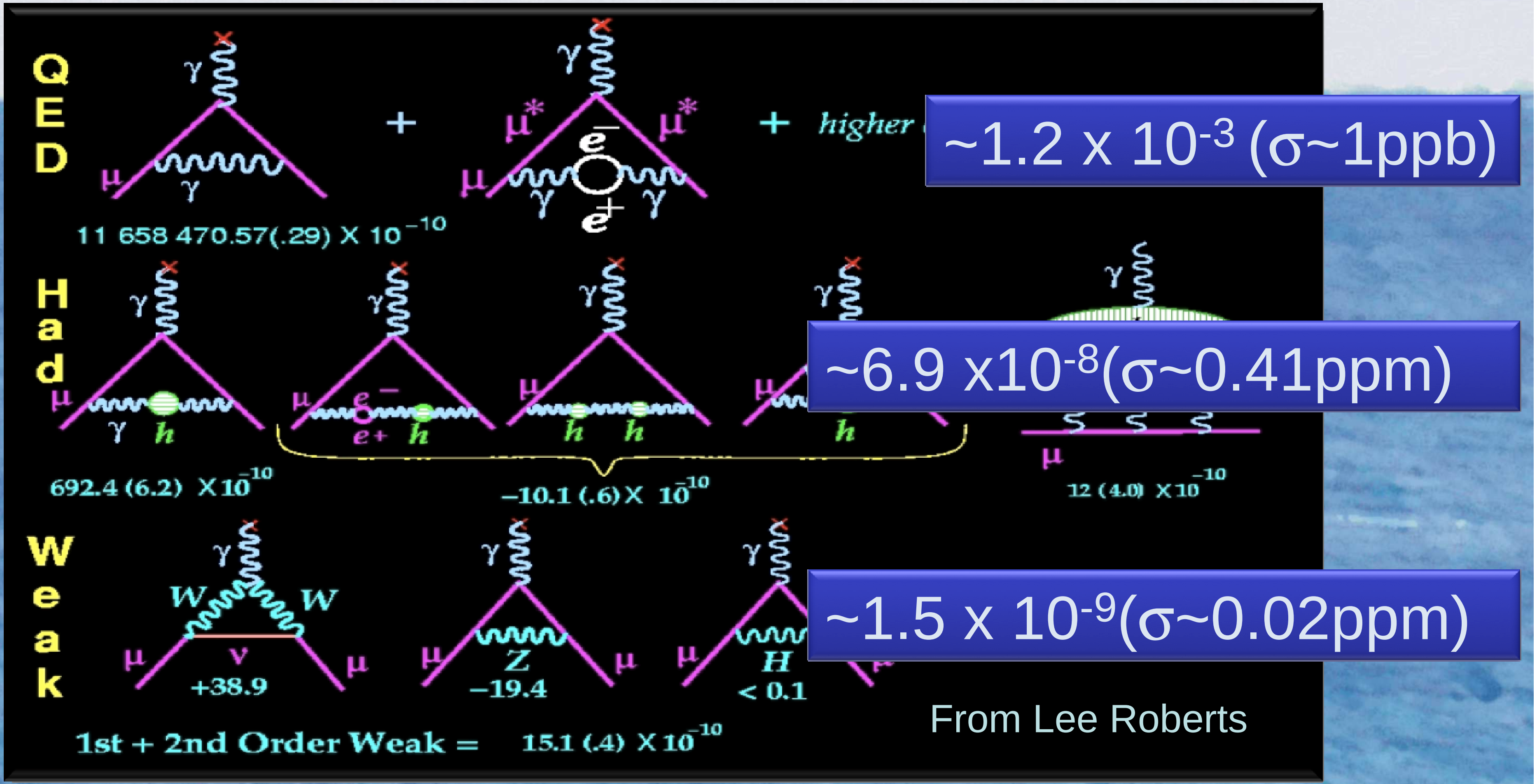
a=1.2e-3 for e, μ, …
a=1.8 for proton

- **Radiative corrections (including NEW PHYSICS) would make g≠2** ⇨ a≠0

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 40{,}000 \qquad \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 290$$

SM Contribution to a≠0

- **Any particle which couples to muon/photon would contribute : QED >> Hadron > Weak**

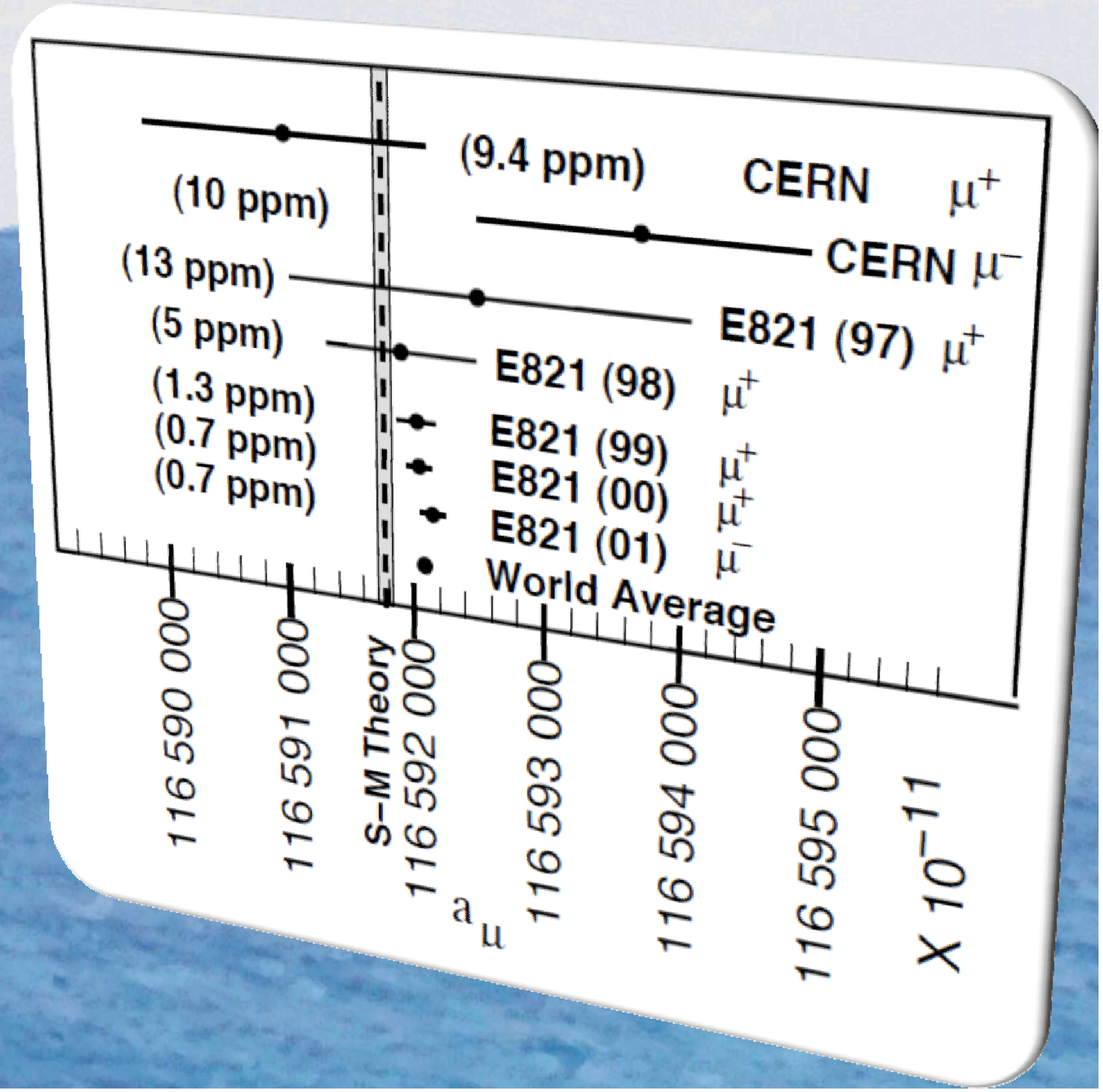


"Final Report" from BNL E821

$$\Delta a_\mu^{(\text{today})} = a_\mu^{(\text{Exp})} - a_\mu^{(\text{SM})} = (295 \pm 88) \times 10^{-11}$$

- E821 at BNL-AGS measured down to 0.7 ppm for both μ+ and μ−
- 3.4 sigma deviation from the SM
  - SM prediction OK?
  - New Physics?
- Need to explore further
- Preferably

NEW METHOD!



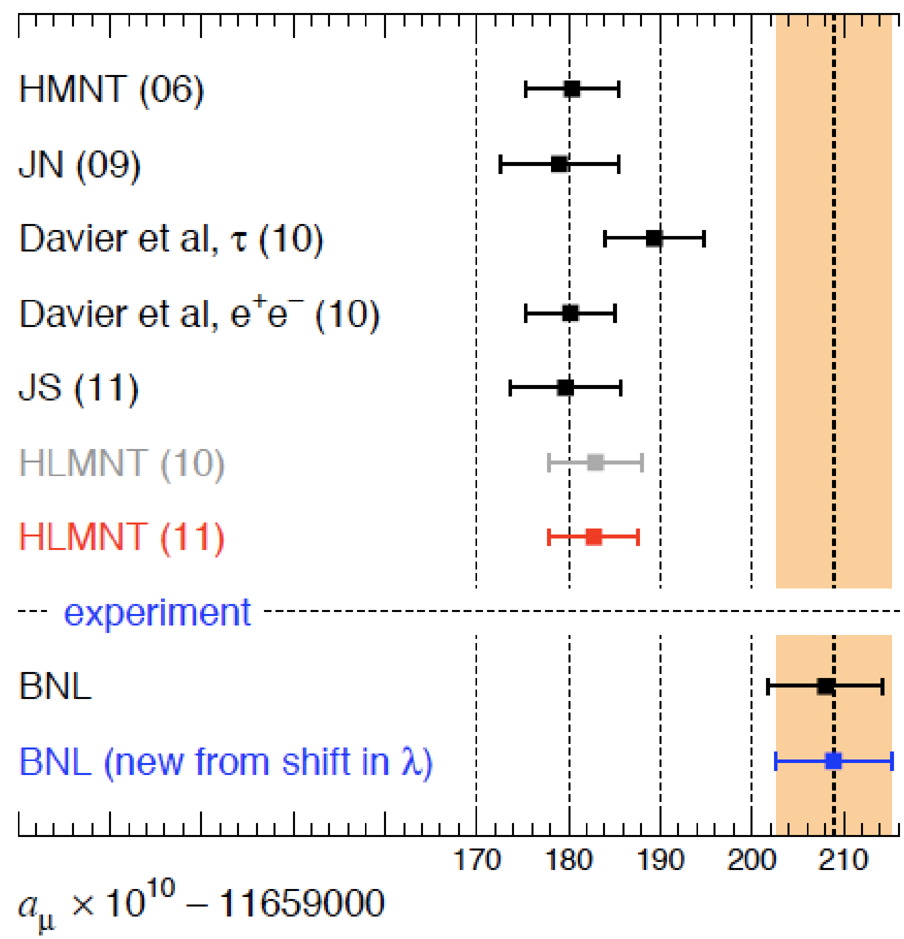
Updates on the SM Prediction

- **Anomaly still alive!**

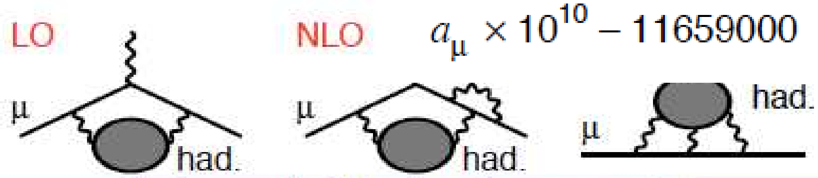
Summary: Standard Mode

QED contribution	11 658 471.808 (0.
EW contribution	15.4 (0.2)
Hadronic contribution	
LO hadronic	**694.9 (4.3**
NLO hadronic	−9.8 (0.1)
light-by-light	10.5 (2.6)
Theory TOTAL	**11 659 182.8 (4.9**
Experiment	**11 659 208.9 (6.3**
Exp − Theory	**26.1 (8.0)**

(Numbe

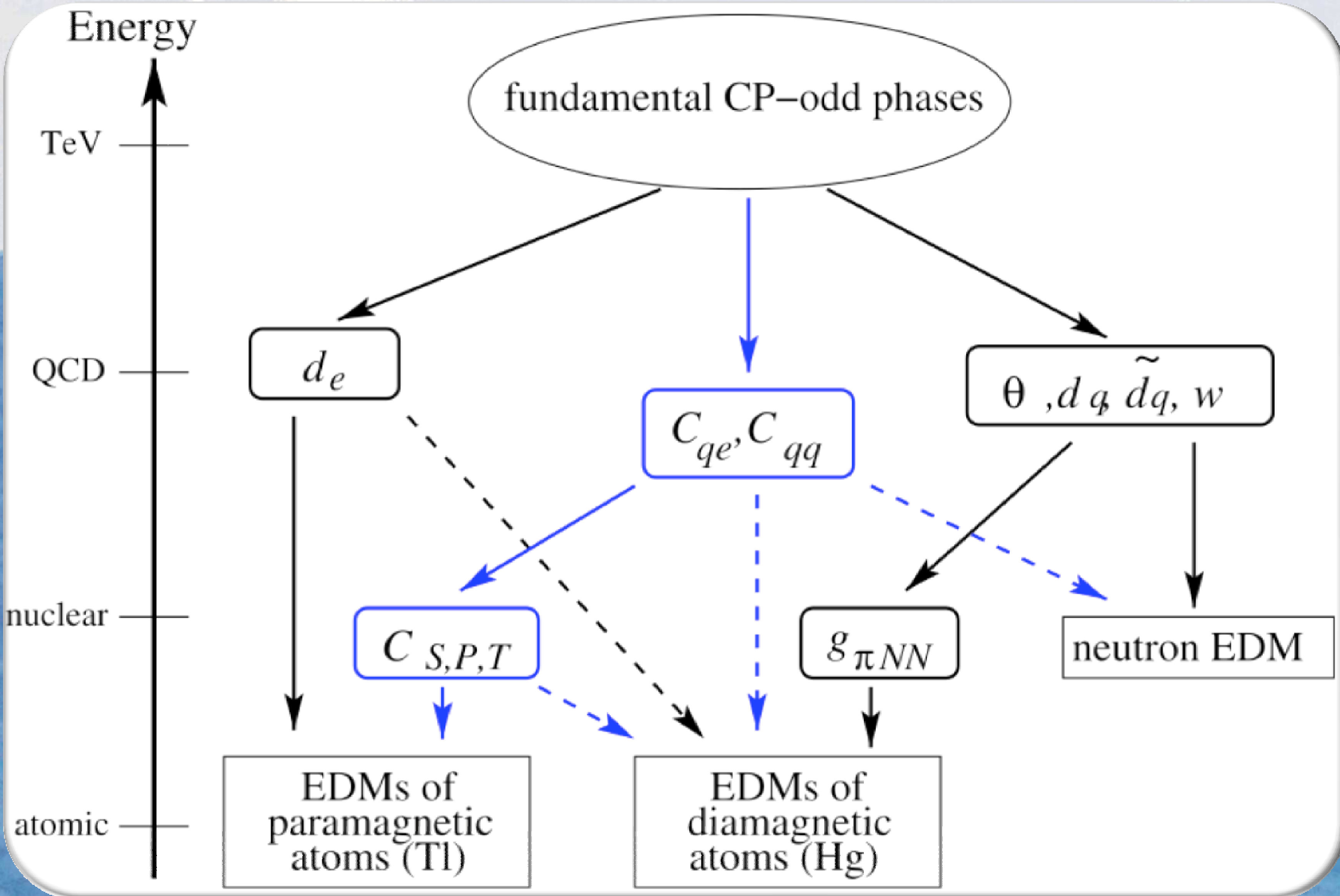


n.b.: hadronic contributions:



Origin of EDM

M.Pospelov and A.Ritz, Ann.Phys. 318 (2005) 119



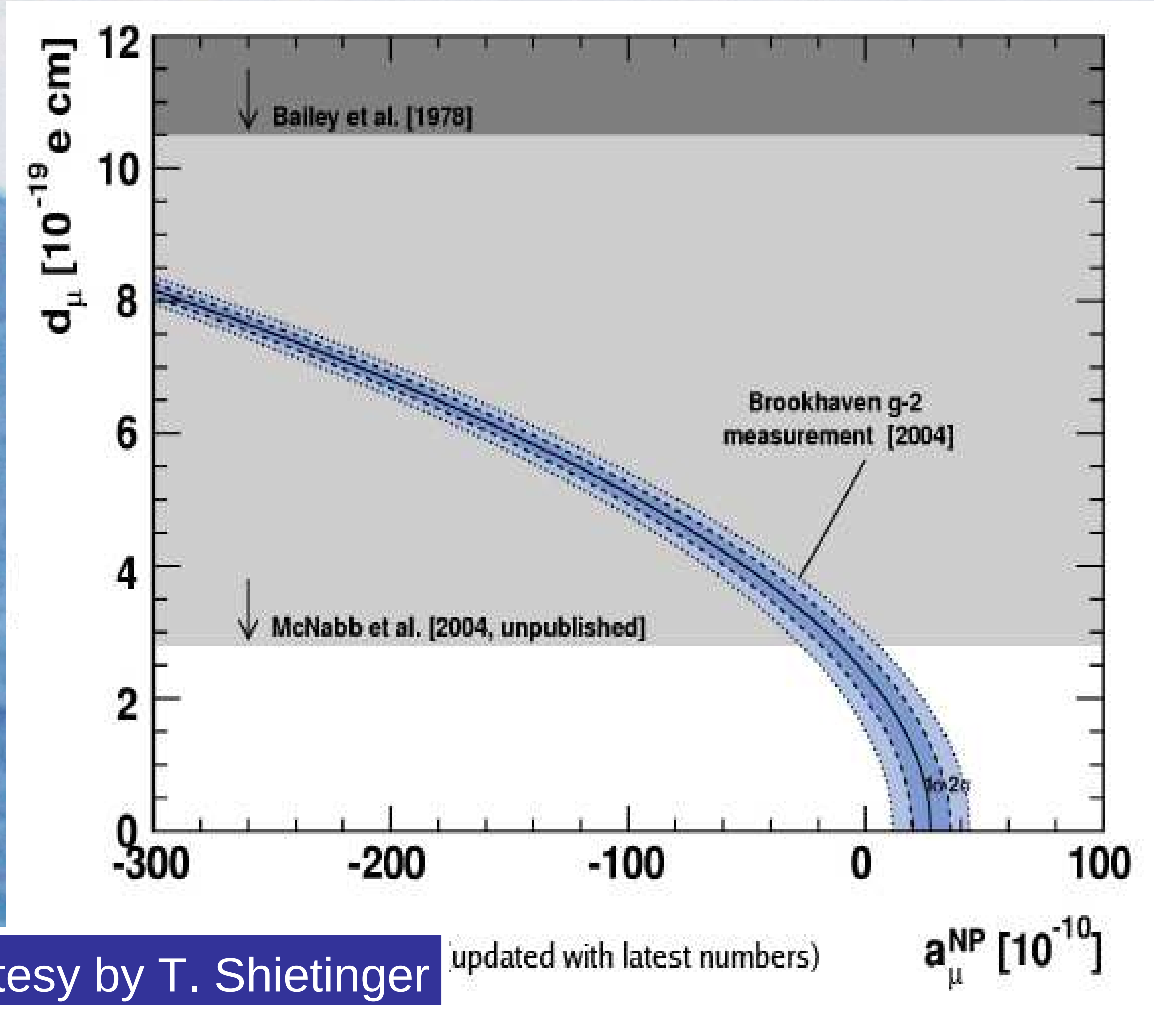
Measured in g-2 experiment

- "Inclusive" precession frequency

$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2}$$

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

- **Experimental limit of EDM is in the similar range!**

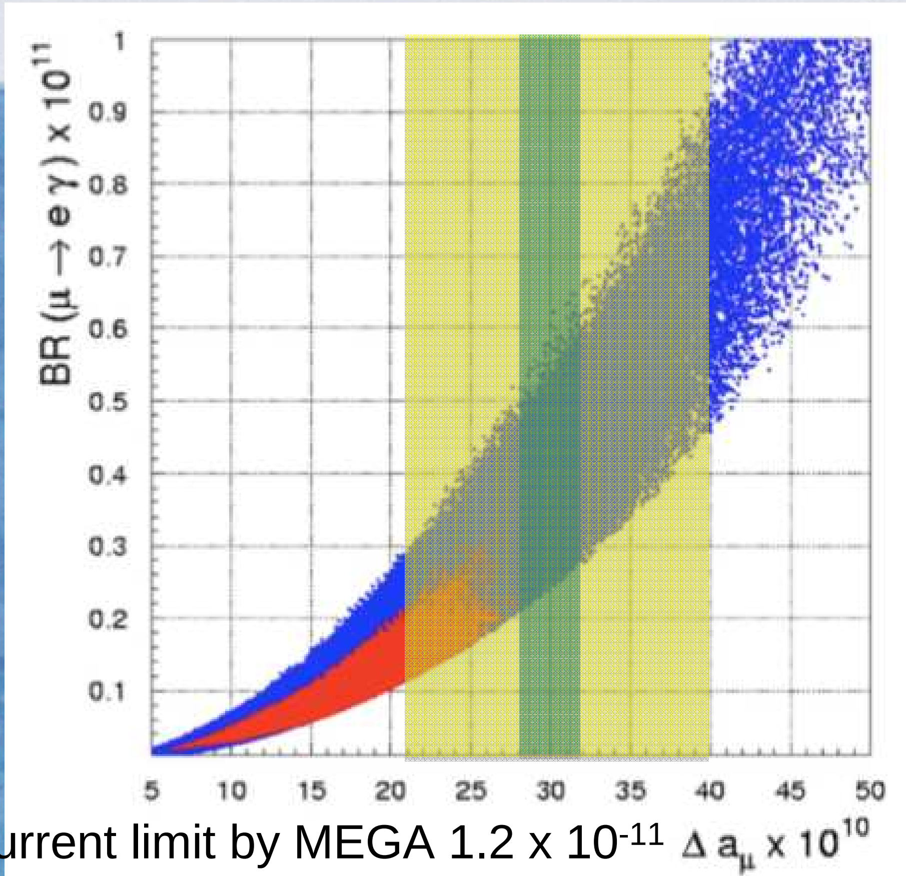


Courtesy by T. Shietinger

g-2, EDM and cLFV

- Large g-2 → Large cLFV → Large EDM

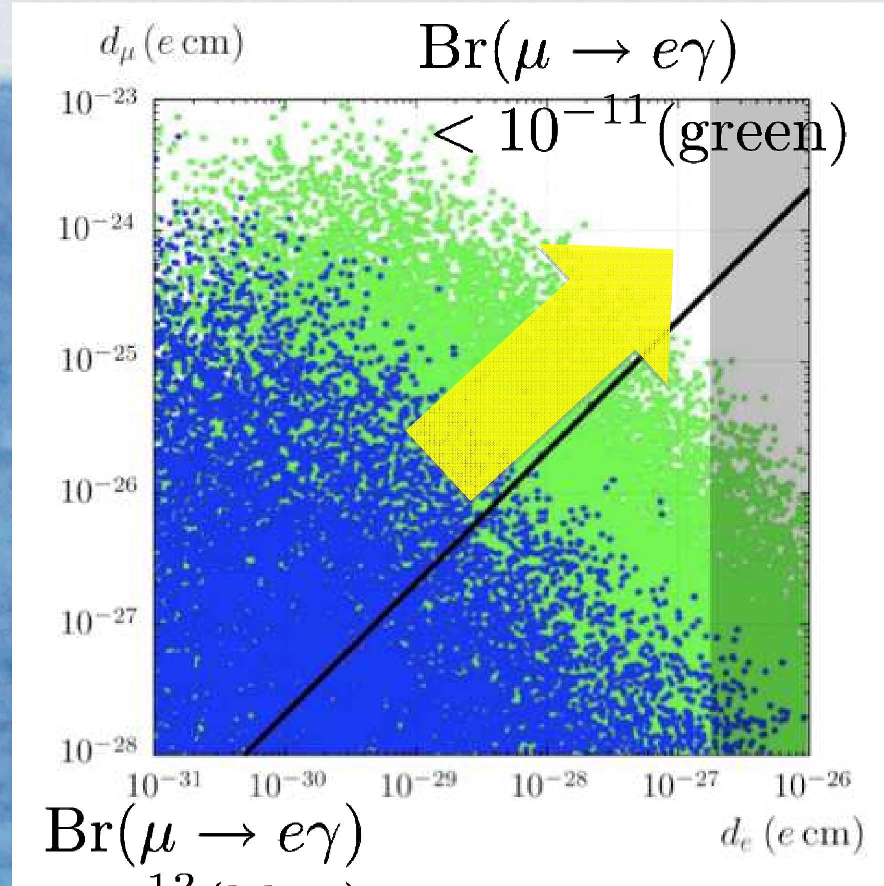
G. Isidori, F. Mescia, P. Paradisi, and D. Temes, PRD 75 (2007) 115019



Current limit by MEGA 1.2 x 10^{-11}

To be superseded by MEG soon

J. Hisano, Nagai, Paradisi

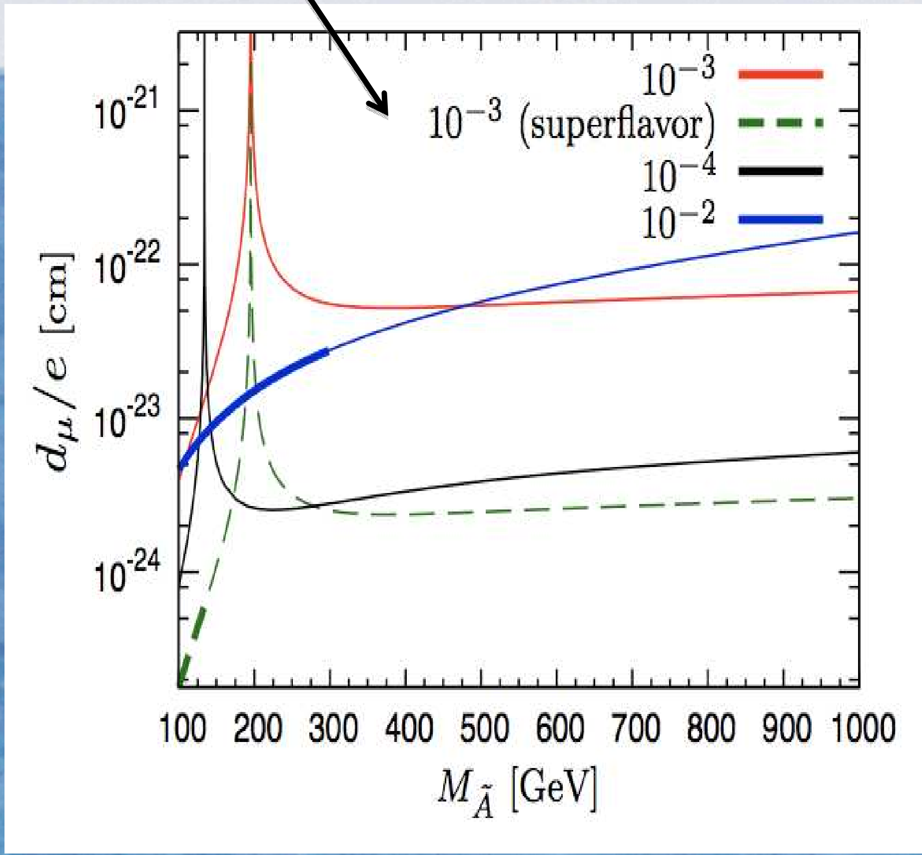


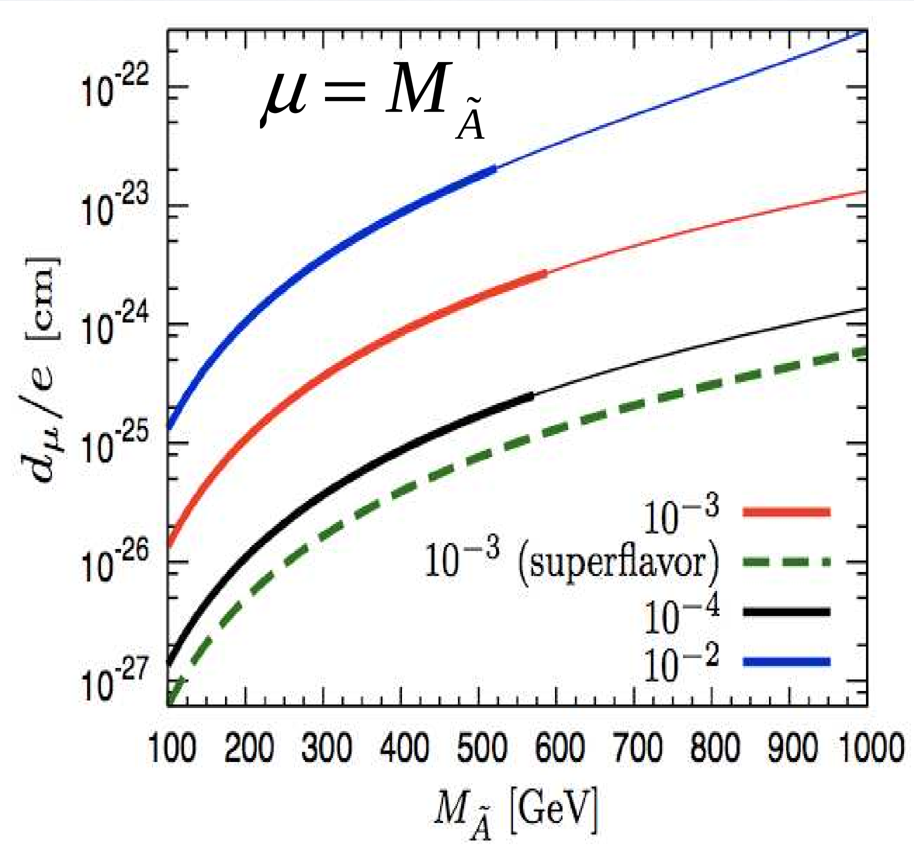
A Large Muon EDM from Flavor?

Gudrun Hiller, (CERN & Dortmund U.) , Katri Huitu, Timo Ruppell, (Helsinki U. & Helsinki Inst. of Phys.) , Jari Laamanen, (Nijmegen U.) . e-Print: arXiv:1008.5091 [hep-ph]

- **Muon EDM is enhanced due to LFV**

Parameter to describe the Flavor mixing in the Slepton sector



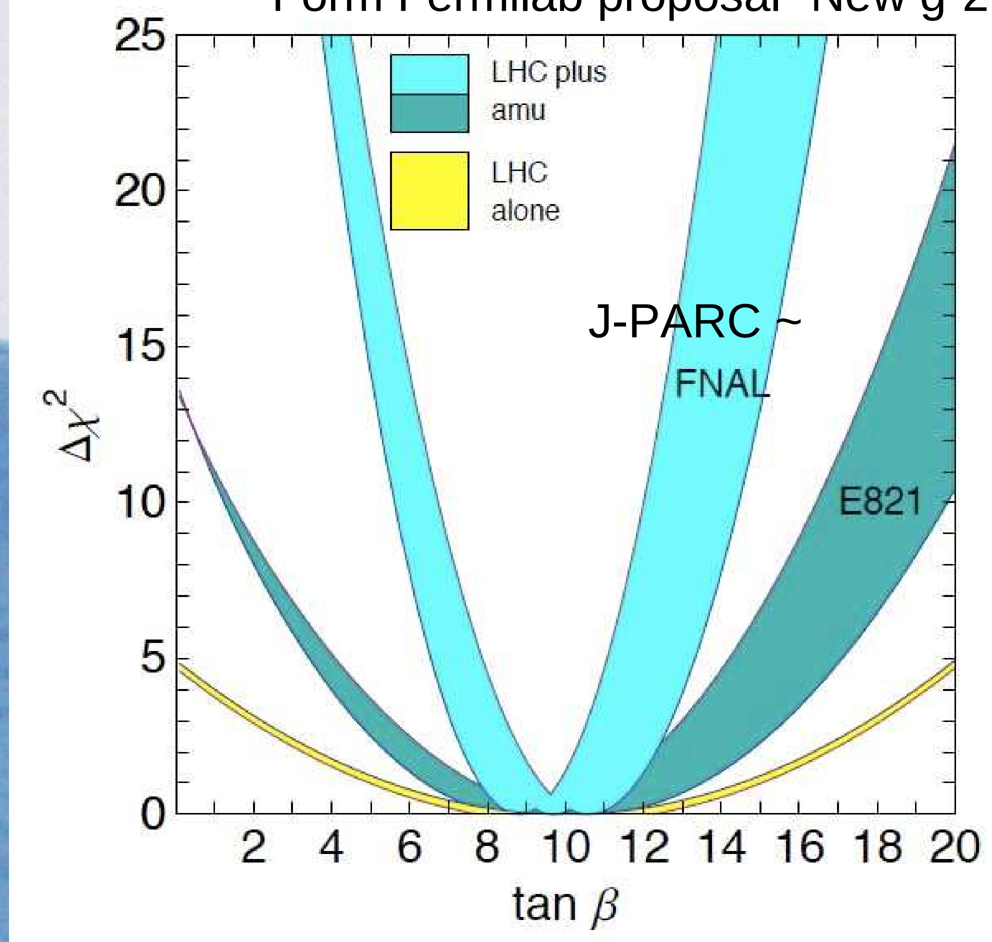


Muon g-2 in the LHC era

- **Even the first SUSY discovery was made at LHC, the muon g-2 measurement remains unique to determine SUSY parameters:**

  μ and tan β

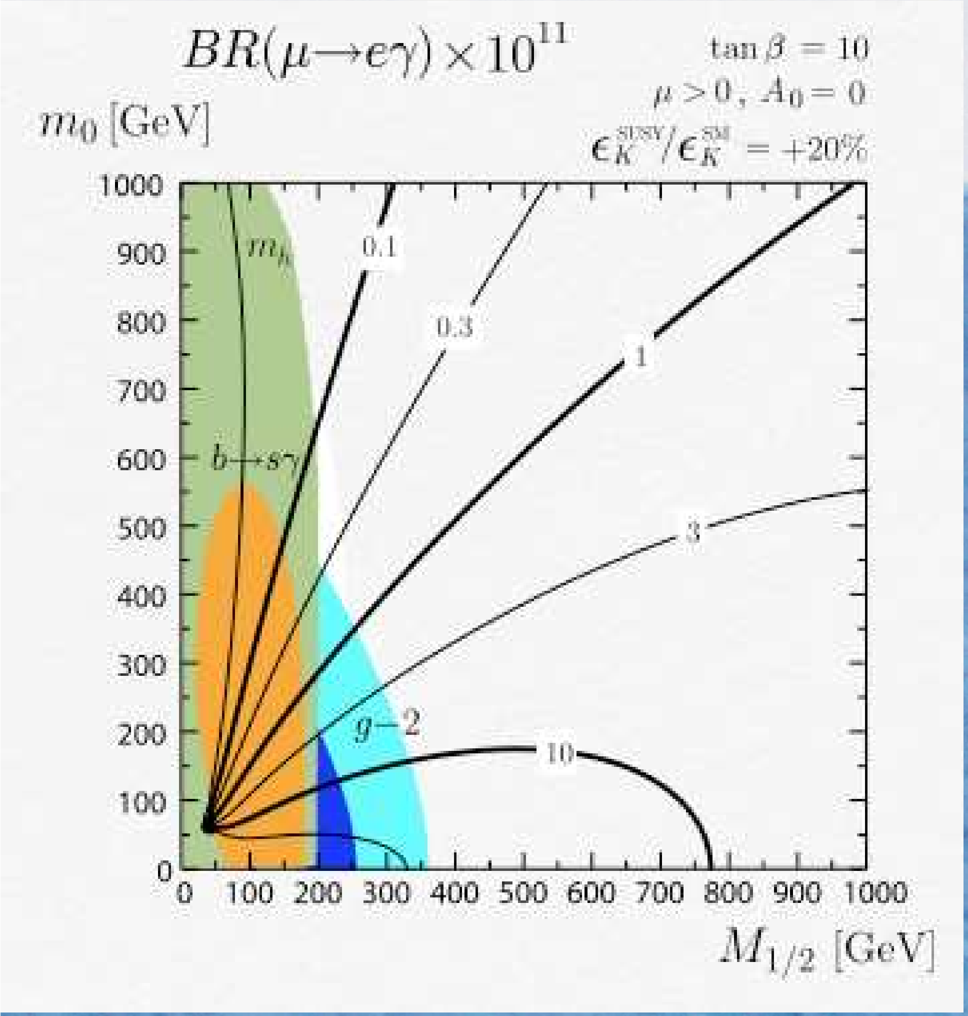
Form Fermilab proposal “New g-2”

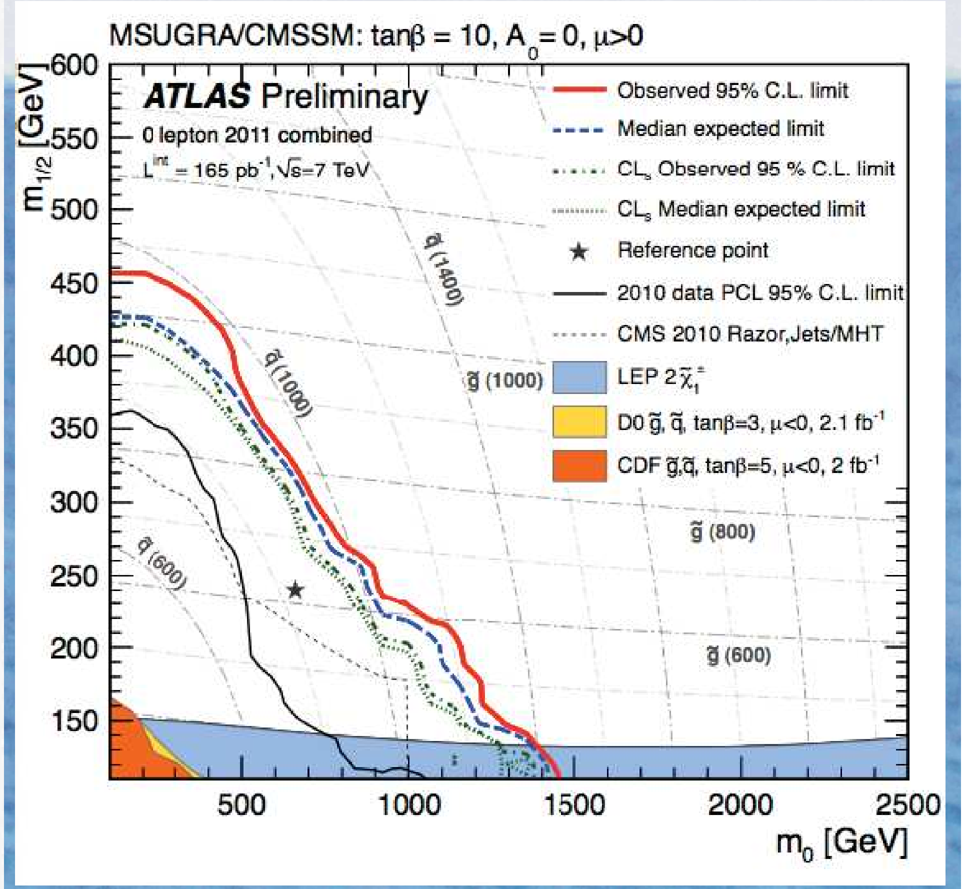


$$a_\mu(\mathrm{SUSY}) \approx (\mathrm{sgn}\,\mu) 13\times 10^{-10} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

LHC Results and Muon Physics

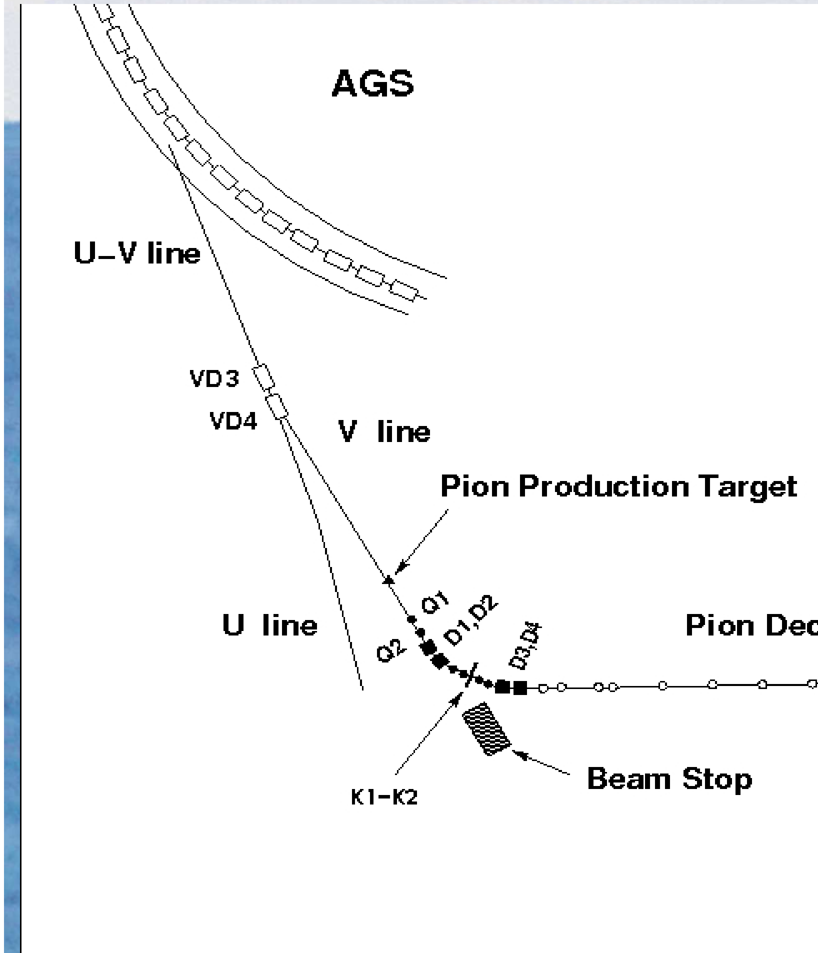
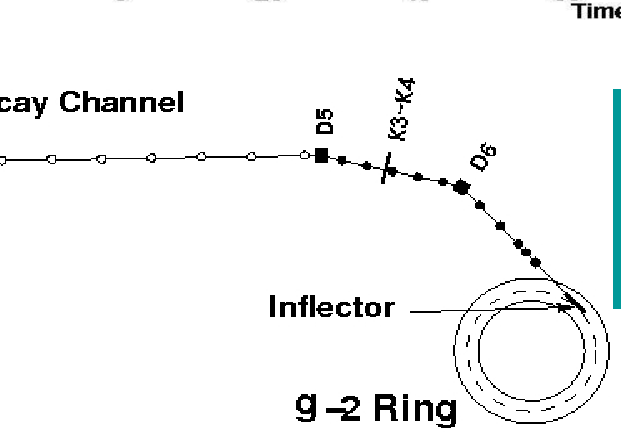
- **Large tanβ?**

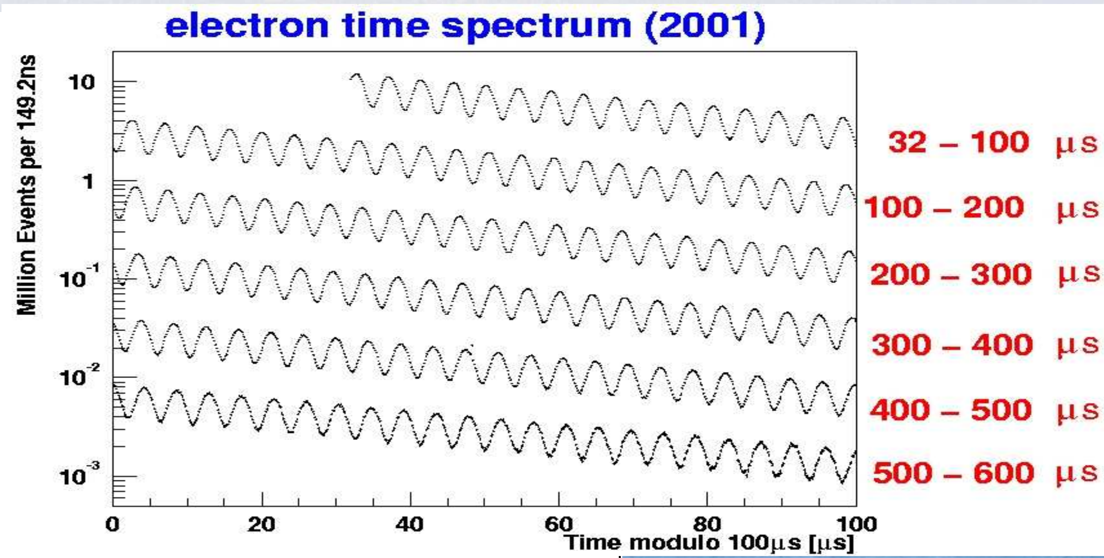




How it is Measured?

- Precession frequency (ω_a) of muon spin in the storage ring is measured;



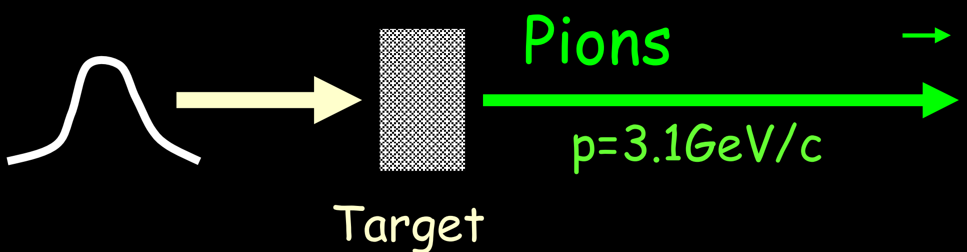
$$\omega_a = -\frac{e}{m} a_\mu B$$

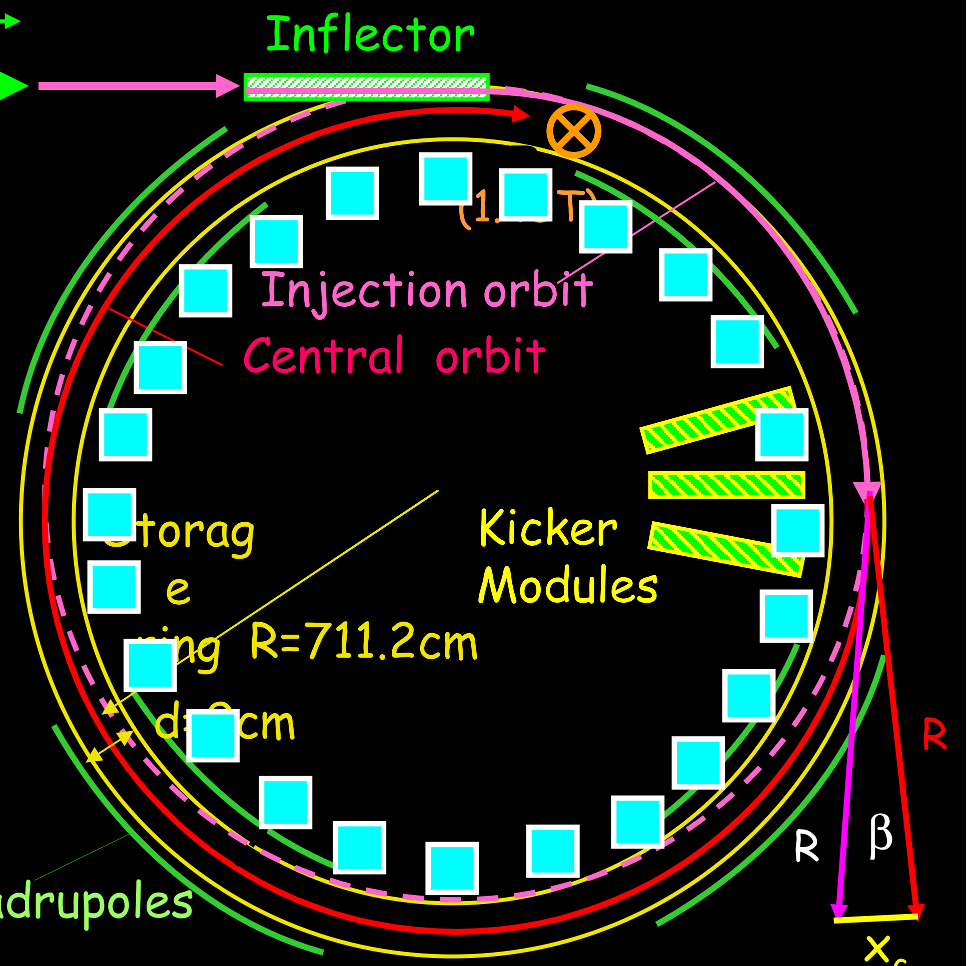

The Muon g-2 Ring
at BNL

Experimental Technique: fill ring, count until all muons are gone; do it again

25ns bunch of
5 X 10^{12} protons
from AGS

$x_c \approx 77$ mm
$\beta \approx 10$ mrad
$B \cdot dl \approx 0.1$ Tm





- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

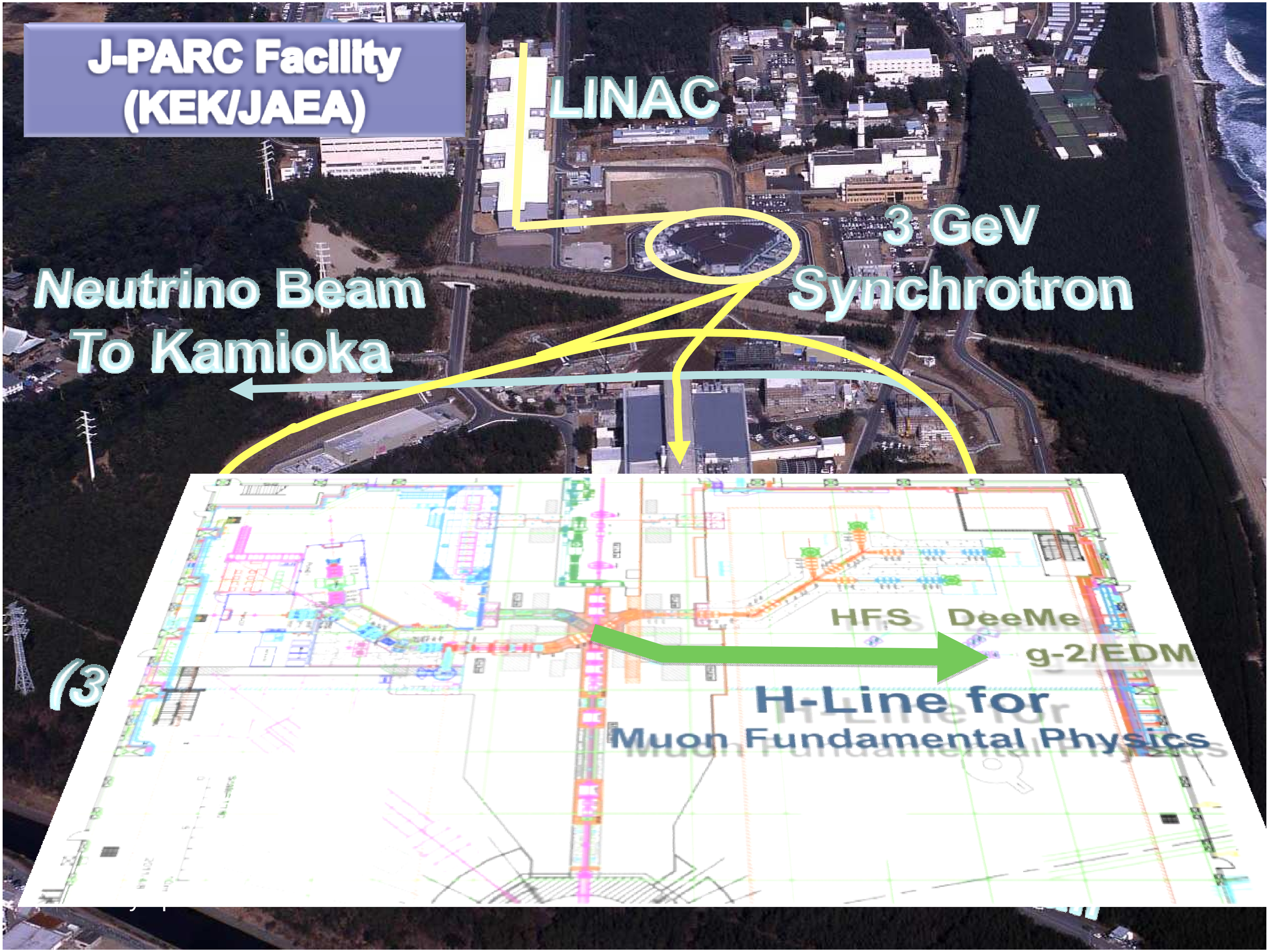
(thanks to Q. Peng)

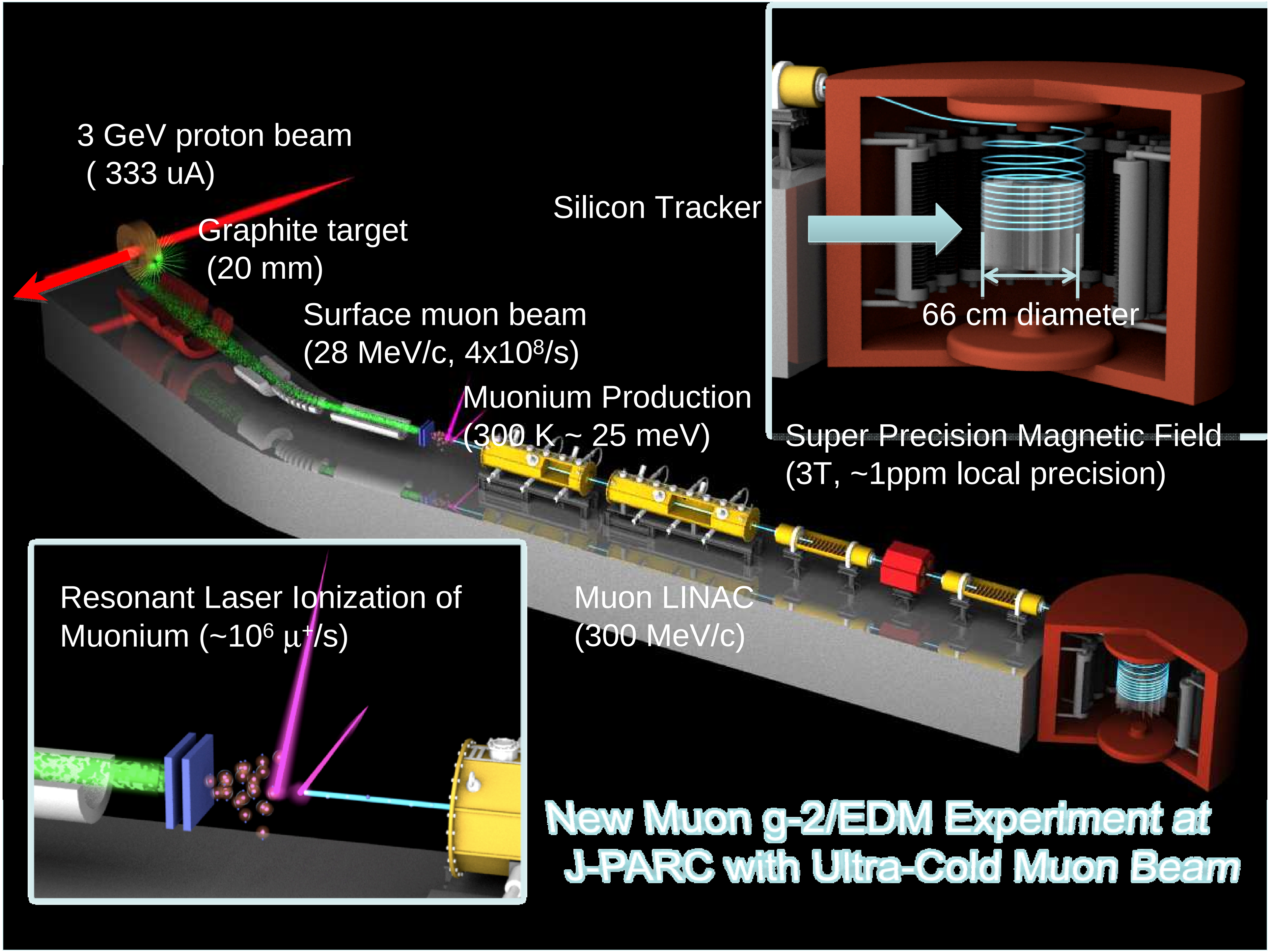
Systematic Uncertainties

from Final Report of BNL E821

- **Major Sources**
  - Pileup
  - Lost Muons
  - CBO
  - Gain Changes
- **Pion dominates to create "flash"**
- **"Pure" Muon Beam w/ Better Quality**

$\sigma_{\text{syst}}\ \omega_a$	R99 (ppm)	R00 (ppm)	R01 (ppm)
Pileup	0.13	0.13	0.08
AGS background	0.10	0.01	‡
Lost Muons	0.10	0.10	0.09
Timing Shifts	0.10	0.02	‡
E-field and pitch	0.08	0.03	‡
Fitting/Binning	0.07	0.06	‡
CBO	0.05	0.21	0.07
Gain Changes	0.02	0.13	0.12
Total for ω_a	0.3	0.31	0.21

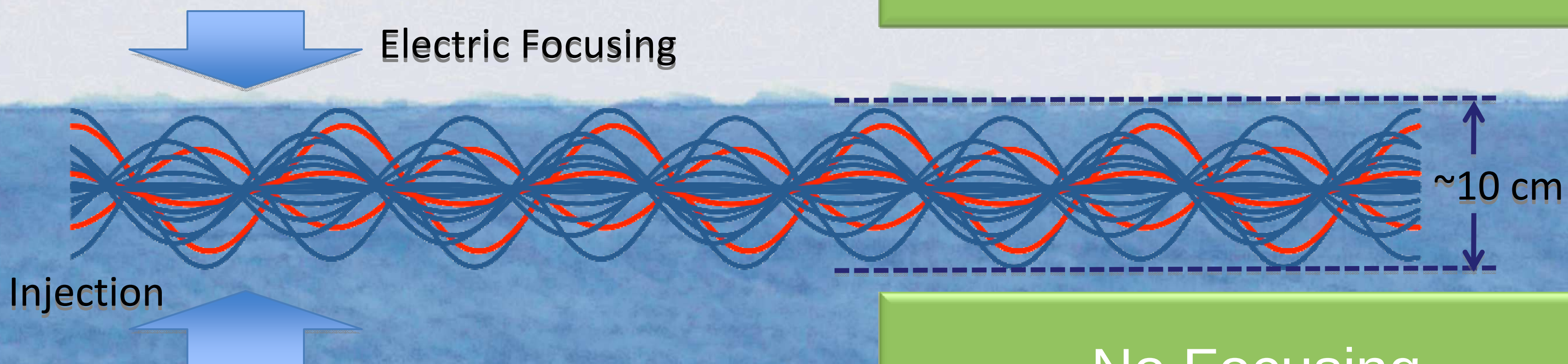

J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
HFS
DeeMe
g-2/EDM
H-Line for
Muon Fundamental Physics


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Muonium Production
(300 K ~ 25 meV)
Silicon Tracker
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10^6 μ+/s)
Muon LINAC
(300 MeV/c)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

Off Magic Momentum?

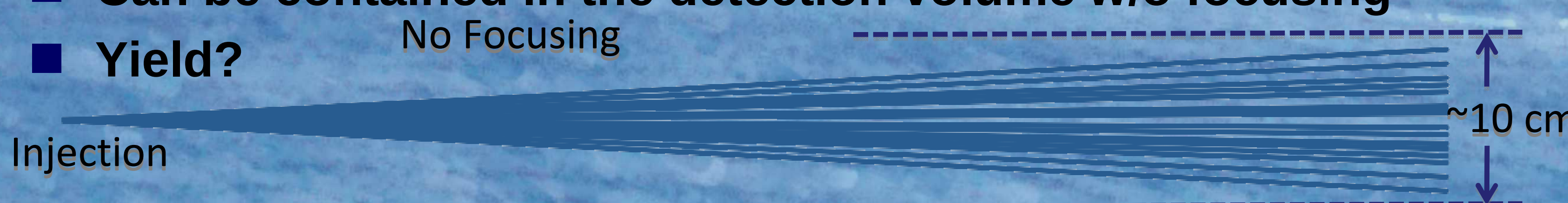
- Tertiary Muon Beam
  - Widely spread over phase space
  - Contamination of pion

Electric Field for Focusing
⇒ Magic Momentum

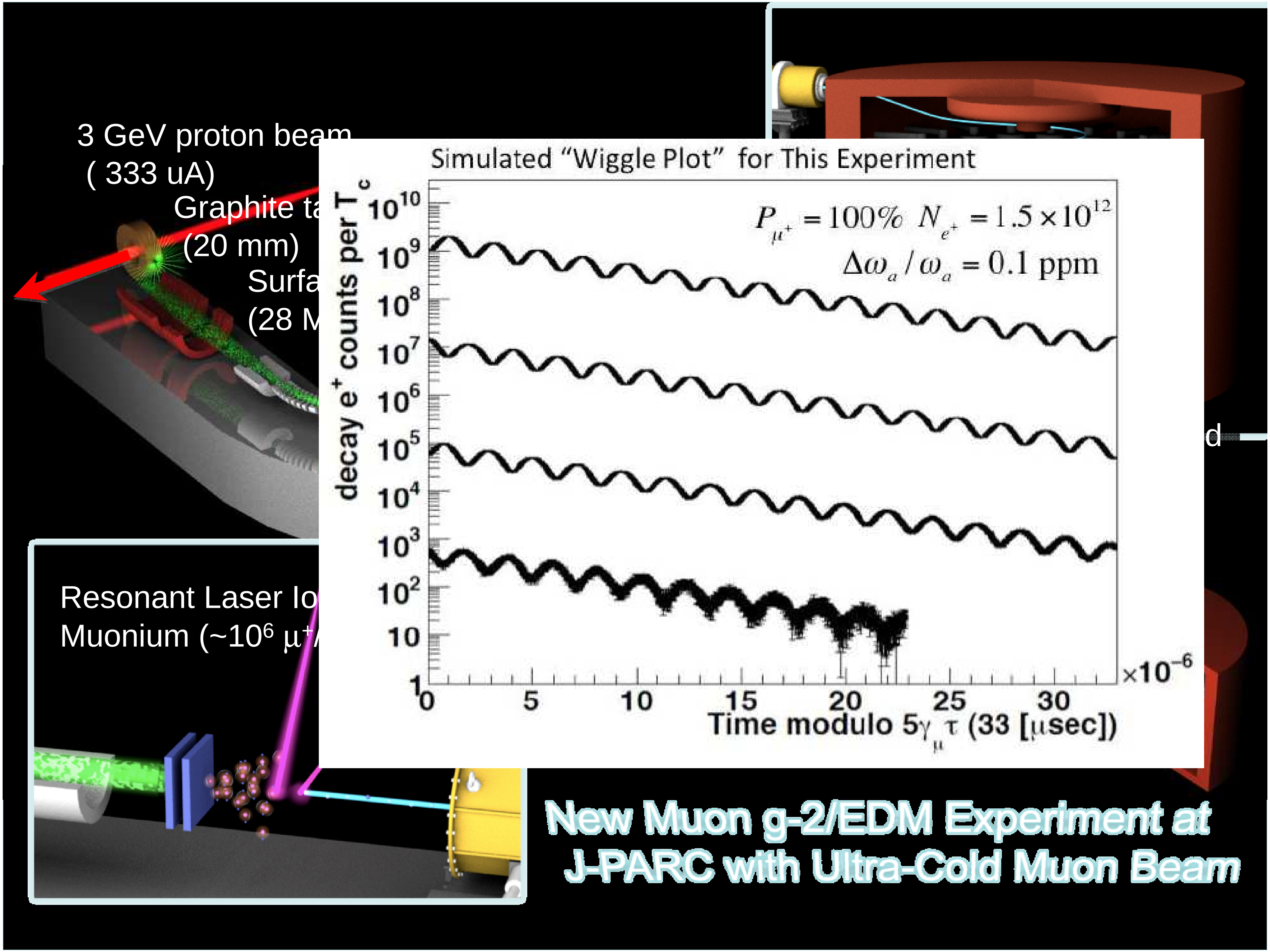


No Focusing
⇒ Any Momentum

- Ultra-Cold Muon Beam
  - Can be contained in the detection volume w/o focusing
  - Yield?



$\sigma(p_T)/p_L \leq 10^{-5}$ → < 10 cm spread over 10 km travel


3 GeV proton beam
(333 uA)
Graphite ta
(20 mm)
Surfa
(28 M
Resonant Laser Io
Muonium (~10⁶ μ⁺/
d
Simulated "Wiggle Plot" for This Experiment
$P_{\mu^+} = 100\%$ $N_{e^+} = 1.5 \times 10^{12}$
$\Delta\omega_a / \omega_a = 0.1$ ppm
decay e⁺ counts per T_c
Time modulo 5γ_μτ (33 [μsec])
×10⁻⁶
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

BNL, FNAL, and J-PARC

- complimentary

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

Magic vs "New Magic"

- **Complimentary!**

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

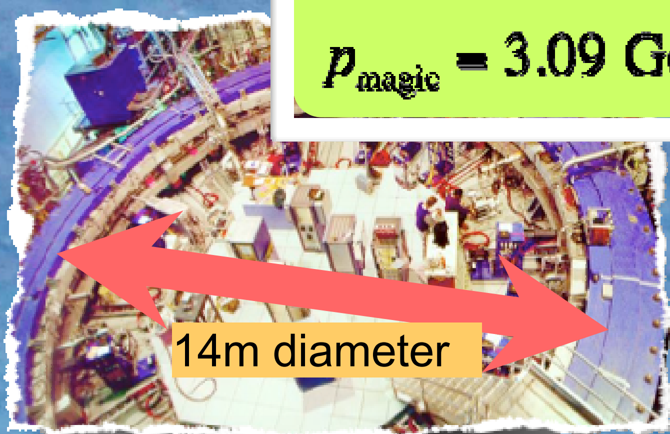
BNL/Fermilab Approach

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

$$\eta \approx 0$$

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

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

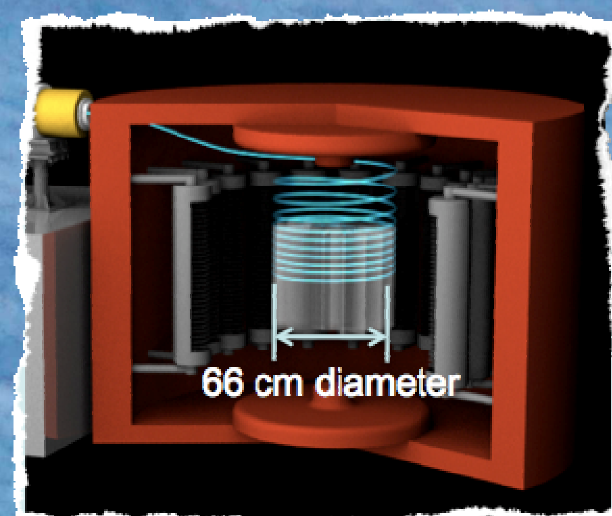


$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

J-PARC Approach

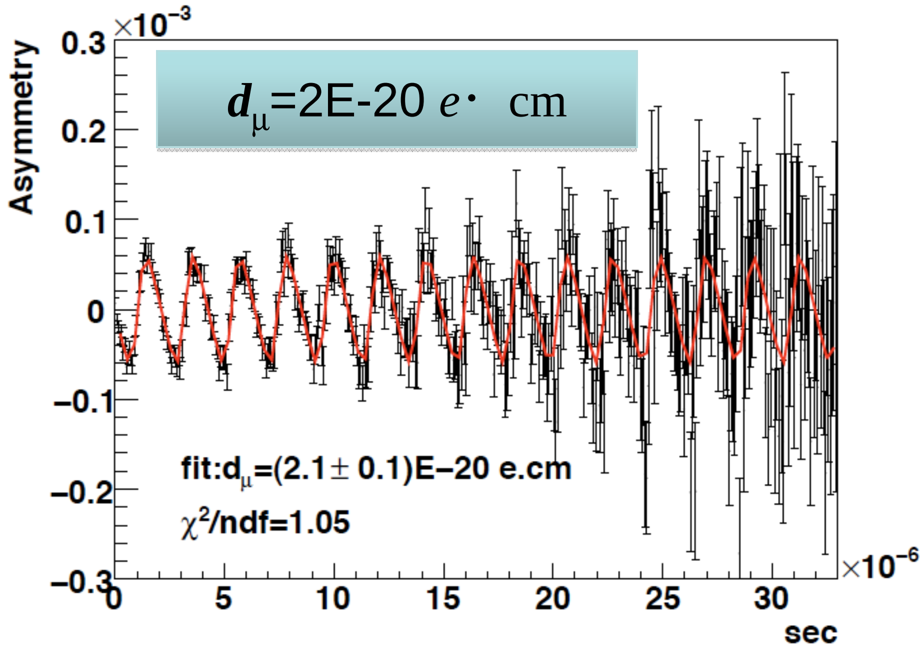
$$\vec{E} = 0$$

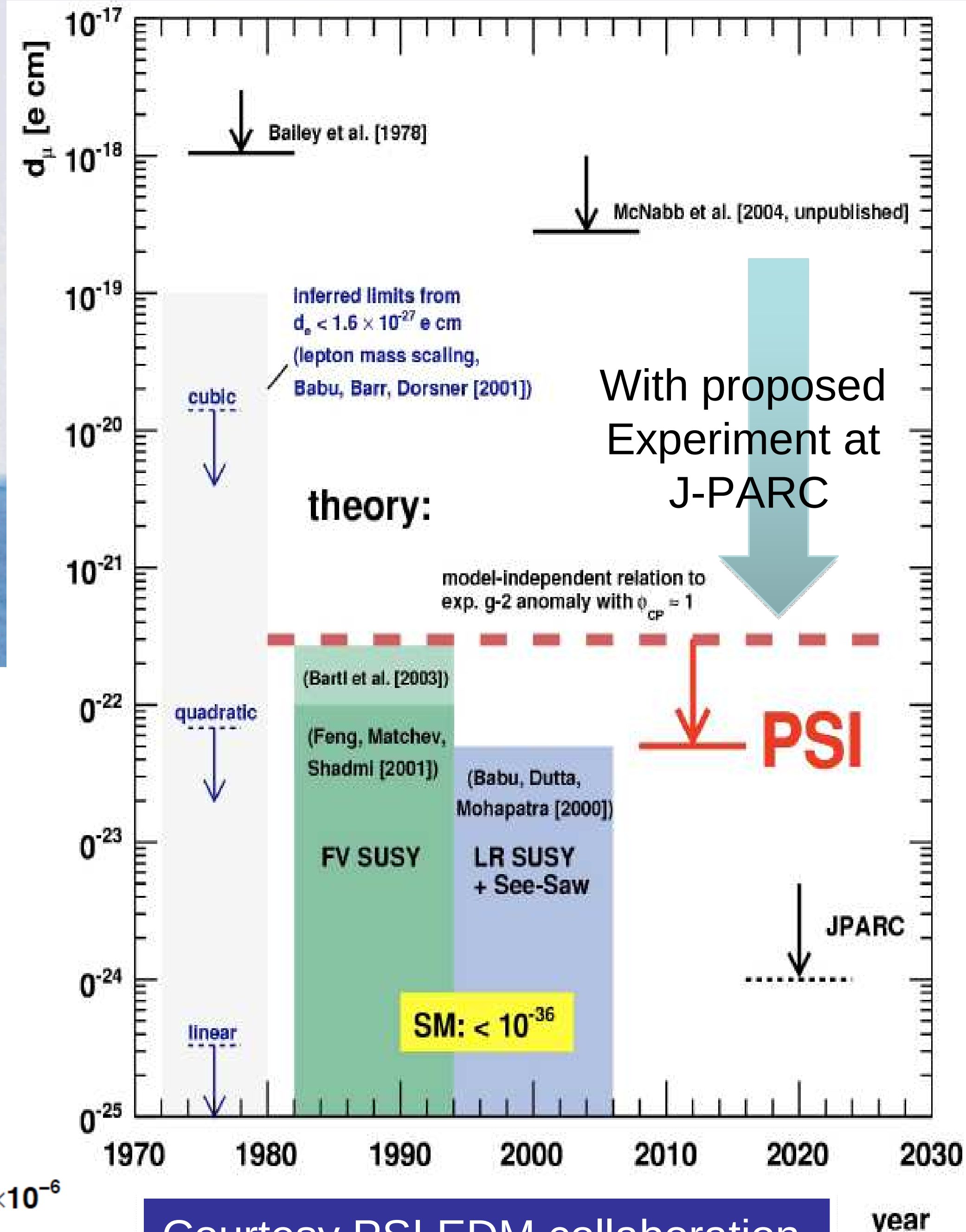
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$



Muon EDM

- Direct CPV in Lepton Sector
- Current Exp. Limit ~ 1e-19
- Sensitivity of J-PARC Exp. <1e-20

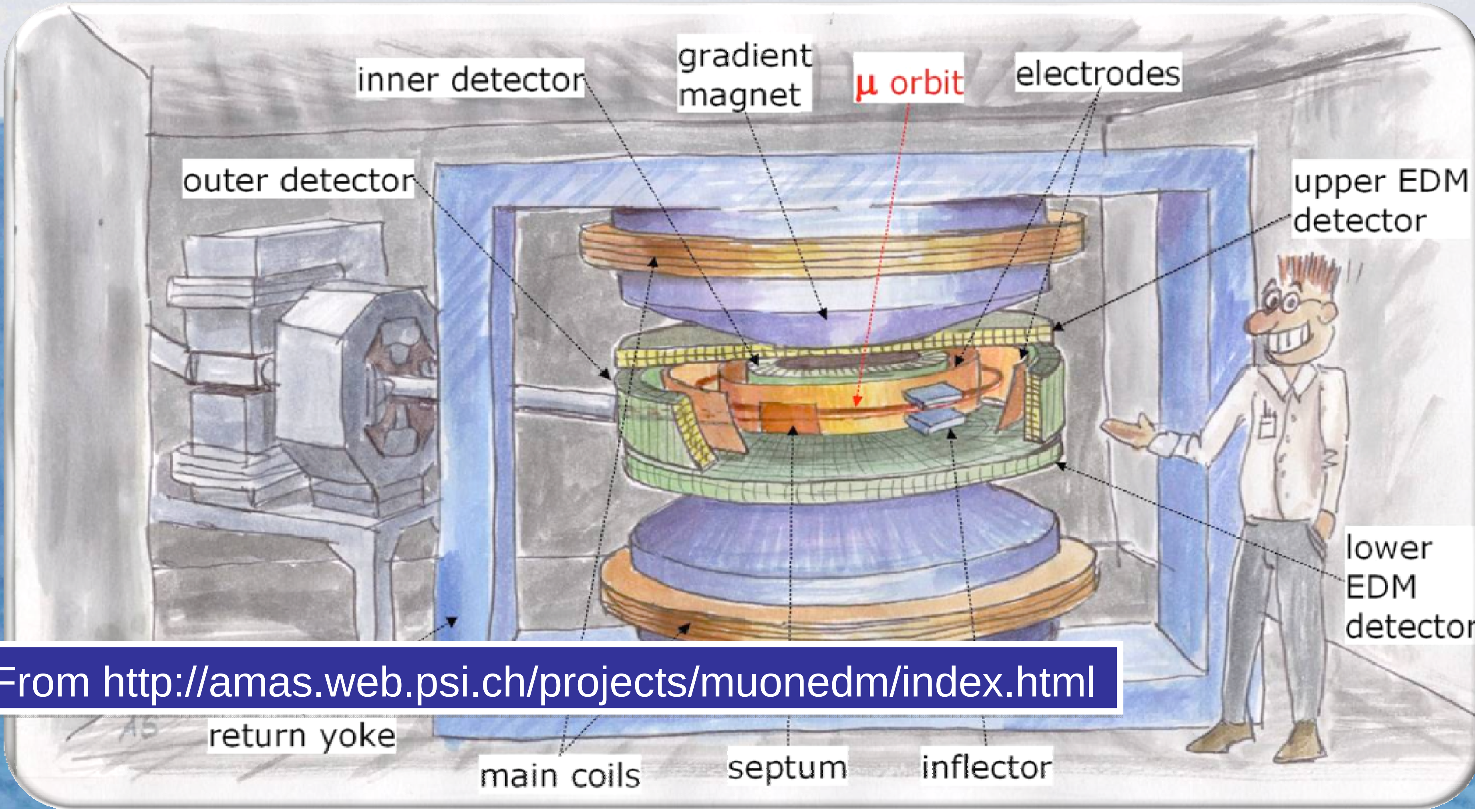




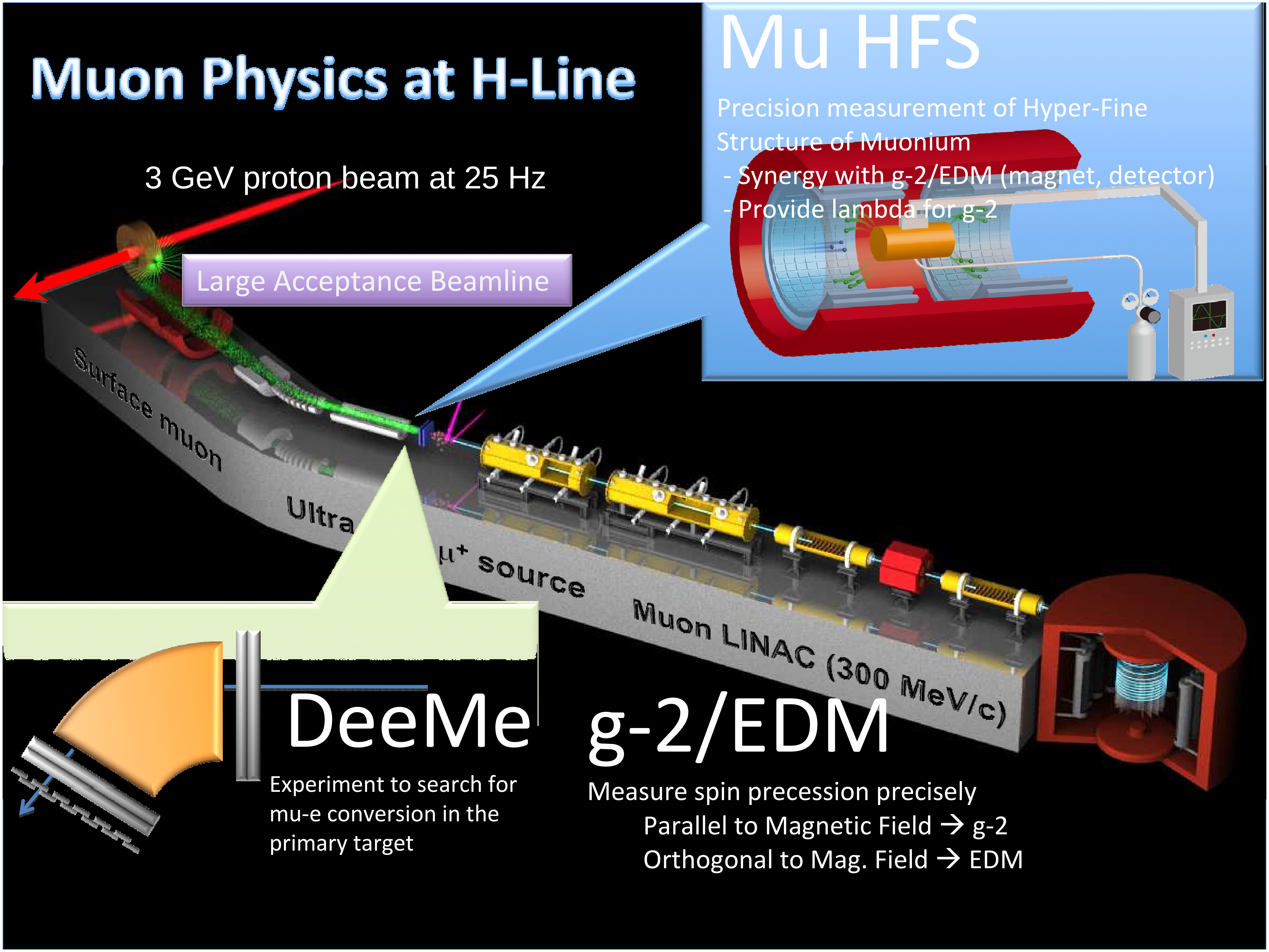
Courtesy PSI EDM collaboration

Muon EDM at PSI

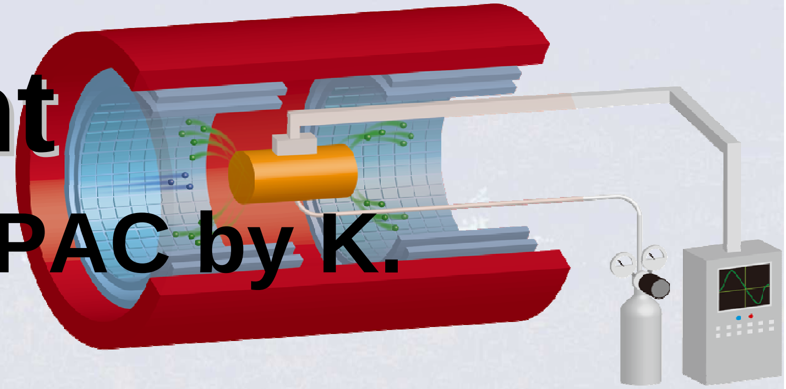
- A nice experimental proposal using "spin frozen" technique!



From http://amas.web.psi.ch/projects/muonedm/index.html


Muon Physics at H-Line
3 GeV proton beam at 25 Hz
Large Acceptance Beamline
Surface muon
Ultra
μ+ source
Muon LINAC (300 MeV/c)
Mu HFS
Precision measurement of Hyper-Fine Structure of Muonium
- Synergy with g-2/EDM (magnet, detector)
- Provide lambda for g-2
DeeMe
Experiment to search for mu-e conversion in the primary target
g-2/EDM
Measure spin precession precisely
Parallel to Magnetic Field → g-2
Orthogonal to Mag. Field → EDM

Mu HFS Experiment



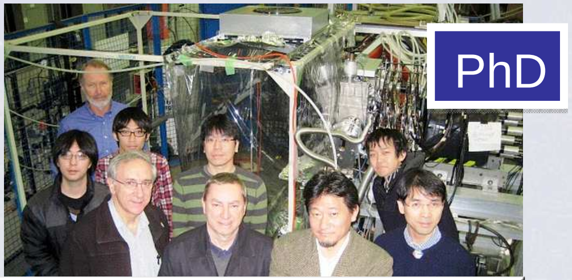
- Proposed to IMSS Muon PAC by K. Shimomura
  - 1st stage approved
- Synergy with g-2/EDM

$$g_\mu - 2 = \frac{R}{\lambda - R}, R \equiv \frac{\omega_a}{\omega_p}, \lambda \equiv \frac{\mu_\mu}{\mu_p}$$

  - Physics
    - lambda is needed for g-2/EDM
      - Past measurement: only two points for linear extrapolation
  - Technologies
    - Ultra-precision magnet: small scale “prototype” for g-2/EDM
    - Detector
- Grant by K. Shimomura and Y. Matsuda

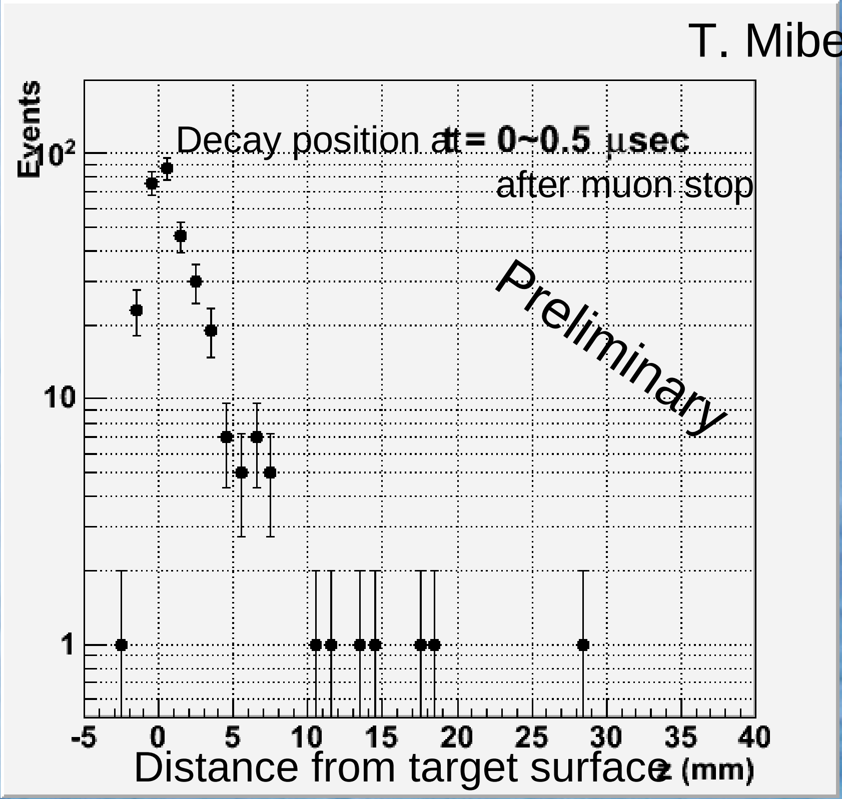
Mu Target R&D S-1249 :
preliminary conclusions and outlook

- **Experimental apparatus with MCP(new!) worked very well.**
- **The first data with aerogel (27mg/cm^3) already indicates that Mu production rate is similar to that of hot-W (2% at 27MeV/c) .**
- **The first beam time was canceled in the middle. But, we have more samples to study the density and structure dependence.**
- **Will continue this fall. (Additional 2 weeks has been approved by TRIUMF EEC.)**



Silica aerogel (27mg/cm^3)

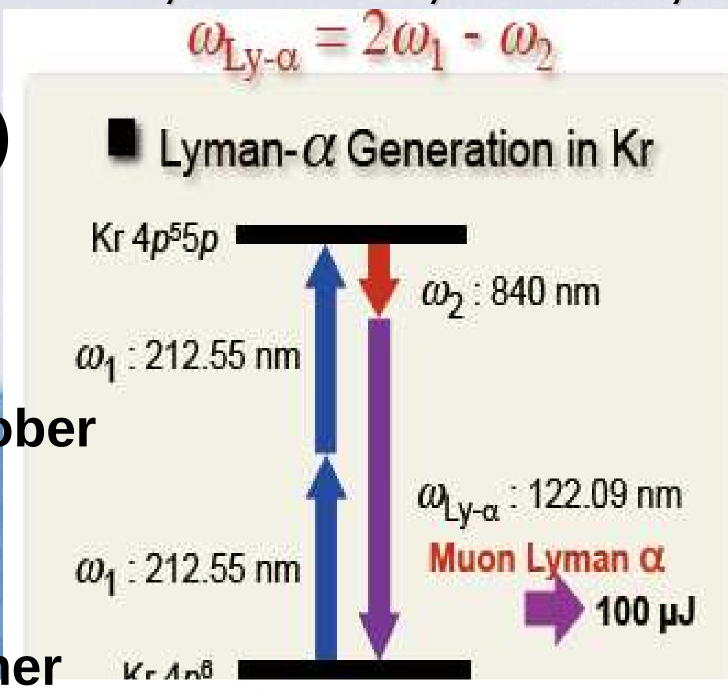
T. Mibe

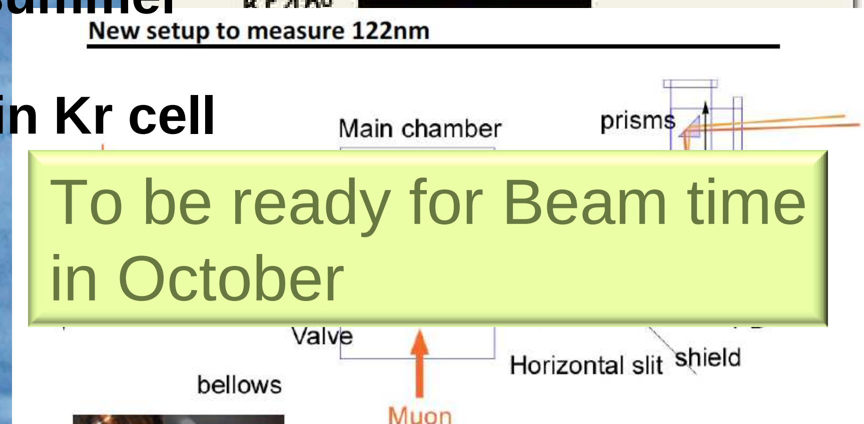


Laser R&D and Ionization Test

N.F. Saito, O. Louchev, S. Wada, K. Yokoyama, K. Ishida, M. Iwasaki, P. Bakule, D. Tomono

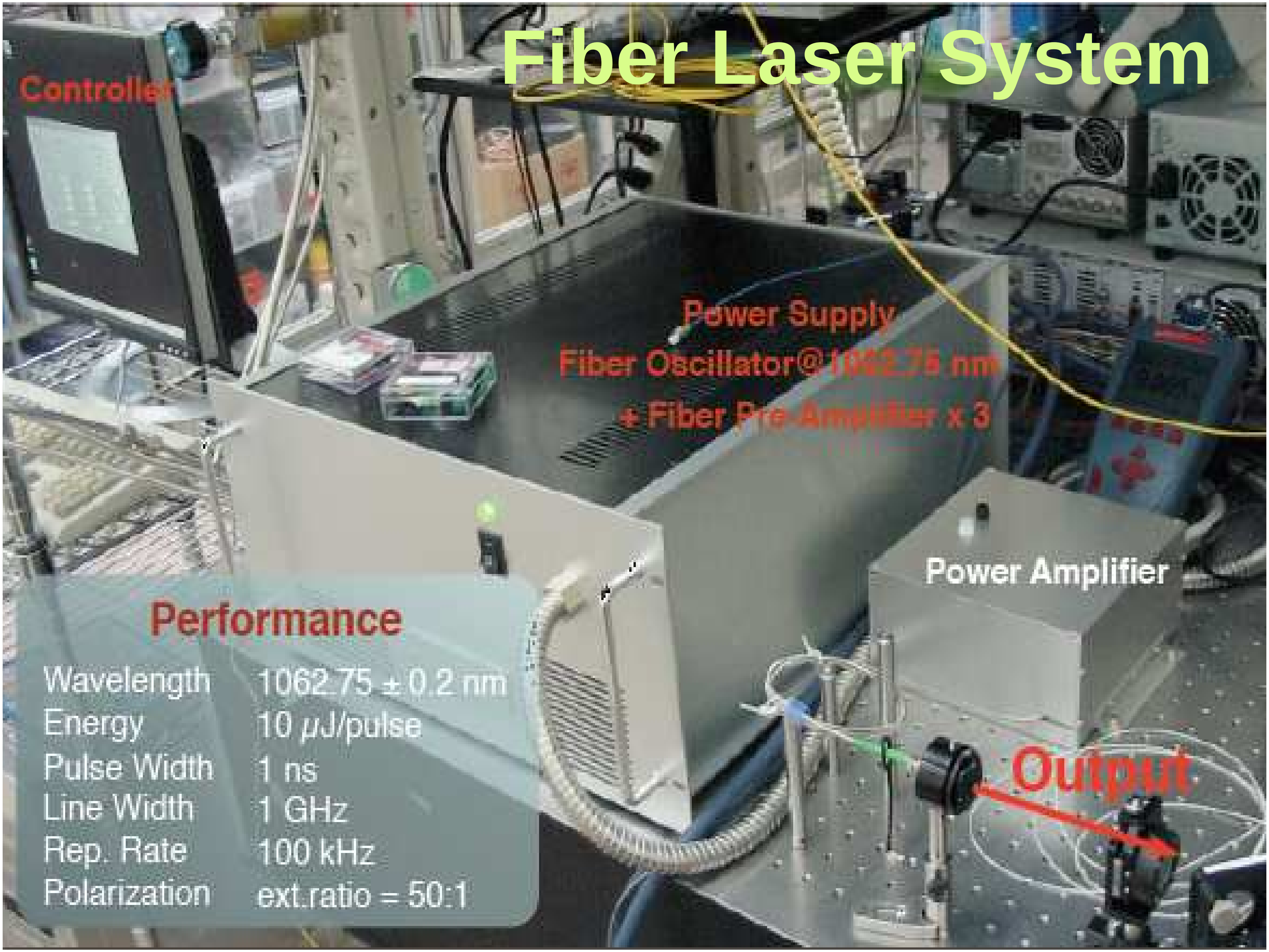
- **Laser Development at RIKEN (x100)**
  - **Omega-1**
    - **Fiber Laser System** ✓
    - **Solid State Amplifier** ✓
    - **Non-linear frequency converter ~ October**
  - **Omega-2**
    - **SLM Seeder**
    - **1st and 2nd Non-linear amplification** } **~ This summer**
  - **2-photon resonant 4-wave mixing in Kr cell ~ October**

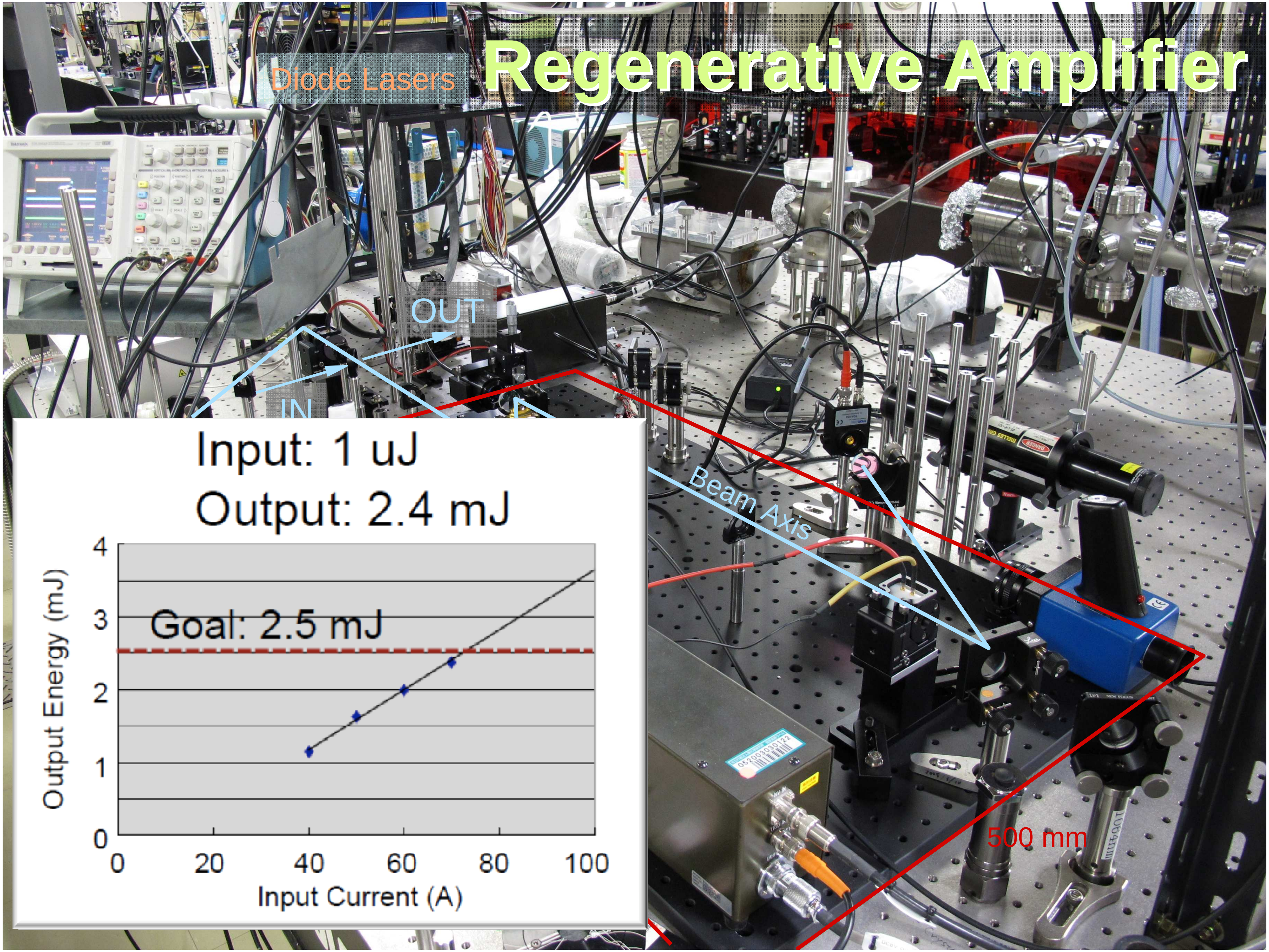




To be ready for Beam time in October

- **Ionization Test at RAL (x10)**
  - **X10 higher power, planned**
  - **April beam time, mostly spent on system recovery**
  - **Delays due to VISA problem, Personnel Change…**


Fiber Laser System
Controller
Power Supply
Fiber Oscillator@1062.75 nm
+ Fiber Pre-Amplifier x 3
Power Amplifier
Output
Performance
Wavelength 1062.75 ± 0.2 nm
Energy 10 μJ/pulse
Pulse Width 1 ns
Line Width 1 GHz
Rep. Rate 100 kHz
Polarization ext.ratio = 50:1

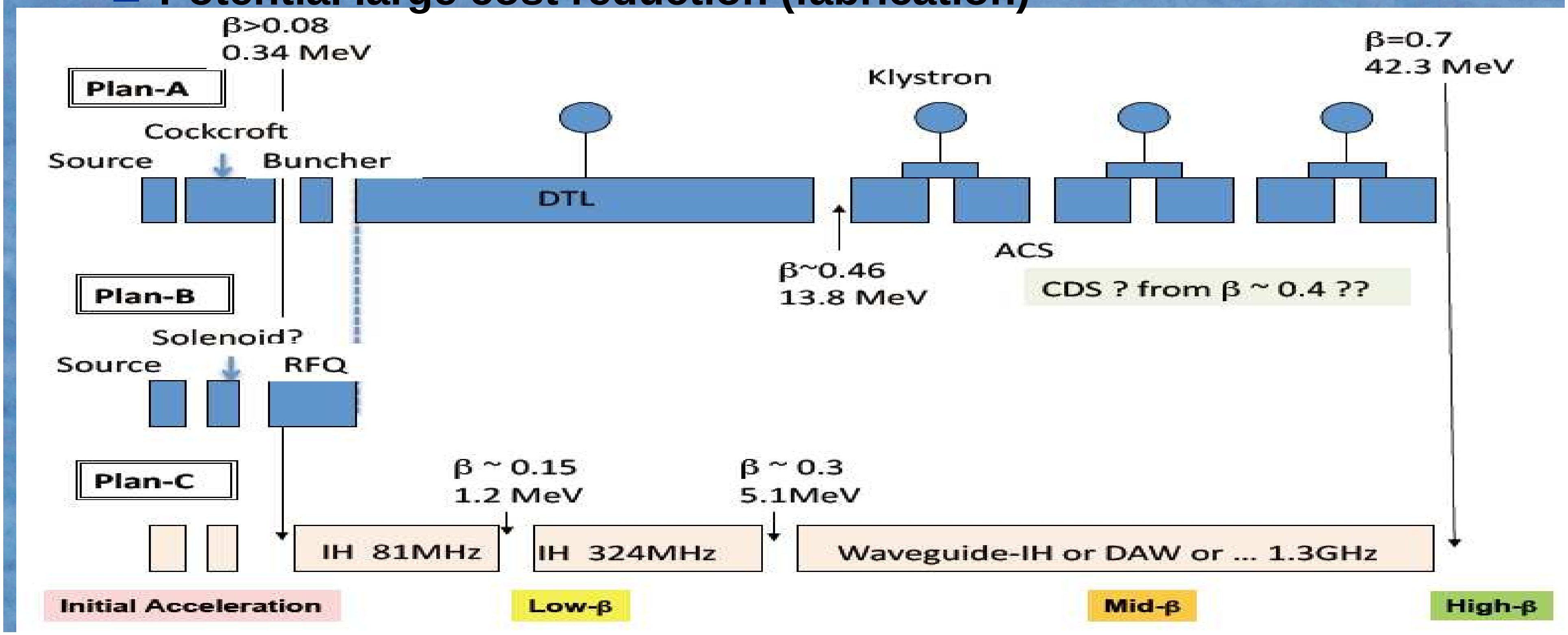


Regenerative Amplifier
Diode Lasers
OUT
IN
Beam Axis
500 mm
Input: 1 uJ
Output: 2.4 mJ
Goal: 2.5 mJ
Output Energy (mJ)
Input Current (A)
0
1
2
3
4
0
20
40
60
80
100

Muon LINAC

N. Hayashizaki, M. Ikegami, N. Toge, and M. Yoshida

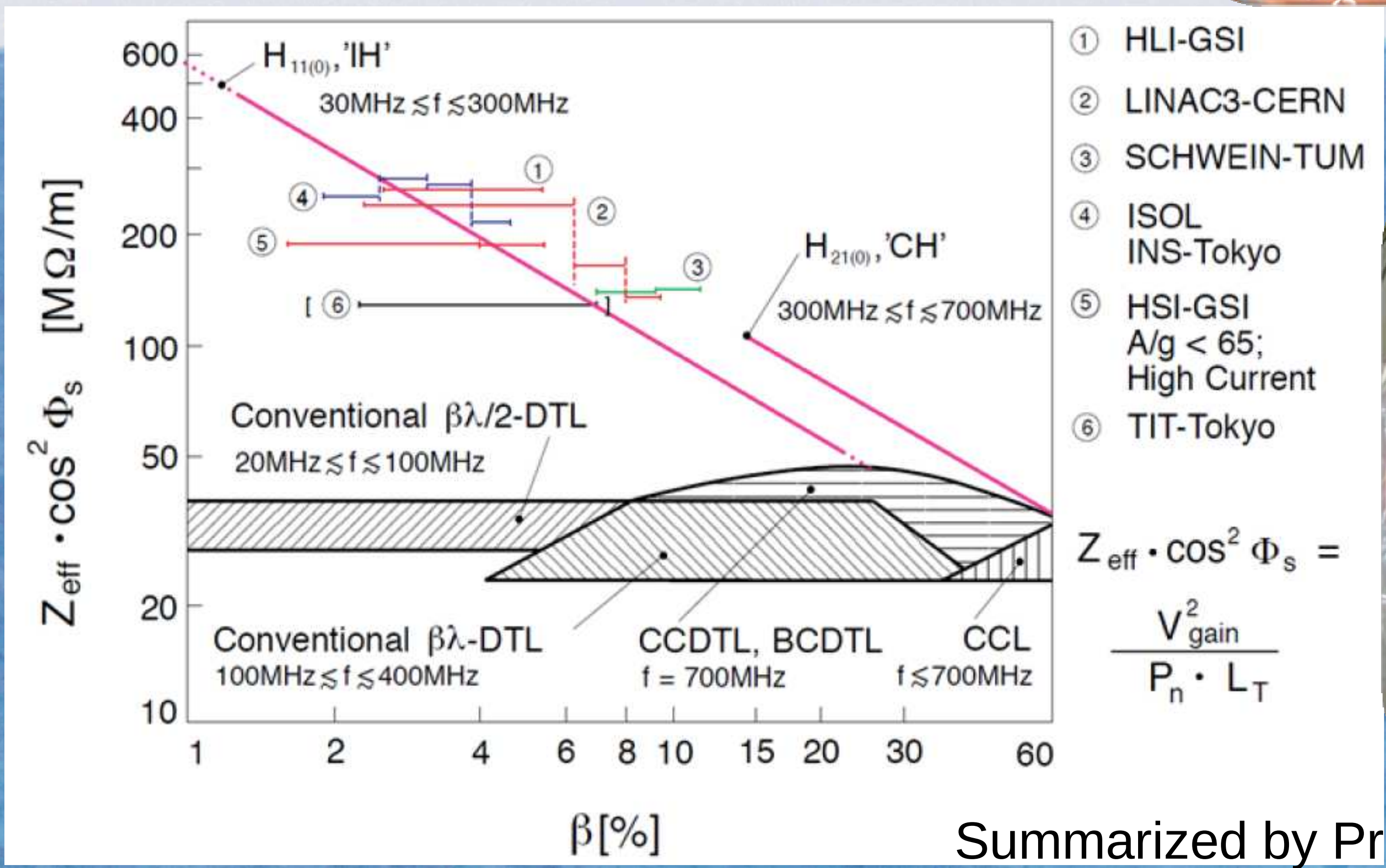
- **Refined cost estimate beyond expectation**
  - **Baseline: DTL+ACS for β<0.7**
- **Working on a different option**
  - **IH (Interdigital-H mode) Linac : higher Shunt Impedance in low-E**
  - **Potential large cost reduction (fabrication)**



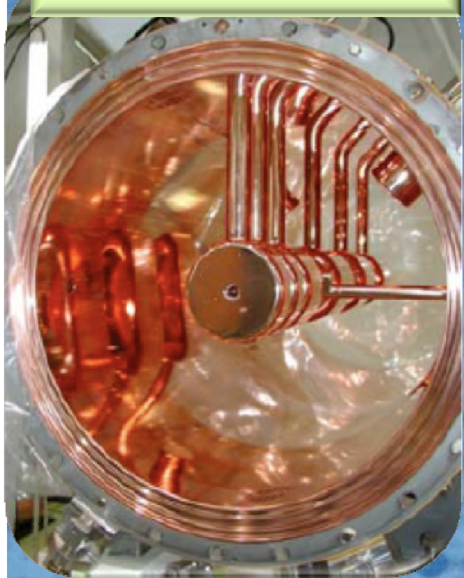
Why IH? Slides from Hayashizaki

- Shunt Impedance is higher
- Construction is easier
  - comes in three pieces

IH Linac



Alvarez Linac



Summarized by Prof. Ratzinger

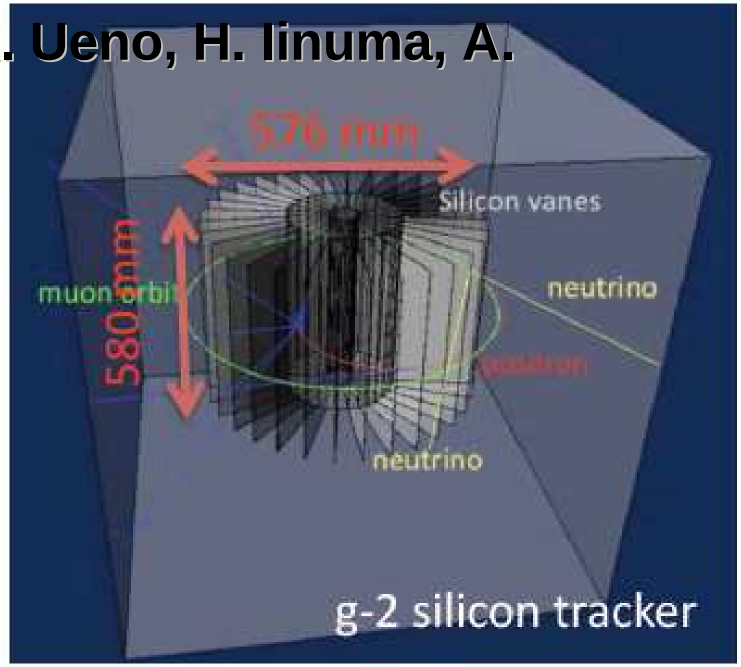
How we conclude on IH?

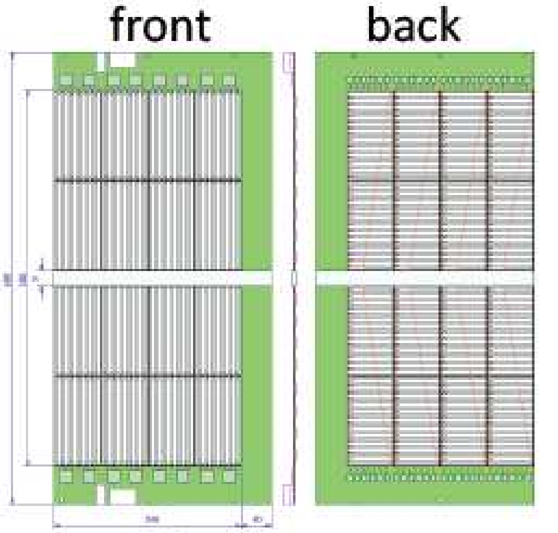
- IH option will be explored to complete the conceptual design this fall
- Move to prototype fabrication
  - TITech team has an experience to produce IH
- Muon acceleration test to be proposed at MUSE
  - Under discussion with relevant group

Detector System

O. Sasaki, T. Mibe, T. Kohriki, T. Kakurai, K. Ueno, H. Iinuma, A. Savoy-Navarro

- **Belle-II DSSD Sensor being evaluated**
  - **With Laser and Source at test bench**
  - **Further study with beam at CERN**
- **French SiLC group → FE**
- **Detector parameter optimization**
  - **Continuing Geant4 efforts**



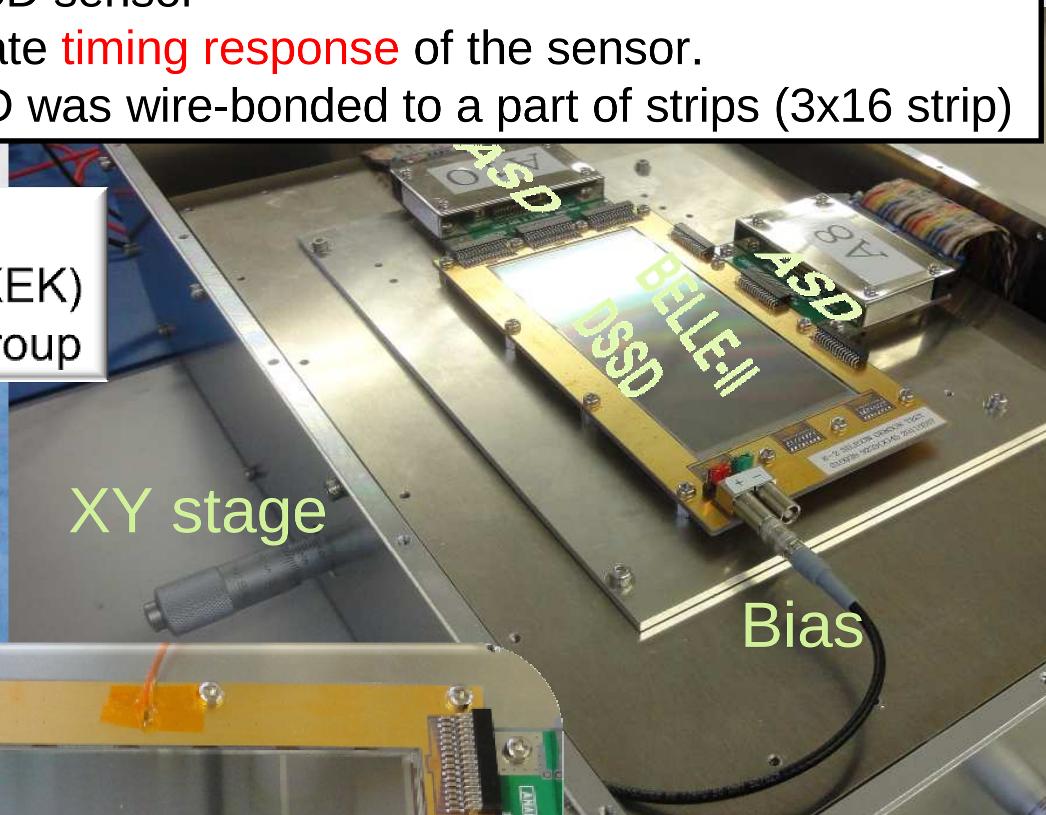


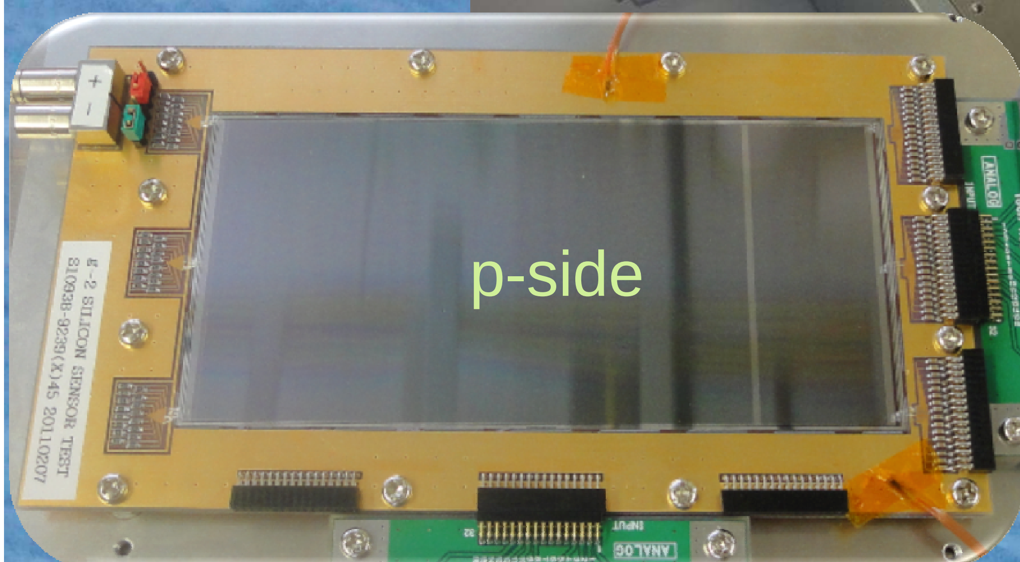
g-2 silicon vane

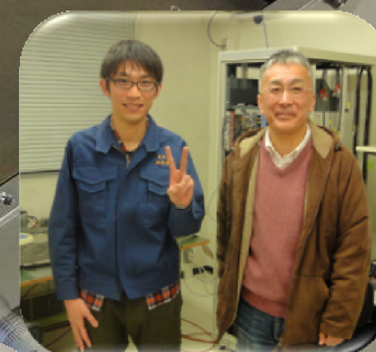
Evaluation of DSSD sensor

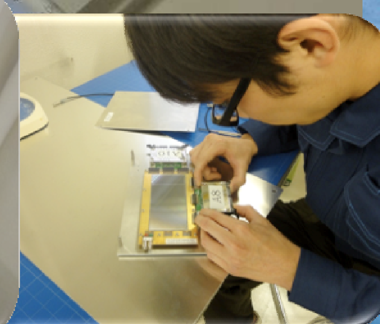
HPK's Belle-II DSSD sensor
was used to evaluate timing response of the sensor.
A fast shaping ASD was wire-bonded to a part of strips (3x16 strip)

Special thanks to
Toru Tsuboyama (KEK)
and Belle-II SVD group





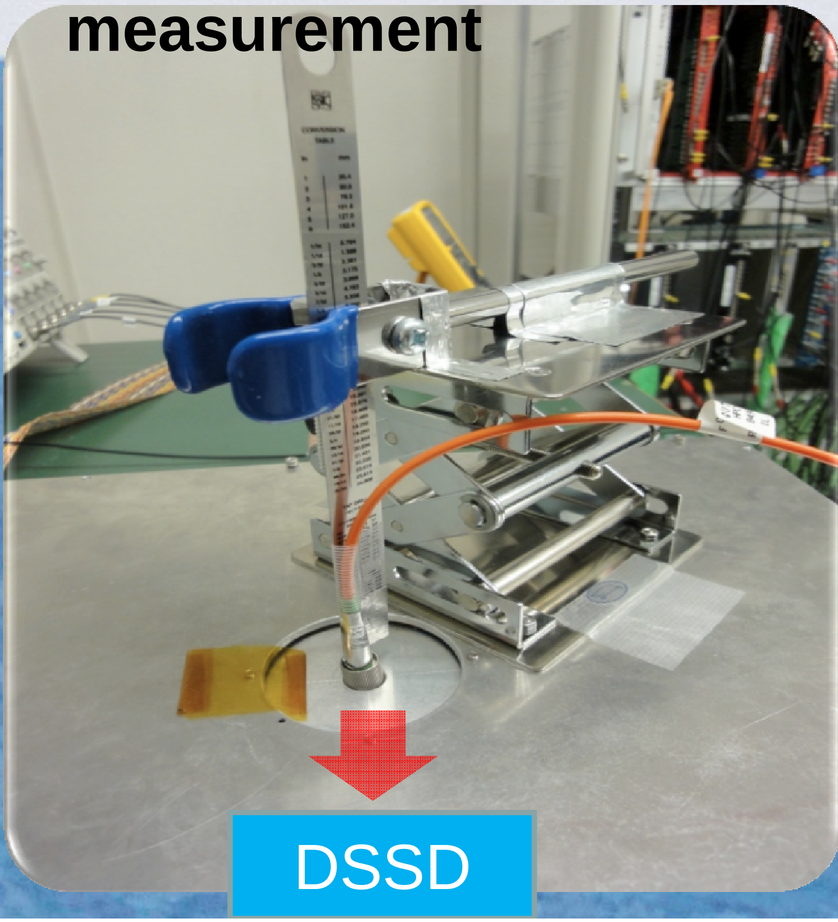




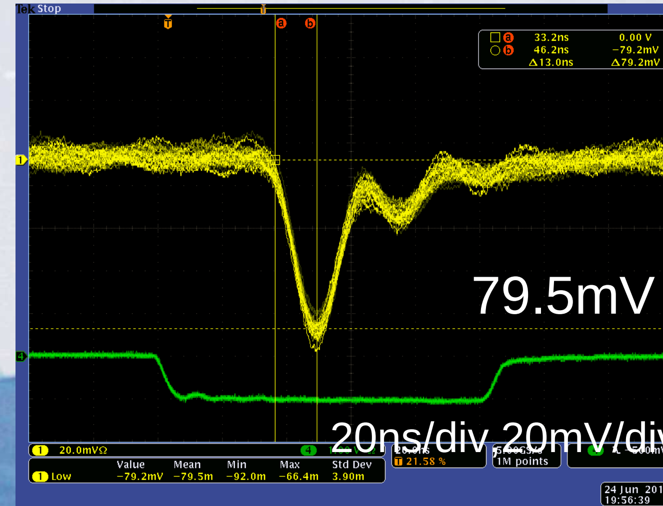
IR Laser Test

T.Kakurai, T. Mibe, K. Ueno

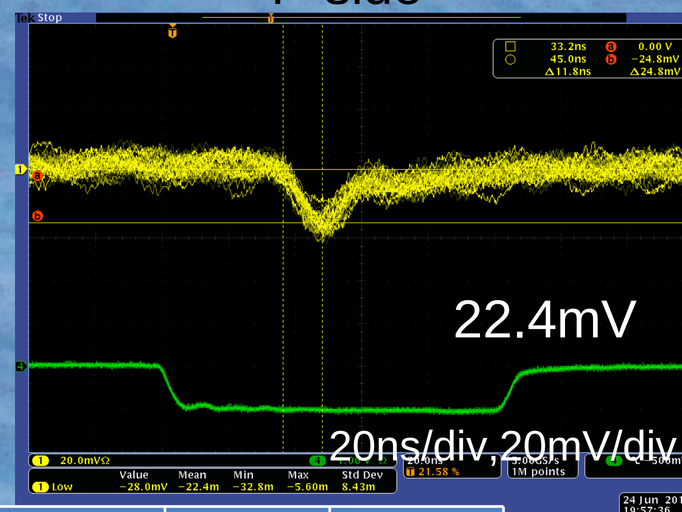
- **Both p and n-side has reasonable signal**
- **Will proceed to time response measurement**



N-side



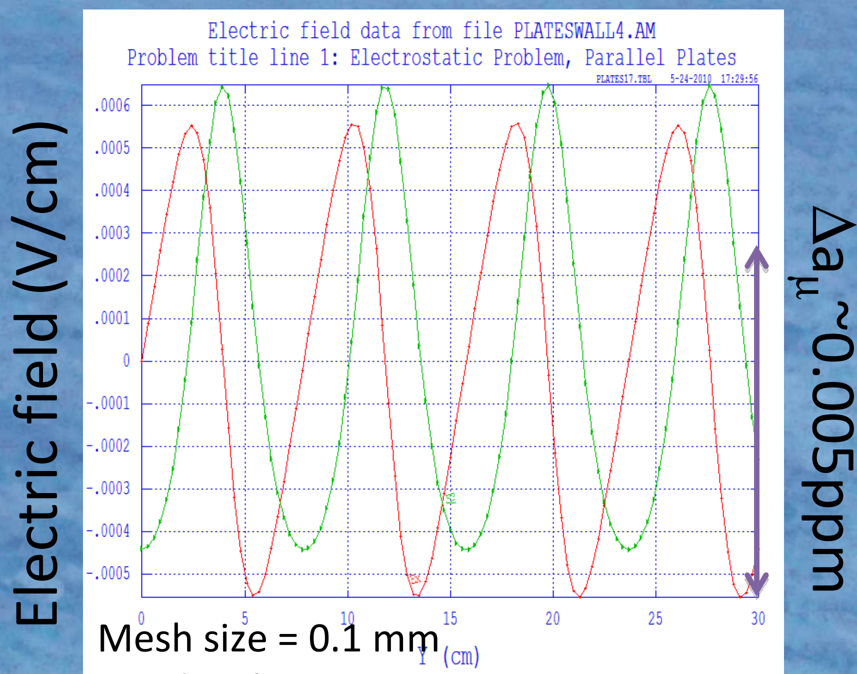
P-side



	P-side	N-side
Pitch[μm]	75	240

Stray Field around Detector

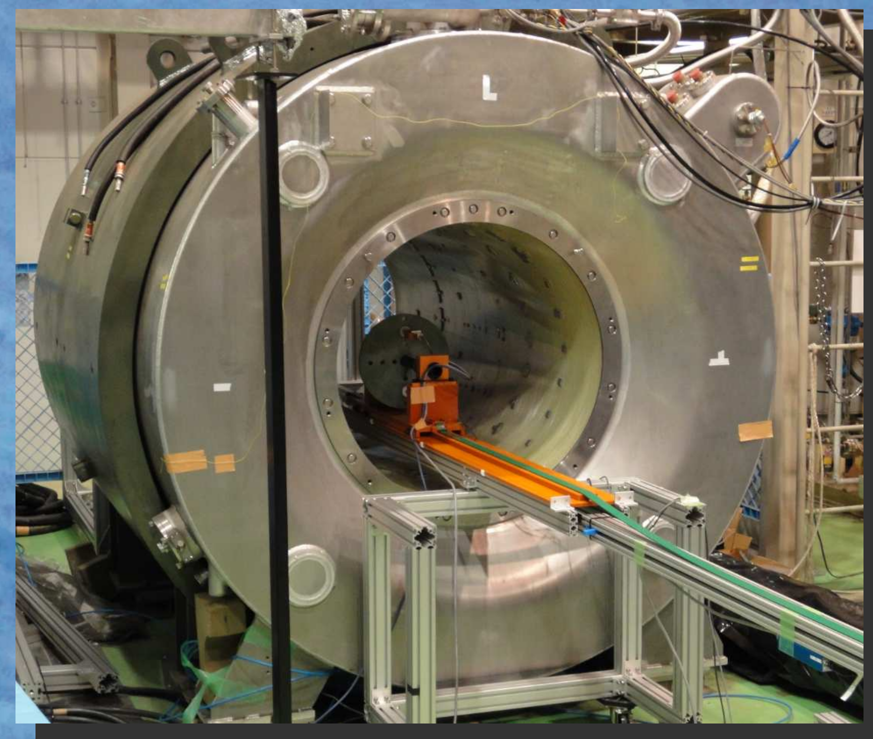
- Stray electric field can be shielded by wire
- Estimated to be negligibly small
- To be tested with HFS magnet soon



Mesh size = 0.1 mm

Window between wires = 0.2 mm

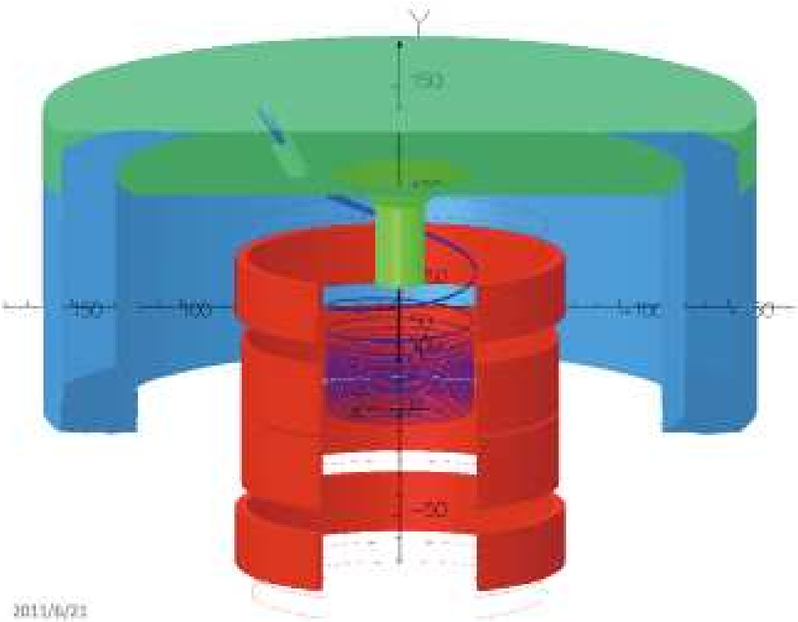
Mesh size may be too coarse to estimate the effect.



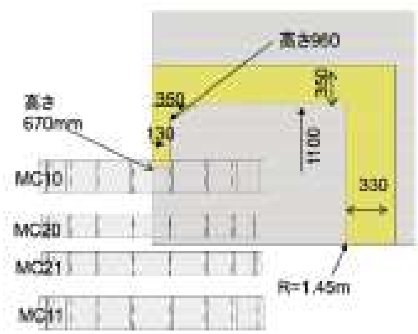
Slide by K. Sasaki

Coil Design Study

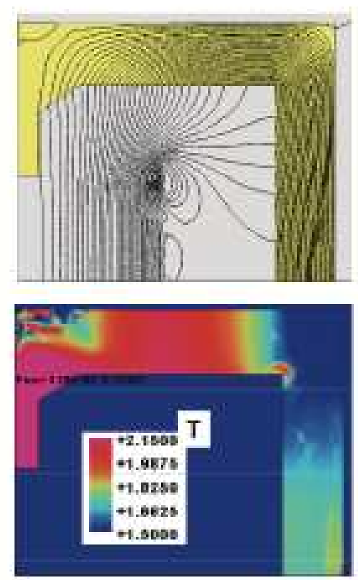
- **Collaboration with the company**
  - Field optimization : mainly done by the company
  - Beam tracking : KEK
- **Requirements**
  - Injection region: Beam could be injected smoothly
  - Storage region: Highly uniform field (< 1 ppm) as well as required Focusing field



	電流(kA)	R(m)	Z(m)	幅R(m)	幅Z(m)
MC10, 11	1707.82	0.8280	±0.5835	0.048	0.274
MC20, 21	737.50	0.8175	±0.149	0.0251	0.170



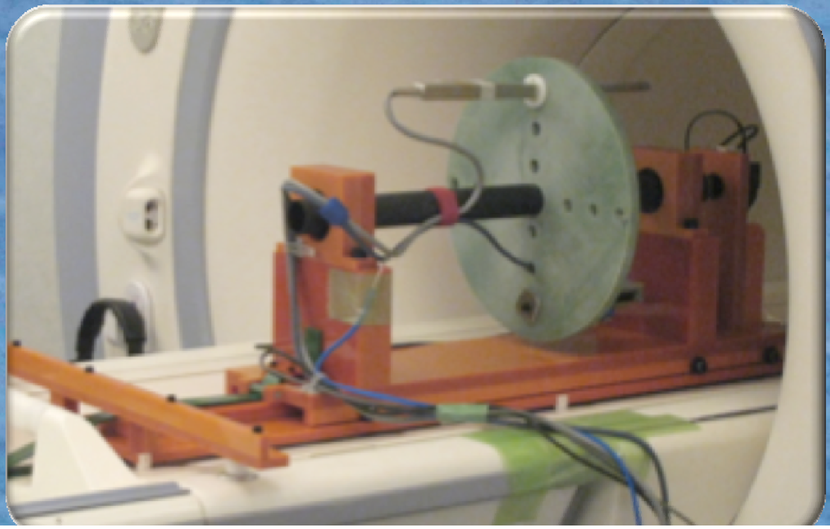
起磁力配置



磁力線(上)と鉄芯の磁化(下)

R&D for Precision Field Measurement K. Sasaki, M. Sugano, and H. Iinuma et al.

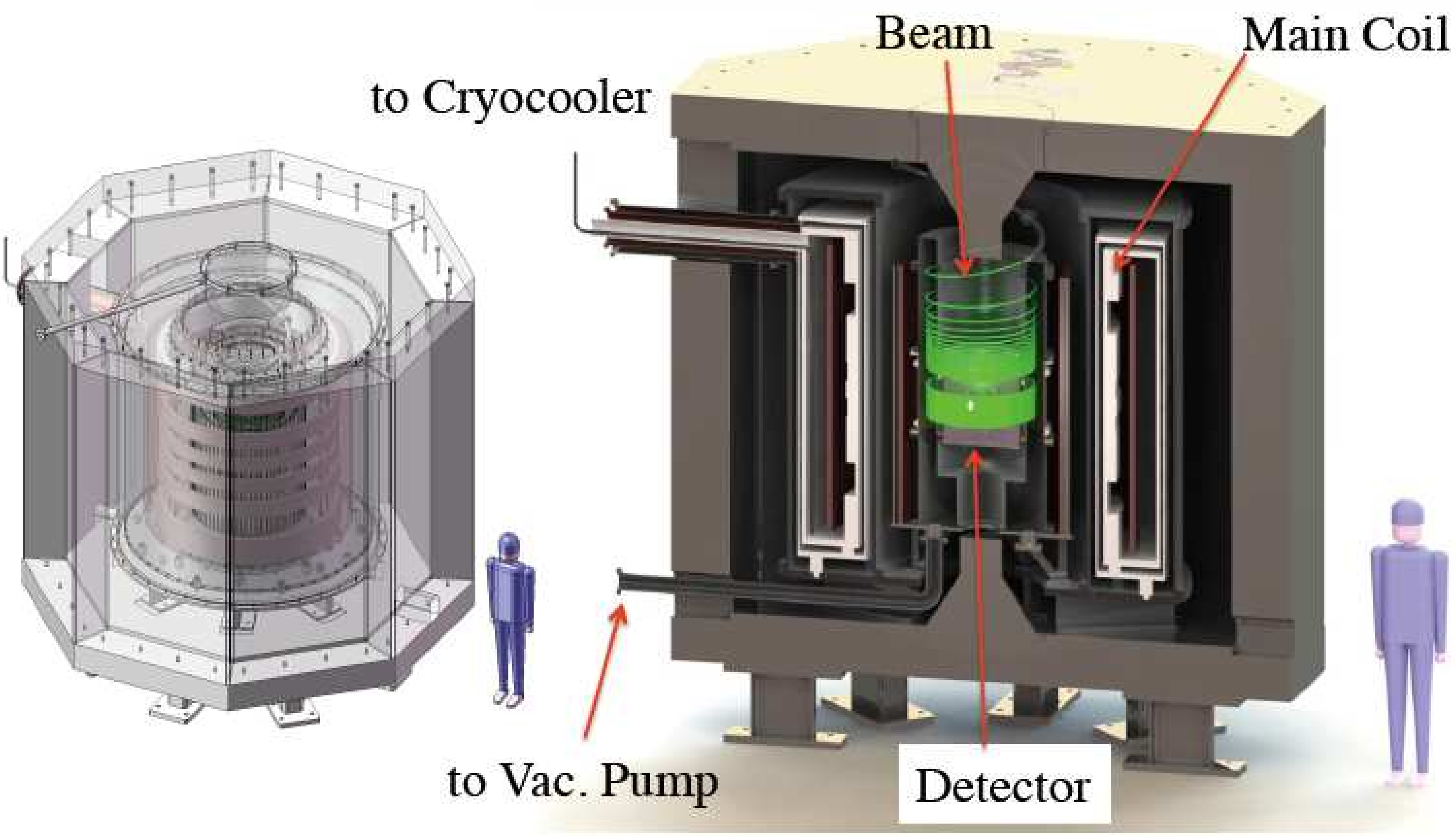
- 3T- MRI at National Institute of Radiological Science done
- NMR and Hall Probes (vector)
- First trial provided < 0.3 ppm stability for NMR (preliminary)
- To be continued



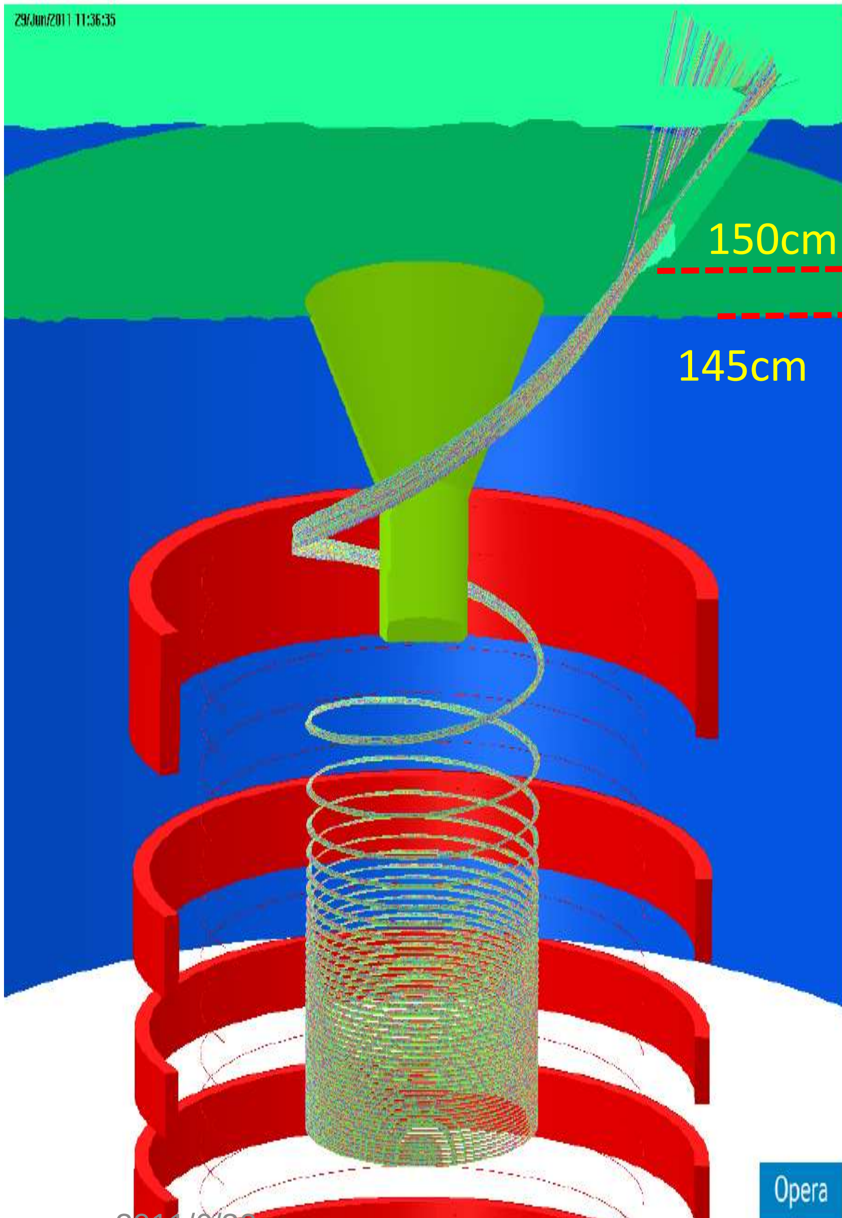
Mechanical Design ~ draft

Slide by K. Sasaki

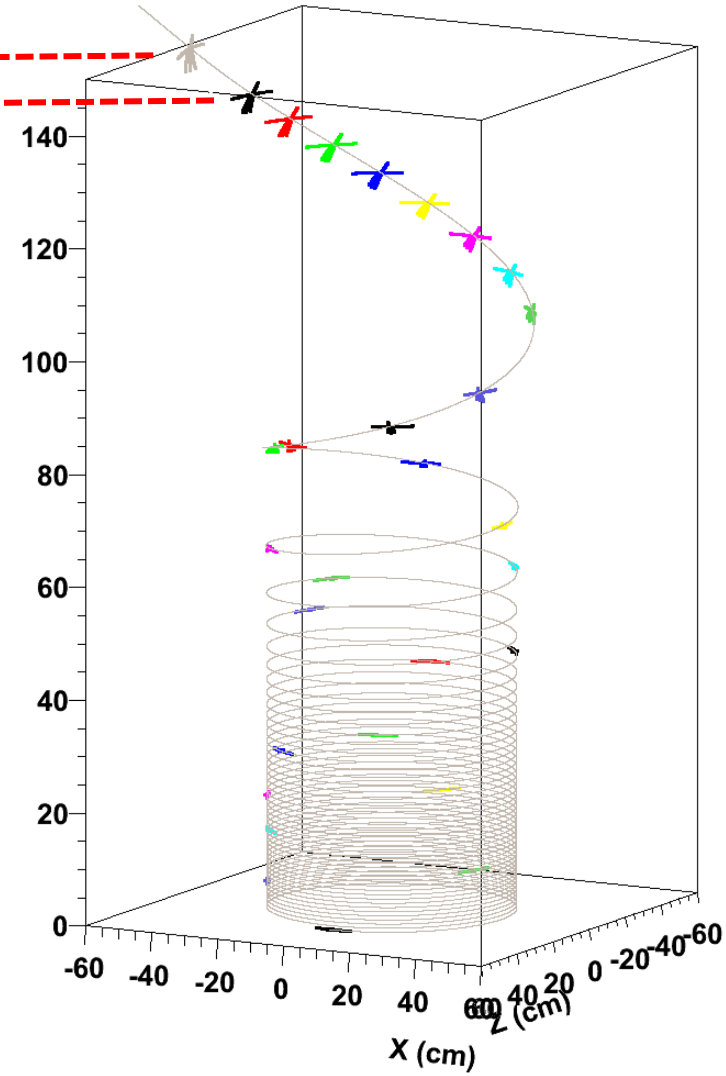
- Made by the company
- Will make the more practical model



Next step for beam injection study



1. Study fine slices inside a tunnel: 145 < y <180cm
2. Straight but cone shape tunnel?
3. Estimate emittance in the field “free” space (y>=150cm) and pass parameters to LINAC team



Slide by H. Iinuma

Summary

- Muon g-2/EDM @ J-PARC is proposed with novel technique : Ultra-Cold Muon Beam
- Key technologies are available and being optimized for the experiment → CDR
  - High intensity proton beam at J-PARC
  - Surface Muon beam at J-PARC MLF
  - Mu production target (TRIUMF-S1249)
  - Laser resonant ionization (RIKEN-RAL)
  - Muon LINAC
  - Hi-precision Magnet
  - Hi-rate silicon tracker

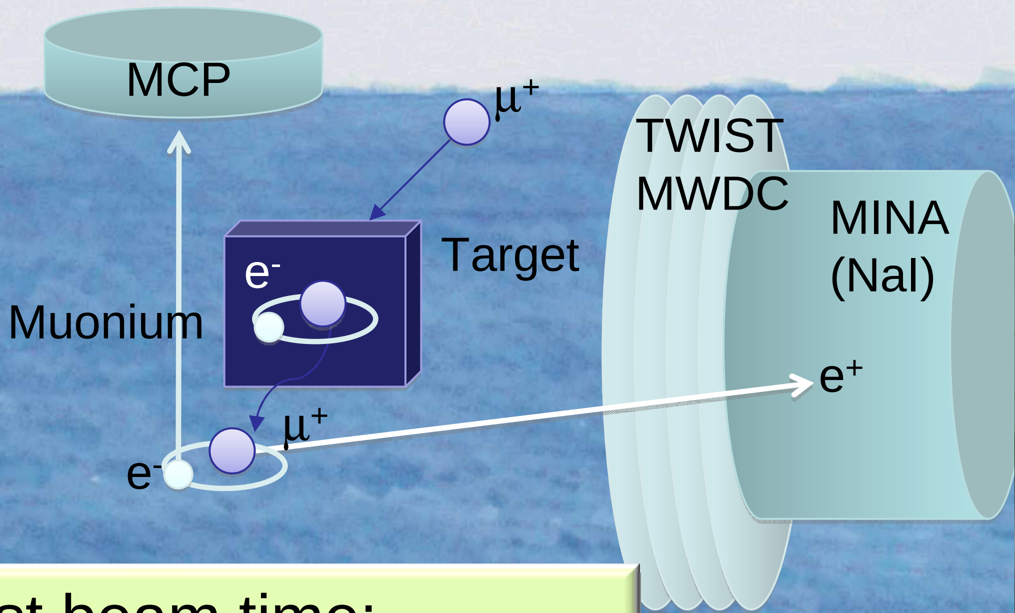
We warmly welcome new challengers to join us!

Mu Production

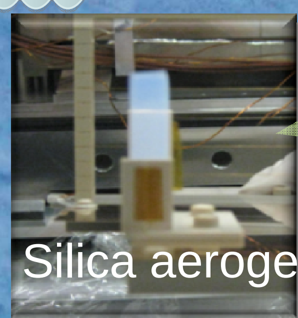
- Test experiment at TRIUMF: S1249
- Beam time for μSR measurements done right after the 1st CM
- Another beam time (last November) for "imaging" interrupt by Acc. problem, but 1/3 was successful
- Next beam time: late September to October
  ⇒(a part of) Thesis topics by Yuya Fujiwara
- Mu session today

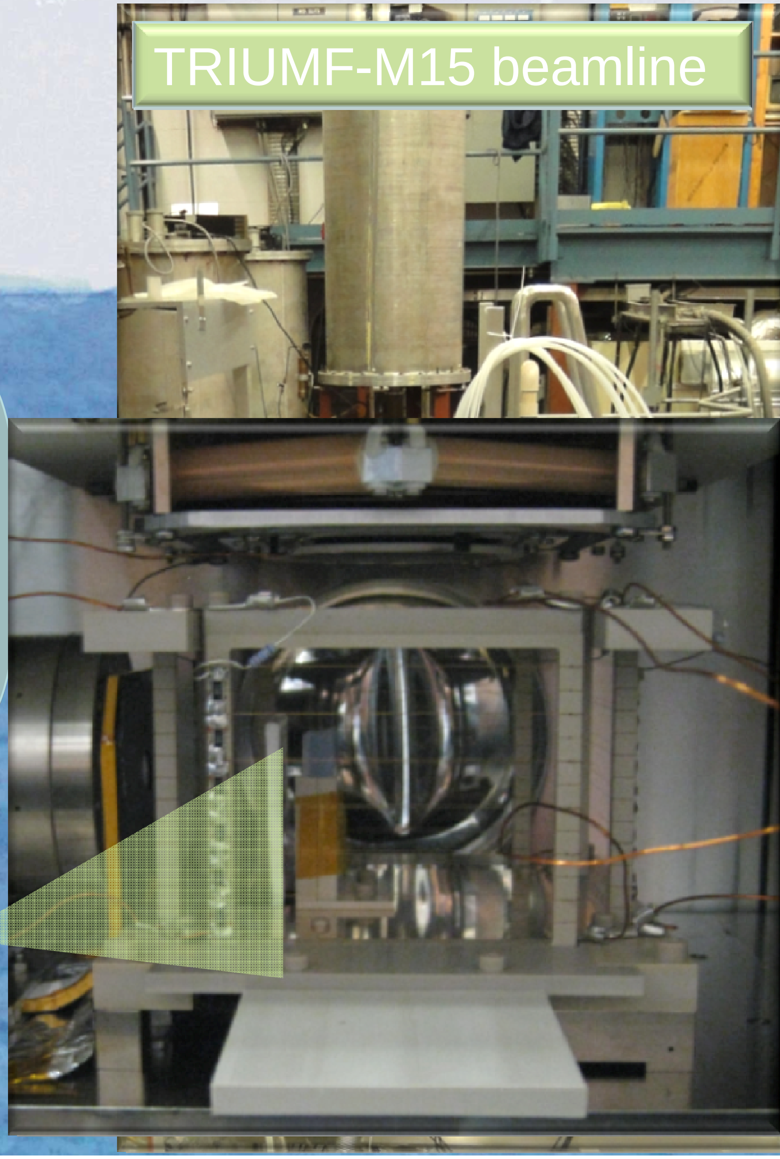
TRIUMF-S1249 : development of muonium production target at room temp.

Goals are to determine
- Muonium production rate and
- Muonium distribution in vacuum



First beam time:
~~Nov 18 – Dec 1, 2010~~
→Nov 18 – 23
(due to TRIUMF machine trouble)





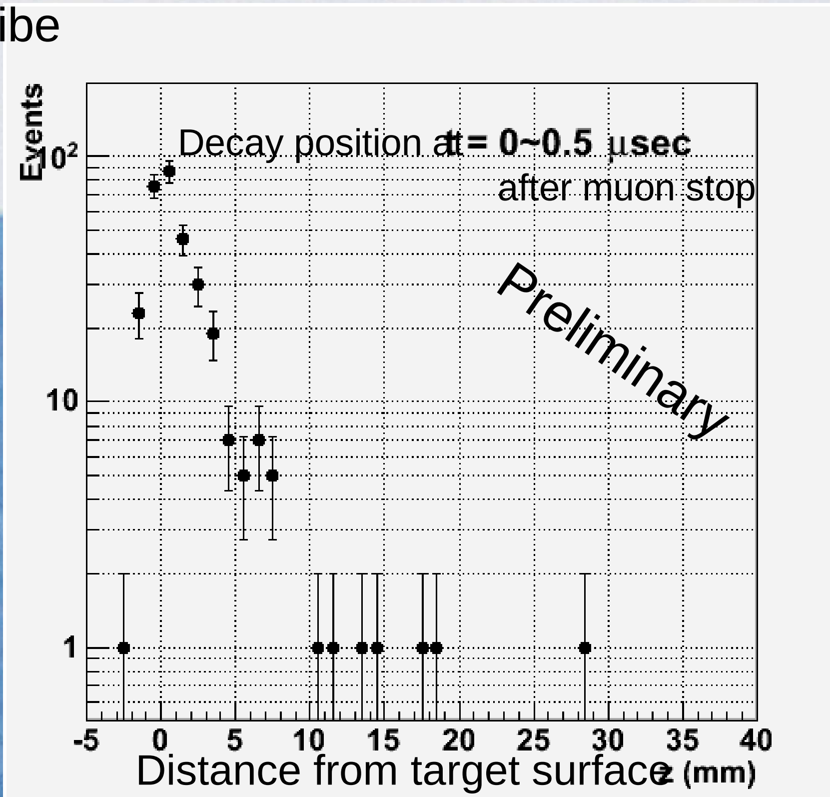
S-1249: Space-time Dist. of Mu

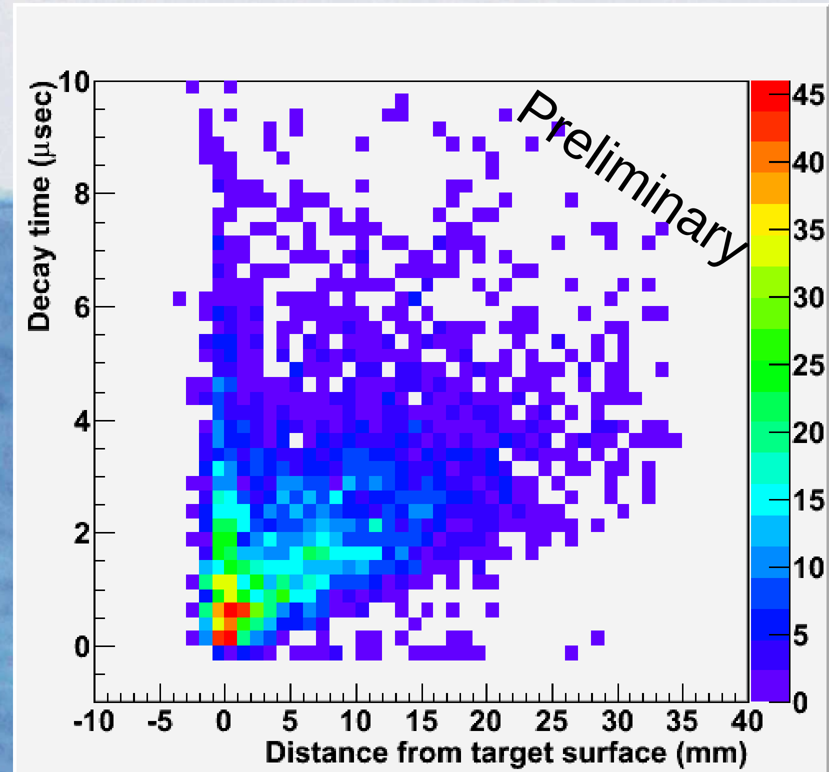
Silica Aerogel

Silica aerogel (27mg/cm^3)

Data from last 2 shifts (16 hours)

T. Mibe

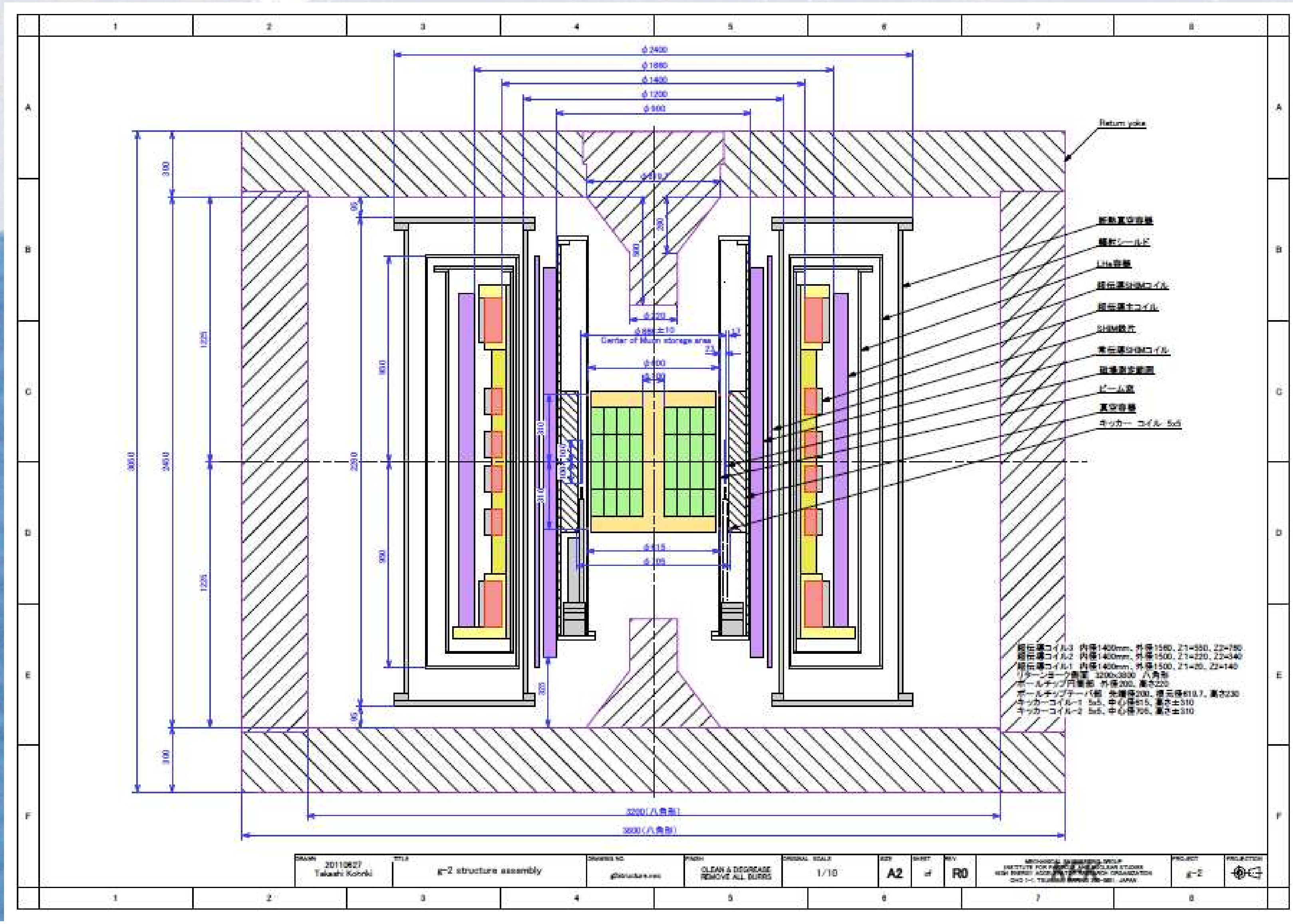




- 4D image of the muonium evaporation from the target was obtained.
- Estimated Mu production rate is 2-4% per stopped muon (preliminary) at 22.7 MeV/c, corresponding to 1-2 % at 27 MeV/c.

Control Drawing

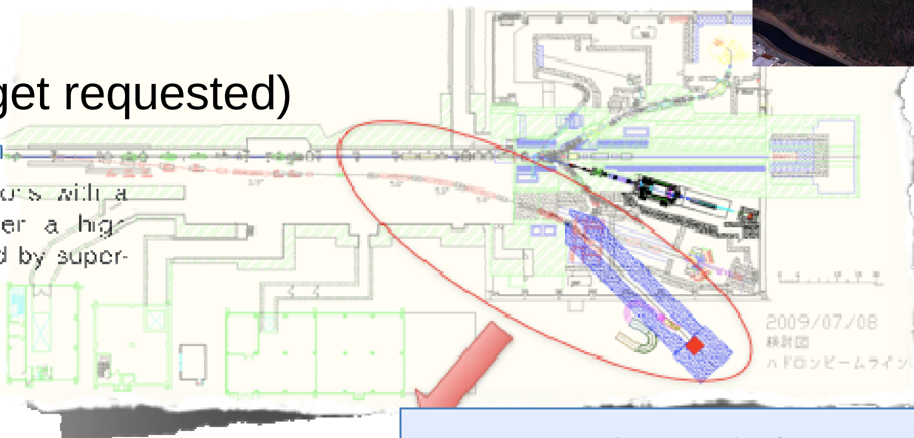
- By Kohriki-san

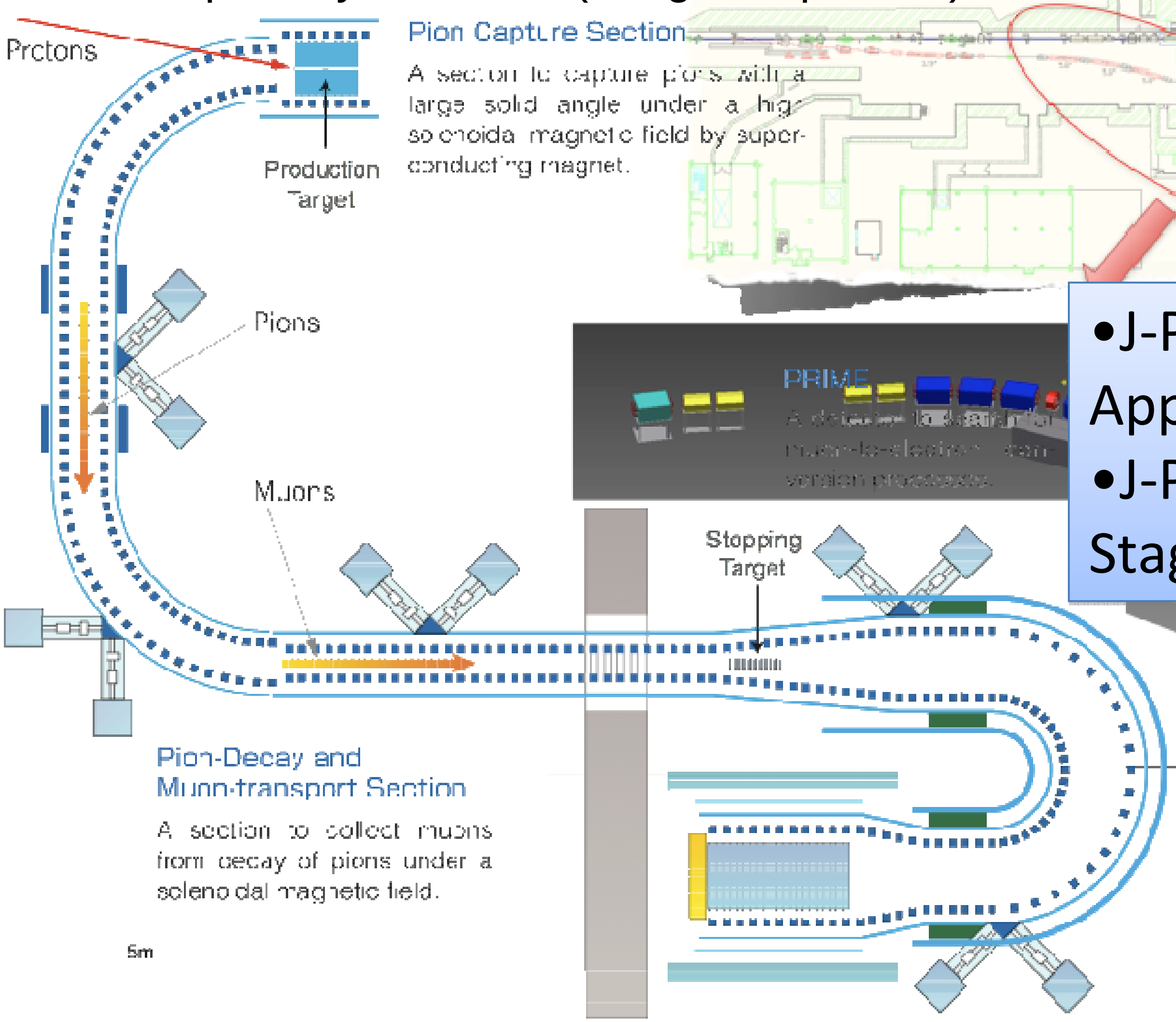


COMET Layout

HD Hall at J-PARC

- Utilize primary beamline (budget requested)





- J-PARC PAC Stage-1 Approval
- J-PARC PAC – Aiming for Stage-2

Major R&D Items:

- Super conductor under high radiation
- High purity proton beam and its monitor
- High-resolution electron detection

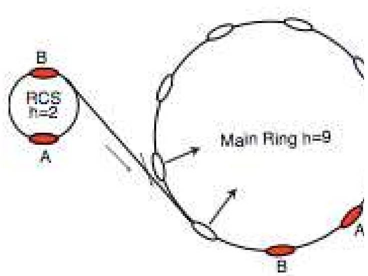
COMET Extinction Studies

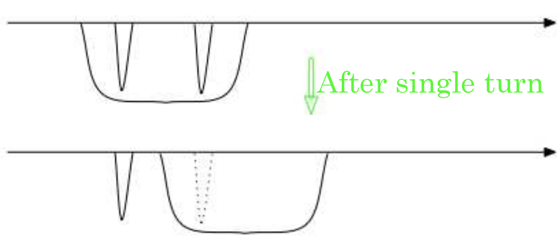
Measurement in the MR

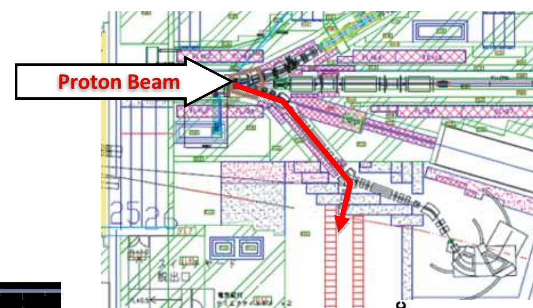
- Double-kick injection
  - Sweeping proton leakage in empty buckets caused by pulse formation inefficiency before LINAC acceleration
  - Kick injected bunches again after a single turn with a delayed phase by a half cycle
  - Improving factor < 10^{-6}

Measurement in the Exp. Hall

- Measure the time structure of the primary proton beam using secondary beam at K1.1BR
  - 800MeV/c, pion dominant, 200k/spill
- Primary Beam Condition
  - h=9, 3 filled and 6 empty
  - 30GeV
  - Bunched Slow Extraction







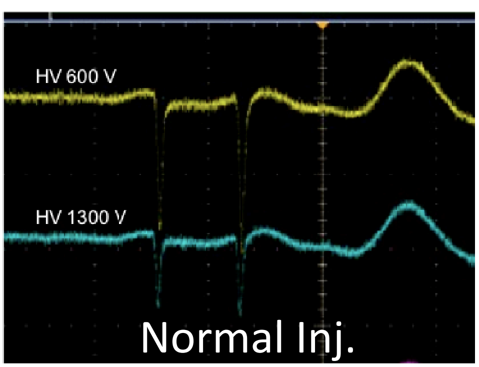
K1.1BR Layout

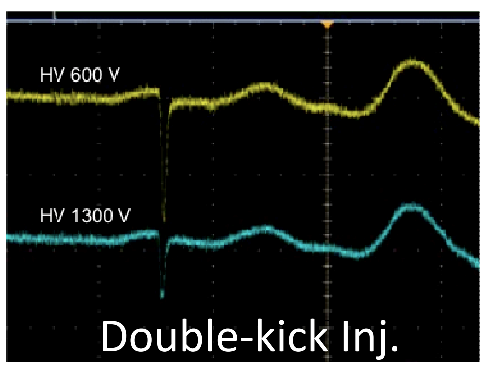
Normal beam inj. to MR

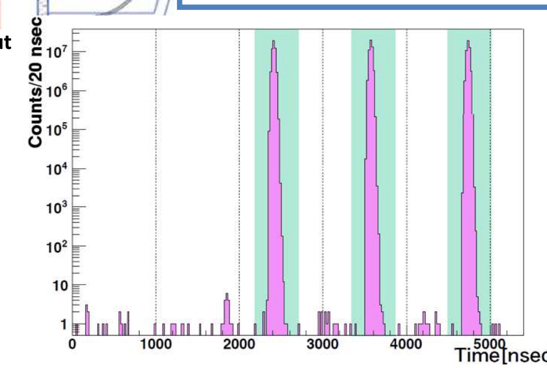
Integration over 20 minutes

Extinction level at

$(5.4\pm0.6)\times10^{-7}$



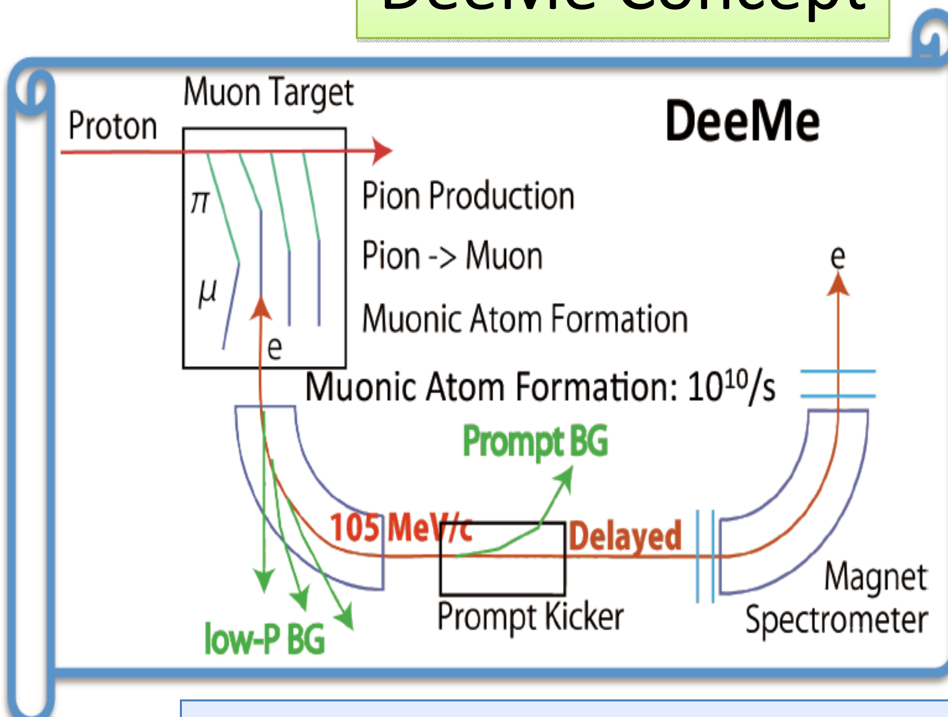




DeeMe at MLF

- ■Signal : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
- ■A single mono-energetic electron
  - •105 MeV
  - •Delayed : ~ 1 micro sec.
- ■No accidental BG
- ■Physics BG
- ■Muon decays in orbit
  - •Remove Low-E in beamline
  - •Limit Hi-E BG by the hi-resolution spectrometer
- ■Beam pion capture -- prompt
  - •Eliminate by timing
- ■Cosmic induced
  - •Live-time duty = 1/20,000
- ■Aim results before mu2e/COMET

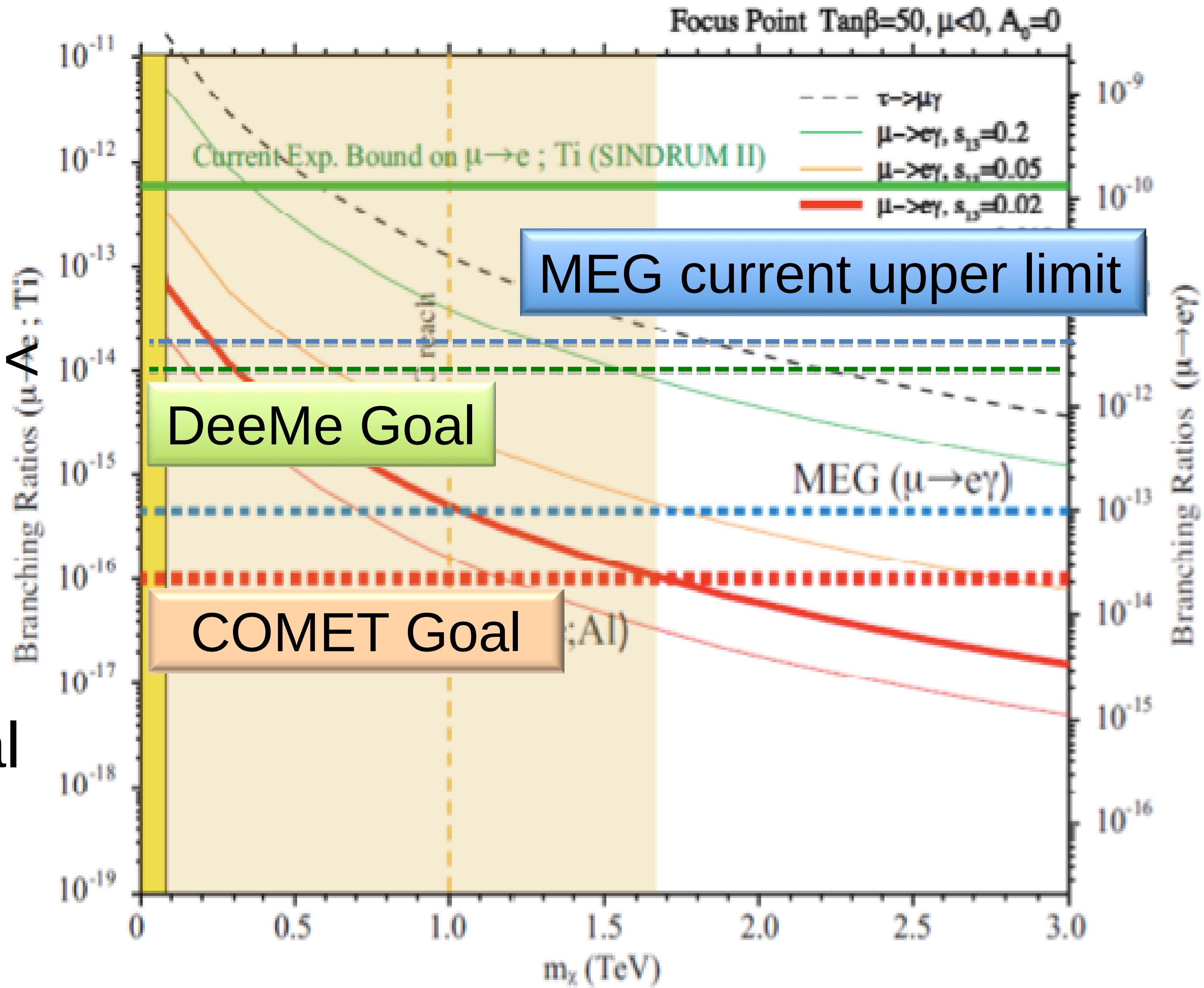
DeeMe Concept



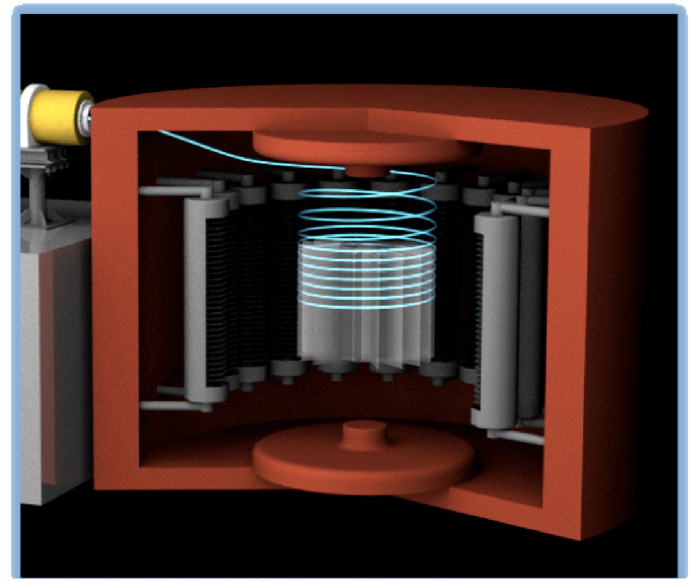
- •KEK/IMSS – Muon PAC Stage-1 Approval
- •J-PARC PAC – Aiming for Stage-1

Prospects of cLFV

- MEG Goal
  1e-13
  - Current upper limit 2e-12
- DeeMe Goal
  1e-14
- COMET Goal
  1e-16

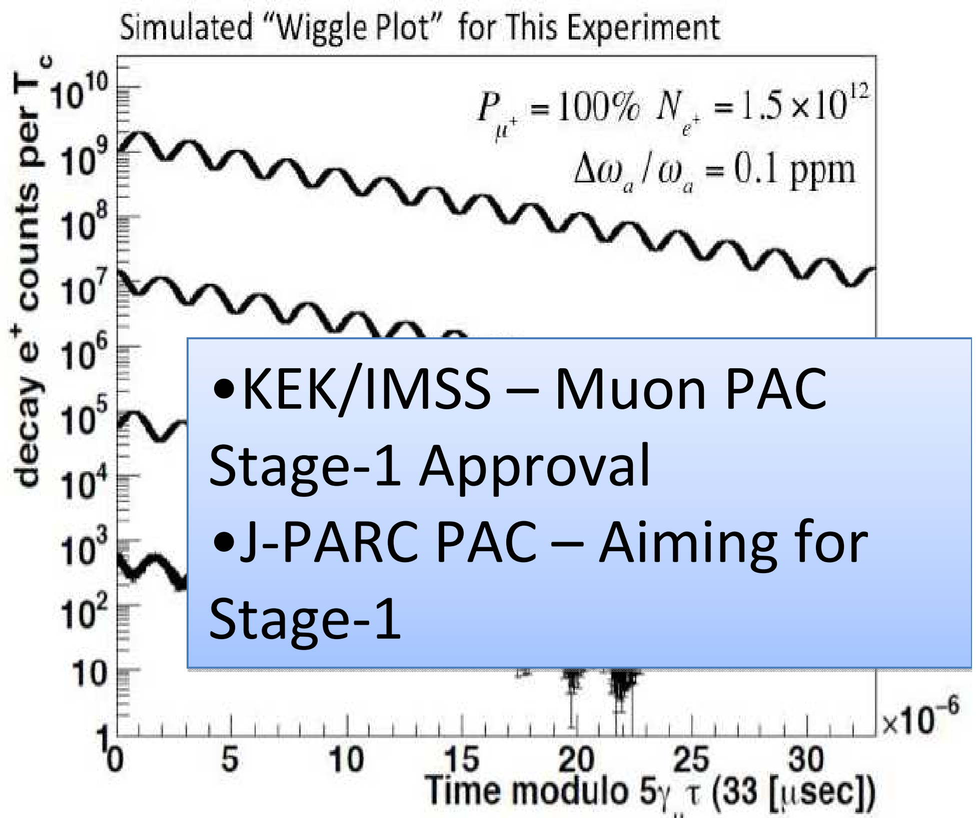


g-2/EDM at MLF



■Utilize Ultra-Slow Muon beam
- •Laser ionization of Muonium
- •Acceleration to 300 MeV/c

■Eliminate the electric field
■Utilize the MRI magnet technology for Ultra-precision magnetic field
■Reduce the muon storage ring x 1/20
■Achieve 0.1 ppm for g-2
■Measure EDM at the same time (< 1e-21 e cm)



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