New Challenges of Precision Measurement of Muon g-2/EDM at J-PARC

Seminar at LPNHE, November 4, 2009

KEK / J-PARC Center

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Outline

- Why Muon g-2 and EDM?
- Current status of Muon g-2 (BNL-E821)
- J-PARC
- New Experiment at J-PARC
- EDM
- Summary

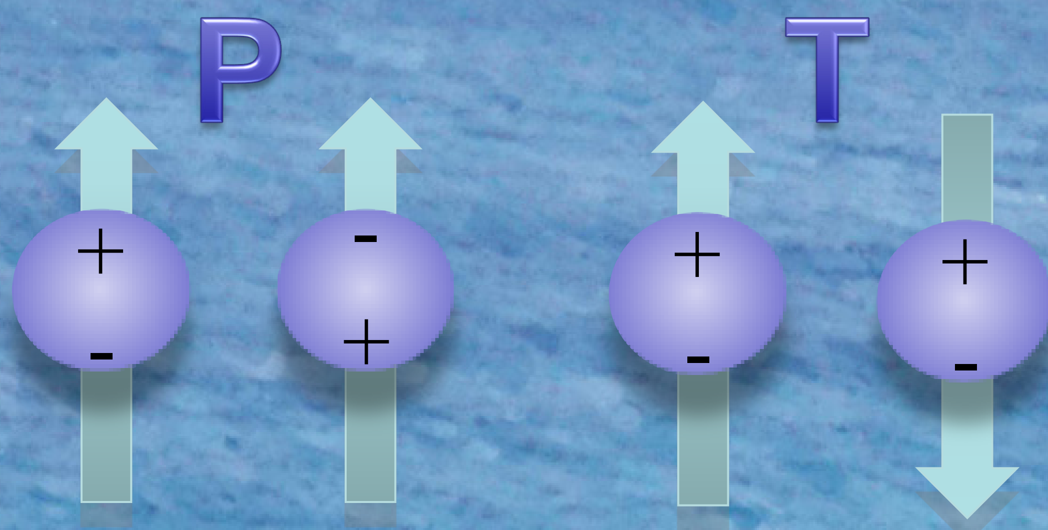
Muon Dipole Moments

- **Magnetic and Electric DMs: both related to Spin of the Particle**
  - **Fundamental physics observable for elementary particles**
- **Play important role in the test of fundamental symmetries**

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

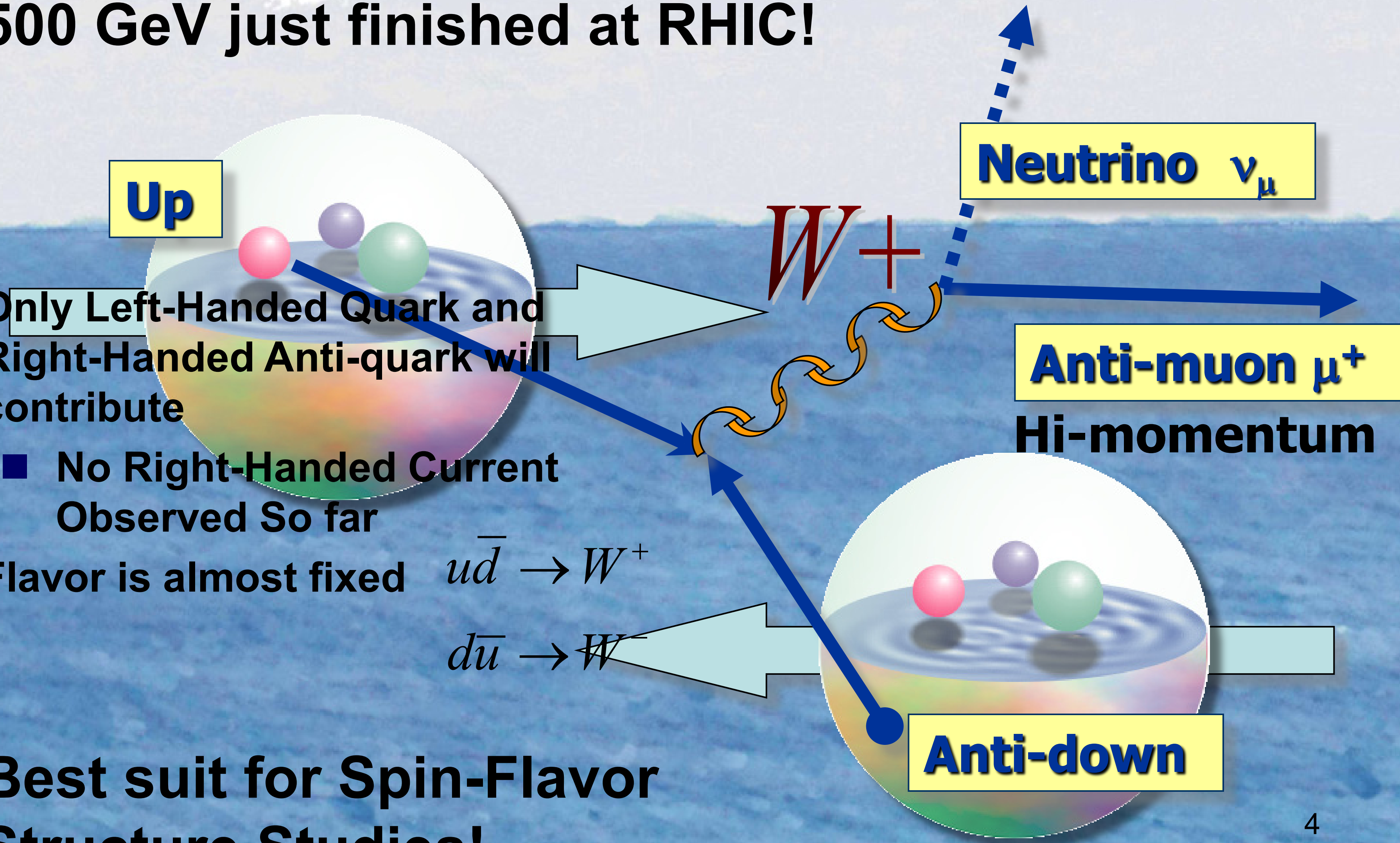
$$\vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}$$

If EDM nonzero, T is violated



Starting W Physics at RHIC!

- The highest energy polarized pp collisions at 500 GeV just finished at RHIC!



- Only Left-Handed Quark and Right-Handed Anti-quark will contribute
  - No Right-Handed Current Observed So far
- Flavor is almost fixed

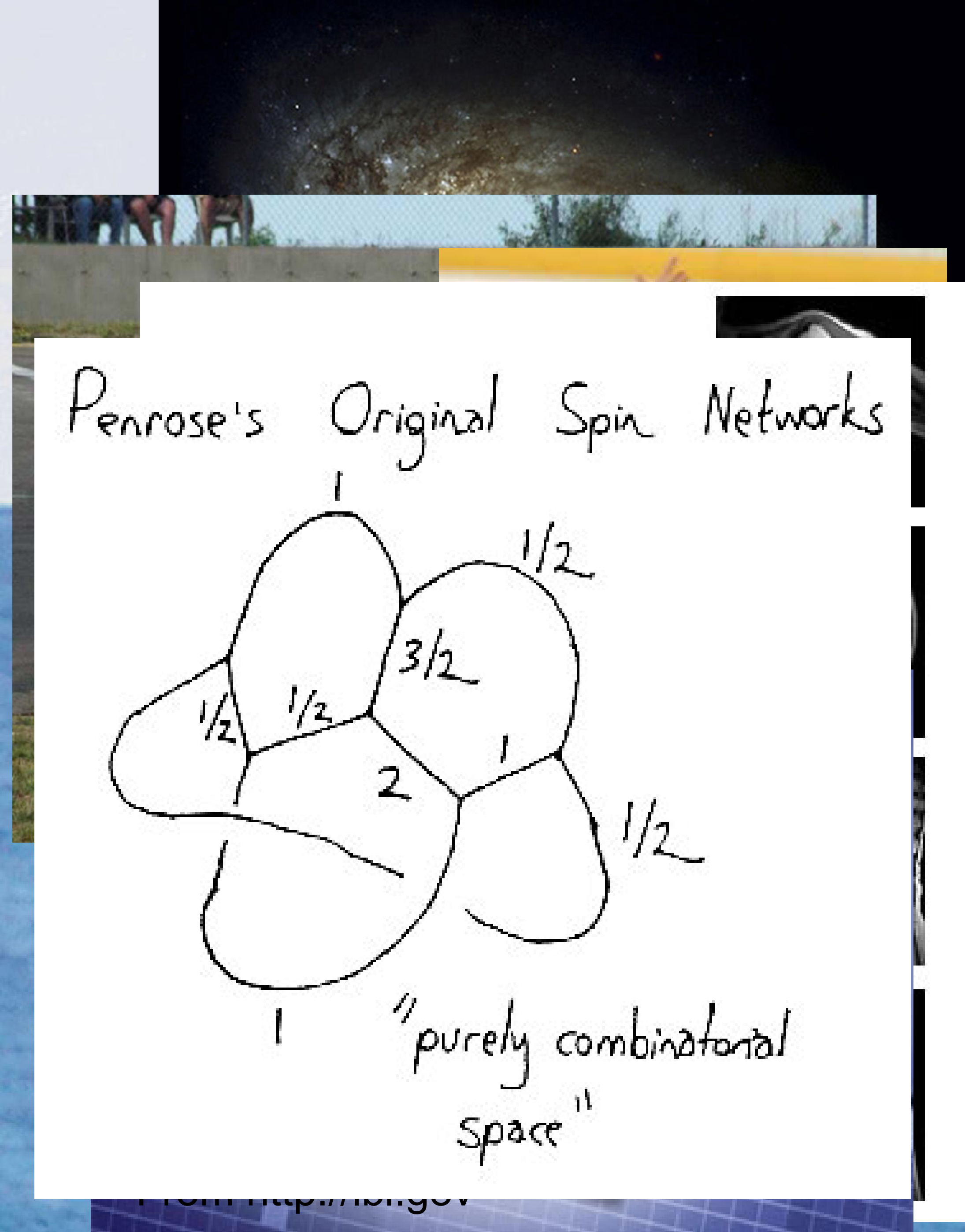
$$u\bar{d} \to W^+$$

$$d\bar{u} \to W^-$$

- Best suit for Spin-Flavor Structure Studies!

Why Spin?

- Fundamental Concept in Physics
  - Appears in Many Different Levels
    - Galaxy to Space-Time Structure
- Fundamental Quantum Number for Elementary Particles
- Important in Symmetry Test
  - Parity
  - Time Reversal



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

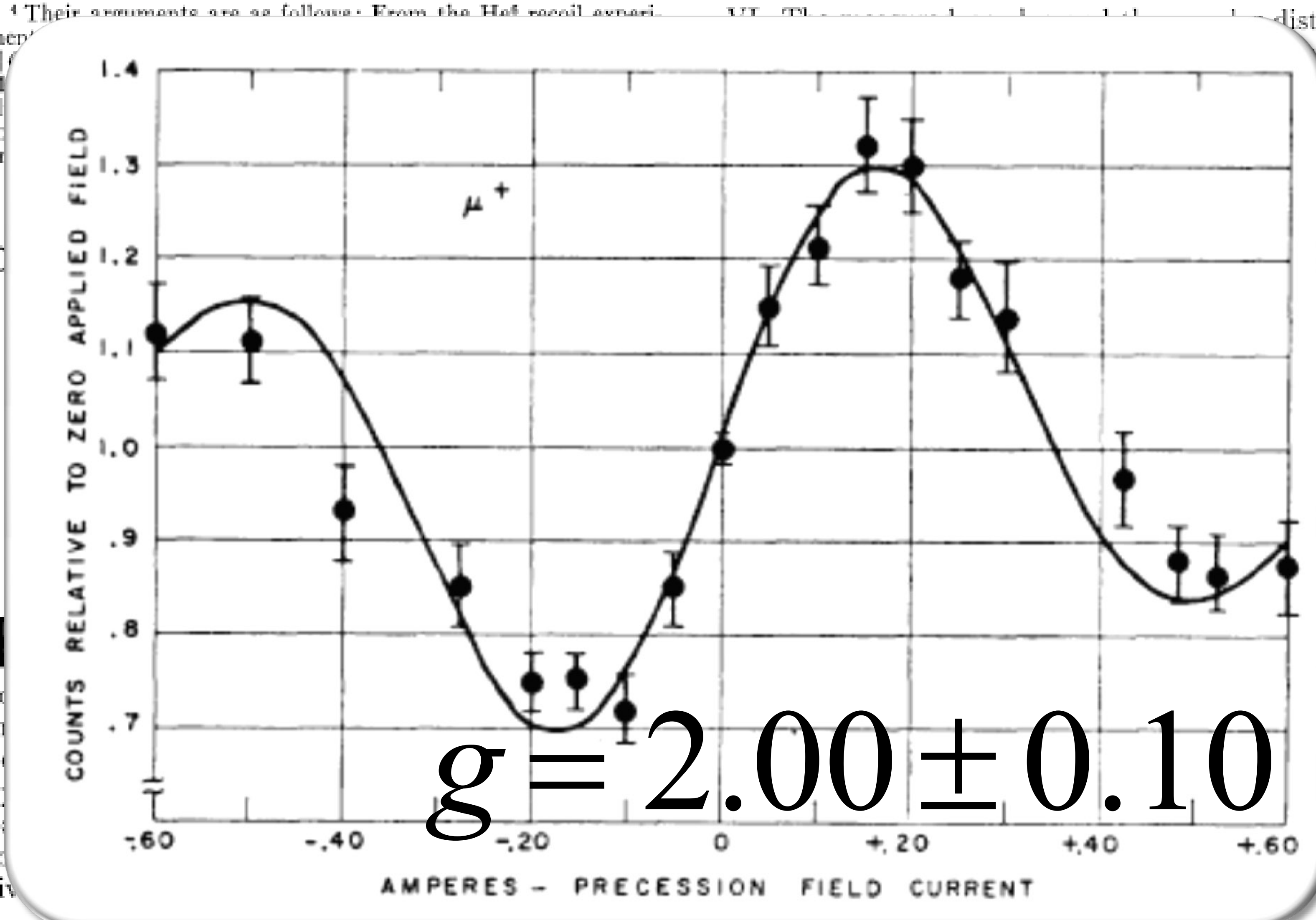
- Dirac equation predicts g=2 ⇨ a=0

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

a=1.2e-3 for e, μ, …
a=1.8 for proton

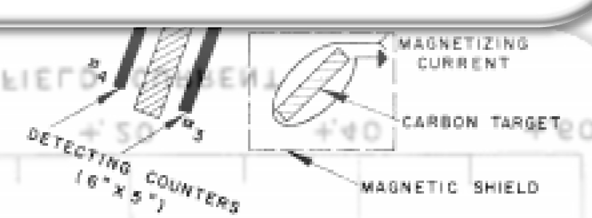
- Radiative corrections (including NEW PHYSICS) would make g≠2 ⇨ a≠0

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



$$\mu^+ \to e^+ + 2\nu. \quad (2)$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion



Discovery of a≠0

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Accurate Determination of the μ^+ Magnetic Moment*

R. L. GARWIN,† D. P. HUTCHINSON, S. PENMAN,‡ AND G. SHAPIRO§
Columbia University, New York, New York

(Received August 4, 1959)

Note added in proof.—Experiments which have recently been reported to us [J. Lathrop, et al. and A. Bearden et al., Phys. Rev. Letters (to be published)] indicate a mass value of $M_\mu = 206.76_{-0.02}^{+0.03} M_e$. This yields a value of $g_\mu = 2(1.00113_{-0.00012}^{+0.00016})$. Although the assigned errors are now slightly greater than above, it is to be noted that the new result represents a direct measurement rather than a lower limit. The agreement

0.0011623

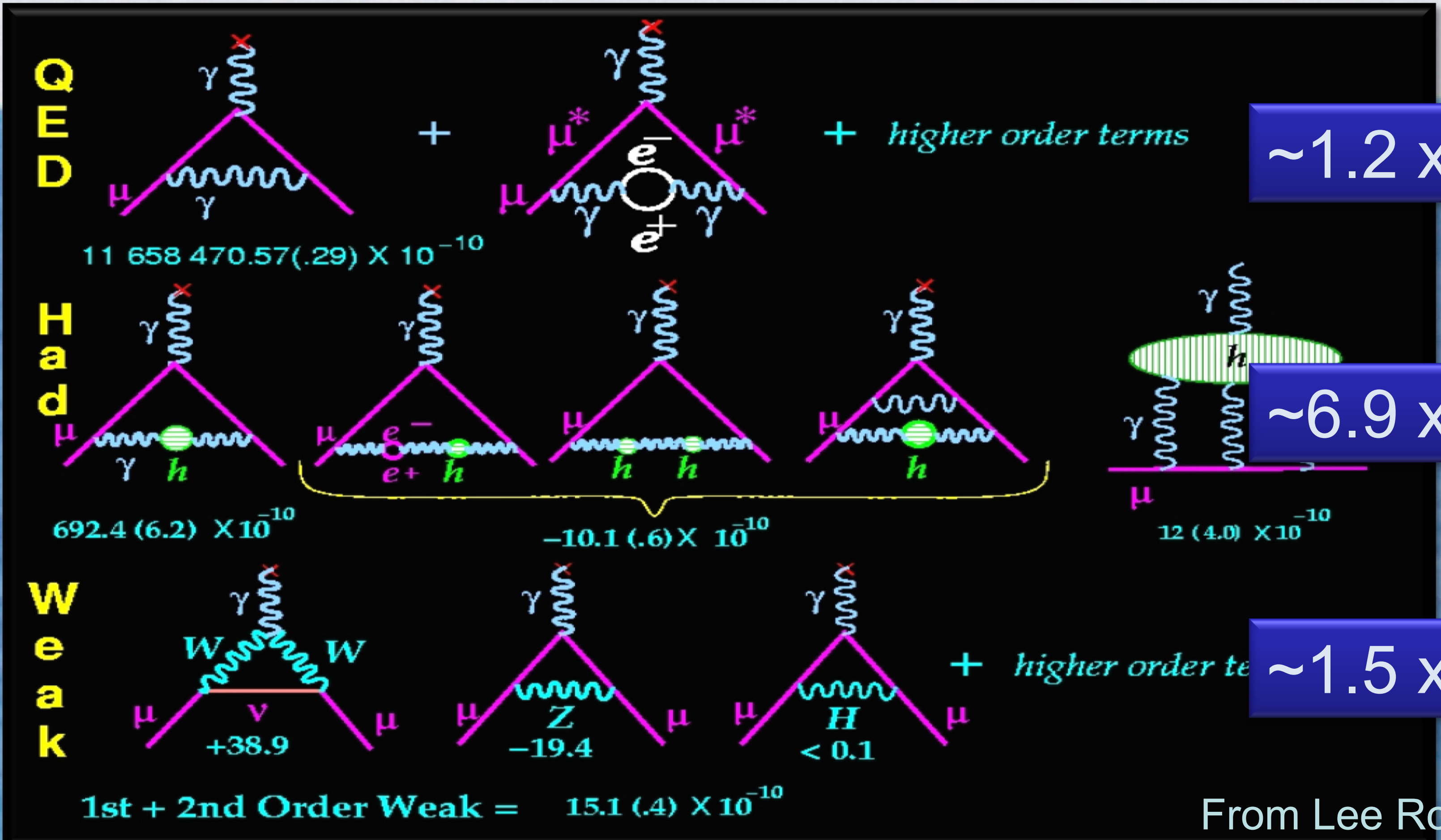
$$a(\mathrm{QED}) = \frac{1}{2}\frac{\alpha}{\pi} + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

electromagnetic properties of the muon, therefore, acquire increased interest as a further test of the identity of the interactions of the two particles.

using an analog time-to-height converter to record the distribution in time of the emitted electrons, achieved an accuracy of 0.7%. A resonance technique, in which

SM Contribution to a≠0

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



~1.2 x 10^{-3}

~6.9 x 10^{-8}

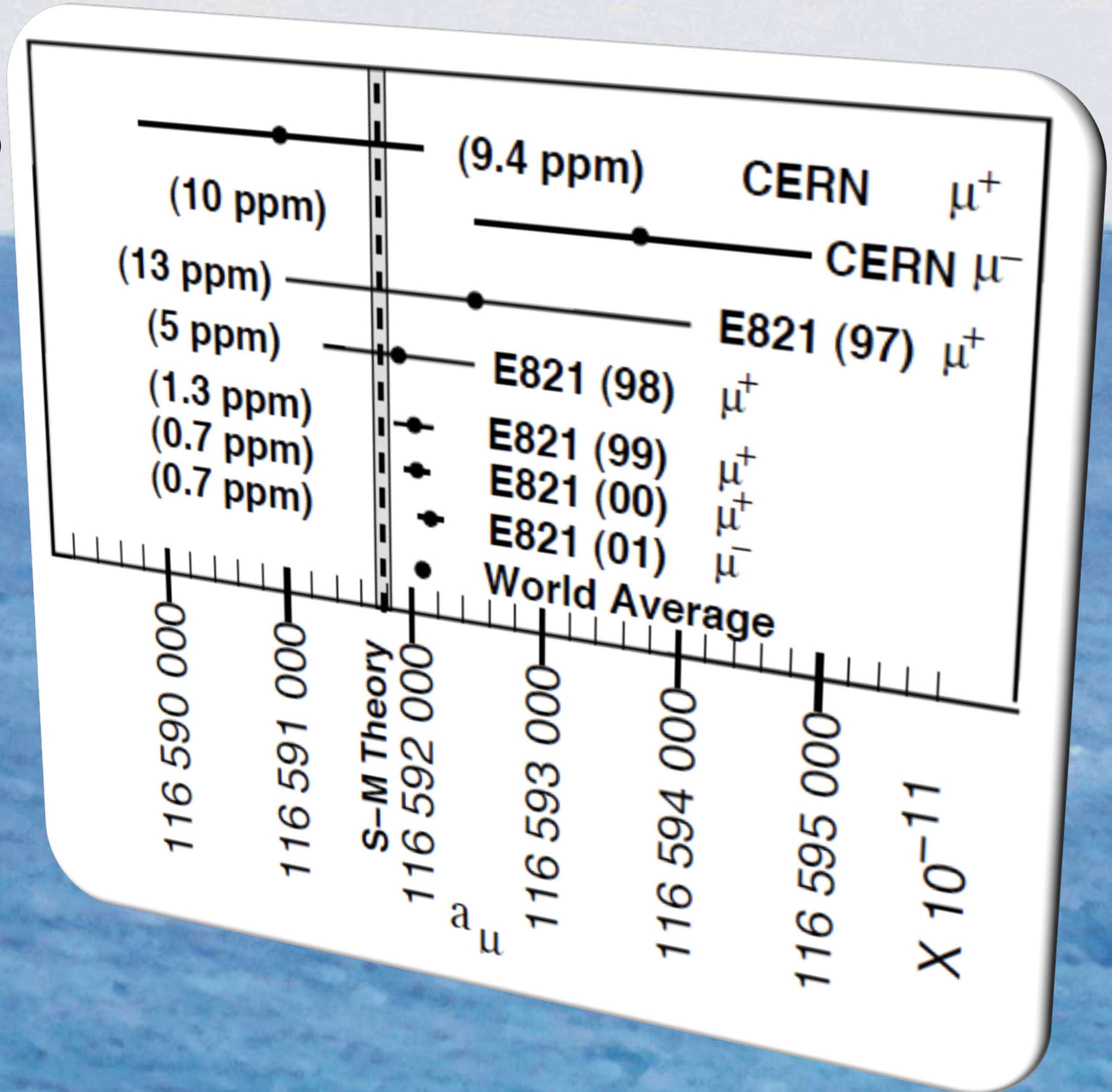
~1.5 x 10^{-9}

From Lee Roberts

Current Precision

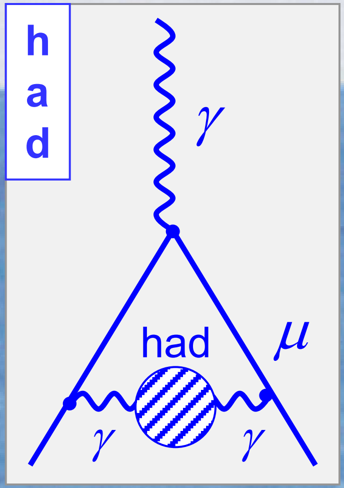
$$\Delta a_\mu^{(\text{today})} = a_\mu^{(\text{Exp})} - a_\mu^{(\text{SM})} = (295 \pm 88) \times 10^{-11}$$

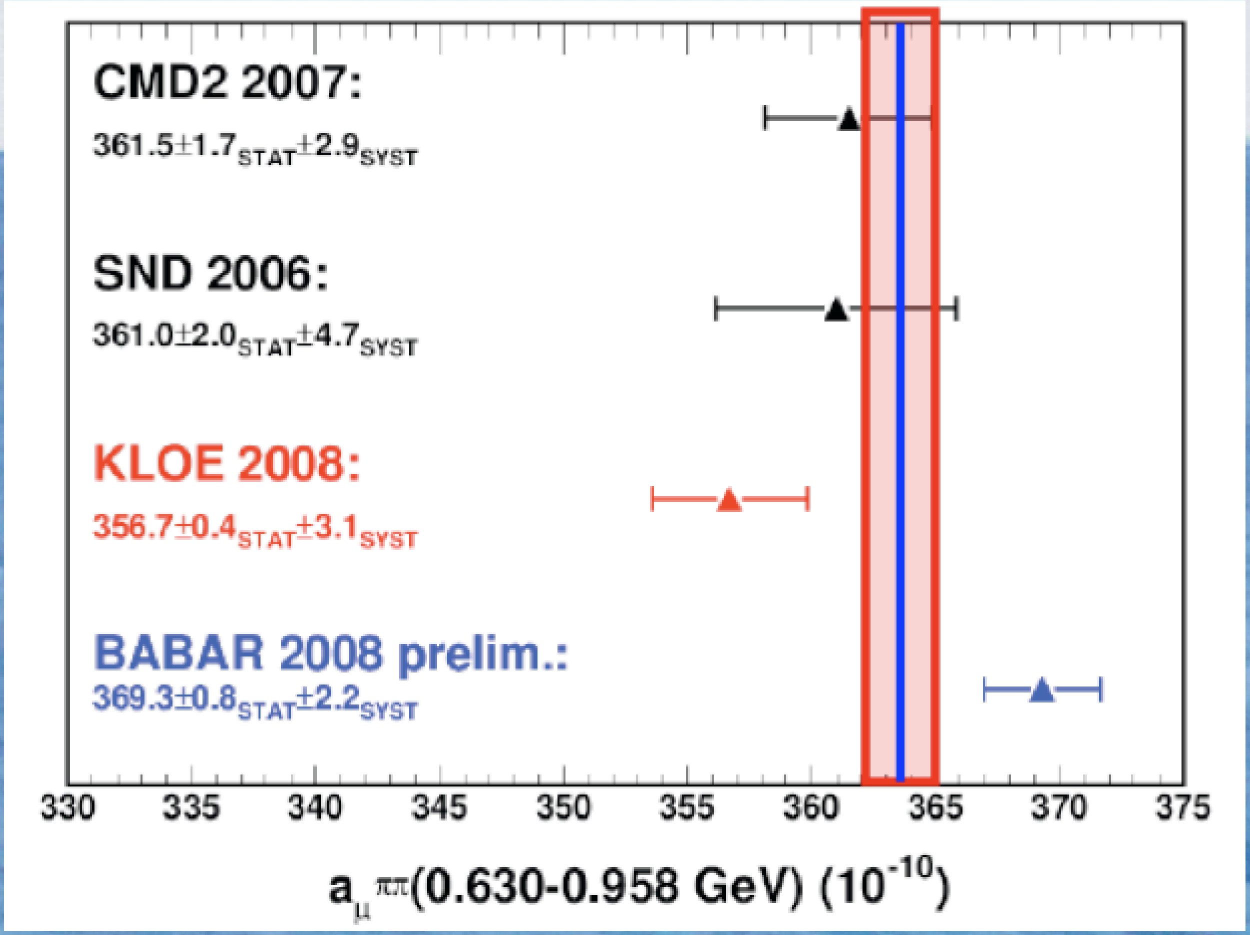
- **E821 at BNL-AGS measured down to 0.7 ppm for both μ+ and μ–**
- **3.4 sigma deviation from the SM**
  - **SM prediction OK?**
  - **New Physics?**
- **Need to explore further**



Hadron vacuum polarization

- Largest contribution among hadronic correction





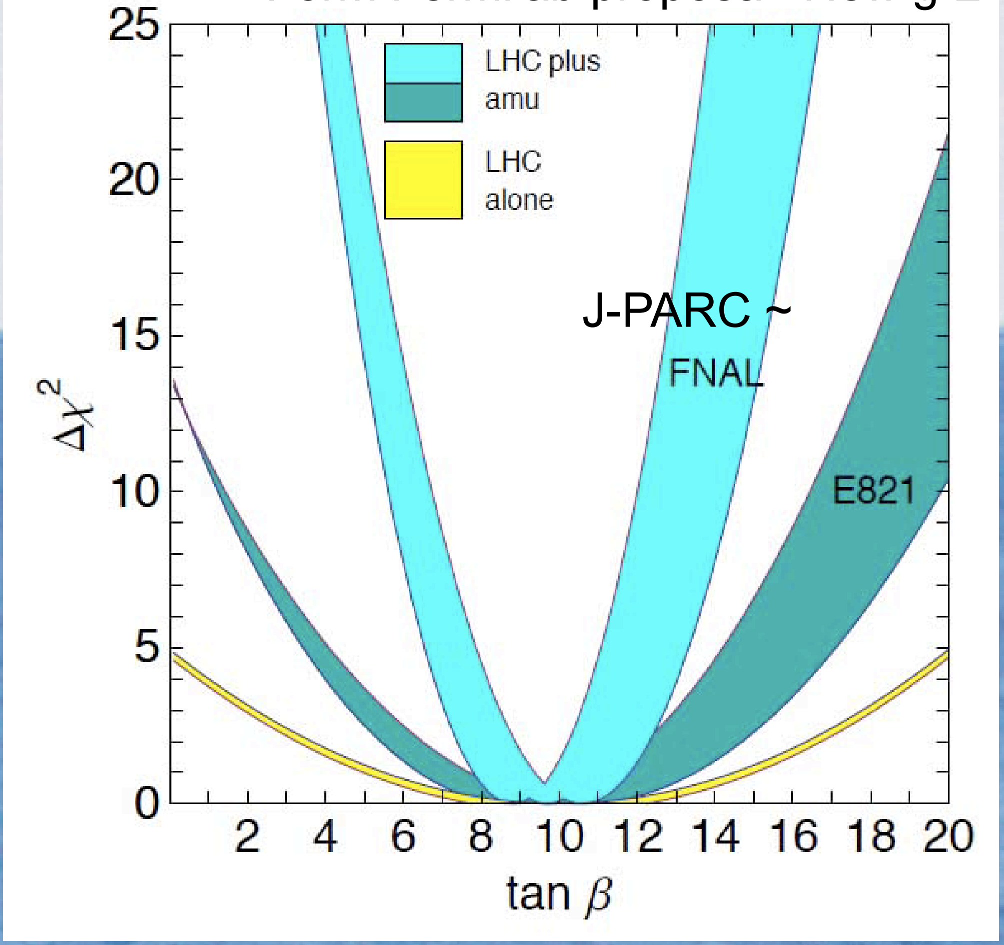
- Discussion with BELLE started

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 $\tan\beta$

Form Fermilab proposal “New g-2”



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

Muon Spin precession

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

$$\eta:\ d_\mu = \frac{\eta}{2}\left(\frac{e}{2m}\right)$$ Electric Dipole Moment

$$d_e = (6.9 \pm 7.4)\times 10^{-28}\, e\cdot\mathrm{cm}$$

Expected to be

$$d_\mu < (1.5 \pm 1.4)\times 10^{-25}\, e\cdot\mathrm{cm}$$

Measured to be

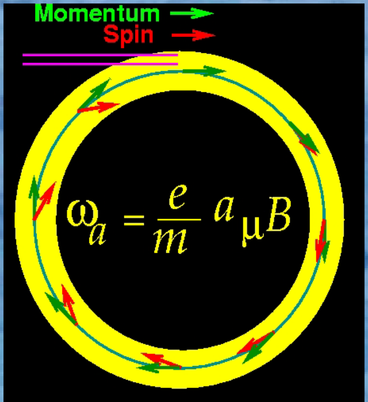
$$d_\mu = (3.7 \pm 3.4)\times 10^{-19}\, e\cdot\mathrm{cm}$$

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

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

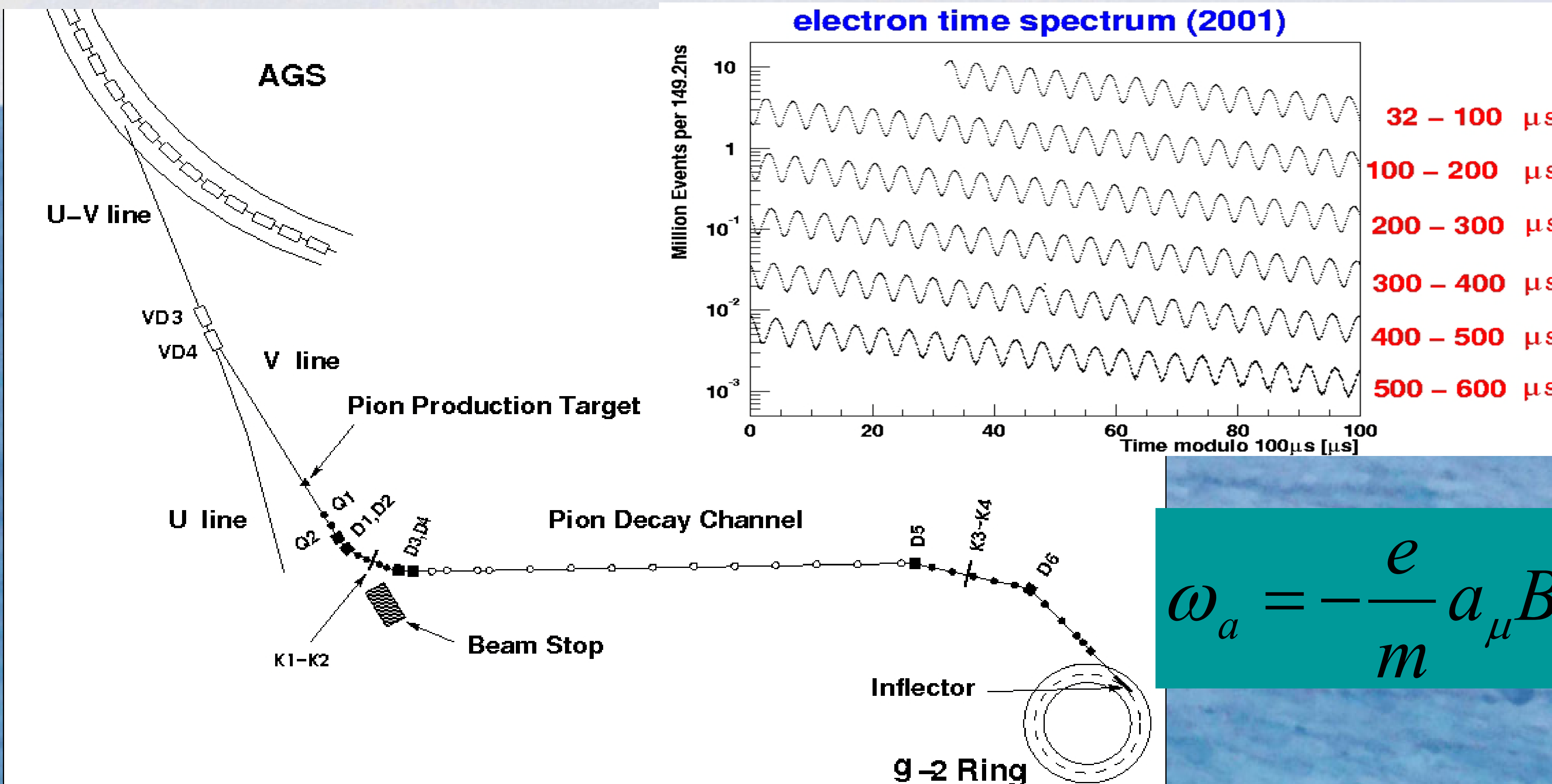
$$p_{\mathrm{magic}} = 3.09\ \mathrm{GeV}/c$$

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



How it is Measured?

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



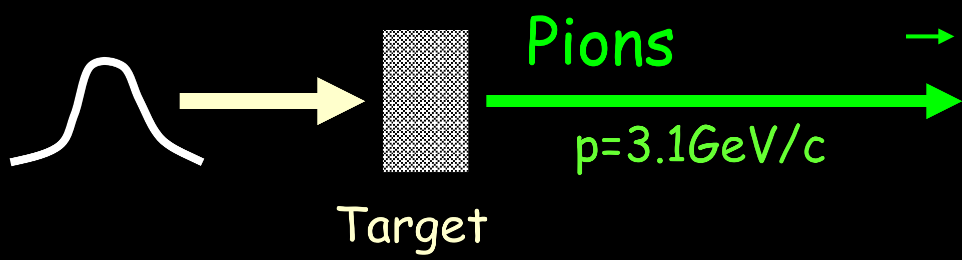
$$\omega_a = -\frac{e}{m} a_\mu B$$

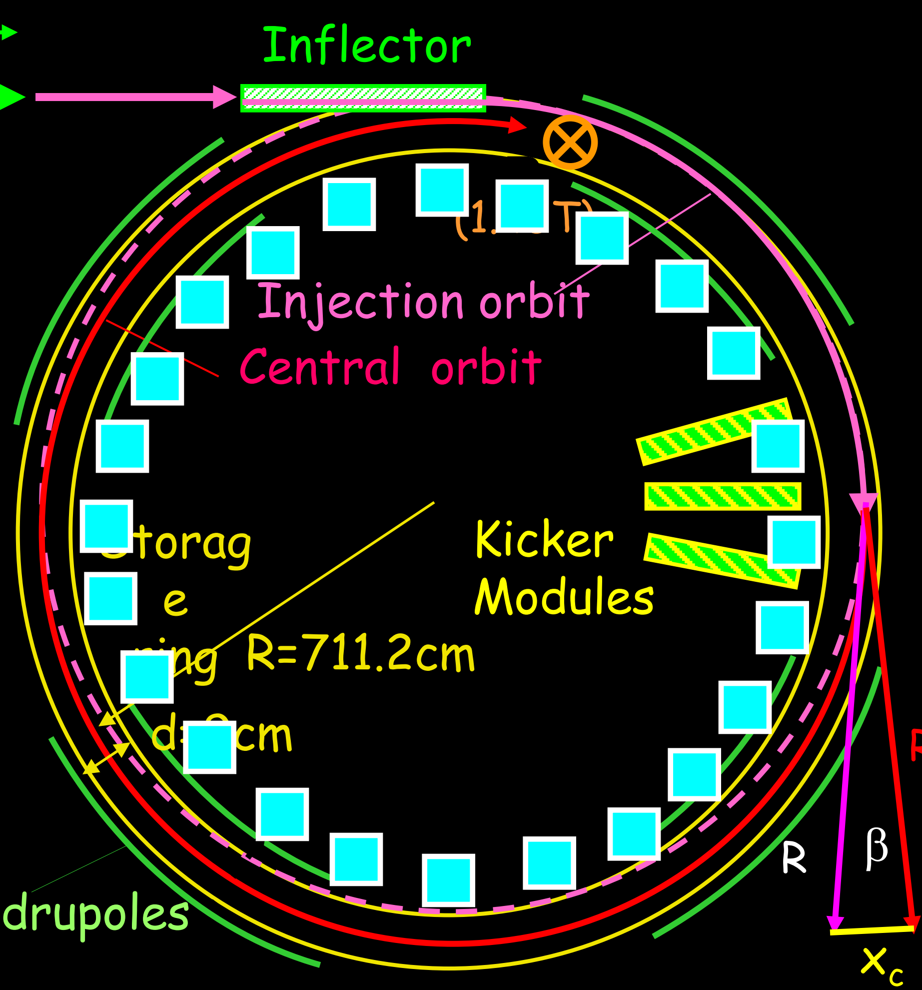

The Muon g-2 Ring
at BNL

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

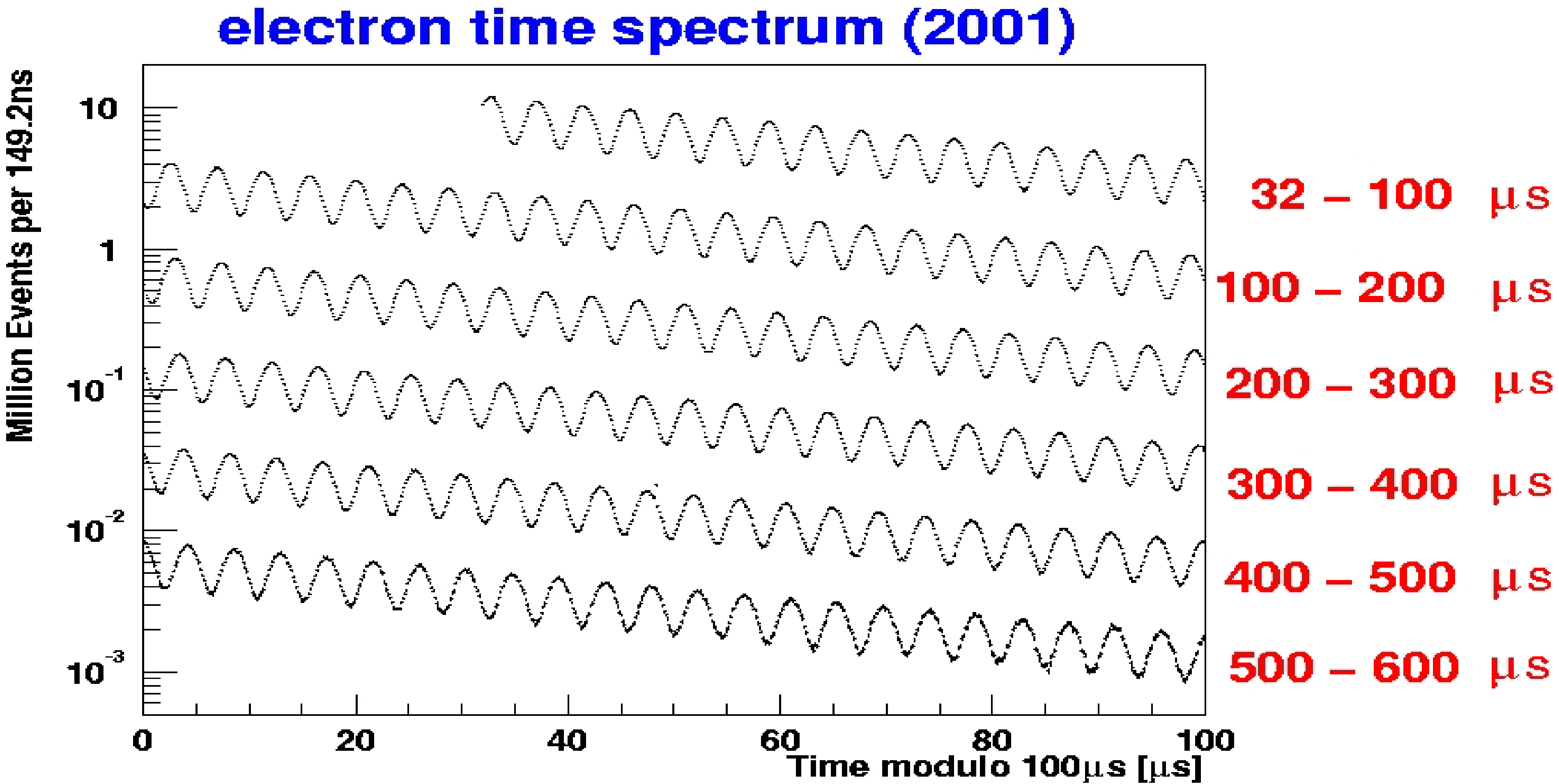
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

(thanks to Q. Peng)

Signal: Oscillation in hi-E electron

- 4E9 electrons; E > 1.8 GeV

$$f(t) \approx N_0 e^{-\lambda t}\left(1 + A\cos\omega_a t + \phi\right)$$



Systematic Uncertainties

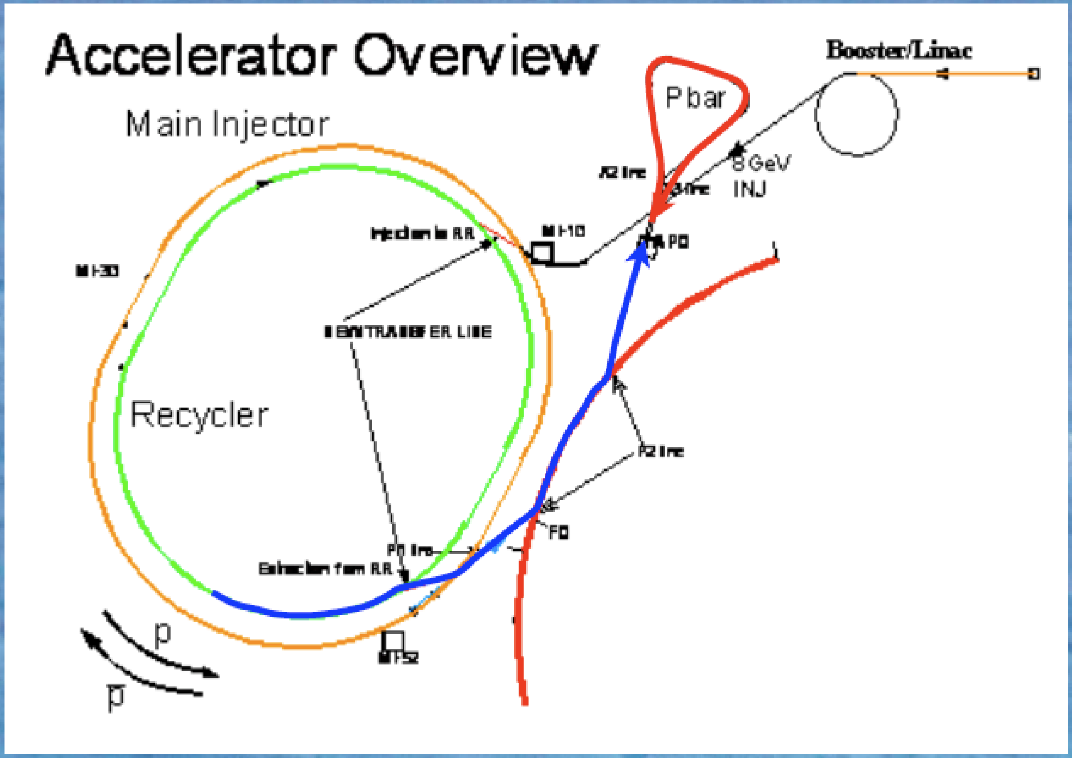
from Final Report of BNL E821

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

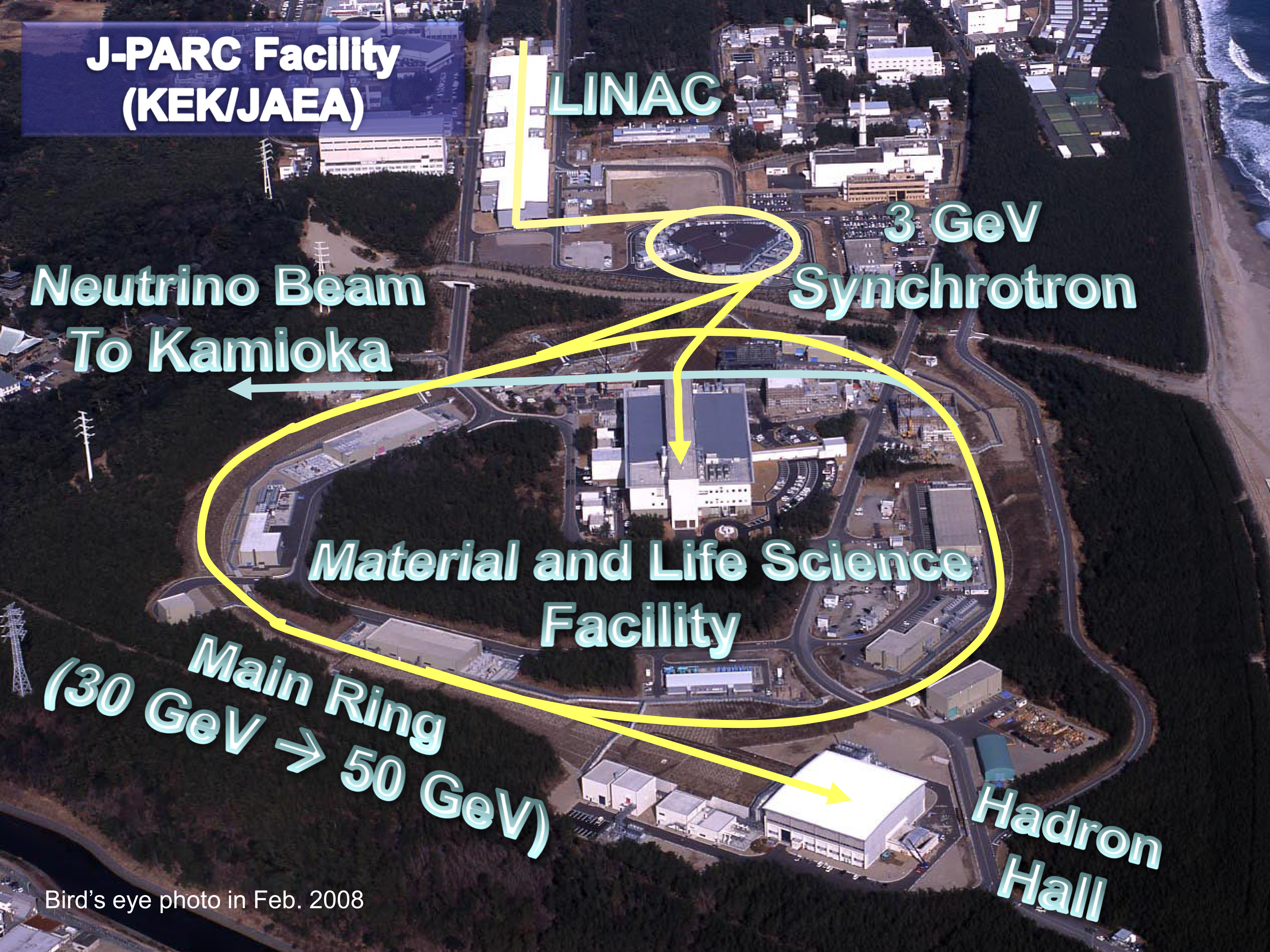
$\sigma_{\mathrm{syst}}\ \omega_a$	R99 (ppm)	R00 (ppm)	R01 (ppm)
Pileup	0.13	0.13	0.08
AGS background	0.10	0.01	‡
Lost Muons	0.10	0.10	0.09
Timing Shifts	0.10	0.02	‡
E-field and pitch	0.08	0.03	‡
Fitting/Binning	0.07	0.06	‡
CBO	0.05	0.21	0.07
Gain Changes	0.02	0.13	0.12
Total for ω_a	0.3	0.31	0.21

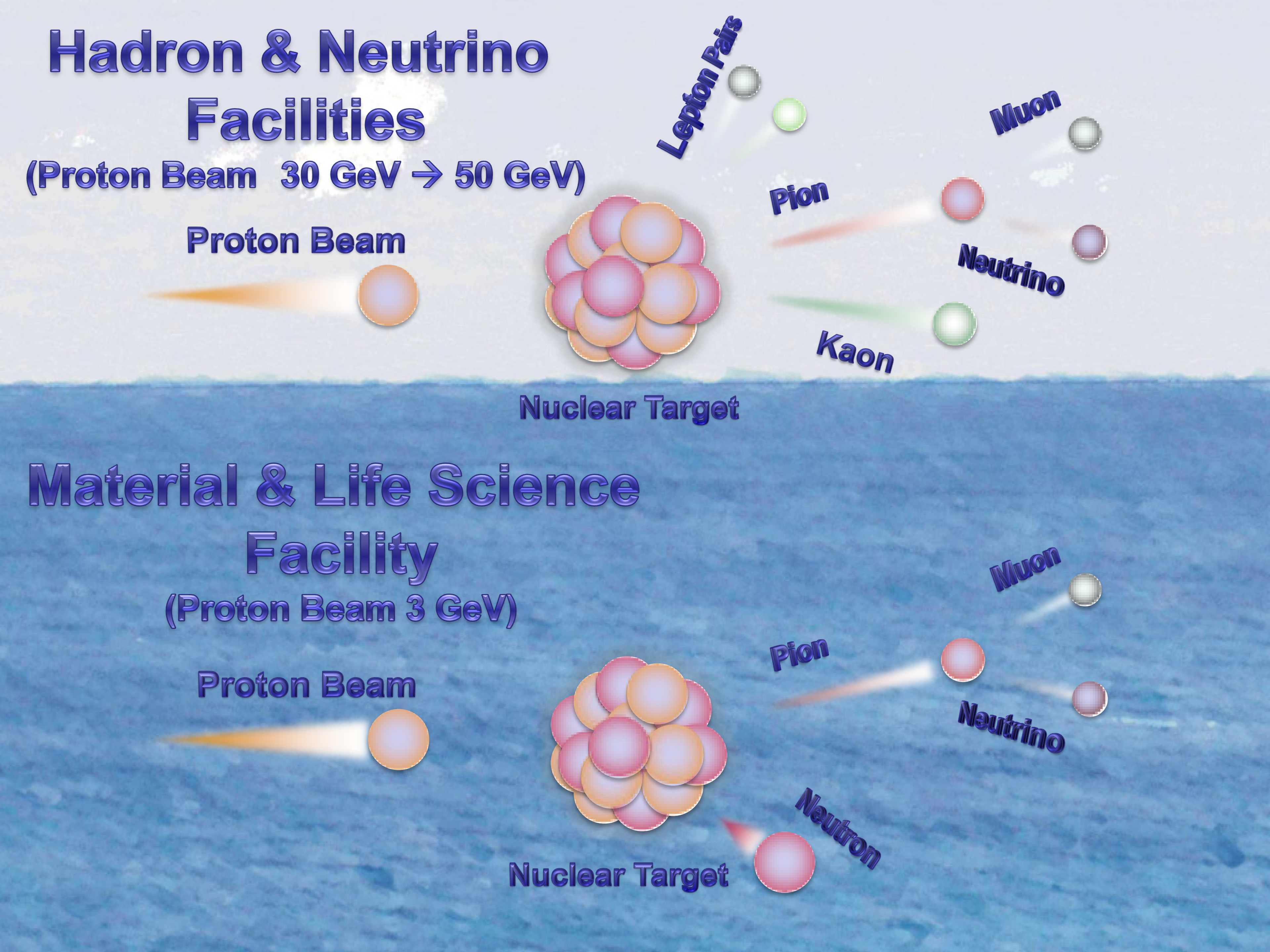
Proposal for g-2@Fermilab

- Submitted to Fermilab PAC
  - Contact persons: Lee Roberts (Boston U)
    Dave Hertzog (UIUC)
  - Cost Estimate: ~$20 M (w/ contingency)
  - Discussed at the last PAC (March 4,5)
  - Encouraging message from the lab



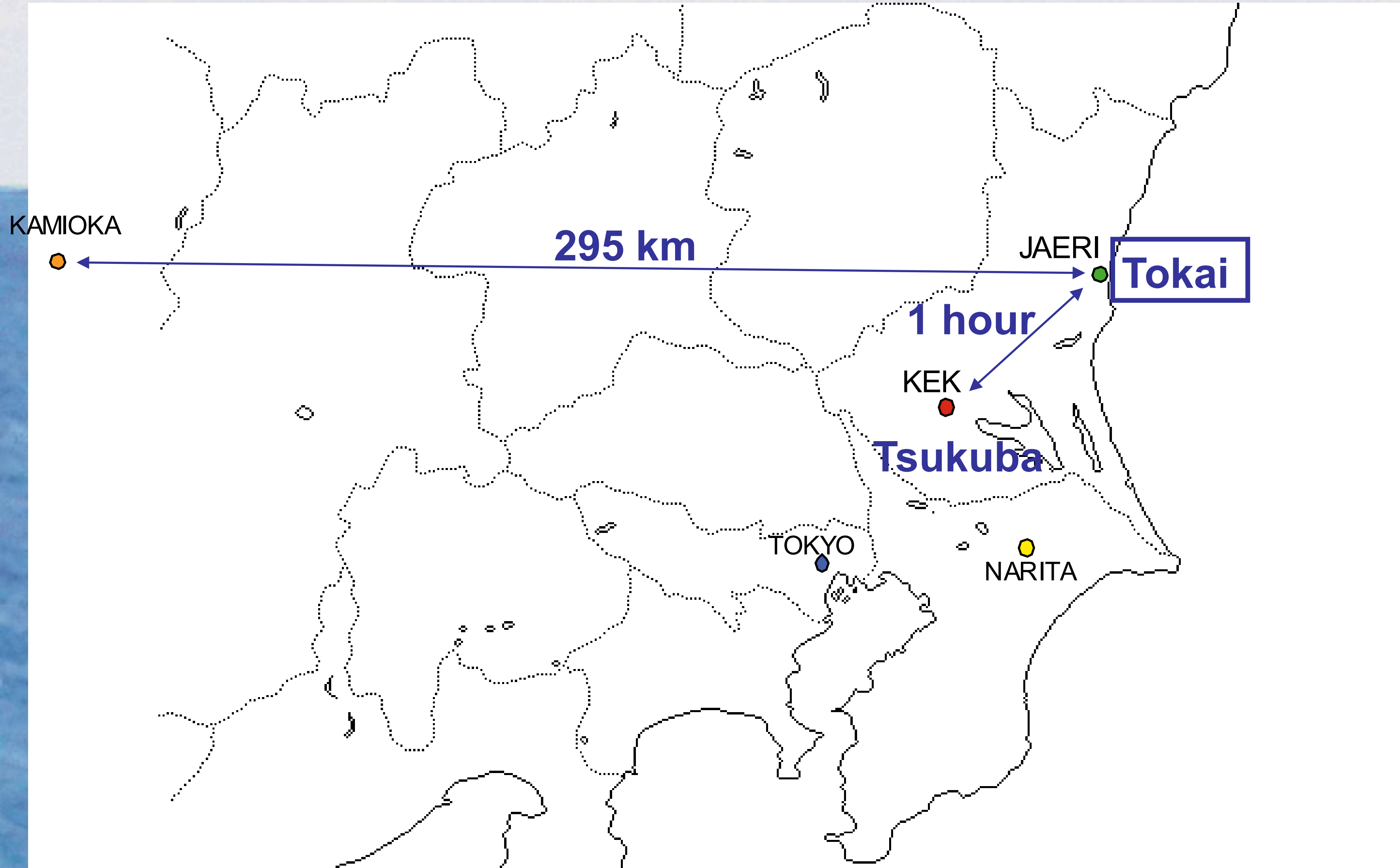
Muon g-2 at J-PARC?


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV → 50 GeV)
Hadron
Hall
Bird's eye photo in Feb. 2008


Hadron & Neutrino Facilities
(Proton Beam 30 GeV → 50 GeV)
Proton Beam
Nuclear Target
Lepton Pairs
Muon
Pion
Neutrino
Kaon
Material & Life Science Facility
(Proton Beam 3 GeV)
Proton Beam
Nuclear Target
Muon
Pion
Neutrino
Neutron

Location of J-PARC at Tokai

- Closer to beach…




祝
30GeV
ビーム加速
祝 J-PAR
MR30GeV加速成功
34 分


祝 ハドロンビームライン
ビーム取り出し・輸送成功
平成 21 年 1 月 27 日　19時35分

J-PARC Inauguration Ceremony

July 6, 2009 in Tokyo

- J-PARC aims to provide answers for
  - How matters (hadrons) are formed?
    - Confinement is understood?
    - How hadron properties are emerged?
  - How matter-dominant universe is emerged?
    - CP violation in quark sector
    - CP violation in lepton sector

⇒Origin of Matter

- Sakharov's necessary conditions
  - violation of matter number: 0νββ, pdecay
  - CP violation
  - out of equilibrium

Hadron Hall at J-PARC

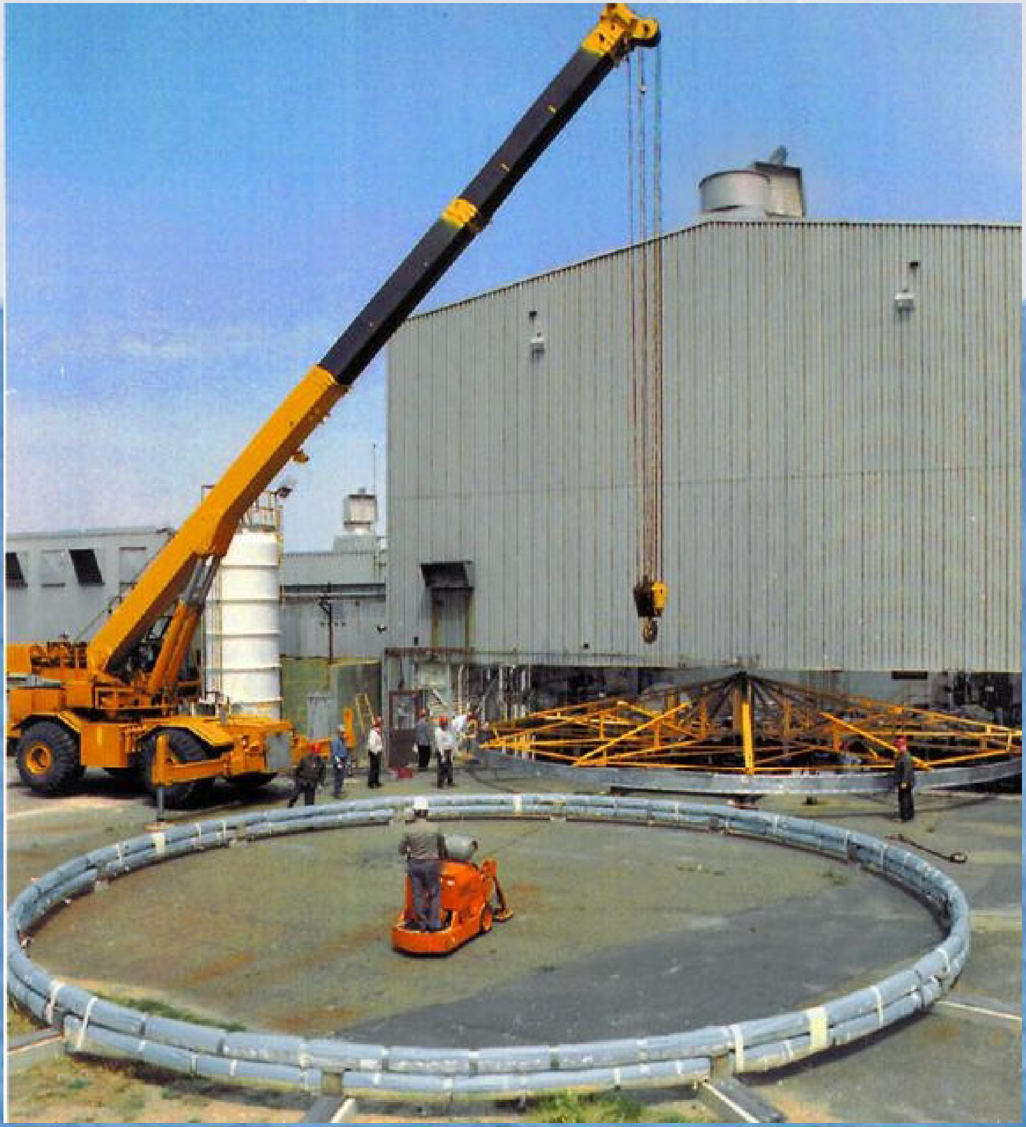
Neutrino Experiment: T2K

Muon g-2/EDM at J-PARC

Parking Lot Solution?

Shipping to J-PARC

- Estimated to be $2.5M
- Need to be refined



Brain-storming!

- **Why at magic gamma?**

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

- **What if no E-field?**

  ⇒requires ultra cooled muon beam Δp/p << 1e-5

  Ultra-Slow Muon Source at J-PARC MLF?

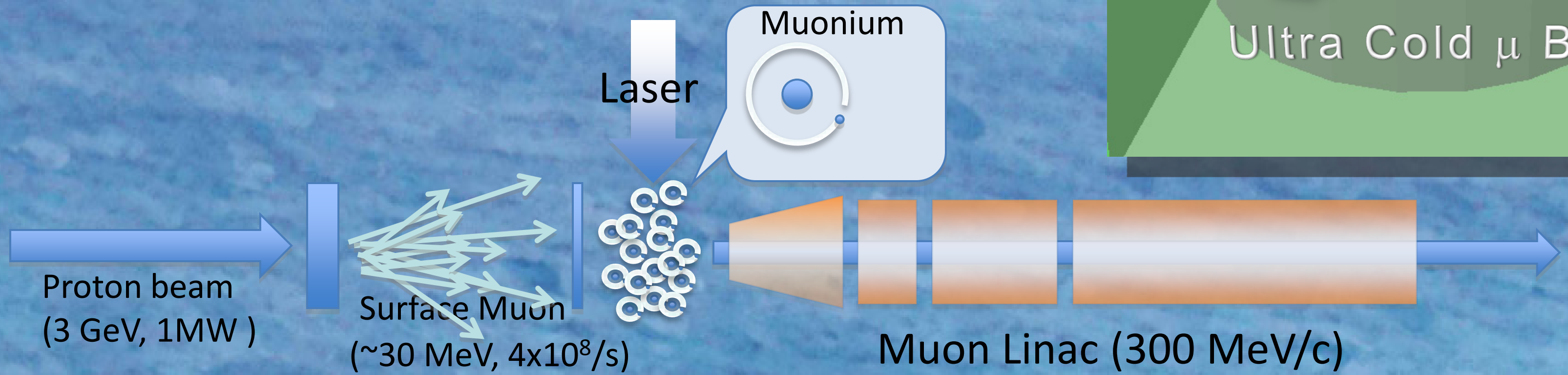
  Muon collider technique? Cooling, FFAG etc.

New Generation of Muon g-2@J-PARC

Proposal in preparation

- Current result is 3.4 sigma above from the SM value
- New generation of muon g-2 experiment is being explored at J-PARC
  - To establish the deviation by improving the statistics and systematics
  - To further explore new physics
- With completely new technique
  - Off magic momentum with ultra-cold muon beam at 300 MeV/c
  - Stored in ultra-precision B field without E-field so that the β x E term drops

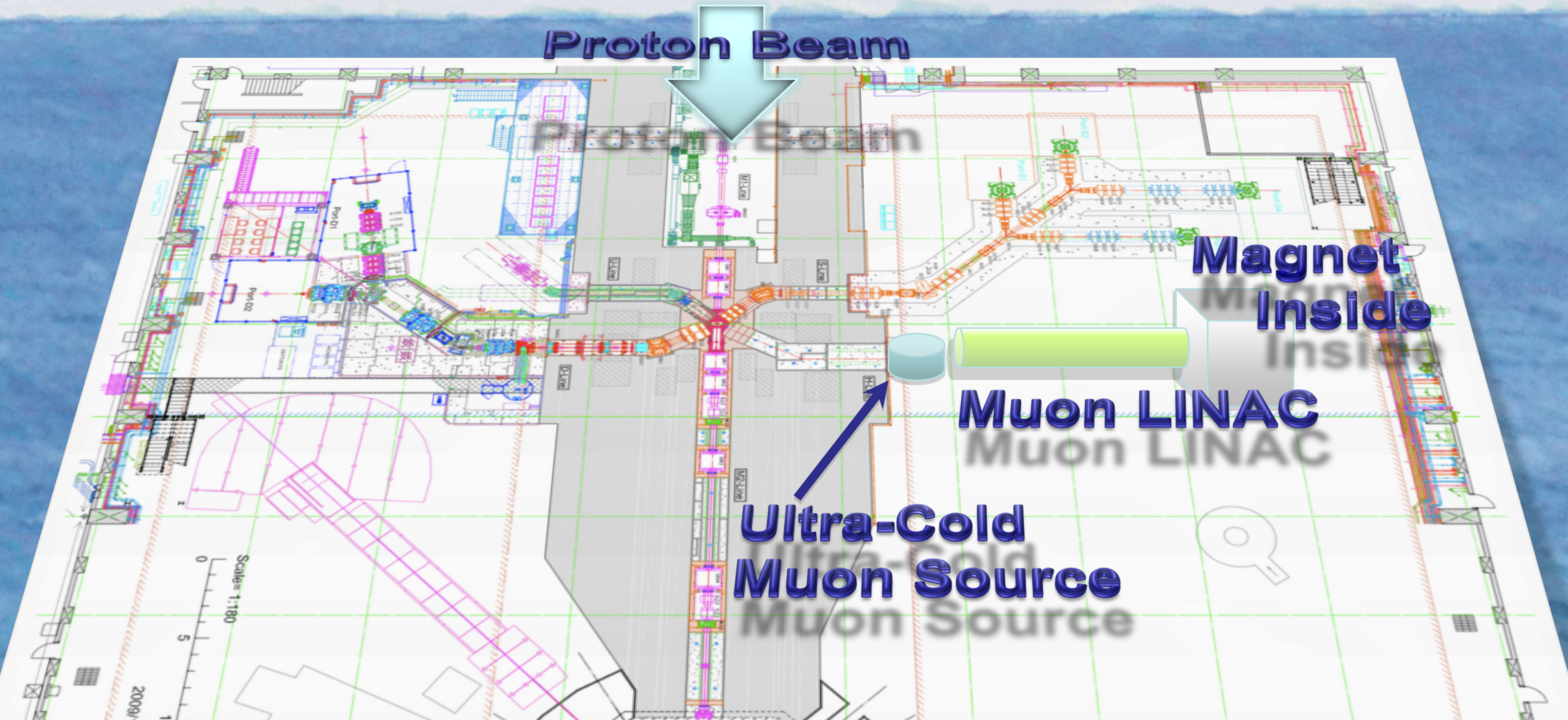
H. Okada



Possible Location at MLF

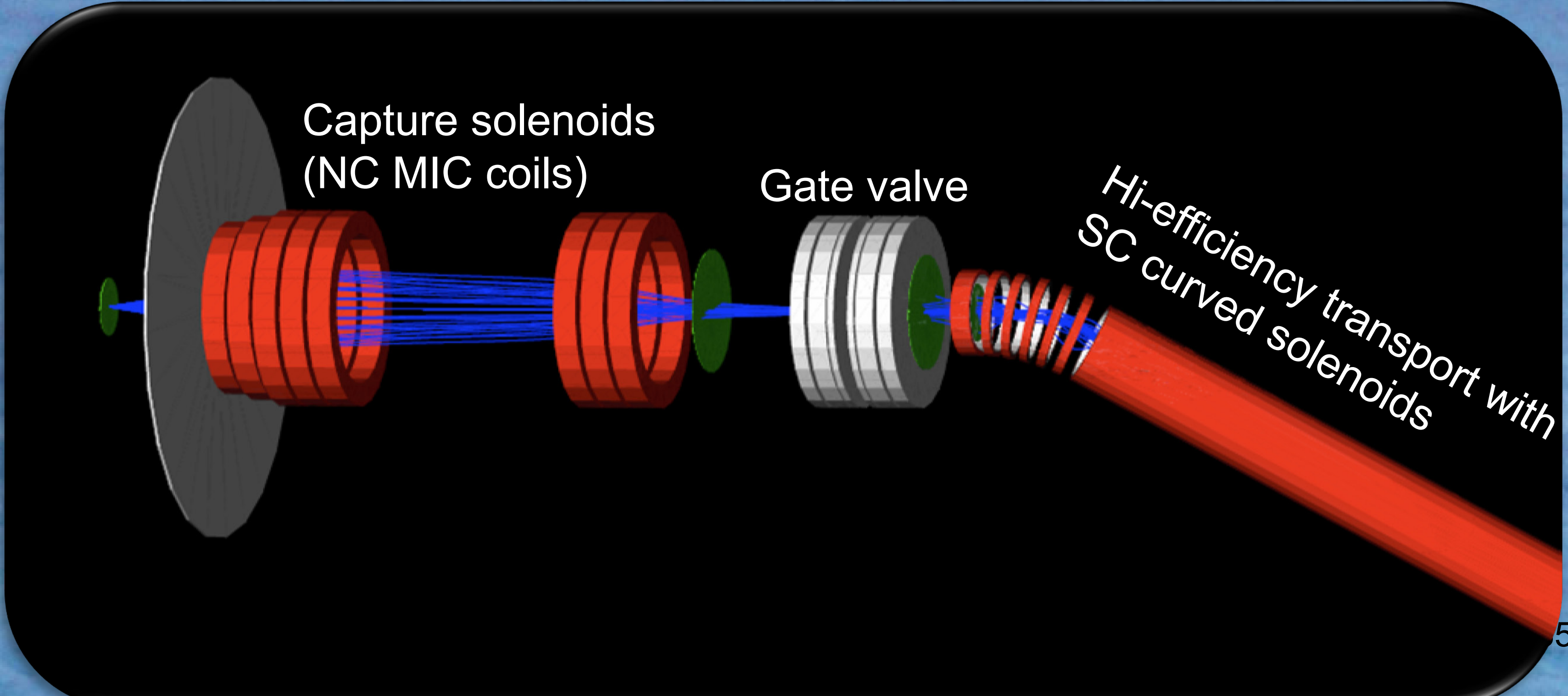
- Hi-momentum port?
  - Large acceptance preferred
  - LINAC ~50 m?
  - Magnetically Shielded Room : 5x5x5 m^3?

Service Lines (Power, Cryo etc) should be considered…



Capture solenoid & beam transport

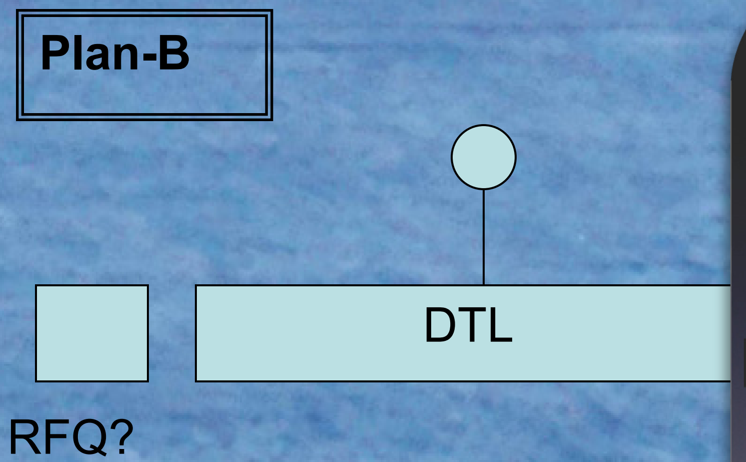
- Being designed by R. Muto et al.
  - Needed to be installed before too much contamination

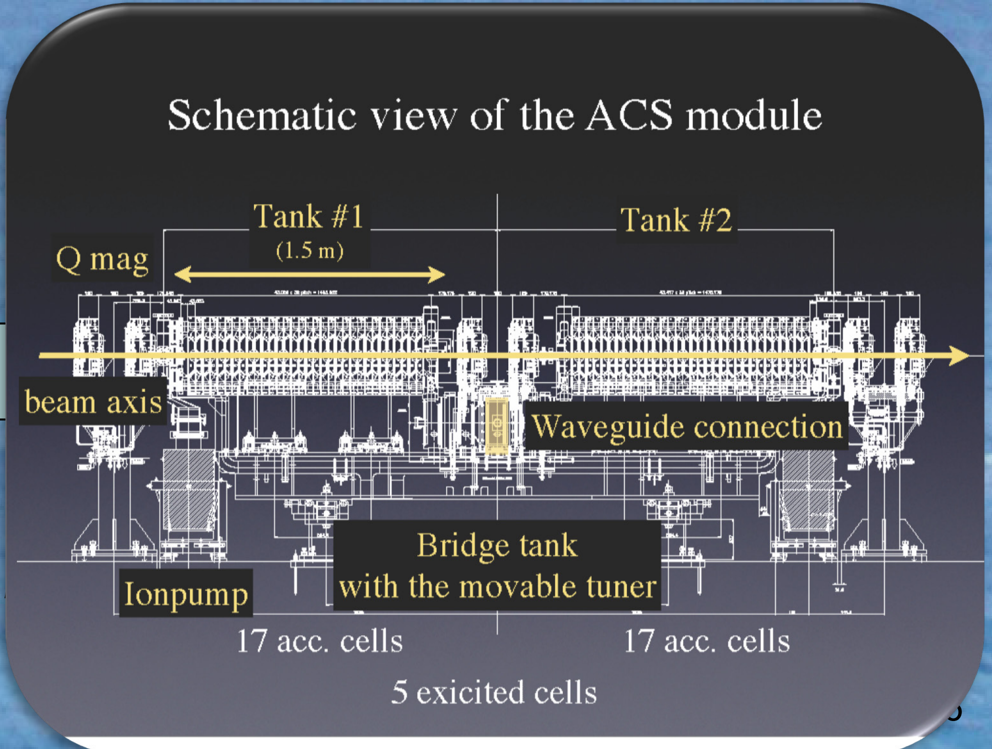


LINAC configuration

M. Ikegami & T. Kamitani et al.

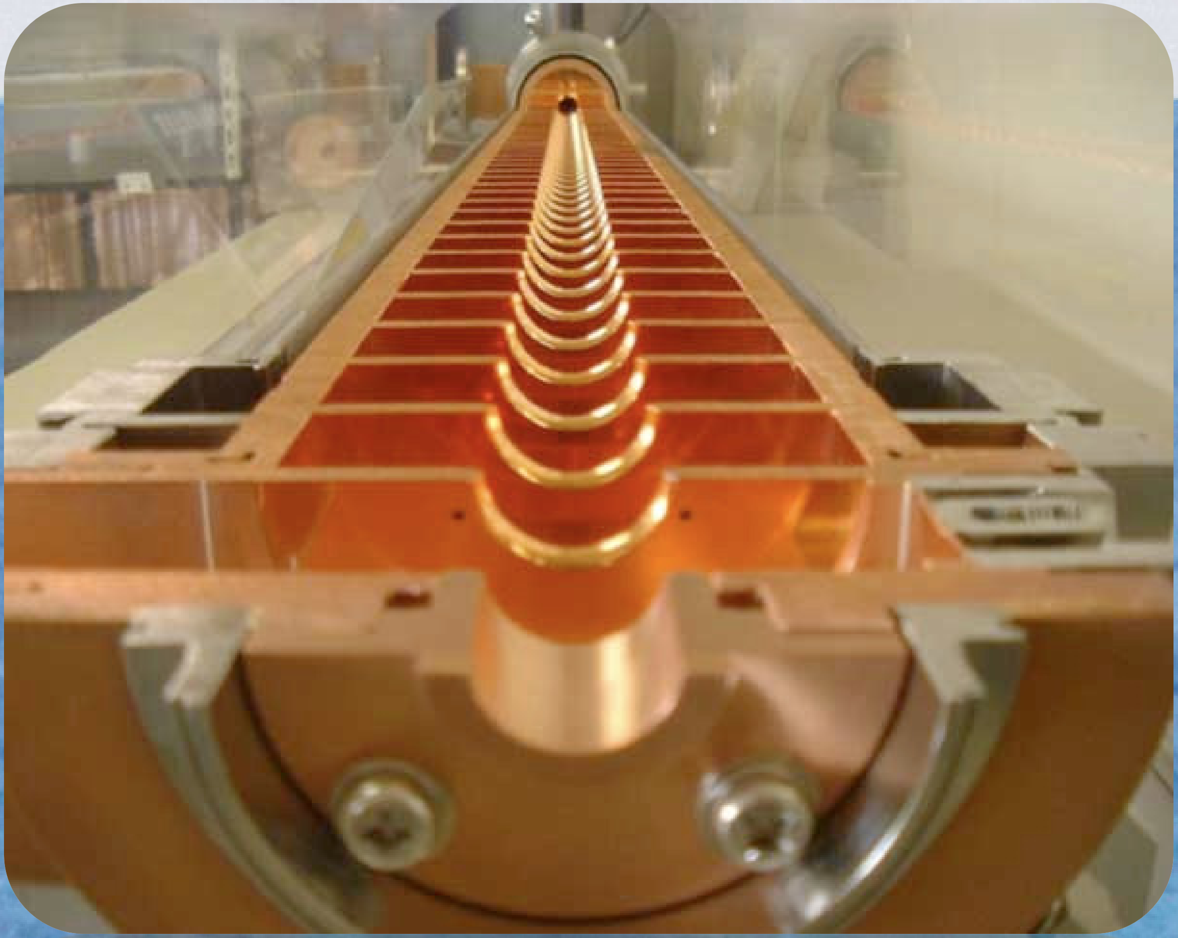
- Low-beta (proton like) LINAC → Hi-beta (electron like) LINAC
- Low-beta options





Hi-beta LINAC → Disk Loaded Type

- Close to electron



Intense Ultra Slow Muon Source @J-PARC

At J-PARC, Aiming at;

From Miyake-san

1) **Repetition Rate**
   25 Hz (At RIKEN-RAL *50 Hz*) factor ***2 times***

2) Surface Muon Yield by **Super Omega Channel**
   4.0×10^8 /s / 1.2×10^6 /s (RIKEN-RAL) = ***333*** *times*

3) Lyman-α Intensity by **Laser Development**
   100 μJ/p / 1 μJ/p (RIKEN-RAL) = ***100*** *times*

Iwasaki, Wada, Midorikawa et al. at RIKEN

Our Goal of Ultra Slow Muon Yield is

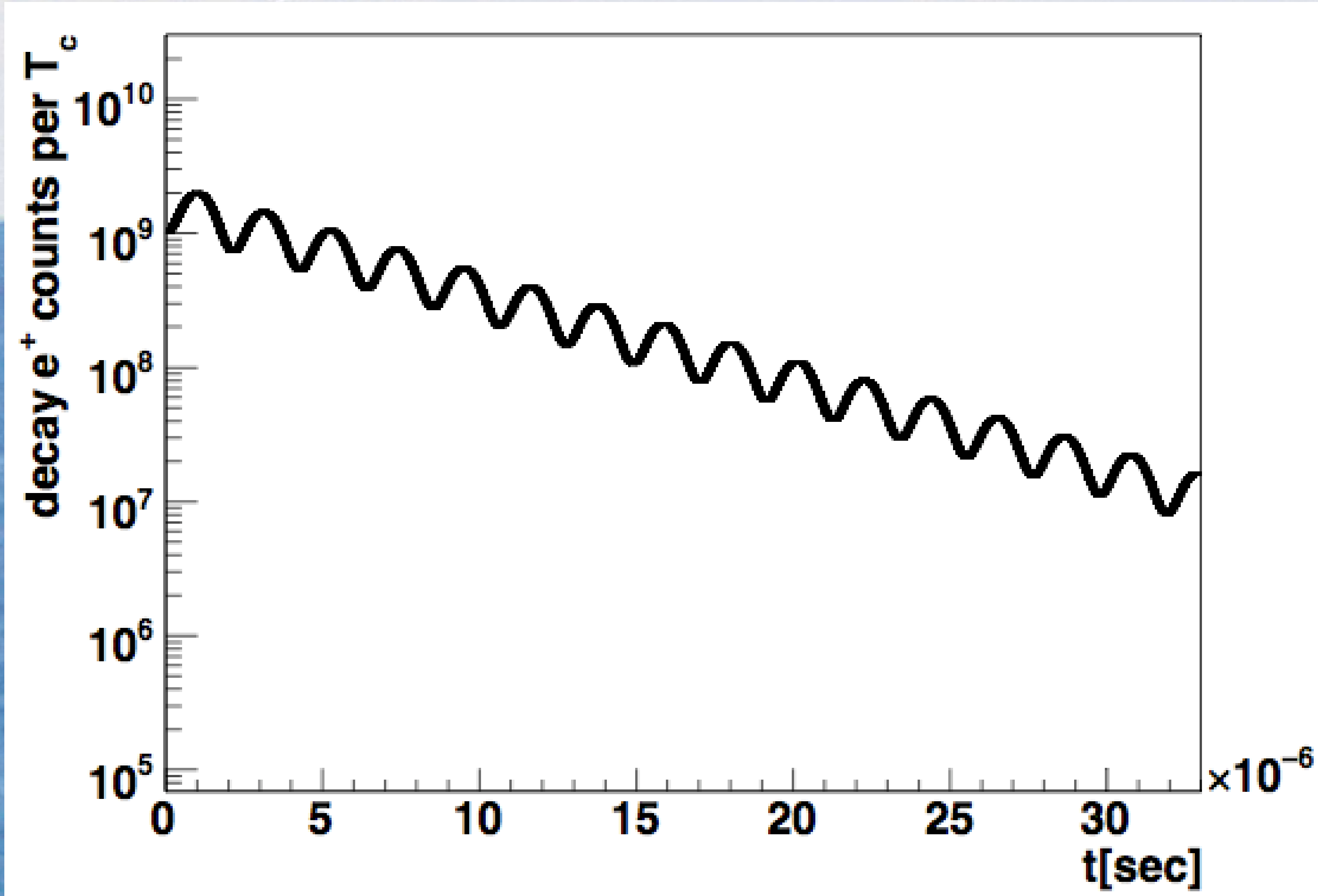
20 /s x 2 x 333 x 100 = 1.3 x 10^6/s (10^4/s without Laser Developments)

Riken-RAL Slow Muon Intensity

Maximum J-PARC Slow Muon Intensity

Expected “Wiggle Plot”

- P=300 MeV/c, B=3T version



BNL, FNAL, and J-PARC

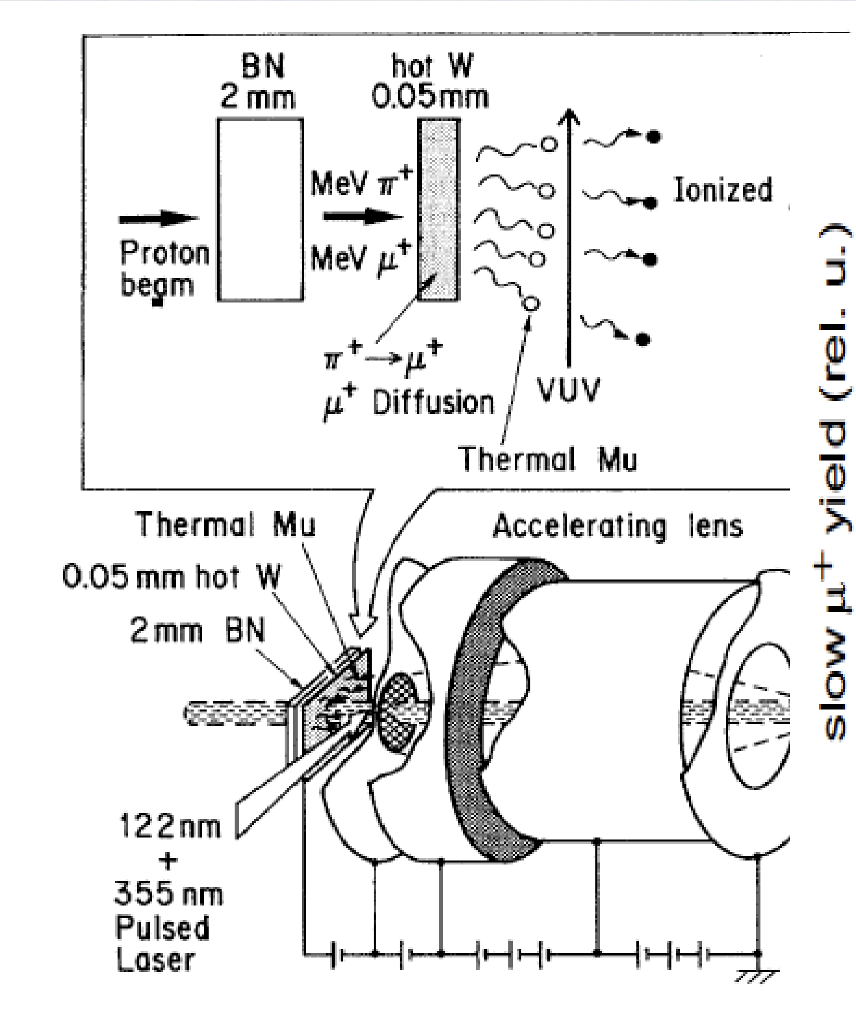
- complimentary

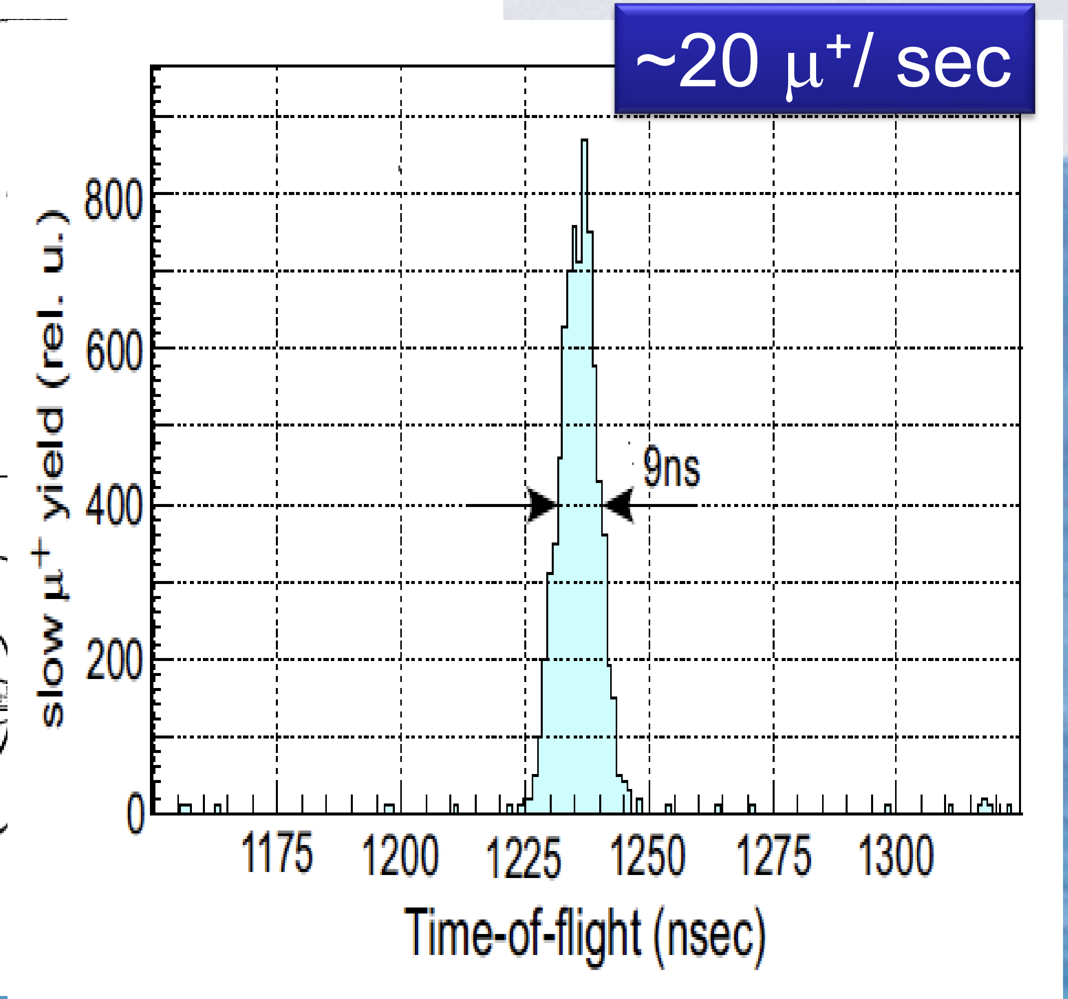
	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.11 ppm

Ultra-Slow Muon Source

K.Nagamine et al. PRL 74 (1995) 4811
Y.Matsuda et al. NP B(Proc) 155 (2006) 346

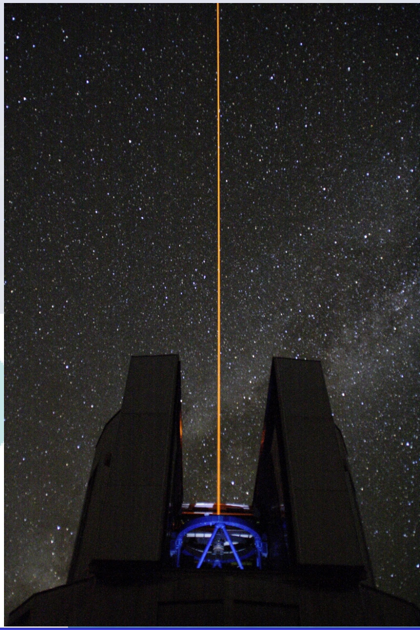
- Laser Ionization of Muonium



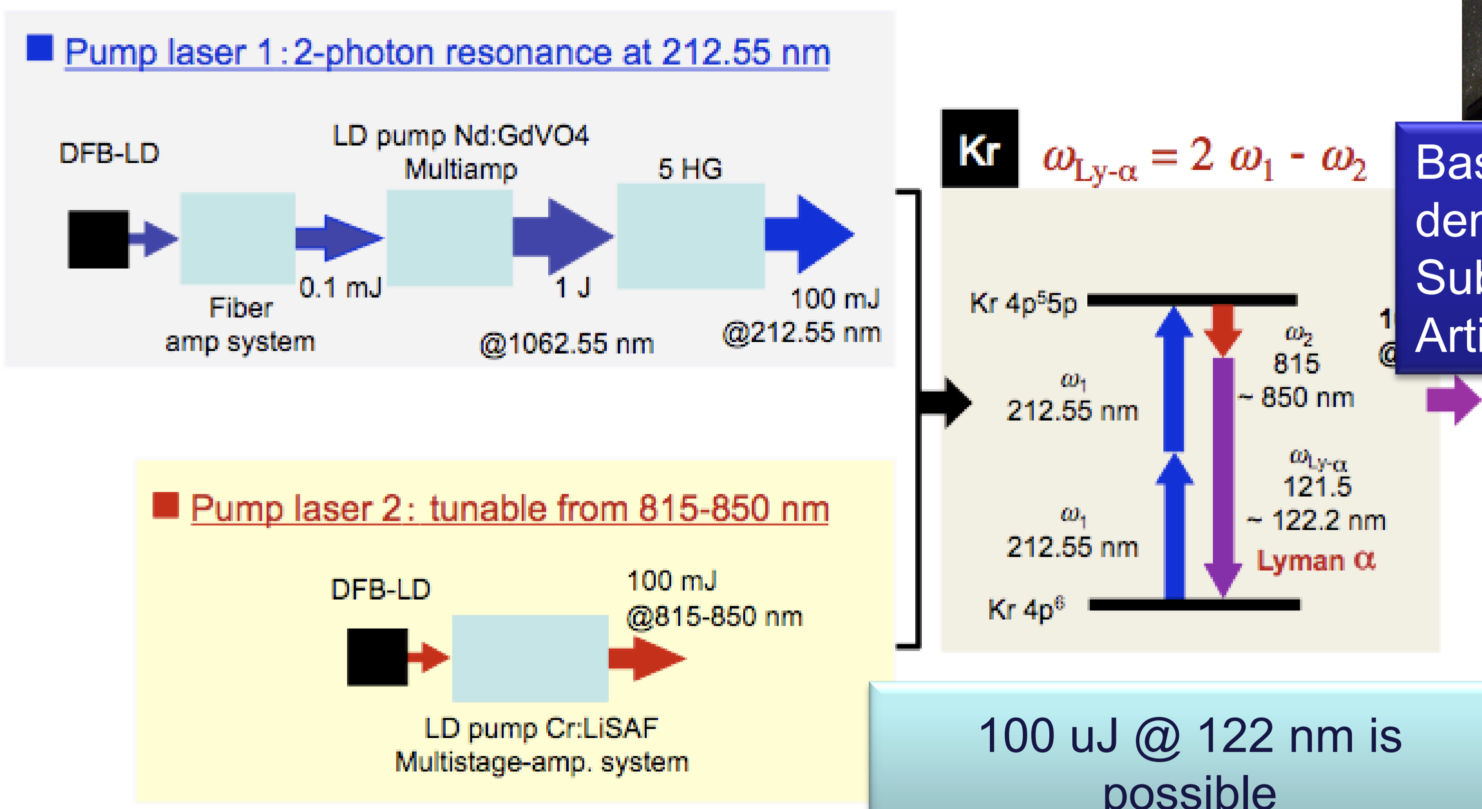


Laser Improvement

- Collaboration with Prof. Wada at RIKEN (led by Prof. Iwasaki)



Schematic Diagram



Base technology is demonstrated at Subaru Observatory's Artificial "Guide-Star".

100 uJ @ 122 nm is possible

Muon Storage Ring

- **BNL-E821 achieved ultra precision as such large magnet (14 m – diameter)**
  - **Local uniformity ~ 100 ppm → 0.1 ppm integrated field**
- **Smaller Ring with Hi Field just matches with MRI technology**
  - **Active shimming – 1 ppm local uniformity**
  - **High field (~ 7 T) with large gap (~ 40 cm) is possible**

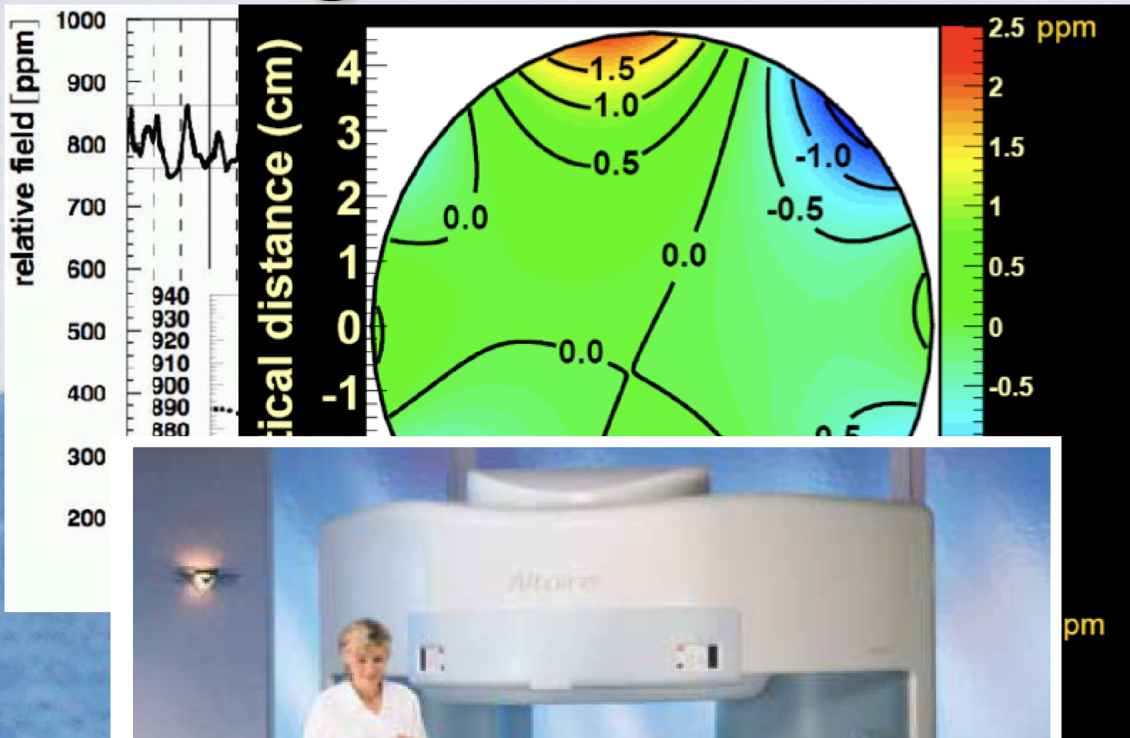
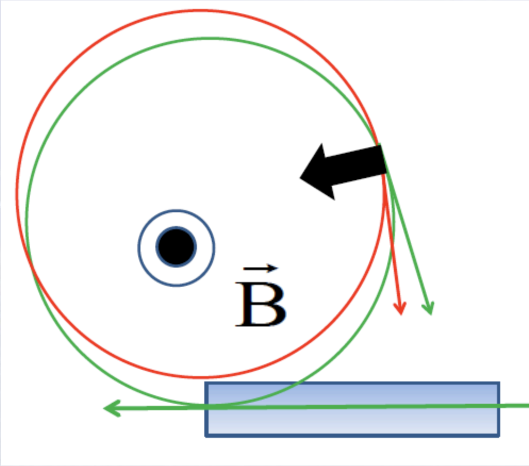


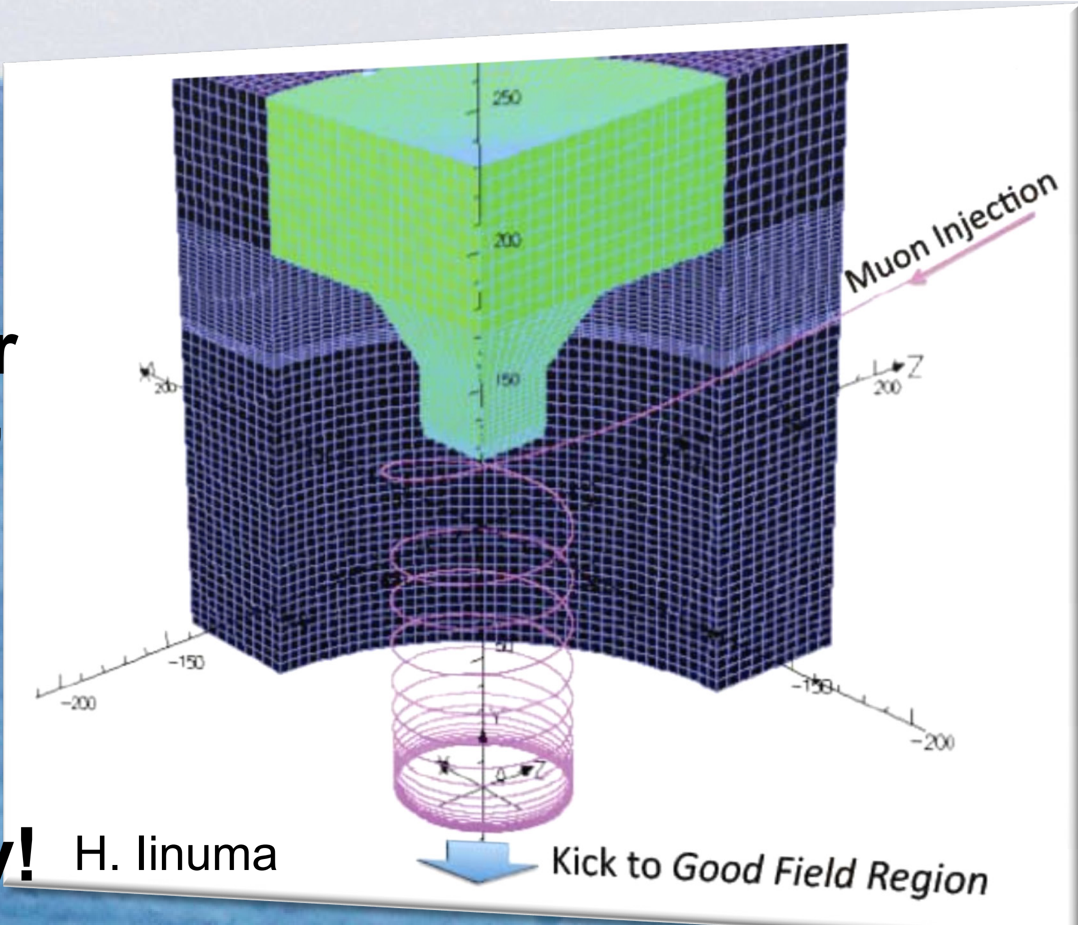
図１：オープンMRI装置の概観図

Spiral Injection Scheme

K. Oide, H. Nakayama and H. Iinuma



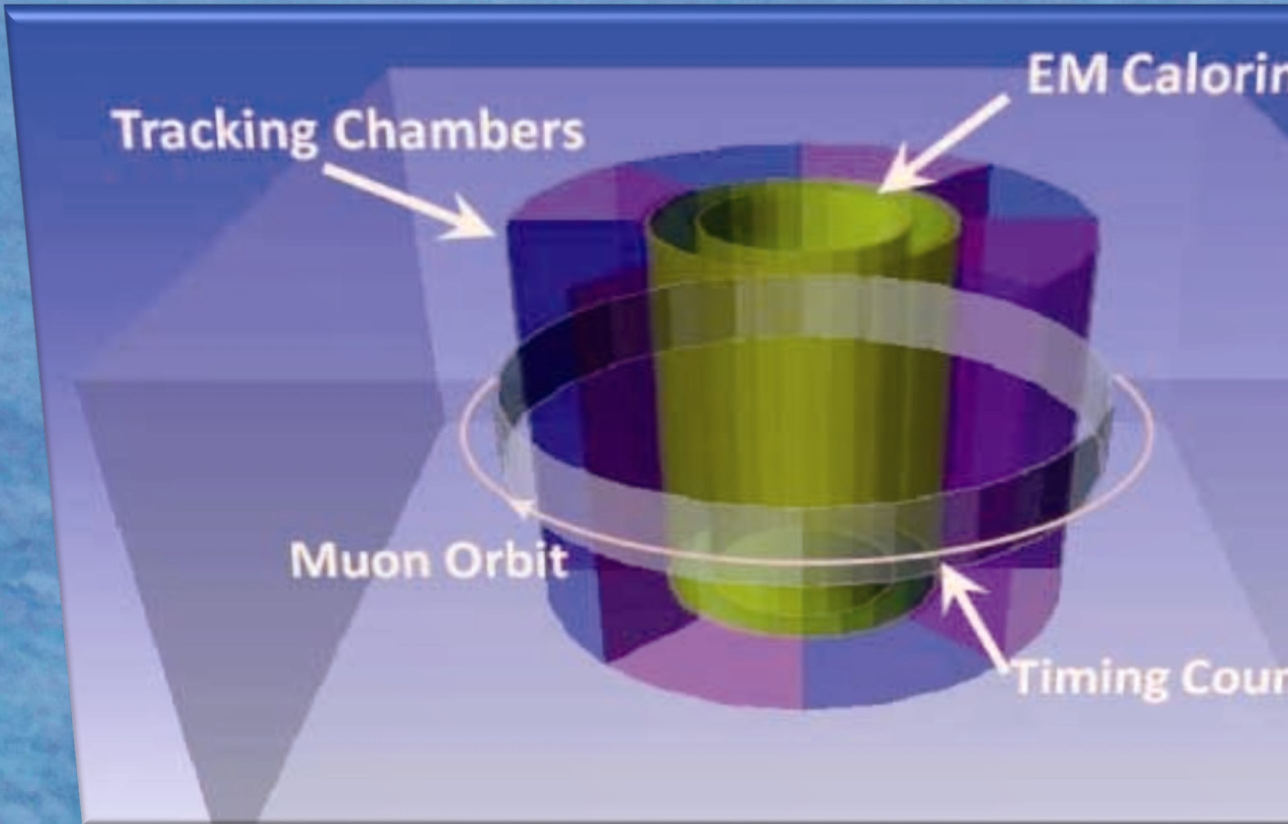
- Inject muon beam with vertical angle to avoid interference in the injection region
- Deflect P_T into P_L by radial field
- Move beam by kicker to "good filed region"
  - Double-kicker or
  - Weak kicker ?
- Better monitoring/ shimming necessary!

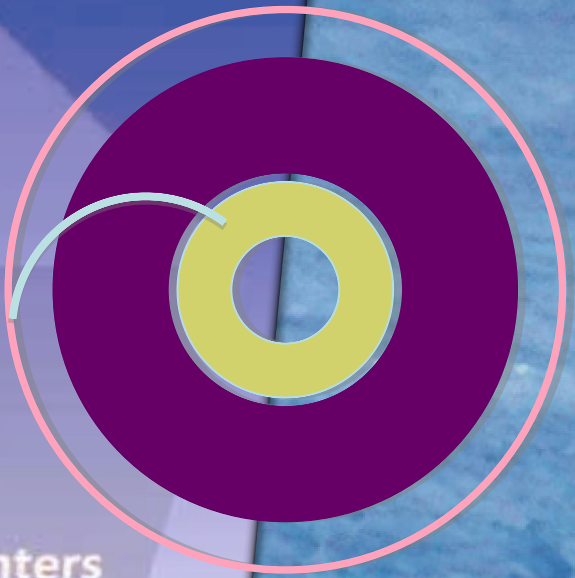


H. Iinuma

Detector Concept

- Tracking device with hi-rate capability
  - Silicon tracker for precision tracking
  - Time structure of measurement : 30 usec meas. 40msec intrvl
- Calorimeter with small Moliere radius / or active absorber
  - Tungsten based sampling calorimeter?

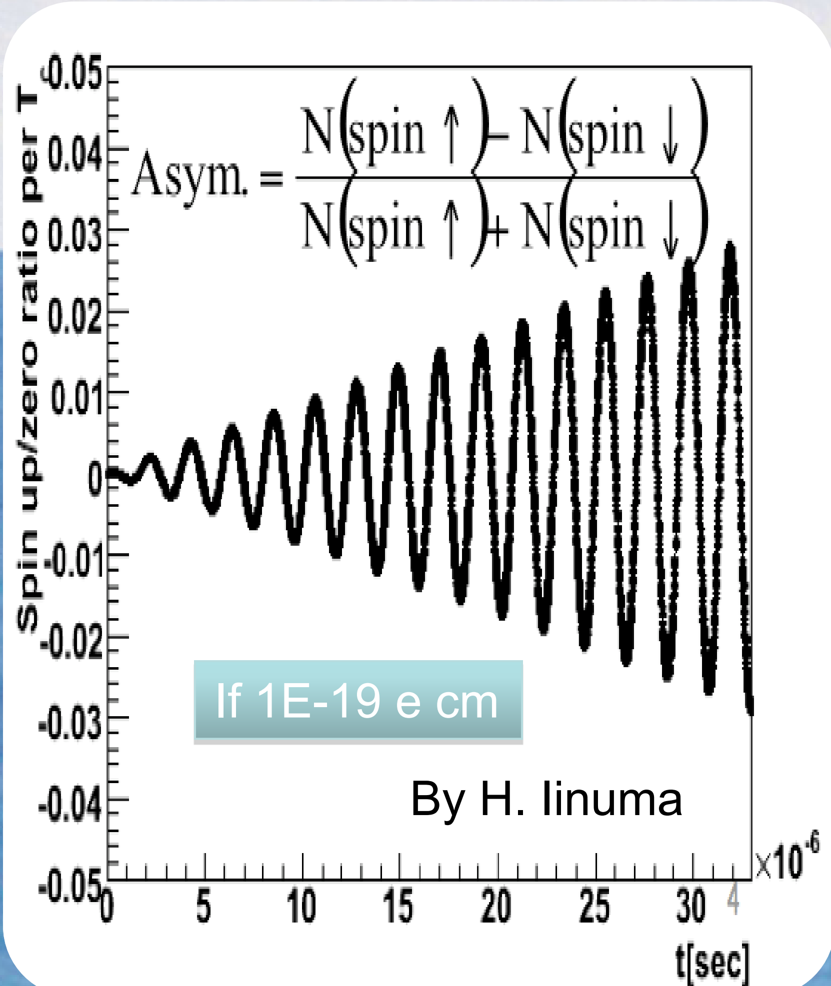


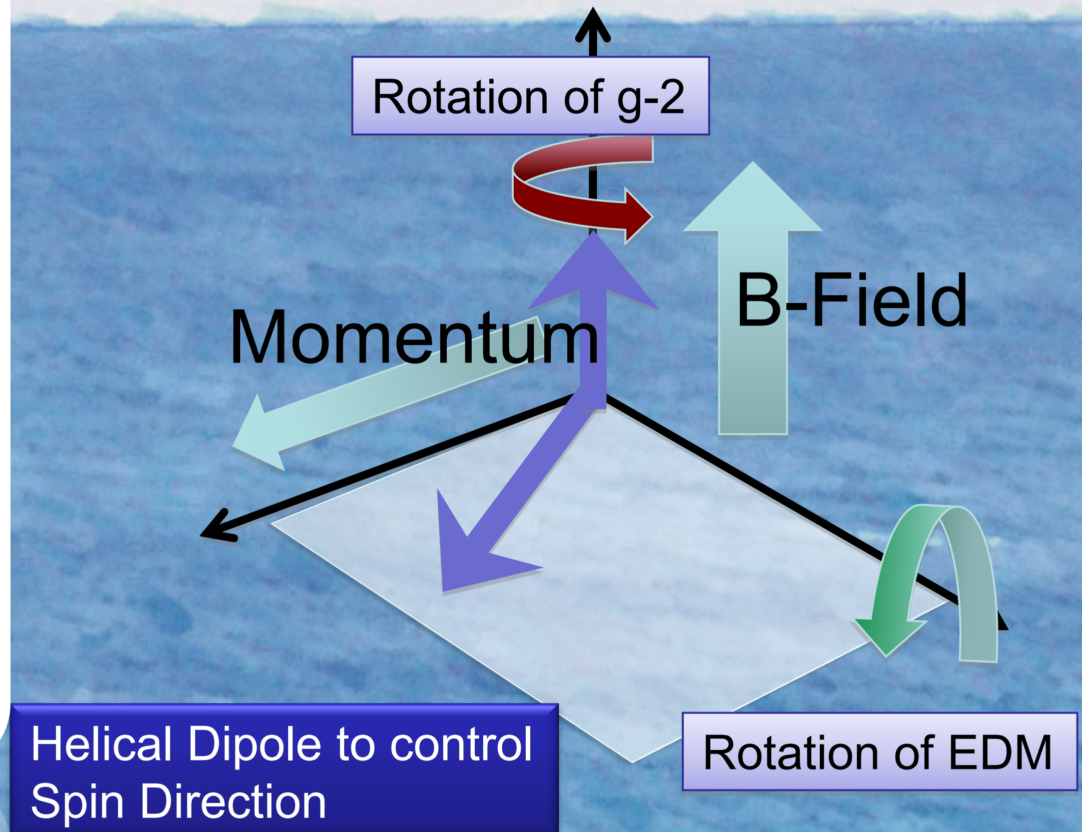


Spin Rotation and EDM

- Rotation axis is orthogonal to g−2 case

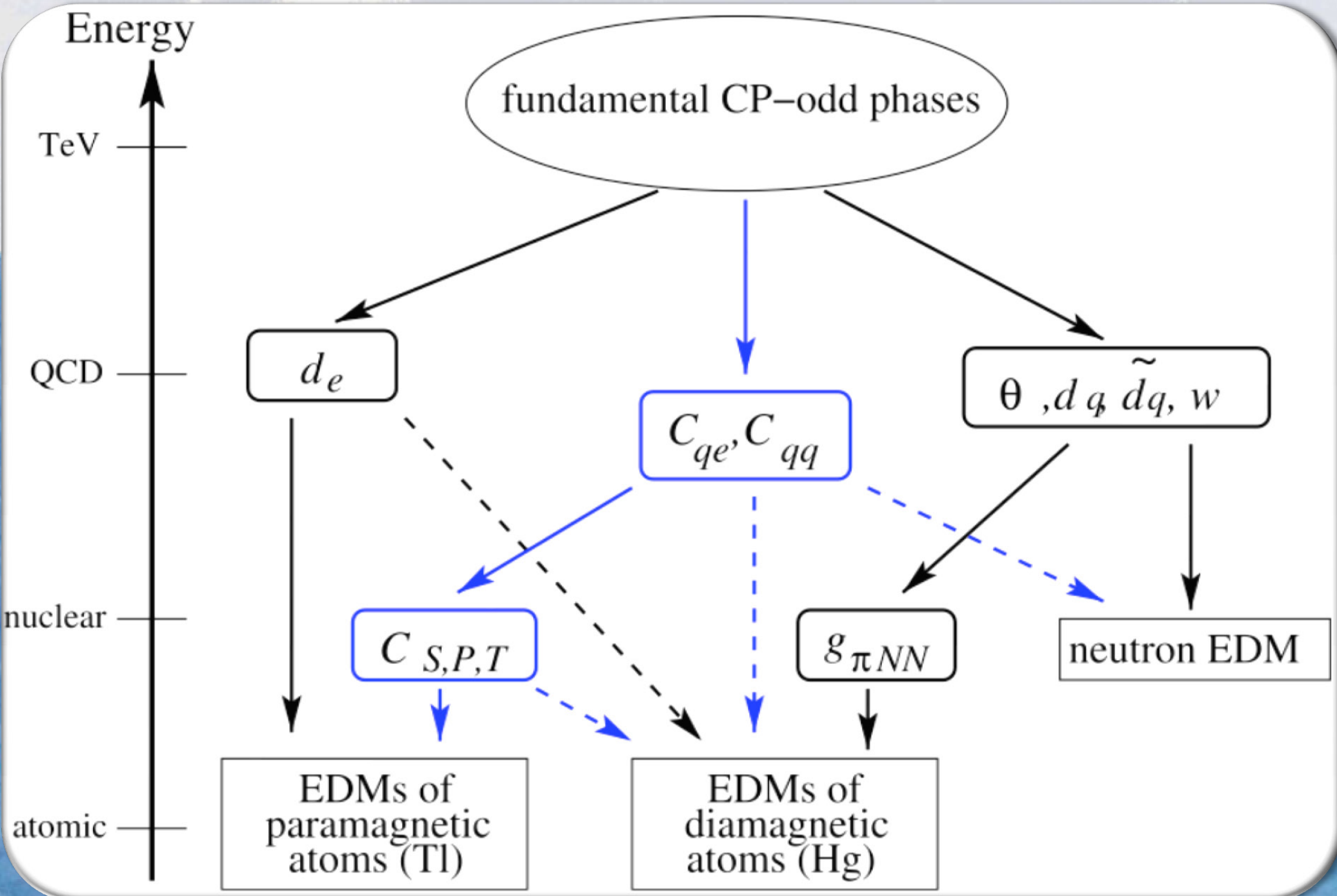
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$





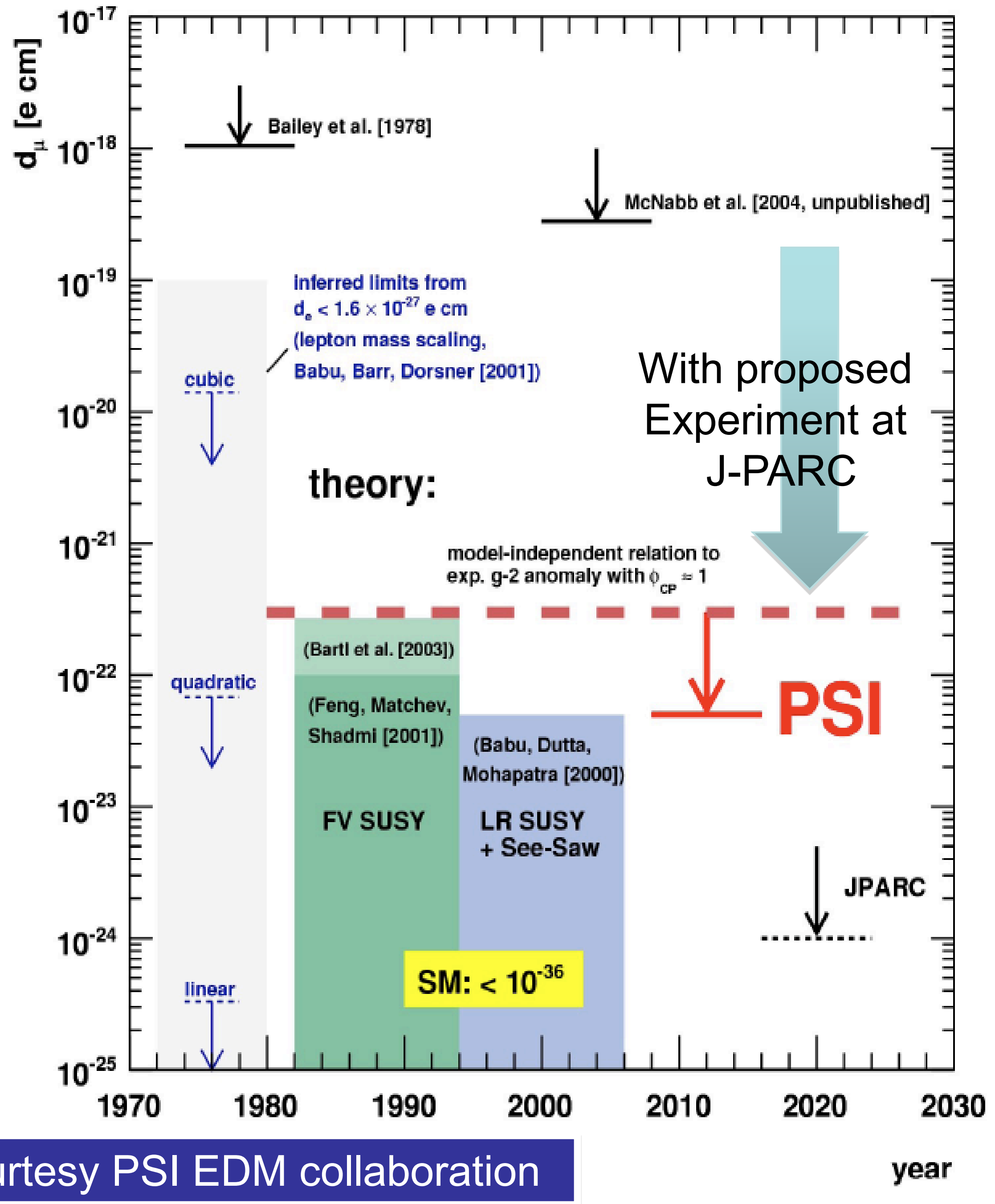
Origin of EDM

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



Muon EDM

- Direct CPV in Lepton Sector
  - CPV Required beyond KM
- Current Exp. Limit ~ 1e-19
- Potential Sensitivity of J-PARC
  - ~ 1e-22 @ MLF

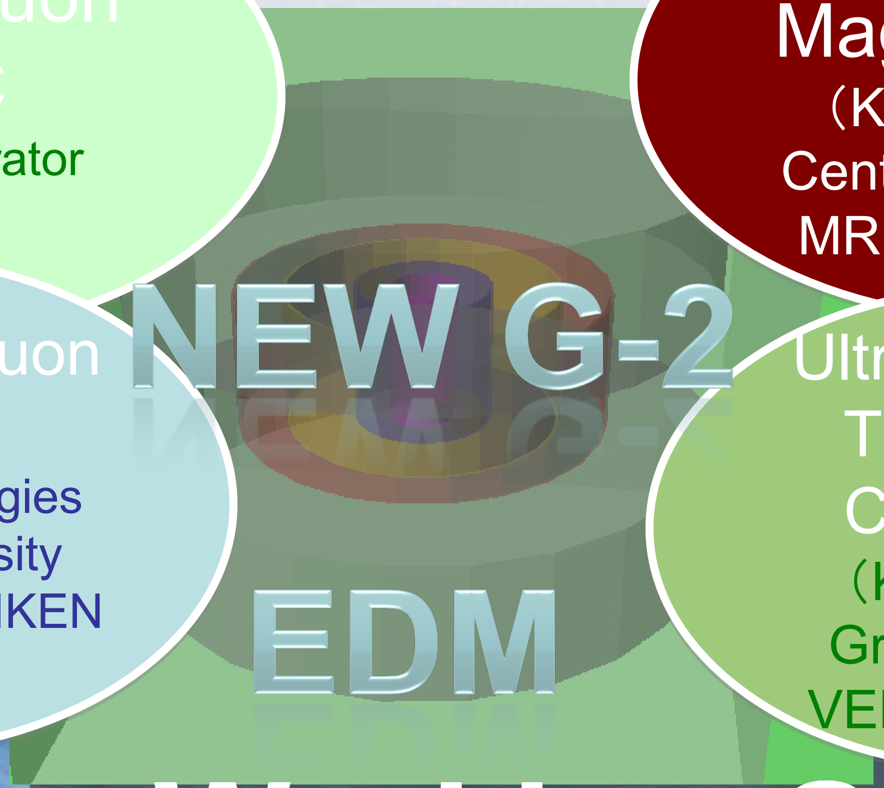


Courtesy PSI EDM collaboration

Collaborative Efforts!

R&D of Muon LINAC
(KEK Accelerator Team)

Precision Magnetic Field
(KEK Cryogenic Center / Progress in MRI technologies)



Ultra Cold Muon Source
(Laser technologies and High Intensity Proton Beam : RIKEN and KEK)

Ultra-Precision Theoretical Calculation
(KEK Theory Group & Belle, VEPP, Babar…)

Muon Working Group

LOI submitted to J-PARC PAC

- Process to handle this experiment is discussed at the latest PAC
- Full proposal is being prepared
- To be discussed at the coming PAC
- Joint committee of J-PARC MR PAC and MLF PAC will follow

Letter of Intent:

New Measurement of Muon Anomalous Magnetic Moment g-2

and Electric Dipole Moment at J-PARC

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Summary

- Proposal is being prepared for New Generation of Muon g-2/EDM Experiment at J-PARC
  - Proposal at Fermilab is proceeding well
  - Completely different systematics
- Intend to start the experiment in 5 years!