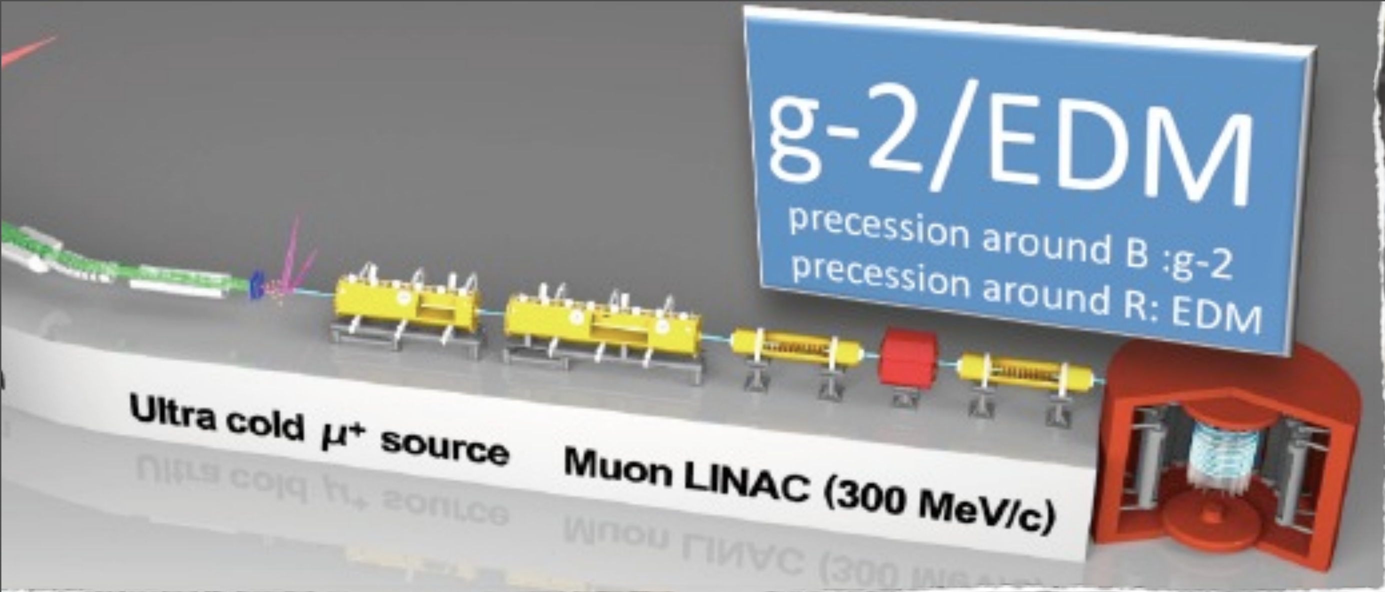


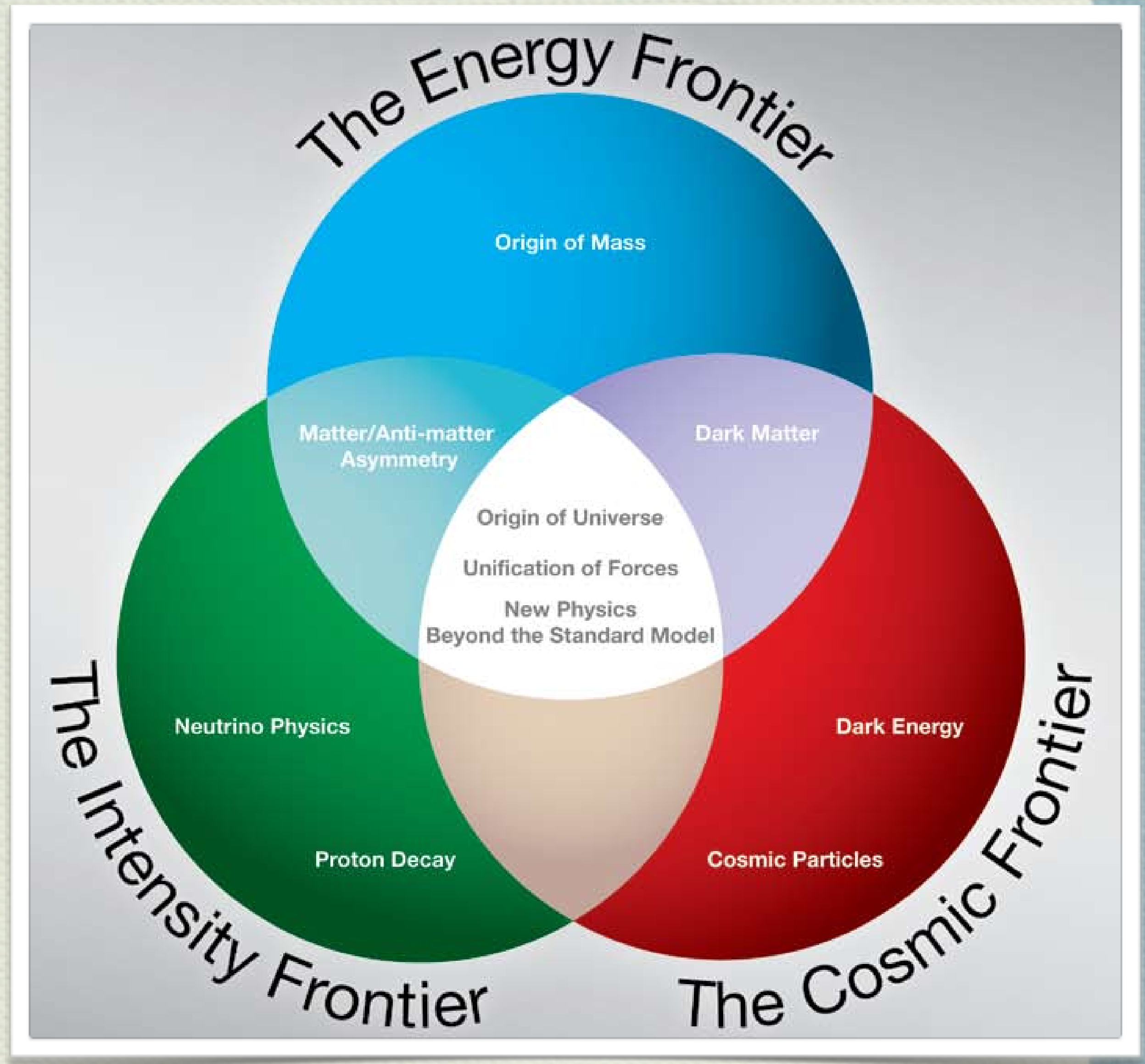
Fundamental Physics with Muon and Neutron in an LHC Era

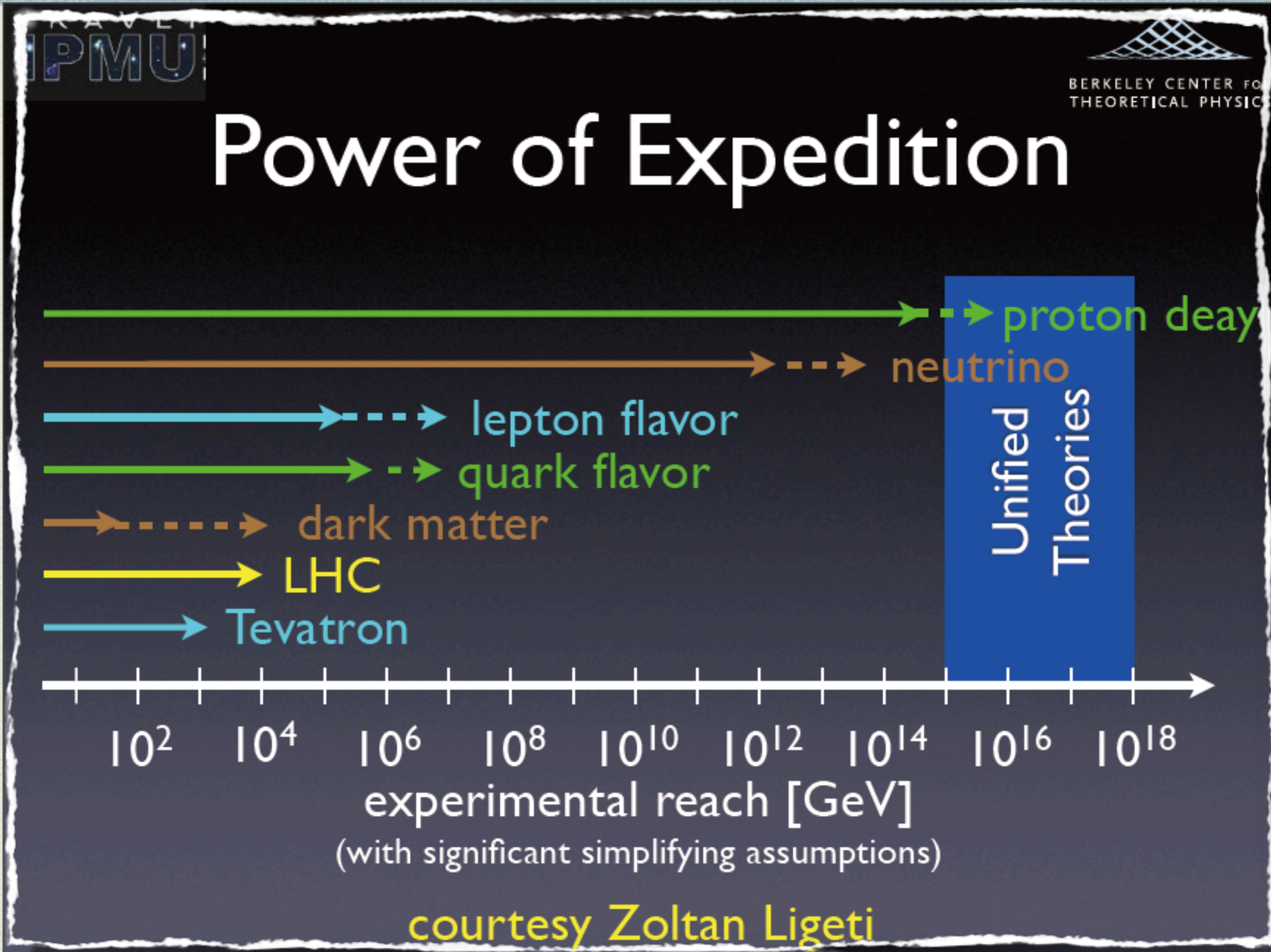
The 2nd WS on Muon g-2 and EDM in an LHC Era

Naohito SAITO (KEK)

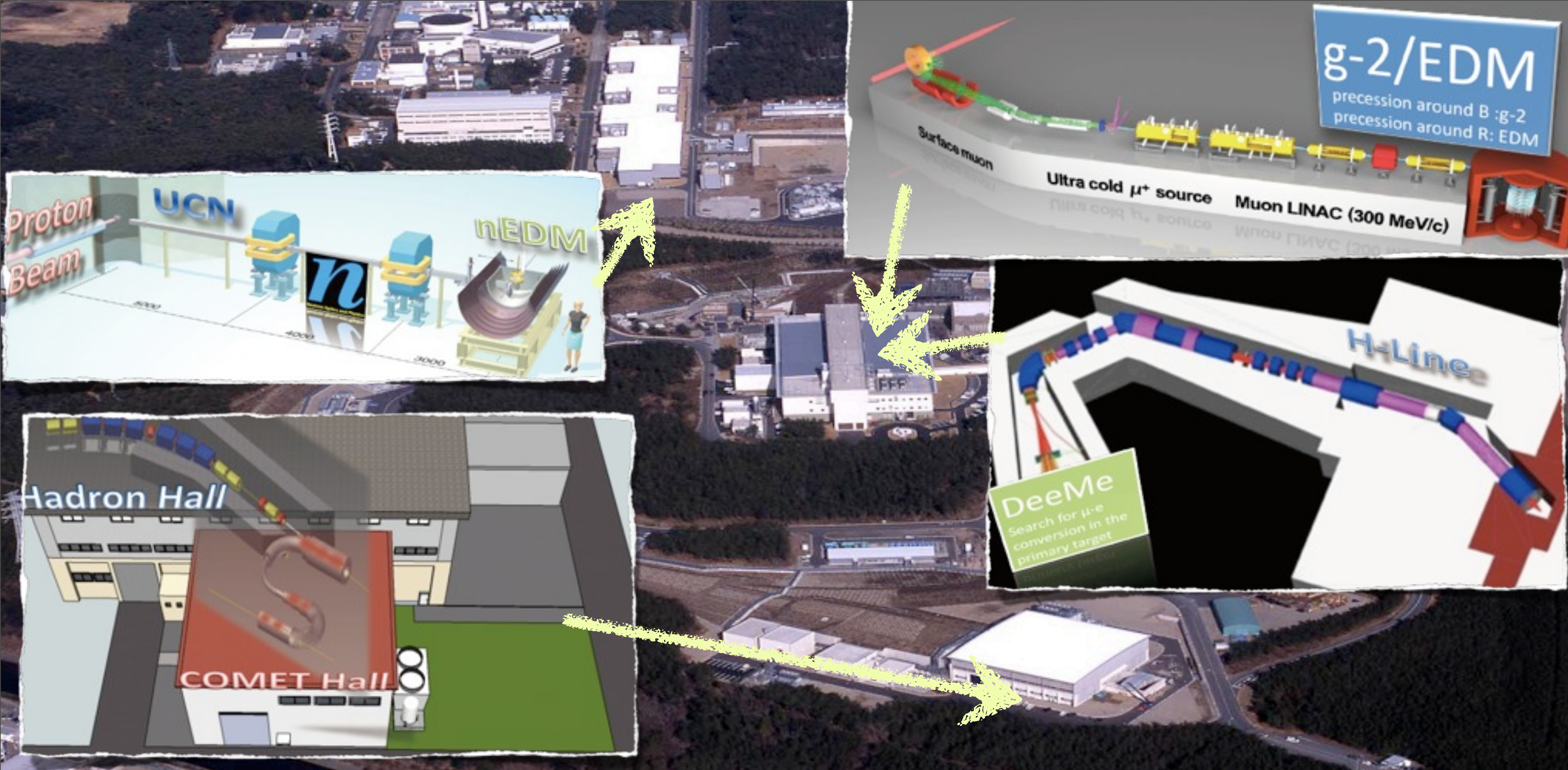
J-PARC : Intensity Frontier

- What is the role of Intensity Frontier?
  - (Energy Frontier and Cosmic Frontier)
- Provide Hints for New Physics with Precision Measurements
- Set the Energy Scale of New Physics
- J-PARC : the High Intensity Proton Driver : ν, K, n, μ
- Muon LFV / g-2 / EDM and nEDM





a slide by Hitoshi Murayama



cLFV: COMET and DeeMe
muon g-2/EDM
neutron EDM

Lepton and EDM Physics at Intensity Frontier Machine : J-PARC

cLFV

Improve by x 100 and more (10^{-12}--> $10^{-14; -16}$)

Search for Charged Lepton Flavor Mixing

Charged Lepton Flavor Mixing and Origin of Matter

g–2

Improve by x 5 (0.1 ppm)

Precision Measurement of Anomalous Magnetic Moment

Muon Precision Experiment to search for New Physics

μEDM

Improve by x 100 and more ($1\times10^{-21; -24}$ e cm)

Search for Electric Dipole Moment

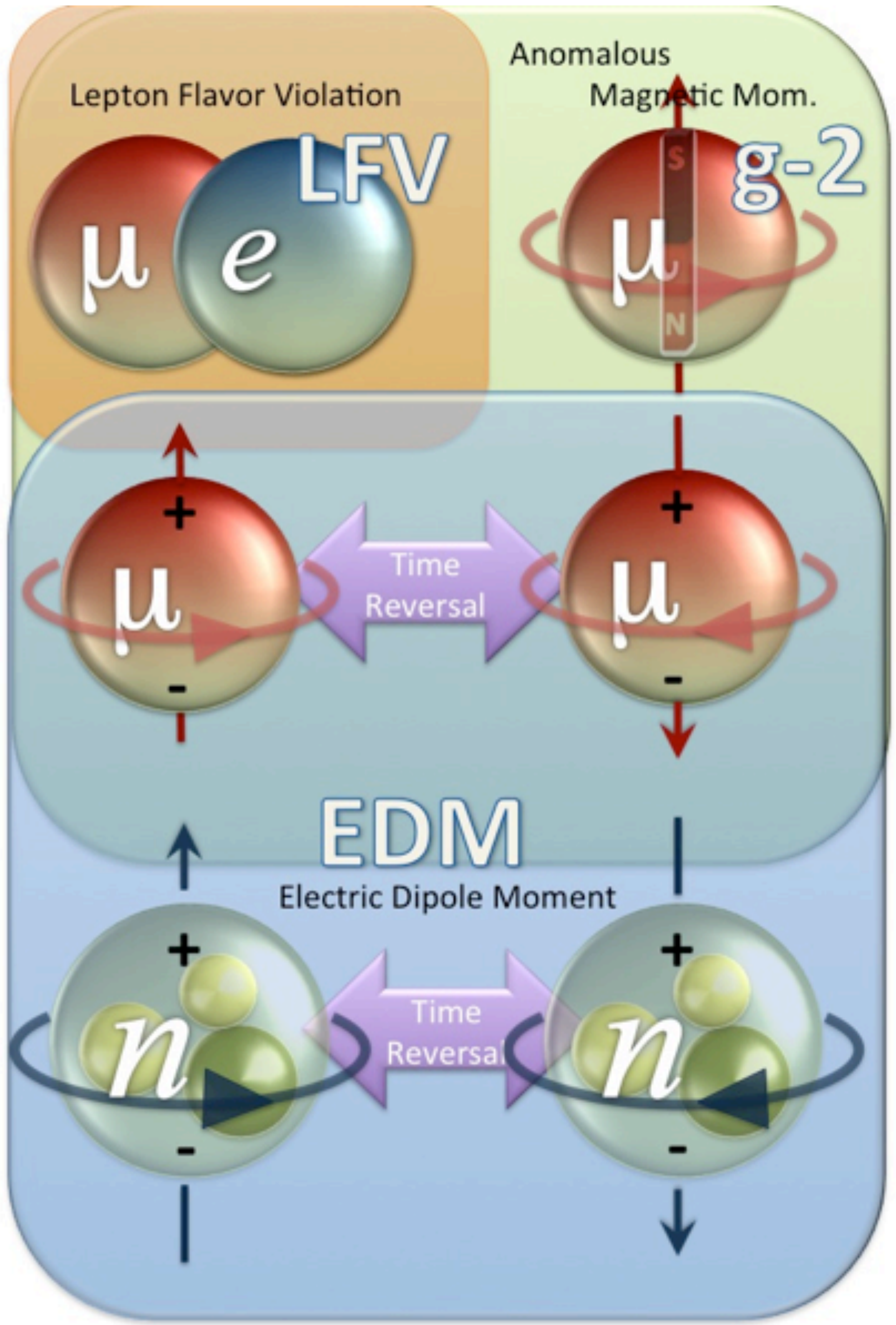
Space-time Symmetry and Origin of Matter

nEDM

Improve by 100 and more ($1\times10^{-28 ; -29}$ e cm)

Search for Electric Dipole Moment

Space-time Symmetry and Origin of Matter



$$\mathrm{EDM} \propto \mathrm{Im}(m^2_{\tilde\mu\tilde\mu})$$

$$\mathrm{cLFV} \propto \Delta m^2_{\tilde e\tilde\mu} + \Delta m^2_{\tilde\mu\tilde e}$$

$$g-2 \propto \mathrm{Re}(m^2_{\tilde\mu\tilde\mu})$$

$$M^2_{\tilde l\tilde l'} = \begin{pmatrix} m^2_{\tilde e\tilde e} & \Delta m^2_{\tilde e\tilde\mu} & \Delta m^2_{\tilde e\tilde\tau} \\ \Delta m^2_{\tilde\mu\tilde e} & m^2_{\tilde\mu\tilde\mu} & \Delta m^2_{\tilde\mu\tilde\tau} \\ \Delta m^2_{\tilde\tau\tilde e} & \Delta m^2_{\tilde\tau\tilde\mu} & m^2_{\tilde\tau\tilde\tau} \end{pmatrix}$$

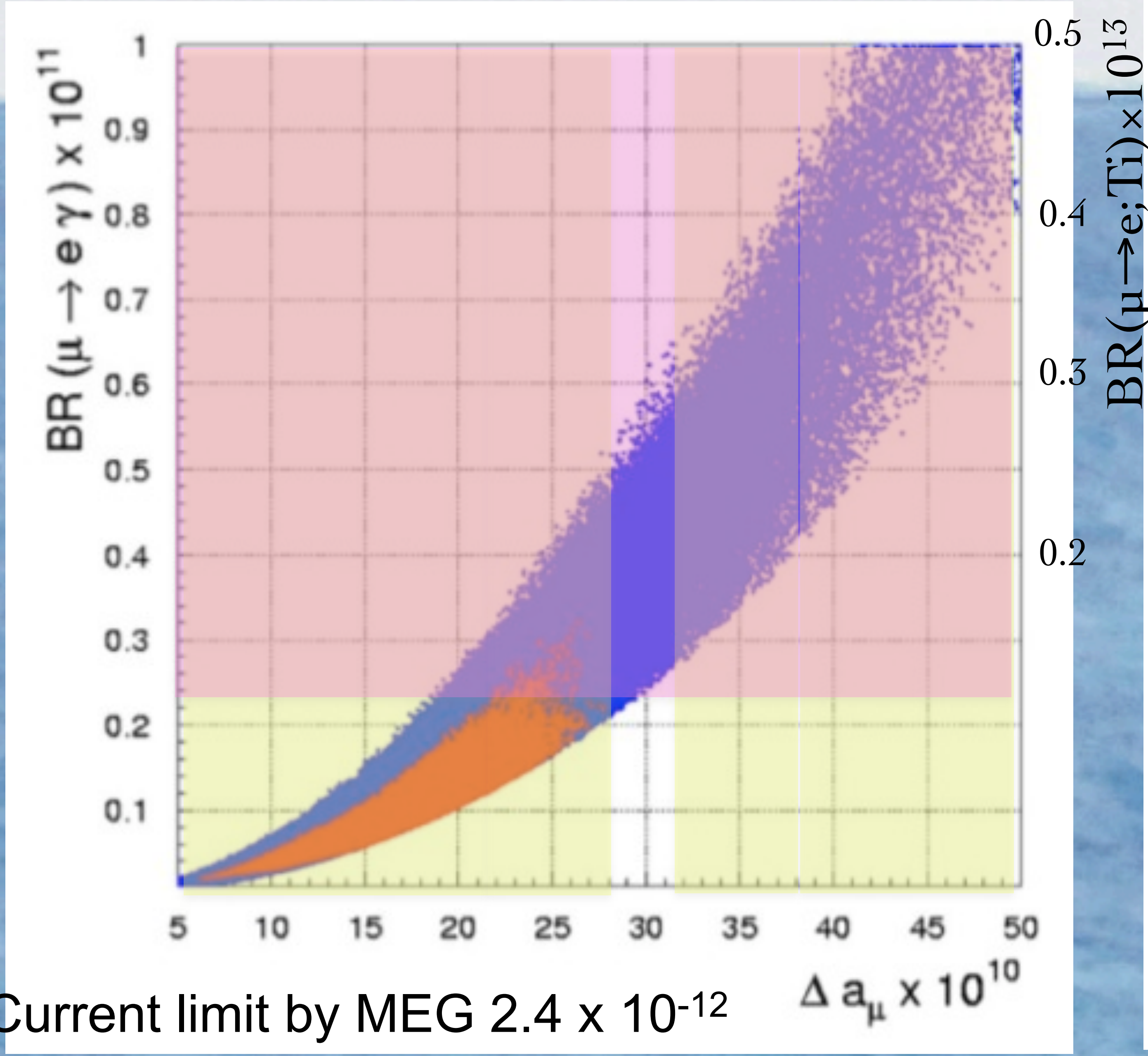
SUSY Mass Matrix

g-2, EDM and cLFV

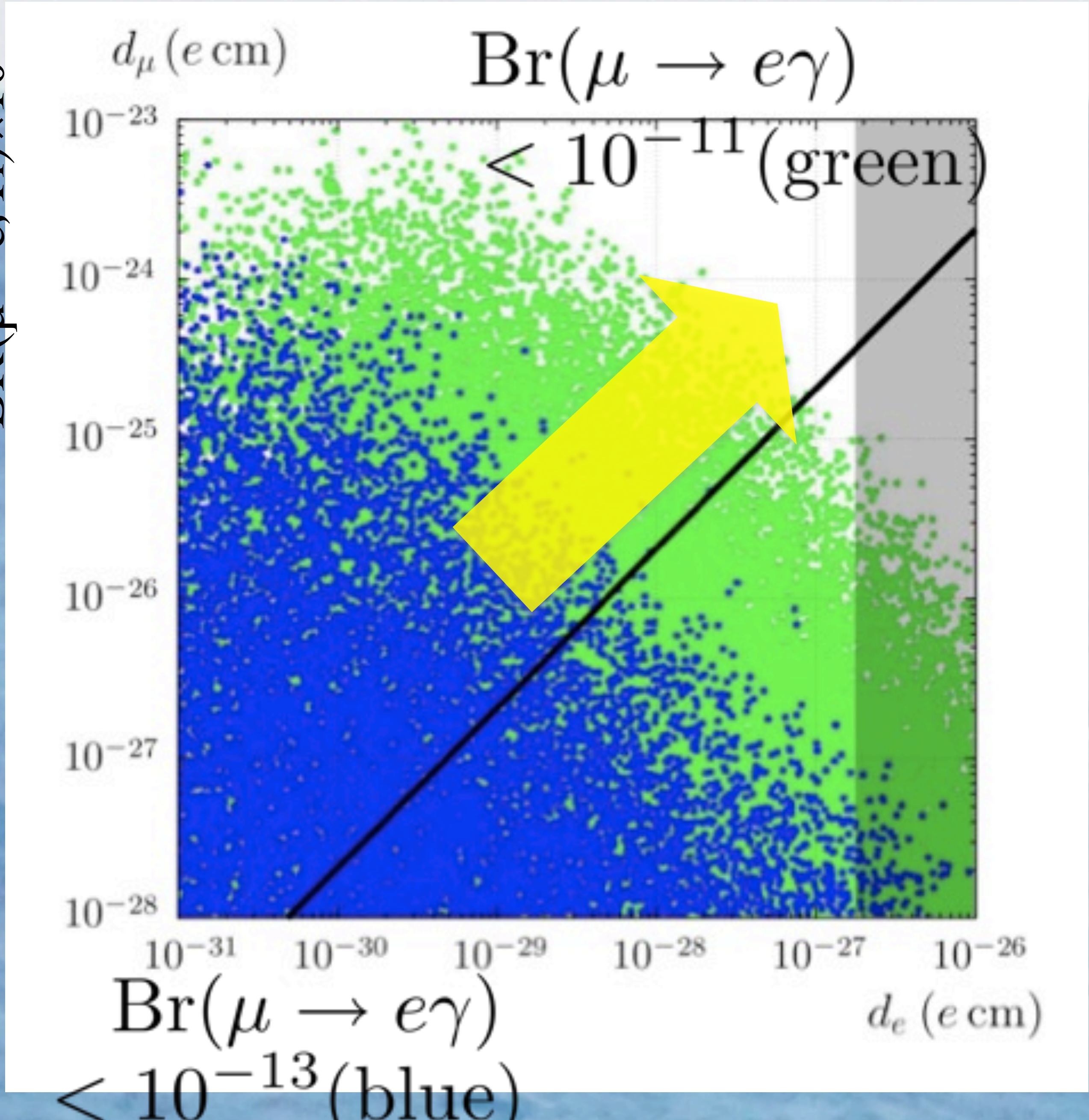
- **Large g-2 → Large cLFV → Large EDM**

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

J. Hisano, Nagai, Paradisi



Current limit by MEG 2.4 x 10^{-12}



“g-2” tension with LHC 1/fb

χ^2 version

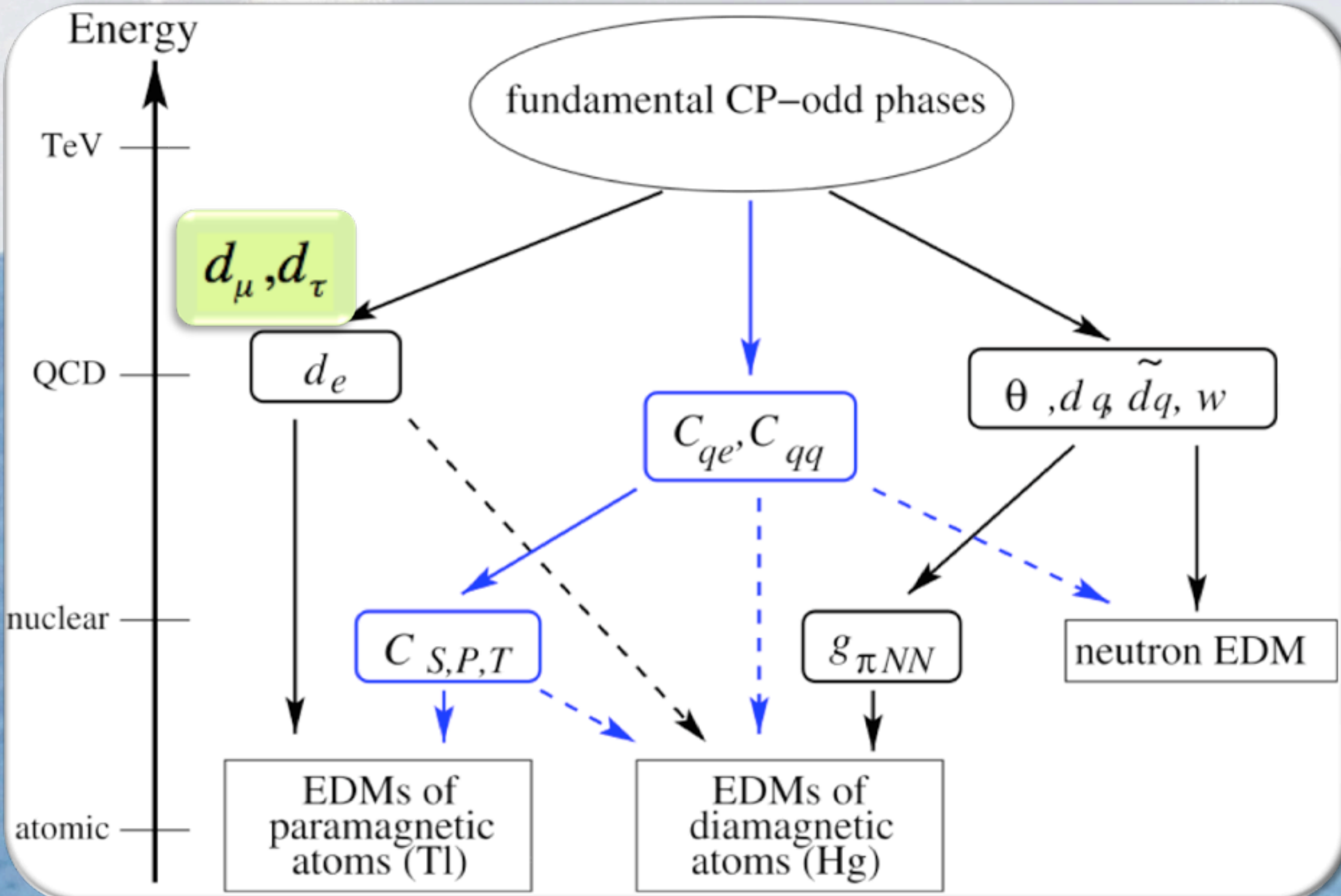
- **Table 1 from** O. Buchmueller, et al, hep-ph> arXiv:1110.3568v1
  - **need new measurements!**

Model	Minimum χ^2/d.o.f.	Prob-ability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (GeV) (no LEP)
CMSSM pre-LHC	21.5/20	37%	360^{+180}_{-100}	90^{+220}_{-50}	-400^{+730}_{-970}	15^{+15}_{-9}	$111.5^{+3.5}_{-1.2}$
CMSSM $\mathrm{LHC}_{1/\mathrm{fb}}$	28.8/22	15%	780^{+1350}_{-270}	450^{+1700}_{-320}	-1100^{+3070}_{-3680}	41^{+16}_{-32}	$119.1^{+3.4}_{-2.9}$
Linear Δ BR$(b \to s\gamma)$	28.0/22	18%	720^{+1170}_{-230}	420^{+1270}_{-270}	-1100^{+2180}_{-2750}	39^{+18}_{-22}	$118.6^{+3.9}_{-1.9}$
$(g-2)_\mu$ neglected	21.3/20	38%	2000^{+}_{-}	1050^{+}_{-}	430^{+}_{-}	22^{+}_{-}	$124.8^{+3.4}_{-10.5}$
Both	20.5/20	43%	1880^{+}_{-}	1340^{+}_{-}	1890^{+}_{-}	47^{+}_{-}	$126.1^{+2.1}_{-6.3}$
NUHM1 pre-LHC	20.8/18	29%	340^{+280}_{-110}	110^{+160}_{-30}	520^{+750}_{-1730}	13^{+27}_{-6}	$118.9^{+1.1}_{-11.4}$
NUHM1 $\mathrm{LHC}_{1/\mathrm{fb}}$	27.3/21	16%	730^{+630}_{-170}	150^{+450}_{-50}	-910^{+2990}_{-1170}	41^{+16}_{-24}	$118.8^{+2.7}_{-1.1}$
Linear Δ BR$(b \to s\gamma)$	26.6/21	18%	730^{+220}_{-90}	150^{+80}_{-20}	-910^{+2990}_{-1060}	41^{+16}_{-22}	$118.8^{+3.1}_{-1.3}$
$(g-2)_\mu$ neglected	20.3/19	38%	2020^{+}_{-}	1410^{+}_{-}	2580^{+}_{-}	48^{+}_{-}	$126.6^{+0.7}_{-1.9}$
Both	19.5/19	43%	2020^{+}_{-}	1410^{+}_{-}	2580^{+}_{-}	48^{+}_{-}	$126.6^{+0.7}_{-1.9}$

Table 1

Origin of EDM

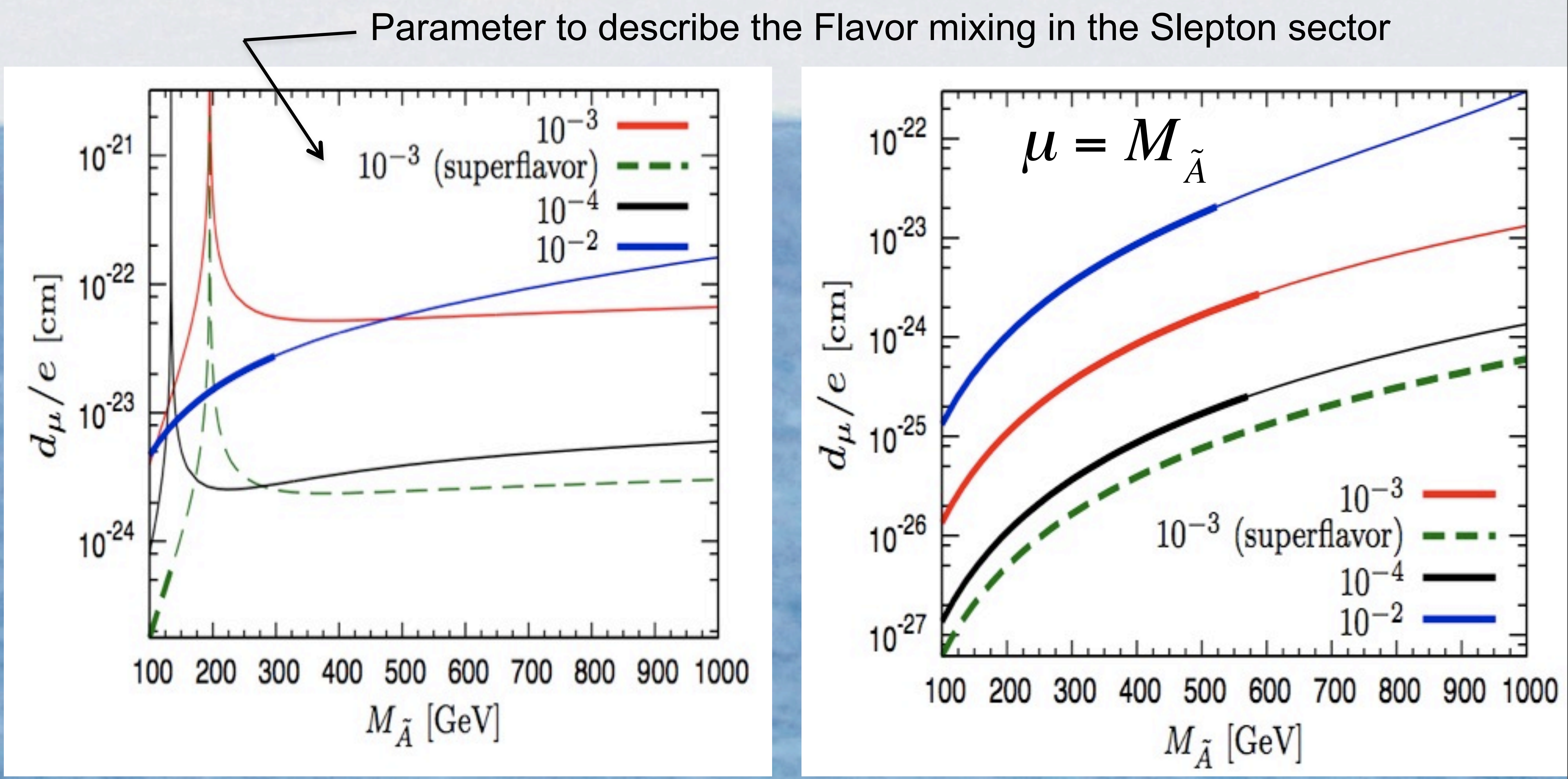
M.Pospelov and A.Ritz,   Ann.Phys. 318 (2005) 119



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**



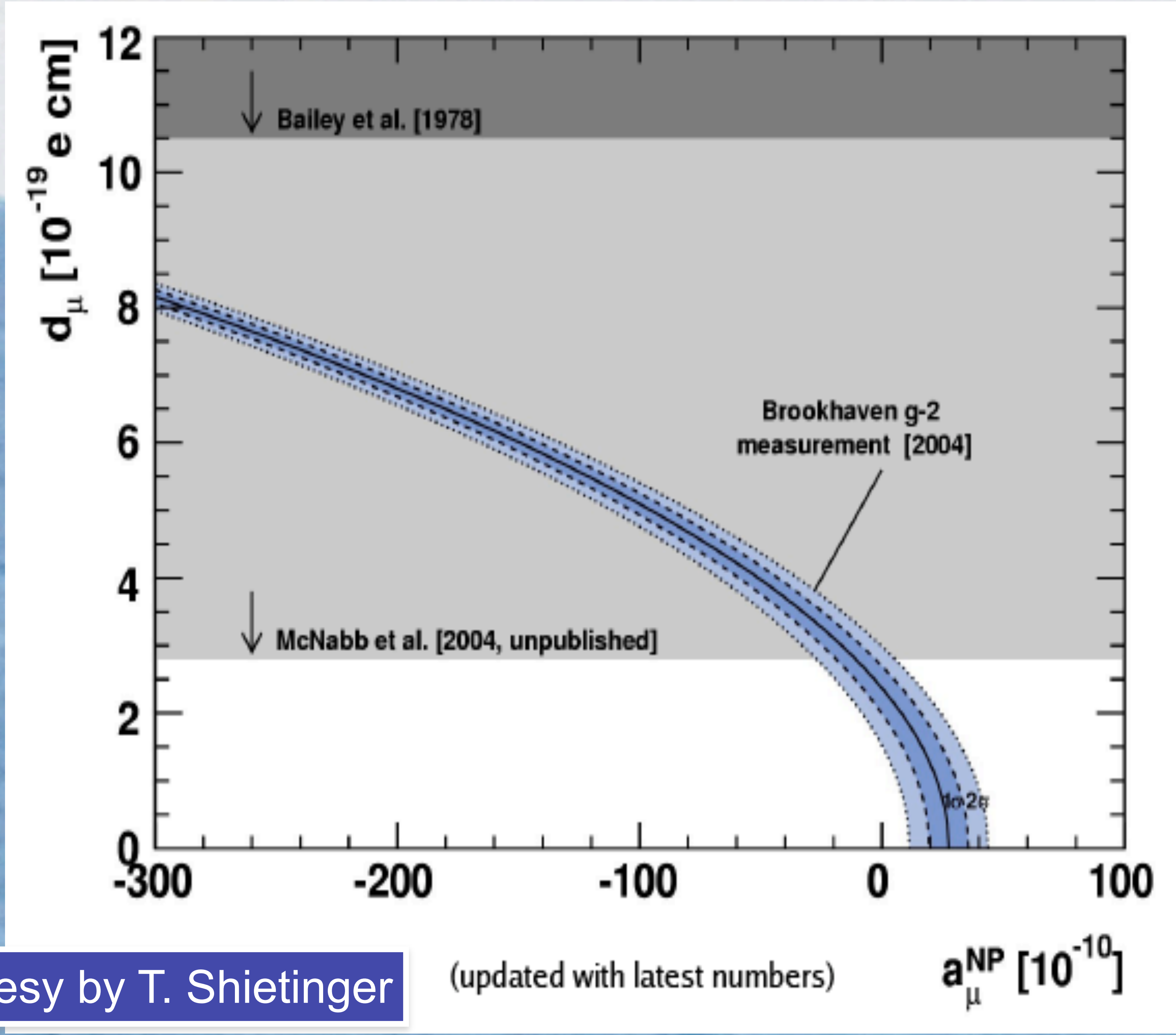
Measured in g-2 experiment

- "Inclusive" precession frequency

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

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

- Experimental limit of EDM is in the similar range!



Courtesy by T. Shietinger

Muon g-2 / EDM

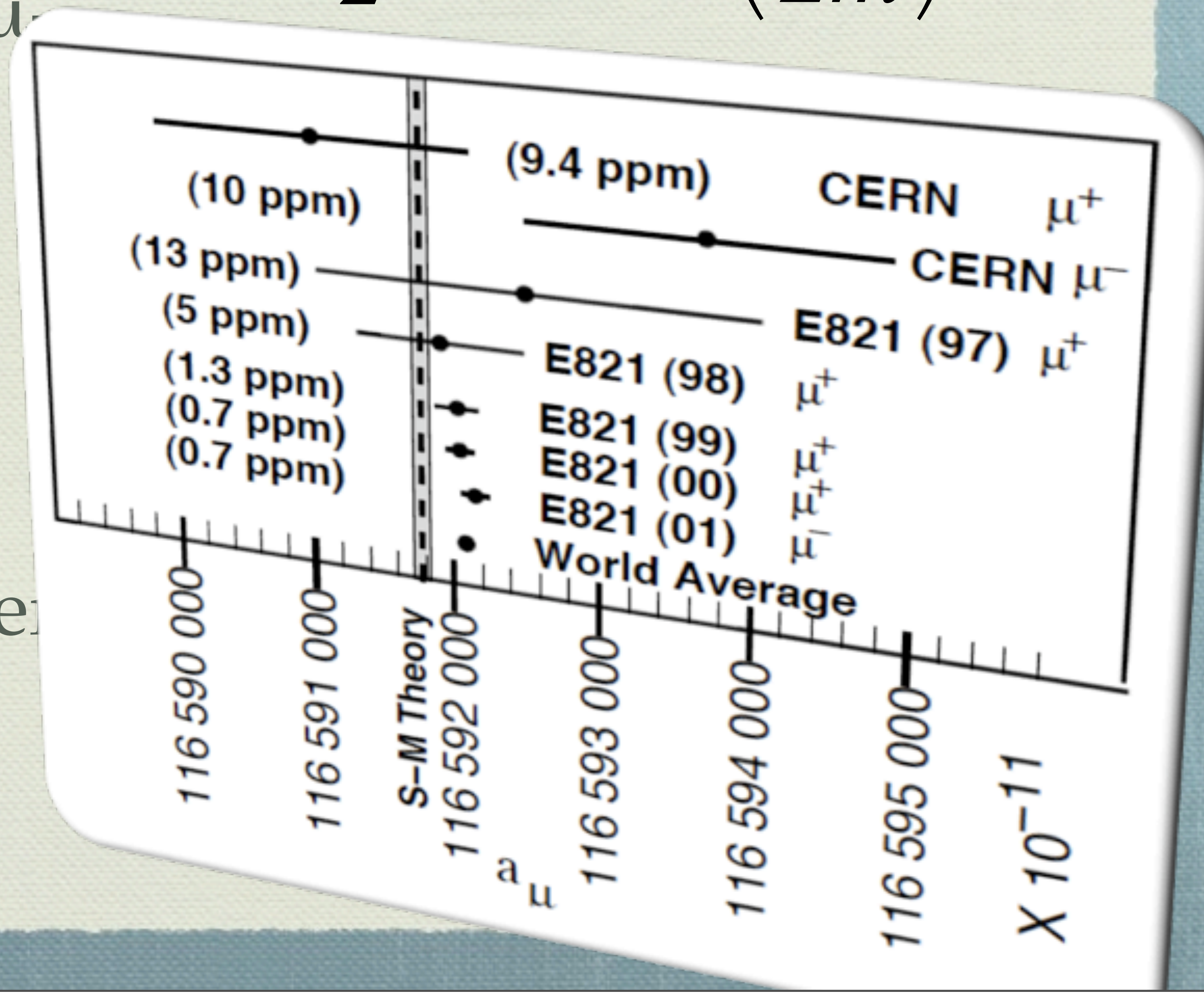
“Final Report” of Anomalous MDM

BNL- E821 Experiment : Phys.Rev.D73:072003,2006.

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

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

- 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 by
- NEW METHOD!



Muon Spin precession

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

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

$$d_\mu = (0.0 \pm 0.9)\times 10^{-19}\, e\cdot\mathrm{cm}$$

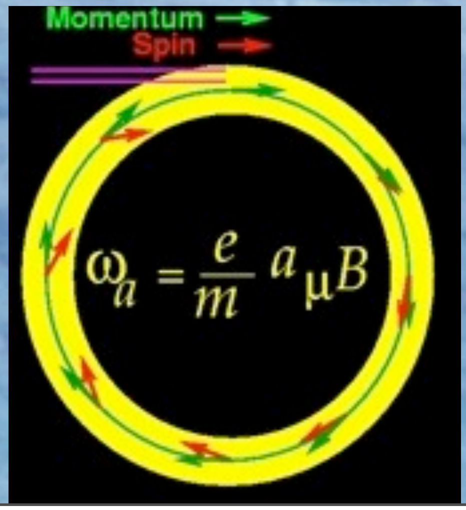
G.W.Benett et al. Phys.Rev.D80:052008,2009

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

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

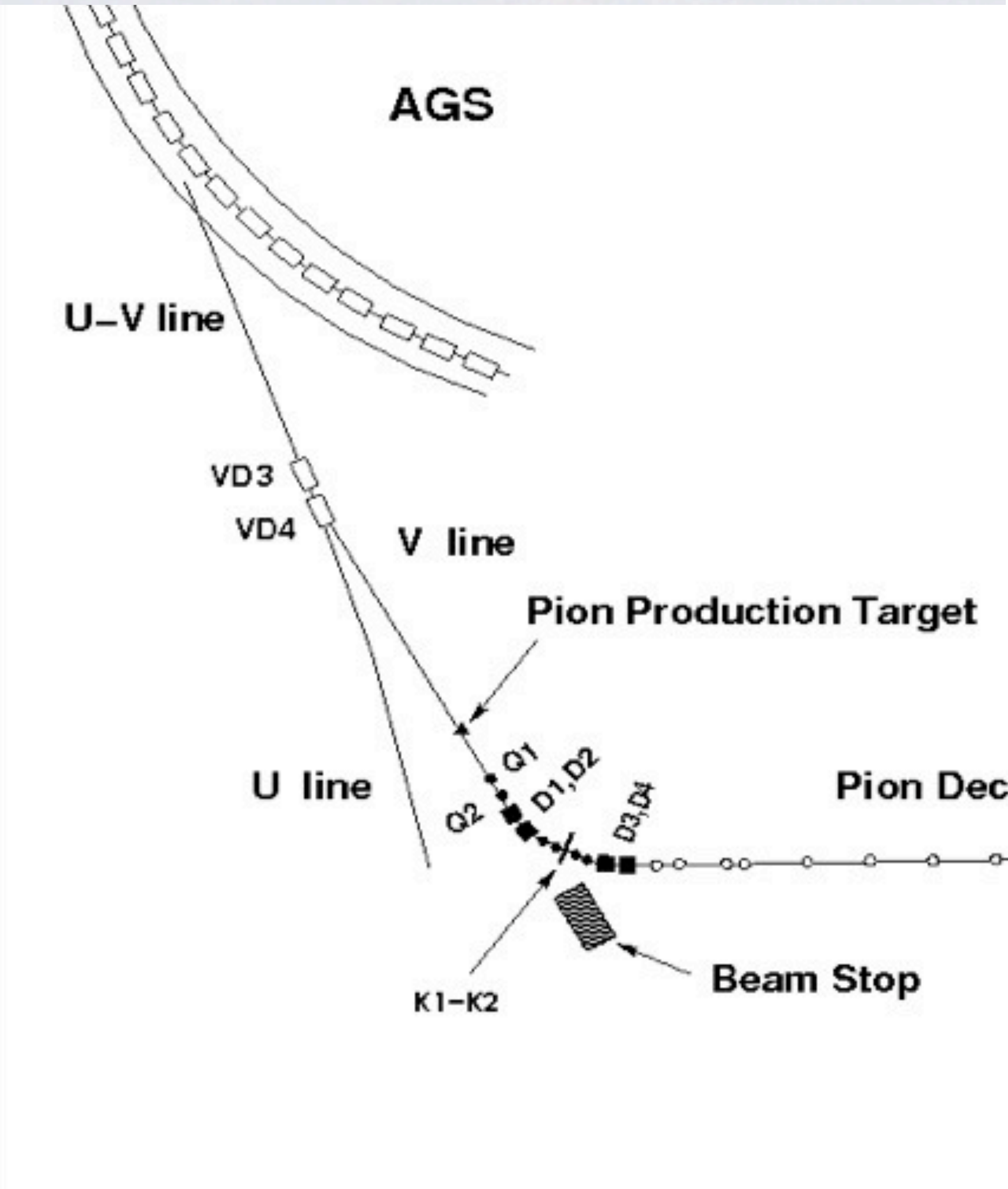
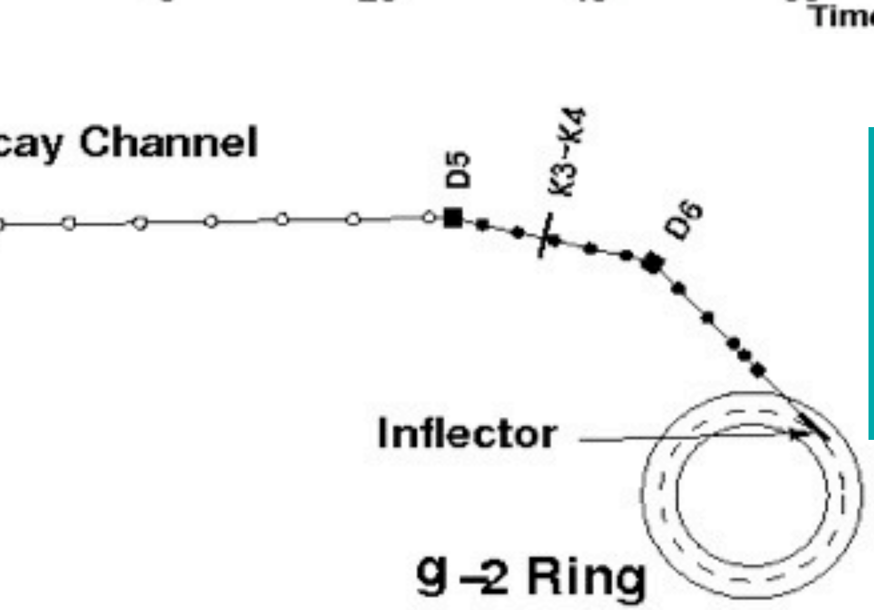
$$p_{\mathrm{magic}} = 3.09\ \mathrm{GeV}/c$$

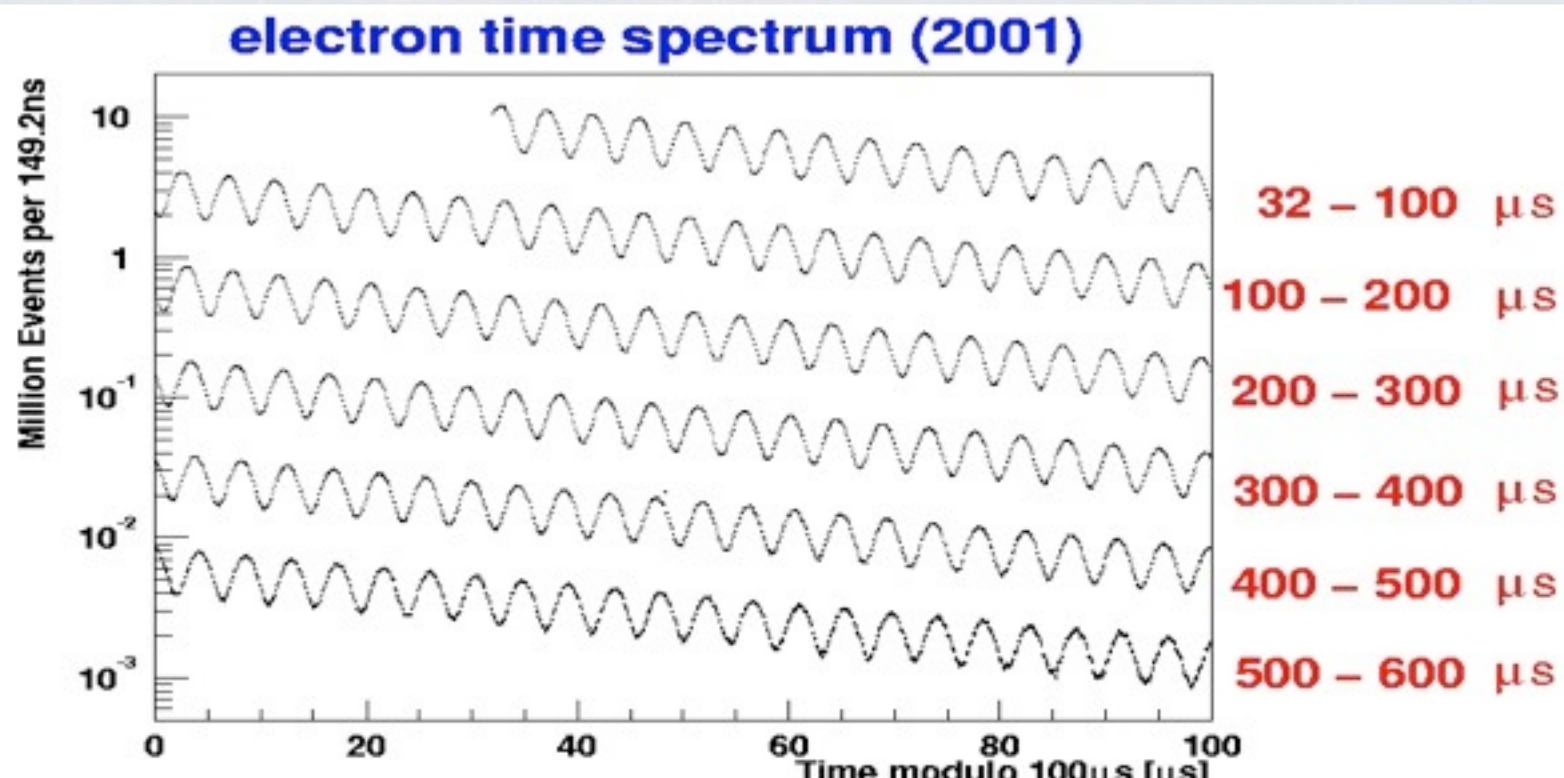
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$



How it is Measured?

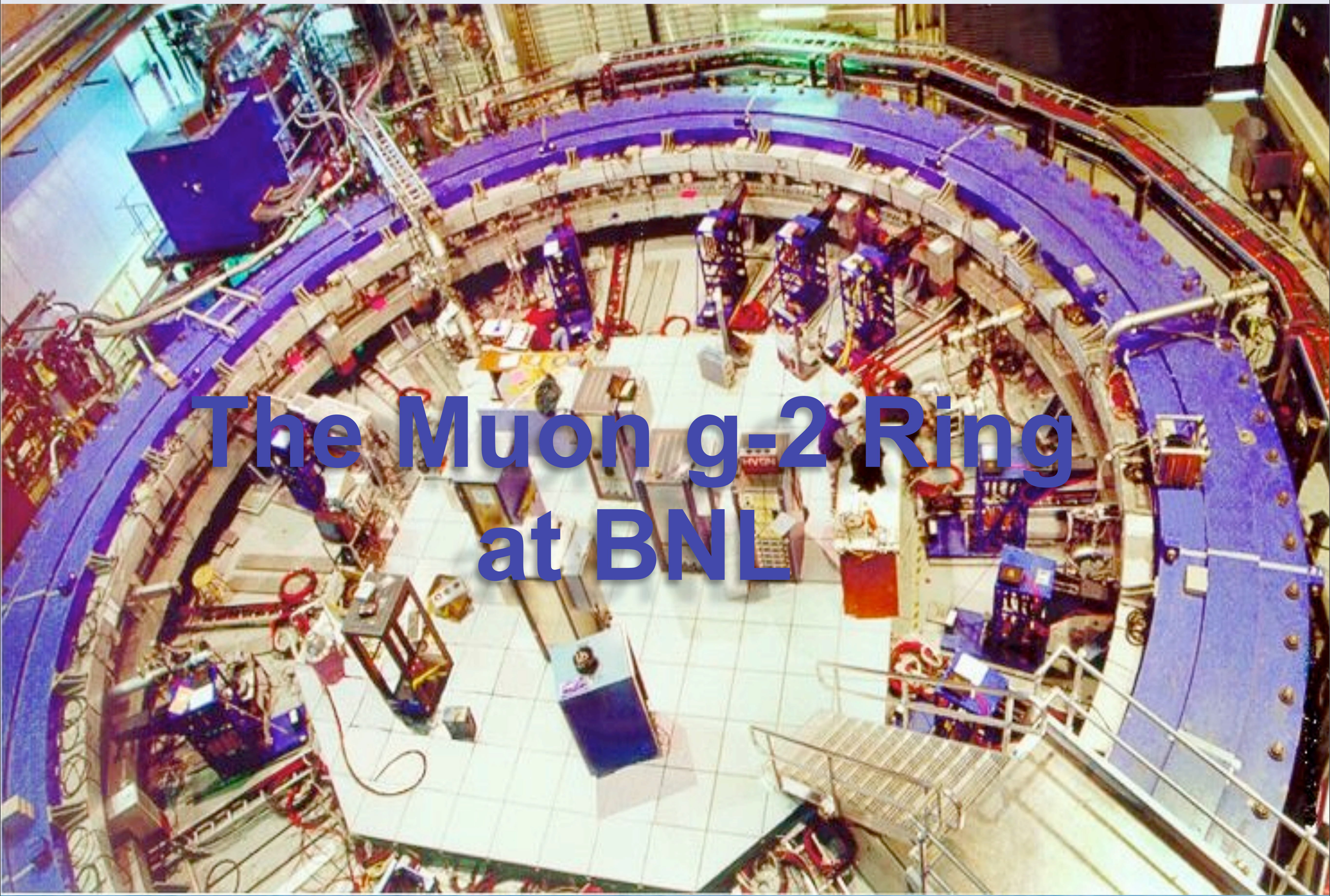
- Precession frequency (ω_a) of muon spin in the storage ring is measured;

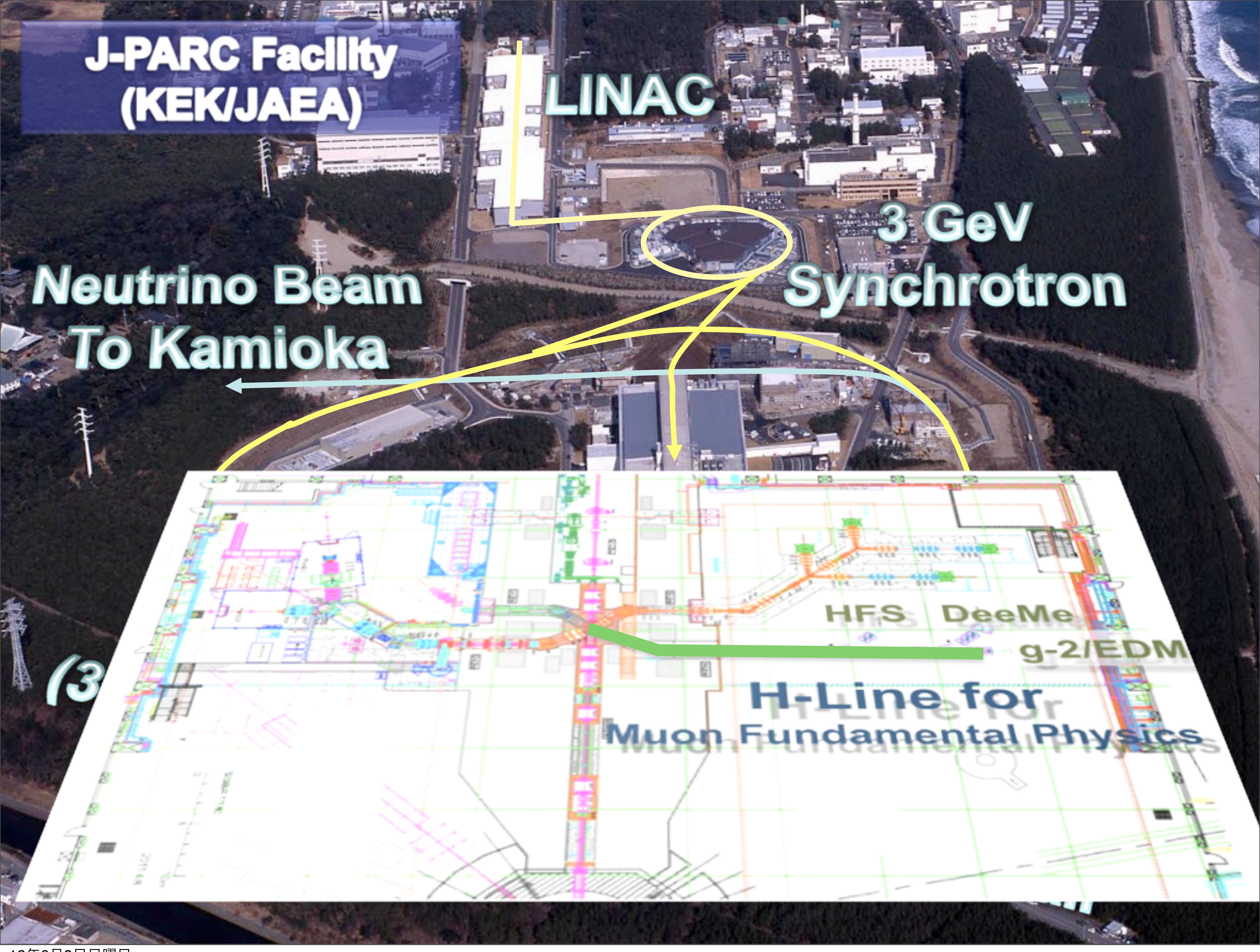





$$\omega_a = -\frac{e}{m} a_\mu B$$

The Muon g-2 Ring at BNL

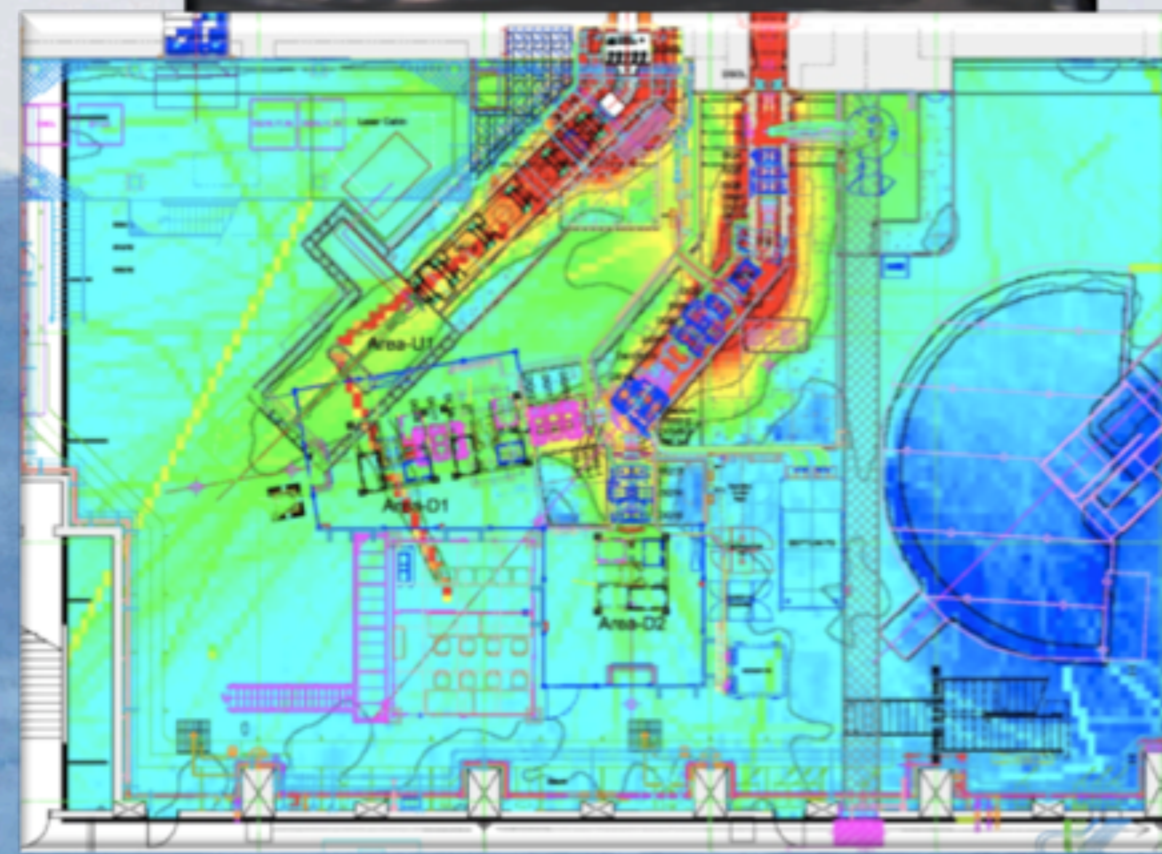



J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
HFS
DeeMe
g-2/EDM
H-Line for
Muon Fundamental Physics
(3

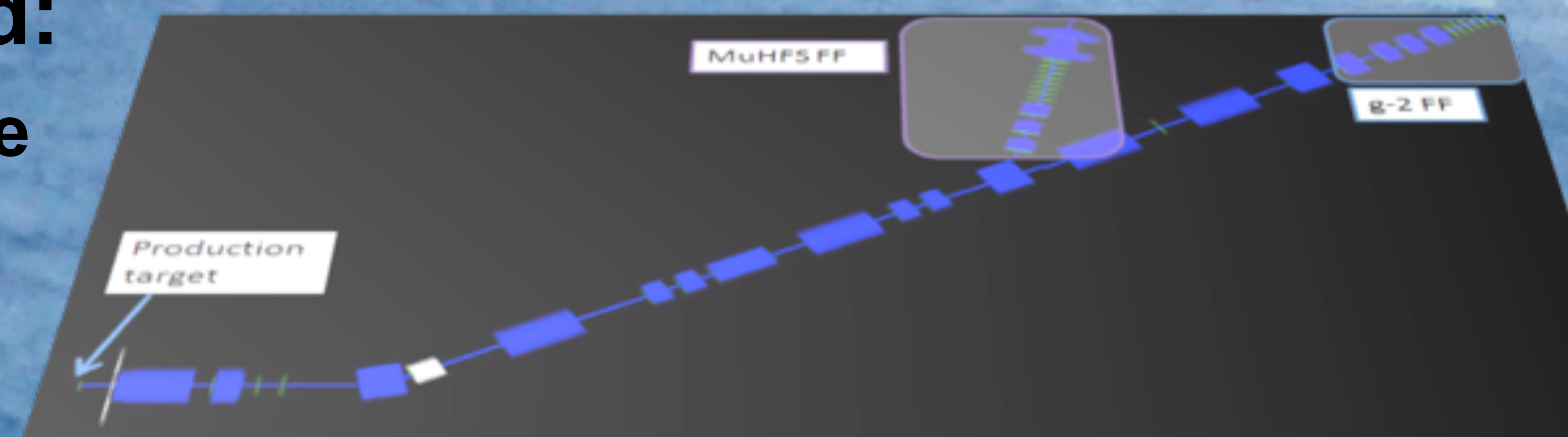
12年6月3日日曜日

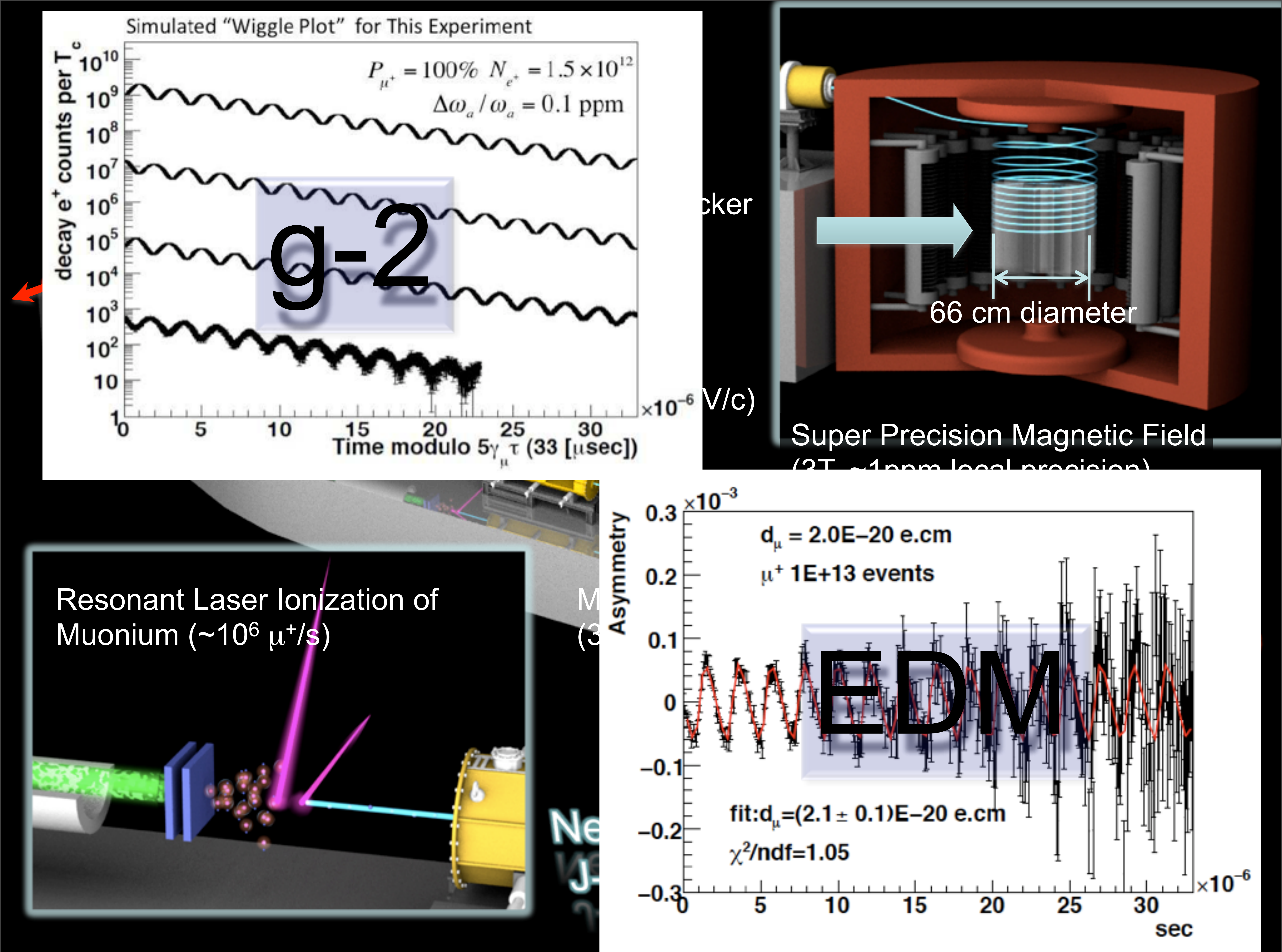
Progress at MLF-MUSE

- **U-Line=Ultra-Slow Muon Beam Line is fully funded**
  - **KEK budget**
  - **JSPS Grant: Shin-Gakujutsu-Ryouiki**
    "Ultra-Slow Muon Microscope" approved



- **"Hot" region is being completed before lost forever**
  - **"Near primary target" magnets are fabricated to be ready for installation this summer**
- **H-Line is fully designed:**
  - **Thanks to MuHFS / DeeMe**

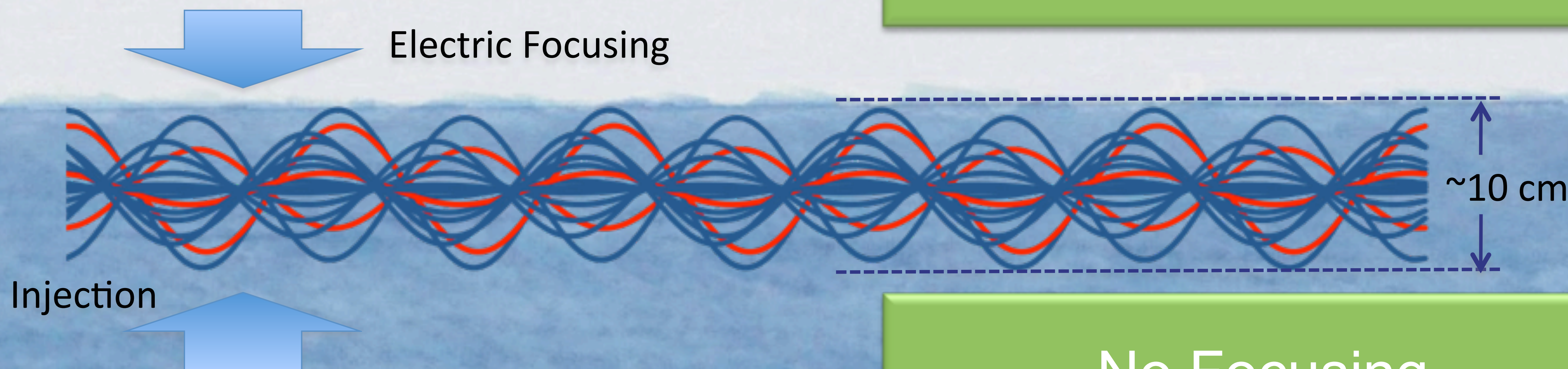



Simulated “Wiggle Plot” for This Experiment
$P_{\mu^+} = 100\%$ $N_{e^+} = 1.5\times10^{12}$
$\Delta\omega_a/\omega_a = 0.1$ ppm
decay e+ counts per Tc
Time modulo 5γμτ (33 [μsec])
×10^-6
g-2
cker
V/c)
66 cm diameter
Super Precision Magnetic Field
Resonant Laser Ionization of
Muonium (~10^6 μ+/s)
dμ = 2.0E–20 e.cm
μ+ 1E+13 events
fit:dμ=(2.1 ± 0.1)E–20 e.cm
χ2/ndf=1.05
Asymmetry
×10^-3
sec
EDM

What's Different?

- **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

Magic vs "New Magic"

- **Complimentary!**

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

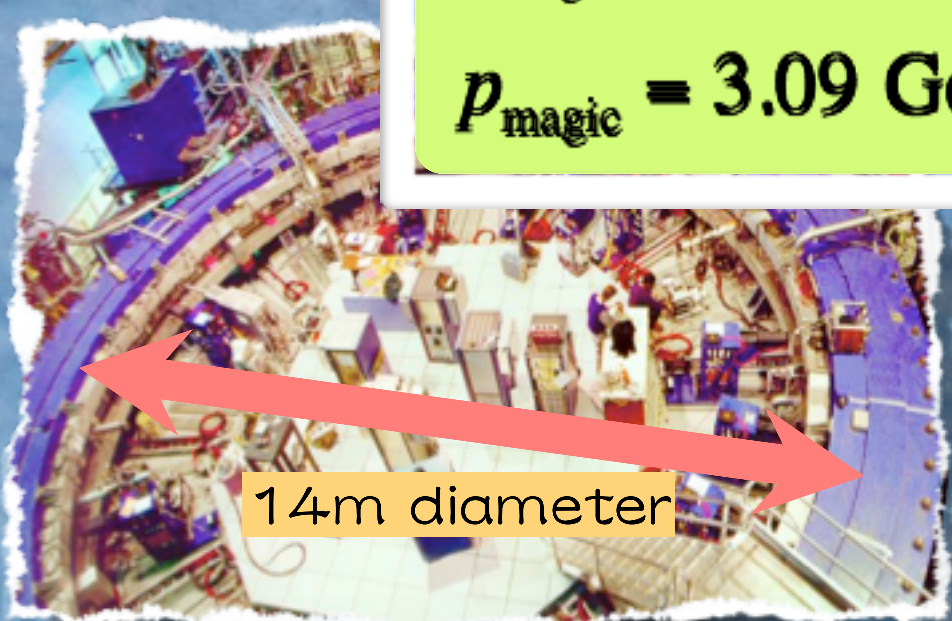
BNL/Fermilab Approach

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

$$\eta \approx 0$$

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

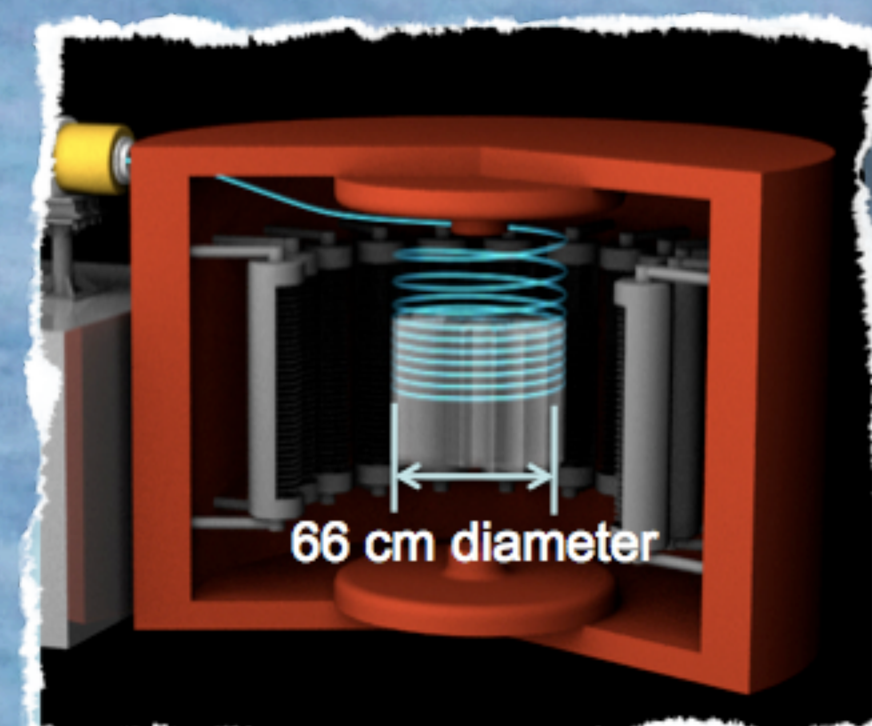
$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$



J-PARC Approach

$$\vec{E} = 0$$

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



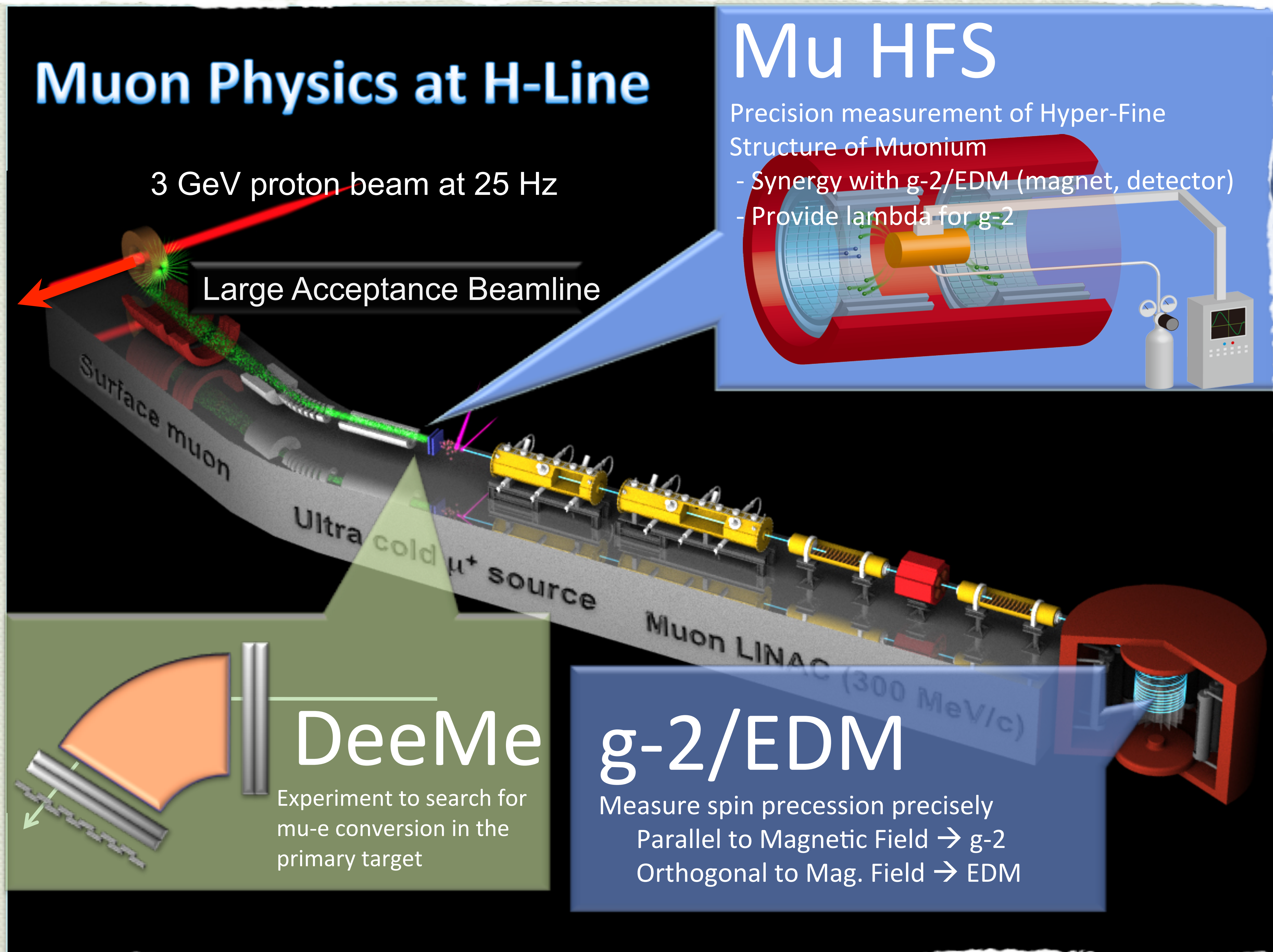
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

BNL, FNAL, and J-PARC

- Both Fermilab and J-PARC intend to start physics run around 2015

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%		$> 90\%$
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


Muon Physics at H-Line
3 GeV proton beam at 25 Hz
Large Acceptance Beamline
Surface muon
Ultra cold 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

12年6月3日日曜日

Milestones

- Demonstration of UCM Production
  - 1e6μ^+/sec or >1% conversion efficiency
- Muon acceleration test
  - RFQ and IH
- Prototyping Precision Magnet
  - Control local precision < 1ppm
- Injection and Kicker
  - Tetst with low-E electron
- High-rate tracker
  - Verify the time response upto > 1 MHz /strip

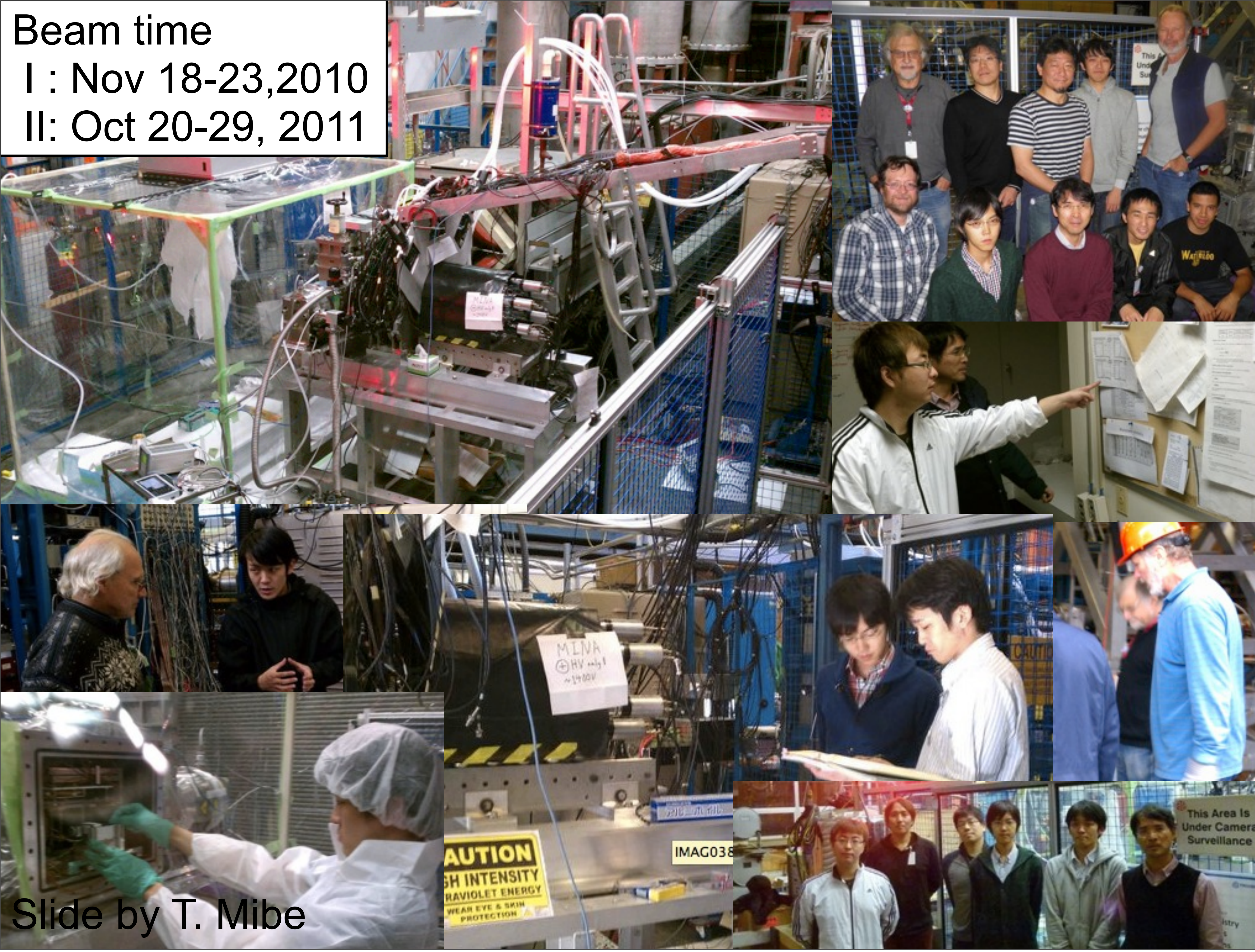
Conceptual Design of the Experiment and R&D

Mu Production (TRIUMF S1249)
Mu Laser Ionization (RIKEN-RAL)
Muon Acceleration (MLF)
Magnet Design and Prototyping
Beam Injection and Storage
Detector Design and Testing

Beam time

I : Nov 18-23,2010

II: Oct 20-29, 2011



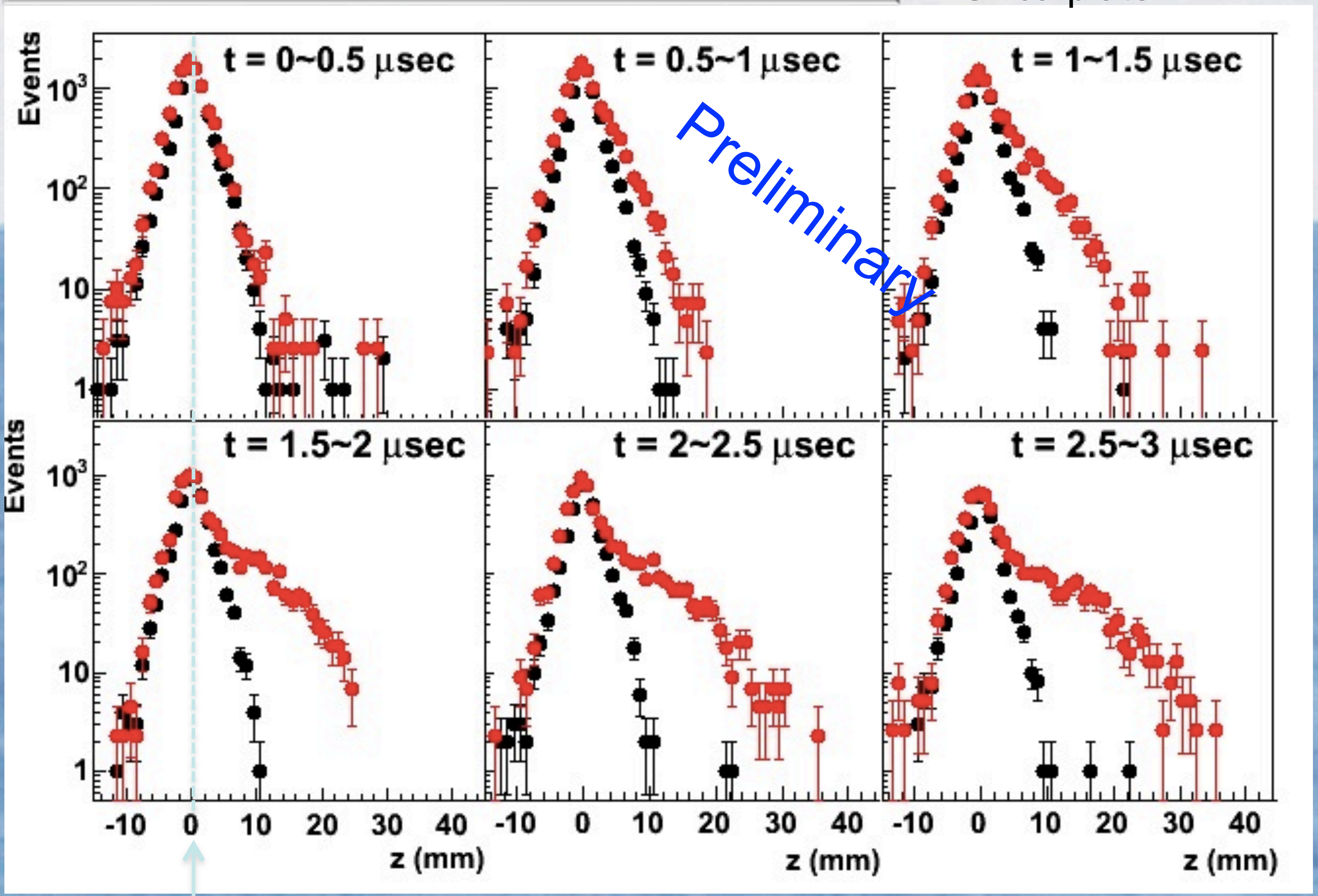
Slide by T. Mibe

Space-time distribution of Mu

New 2011 data

- Aerogel 27mg/cc
- Silica plate

Reconstructed decay vertex position



Distance from target surface

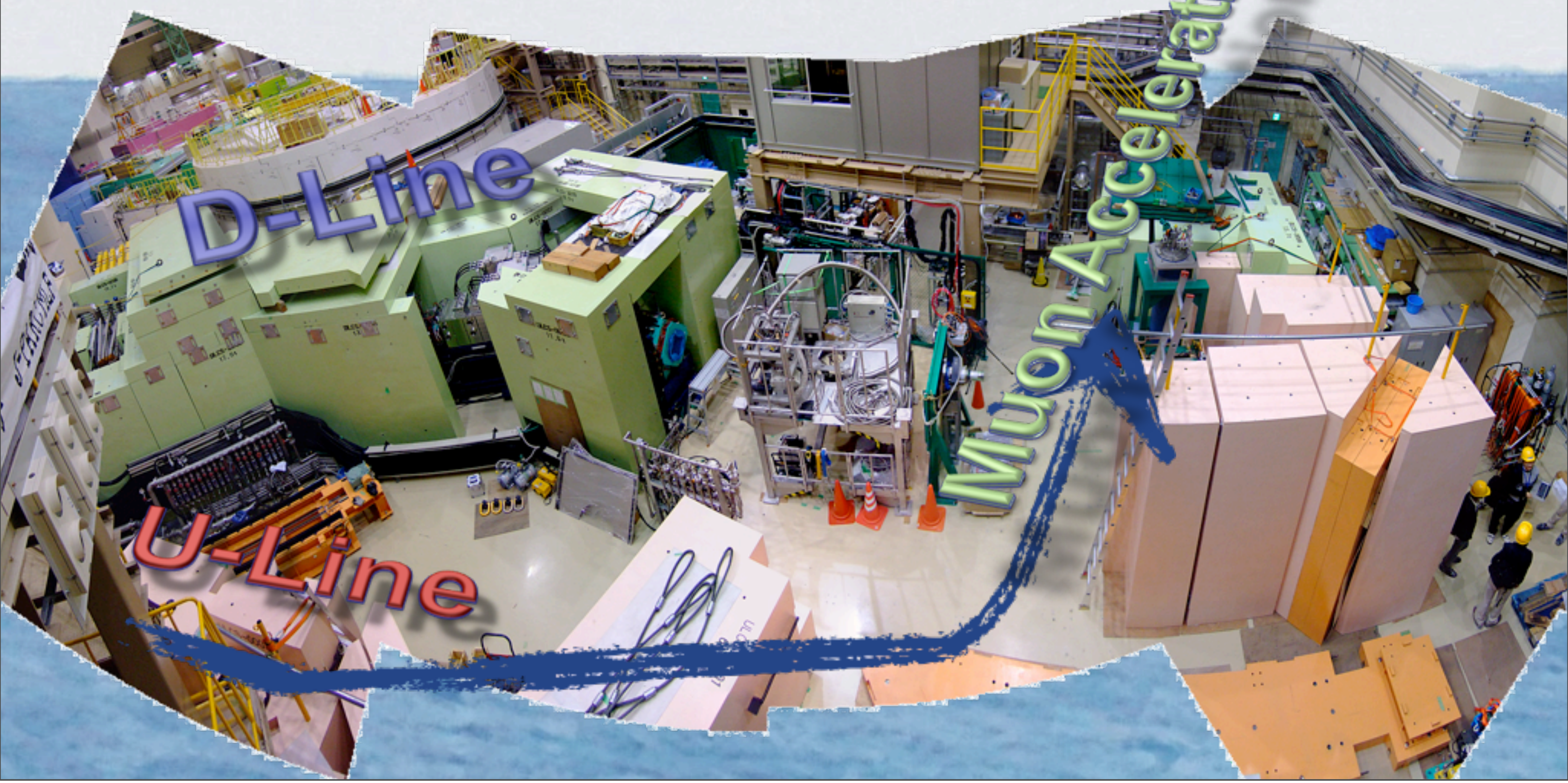
Target surface

- Silica plate data is used to estimate the background distribution.
- Enhancement in aerogel data is due to Mu emission in vacuum.
- Such Mu signals are observed in all aerogel densities.
- No strong density dependence was observed in online analysis.

Slide by T. Mibe

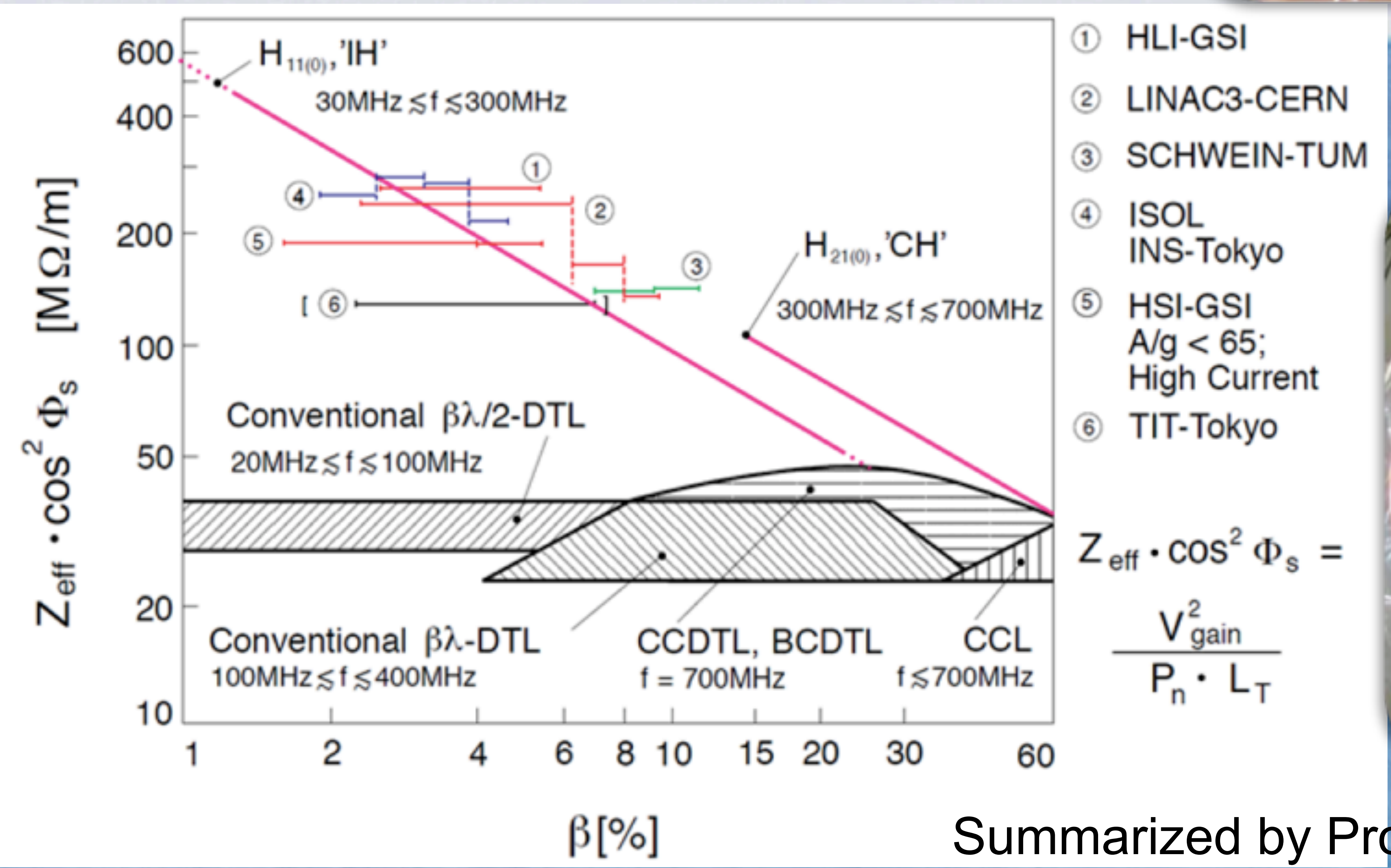
Muon Acceleration Test @U-Line

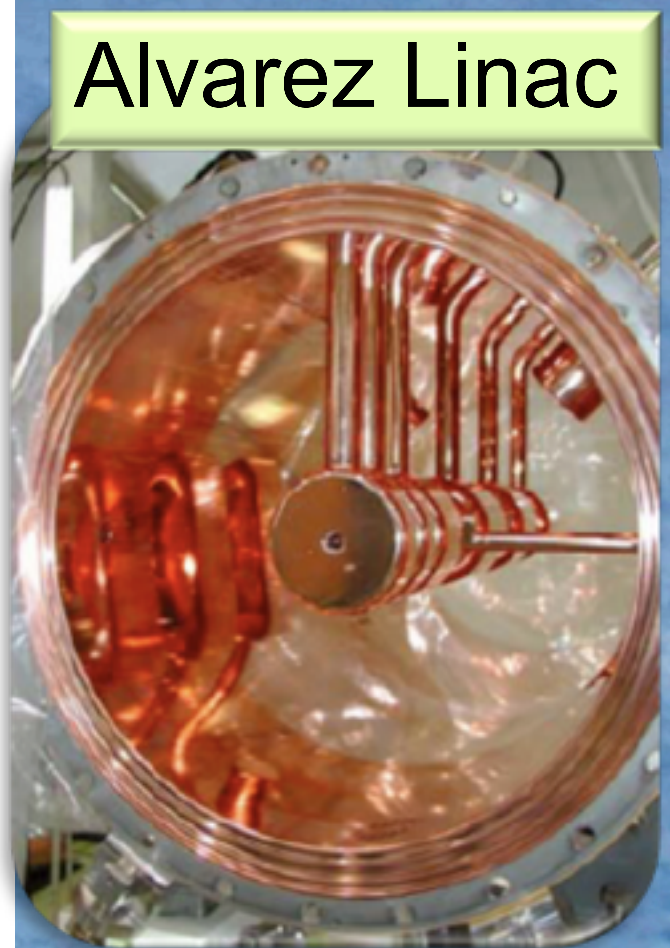
- USM is expected at U-Line, Fall, 2012
- RFQ (on loan) and IH are secured



Why IH? Slides from Hayashizaki

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

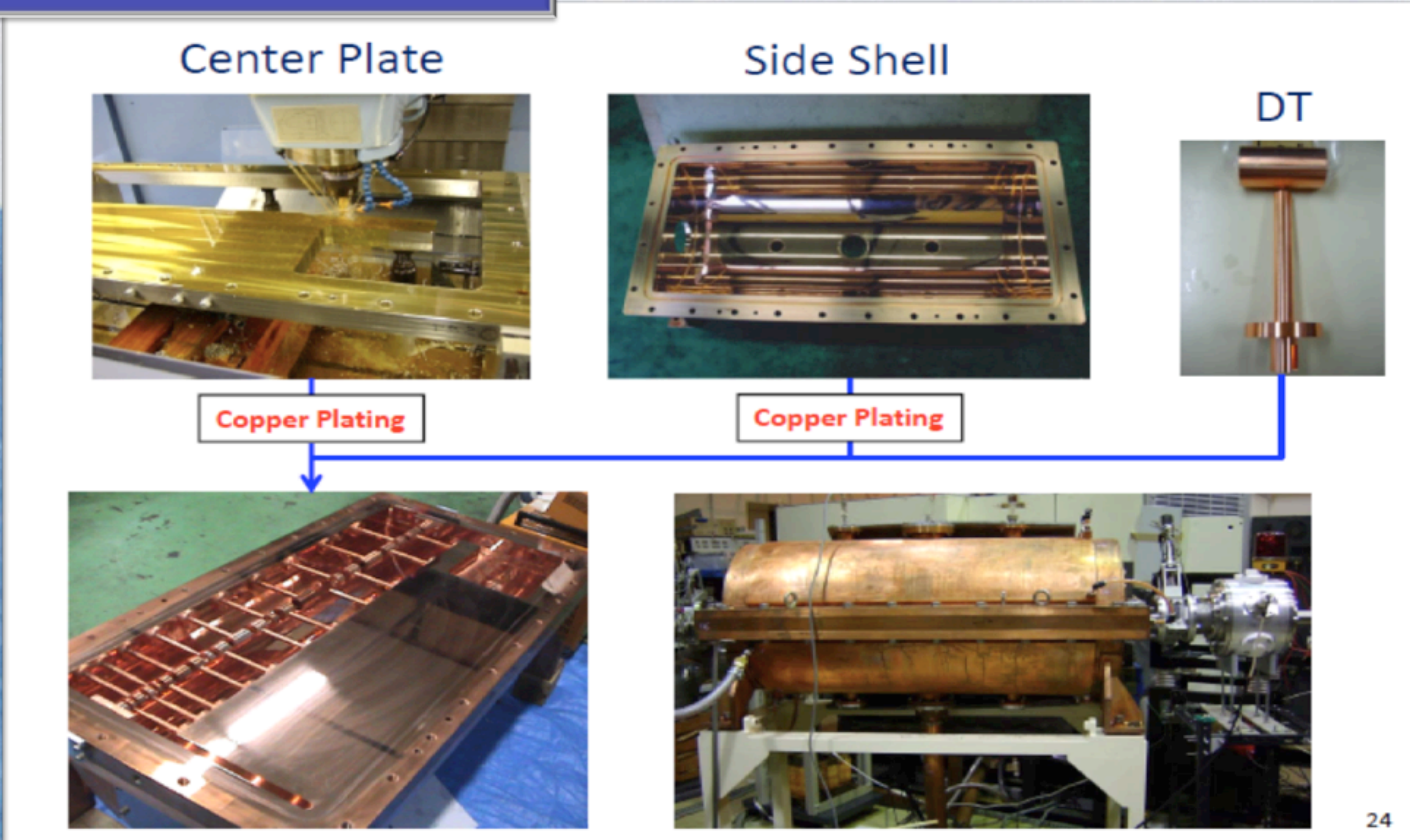




Summarized by Prof. Ratzinger

APF IH LINAC at TokyoTech

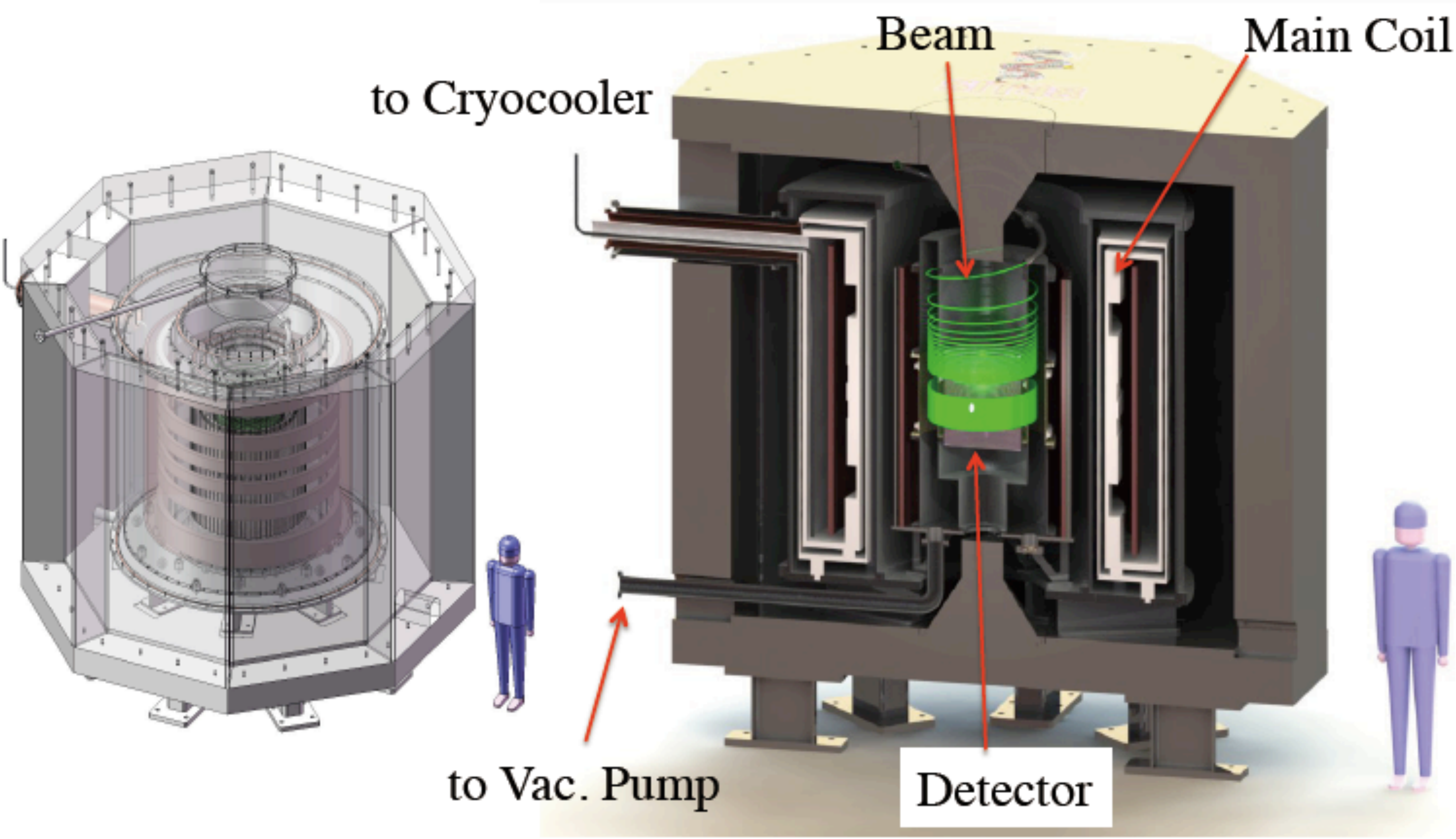
Fabrication Process



Mechanical Design ~ draft

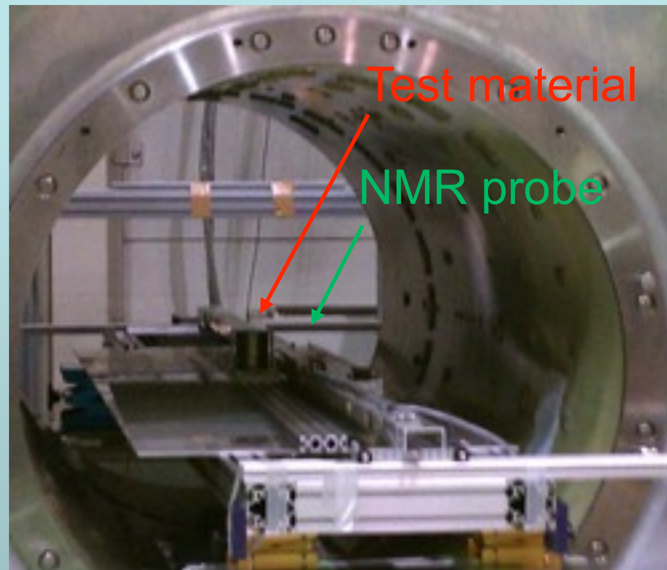
Slide by K. Sasaki

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

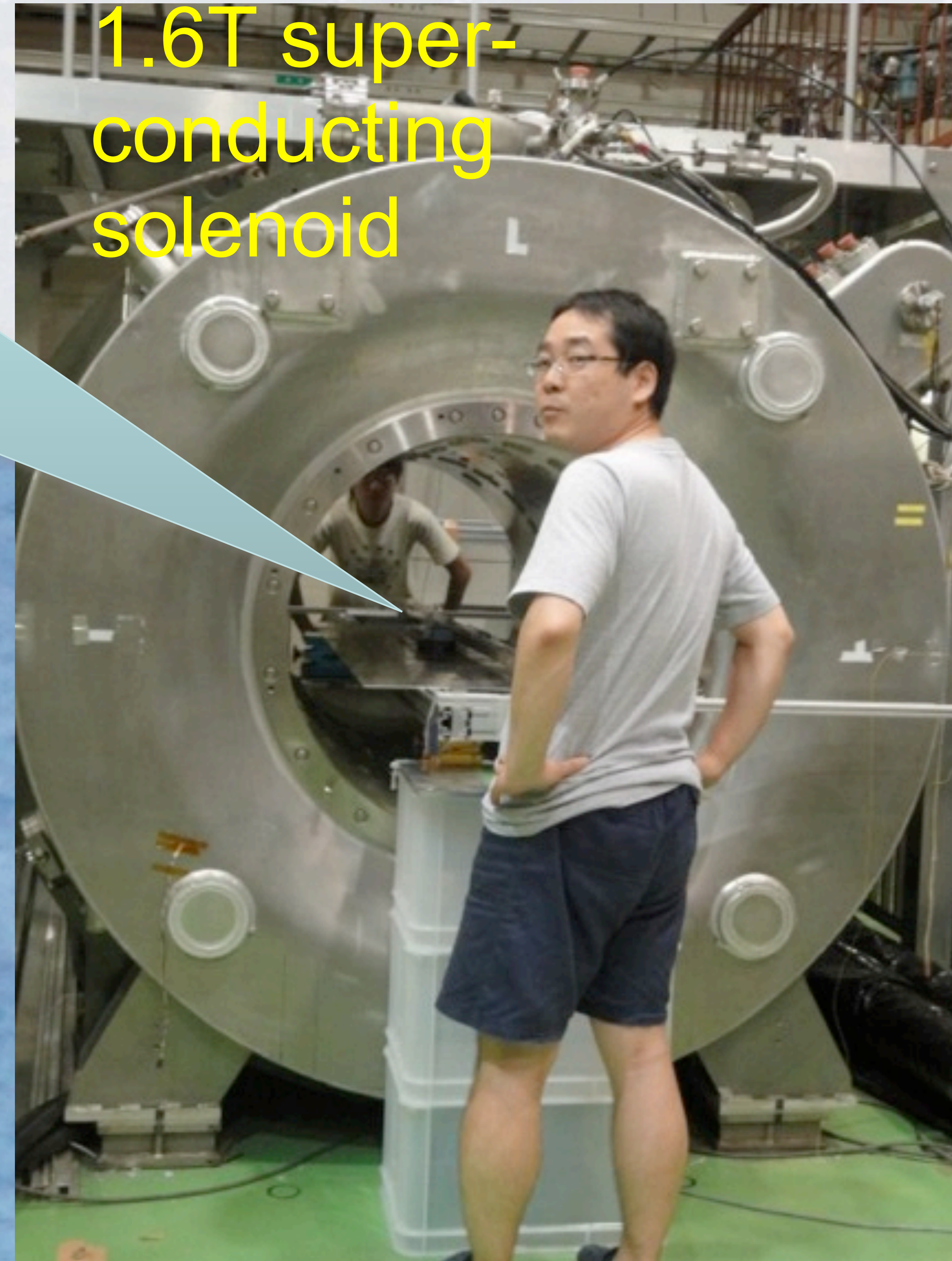


Effect of detector components in the precision B-field

K. Sasaki, T. Kakurai
T. Mibe, O. Sasaki



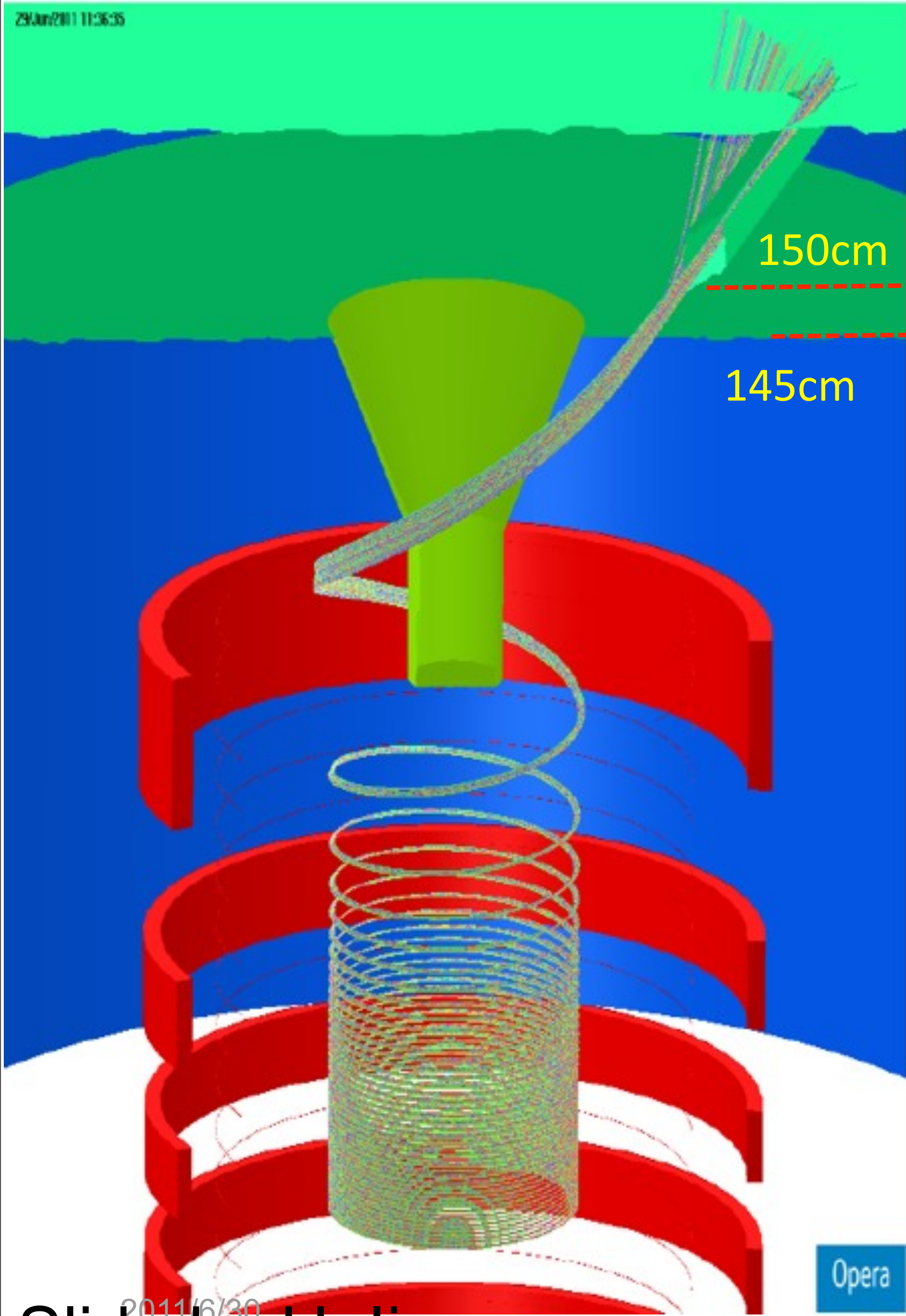
NMR controller

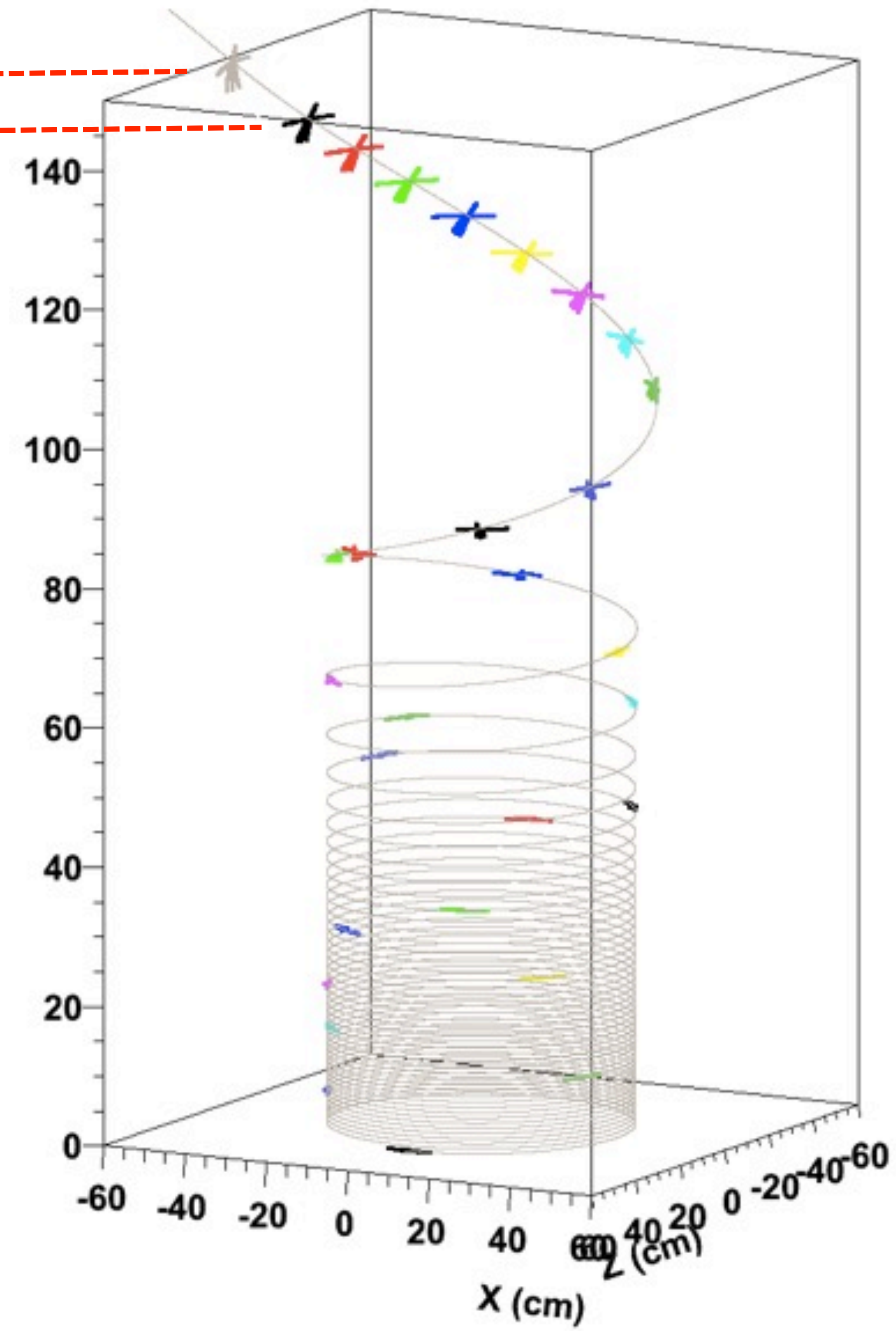


- B-field in the vicinity of material and detector components were measured by NMR probe.

Next step for beam injection study

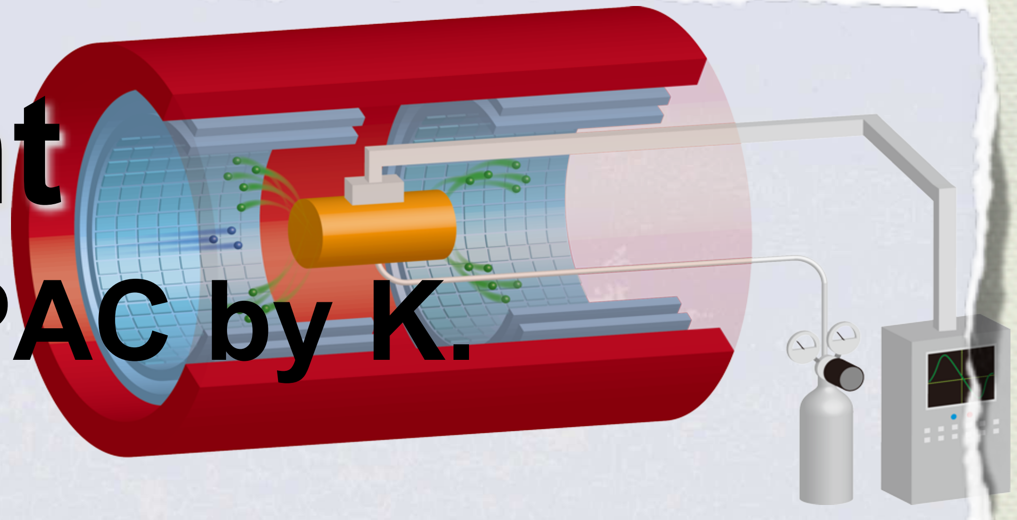
1. Study fine slices inside a tunnel: 145 < y <180cm
2. Straight but cone shape tunnel?
3. Estimate emittance in the field "free" space (y>=150cm) and pass parameters to LINAC team





Slide by H. Iinuma

Mu HFS Experiment



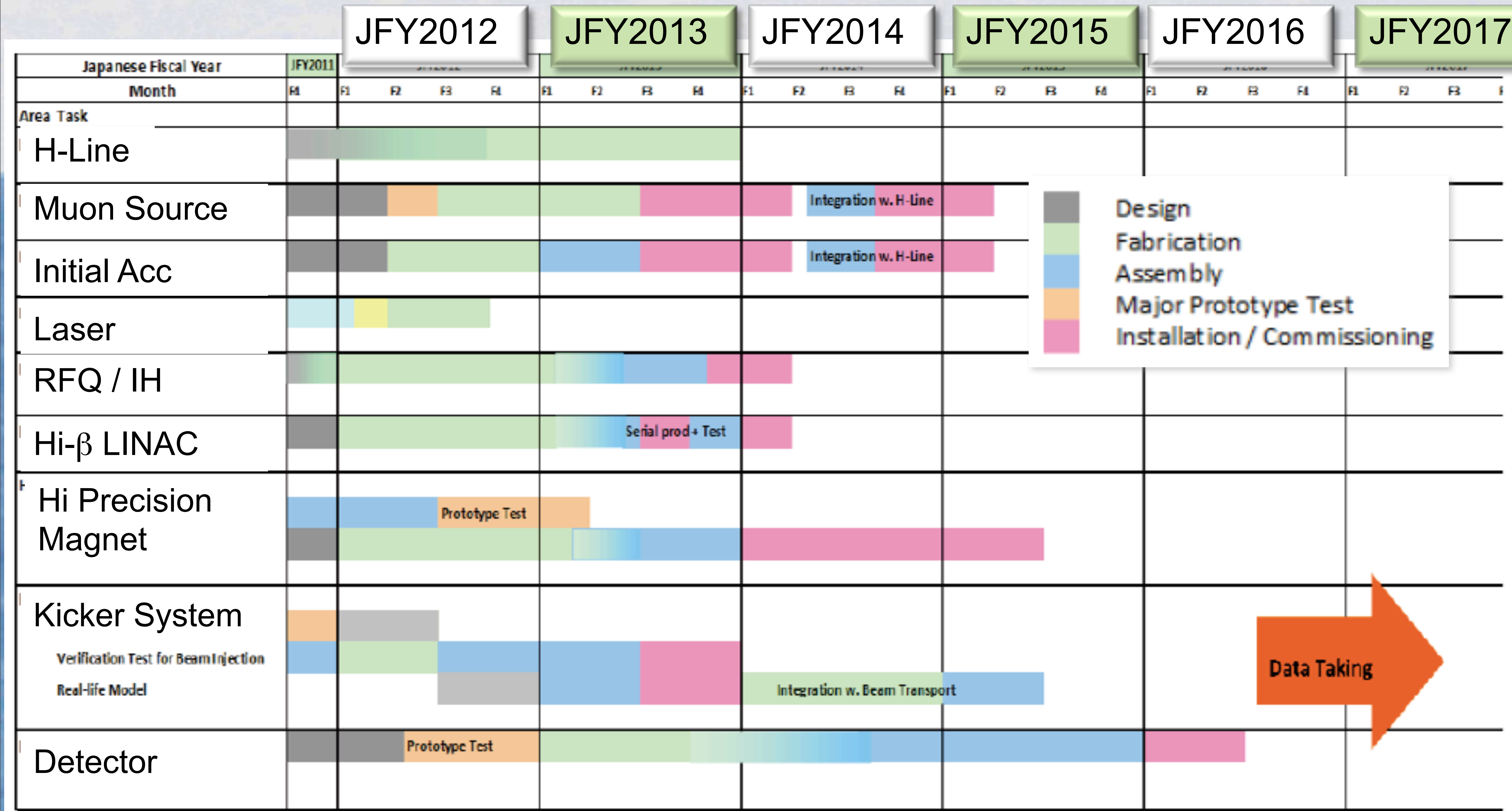
- **Proposed to IMSS Muon PAC by K. Shimomura**
  - **1st stage approved**
- **Synergy with g-2/EDM**

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

  - **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**

Schedule

- Need to be competitive with Fermilab g-2

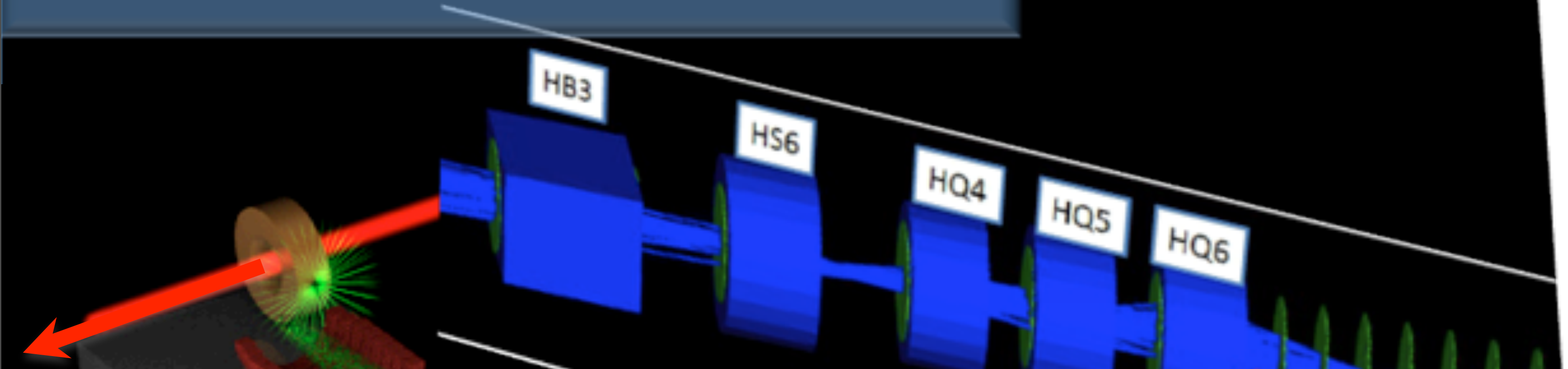


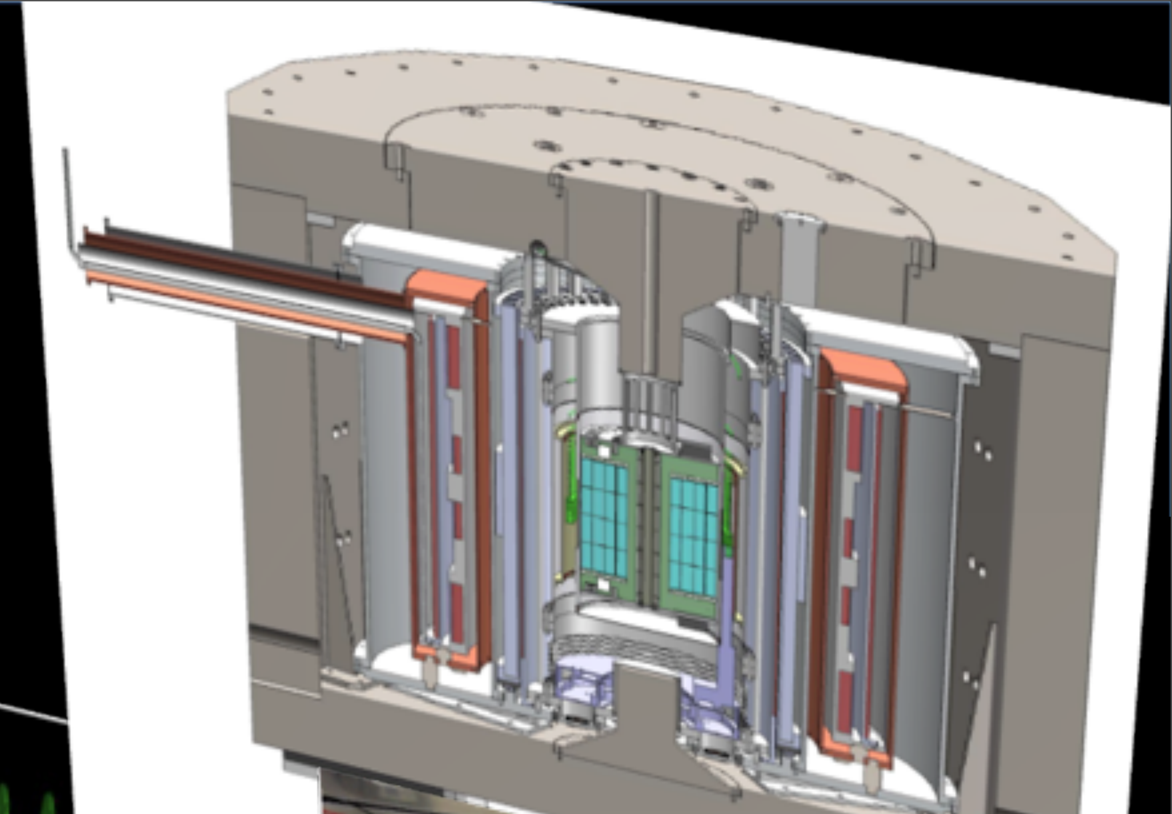
g-2/EDM

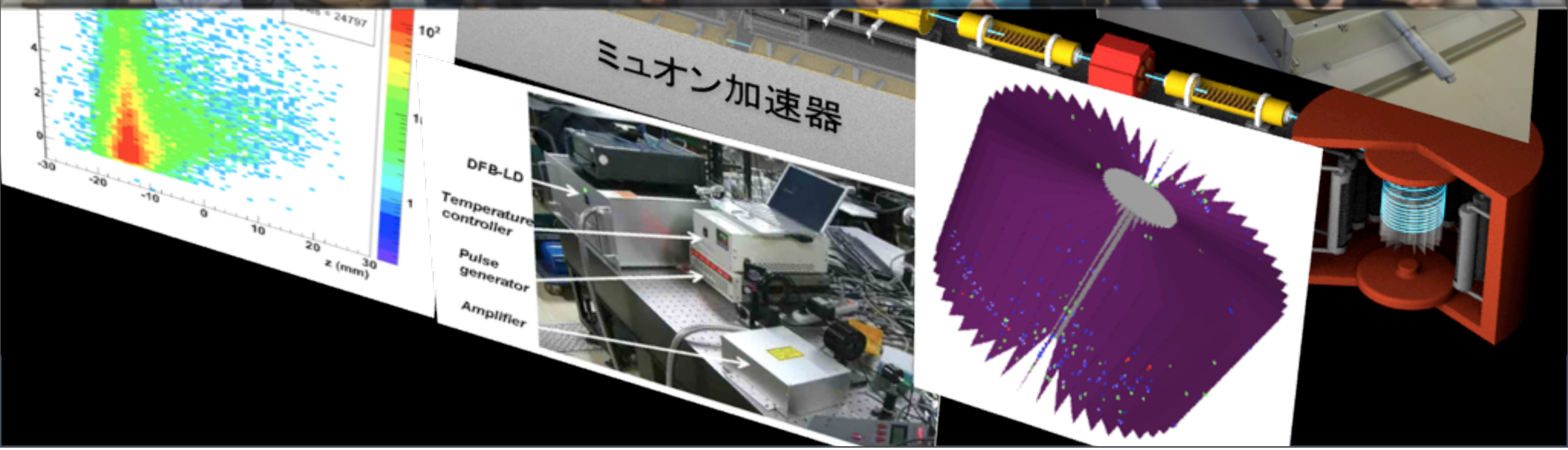
Simultaneous Measurement

Parallel to B：g-2

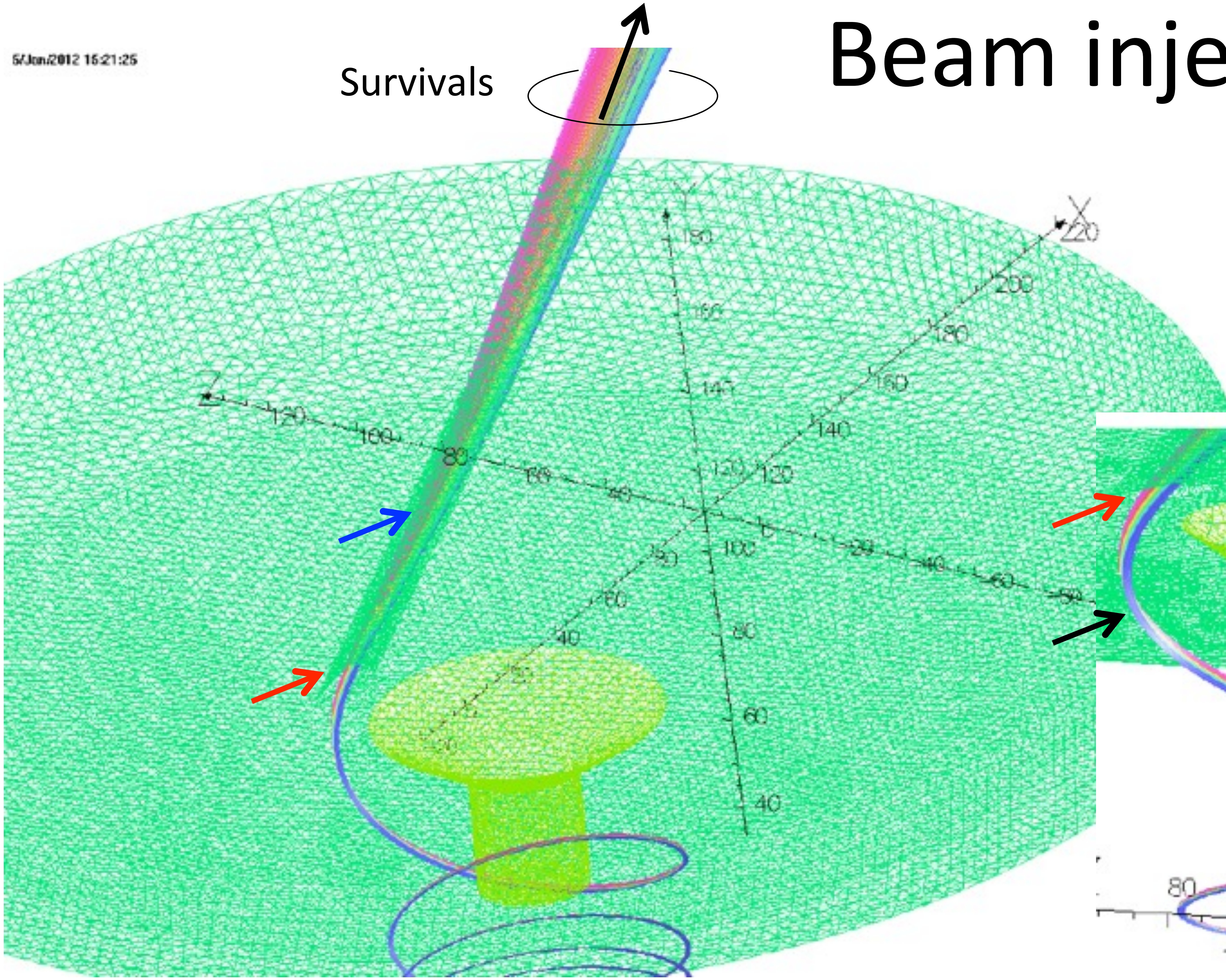
Orthogonal to B：EDM

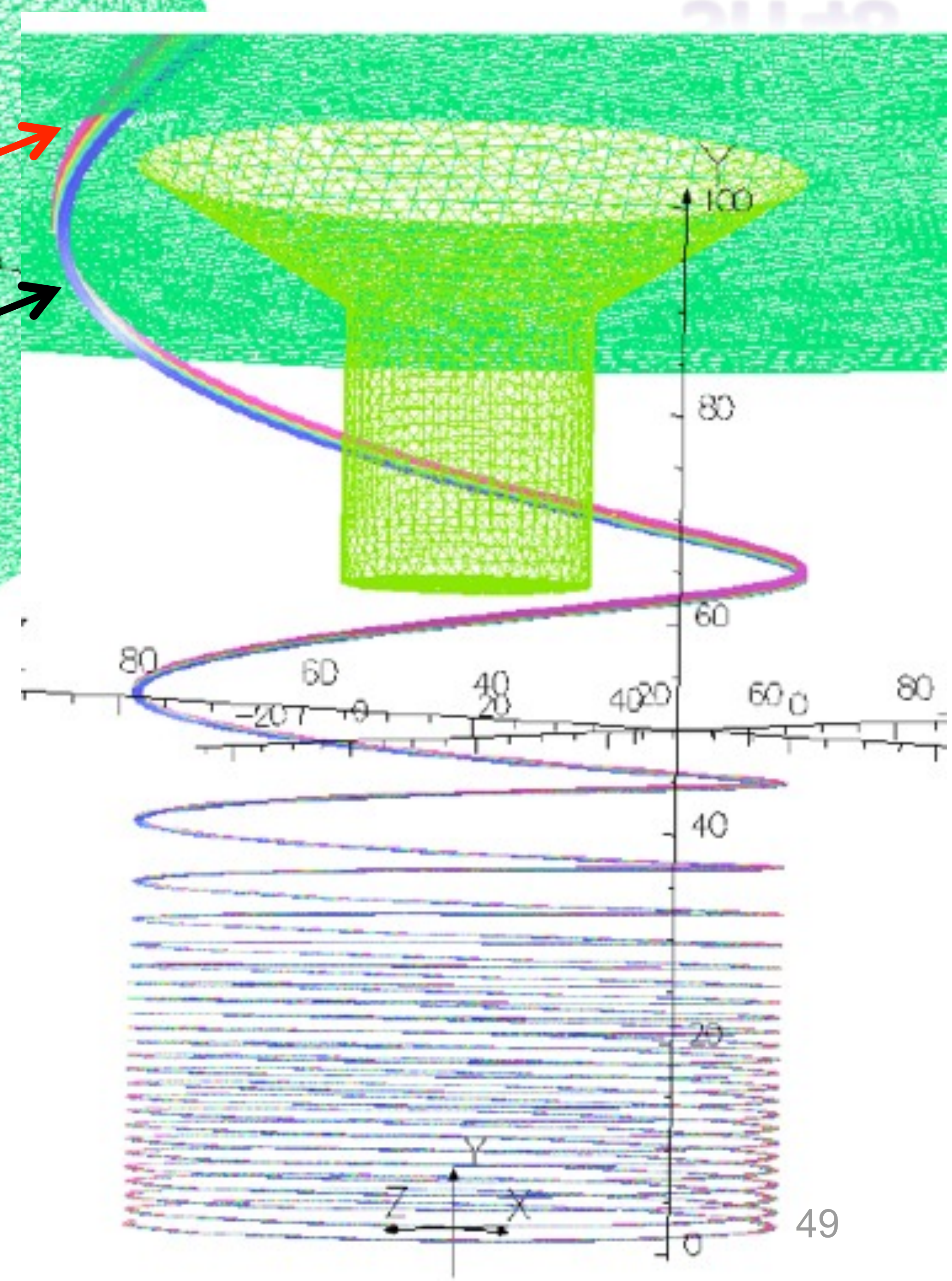


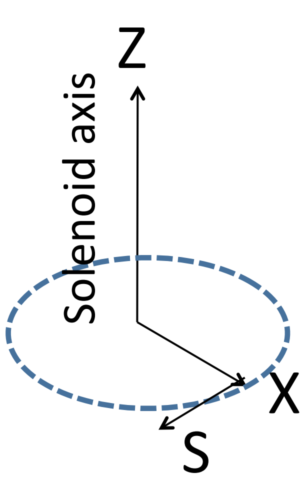




Beam injection status







Beam acceptance estimation using "time-reversal" beam at:

(1)Injection area (95cm)

(2)Exit of tunnel (110cm)

- Inside of tunnel (130cm)

R&Ds for early-to-late effects

T. Kakurai, T. Mibe,
O. Sasaki, T. Kohriki

- **We have built a silicon-sensor test system with IR laser. The IR laser could be pulsed at repetition rate as high as 80MHz with an asynchronous external trigger. Systematic studies on early-to-late effects are in progress.**

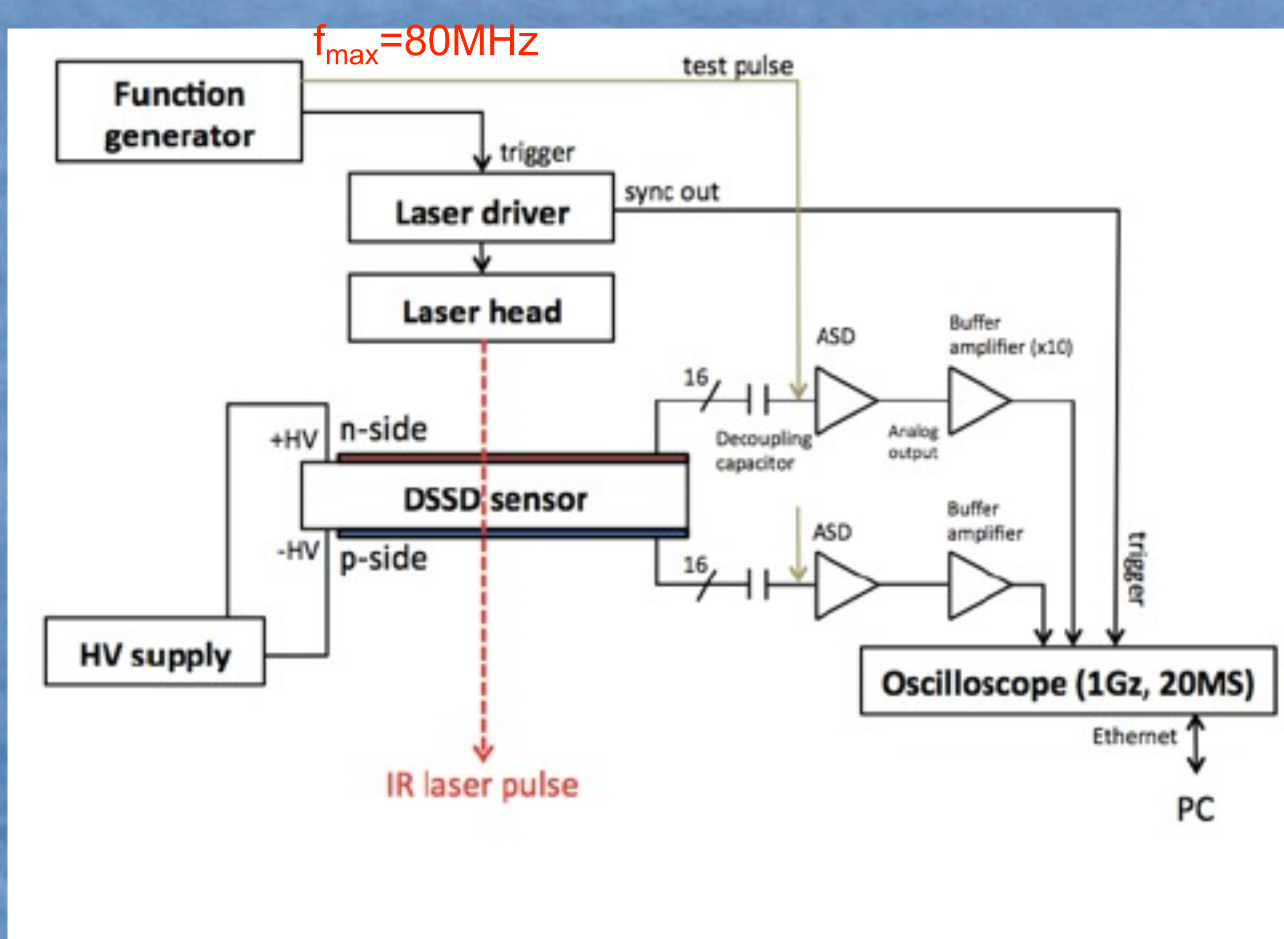
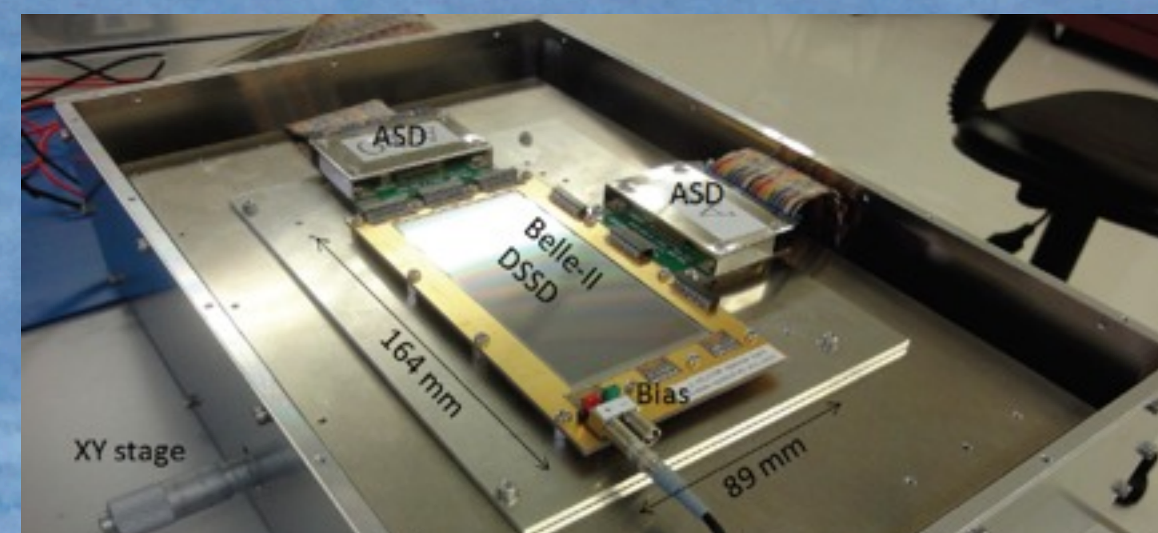
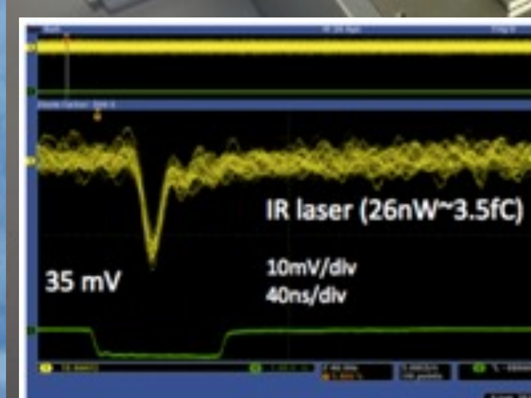


Figure 7.28: Diagram of the silicon sensor test set up





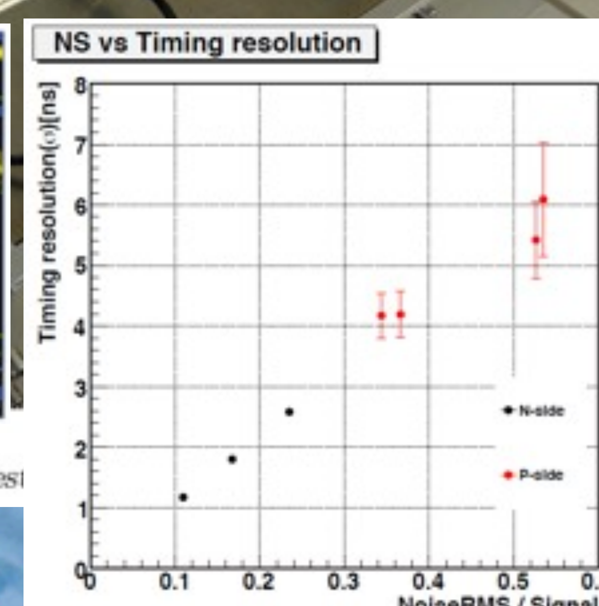
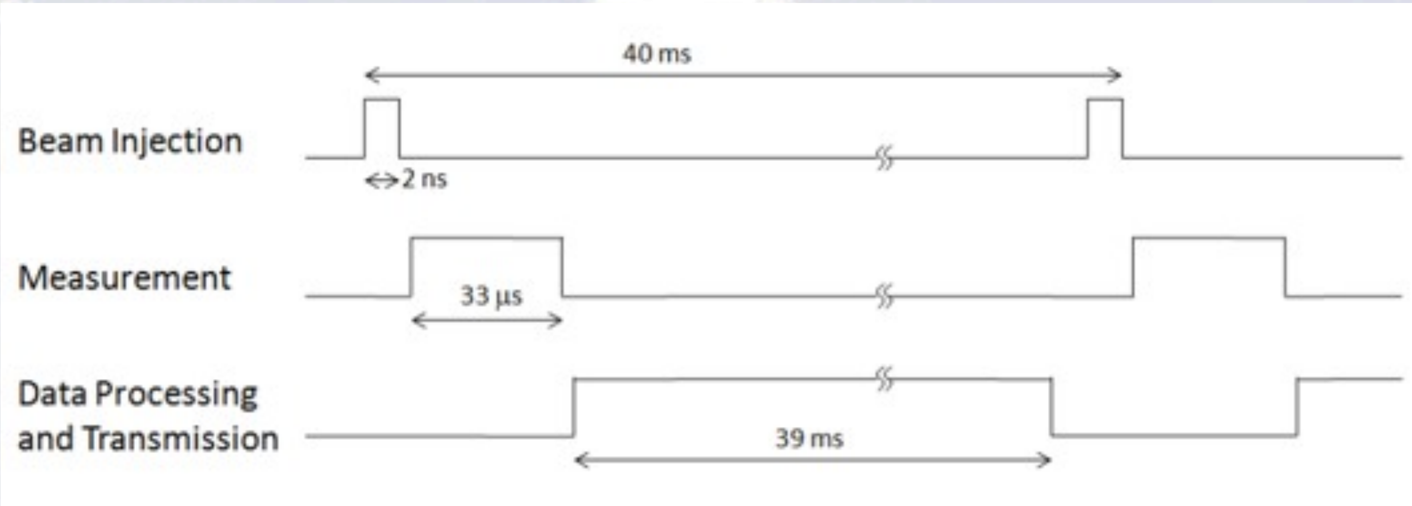
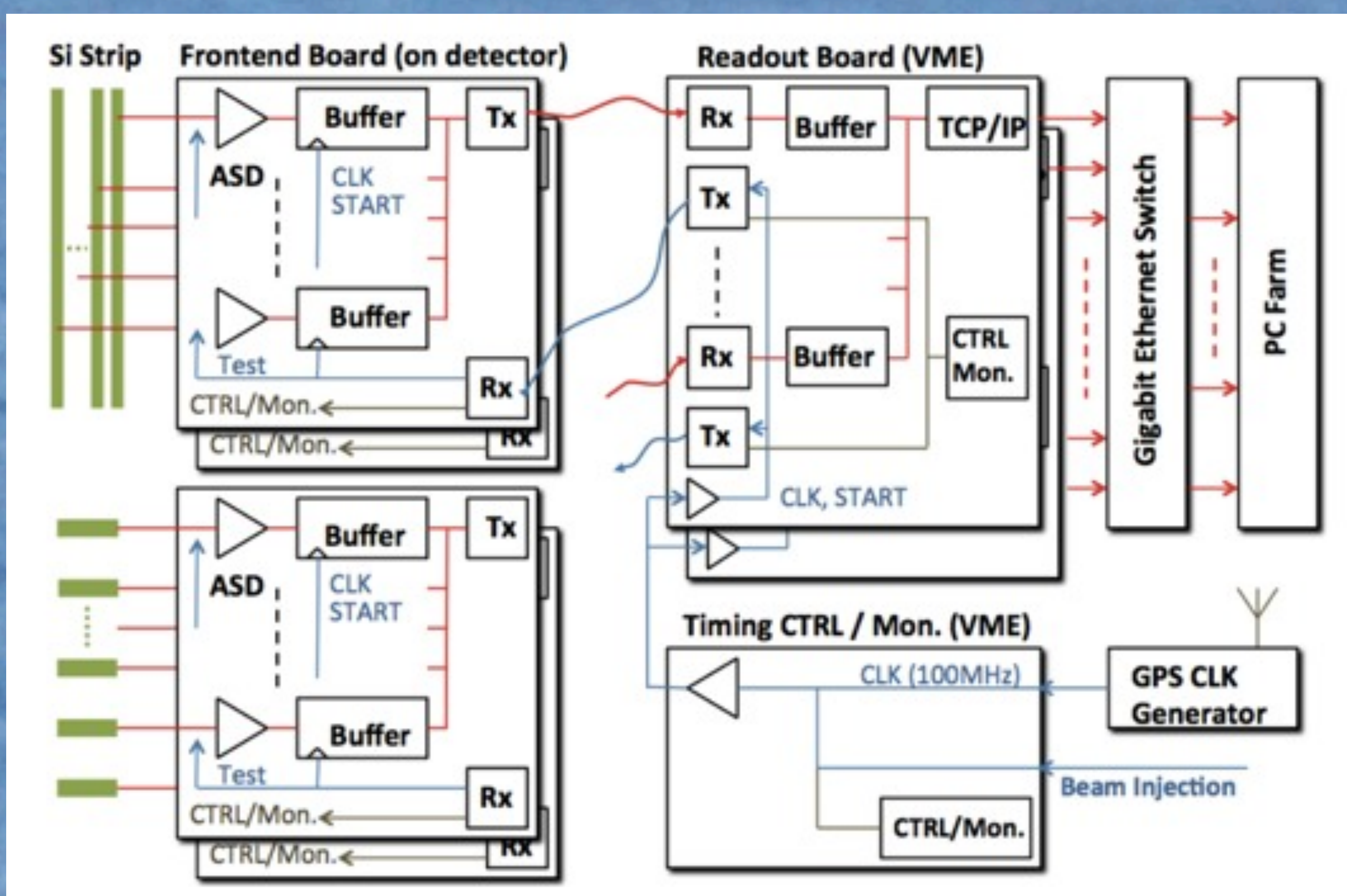


Figure 7.29: The DSSD tes

Readout electronics and DAQ

O. Sasaki
T. Mibe





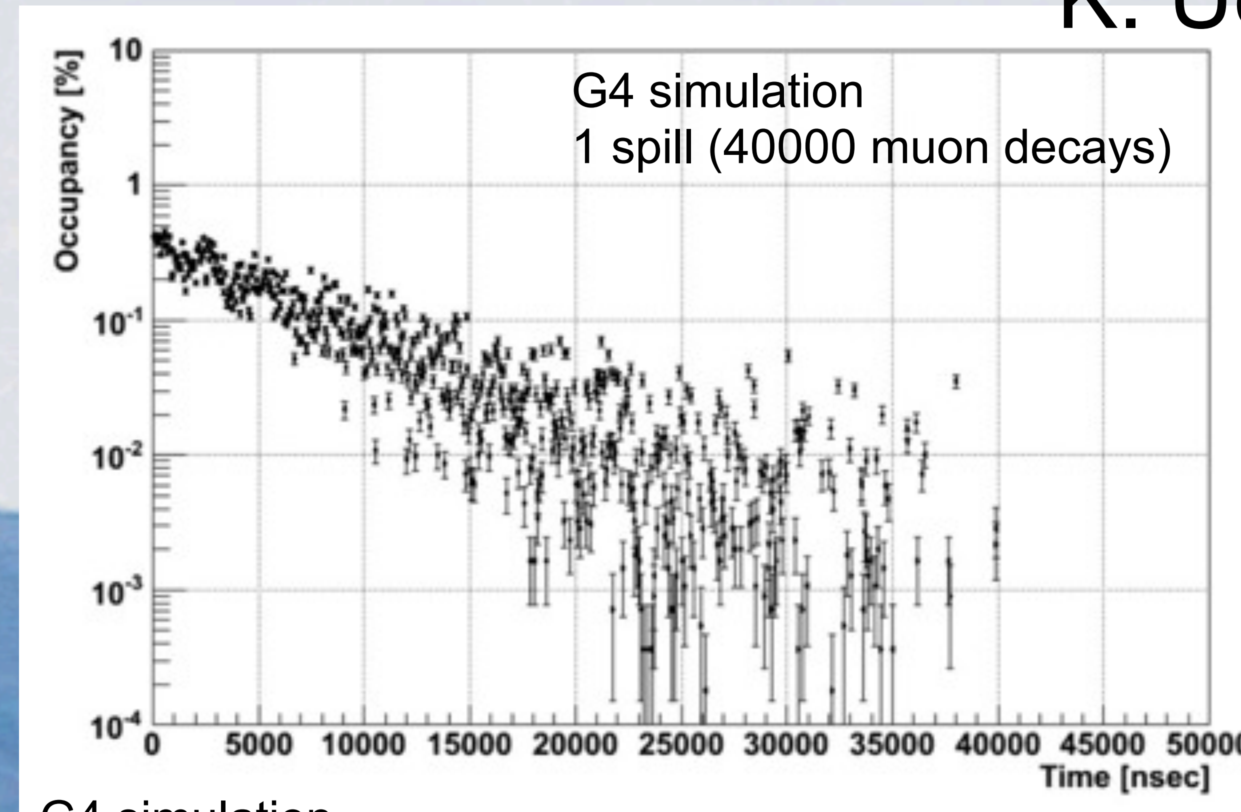
- **Readout electronics and DAQ are designed to match the time structure of the J-PARC beam.**
- **Signals in Silicon sensors are amplified and digitized at Front end, then transmitted to the backend readout boards.**
- **The system clock utilizes the high precision Rb frequency standard with remote calibration from the national frequency standard NMIJ as well as GPS ($\Delta f/f < 3\times10^{-11}$/s).**

Quantity	Value
Hit data size	8 byte/hit
Number of hits per frontend	11.5k hits/spill
Data size from frontend board	2.3MB/s (92kB/spill)
Data size from readout board	18MB/s (740kB/spill)
Total data size	440MB/s (18MB/spill)
Total data size(w/ reduction)	280MB/s (11MB/spill)
Disk write speed of PC	100MB/s (4MB/spill)
Number of PC	10
Data storage space	2.8 PB

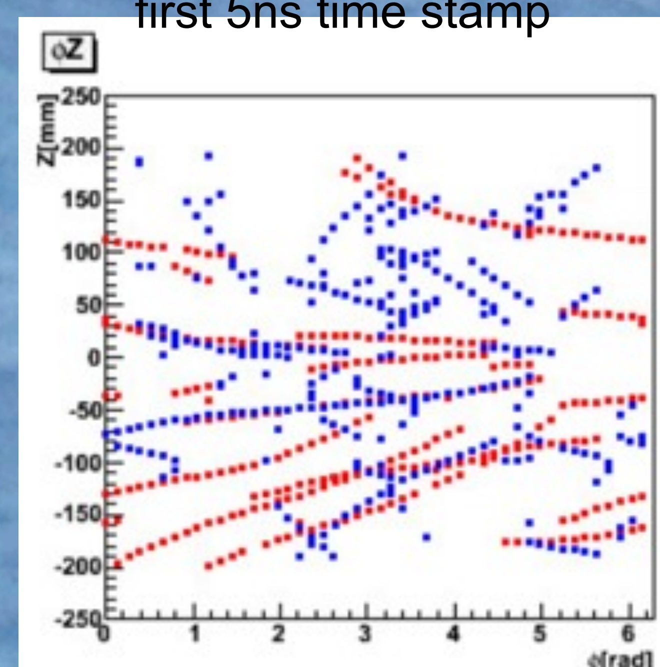
Raw occupancy and hit distributions

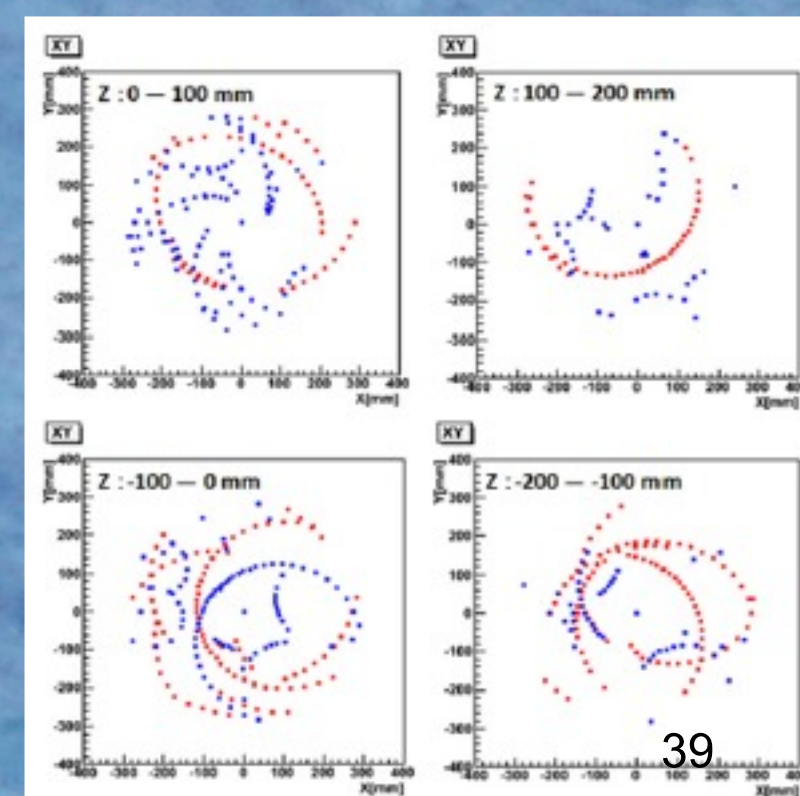
K. Ueno

- A GEANT4 simulation has been carried out to evaluate positrons hits as well as background hits.
  - BG consists of EM processes: such as bremsstrahlung, annihilation, pair creation etc...
- Occupancy is less than 0.5% per 5ns time stamp (5 hits/strip/spill).
- Positron tracks at the beginning:
  - 15 signal e+ tracks with p>200 MeV at first 5ns
  - 30 BG e+ tracks with p<200 MeV at first 5ns
  - Strong hit correlations in ϕZ plane and XY plane.

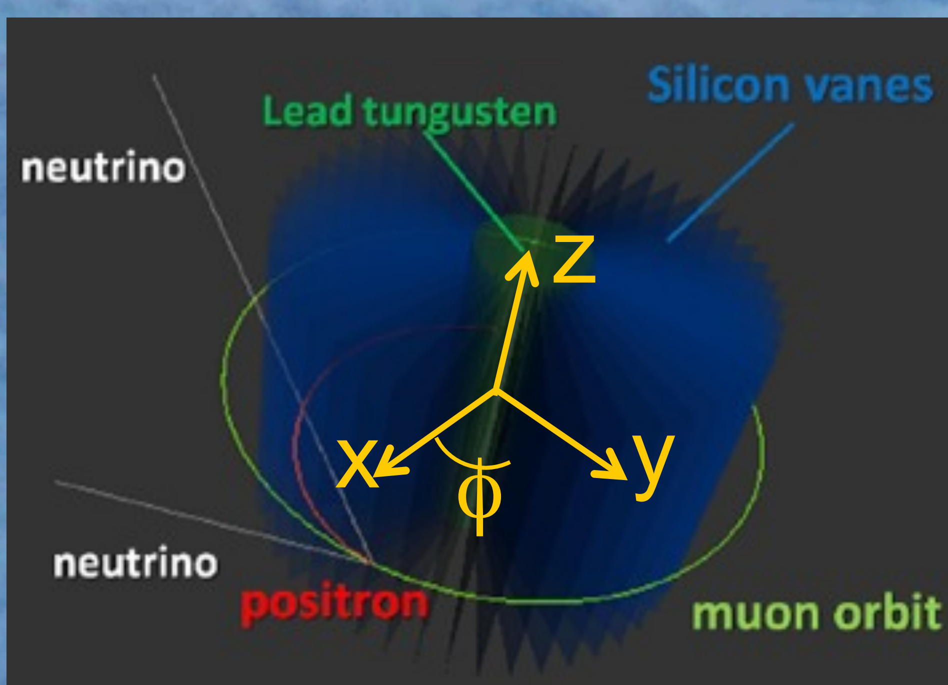


G4 simulation
first 5ns time stamp





- signal e+ (p>200MeV/c)
- BG e+ (p<200MeV/c)

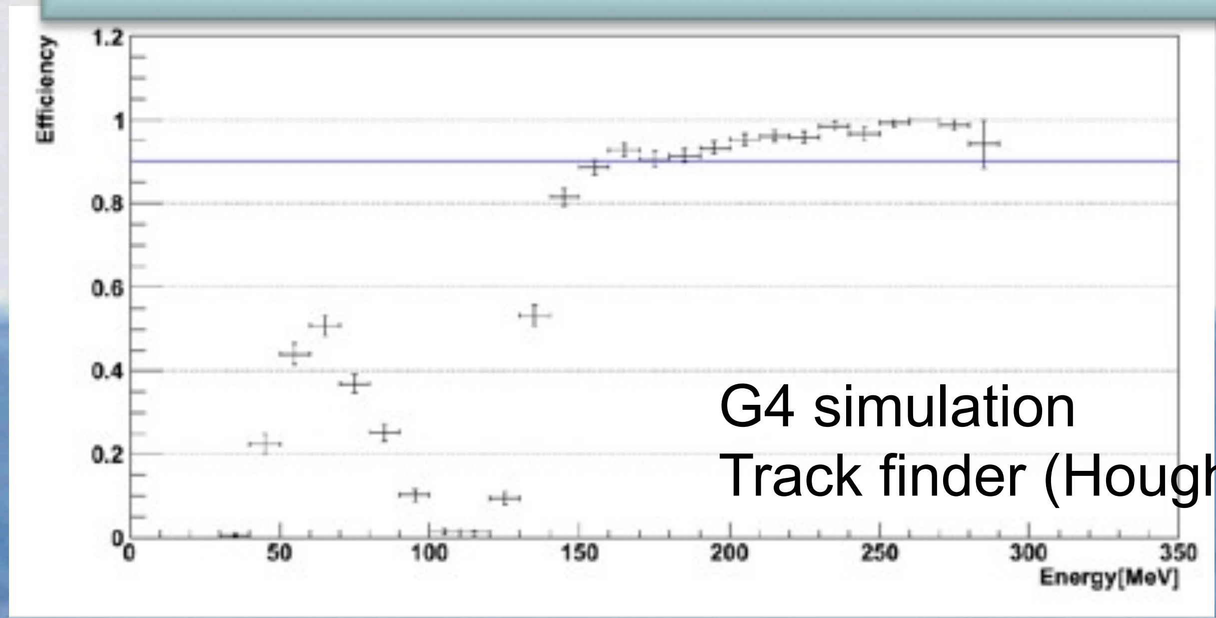


Track reconstruction

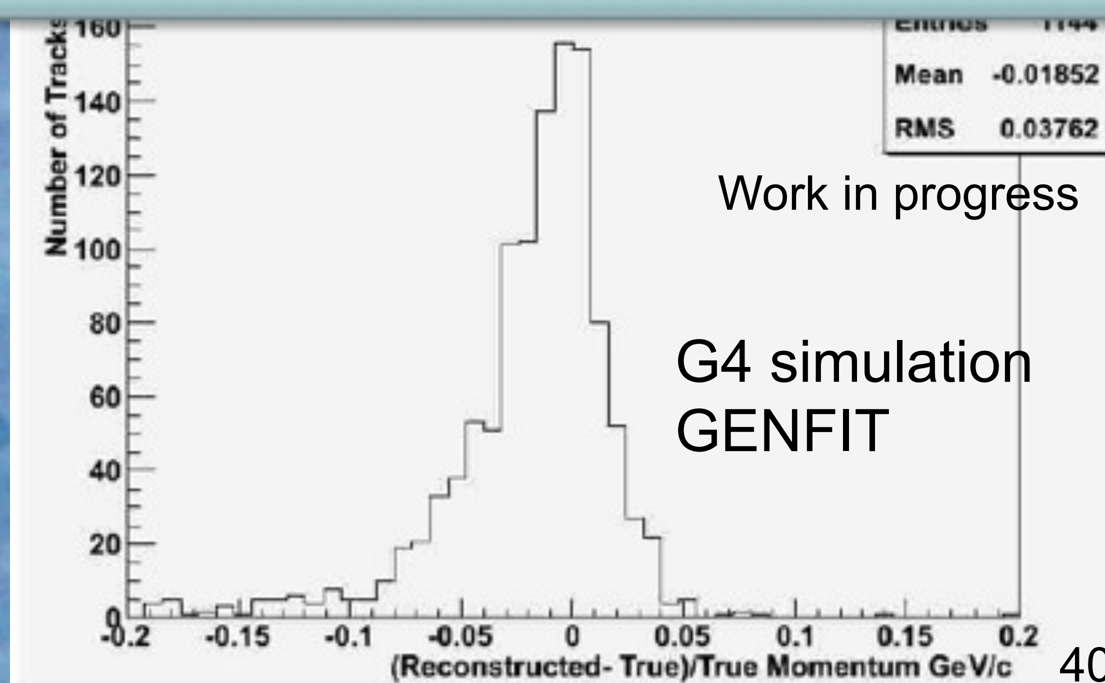
K. Ueno
W. Da Silva
F. Kapusta

- **Track finding**
  - **Initial search with Hough transformation algorithm in ϕz plane**
  - **Track finding efficiency for a single-track is >90%.**
  - **Studies on finding multi-tracks is in progress.**
- **Track fitting**
  - **Fitter with GENFIT (track fitting tool kit with Karman filter) is being developed.**
- **Reconstruction of multi-track**

single track finding efficiency

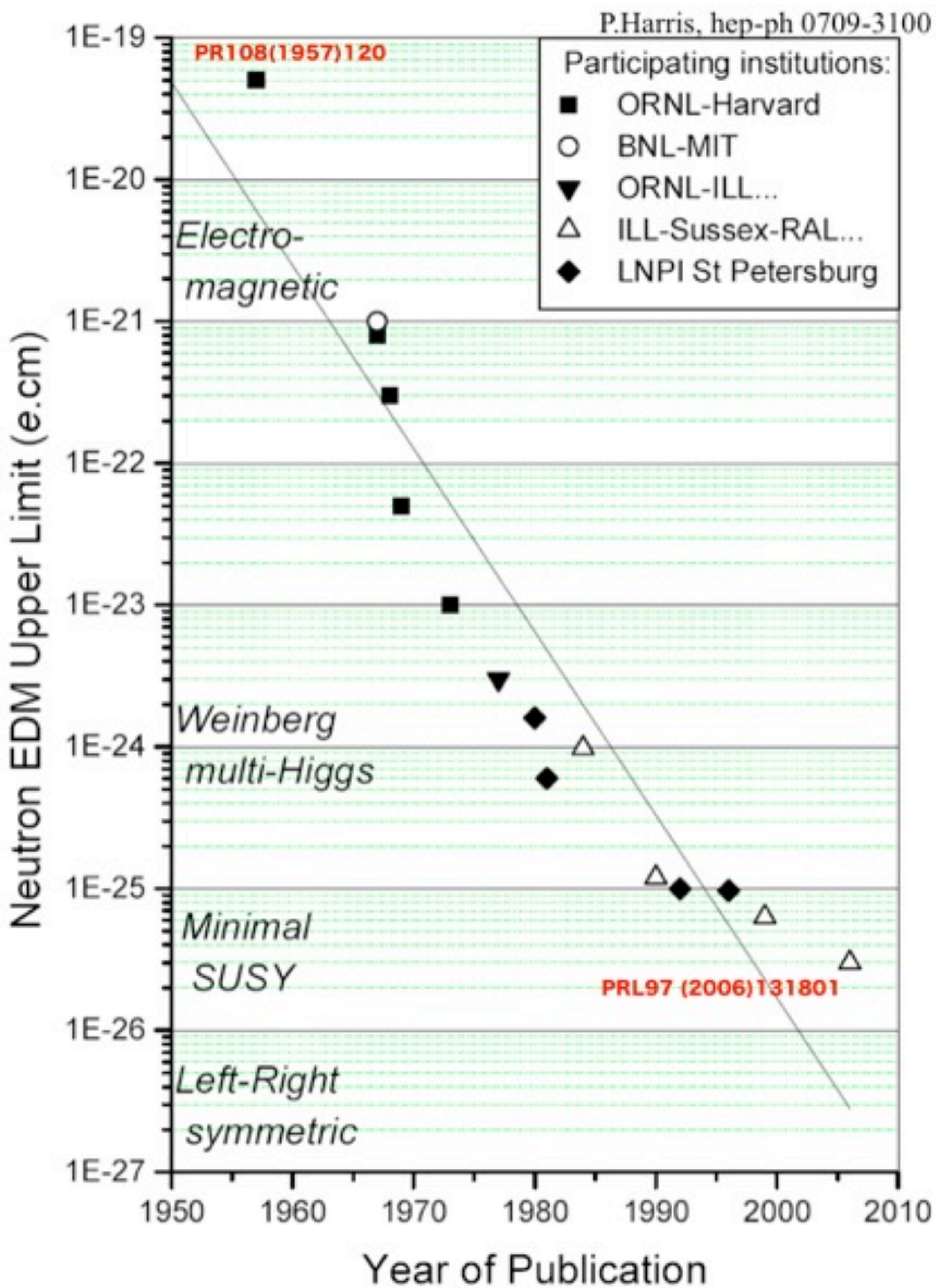


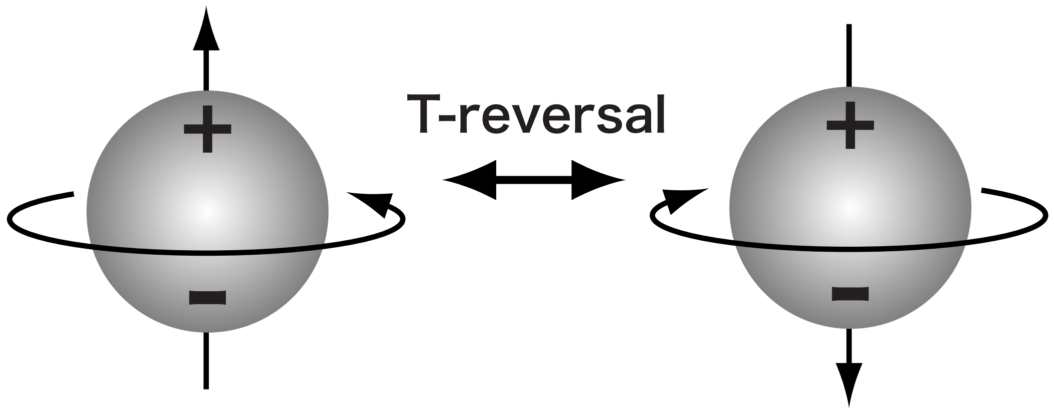
track momentum reconstruction



neutron EDM

Neutron Electric Dipole Moment





Standard Model : 10^{-32} e・cm

SUSY : 10^{-27} e・cm

nEMD is a powerful tool
for Beyond Standard Models

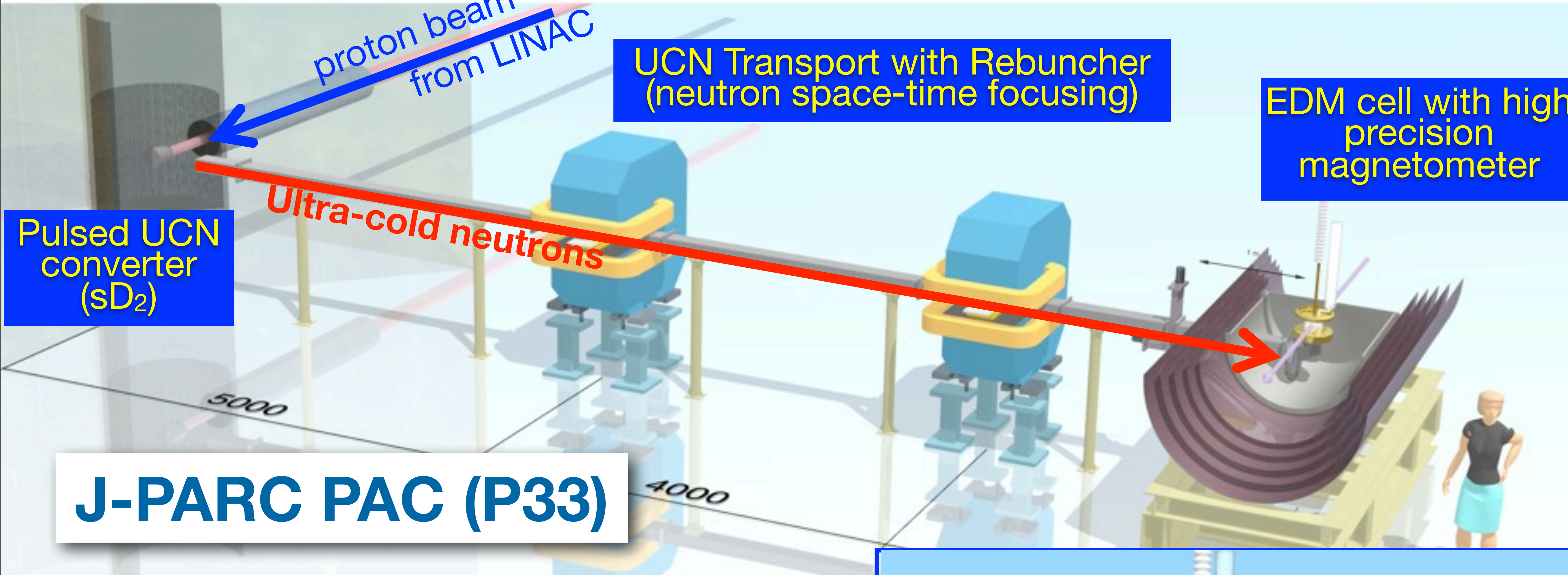
Present Upper Limit
2.9×10^{-26} e・cm

More precisely !

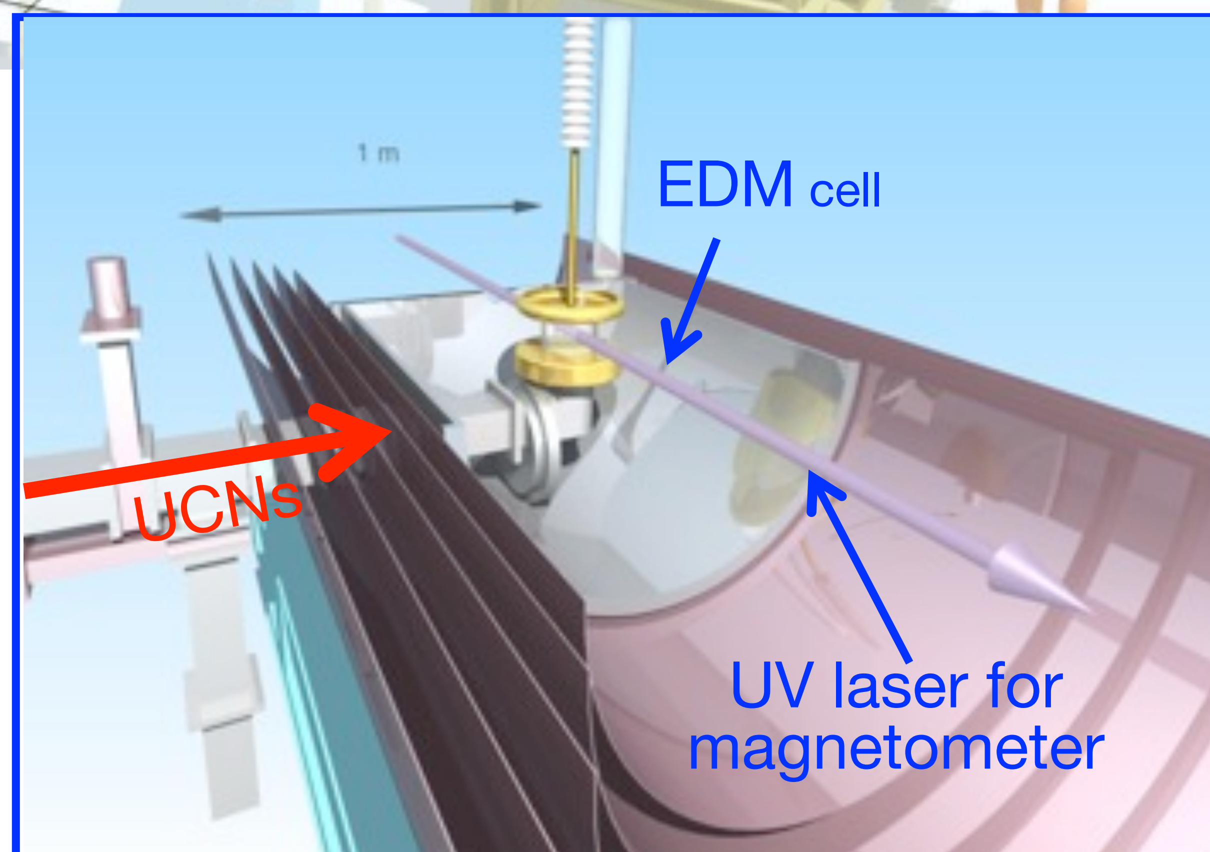
(Baker et al., PRL97 (2006) 131801)

12年6月3日日曜日

nEDM at J-PARC



Large production by J-PARC LINAC
(instantaneous high power : 20 MW)
+
Transport optics
(focusing with pulsed neutron decelerator)
+
High precision measurement
(magnetometer using UV laser)



$$\Delta d_n = \frac{\hbar/2}{E(TN)^{1/2}}$$

$$N = \rho_{ph} V_{ph}$$

	ILL	PSI	SNS	TRIUMF	J-PARC
ρ_{ph} [$cm^{-3}(m/s)^{-3}$]	0.004	0.7	O(1)	19	1.2 (→≤86)
E [kV/cm]	13	13	50	[>13]	[13]
T_i [s]	130	130	500	[>130]	[130]
共磁束計	Hg	Hg	^3He	Xe	Hg
一次ビーム	[原子炉]	DC	[冷中性子導入]	DC	Pulse
最大瞬間強度	-	1.3MW	-	0.2MW	20MW
利用する平均強度	-	13kW	-	5kW	2kW
超冷中性子輸送	導管	導管	輸送無し [生成領域で計測]	導管	時間収束 (→位相空間重ね合わせ)
到達感度 [e cm/E_c=90neV]	2.6×10^{-26}	5×10^{-27} →5×10^{-28}	$O(10^{-28})$	$O(10^{-28})$	1×10^{-27} (→2×10^{-28})
物理測定開始	-	2012→2014	2015?	2014-5	2014(→2018?)

Current Status

- COMET - Stage-1 approved
  - Continuing R&D; Writing TDR ; Staging plan adopted by collaboration; Aiming for budget request
- Muon g-2/EDM - Stage-1 recommended
  - Continuing R&D ; Milestones setup; Aiming for budget request
- DeeMe
  - Deferred ; Continuing R&D
- nEDM
  - Deferred ; Continuing R&D

Born as French, Return as Japanese

- Innovative CERN experiment
- Successful US "continuation"
- Creative Japanese "grand-child"

Forms of FJ Connection

- SAKURA : like W. da Silva and Tsutomu Mibe
- FJPPL : like F. Kapusta and N. Saito
- KEK Visitor Program : two weeks to two months
- JSPS Post Doctoral Fellowship for Foreign Scientists
- Graduate Course in Universities in Japan:
    - Saito-Lab (g-2/EDM, RHIC Spin), Matsuda-Lab (MuHFS, Anti-H) (U-Tokyo)
    - Kuno-Lab (COMET, MuSIC) (Osaka)
    - Muon-Lab (Sokendai = Graduate course in "KEK") (COMET, g-2/EDM)
    - Kawagoe-Lab (ILC, ATLAS, nEDM, and Muon) (Kyushu)

Summary

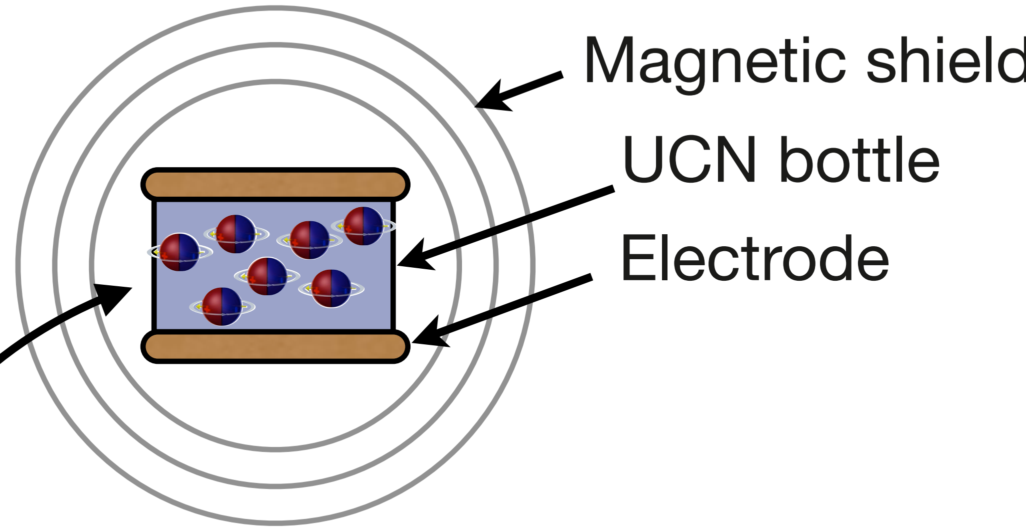
- We are exploring the new opportunities of Intensity Frontier at J-PARC
    - Muon g-2/EDM : simultaneous measurement; synergy with Mu HFS
    - LFV : DeeMe and COMET
    - nEDM: new method with neutron beam optics
- Should be realized in a timely manner to be competitive with other projects
- We invite French Physicists to J-PARC!

Neutron Electric Dipole Moment

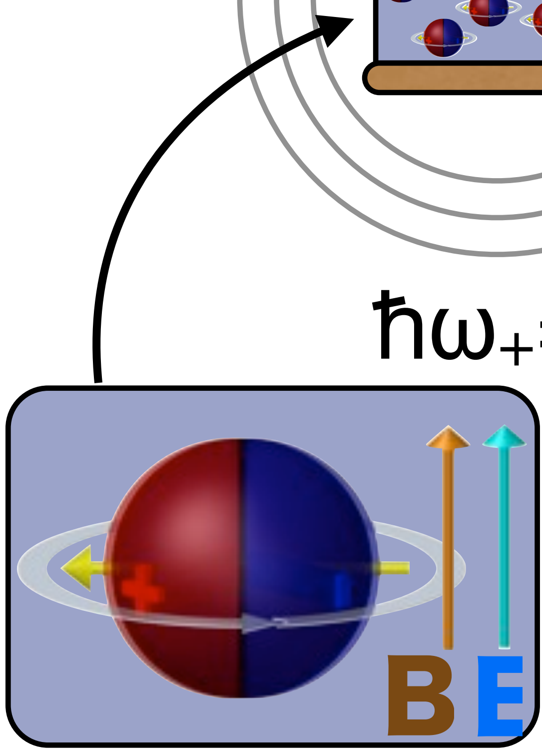
How to measure nEDM

(1) Store UCNs in cell

(2) measure precession number in electric field

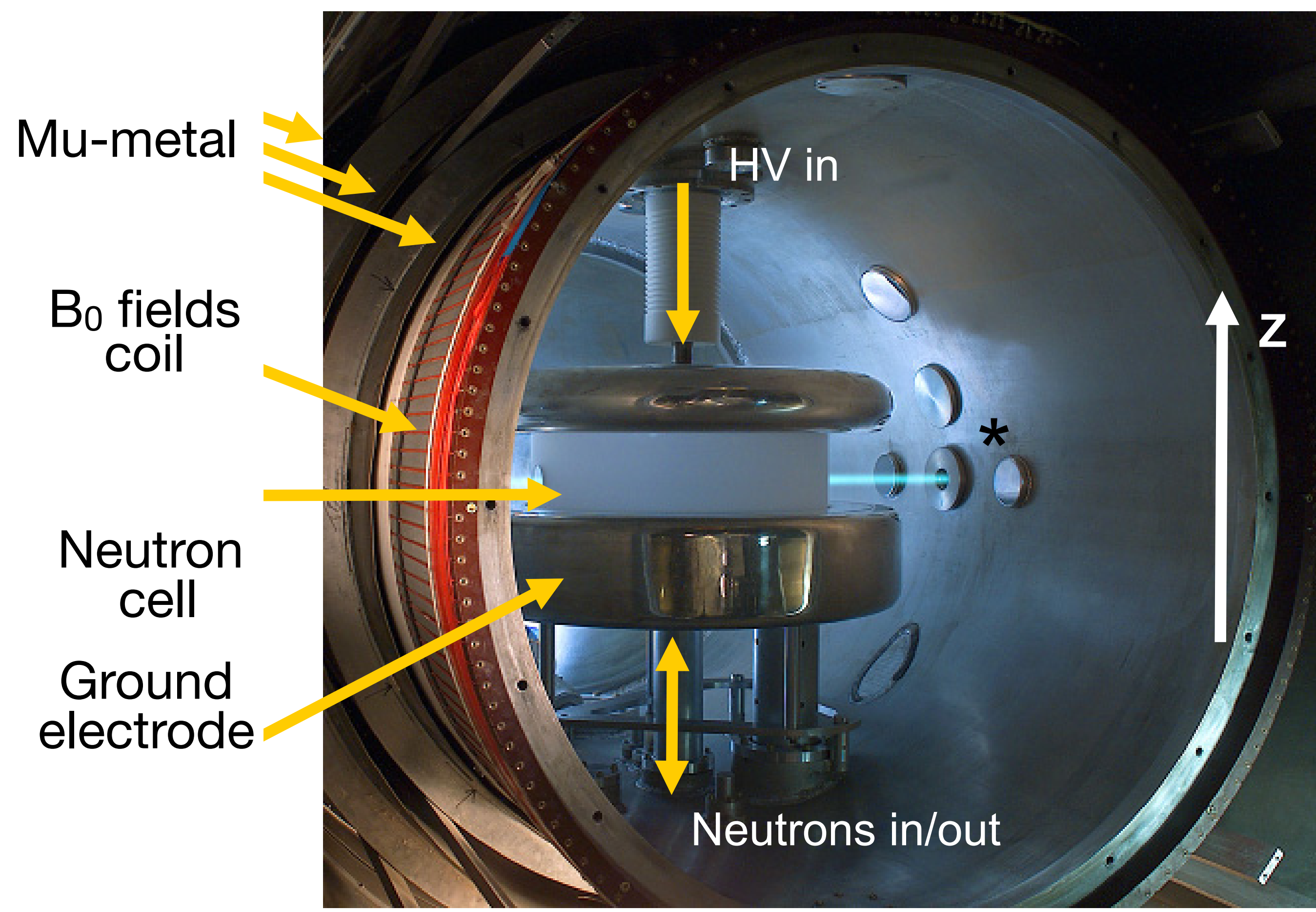


$$\hbar\omega_{+}=2\mu_{n}B+2d_{n}E$$



30 Hz	**50 nHz**
1 μT	**1 fT equiv.**

ILL experiment



We require **uniform magnetic field**

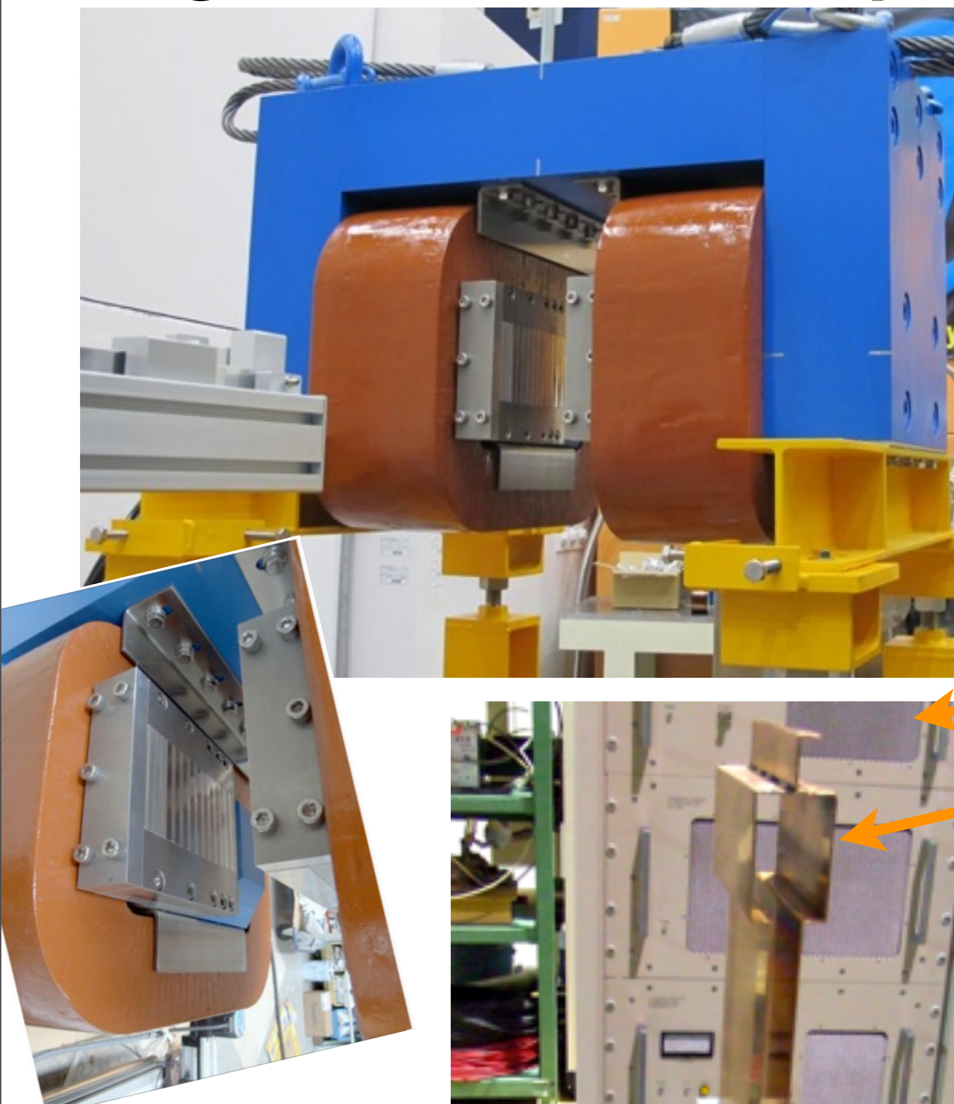
high precision measurement of the field

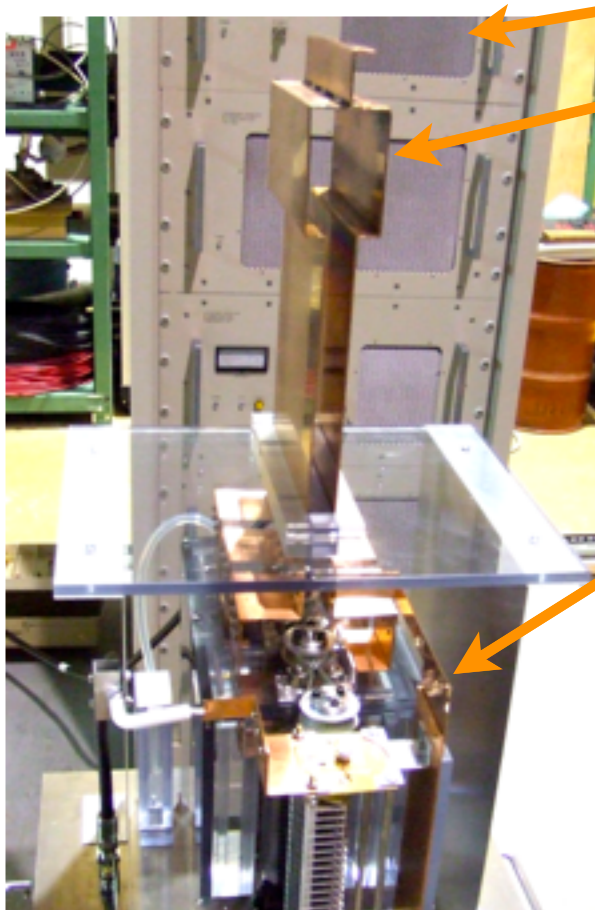
Compact cell → **dense UCNs!!**

UCN Rebuncher

Prototype

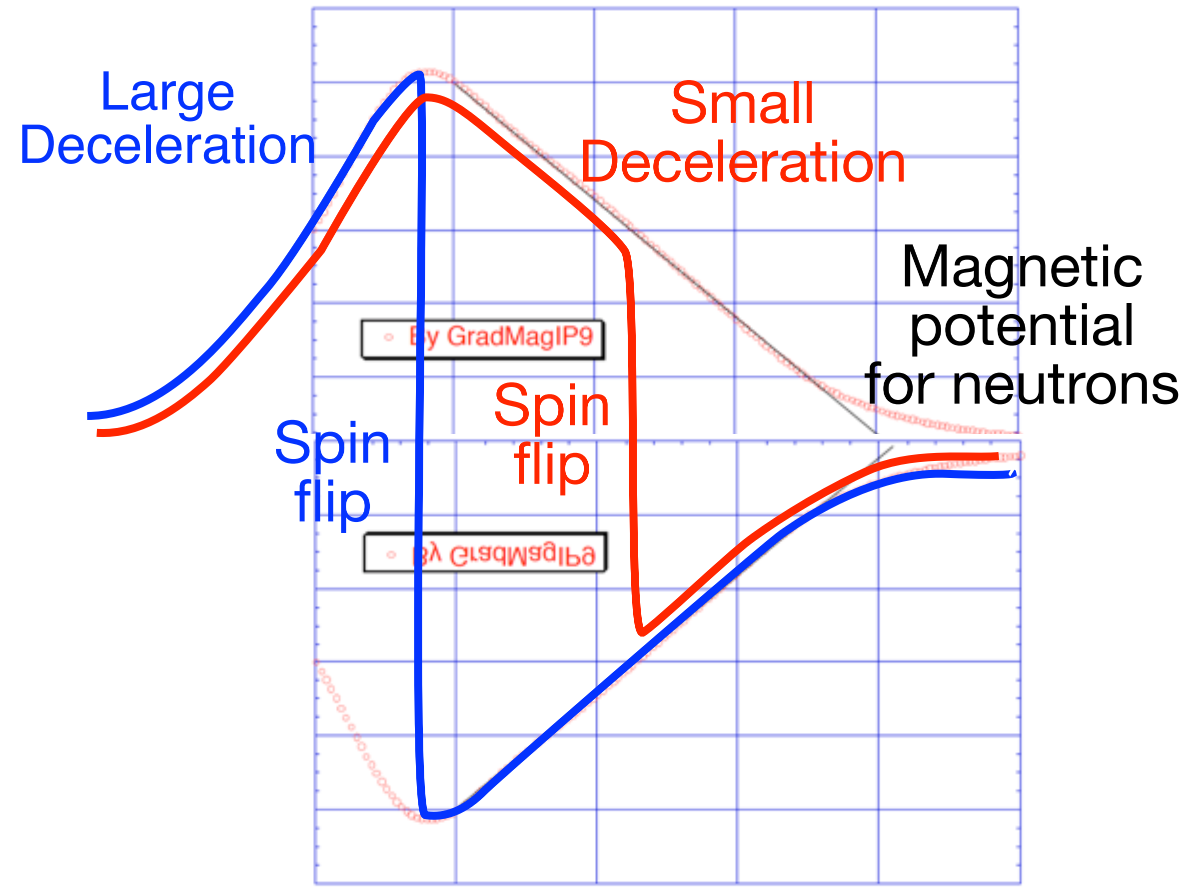
Magnet with anisotropic interpole





Resonance condition with RF of 15-30MHz.

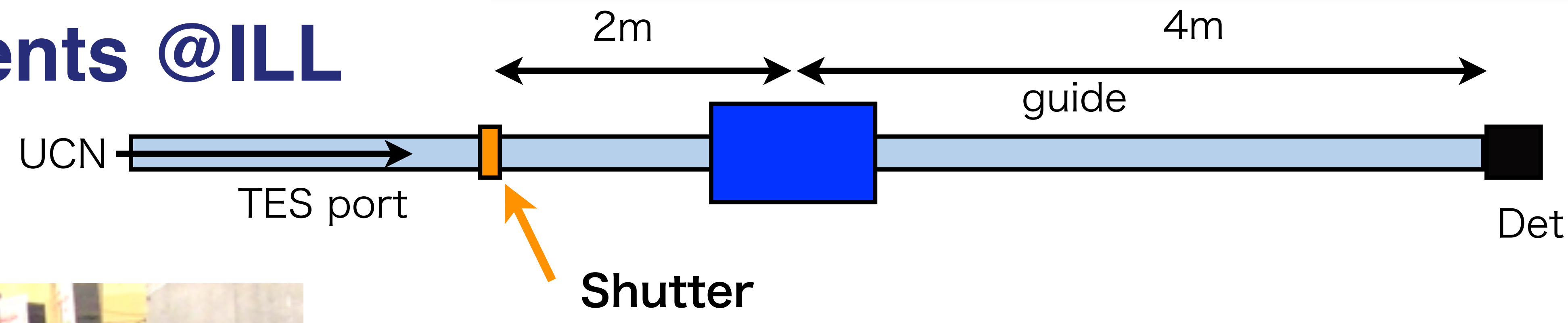
AFP flipper for acceleration / deceleration

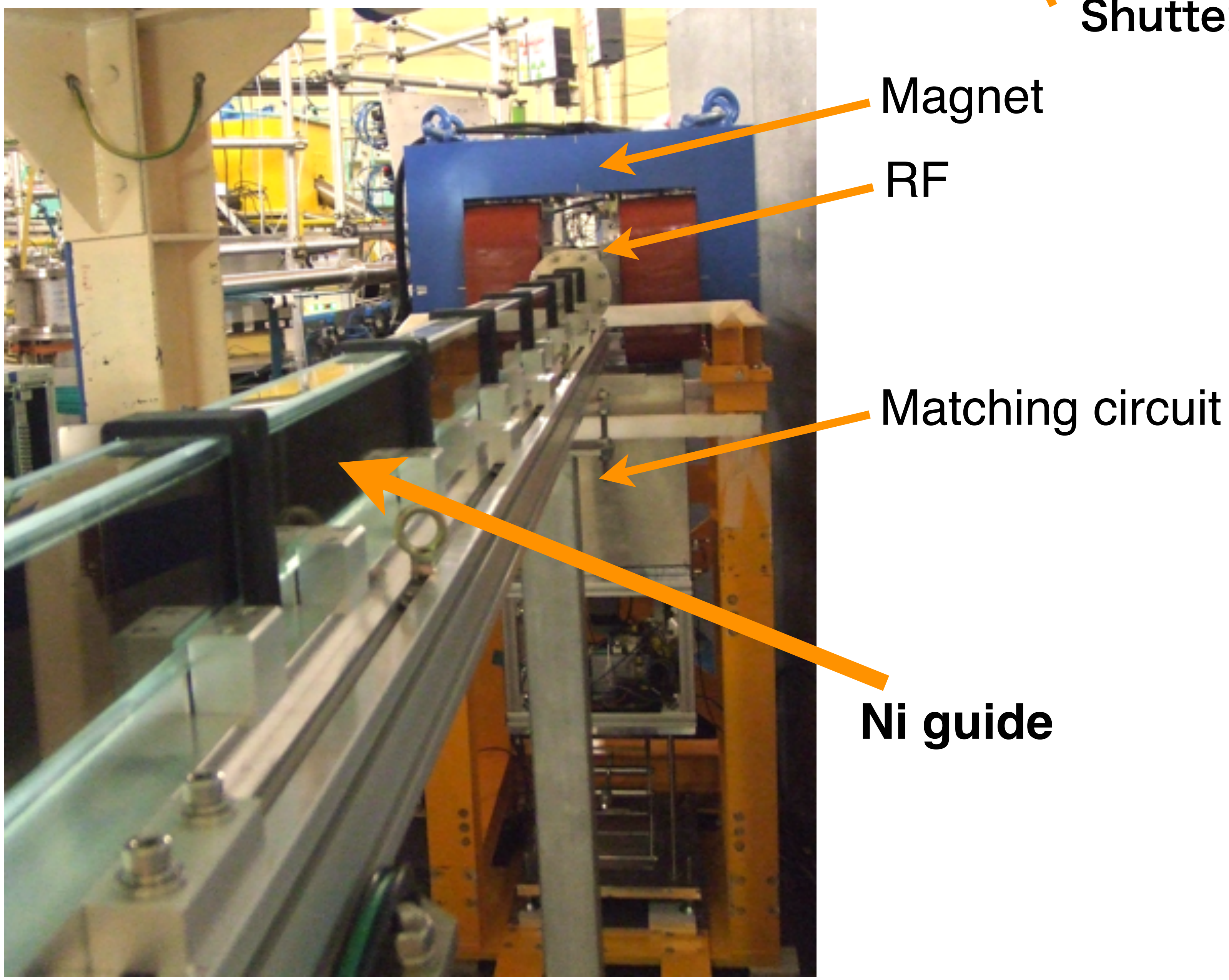


Spin flipper with changing frequency functions as rebuncher.

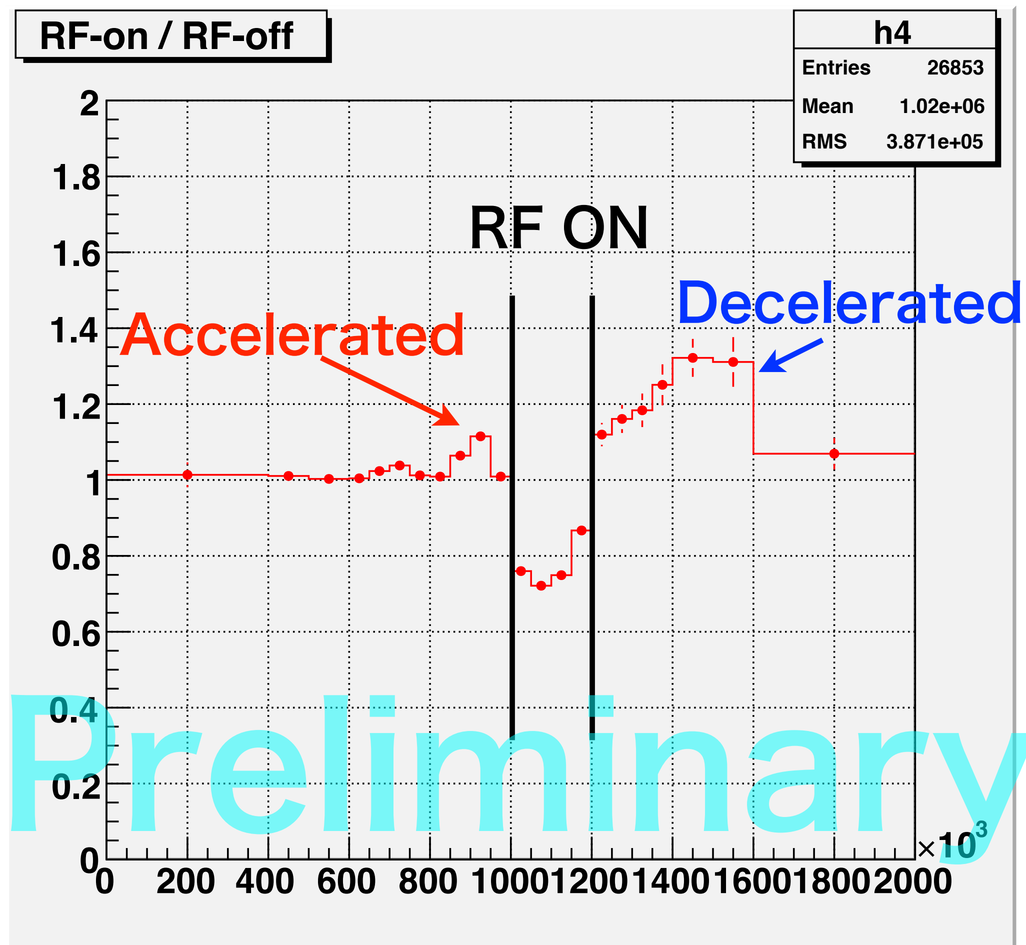
UCN Rebuncher

Test experiments @ILL





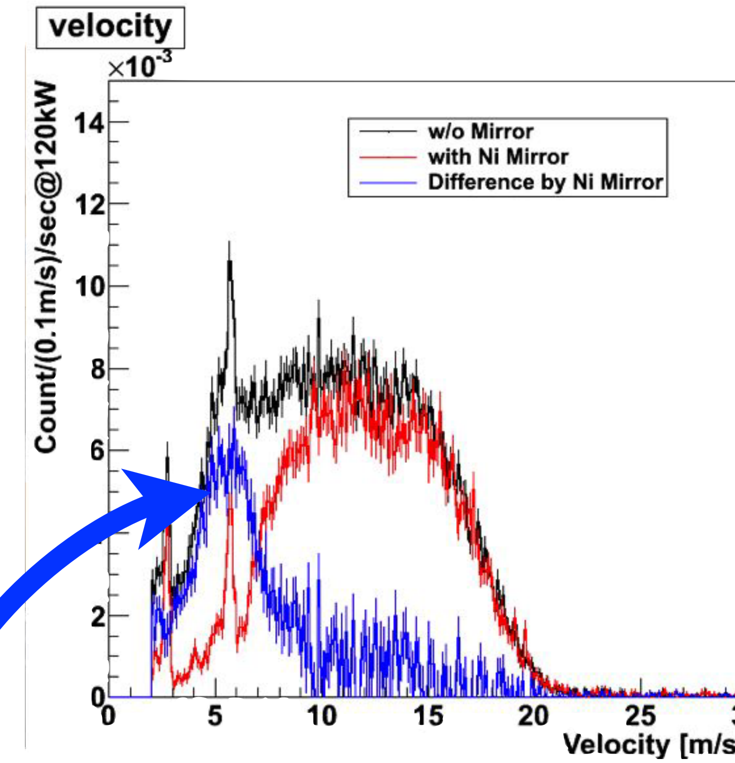
Demonstration of UCN acceleration and deceleration



R&D

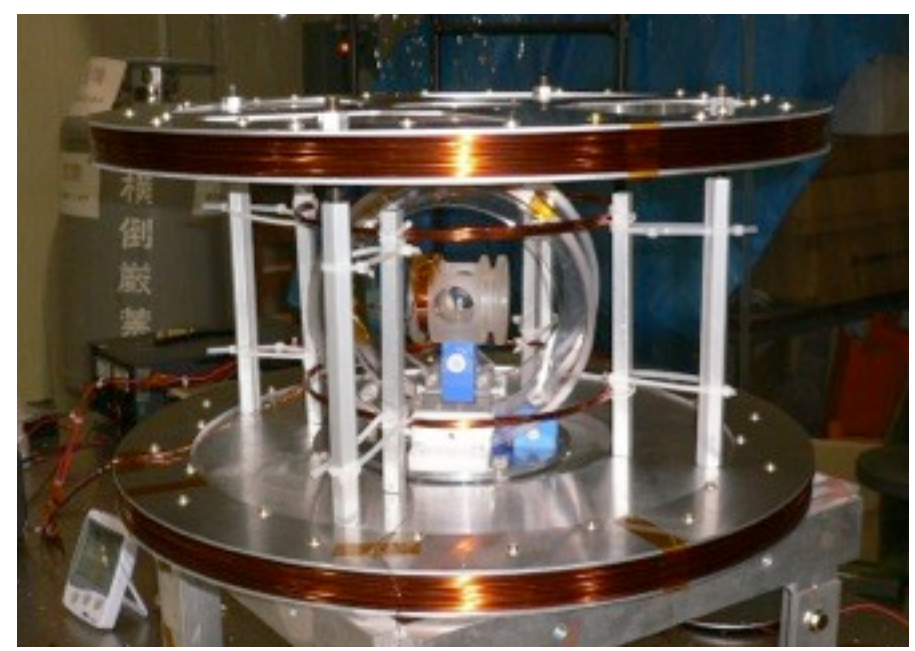
J-PARC MLF BL05 NOP
Neutron Optics and Physics

Doppler Shifter



Now we can get UCNs at our own beamline.

Hg Laser



Hg Laser Co-magnetometer to measure magnetic field in the cell

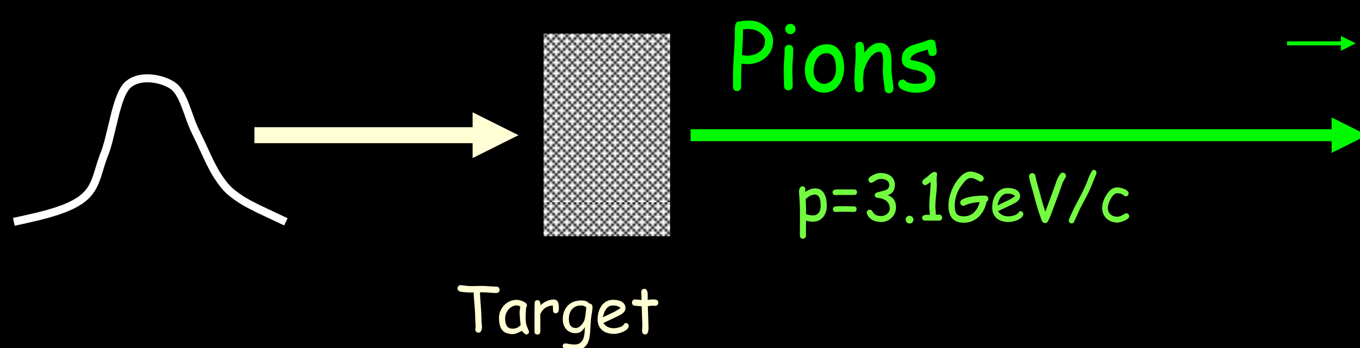
Possible Issue g-2/EDM and DeeMe

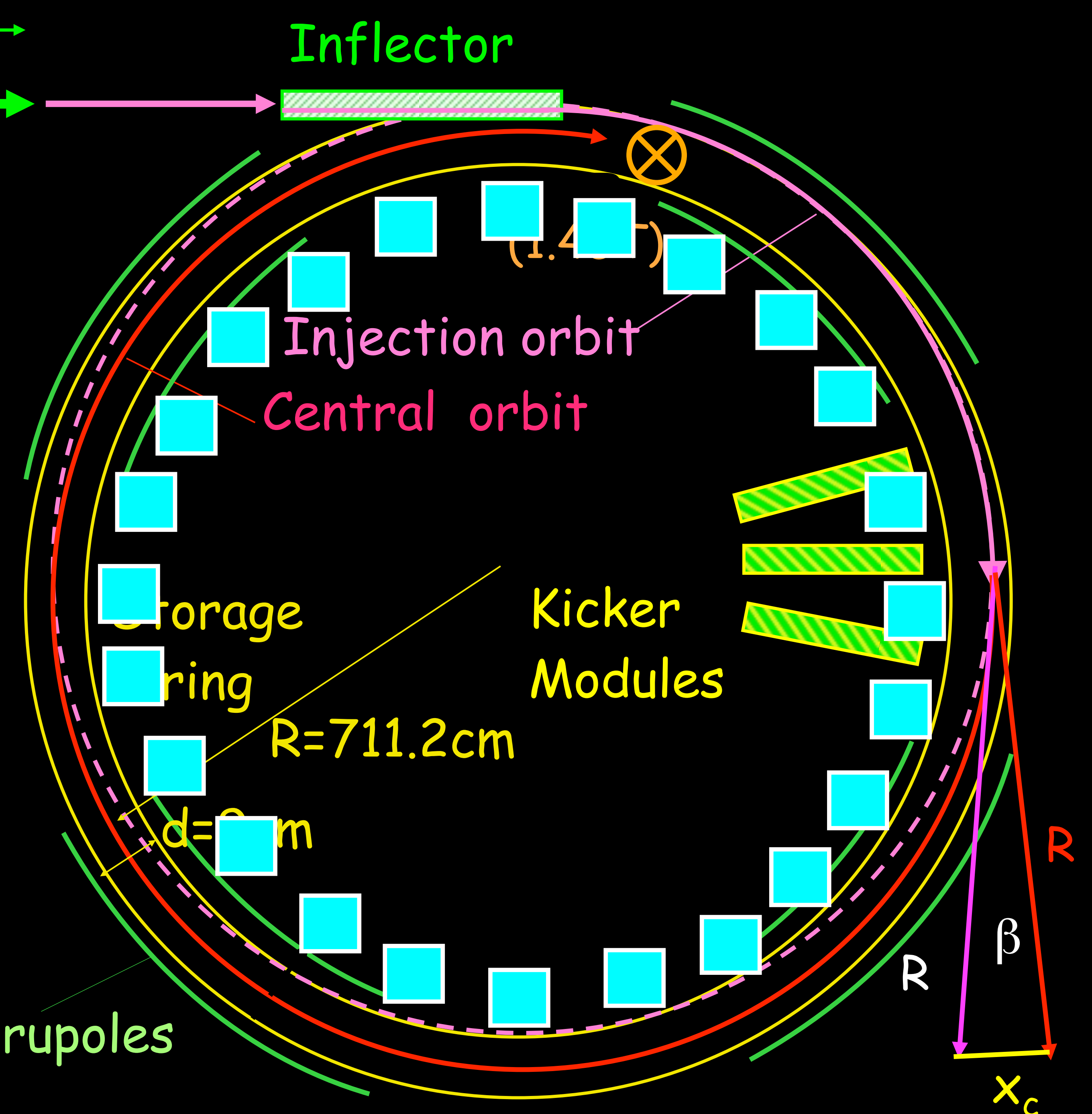
- Muon g-2/EDM and DeeMe are collaborative efforts including both IPNS and IMSS
    - "IMSS side" is the primary owner of H-Line
    - "IPNS side" is the primary proponent of the experiment
- Priority, Responsibility should be clearly defined under the directors of two labs --> Two PACs are separately evaluating the program
- MOU would be the solution

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

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

Electric Quadrupoles

(thanks to Q. Peng)

12年6月3日日曜日

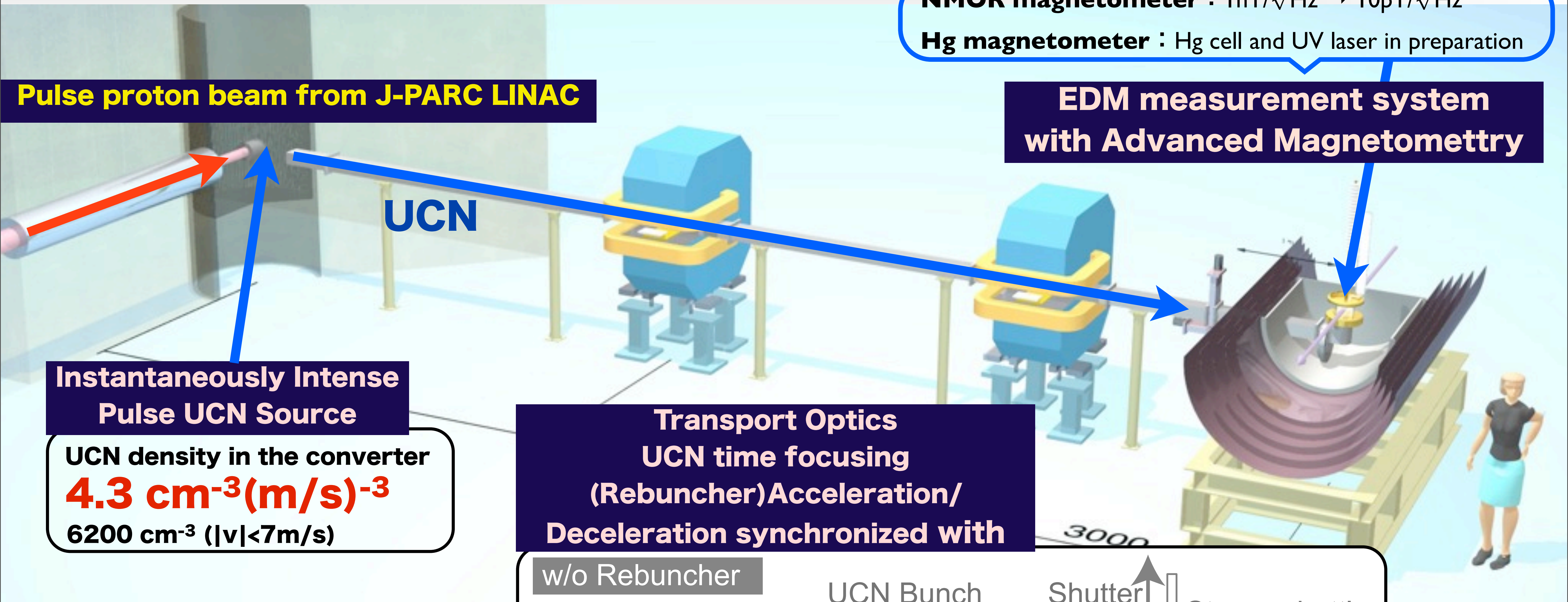
bakup slides

Measurement of neutron EDM (J-PARC P33)

NMOR magnetometer：1nT/√Hz → 10pT/√Hz
Hg magnetometer：Hg cell and UV laser in preparation

Pulse proton beam from J-PARC LINAC

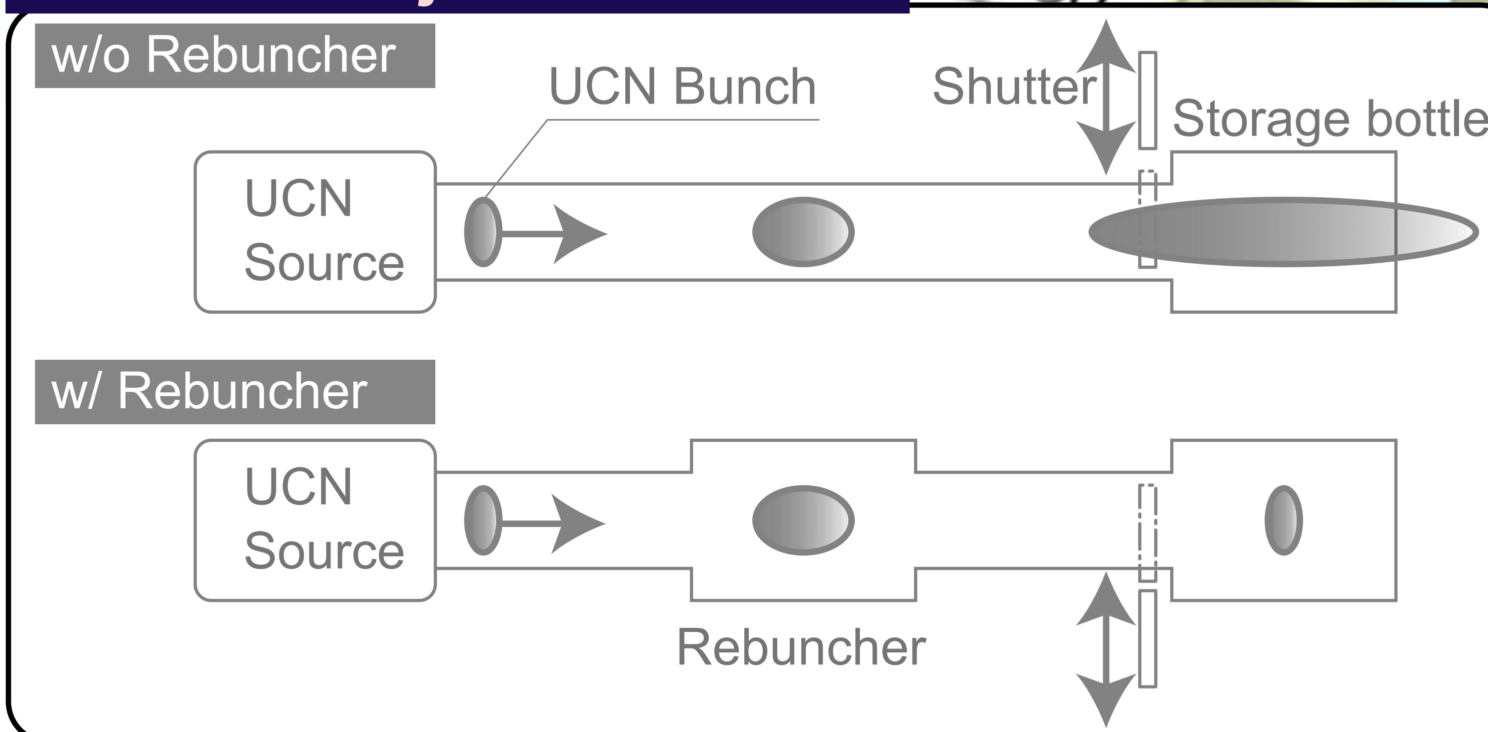
EDM measurement system with Advanced Magnetomettry



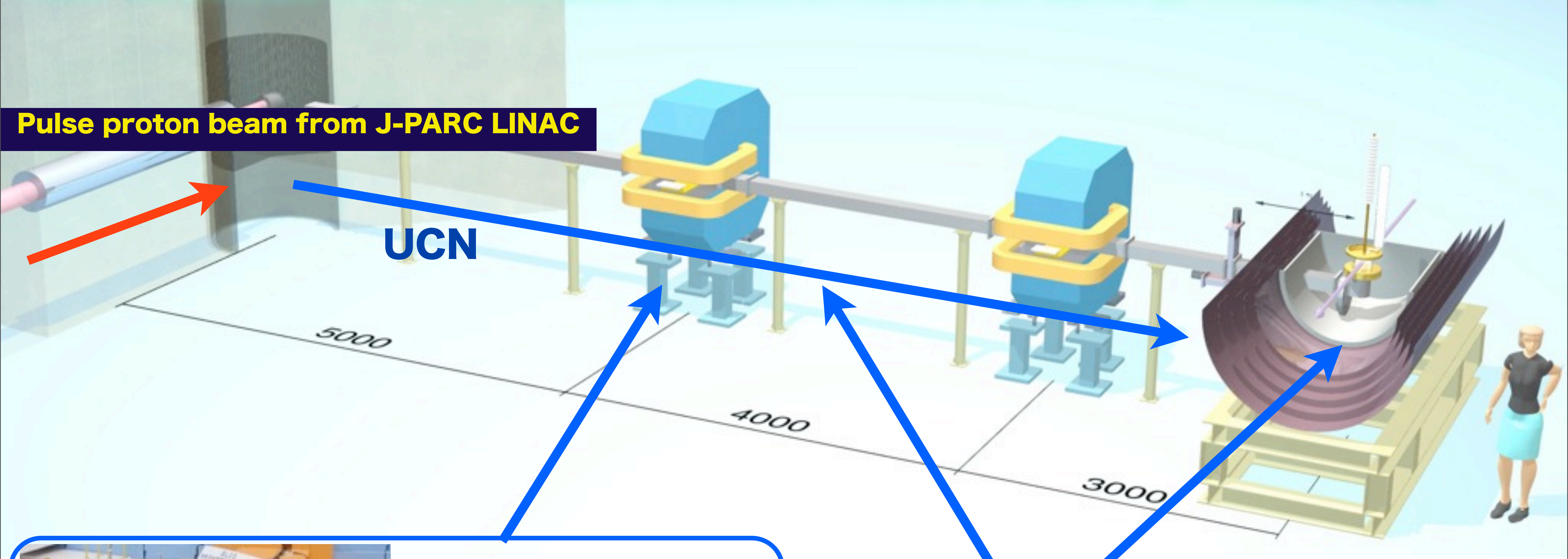
Instantaneously Intense Pulse UCN Source

UCN density in the converter
4.3 cm^{-3}(m/s)$^{-3}$
6200 cm^{-3} (|v|<7m/s)

Transport Optics
UCN time focusing
(Rebuncher)Acceleration/
Deceleration synchronized with



R&D activities for the Measurement of neutron EDM (J-PARC P33)



Demonstration of Rebuncher Optics

-Static field Magnet : ready

-RF System and Tuner Phase-Lock-Loop Circuit : ready

-UCN Transportation : transmittance to be improved

→ in progress at J-PARC/MLF BL05

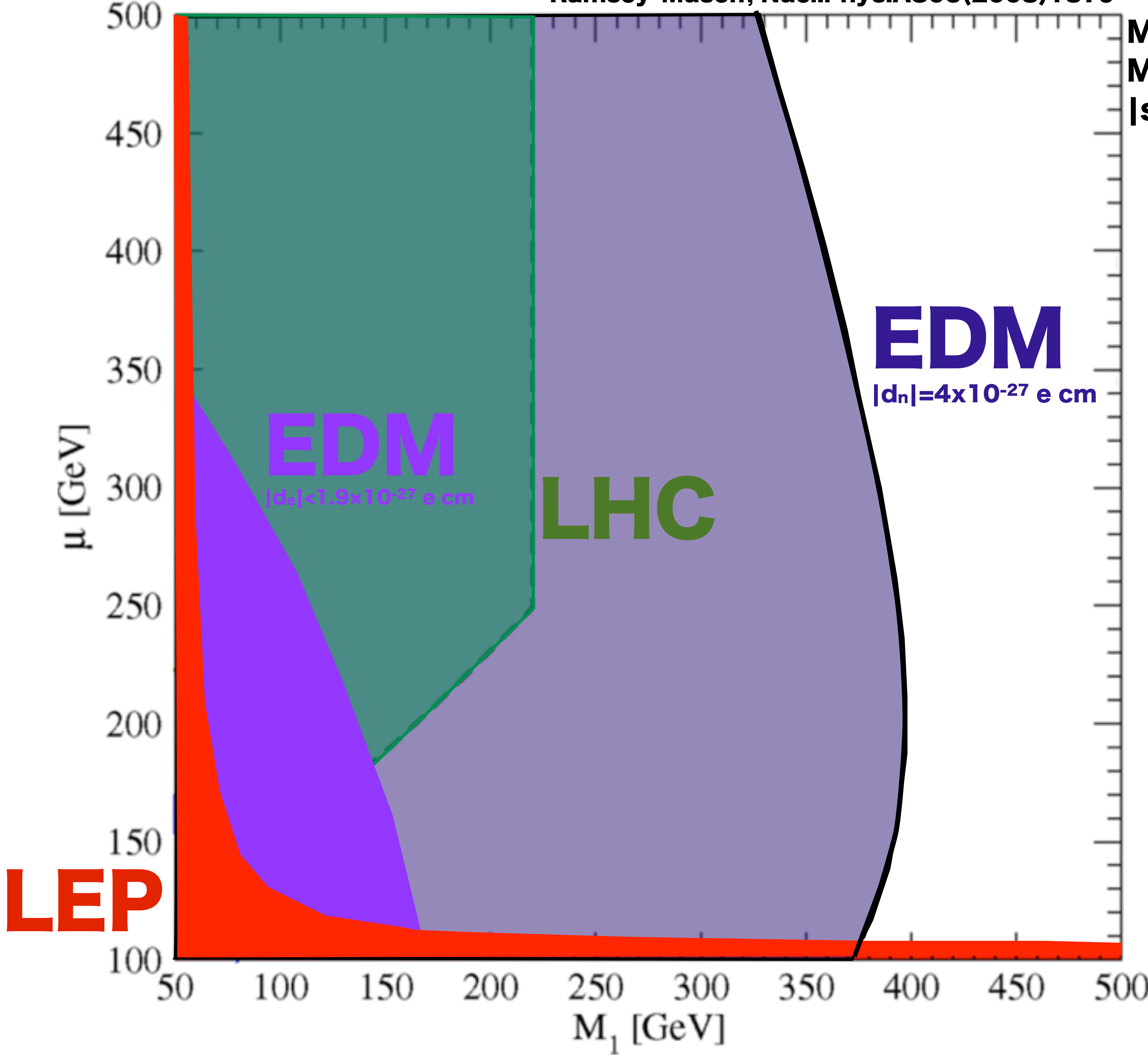
Study of wall surface for UCN guide and cell

-Angular distribution of non-specular reflection
-Probability of non-specular reflection
-Reflectivity of specular reflection

→ in progress at J-PARC/MLF BL05 and BL16

Discovery Potentials

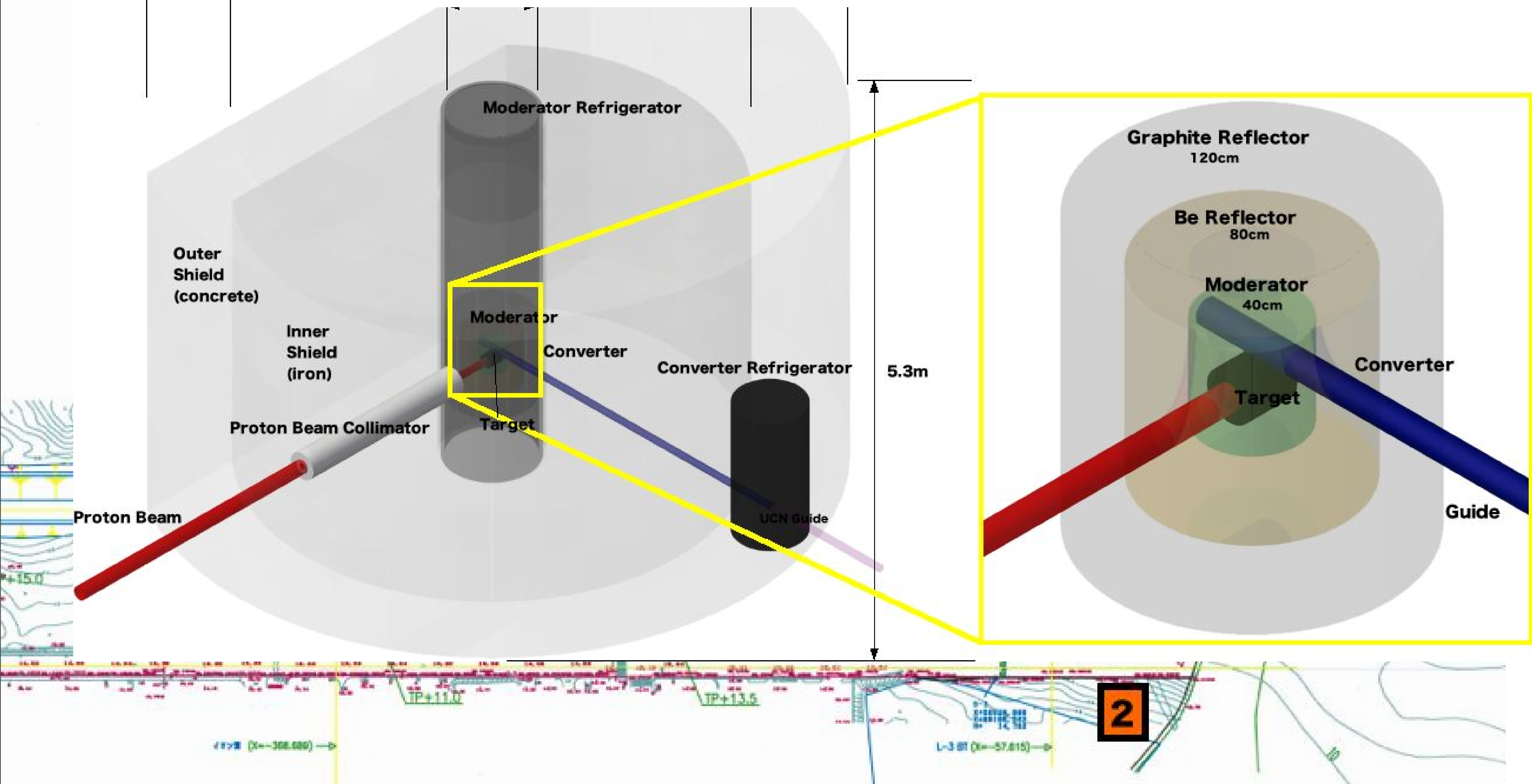
Ramsey-Musolf, Nucl.Phys.A805(2008)137c



$M_2=2M_1$
$M_A=1$TeV
$|\sin\phi_\mu|=0.5$

nEDM at J-PARC

compact target and shield,
sD2 converter for UCN



candidates target building for UCN

UCN Converter

C.-Y.Liu, Dissertation, Princeton Univ. (2002)

converter	He-II	Solid ortho-D_2	α-O_2
interaction	phonon	phonon	magnon?
converter temperature	0.7K	5K	2K
optimal neutron temperature	9K	29K	12K
production rate (30K neutrons)	$90\times10^{-11}\Phi_0$ cm^{-3} s^{-1}	$1300\times10^{-11}\Phi_0$ cm^{-3} s^{-1}	~$1000\times10^{-11}\Phi_0$ cm^{-3} s^{-1}
ideal lifetime (no wall loss, no upscattering)	886 s	146 ms	489 ms

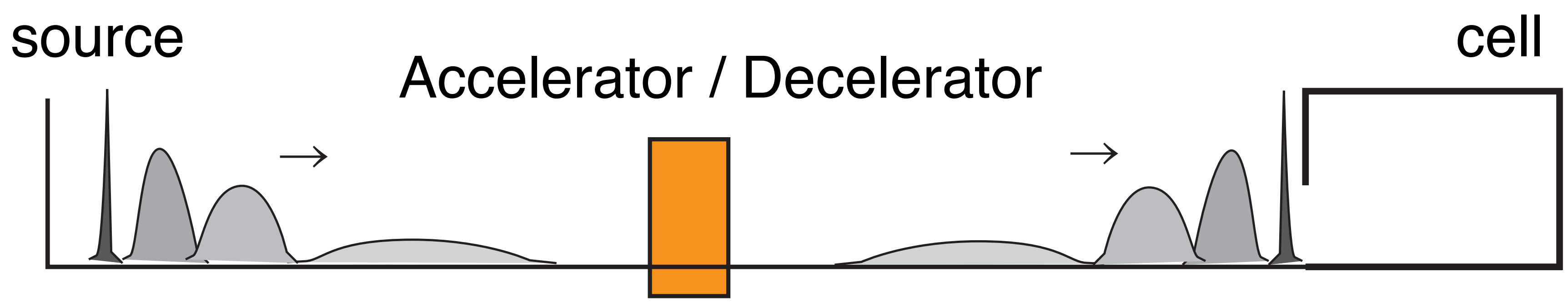
low loss

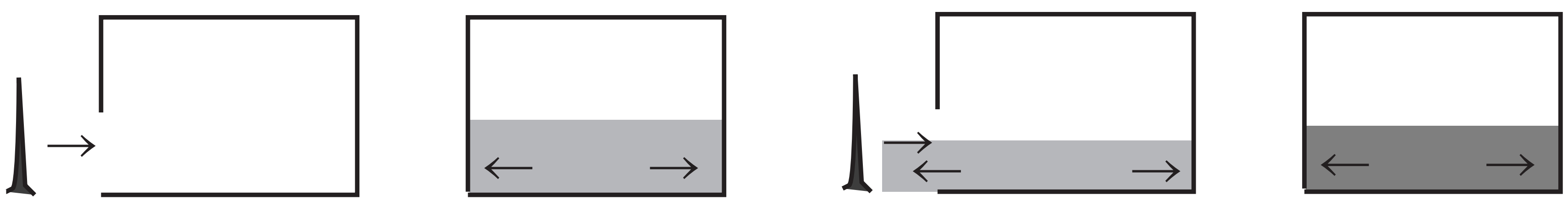
large production rate

→Large production, Extract immediately, Transport with keeping density

$\rho_{UCN}=10^{-11}\Phi_0$
(thermal moderator)

UCN Rebuncher



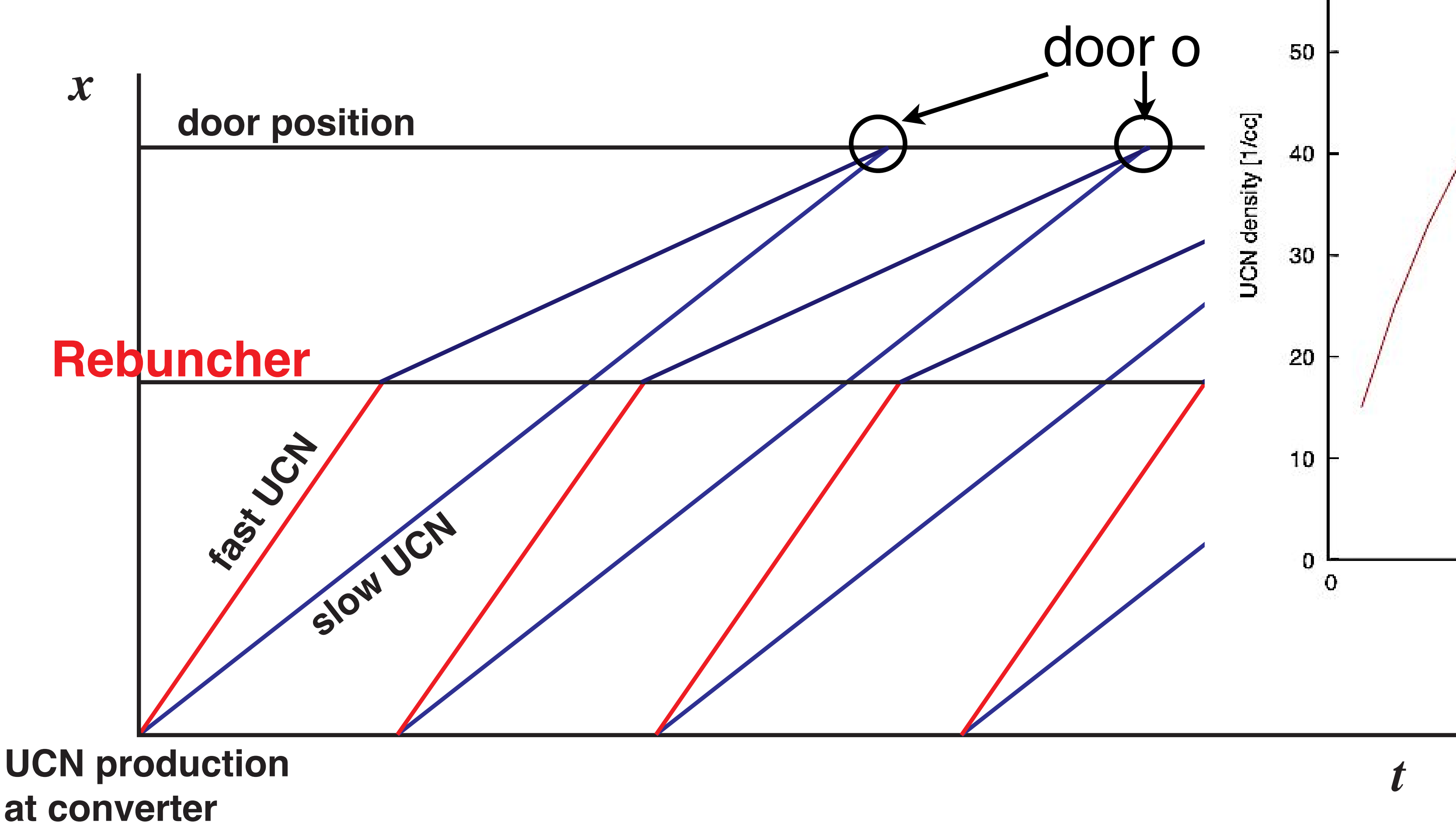


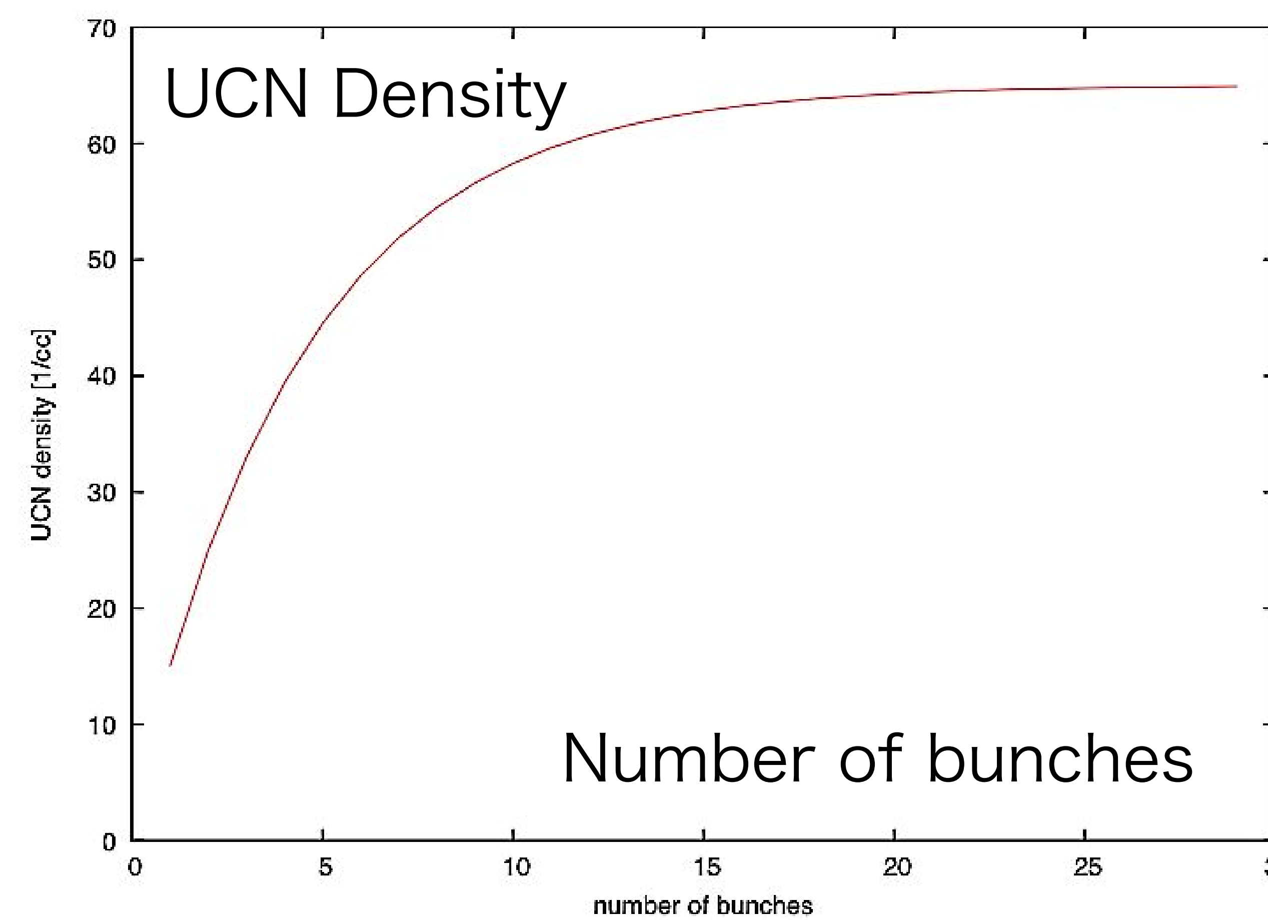
take in pulsed UCN while door is open

the door closes, UCNs broaden in the bottle

take in next pulsed U some UCNs overflow the others stay.

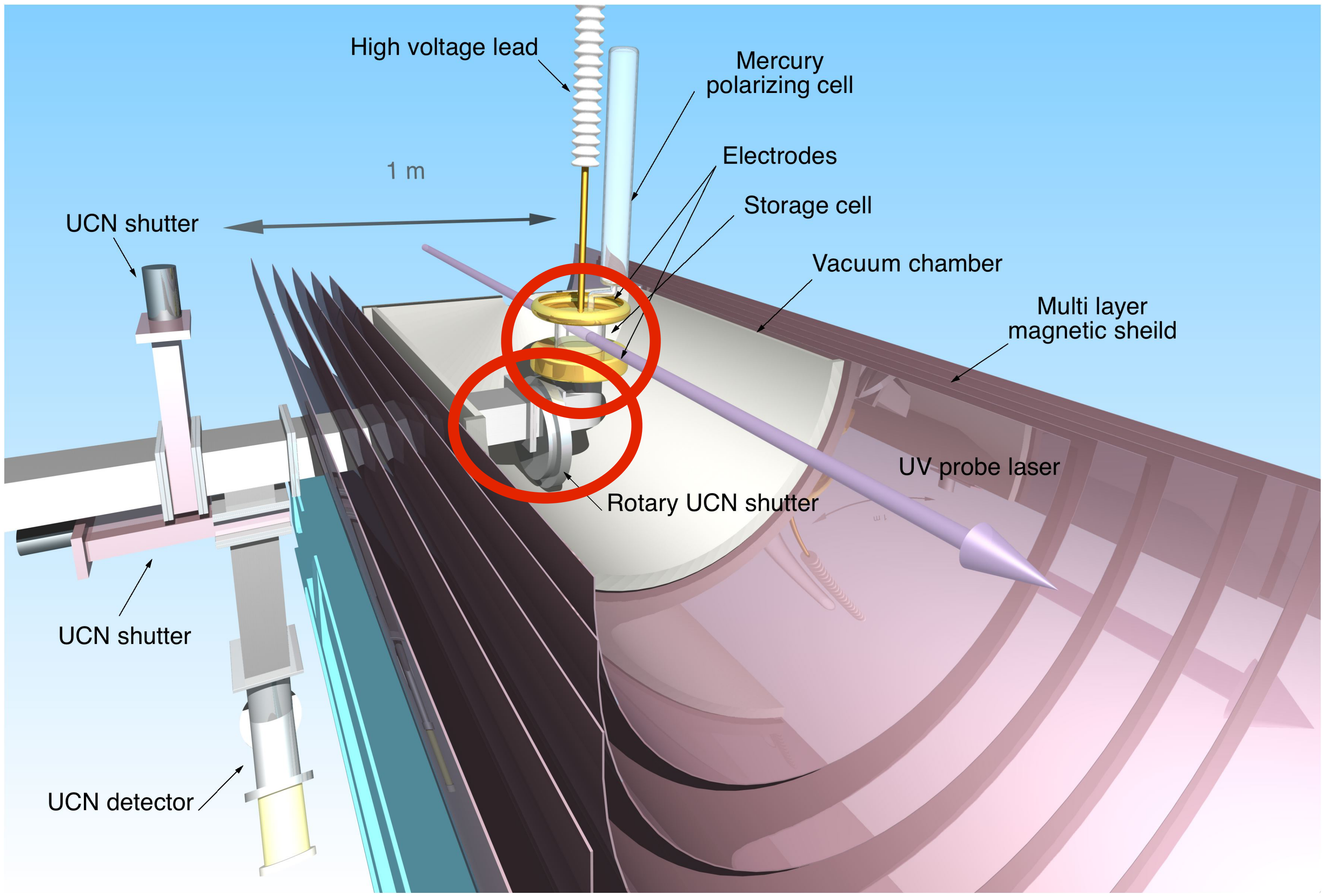
Density grows up with number of bunches until the overflow is equal to the injection.



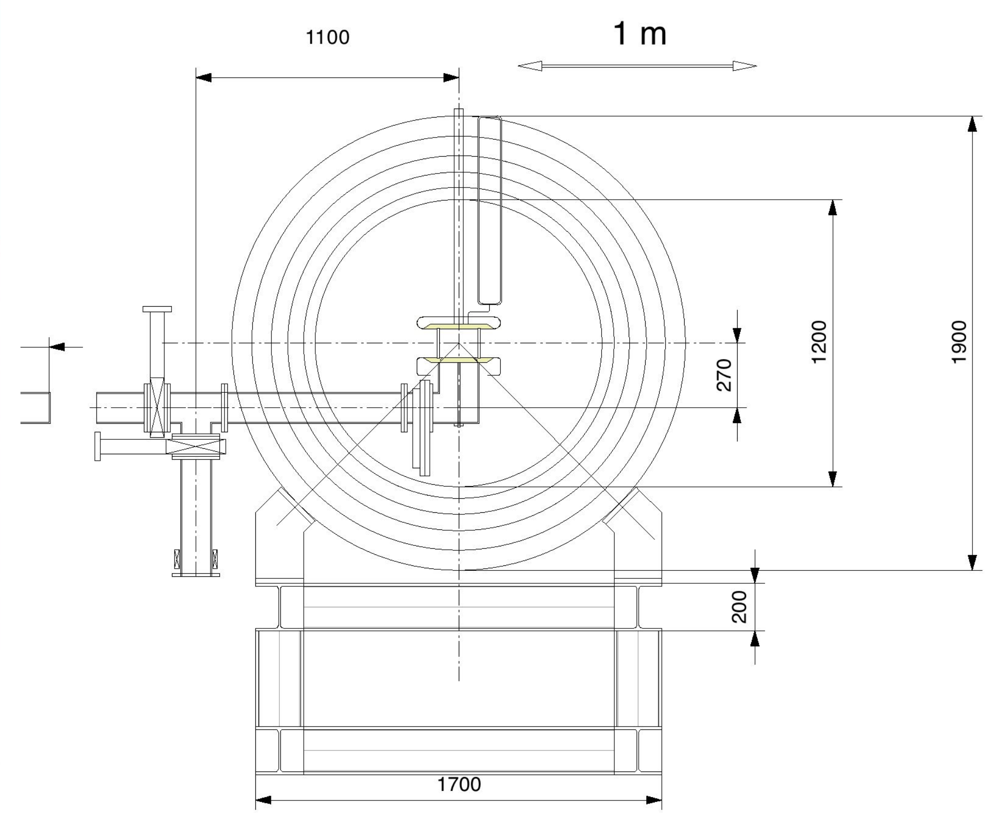


EDM cell

Fast door for injection rebunched pulse must be developed.



measurement system
is similar to ILL experiment.



星取表

- フレーバー物理の果たす役割は大きい。
- 多くのプロセスを測ることがことが重要

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

Table 8: "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.

Anatomy **and Phenomenology of FCNC and CPV Effects in SUSY Theories.**
W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi, D.M. Straub, . TUM-HEP-727-09, MPP-2009-133, Sep 2009. 87pp. Temporary entry
Published in **Nucl.Phys.B830:17-94,2010**.

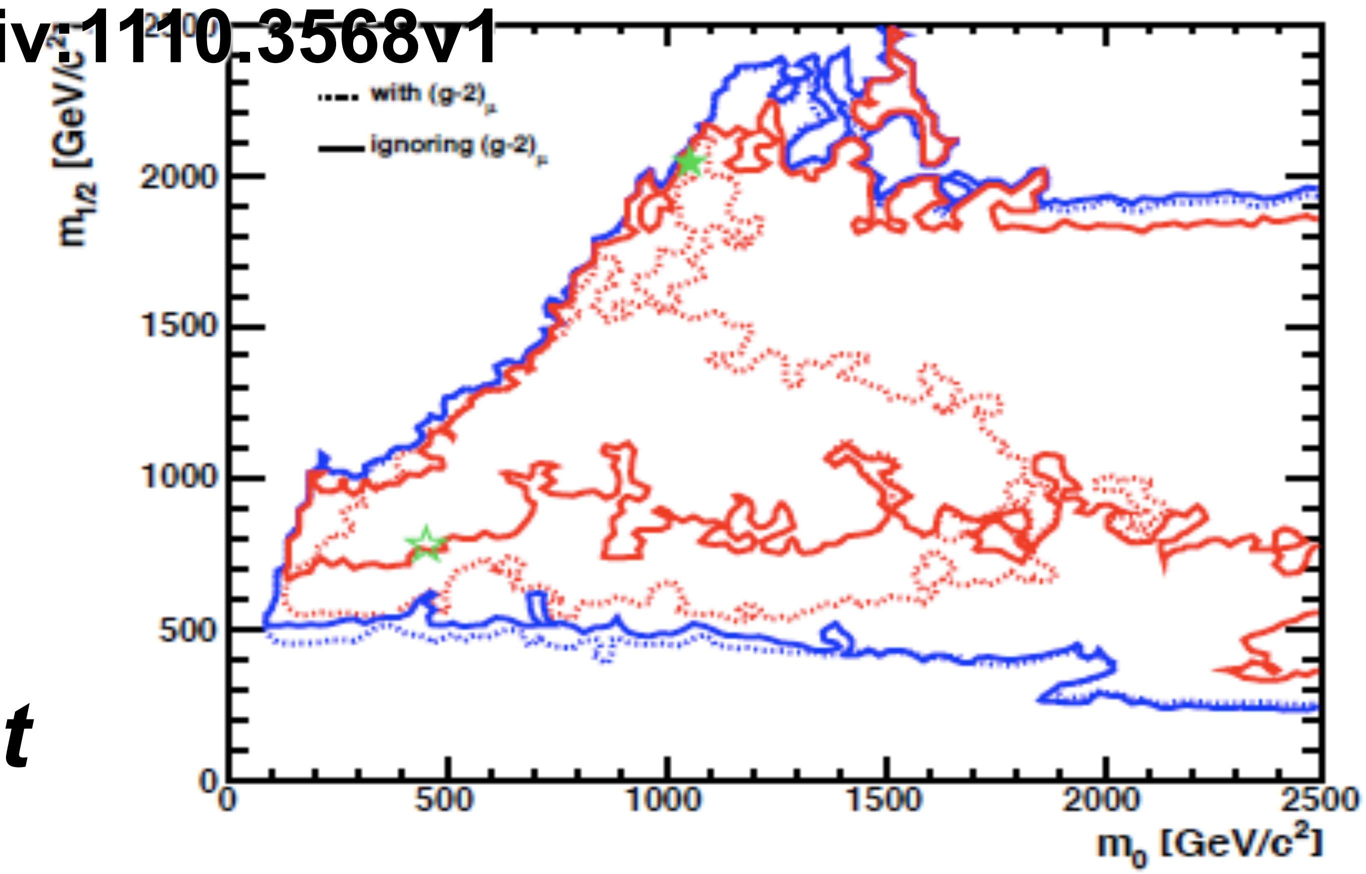
“g-2” tension with LHC 1/fb

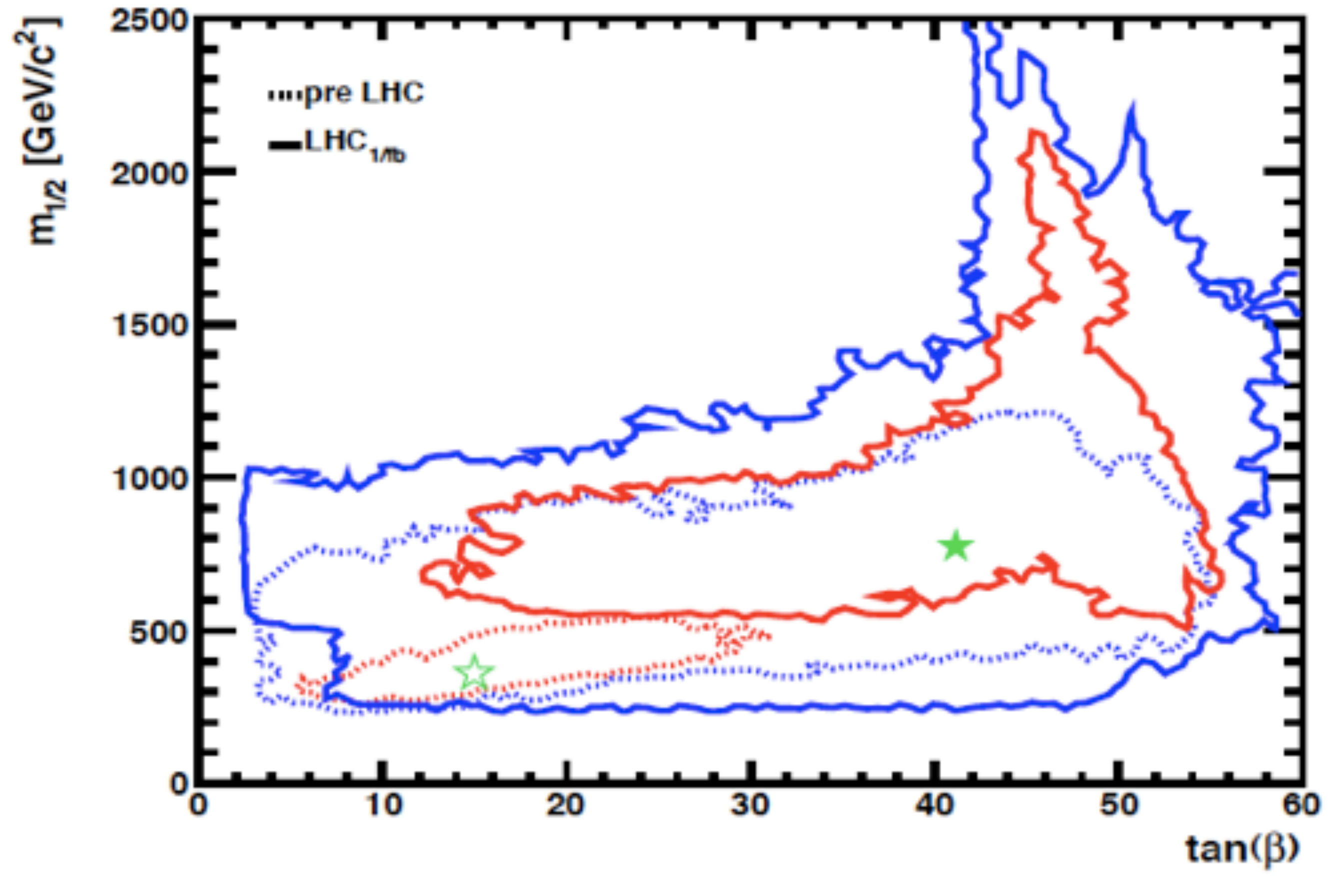
CMSSM

O. Buchmueller, et al, hep-ph> arXiv:1110.3568v1

- *(g—2)* $_{\mu}$ **pull down Gaugino-mass and push up the tan β to ~ 40**

- ***it will be important to subject the (g − 2)$_{\mu}$ constraint to closer scrutiny, and the upcoming Fermilab and J-PARC experiments on (g − 2)$_{\mu}$ are most welcome and timely in this regard.***



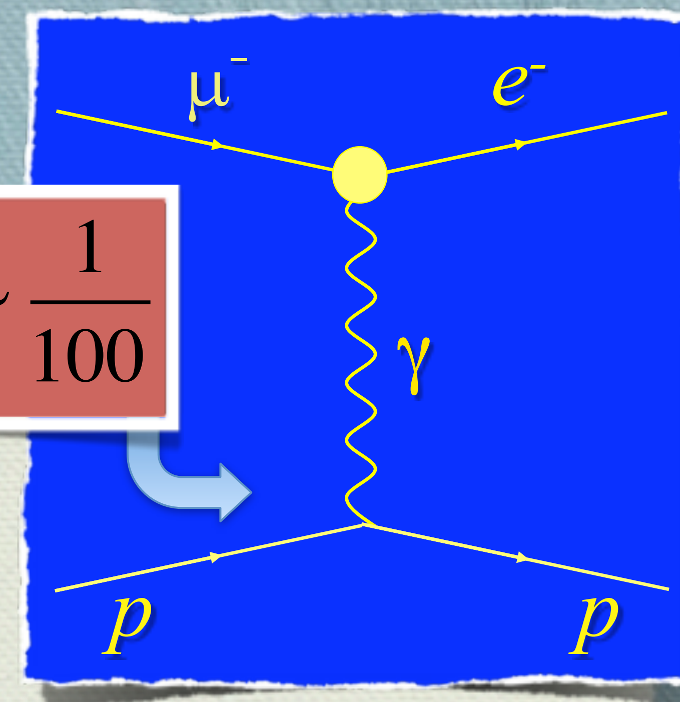


μ-e Conversion Experiments
COMET & DeeMe

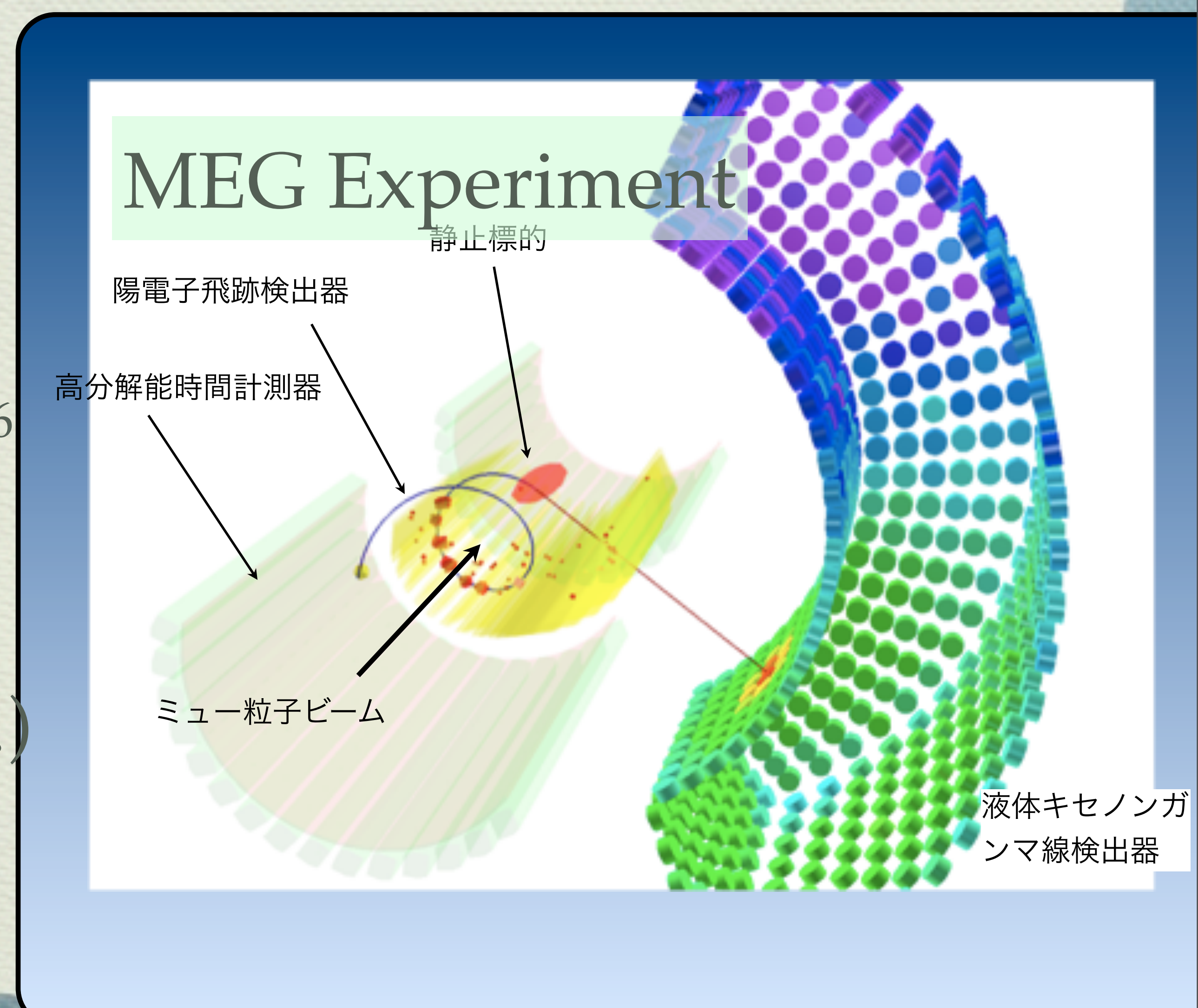
Search for μ-e Conversion

COherent Muon-to-Electron Transition

$$\frac{B(\mu N \rightarrow eN)}{B(\mu \rightarrow e\gamma)} \sim \frac{1}{100}$$

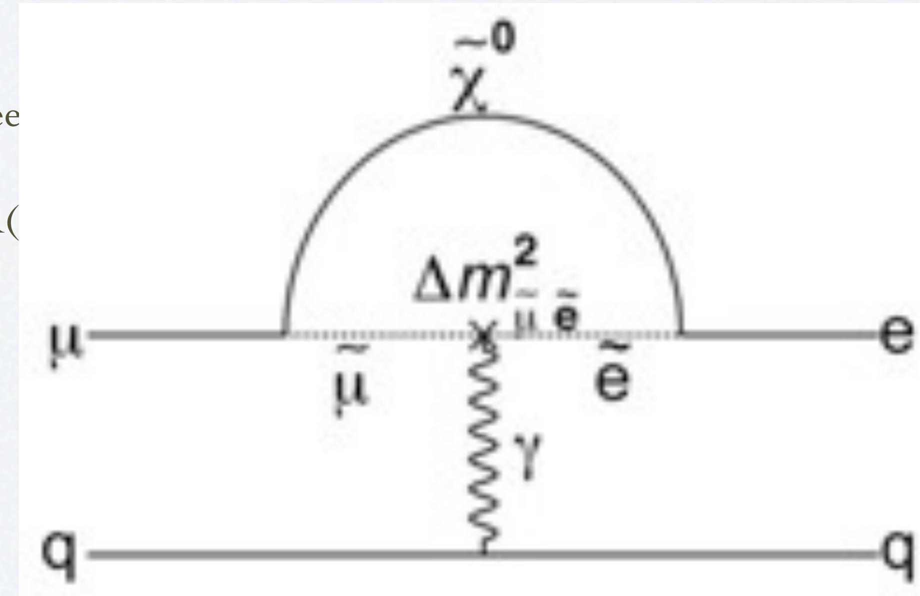


- Muon bound to atomic state converts into electron
- Forbidden in the SM
  - cf. Br~10^{-50} thru ν oscillation
  - Clear Evidence of New Physics
- Goal : Single Event Sensitivity : 10^{-16}
- MEG@PSI : Search for μ→eγ
  - 2009-2010 Br < 2.4×10^{-12} (90% C.L.)

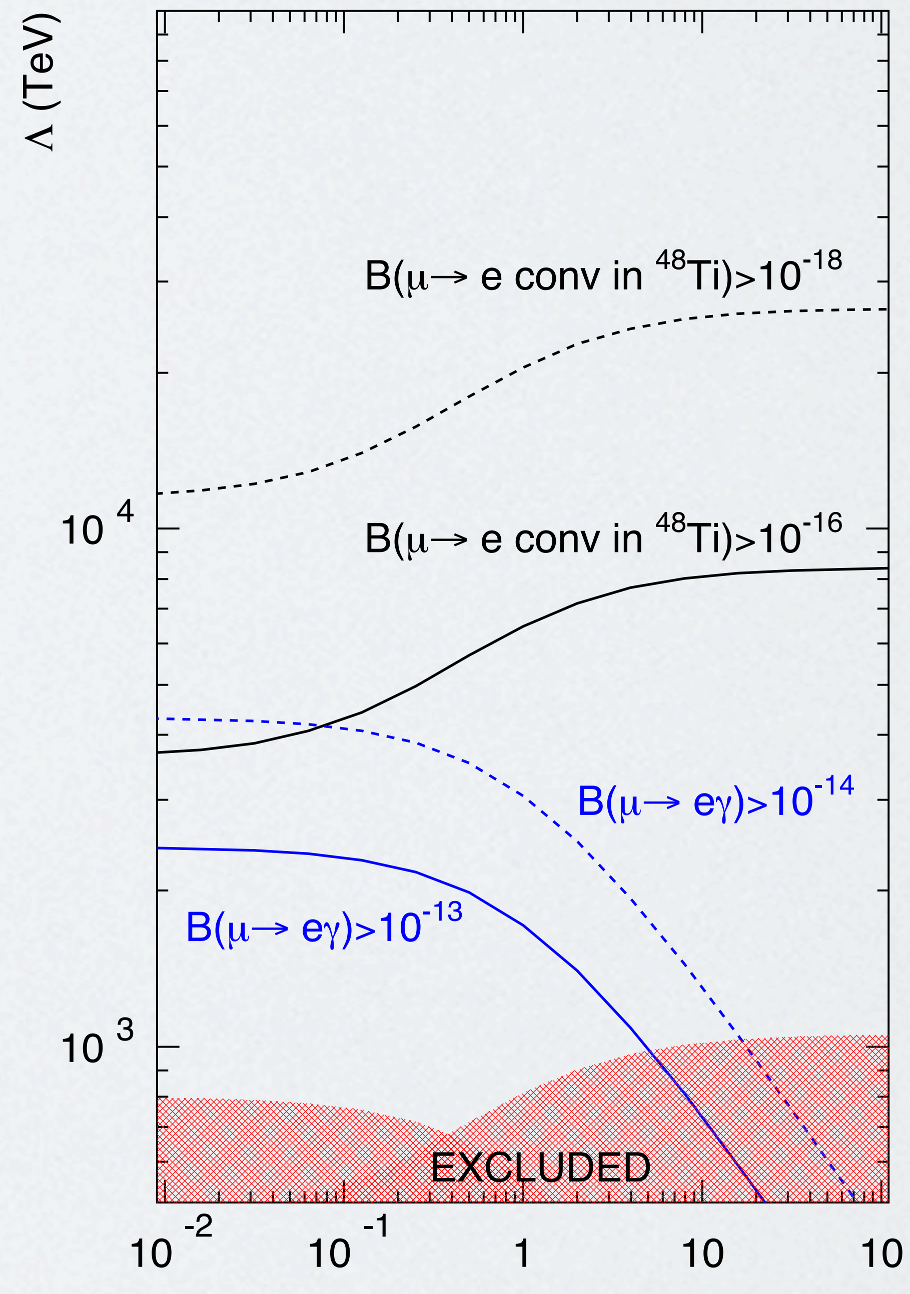


Theoretical Models

- SUSY-GUT, SUSY-see
  - BR = 10^{-14} = BR(
  - $\tau \rightarrow l\gamma$

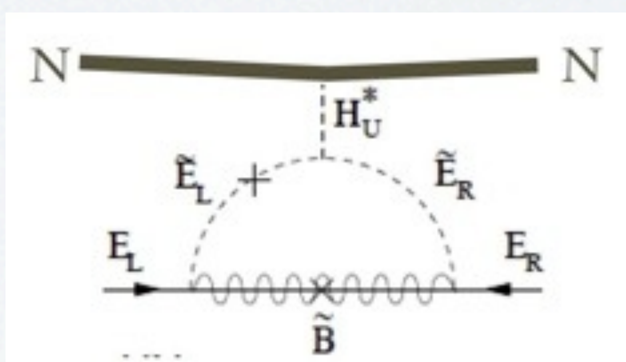


$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$



Andre de Gouvea, W. Molzon, Project-X WS (2008)

- SUSY-seesaw (Higgs Mediated process)
  - BR = 10^{-12}~10^{-15}
  - $\tau \rightarrow l\eta$

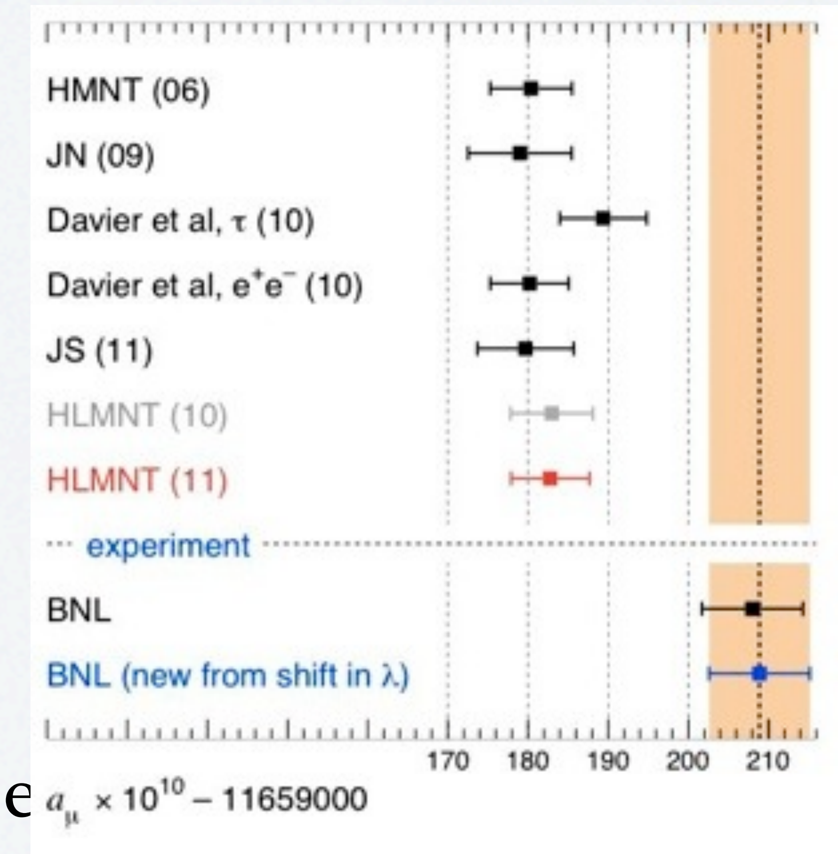


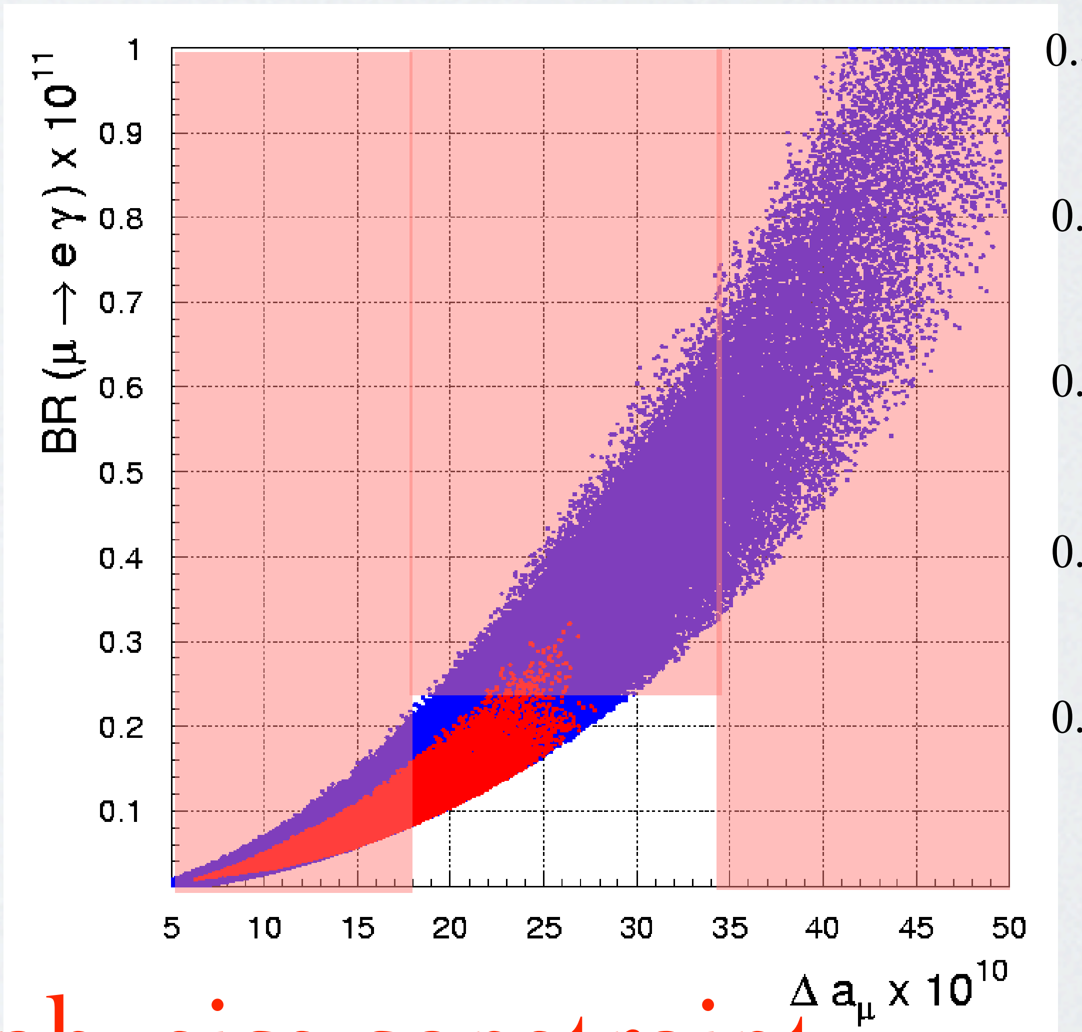
- Doubly Charged Higgs Boson (LRS *etc.*)
  - Logarithmic enhancement in a loop diagram for $\mu^- N \rightarrow e^- N$, not for $\mu \rightarrow e\gamma$
    - M. Raidal and A. Santamaria, PLB 421 (1998) 250
- and many others

mu-e & g-2

- muon g-2
  - Δa_μ: off by 3.3σ

G. Ishidori *et al.*, PRD *75* (2007) 115019





- μ → e
  - 2009-2010
    BR < 2.4×10^{-12} (90%C.L.)
  - more data in 2011

B physics constraint

Recent Upper Limits

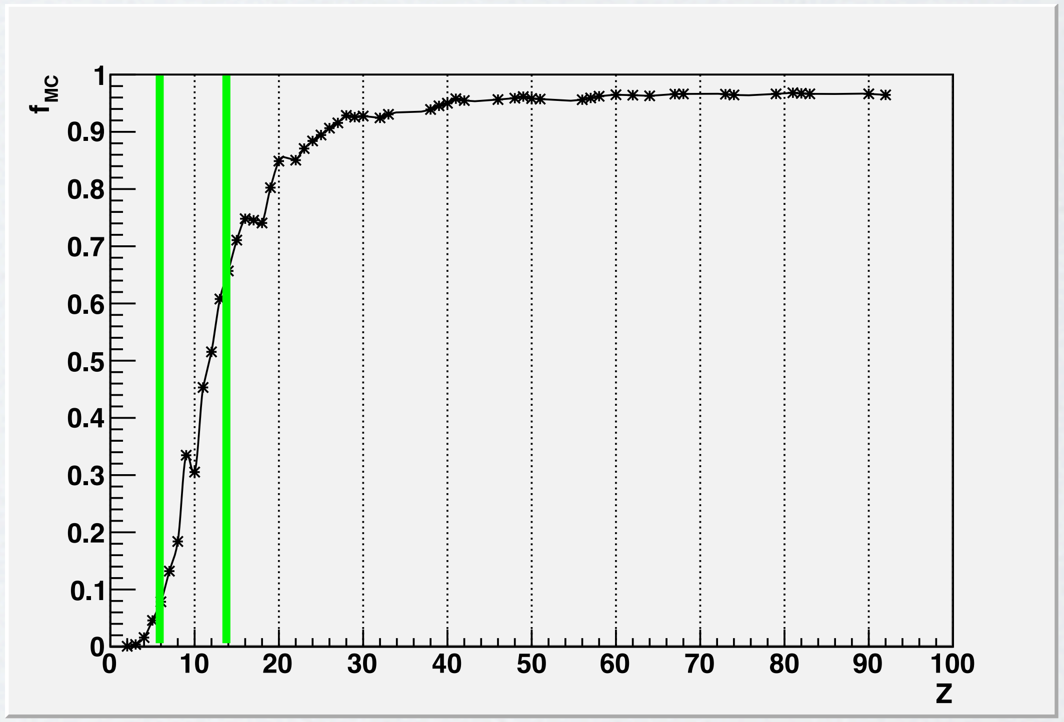
SINDRUM-II: BR[μ^- + Au → e^- + Au] < 7×10^{-13}

SINDRUM-II: BR[μ^- + Ti → e^- + Ti] < 4.3×10^{-12}

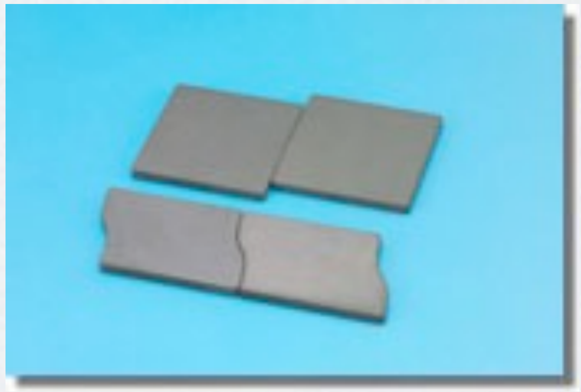
TRIUMF: BR[μ^- + Ti → e^- + Ti] < 4.6×10^{-12}

Target Material

- f_{MC}: muonic nuclear-capture rate
  - $(1-f_{MC})=f_{DIO}$ larger Z is preferred.
- τ_{μ^-} > 300 nsec (light Z) to avoid the prompt BG
- Target hit by primary protons



- Silicon-Carbide (SiC):
  - good thermal shock resistance: ΔT=450°C
  - high melting point: >1450°C
  - good radiation resistance
    - 10 dpa @ 1000°C or more
- f_C: Fraction of the atomic capture of muon to the atom of interest: proportional to Z (Fermi-Teller Z law)
  - Single-element material: f_c = 1
  - Silicon-Carbide --- Si:C = 7:3



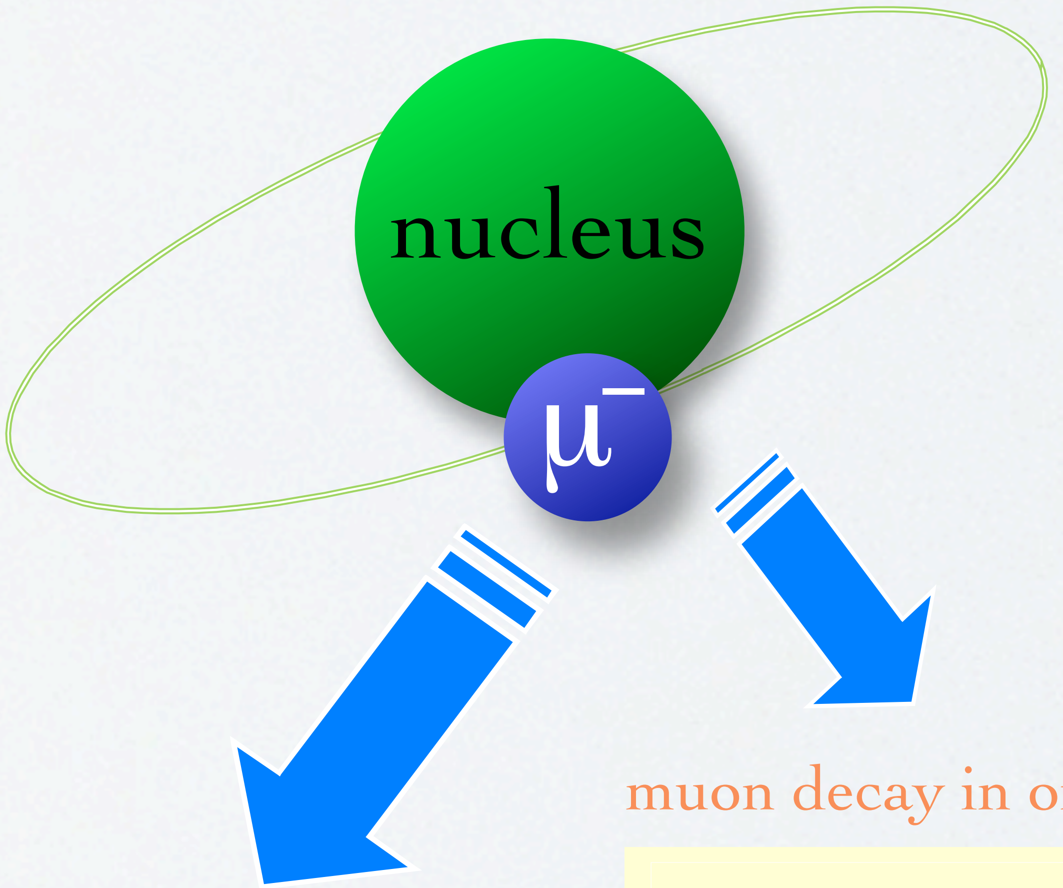
Silicon Carbide
- CERASIC

target material	$f_C \times f_{MC}$
Graphite	0.08
Silica-carbide (SiC)	0.46

SiC Muon Target: 6 times higher physics sensitivity than Graphite.

What is mu-e Conversion ?

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

lepton flavours changes by one unit

- $E_{\mu e} \sim m_\mu - B_\mu$
  - B_μ: binding energy of the 1s muonic atom

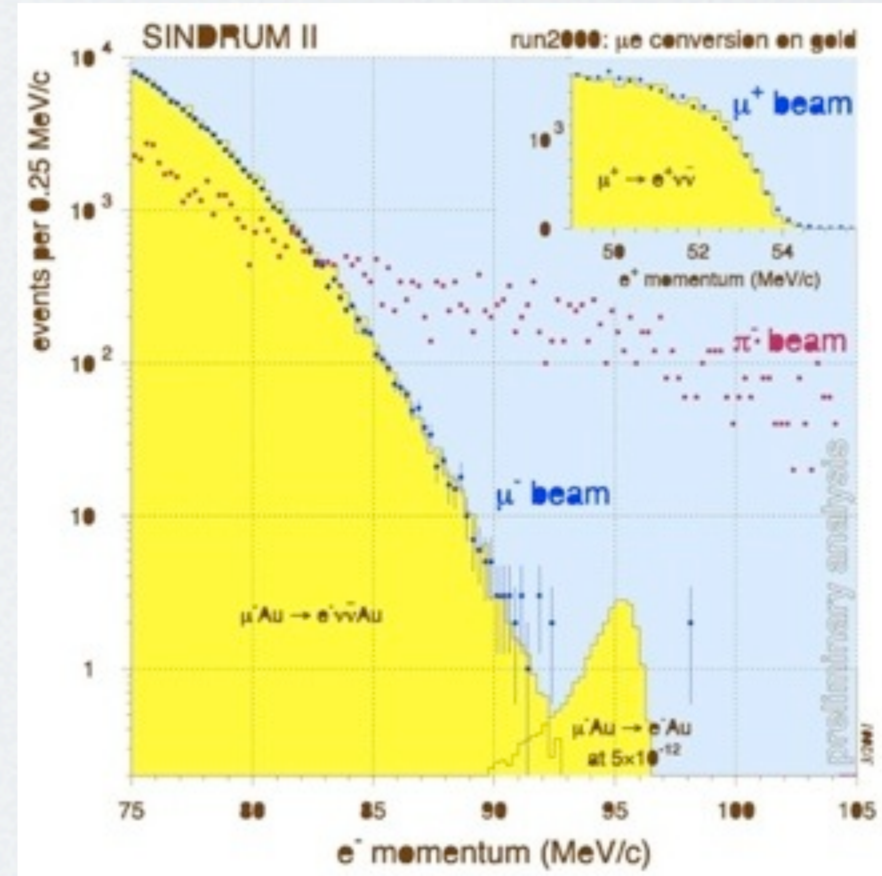
$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Principle of Measurement

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - $E_{\mu e} \sim m_\mu - B_\mu$:105 MeV
    - Delayed : ~1μS

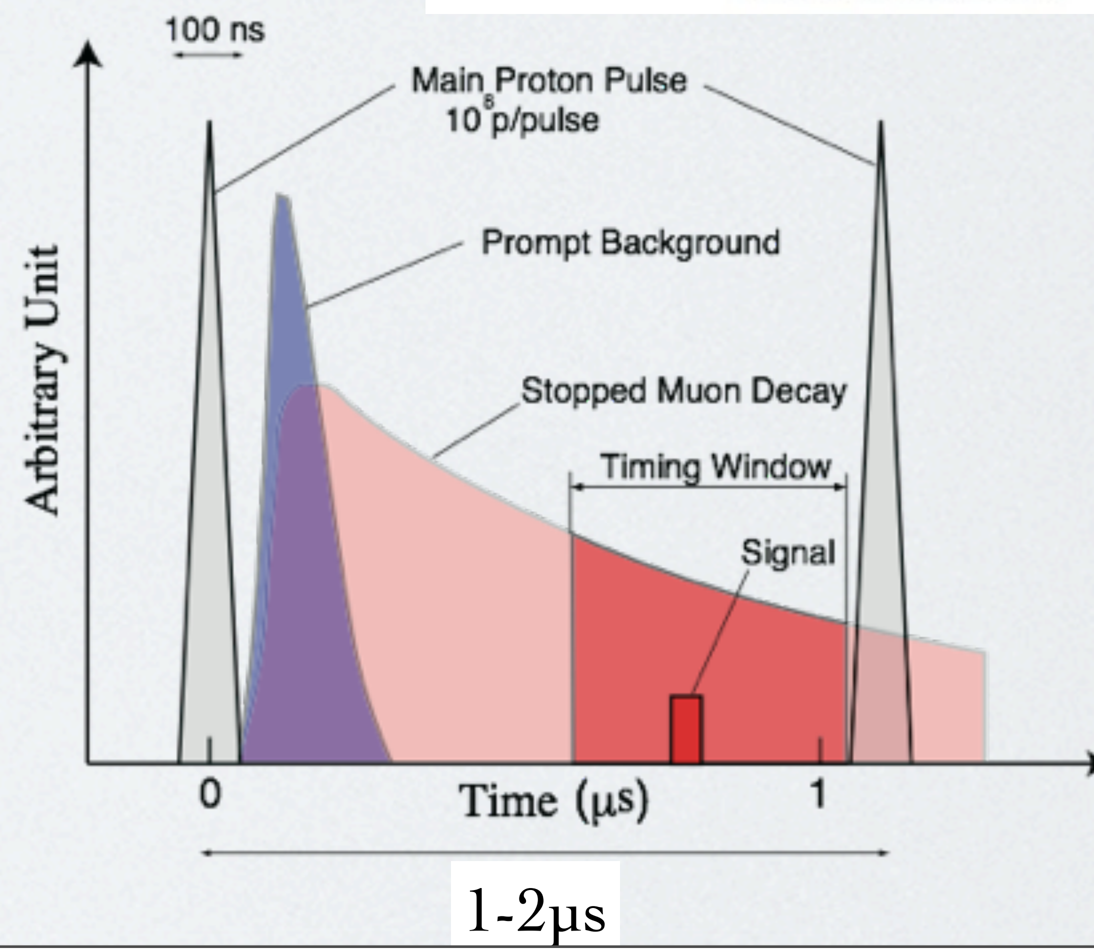
SINDRUM II

BR[$\mu^- + Au \rightarrow e^- + Au$] $< 7 \times 10^{-13}$



- No accidental backgrounds
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$

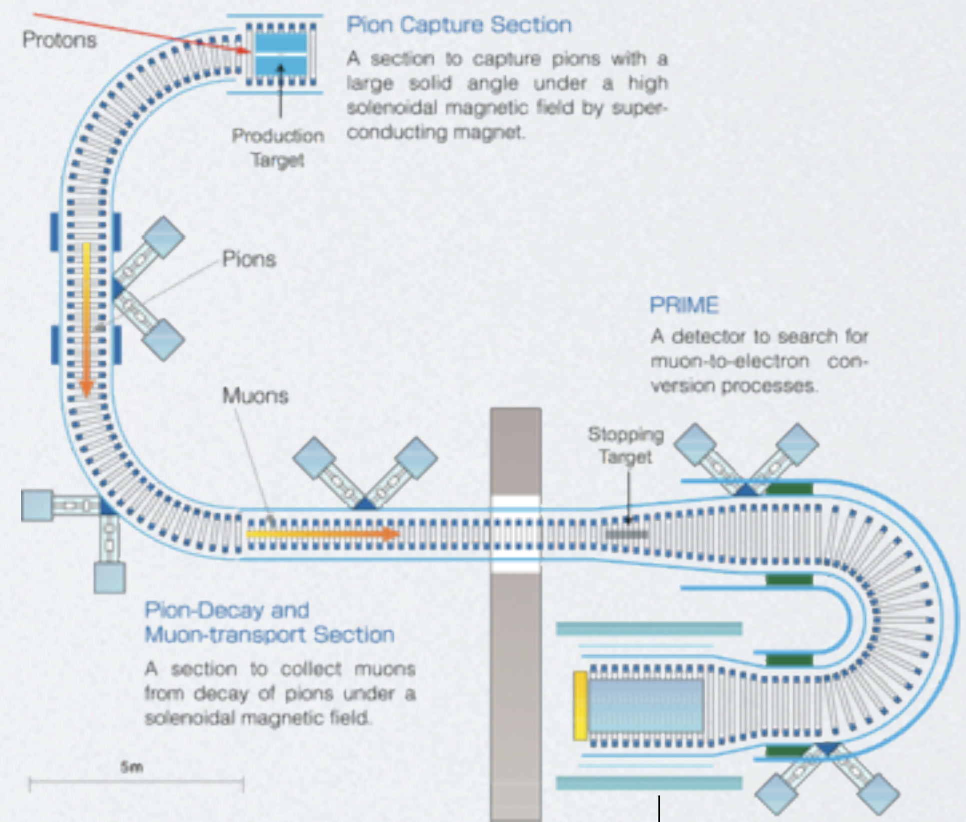
      $\gamma \rightarrow e^+ e^-$

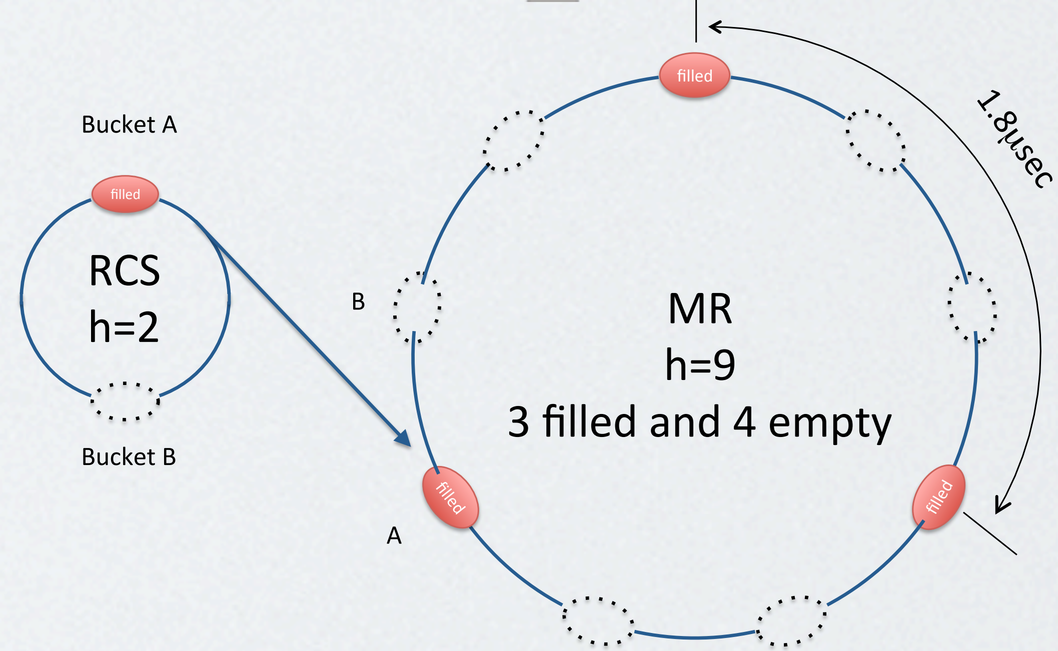


$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

COMET Experiment at J-PARC

- Target S.E.S. 2.6×10^{-17}
- Pulsed proton beam at J-PARC
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- pion production target in a solenoid magnet
- Muon transport & electron momentum analysis using C-shape solenoids
  - smaller detector hit rate
  - need compensating vertical field
- Tracker and calorimeter to measure electrons
- Recently staging plan showed up. The collaboration is making an effort to start physics DAQ as early as possible under this.

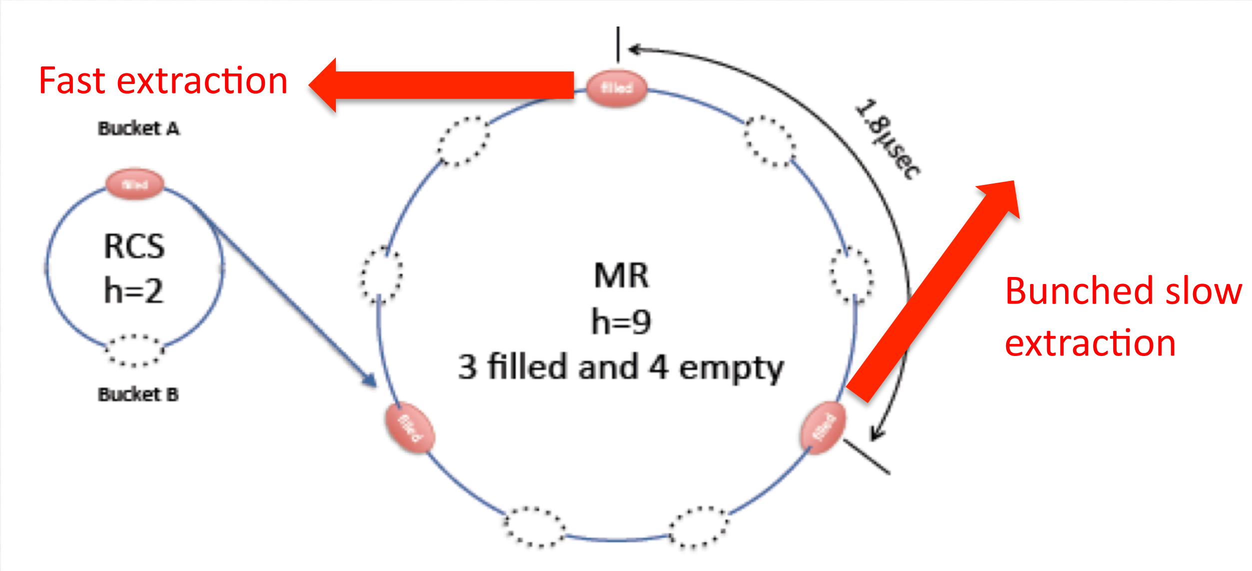


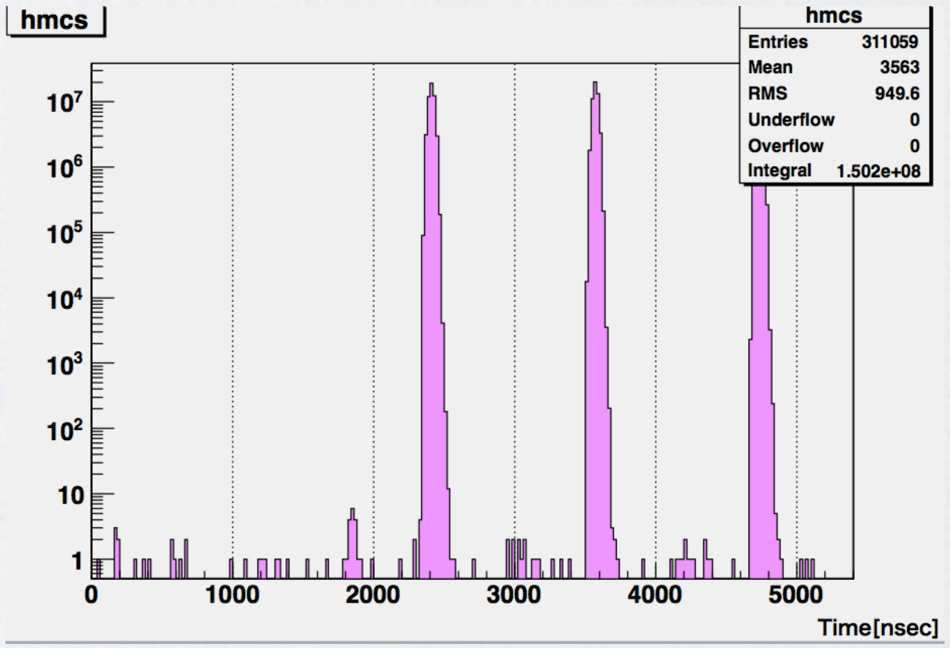


COMET R&D Status

proton beam

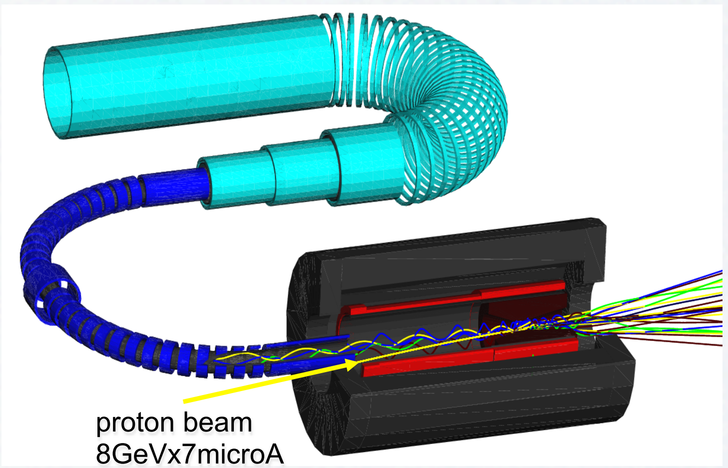
- Proton beam study (Extinction ratio Measurement)
- Measurement at MR abort line (Fast Extraction) and Secondary beam line (Slow Extraction)
  - Both provided consistent result
  - Extinction: $(5.4 \pm 0.6)\times10^{-7}$
- Further improvement expected ($O(10^{-6})$) by double injection kicking
- External extinction device improves even more ($O(10^{-3})$)
  - US-Japan cooperative research program

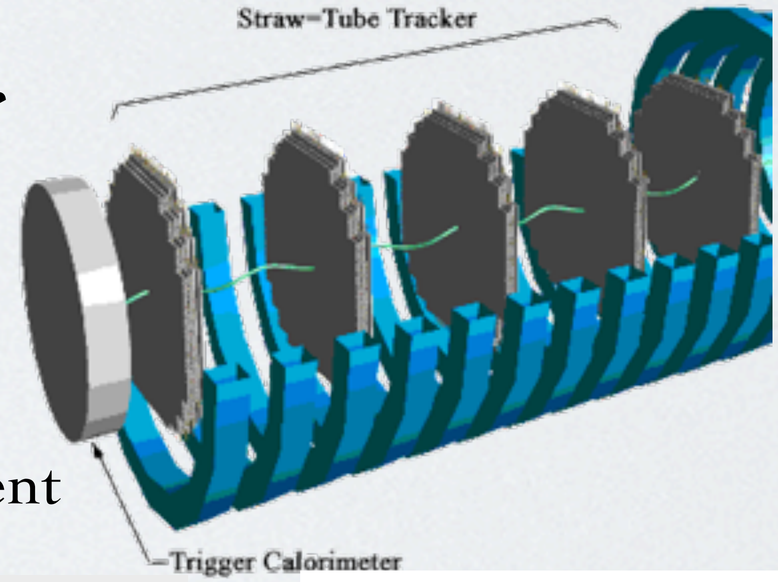




R&D Status

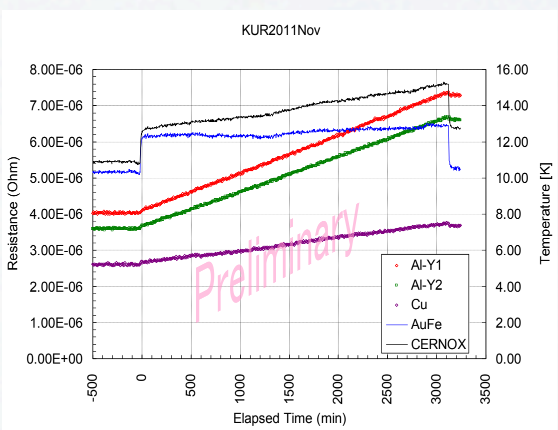
SC Magnet & Detector

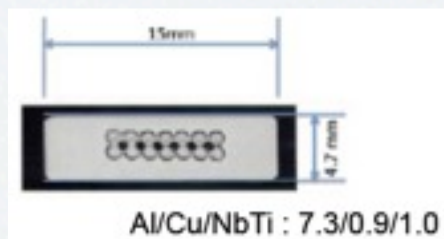


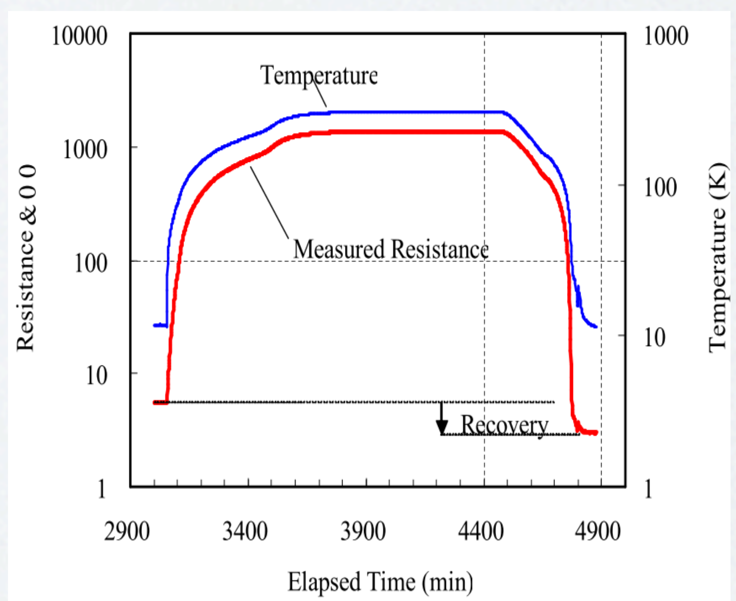


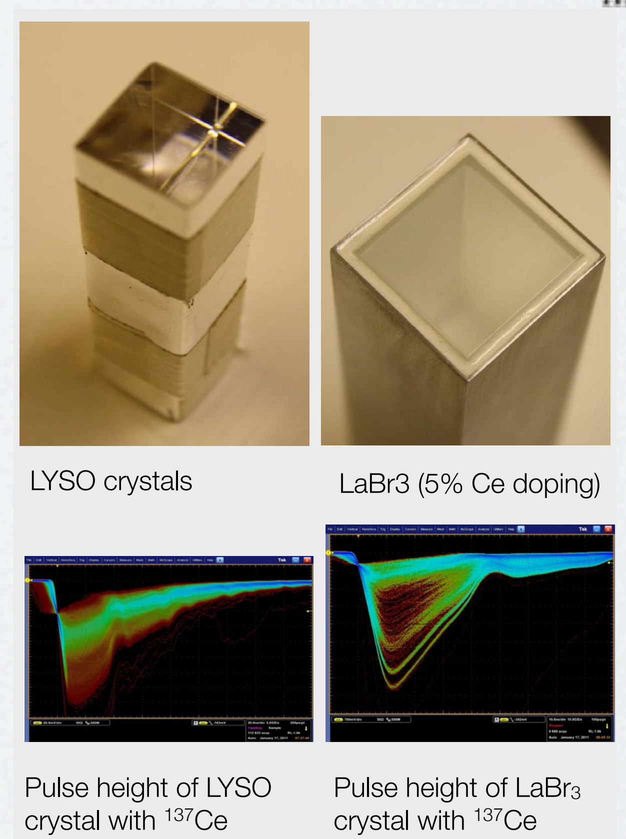
Al stabilized conductor

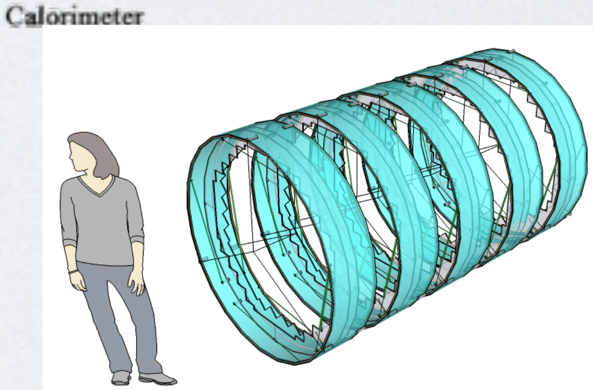
Crystal development











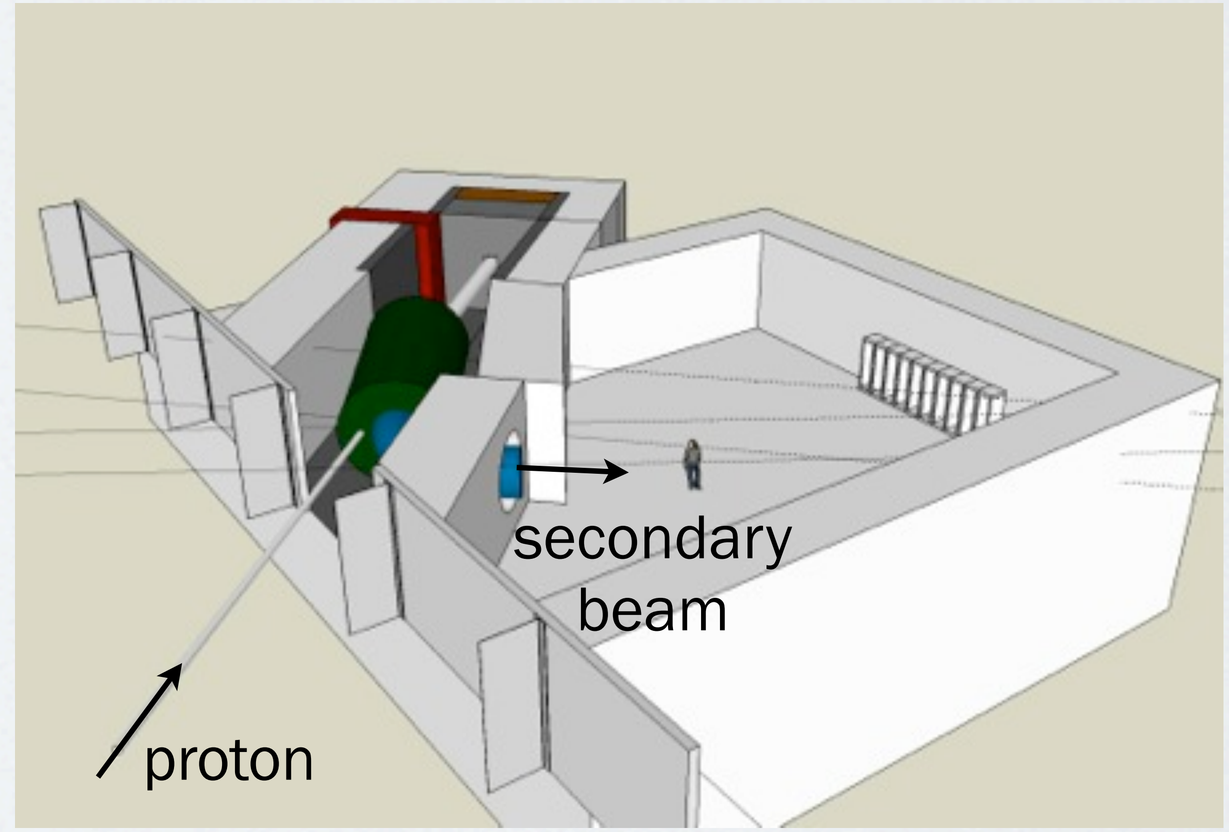
Neutron irradiation at a research reactor

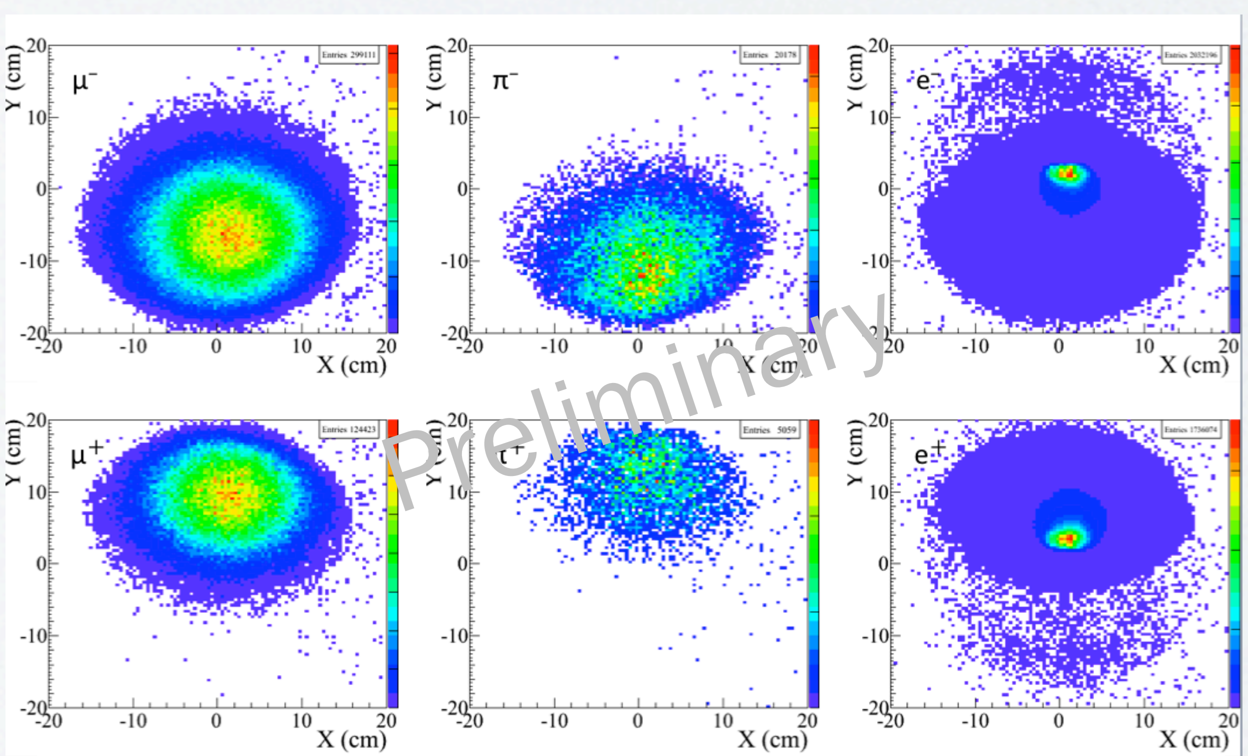
Straw-tube tracker

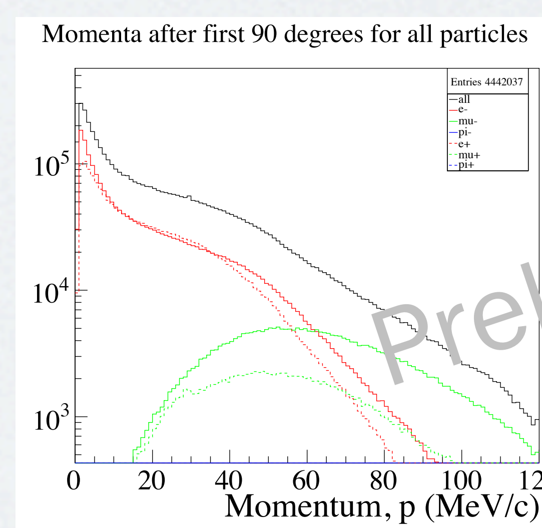
COMET Staging Plan

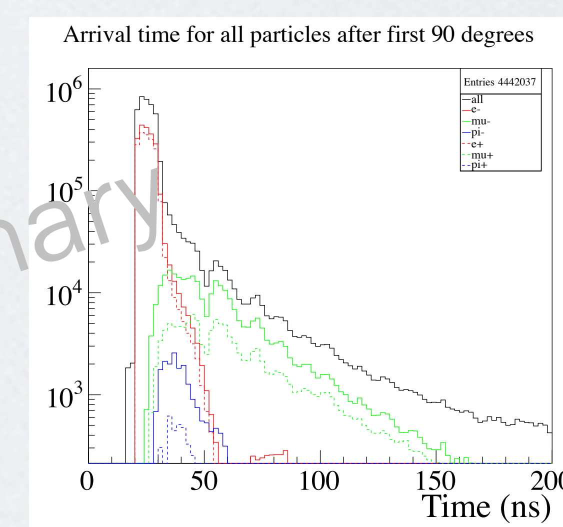
Beam Profiles

- Beam profiles after 90 degree bend
- Enough muon yield
  - less BG suppression
- Lower proton current operation 1-5 kW





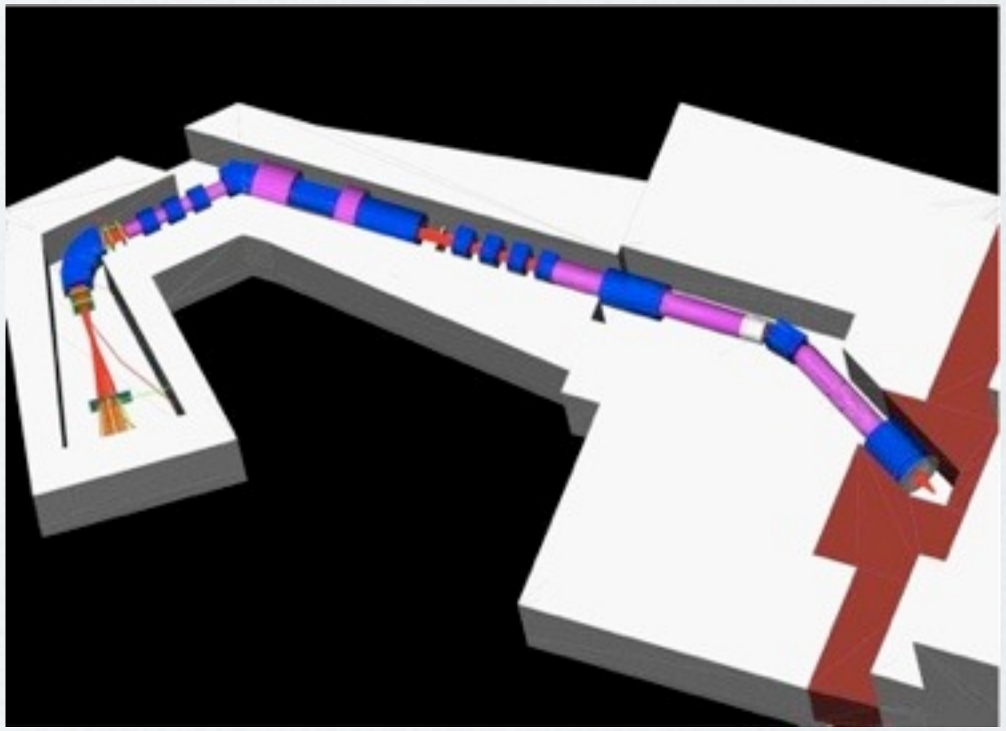


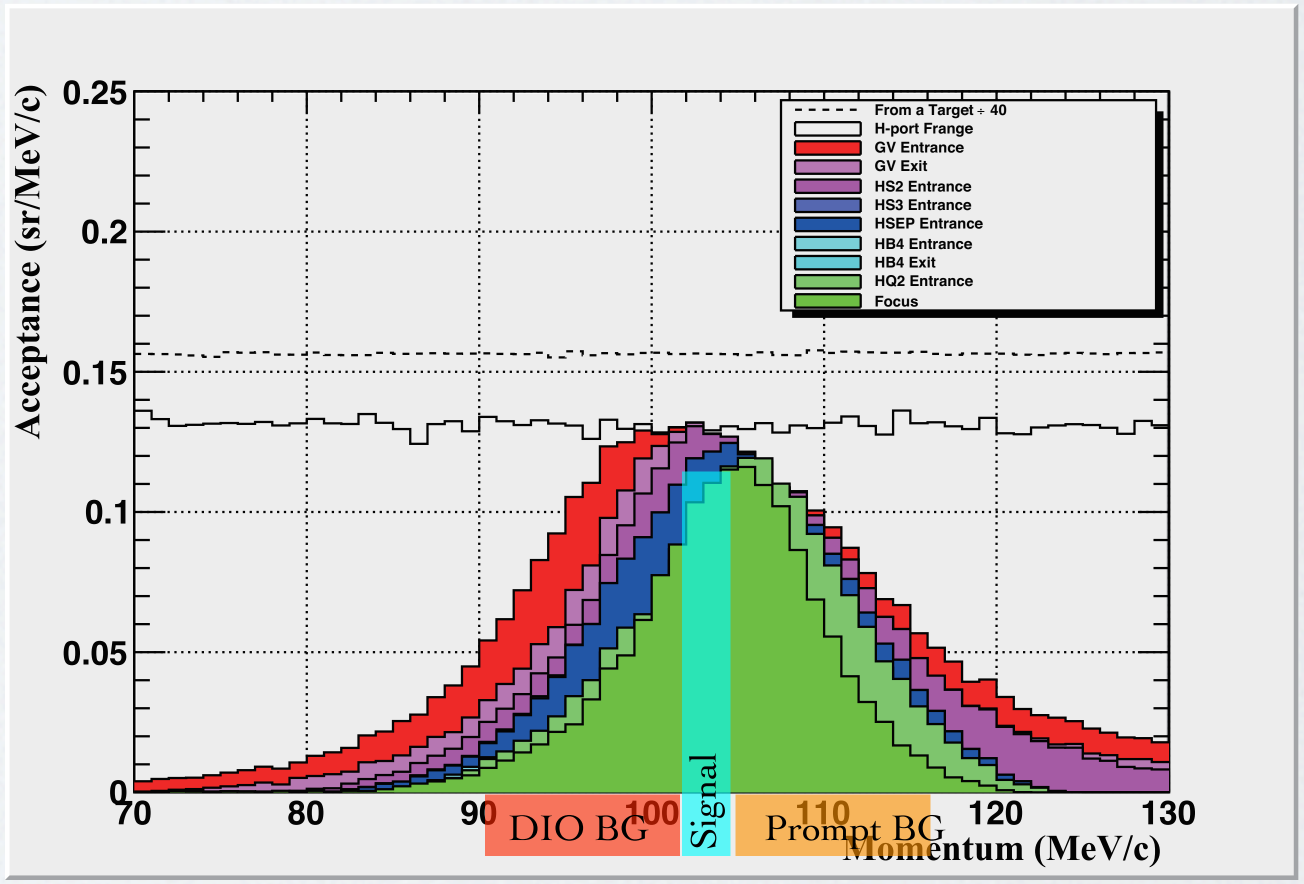



Hadron Hall
COMET Hall

DeeMe at J-PARC

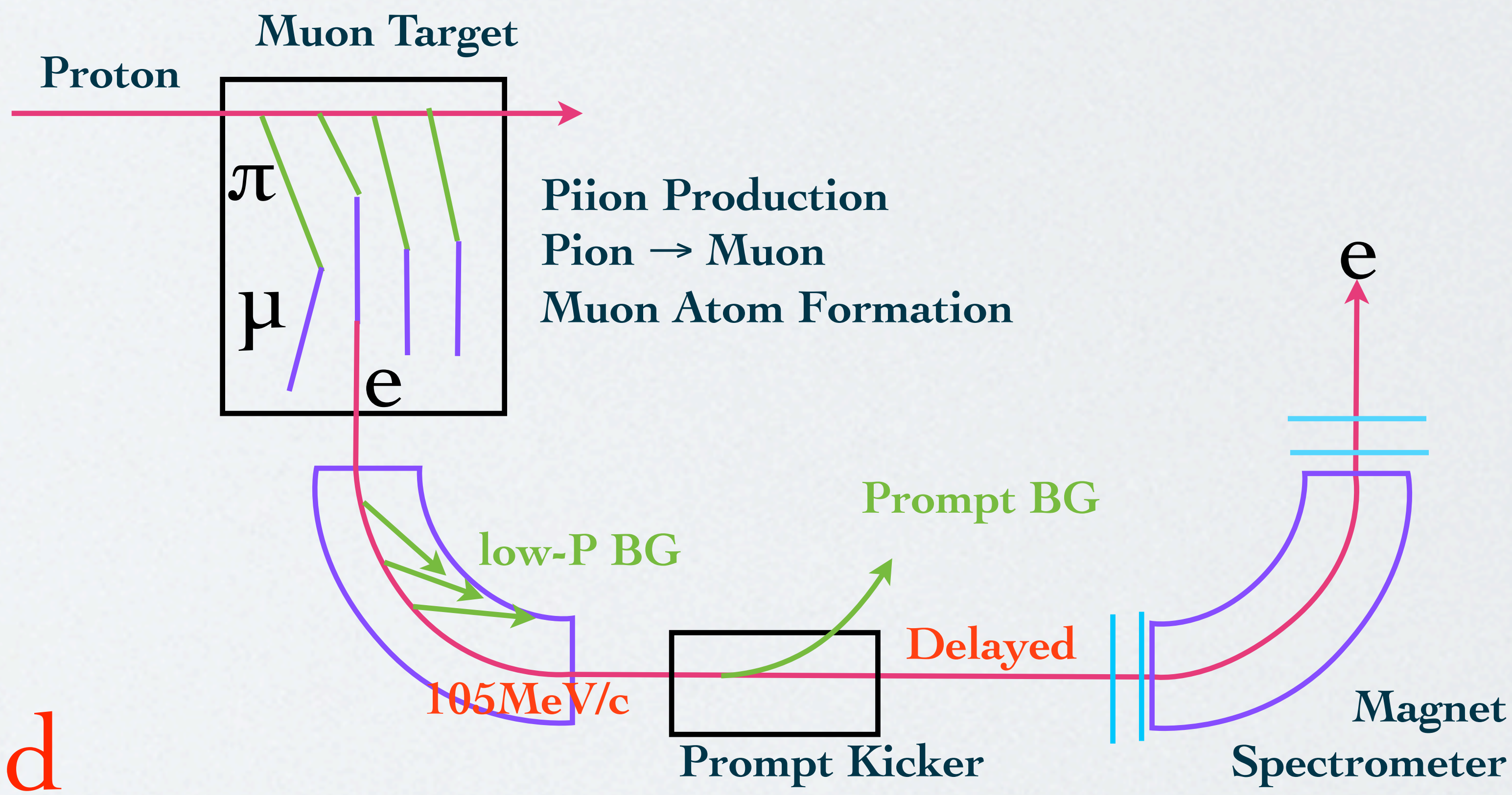
- mu-e conversion search at J-PARC with a S.E.S. of 10^{-14}
- Primary proton beam from RCS
  - 3GeV, 1MW
- Pion production target as a muon stopping target
- Beam line as a spectrometer
  - Kicker magnets to remove prompt background
- Multi-purpose beam line for DeeMe, HFS, g-2/EDM is under construction





DeeMe Experiment

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed：~1μS



- **<u>No accidental backgrounds</u>**

- Physics backgrounds

Delayed

- Muon Decay in Orbit (DIO)
  - $E_e > 102.5$ MeV (BR:10^{-14})
  - $E_e > 103.5$ MeV (BR:10^{-16})

- Low Energy main part:
  suppressed by the beamline.
- High Energy tail:
  Magnet Spectrometer ($\Delta p < 0.3\%$)

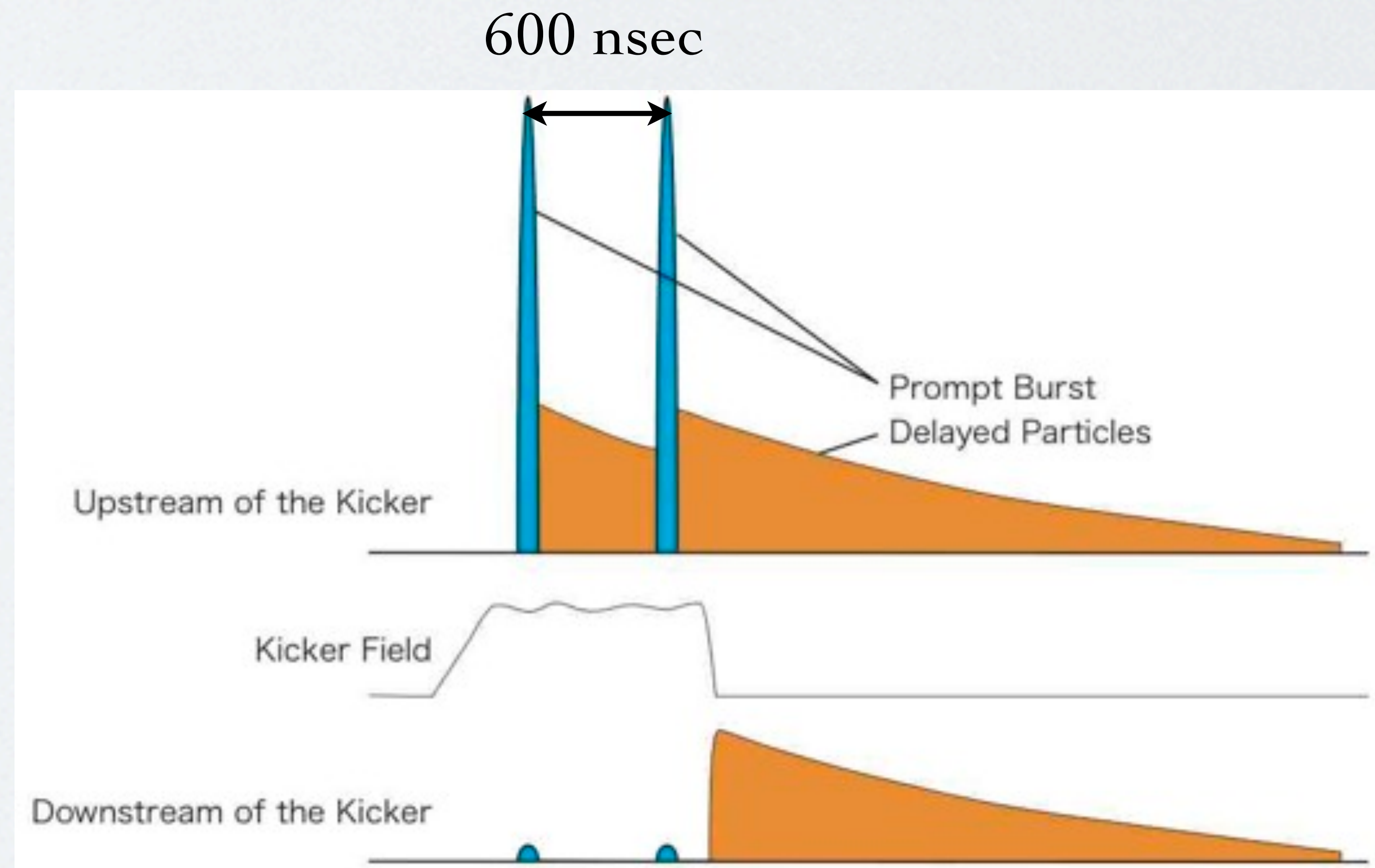
Prompt

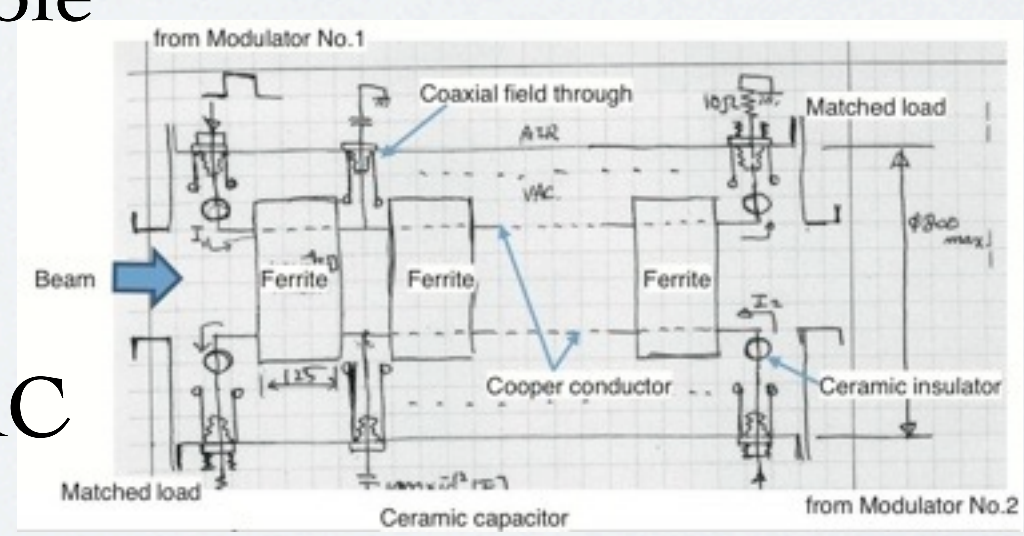
- Beam Pion Capture
  - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
    $\gamma \rightarrow e^+ e^-$

- Main pulse:
  Kicker to reduce the detector rate.
- after-protons:
  Suppressed owing to the extremely small after-protons from J-PARC/RCS: $R_{AP} < 10^{-17}$.

Secondary Beam line Kicker

- Prompt burst: coincide with the primary proton
  - 50M particles/pulse (based on the meas. in 2009)
- Reduce the prompt burst by kicker <1/10^3 down to the acceptable range
  - 33k/pulse
  - Design by J-PARC experts

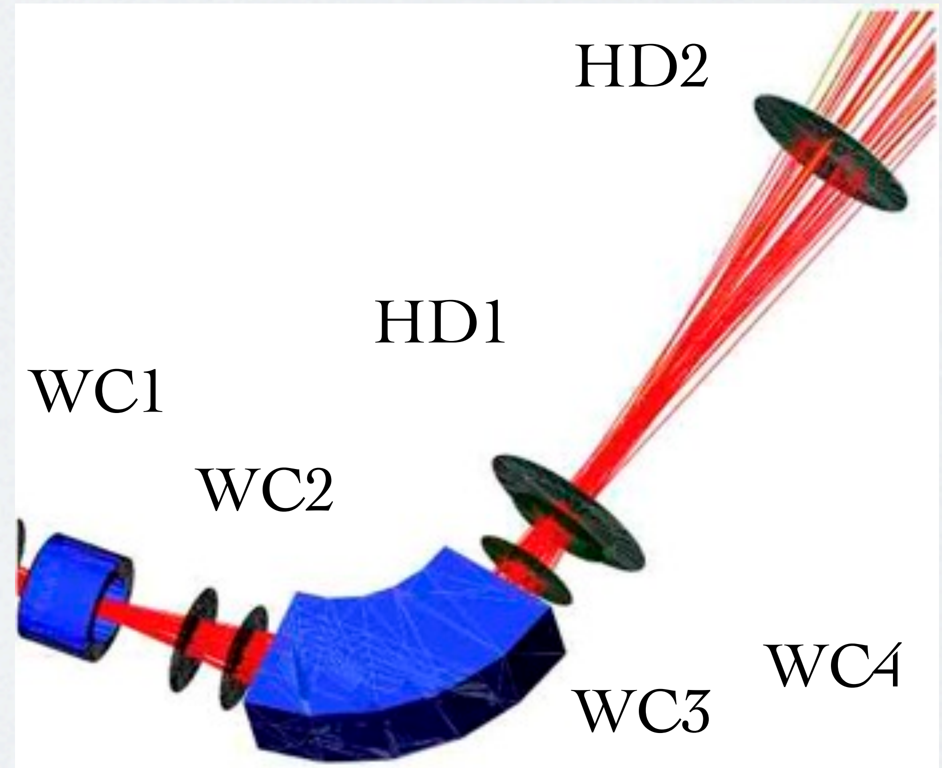




H. Matsumoto & H. Kobayashi

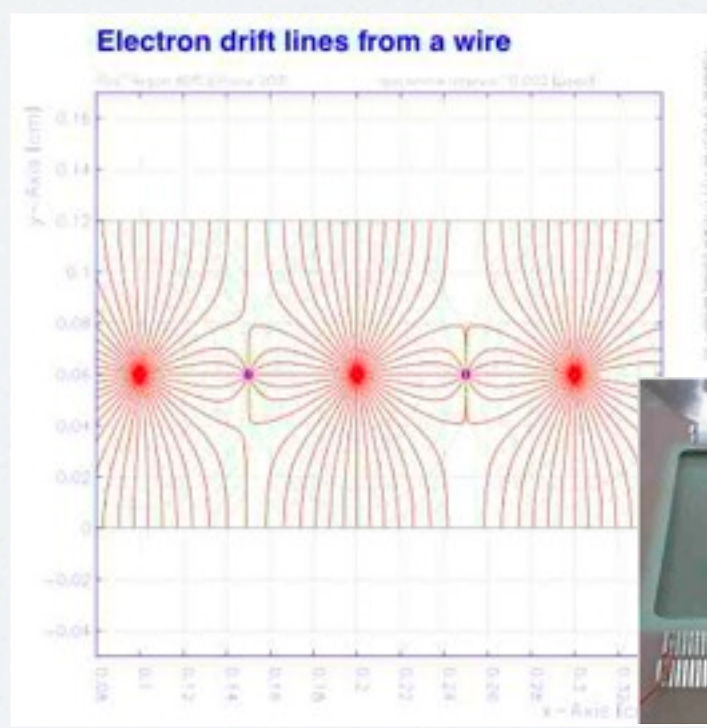
DeeMe Detector

- Momentum analysis using a dipole magnet spectrometer
- Prompt burst=33k/pulse
- BH1,2: hodoscope
  - Gating PMT, realized in COMET R&D
- WC1-4: wire chamber with micro cell
  - R&D in progress
- σ< 0.5 MeV/c

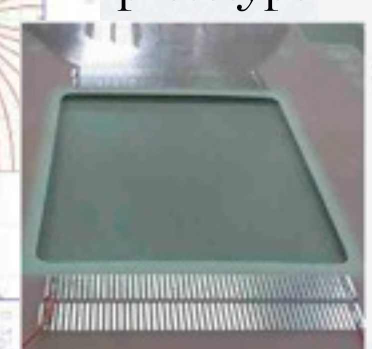


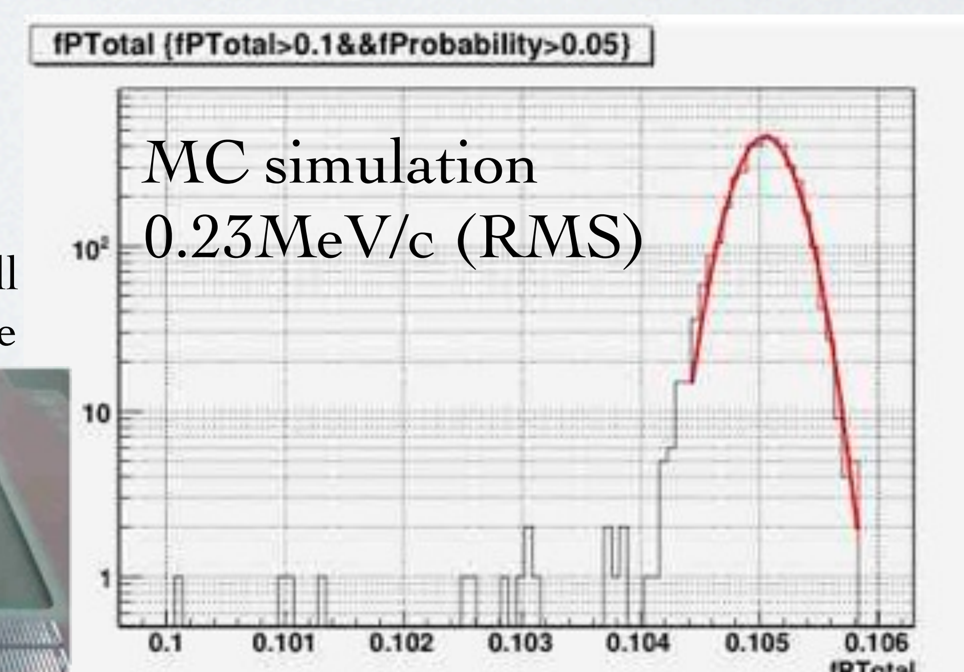
DeeMe実験のGEANT シミュレーション

Gating PMT base circuit



micro-cell prototype





DeeMe Status

- KEK/IMSS Muon PAC: Stage-1 approved.
- J-PARC PAC: Under Examination.
  - Scientific merit is recognized.
  - Encouraged for further R&D and H-line construction.

- A muon group in J-PARC/IMSS already started the procurement of magnets in the tunnel of H-line.

- Preliminary measurement of the after-protons were performed with very promising result. An improved measurement is in progress in February, 2012.