ミューオン素粒子物理実験

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はじめに

- 物理の意義から様々な実験計画（金と時間も）、技術的な課題、進捗状況等

- 国内だけでなく国際的な状況も

目次

- g-2/EDM
  - g-2/EDM at J-PARC
  - g-2 at FNAL
  - EDM at PSI
- LFV
  - ($\mu \rightarrow e\gamma$)
  - $\mu - e$ conversion
    - Mu2e
    - COMET
    - DeeMe
  - $\mu \rightarrow eee$
  - $\mu^- e^- \rightarrow e^- e^-$
- Muonium HFS
- MuSIC

MUON G-2/EDM

Muon g-2/EDM at J-PARC

- $\Delta a_\mu^{(today)} = a_\mu^{(Exp)} - a_\mu^{(SM)} = (295 \pm 88) \times 10^{-11}$
  - E821 at BNL-AGS 0.7 ppm
  - 3.4 sigma deviation from the SM
  - 3.1 GeV/c pion 入射
- 当初はBNLのリングを移設事を検討
  - 海上輸送
  - 移設費試算 $2.5M

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

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

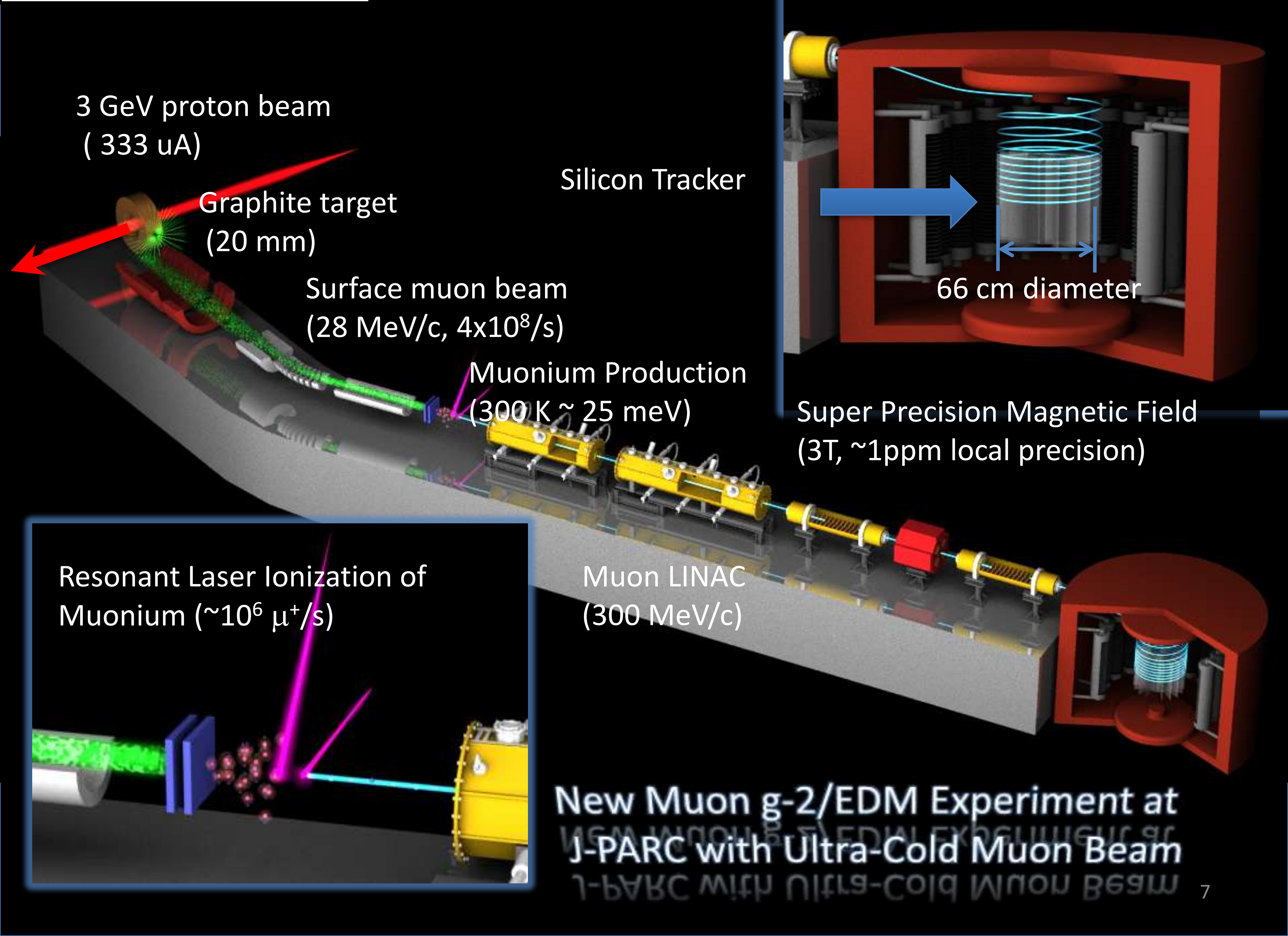
→

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

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

Muon g-2/EDM at J-PARC

- マジックモーメンタムをやめられないか？
- 電場なしで実験出来ないか？


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Silicon Tracker
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV)
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10⁶ μ⁺/s)
Muon LINAC
(300 MeV/c)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

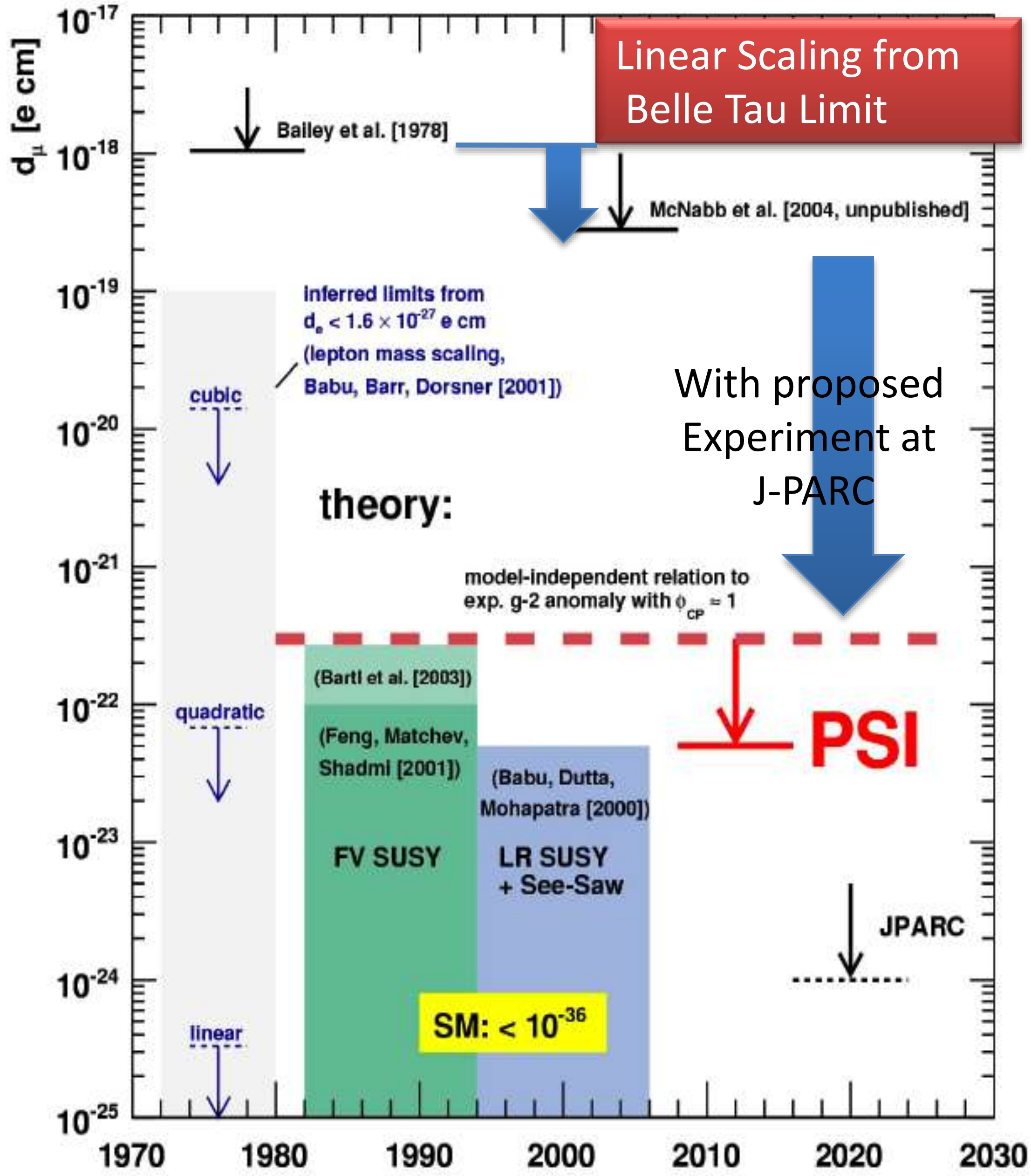
BNL, FNAL, and J-PARC

- 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

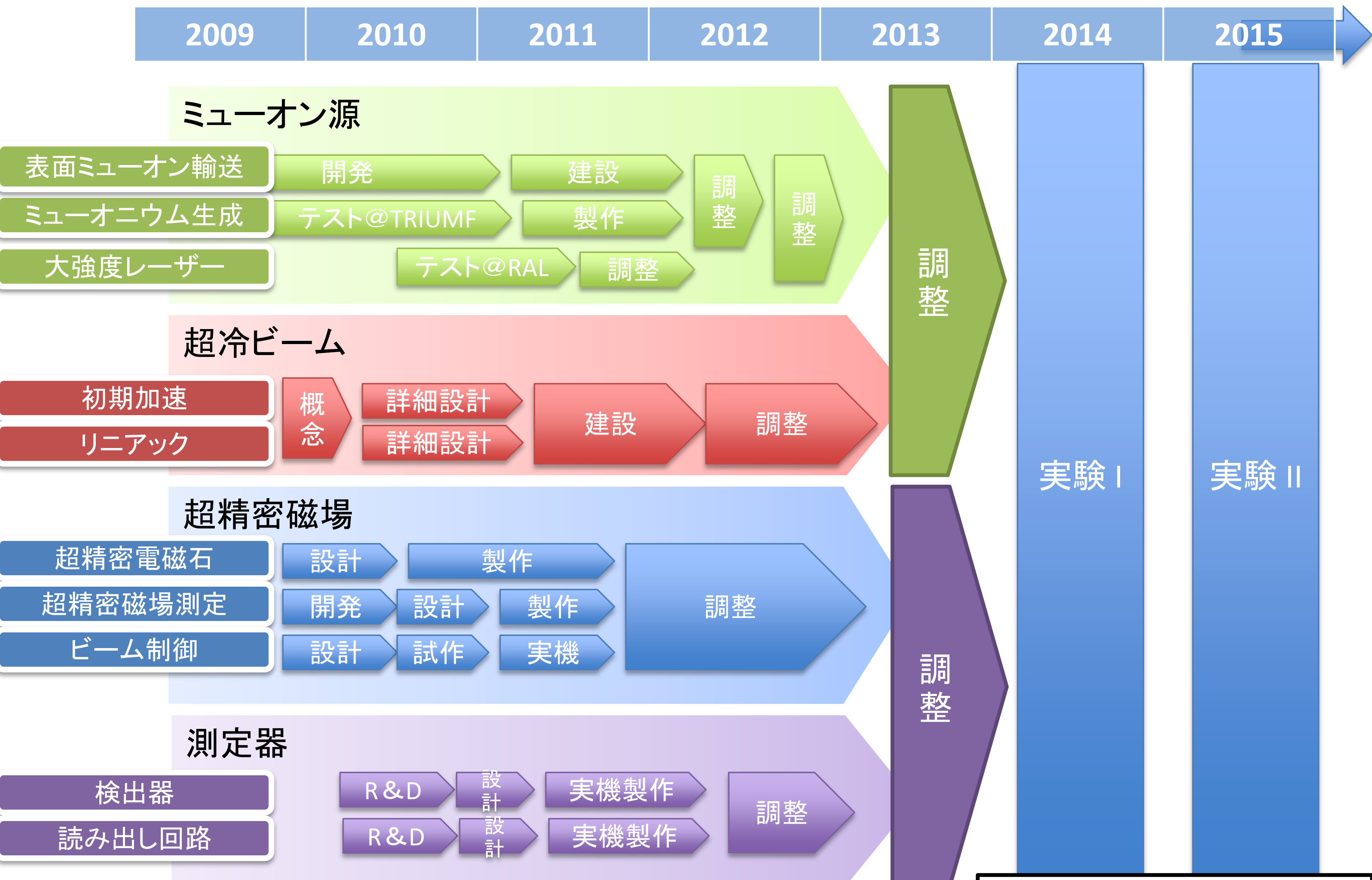
Muon EDM

- Direct CPV in Lepton Sector
  - CPV Required beyond KM
- Current Exp. Limit ~ 1e-19
- Potential Sensitivity of J-PARC Exp.
  - < 1e-21 @ MLF



Courtesy PSI EDM collaboration

ミューオン g-2/EDM実験計画　v1.1 (2010.04.30)



機構シンポジウム KEK　2010.5.11 齊藤、三部

Cost Estimate

- Very preliminary…

TABLE XV: Preliminary estimate of the cost of this experiment.

Item	Cost (Oku-yen)
Surface Muon Transport	Facility
Ultra-Cold Muon Source	
High-power Laser System	3.0
Initial Acceleration System	0.5
Muon LINAC	15
Ultra-precision Magnet	
Solenoid	10
Field Monitor	1
Detector System	
Silicon Tracker	1.5
Readout Electronics	0.5
TOTAL	32 + Facility

Fermilab a_μ Experiment:

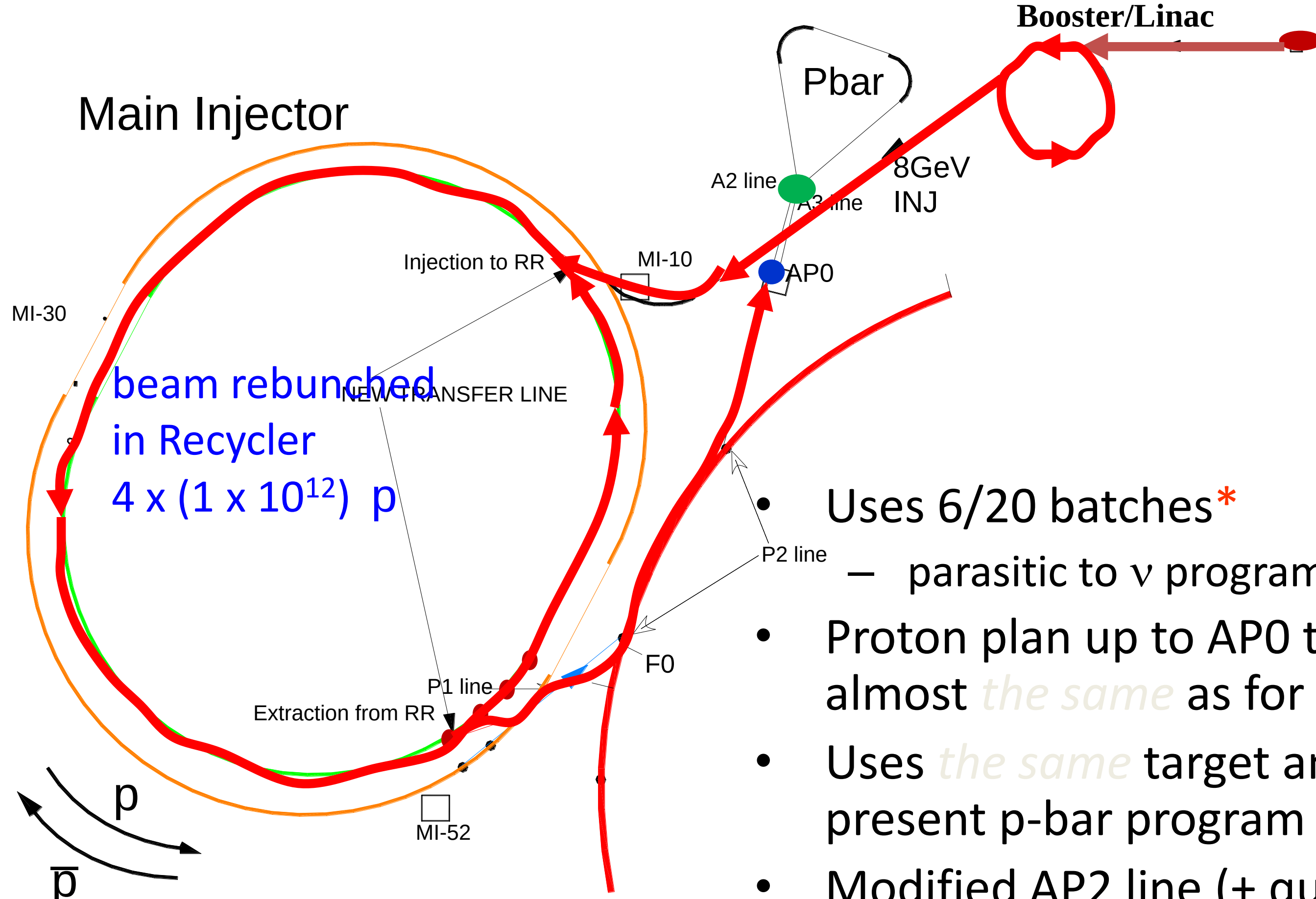
- E821 at Brookhaven
  - superferric storage ring, magic γ, $\langle B \rangle_\theta$ $\pm$ 1 ppm

$$\left.\begin{aligned}\sigma_{\rm stat} &= \pm 0.46\ \text{ppm} \\ \sigma_{\rm syst} &= \pm 0.28\ \text{ppm}\end{aligned}\right\} \sigma = \pm 0.54\ \text{ppm}$$

- **P989 at Fermilab**
  - move the storage ring to Fermilab, improved shimming, new detectors, electronics, DAQ,
  - new beam structure that takes advantage of the multiple rings available at Fermilab, more muons per hour, less per fill of the ring

$$\left.\begin{aligned}\sigma_{\rm stat} &= \pm 0.1\ \text{ppm} \\ \sigma_{\rm syst} &= \pm 0.1\ \text{ppm}\end{aligned}\right\} \sigma = \pm 0.14\ \text{ppm}$$

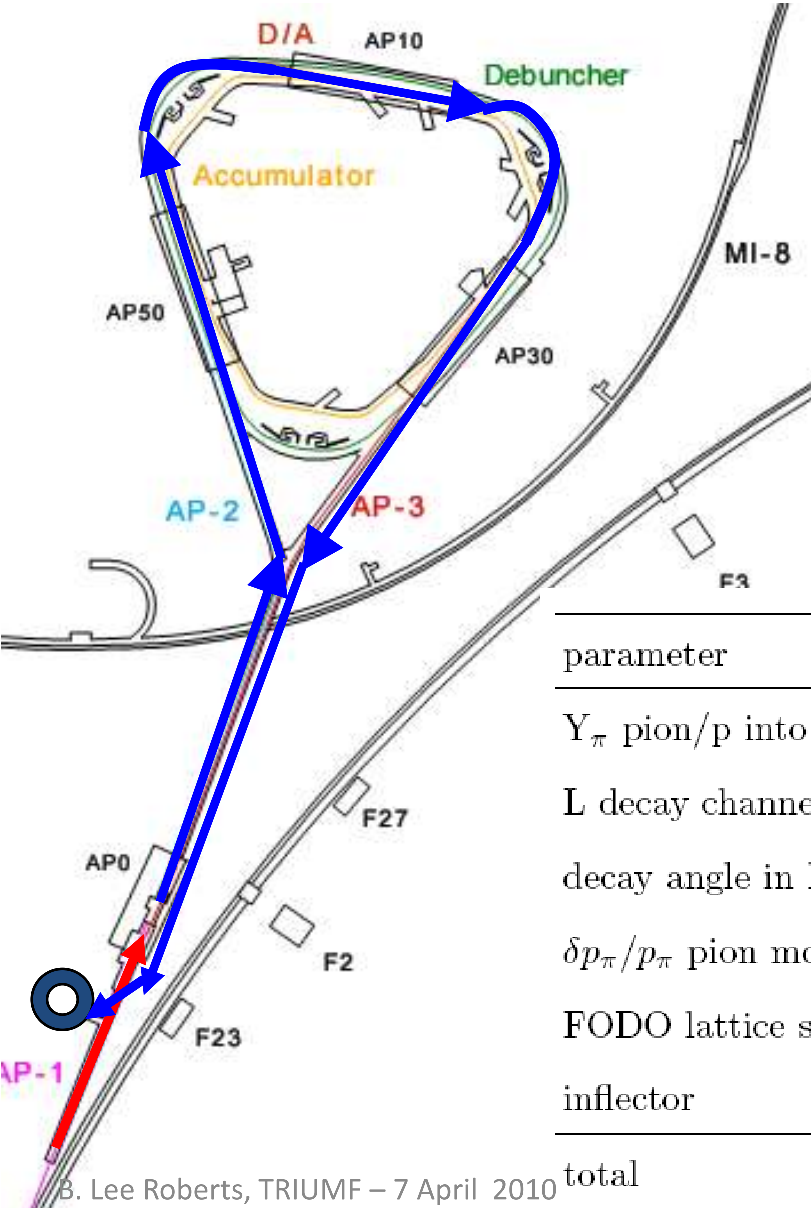
Polarized muons delivered and stored in the ring at the magic momentum, 3.094 GeV/c



- Uses 6/20 batches*
  - parasitic to ν program
- Proton plan up to AP0 target is almost the same as for Mu2e
- Uses the same target and lens as the present p-bar program
- Modified AP2 line (+ quads)
- New beam stub into ring
- Needs simple building near cryo services

*Can use all 20 if MI program is off

The 900-m long decay beam reduces the pion “flash” by x20 and leads to 6 – 12 times more stored muons per proton (compared to BNL)



Flash compared to BNL

parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

Stored Muons / POT

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

Frozen spin : muons @ PSI

Idea for PSI

- p = 125MeV/*c*
- $N = 2 \cdot 10^5$/s
- P = 92%
- B = 1T
- E = 0.64MV/m
- R = 42cm
- Reach: 5×10^{-23} e · cm / y

3-4 orders below current limit

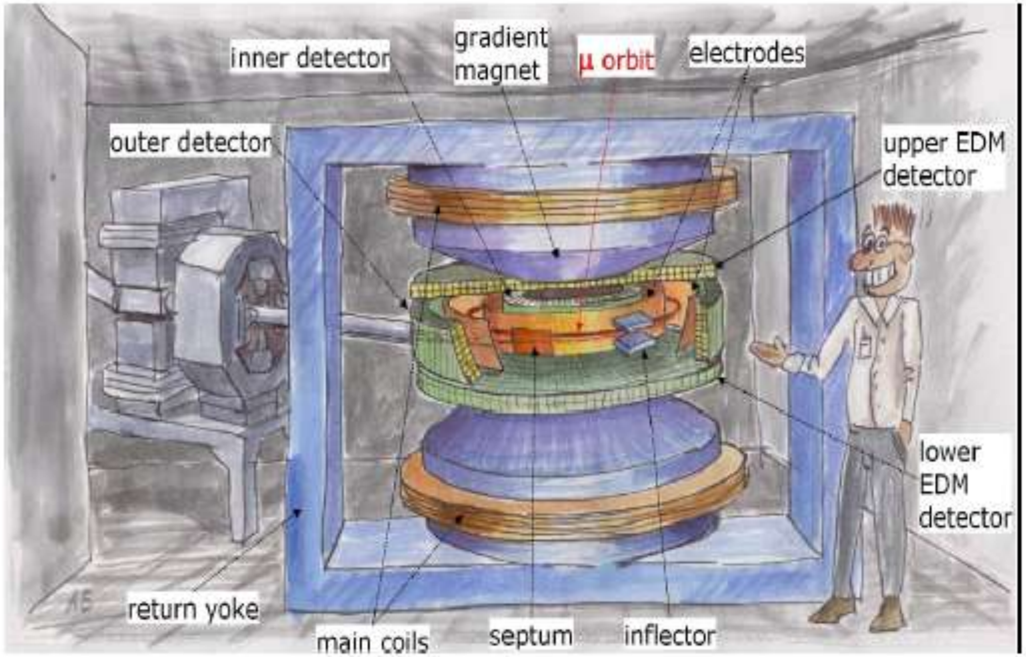


Table top experiment!

Adelmann, Kirch, Onderwater & Schietinger, J. Phys. G: Nucl. Part. Phys. 37 085001 (2010)

MU-E CONVERSION

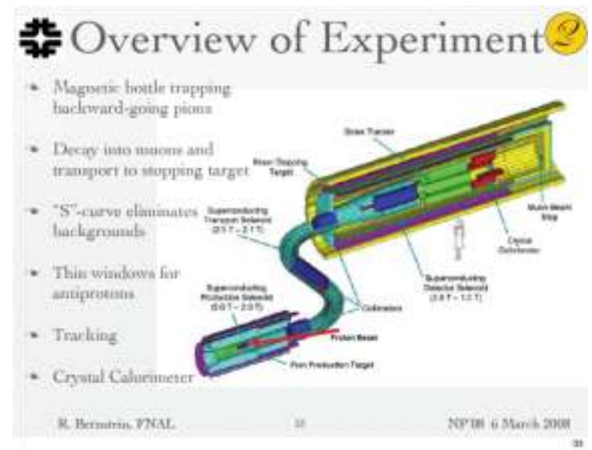
Search for μ-e conversion in nuclei (plans)

Current bounds:

$$R_{\mu e}(N) \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')}$$

$R_{\mu e}(\mathrm{Ti}) < 6 \times 10^{-13}$ (SINDRUM II, 93')

$R_{\mu e}(\mathrm{Au}) < 7 \times 10^{-13}$ (SINDRUM II, 00')



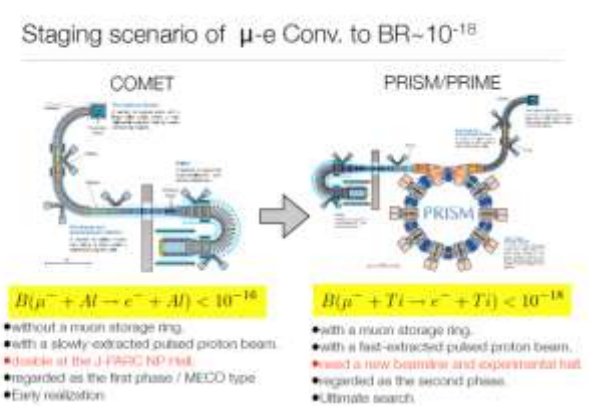
(From Prebys's talk in NP08)

Next experiments aim at Rμe ~10^{-16}.

- Mu2e (Fermilab): $R_{\mu e}(\mathrm{Al}) \sim 6 \times 10^{-17}$
- COMET (J-parc): $R_{\mu e}(\mathrm{Al}) \sim 5 \times 10^{-17}$

Cf PRISM/PRIME (J-parc): $R_{\mu e}(\mathrm{Ti}) \sim 10^{-18}$

Muon storage ring is used.



(From Kuno-san's talk)

These experiments are competitive to MEG.

When photon-mediation dominates conversion,

$$R_{\mu e} \sim 10^{-2} \times Br(\mu \to e\gamma)$$

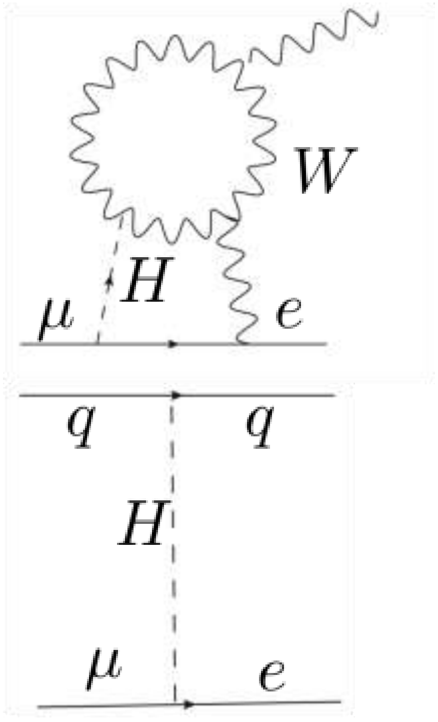
LFV in decoupling case

When SUSY particle masses are larger than O(1-10) TeV, SUSY contributions to flavor changing processes are suppressed below the experimental bounds even if squark and slepton mixings are not small.

Even in this case, the Higgs exchange contributes to LFV processes, since SUSY SM has two doublet Higgs bosons. LFV Higgs coupling is generated after integrating SUSY particle at one-loop.

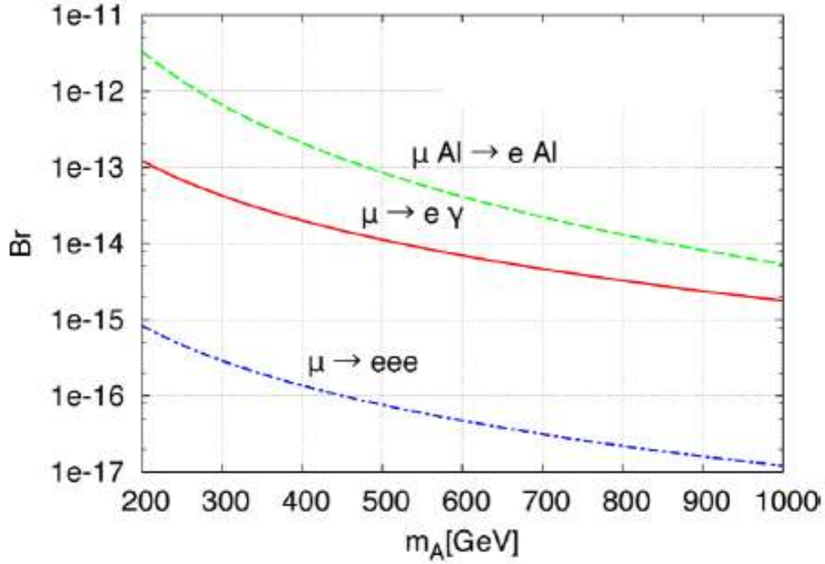
$$-\mathcal{L}_Y = \bar{e}_{Ri} f_{li} L_i H_1 + \bar{e}_{Ri} \Delta_{ij} L_j H_2 + h.c.$$

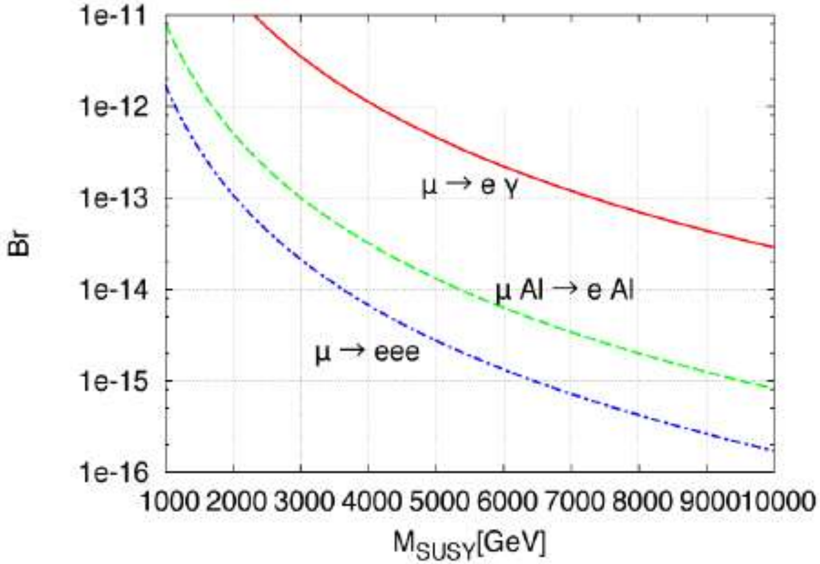
Tree One-loop (Babu & Kolda)



LFV in decoupling case

Higgs exchange contribution v.s. SUSY 1 loop contribution





$$\tan\beta = 50,\ \delta_{12} = 10^{-2} (\Delta_{12} \simeq 5 \times 10^{-6})$$

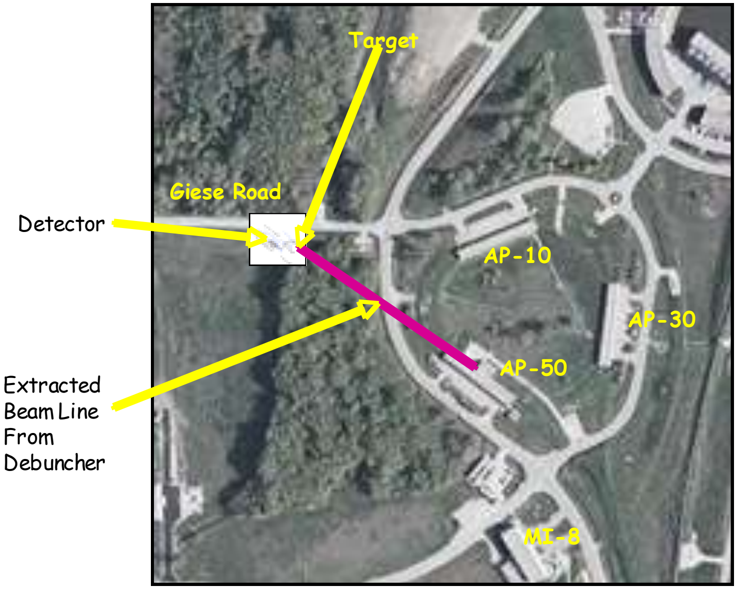
(Hisano et al, 10)

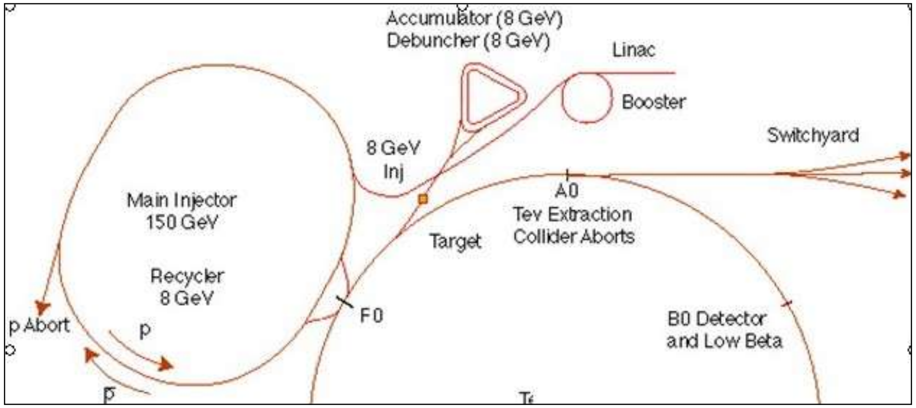
Lesson:
When a new particle is found, we need to check whether it has LFV interaction or not.

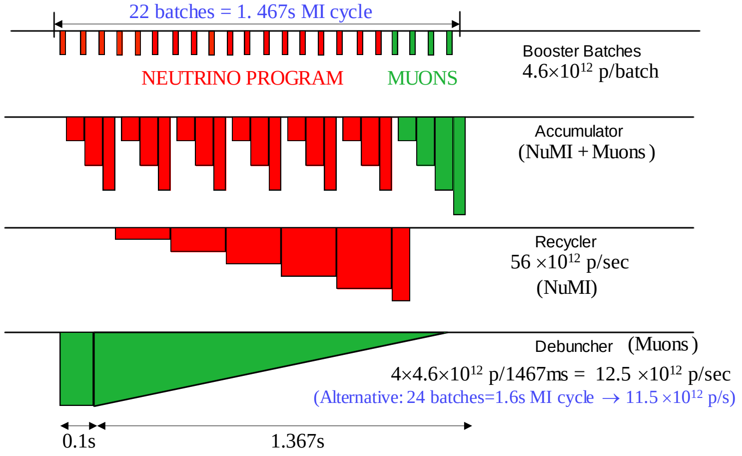
Mu2E @ Fermilab

- The mu2e Experiment at Fermilab.
  - Proposal has been submitted.
    - CD-0
  - After the Tevatron shut-down
    - uses the antiproton accumulator ring
    - the debuncher ring to manipulate proton beam bunches

Fermilab Accelerators



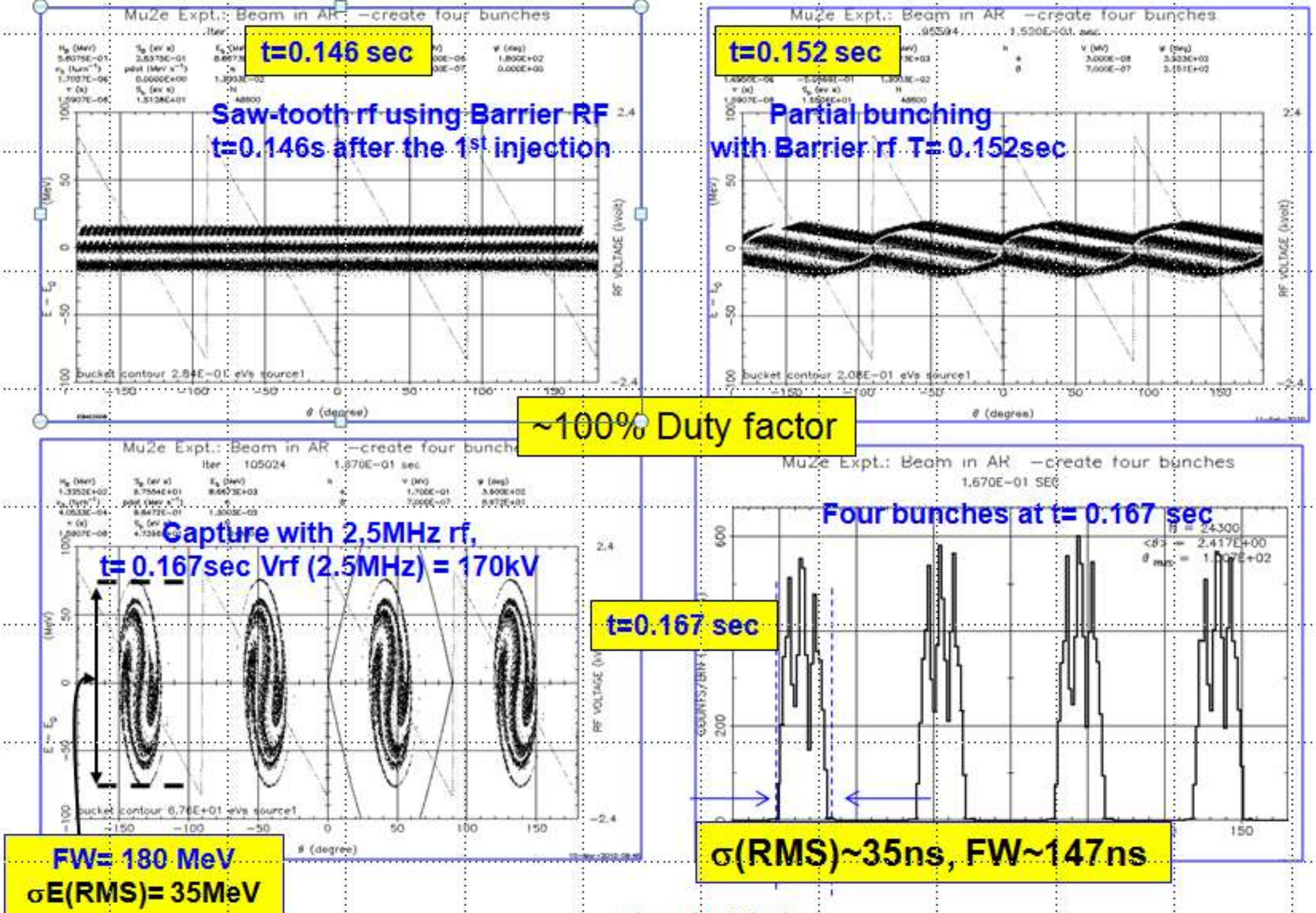




ESME Simulations – Scenaroi-I

Bunching using Barrier saw-tooth rf and 2.5 MHz rf.

Beam is ready for the Mu2e experiment in ≈33 ms after the 3rd injection



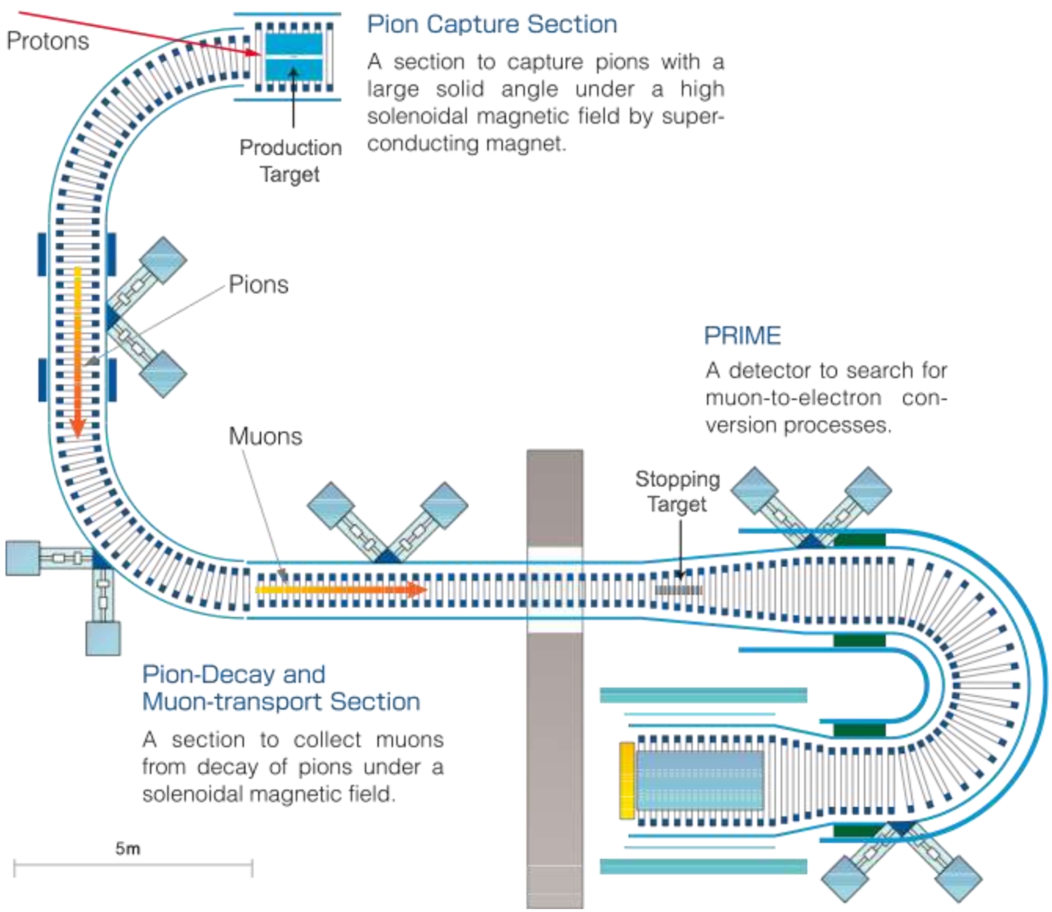
9

Chandra Bhat

COMET at J-PARC

- 10^{-16} の感度を目指す
- J-PARCの陽子ビームを8GeVでバンチ構造を保ったまま実験室に取り出し、muonic atomを生成
- ビームエクスティンクション　10^{-9}が必須
- 大アクセプタンソレノイド電磁石

Overview of the COMET Experiment

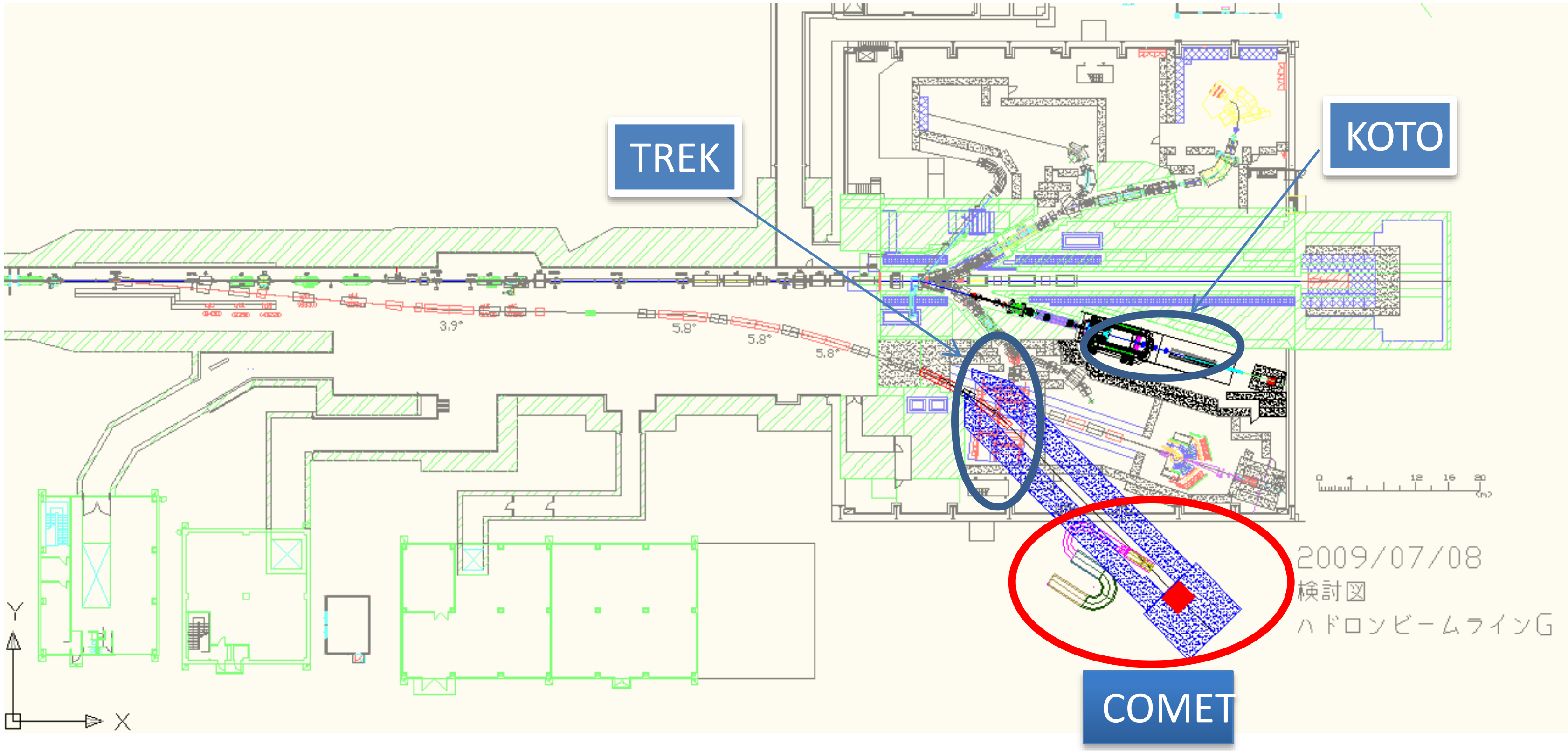


- Proton Beam
  - $p \rightarrow \pi \rightarrow \mu$
- The Muon Source
  - Proton Target
  - Pion Capture
  - Muon Transport
- The Detector
  - Muon Stopping Target
  - Electron Transport
  - Electron Detection

Experimental Space

A possible layout

- Target and beam dump outside the hall
- Share the upstream proton transport line with the high p beam line
- External extinction device in the switch yard



Toward Starting Experiment

- R&D work in progress
  - Detector, SC magnet, Proton extinction

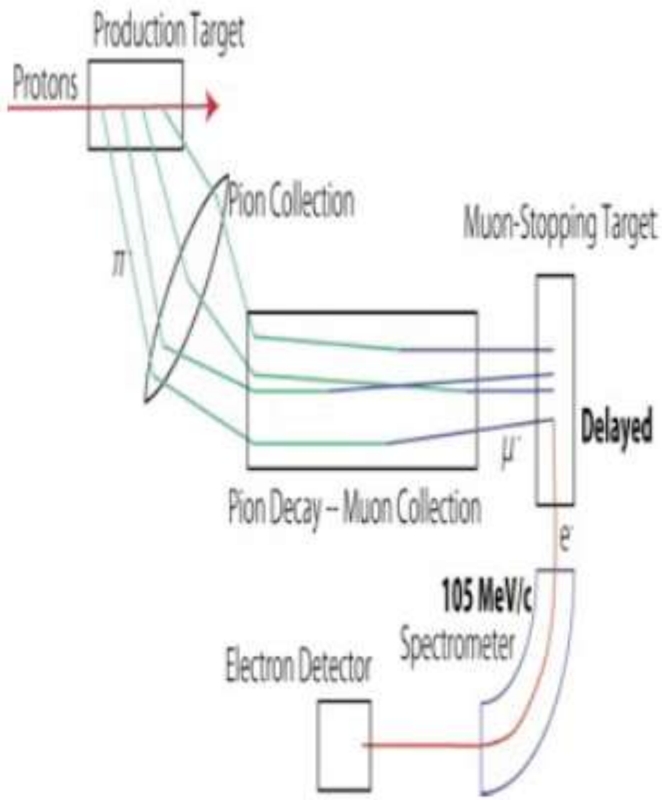
Funding starting

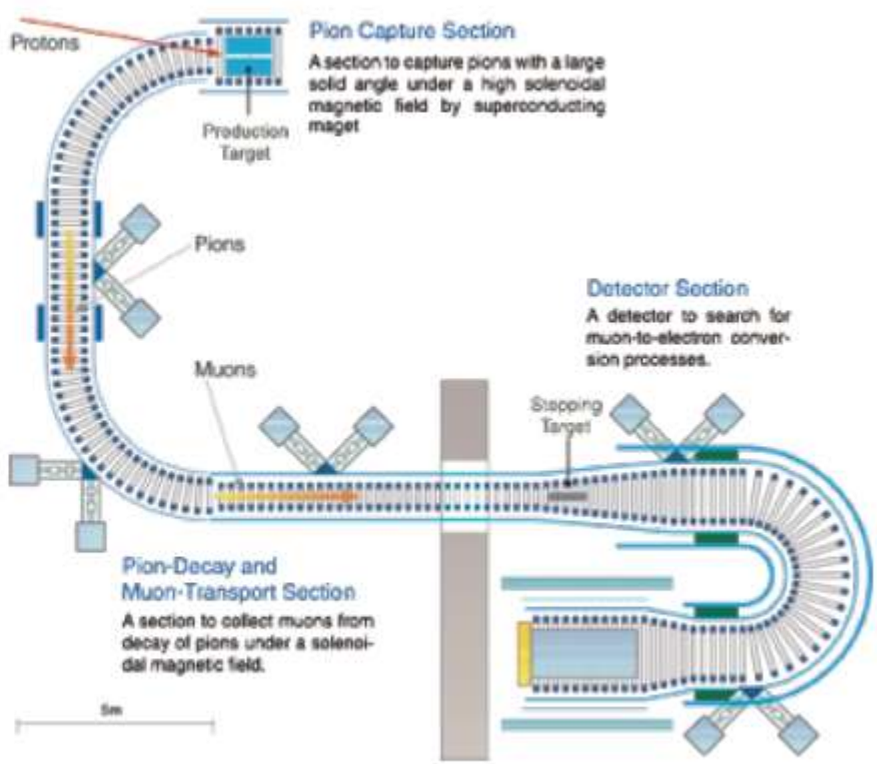
1st year	design & order of SC wires
2nd year	construction
3rd year	
4th year	
5th year	engineering run
6th year	physics run

Item	Cost (Oku JPY)
Proton beam line	
Proton beam line magnets	17
Proton beam dump	2
Radiation shielding for a proton beam line	3
Superconducting Solenoid	35.7
Detector	
Electron tracker	2.1
Electron calorimeter	2.3
Cosmic ray shield	3
DAQ system	0.5
Infrastructure	
Refrigeration	4.7
Pion production system and tungsten shielding	2.3
Civil construction	
Extension of the NP experimental hall	3
Total	75
Total (with 20% contingency)	90

DeeMe

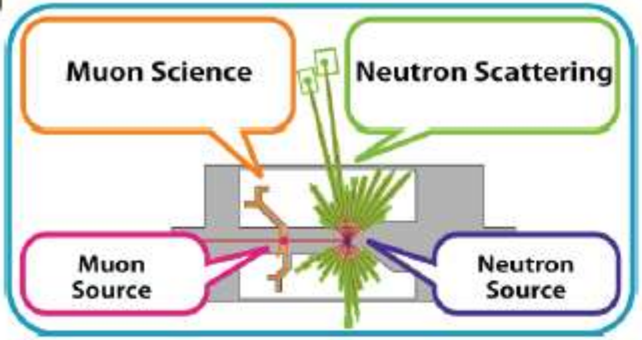
- COMETよりも感度が低くてもよいので、低予算でできないものか？

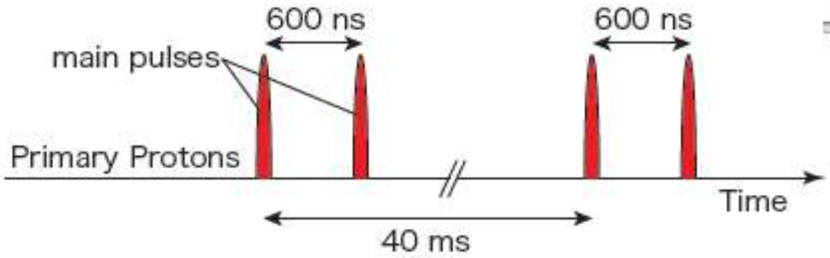


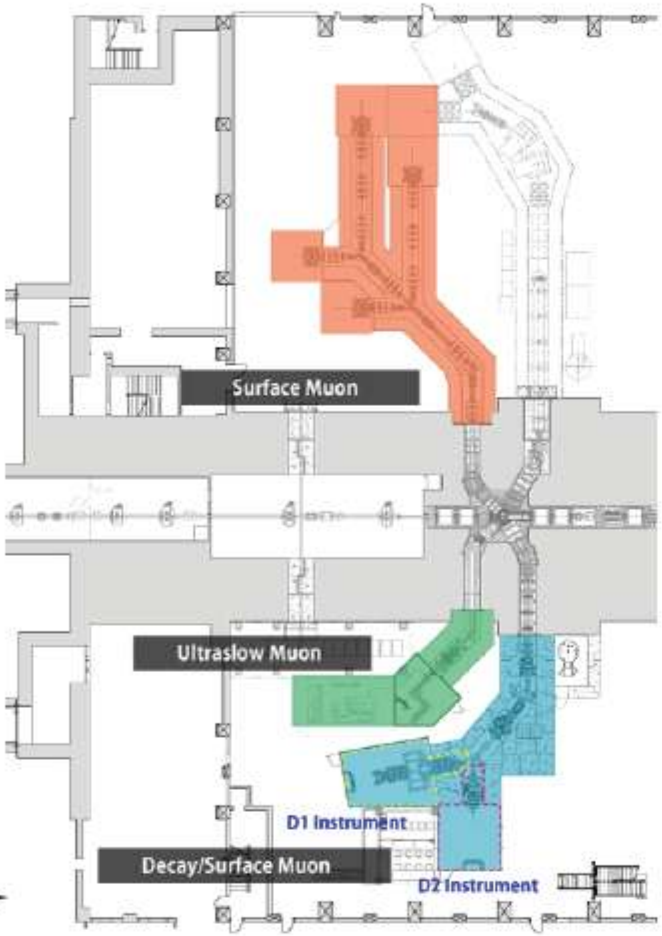


COMET: BR[Al] < 10^{-16}

J-PARC MLF Muon Facility



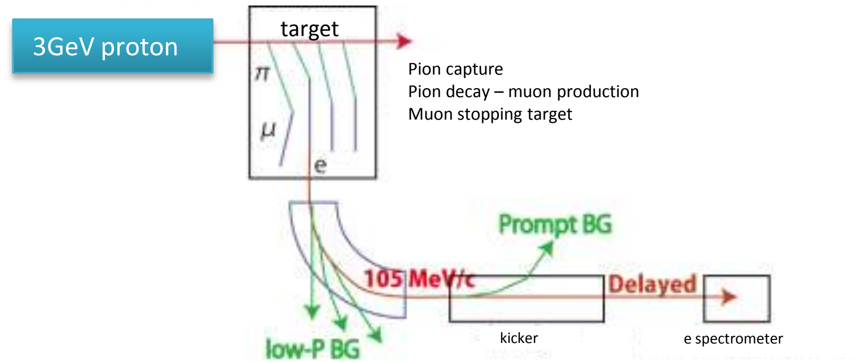


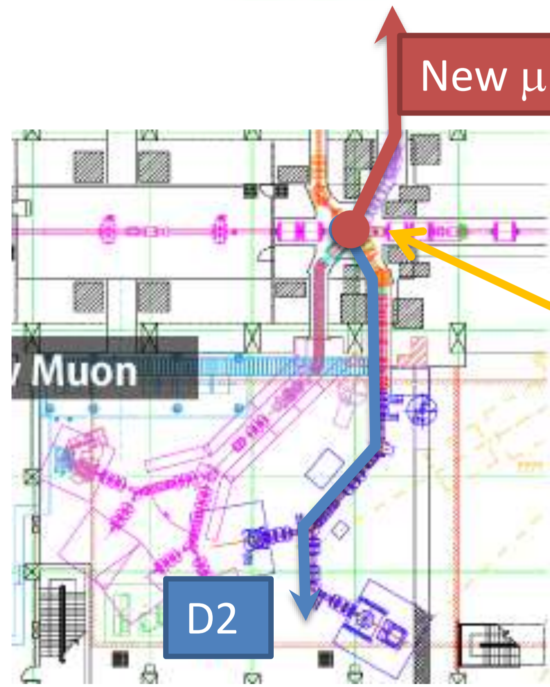


DeeMe

Another m-e conversion search at J-PARC

- Mu-e conversion electron directly comes from the target?
- 10^{10} muon stops/sec/MW
- Transport 105MeV/c delayed electrons
- Expected reach (crude)
  - D2 beam line (40msr)
    - 8×10^{-13} for C (10^7 sec)
    - 2×10^{-13} for Al (10^7 sec)
  - New beam line (150msr)
    - 10^{-14} for Al (2×10^7 sec)
  - cf SINDRUM II limit: 7×10^{-13}

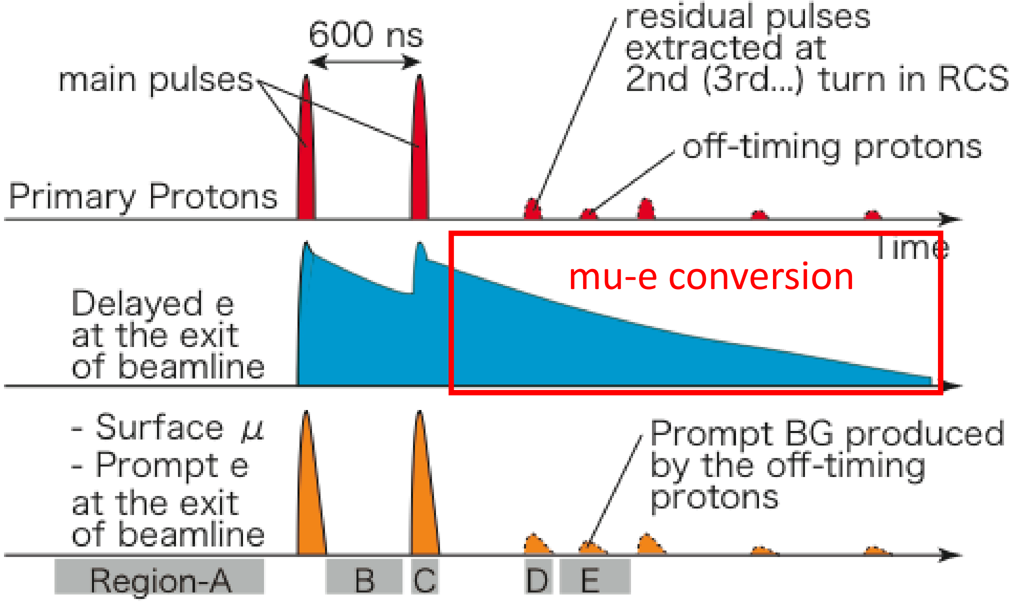




Graphite target with water cooling

Background

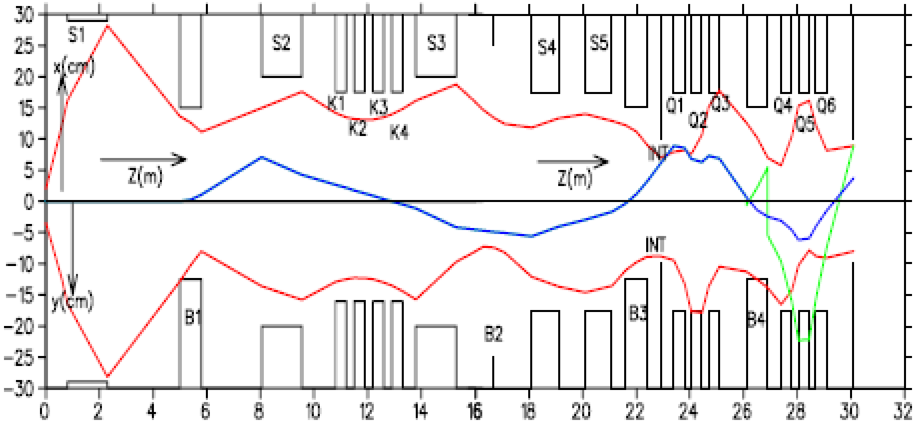
- Event signature
  - P_e = 105 MeV/*c*
  - T_e > ~μsec

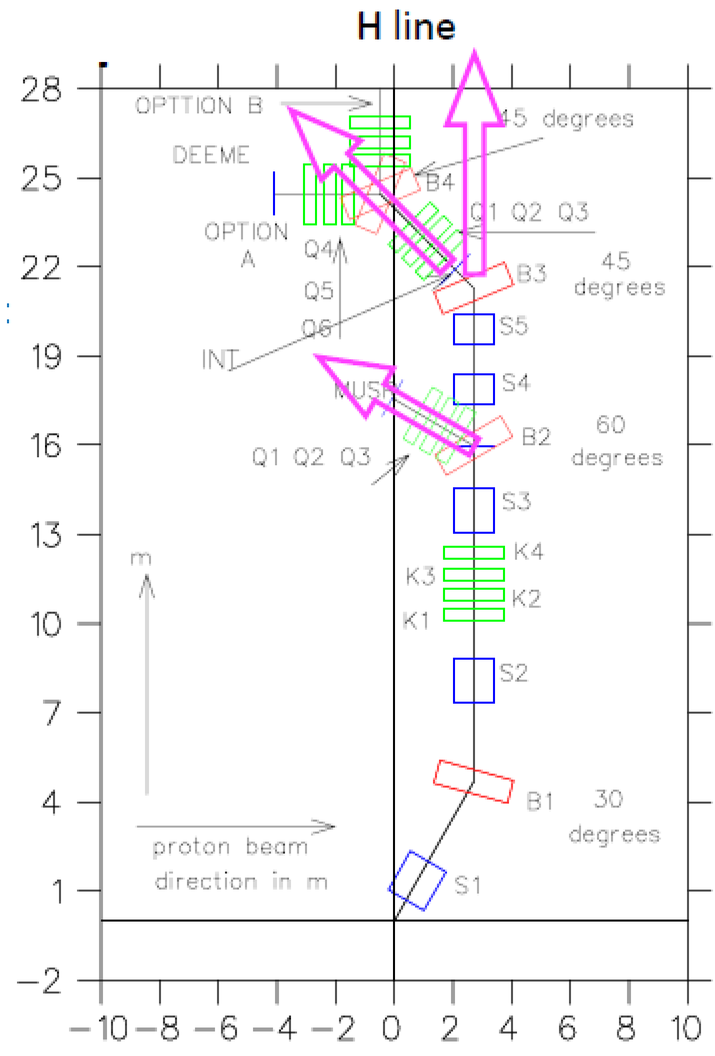


- Any particle production 1μsec later than the prompt proton timing?
  - Only decay product of μ
    - Michel electron P_e<55MeV/c
- If any off-timing proton exists, that can be BG
  - Extinction < 10^{-14}

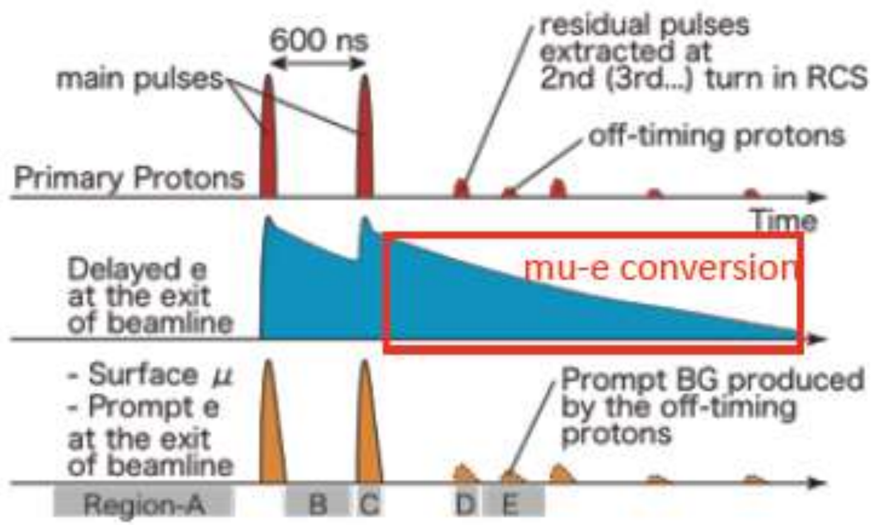
MLF muon beam line

- 限られたビームラインポート
  - g-2
  - DeeMe
  - μSR





DeeMe @ J-PARC MLF



	Sensitivity	Schedule
DeeMe	$\sim 10^{-14}$	~2015
COMET	$<10^{-16}$	2017~

DeeMe does not replace COMET.

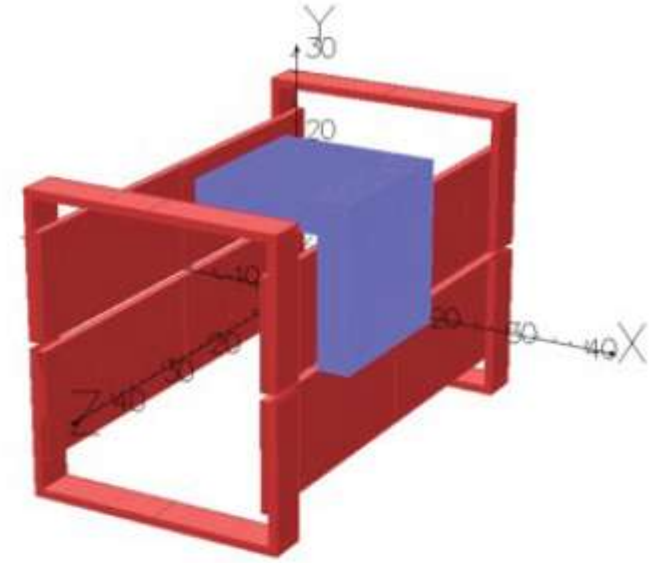
DeeMe will gain momentum of muon-CLFV research field.

Sound scenario to secure the world-first discovery.

DeeMe コストと予定

- 1年以内にプロポーザル提出を目標
- ビームライン建設 ２－３年
- データ収集 １年以上

- コストの大部分はビームライン
  - g-2, muSRとシェア
  - 最上流部のソレノイドが最も高くて20-30億円（シールド込）
    - どんな実験をやるにせよ早く手当しないと建設が難しくなる
  - キッカー ＜3億円



Kicker Spec.

- B > 385 Gauss
- Gap = 320 mm
- Width = 320 mm
- L = 400 mm
- Δt < 300 nsec

Conceptual Design on-going by KEK Accelerator Group (Matsumoto-san et al.)

- “It can be built.”

OTHER LFV SEARCH EXPERIMENTS

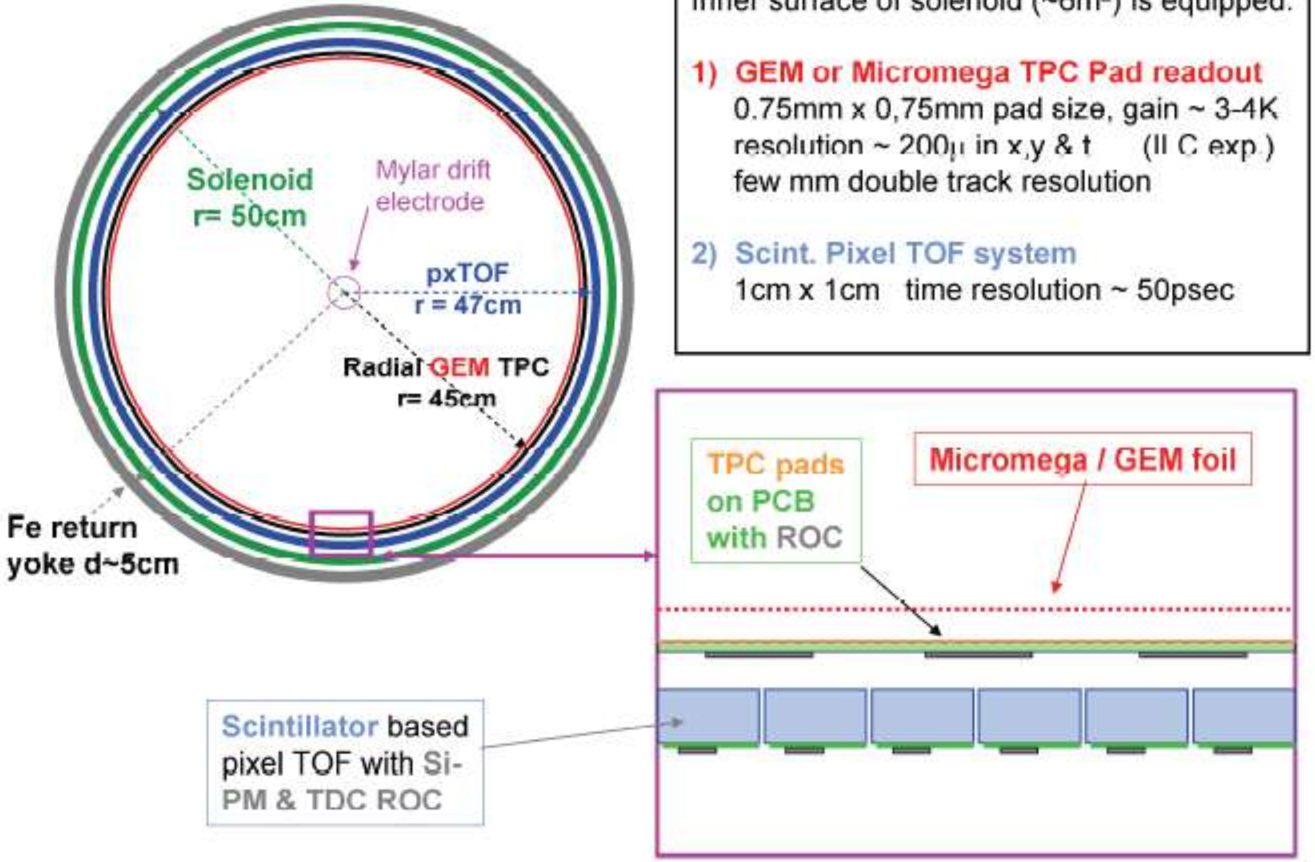
PAUL SCHERRER INSTITUT

Cross-section of $\mu \rightarrow$ 3e Experiment

Inner surface of solenoid (~6m^2) is equipped:

1) GEM or Micromega TPC Pad readout
   0.75mm x 0,75mm pad size, gain ~ 3-4K
   resolution ~ 200μ in x,y & t (ILC exp.)
   few mm double track resolution

2) Scint. Pixel TOF system
   1cm x 1cm time resolution ~ 50psec



$\mu^- e^- \rightarrow e^- e^-$

A new idea to search for charged lepton flavor violation using a muonic atom

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[2] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[3] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan*

(Dated: March 9, 2010)

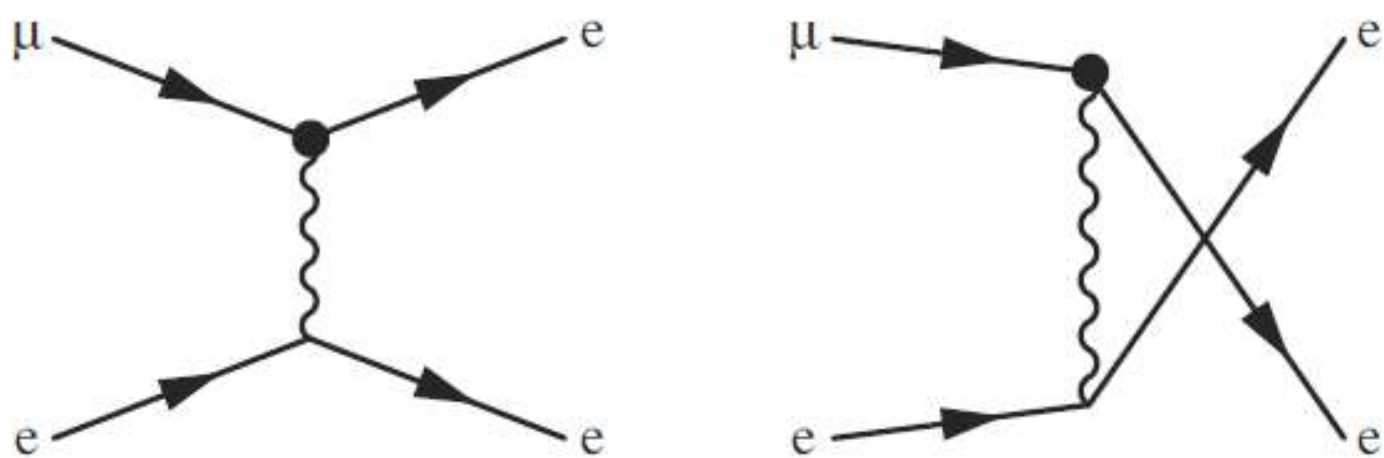


FIG. 1: The process $\mu^- e^- \rightarrow e^- e^-$ induced from the photonic interactions. The black dot indicates the effective interaction that is absent from the Standard Model.

MUONIUM HFS

Muonium

- Pure leptonic bound system, free from finite size effect.
- Good example for testing QED,
- HFS,1s-2s, Lamb shift

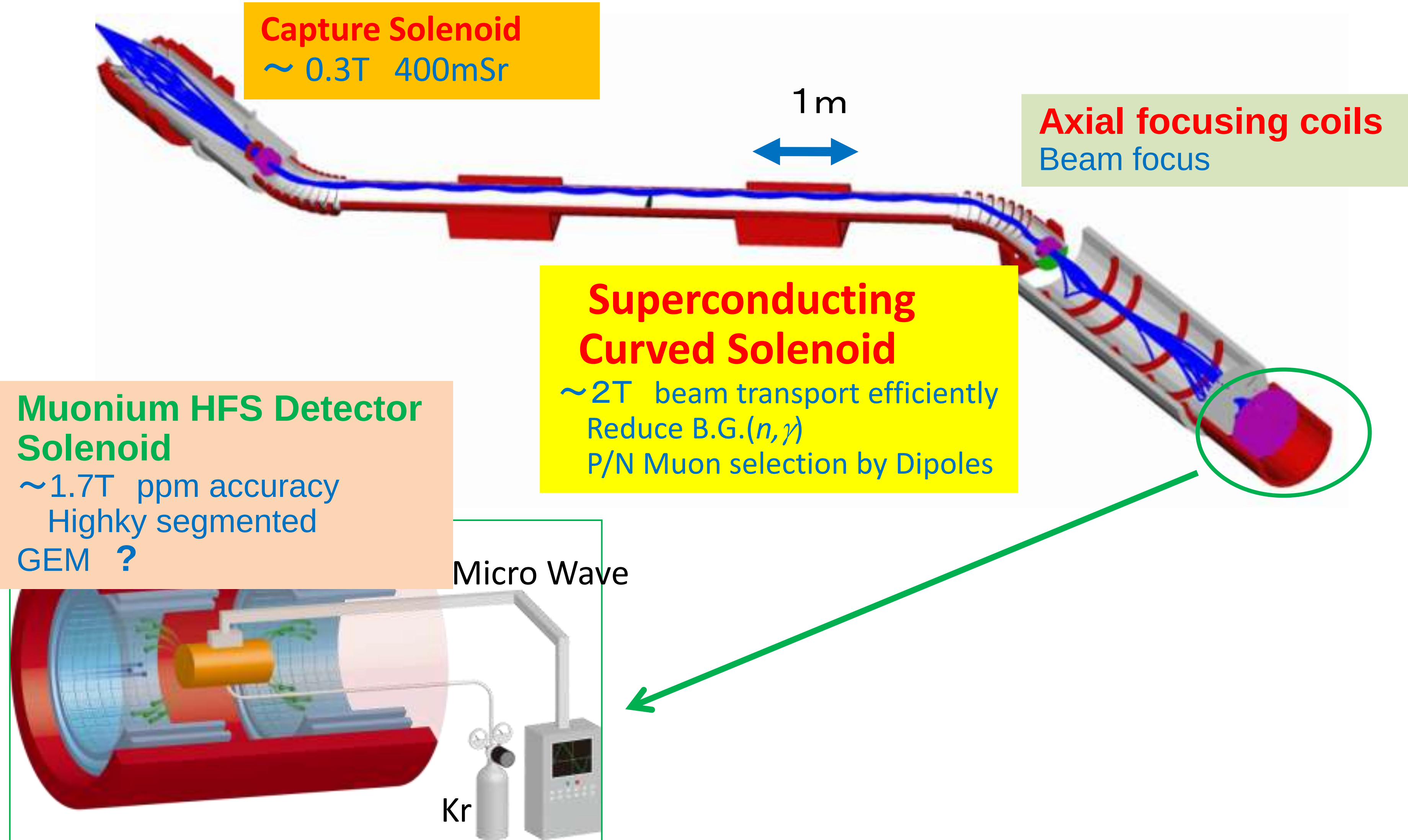
- Muonium ground state hyperfine interval measurement is related to

  Determination of fine structure constant α

  Test of CPT and Lorentz Invariance

  and so on.

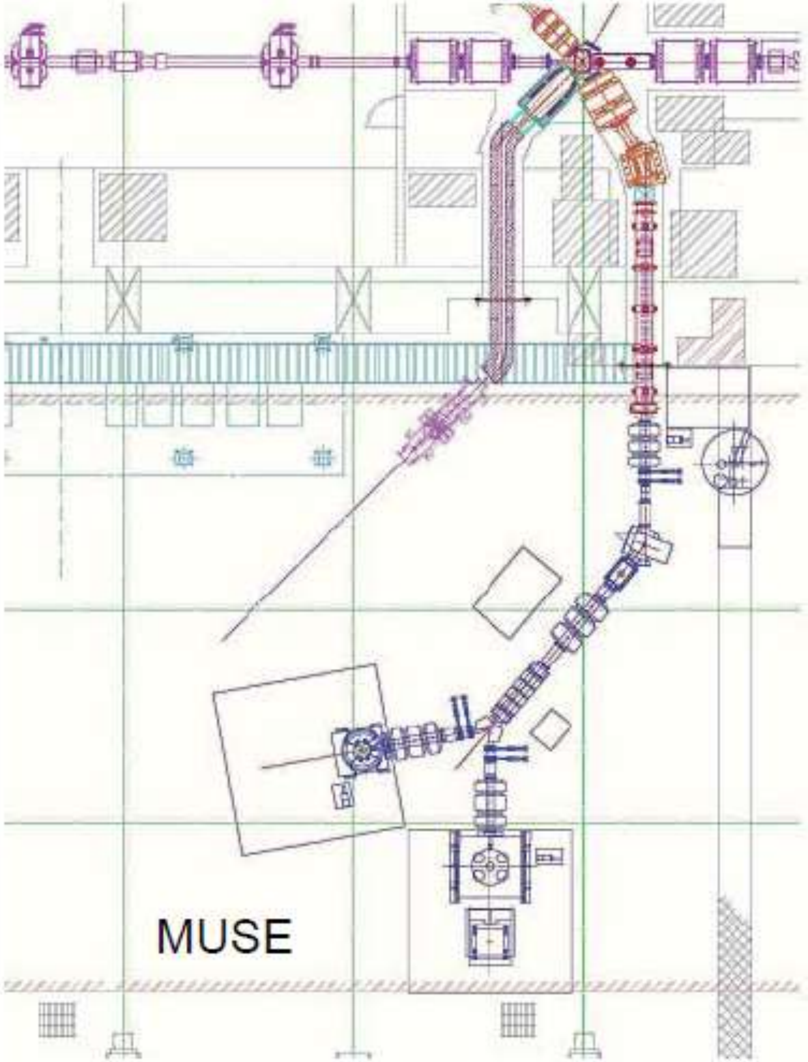
Possible Setup for Muonium HFS measurement
J-PARC MUSE



MUSIC

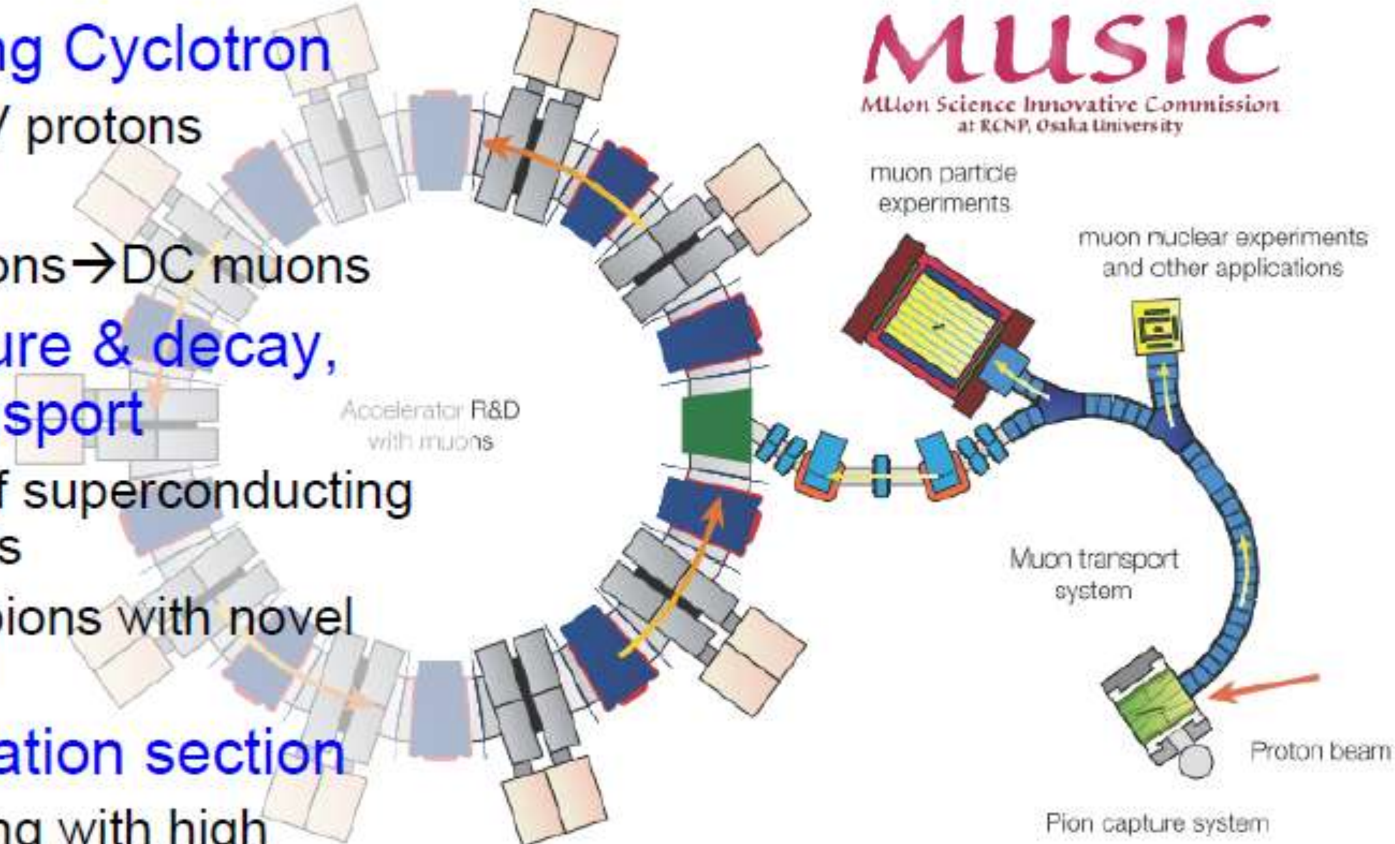
MUSE vs. MuSIC

	MUSE	MuSIC
Location	J-PARC	RCNP
Beam power	1000kW	0.4kW
	Surface muon	Decay + Surface
Intensity	10^8/sec	10^7-10^8/sec
Time structure	Pulsed (25Hz)	Continuous
Beam polarization	High	Medium
Multiple use	Many channels	Only one channel

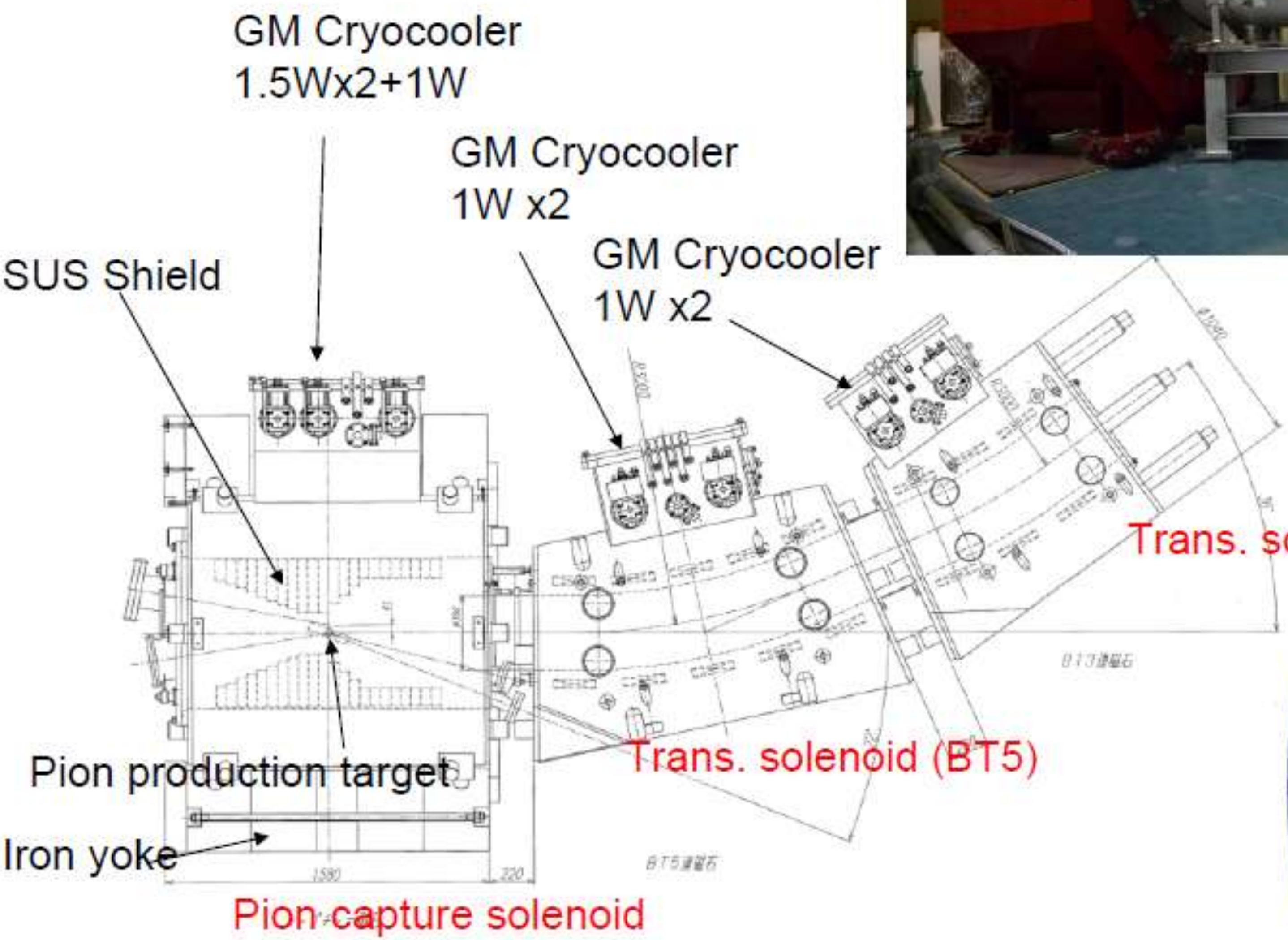


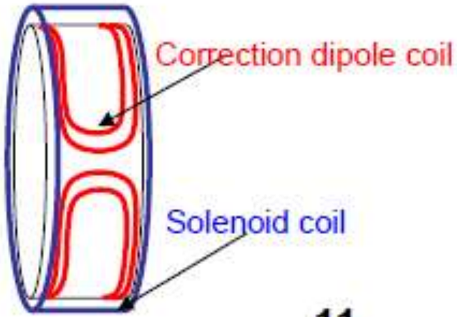
MuSIC – Muon Channel at RCNP

- RCNP Ring Cyclotron
  - 400 MeV protons
  - 1 μA
  - DC protons→DC muons
- Pion capture & decay, muon transport
  - Series of superconducting solenoids
  - Collect pions with novel method
- Phase rotation section
  - FFAG ring with high gradient RF cavities



Magnet layout in 2010





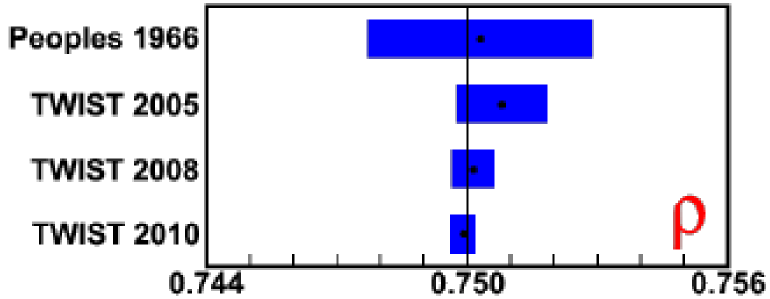
Element coil of Trans. solenoid

TRIUMF In house particle physics

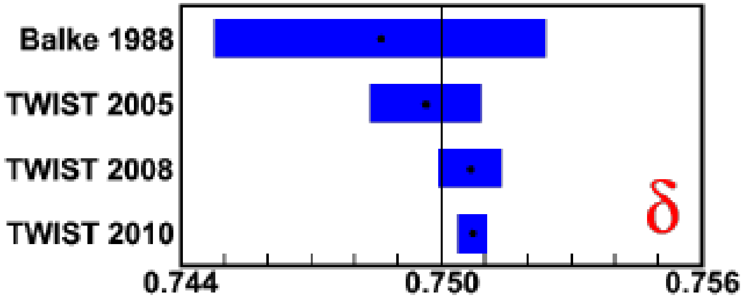
- Precision measurements:
- Twist :2006-7 data blind analysis results reported. Final evaluation of the results .

- Pienu:Measurement of branching ratio to .1% .Limits on pseudo-scalar part of the weak interaction Lagrangian.
- e/μ inversality

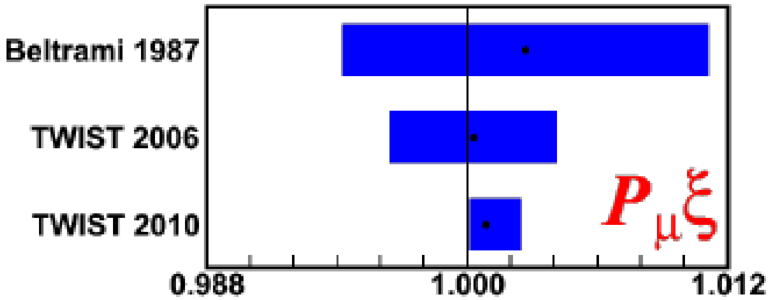
Comparisons with previous results



$$\rho = 0.74991 \pm 0.00009\ (\text{stat}) \pm 0.00028\ (\text{syst})$$



$$\delta = 0.75072 \pm 0.00016\ (\text{stat}) \pm 0.00029\ (\text{syst})$$

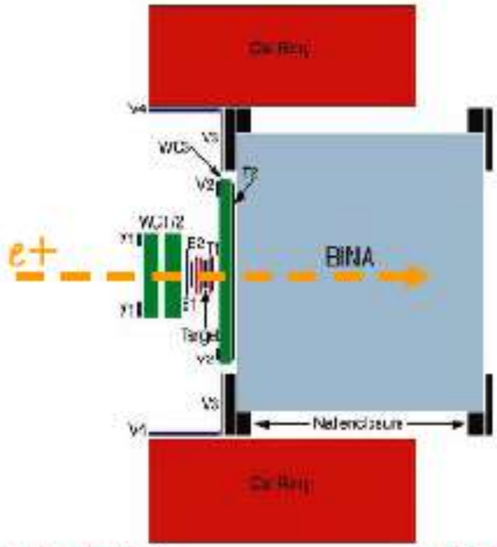


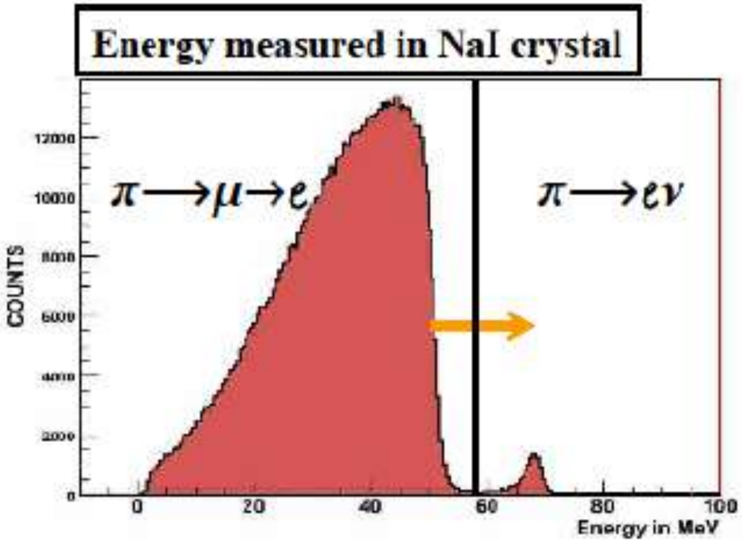
$$P_\mu \xi = 1.00084 \pm 0.00035\ (\text{stat})\ {}^{+0.00165}_{-0.00063}\ (\text{syst})$$

PIENU Experiment

Requirements

- Good beam quality → small momentum bite
- low background
  - Trigger from beam e^+
  - Pileup from beam e^+ hitting beam or detector components





Muon Programs at LANL

Muon Active Interrogation (10M+ for FY10)

Development of large acceptance muon linac.
Construction of a COMET type solenoid at LANSCE.
Project's funding is doubled every year. Our budget will be equal to the US revenue in 15 years.

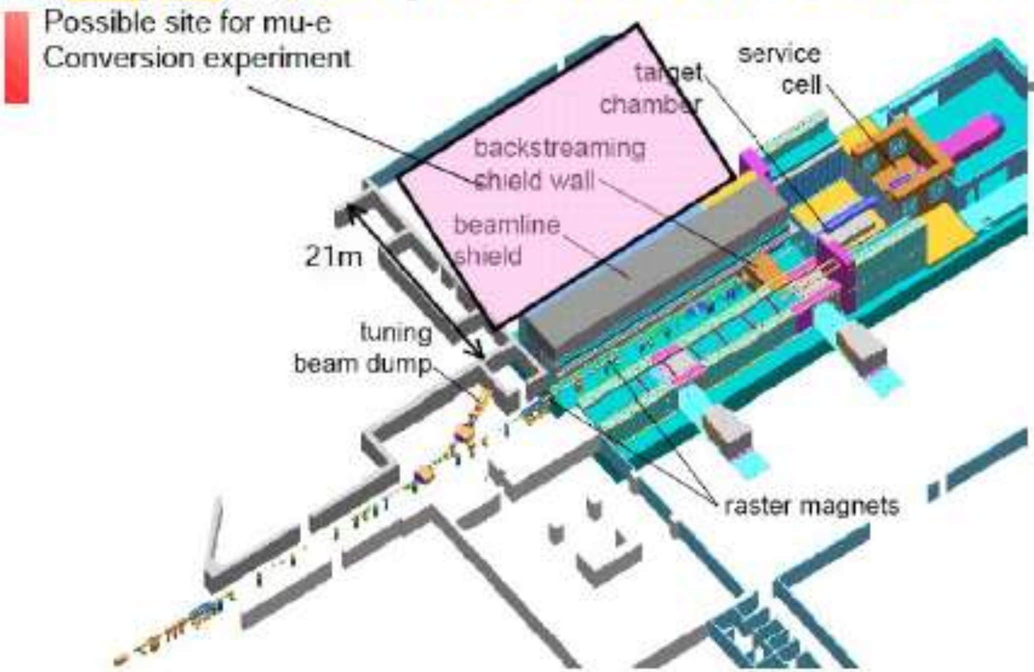
Muon Accelerator R&D

For muon active interrogation and also for future neutrino factory.
Large acceptance muon linac.
Expecting internal funding from LANL (LDRD, 1M for FY11 - 13).

Muon to Electron Conversion Experiment (LDRD 1M)

More efficient muon production than 8 GeV and more power.
Free beam (or almost free).
Benefit from Muon Active Interrogation project.

Muon Electron Conversion Experiment In Front of MTS



LDRD funding approved for the design study (FY09 – 11).

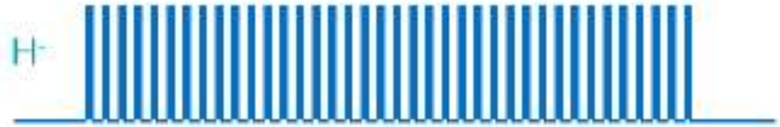
Basic studies for the experiment are being carried out.

In front of MTS using negative hydrogen beam.

If MTS were to be canceled, we could use full H^+ beam.
Obama killed Global Nuclear Energy Partnership and MTS is related to GNEP.

- MTS macro pulse: H^+, 17 mA peak current

- Mu-e conversion experiment macro pulse: H^-, 12 mA peak current, chopped to 100 ns pulse every 1-2 μs



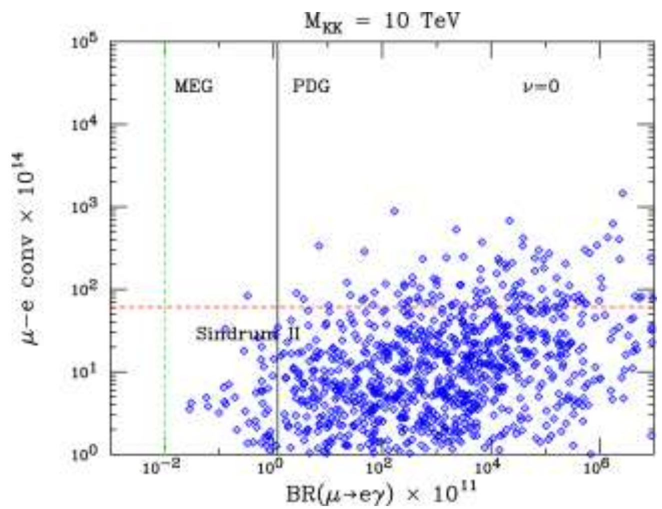
BACKUP

Non-SUSY models at TEVs

Many proposed TeV-scale models have new particles, which have lepton-flavor numbers or have lepton-flavor violating interactions.

SM on Randall&Sundrum BG

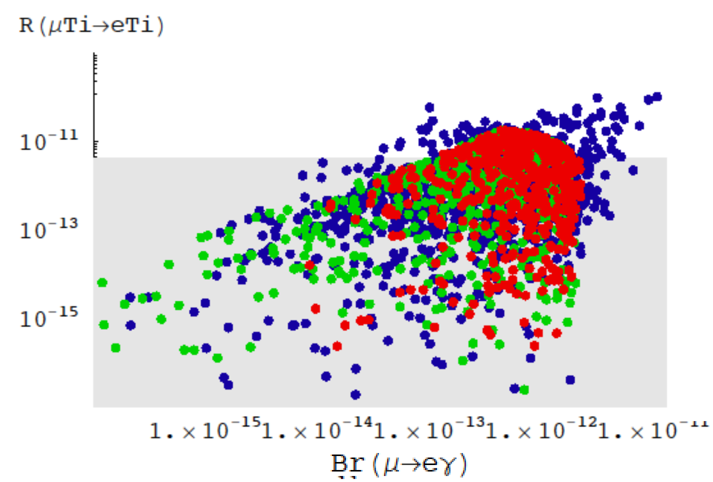
- SM particles propagate over curved 5th dim. space.
- Overlapping of wave functions of quark/lepton and Higgs explains hierarchical structure.
- Kaluza-Klain particles have large flavor-violating interactions.



(Agache et al)

Littlest-Higgs model with T parity

- SM Higgs is pseude NG boson.
- T parity is imposed to escape from EW precision test and also to introduce the DM candidate.
- T-odd mirror leptons/quarks have flavor-violating interactions.



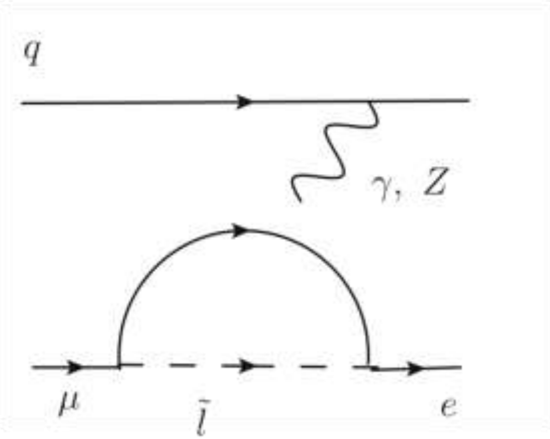
(Blanke et al)

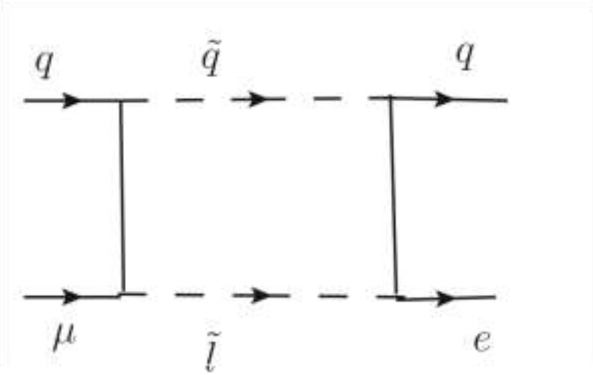
What is the BSM if cLFV is found?

In SUSY SM, μ-e conversion in nuclei and , μ->3e are dominated by photon-mediated diagrams while box and Z mediated diagrams contribute.

$$Br(\mu \to 3e) \simeq 7 \times 10^{-3} Br(\mu \to e\gamma)$$

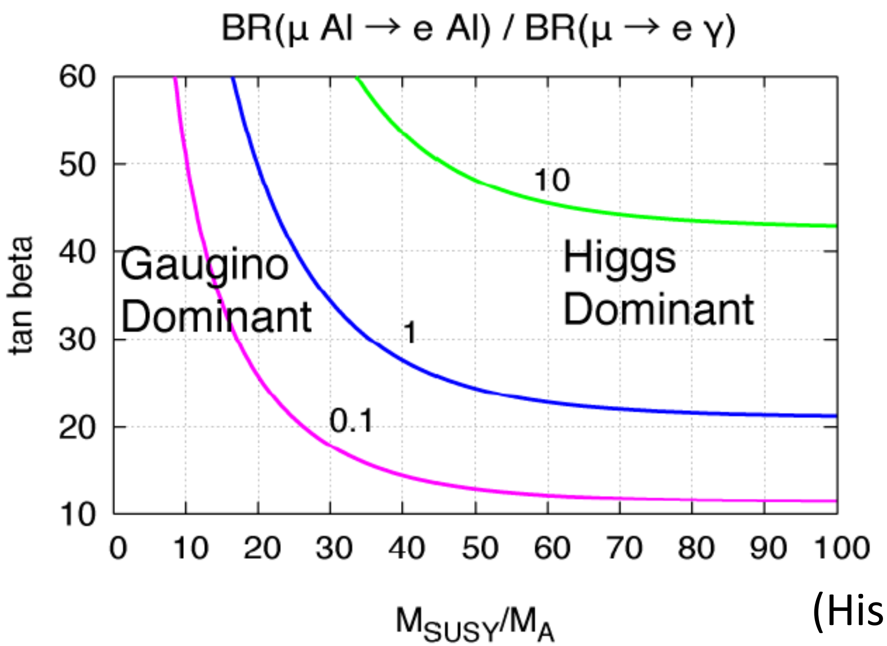
$$R_{\mu e}(\mathrm{Ti}) \simeq 6 \times 10^{-3} Br(\mu \to e\gamma)$$





What is the BSM if cLFV is found?

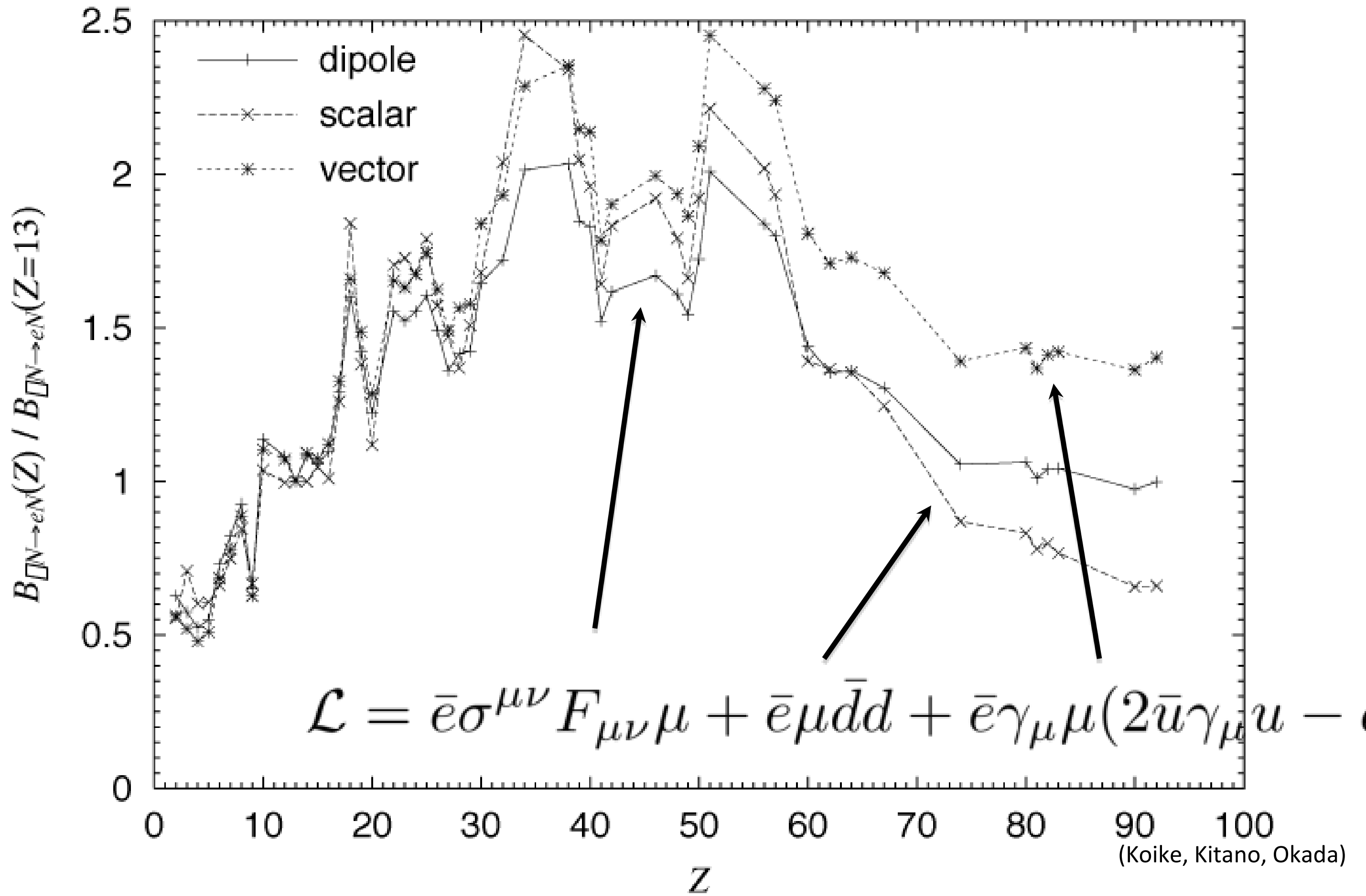
In SUSY SM, the Higgs mediation contribution is sizable when SUSY particle masses are larger O(1-10)TeV. Ratio between μ-e conversion rate and Br(μ-eγ) is modified.



(Hisano et al, 10)

What is the BSM if cLFV is found?

Atomic number (Z) dependence of μ–e conversion rate reveals the responsible operators for muon LFV.



$$\mathcal{L} = \bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu + \bar{e}\mu\bar{d}d + \bar{e}\gamma_\mu\mu(2\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)$$

(Koike, Kitano, Okada)