---DeeMe---
Experimental Search for μ-e Conversion in Nuclear Field at Sensitivity of 10^{-14} with Pulsed Proton Beam from RCS

M. Aoki, Osaka University
on behalf of DeeMe Collaboration

NuFact2012, 25 July, 2012

DeeMe Collaboration

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(5) JAEA
(6) KEK IPNS
(7) TRIUMF

μ−e Conversion in Nuclear Field

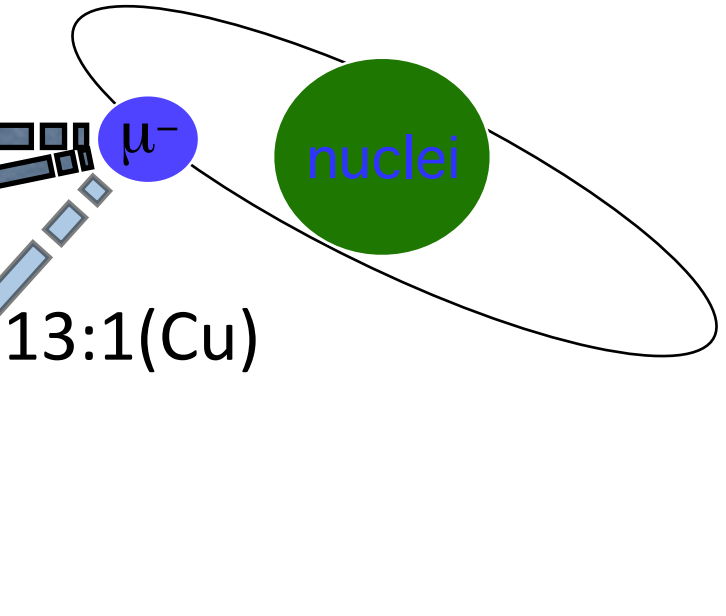
- Muonic Atom (1S state)

Muon Capture(MC)

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

Muon Decay in Orbit (DIO)

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



  - MC:DIO = 1:1000(H), 2:1(Si), 13:1(Cu)
  - τ(free μ-) = 2.2 μs
  - τ(μ⁻;Si) = 0.76 μs

- Charged Lepton Flavor Violation (CLFV)

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

μ-e Conversion in Nuclear Field

$$\mathrm{BR}[\mu^- + (A, Z) \rightarrow e^- + (A, Z)] \equiv \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)]}$$

Clear evidence of the new physics

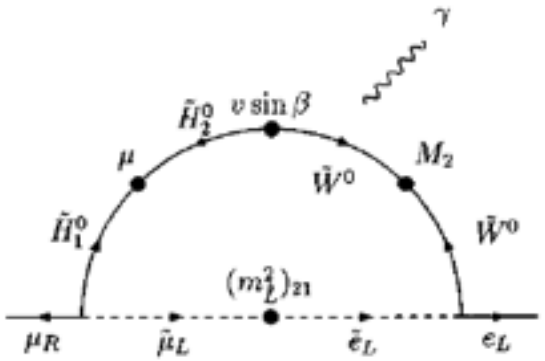
μ-LFV

- light m_ν: seesaw
  - heavy $M_{\nu R} \rightarrow$ light m_ν

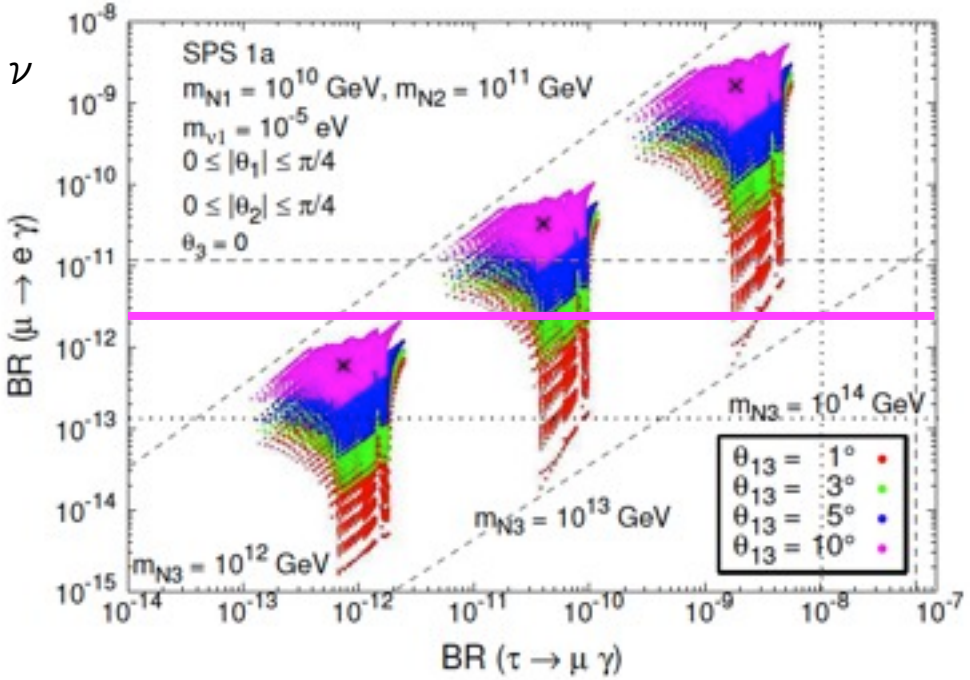
$$m_\nu = \frac{f_\nu^2 \langle h \rangle^2}{M_{\nu_R}}$$

- SUSY

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



S. Antusch et al., JHEP11(2006)090



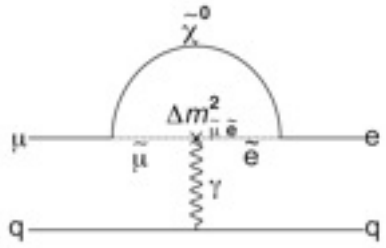
T2K (2011): $0.03 < \sin^2 2\theta_{13} < 0.3$ (90%C.L.)
$\rightarrow 5° < \theta_{13} < 15°$
Daya Bay (2012): $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$
$\rightarrow \theta_{13} > 8°$

Discovery: right around the corner.

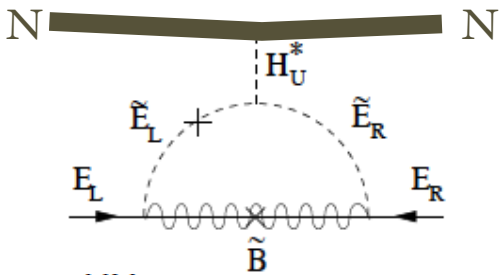
Photonic and Non-photonic

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

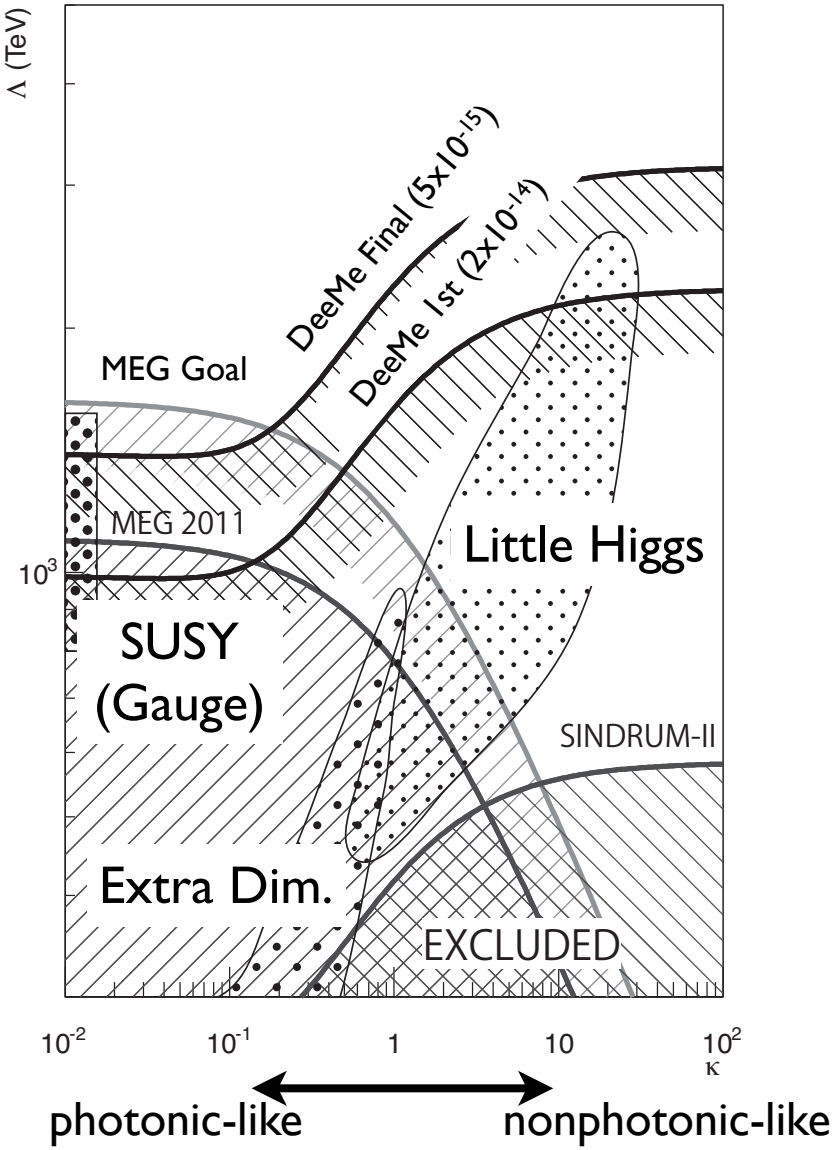
- SUSY-GUT, SUSY-seesaw (Gauge Mediated process)
  - BR = 10^{-14} - 10^{-16} = BR(μ→eγ) × O(α)
  - τ→lγ



- SUSY-seesaw (Z, Higgs Mediated process)
  - BR = 10^{-12}~10^{-15}
  - τ→lη



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



original plot by Andre de Gouvea

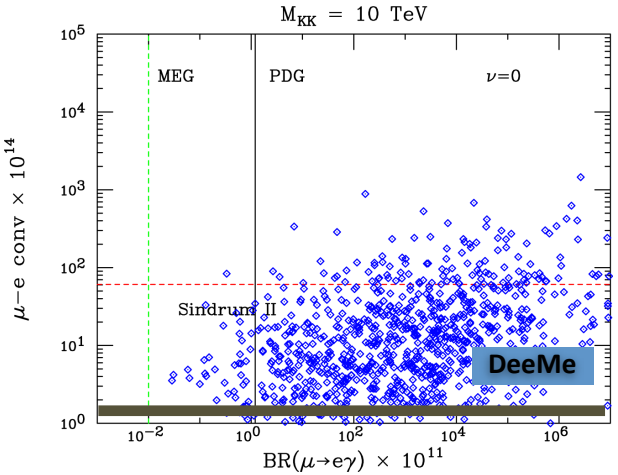
A transparency of J. Hisano at IFMF WS 2010 (DeeMe lines added by M. Aoki)

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

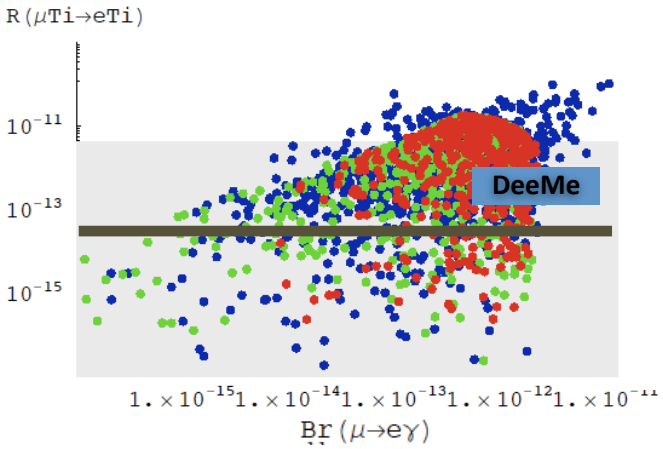
- SM particles propagate over curved 5th dim. space.
- Overlapping of wave functions of quark/lepton and Higgs explains hierarchical structure.
- Kaluza-Klain particles have large flavor-violating interactions.



(Agache et al)

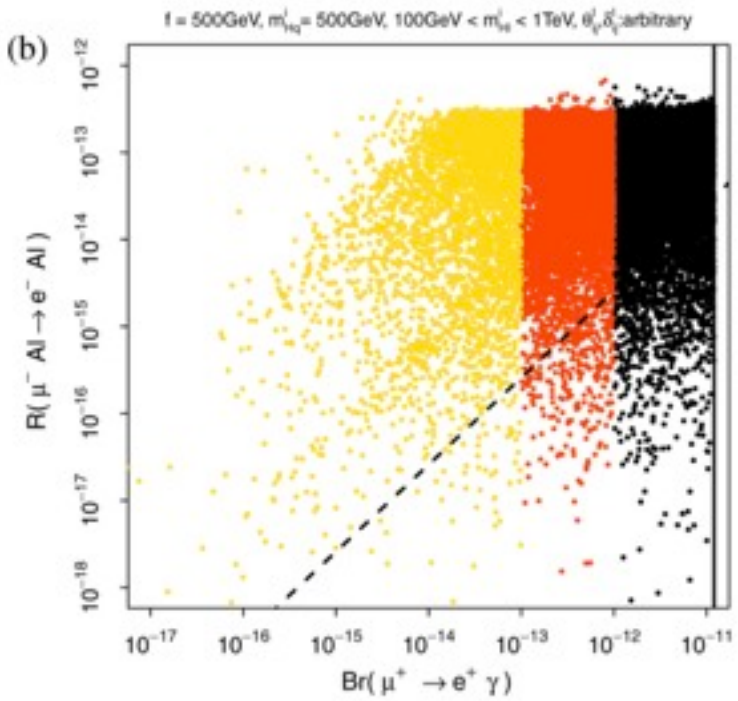
Littlest-Higgs model with T parity

- 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.



Models

Littlest Higgs w/T-parity



T. Goto, Y. Okada and Y. Yamamoto
PRD83(2011)053011

Z-penguin

cLFV Process	A 1	A 2	A 3	B 1	B 2	B 3
$\mu \to e\gamma$	1.9×10^{-12}	1.2×10^{-13}	1.3×10^{-13}	1.7×10^{-12}	1.5×10^{-15}	3.6×10^{-15}
$\tau \to e\gamma$	2.9×10^{-11}	3.6×10^{-13}	3.4×10^{-13}	2.4×10^{-11}	2.1×10^{-13}	8.7×10^{-13}
$\tau \to \mu\gamma$	2.7×10^{-12}	3.4×10^{-13}	3.3×10^{-13}	2.3×10^{-12}	2.0×10^{-15}	7.7×10^{-16}
$\mu \to 3e$	2.9×10^{-14}	3.3×10^{-15}	2.7×10^{-15}	3.0×10^{-14}	2.4×10^{-15}	1.8×10^{-15}
$\tau \to 3e$	5.5×10^{-16}	7.6×10^{-17}	1.3×10^{-16}	5.3×10^{-16}	3.4×10^{-17}	9.2×10^{-17}
$\tau \to 3\mu$	2.9×10^{-14}	4.4×10^{-15}	4.7×10^{-15}	3.1×10^{-14}	3.2×10^{-15}	3.6×10^{-15}
$\mu - e$, Au	1.2×10^{-13}	2.5×10^{-14}	2.7×10^{-14}	1.4×10^{-13}	2.0×10^{-14}	2.1×10^{-14}
$\mu - e$, Ti	6.7×10^{-14}	2.8×10^{-14}	2.2×10^{-14}	8.4×10^{-14}	2.2×10^{-14}	1.6×10^{-14}
$\tau \to e\eta$	4.3×10^{-17}	4.5×10^{-18}	1.3×10^{-17}	4.6×10^{-17}	4.7×10^{-18}	1.3×10^{-17}
$\tau \to \mu\eta$	4.0×10^{-15}	4.2×10^{-16}	4.7×10^{-16}	4.3×10^{-15}	4.3×10^{-16}	4.9×10^{-16}

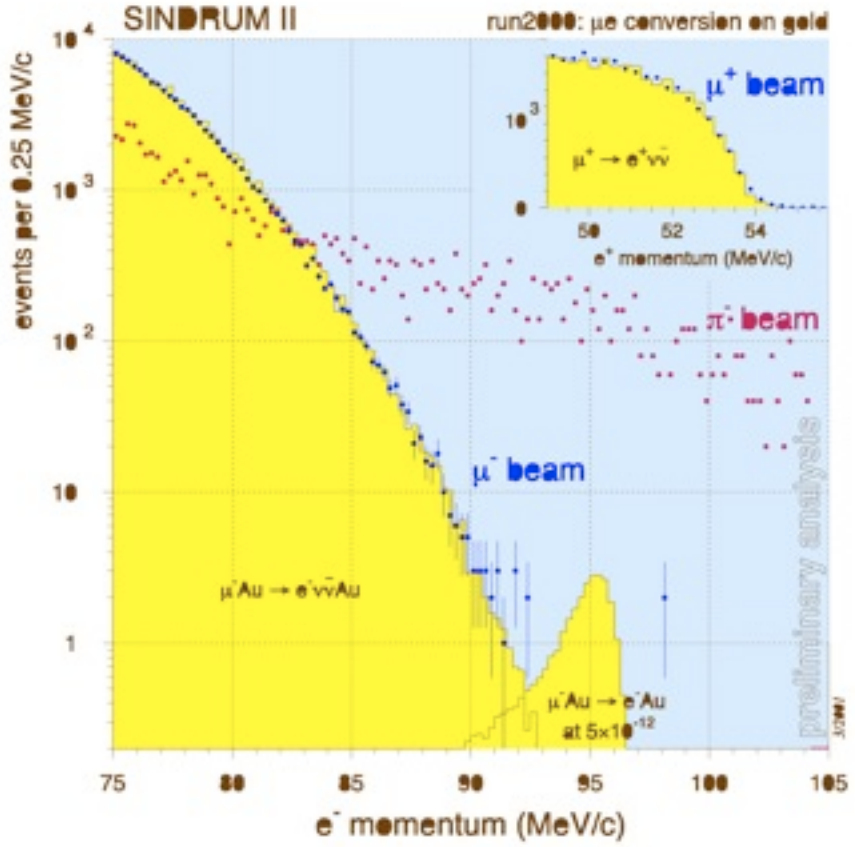
Table 3: Results for several lepton flavour violating processes for the benchmark points of Table 2 supplemented with three different singlet spectra.

A. Abada et al., arXiv:1206.6497

Principle of Measurement

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

SINDRUM II



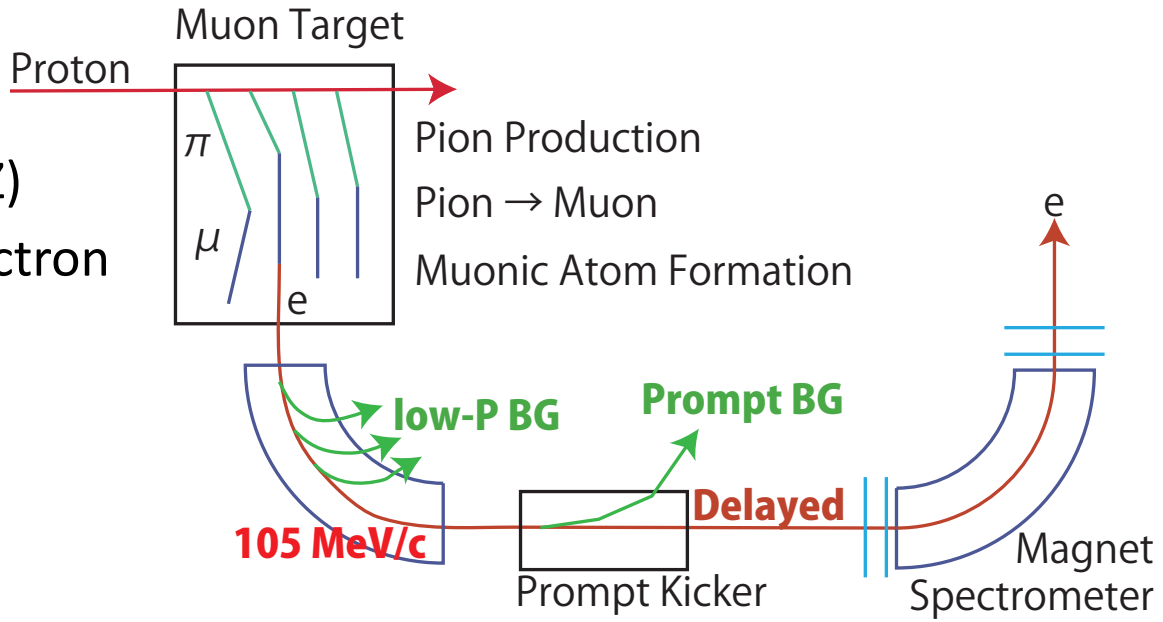
Recent Upper Limits

SINDRUM-II: BR[$\mu^- + Au \rightarrow e^- + Au$] < 7×10^{-13}

SINDRUM-II: BR[$\mu^- + Ti \rightarrow e^- + Ti$] < 4.3×10^{-12}

TRIUMF: BR[$\mu^- + Ti \rightarrow e^- + Ti$] < 4.6×10^{-12}

DeeMe(P41)



- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
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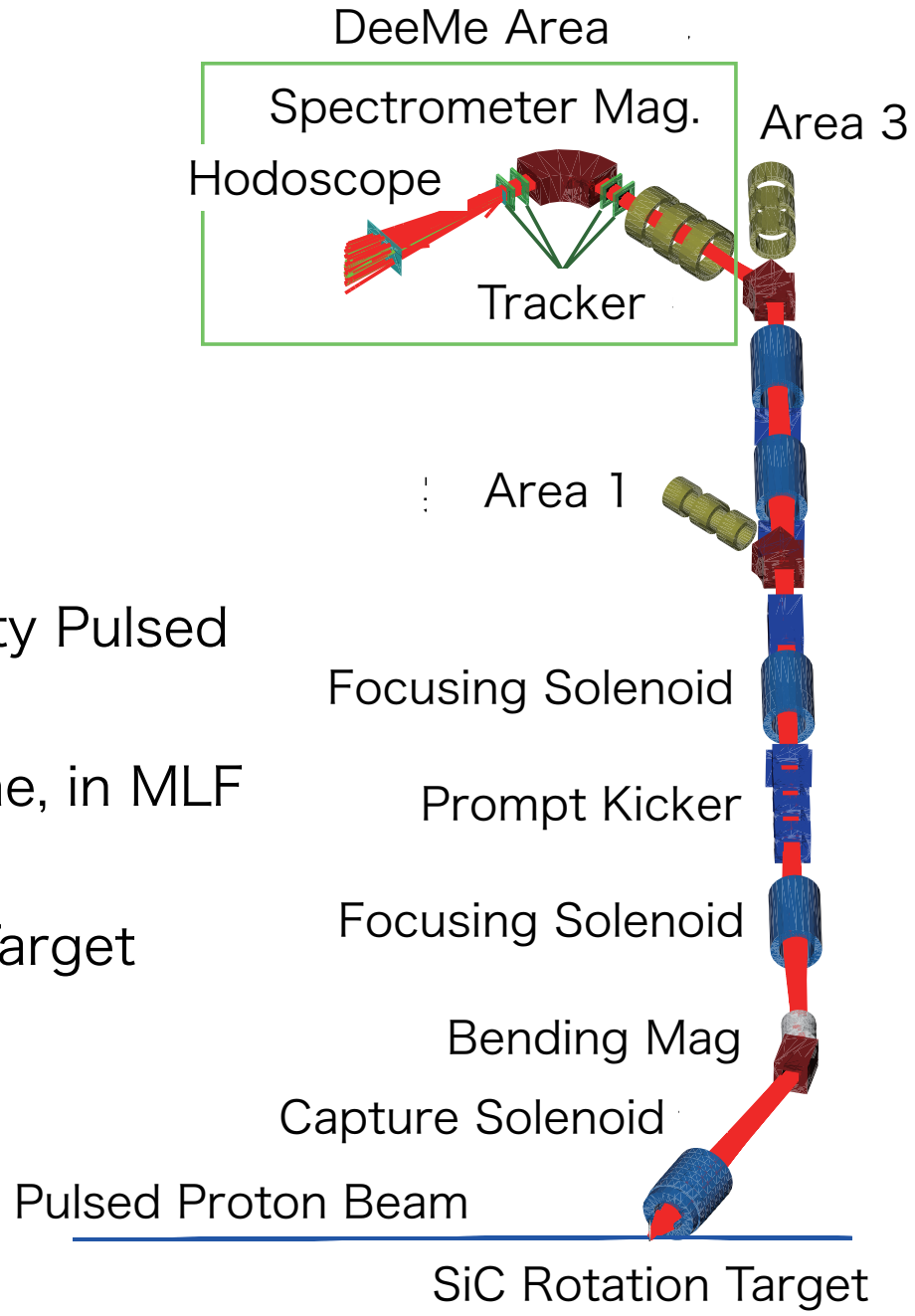
  - Beam Pion Capture
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - Prompt timing

- Low Energy main part: suppressed by the beamline.
- High Energy tail: Magnet Spectrometer ($\Delta p <$ 0.3%)
- Main pulse: Kicker to reduce the detector rate.
- after-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{AP}<10^{-17}$.

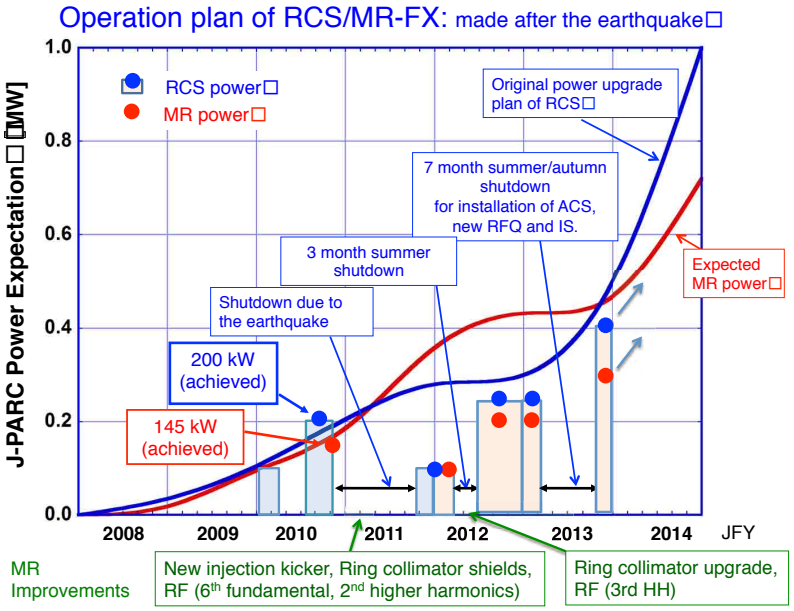
DeeMe

- Search for μ-e conversion in nuclear field at 10^{-14}
- J-PARC RCS
  - High Power High Quality Pulsed Proton Beam
- H-Line, multipurpose beamline, in MLF
  - Large Acceptance
- SiC Muon Production/Stop Target
  - $\mu^- + Si \rightarrow e^- + Si$
- Electron Spectrometer
- Prompt Kicker

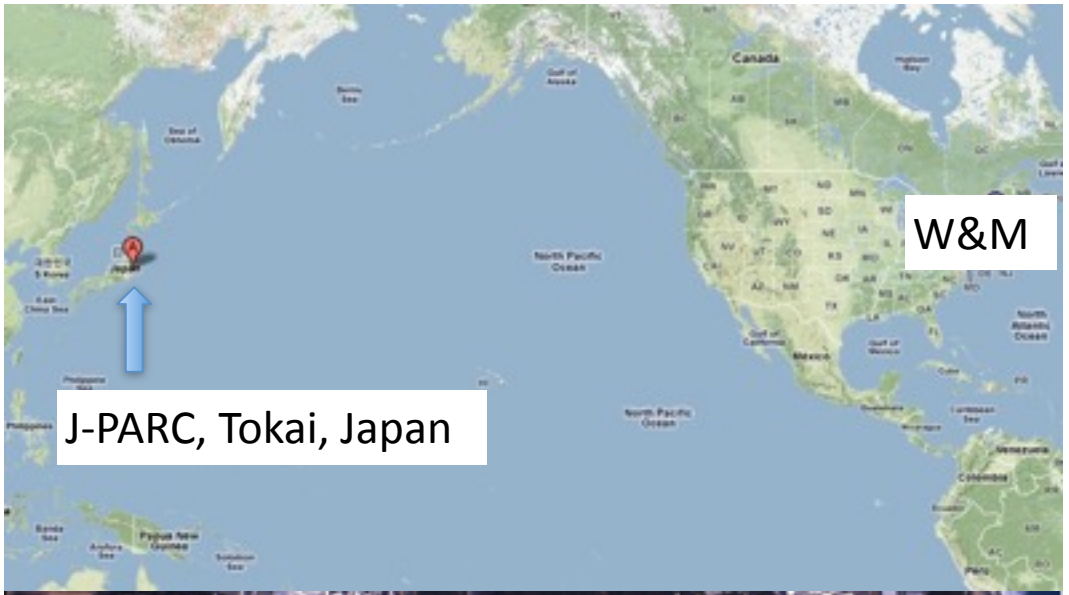


Site: J-PARC

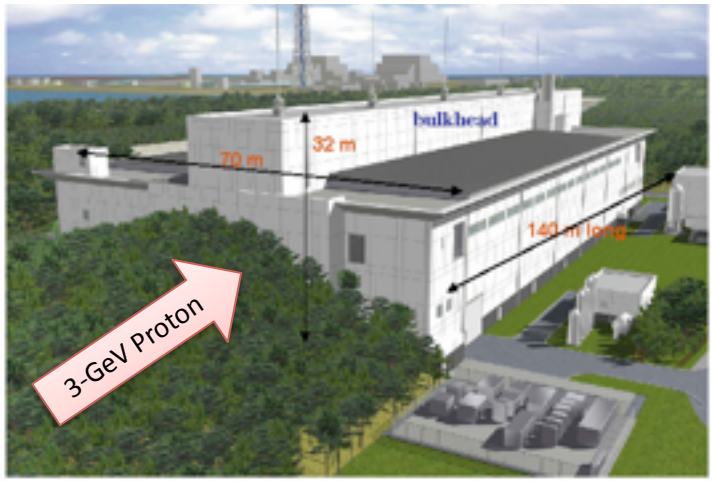
- LINAC
  - H^-, 400 MeV, 50 mA
  - 50 Hz
- RCS
  - 3 GeV, 333 μA, 1MW
  - 25 Hz, Fast Extraction
  - Material and Life-science Facility (MLF)
- MR
  - 30 GeV, 15 μA
  - Fast and Slow EX

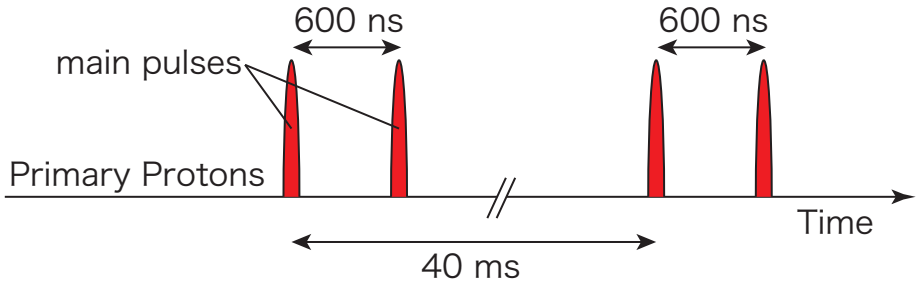


T. Koseki @J-PARC PAC presentation

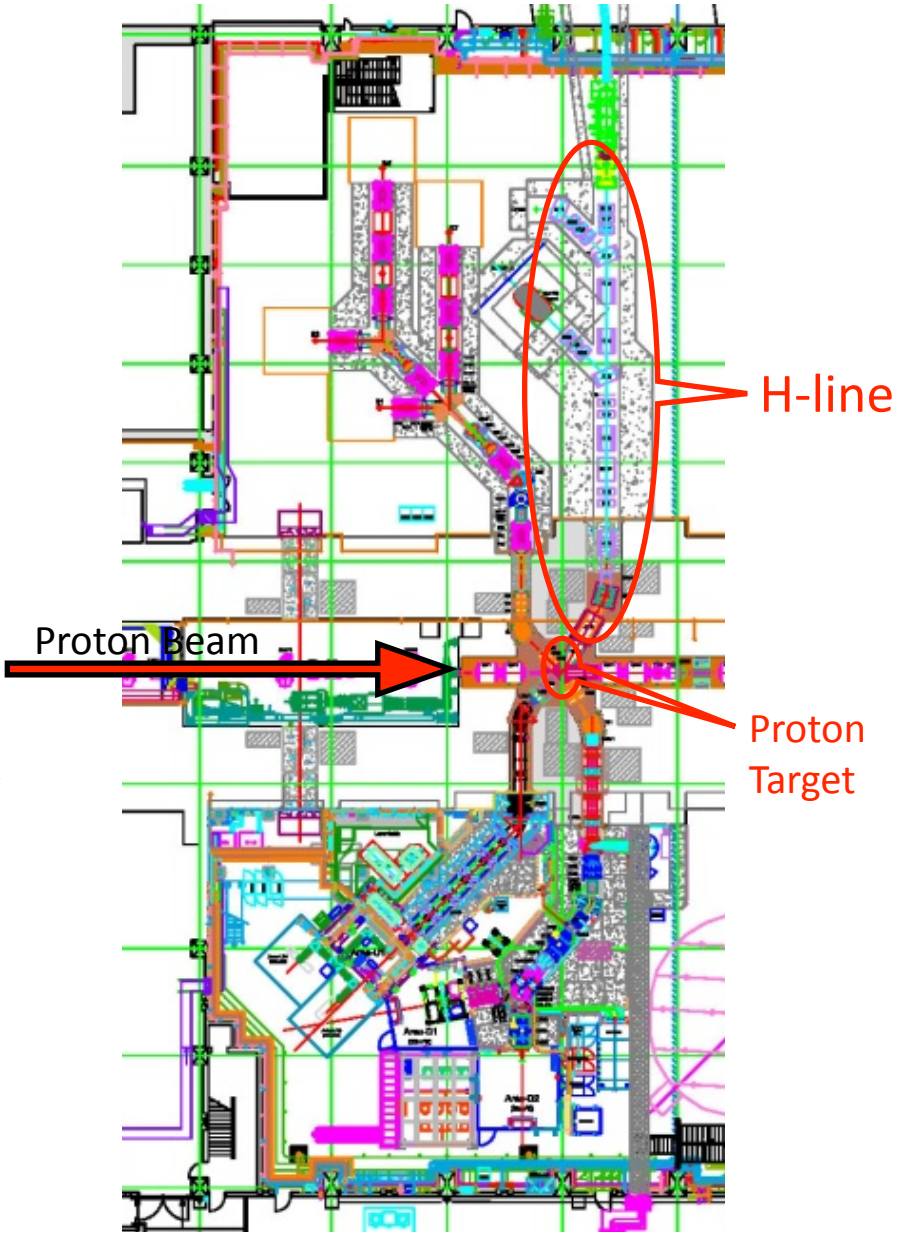


J-PARC MLF Muon Facility



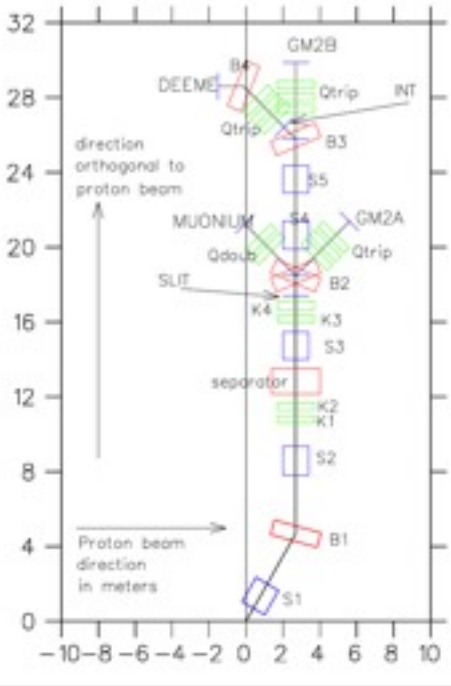


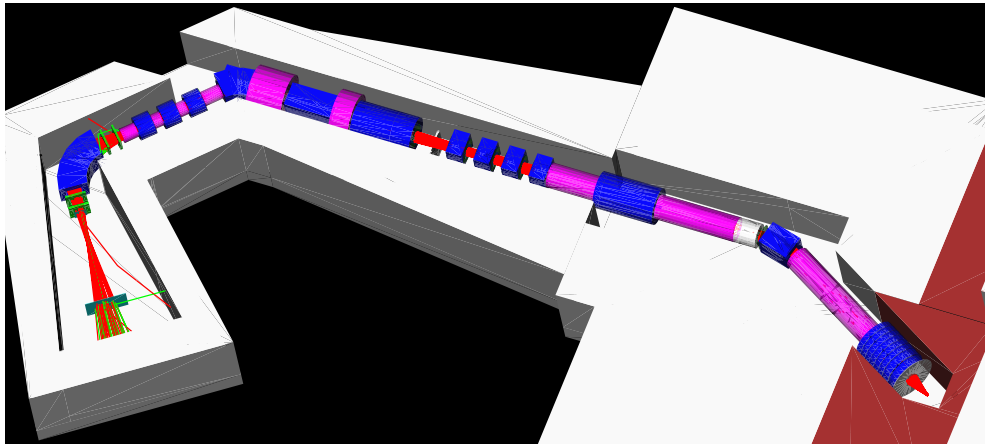
- 1 MW : 3 GeV, 333 μA
  - High statistics
- Fast-Extracted Pulse Beam: 25 Hz 50 pulses
  - Extremely small after-protons

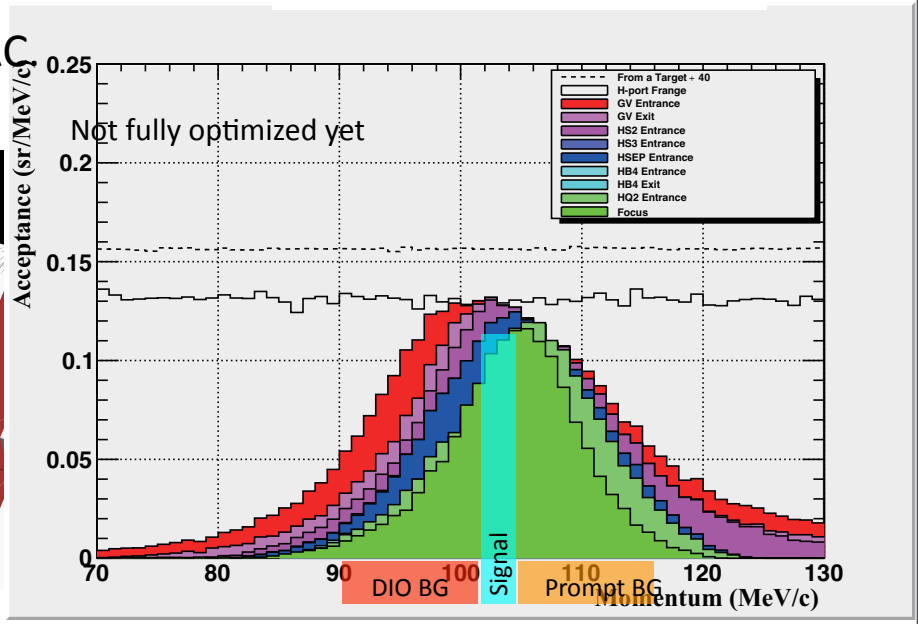


H-Line

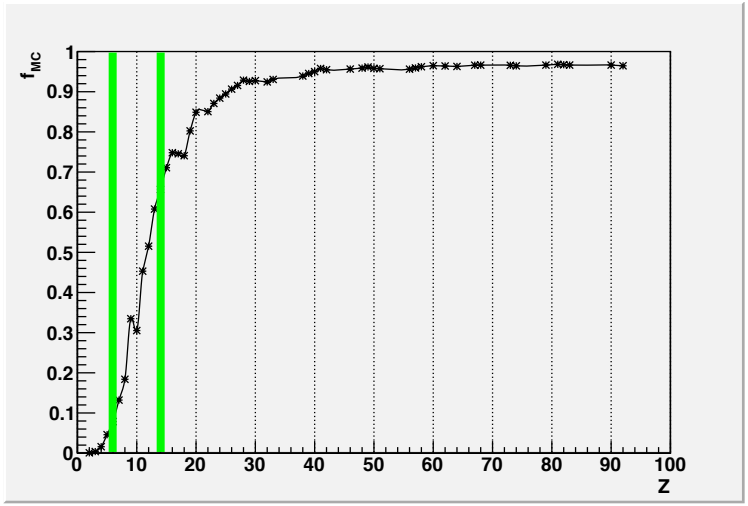
- the 1st concept by **Jaap Doornbos** (TRIUMF)
  - **multi purpose beamline**
    - **DeeMe + g-2 + muonium-HFS**
  - large acceptance
    - > 110 msr
  - straight section for kickers and a separator.
  - moderate Δp so that the BG's can be monitored simultaneously.
    - DIO backgrounds (p < 102.5 MeV/c)
    - Prompt backgrounds (p > 105.0 MeV/c)
- Detailed design is ongoing by MUSE/IMSS/J-PARC



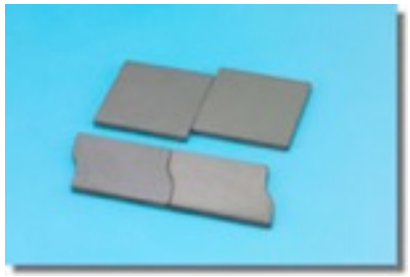




SiC Target



- f_{MC}: muonic nuclear-capture rate
  - $(1-f_{MC})=f_{free\text{-}decay}$ --- useless muons: large f_{MC} is better: larger Z.
- On the other hand, τ_{μ^-} > 300 nsec (light Z) to avoid the prompt background
- f_C: Fraction of the atomic capture of muon to the atom of interest
  - single-element material: $f_c = 1$
  - composite material: proportional to Z (Fermi-Teller Z law)
    - Silicon-Carbide --- Si:C = 7:3
- Silicon-Carbide:
  - good thermal shock resistance: ΔT=450°C
  - high melting point: >1450°C
  - good radiation resistance
    - 10 dpa @ 1000°C or more



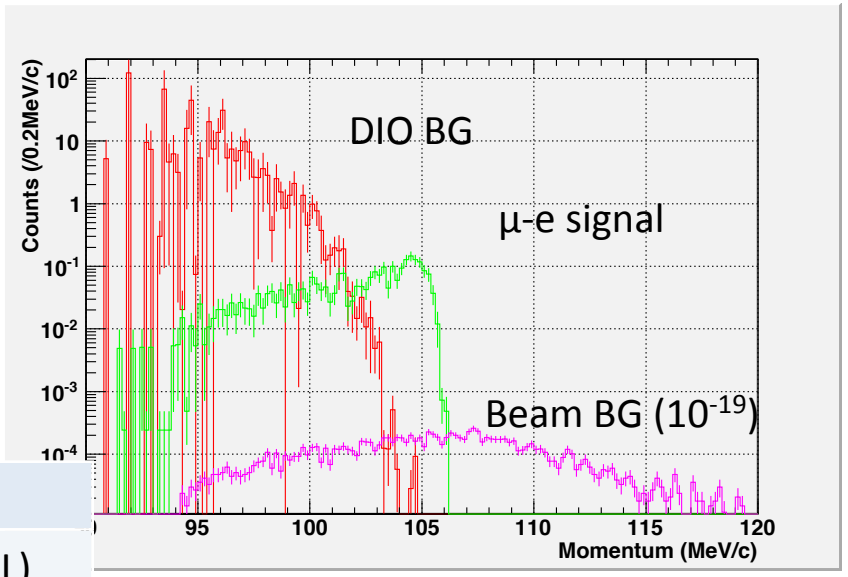
Silicon Carbide
- CERASIC

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

SiC Muon Target: 6 times higher physics sensitivity!!!

Sensitivity and Backgrounds

- Signal Sensitivity
  - S.E.S.: 2×10^{-14} (1 MW, 2×10^{7}sec)
- Backgrounds
  - $R_{AP} < 9 \times 10^{-19}$
  - Detector live-time Duty = 1/20000



Signal Region: 102.0 -- 105.6 MeV/*c*

DIO Background	0.09
After-Proton Background	< 0.027 (<0.05 90%CL)
Cosmic-Muon Induced Electron BG	<0.018 (MC stat. limited)
Cosmic-Muon Induced Muon BG	<0.001
Radiative Muon Capture BG	<0.0009

- If we could extend the running-time up to 8×10^{7} sec
  - Standard Cut: S.E.S.= 0.5×10^{-14} (N_{BG}<0.64)
  - Tighter Cut: S.E.S.= 0.6×10^{-14} (N_{BG}<0.17)

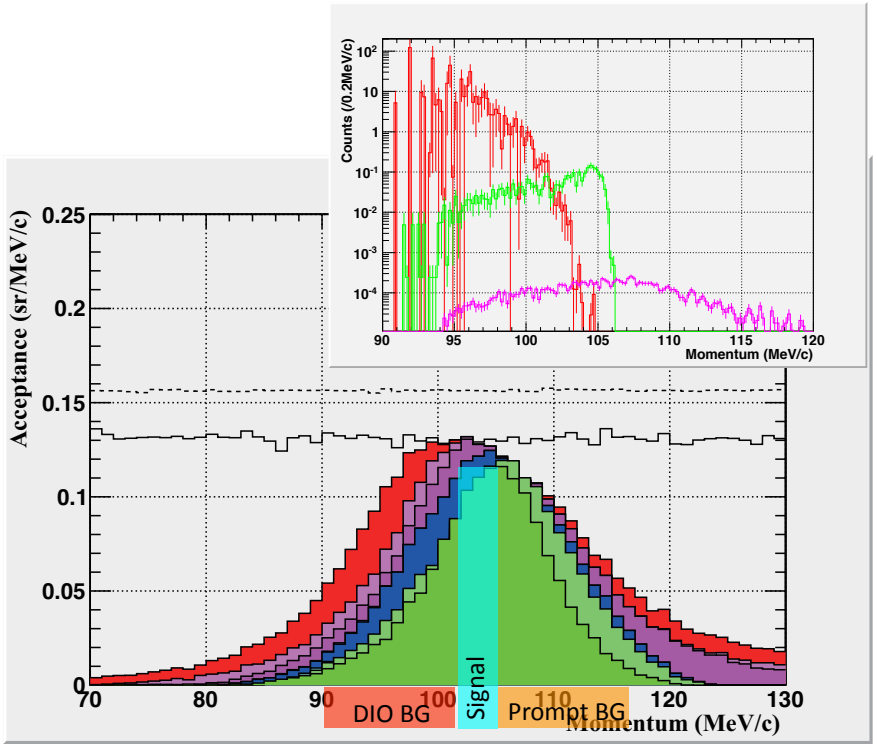
  N_{BG} could be much less with improved BLM system.

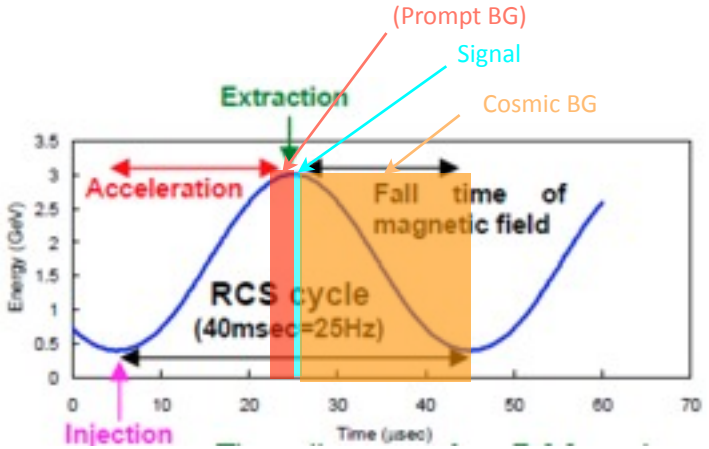
In-situ Monitoring of Backgrounds

- Moderate Δp of H-line makes it possible to monitor backgrounds in situ.
  - DIO backgrounds (p < 102.0 MeV/c)
  - After-Proton backgrounds (p > 105.6 MeV/c)

- Signal Sensitivity Calibration
  - Calibrated by using number of DIO electrons.
  - N_{DIO}=300 (2e7 sec)

- Background Monitoring
  - DIO electrons
    - shape
    - yield
  - After-Proton Backgrounds
    - p>105.0 MeV/c (direct upper limit)
    - Beam-loss counters in RCS(pre-, post-)
  - Cosmic-induced Backgrounds
    - Beam-on: 50μsec/sec
    - Beam-off: >500msec/sec





Status of DeeMe

- Proposal submitted to IPNS PAC in Jan. 2011.
  - Under examination. Discussion is ongoing.
- Proposal submitted to IMSS/MUSE(MLF muon facility group) S-type program in Jan. 2011.
  - **Stage-1 was already approved in Jan. 2011.**
  - Working very hard on the implementation with MUSE group.
    - SiC rotating target development by KAKENHI(S).
    - H-line design/construction.
- Grant-in-Aid for Scientific Research (S) was adopted
  - **1.678 Oku-Yen for detector and target construction**.
- US-Japan Cooperation Program with BNL C-AD has started.
  - H-Line physics program: DeeMe, g-2/EDM, muonium-HFS.
  - starting-up of **Prompt Kicker development with BNL**.

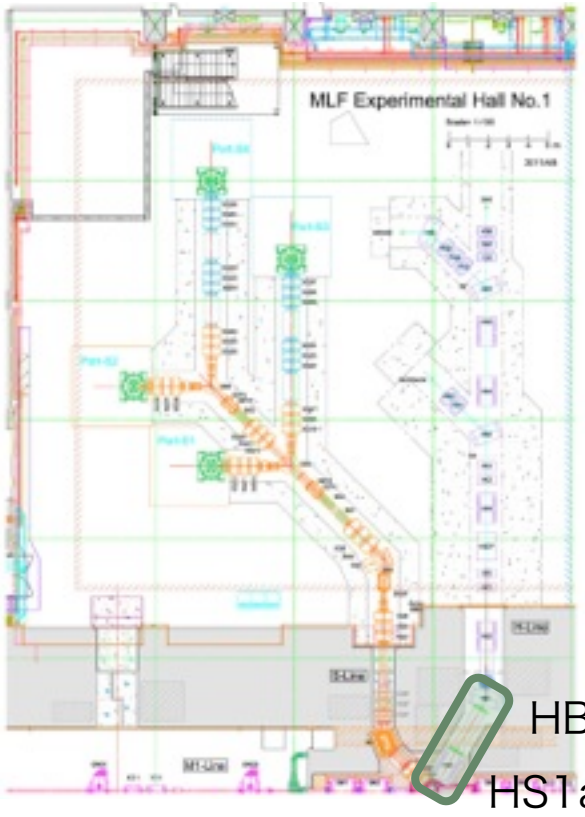
Research and Developments

- After-protons from RCS
  - Developed a measurement at level of $R_{AP} < 10^{-17}$.
- H-line
  - Large Acceptance (> 110 msr).
- SiC Target
  - Larger Young modulus.
  - Affects to the neutron facility.
- Electron Spectrometer
  - Drift Wire Chamber: that can be operated after 33k of the prompt burst.
- Prompt Kicker
  - Large Aperture (320-mm × 320-mm)
  - High Field > 385 G
  - Fast fall < 300 nsec

H-line Construction Status

H-line is multipurpose beamline

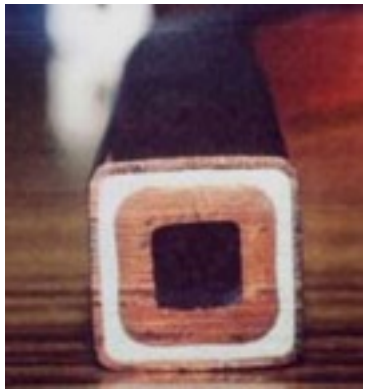
- DeeMe
- g-2/EDM
- muonium HFS
- μCF and other muon programs

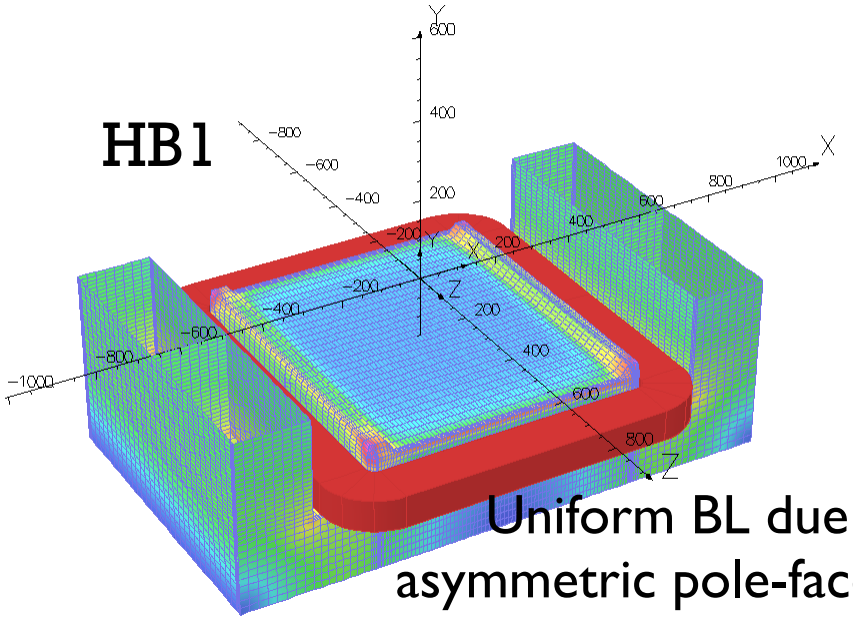


Front-end magnets are already fabricated.

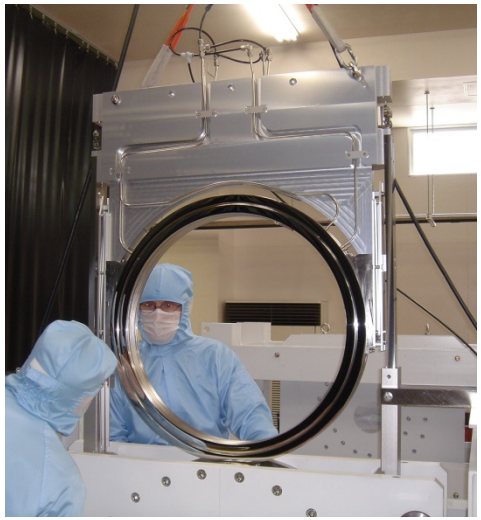
New Developments

Air-core solenoid with small field ripples (1/500) by utilizing shunted secondary-coil (MIC).





Uniform BL due to asymmetric pole-face sims: Full-3D Magnet Design



Extremely-large pillow seal.
600 mm$^{\Phi}$

SiC Rotating Target

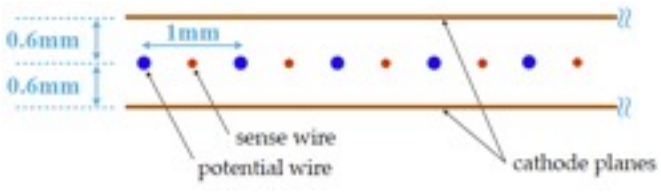
- Extremely important to increase the physics sensitivity:
  - $f_C \times f_{MC}$ = 0.08(C), 0.46(SiC).
  - proton loss: 5% → ~10%
    Discussion with neutron group is ongoing
- Development of a graphite rotating target has almost completed. It will be installed in the summer 2013.
- Build another one with SiC fins instead of graphite fins; planning to install in 2014.

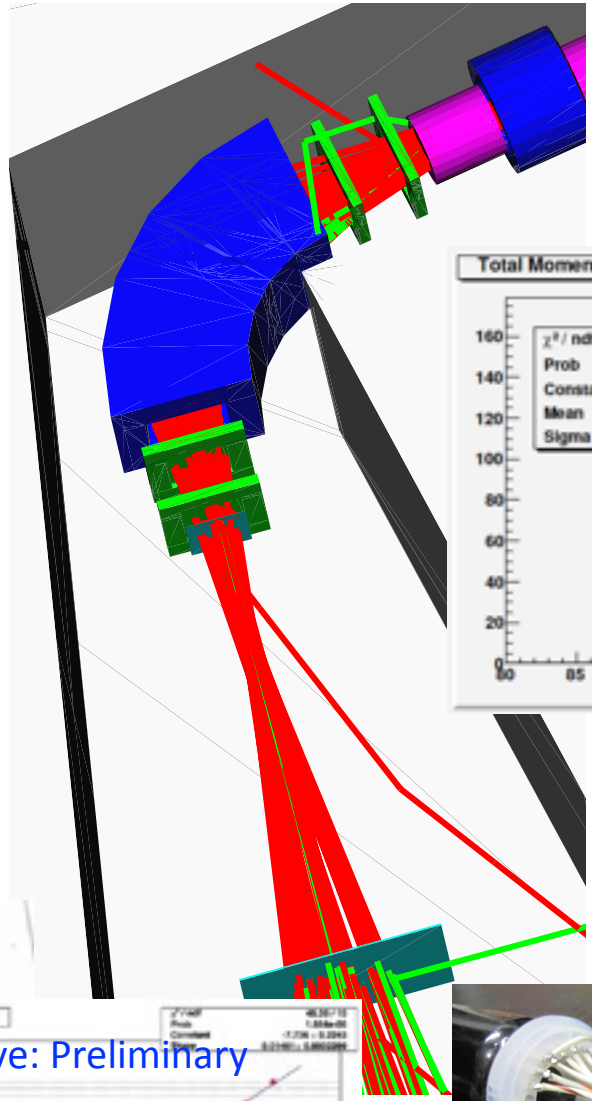
graphite fins

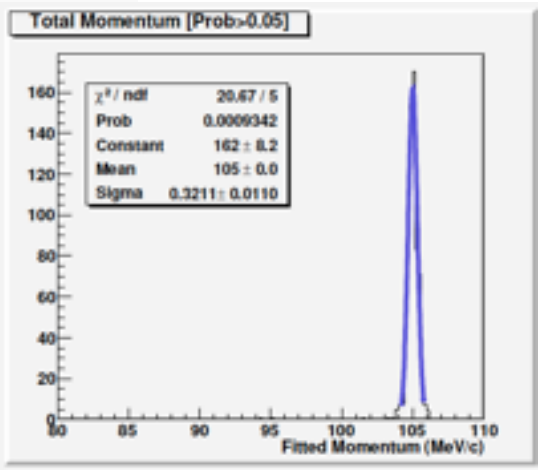
rotating target module

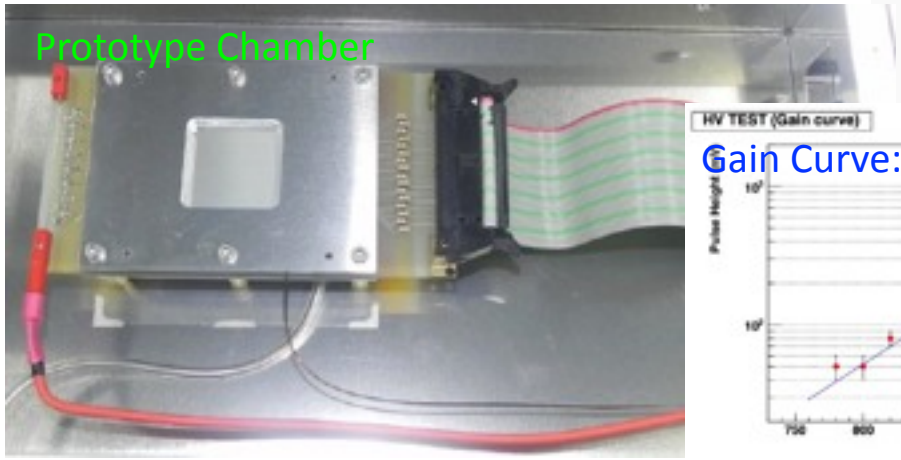
Detector

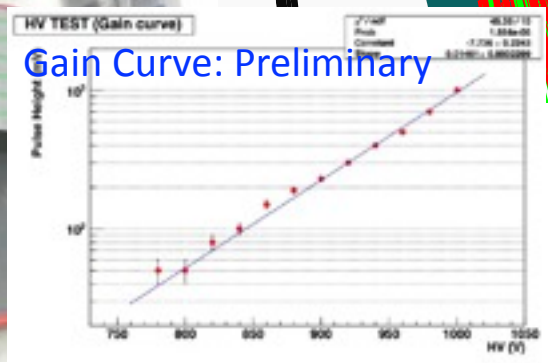
- prompt burst = 33k per pulse
  even after suppressed by the kicker.
- BH1,2: hodoscope
  - gating PMT
- WC1-4: wire chamber
  - micro-cell MWPC
  - prototype fabricated.
  - beam test in coming winter.



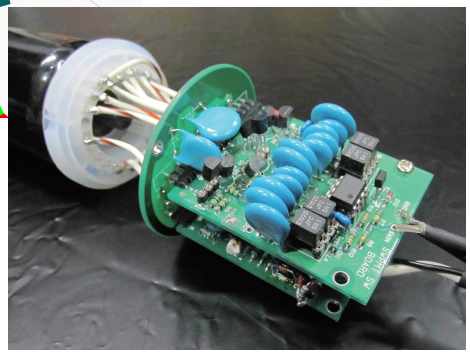








gating PMT



Cost

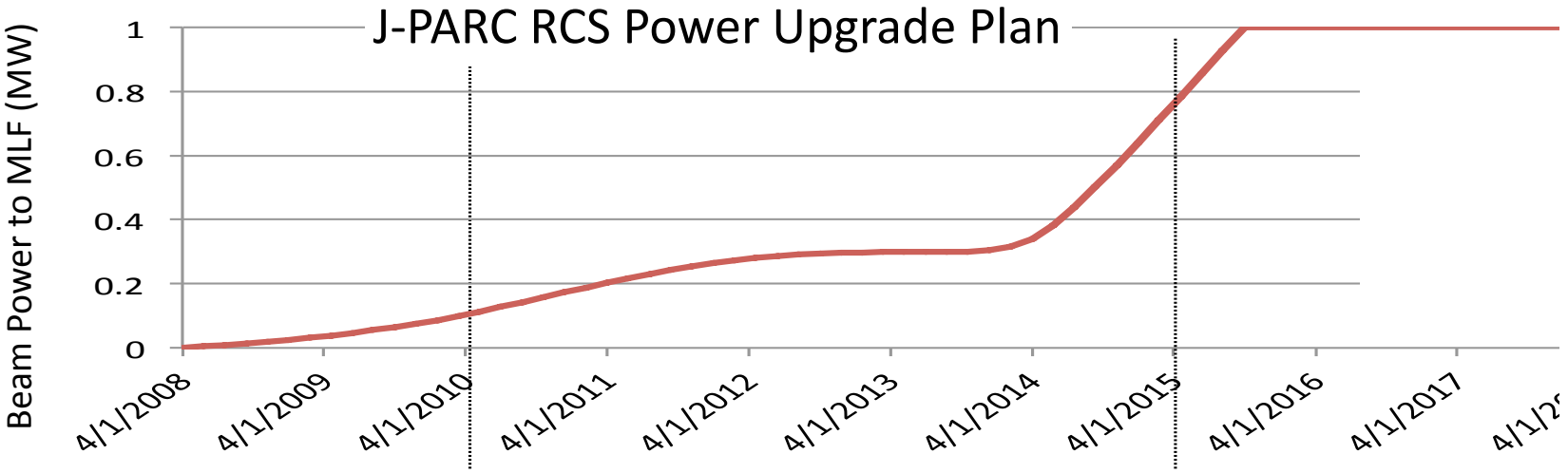
Item	Cost (kJPY)	Note
Detector		
Spectrometer Magnet	20,000	
Magnet Power Supply	10,000	
Hodoscope	10,000	
Tracking Chamber R&D	3,000	
Tracking Chamber	40,000	w/ front-end
Readout Back-end	10,000	
Sub total	*93,000*	
Muon Target Modification		
SiC Target	*25,000*	
Man Power		
postdoc × 2	*45,000*	
Beamline		
H-line Construction	---	borne by IMSS/MUSE
Prompt Kicker		
Kicker Magnets	60,000	
Kicker Power Supply	160,000	
Sub Total	*220,000*	

Grant-in-Aid for Scientific Research (S) -- adopted 2012 -- 2016 JFY

submitted to MEXT

US-Japan cooperation program with BNL has just started.
Exp. can start w/ half of them.

Schedule



SiC Target	fabrication — test — installation
Spectrometer	design — const. — test&inst.
H-Line	construction
Prompt Kicker	design — test — construction
Run	

Summary

- There is a competitive merit of physics in searching for μ-e conversion at sensitivity of 10^{-14} in timely manner.
- It will maximize the achievements at J-PARC.
- DeeMe already has Stage-1 approval from IMSS/MUSE PAC, and MUSE is fully supporting the DeeMe toward the timely realization.
- The installation of front-end magnets of H-line is scheduled in the this summer.
- Grant-in-Aid for Scientific Research (S) is adopted for the construction of detector and SiC target and postdoc.
- Collaboration with BNL C-AD group on the development of the prompt kicker under the framework of US-Japan cooperation program has started.
- We have successfully developed a technique to measure the after-protons. $R_{AP} < 9 \times 10^{-19}$, and this could be more smaller with improved detector system.
- A realistic Monte Carlo study shows that major backgrounds are small enough.
- The DIO, after-protons and cosmic-induced backgrounds can be measured *in-situ*.
- DeeMe collaboration does not see any technical difficulties in the realization of the proposed experiment, and moving forward to the implementation of the experiment in MLF/MUSE facility.

End of Slides