CLFV2016
Charlottesville

Search for Muon to Electron Conversion at J-PARC MLF

The Current Status of DeeMe Experiment

Yohei Nakatsugawa
KEK IMSS

Outline

- Physics Motivation
- DeeMe Experiment
- Current Status
  - Beamline
  - Spectrometer Magnet
  - Detector
  - After-Proton Measurement
  - Muon Production Target
- Summary & Prospects

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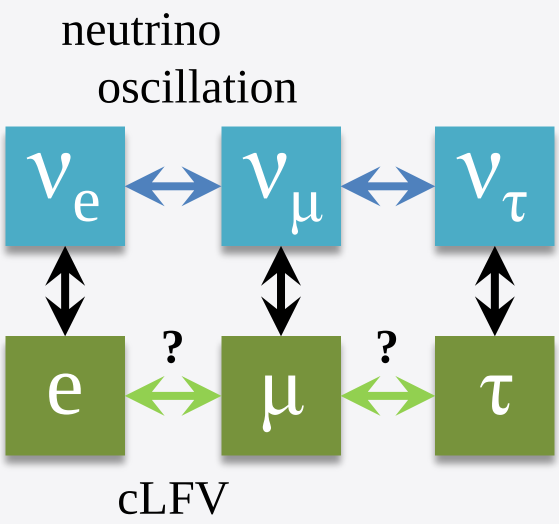
CLFV in muon



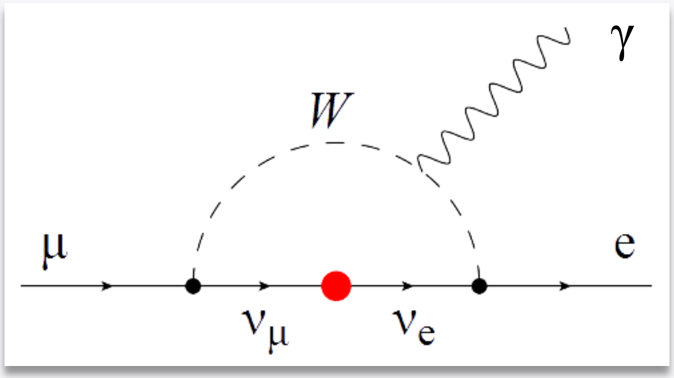
- Lepton Flavor Violation is forbidden in the original Standard Model.
- Neutrino oscillation = Flavor Violation of neutral lepton
- Charged Lepton Flavor Violation (CLFV)
  - process : $\mu \rightarrow e\gamma$, $\mu \rightarrow e\,e\,e$, $\mu N \rightarrow e N$

    … **not observed yet**

- CLFV induced by neutrino flavor mixing

$$\mathrm{BR}(\mu \rightarrow e\gamma) = (\Delta m_{\nu ij}^{2} / M_W^{2})^2 \sim \mathbf{10^{-50}}$$

too small to be observed experimentally
<u>in the framework of the Standard Model</u>



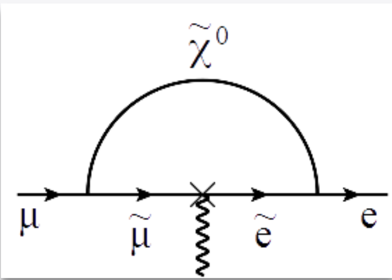
experimental observation of CLFV process

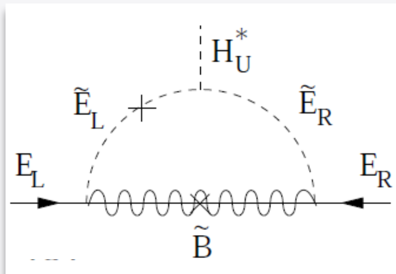
||

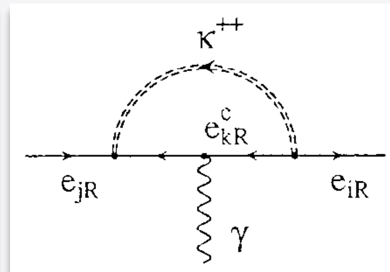
clear evidence of the new physics beyond the Standard Model

CLFV in muon

- Theoretical models beyond the Standard Model
  (SUSY-GUT, SUSY-seesaw, Doubly Charged Higgs , etc..)







sizable branching ratio of CLFV

predicted branching ratio = $\mathbf{10^{-14} \sim 10^{-18}}$ (ex. SUSY-GUT)

- Current upper limit from experiments

$\mu^- N \rightarrow e^- N$	$\mu^+ \rightarrow e^+ \gamma$
SINDRUM-II : BR(μ^- Au $\rightarrow$ e– Au) < 7 × 10^{-13}	MEG : BR($\mu^+ \rightarrow e^+ \gamma$) < 4.2 × 10^{-13} (new!)
SINDRUM-II : BR(μ^- Ti $\rightarrow$ e– Ti) < 4.3 × 10^{-12}	
TRIUMF : BR(μ^- Ti $\rightarrow$ e– Ti) < 4.6 × 10^{-12}	

The discovery is right around the corner.

⇒ A new experimental search with sensitivity under 10^{-13} should be started in a timely manner.

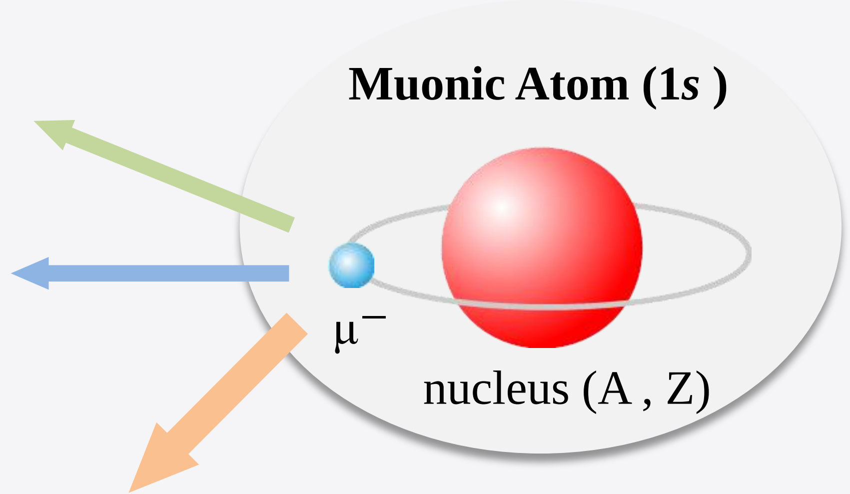
Muon to Electron Conversion in the Nuclear Field

Decay-In-Orbit (DIO)

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

Muon Capture

$\mu^- + N(A, Z) \rightarrow \nu_\mu + N(A,Z\text{-}1)$



μ - e conversion (CLFV)

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

- mono-energetic signal electron (~**105 MeV/c**)
- no accidental backgrounds
- Backgrounds

▪ **Decay-In-Orbit**

nucleus recoil ... higher tail extended
→ signal momentum

the most important BG.

▪ Radiative Pion Capture ← **prompt timing**

$\pi^- + N(A,Z) \rightarrow N(A,Z\text{-}1)^*$
$\rightarrow \gamma + N(A,Z\text{-}1)$, $\gamma \rightarrow e^+ e^-$

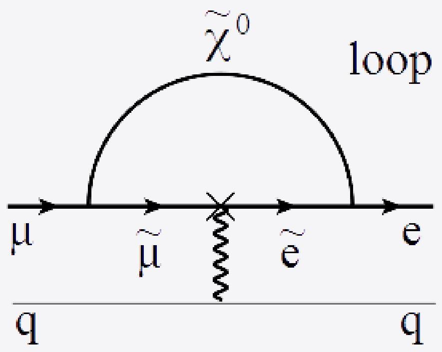
▪ Beam related BG (After-Proton)

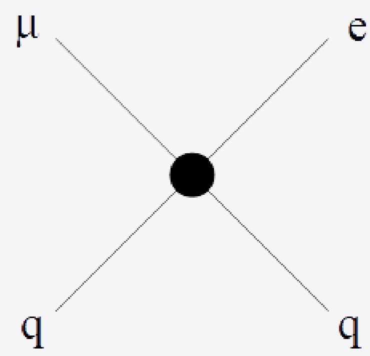
Sensitivity to Reaction Mechanism

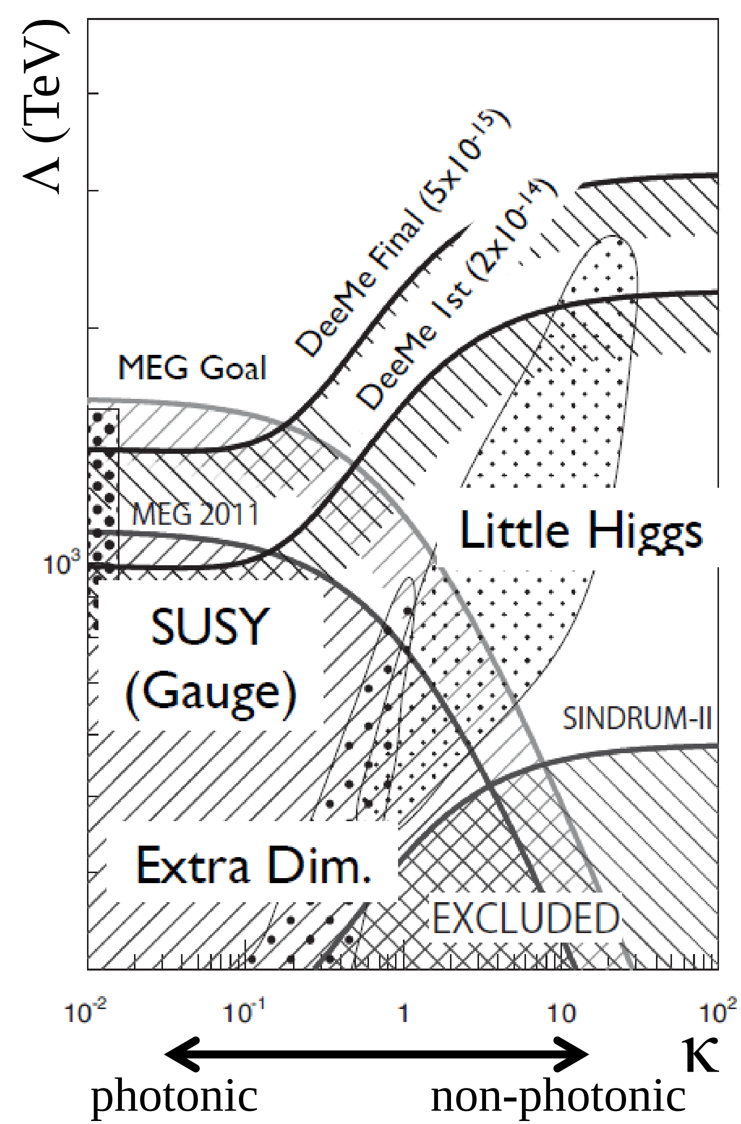
- Effective Lagrangian

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\overline{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\overline{\mu}_L\gamma^\mu e_L)(\overline{q}_L\gamma_\mu q_L)$$

photonic **non-photonic**







μ − e conversion in the nuclear field

... **sensitive to both photonic and non-photonic processes**

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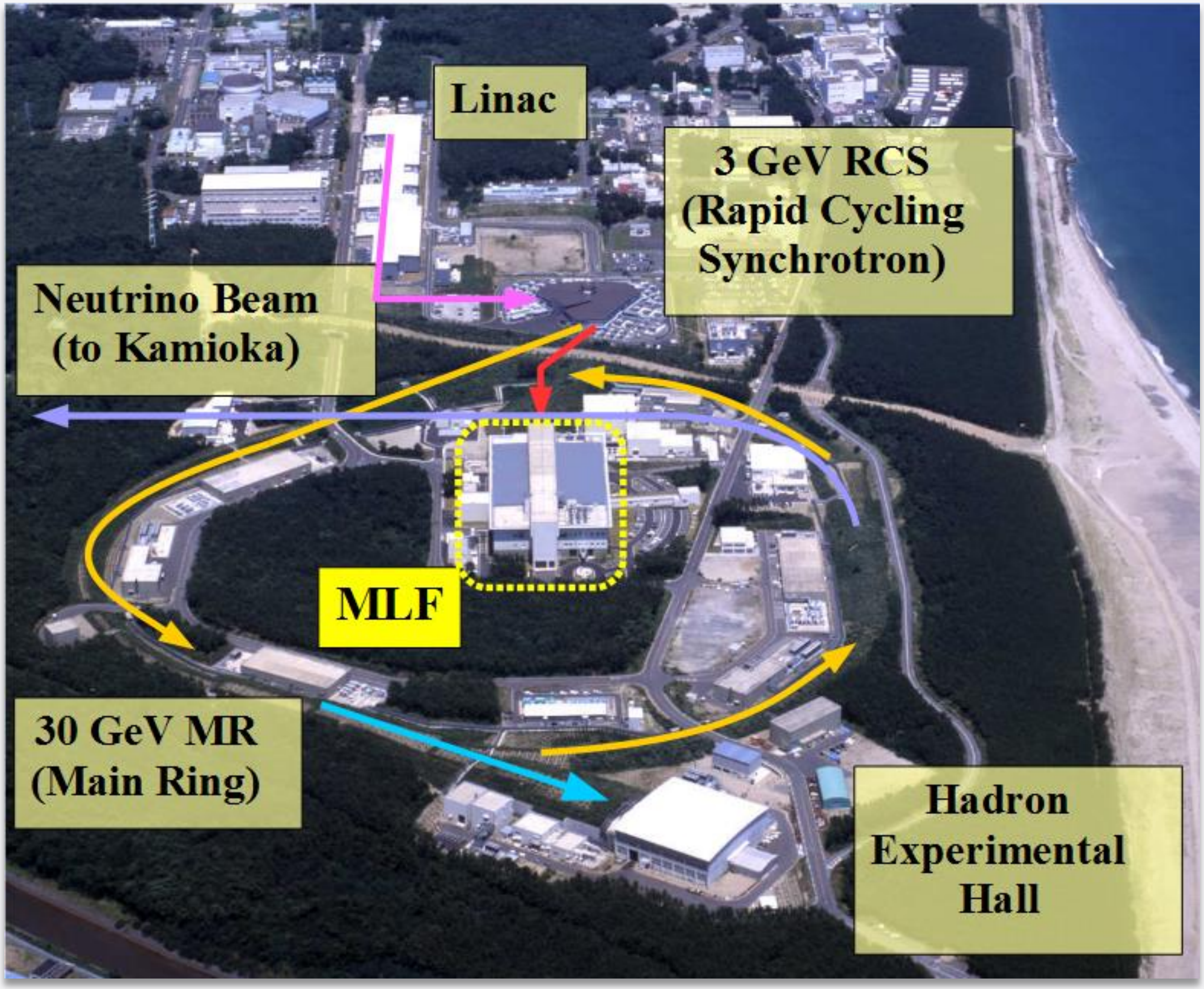
DeeMe Experiment @ J-PARC

- new μ – e conversion search , **DeeMe** at **J-PARC Material and Life Science Experimental Facility (MLF)**



- MLF

primary proton beam

▪**3 GeV, 500 kW**
→ will be upgraded to **<u>1 MW</u>** .

muon production target
→ 4 beamlines (MUSE)

neutron production target
→ more than 20 beamlines

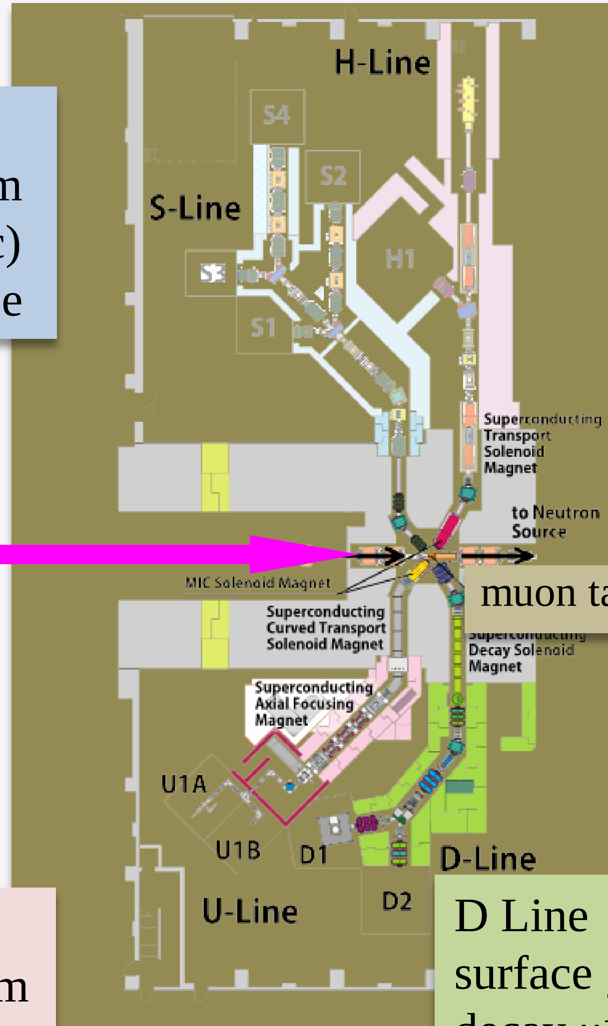
MLF MUSE

- **J-PARC MLF Muon Science Establishment (MUSE)**

S Line
surface μ^+ beam
(30 MeV/c)
material science

3GeV proton beam

muon target

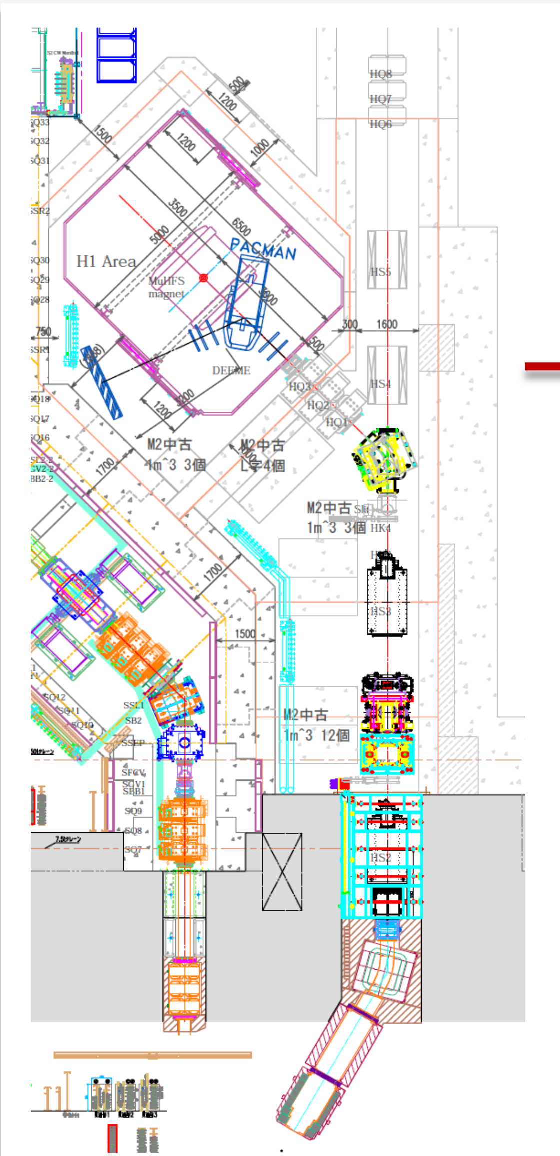


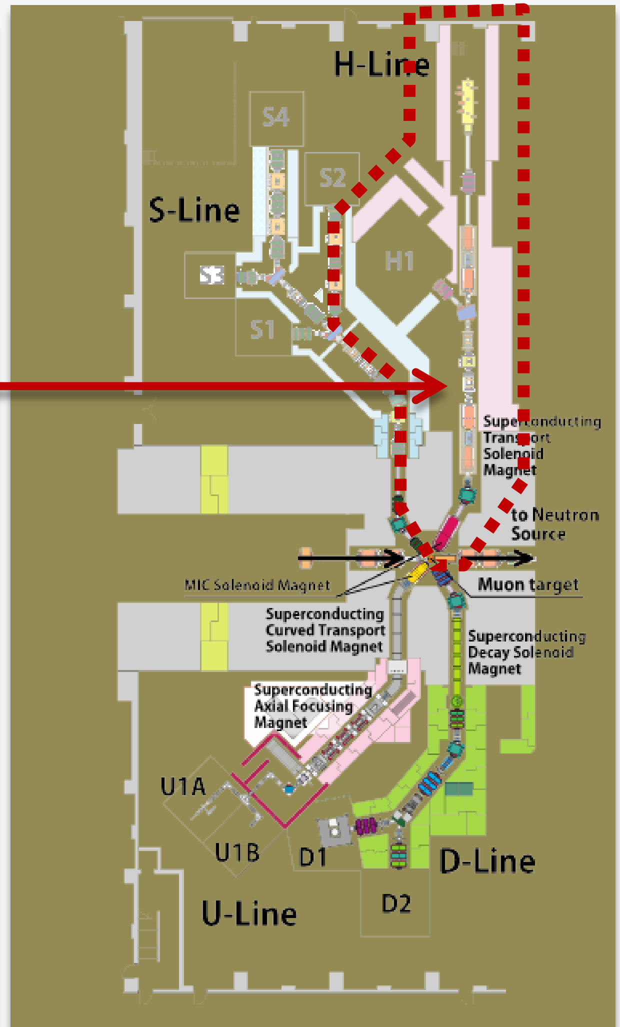
U Line
ultra slow μ^+ beam
(0.05-60 keV)
material science

D Line
surface μ^+ beam (30 MeV/c)
decay μ^+/μ^- beam (5-120 MeV/c)
material science
in operation for users' experiment

MLF MUSE

J-PARC MLF Muon Science Establishment (MUSE)





H Line

<u>for fundamental physics</u>

multipurpose beamline

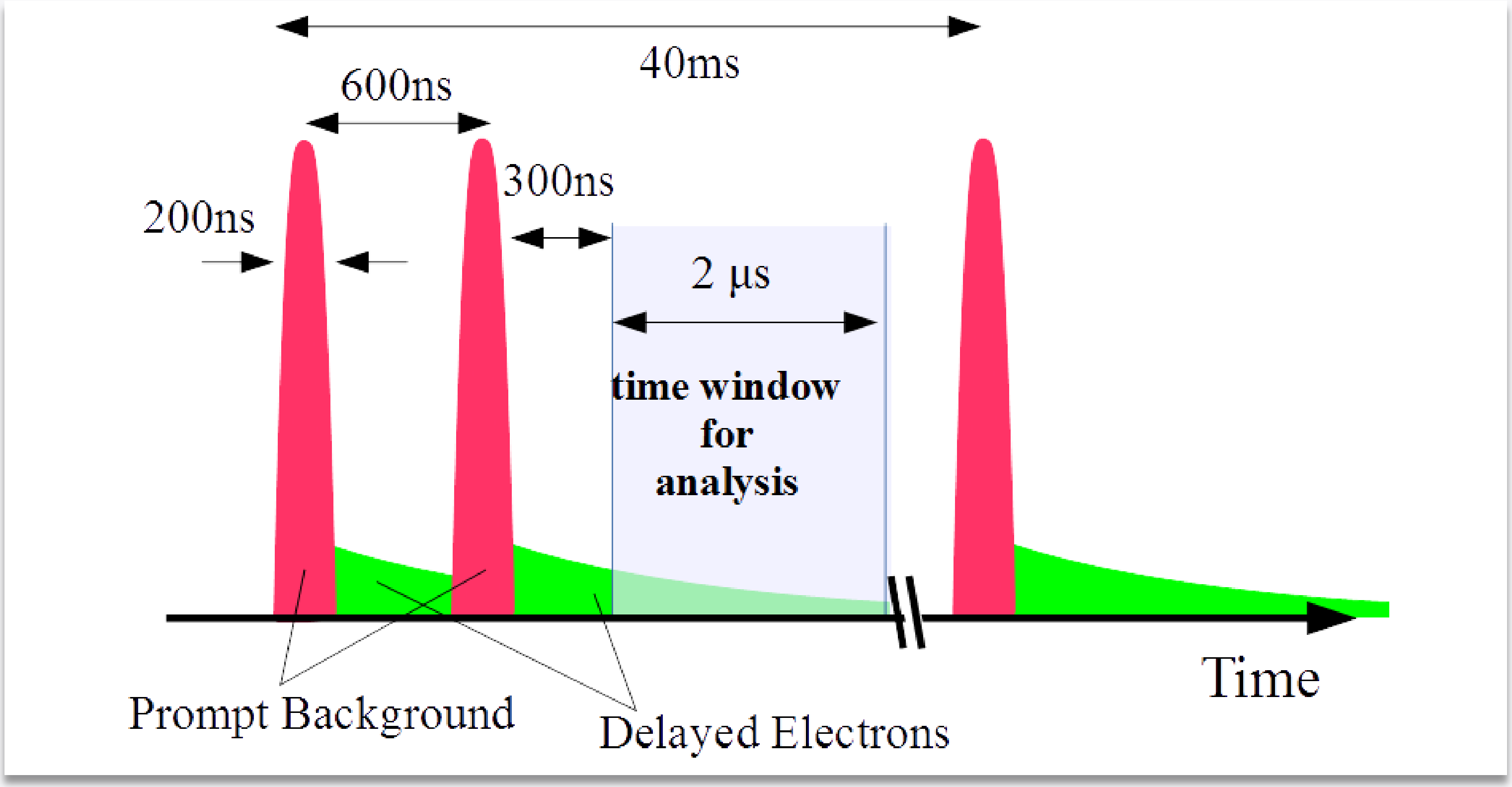
- μ-e conversion search (DeeMe)
- muonium hyperfine splitting
- g-2/EDM
- muon microscopy

conceptual design
by Jaap Doornbos (TRIUMF)

Beam Structure & Time Window

- pulsed proton beam 25 Hz double pulse: 200nsec width, 600nsec interval

Time window for analysis at 300nsec after the second pulse
⇒ reject the prompt burst



- **beam energy = 3 GeV**

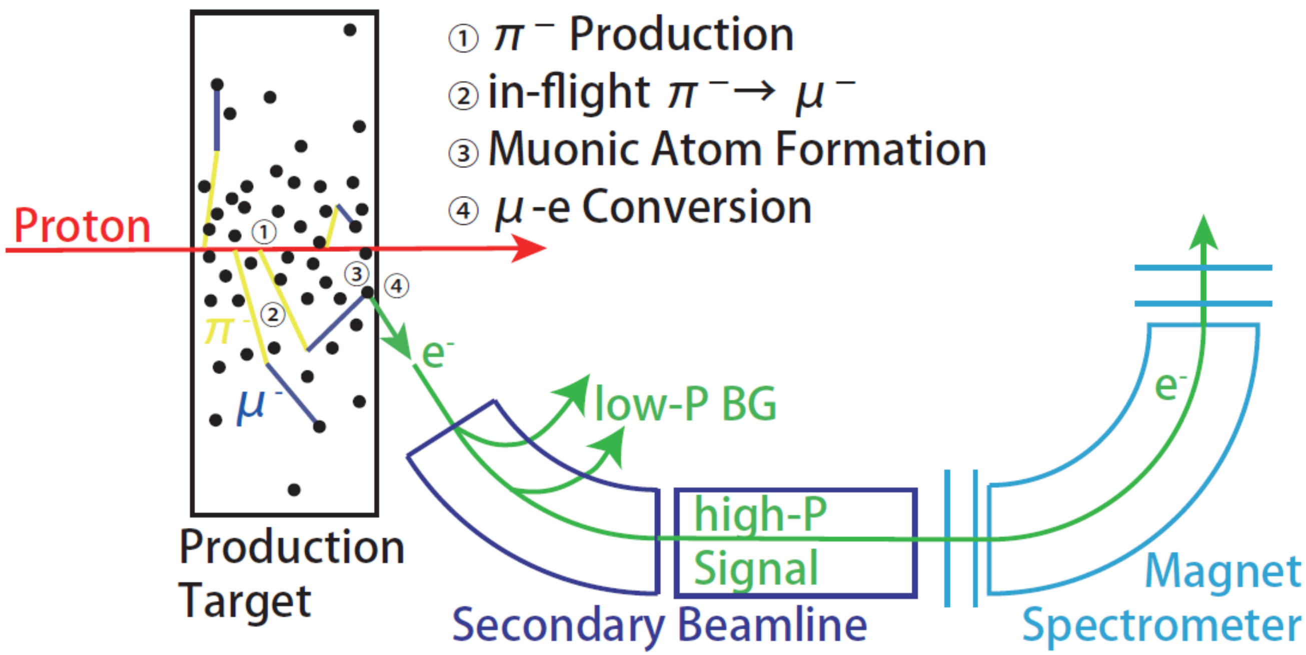
  < $\bar{\mathbf{p}}$ production threshold
  ⇒ no $\bar{p}$ induced backgrounds

- **fast extracted beam**

  no off-timing proton
  ⇒ no prompt background
  at time window

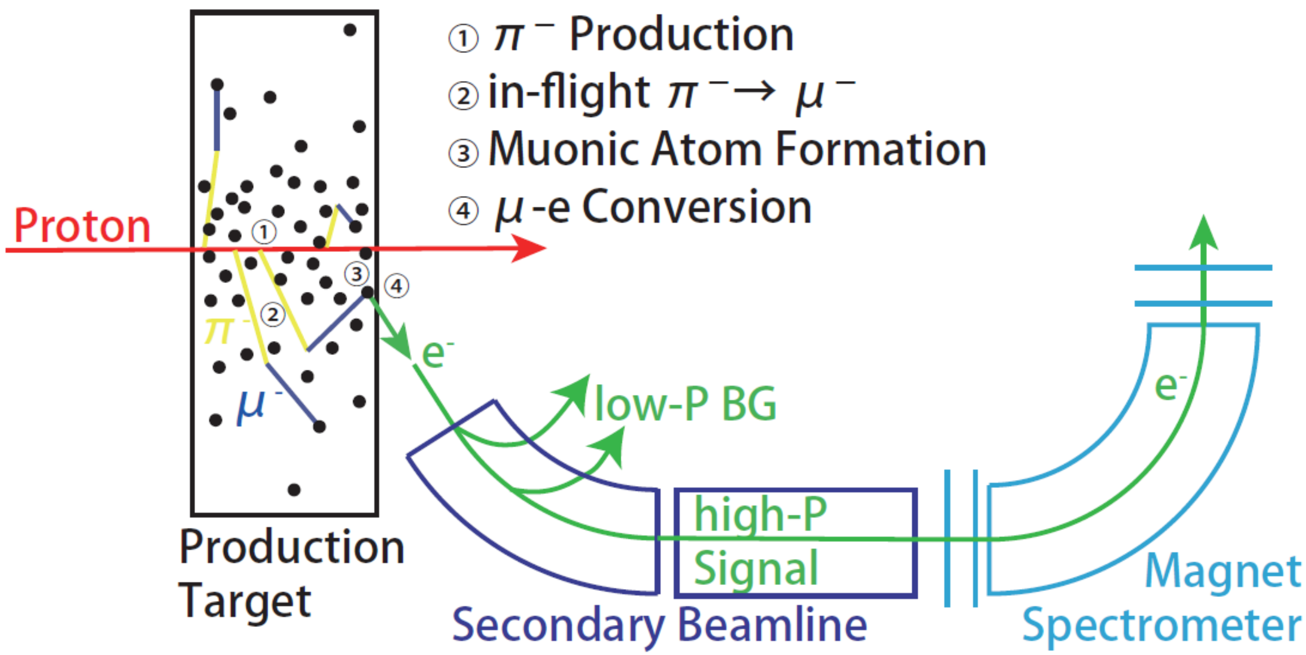
Principle of Experiment

Concept of DeeMe



Principle of Experiment

Concept of DeeMe



= μ^- stopping target

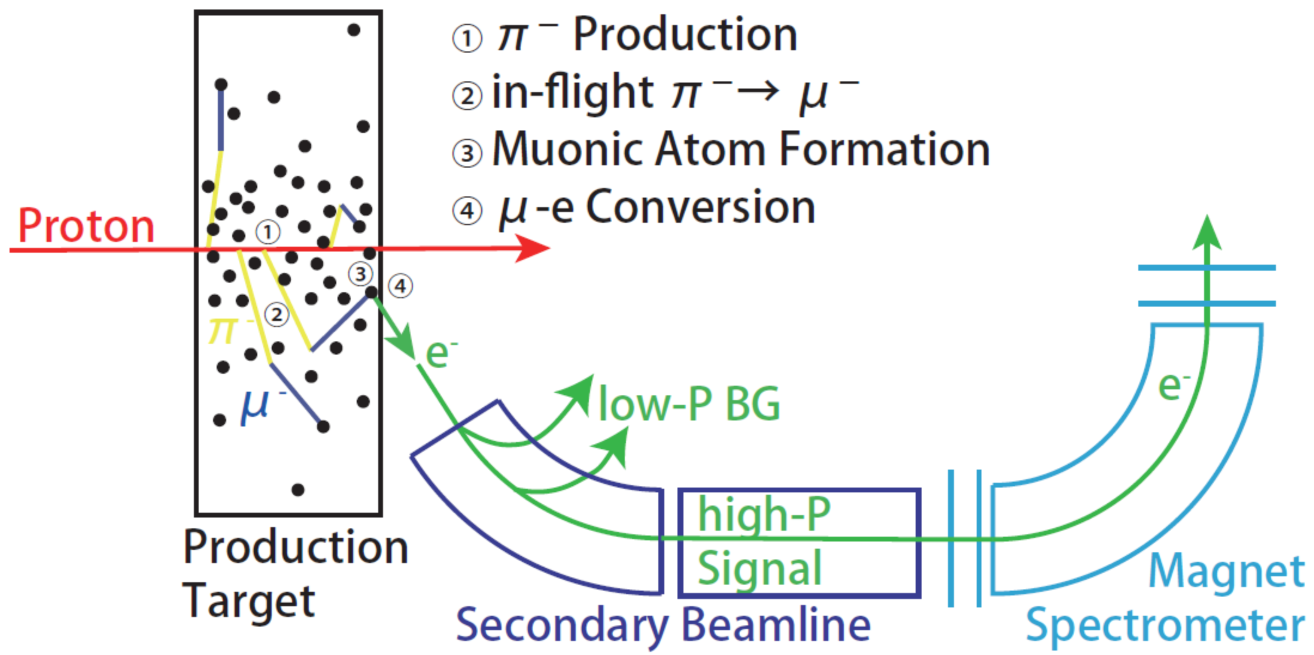
utilize muonic atoms
formed in the production target

→ NO π^- decay volume
NO additional stopping target

↔ conventional μ–e search

Principle of Experiment

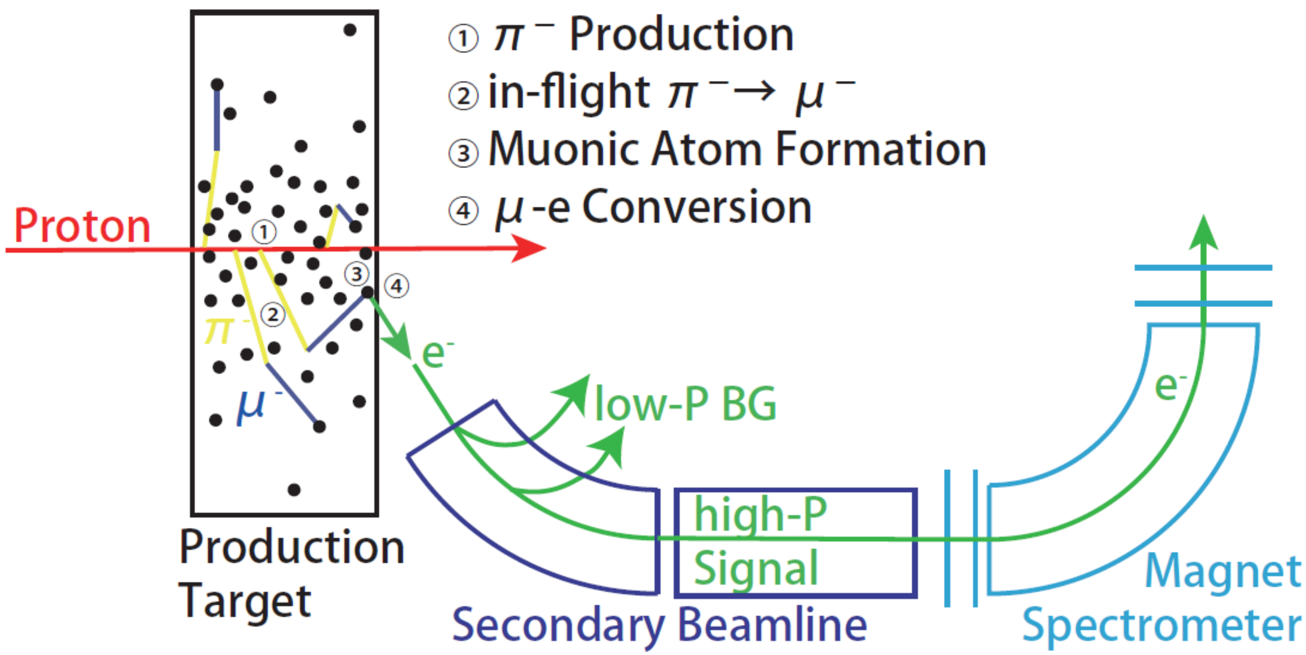
Concept of DeeMe



- transport signal electrons (105 MeV/c) ⇒ ▪momentum selection
- Beam optics is optimized for signal electrons. ▪suppress low momentum backgrounds

Principle of Experiment

Concept of DeeMe

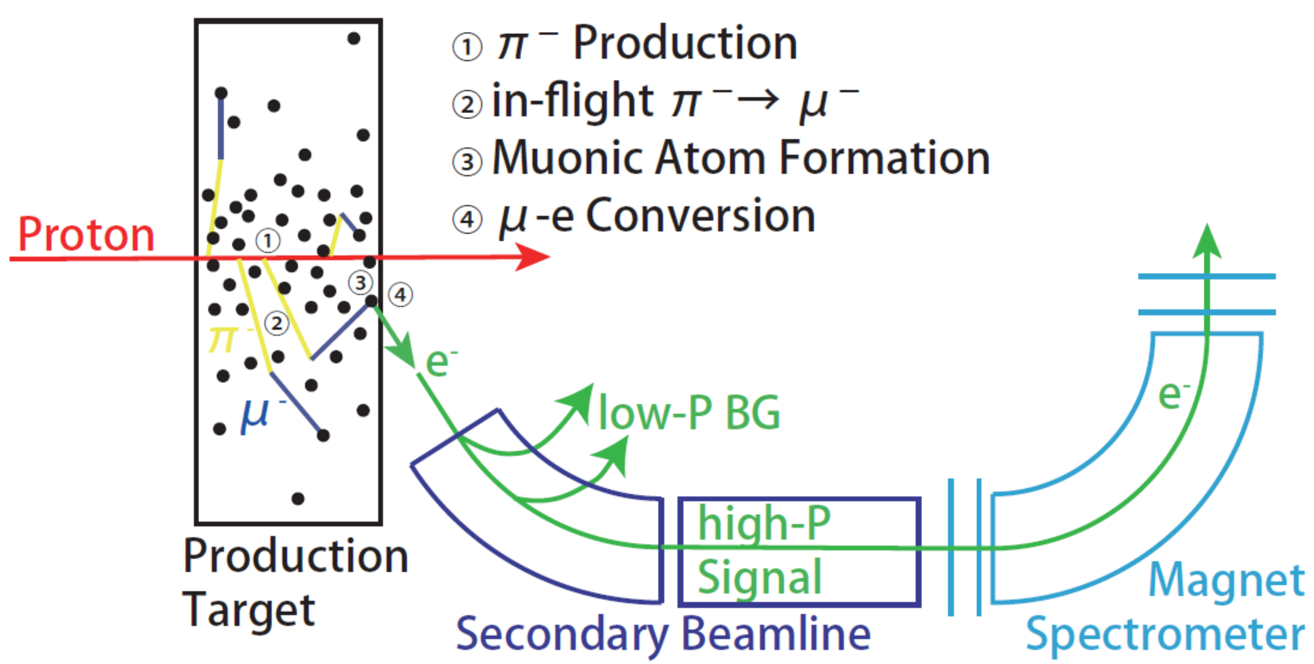


- momentum analysis
- identify signal electrons
- DIO spectrum

- spectrometer magnet
  &
  tracking device (MWPC)

Principle of Experiment

Concept of DeeMe



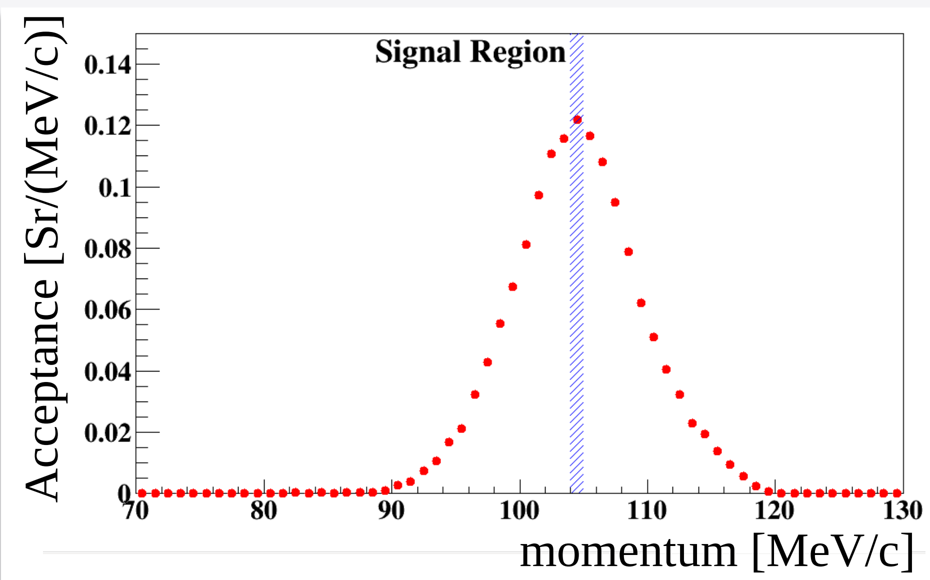
- Fully utilizing existing facility (high quality beam from RCS, muon target, etc)

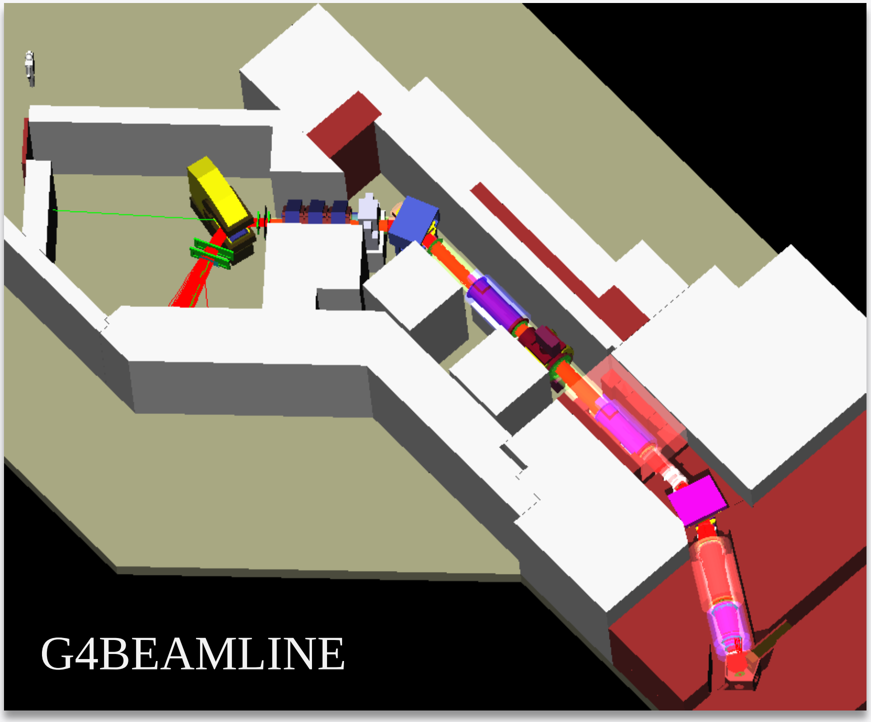
... Early realization of the experiment

new physics result in timely manner

Performance of H Line

- Transmission Efficiency
  - simulated by **G4BEAMLINE**
  - beam optics
    optimized for signal electron (105MeV/c)
  - acceptance at the spectrometer
    as a function of momentum





- ~ **120 mSr/(MeV/c)**
  @ signal momentum
  ⇒ **Higher sensitivity than ever before**

- wide range acceptance (90 – 120 MeV/c)
  ⇒ **Background monitoring**

Sensitivity , Backgrounds

Single Event Sensitivity

- 1-year run (**2 × 10⁷sec**) , with **1 MW** beam , H Line acceptance ...

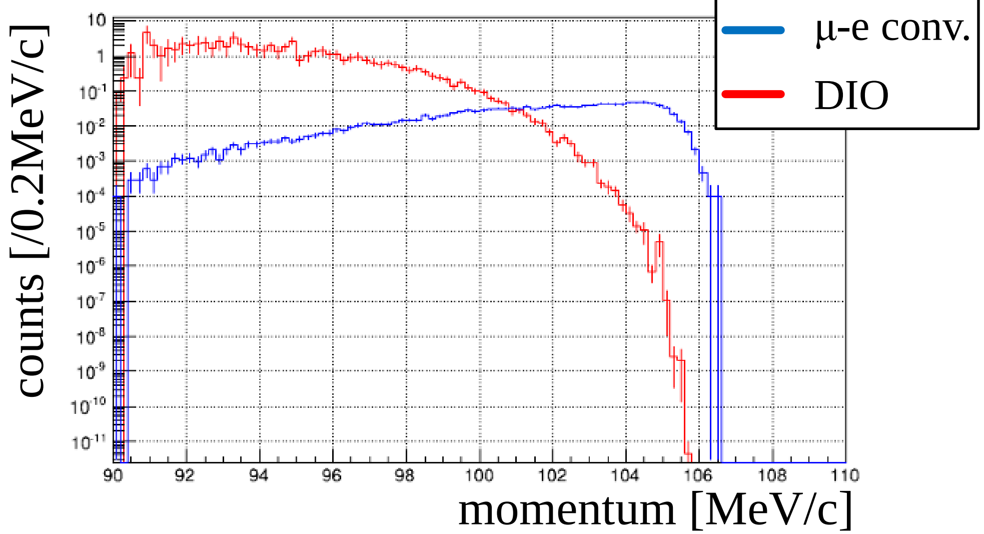
1.2 × 10^{-13} for **Carbon** Target

developing **SiC target** →

2.1 × 10^{-14} for **SiC**

c.f.
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}

Expected Spectrum of reconstructed momentum for **Carbon Target**



Background

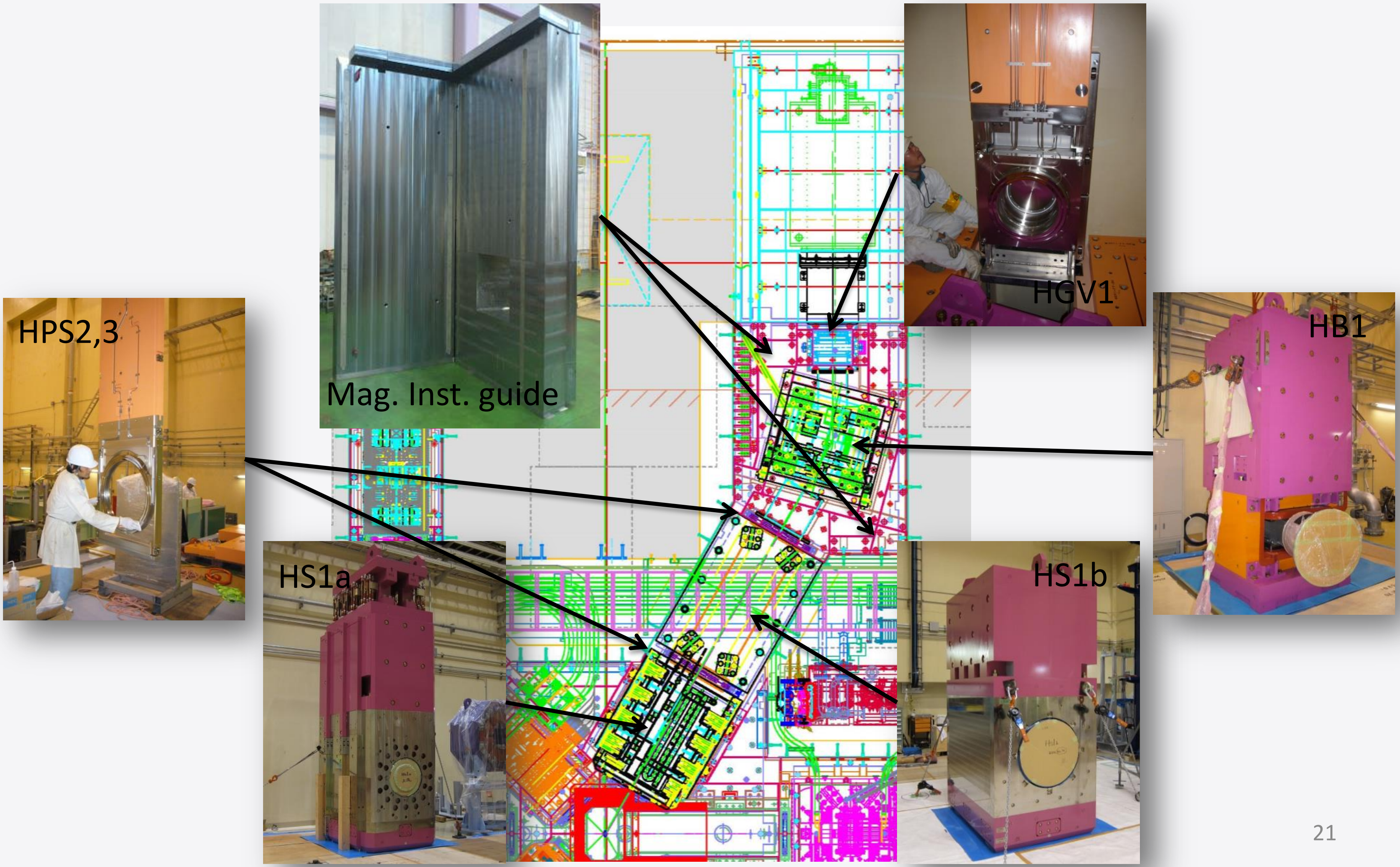
for carbon target ...

- Decay-In-Orbit 0.015
- After proton < 0.027
  (After proton rate < 10^{-18})
- Cosmic-ray induced
  e < 0.018 , μ < 0.001
  (Detector live-time duty = 1/20000)

Outline

H Line

- Frontend devices in H Line were placed.

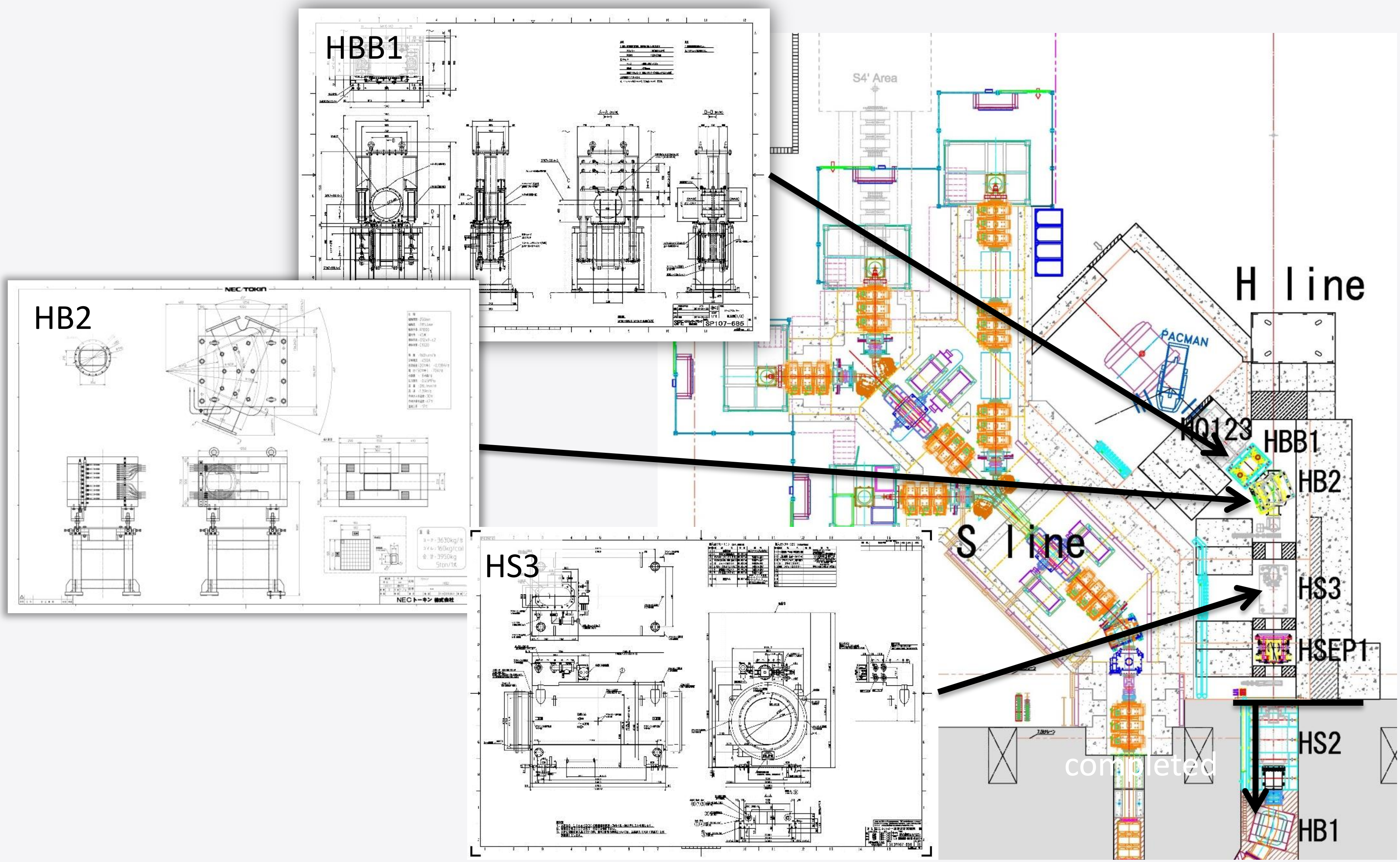


H Line

- Frontend devices in H Line were placed.

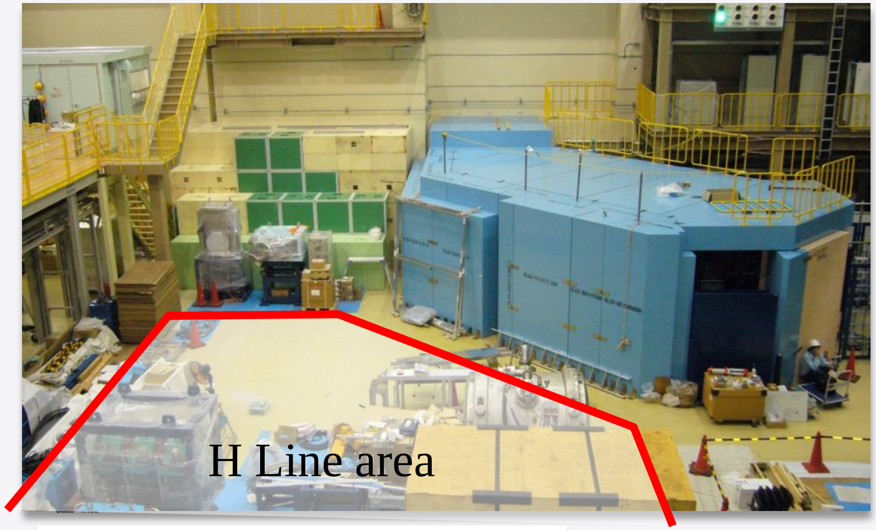
H Line

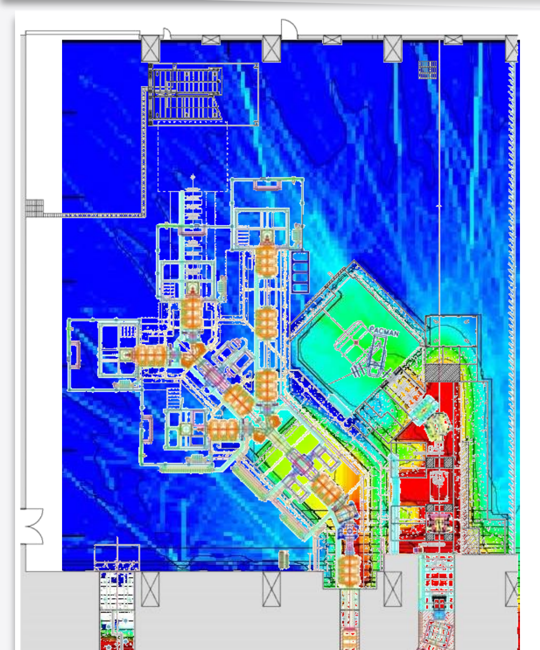
- Down Stream Magnets



H Line

- H Line under construction





- Beamline shield is designed based on Full M.C. simulation of dose using PHITS by N. Kawamura(KEK IMSS).
- Construction of beamline shield will start soon.

current status of the Exp. Hall

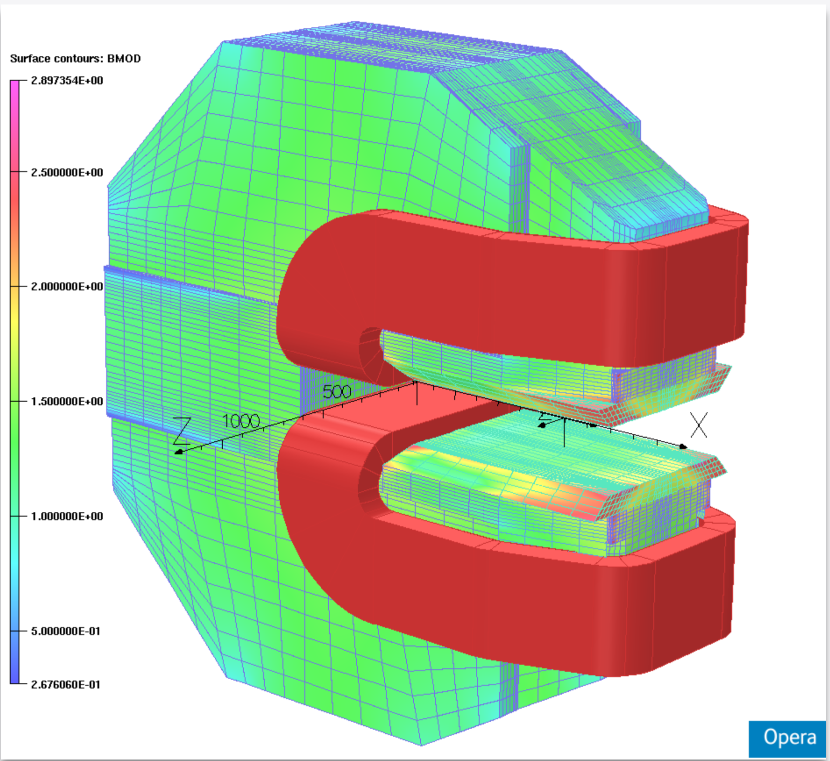
Outline

Spectrometer Magnet

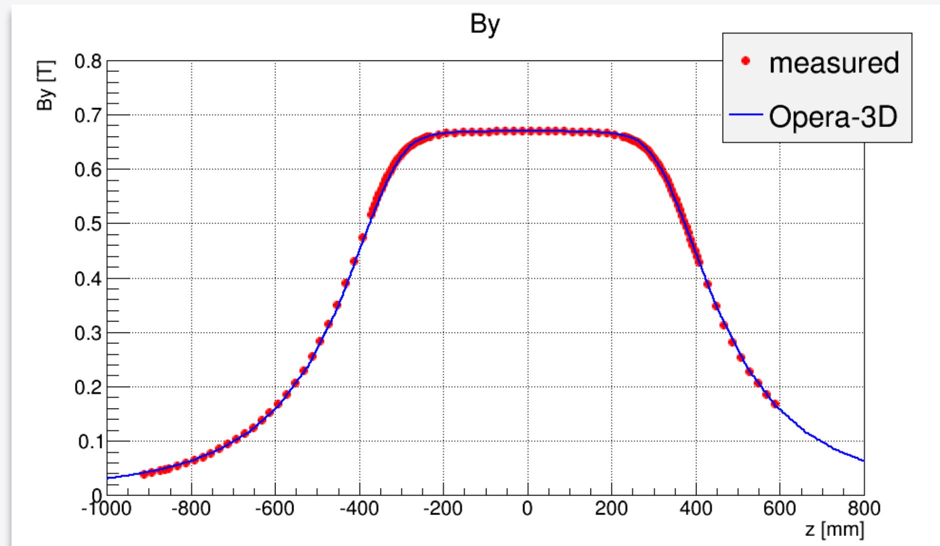
- PACMAN Magnet
  - used for PIENU exp. @ TRIUMF, Canada
  - transported from TRIUMF to J-PARC
  - central field = **0.4 T** (300A)
    for **105 MeV/c** , **70 degree** bending
  - Test operation was successfully done in J-PARC MLF.
  - Field measurement was performed.

Spectrometer Magnet

- Field calculation by Opera-3d



- Comparison between Opera-3d and measured



- tune magnet shape and B-H curve
  ⇒ fit calculation to measured.

- A field map for momentum analysis was created by Opera-3d based on field measurement.

PACMAN is ready !

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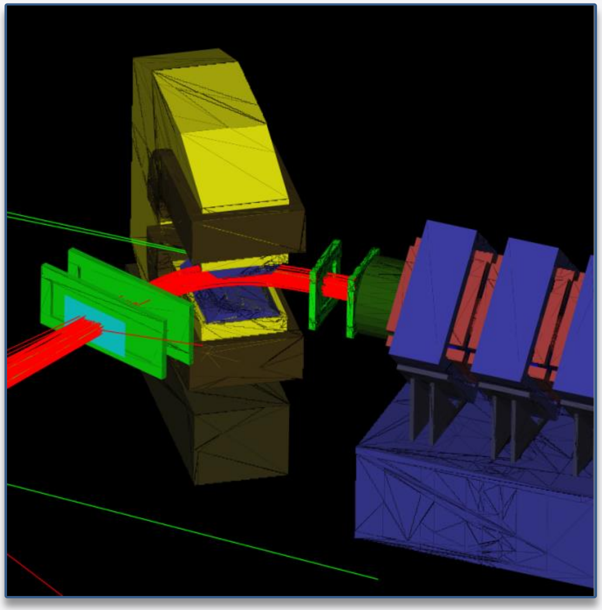
Detector

- Tracking Device

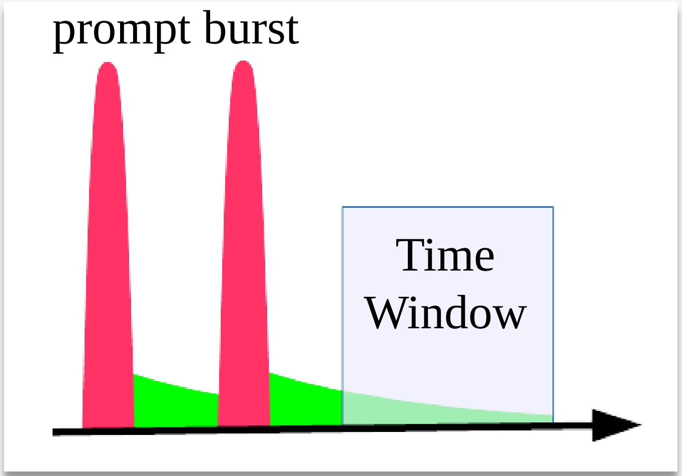
Thin **Multi Wire Proportional Chamber (MWPC)**

2 upstream + 2 downstream of the magnet
= totally **4 chambers**

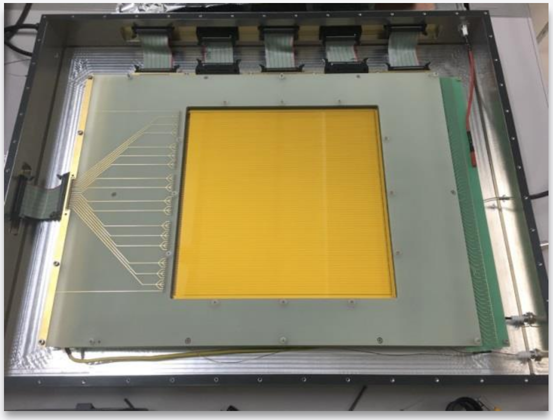


- Requirements

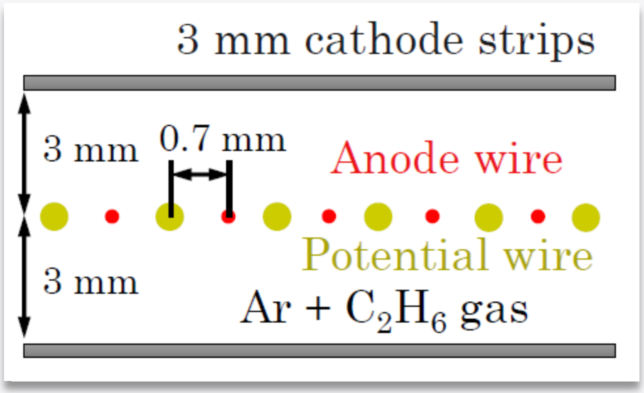
- position resolution = **0.3 mm**, thickness = **0.1% X_0** $\Rightarrow$ $\delta P <$ **0.5 MeV/c** (RMS)
- tolerate to beam bunch of **10^8 MIP**
- instantaneous hit rate ~ **70 GHz/mm^2**
- return to operational **300 nsec** after beam pulse to detect delayed electrons



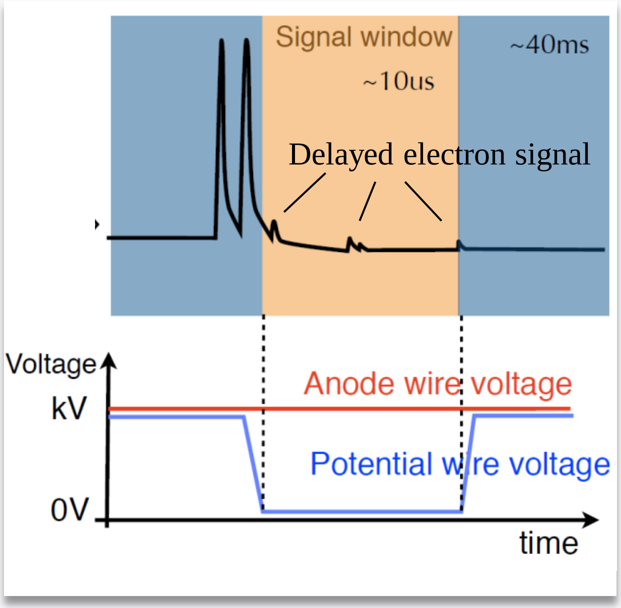
Detector



- MWPC
  - 300 mm × 300 mm
  - wire pitch = 0.7 mm
  - cathode strip
    x: 3mm width
    y: 15mm width
    → Flash ADC readout



- HV Switching
  - anode = ~1500 V
  - switch the voltage for potential wire



~1500 V

- usual
- detector protection during the burst, no space charge creation

⟷

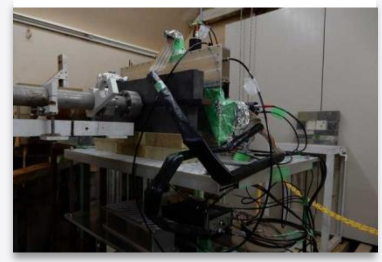
0 V

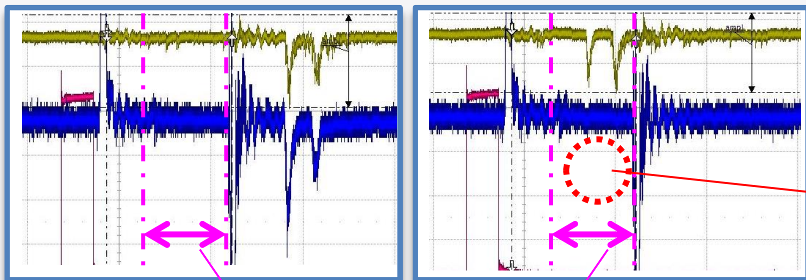
- after prompt burst
- delayed signal detection

Detector

Beam tests

- Muon beamline (D-Line) @ MLF , J-PARC
- Electron Linac @ Research Reactor Institute, Kyoto Univ.



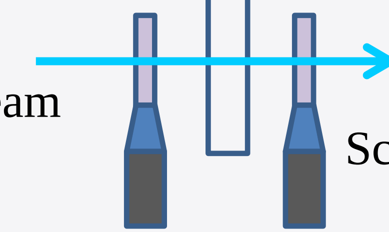


HV Switching Period

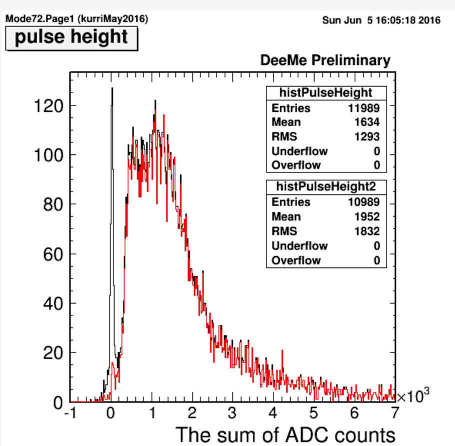
Scinti. Signal

MWPC Signal

- disappeared during switching period



- Good performance of HV Switching



- gain of cathode strip
  ... clear separation between pedestal and signal

- Further analysis is ongoing.

Poster Presentation by Natsuki Teshima

"Delvelopment of High-Rate-Tolerant HV-Switching Multi-Wire Propotional Chamber and Its Readout Electronics for DeeMe Experiment"

All MWPC's will be ready soon.

2 already available (a little modification)
2 assembling

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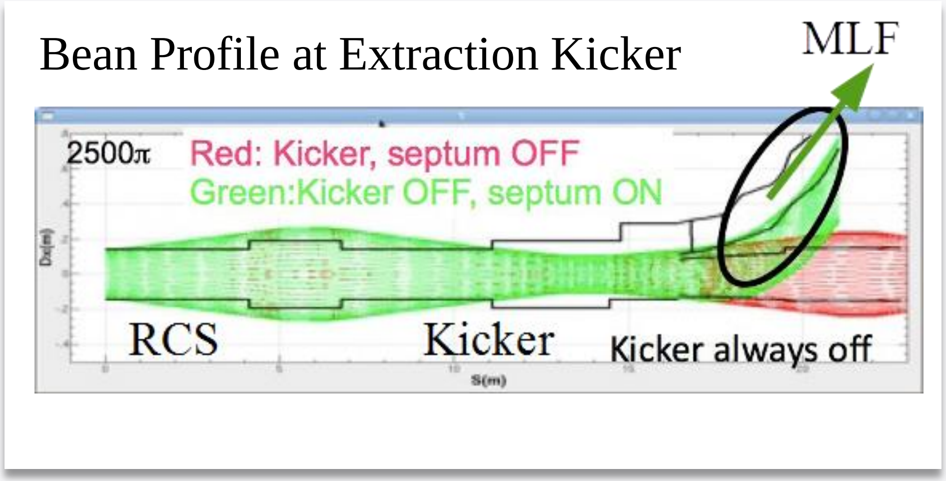
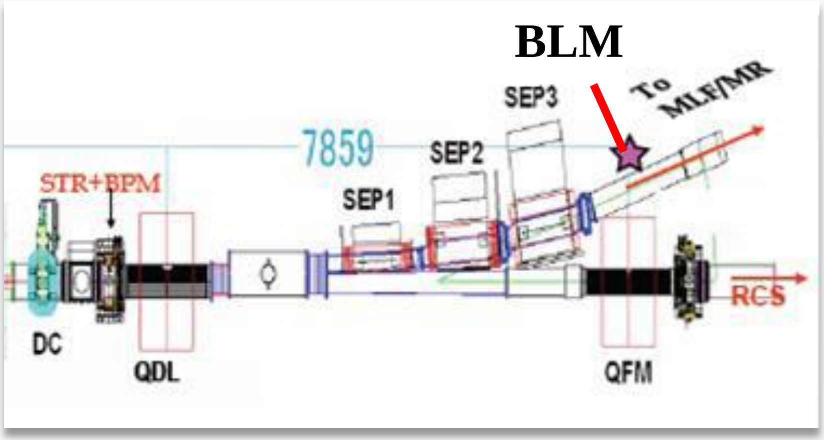
After-Proton Background

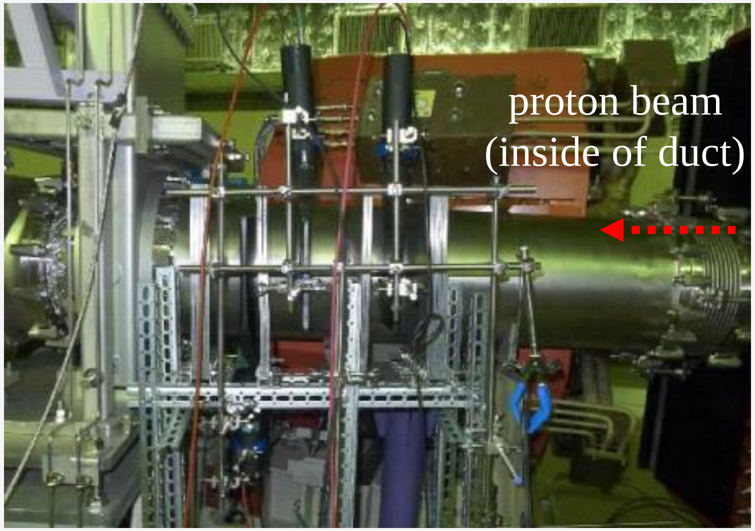
- After-Proton
  - residual protons in RCS (synchrotron)
  - **Fast Extraction**
    → no After-Proton, in principle
  - may be created by beam halo in RCS
    and extracted to MLF when kicker is off
  - **induce prompt background**
    in the analysis time window



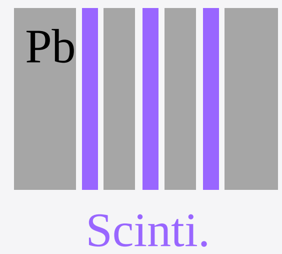


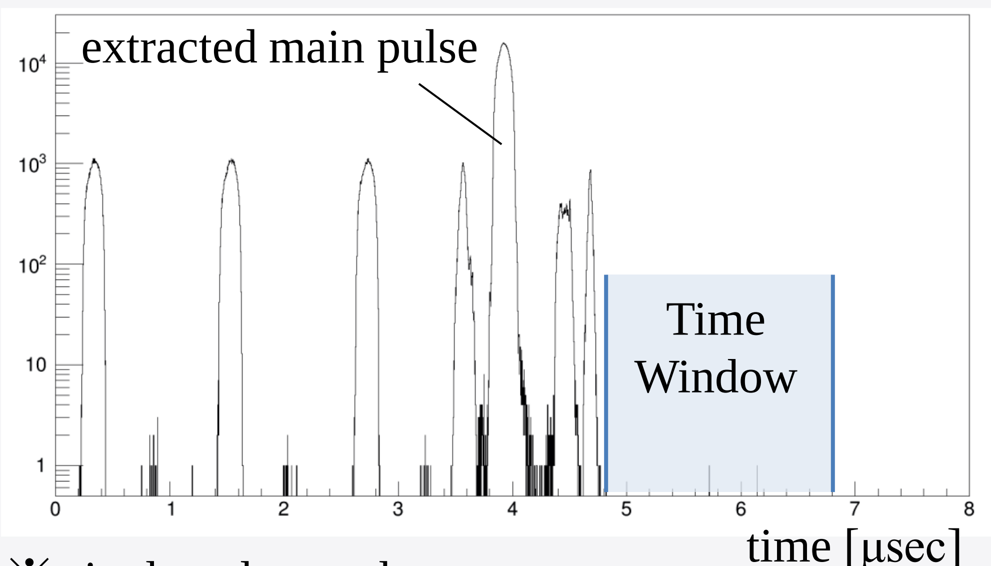
- After-Proton Measurement
  - count protons by
    Beam Loss Monitor (**BLM**)
  - $f = \dfrac{\text{After-Proton}}{\text{BLM hits}} = 40$ (MC)

After-Proton Background



- Beam Loss Monitor
  - 3 Scintillators + Pb absorber
  - coincidence signal of 3 Scintillators





※ single pulse mode

- After-Proton Rate
  - total protons extracted = 3.5×10^{20} (2 weeks)
  - hits in the time window = 3

$$\Rightarrow \mathbf{R_{AP} = 3.4 \times 10^{-19}}$$

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Silicon Carbide Muon Production Target

- current muon production target of MLF
  = **graphite (C)**

- Larger muonic nuclear-capure rate ($\mathbf{f_{MC}}$)
  is desirable for more sensitive experiment.

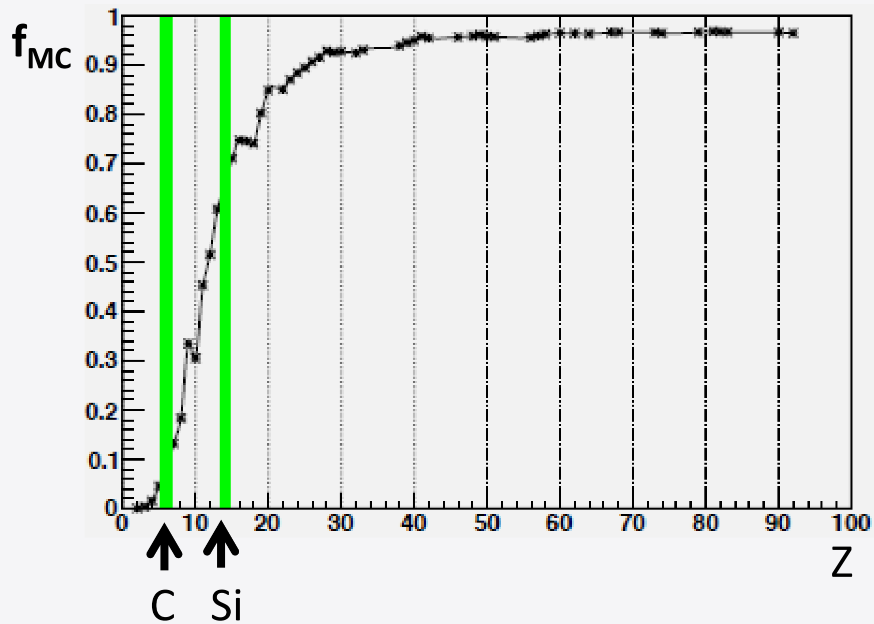
$\tau_{\mu-}$ > **300 nsec** (light Z)
to avoid the prompt background
▪$\tau_{\mu-}$ (in **silicon**) = **0.76 μsec**

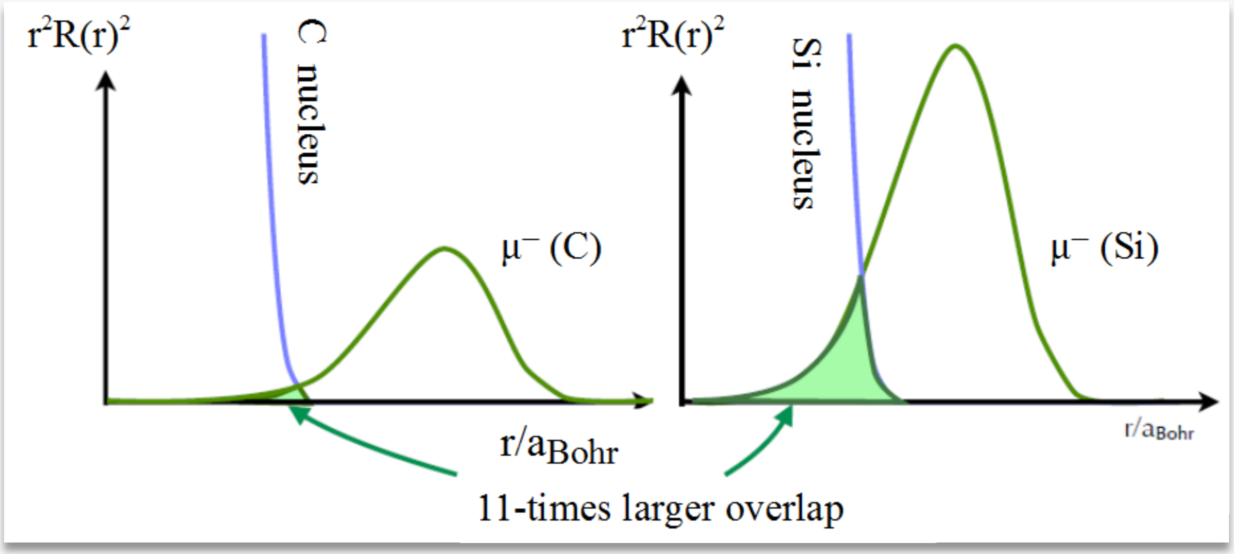
$\mathbf{f_C}$: Fraction of the atomic capture
of muon to the atom of interest

▪single-element
material : f_C = 1

▪composite material:
proportional to Z
(Fermi-Teller Z law)

Silicon-Carbide (SiC)
→ **Si : C = 7 : 3**



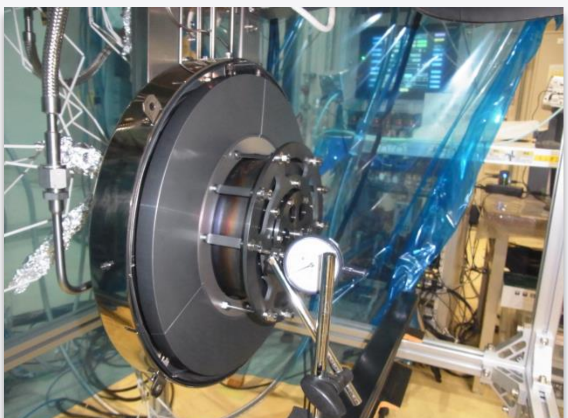


Silicon Carbide Muon Production Target

- SiC target ~ **6 times higher physics sensitivity** than current carbide target

Material	$\Sigma f_c \times f_{MC}$
Graphite (C)	0.08
Silicon Carbide (SiC)	0.46

- Rotating SiC target



prototype of
SiC rotating target

compared with graphite ...

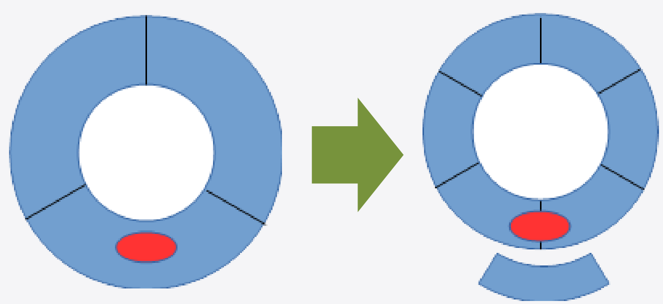
10 times strength → ← 80 times thermal stress

8 times larger risk under beam irradiation

- SiC target is under development.

> increase disk partition and reduce disk radius
→ lower thermal stress and thermal difference.

current design



beam

> additional SiC
→ stop more π, μ

Outline

- Physics Motivation
- DeeMe Experiment
- Current Status
  - Beamline
  - Spectrometer Magnet
  - Detector
  - After-Proton Measurement
  - Muon Production Target
- Summary & Prospects

Summary & Prospects

- DeeMe , μ – e conversion search at J-PARC MLF
  - Sensitivity : **1.2 $\times 10^{-13}$** for **C** target , **2.1 $\times 10^{-14}$** for **SiC** target
- A new beamline (H Line) is under construction.
- The spectrometer magnet is ready.
  - test operation, field magnet, Opera-3d
- HV-Switchin MWPC was developed.
  - All MWPC's will be ready soon.
- After-Proton measured
- SiC muon production target under development
- DeeMe will start data taking soon after H Line completed (Japan FY 2016).

DeeMe Collaboration

M.Aoki [1], D.Bryman [2], Y.Furuya [3], M.Ikegami [4], Y.Irie [3,4], N.Kawamura [5,11], M.Kinsho [6], H.Kobayashi [4], S.Makimura [5,11], H.Matsumoto [4], S.Meigo [6], T.Mibe [7], S.Mihara [7], Y.Miyake [5,11], D.Nagao [1], Y.Nakatsugawa [5], H.Natori [7], H.Nishiguchi [7], T.Numao [8], C.Ohomori [4], S.Ritt [10], P.K.Saha [6], N.Saito [7,11], Y.Seiya [3], K.Shimomura [5,11], P.Strasser [5,11], N.Teshima [3], N.D.Thong [1], N.M.Truong [1], K.Yamamoto [6], K.Yamamoto [3], M.Yoshii [4], K.Yoshimura [9]

(1) Osaka University
(2) UBC
(3) Osaka City University
(4) KEK Accelerator
(5) KEK IMSS
(6) JAEA
(7) KEK IPNS
(8) TRIUMF
(9) Okayama University
(10) PSI
(11) J-PARC Center

Backup

Single Event Sensitivity

- **Single Event Sensitivity (S.E.S)**

$$S = \frac{1}{R_{\pi^-} \times f_{\pi^- \to \mu^- \mathrm{stop}} \times f_C \times f_{MC} \times A_{\mu-e} \times T}$$

$R_{\pi^-} \times f_{\pi^- \to \mu^- \mathrm{stop}} = \mu^-$ stopping rate per second

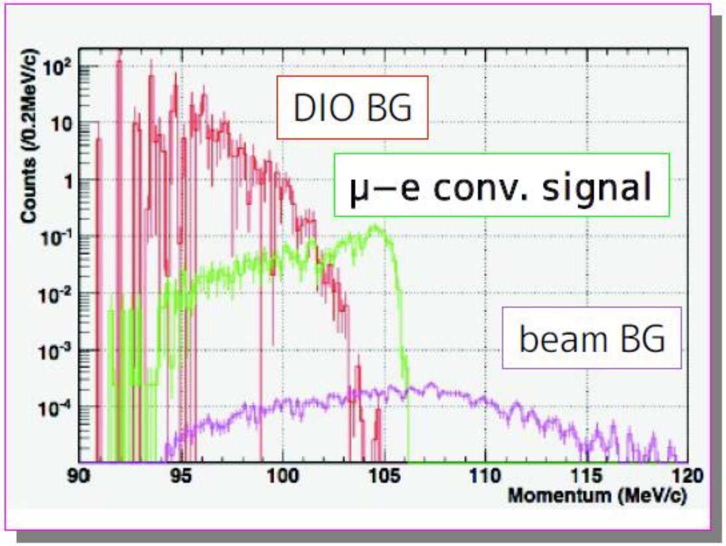
$f_C =$ atomic captur rate

$f_{MC} =$ muon nuclear capture fraction

$A_{\mu-e} =$ total acceptance for μ-e electrons

$T =$ time length of the measurement

- Running time = **2 × 10^7 sec** (1 year run)
- Background (MC estimated)
  - Decay in Oribit **0.09**
  - After proton rate (R_{AP}) < 10^{-18}
    - →After proton < **0.027** (0.05 90% C.L.)
  - Cosmic induced
    - e < **0.018** , μ < **0.001**
    - →Detector live-time duty = **1/20000**
    - ⇒ Cosmic ray backgrounds are well suppressed.



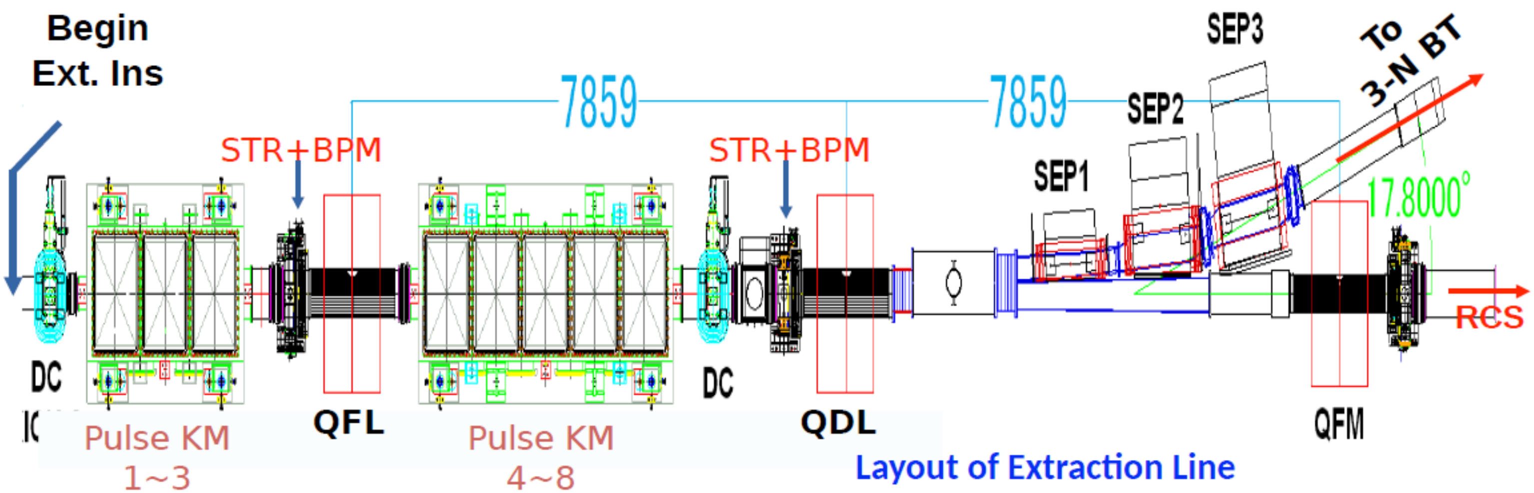
- **S.E.S estimated by Monte Carlo study**
- **2.1 × 10^{-14}** for <u>SiC</u> target
- **1.2 × 10^{-13}** for <u>C</u> target

current upper limit

BR(μ⁻ Au → e⁻ Au) < **7 × 10^{-13}**

(SINDRUM-II)

Source of After Proton



Layout of Extraction Line

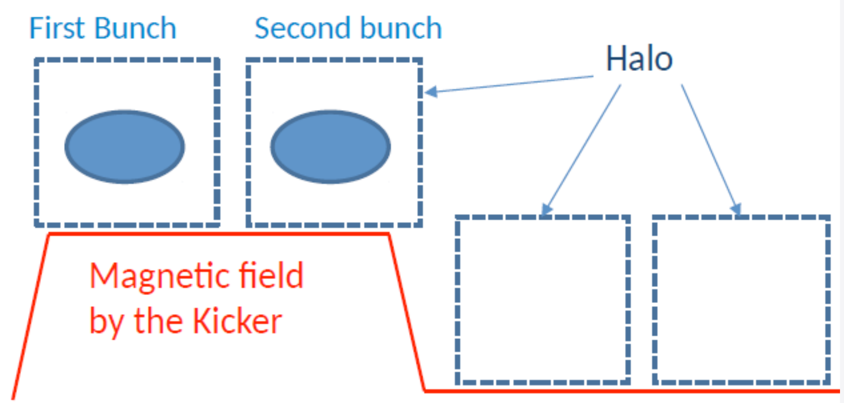
$$\sum_{1}^{8} \text{KM Kick angle} \approx 17 \text{ mrad}$$

Naive estimation:

If the rest proton exists and extracts without pulse kicker magnets, a particle needs to have an inclination (x') ≧17 mrad

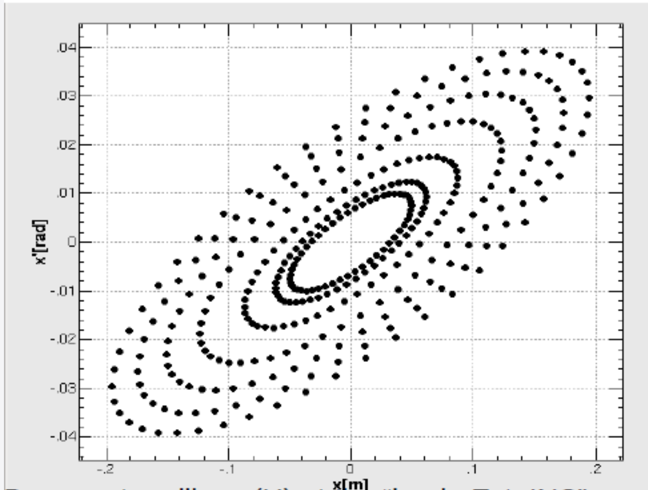
➔An emittance of ≈ 2200 πmm mrad!

□4 times of the RCS phisycal aperture (486πmm mrad) or 7 times of the RCS collimator aperture (324πmm mrad).



Time structure of extraction beam and after proton

Source of After Proton（Con’t）



Beam outer ellipse (H) at the “begin Ext. INS”.
(324 ~ 5000 πmm mrad)

We estimated the possible initial conditions that the proton can extract with no kicker excitation. As a result, the protons that has 2500πmm-mrad. emittance can partially extract. however, some particles hit the branch chamber.

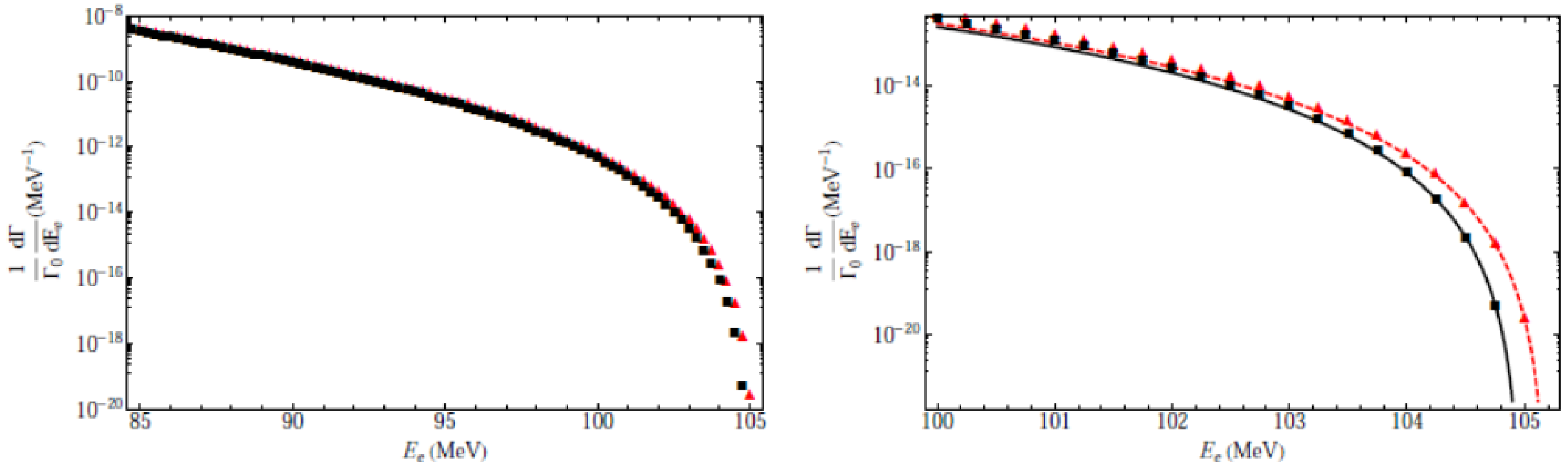
→We can catch the existence of after proton by monitoring scintillator signals near this point!

DIO Spectrum Measurement

- Decay In Orbit (DIO) ... major background for μ-e conversion search

  Knowledge about DIO spectrum is very important for background estimation.

- Theoretical model



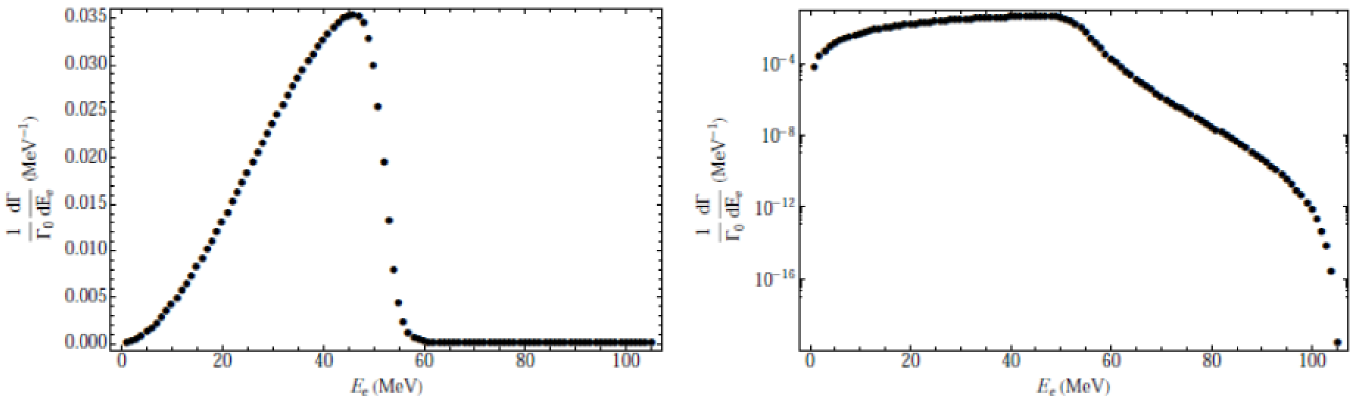
■ DIO spectrum calculated by **Czarnecki** (including nuclear recoil)

▲ without recoil

DIO Spectrum Measurement

- Measurement of DIO spectrum @ 50~70 MeV/c

  → compare with theoretical calculation



- Concept of DIO measurement

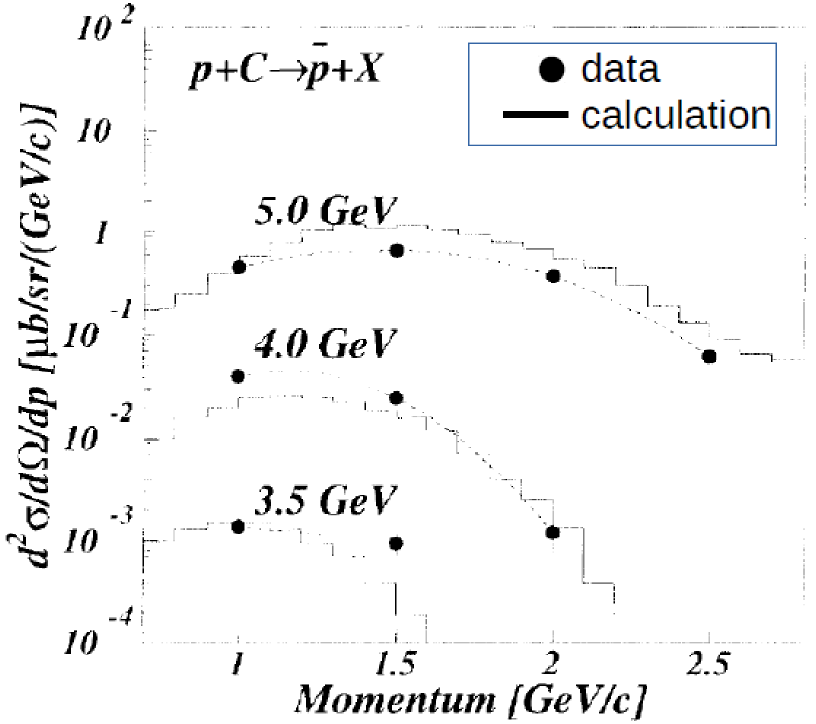
  similar to momentum calibration … μ- stopped in the secondary target
  measure the momentum of DIO electron
  by the spectrometer

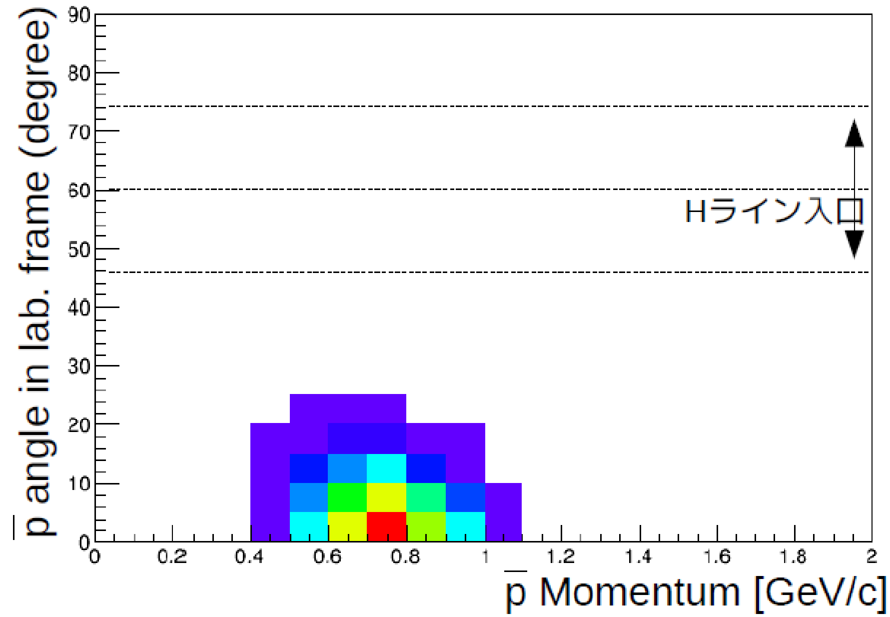
- Monte Carlo simulation

  - similar way to momentum calibration
  - 10 MeV/c μ- extraction by H-line
  - secondary target = 500μm thickness Graphite foil
  - ~ **4000** DIO electron / day @ 50~70 MeV/c

Subthreshold $\bar{p}$ Production 断面積

標的 = ^{12}C, 5.1° in lab. frame

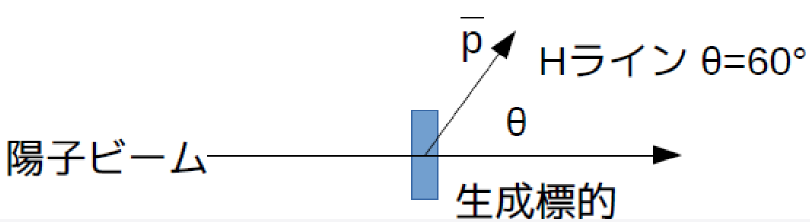




- ビームエネルギー 3 Gev, C標的での各運動量、角度における $\bar{p}$ 生成断面積 (first chance collision model)

- モデル計算と実験データ
  Sugaya et.al nucl. phys. A 634(1998) 115-140

→モデル計算とデータはよくあっている



Hライン ... **60°** の方向
ビーム入口 **± 14°**

→ **Hラインへ飛ぶ反陽子は生成されない**