DeeMe

–muon-electron conversion search experiment–

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on behalf of the DeeMe collaboration

The 23rd International Workshop on Neutrinos from Accelerators (NUFACT2022)

Outline

- Charged Lepton Flavor Violation
- DeeMe at J-PARC
- J-PARC MLF H-Line
- Principle of Experiment
- Detector Performance
- DeeMe Commissioning
- Summary

The DeeMe Collaboration

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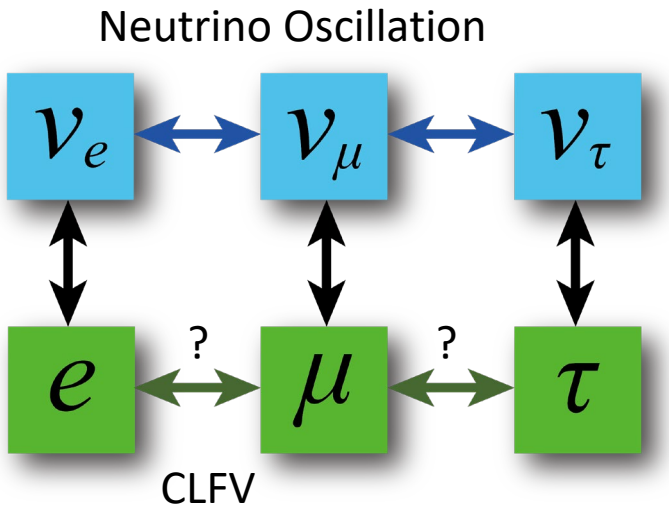
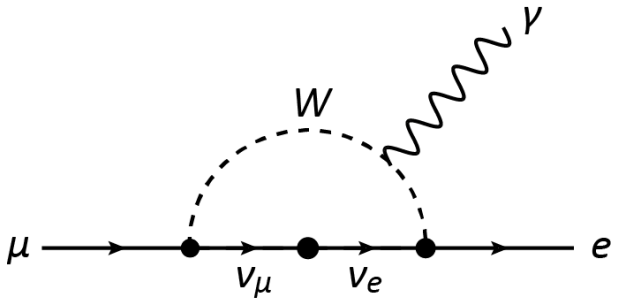
Charged Lepton Flavor Violation



- Lepton Flavor Violation is forbidden in the original Standard Model.
- Neutrino oscillation
  = Flavor Violation of neutral lepton
- Charged Lepton Flavor Violation (CLFV)
  - $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$
  - not observed yet …

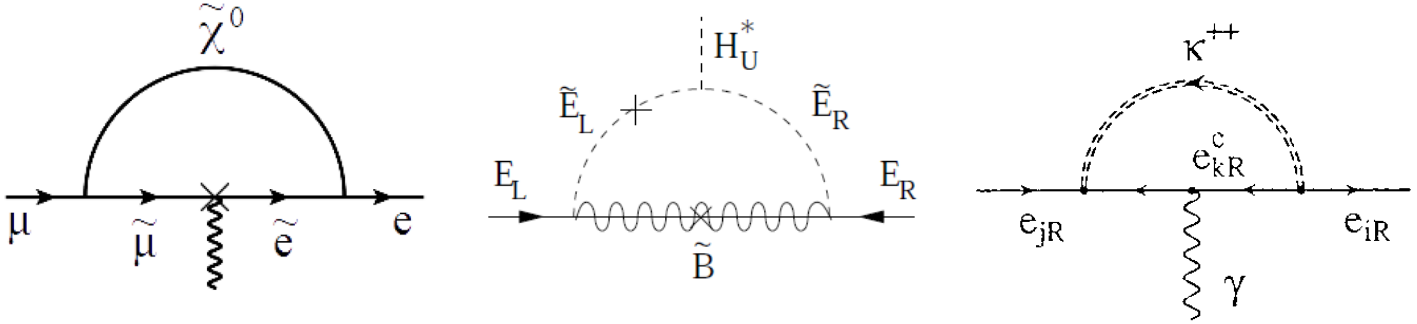
- CLFV induced by neutrino flavor mixing
  - $Br(\mu \to e\gamma) \sim \frac{\alpha}{4\pi}\left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-54}$
  - too small to be observed experimentally in the framework of the Standard Model



Experimental Observation of CLFV process is
a clear evidence of the new physics beyond the Standard Model

Charged Lepton Flavor Violation (2)

- Theoretical Models predicting CLFV beyond the Standard Model
  - SUSY GUT, SUSY-Seesaw, Doubly Charged Higgs, etc…



  - Predicted branching ratio : 10^{-14} ~ 10^{-18} (ex. SUSY-GUT) ⇦ **Sizable branching ratio of CLFV**

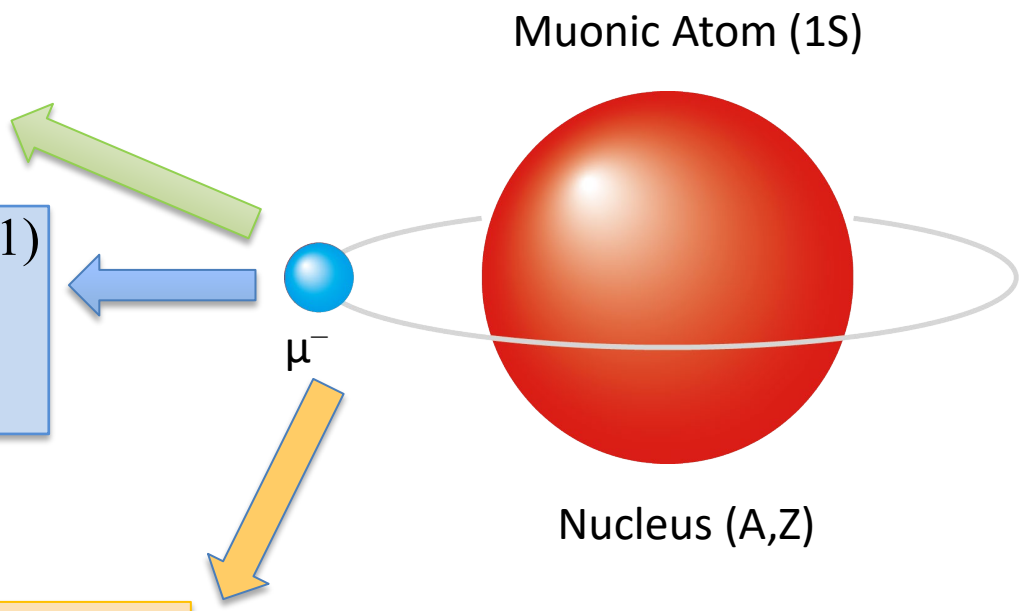
- Current upper limits from experiments

$\mu^- N \rightarrow e^- N$	$\mu^+ \rightarrow e^+\gamma$
SINDRUM-II : $Br(\mu^- Au \rightarrow e^- Au) < 7 \times 10^{-13}$	MEG : $Br(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$
SINDRUM-II : $Br(\mu^- Ti \rightarrow e^- Ti) < 4.3 \times 10^{-12}$	
TRIUMF : $Br(\mu^- Ti \rightarrow e^- Ti) < 4.6 \times 10^{-12}$	

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

What May Happen to Muonic Atoms

- Standard Model
  - Muon decay in orbit (DIO) : $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
    92% for C, 33% for Si
  - Muon capture (MC) : $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z\text{-}1)$
    8% for C, 66% for Si
    Life time : 2.0μs, 0.76μs



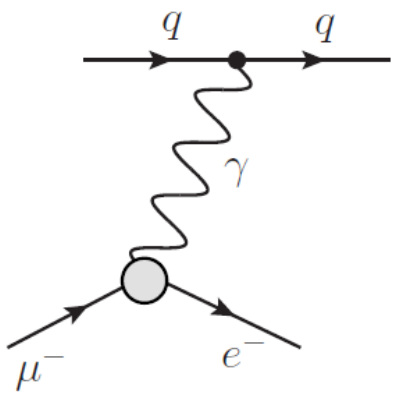
- New Physics
  - Muon to electron conversion : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
    Charged lepton flavor violation (CLFV)
    Mono-energetic e^- with ≈ 105 MeV
    Delayed signal by ~1 μs

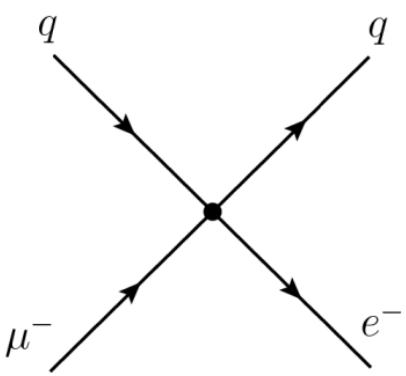
Sensitivity to Reaction Mechanism

- Effective Lagrangian

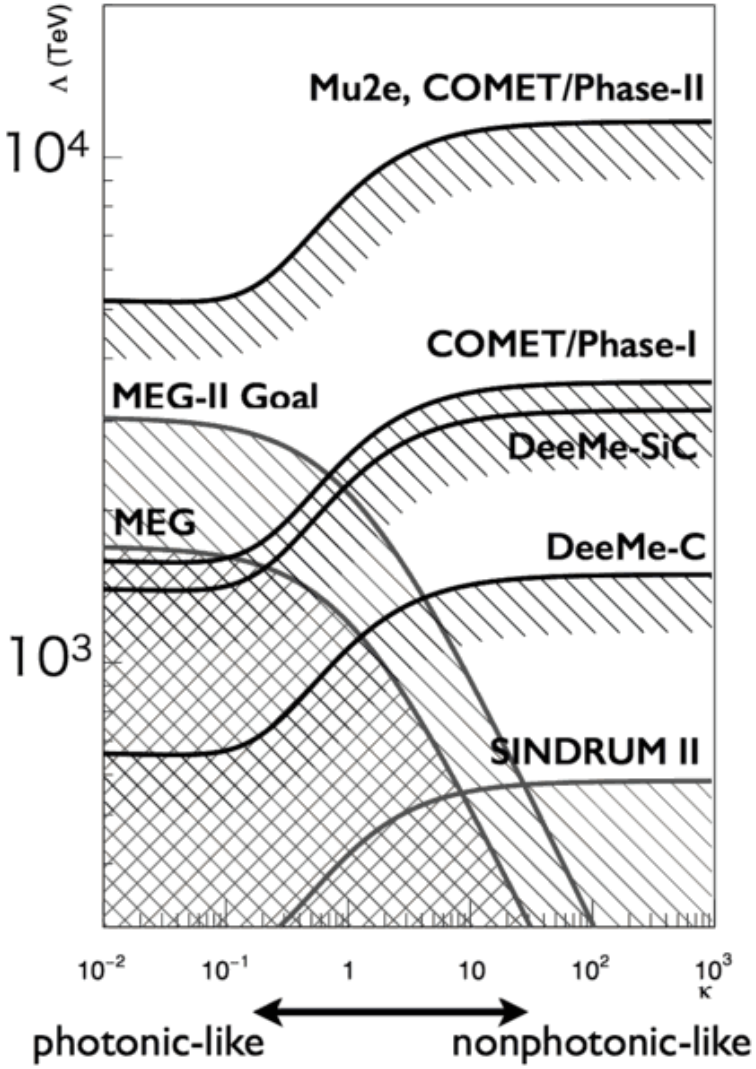
Photonic — Non-photonic

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\overline{\mu_{\mathrm{R}}}\sigma^{\mu\nu}e_{\mathrm{L}}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\overline{\mu_{\mathrm{L}}}\gamma^\mu e_{\mathrm{L}})(\overline{q_{\mathrm{L}}}\gamma_\mu q_{\mathrm{L}})$$





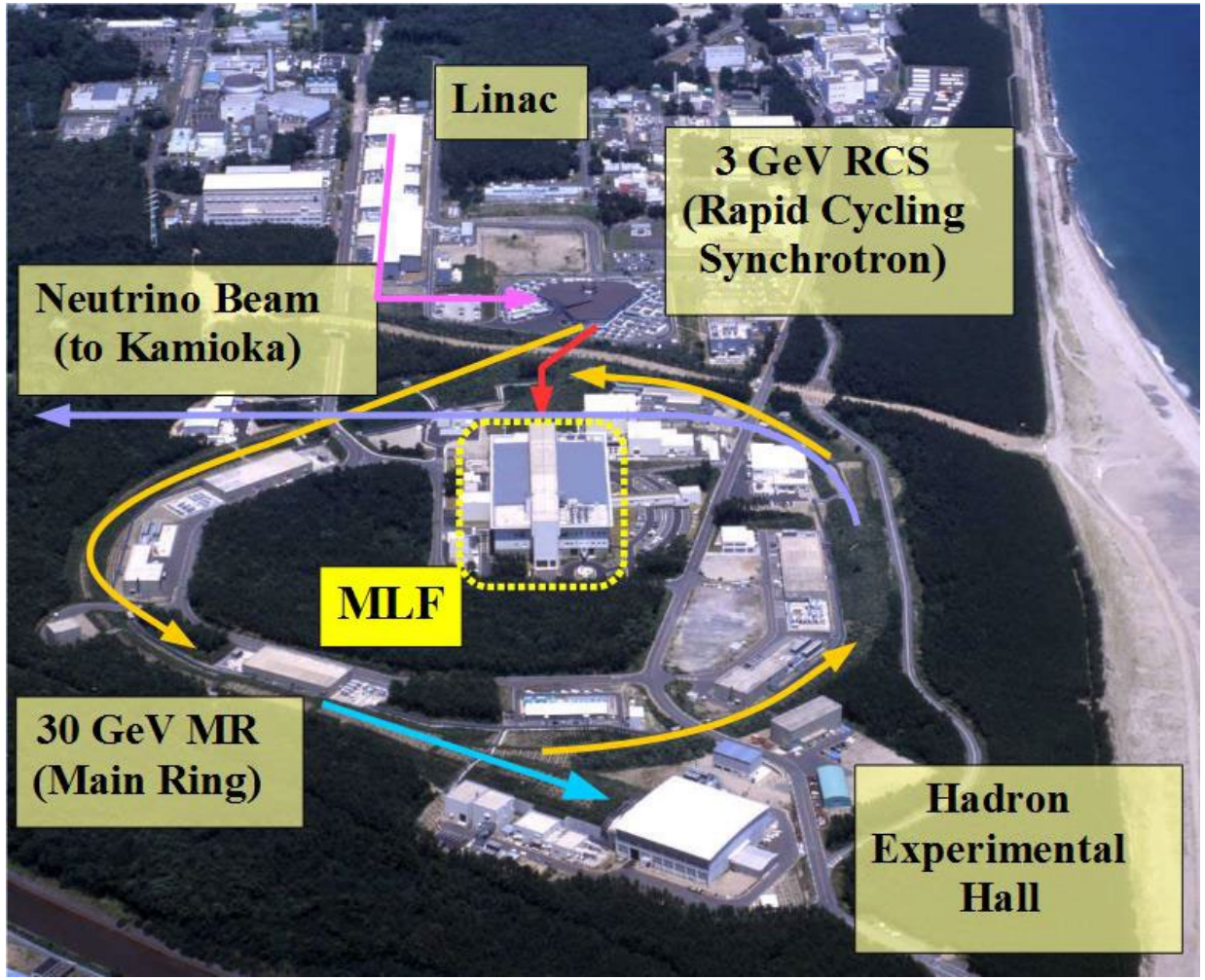
- It is important to probe the CLFV with as many different approaches as possible.
  - DeeMe is sensitive to both photonic and non-photonic processes.



Original graph by A. de Gouvêa, P. Vogel
Prog. Part. Nucl. Phys. 71, 75-92 (2013)

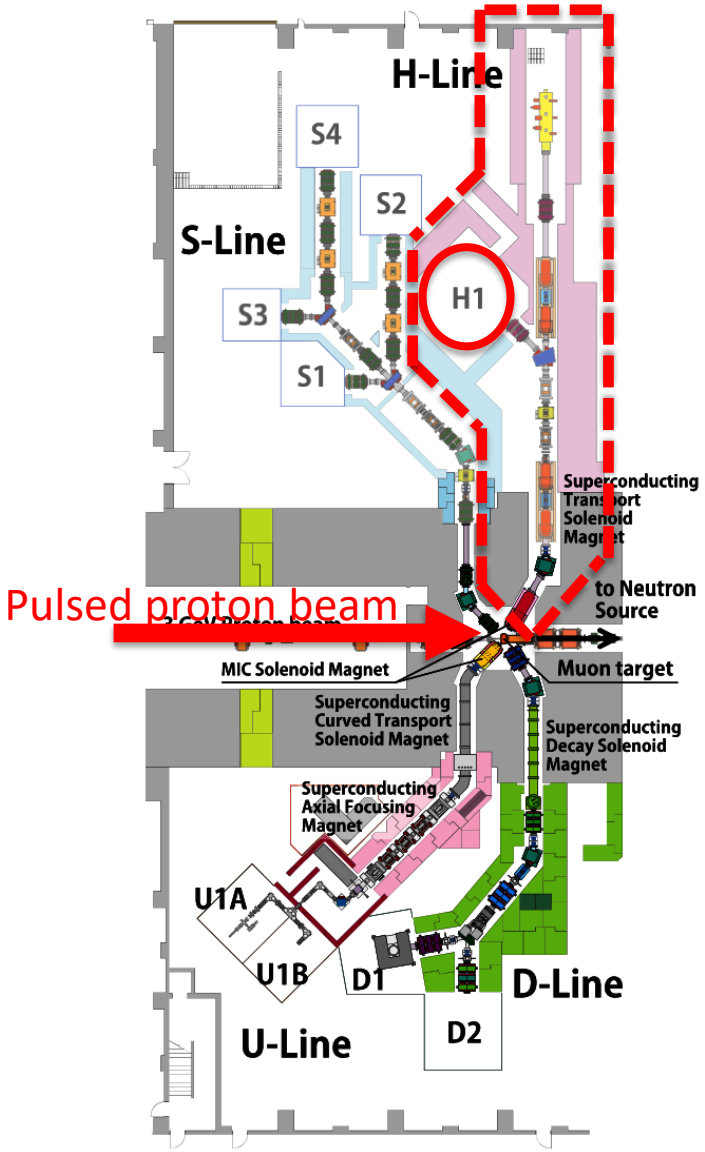
DeeMe Experiment at J-PARC

- DeeMe is conducted at J-PARC Materials and Life Science Experimental Facility (MLF).

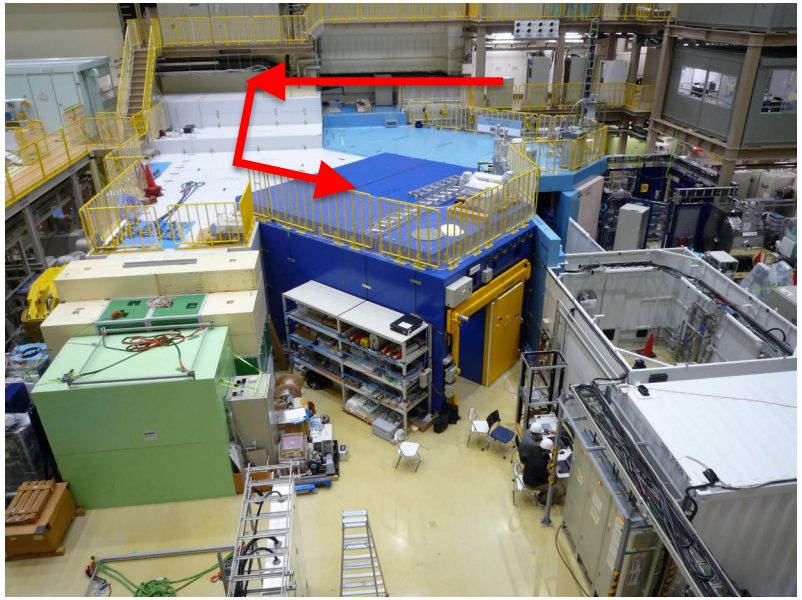


- Pulsed proton beam from 3-GeV RCS
- Fast extraction
- 830 kW → 1 MW (design power)
- 25 Hz double pulses

J-PARC MLF H-Line



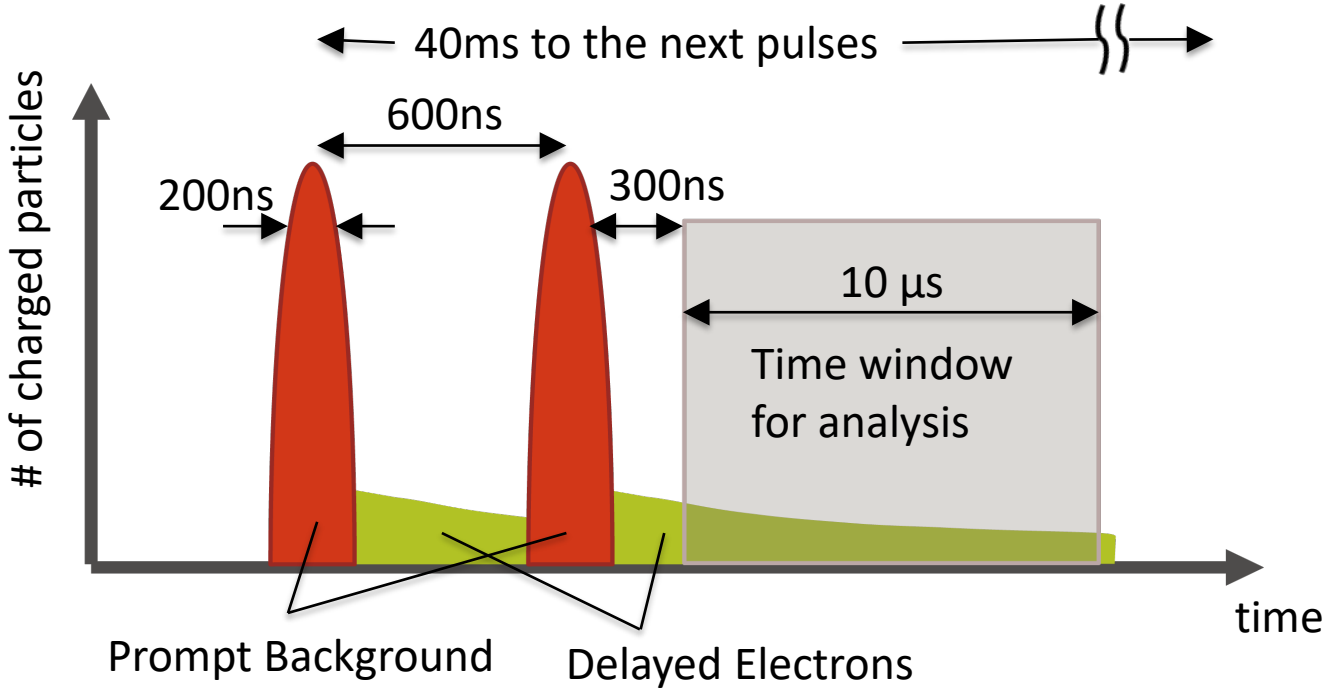
- H-Line
  - For fundamental physics
  - multipurpose beam line
  - Construction was completed in January 2022.
  - The DeeMe spectrometer was installed in the H1 area.



Beam Structure and Analysis Time Window

- Pulsed proton beam : 25 Hz, double pulse : 200 ns width, 600 ns interval

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

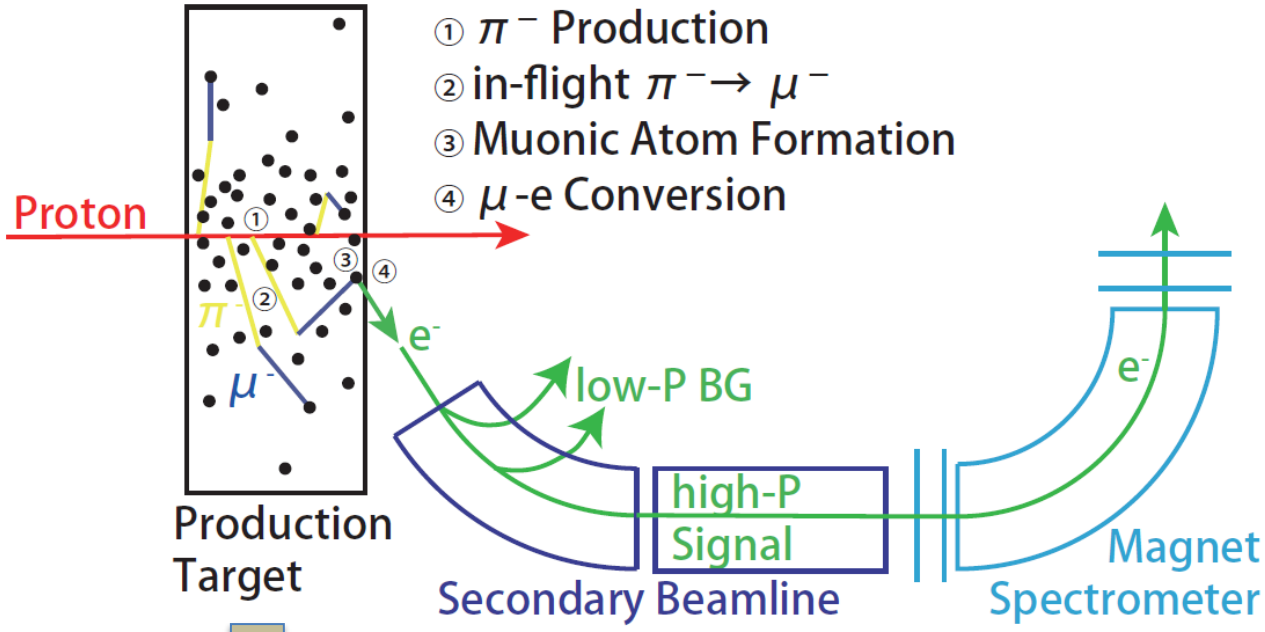


- Beam energy = 3 GeV
  < p-bar production threshold
  ⇒ no p-bar induced background

- Fast extracted beam
  no off-timing proton
  ⇒ no prompt background at the time window

Principle of Experiment

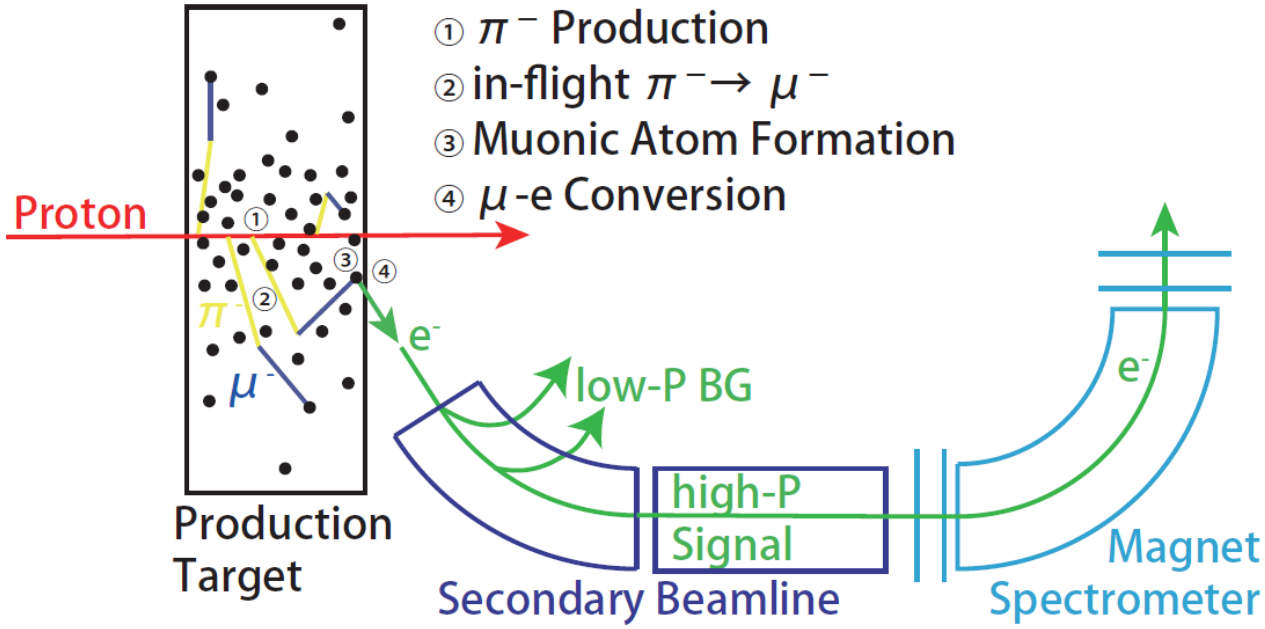
- Concept of DeeMe



- π^- production target = π^- decay & μ^- transport section = μ^- stopping target → NO π^- decay volume, NO additional stopping target
- Utilize muonic atoms formed in the production target ↔ conventional μ-e conversion search

Principle of Experiment

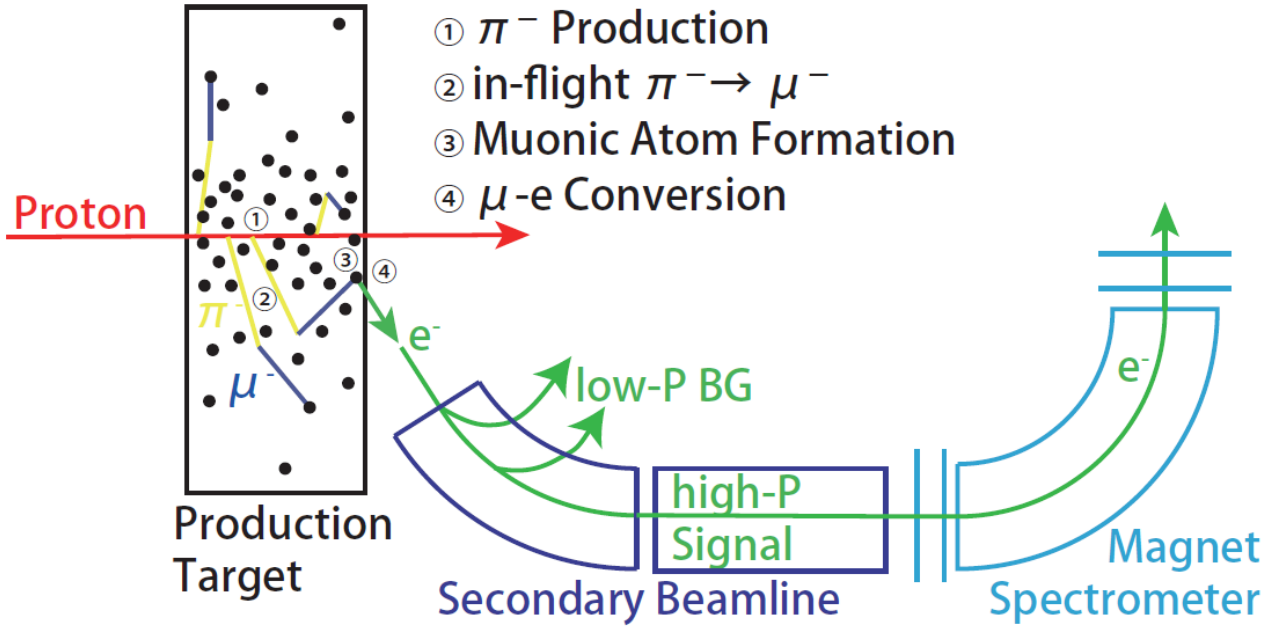
- Concept of DeeMe



- Transport signal electrons (105MeV/c) ⇒ Momentum selection
- Beam optics is optimized for signal electrons Suppress low momentum backgrounds

Principle of Experiment

- Concept of DeeMe

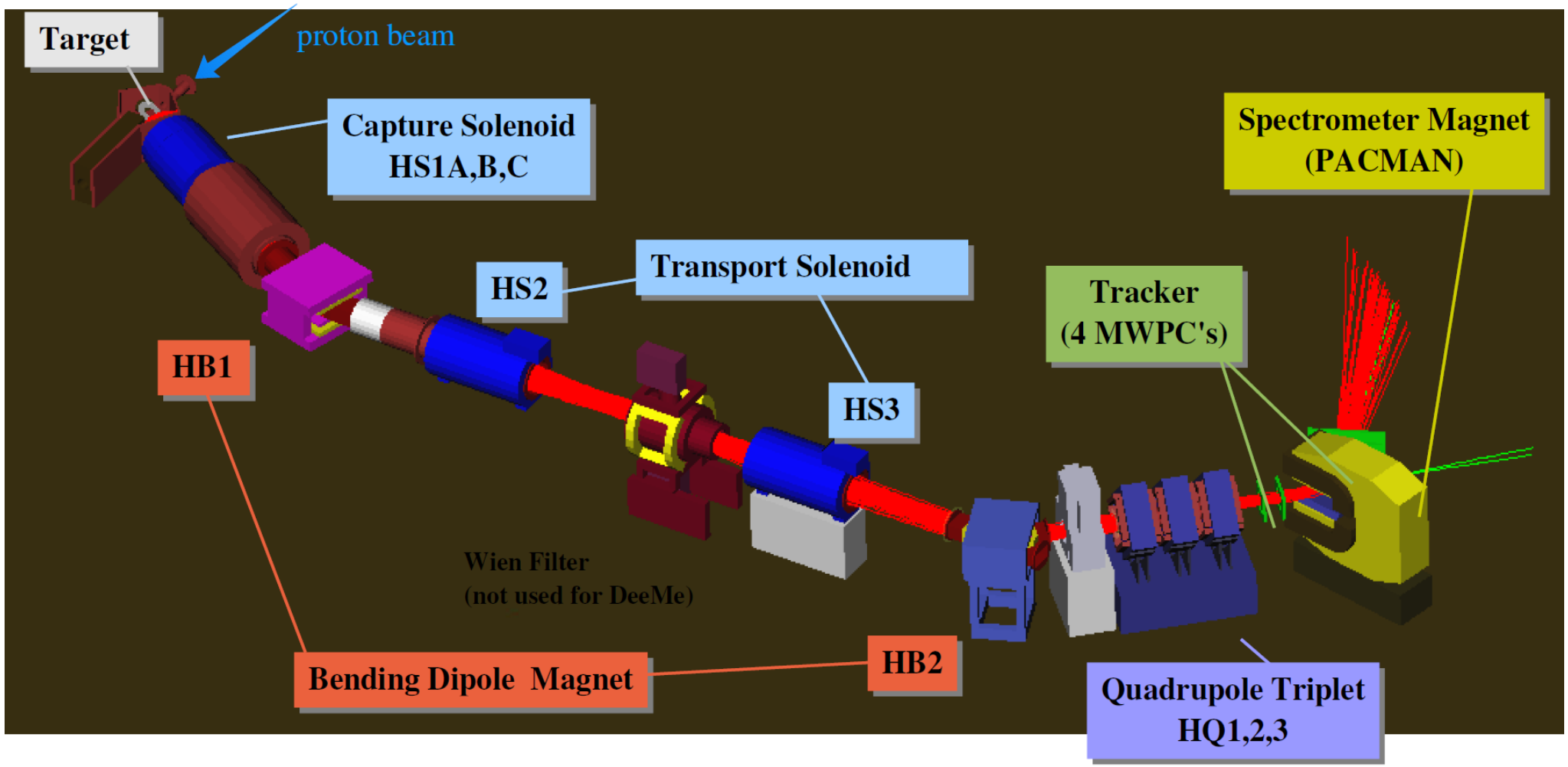


- Analyze momentum
- Identify signal electrons
- Measure DIO spectrum

- Spectrometer dipole magnet & tracking device (MWPC)

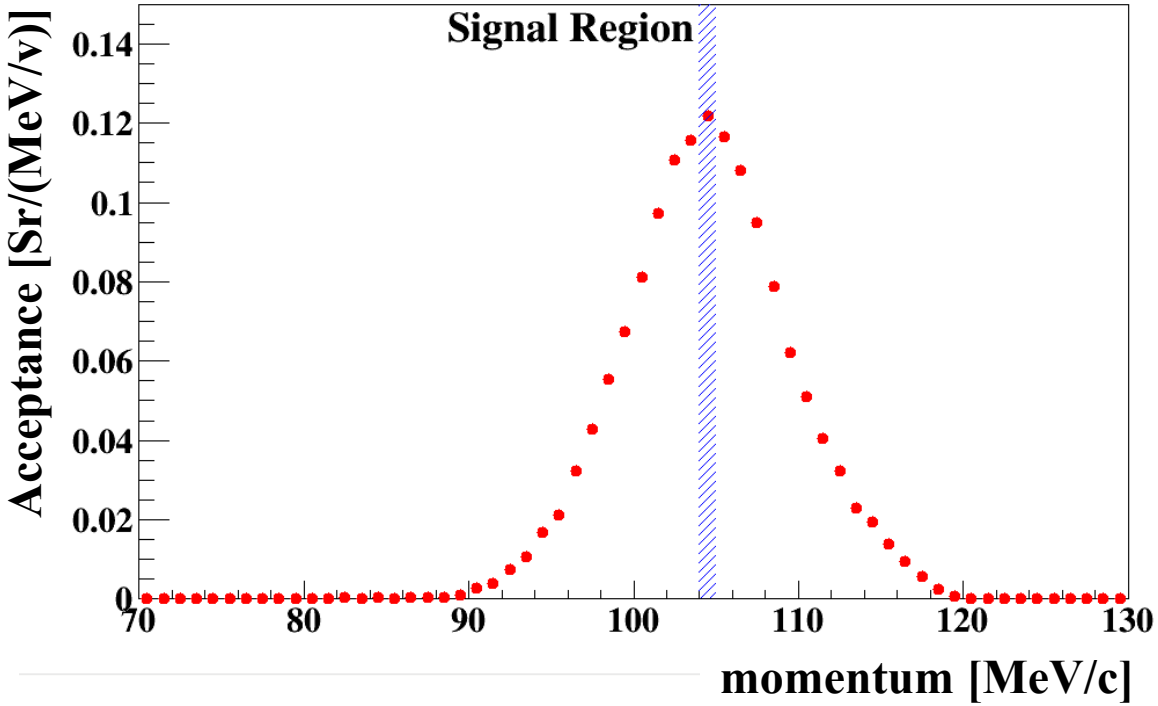
DeeMe Experimental Components

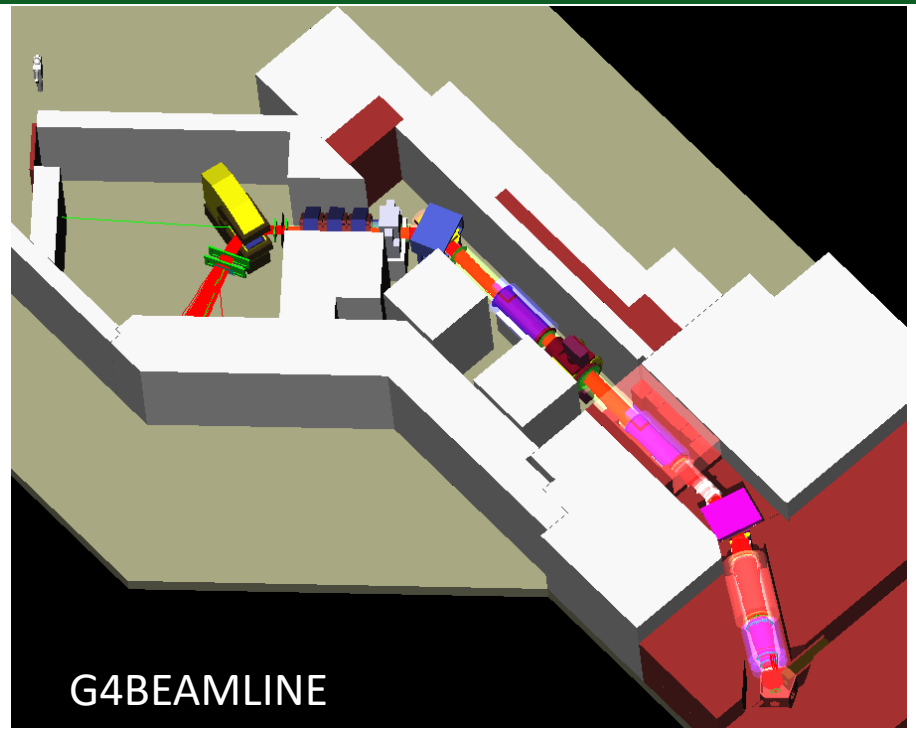
- Combination of a proton target, the H-Line, and the spectrometer



Performance of H-Line

- Transmission efficiency
  - Simulated by G4BEAMLINE
  - Beam optics optimized for signal electron (105 MeV/c)
  - Acceptance at the spectrometer as a function of momentum

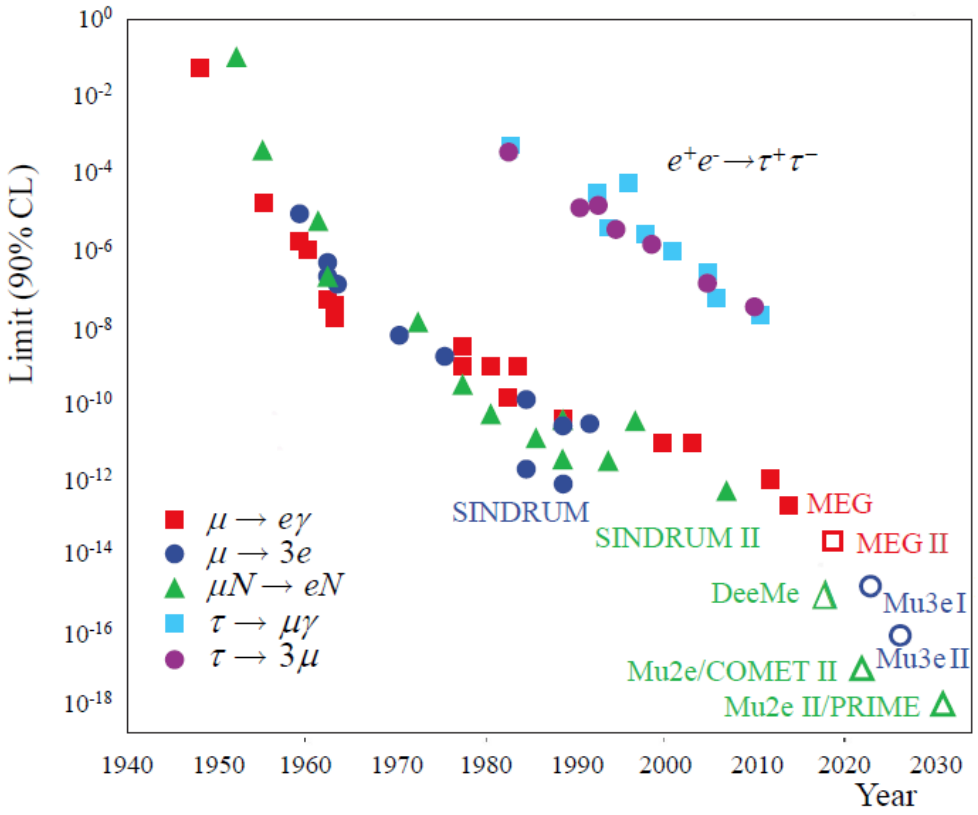




- ~120 msr/(MeV/c) at signal momentum
  ⇒ Higher sensitivity than ever before

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

Sensitivity Goal



Eur. Phys. J. C 78 (380) 2018.

- Current upper limits for μN→eN
  - TRIUMF
    - $< 4.6 \times 10^{-12}$ (Ti target)
  - SINDRUM-II at PSI
    - $< 4.3 \times 10^{-12}$ (Ti target)
    - $< 7 \times 10^{-13}$ (Au target)

Single event sensitivity (S.E.S.) :
branching ratio @ 1 event observation

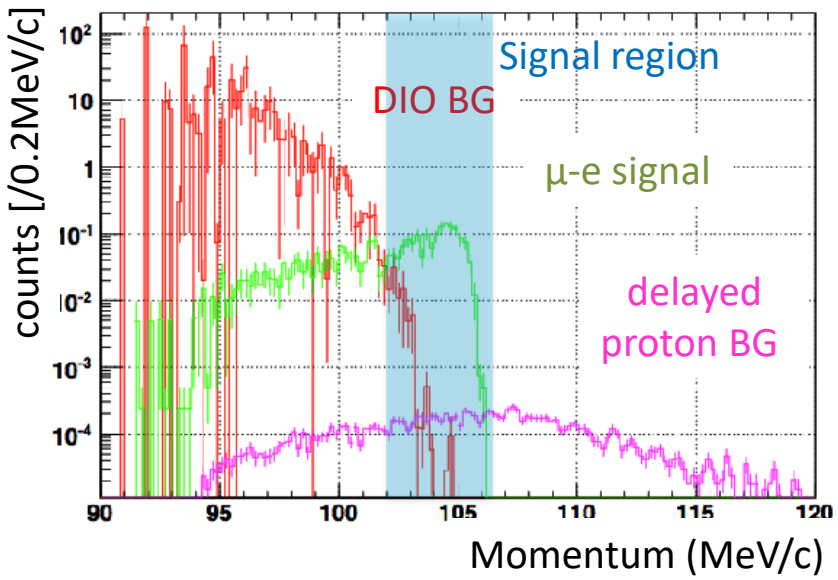
- DeeMe aims to achieve
  - 1-year run (2×10^7 sec) with 1 MW beam
    - S.E.S. $< 1 \times 10^{-13}$ (C target)

    to observe the CLFV

    or to improve the current limit by ×~10

Backgrounds

- Low-momentum background suppressed by the beamline
- High-momentum tail measure momentum → need Δp < 1 MeV/c spectrometer



RCS 1MW, beam time 2×10^7 sec

- Physics background
  - 1-year run (2×10^7 sec)
  - Beam pion/muon capture

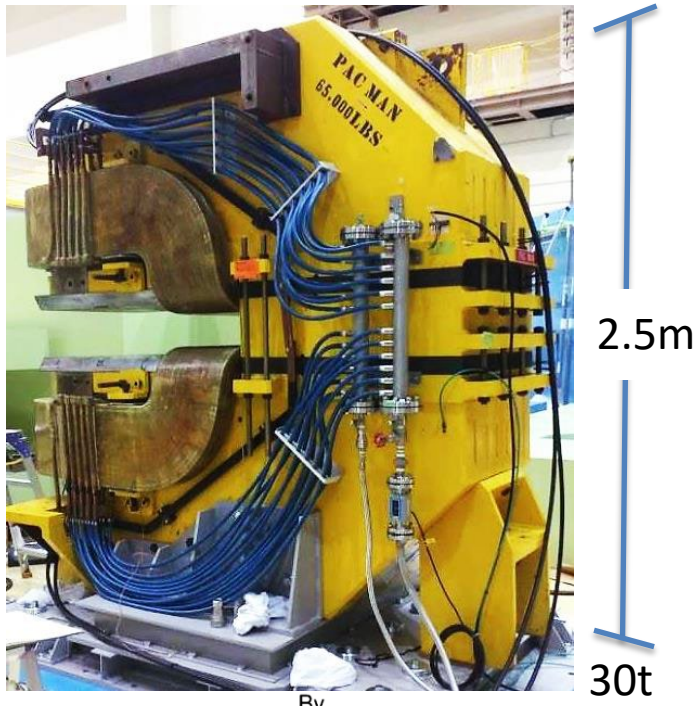
    $\pi^-/\mu^- + (A, Z) \rightarrow (A, Z\text{-}1)^* \rightarrow \gamma + (A, Z\text{-}1)$,

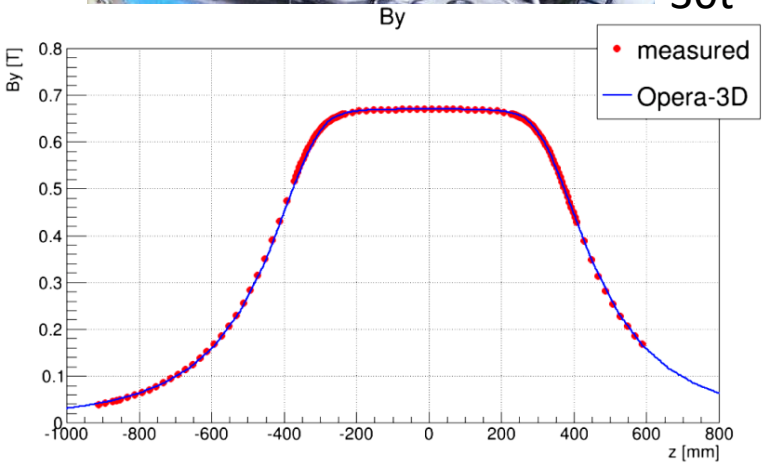
    $\gamma \rightarrow e^+e^-$ at the beam-prompt timing
  - Muon Decay in Orbit (DIO) 0.09
  - Delayed protons at the irregular timing induce backgrounds < 0.027 (< 0.05 90%C.L.)
  - Detector live-time duty = 1/20000

    → Cosmic ray backgrounds are suppressed

    e: < 0.018, μ: < 0.001
  - No antiprotons (Ep = 3 GeV << 5.6 GeV)

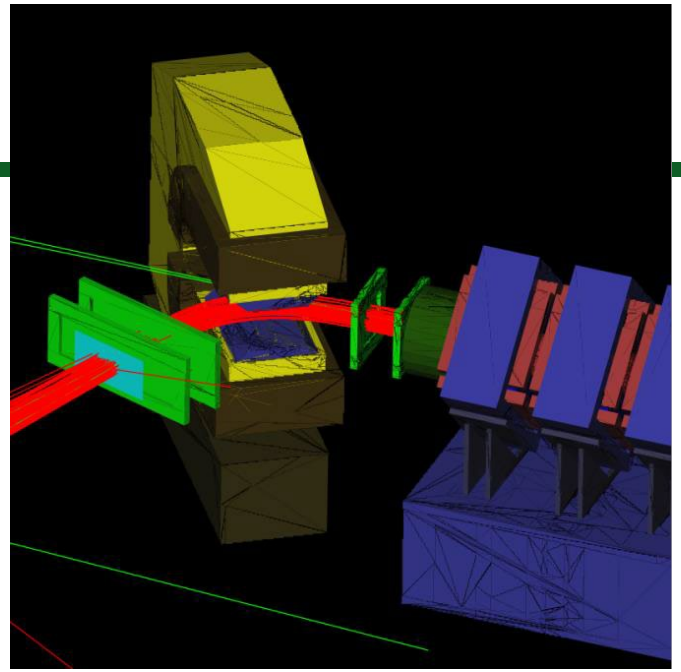
Spectrometer Magnet, PACMAN





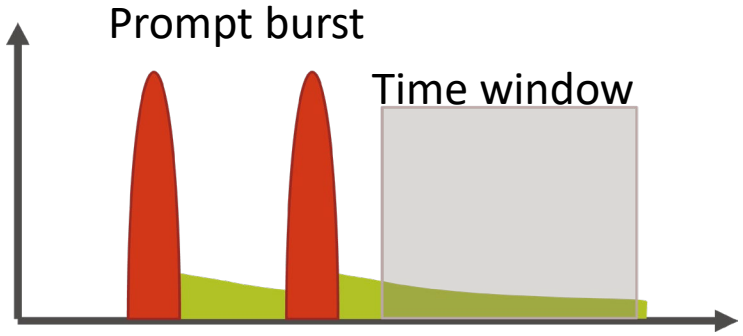
- Dipole magnet PACMAN
- Used in PIENU experiment in TRIUMF until 2012
- Shipped to J-PARC in 2014
- Normal field strength : 0.4 T (300A) in the central part
  - For electrons with 105 MeV/c bending 70 degrees
  - Good agreement between field measurement and Opera-3D calculations.

Detector (MWPC)



- Tracking Device
  - Thin Multi Wire Proportional Chamber (MWPC)
  - 2 upstream + 2 downstream of the magnet
    = totally **4 chambers**

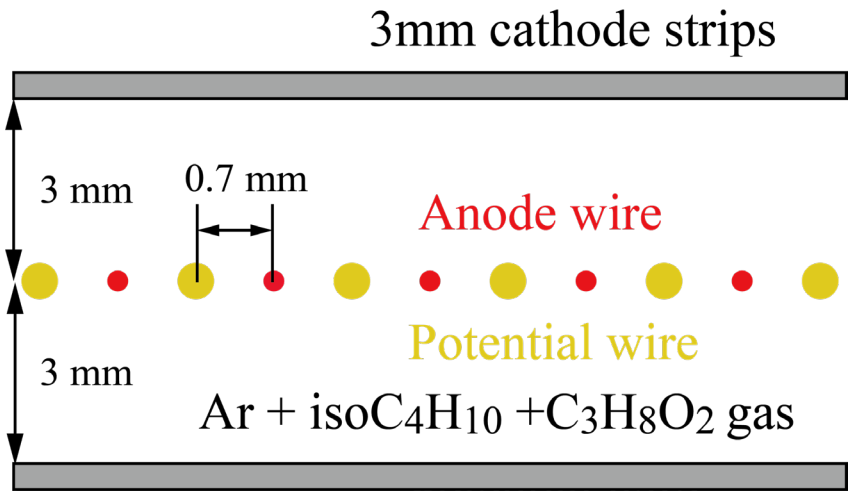
- Requirements
  - position resolution = **0.3 mm**, thickness = **0.1% X_0** ⇒ δP < **0.5 MeV/c** (RMS)
  - tolerate to beam bunch of **10^8 MIP**
  - instantaneous hit rate ~**70 GHz/mm²**
  - return to operational **300 nsec** after beam pulse to detect delayed electrons.
    ⇒ HV Switching MWPC

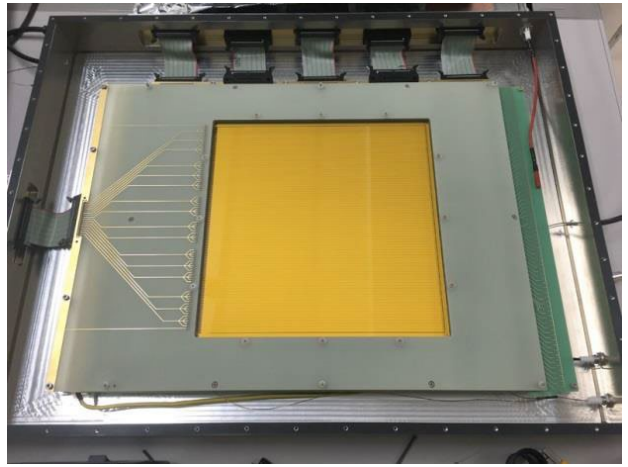


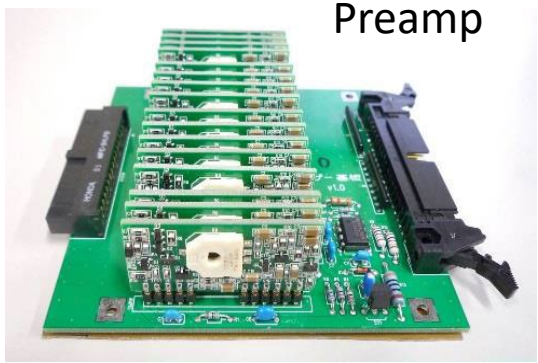
Detector (MWPC)

- MWPC
  - active area : 250 mm × 200mm
  - wire pitch : 0.7 mm
  - cathode strip
    - x: 3mm width
    - y: 15mm width

    → Flash ADC readout
  - Ar : $isoC_4H_{10}$: $C_3H_8O_2$ = 75:15:10

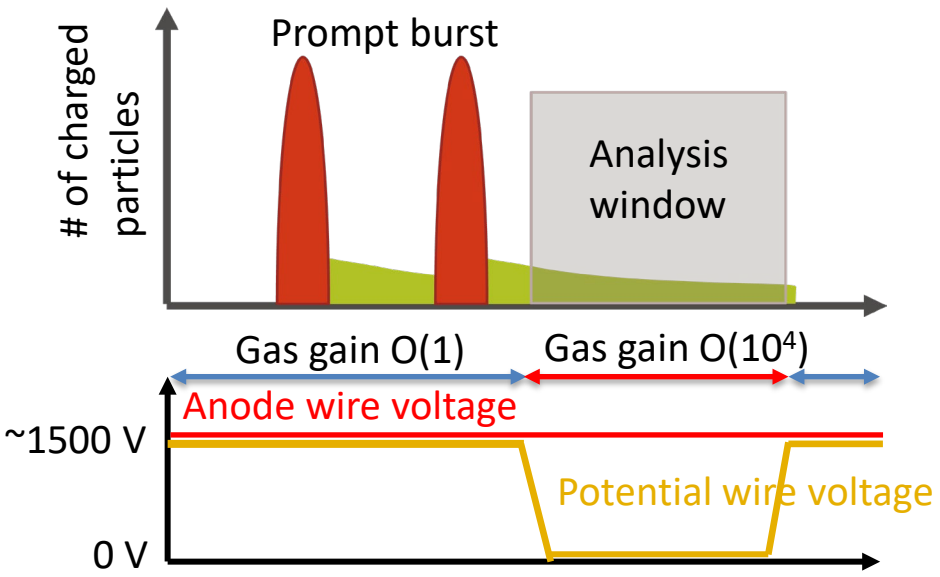






HV Switching MWPC

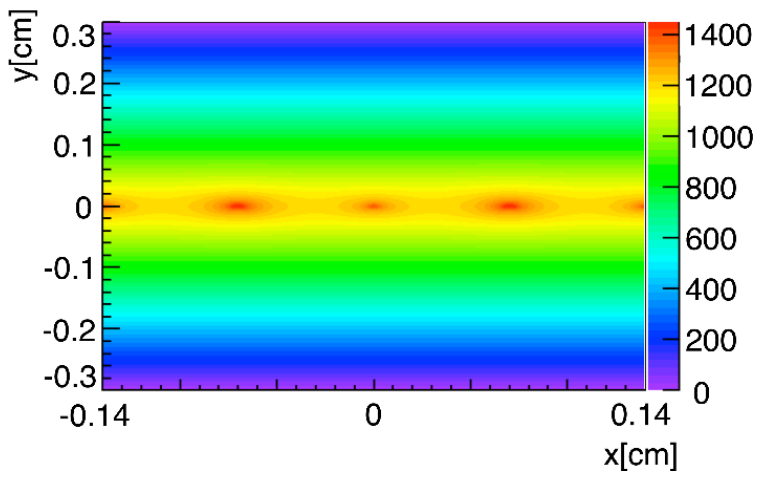
- HV Switching
  - anode = ~ 1500V
  - switch the voltage for potential wire



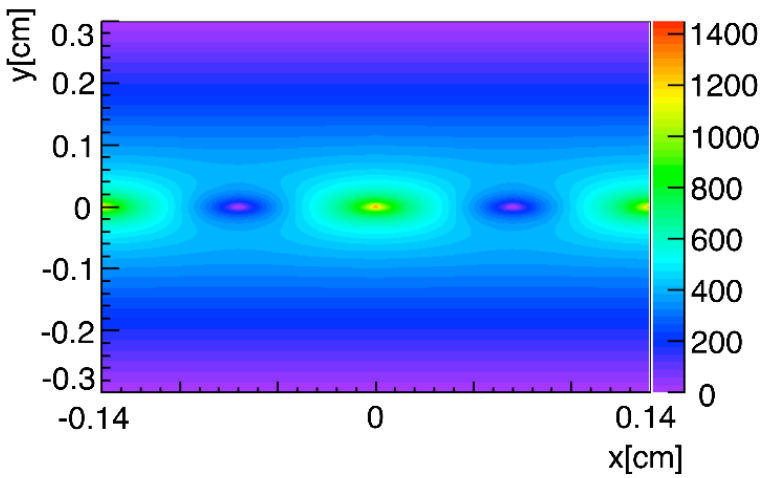
~1500 V
- usual
- detector protection during the burst, no space charge creation

0 V
- in the time window after prompt burst
- delayed signal detection

Electric field contour



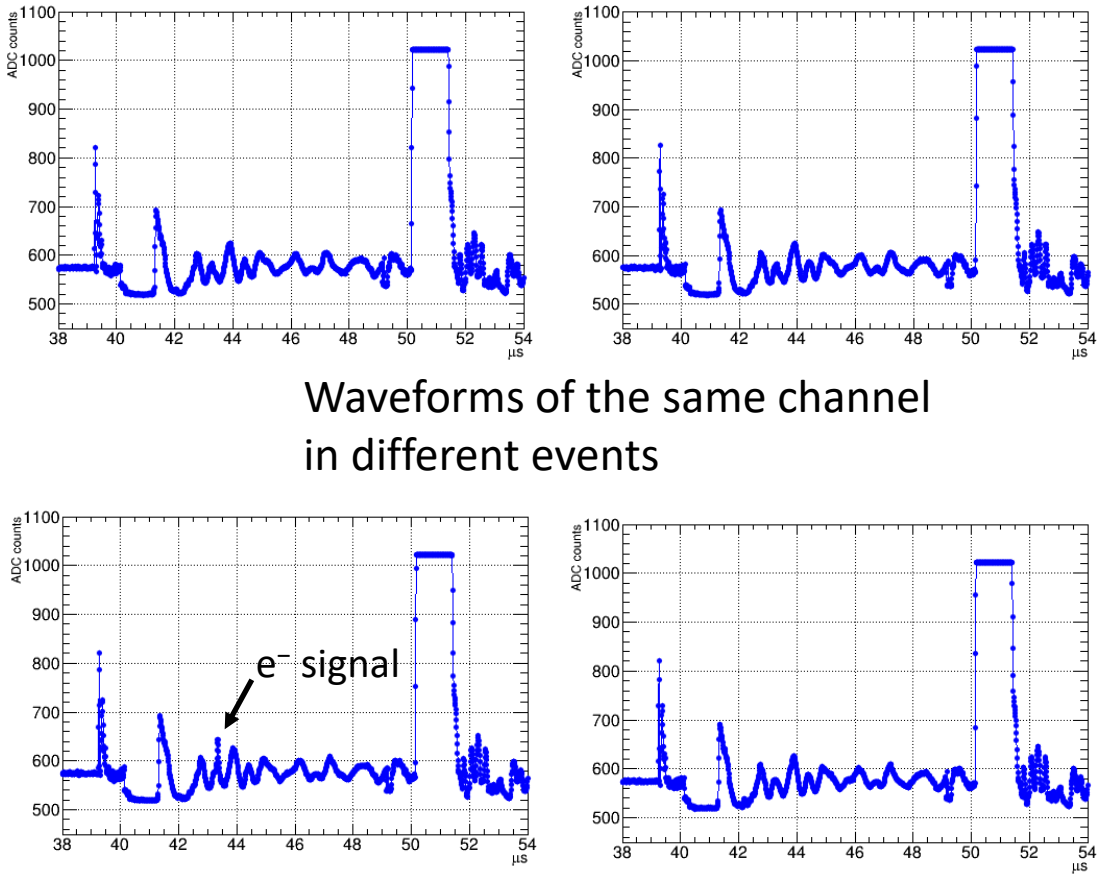
Anode wire : ~1500V
Potential wire : ~1500V
Gas gain : 3



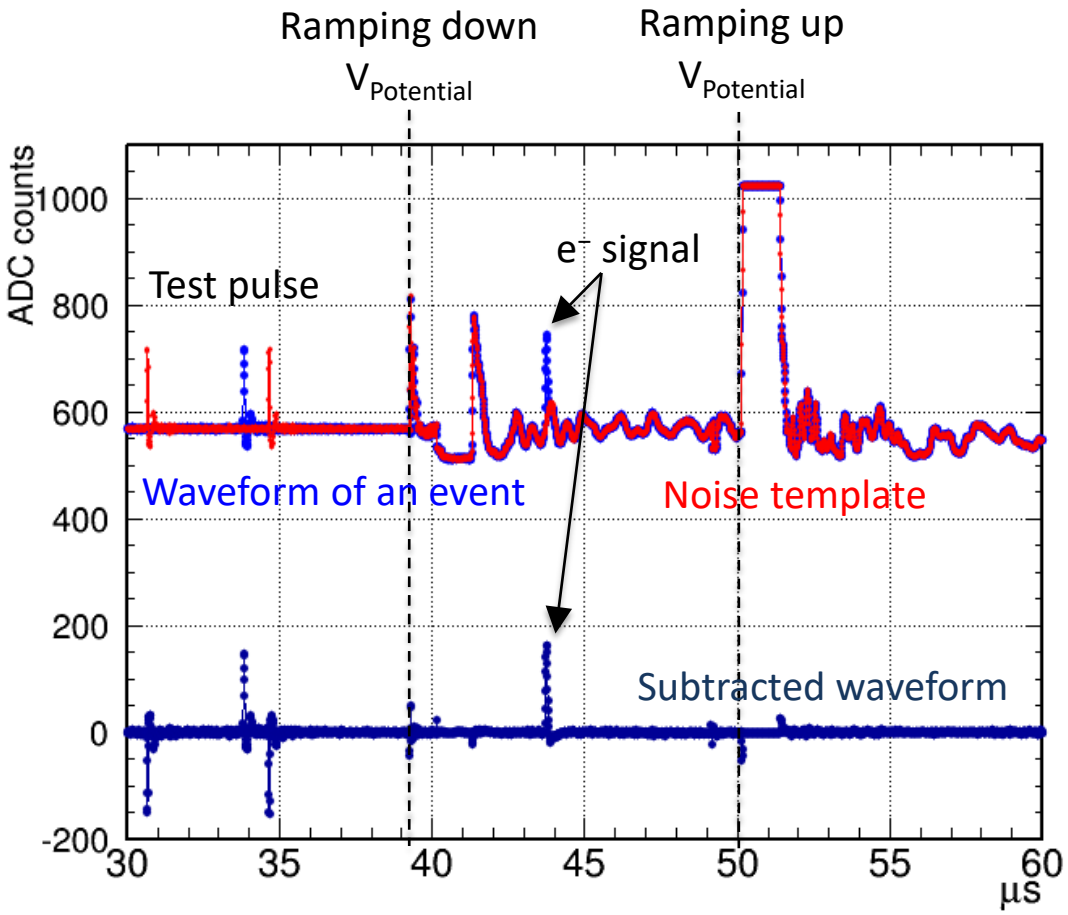
Anode wire : ~1500V
Potential wire : 0V
Gas gain : ~10^4

MWPC Waveform Analysis

- Noise of HV switching has always the same shape.
- Template subtraction eliminates baseline vibration by the HV switching



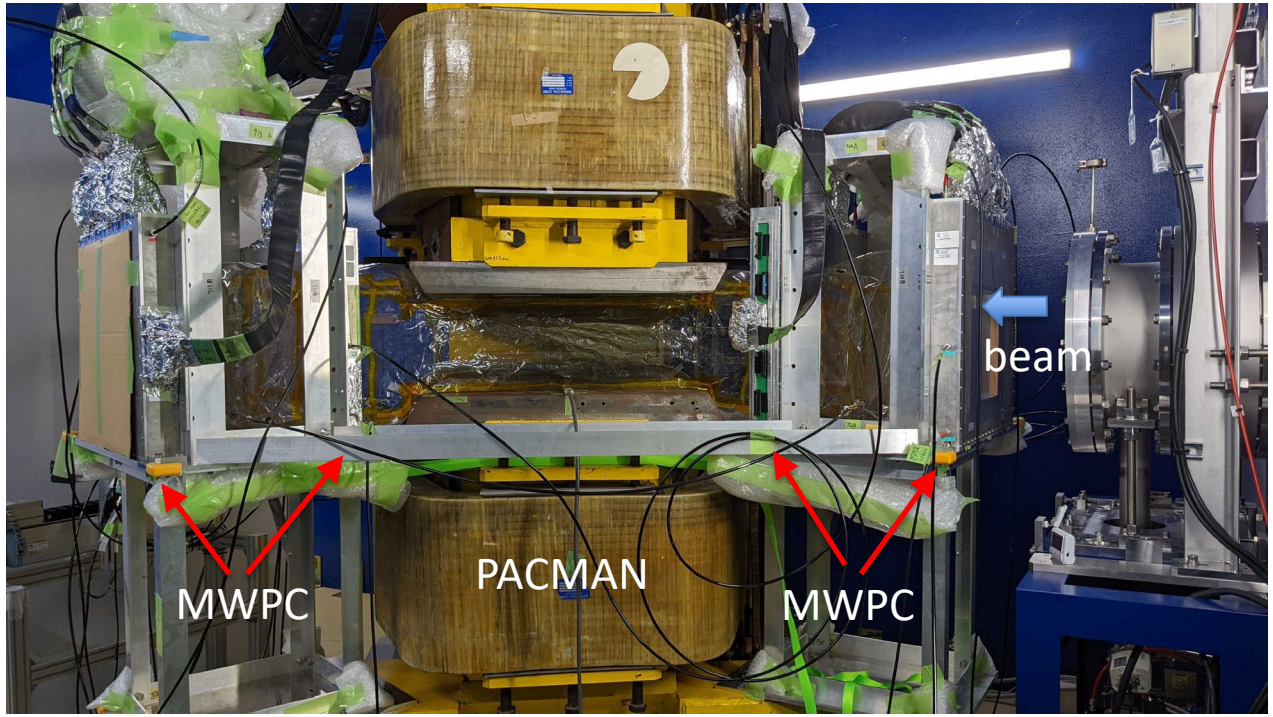
Waveforms of the same channel
in different events

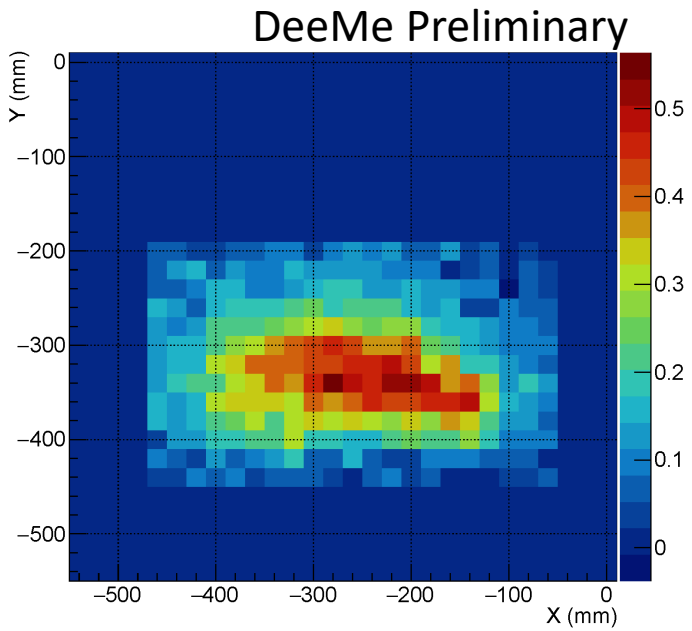


- Select four hits from the four MWPCs and calculate the momentum.

DeeMe Commissioning

- The DeeMe commissioning run was performed in June 2022.
- Every system worked well.



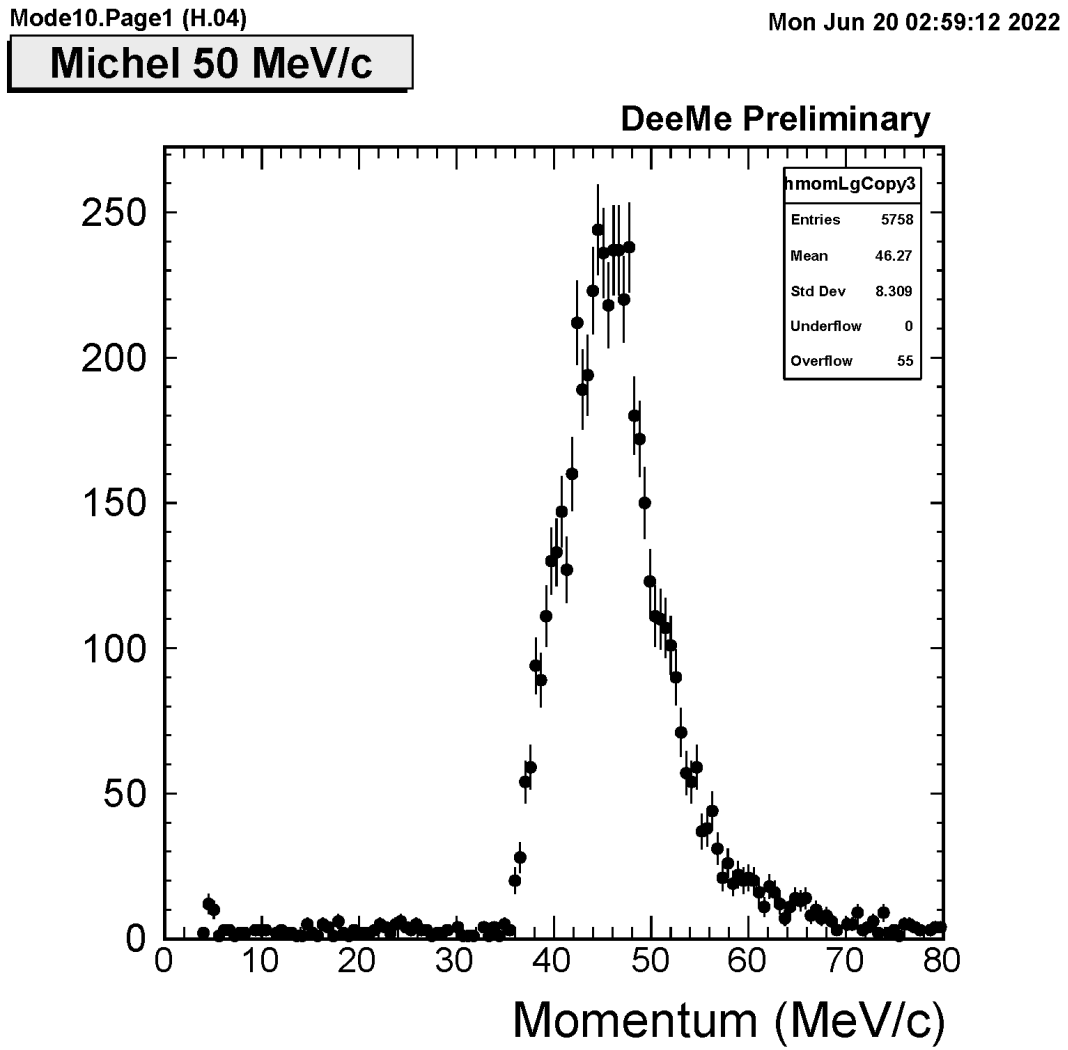


Prompt burst
105 MeV/c electron
beam profile

- Ready to take physics data.

DeeMe Commissioning

- Quick data analysis
  - Positron data set at 50 MeV/c for Michel edge measurement
  - Positron momentum was reconstructed successfully.
  - More calibration is needed.



Summary

- Muon-electron conversion search experiment, DeeMe, is performed at J-PARC MLF H-Line with S.E.S. of 1×10^{-13}.

- The HV Switching MWPC was developed to avoid the prompt burst.

- The DeeMe commissioning run was conducted in June 2022.
  Every system worked well.

- DeeMe is ready to take physics data.

Backups

High Burst Torelant MWPC

- Need to suppress delayed noise that occurs after the hitting of prompt charged particles.
- Added methylal ($C_3H_8O_2$) to Ar + $isoC_4H_{10}$ gas.