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Unravelling the mysteries of matter, life and the universe.

J-PARC

Charged Lepton Flavor Physics

Satoshi Mihara
KEK/J-PARC/Sokendai

Session for research topics for future

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matter, life and the universe.

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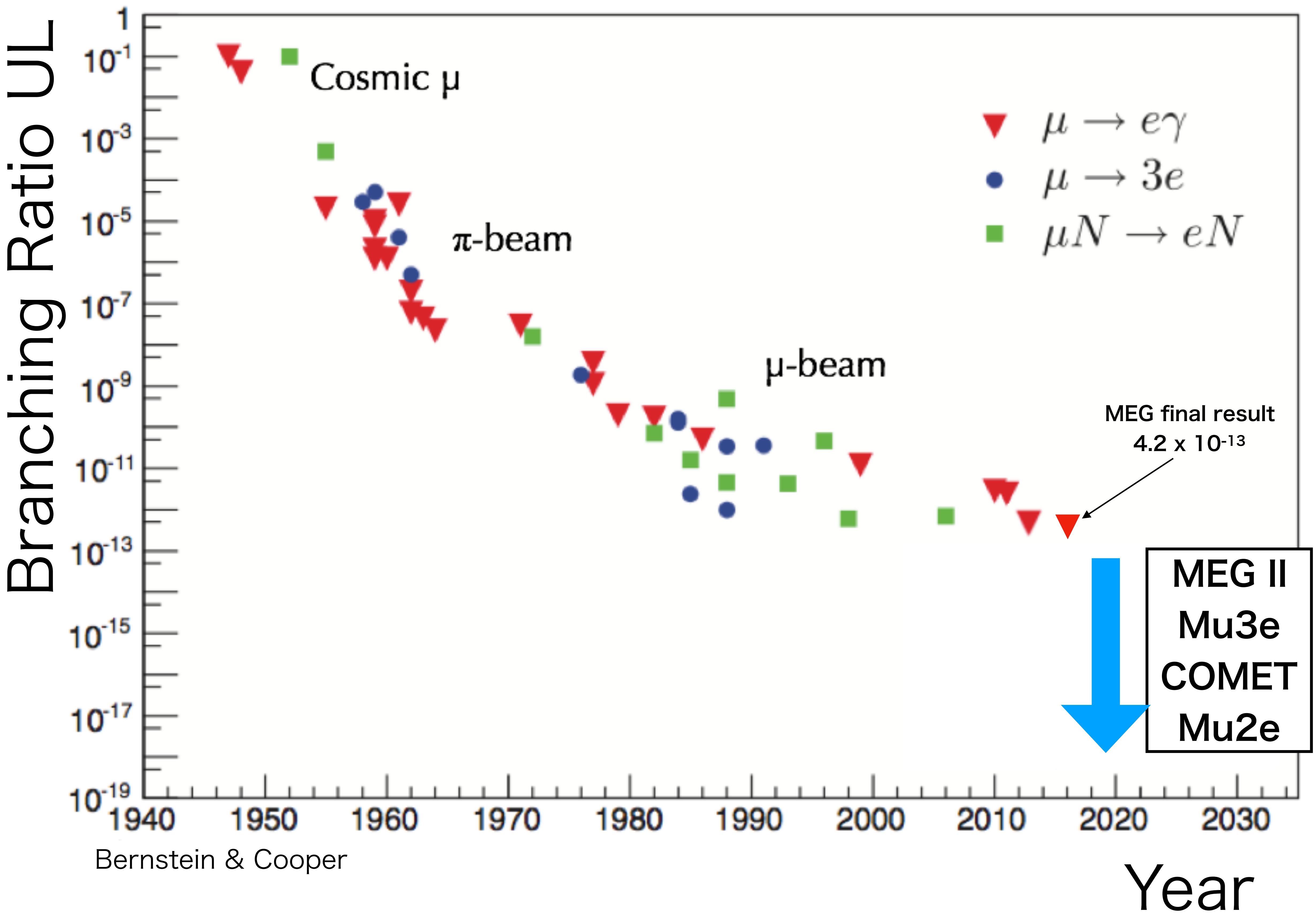
Outline

- Introduction
- CLFV physics with DC muon beam
- CLFV physics with pulsed muon beam
- CLFV physics with tau leptons
- Schedule and summary

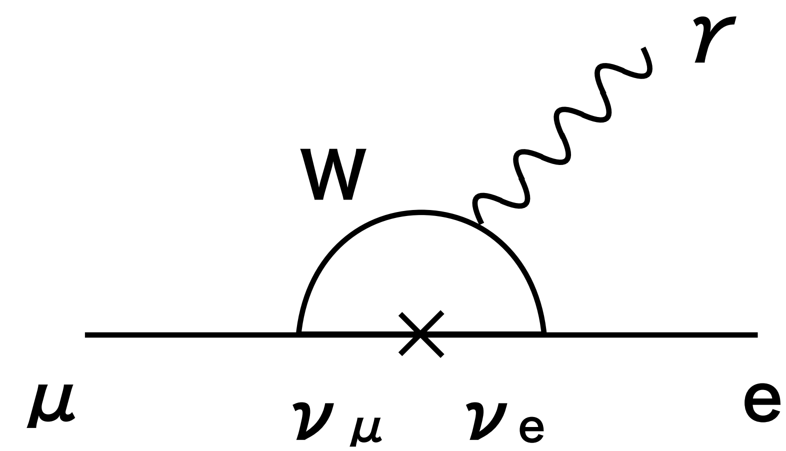
Introduction

Charged Lepton Flavor Violation

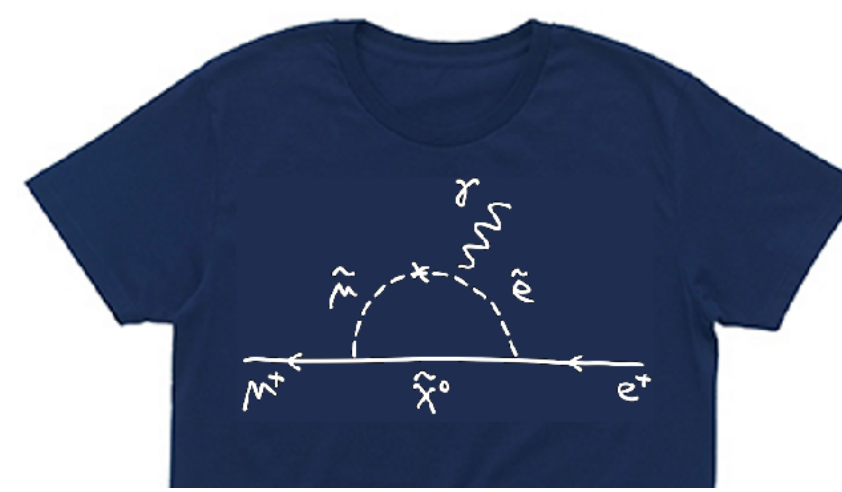


Bernstein & Cooper

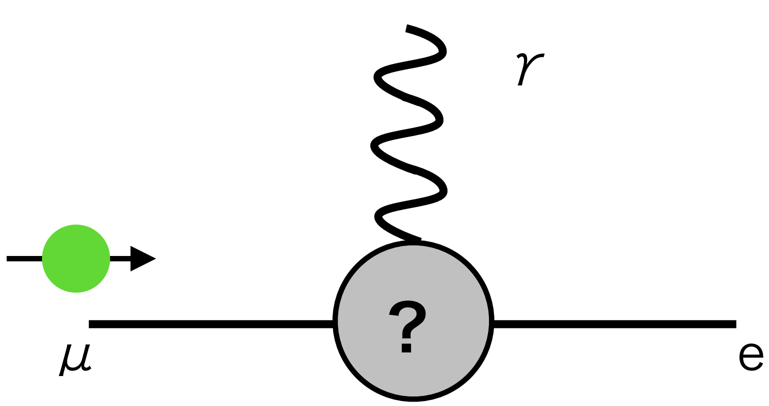
Charged Lepton Flavor Violation



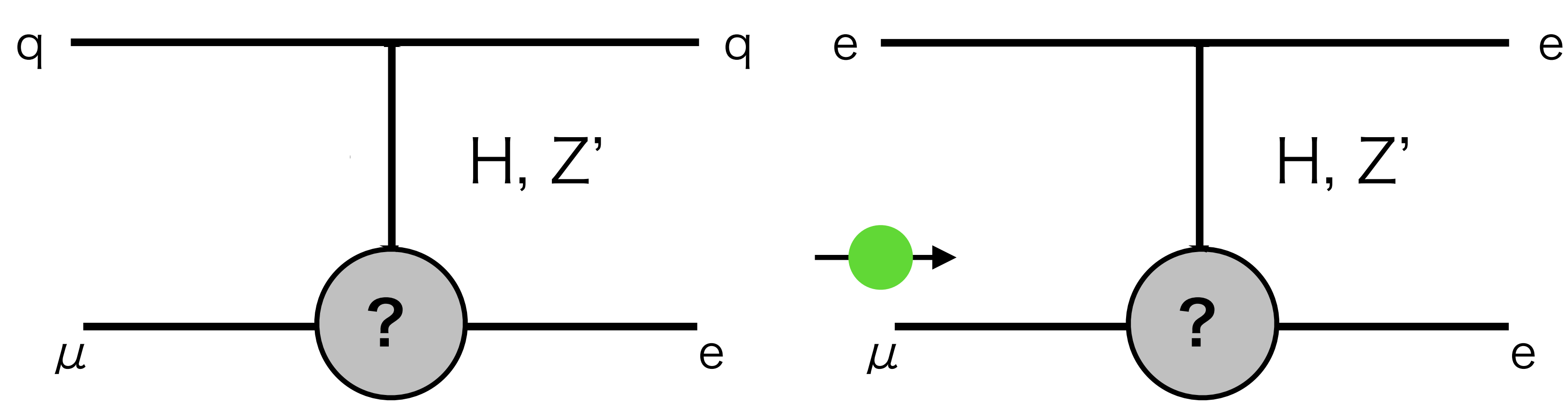
- cLFV rate in the Standard Model with non-zero neutrino mass is too small to be observed in experiments; O(BR) < 10^{-50}
  - No SM Physics Background
  - Observation = clear evidence of NP
- Motivated by many kinds of new physics models BSM



μ→eγ



μ-e conv.　　μ→eee



Current Status of Charge Lepton Flavor Violation Search

- $\mu \rightarrow e\gamma$
  - MEG $Br(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$
- $\mu \rightarrow eee$
  - SINDRUM $BR(\mu \rightarrow eee) < 1.0 \times 10^{-12}$
- μ-e conversion
  - SINDRUM II $R(\mu\text{-}e\text{: Au}) < 7 \times 10^{-13}$

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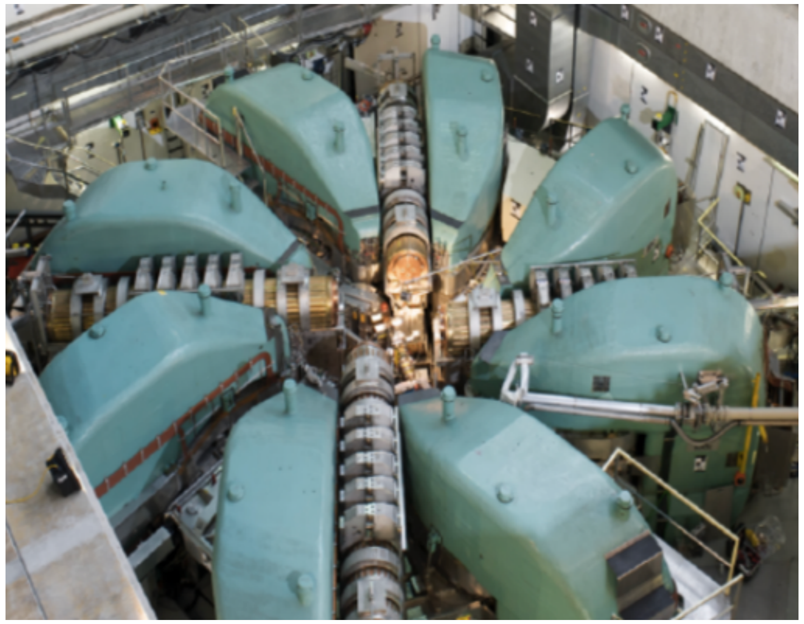
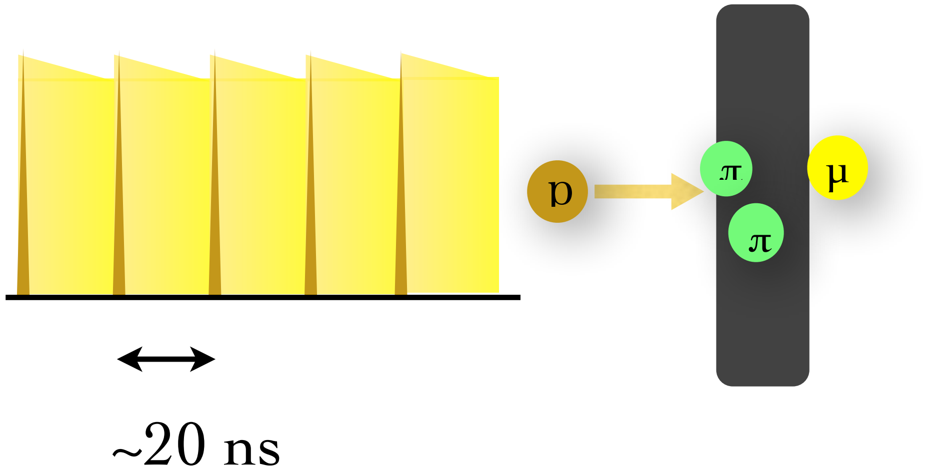


PSI Ring Cyclotron
590MeV, 1.4MW



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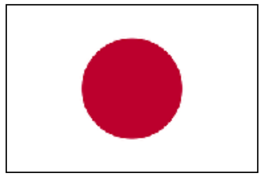
→ **MEG II**

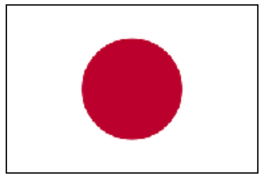


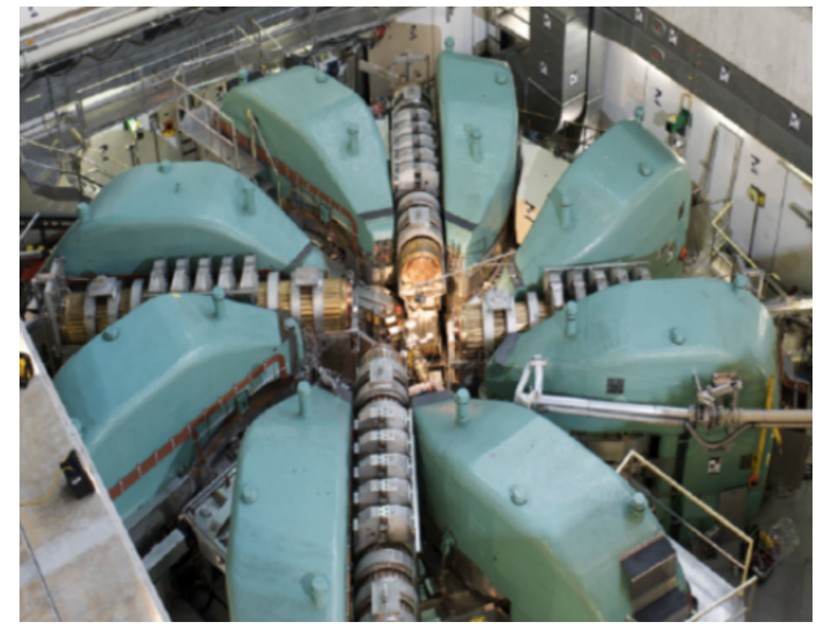

- $\mu \to eee$
  - SINDRUM $BR(\mu \to eee) < 1.0 \times 10^{-12}$

→ **Mu3e**

- μ-e conversion
  - SINDRUM II $R(\mu\text{-}e: Au) < 7 \times 10^{-13}$

→ **COMET/Mu2e**



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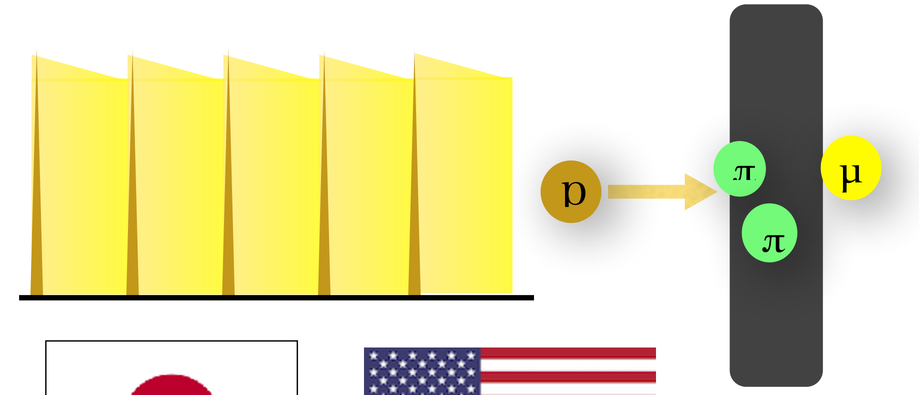

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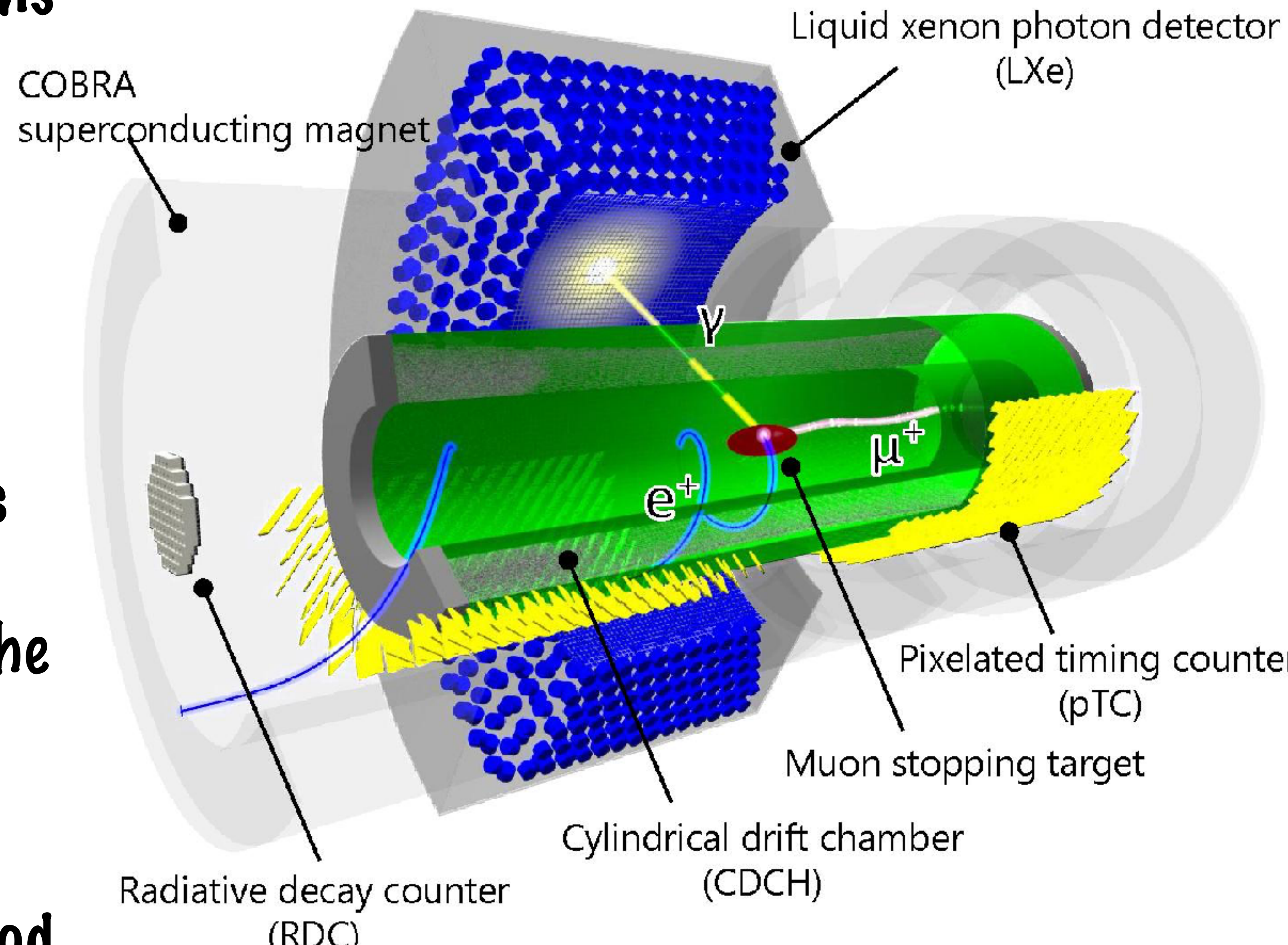
CLFV Physics with DC muon beam

US-Japan meeting, 15-16 April, 2019 at Univ. of Hawaii

MEG II: μ→eγ search using DC muon beam

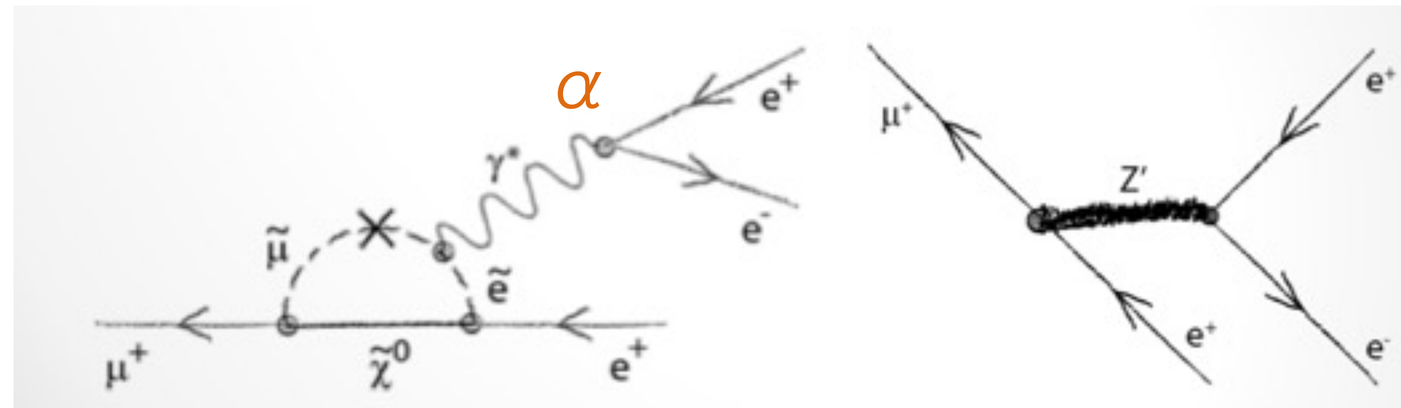
- Twice better resolutions than MEG in all components
- Double the muon beam rate
  - 7×10^{7} muon stops/s
- New detector to tag the radiative muon decay event
- New calibration method

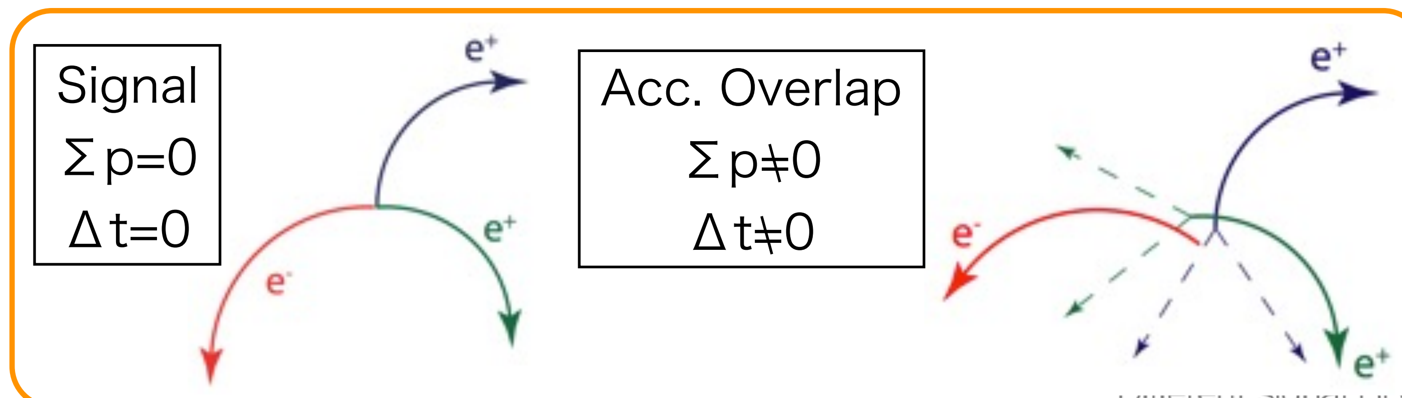


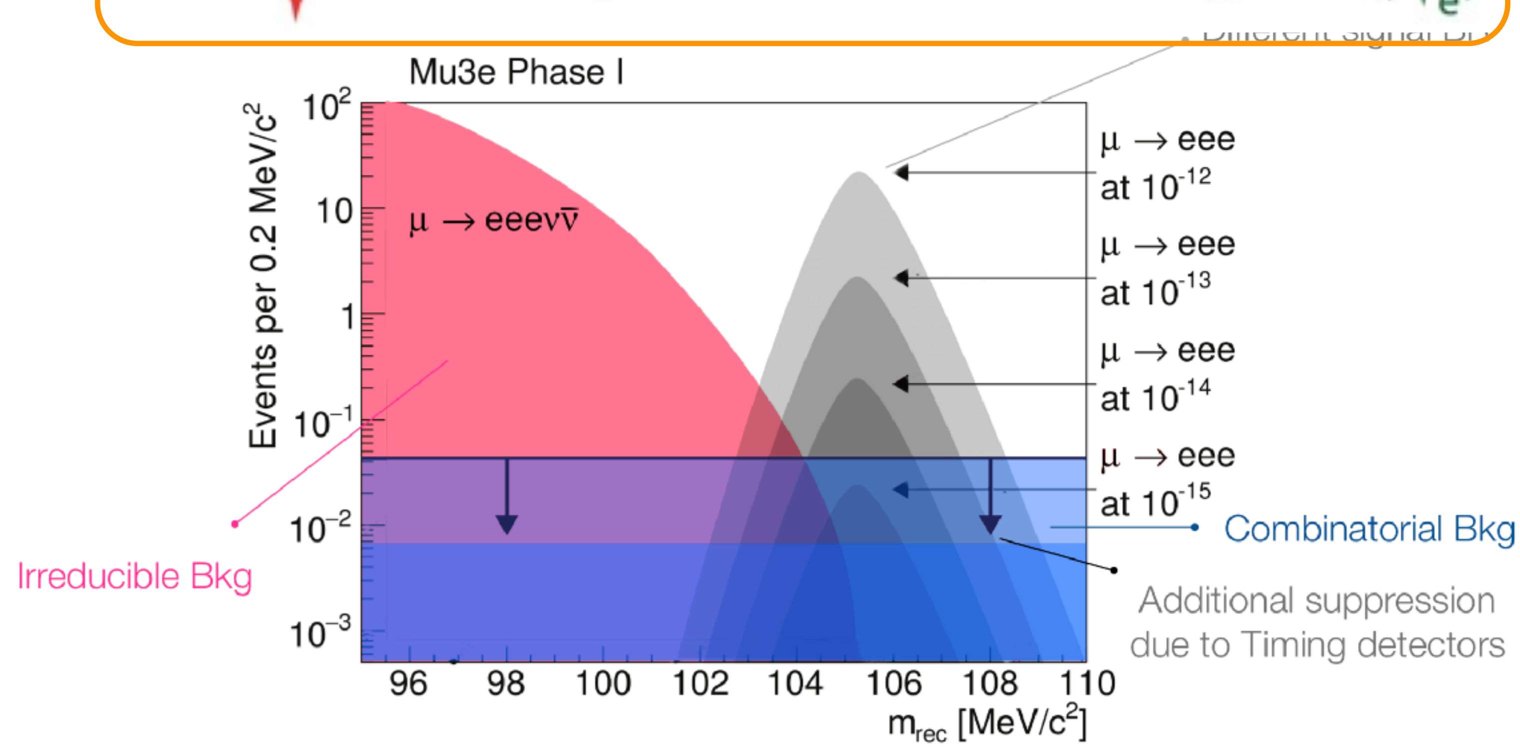
Target Sensitivity : 6×10^{-14} in 3 years running

Mu3e: μ→eee Search using DC Muon Beam

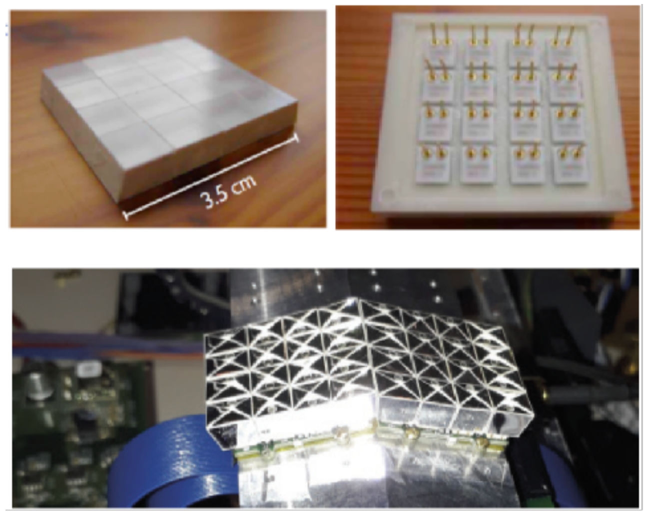
- Another channel sensitive to cLFV with DC muon beam
  - 1.0x10^{-12} (90% C.L.) by SINDRUM
  - Goal : 10^{-16} in 2 steps
- Measure all electron tracks with extreme precision
- Background source
  - $\mu^+ \rightarrow e^+e^+e^-\overline{\nu}\nu$
  - Accidental overlap
- Beamline is shared with MEG II



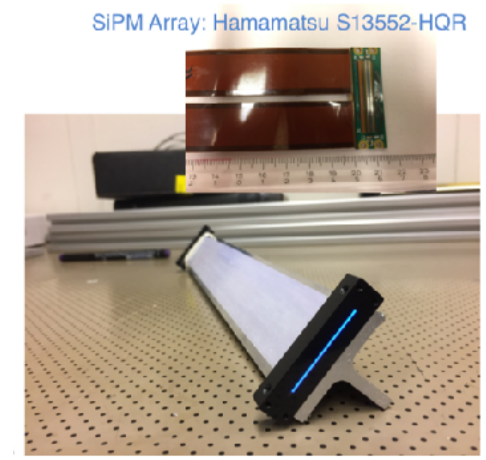


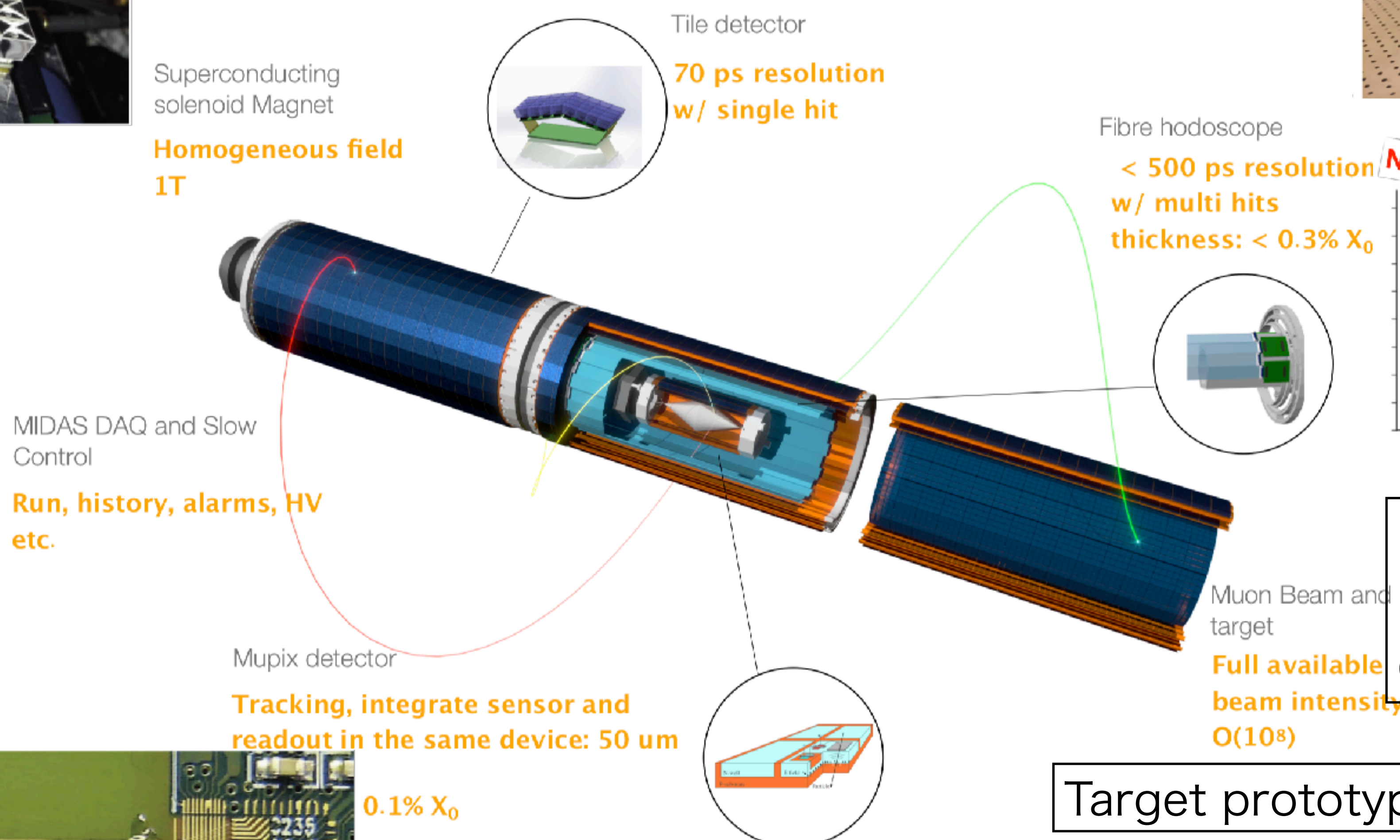


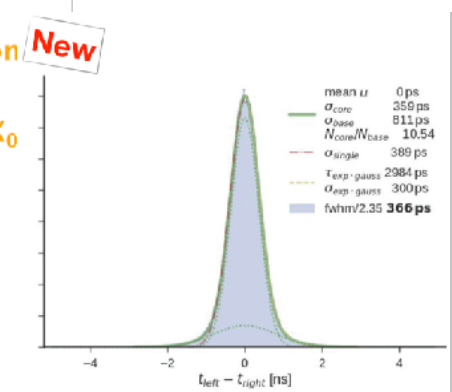
Detector Preparation



Tile detector prototype
Good enough σ_t

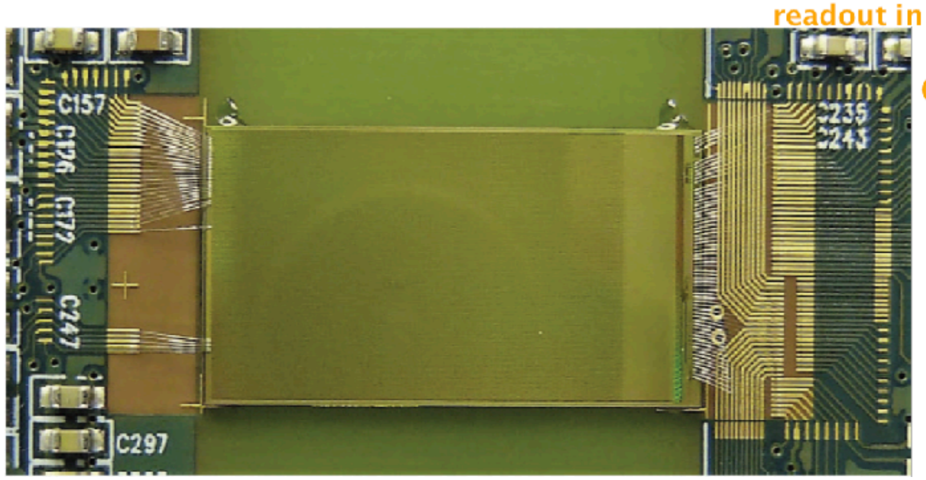






Fiber hodoscope
prototype
Good enough σ_t

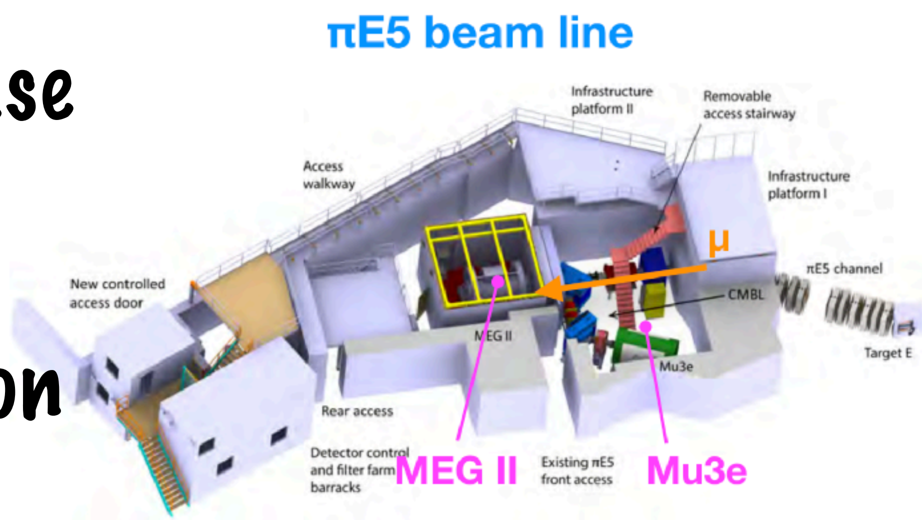
Target prototype

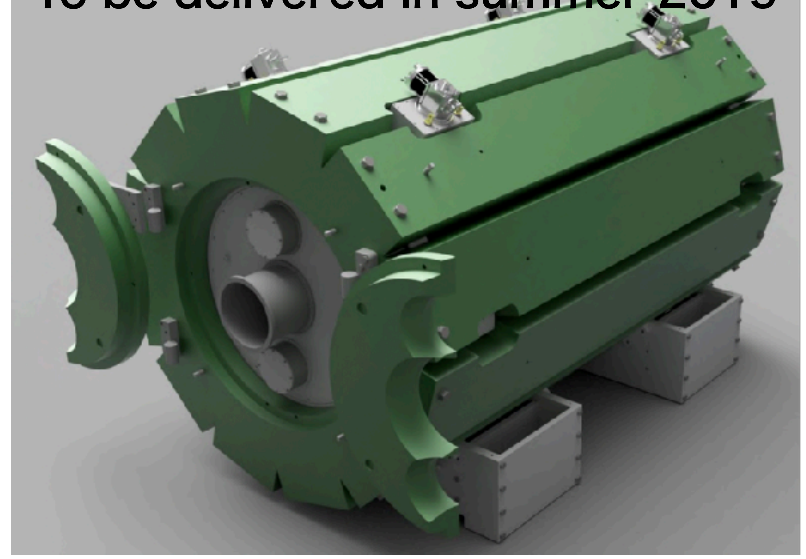


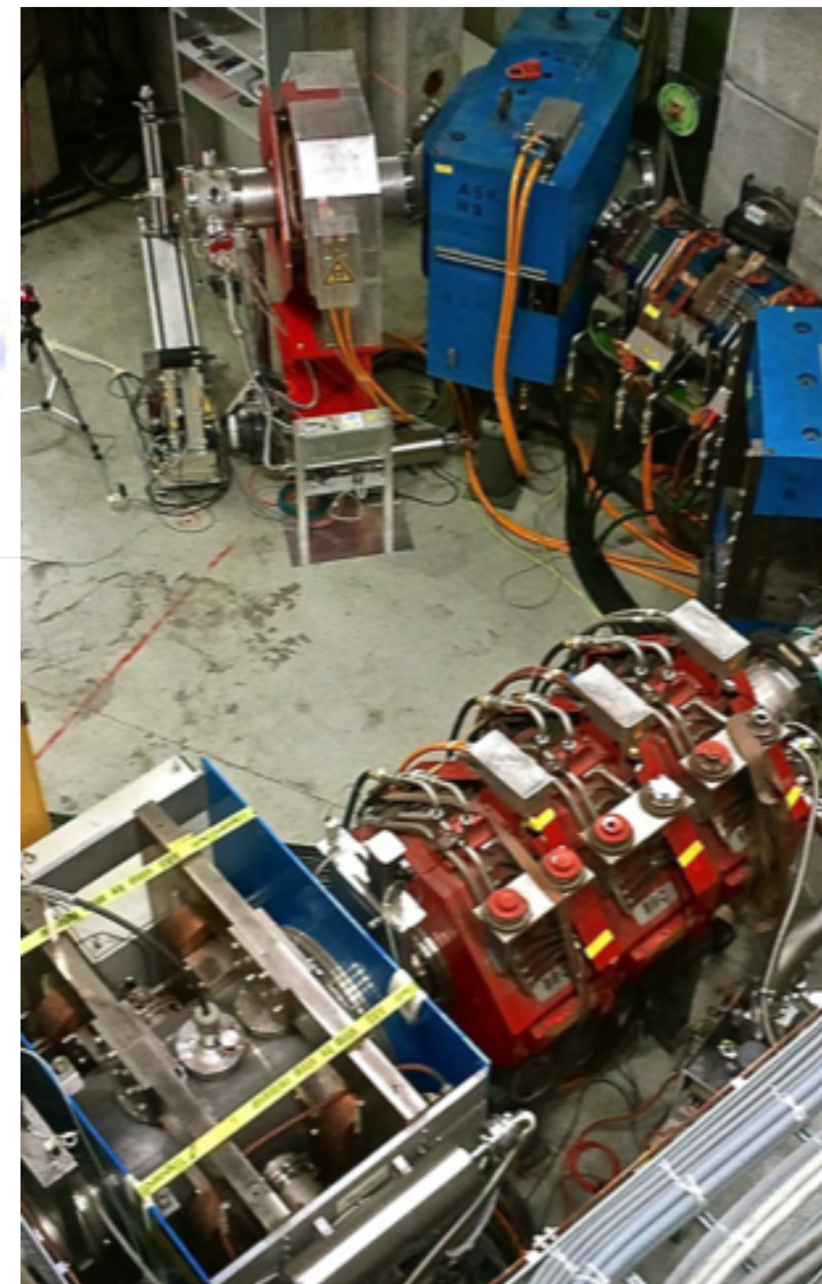
1st large-area prototype
MuPix8 is being tested
MuPix9 & MuPix10 follow

Mu3e Status

- Moving from R&D phase to construction phase
  - Ready for production in 2019
  - Detector construction in 2020
- Commissioning start in 2021




To be delivered in summer 2019



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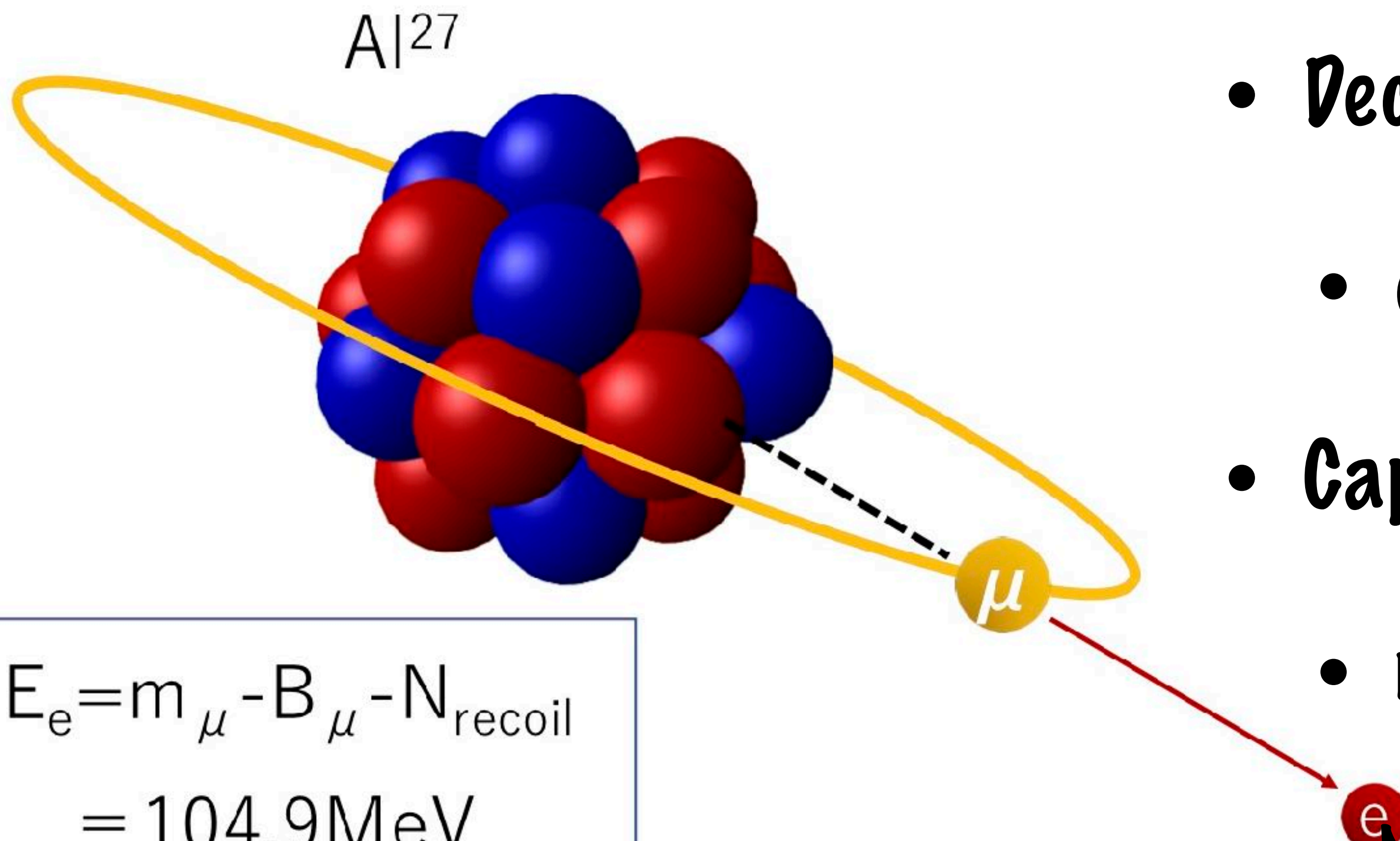
Mu-e conversion

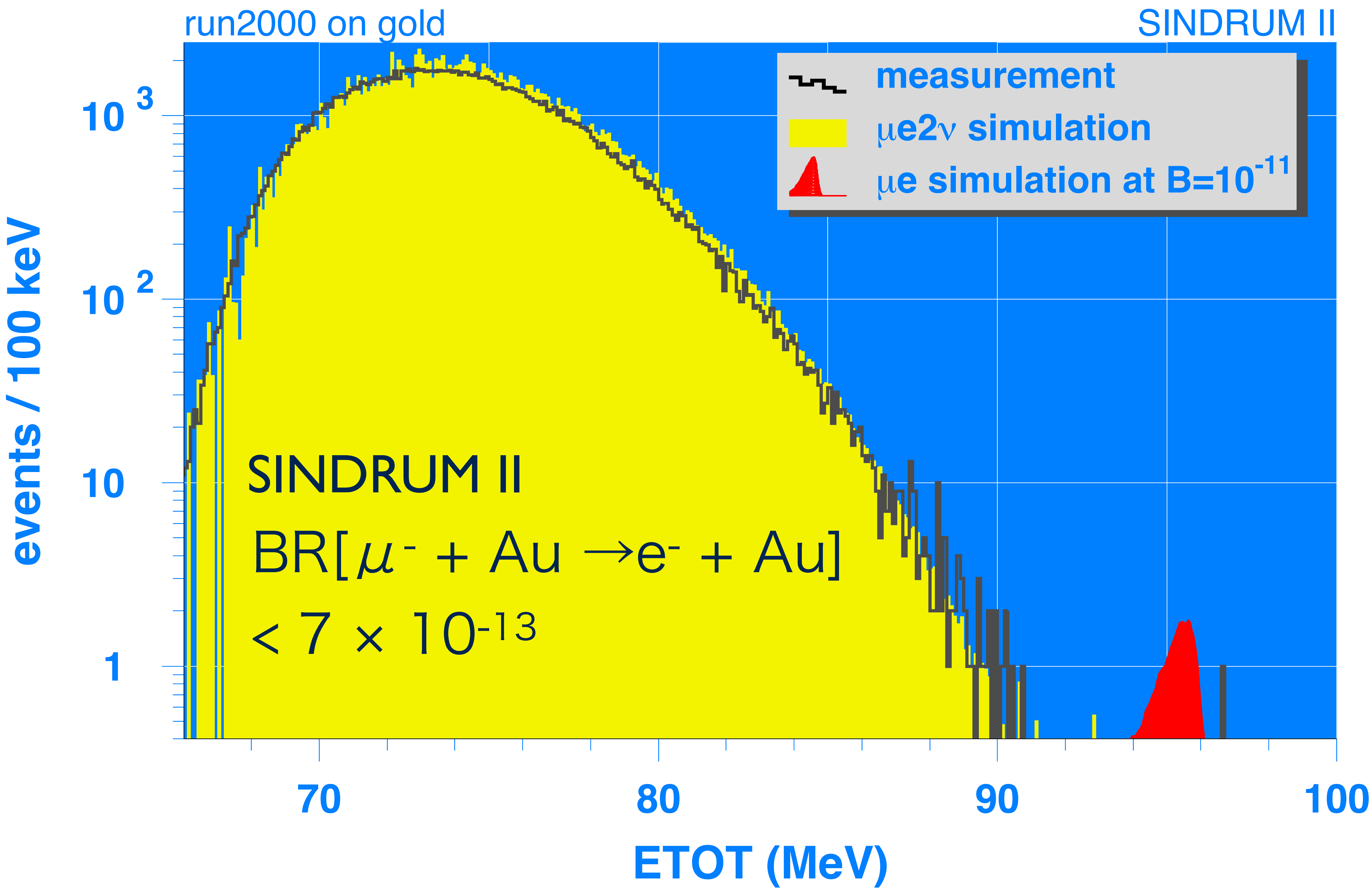


$E_e = m_\mu - B_\mu - N_{recoil}$
$= 104.9 MeV$

- Atomic capture of μ^-
  - Decay in orbit (DIO) $\mu^- \to e^- \bar{\nu}_e \nu_\mu$
    - electron gets recoil energy
  - Capture by nucleus $\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$
    - resultant nucleus is different
  - $\tau_\mu^N < \tau_\mu^{free}$ (τ_μ^{Al} = 860 nsec)
  - μ-e conversion $\mu^- + (A,Z) \to e^- + (A,Z)$

- $E_{\mu e}(Al) \sim m_\mu - B_\mu - E_{rec} = 104.97 MeV$
  - B_μ: binding energy of the 1s muonic atom

Electron Energy Spectrum



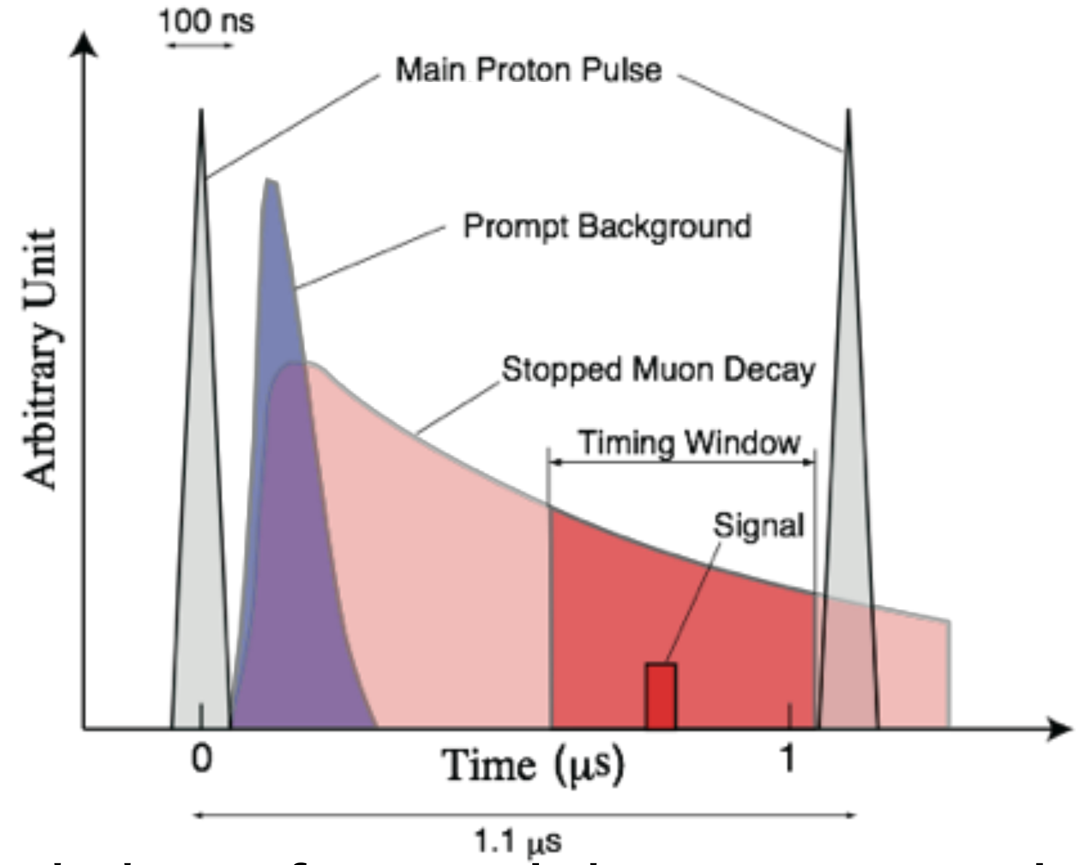
SINDRUM II

$BR[\mu^- + Au \rightarrow e^- + Au]$

$< 7 \times 10^{-13}$

μ-e Conversion Signal and Background

- Signal
  - Electron from the muon stopping target with a characteristic energy with a delayed timing
- Background
  - Decay in Orbit Electron
  - Radiative muon capture
  - Cosmic-ray
  - Anti-protons
  - and others



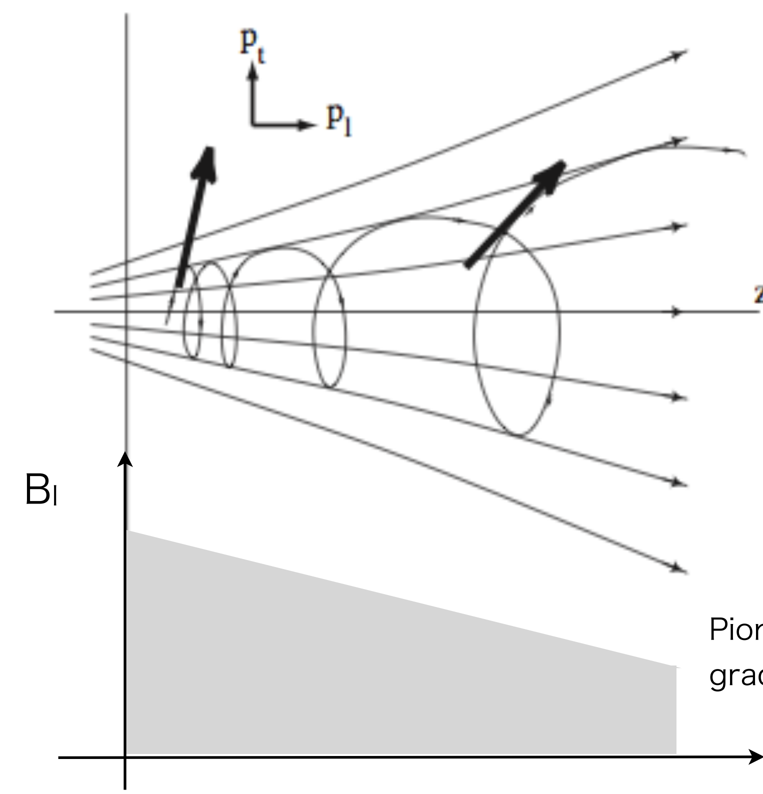
Tiny leakage of protons in between consecutive pulses can cause a background through **Beam Pion Capture process**:

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

$$R_{ext} = \frac{\text{Number of protons between pulses}}{\text{Number of protons in a pulse}}$$

More Muons

- Pion production in magnetic field
- Pion/muon collection using gradient magnetic field
- Beam transport with curved solenoid magnets



Pion/muon collection using gradient magnetic field

ISSN 1063-7788, Physics of Atomic Nuclei, 2010, Vol. 73, No. 12, pp. 2012–2016. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © R.M. Djilkibaev, V.M. Lobashev, 2010, published in Yadernaya Fizika, 2010, Vol. 73, No. 12, pp. 2067–2071.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Search for Lepton-Flavor-Violating Rare Muon Processes

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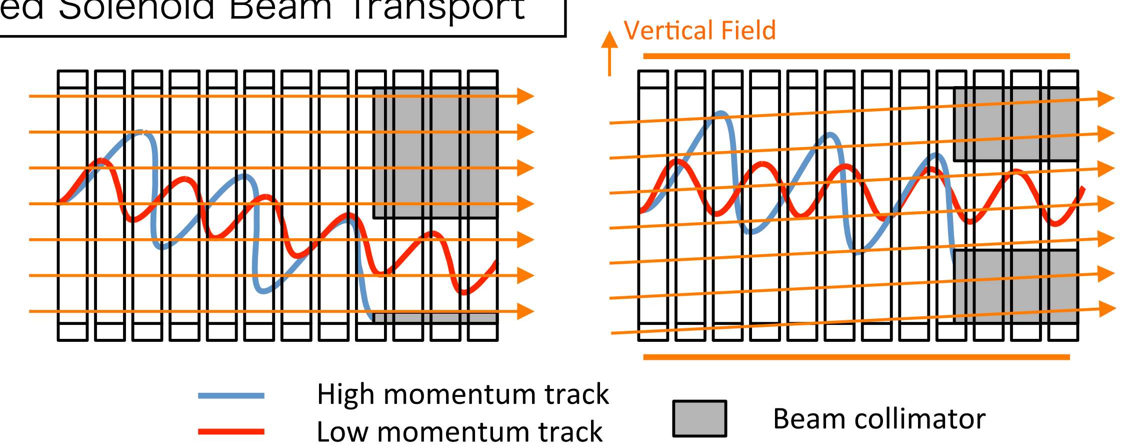
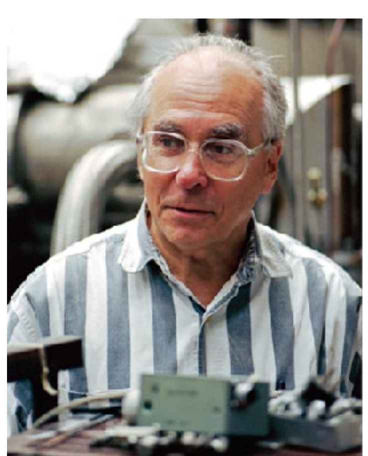
Received March 26, 2010; in final form, July 12, 2010

Curved Solenoid Beam Transport





Vladimir Lobashev 1934-2011
CERN Courier Vol 51, No 8

- Momentum and charge separation
- Same scheme used in COMET Phase-II electron spectrometer

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COMET at J-PARC


J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Neutrino beam to Kamioka
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetition : 25 Hz
Design Power : 1 MW
Material and Life
Science Facility
Main Ring
Max Energy : 30 GeV
Design Power for FX : 0.75 MW
Expected Power for SX : > 0.1 MW
Nuclear and Particle
Physics Exp. Hall


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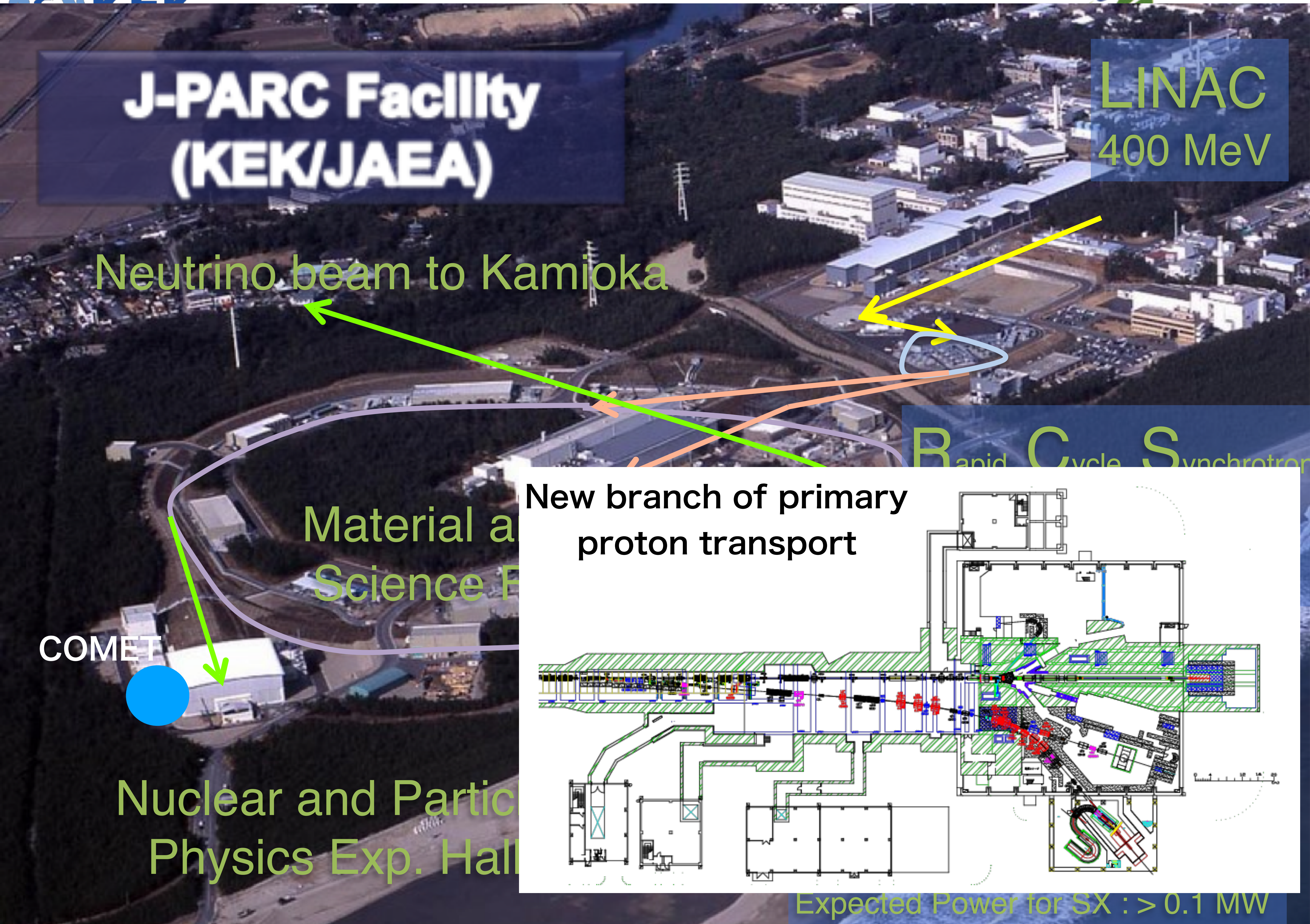
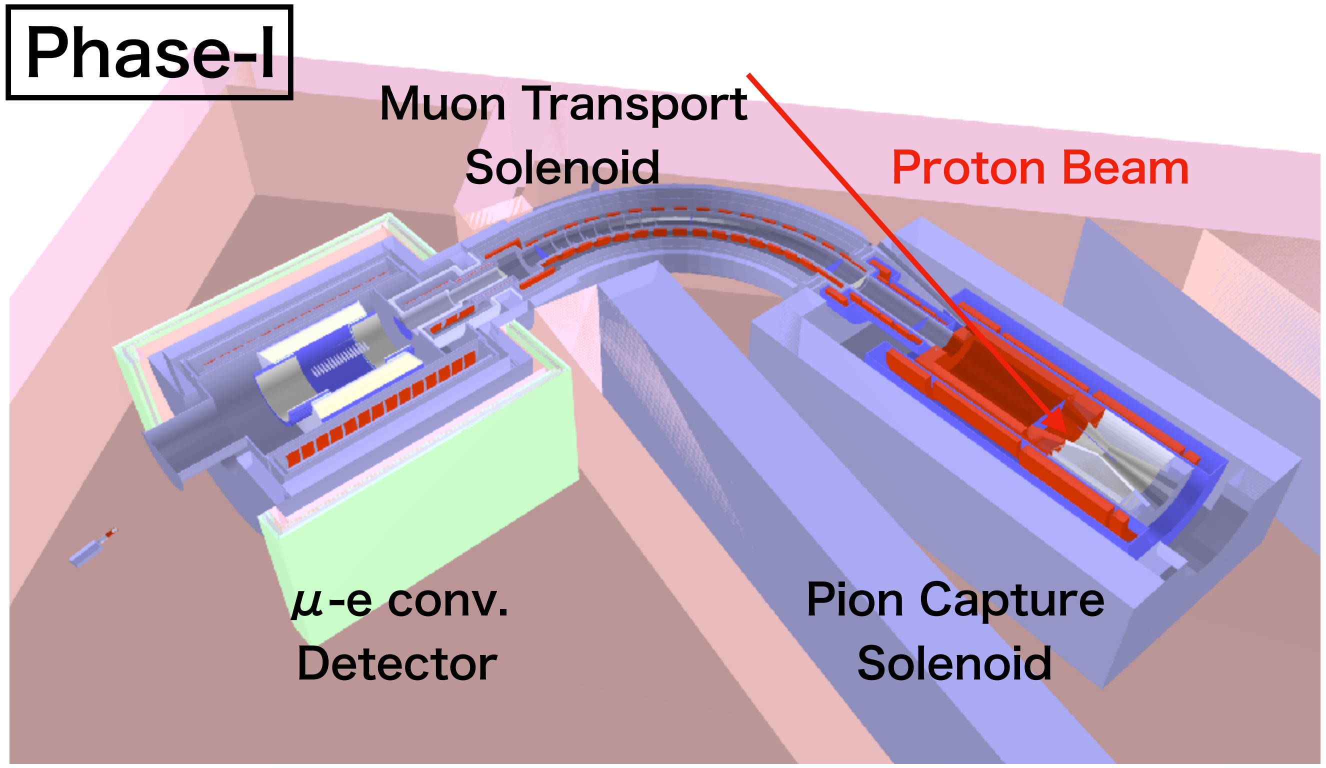
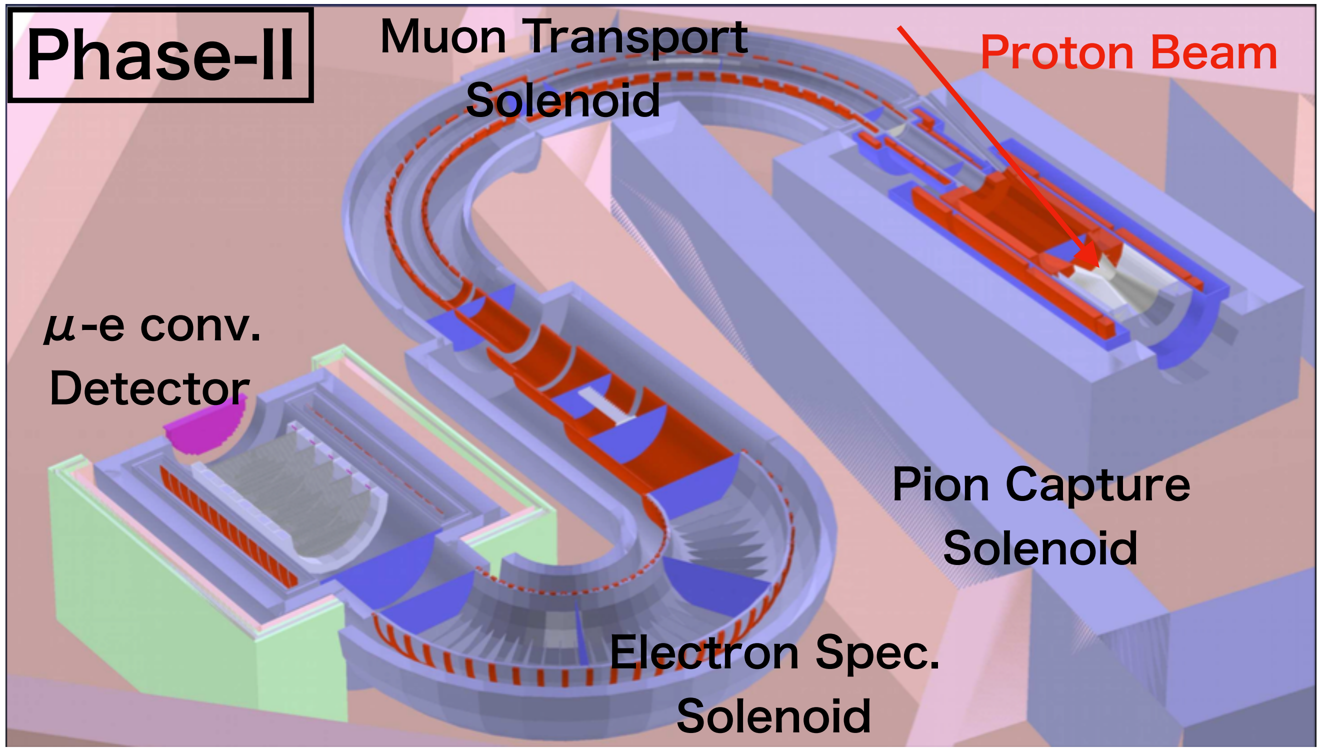

J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Neutrino beam to Kamioka
Rapid Cycle Synchrotro
Material a
Science F
COMET
New branch of primary
proton transport
Nuclear and Partic
Physics Exp. Hall
Expected Power for SX : > 0.1 MW

COMET

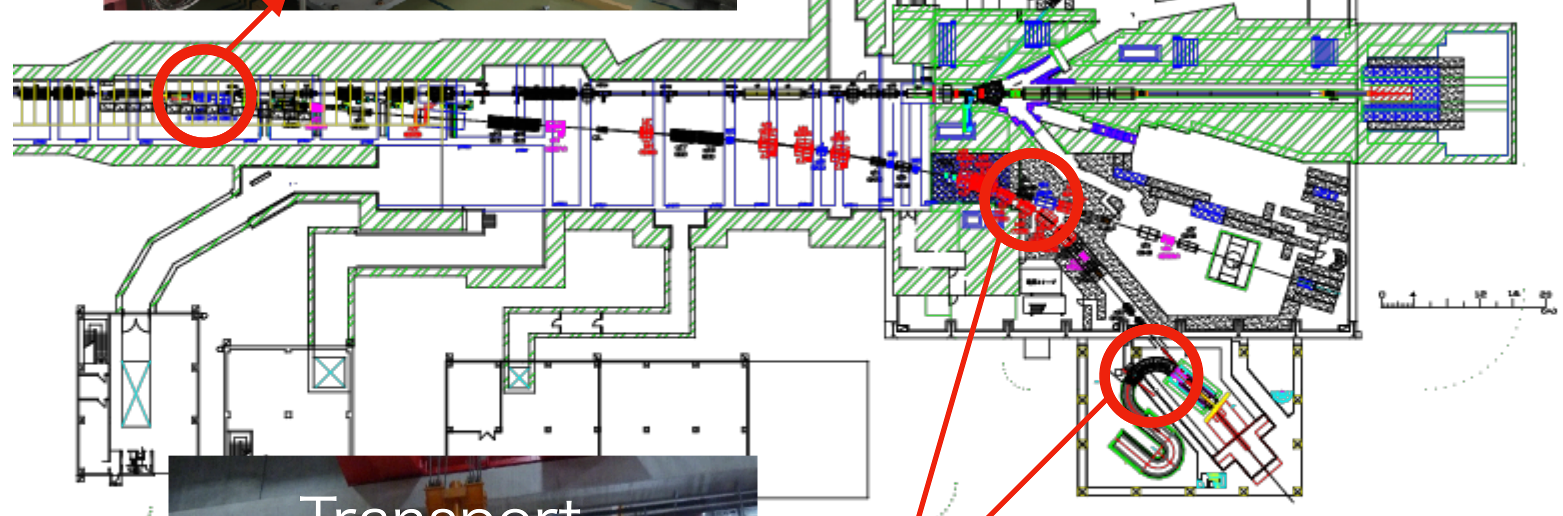
- **Target S.E.S. 2.6×10^{-17}**
- 8GeV Pulsed proton beam at J-PARC
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- pion production target in a solenoid magnet
- Muon transport & electron momentum analysis using C-shape solenoids
  - smaller detector hit rate
  - need compensating vertical field
- Tracker and calorimeter to measure electrons
- COMET decided to take a staging approach to realize this. The collaboration is making an effort to start physics DAQ as early as possible under this.
  - Phase-I 8GeV-3.2kW, $< 10^{-14}$
  - Phase-II 8GeV-56kW, $< 10^{-16}$

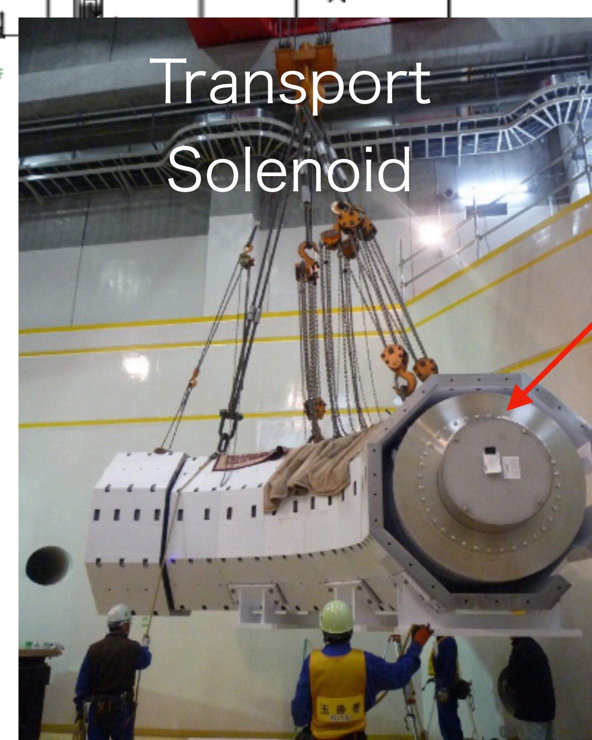


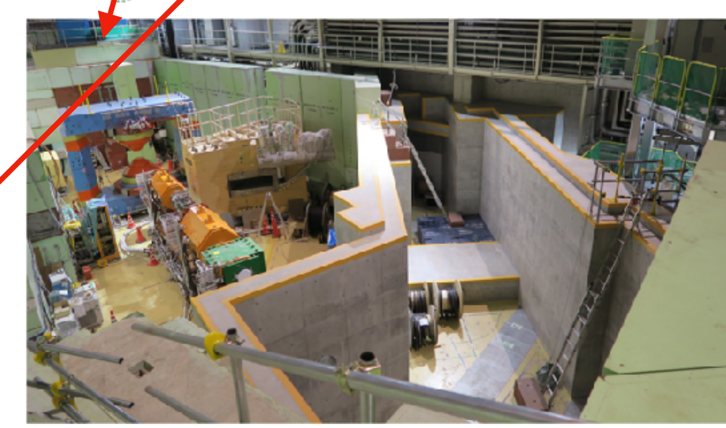


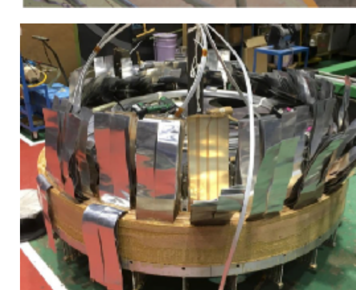
Status of COMET Phase I

- Facility
  - Proton beam line & SC magnet system
- Detectors
  - Phase-I Physics Detector (CDC & TC)
  - Phase-I Beam measurement Detector (Straw tracker and LYSO Ecal)

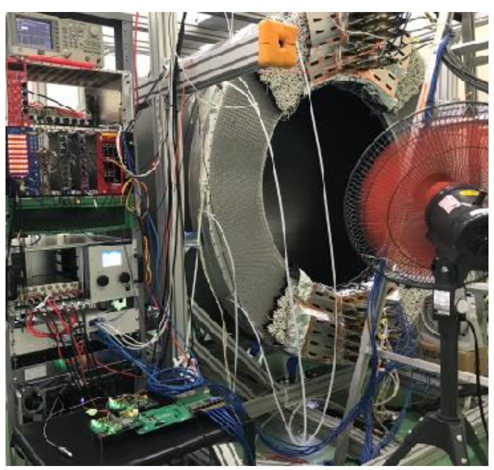




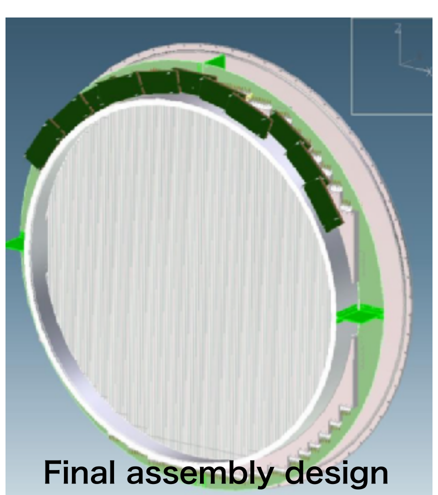




CDC CR test at KEK



Straw tracker & Ecal Prototype



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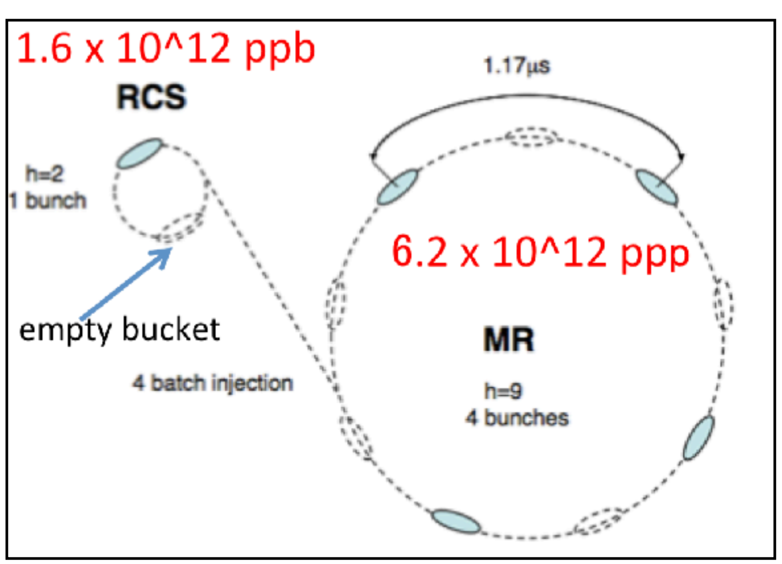
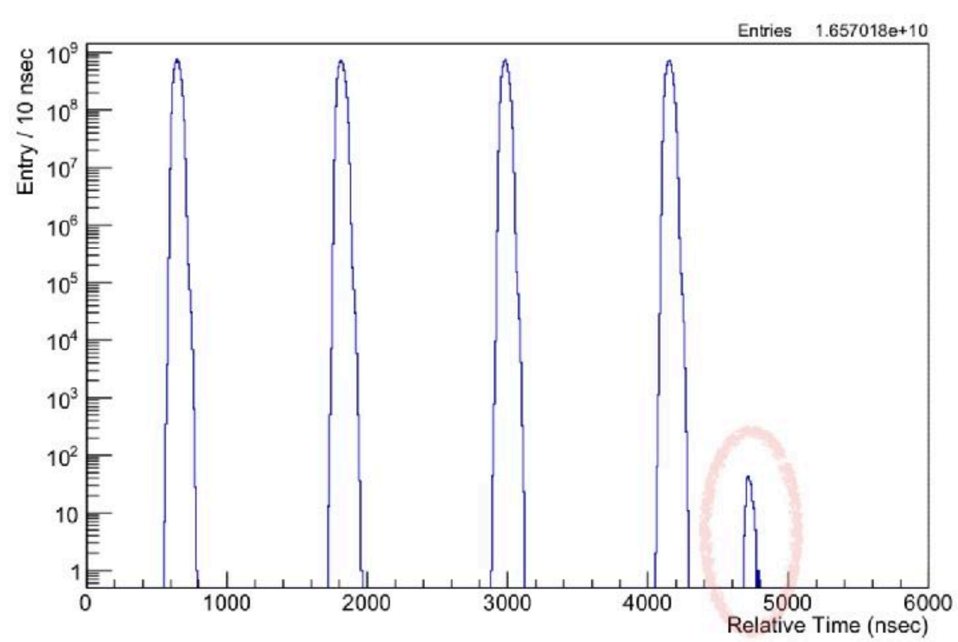
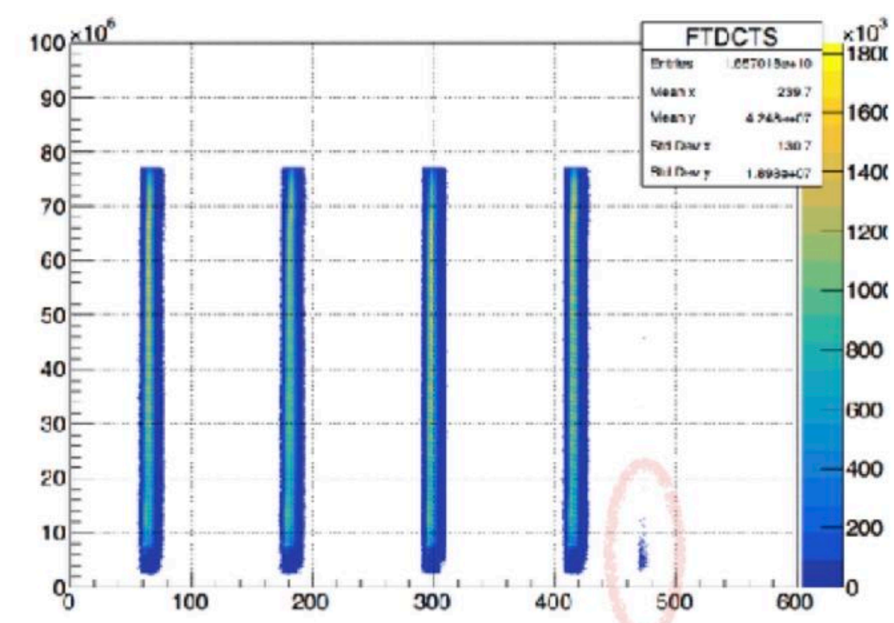
COMET Proton Beam R&D

- COMET requires MR operation at 8GeV (instead of 30GeV for HD hall experiments and T2K)
- Proton beam extracted from MR **without destroying the bunch structure to generate pulsed-muon beam** with a suitable pulse timing
- Proton beam extinction factor measurement using secondary beam in 2018
  - 1-2x10^{-10} extinction factor has already been achieved by masking K4 rear bunch







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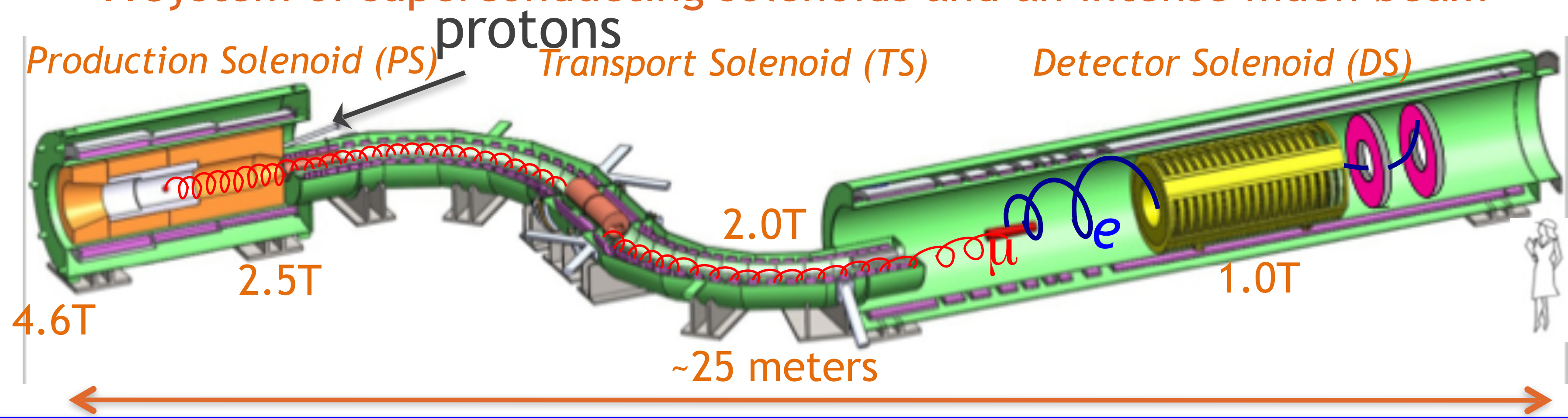
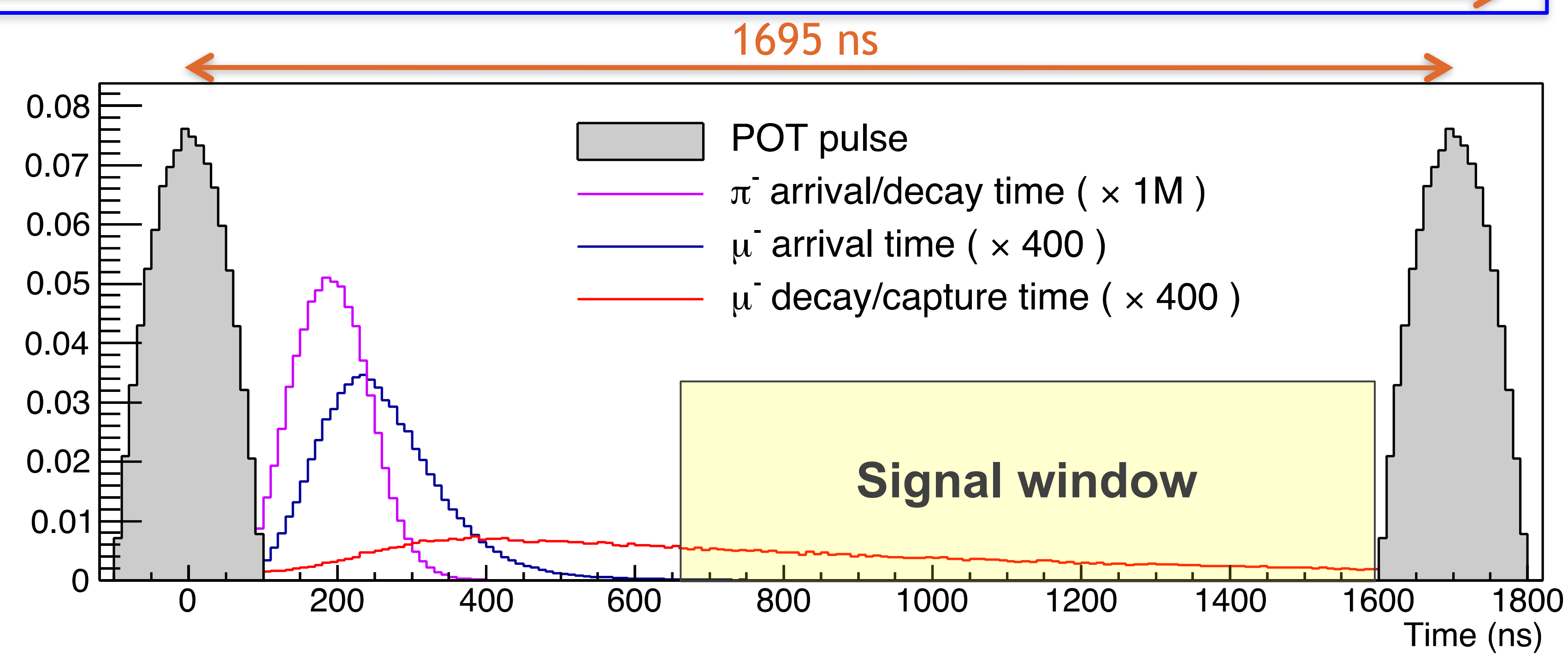
Mu2e at FNAL

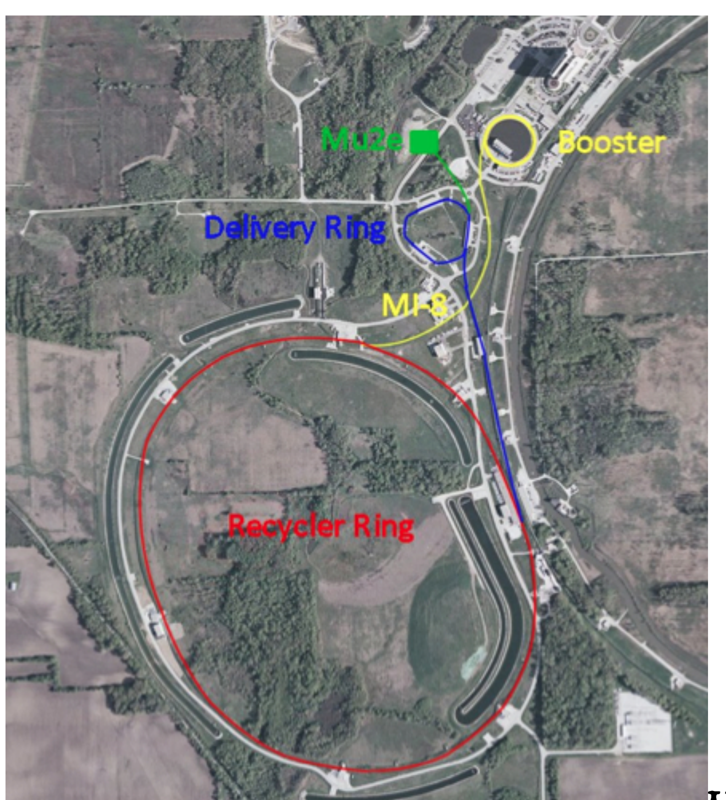
Mu2e

- **A search for Charged Lepton Flavor Violation:** $\mu N \rightarrow eN$
  - Expected sensitivity of 6×10^{-17} @ 90% CL, x10,000 better than SINDRUM-II
  - Probes effective new physics mass scales up to 10^4 TeV/c^2
  - Discovery sensitivity to broad swath of NP parameter space

A System of superconducting solenoids and an intense muon beam







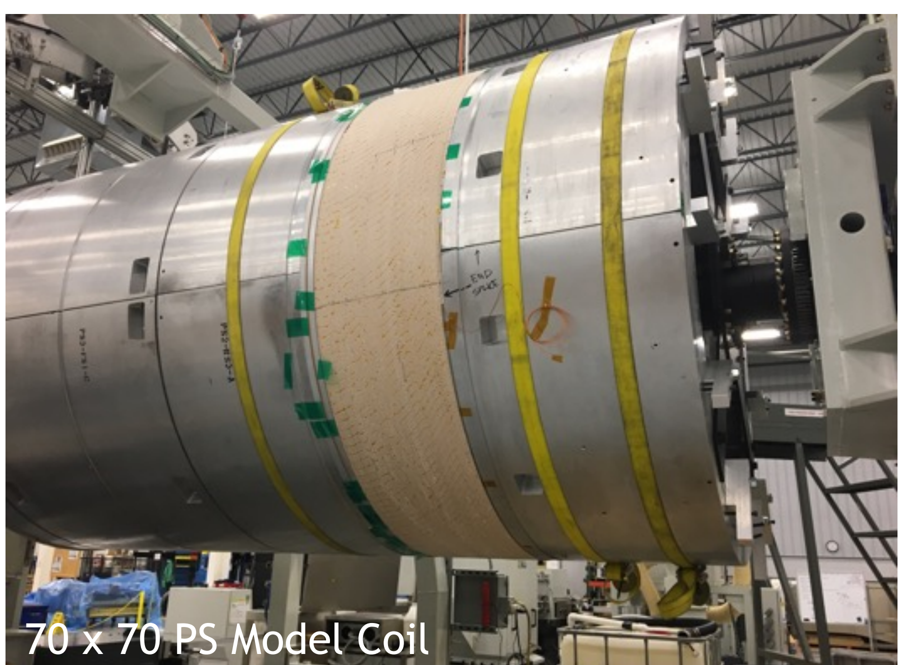
- **Mu2e makes use of existing infrastructure at Fermilab**
- **Mu2e uses 8 kW of protons**
  - From the Booster (8 GeV) & Re-bunched in the Recycler
  - Slow-spill from Delivery Ring
    - Accumulator/Debuncher for Tevatron anti-protons
    - Revolution period 1695 ns
- **Mu2e will run simultaneously with NOvA and SBN**

Mu2e Status

- Installation of beamline magnets nearly complete
- TS components being devolved to FNAL
- PS model coil successfully completed
- Cryogenics in preparation


M4/M5 Beamline

Delivery Ring installation Complete
(in operation for Muon g-2 experiment)

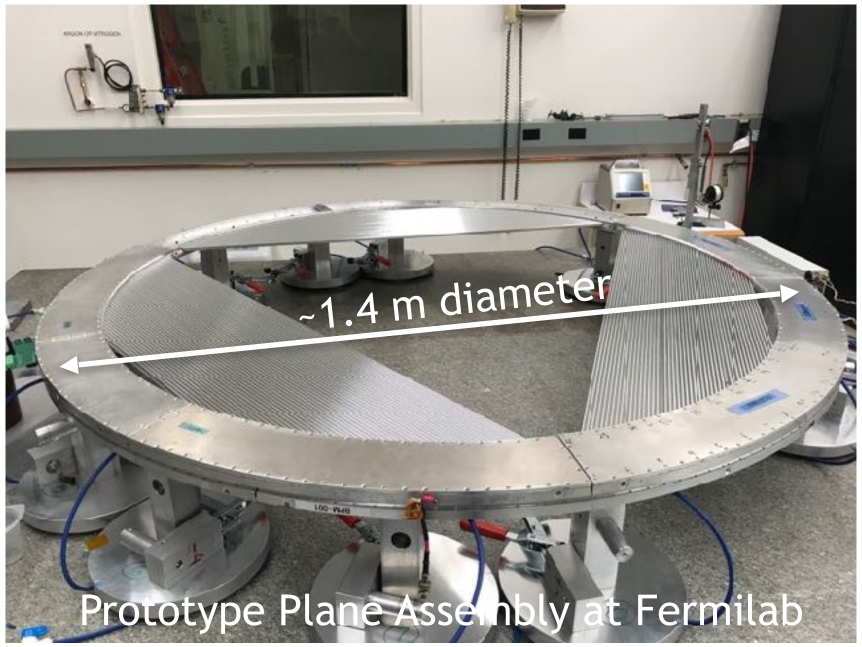

70 x 70 PS Model Coil


Completed TS coils at ASG, Italy

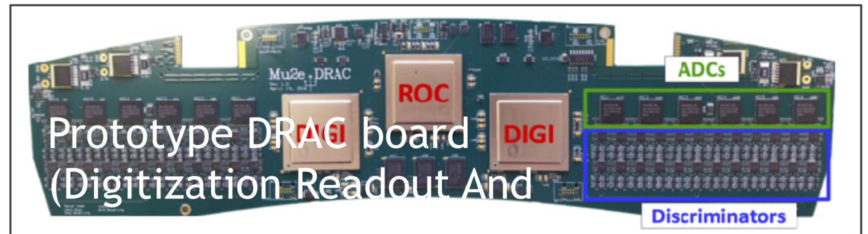

Completed TS Unit (4 coils)

Mu2e Detectors

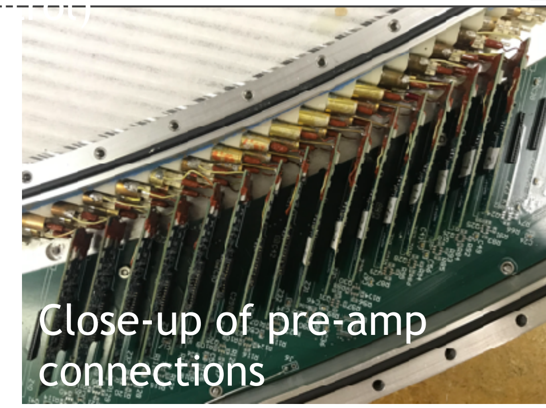
Straw-tube tracker

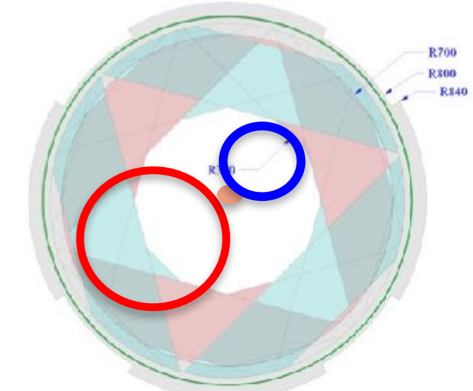


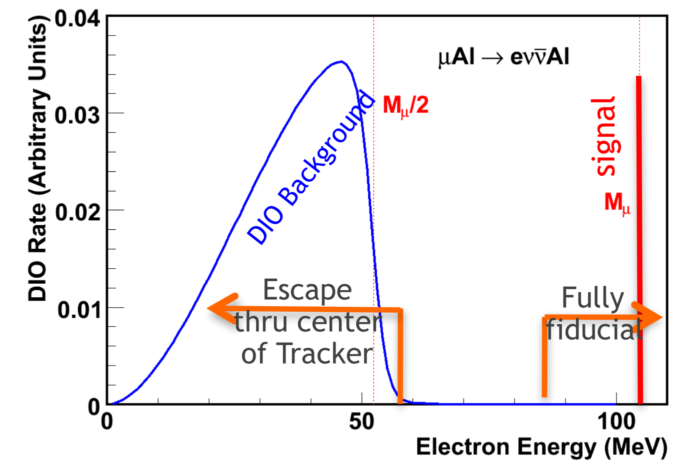
Prototype Plane Assembly at Fermilab



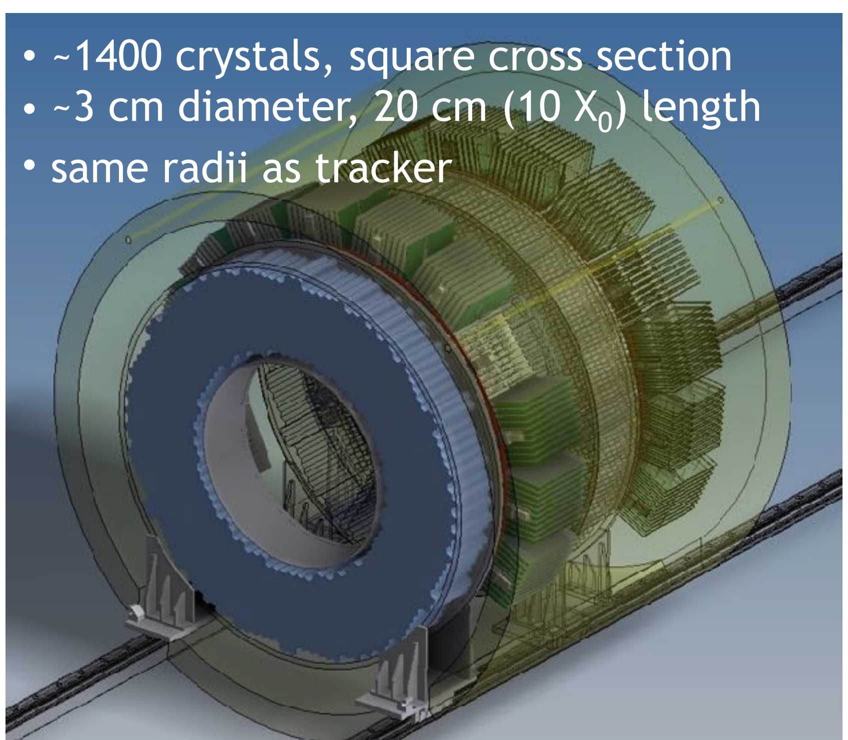
Prototype DRAC board (Digitization Readout And Control)


Close-up of pre-amp connections





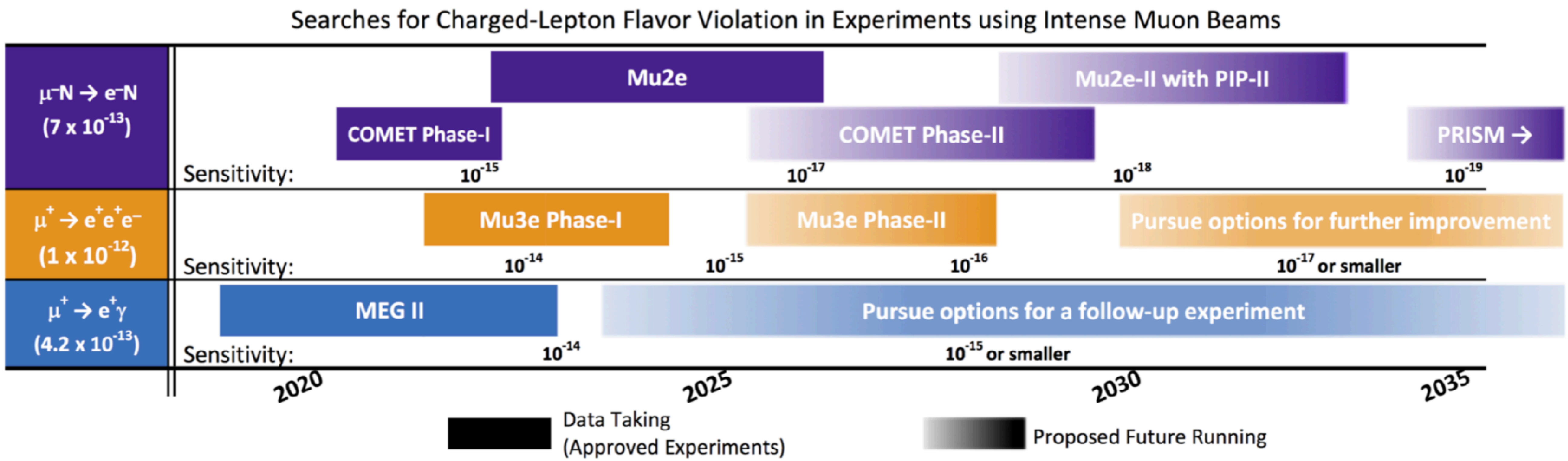
CsI Calorimeter



Prototype crystals for testing

- **CsI crystal calorimeter**
  - Important for particle ID
  - ~7% energy resolution @ 105 MeV
  - <200 ps timing resolution
- **2 disks oriented transverse to beam line, 70 cm apart**
- **Readout : 2 photo-sensors per crystal (MPPCs)**

A Possible Time Line

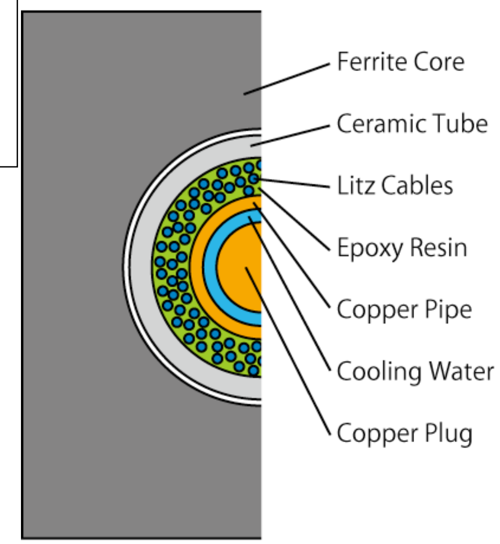


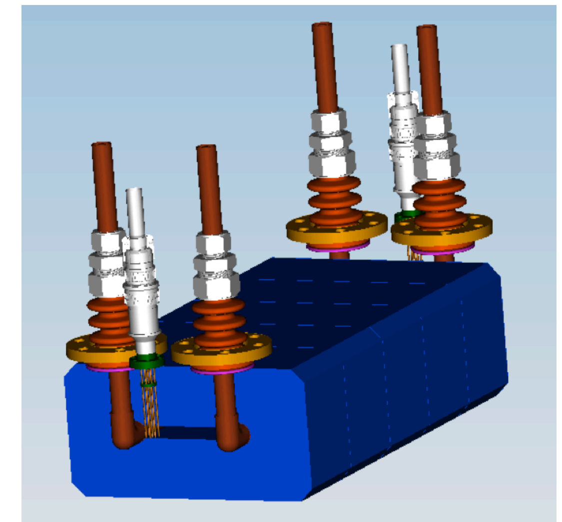
Input to Eur. Particle Physics Strategy
"Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities"

US-Japan Collaborative work in mu-e conversion search

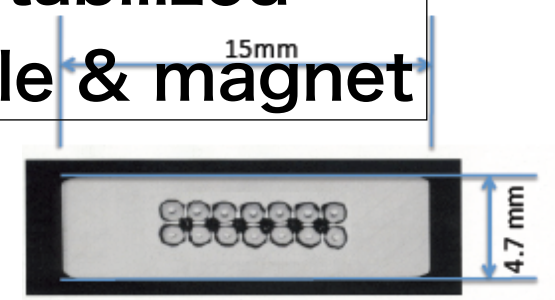
- < FY 2015
- AC diple magnet R&D
- Al stabilized SC development and test coil production
- Al-cap experiment at PSI

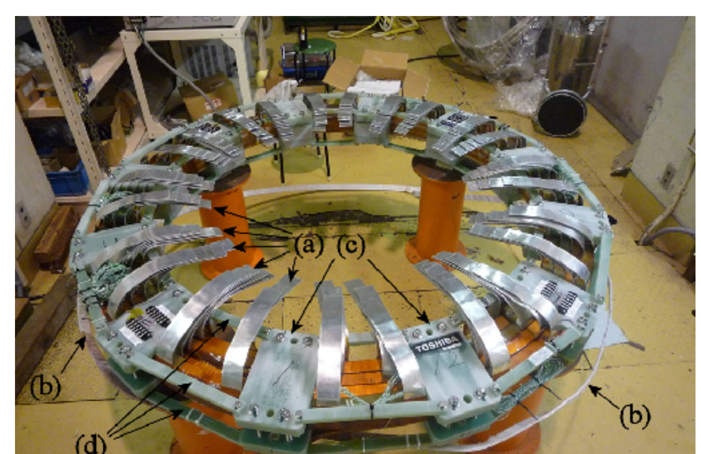
AC-dipole R&D



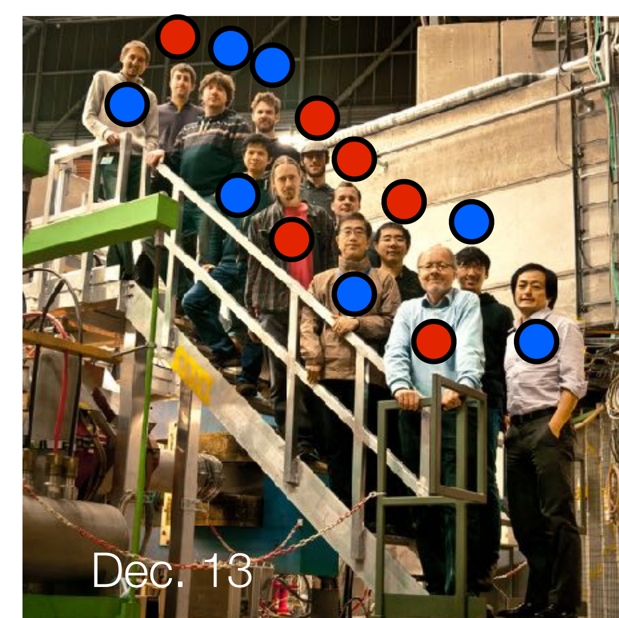


Al stabilized SC cable & magnet





Al-cap exp. at PSI



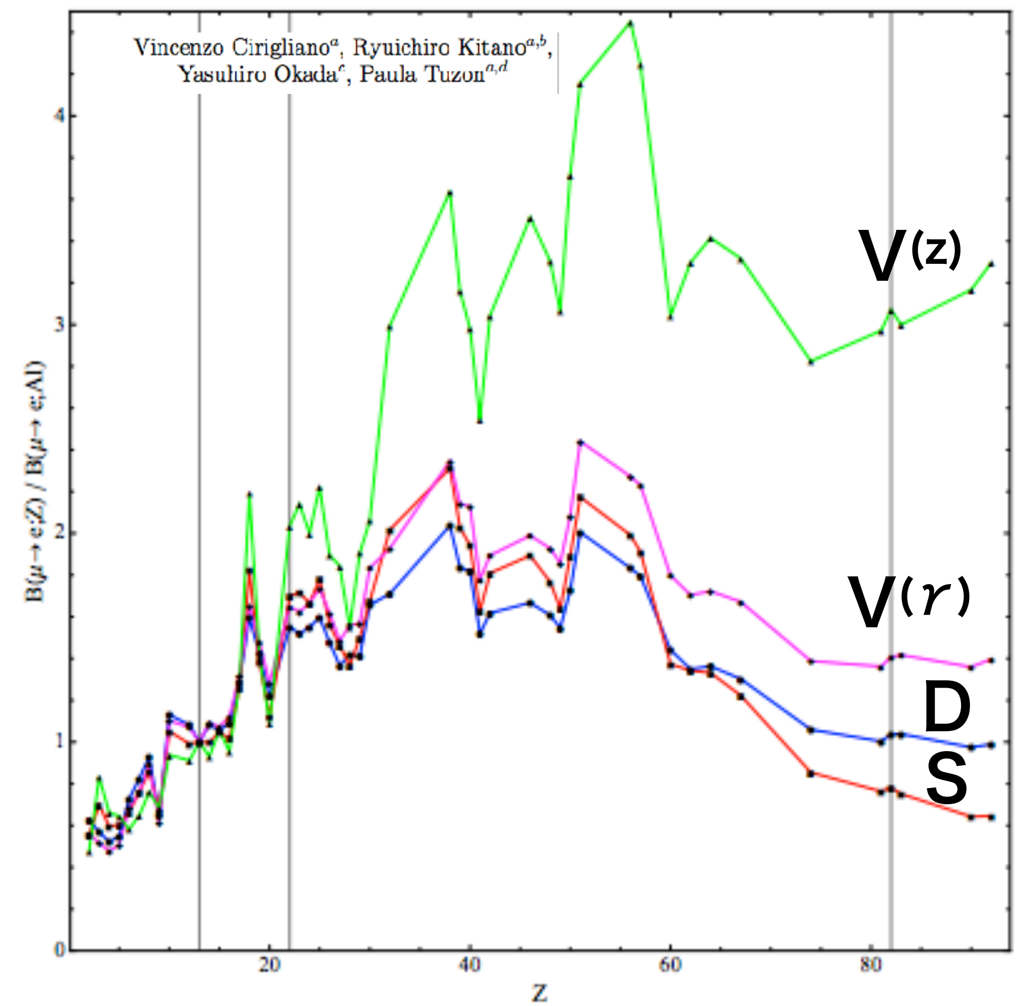
Summary

- Future plans of muon CLFV
  - MEG II & Mu3e
  - COMET & Mu2e
- COMET & Mu2e had been working together in the US-Japan program
  - AC-diple development, SC Al-stabilized wire R&D, and SC magnet R&D
- Collaborative efforts between COMET and Mu2e continue

Backup

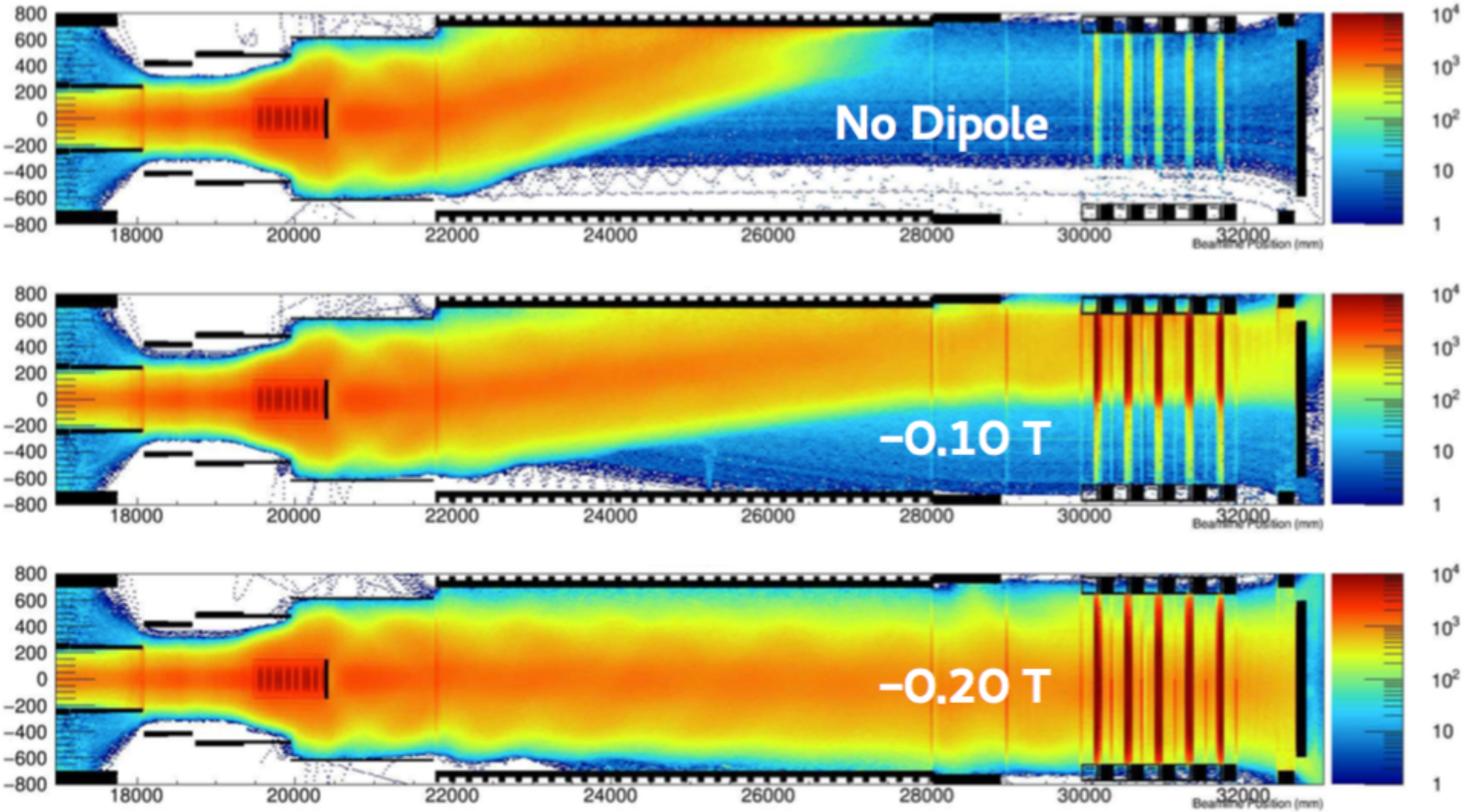
If the signal is found…

- Comparison of signal rates of μ→eγ, μ→eee, and μ-e conversion will clarify the physics behind cLFV reactions
- Even discovery only in μ-e conversion
  - Different target material contains different quark contents
  - May be possible to see the target dependence on the mu-e conversion rate
  - Discriminate the principal interaction of the mu-e conversion?
    - Vector type, Dipole type, or Scaler type?
- Possible taget
  - DeeMe: C (& Si)
  - COMET & Mu2e: Al (& Ti in future? & Pb in far future ??)



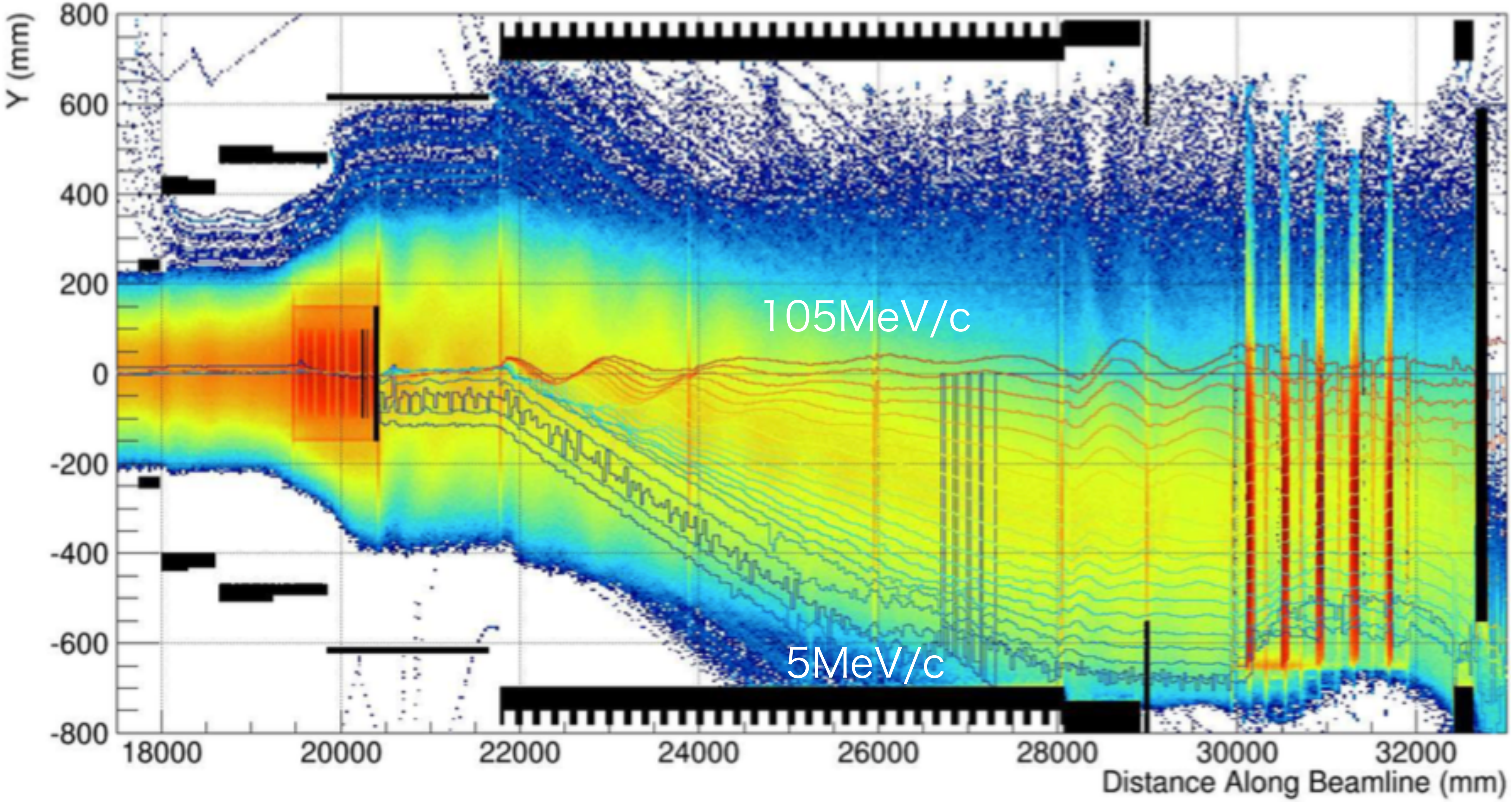
	Al	Ti
lifetime	864 ns	330 ns
time window	0.3	0.2
signal	1	1.5
net	0.3	0.3

Optimization of the Electron Spectrometer Solenoid



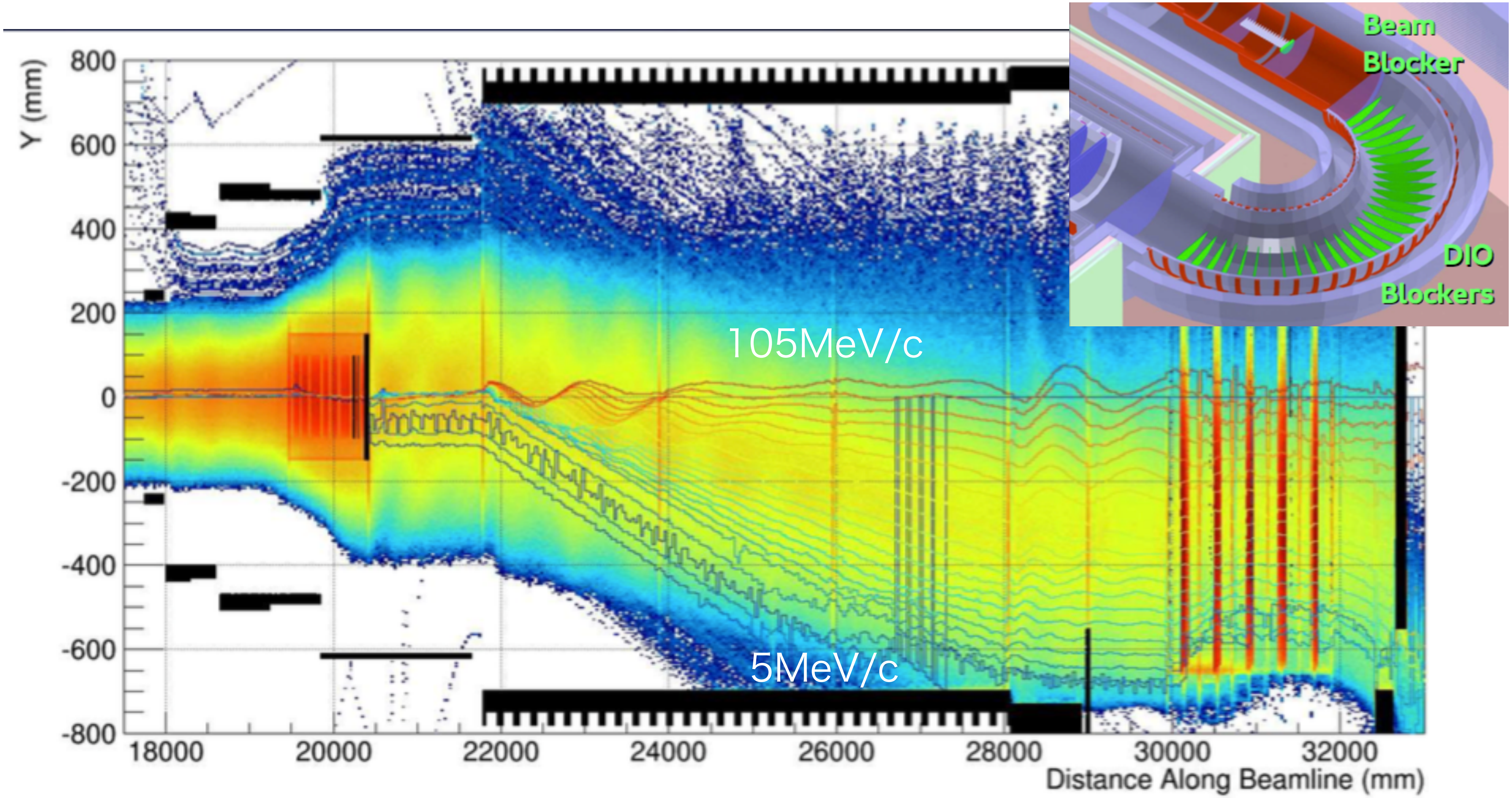
105MeV electron generated isotropically at the target

Performance of the Electron Spectrometer Solenoid



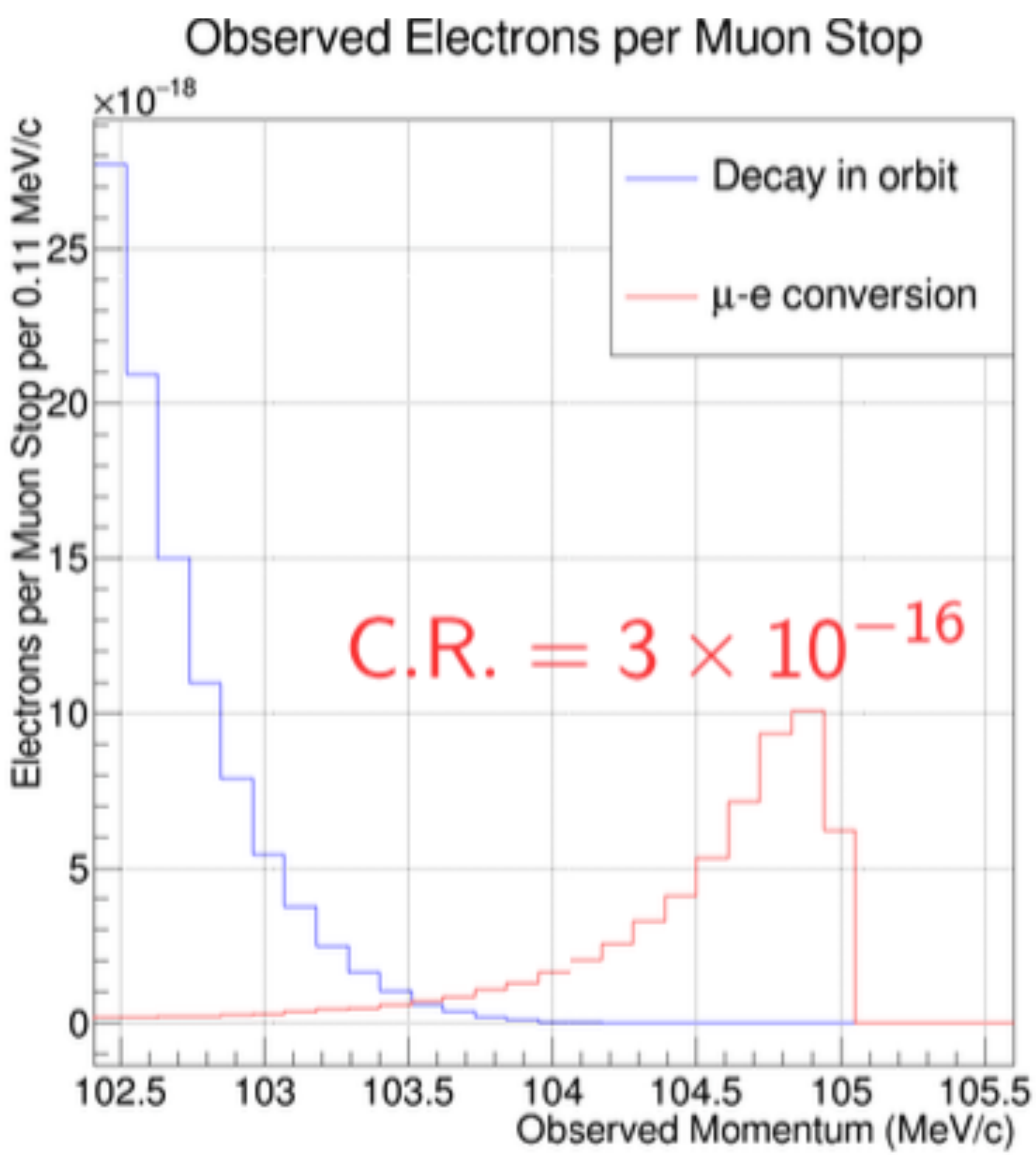
Heat map shows path of electrons between 60 and 65MeV/c

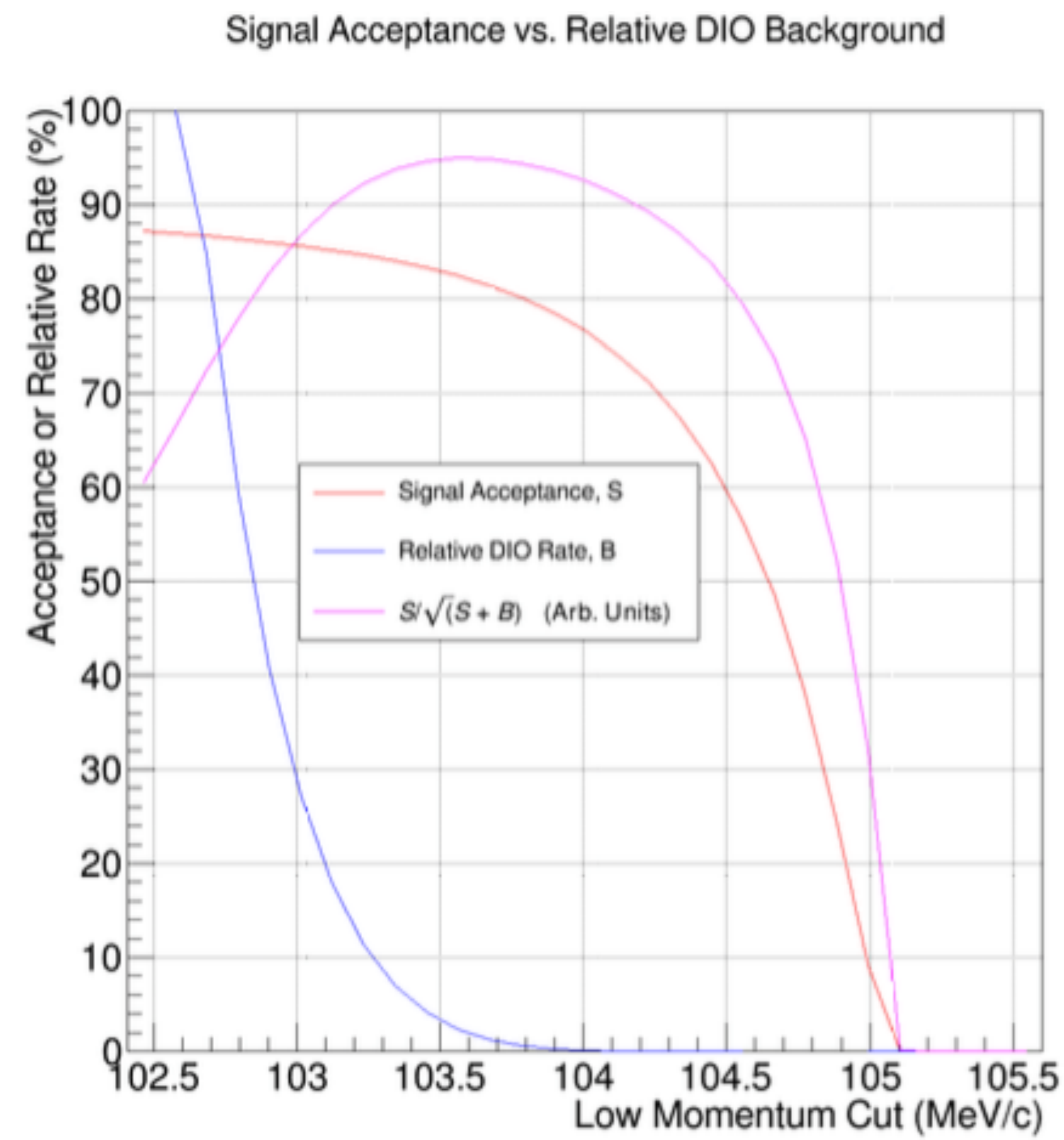
Performance of the Electron Spectrometer Solenoid



Heat map shows path of electrons between 60 and 65MeV/c

Phase-II Sensitivity





- Threshold is optimized to maximize $S/\sqrt{(S+B)}$
- Single event sensitivity of 2.6×10^{-17} with 1.84×10^{7} sec DAQ

Mu2e Civil Construction

Mu2e ground breaking April 2015

Completed Mu2e hall – Dec 2016

Detector Hall – April 2016

- Mu2e beam line and experimental hall are complete