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Prospects of Charged Lepton Flavor Experiments

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KEK/J-PARC/Sokendai

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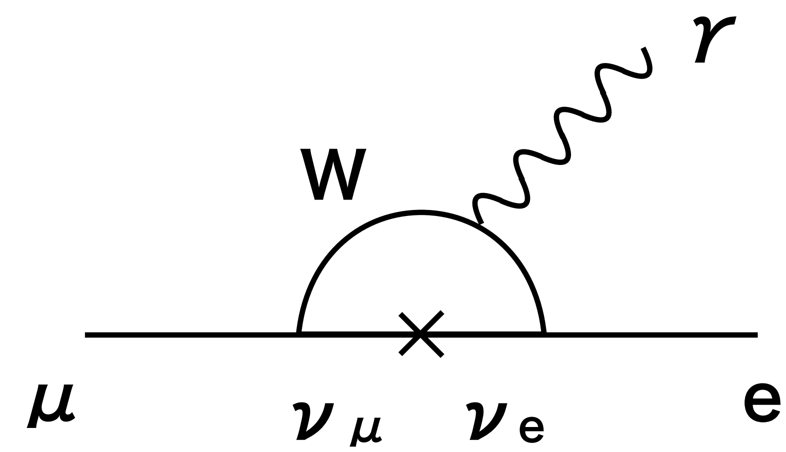
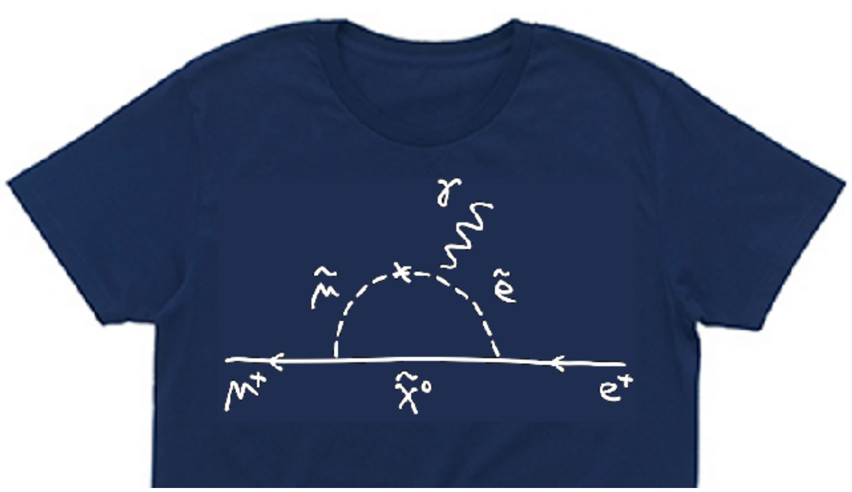
Outline

- Introduction
- CLFV physics with DC muon beam
- CLFV physics with pulsed muon beam
- CLFV physics with tau leptons
- CLFV physics at collider experiments
- Prospects and summary

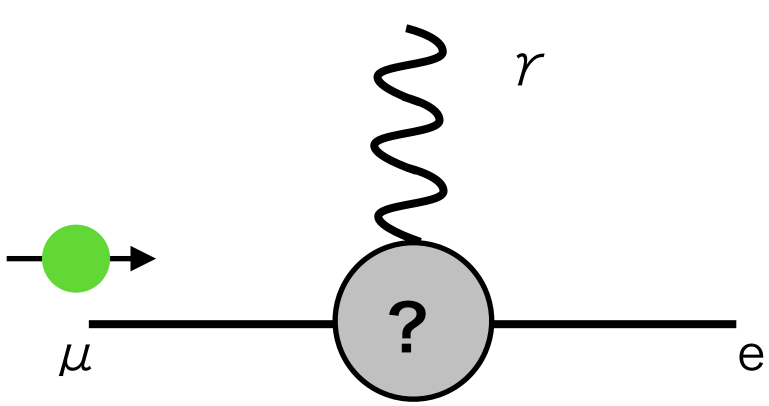
Charged Lepton Flavor Violation



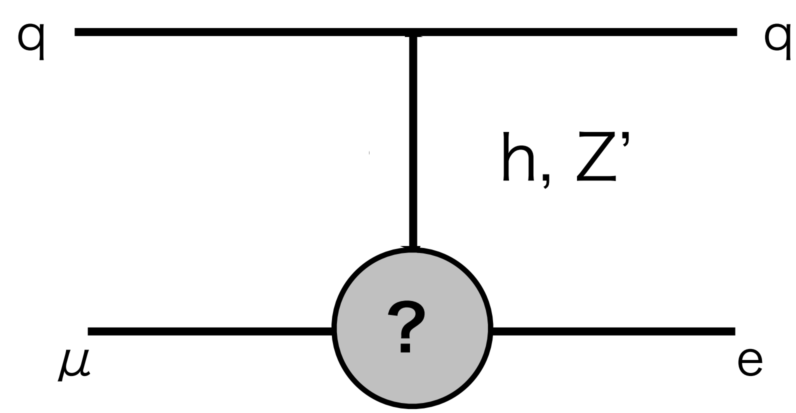
- cLFV rate in the Standard Model with non-zero neutrino mass is too small to be observed in experiments; O(BR) < 10^{-50}
  - No SM Physics Background
  - Observation = clear evidence of NP
- Motivated by many kinds of new physics models BSM
- Origin of neutrino mass



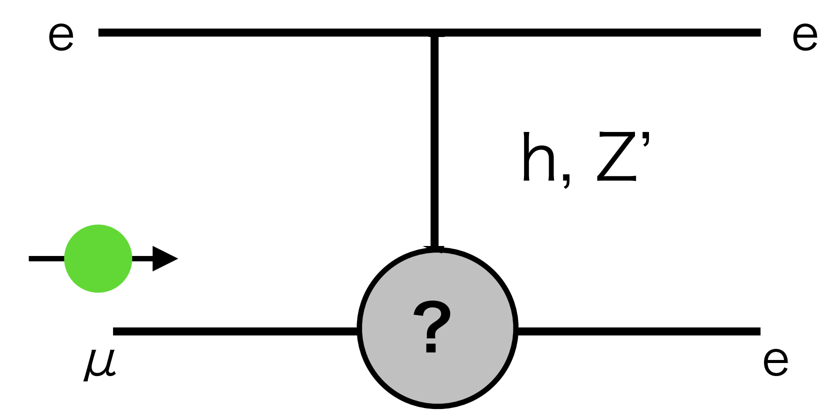
μ→eγ



μ-e conv.

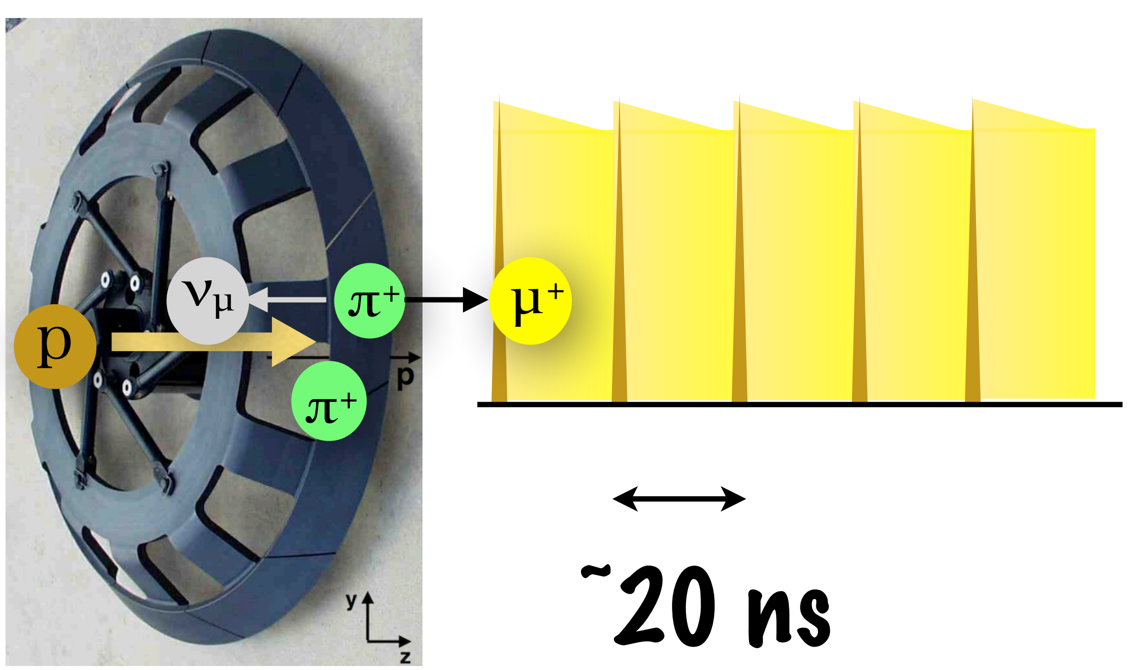


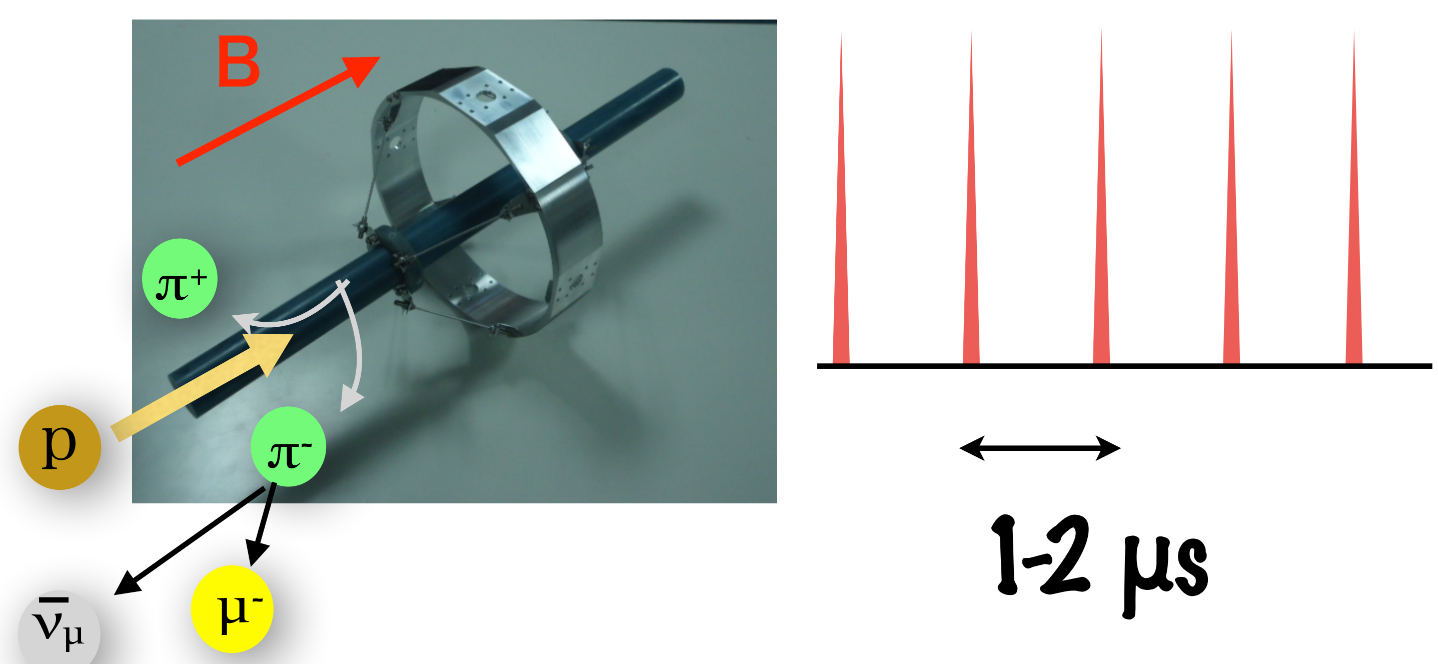
μ→eee

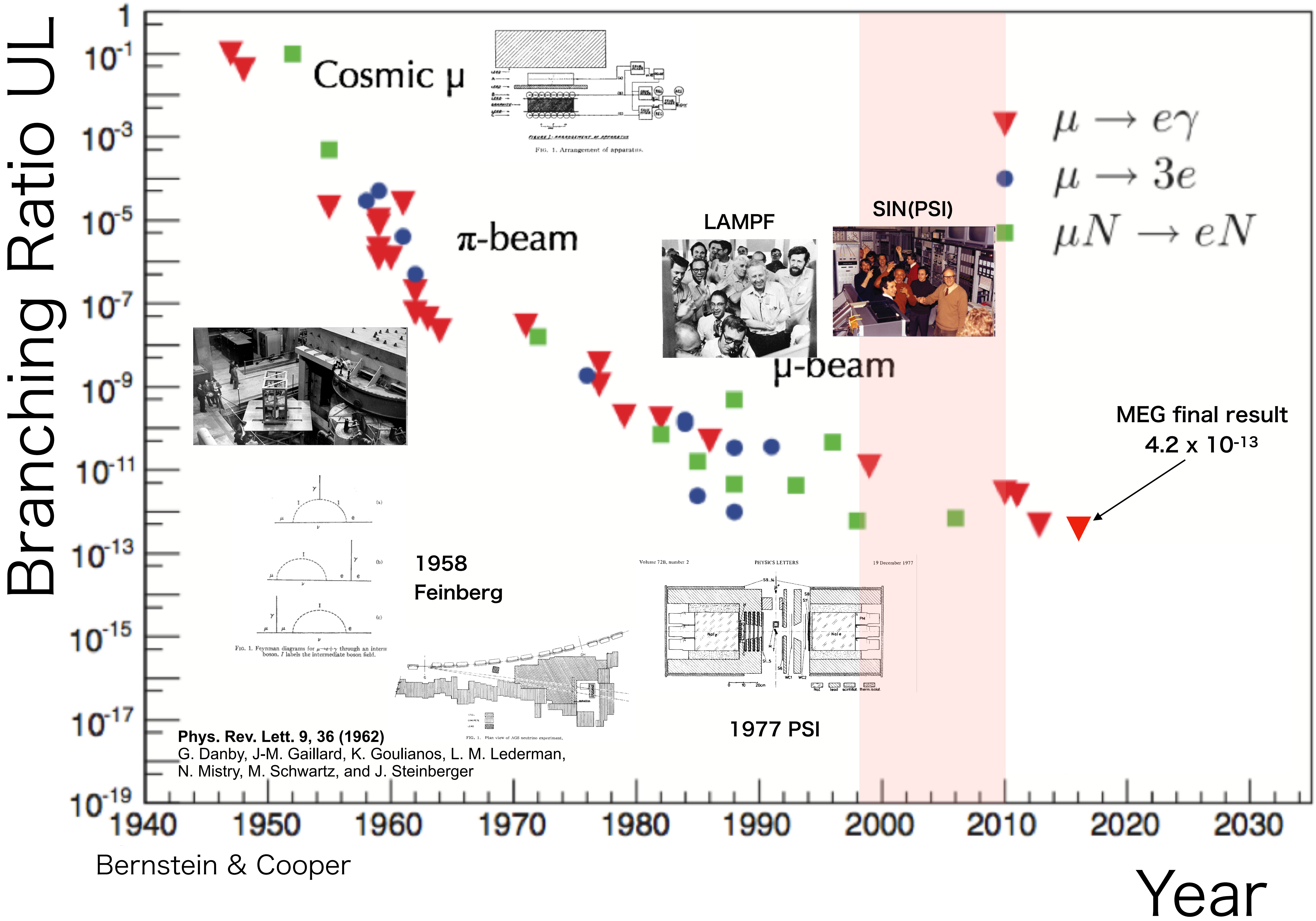


DC Beam and Pulsed Beam

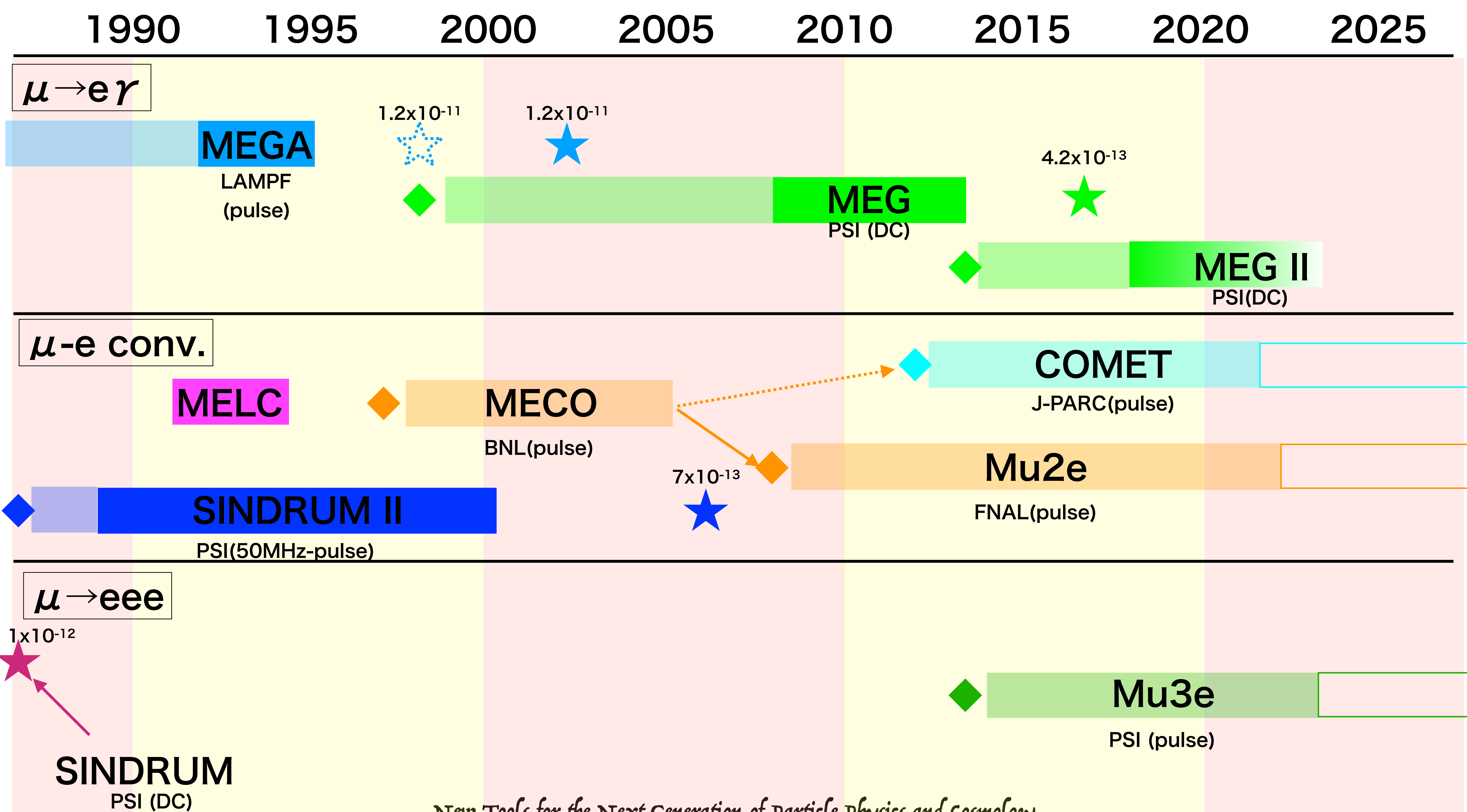
- DC beam for coincidence experiments
  - Decay of pions stopping on the material surface. Muons are polarized
  - μ→eγ, μ→e e e
- Pulse beam for non-coincidence experiments
  - Pion decay in flight
  - μ-e conversion






Branching Ratio UL
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
Year
Cosmic μ
π-beam
μ-beam
LAMPF
SIN(PSI)
$\mu \to e\gamma$
$\mu \to 3e$
$\mu N \to eN$
MEG final result
4.2×10^{-13}
1958
Feinberg
1977 PSI
Phys. Rev. Lett. 9, 36 (1962)
G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman,
N. Mistry, M. Schwartz, and J. Steinberger
Bernstein & Cooper

Muon cLFV experiments



Current Status of Charge Lepton Flavor Violation Search

- $\mu \to e\gamma$
  - MEG $Br(\mu \to e\gamma) < 4.2 \times 10^{-13}$

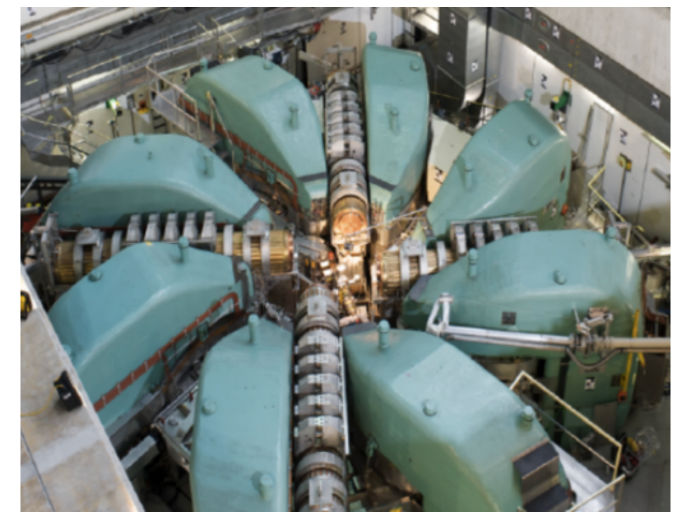
→ **MEG II**

- $\mu \to eee$
  - 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**

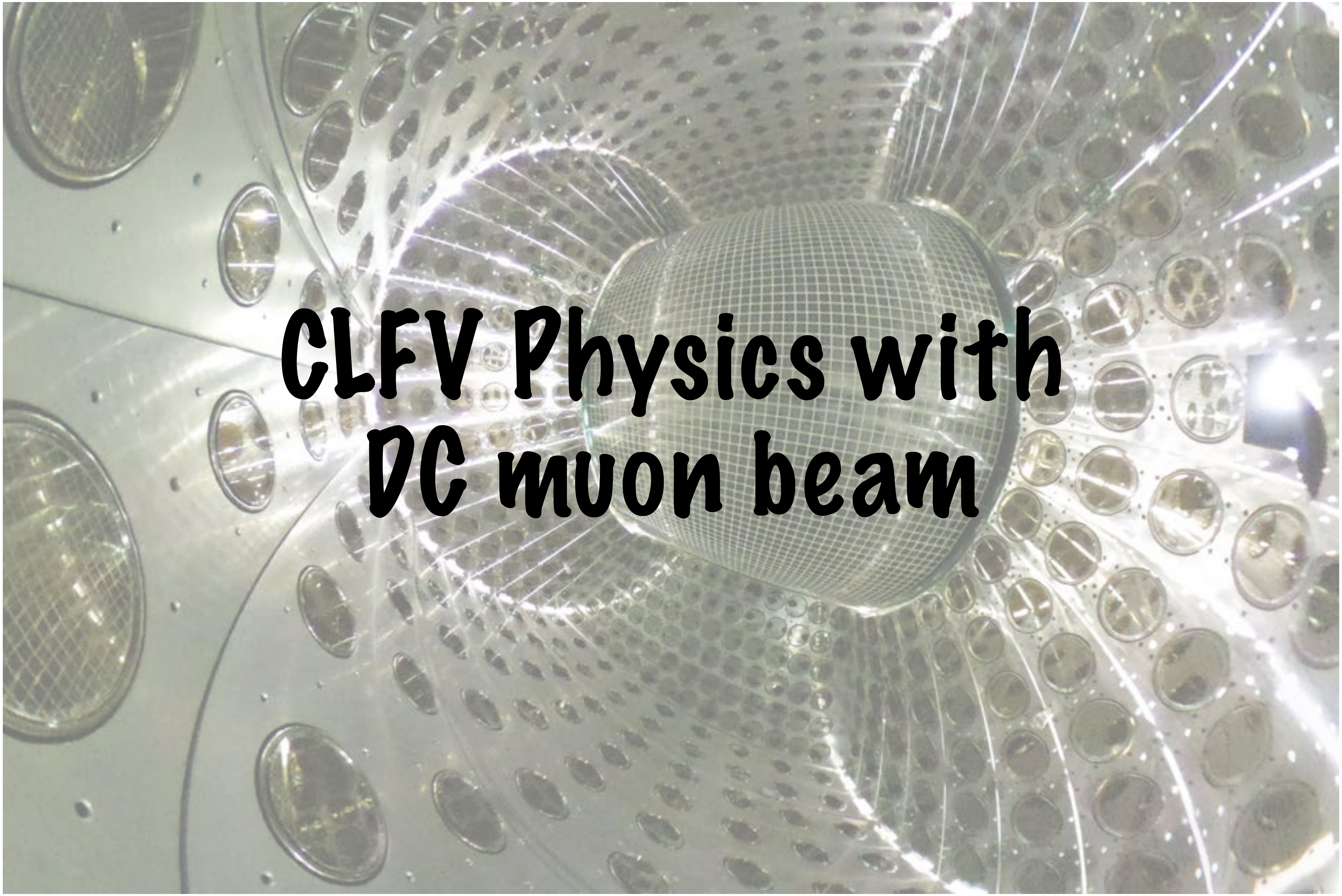


PSI Ring Cyclotron
590MeV, 1.4MW

FNAL
8GeV, 8kW

J-PARC
8GeV, 3.2-56kW

CLFV Physics with DC muon beam



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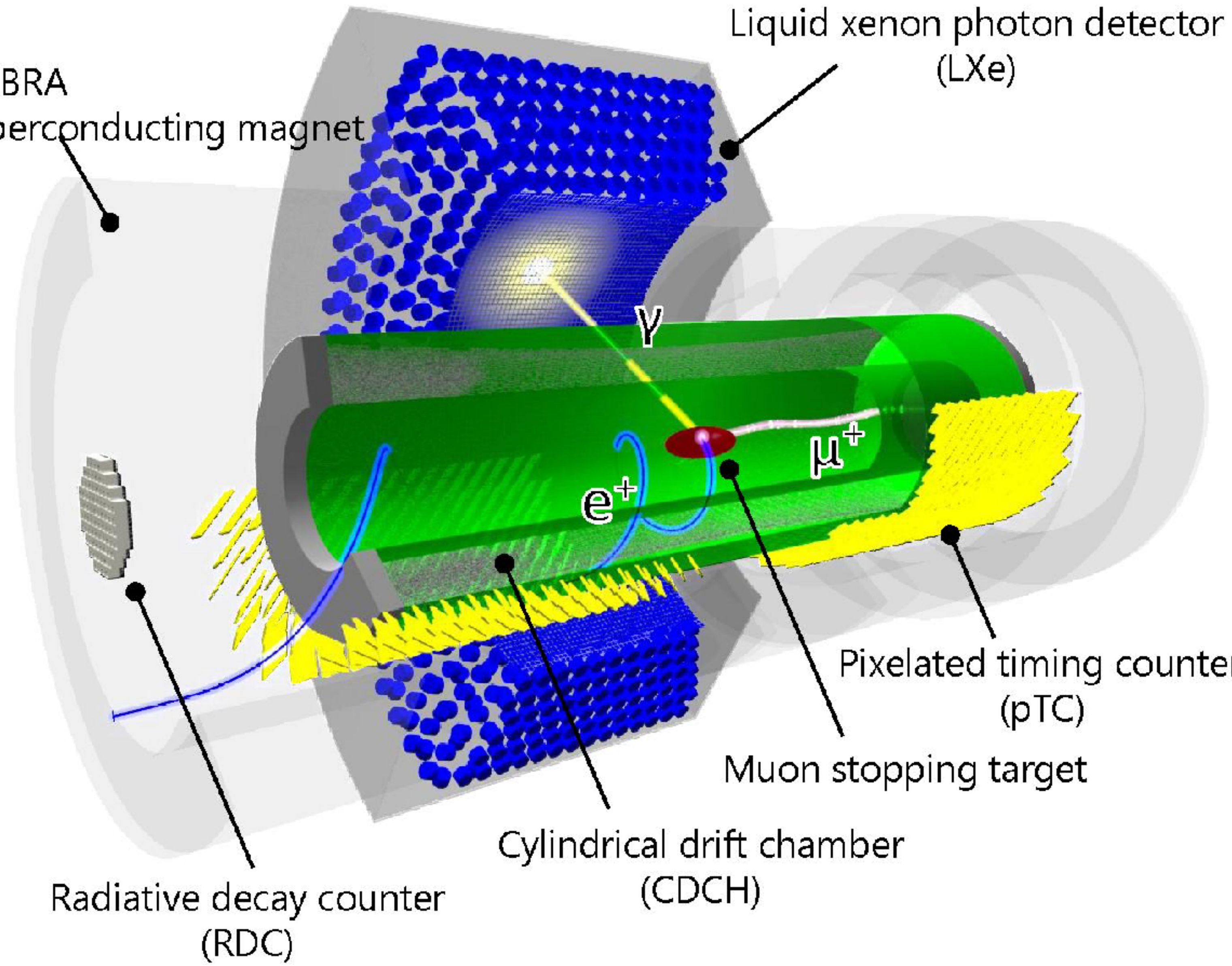
MEG II: $\mu^+ \rightarrow e^+\gamma$ search

- MEG achieved 4.2×10^{-13} @ 90% C.L.
  - Background was dominated by Accidental event overlaps
- MEG II aims at 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

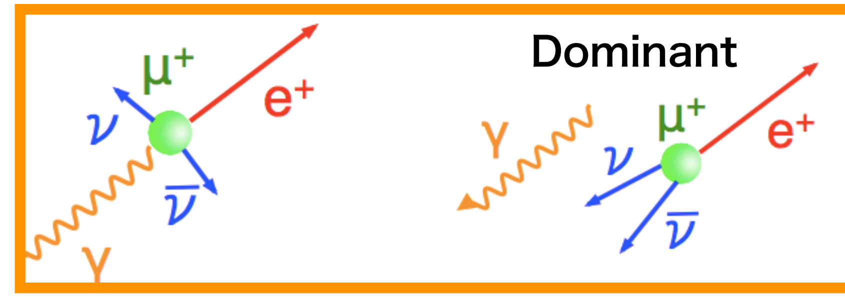


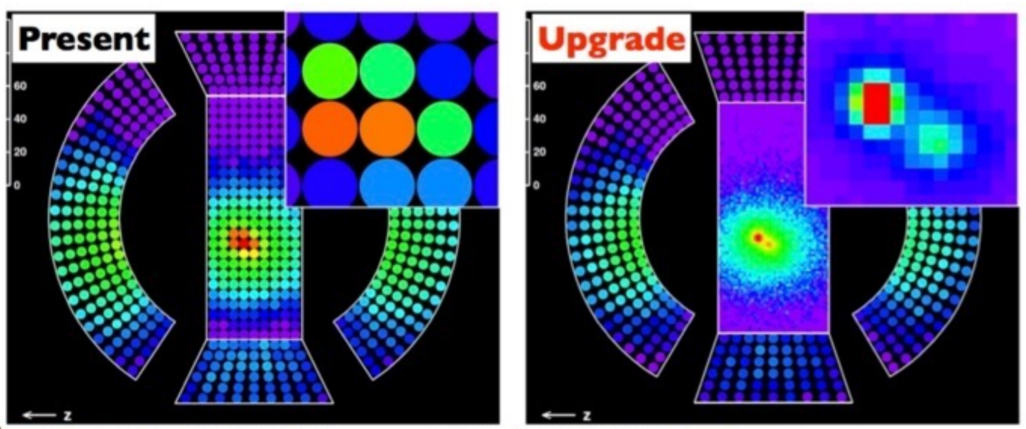
Target Sensitivity : 6×10^{-14} in 3 years running

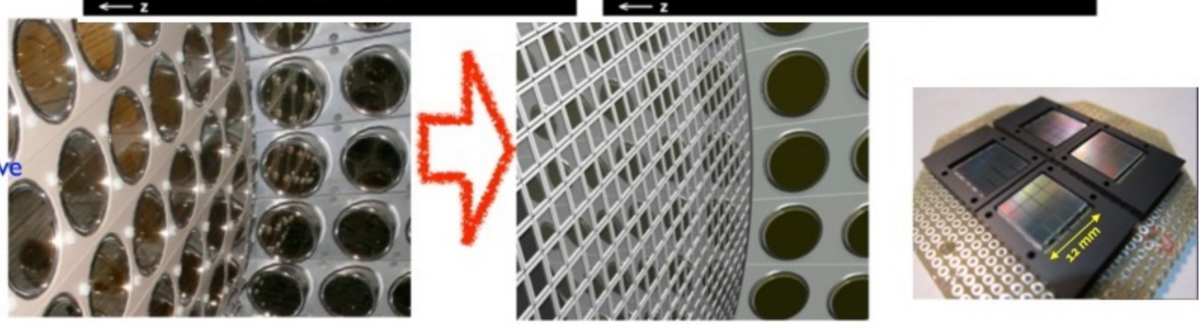
Highlight of MEG II Detector Upgrade

- Based on experience in MEG I
  - Liquid Xe PD, Positron DC, Timing Counter

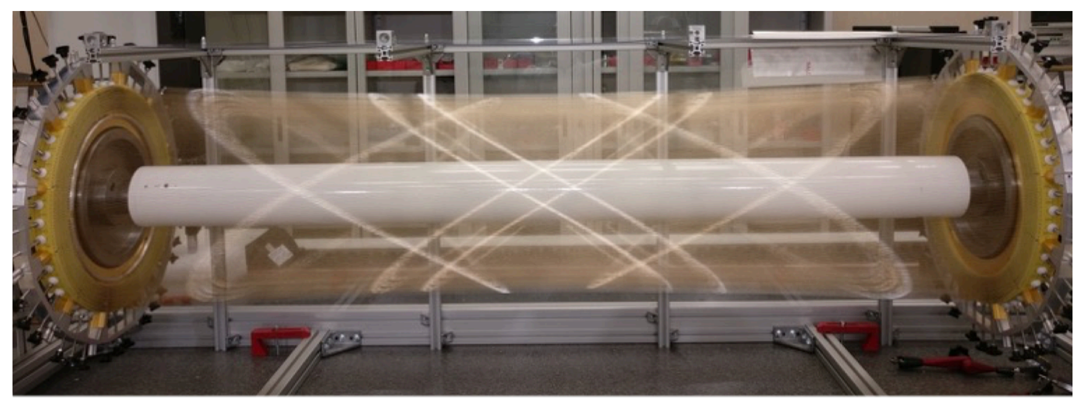
Background



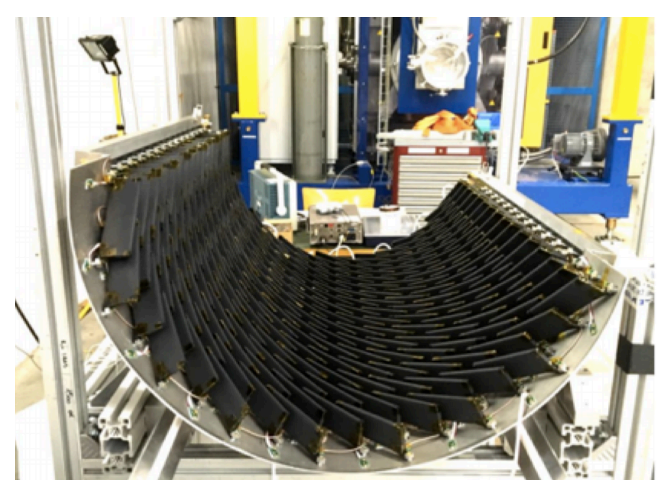


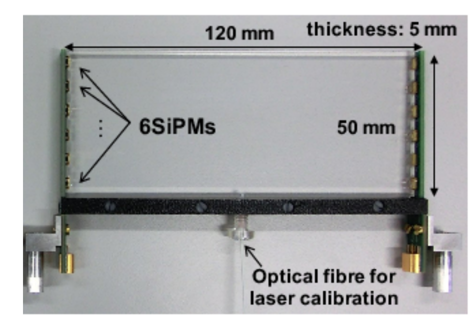


LXe
2inch PMT →VUV SiPM



Single Volume
Low mass
Stereo-wire DC

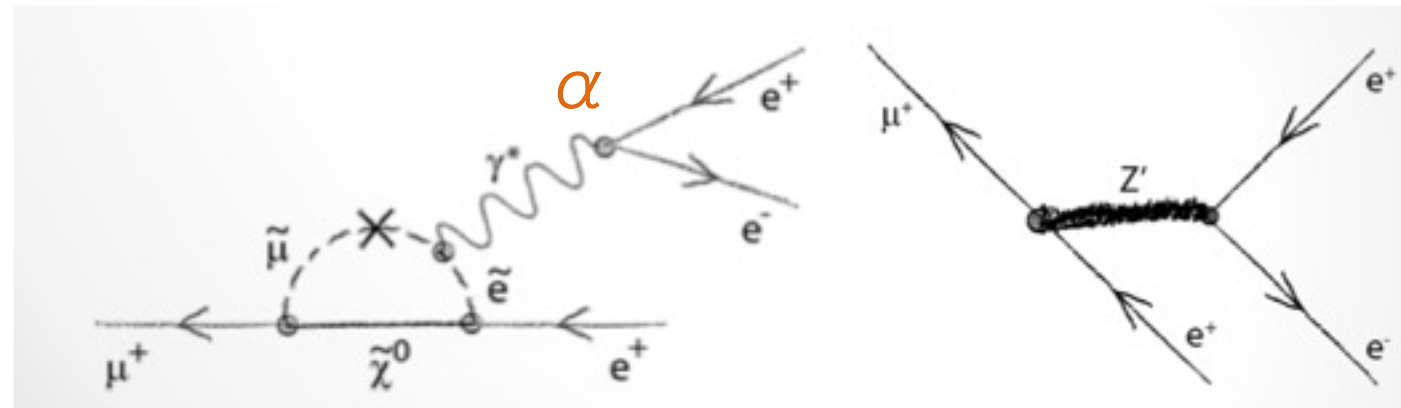


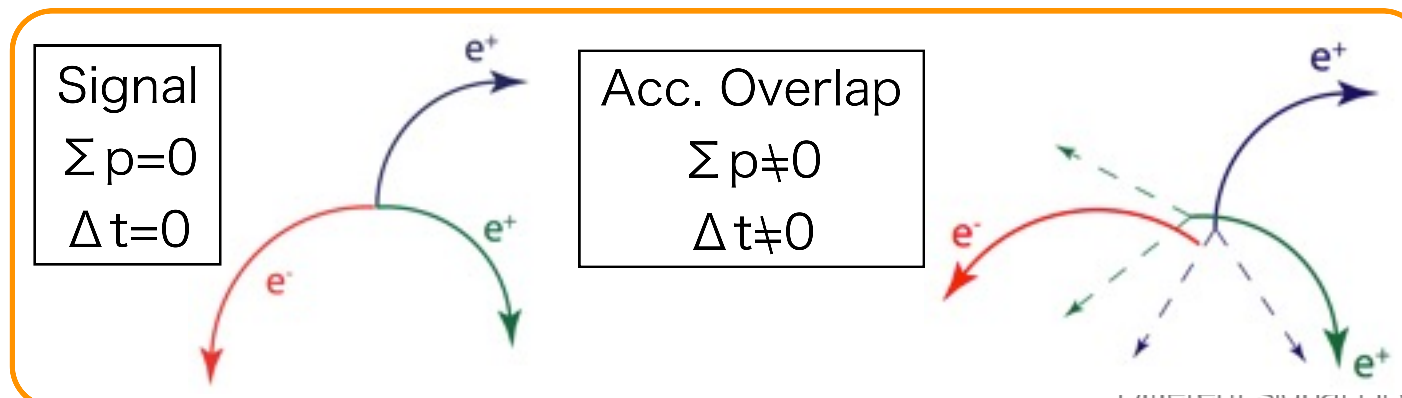


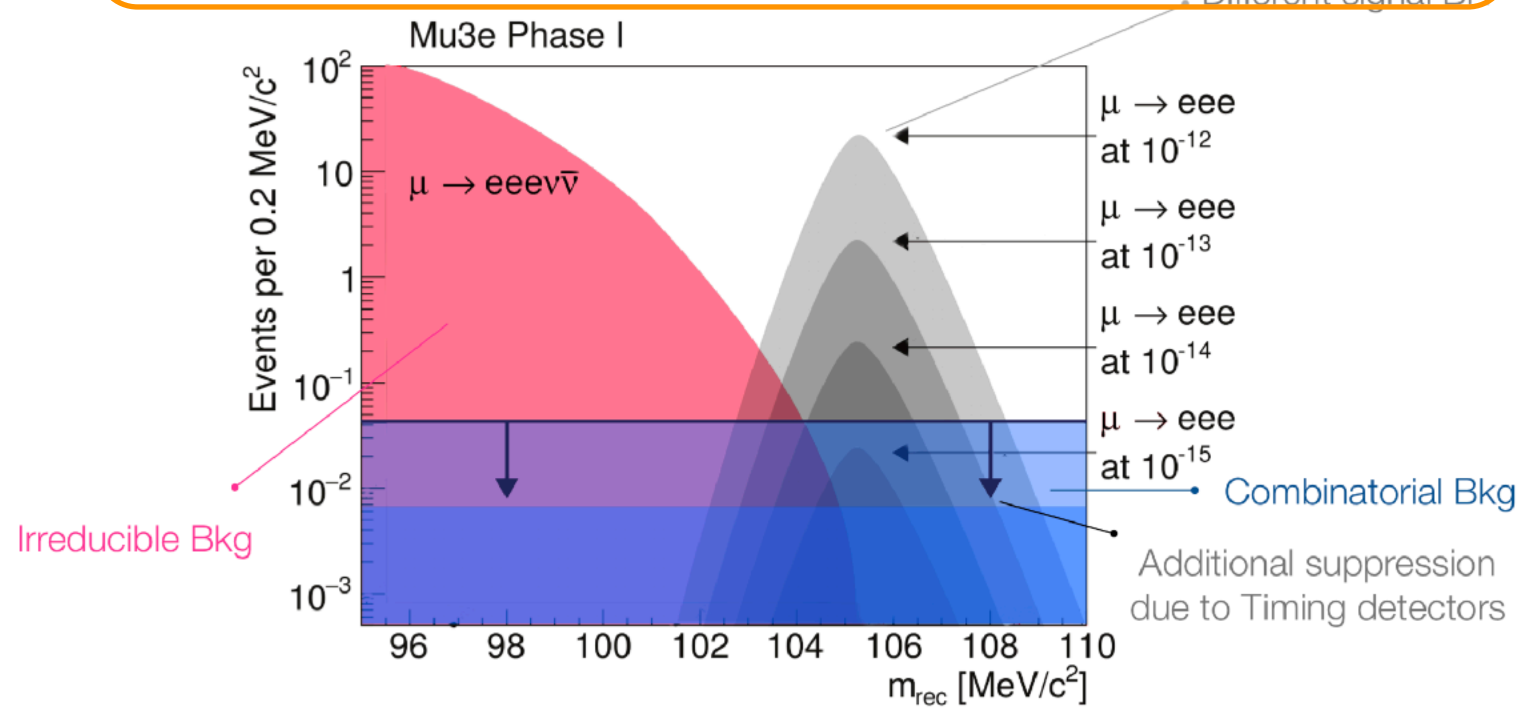
Pixelated TC
with SiPM readout
σ_t~35psec

Mu3e: μ→eee Search

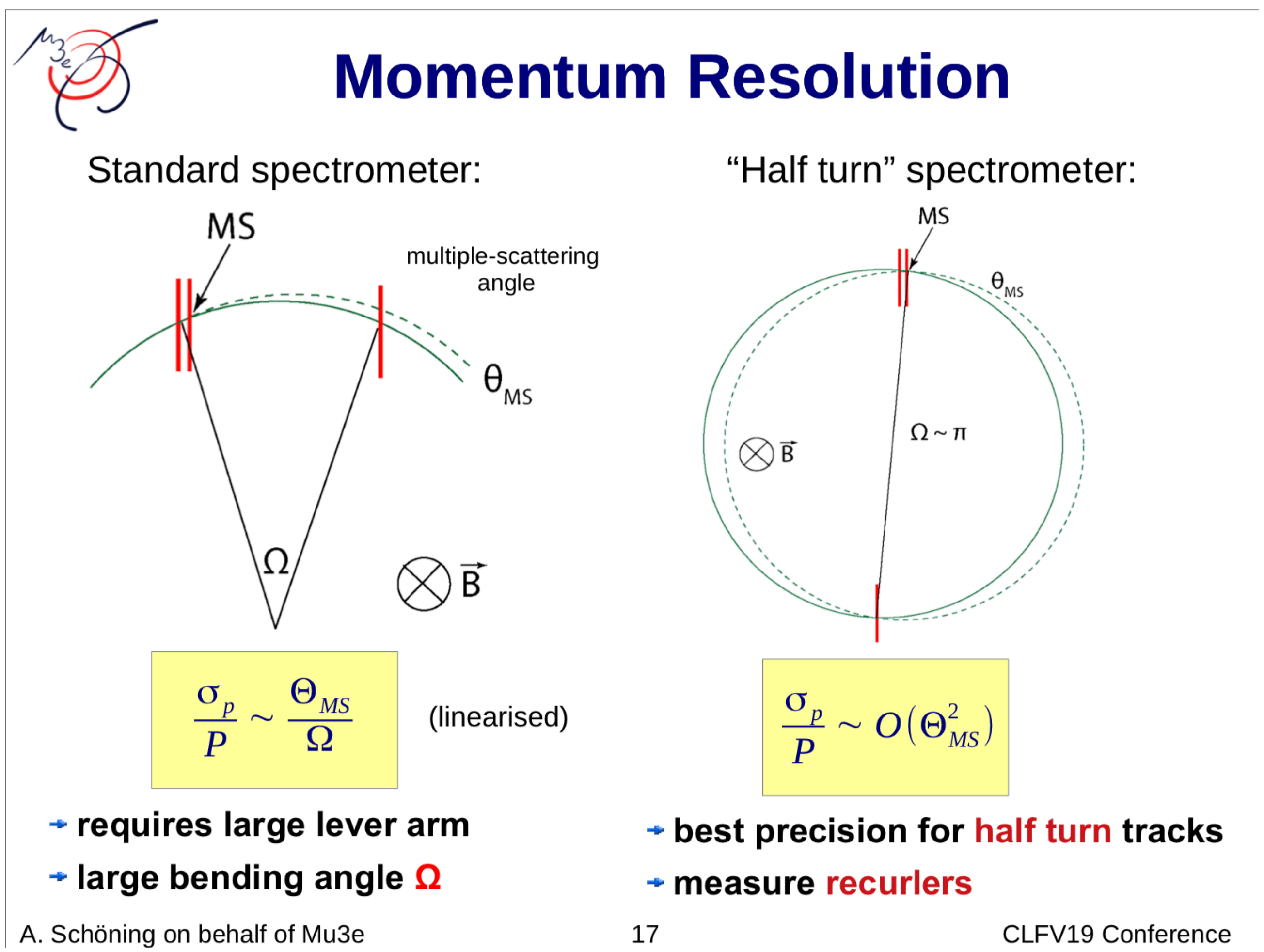
- Another channel sensitive to cLFV with DC muon beam
  - 1.0×10^{-12} (90% C.L.) by SINDRUM
  - Goal : 10^{-16} in 2 steps
- Measure all electron tracks with extreme precision
- Background source
  - $\mu^+ \to e^+ e^+ e^- \nu \bar{\nu}$
  - Accidental overlap
- Beamline is shared with MEG II

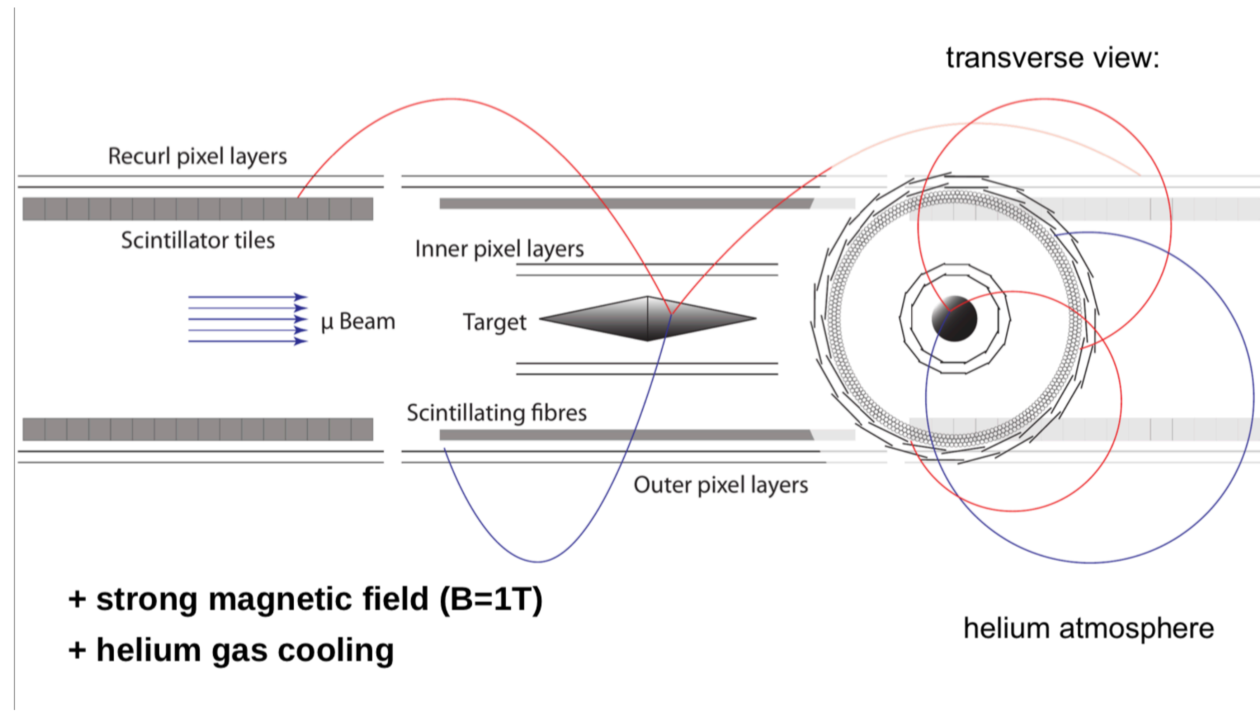






Momentum Resolution





Ultra-thin silicon pixel detector 1 per mil radiation length/layer

A. Schöning, CLFV19

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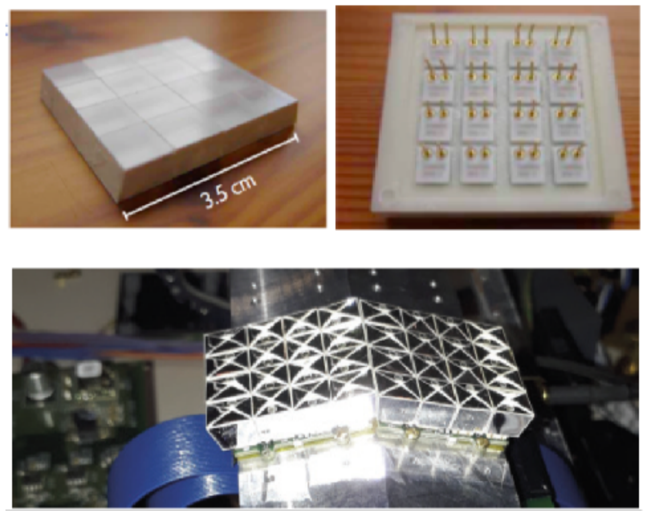
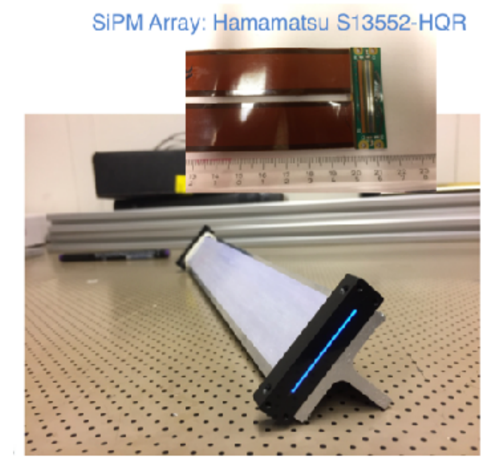
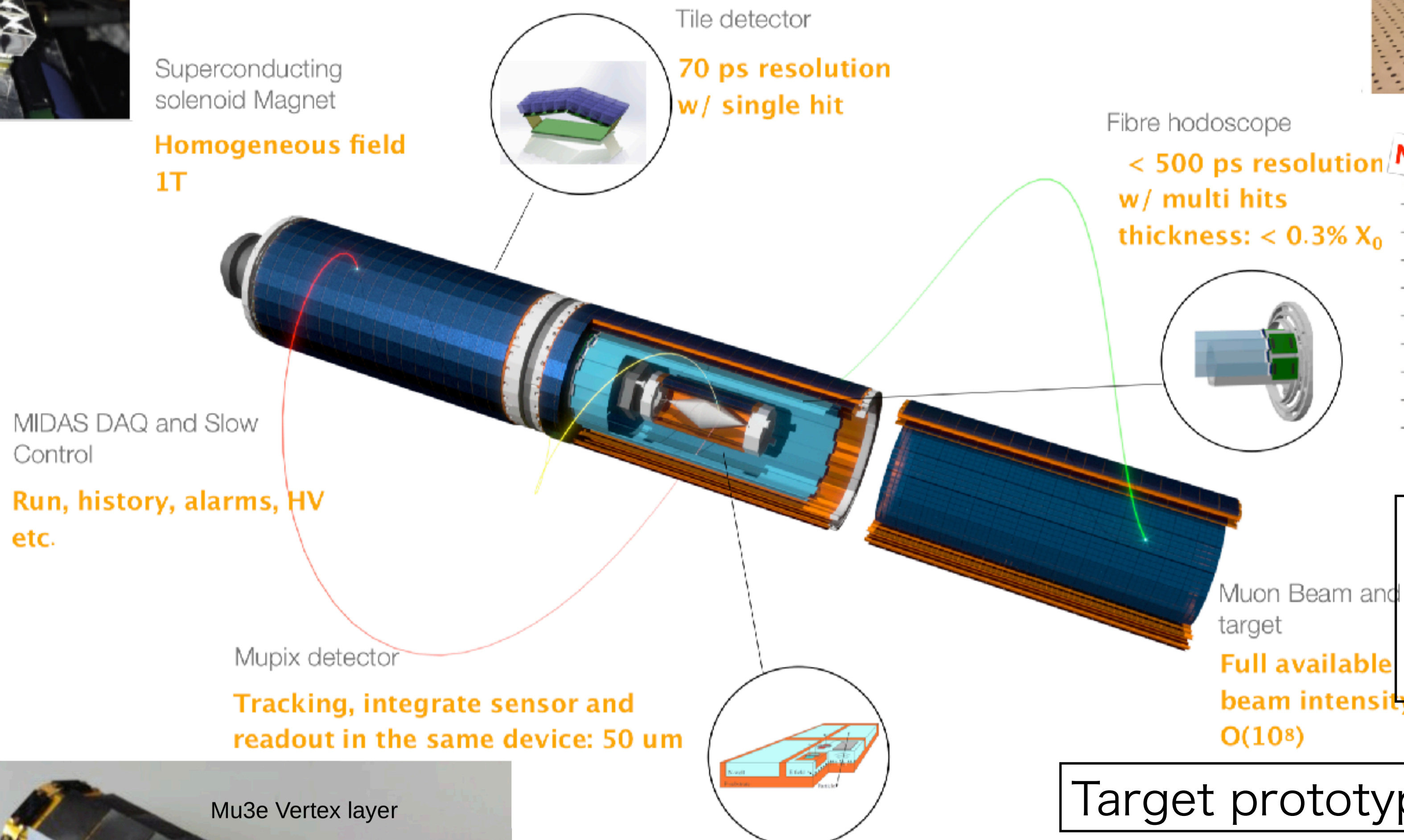
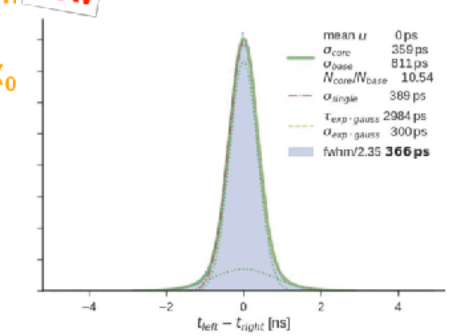
Detector Preparation



Tile detector prototype
Good enough σ_t

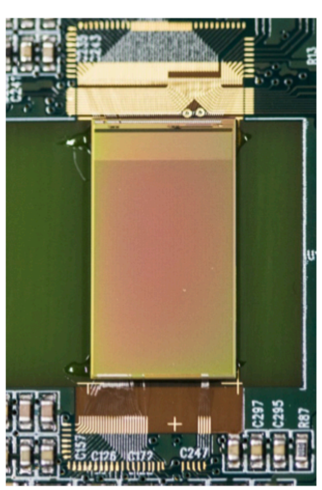




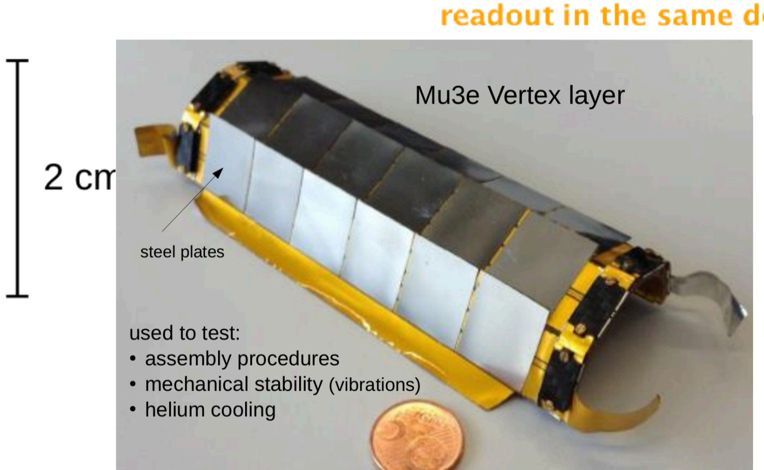


Fiber hodoscope
prototype
Good enough σ_t

MuPix8 prototype (2018)



pixel size 80 x 80 μm^2

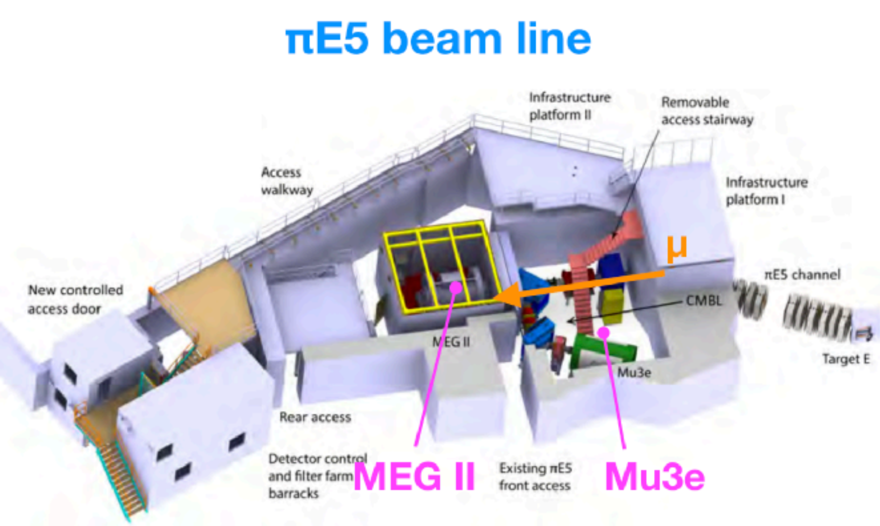


1st large-area prototype
MuPix8 is being tested
MuPix9 & MuPix10 follow

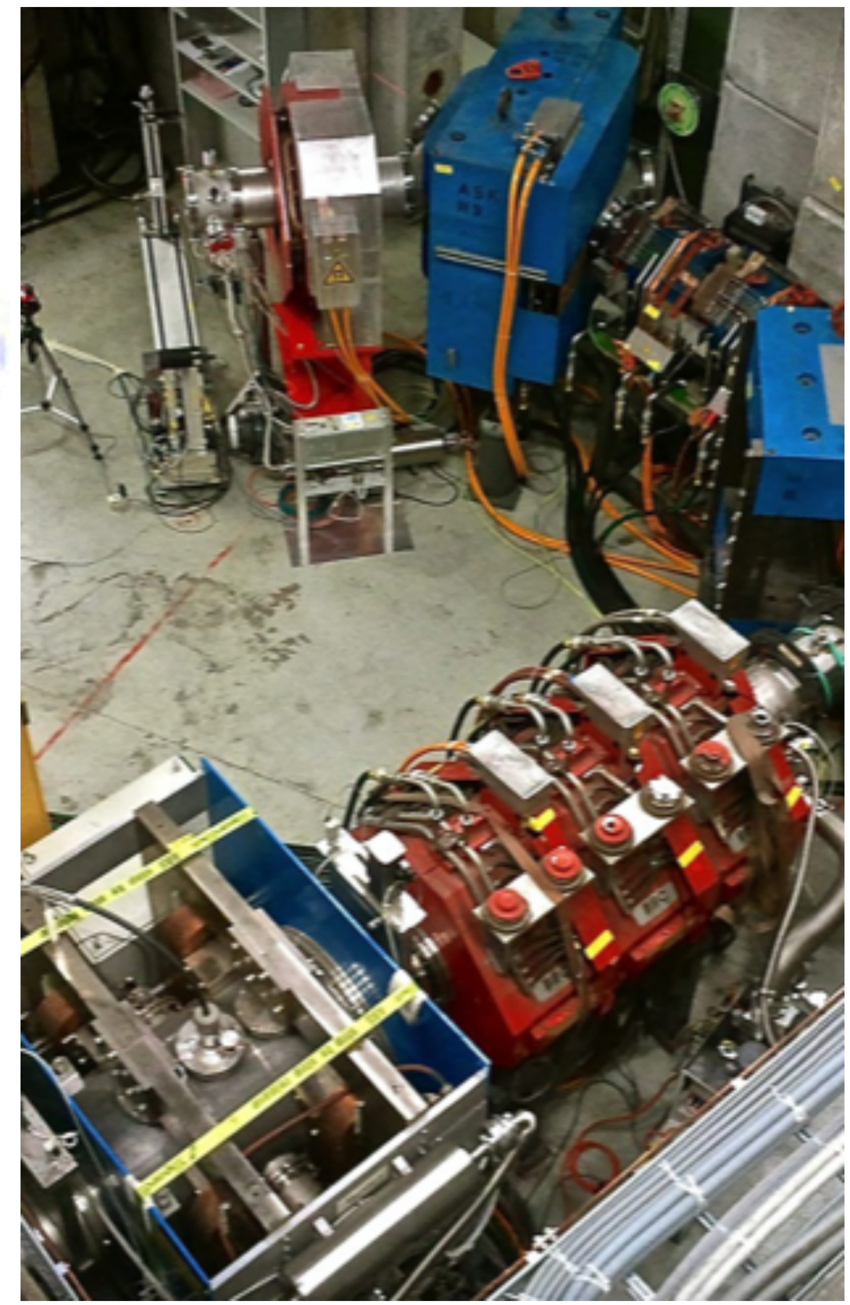
Target prototype

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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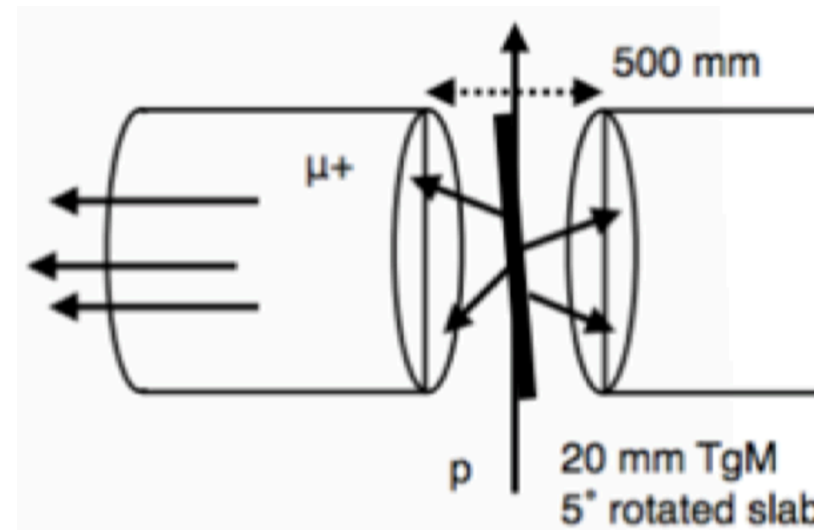
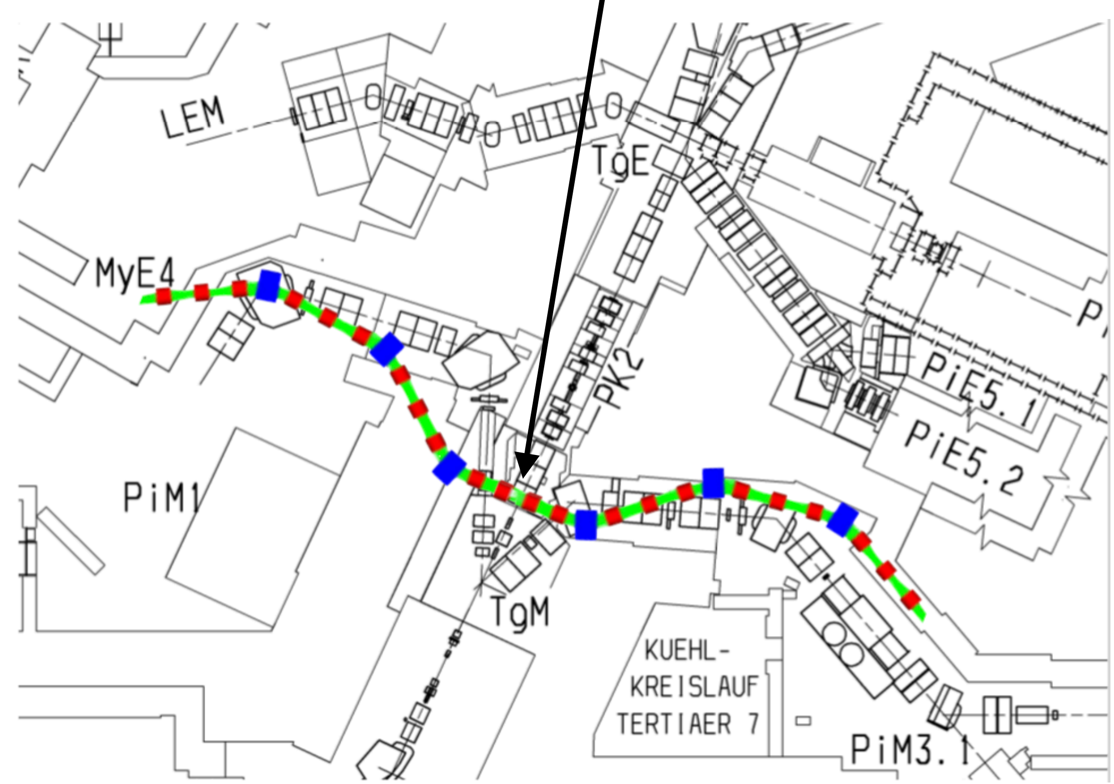
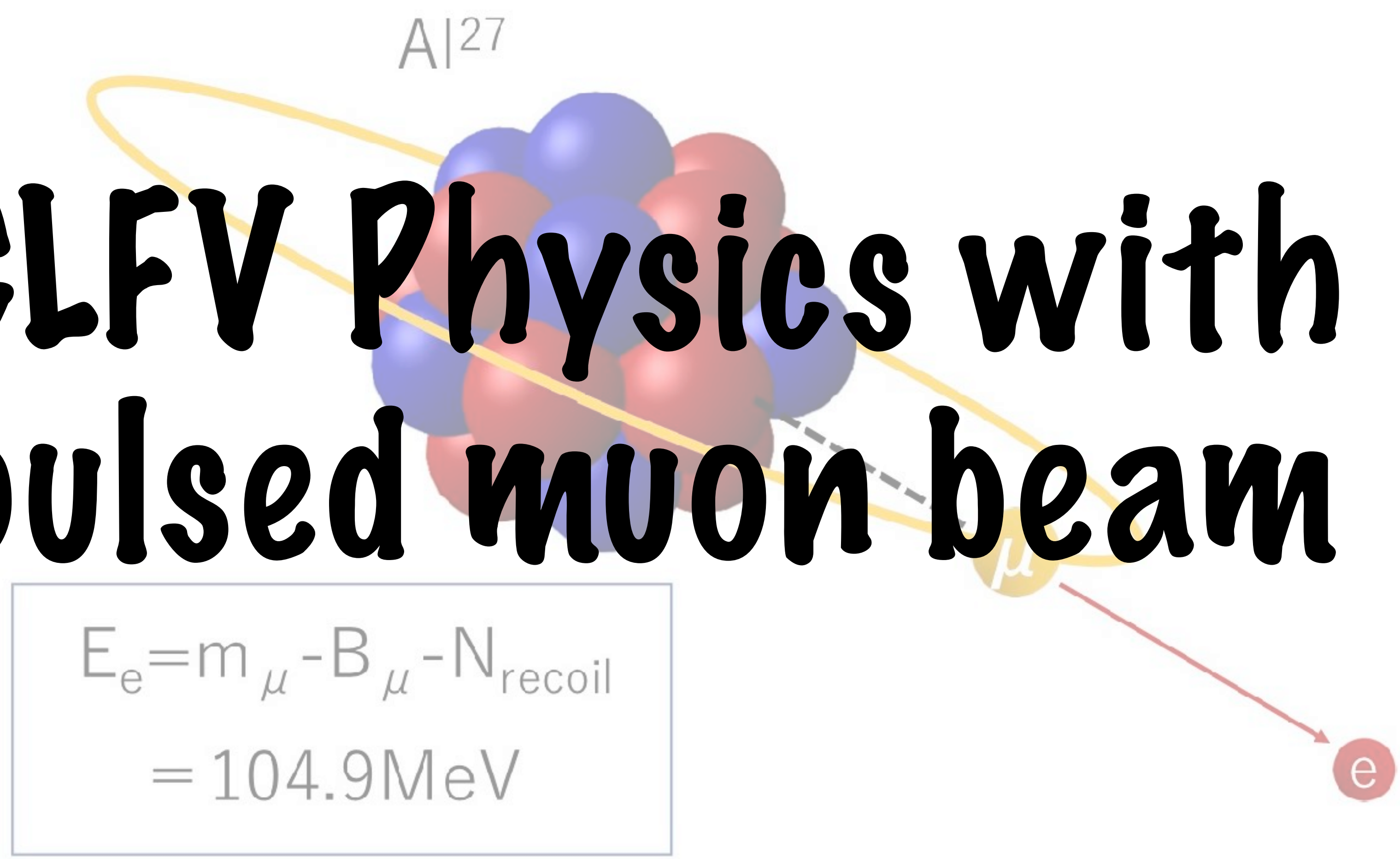
Future prospects of High-intensity DC muon beam

- PSI HiMB project
  - Development of high-intensity beam by modification of existing target (TgM) and beam lines → goal of 10^{10} surface-μ^+/s
- New Target M Station (TgM) with 20mm thick graphite slab at 5°
- Split capture solenoid channel close to target
  - One side: particle physics (high-intensity)
  - Other side: materials science (high-intensity, high-polarization)
- Normal conducting solenoids Front-end: radiation hard Copy of existing μE4 solenoids
- First (simple) beam optics shows that $O(10^{10})$ μ^+/s can be transported

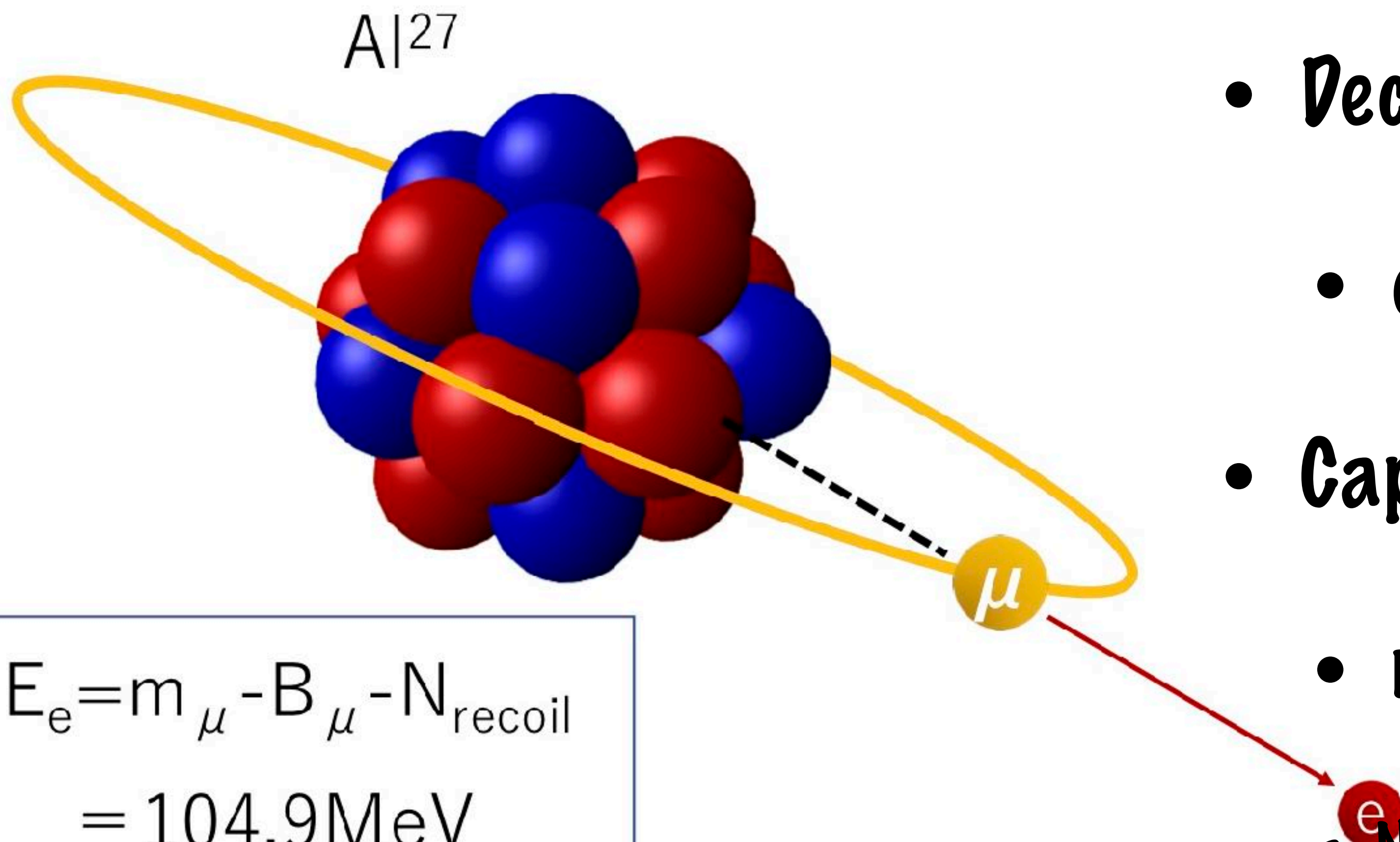




CLFV Physics with pulsed muon beam



Mu-e conversion

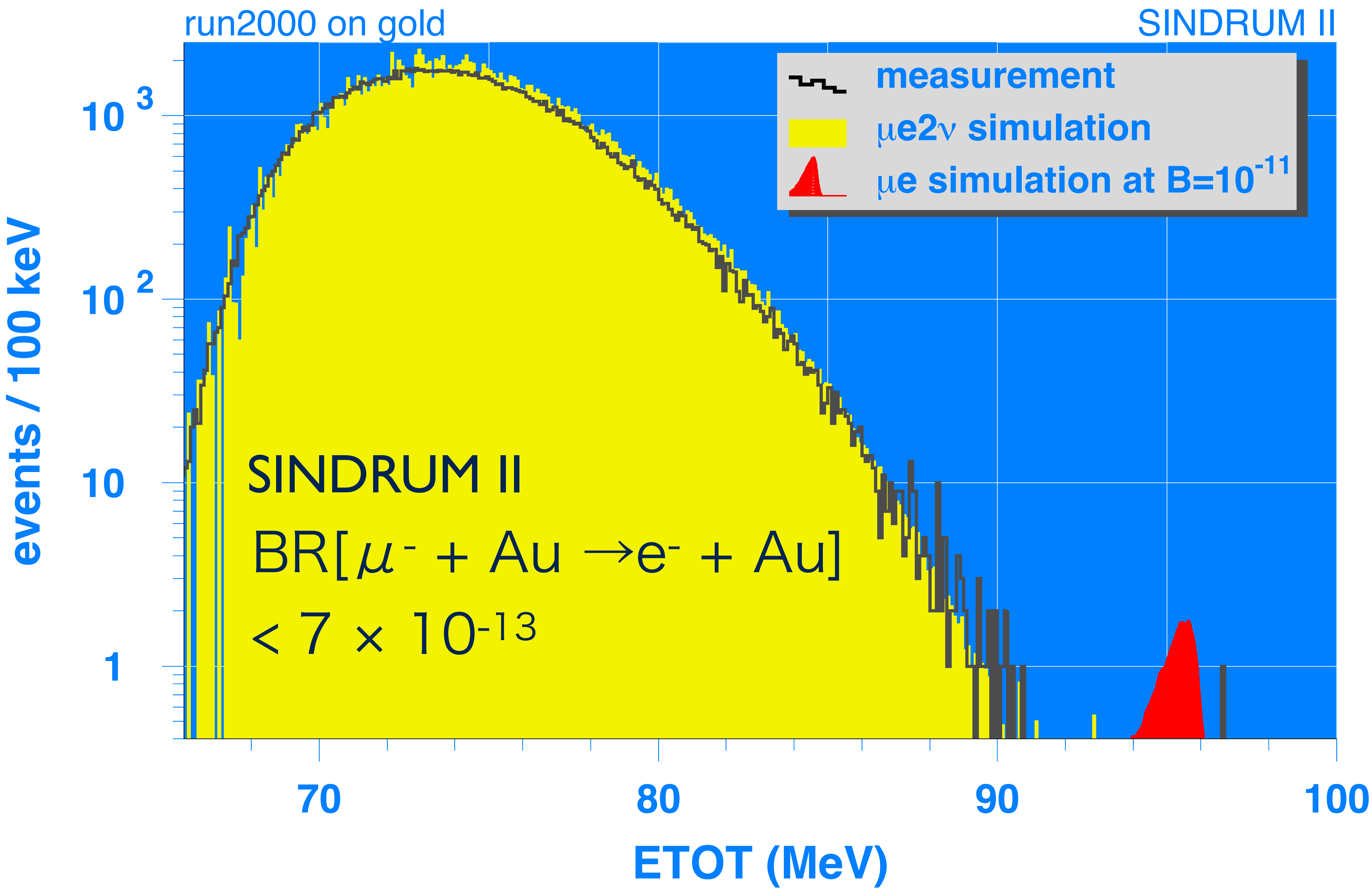


$E_e = m_\mu - B_\mu - N_{recoil}$
$= 104.9\text{MeV}$

- 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
  - $\tau_\mu^N < \tau_\mu^{free}$ ($\tau_\mu^{Al} = 860$ nsec)
  - μ-e conversion $\mu^- + (A,Z) \to e^- + (A,Z)$

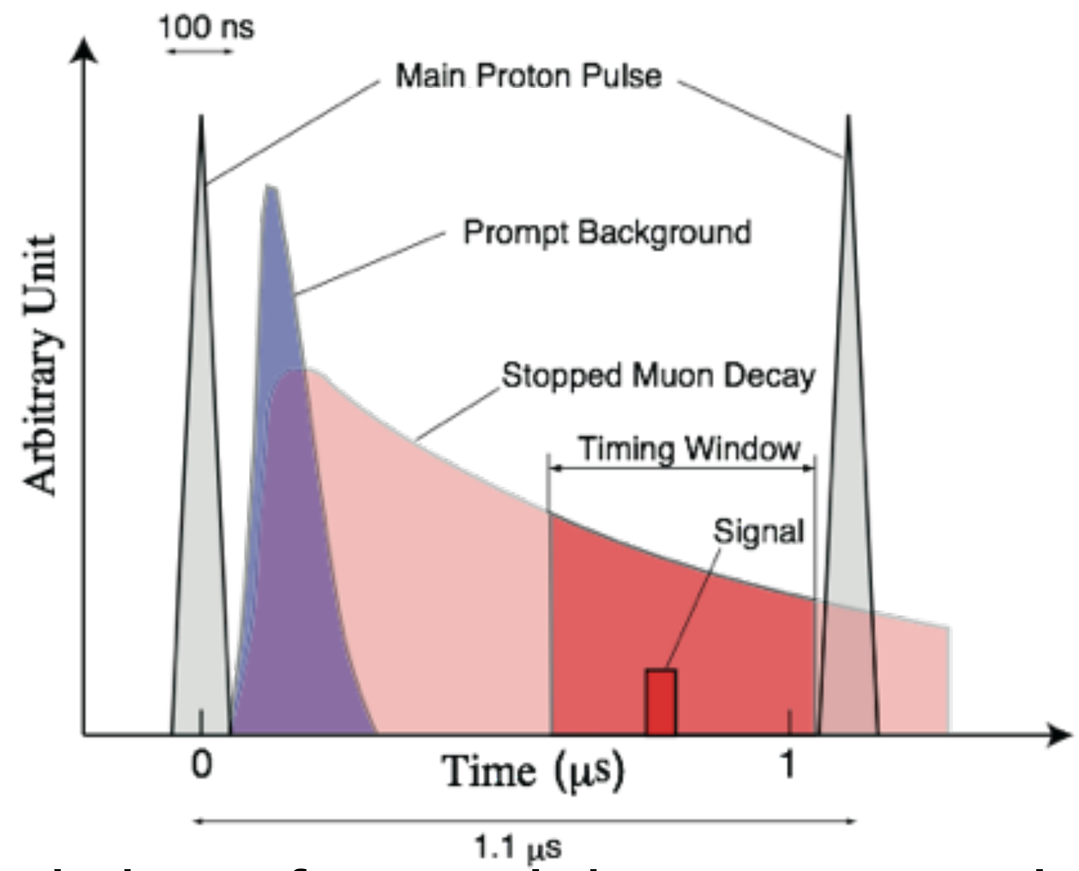
- $E_{\mu e}(Al) \sim m_\mu - B_\mu - E_{rec} = 104.97\text{MeV}$
  - B_μ: binding energy of the 1s muonic atom

Electron Energy Spectrum



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:

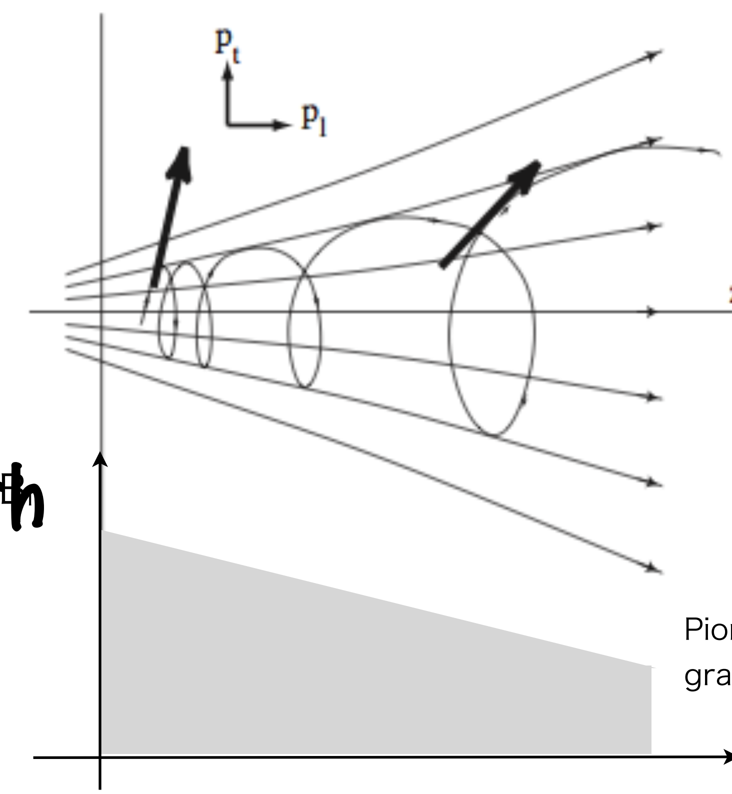
- $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$

  $\gamma \rightarrow e^+ e^-$

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

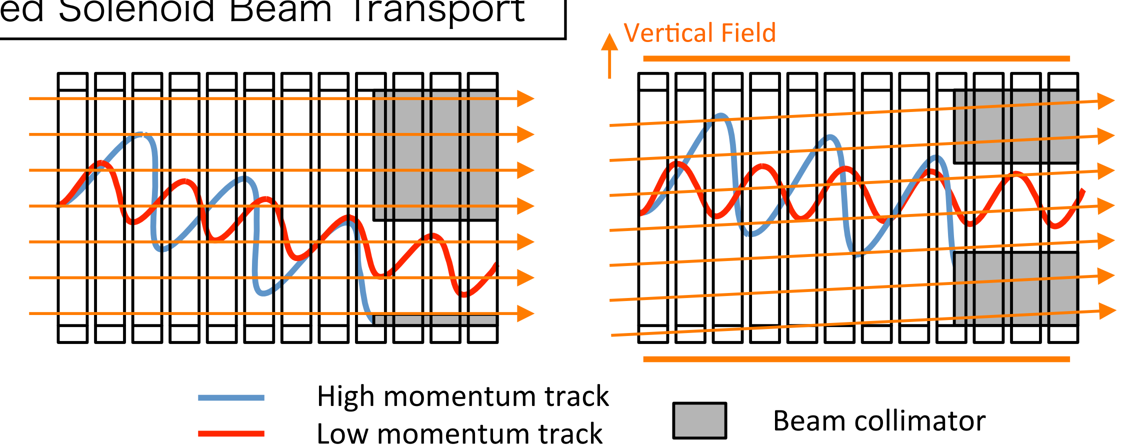
MELC Proposal

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



Pion/muon collection using gradient magnetic field

Curved Solenoid Beam Transport



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ELEMENTARY PARTICLES AND FIELDS
Experiment

Search for Lepton-Flavor-Violating Rare Muon Processes

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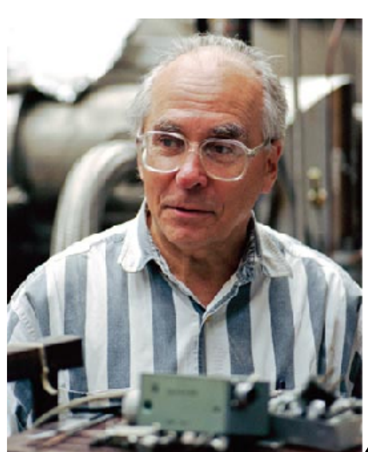

Vladimir Lobashev 1934-2011
CERN Courier Vol 51, No 8

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

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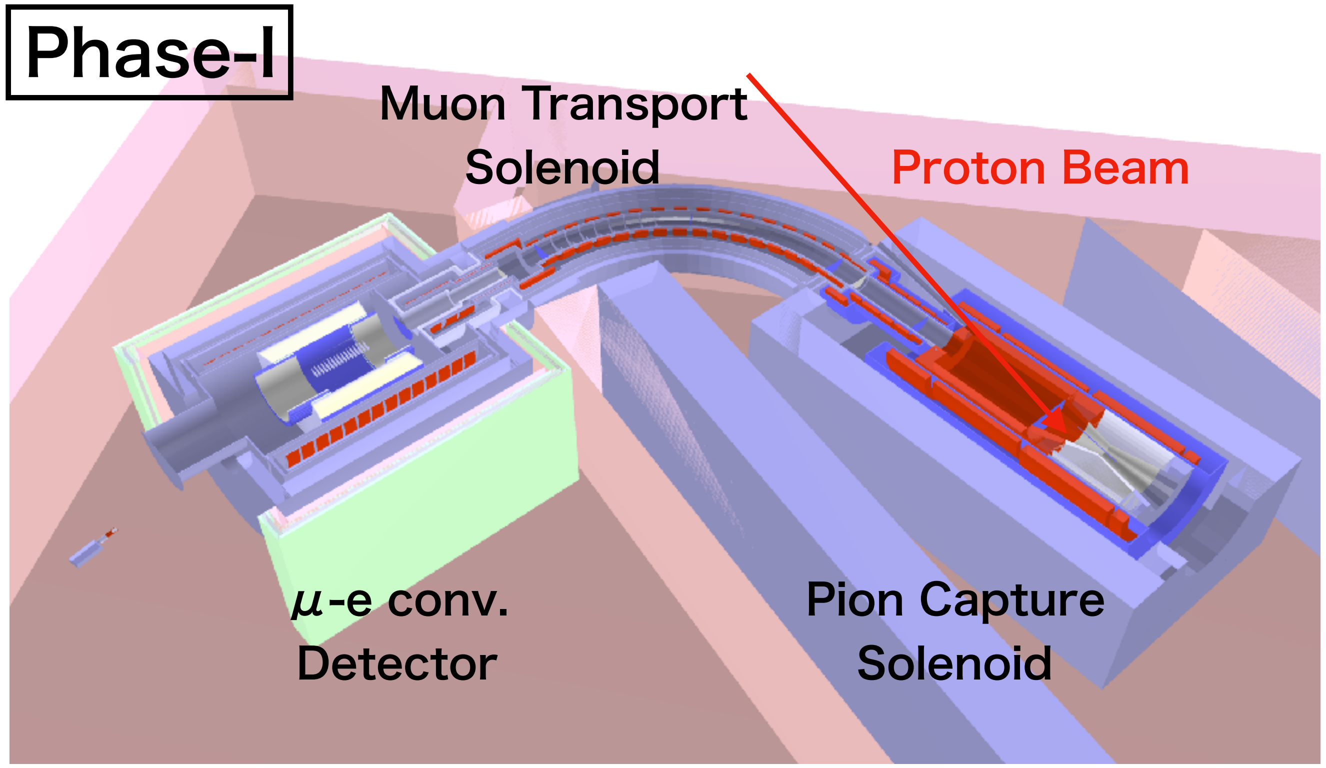
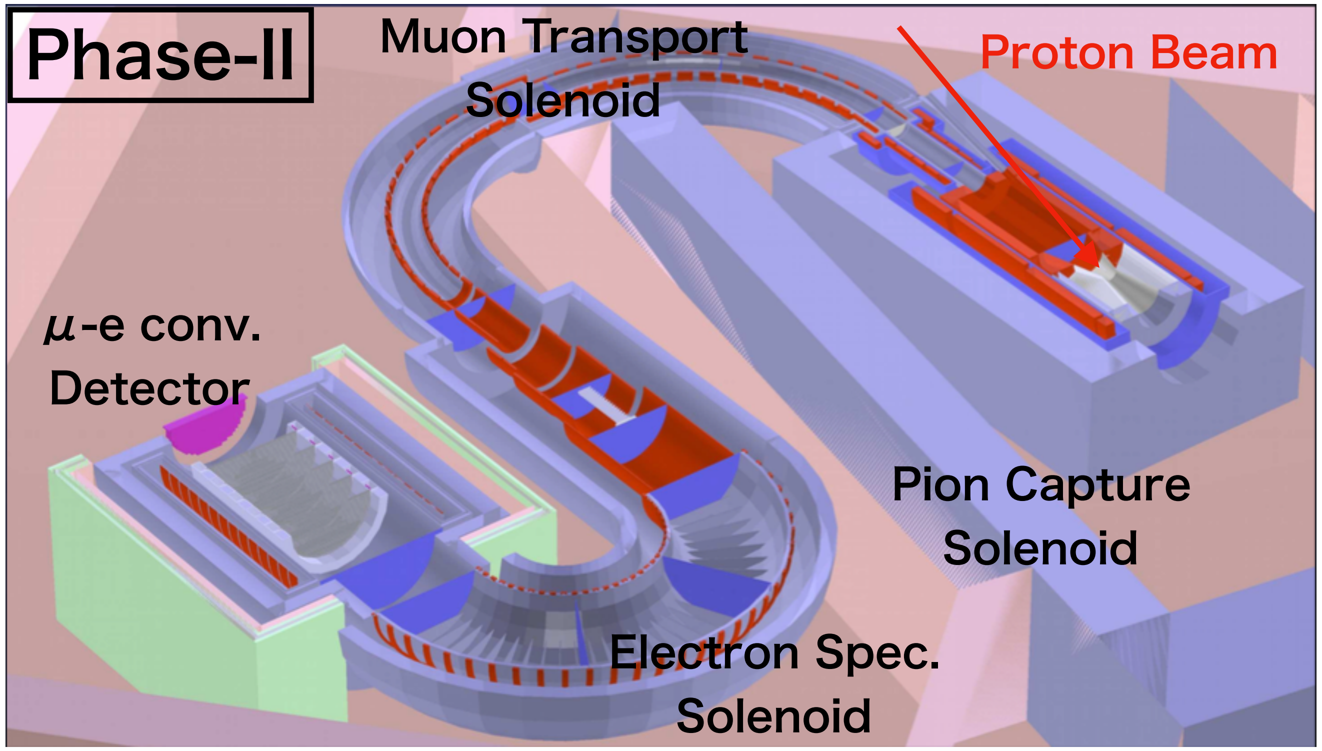
COMET at J-PARC

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}





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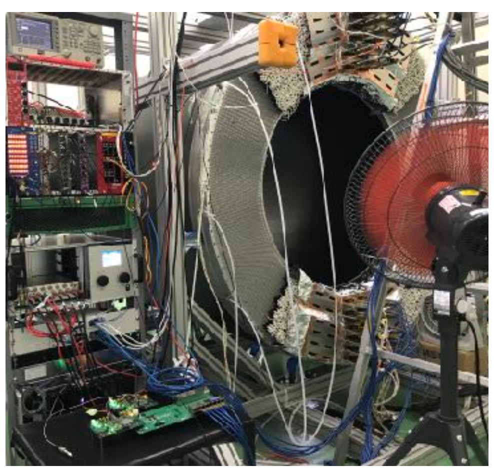
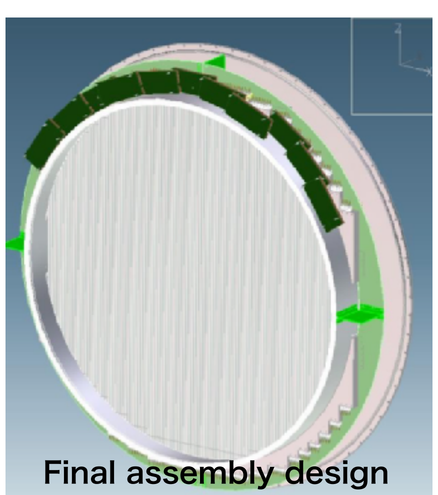
Status of COMET Phase I

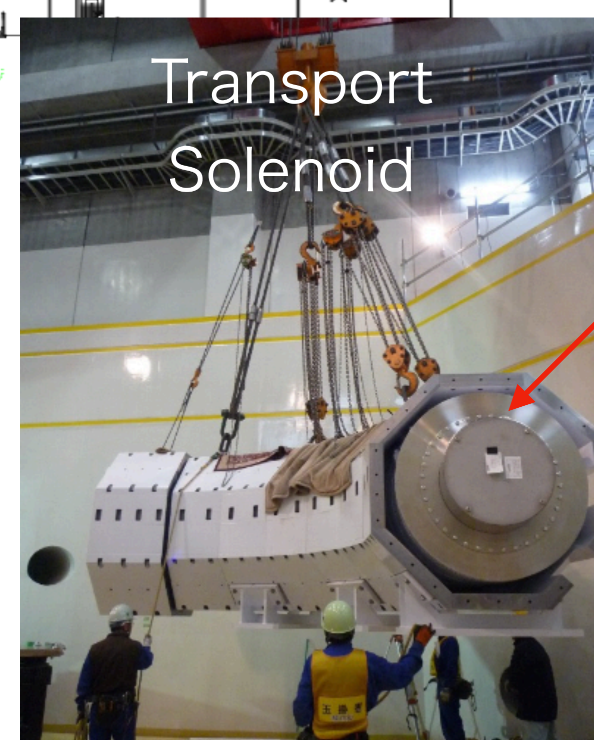
- Facility
  - Proton beam line & SC magnet system
- Detectors
  - Phase-I Physics Detector (CDC & TC)
  - Phase-I Beam measurement Detector (Straw tracker and LYSO Ecal)

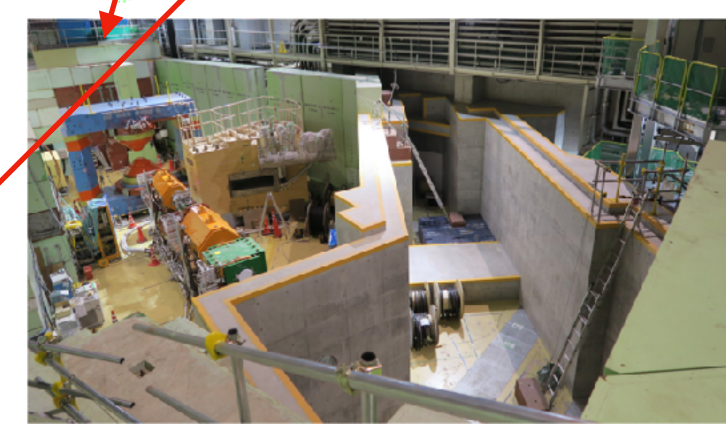


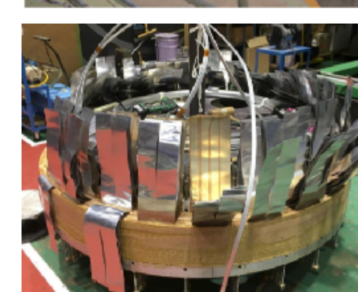
CDC CR test at KEK

Straw tracker & Ecal Prototype



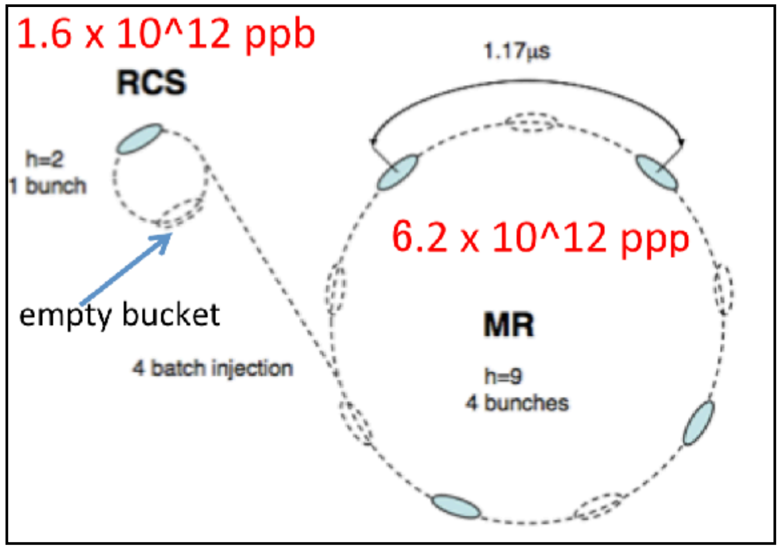


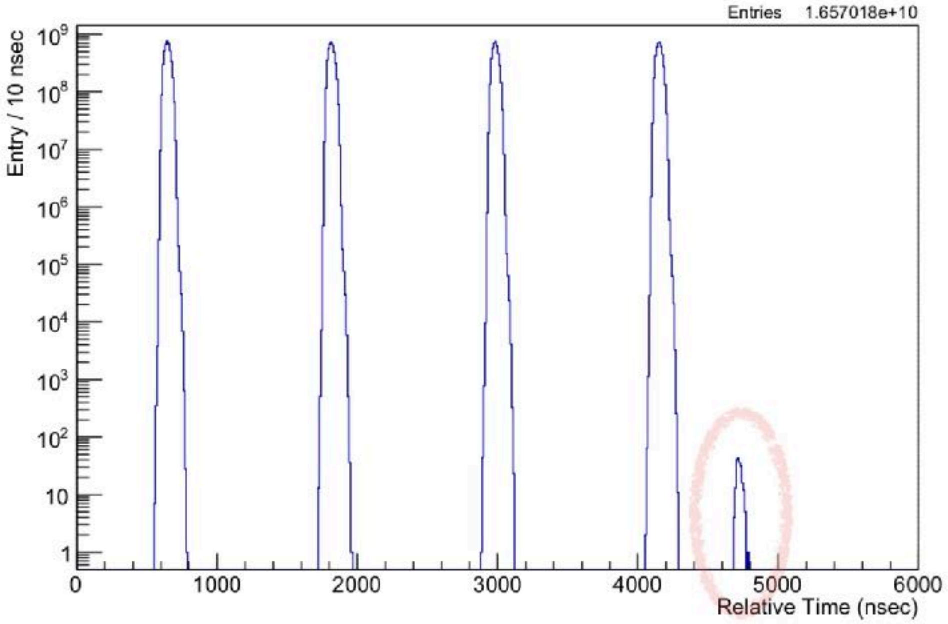


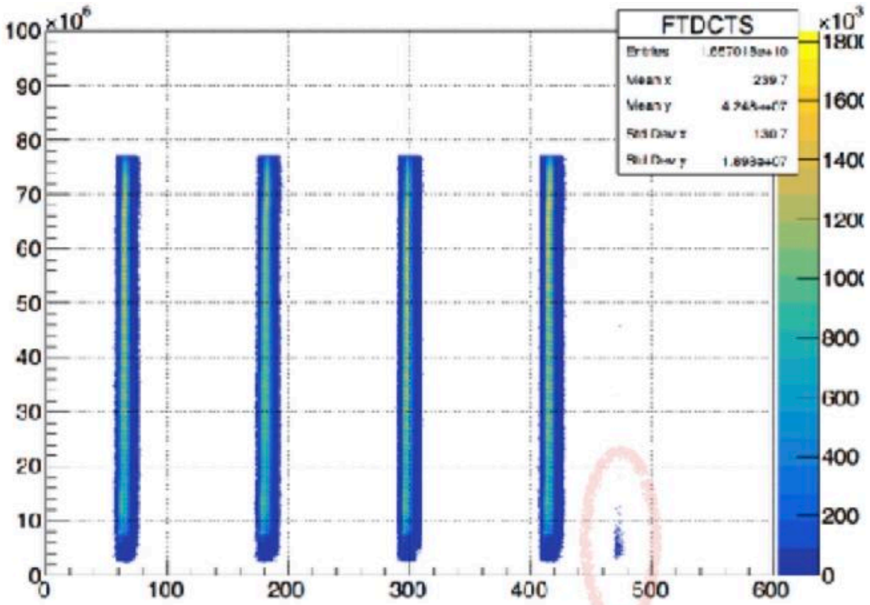


COMET Proton Beam R&D

- 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



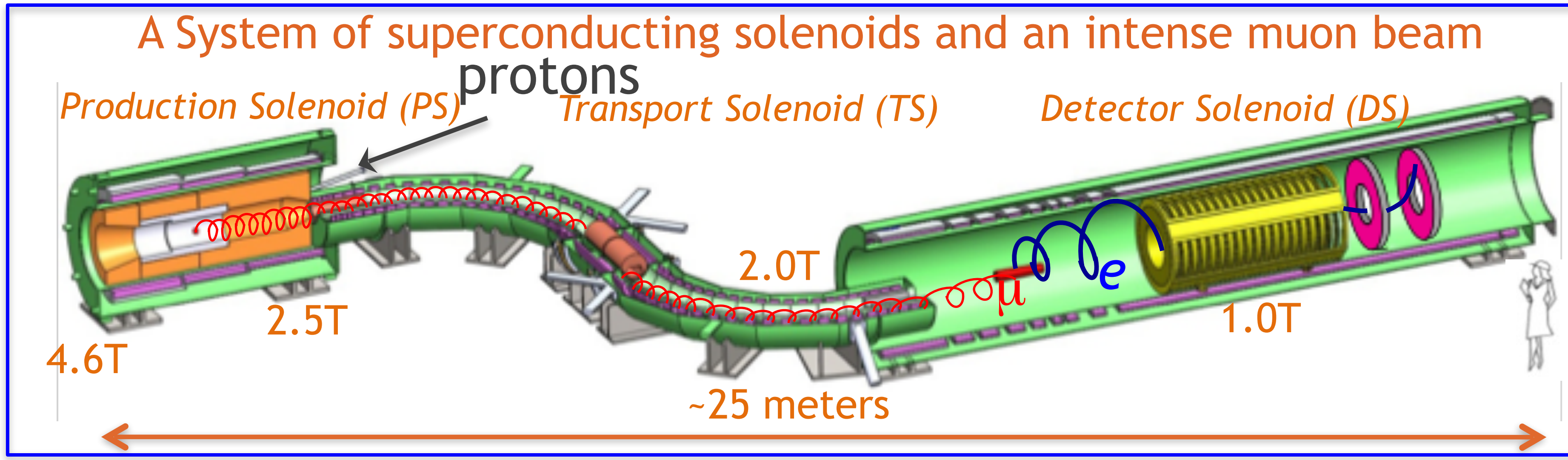


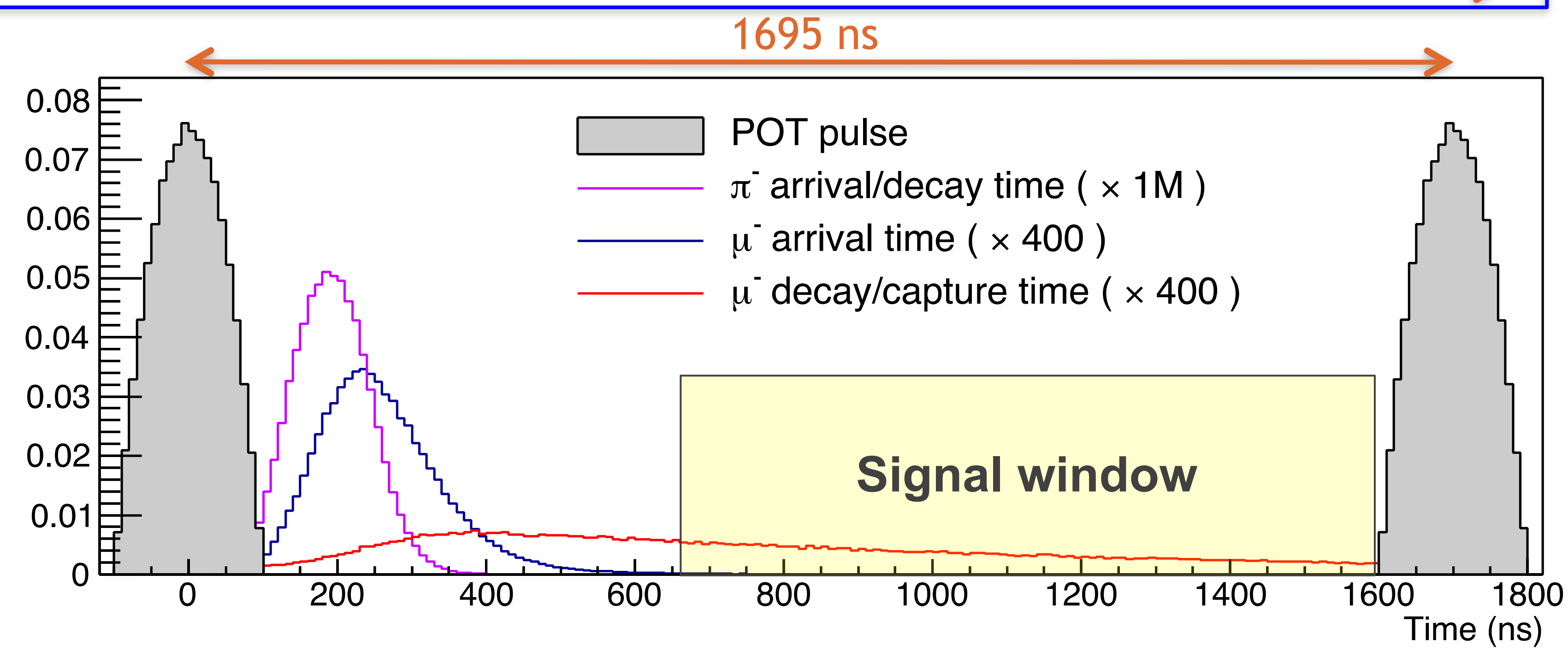


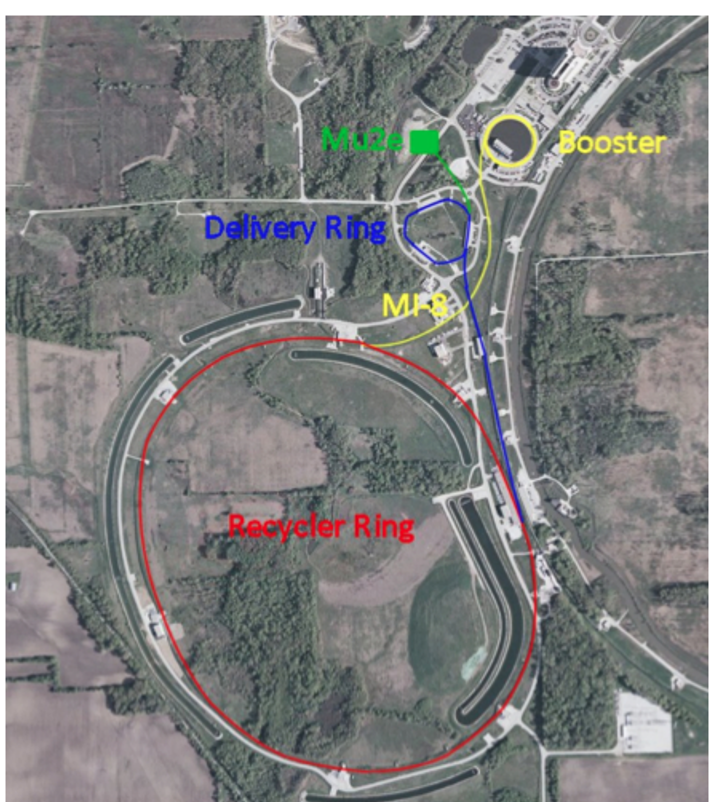
Mu2e at FNAL

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







- **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**

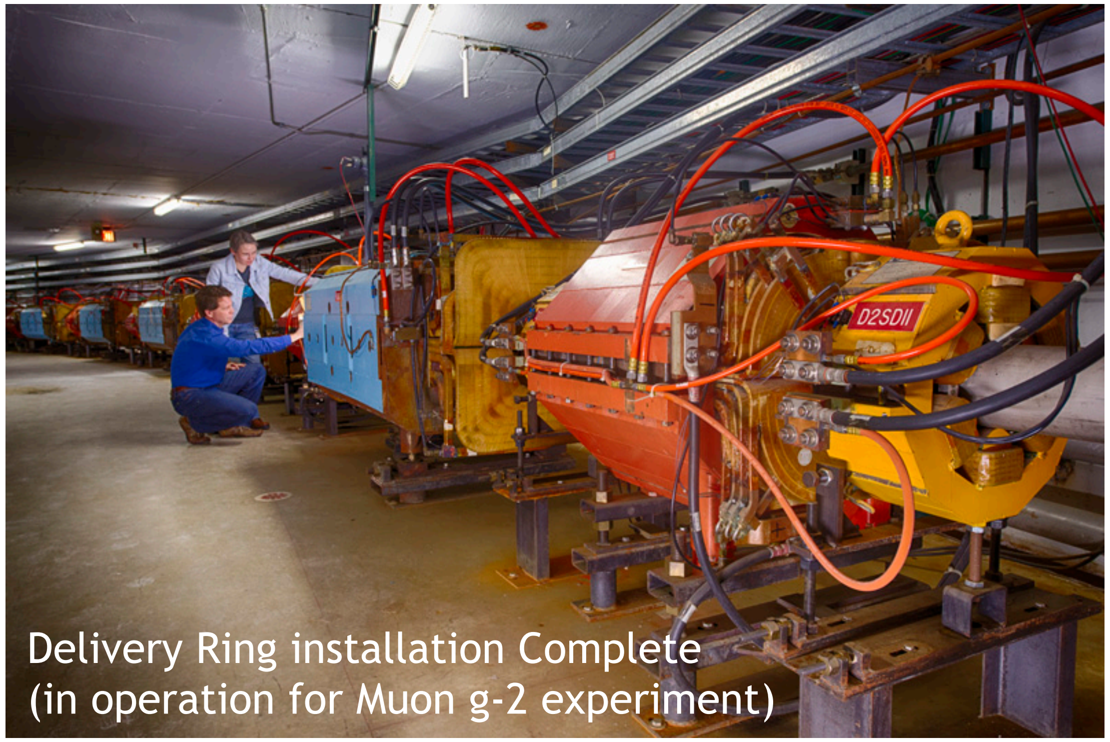
KEK
Unravelling the mysteries of matter, life and the universe.

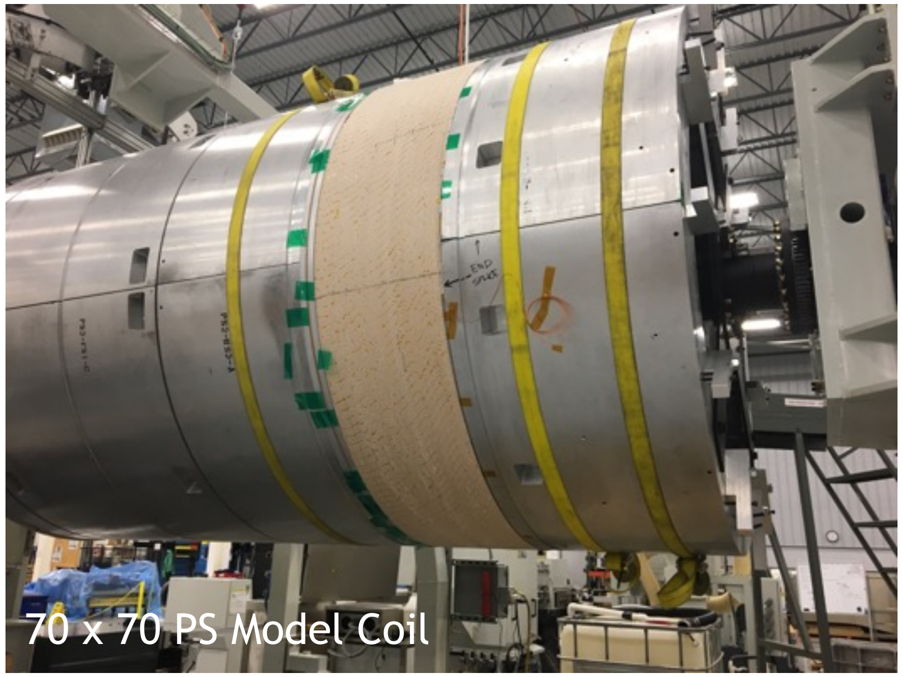
J-PARC

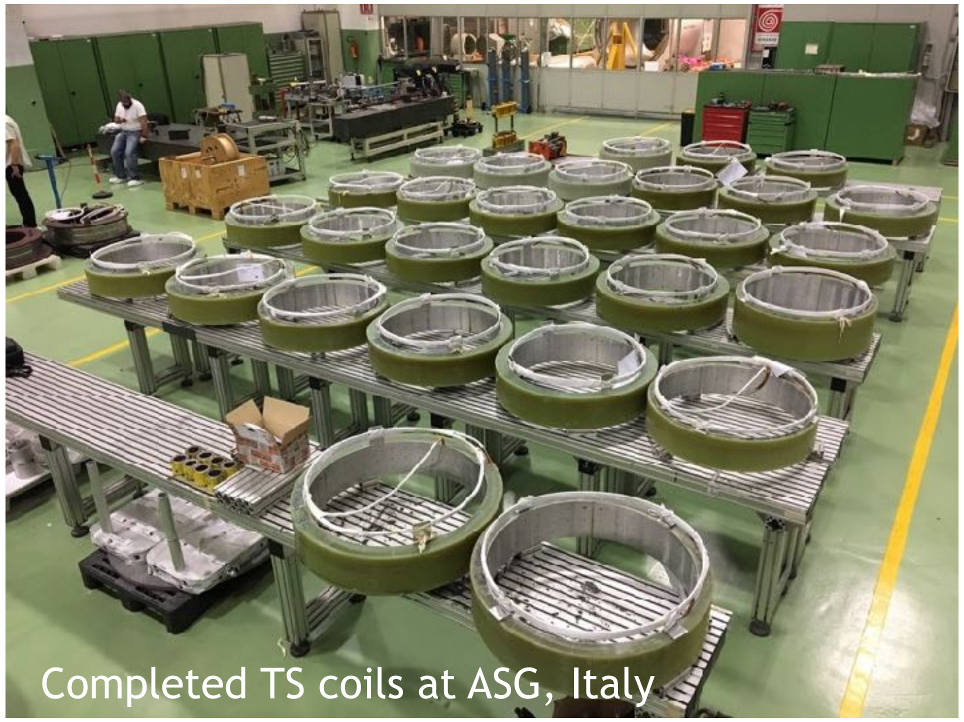
Mu2e Status

- 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)

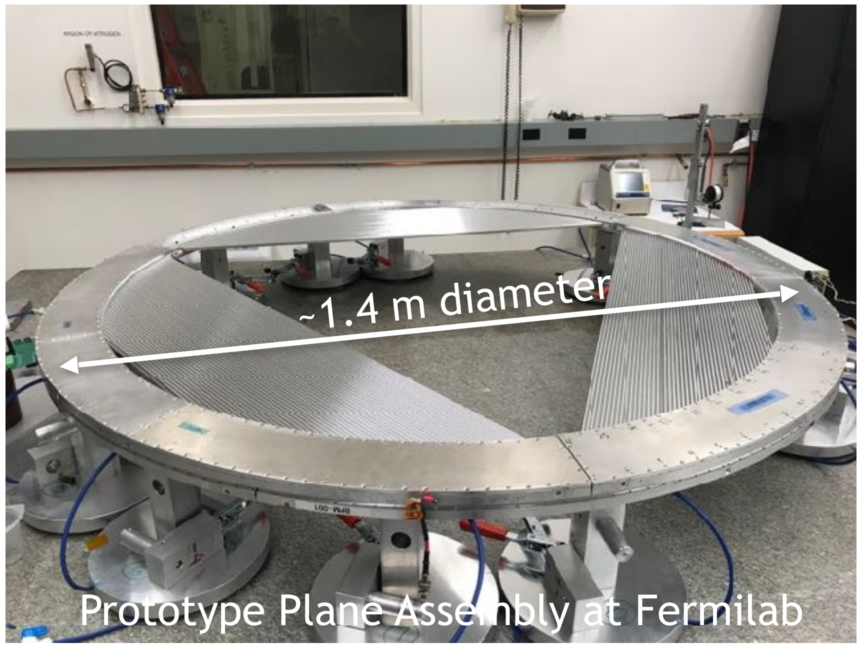

70 x 70 PS Model Coil

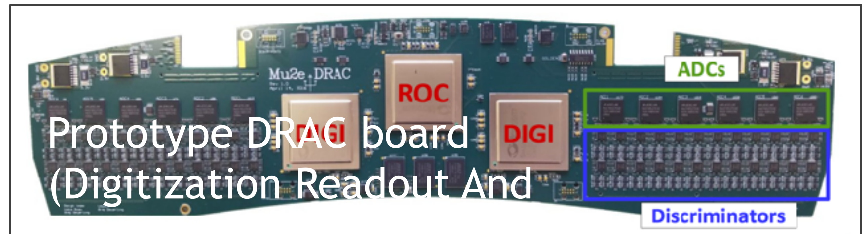

Completed TS coils at ASG, Italy

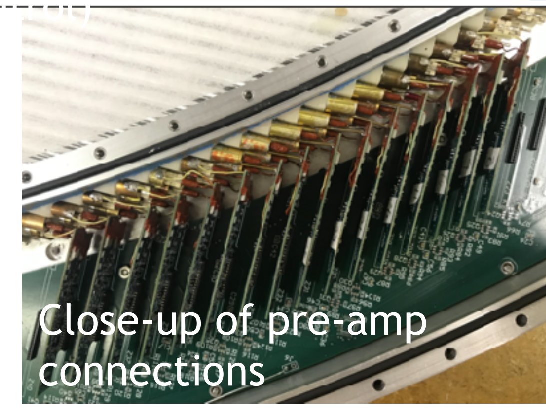

Completed TS Unit (4 coils)

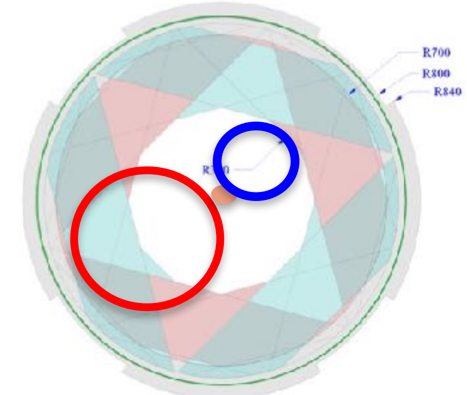
Mu2e Detectors

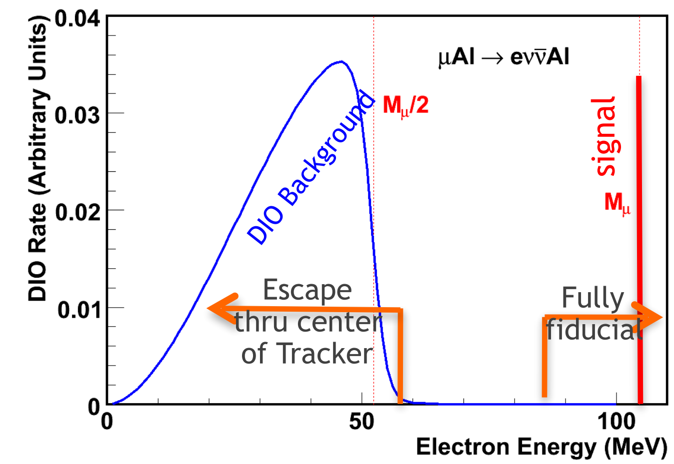
Straw-tube tracker



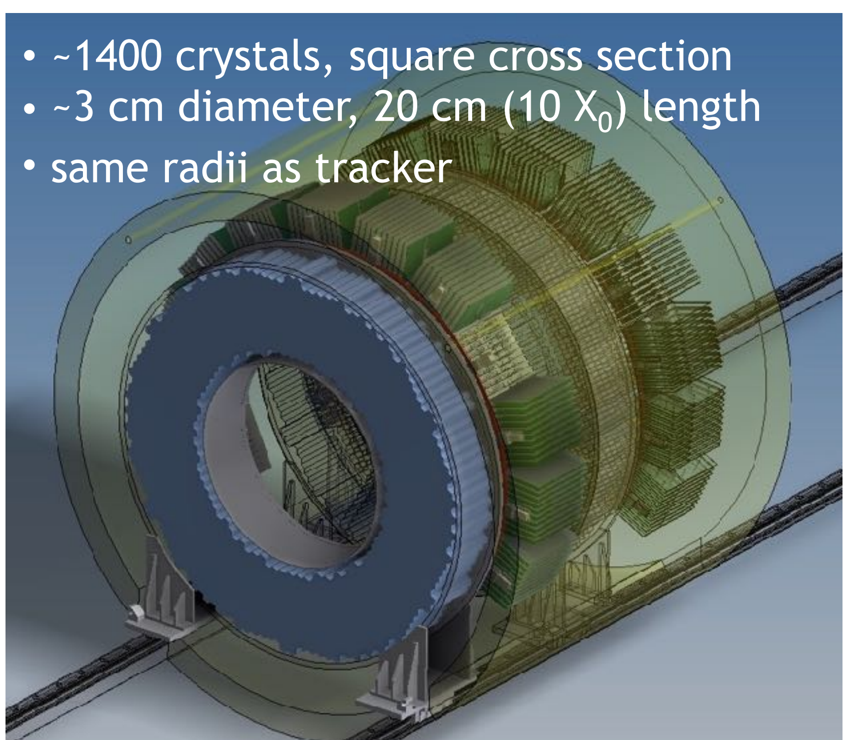






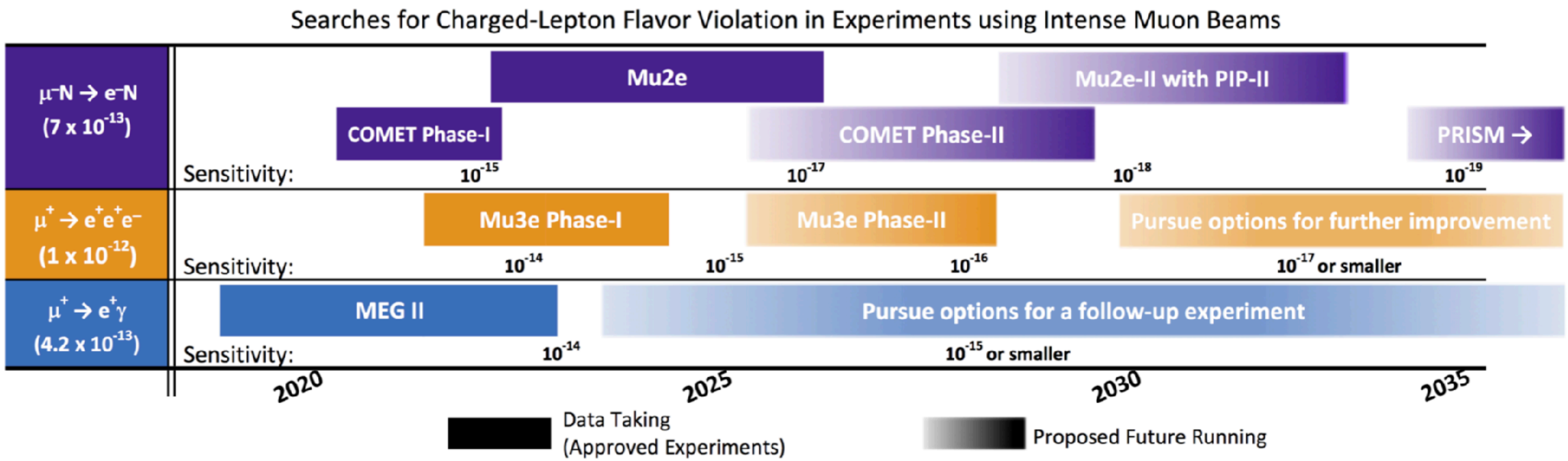


CsI Calorimeter



- 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

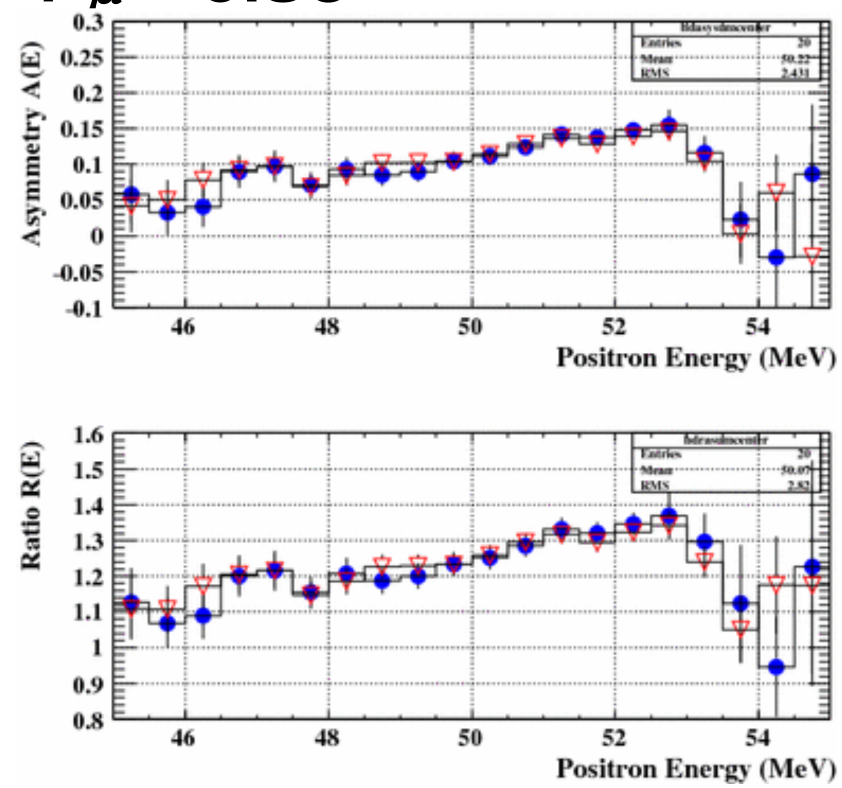


Input to Eur. Particle Physics Strategy
"Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities"

Once the signal is found…

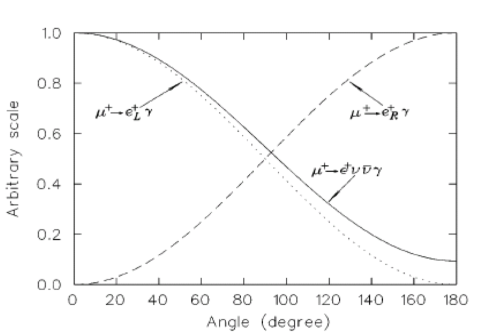
- MEG II
  - Muon bram is polarized (P_μ=-0.85)
  - Gamma angular distribution
- Mu3e
  - Invariant mass distribution $m_1(e^+e^-)$ vs. $m_2(e^+e^-)$

P_μ=-0.85

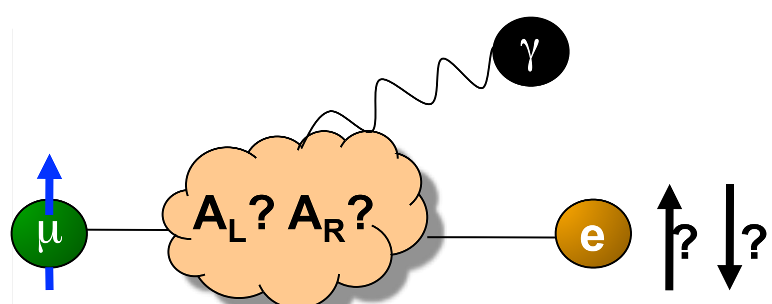


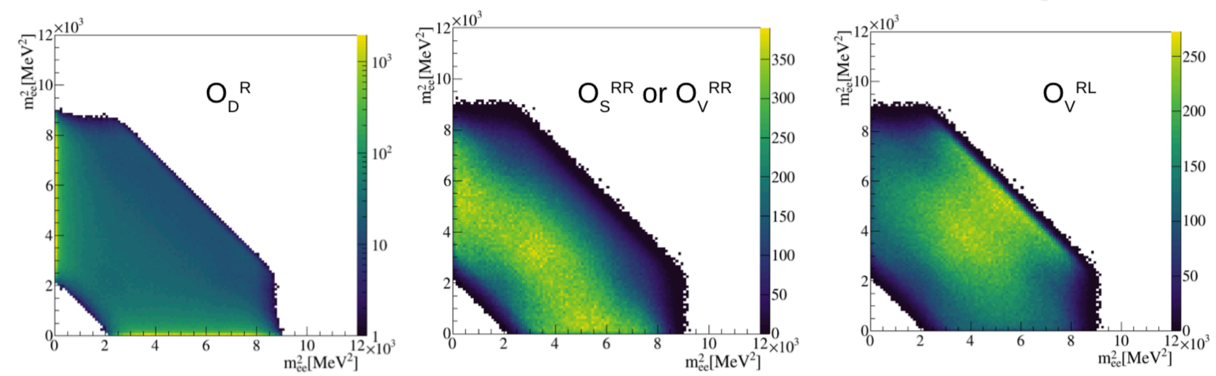
MEG, EPJ 2016 76:223

$$\mathscr{L}_{\rm eff} = \frac{1}{\Lambda^2}\left[C_D^L \mathscr{O}_D^L + C_D^R \mathscr{O}_D^R + C_S^{LL}\mathscr{O}_S^{LL} + C_S^{RR}\mathscr{O}_S^{RR} + C_V^{LL}\mathscr{O}_V^{LL} + C_V^{RR}\mathscr{O}_V^{RR} + C_V^{LR}\mathscr{O}_V^{LR} + C_V^{RL}\mathscr{O}_V^{RL}\right] + \text{h.c.}$$



Kuno and Okada, PRL 77(1996)434

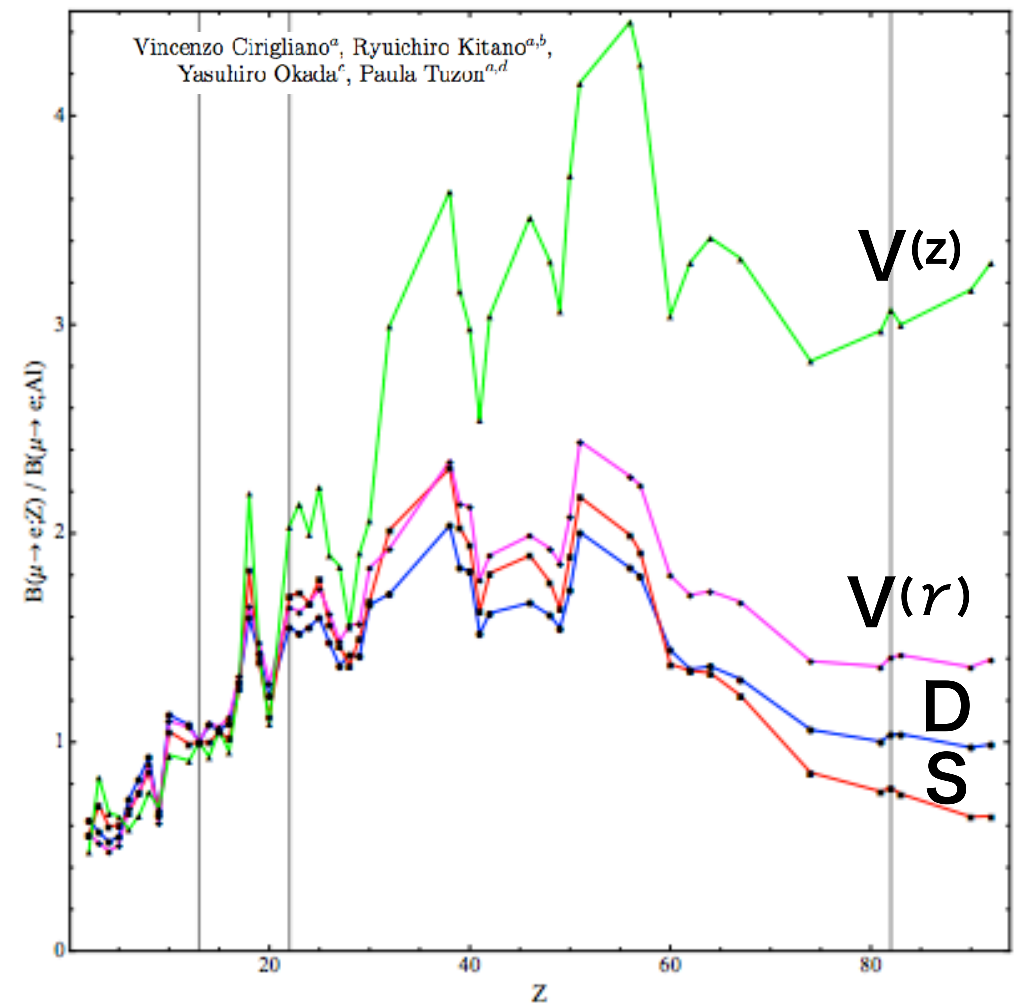




thesis A.-K.Perrevoort

Once the signal is found...

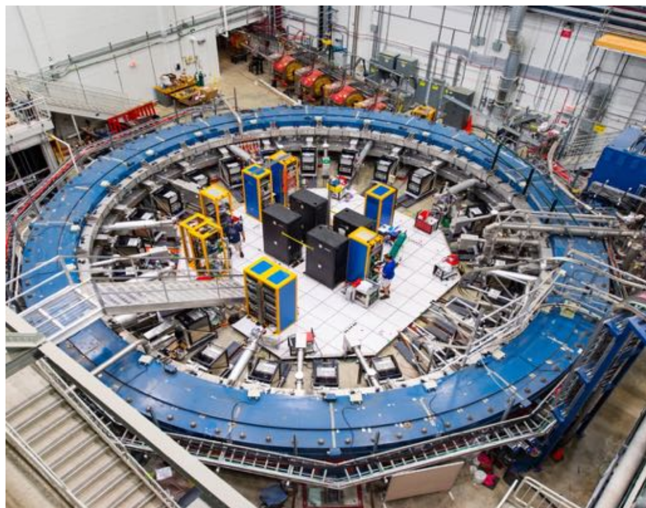
- Comparison of signal rates of μ→eγ, μ→eee, and μ-e conversion will clarify the physics behind cLFV reactions
- Even discovery only in μ-e conversion
  - Different target material contains different quark contents
  - May be possible to see the target dependence on the mu-e conversion rate
  - Discriminate 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 ??)

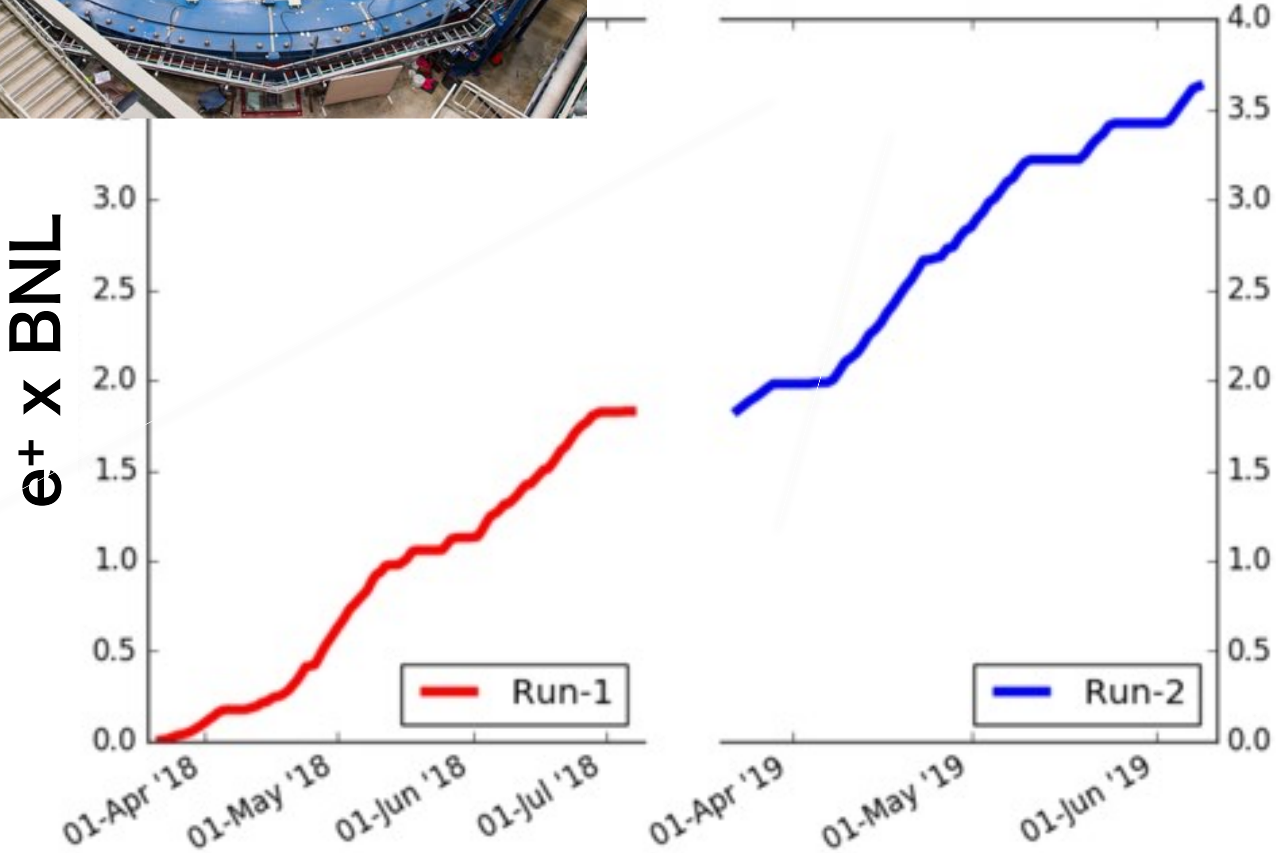


	Al	Ti
lifetime	864 ns	330 ns
time window	0.3	0.2
signal	1	1.5
net	0.3	0.3

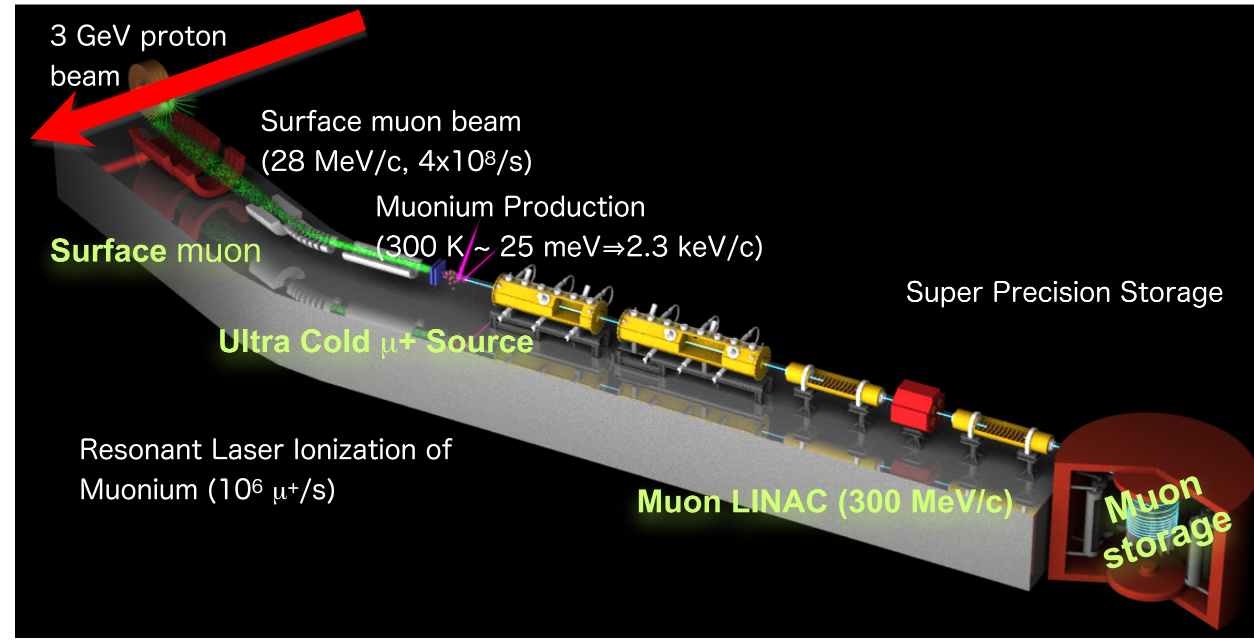
Muon g-2/EDM Experiments

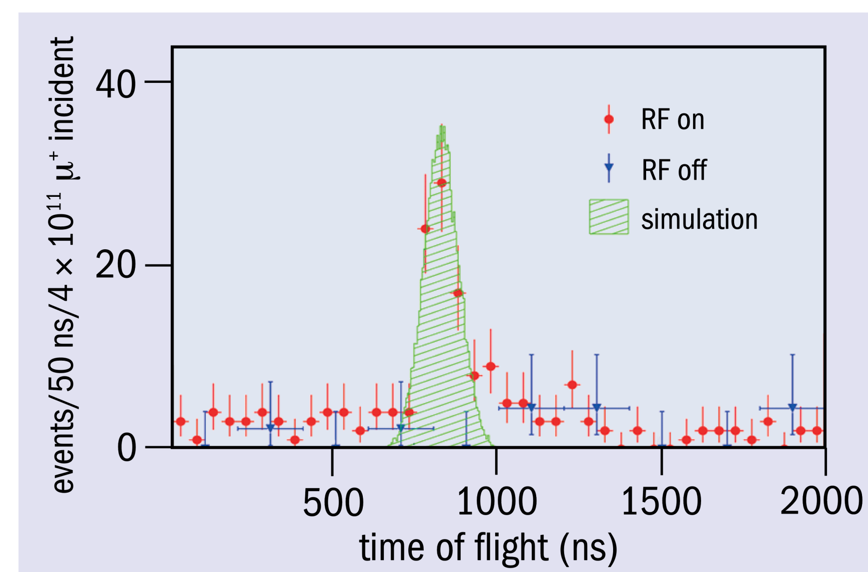
FNAL E989





J-PARC E34(g-2/EDM)





"Muons accelerated in Japan"
July 2018, CERN Courier

- Run 1 data are being analyzed:
  - 2 independent analyses for wp and 6 for wa
- Run 2 data collection is ending early July

L. Roberts CLFV 2019

Summary

- Strong physics motivation to search for muon CLFV reactions
- Future plans of muon CLFV experiments
  - MEG II & Mu3e
  - COMET & Mu2e
- Important to achieve similar sensitivities in all channels to clarify the physics behind signal (even in case of exclusion)
- More physics results expected in coming years