Image: https://en.wikipedia.org/wiki/Bandra-Worli_Sea_Link
Designed by Saurabh Sandilya

CKM2016

9th International Workshop on the CKM Unitarity Triangle

TIFR, Mumbai

Nov. 28 – Dec. 2, 2016

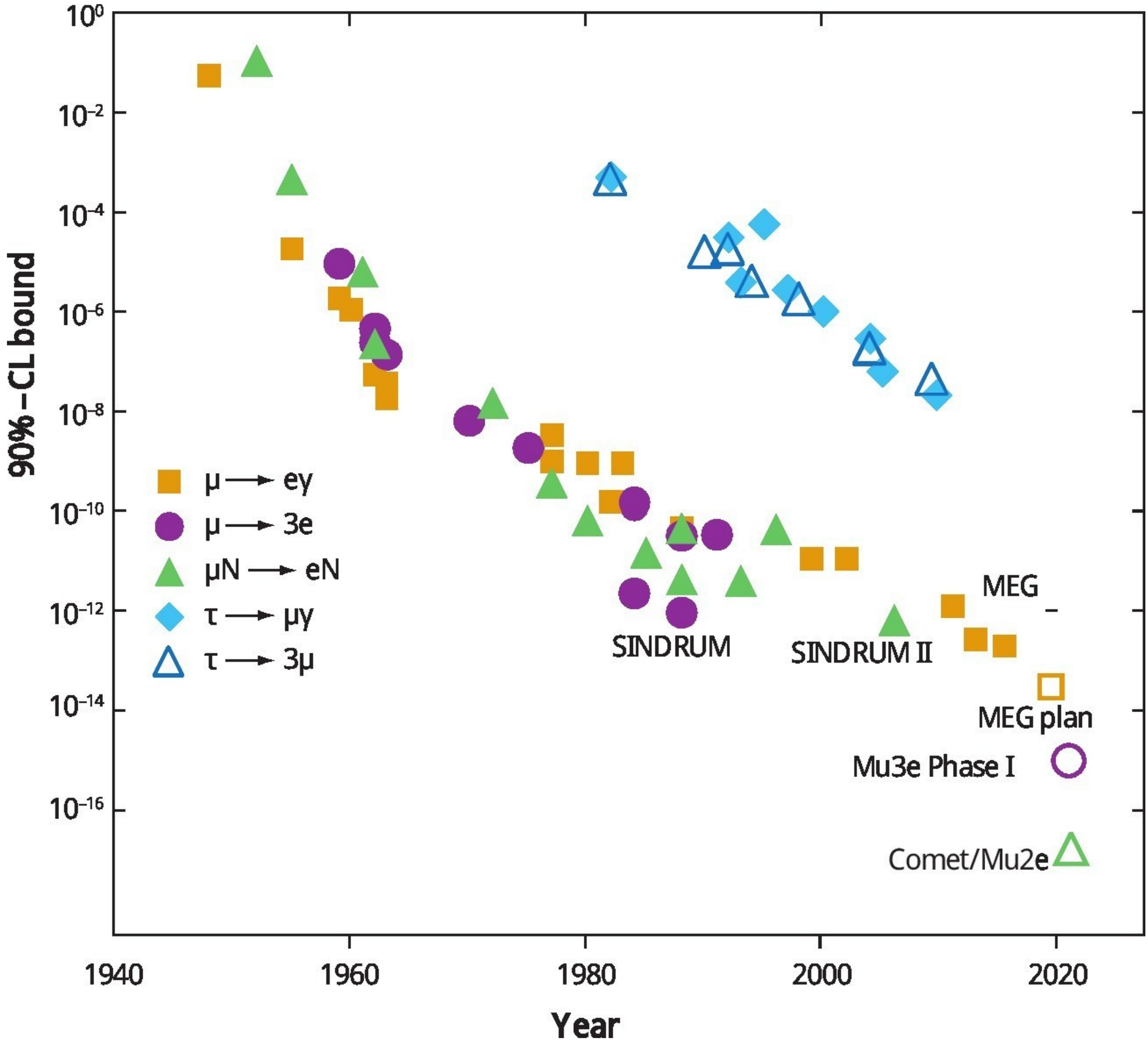
Experimental status of muon lepton flavor violation

Paolo W. Cattaneo INFN Pavia

Image: https://en.wikipedia.org/wiki/Bandra-Worli_Sea_Link
Designed by Saurabh Sandilya

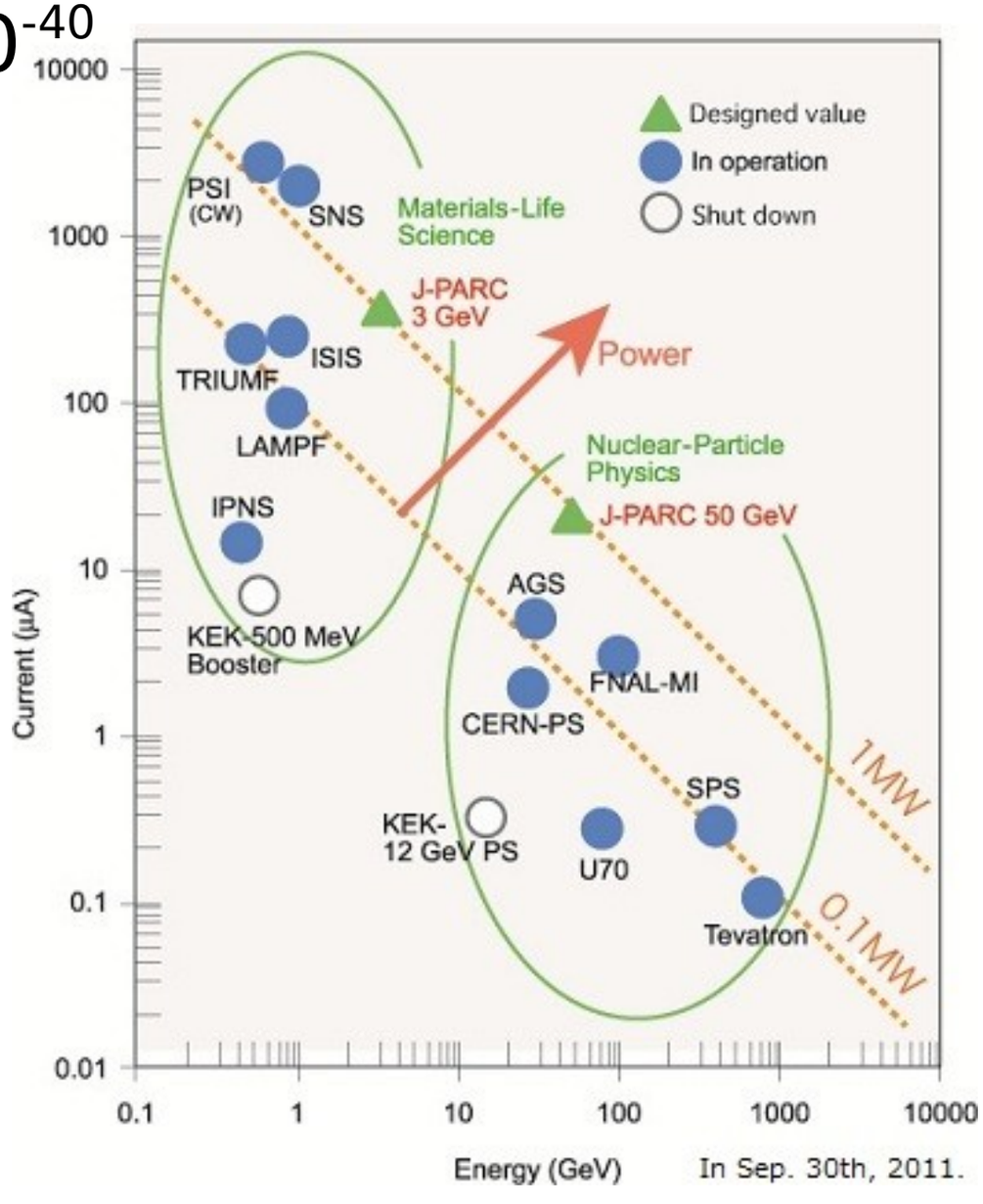
CKM2016

9th International Workshop

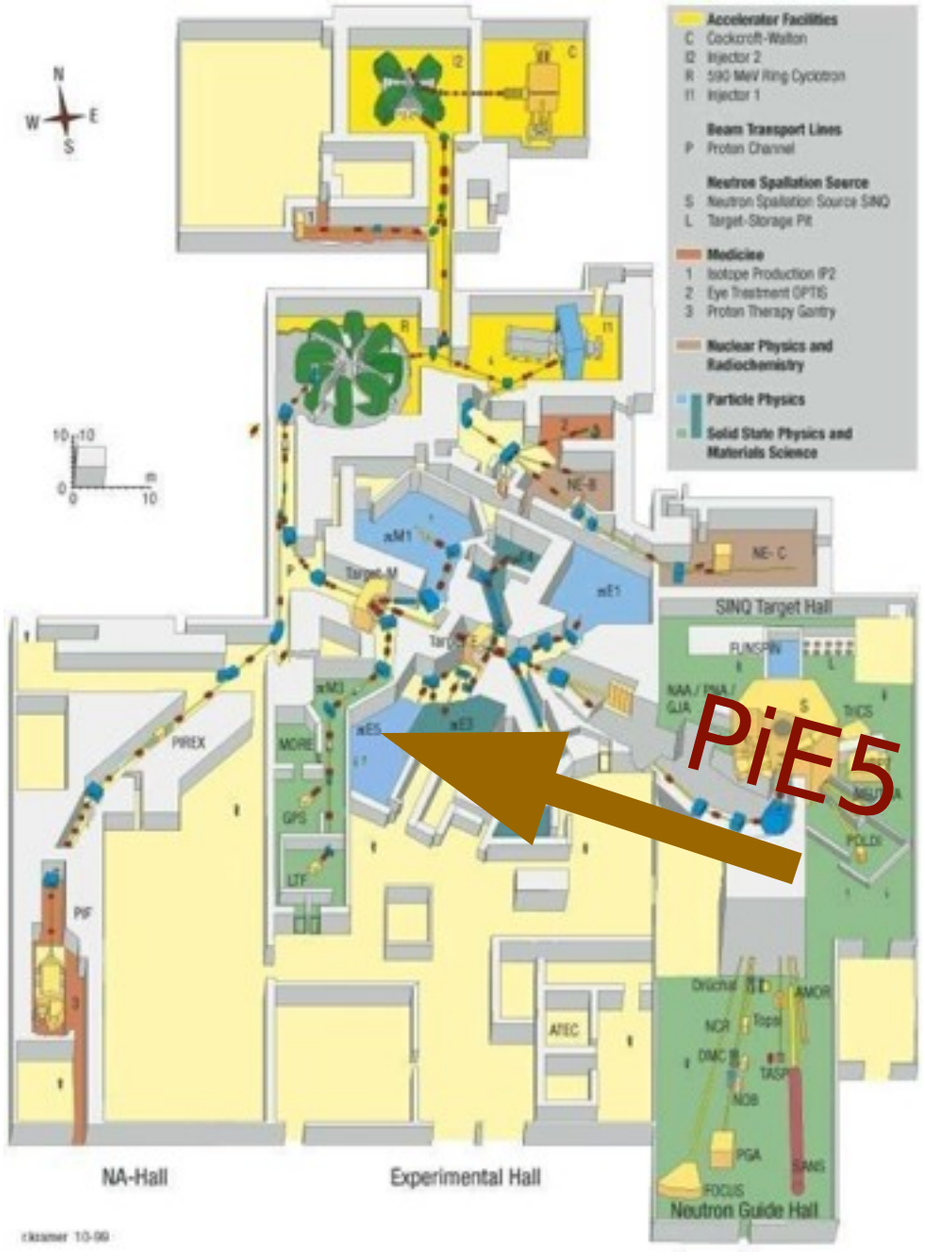

90% – CL bound
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
μ ⟶ eγ
μ ⟶ 3e
μN ⟶ eN
τ ⟶ μγ
τ ⟶ 3μ
SINDRUM
SINDRUM II
MEG
MEG plan
Mu3e Phase I
Comet/Mu2e
1940
1960
1980
2000
2020
Year

cLFV Experiments with μ^+

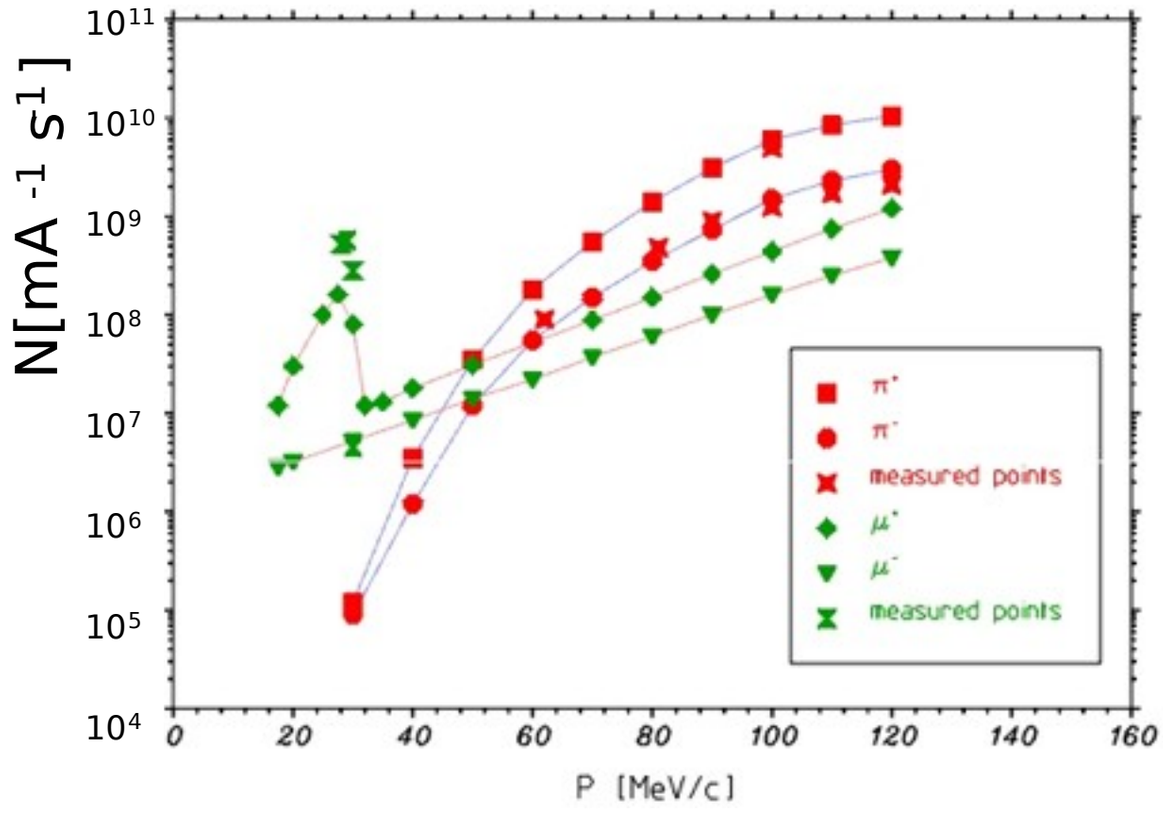
- No theoretical uncertainties $Br_{SM}<10^{-40}$
- No Standard Model background
- Large amount of μ available thanks to current high-power p machines
  - Lower energy machine preferred to perform searches using stopped muons in most cases
  - Normal μ decay modes well understood
- Sensitive to many BSM models. Able to discriminate between them



PSI DC μ^+ Beam

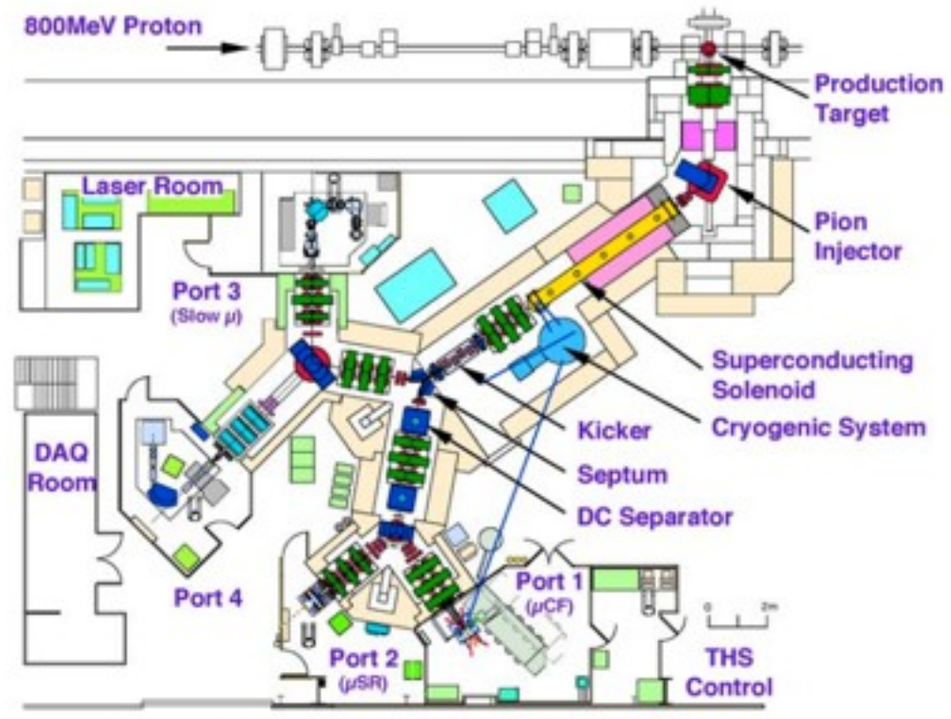


Injection Energy	72 MeV
Extraction Energy	590 MeV
Extraction Momentum	1.2 GeV/c
Energy spread (FWHM)	ca. 0.2 %
Beam Emittance	ca. 2π mm×mrad
Beam Current	2.2 mA DC
Accelerator Frequency	50.63 MHz
Time Between Pulses	19.75 ns
Bunch Width	ca. 0.3 ns
Extraction Losses	ca. 0.03%

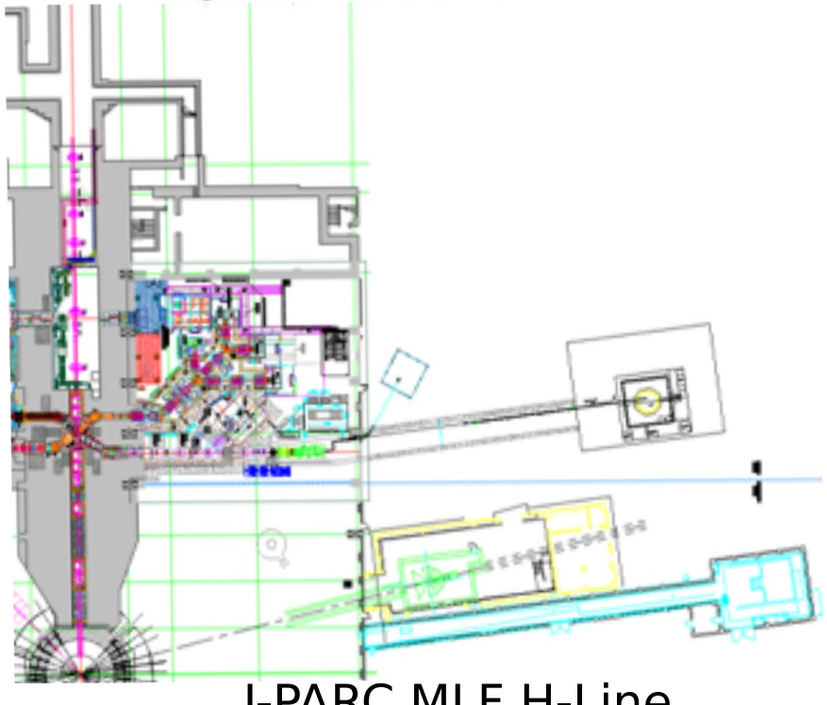


Pulsed Muon Beam Facility

- RIKEN-RAL muon facility
  - 800MeV-300μA, 50Hz
  - Surface μ: 1.5×10^{6} μ/s
- J-PARC MLF
  - 3GeV, 1MW (goal), 25Hz
  - Surface μ: > 3×10^{7} μ/s (as of 2016 Jan)
  - 3×10^{8} μ/s at H-Line (future)

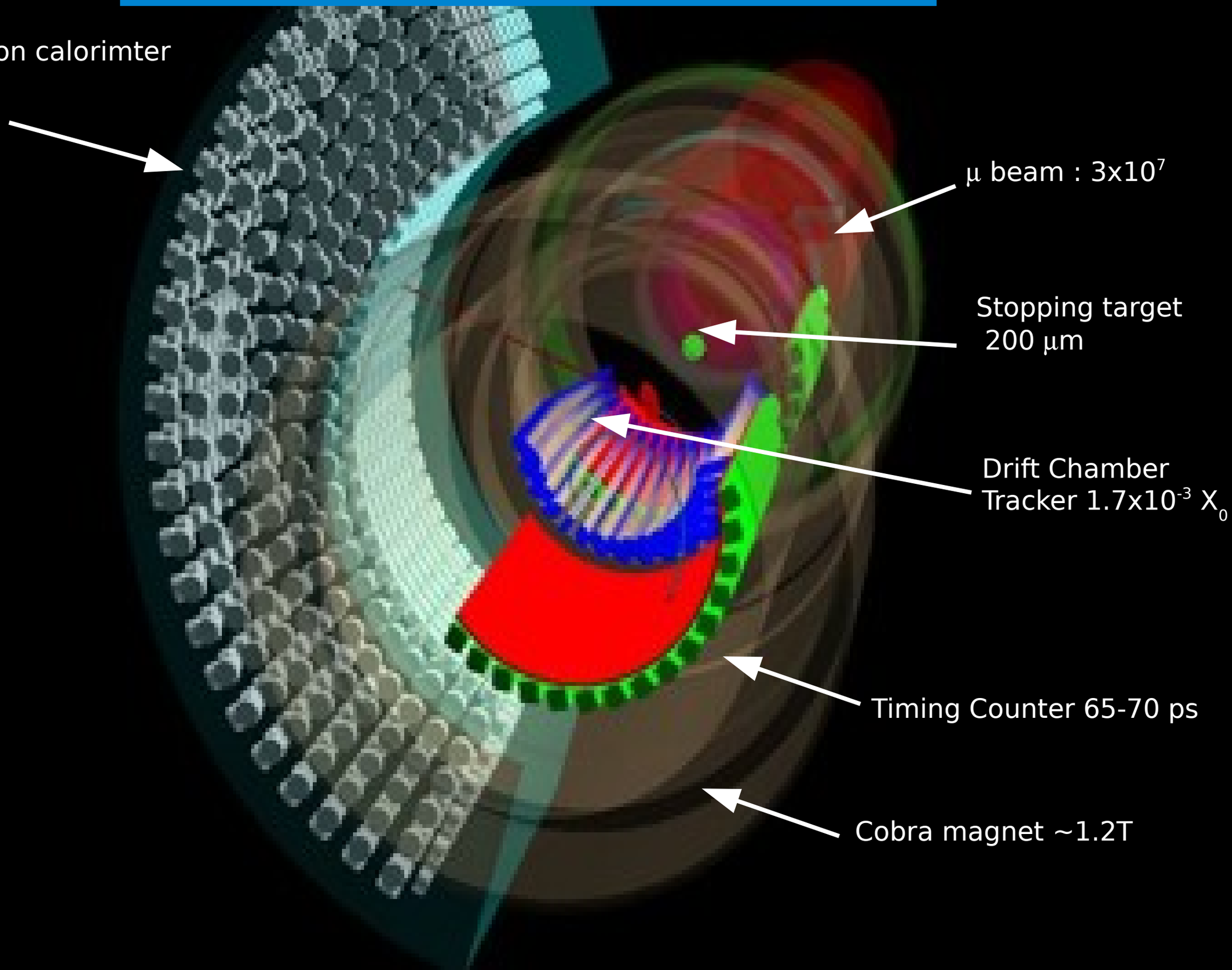


Layout of the RIKEN-RAL Muon Facilty

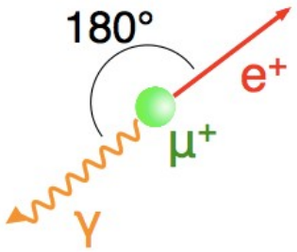


J-PARC MLF H-Line

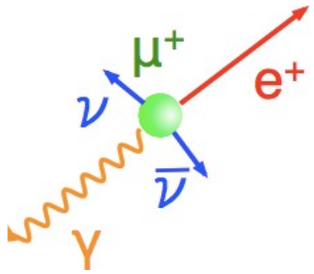
MEG Detector

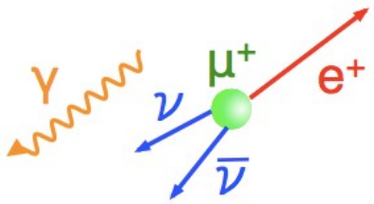


Signal

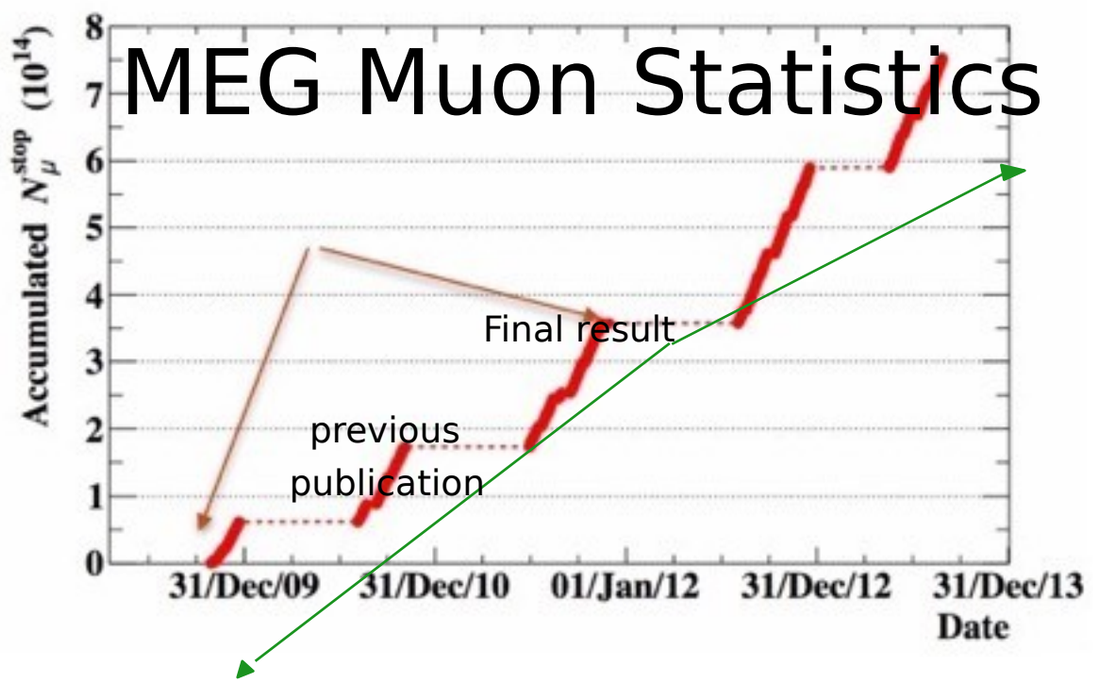


Background





Accidental background dominates



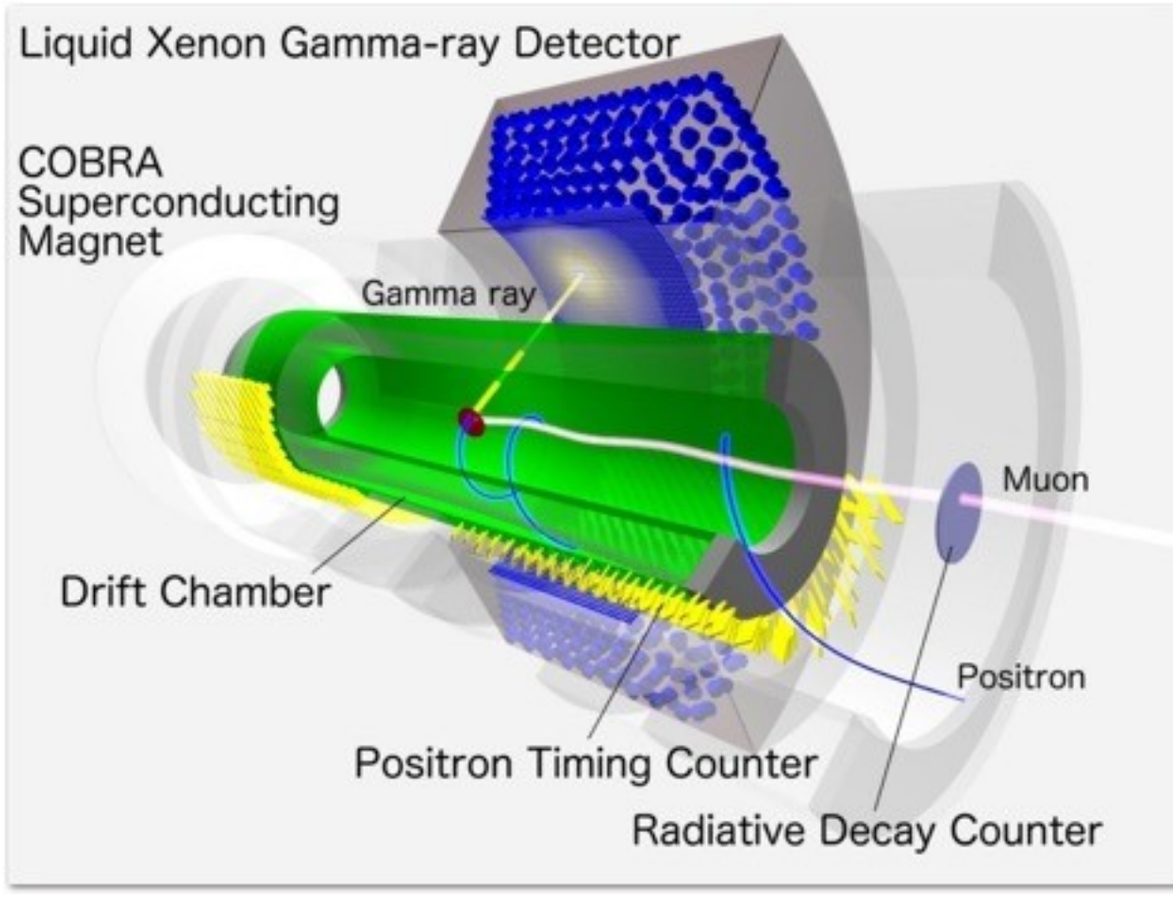
- MEG@PSI

Search for $\mu^+ \to e^+ \gamma$ using 3×10^7 Hz muon beam

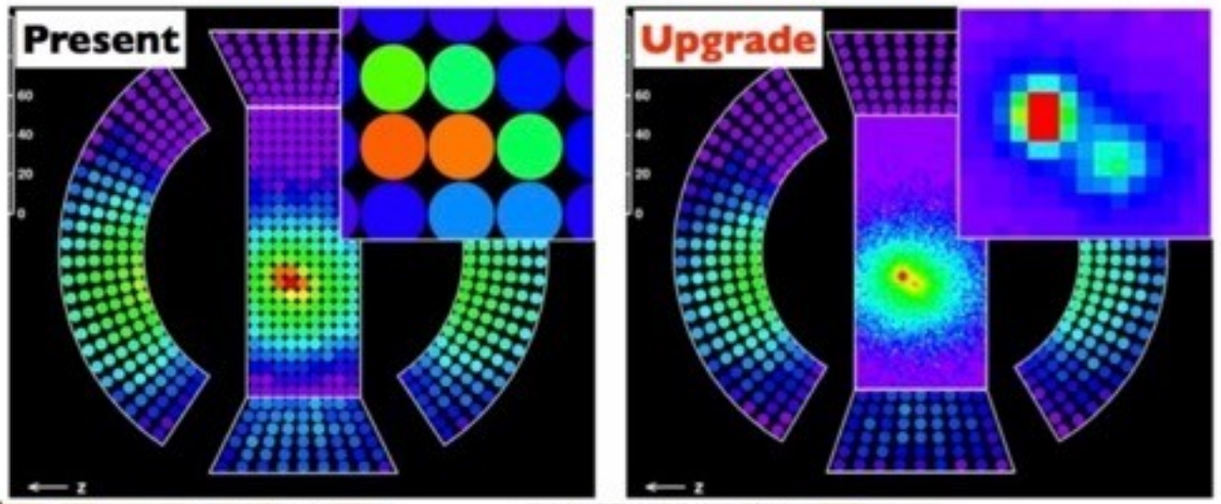
- Data taken in in 2008-2013
- Data in 2009-2010 2.4×10^{-12} @ 90% C.L. ($S = 1.6 \times 10^{-12}$) PRL 107 171801 (2011)
- Data in 2009-2011 5.7×10^{-13} @ 90% C.L. ($S = 7.7 \times 10^{-13}$) PRL 110 201801 (2013)
- Final upper limit published: 4.2×10^{-13} @ 90% C.L. ($S = 5.3 \times 10^{-13}$) EPJC 76(8), 1-30
- Factor of 30 better than pre-MEG result 1.1×10^{-11} (MEGA)

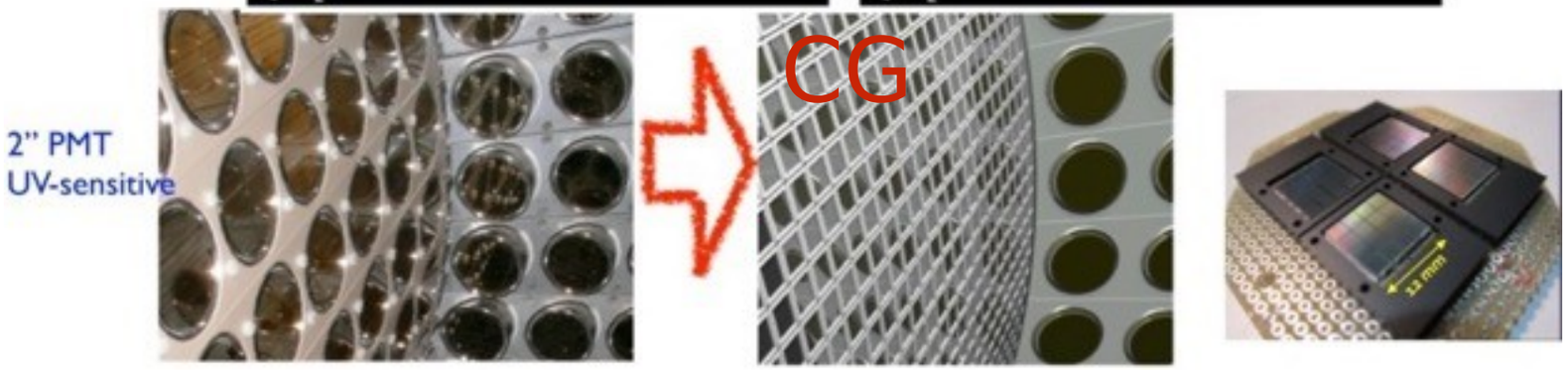
MEG II

- Improve resolutions by about factor 2 everywhere:
  - p_e
  - E_γ
  - $\Theta_{e\gamma}$
  - $t_{e\gamma}$
- μ beam rate of 7×10^{7} Hz to reach the sensitivity of 4×10^{-14}
- Engineering run in 2017

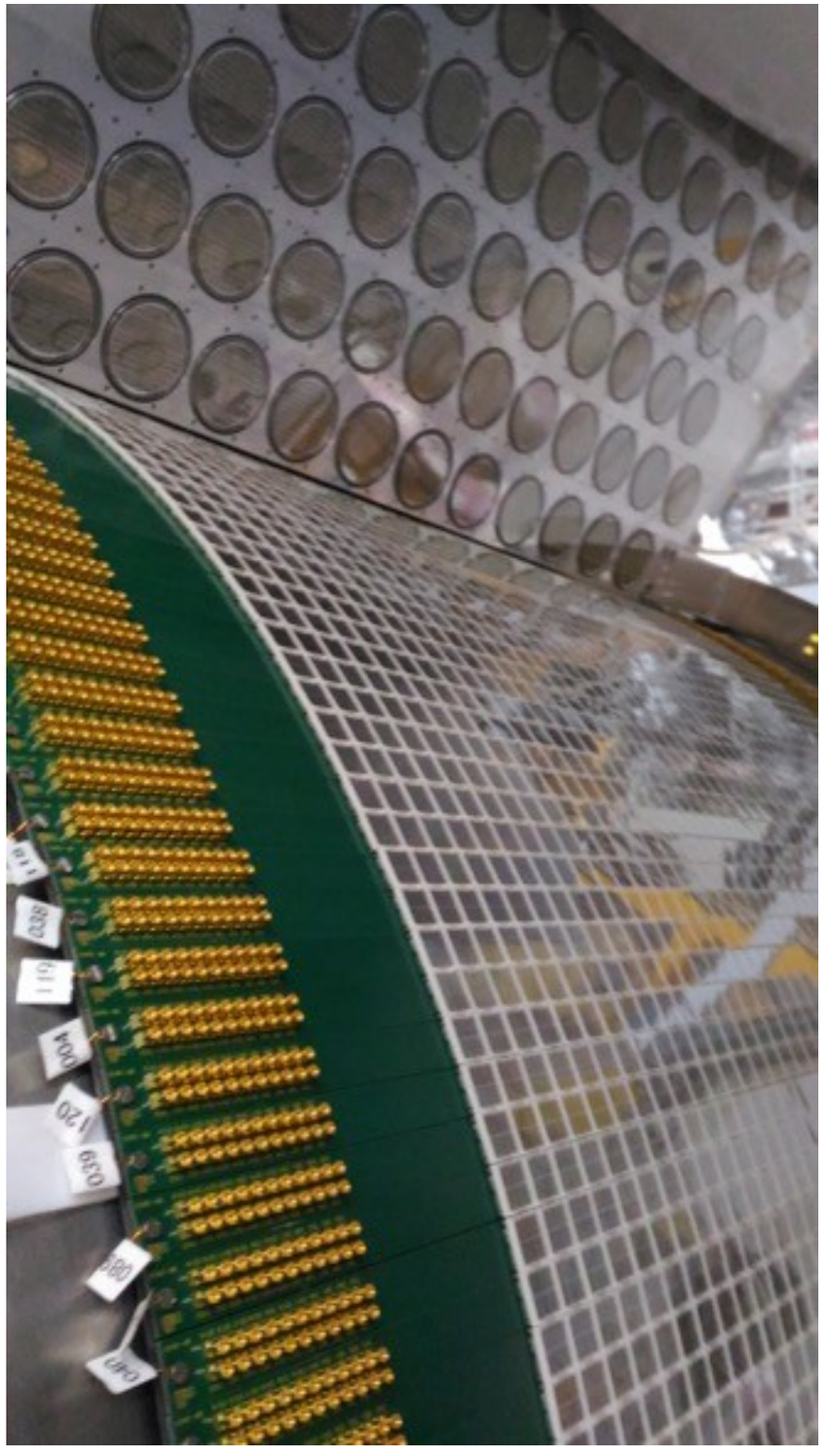


MEG II LXe Upgrade





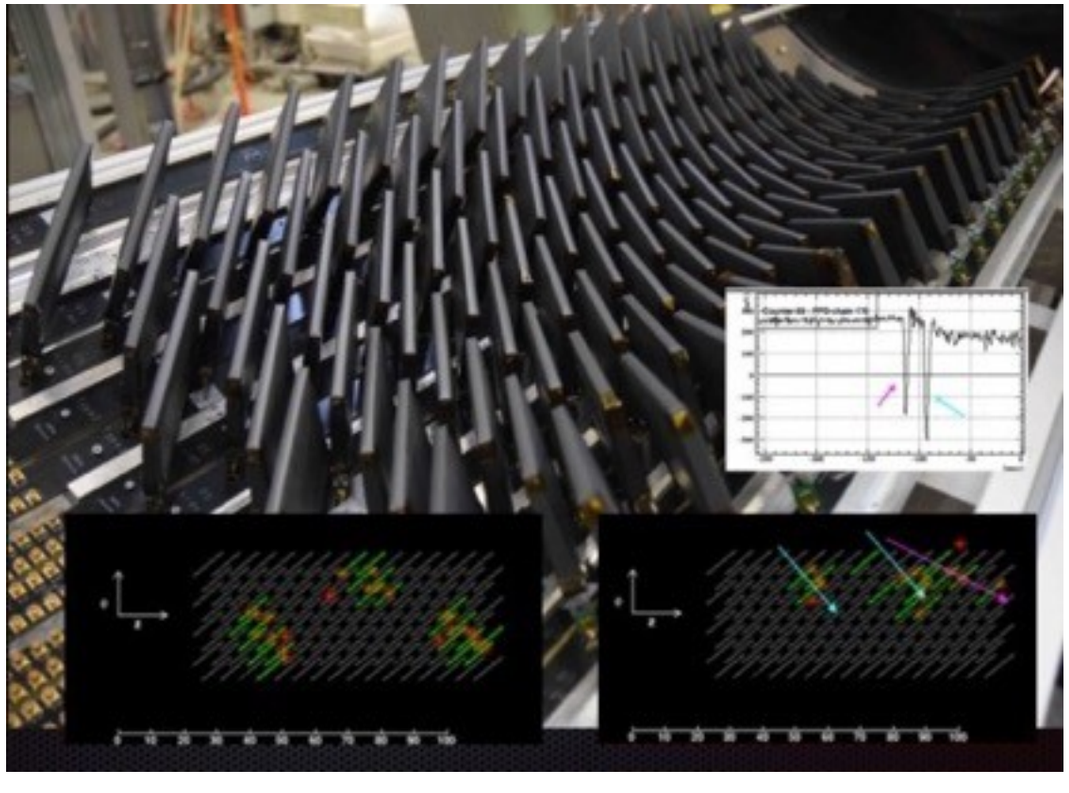
- Replace 2-inch PMTs with VUV-SiPM to cover the front face
- 4000 SiPM with minimum material
- Installation completed begin 2017



MEG II Positron Spectrometer

- Drift chamber
  - Single volume, 2m long stereo wire & low mass
  - More hits provides better resolutions
    - σ_{Ee} = 130keV, σ_{angles} = 5mrad

- Timing counter
  - Pixelated plastic scintillators read by SiPM
  - Best resolutions σ=30ps anticipated for multiple counter hits events



- & Upgrade of Trigger / DAQ

Mu3e: μ→eee search with DC Muon Beam

Another channel sensitive to cLFV with DC muon beam

1.0×10^{-12}(90% C.L.) by SINDRUM 1988!!

Goal : 10^{-16} in two steps

Phase I in 2018-2020

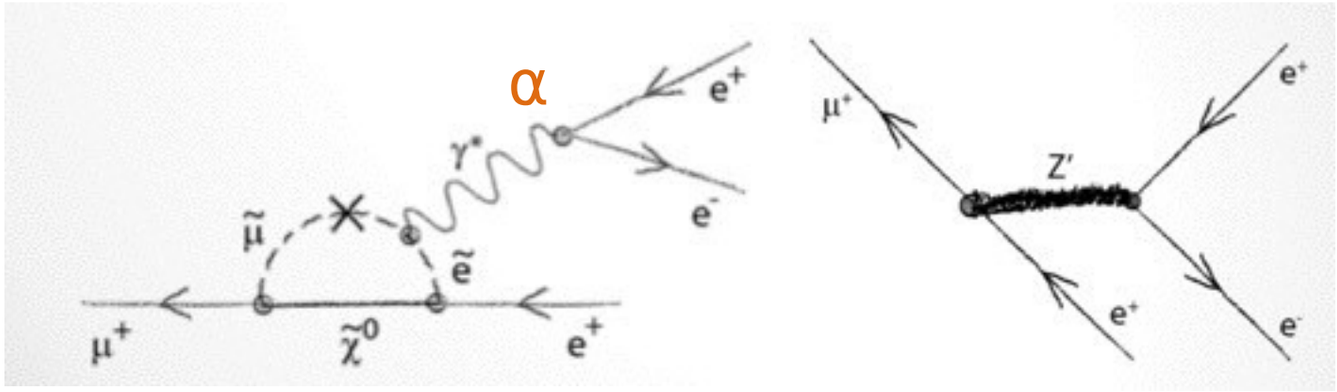
Sensitivity:10^{-15}

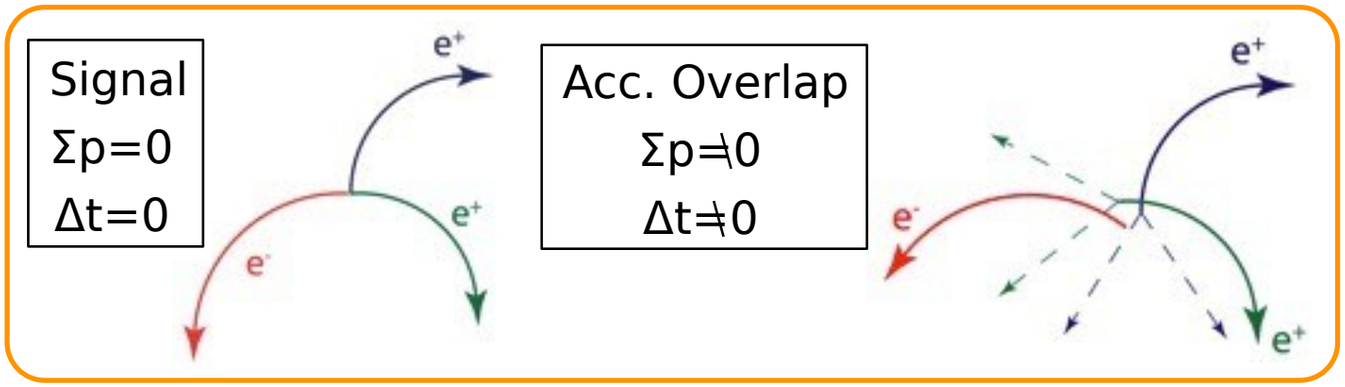
Decay rate 10^{8} Hz

Phase II in >2020

Sensitivity:10^{-16}

Decay rate 10^{9} Hz

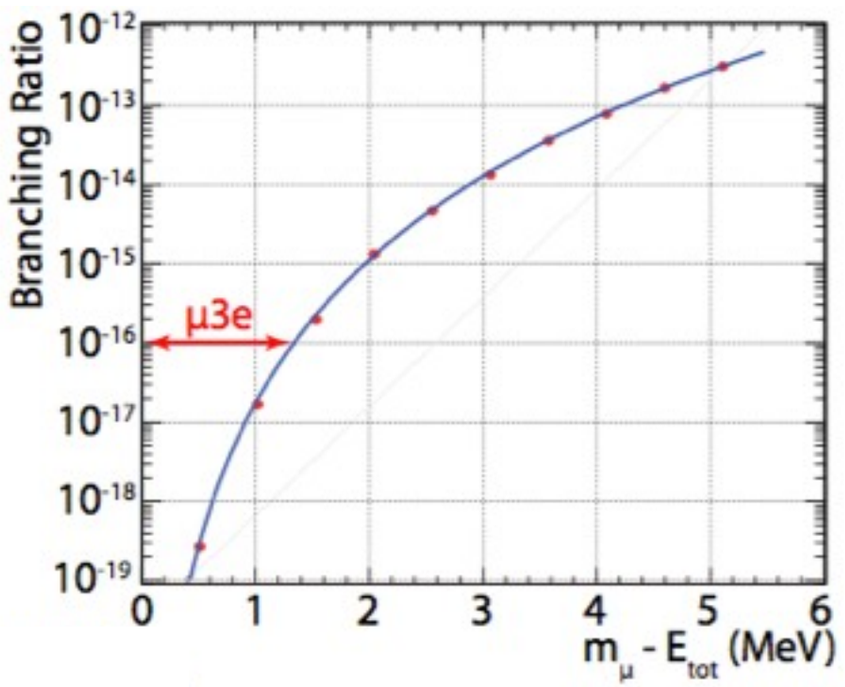




Measure all low momentum electron tracks precisely without pile-up

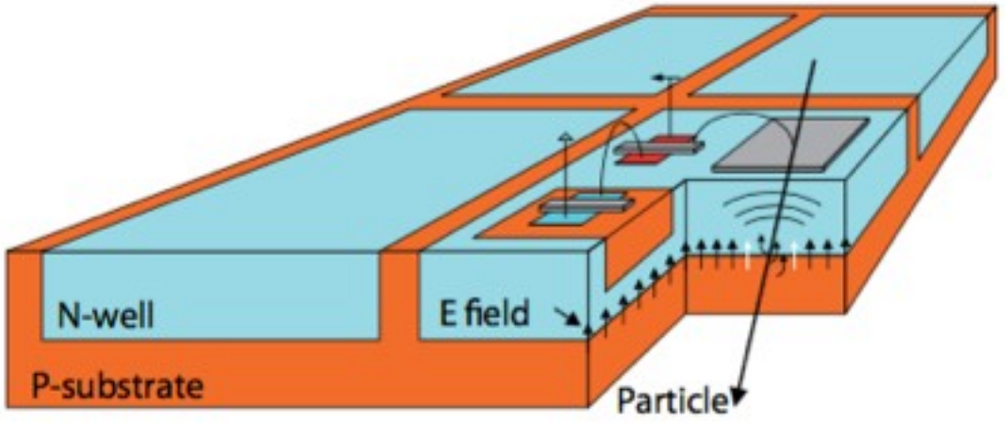
Most severe BG

$$\mu^{+}\to e^{+}e^{+}e^{-}\nu\bar{\nu}$$



Suppress BG by more than 16 orders of magnitudes

Mu3e: Detector Technology

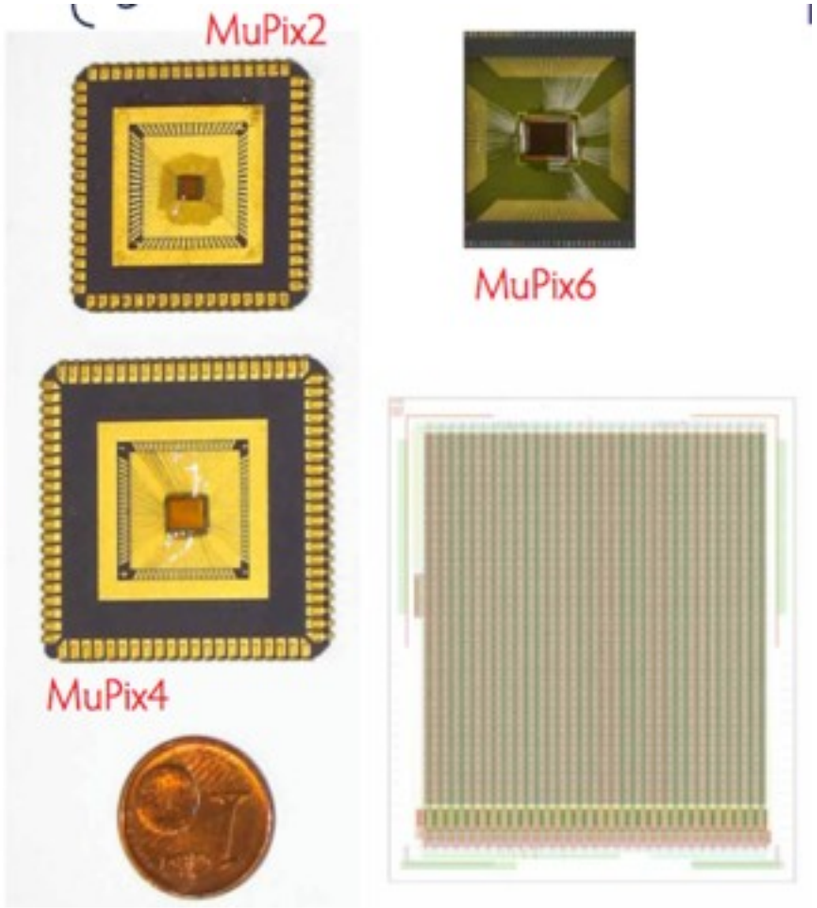


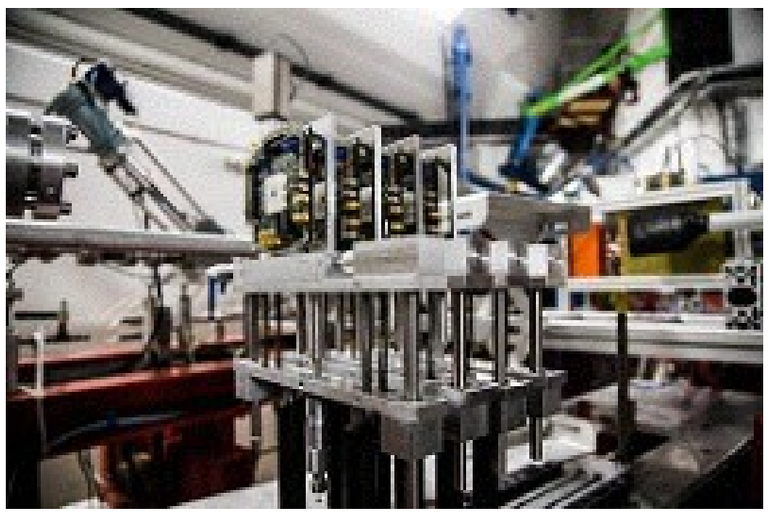
. NIM A 582 (2007) 876

High voltage monolithic active pixel sensors - Ivan Peri

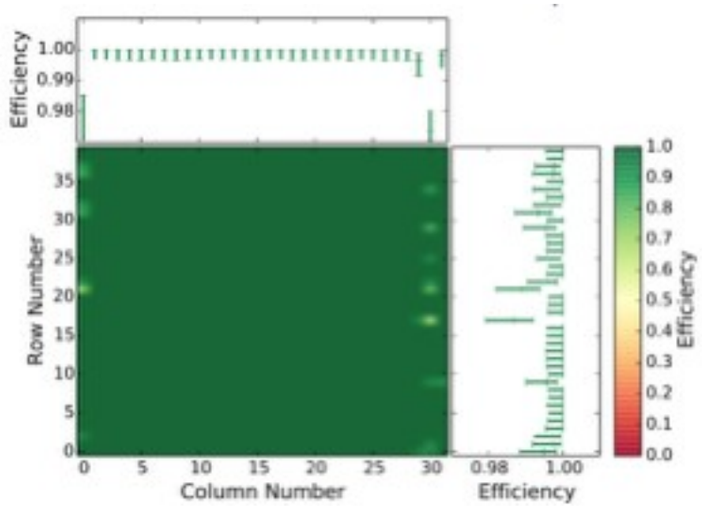
- thinned down to < 50 µm
- Logic on chip: Output zero suppressed hit addresses and timestamps

5 generations of prototypes, MuPix7 is current generation with all features of final sensors





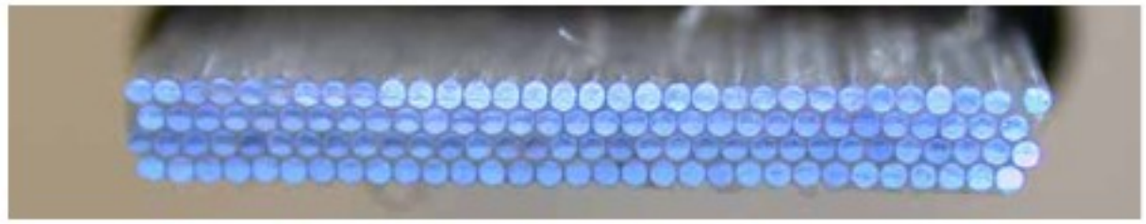
Mainz test beam in June 2016

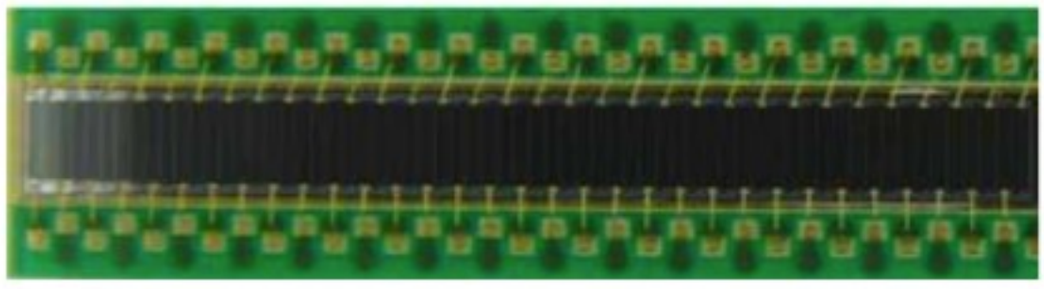


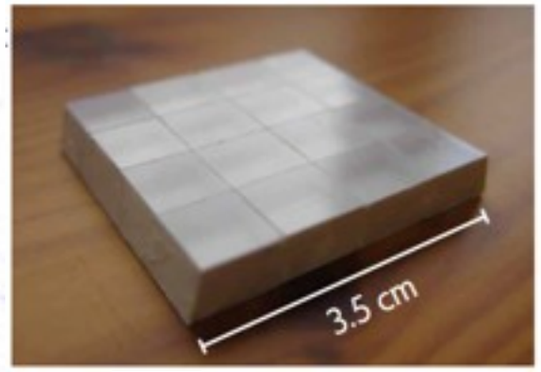
Efficiency above 99%

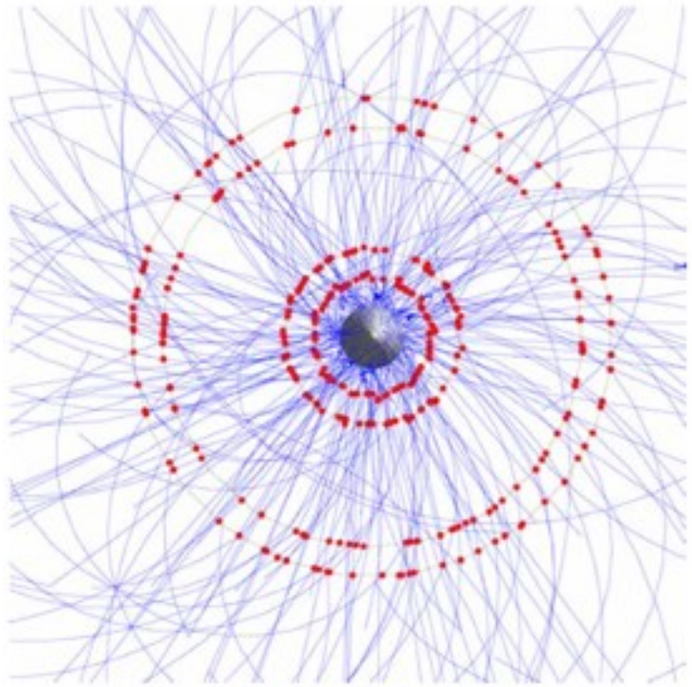
Mu3e: Timing Measurement

- Precise timing measurement is critical to reduce accidental BGs
  - Scintillating fibers O(1nsec)
  - Scintillating tiles O(100psec)

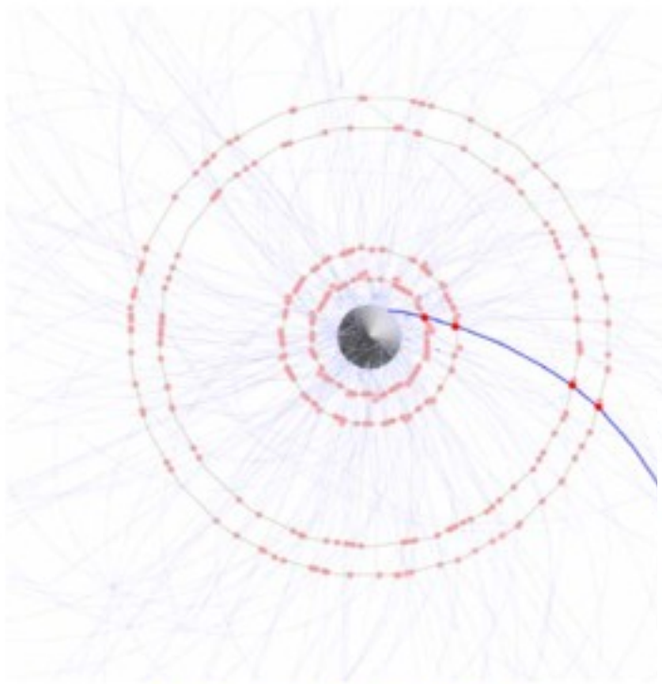




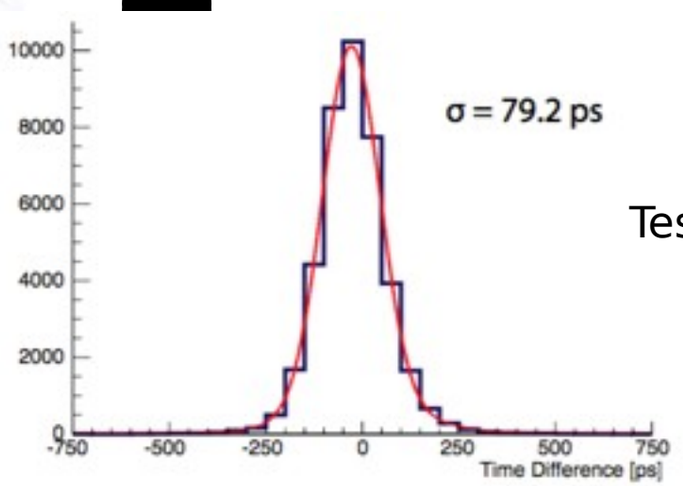




Pixels: O(50 ns)



Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

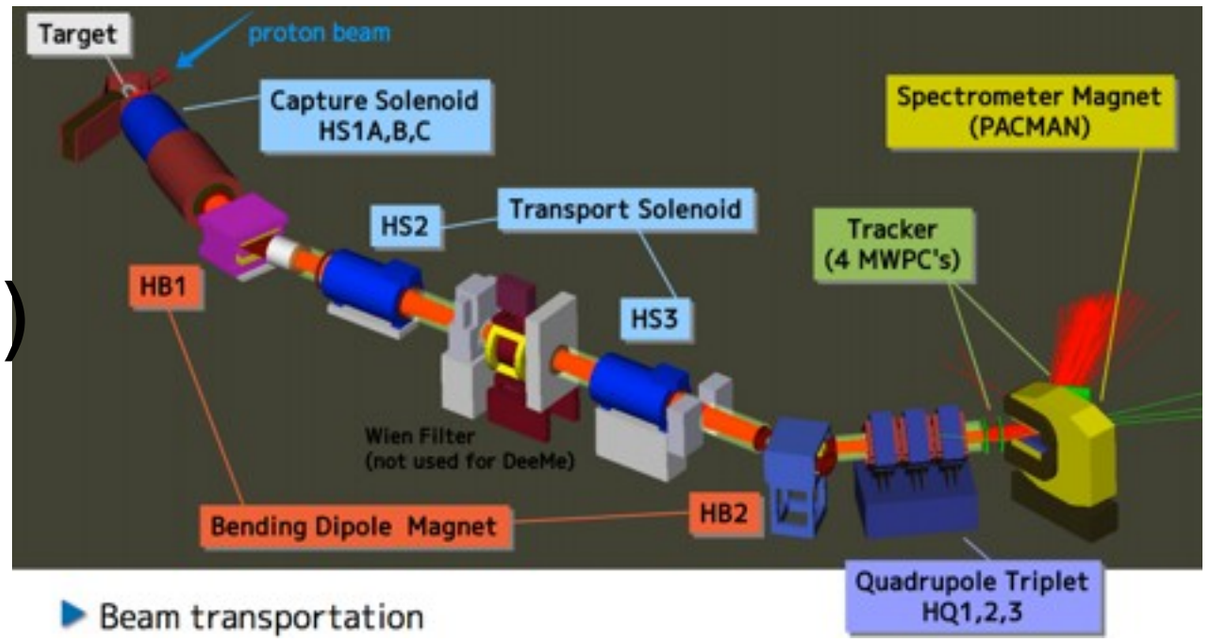


Test beam with Tiles SiPM and ASIC

μ-e conversion searches

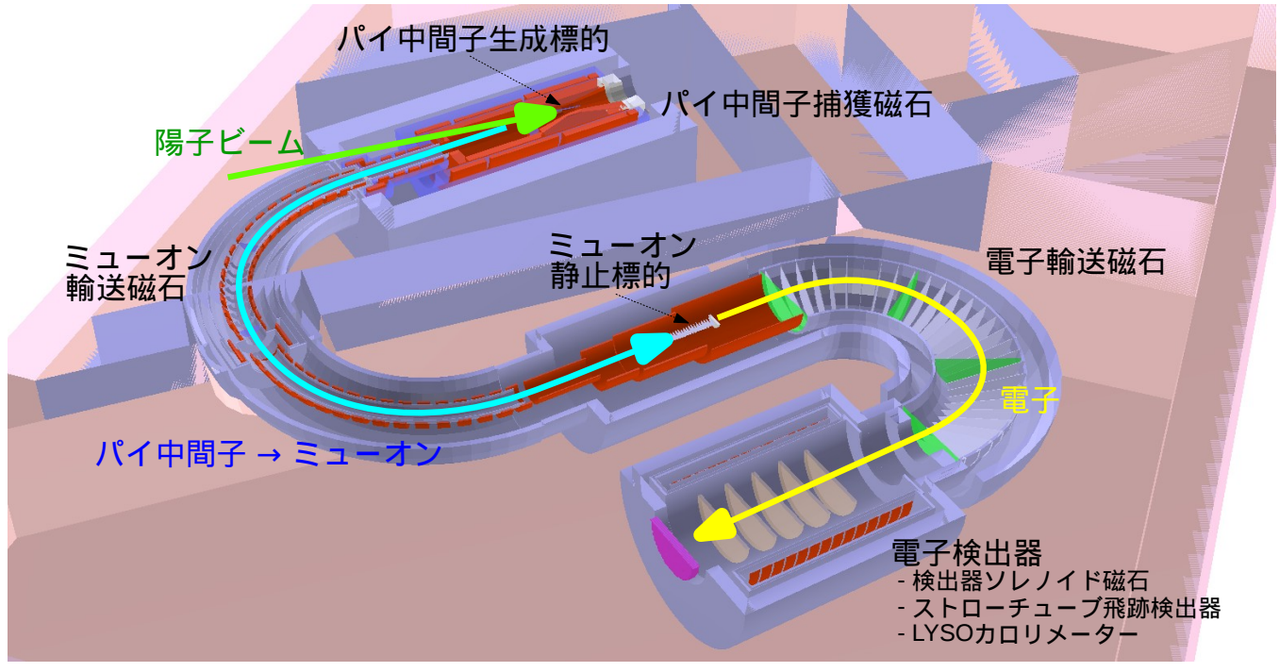
Sensitivity limited by integrated rate not by resolution !!

Existing limit 7.0×10^{-13}(Au)



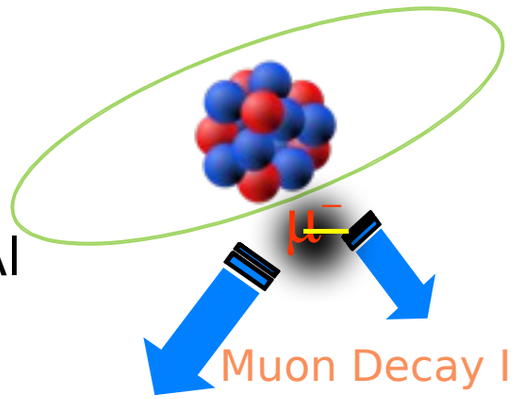
- J-PARC
  - DeeMe
  - COMET Phase-I & II
- FNAL
  - Mu2e

10^{-14}-10^{-16} sensitivity

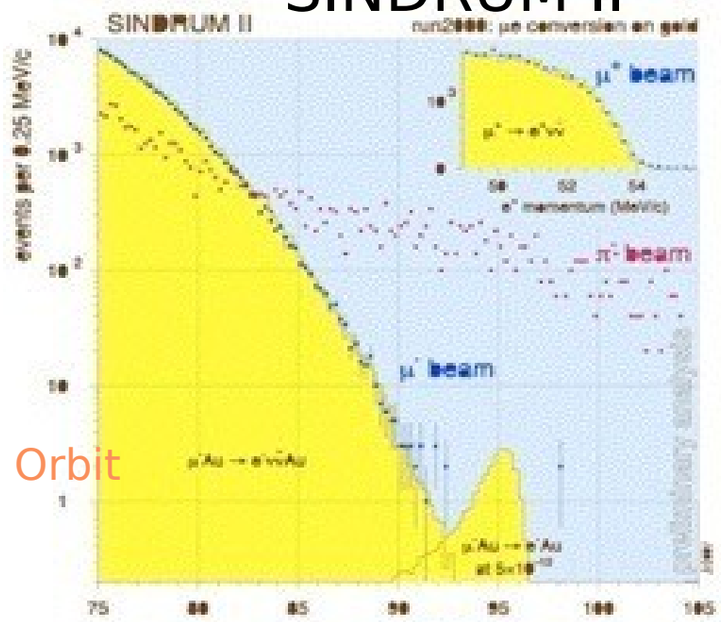


Experimental Techniques

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - $E_{\mu e} \sim m_\mu - B_\mu - E_{rec}$:105 MeV for Al
  - Delayed : 1 μs
  - No accidental backgrounds



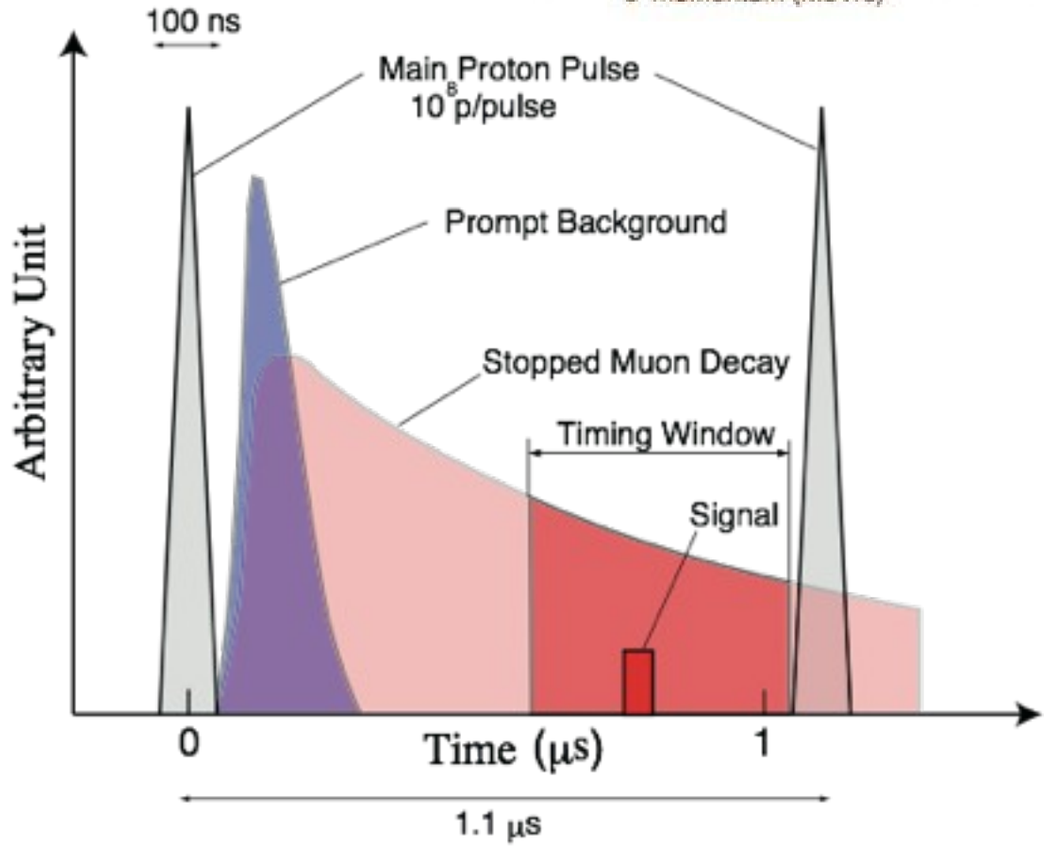
SINDRUM II



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

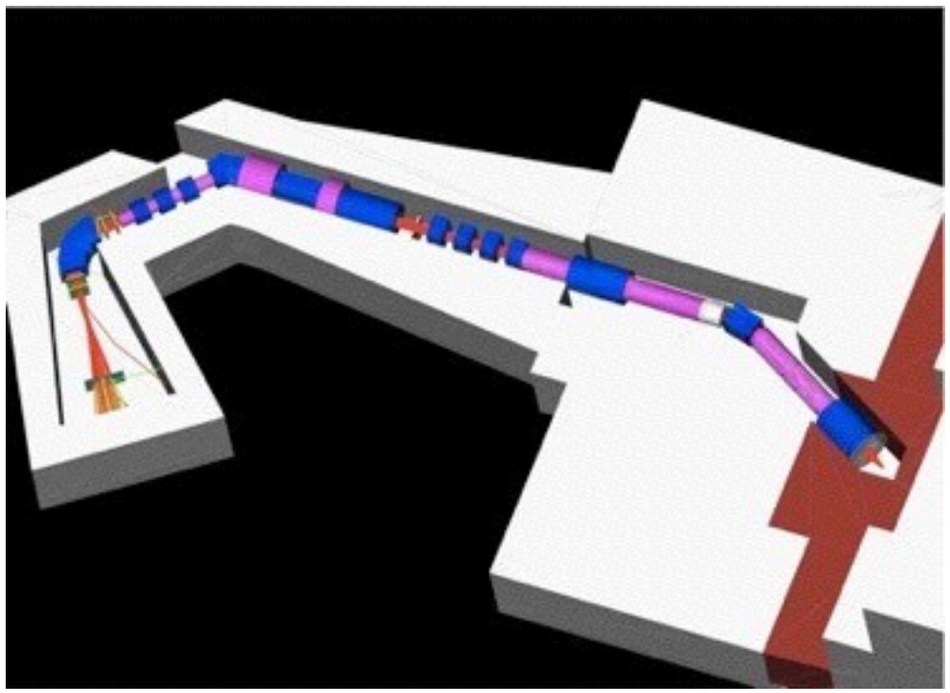
    $\gamma \rightarrow e^+ e^-$

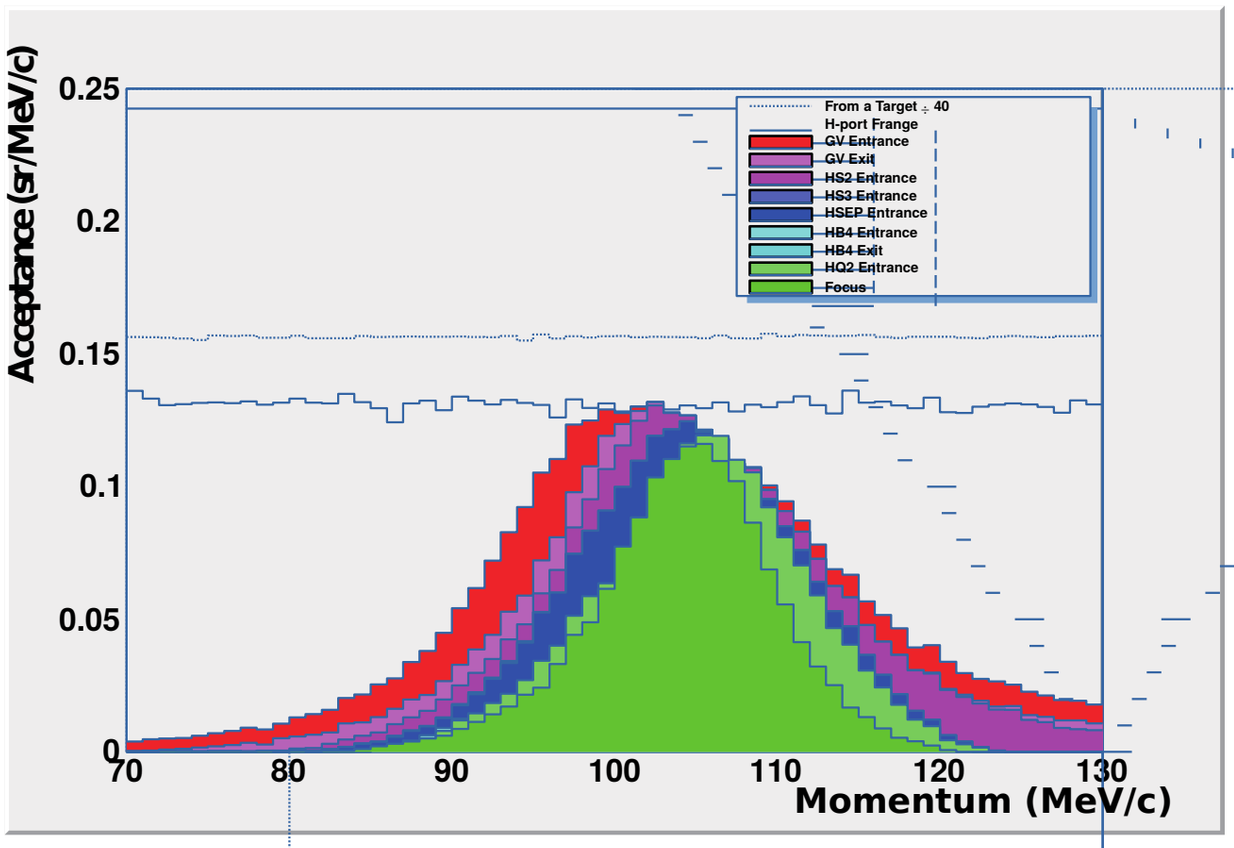
$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$



DeeMe at J-PARC

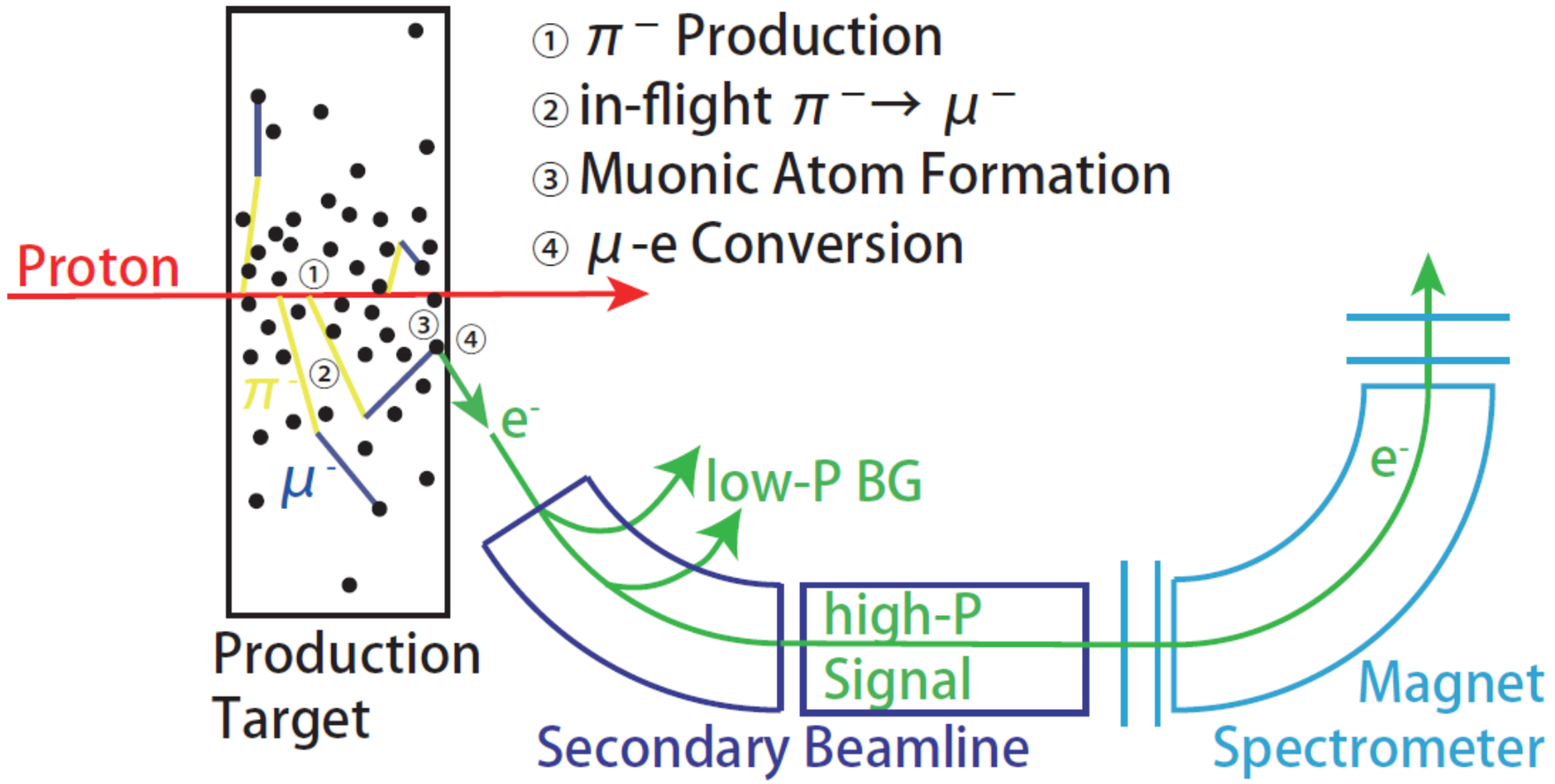
- mu-e conversion search at J-PARC with a S.E.S. of 10^{-14}
  - Primary proton beam from RCS
    - 3GeV, 1MW
  - Pion production target as a muon stopping target
  - Beam line as a spectrometer
    - Kicker magnets to remove prompt background
  - Multi-purpose beam line for DeeMe, HFS, g-2/EDM is under construction





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

Sensitivity , Backgrounds

Single Event Sensitivity

- 1-year run (**2** × **10** **7** **sec**) , 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.

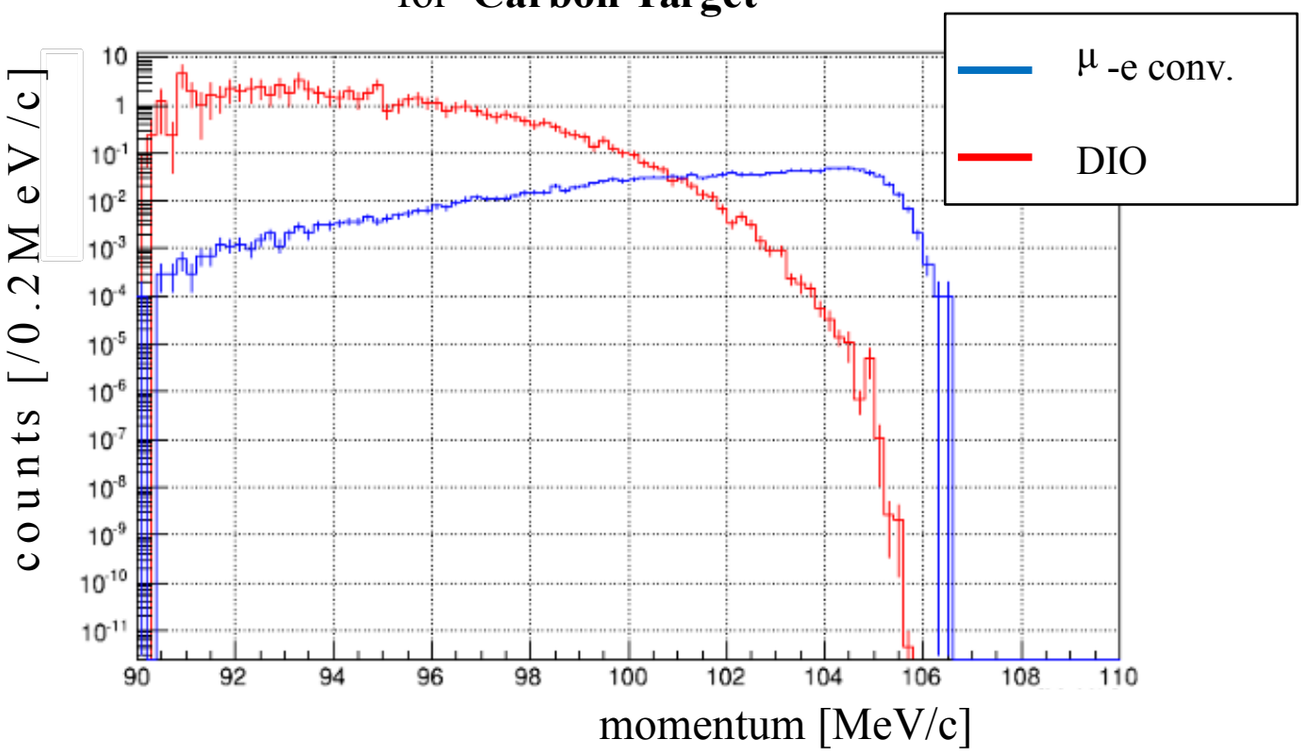
SINDRUM-II : BR(μ^- Au → e− Au) < 7 × 10 -13

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

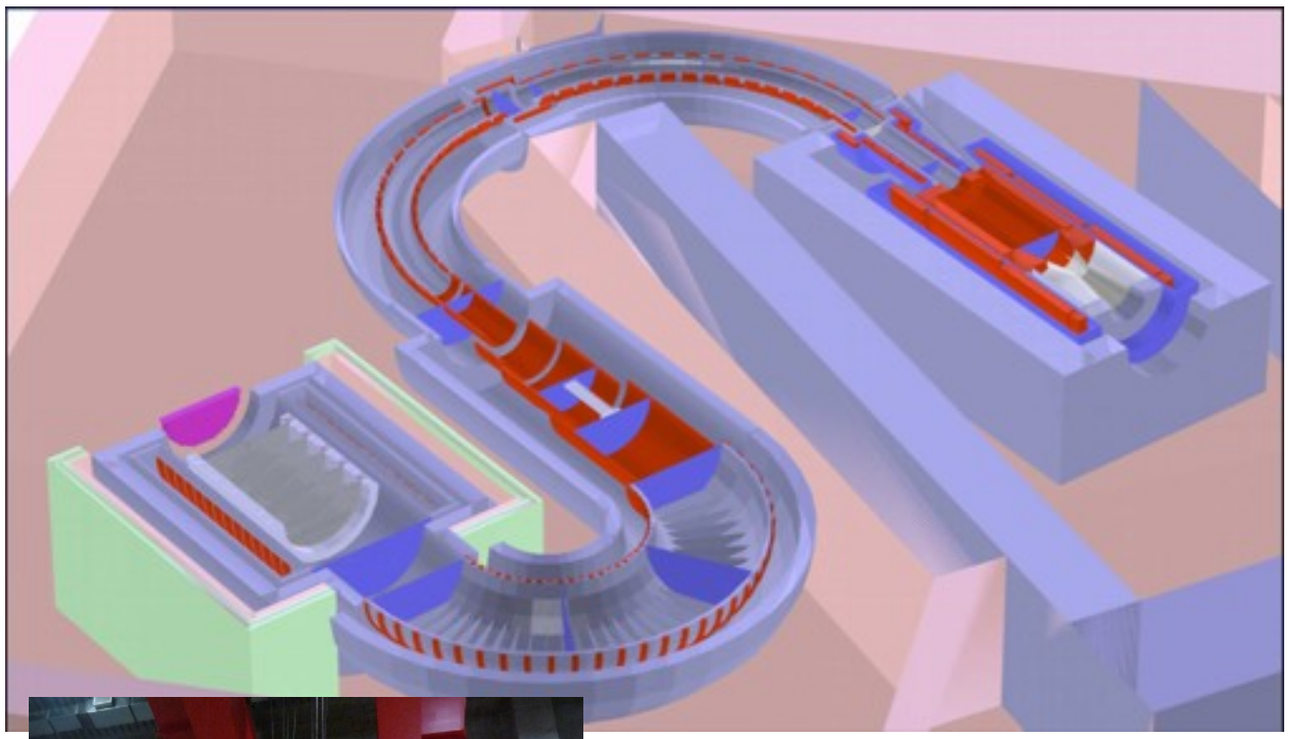
  e < 0.018 , μ < 0.001

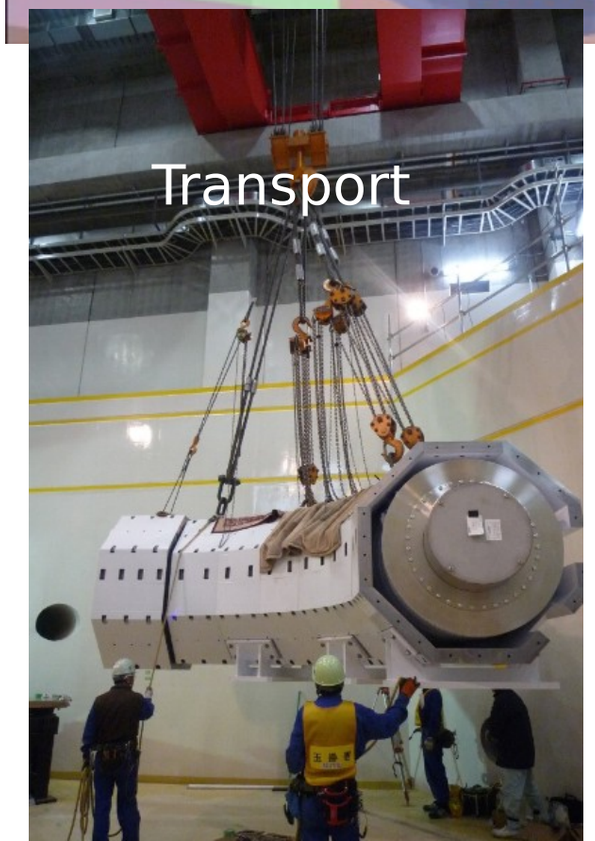
  (Detector live-time duty = 1/20000)

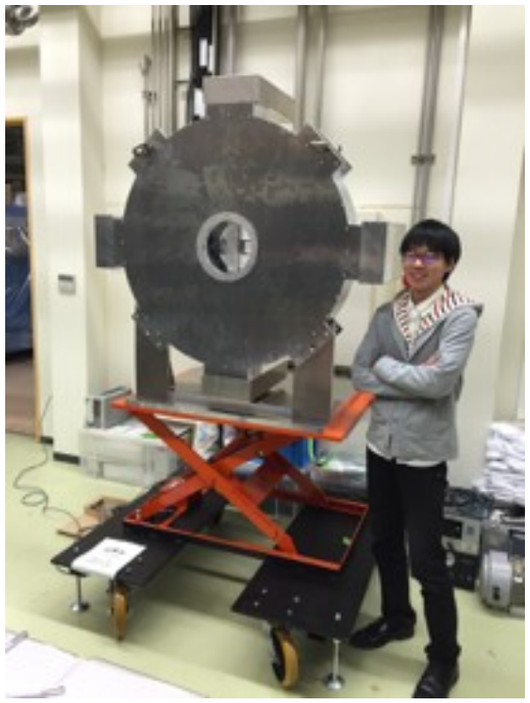
COMET at J-PARC

- Target S.E.S. 2.6×10^{-17}
- Rate 1.3×10^{9} μ/s (phase I)
  5.0×10^{9} μ/s (phase II)

- 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
- Recently staging plan showed up. The collaboration is making an effort to start physics DAQ as early as possible under this.

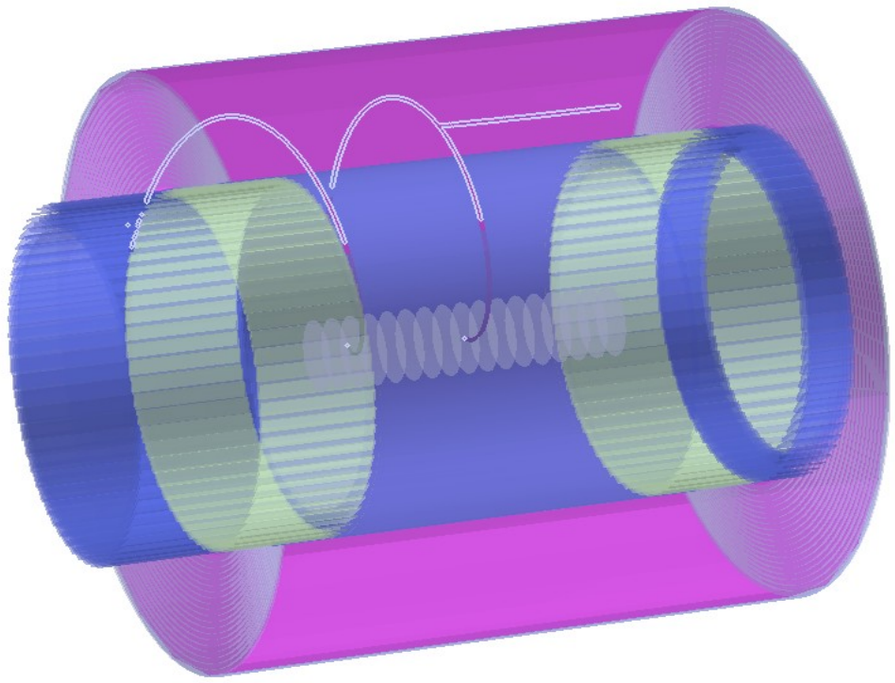




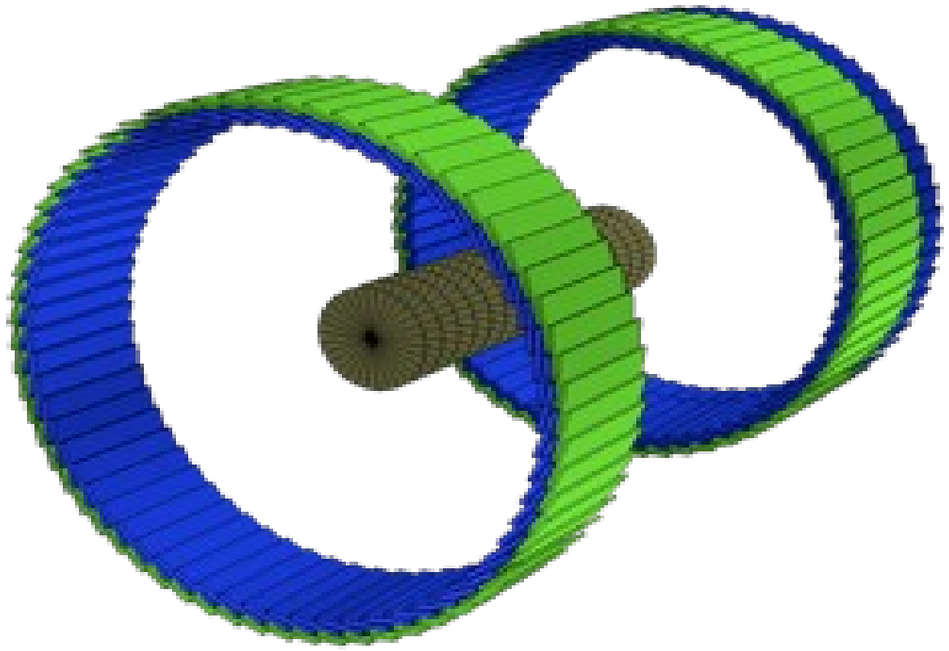


COMET Detector

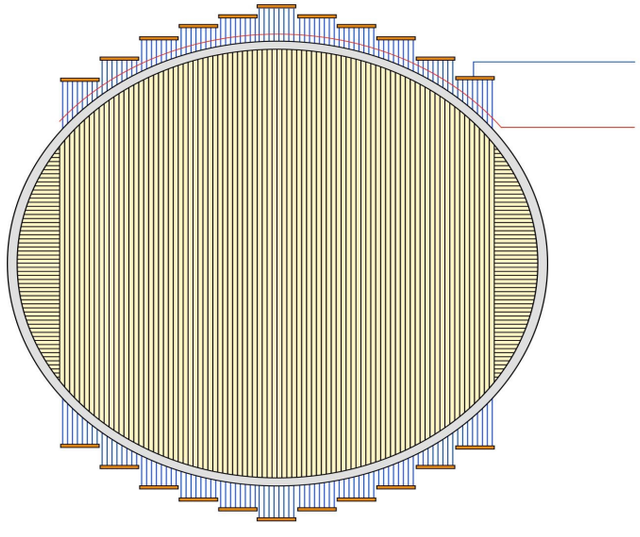
Cylindical Drift Chamber



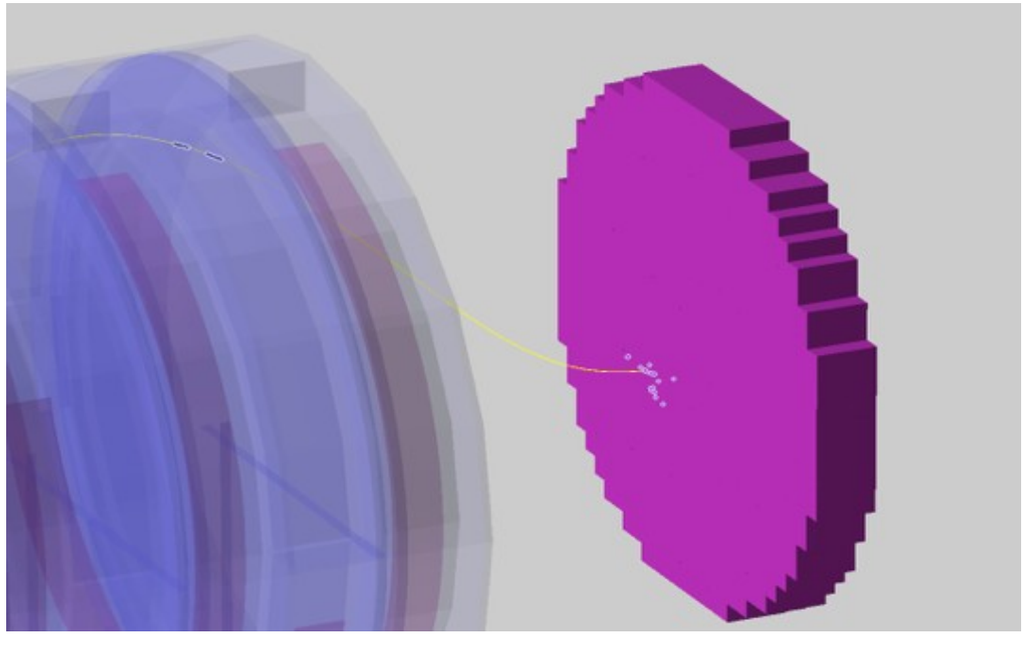
Cerenkov Trigger Todoscope



Straw Tracker

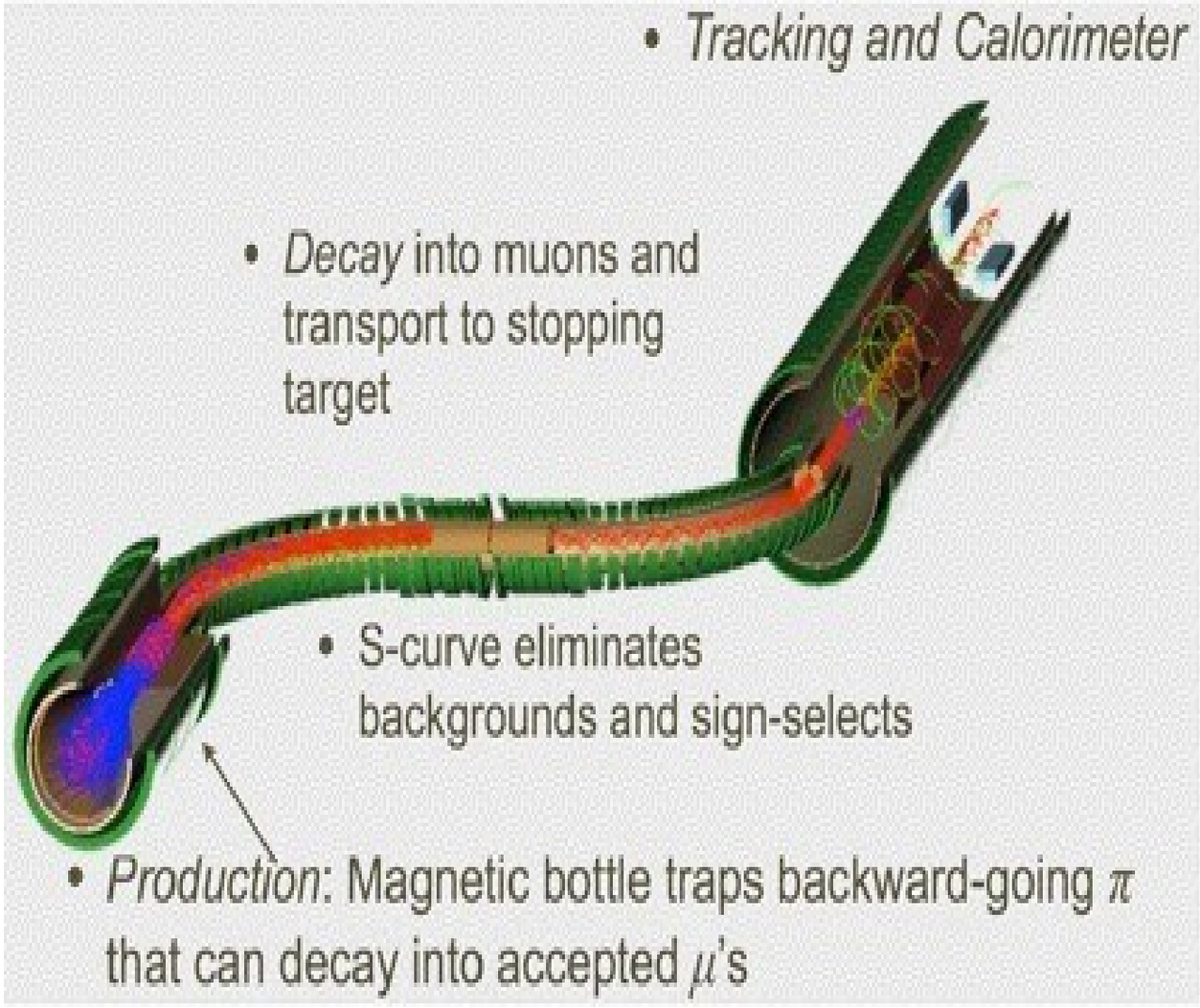


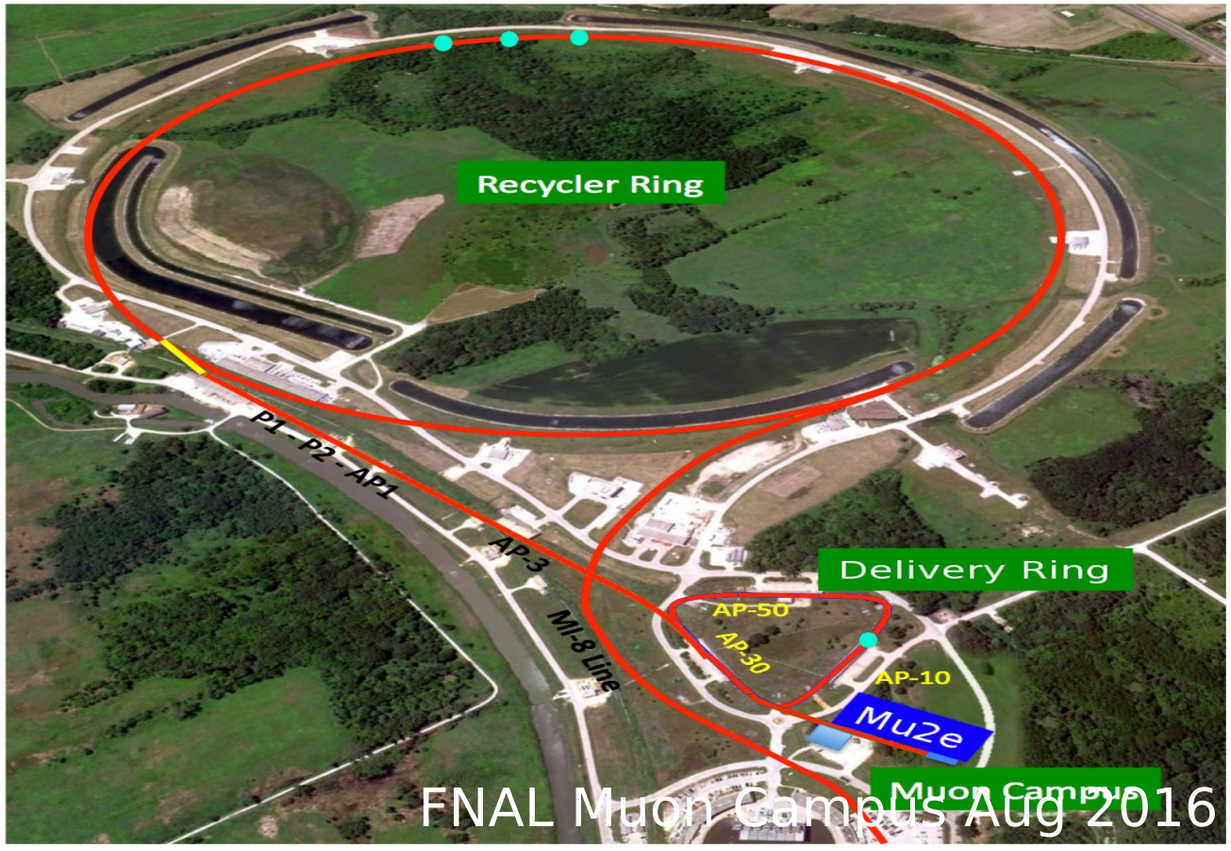
Electron CALorimeter



Mu2e at FNAL

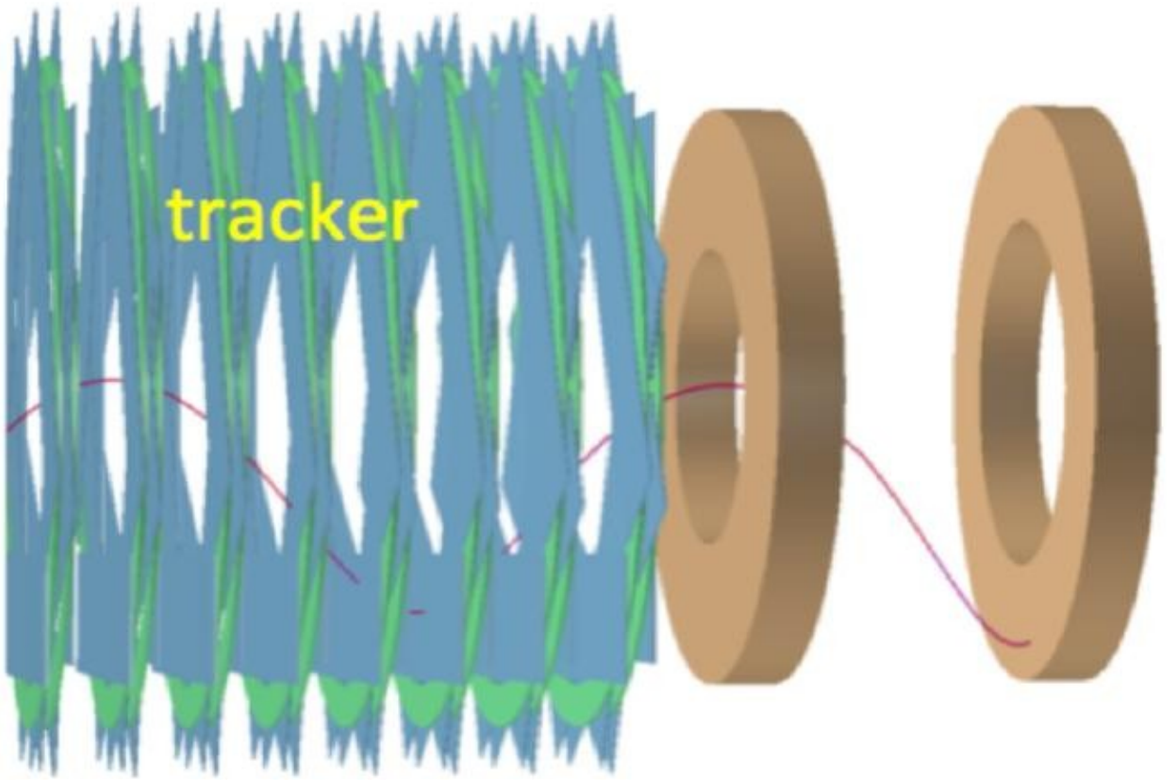
- Target S.E.S. 2.0×10^{-17}
- uses the antiproton accumulator/debuncher rings to manipulate proton beam bunches
- pion production target in a solenoid magnet
- S-shape muon transport to eliminate BG and sign-select
- Tracker and calorimeter to measure electrons

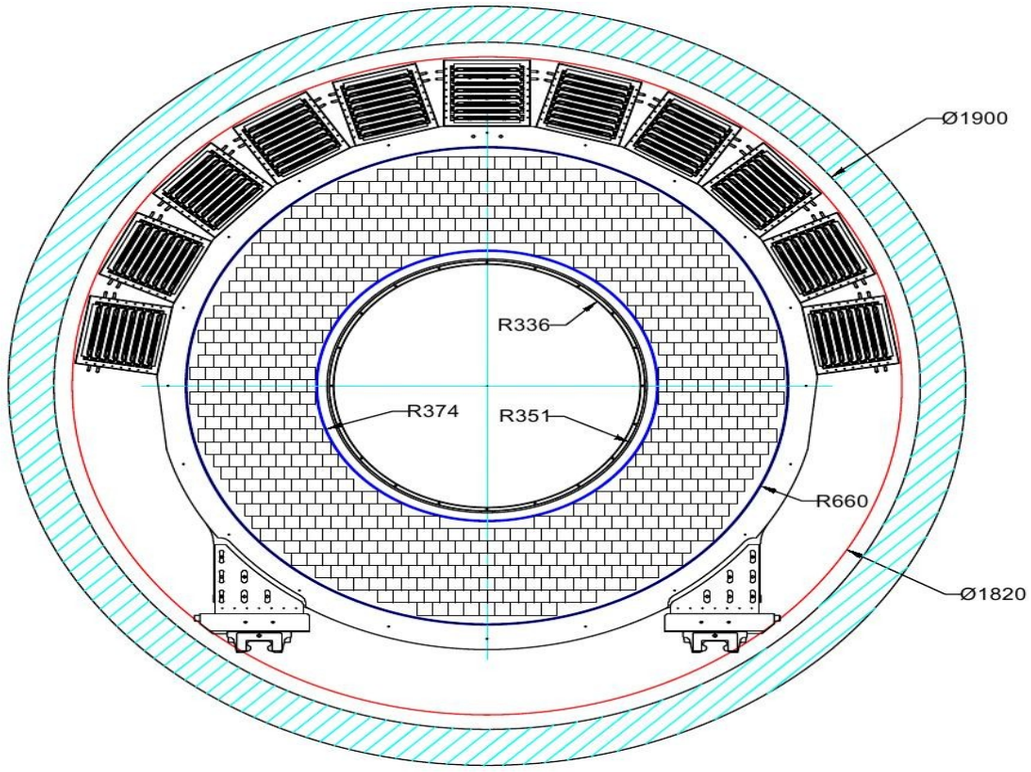


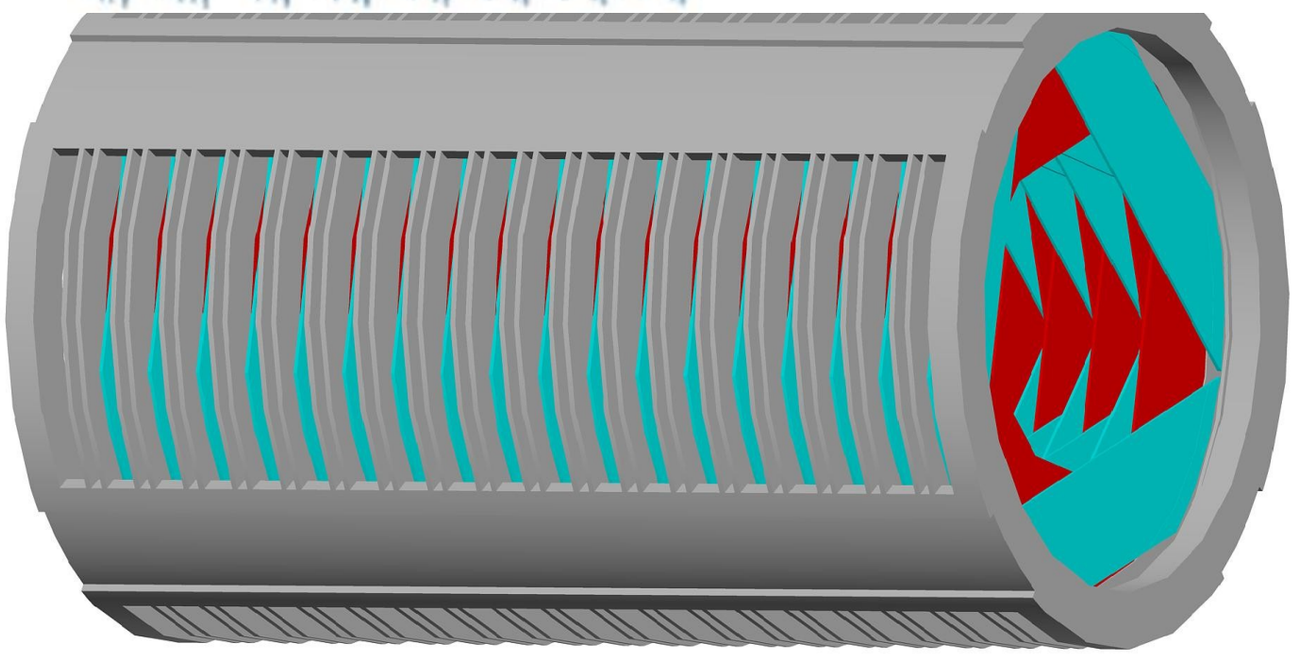


Mu2e detector

A single electron must be detected
It is a straw tracker complemented by a CsI calorimeter



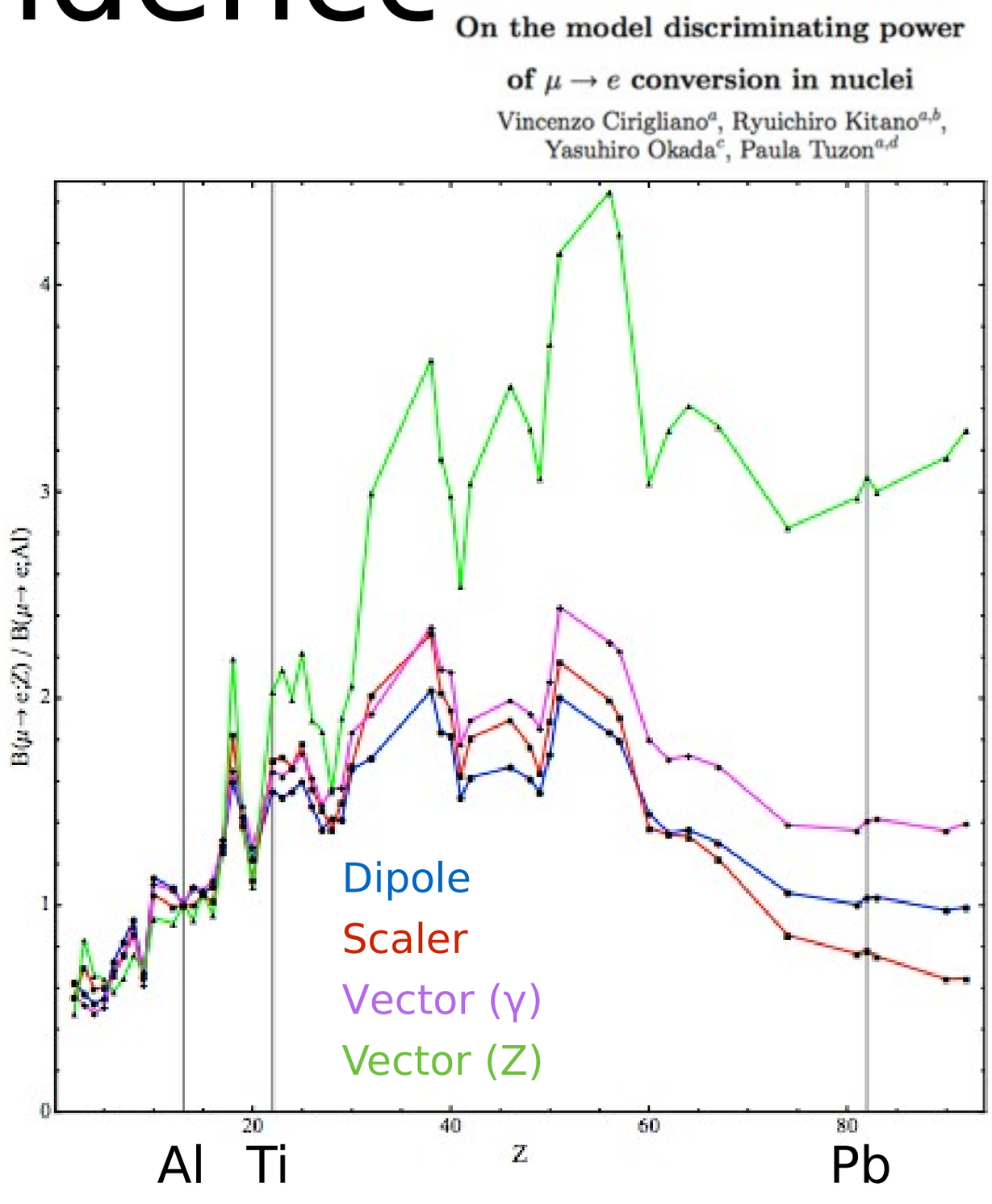


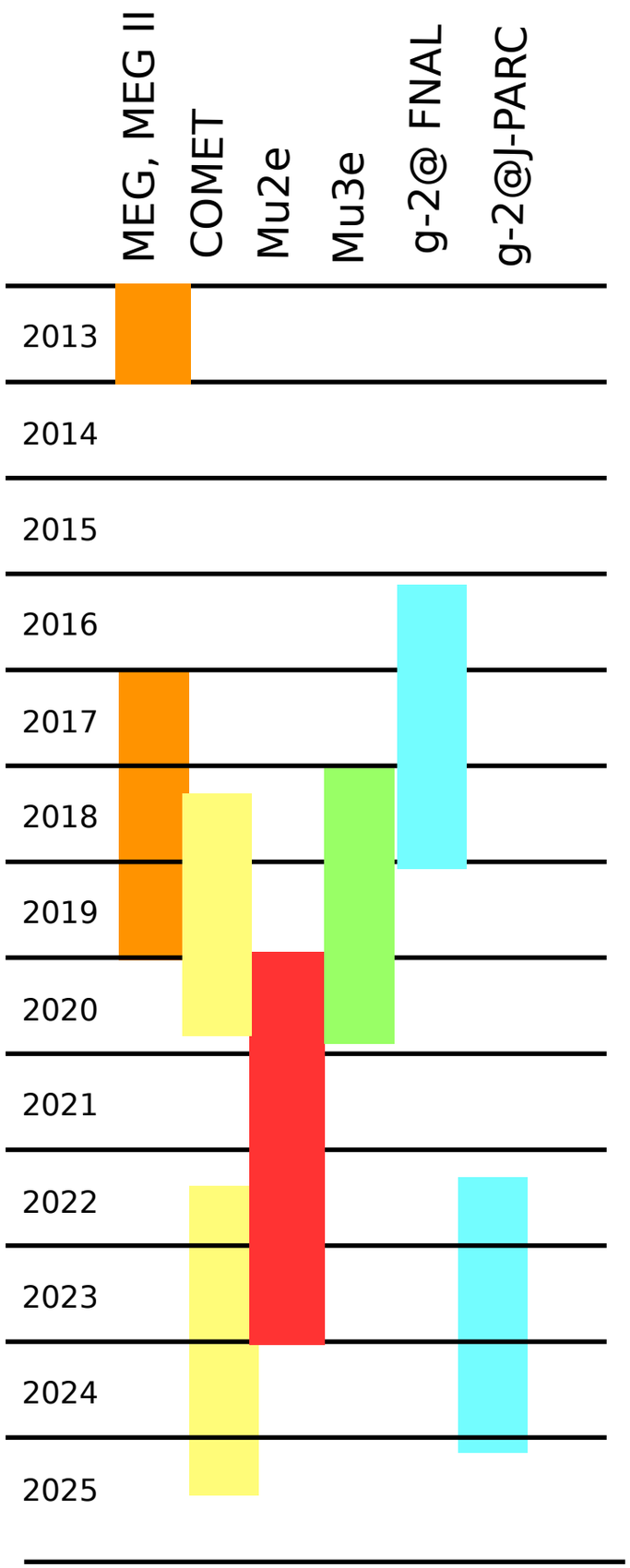


Muon Stopping Target Dependence

- 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





Summary

- cLFV experiments using muons
- MEG new result
  - Br(μ→eγ) < 4.2x10 $^{-13}$ @ 90% C.L.
- MEG II, DeeMe, COMET, Mu2e, Mu3e in preparation