Status of charged lepton flavor violation experiments

Precision theory for precision measurements at LHC and future colliders, Quy Nhon, Sep. 2016

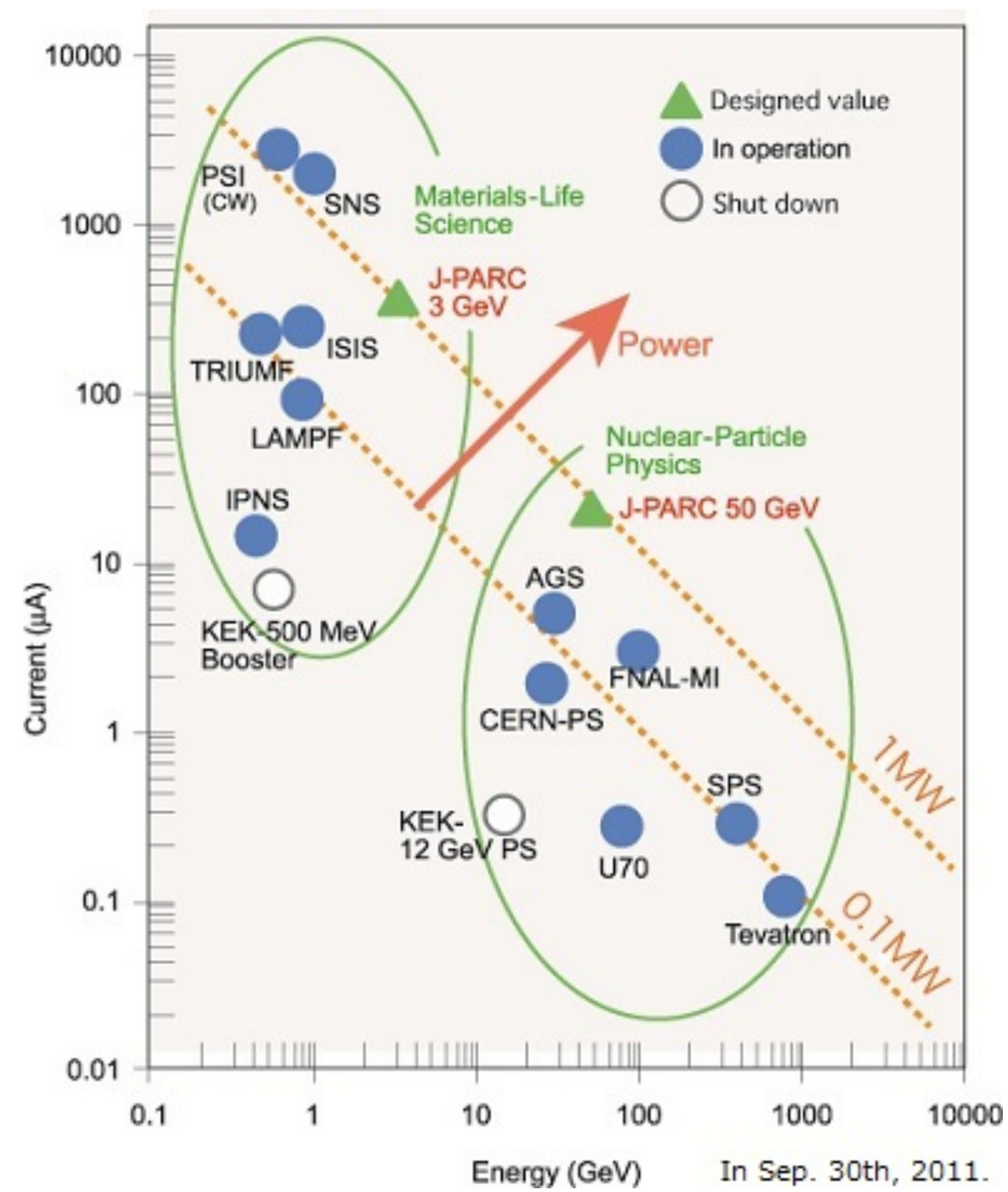
Satoshi MIHARA
KEK/J-PARC/Sokendai

Outline

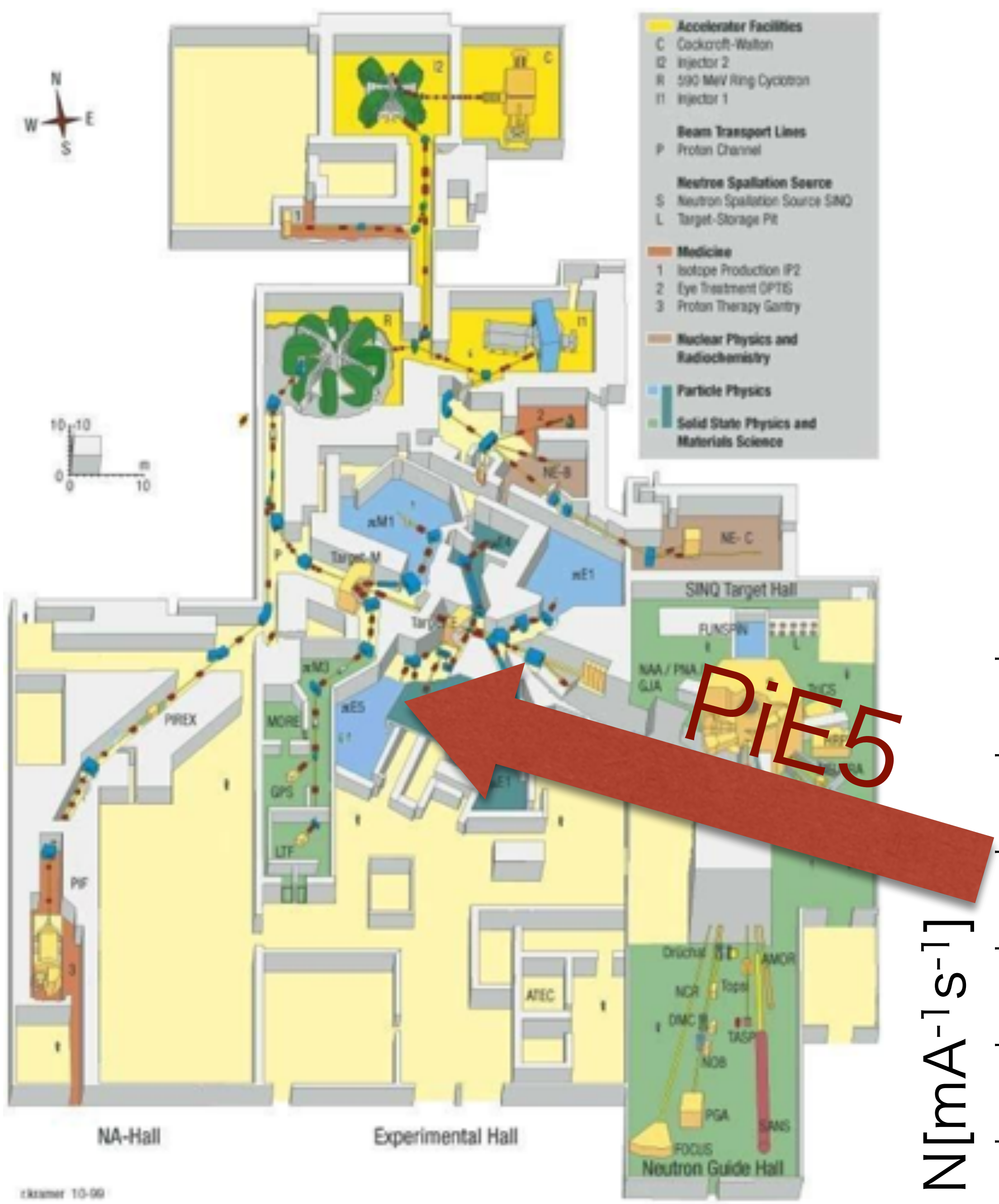
- Introduction
- CLFV experiments using muons
  - DC muon beam experiments
  - Pulsed muon beam experiments
- (CLFV experiments at colliders)
- Summary

cLFV Search Experiments

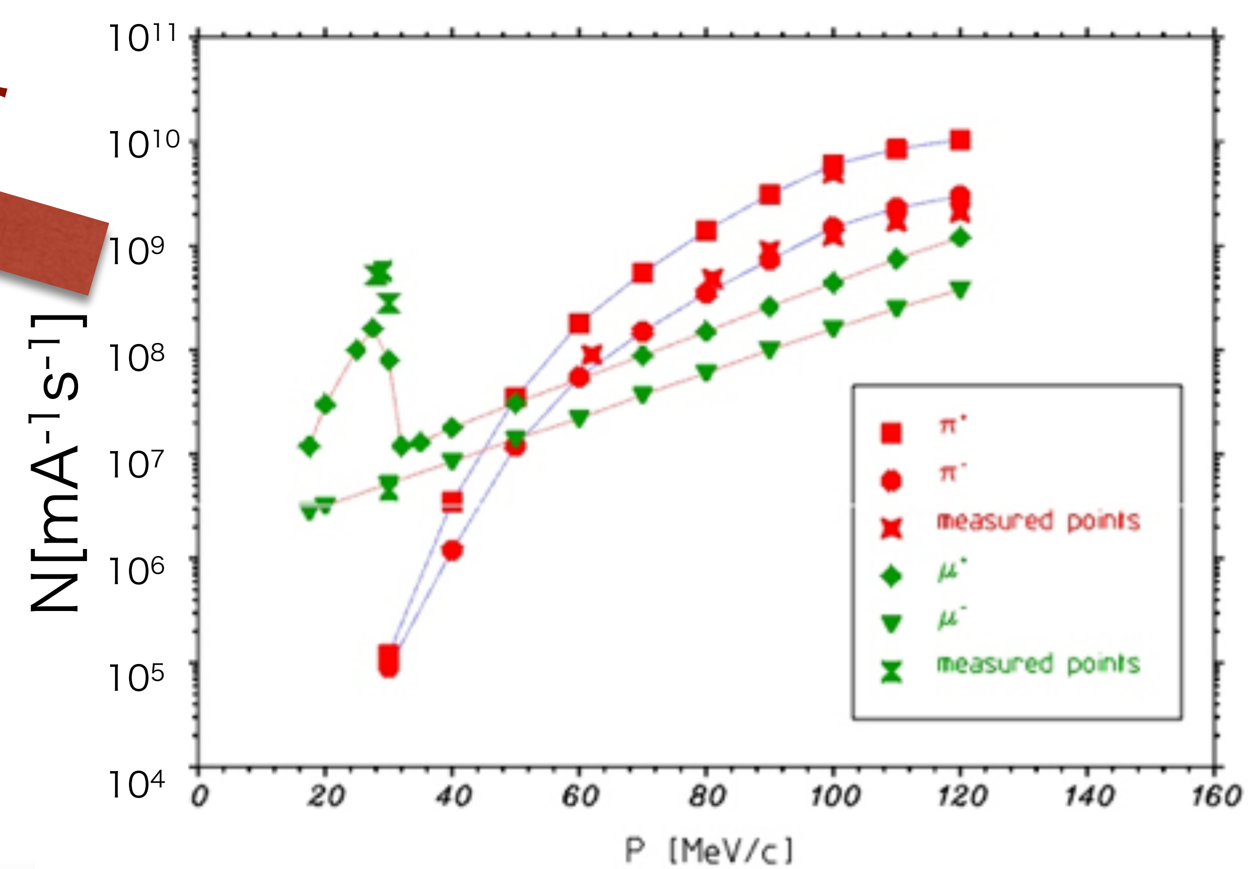
- No Standard Model background
- Large amount of muons available thanks to current high-power proton machines
  - Lower energy machine preferred to perform searches using stopped muons in most cases
  - Normal muon decay modes well understood
  - taus at B factories (or future tau/charm factory)
- Many BSM models predict the existence



PSI DC Muon Beam

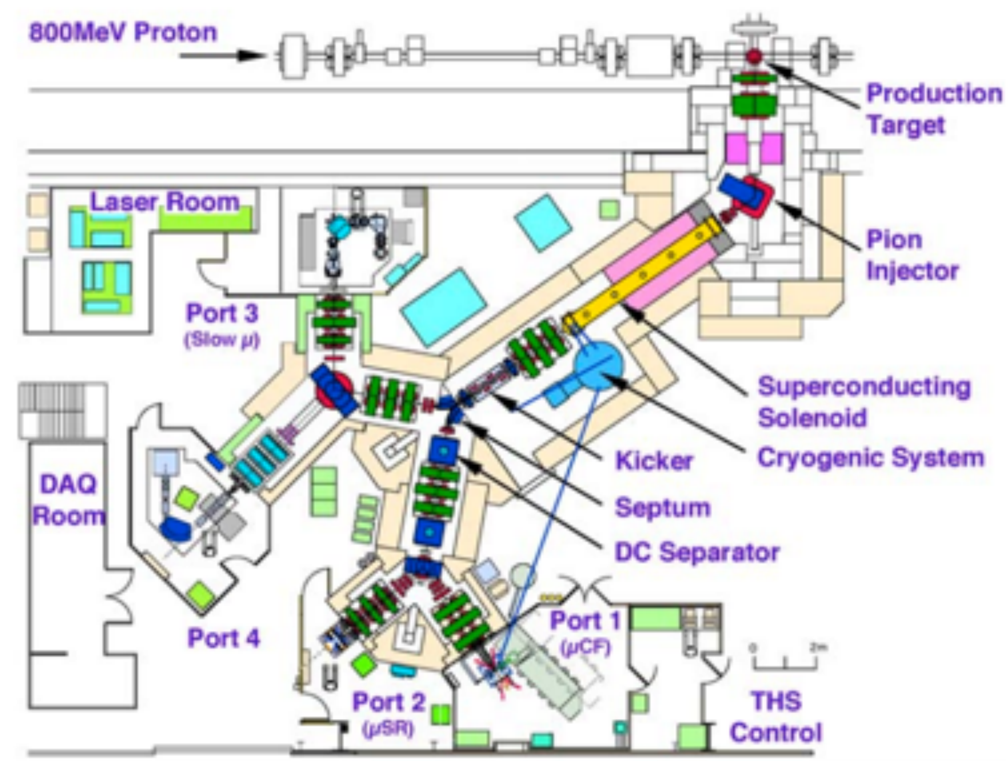


Injection Energy	72 MeV
Extraction Energy	590 MeV
Extraction Momentum	1.2 GeV/c
Energy spread (FWHM)	ca. 0.2 %
Beam Emittance	ca. 2π mm×mrad
Beam Current	2.2 mA DC
Accelerator Frequency	50.63 MHz
Time Between Pulses	19.75 ns
Bunch Width	ca. 0.3 ns
Extraction Losses	ca. 0.03%

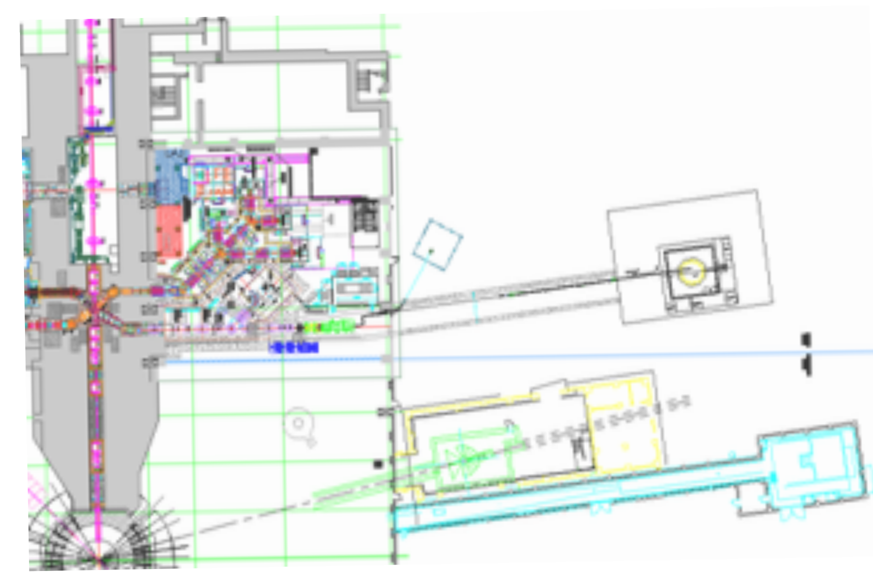


Pulsed Muon Beam Facility

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



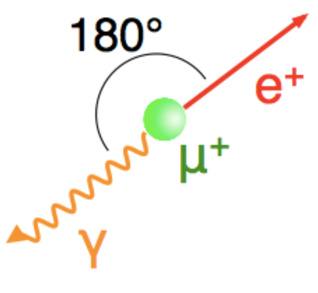
Layout of the RIKEN-RAL Muon Facilty



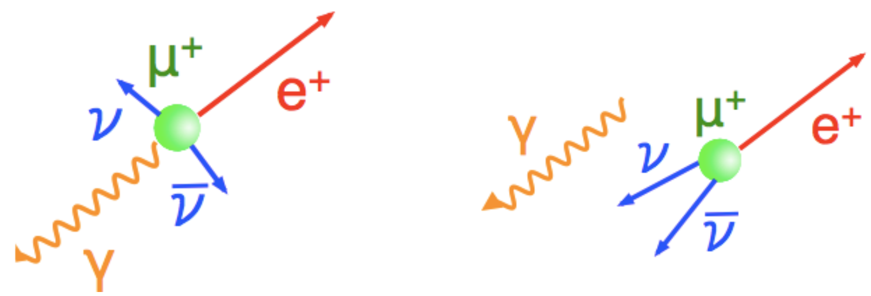
J-PARC MLF H-Line

MEG & MEG II

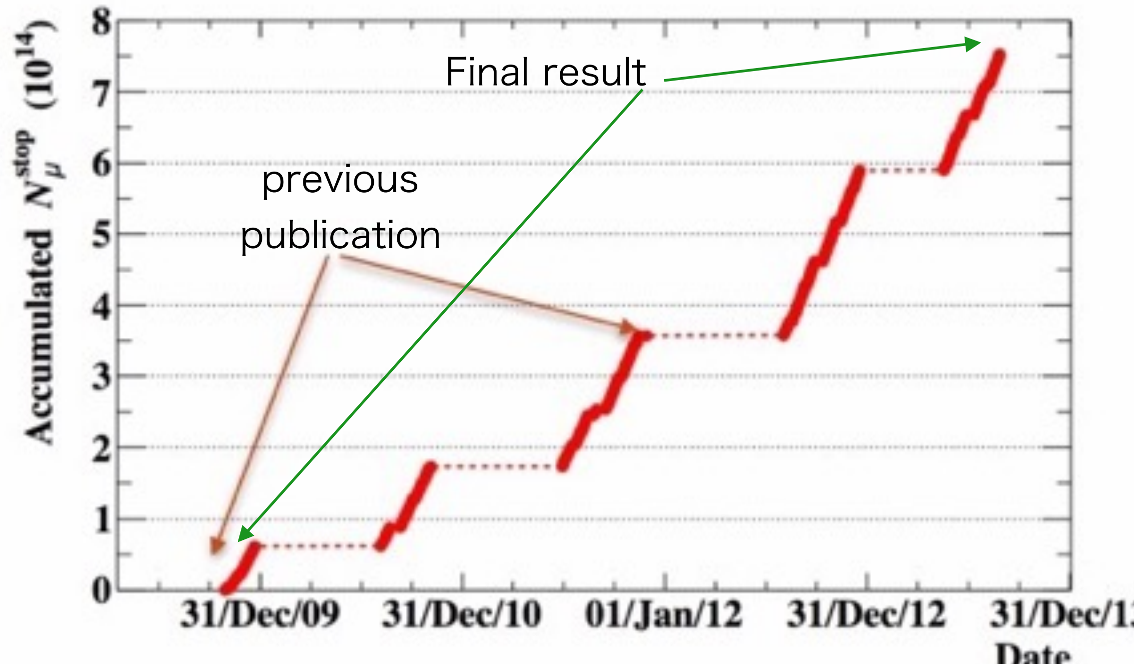
Signal



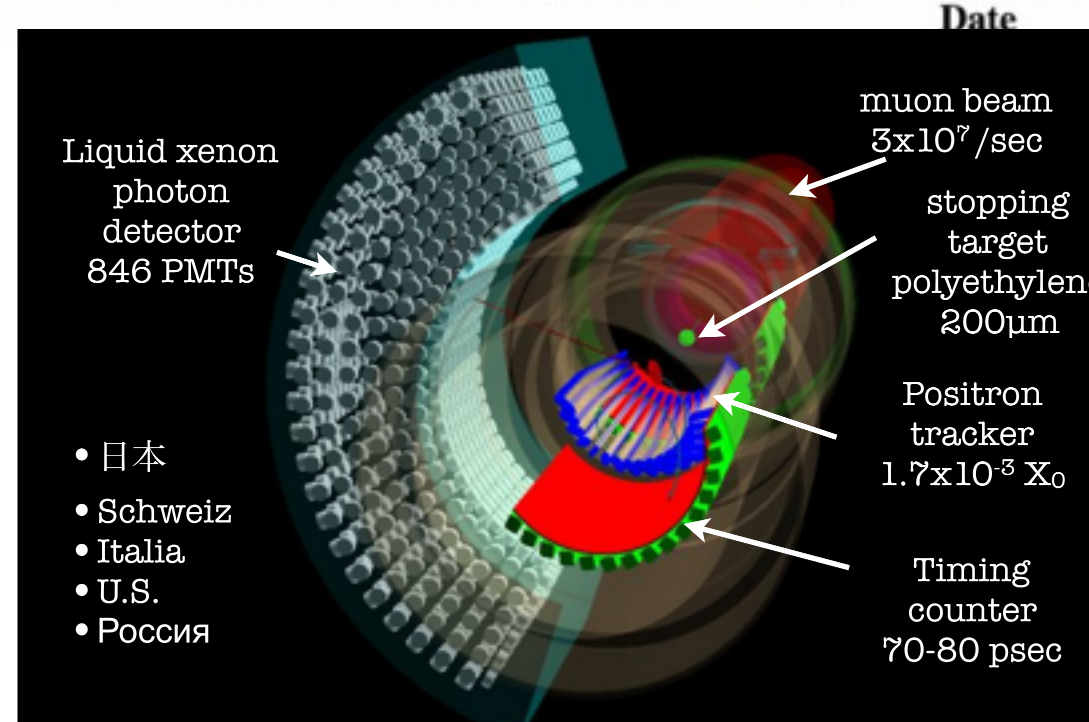
Background



MEG Muon Statistics

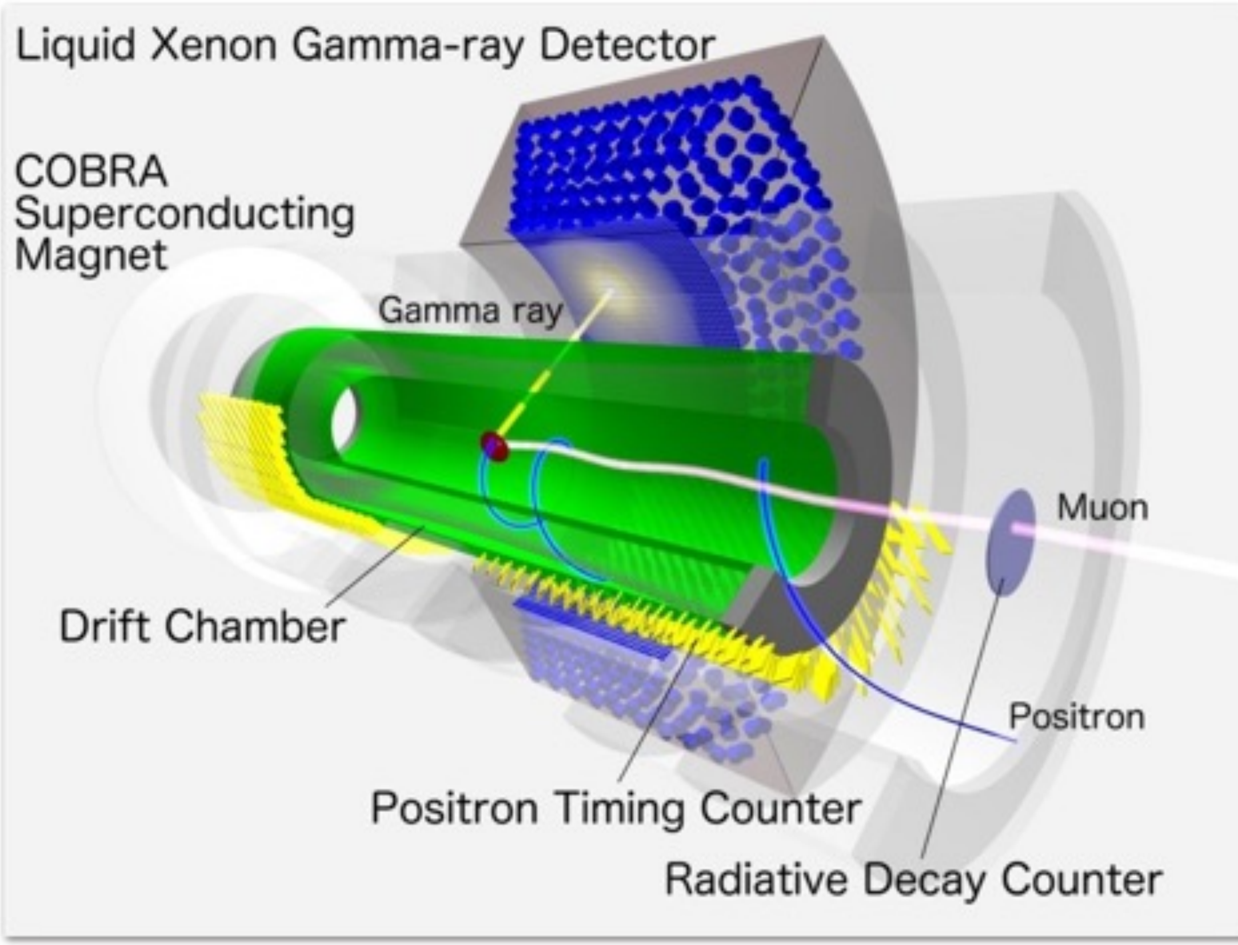


- MEG@PSI
  - Search for $\mu^+ \to e^+ \gamma$ using 3×10^7 Hz muon beam
  - Liquid Xe photon detector & COBRA positron spectrome
  - DAQ in 2008-2013
  - **Final upper limit result published: 4.2×10^{-13} @ 90% C.L.**
  - European Physical Journal C, 76(8), 1-30
- Detector upgrade to achieve 10 times better sensitivity : MEG II

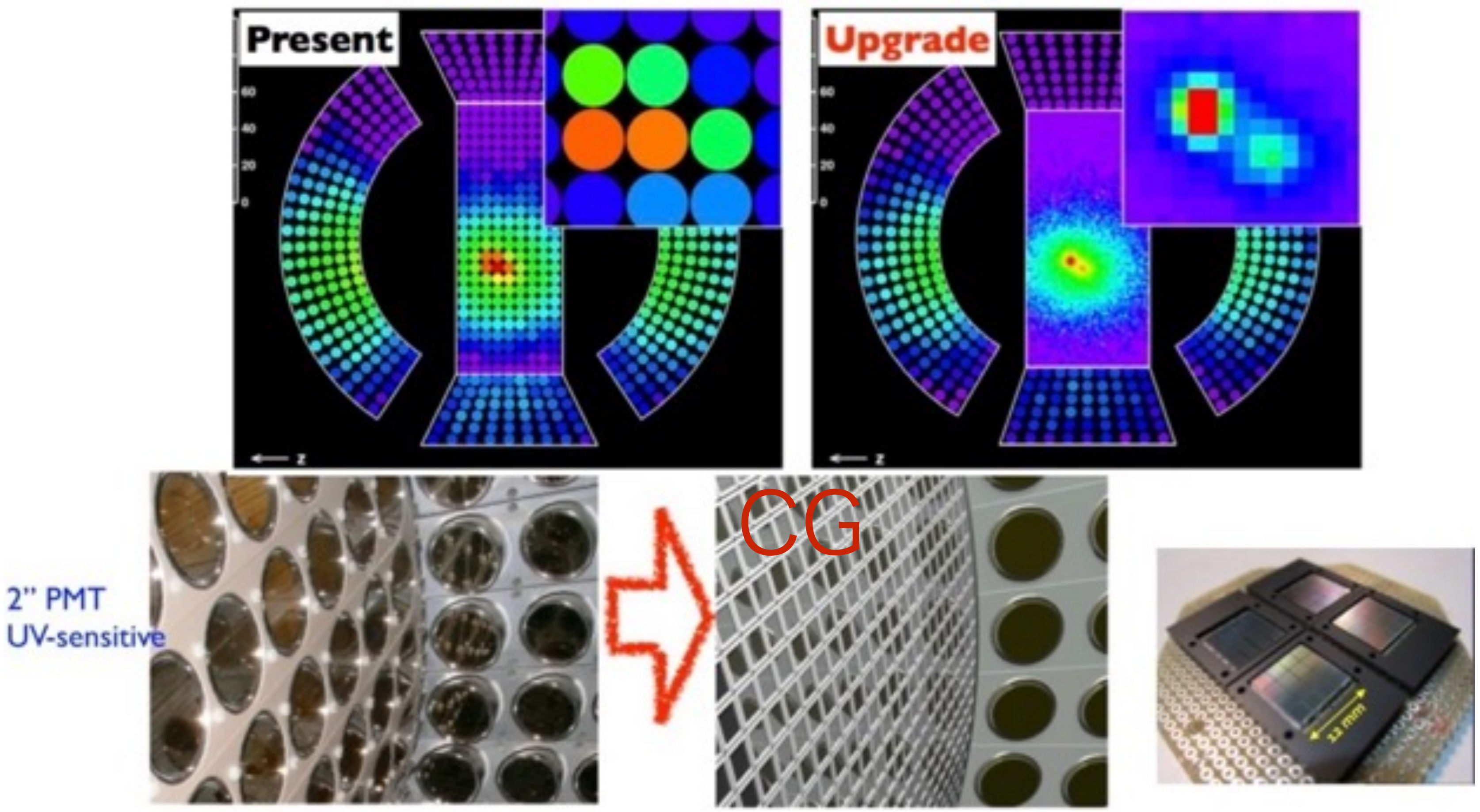


MEG II

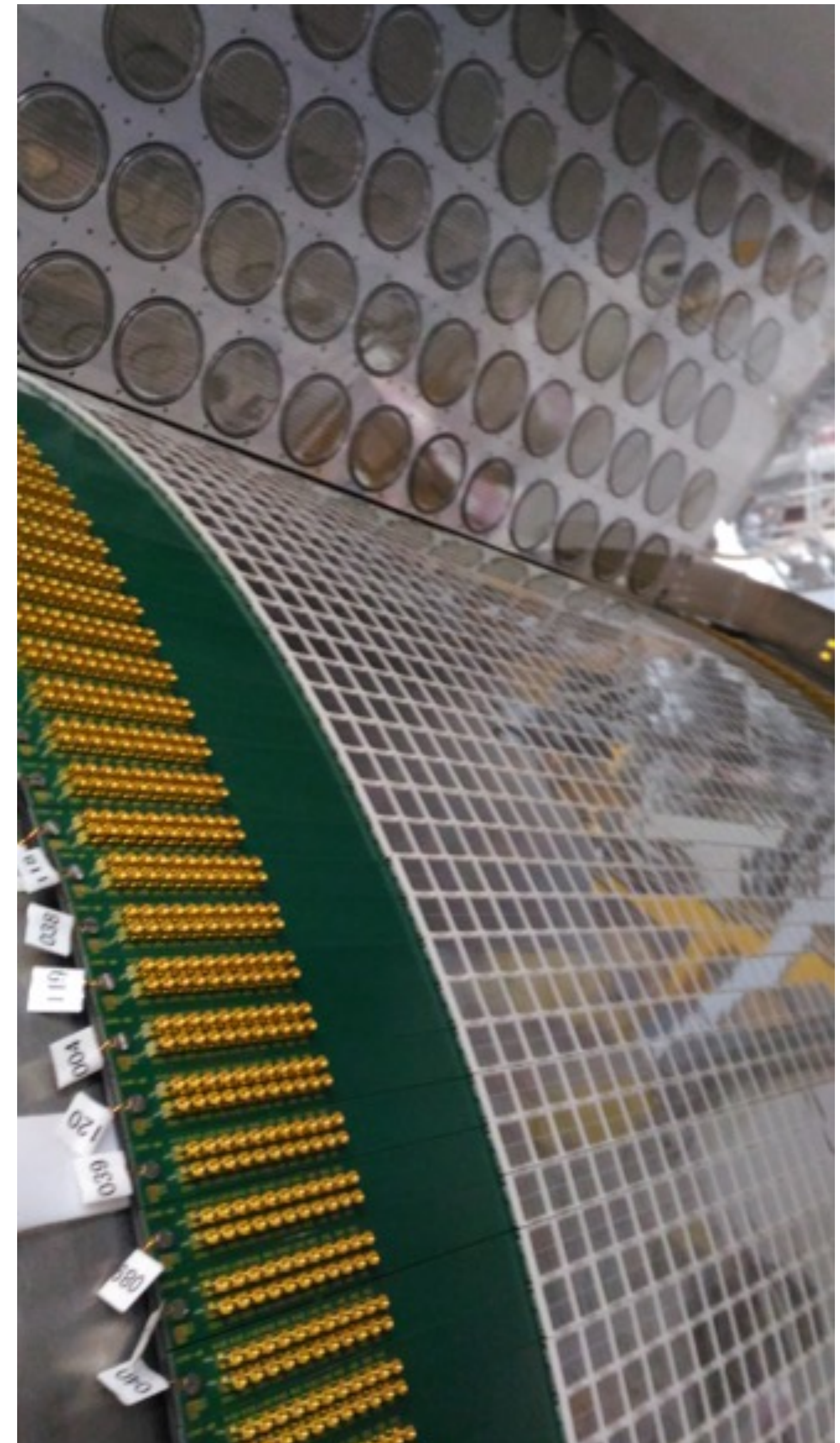
- Improve resolutions by about factor 2 everywhere
- μ beam rate of 7×10^{7} Hz to reach **the sensitivity of 4×10^{-14}**
- Engineering run in 2016



MEG II LXe Upgrade



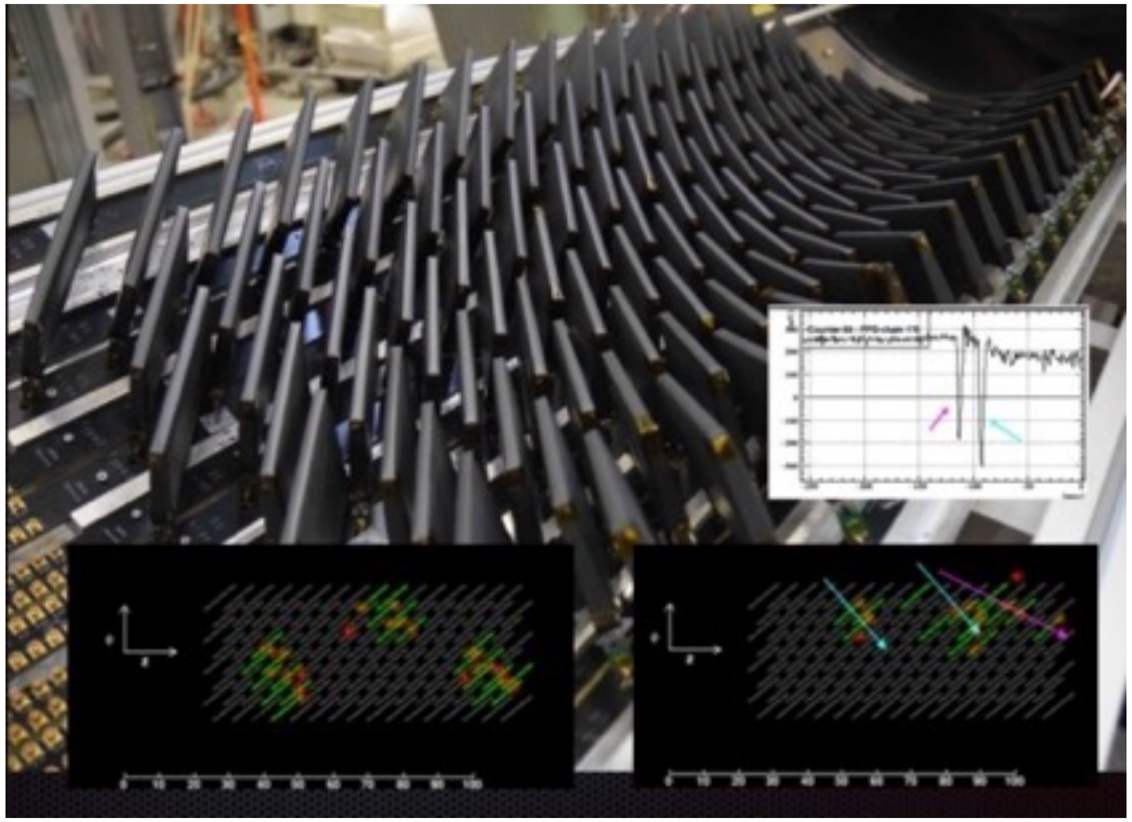
- Replace 2-inch PMTs with VUV-SiPM to cover the front face
- 4000 SiPM with minimum material
- Installation completed July/2016



MEG II Positron Spectrometer

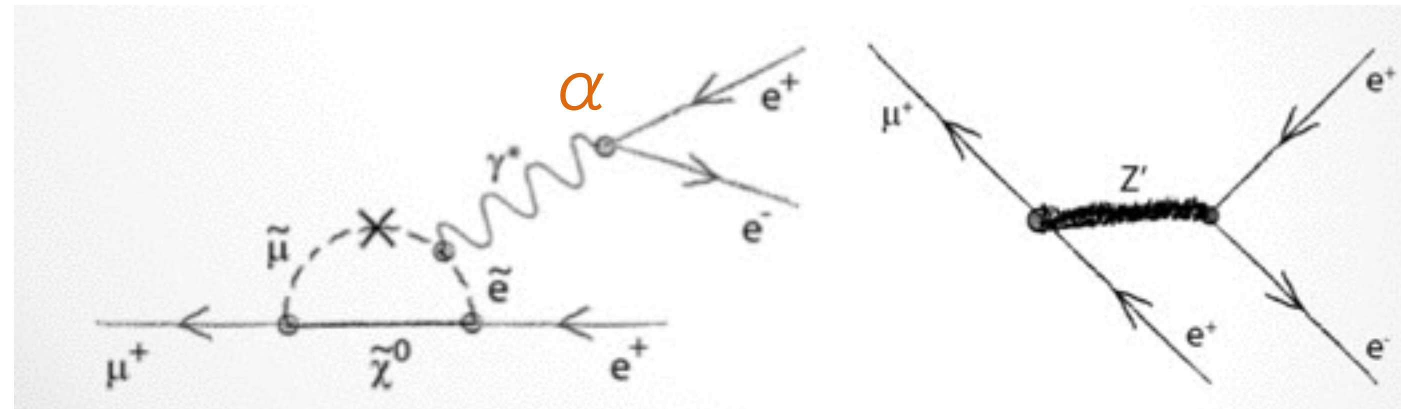
- **Drift chamber**
  - Single volume, 2m long stereo wire & low mass
  - More hits provides better resolutions
    - σ_{Ee} = 130keV, σ_{angles} = 5mrad

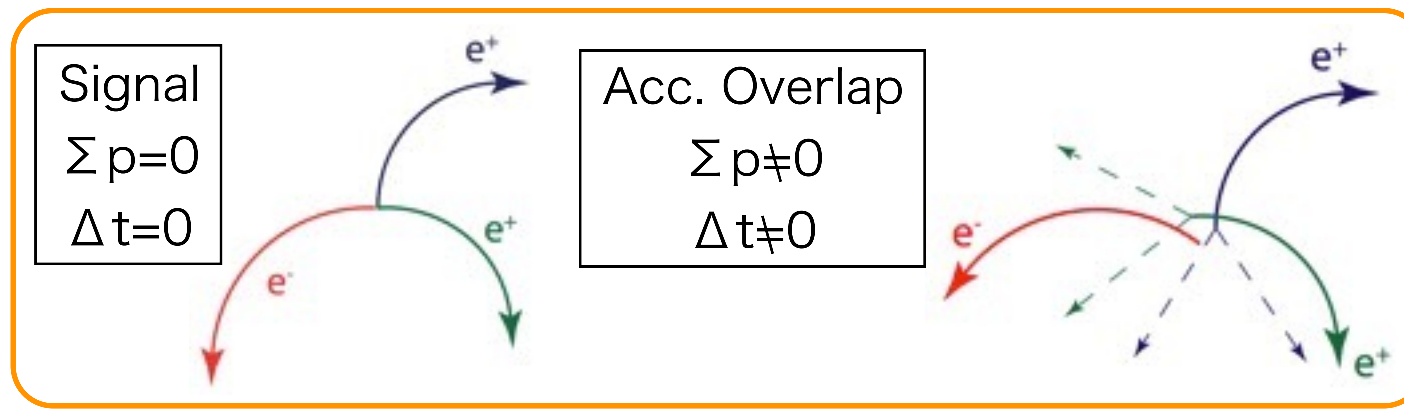
- **Timing counter**
  - Pixelated plastic scintillators read by SiPM
  - Best resolutions σ~30psec anticipated for multiple counter hits events
- **& Upgrade of Trigger / DAQ**



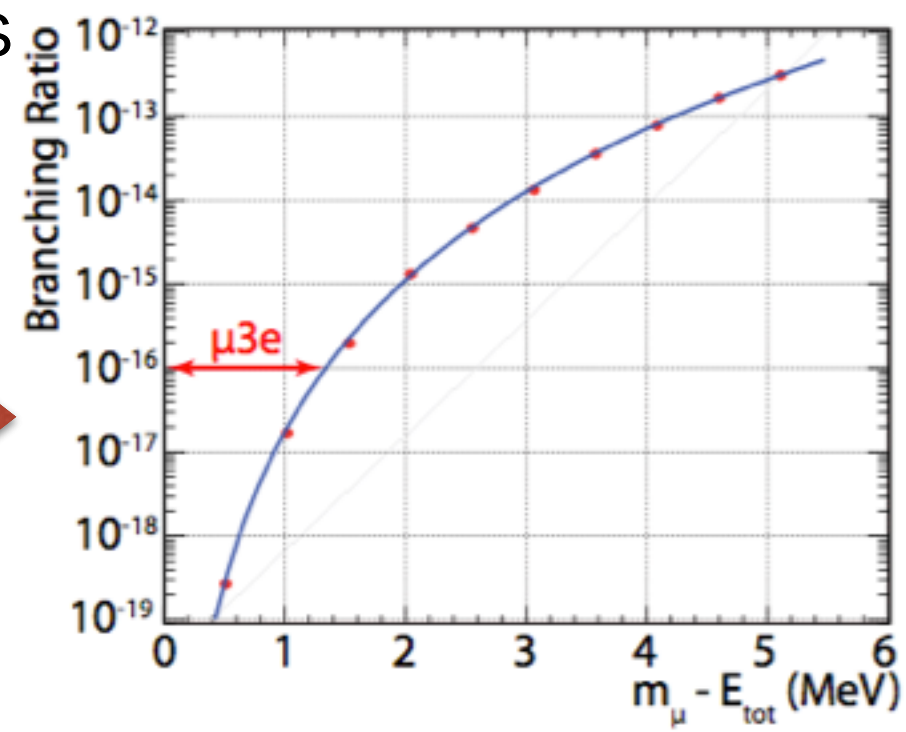
Mu3e: $\mu \rightarrow eee$ Search using DC Muon Beam

- Another channel sensitive to cLFV with DC muon beam
  - 1.0×10^{-12} (90% C.L.) by SINDRUM
  - **Goal : 10^{-16} in 3 steps**
    - **Phase I in 2018-2020 Sensitivity:~10^{-15}**



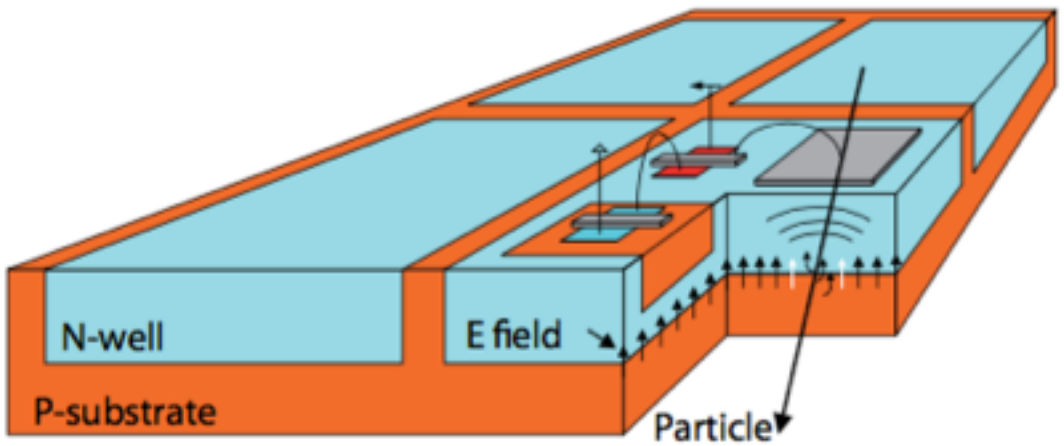


- Measure all electron tracks precisely
- most severe BG
  - $\mu^{+}\rightarrow e^{+}e^{+}e^{-}\nu\bar{\nu}$



Suppress BG by more than 16 orders of magnitudes

Mu3e: Detector Technology

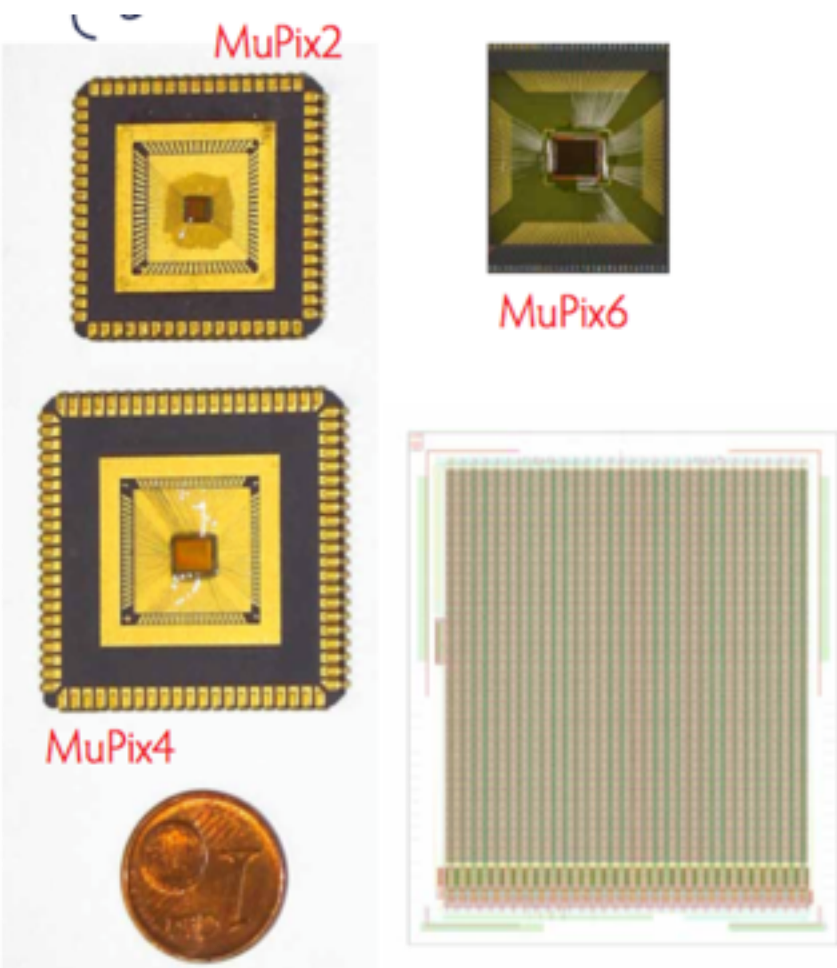


NIM A 582 (2007) 876

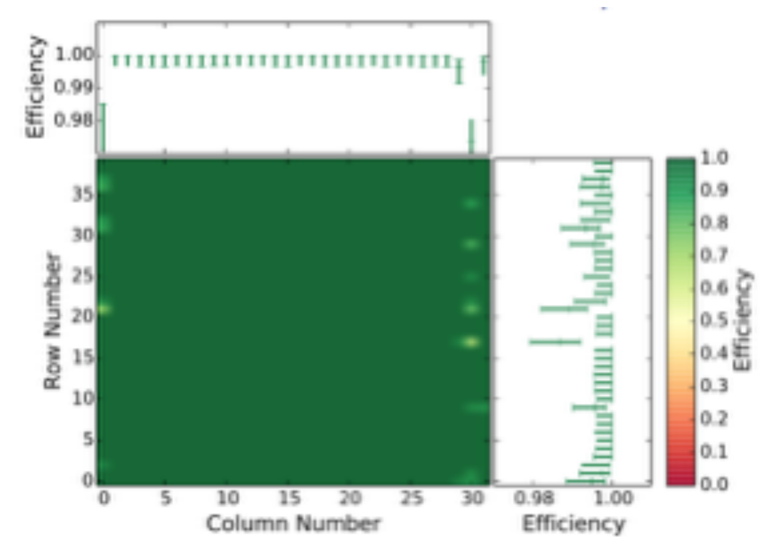
High voltage monolithic active pixel sensors - Ivan Perić

- 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



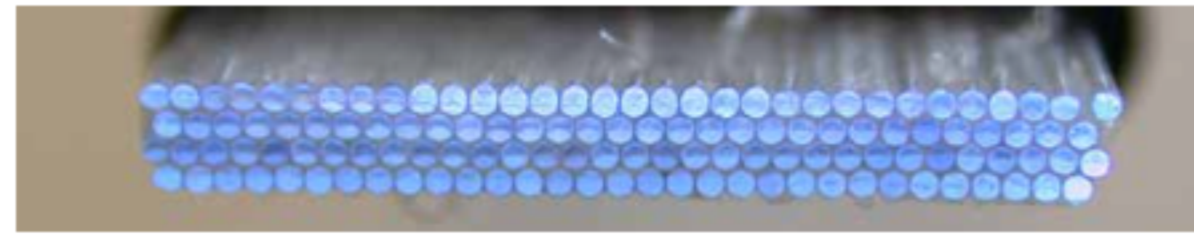
Mainz test beam in June 2016

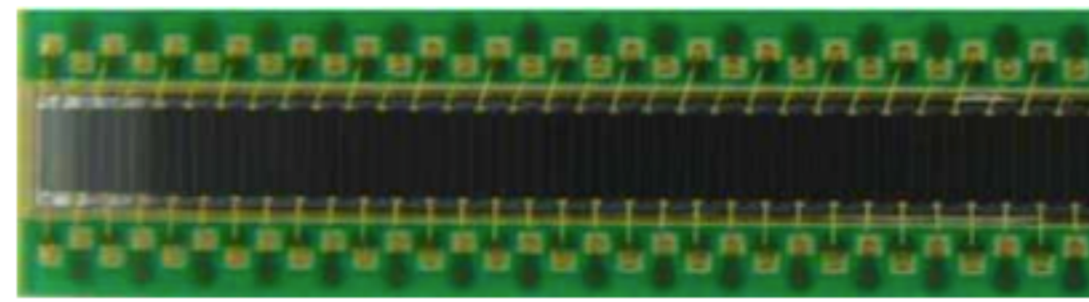


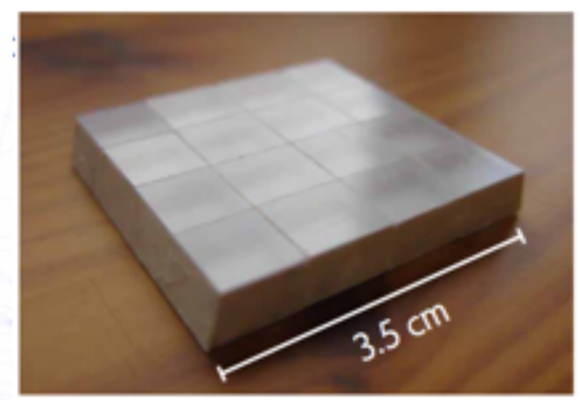
Efficiency above 99%

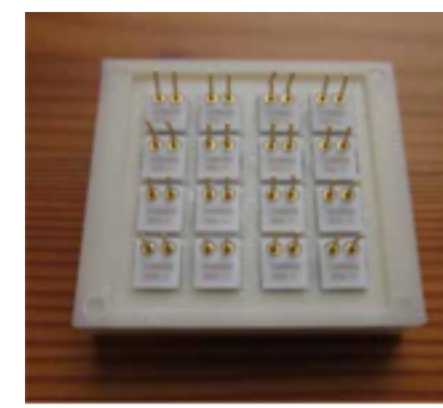
Mu3e: Timing Measurement

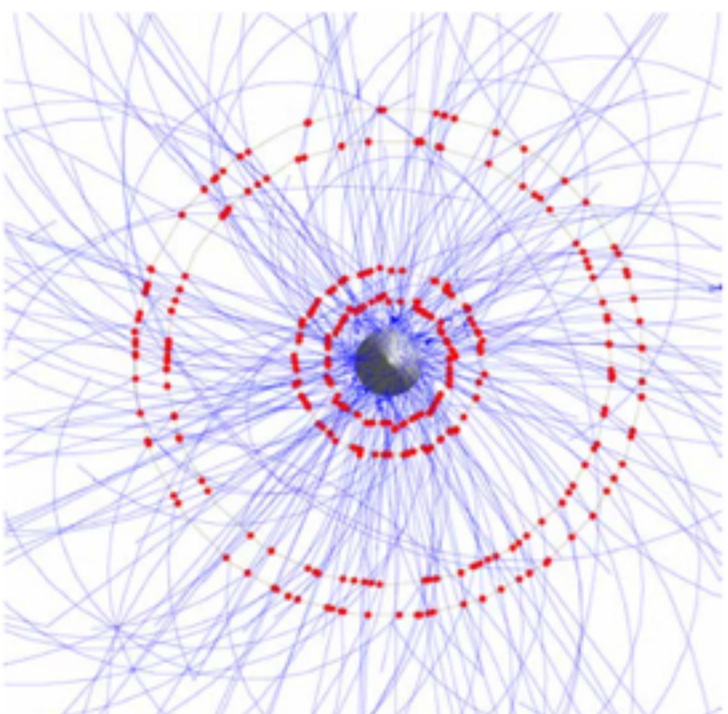
- Precise timing measurement is critical to reduce accidental BGs
  - Scintillating fibers O(1nsec)
  - Scintillating tiles O(100psec)



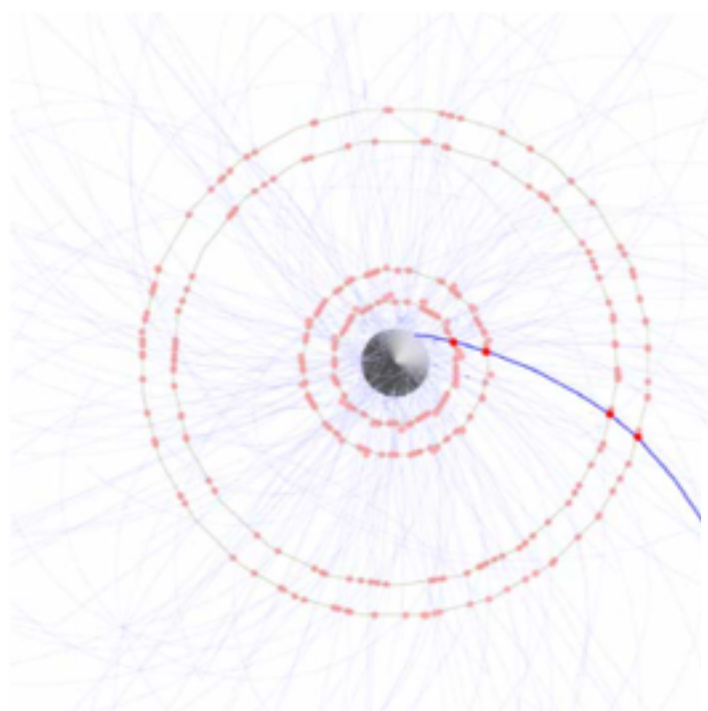




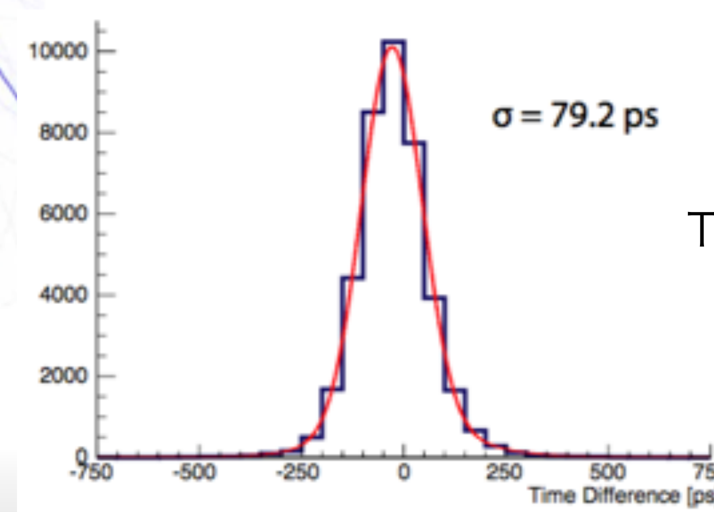




Pixels: O(50 ns)



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

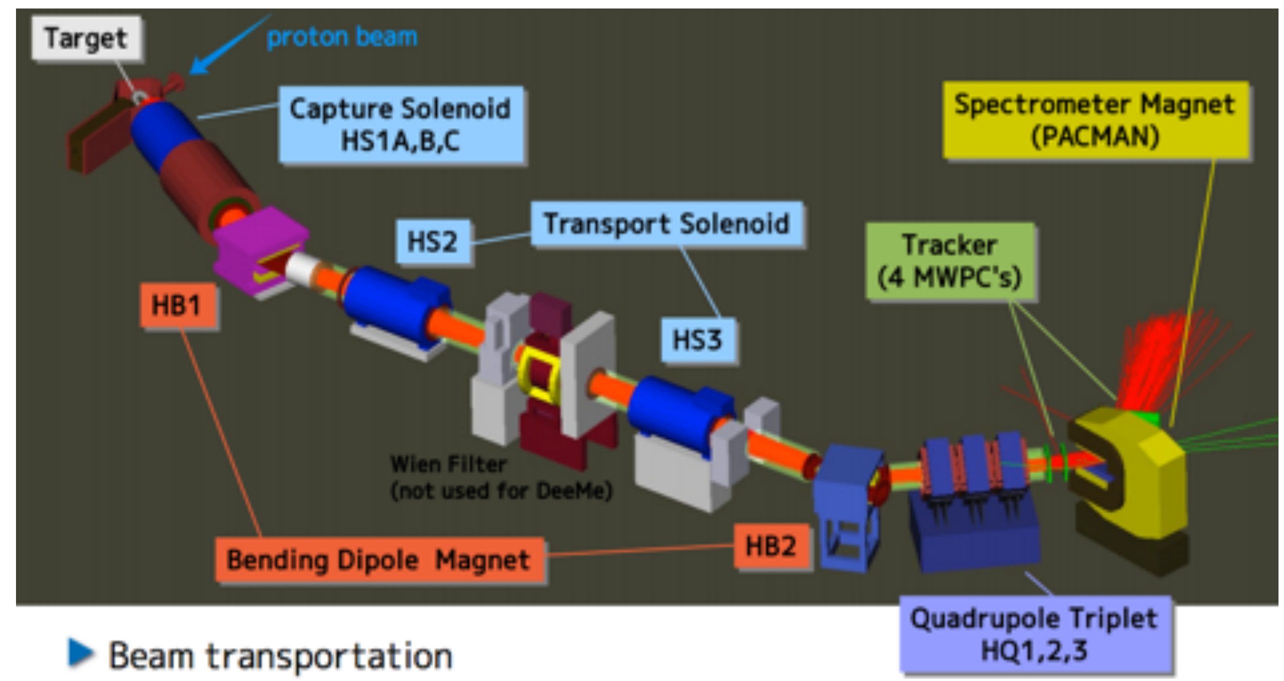


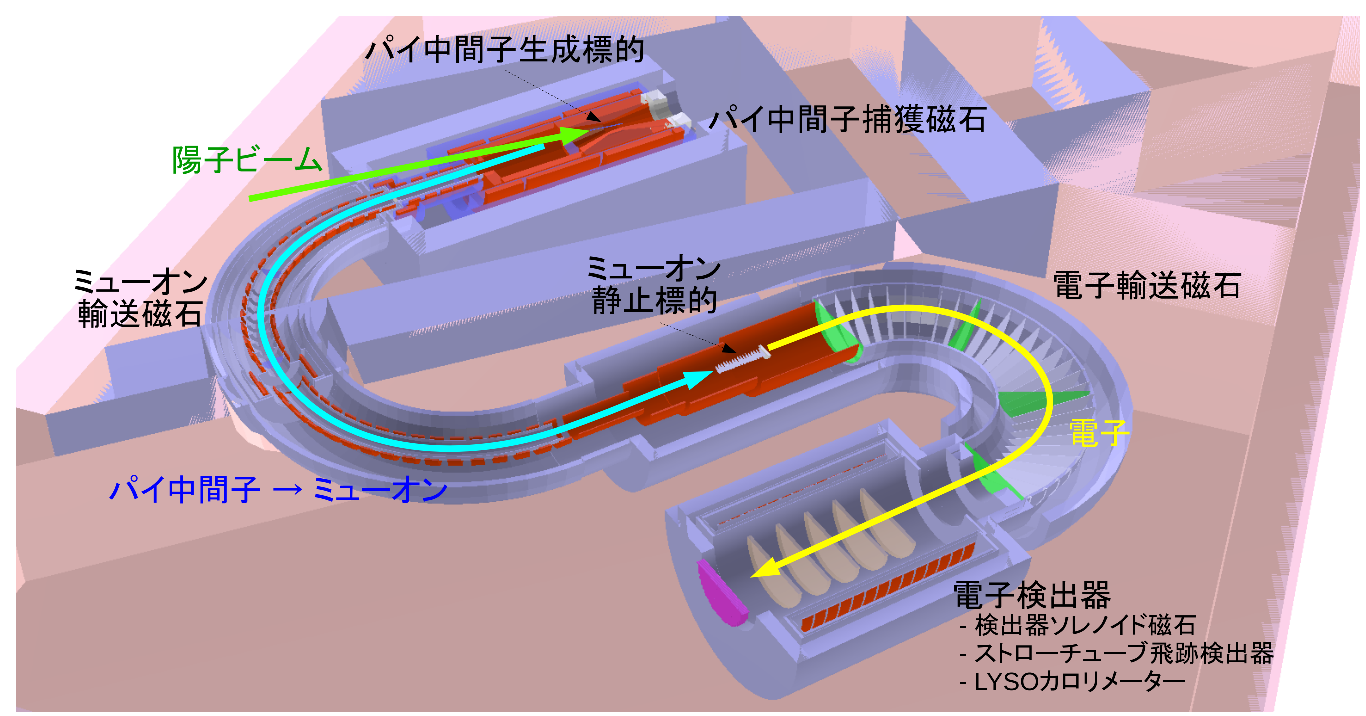
Test beam with Tiles
SiPM and ASIC

μ-e Conversion Searches

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

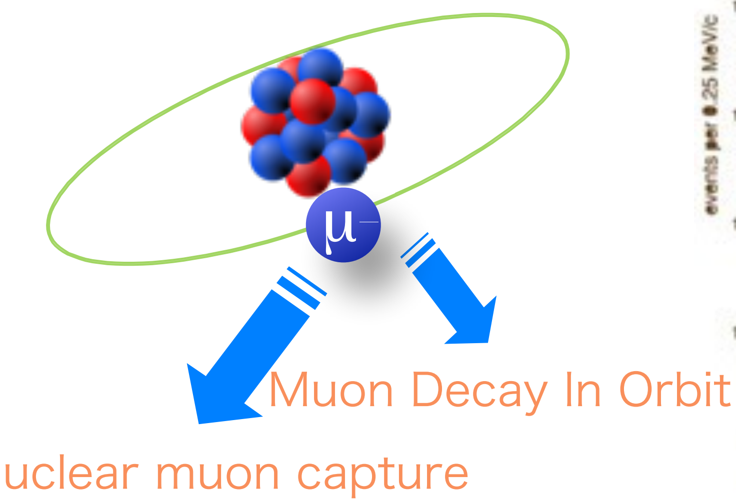
10^{-14} ~ 10^{-16} sensitivity



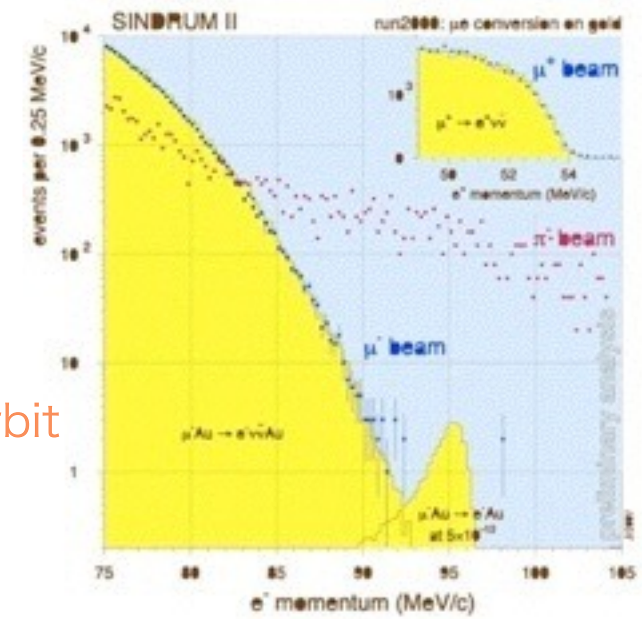


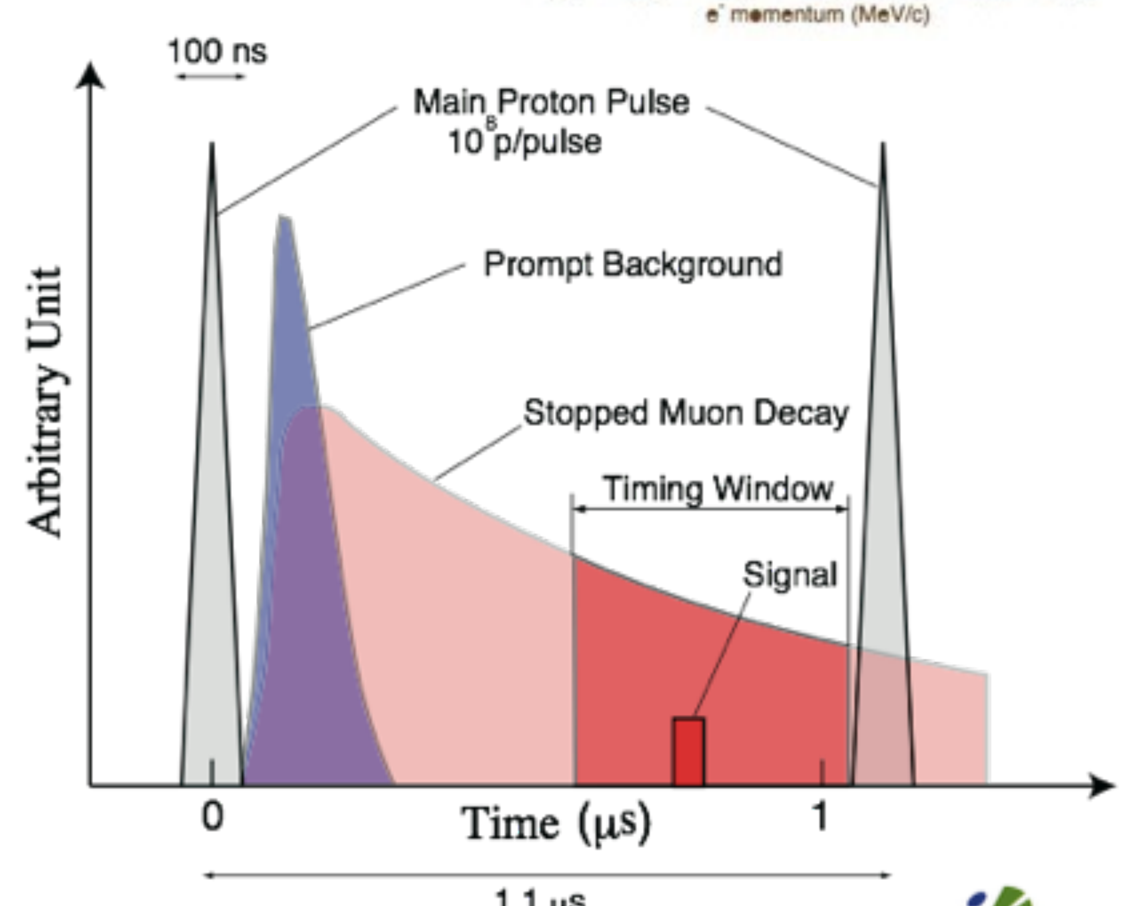
Experimental Techniques

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



SINDRUM II

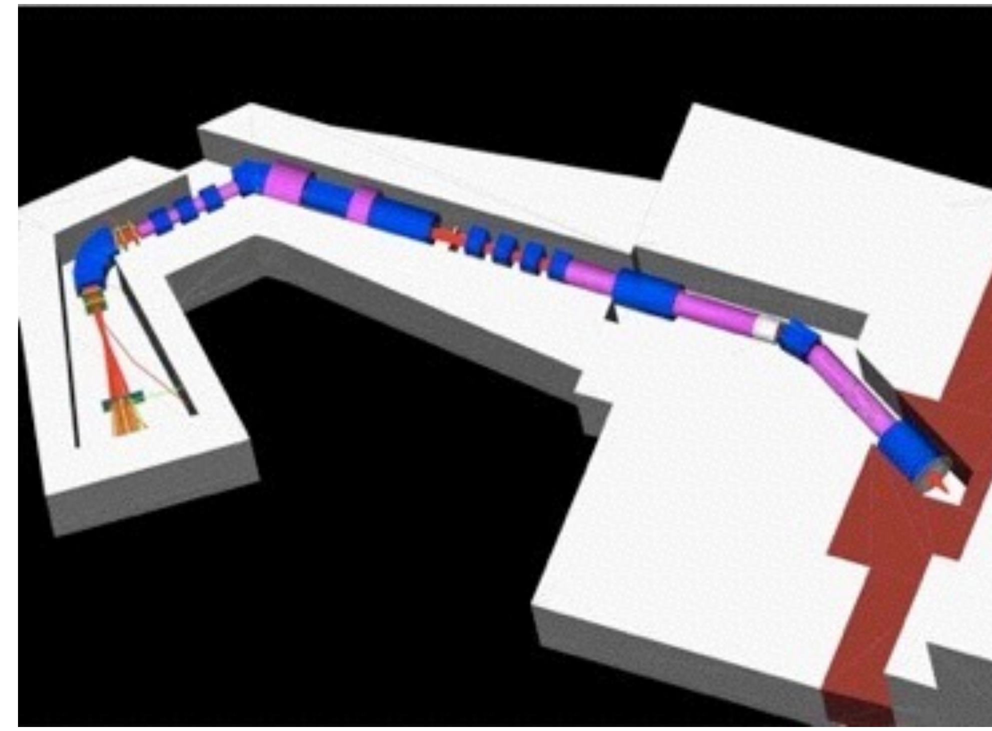


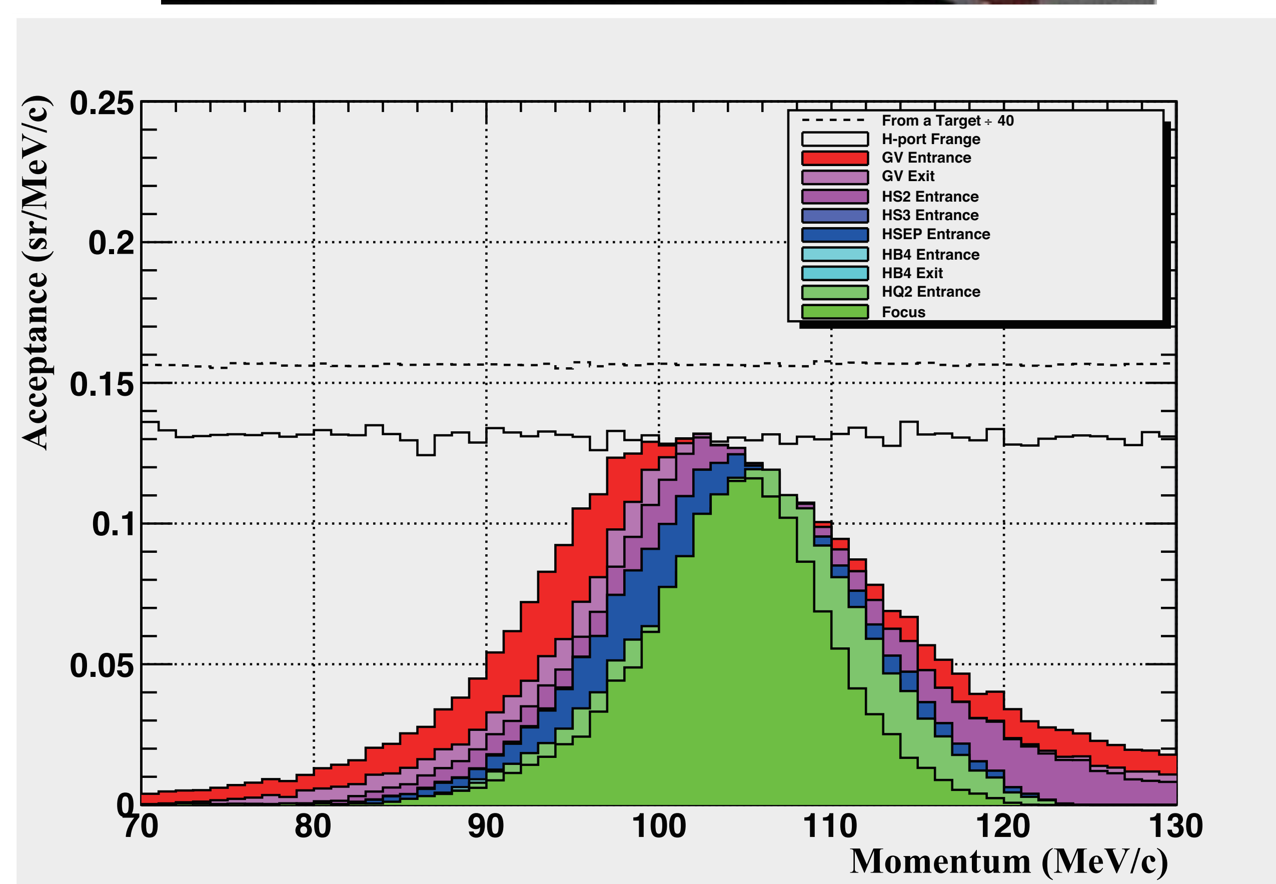


$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

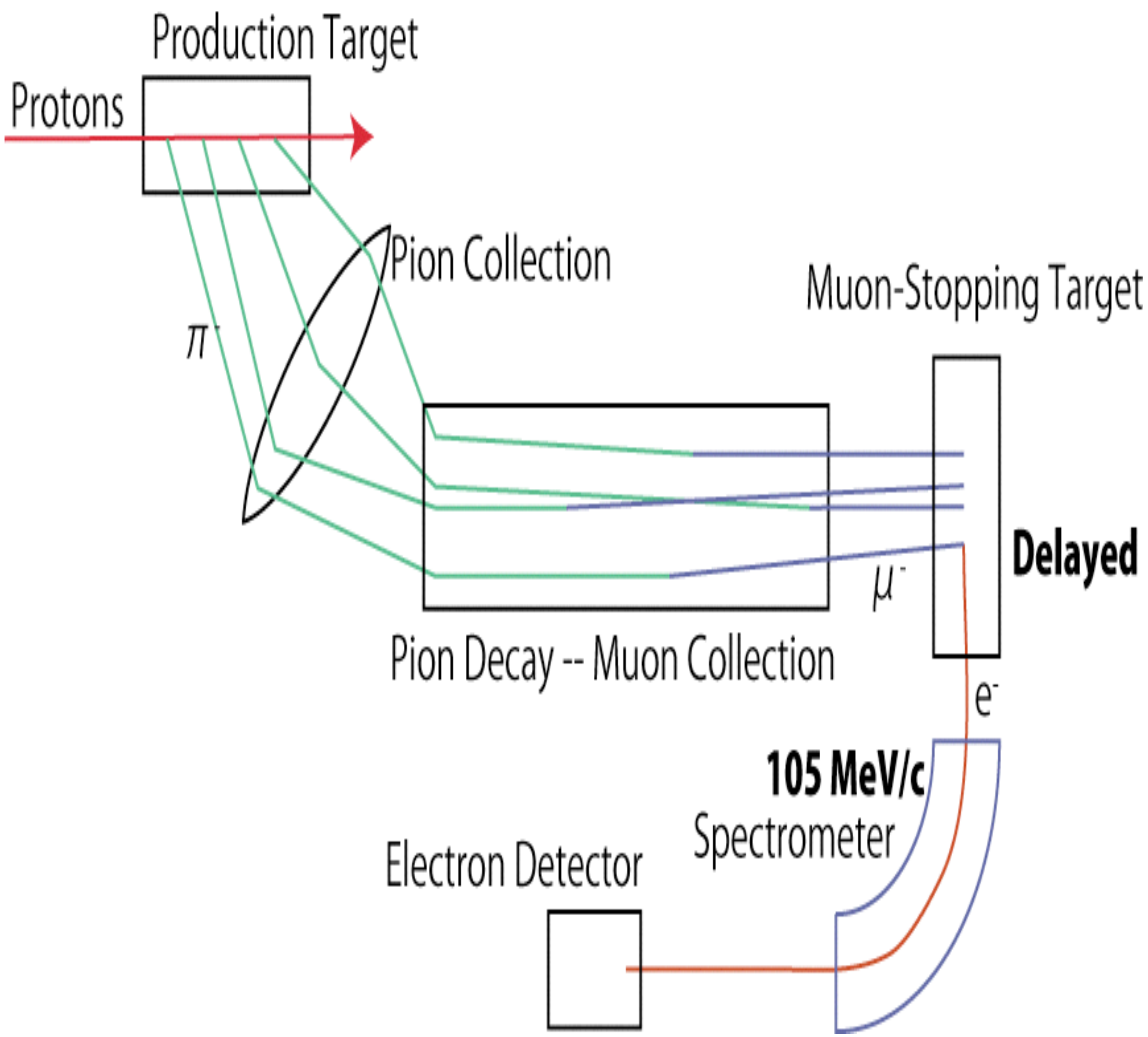
DeeMe at J-PARC

- **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

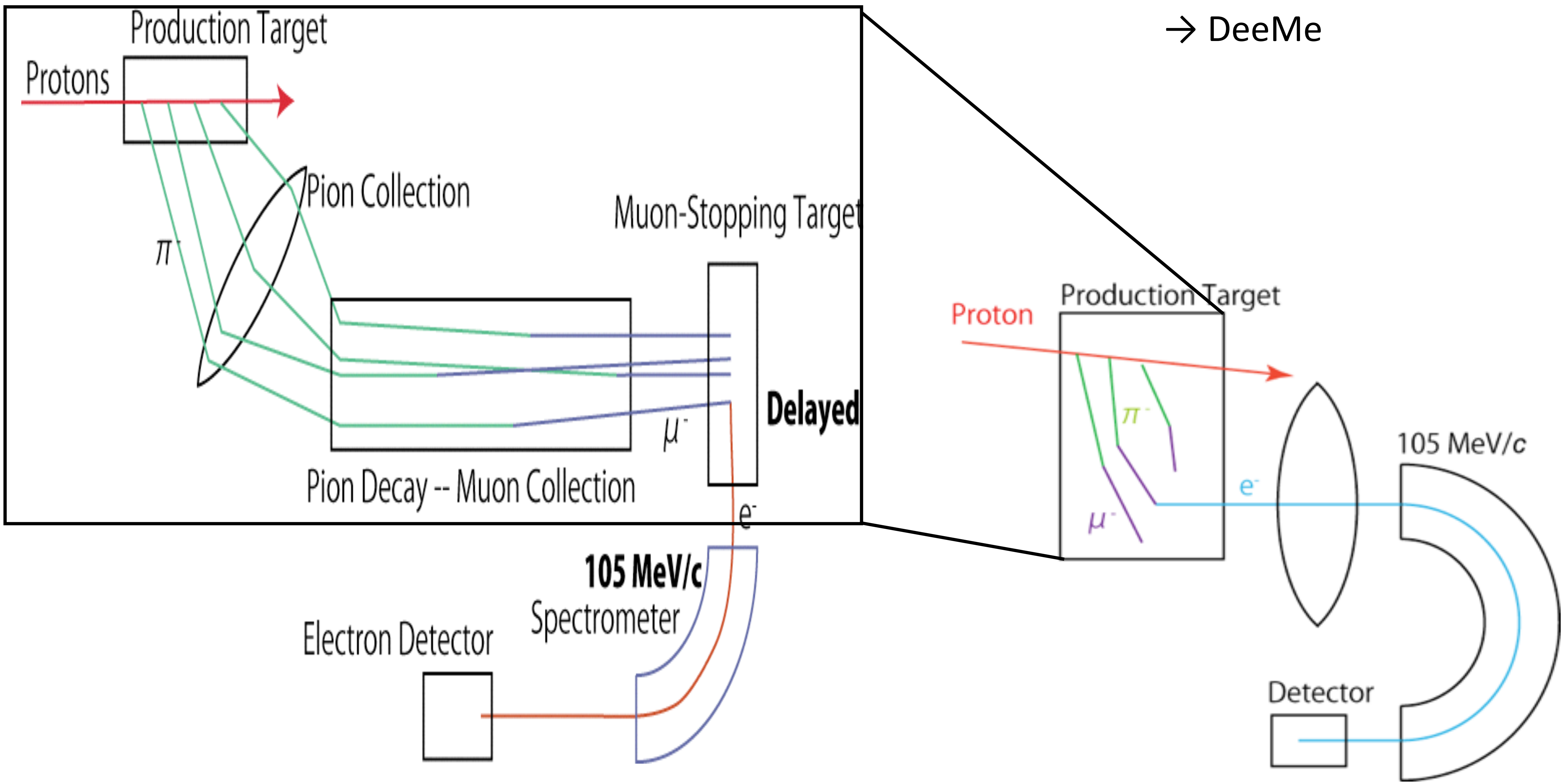




Principle of DeeMe

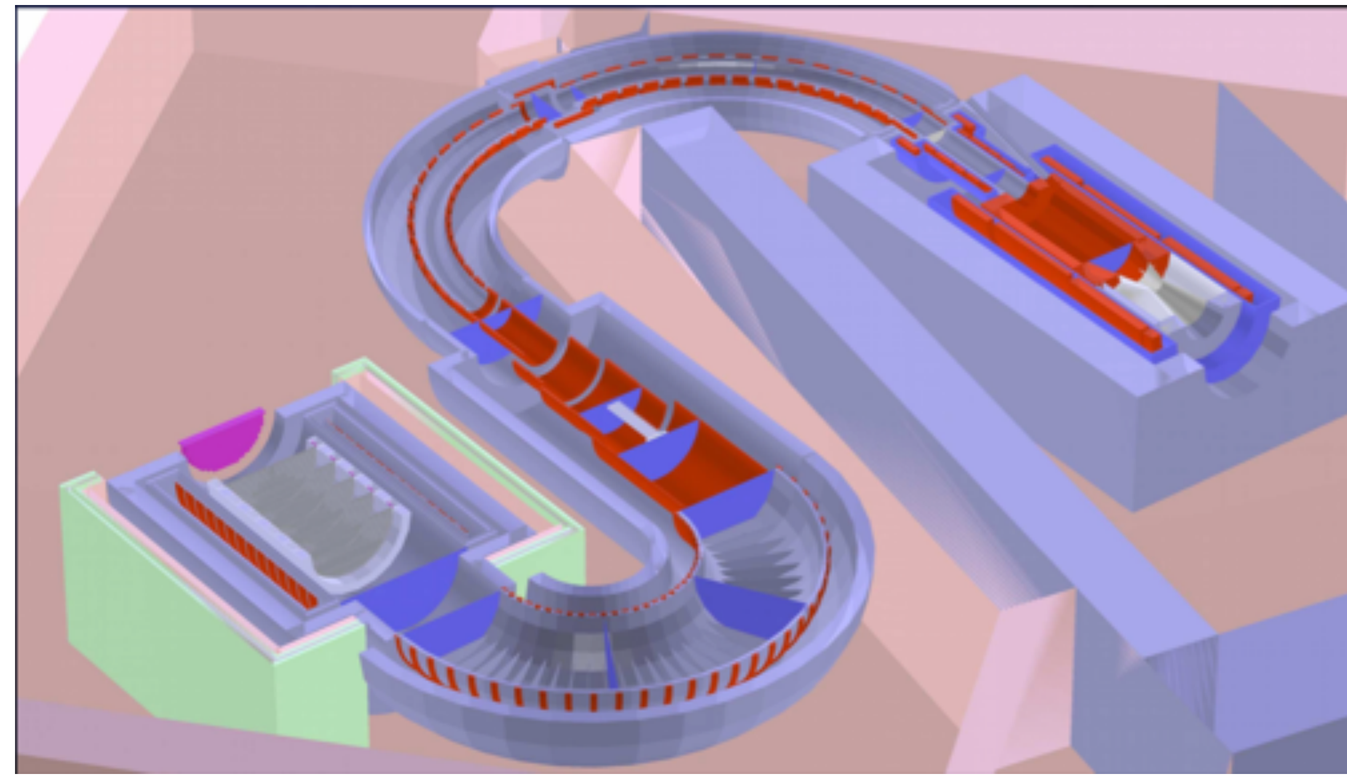


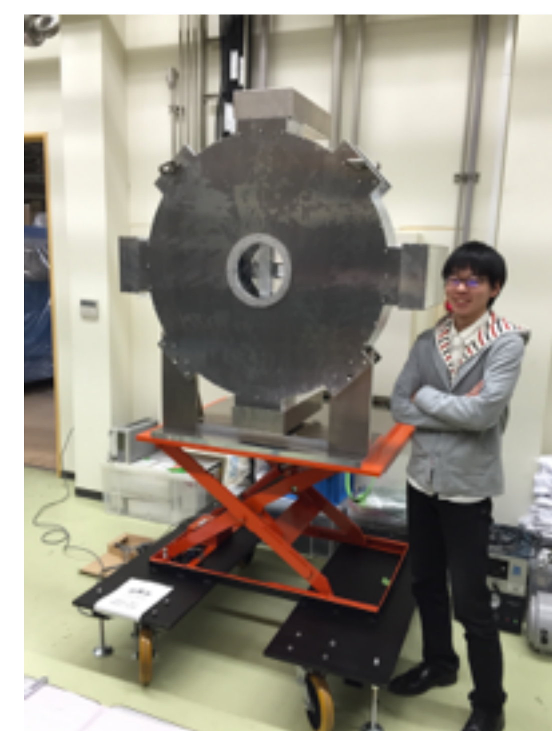
Principle of DeeMe



COMET at J-PARC

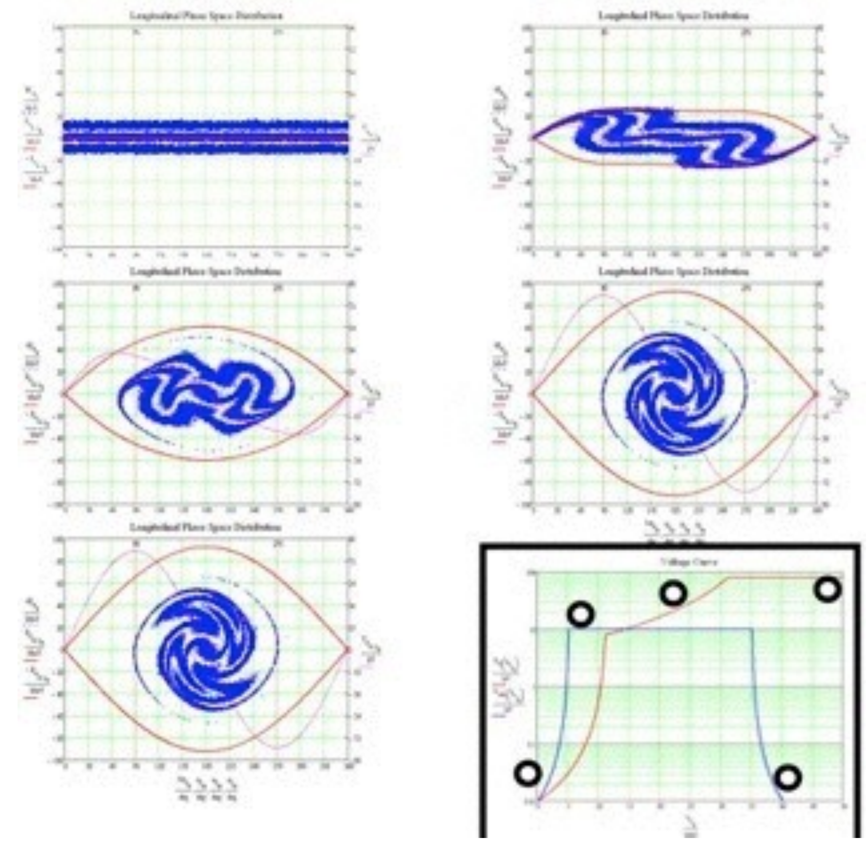
- **Target S.E.S. 2.6×10^{-17}**
- Pulsed proton beam at J-PARC
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- pion production target in a solenoid magnet
- Muon transport & electron momentum analysis using C-shape solenoids
  - smaller detector hit rate
  - need 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.



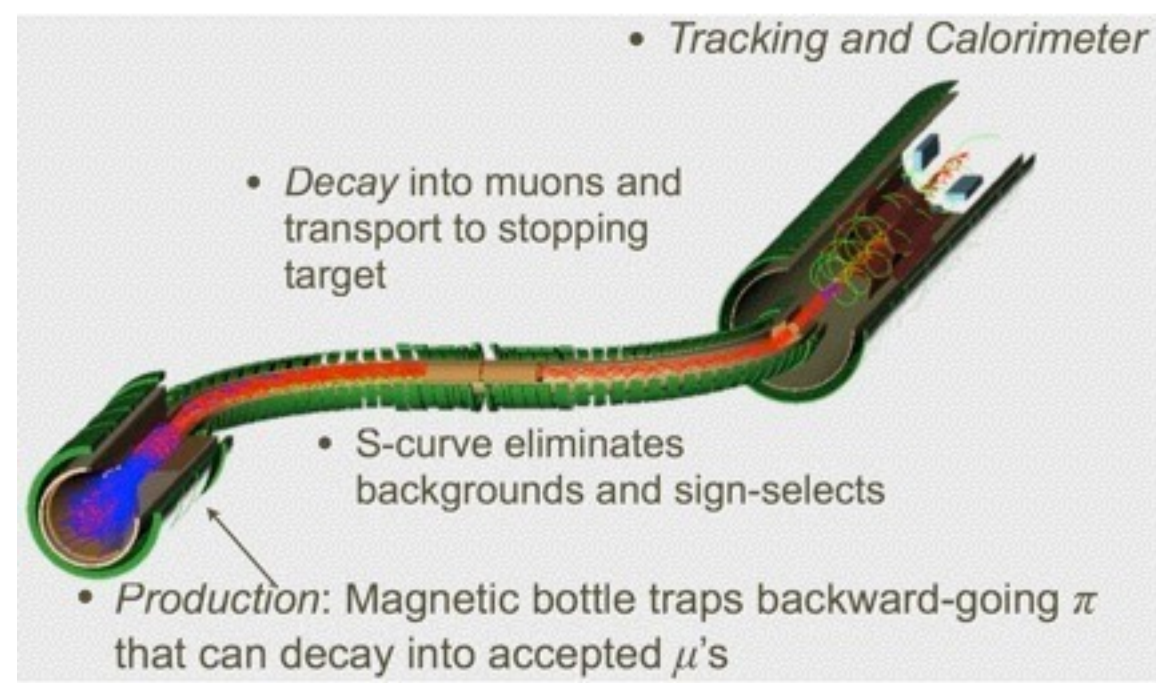


Mu2e at FNAL

- **Target S.E.S. 2×10^{-17}**
- uses the antiproton accumulator/debuncher rings to manipulate proton beam bunches
- No interference with NOvA experiment
  - Mu2e uses beam NOvA can't
- pion production target in a solenoid magnet
- S-shape muon transport to eliminate BG and sign-select
- Tracker and calorimeter to measure electrons



FNAL Muon Campus Aug 2016



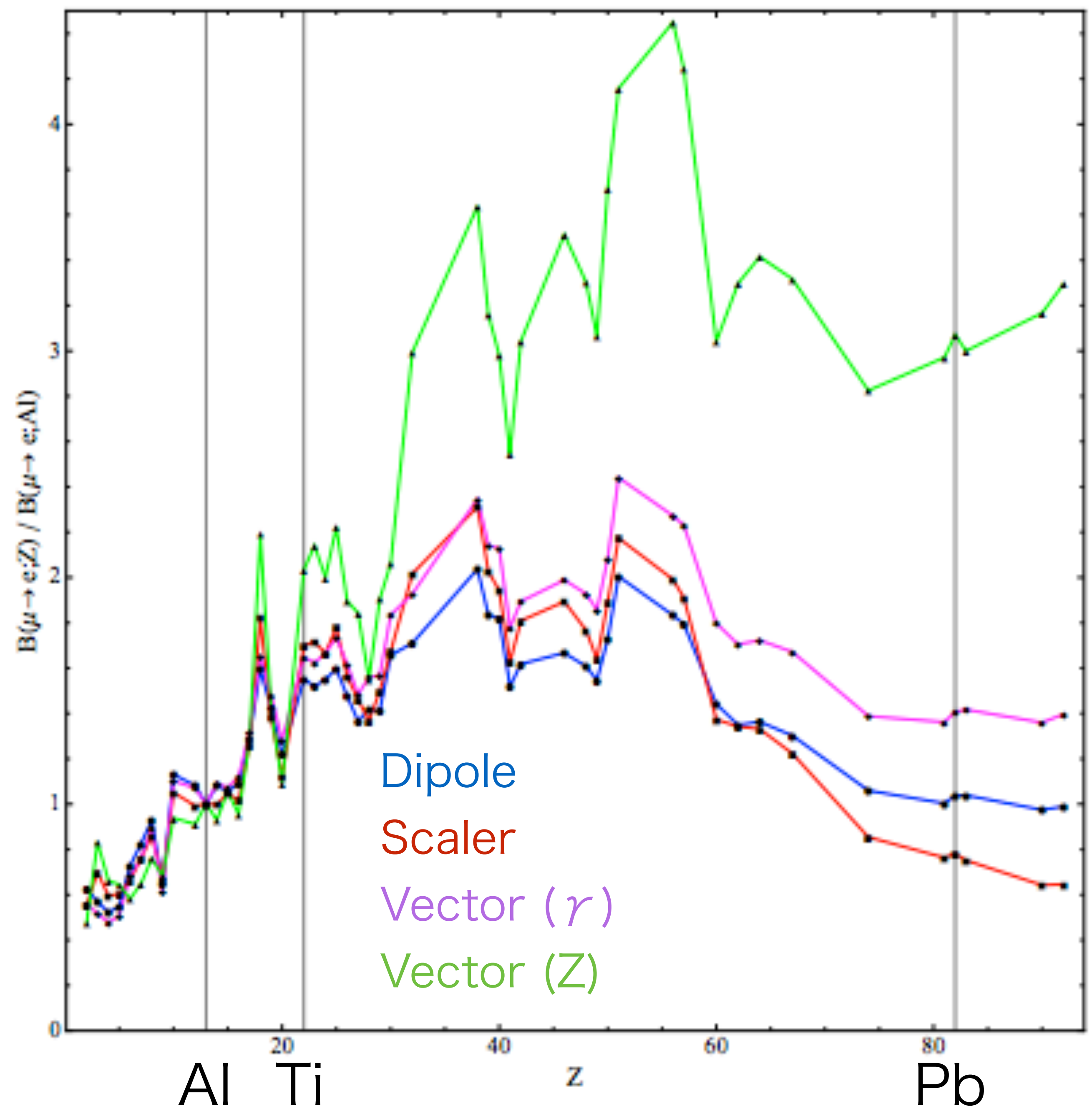
Muon Stopping Target Dependence

- 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

On the model discriminating power of $\mu \to e$ conversion in nuclei

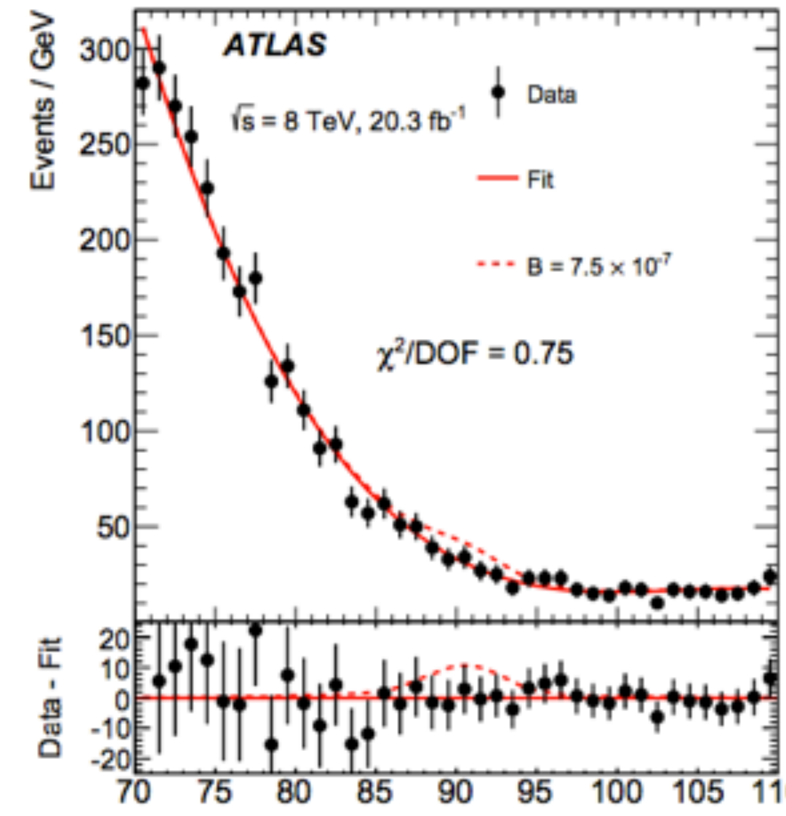
Vincenzo Cirigliano[a], Ryuichiro Kitano[a,b], Yasuhiro Okada[c], Paula Tuzon[a,d]



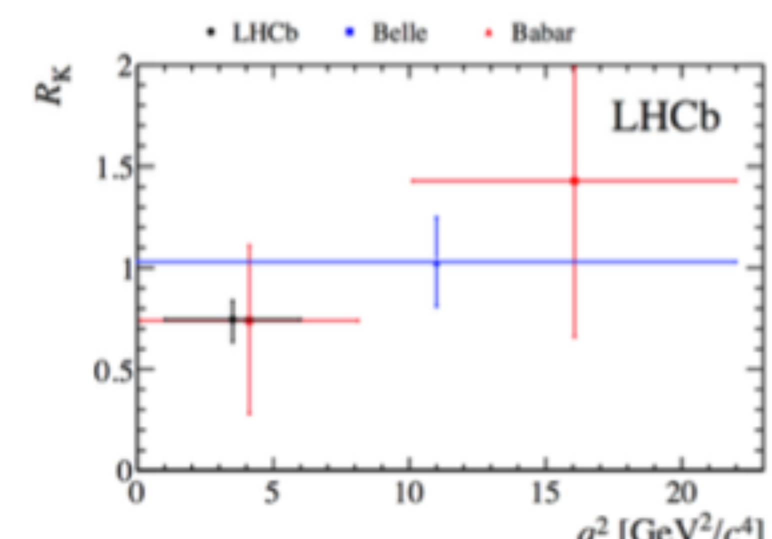
cLFV Searches and Lepton Universality Tests at Colliders

- cLFV searches
  - H/Z boson decays to e/μ, τ at LHC
  - tau lepton decays at LHC, BES III & Belle (and Belle II soon!)
- Tensions in B-Physics
  - $B^0 \to D(*)\ \tau\nu_\tau / l\nu_l$ 3.9σ : LHCb + BaBar + Belle
  - $B^+ \to K^+ \mu\mu$ / ee 2.6σ : LHCb
  - Anomalies $b \to sll$, esp. P'5 in $B \to K^*\mu\mu$ @ LHCb 3.4σ & Belle 2.1σ
    - New physics effect or long distance charm loop?

arXiv:1604.08221

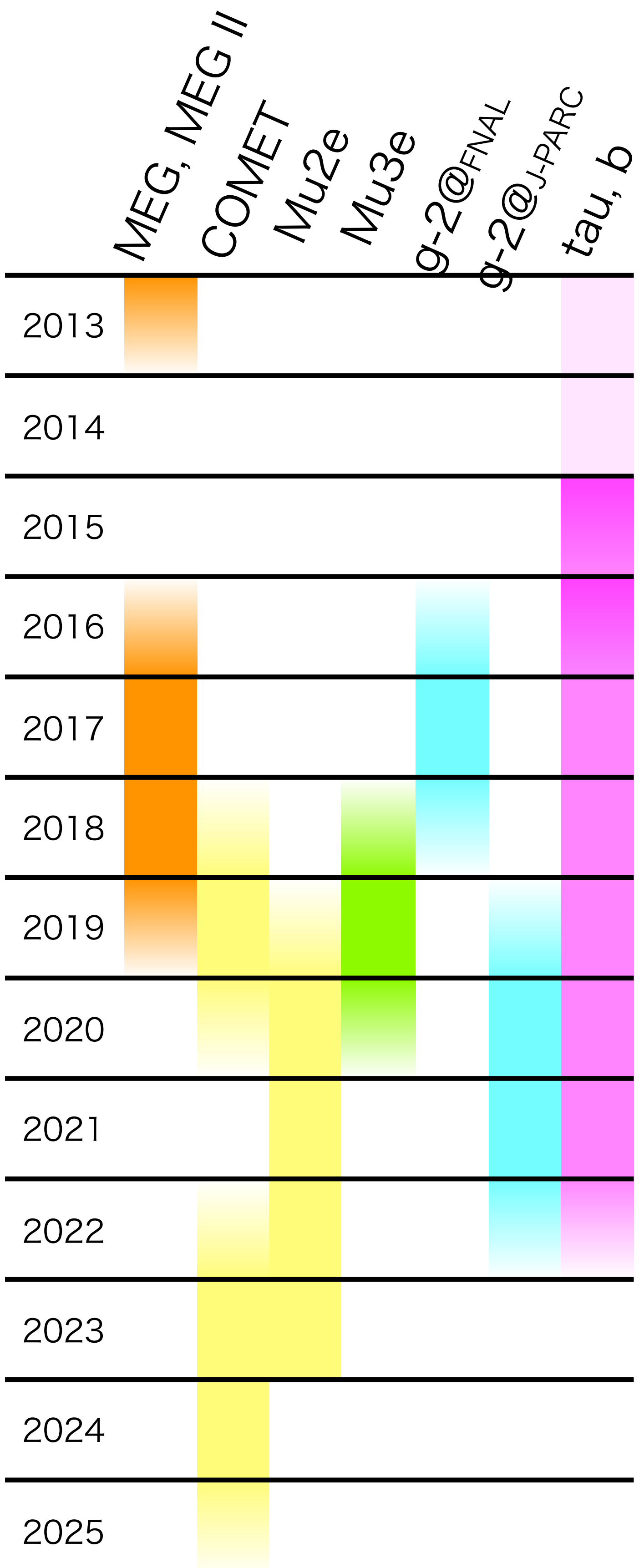


NuFACT16, Marc Bret



NuFACT16, F. Lionetto

Summary



- cLFV experiments using muons
- MEG new result
  - Br($\mu \to e\gamma$) < 4.2×10^{-13} @ 90% C.L.
- MEG II, DeeMe, COMET, Mu2e, Mu3e in preparation
- New results from LHC experiments and BES III, Belle & Belle II