New cLFV search experiments using the mu-e conversion process

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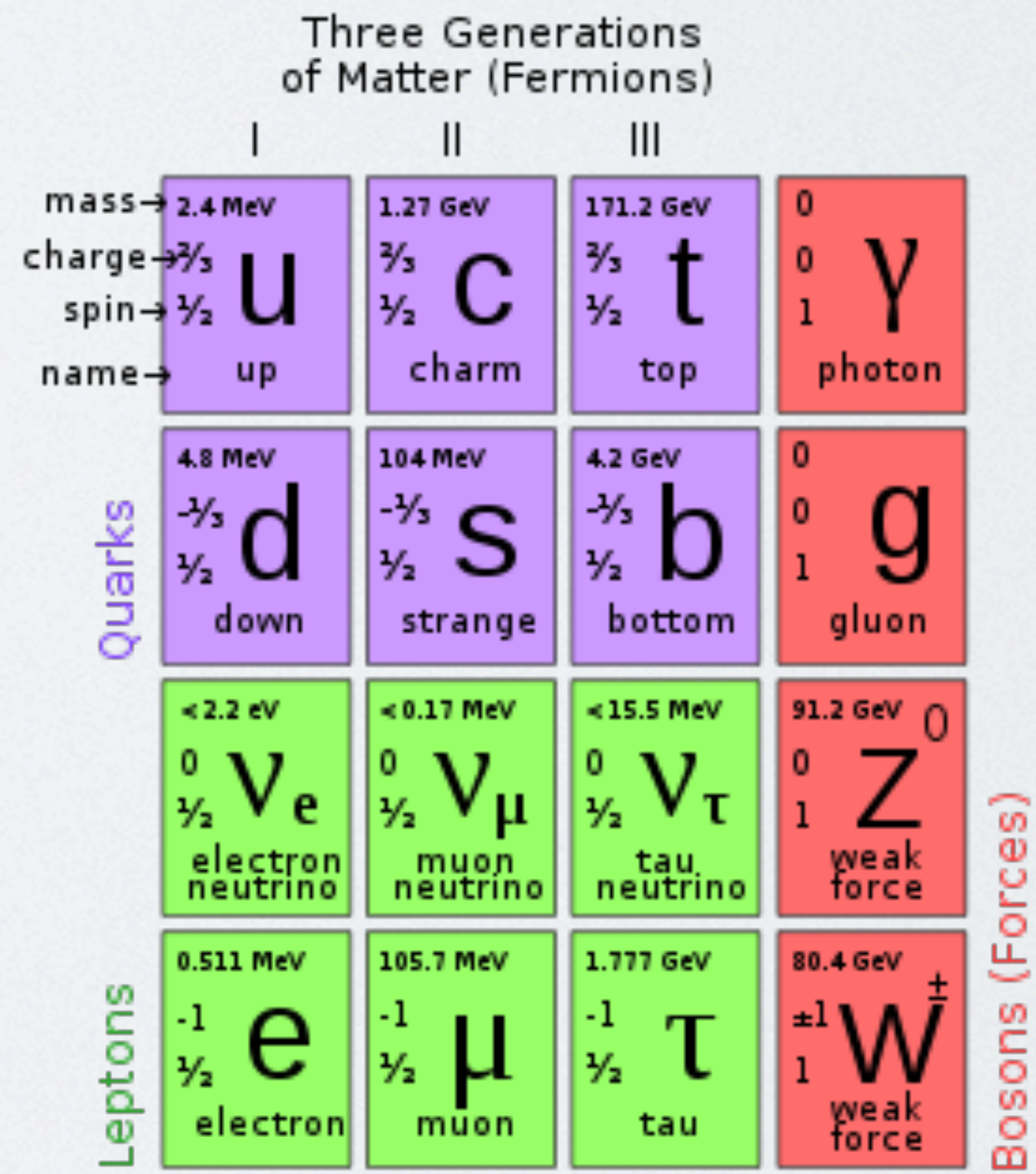
Outline

- Muon in Particle Physics - from an experimentalist point of view
- Why Muon cLFV ?
- Mu-e conversion search experiments
- Summary

Muon in Particle Physics

- Muon discovery in 1936
- 1st $\mu \rightarrow e\gamma$ search in 1947 by Hincks and Pontecorvo
    - "meson" $\rightarrow e\nu$ hypothesis not consistent with an experiment
    - Verification of $e\gamma$ hypothesis
- Theoretical calc. of $Br(\mu \rightarrow e\gamma)$ found to be inconsistent with the exp. limit by Feinberg in 1958
    - two neutrino models
- Experimental confirmation of $\nu_\mu \neq \nu_e$ in 1962 by Lederman et al.
- "Lepton Flavor" concept



from wikipedia

- Muon played an important role to establish the SM of the elementary particle physics.

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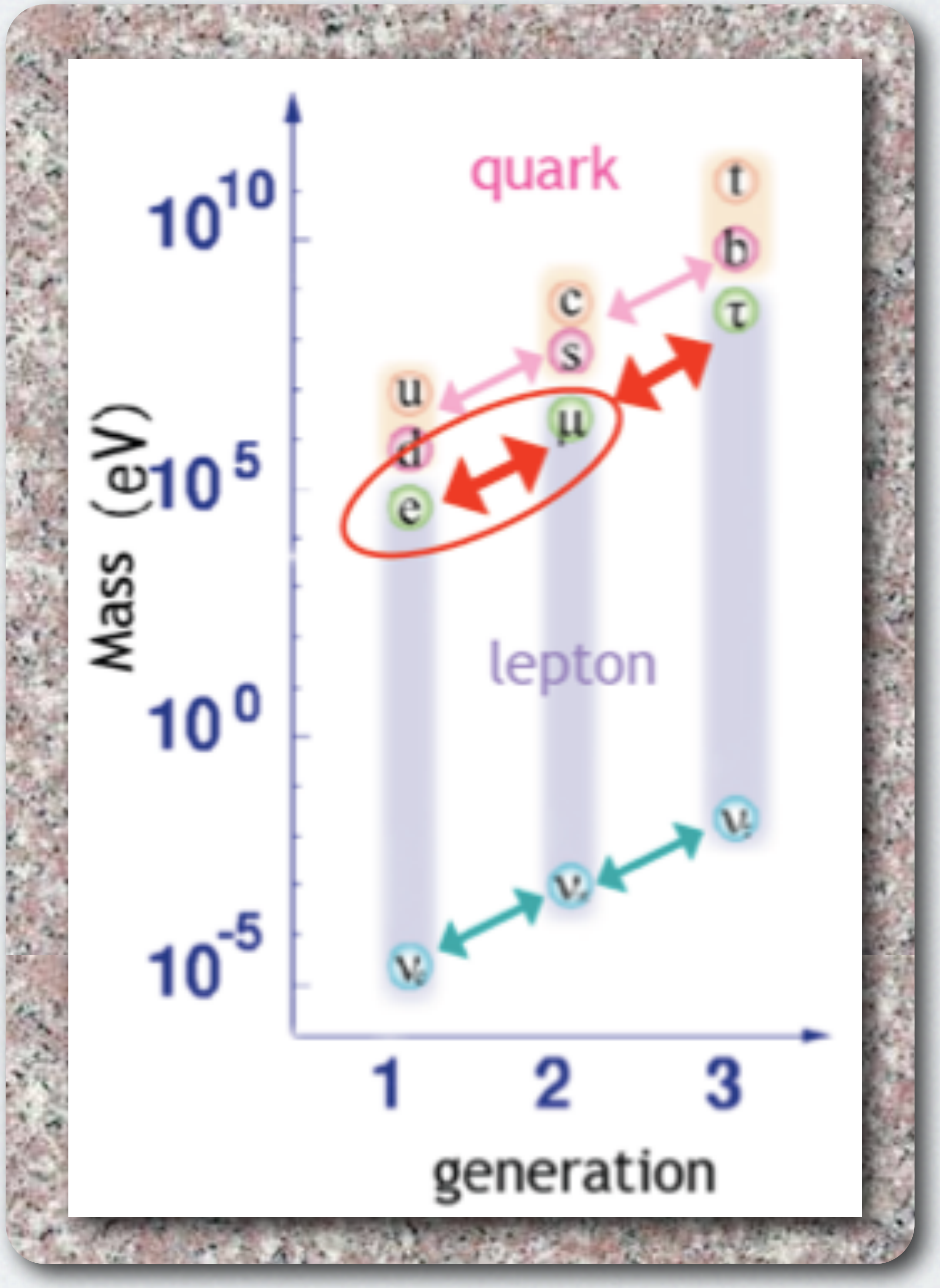
- Muon played an important role to establish the SM of the elementary particle physics.
- Will it be same in the future?

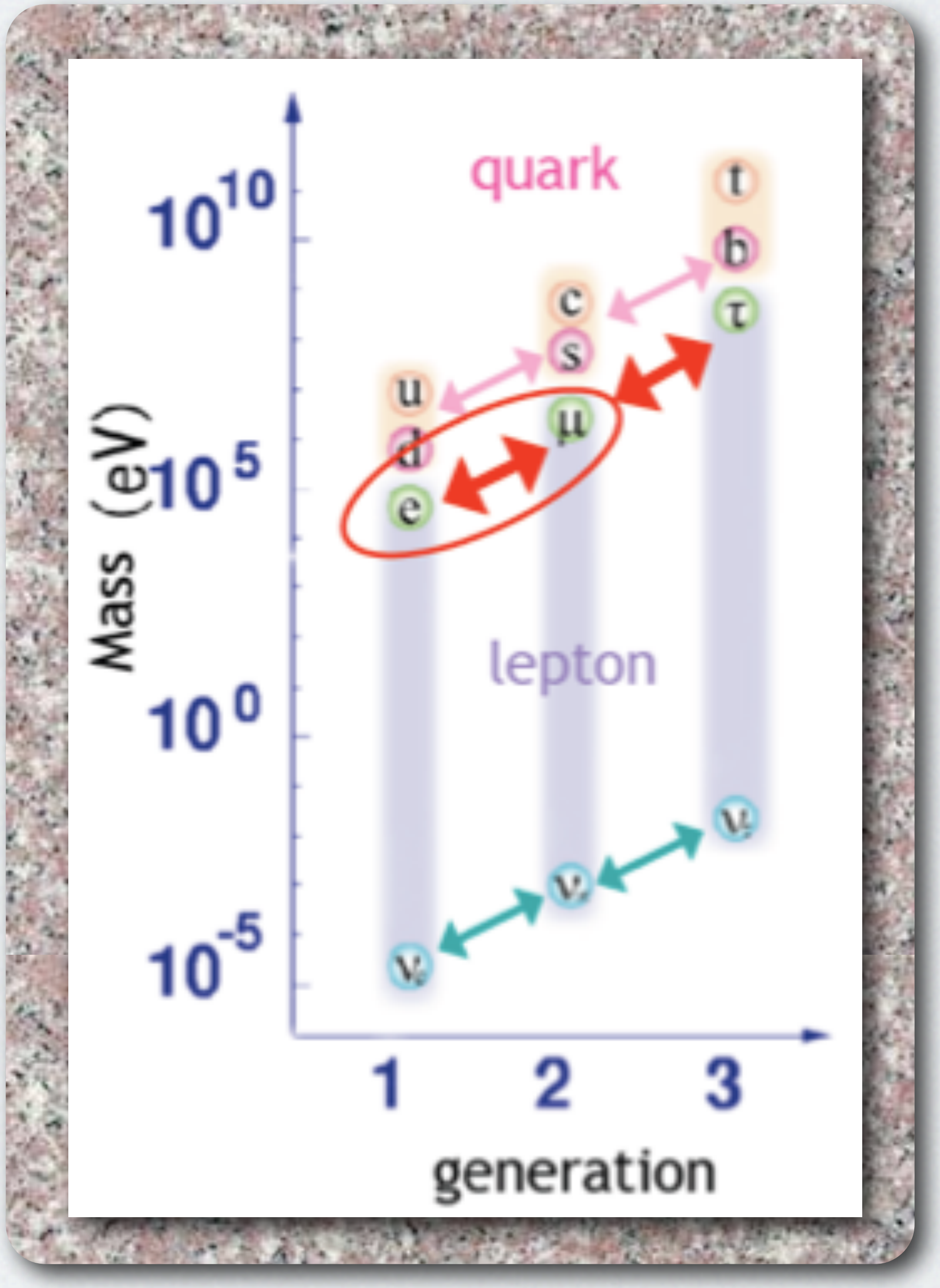
Flavor Physics

- SUSY-GUT
- Quark mixing
- Neutrino mixing



Flavor Physics

- SUSY-GUT
- Quark mixing
- Neutrino mixing
- Charged Lepton mixing

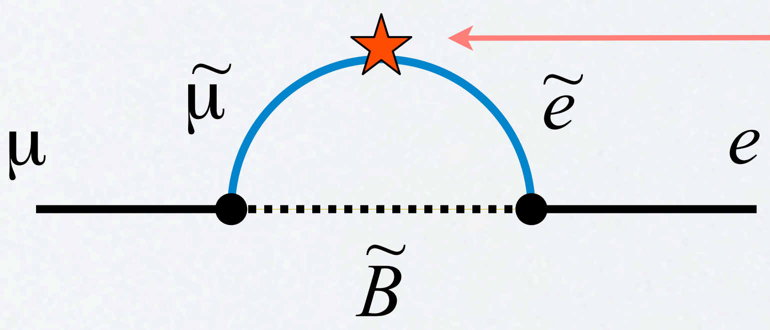


Why Muon cLFV?

- Why cLFV?
  - no SM background →Suitable for New physics searches
  - no ambiguity caused by hadronic interactions
- Why Muon?
  - Muon decays to electron and neutral particle(s) with relatively long life time
  - Easy to produce from pion decay

What can we learn from muon cLFV?

- Slepton mass matrix information (supposing SUSY)



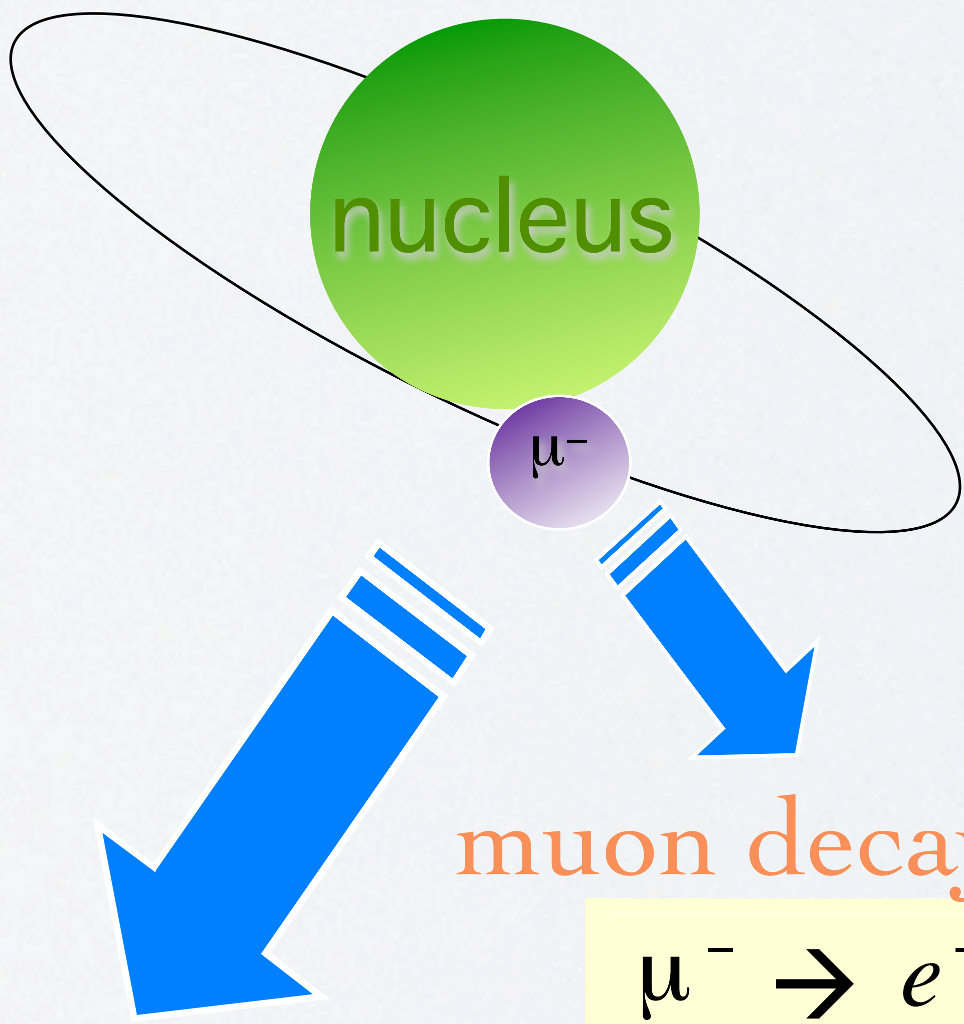
$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

- off-diagonal elements carries information on
  - SUSY breaking
  - LFV interaction at high-energy scale

mu-e conversion search experiment

What is a μ-e Conversion ?

1s state in a muonic atom



Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

lepton flavors changes by one unit

muon decay in orbit

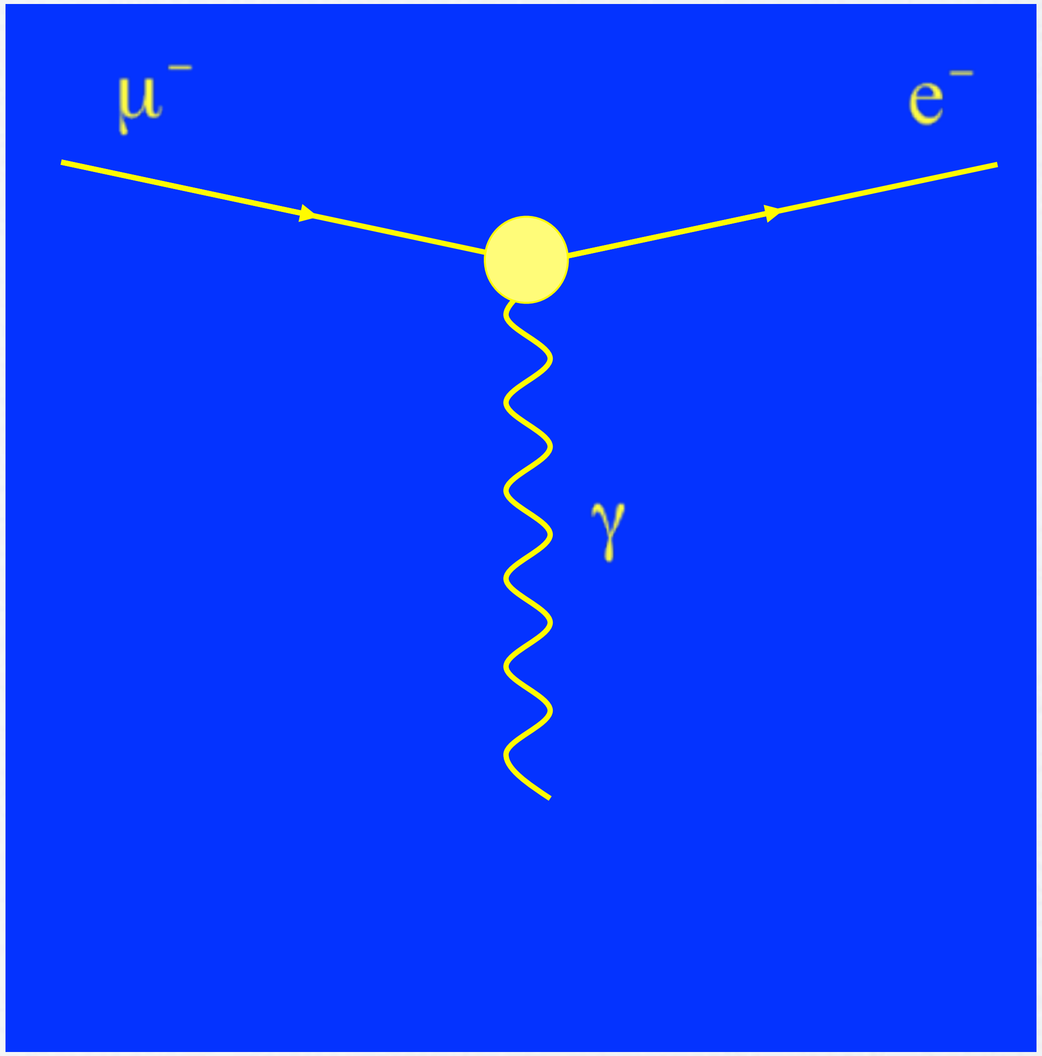
$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

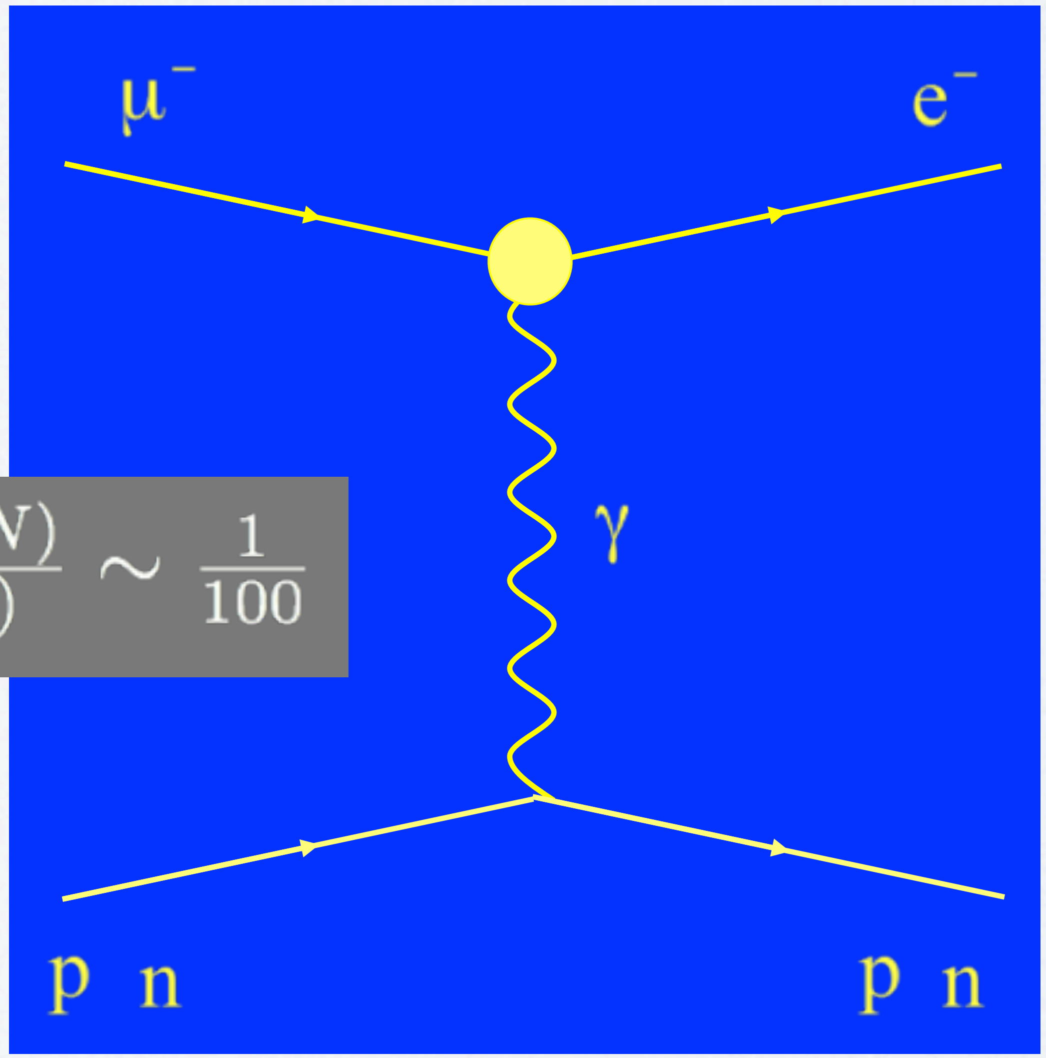
$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

$\mu \rightarrow e\gamma$ and μ-e conversion



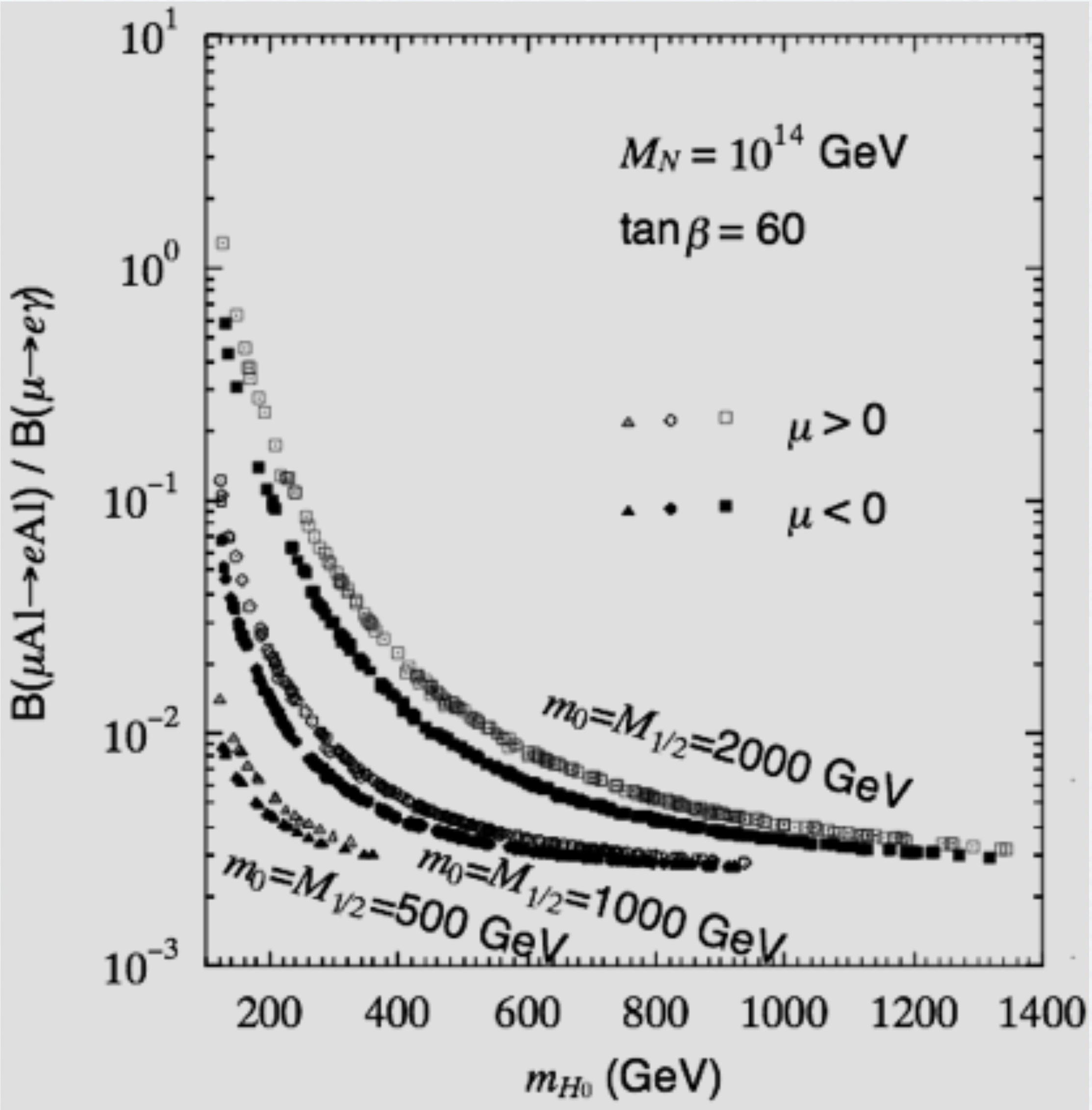
μ→eγ and μ-e conversion

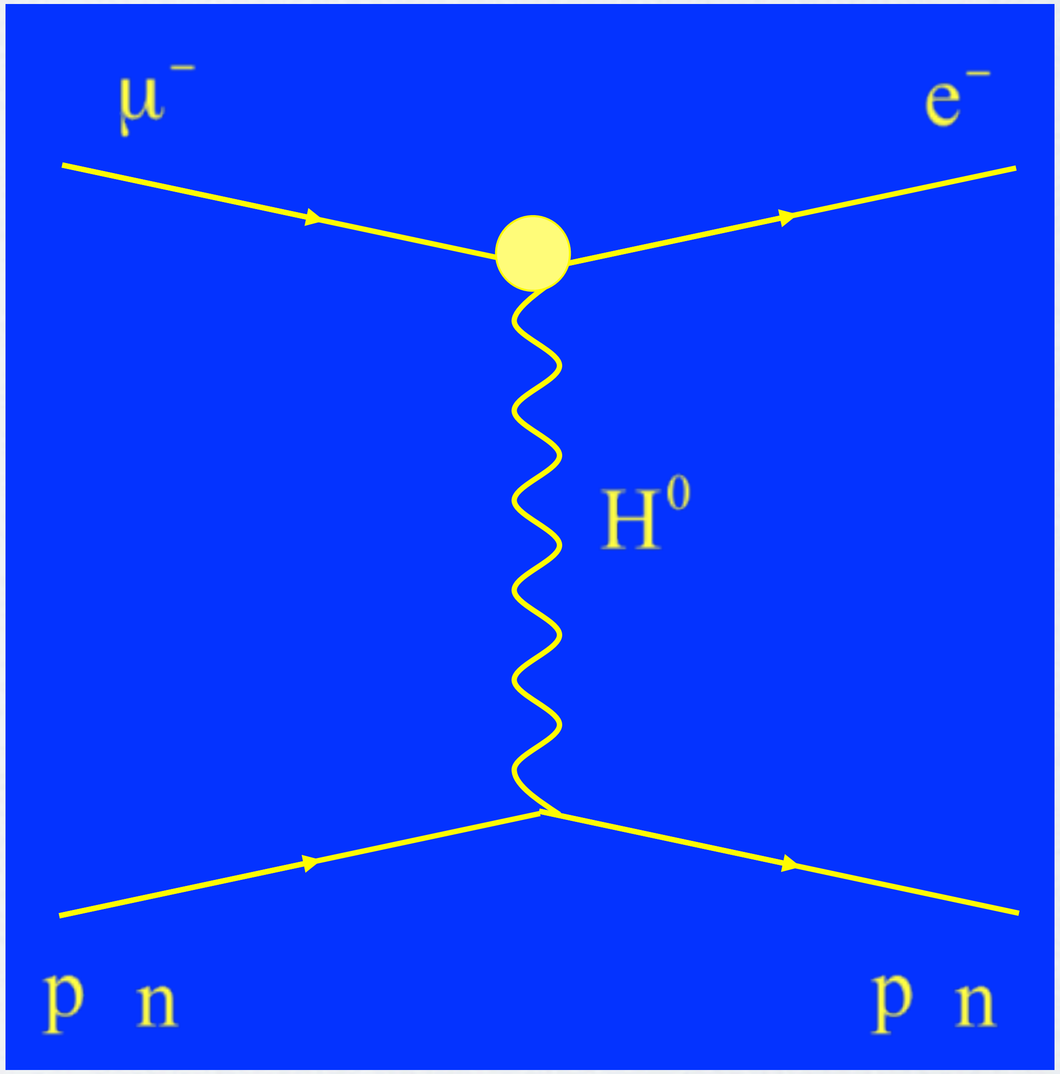


$$\frac{B(\mu N \to e N)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$

- If μ→eγ exits, μ-e conv. must be

μ→eγ and μ-e conversion

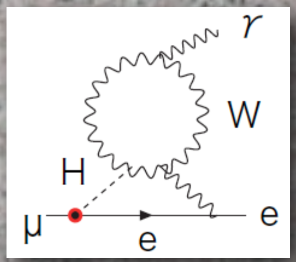


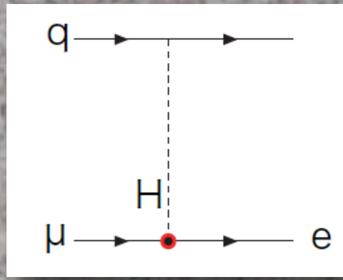


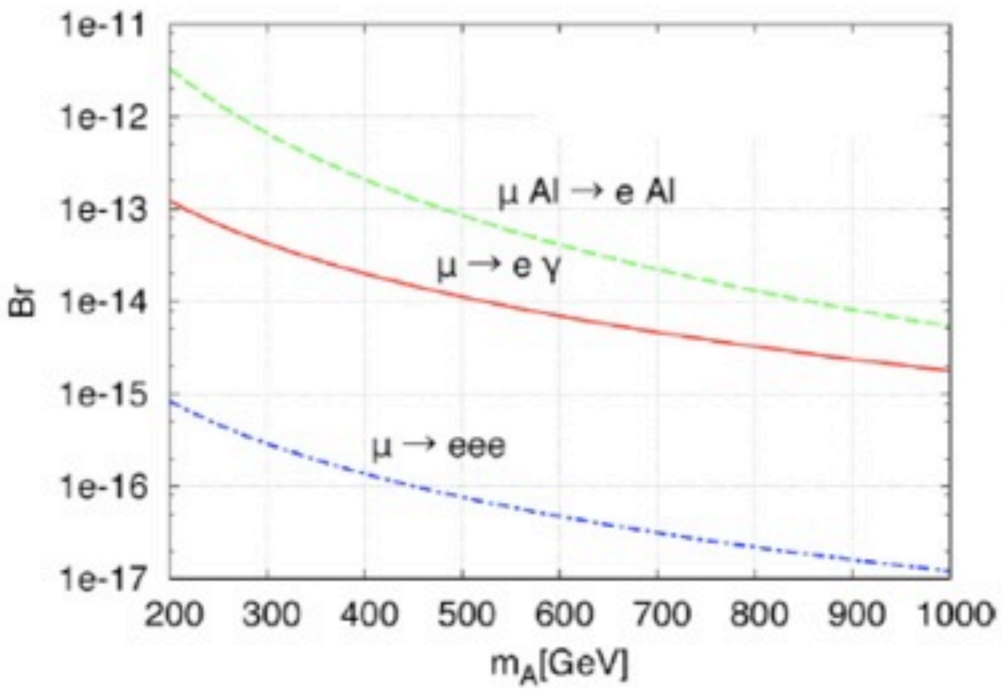
- If μ→eγ exits, μ-e conv. must be
- Even if μ→eγ is not observed, μ-e conv may be
  - Loop vs Tree
  - Searches at LHC

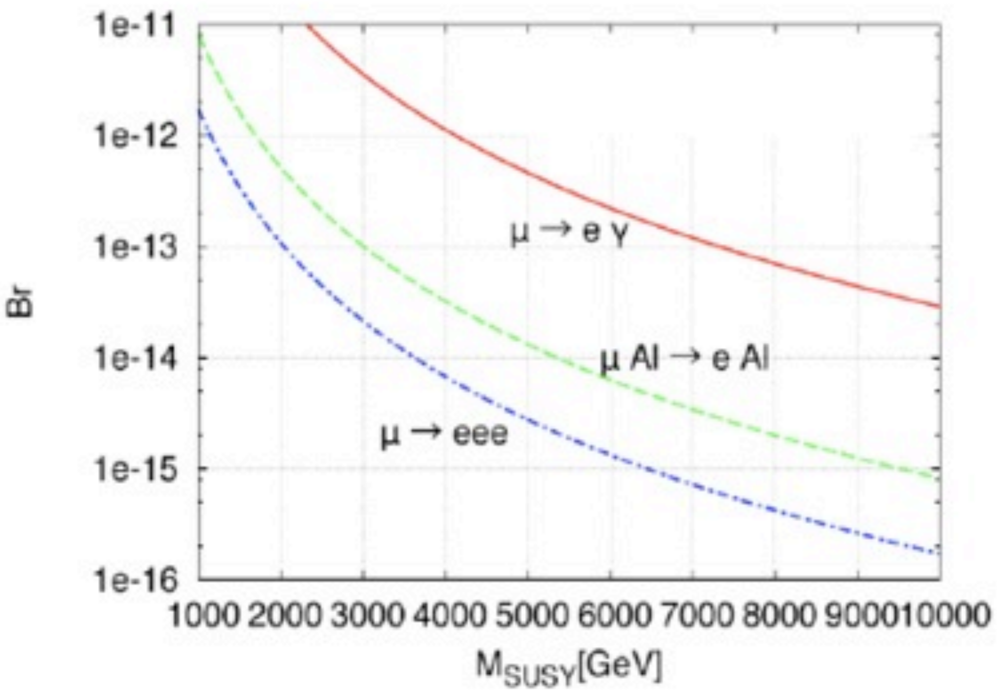
μ→eγ and μ-e conversion

Higgs exchange vs SUSY 1-loop







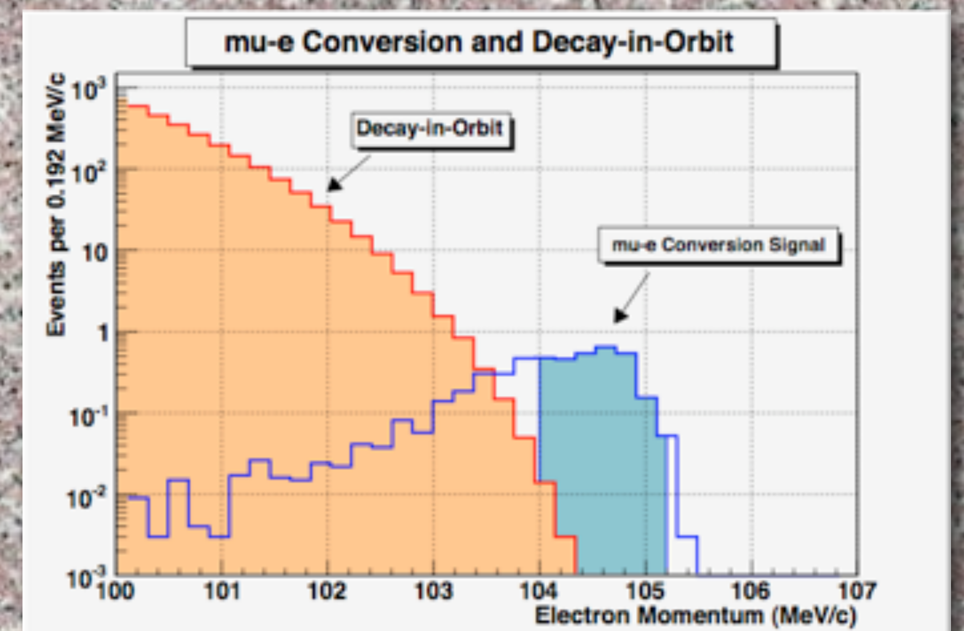


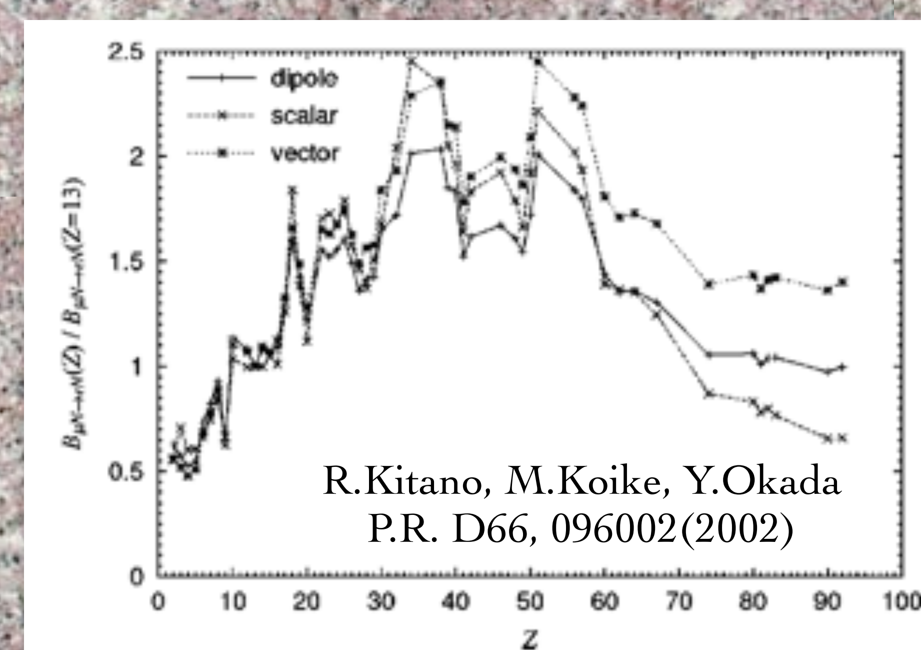
Hisano et al. '10

- Important to measure both μ→eγ and μ-e with similar sensitivity

μ-e conversion signal

- $E_{\mu e} \sim m_\mu - B_\mu$
  - B_μ: binding energy of the 1s muonic atom
- Improvement of a muon beam is possible, both in purity (no pions) and in intensity (***thanks to muon collider R&D***). A higher beam intensity can be taken because of no accidentals.
- Potential to discriminate different models through studying the Z dependence



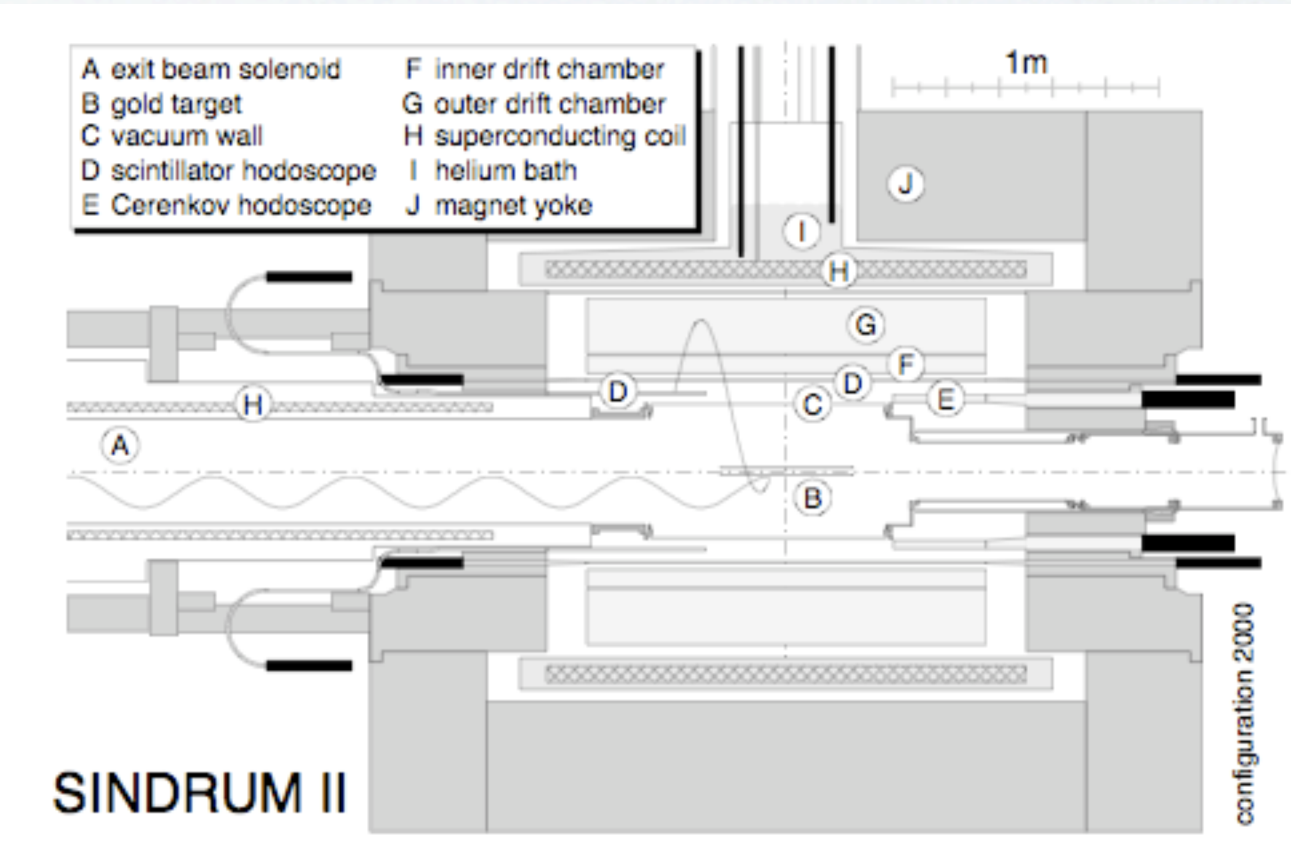


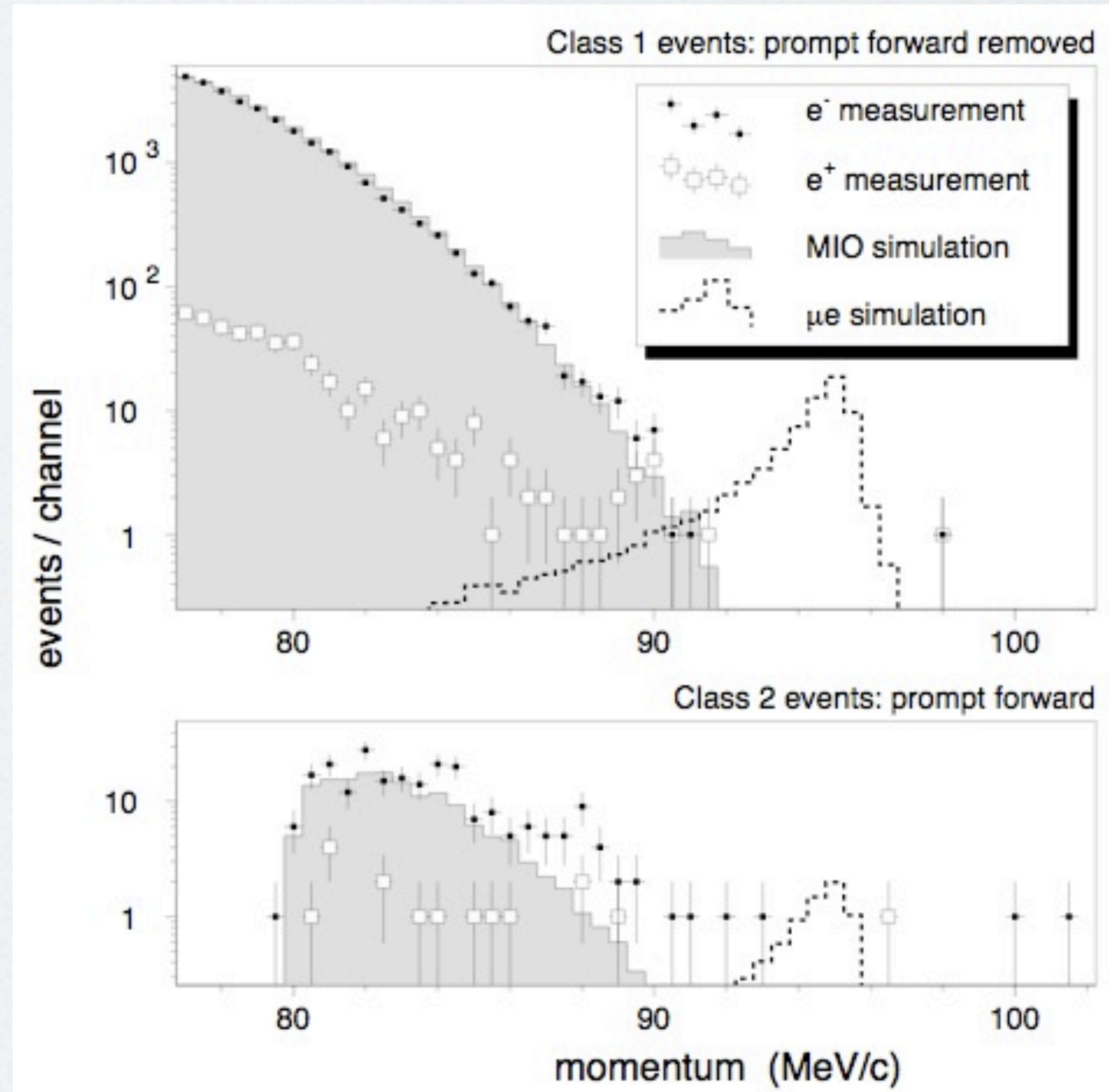
R.Kitano, M.Koike, Y.Okada
P.R. D66, 096002(2002)

The SINDRUM-II Experiment (at PSI)

Published Results

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$





SINDRUM-II used a continuous muon beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed.

Future mu-e conversion search experiments

- Mu2e at FNAL
- COMET and DeeMe at J-PARC

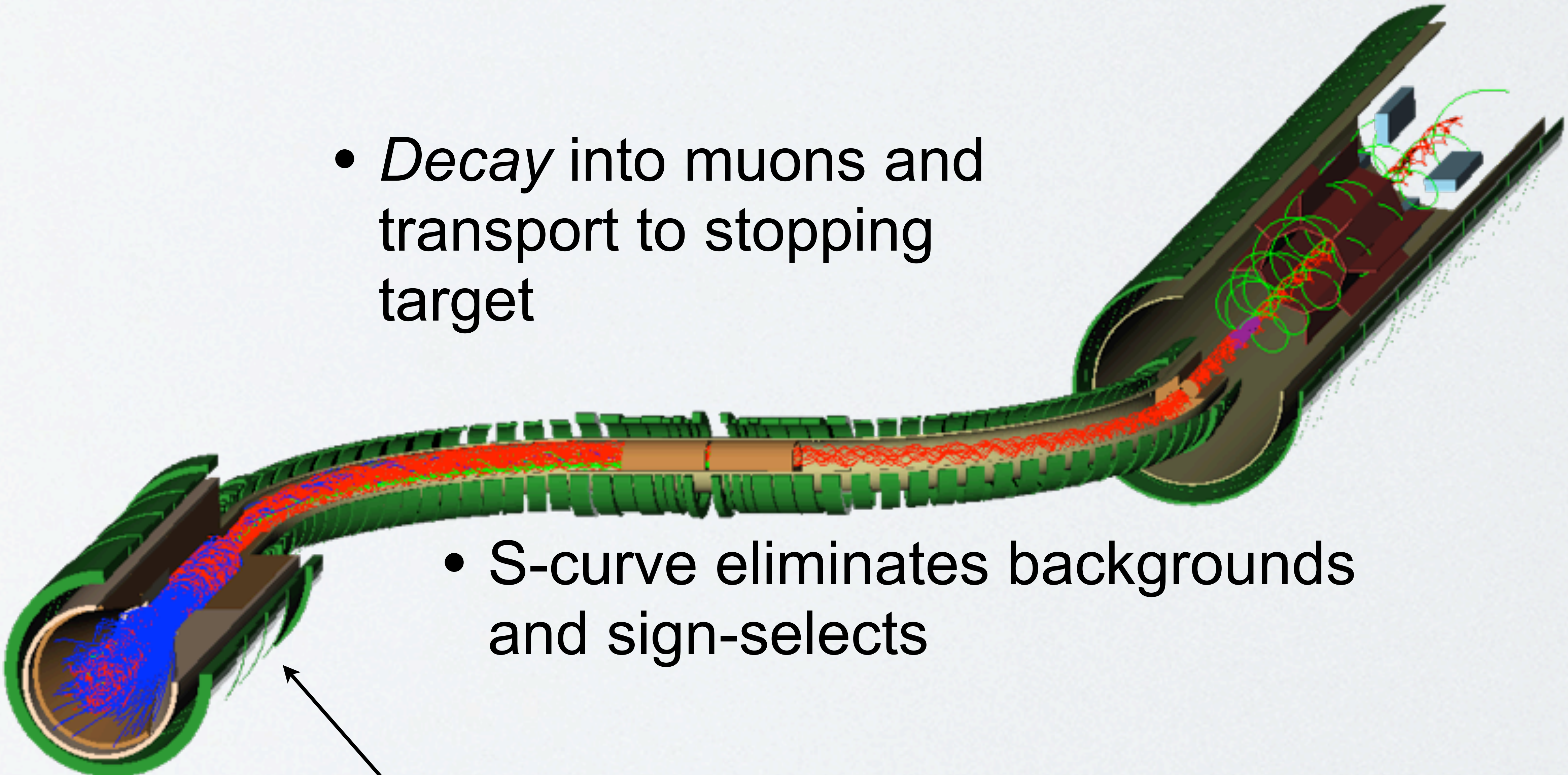
Mu2e

mu-e conversion search at FNAL

Detector and Solenoid

- *Tracking and Calorimeter*

- *Decay* into muons and transport to stopping target

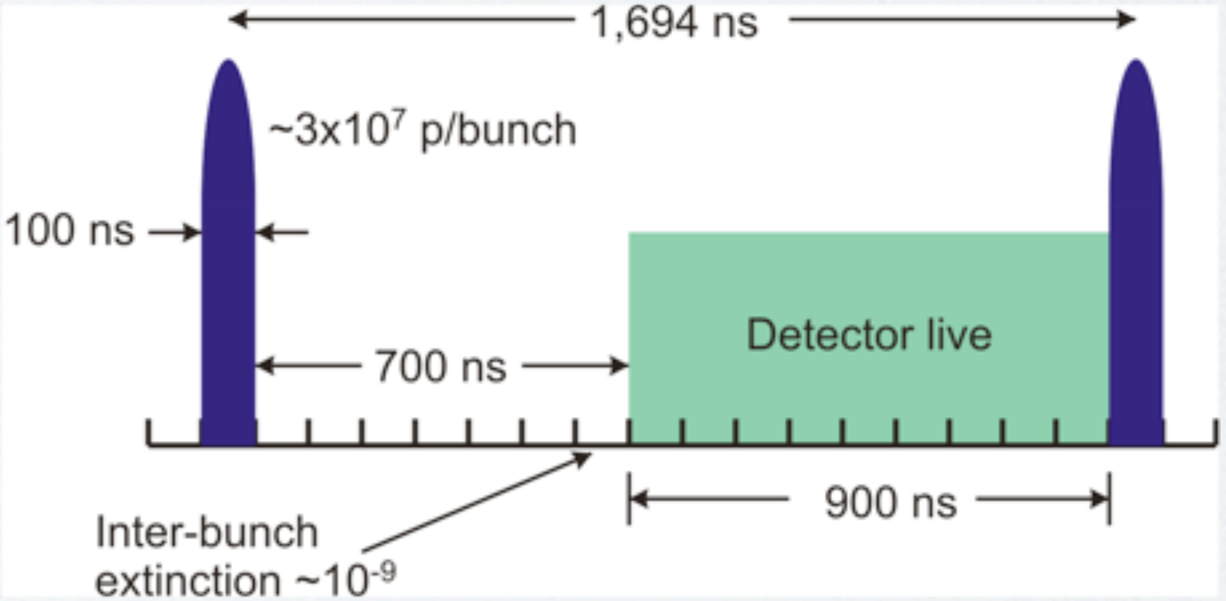


- S-curve eliminates backgrounds and sign-selects

- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ's

Pulsed Beam Structure for Mu2e

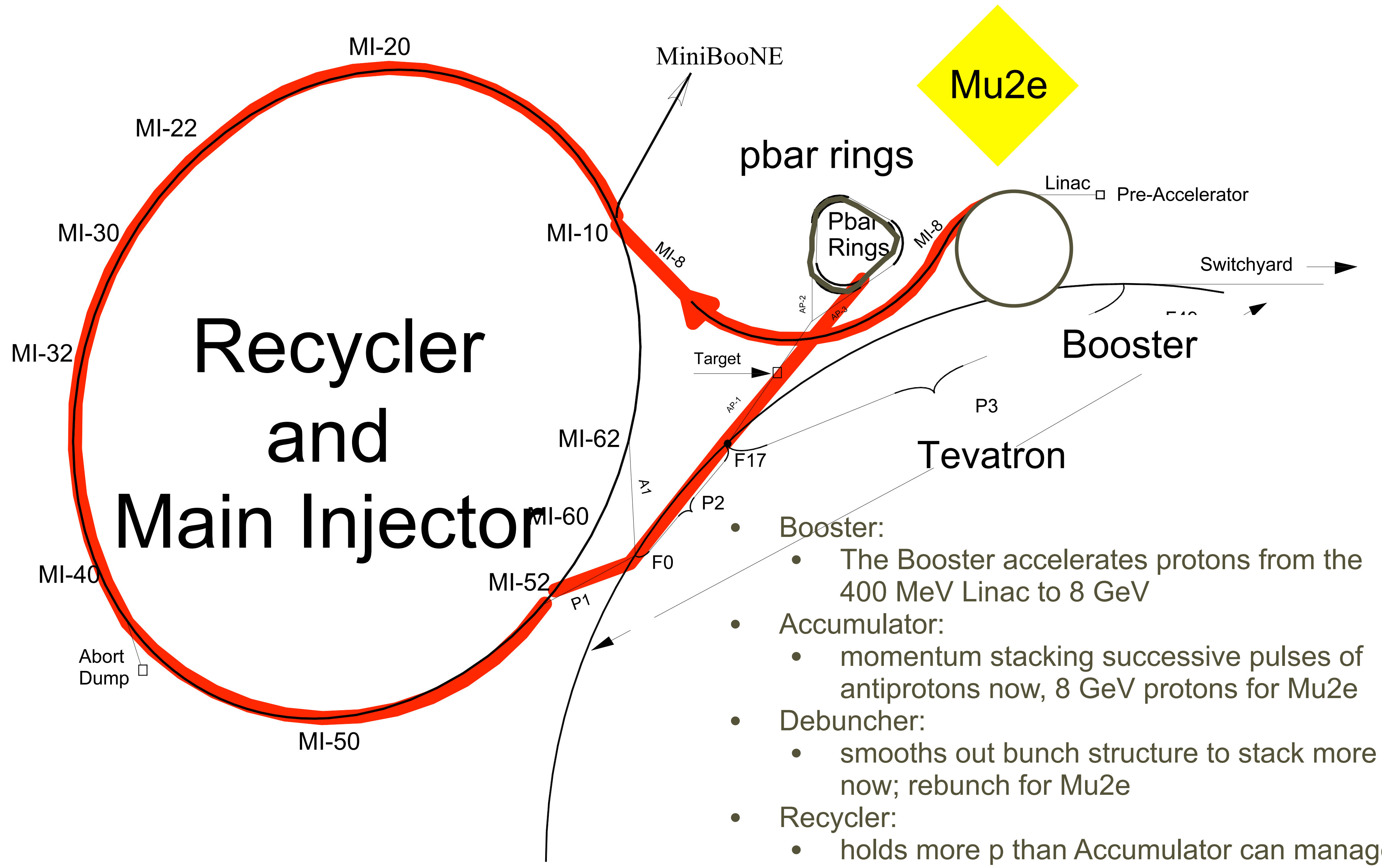
- Tied to prompt rate and machine: FNAL near-perfect
- Want pulse duration << τ_μ^{Al} , pulse separation ≥ τ_μ^{Al}
  - FNAL Debuncher has circumference **1.7μsec** !
- Extinction between pulses < 10^{-9} needed
  - = # protons out of pulse/# protons in pulse



- 10^{-9} based on simulation of prompt backgrounds

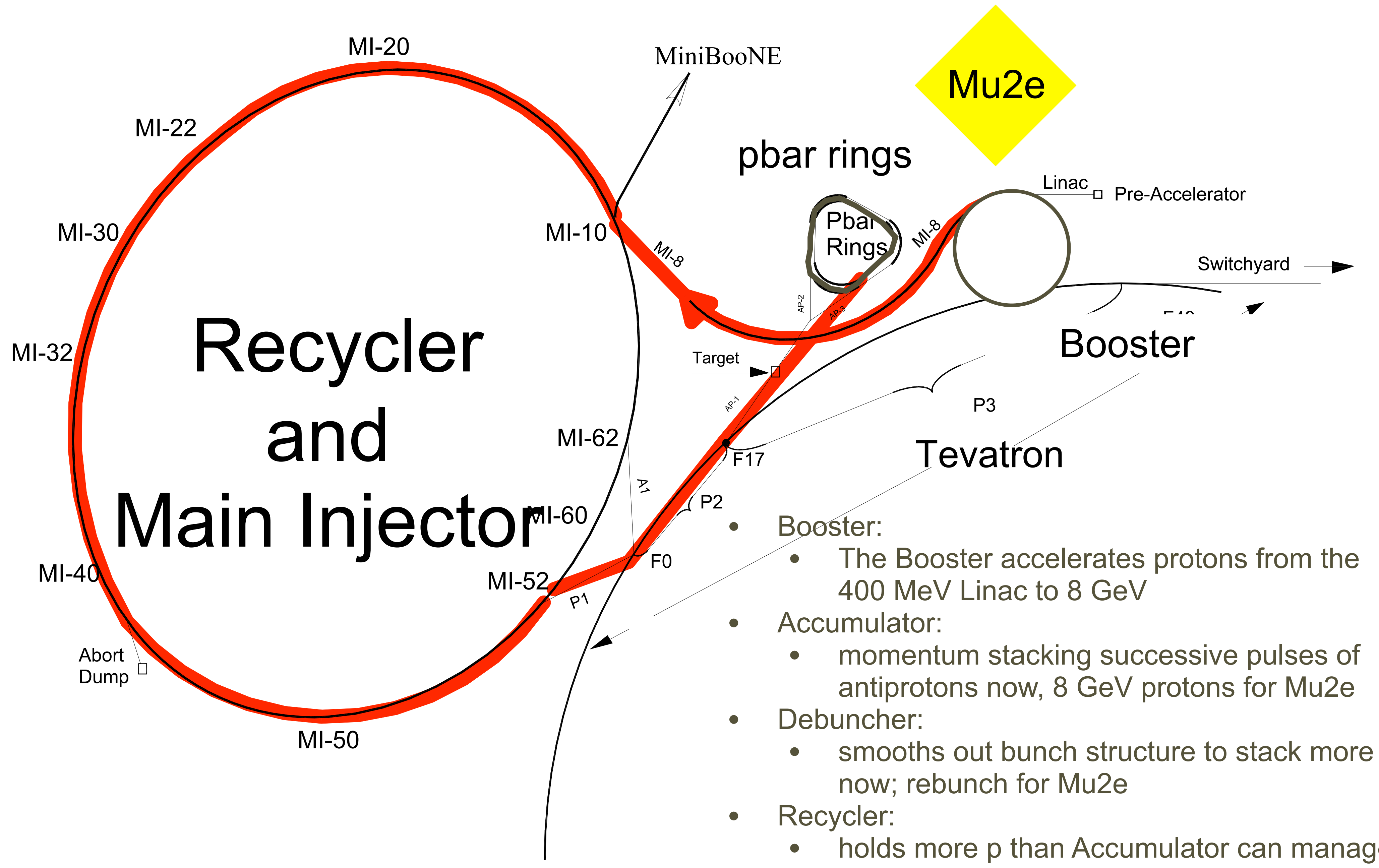
M. Syphers, FNAL

“Boomerang” Scheme



- Booster:
  - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
  - momentum stacking successive pulses of antiprotons now, 8 GeV protons for Mu2e
- Debuncher:
  - smooths out bunch structure to stack more p now; rebunch for Mu2e
- Recycler:
  - holds more p than Accumulator can manage, “store” here; transport line for Mu2e

"Boomerang" Scheme



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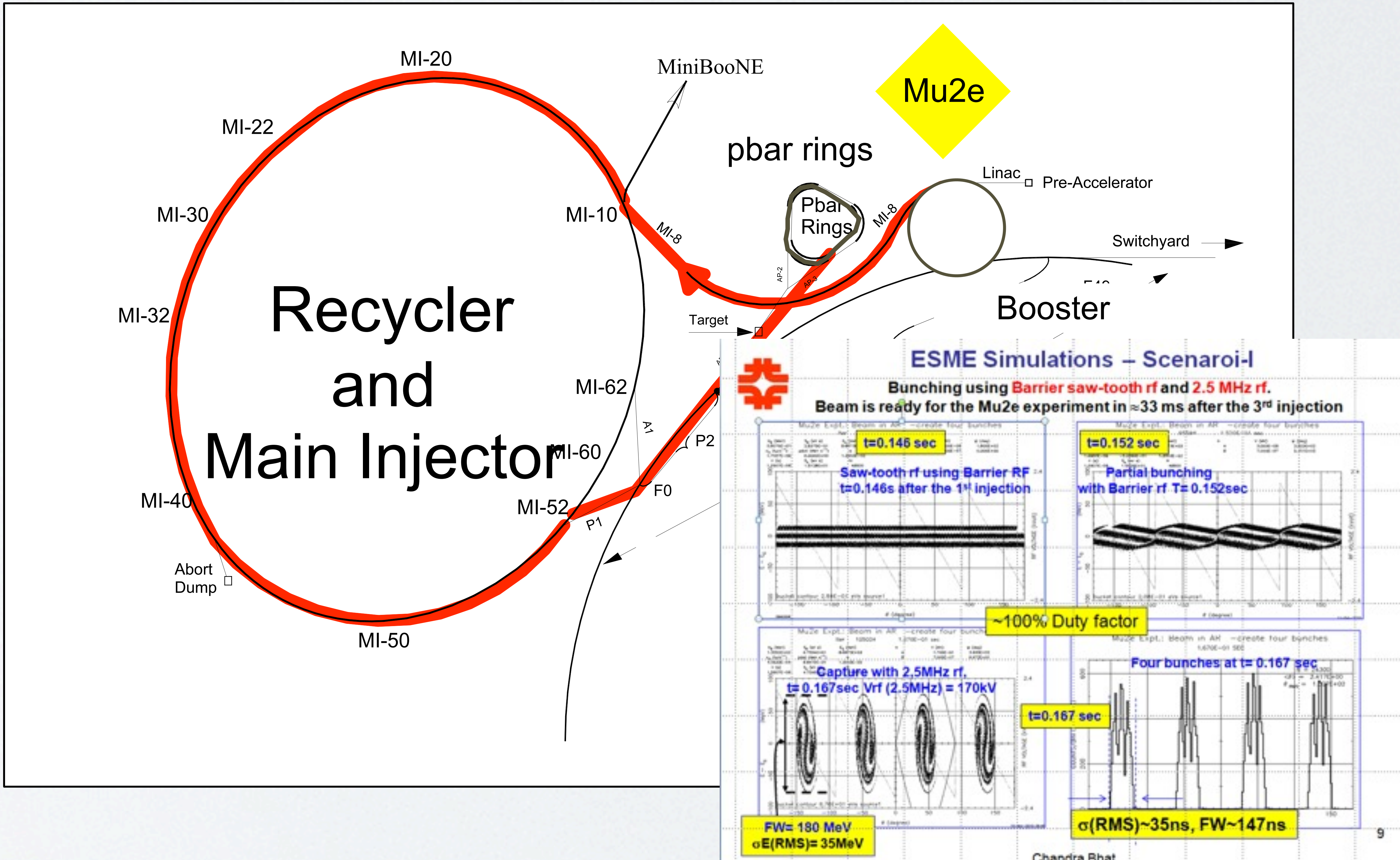
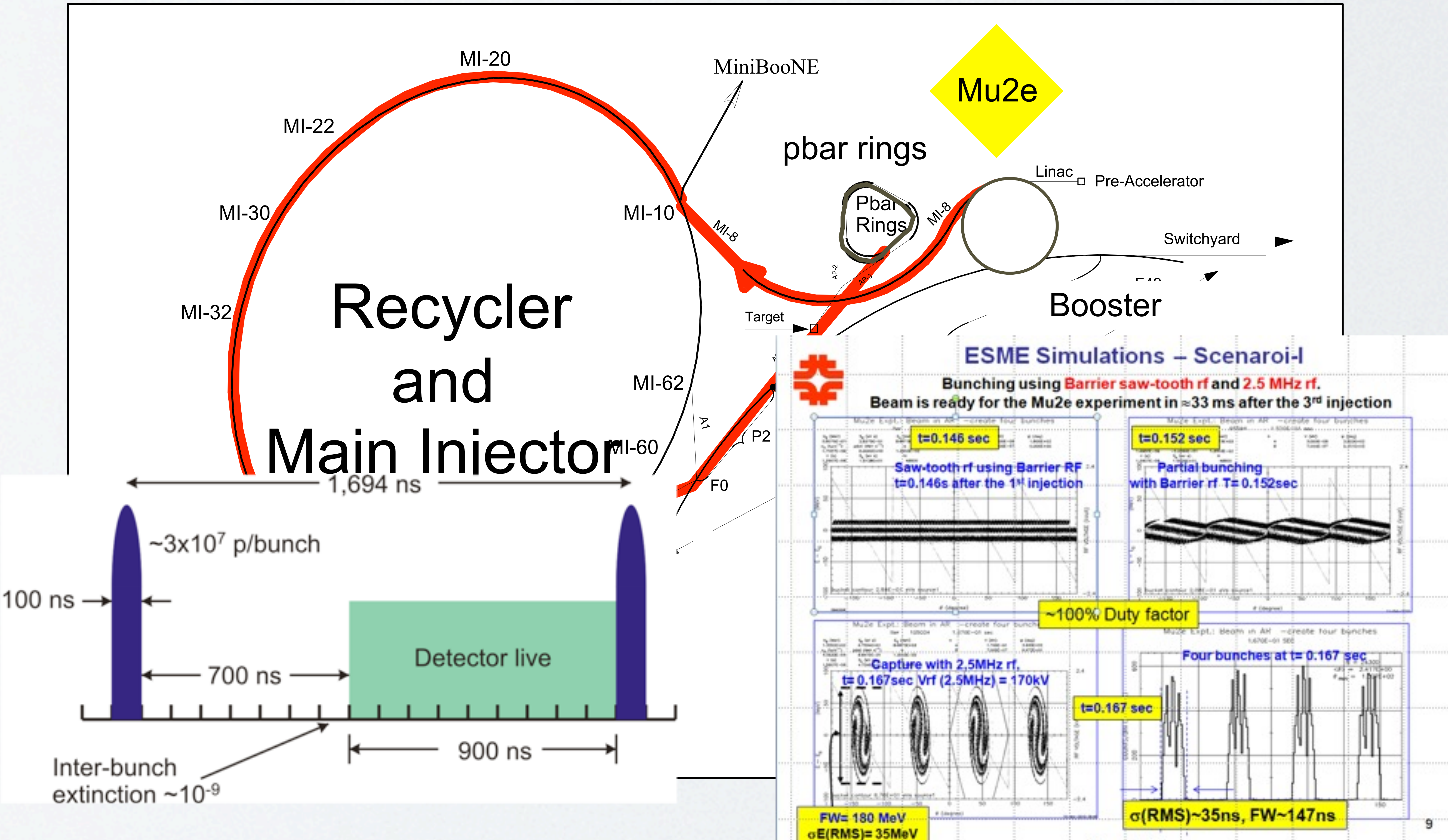
R. Bernstein, FNAL

“Boomerang” Scheme



C. Bhat and M. Syphers Mu2e Acc WG meeting Mar 9, 2010

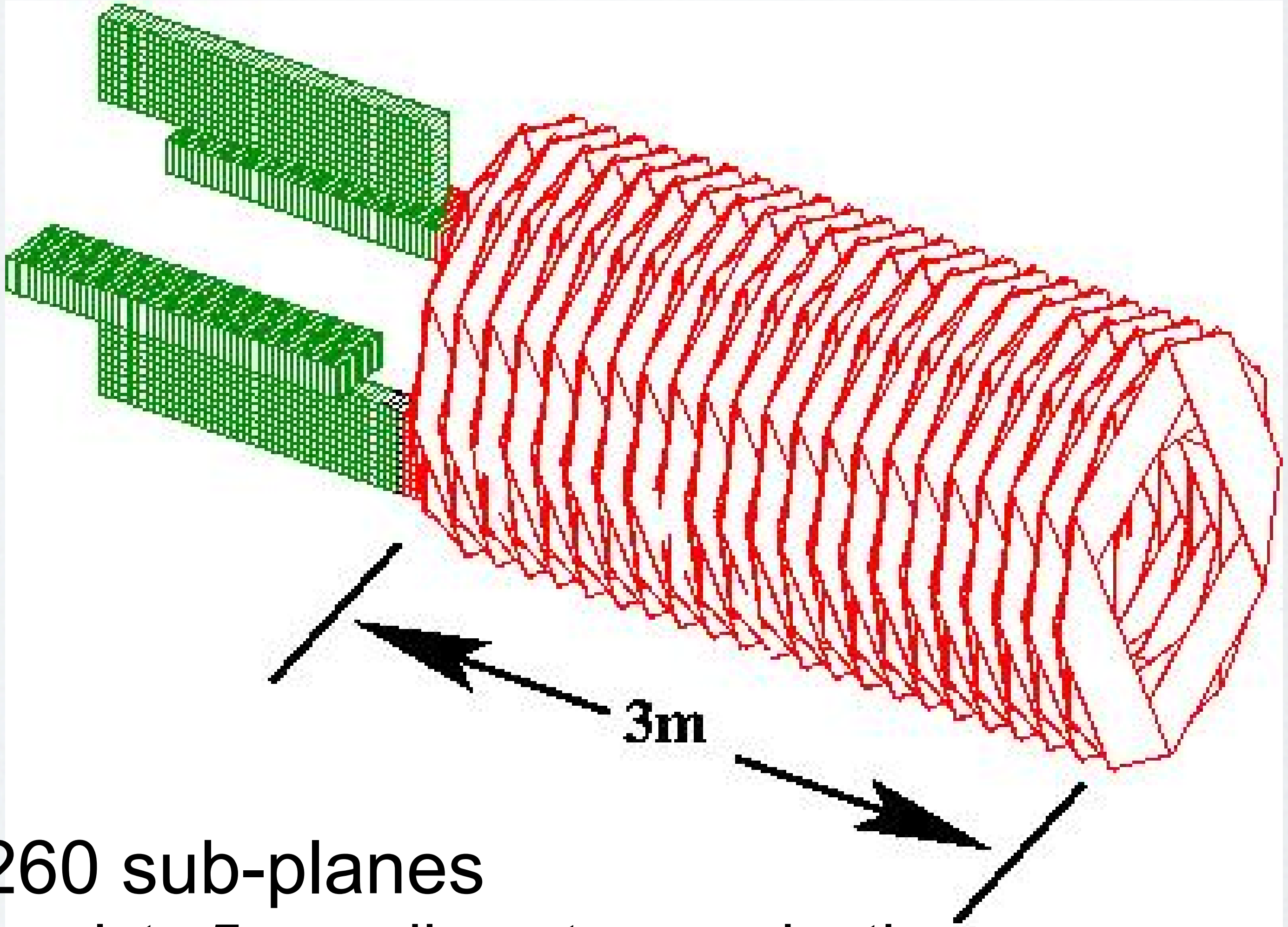
“Boomerang” Scheme



C. Bhat and M. Syphers Mu2e Acc WG meeting Mar 9, 2010

Detector

- T-Tracker (straw tubes with axes *transverse* to muon beam)
- Immersed in solenoidal field, so electrons follow near-helical path
- Electrons (DIOs!) with $p_T < 55$ MeV do not pass through detector, but down the center



- 260 sub-planes
  - sixty 5 mm diameter conducting straws
  - length from 70-130 cm
  - total of 13,000 channels

Calorimeter:

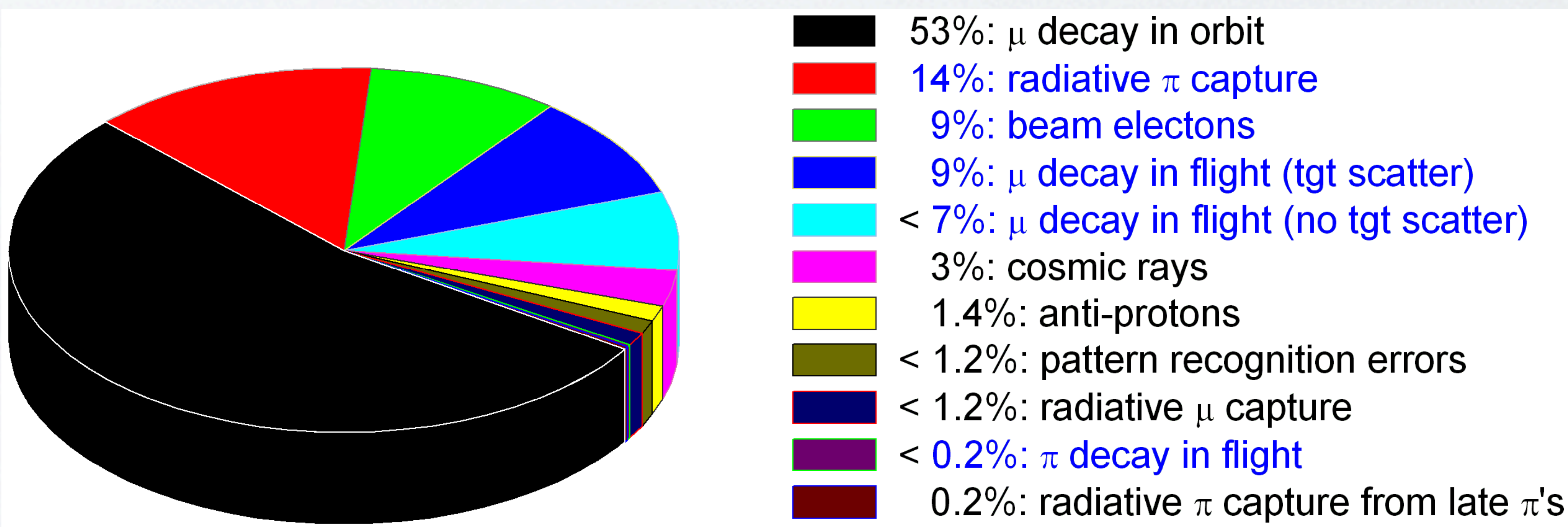
$\sigma/E = 5\%$, 1024 3.5 × 3.5 × 12 cm $PbWO_4$

INFN/Dubna investigating LYSO

Final Backgrounds

- For $R_{\mu e} = 10^{-15}$
  ~40 events / 0.4 bkg
  (LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
  ~4 events / 0.4 bkg

Source	Number
DIO	0.225
Radiative π capture	0.072
μ decay-in-flight	0.072
Scattered e-	0.035
π decay in flight	<0.0035

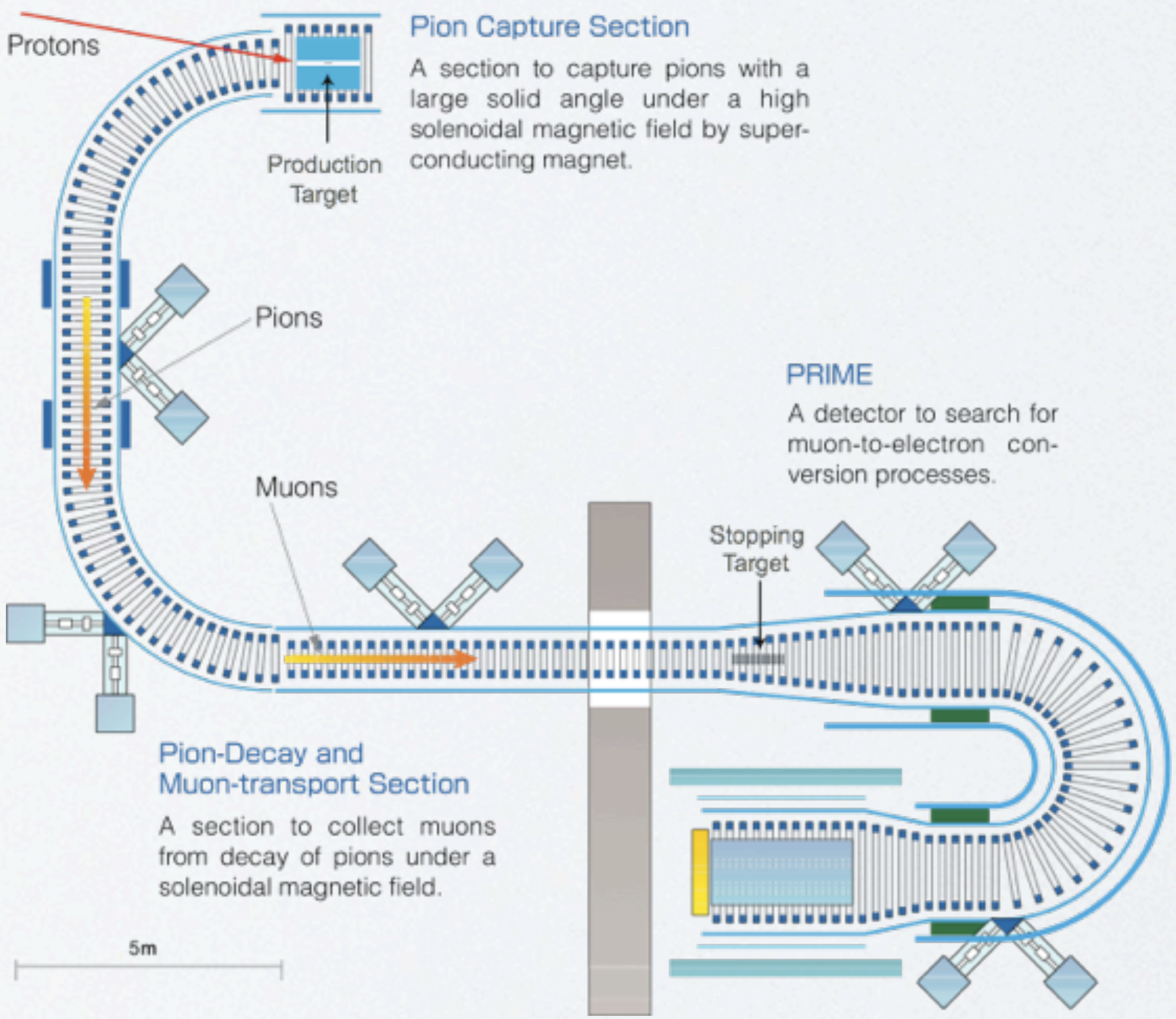


R. Bernstein, FNAL

COMET

mu-e conversion search at J-PARC

Overview of the COMET Experiment

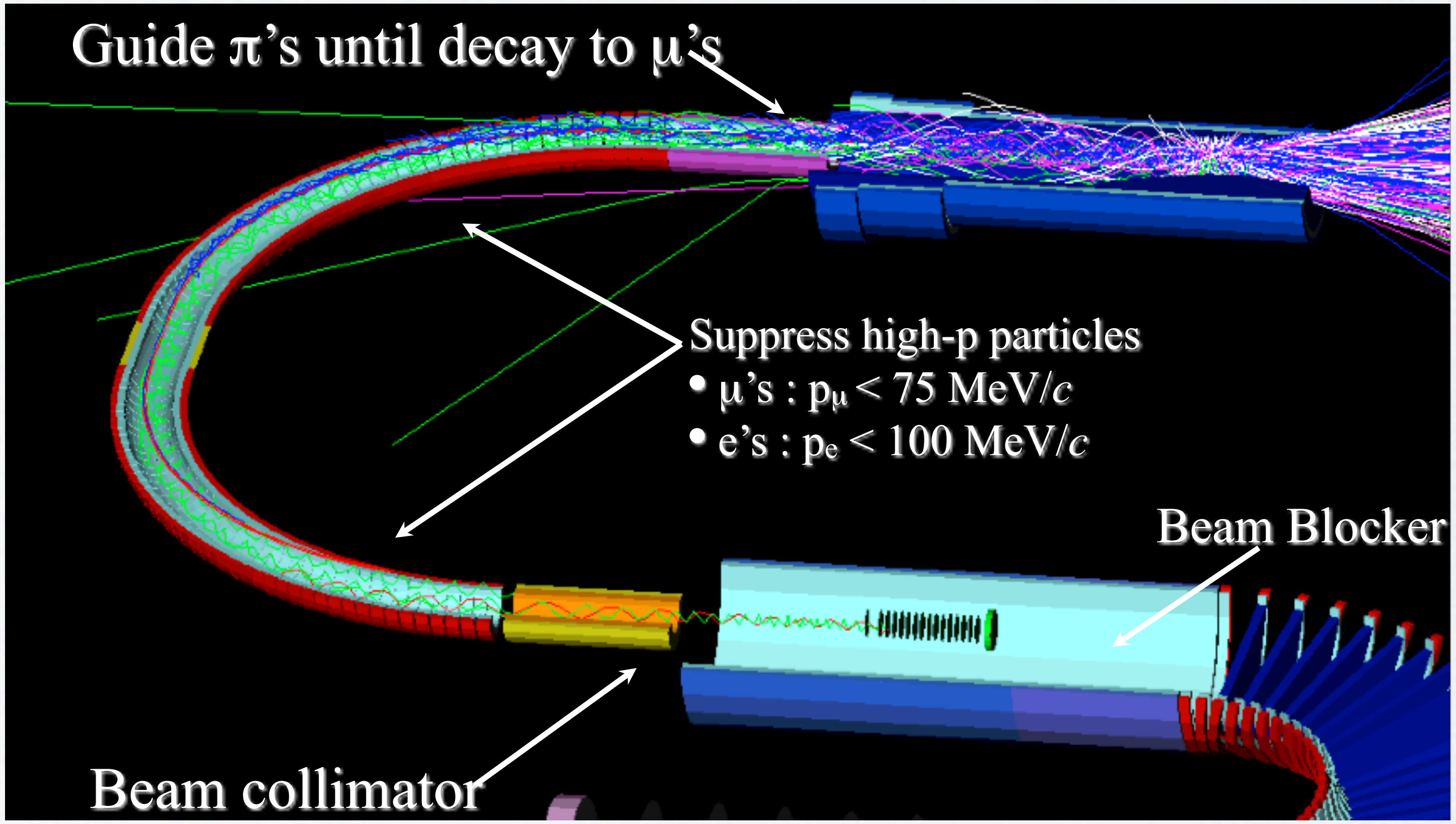


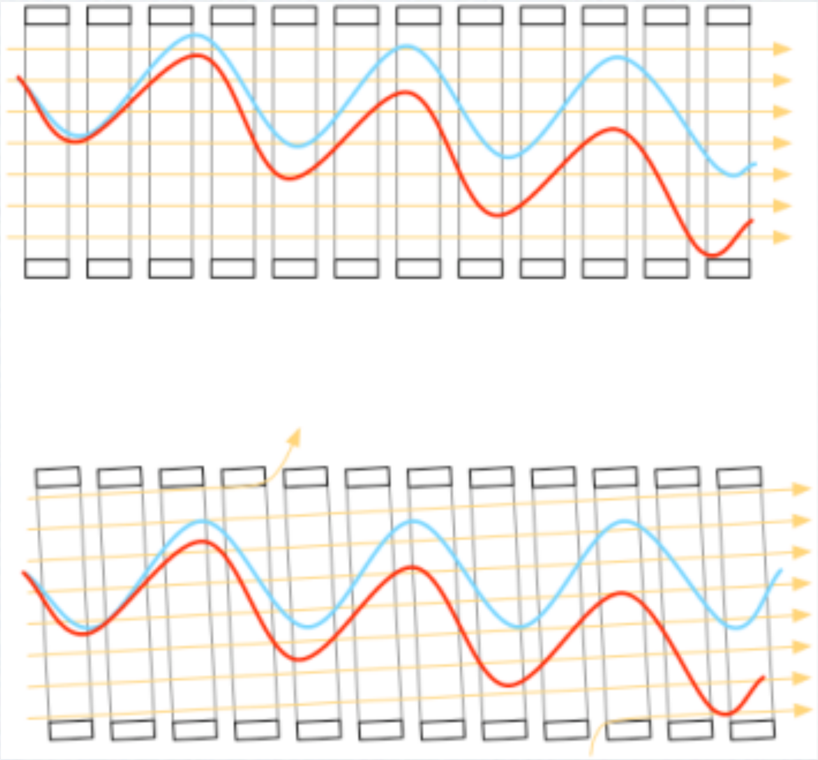
Target Sensitivity: 10^{-16} (90% C.L. Upper Limit)

- **Proton Beam**
  - $p \rightarrow \pi \rightarrow \mu$
- **The Muon Source**
  - Proton Target
  - Pion Capture
  - Muon Transport
- **The Detector**
  - Muon Stopping Target
  - Electron Transport
  - Electron Detection

Muon transport through a curved solenoid

- Transport muons in a wide momentum range efficiently
- Momentum selection by a collimator





$$D[m] = \frac{1}{0.3 \times B[T]} \times \frac{s}{R} \times \frac{p_l^2 + \frac{1}{2}p_t^2}{p_l}$$

Signal Sensitivity
2×10^7 sec running

- Single event sensitivity

$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - N_μ is a number of stopping muons in the muon stopping target. It is $2.0\text{x}10^{18}$ muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.031.

total protons	$8.5\text{x}10^{20}$
muon yield per proton	0.0035
muon stopping efficiency	0.66
# of stopped muons	$2.0\text{x}10^{18}$

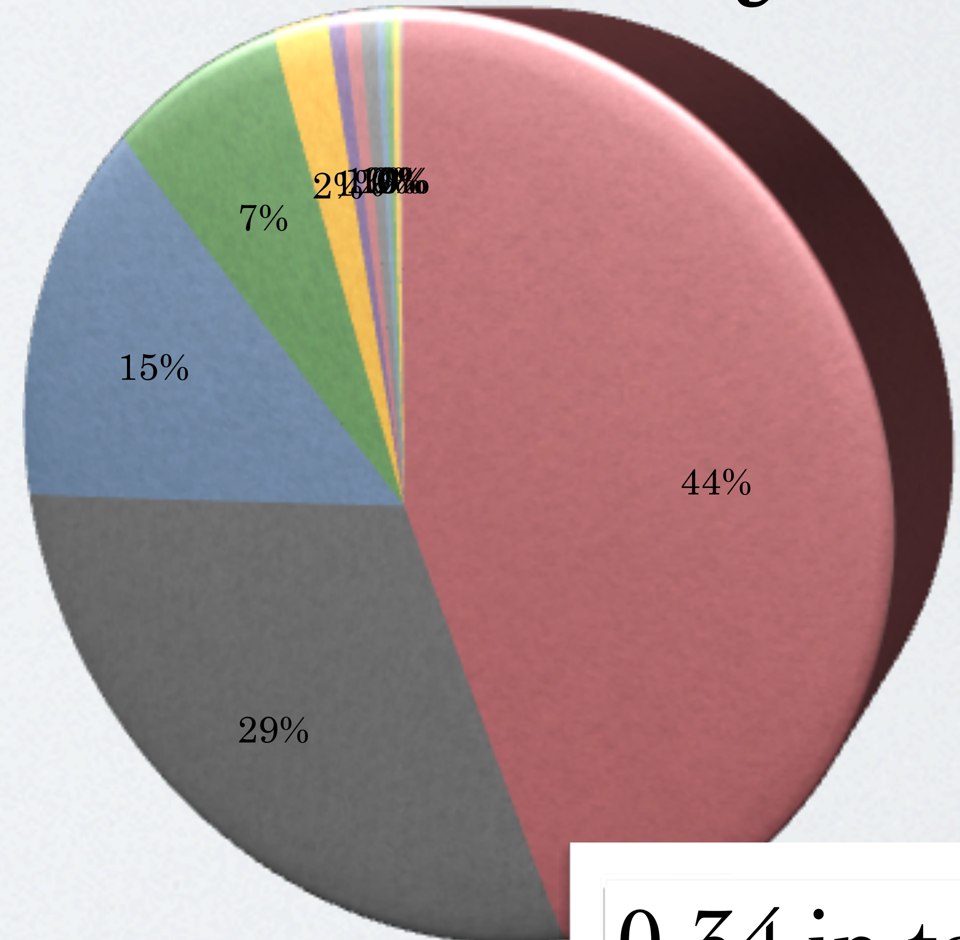
Single event sensitivity
$2.6 \text{ x } 10^{-17}$

90% C.L. upper limit
$6.0 \text{ x } 10^{-17}$

Background Estimation Summary

Intrinsic backgrounds	originate from muons stopping in the muon stopping target.	✓muon decay in orbit ✓radiative muon capture ✓muon capture with particle emission
Beam-related backgrounds	caused by beam particles, such as electrons, pions, muons, and anti-protons in a beam	✓radiative pion capture ✓muon decay in flight ✓pion decay in flight ✓beam electrons ✓neutron induced ✓antiproton induced
Other backgrounds	caused by cosmic rays	✓cosmic-ray induced ✓(pattern recognition error)

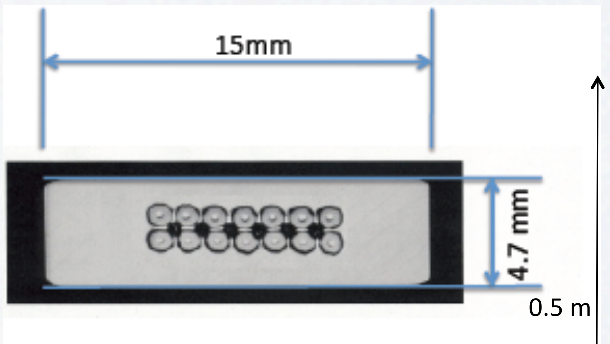
Assuming proton beam extinction $< 10^{-9}$

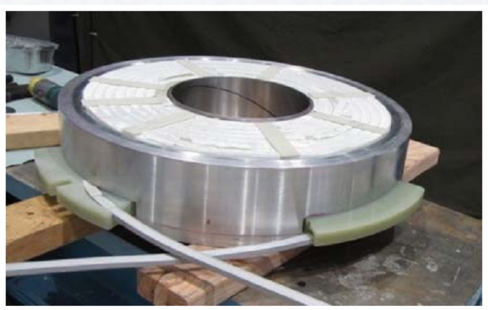


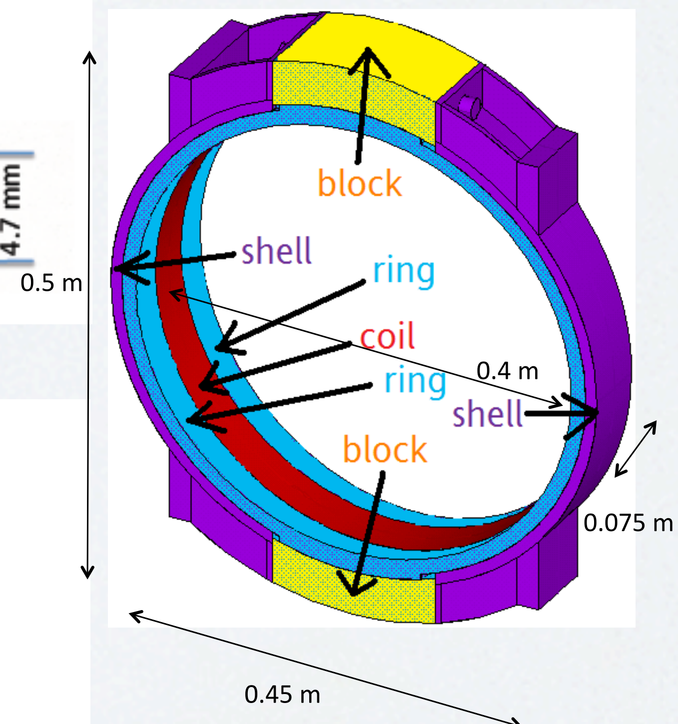
0.34 in total

- Muon Decay in Orbit 0.15
- Beam Electrons <0.1
- Radiative Pion Capture 0.05
- Neutron Induced 0.024
- Anti-proton induced 0.007
- Delayed-pion Radiative Capture 0.002
- CR Muons 0.002
- Electrons from CR Muons 0.002
- Radiative Muon Capture <0.001
- Muon Cpture with n Emission <0.001
- Muon Capture with Charged Part. Emission <0.001
- Muon Decay in Flight <0.0002
- Pion Decay in Flight <0.0001

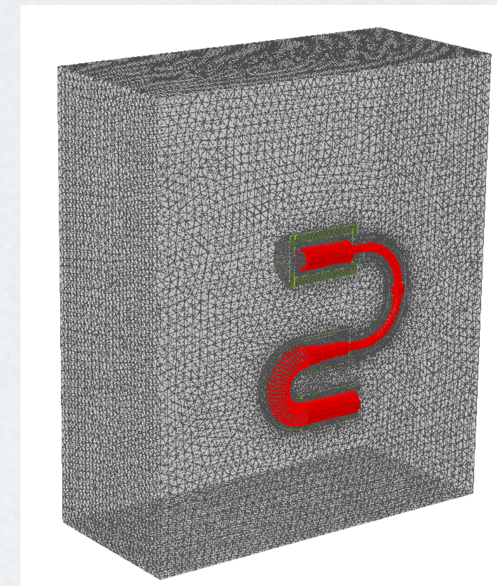
COMET R&D Status

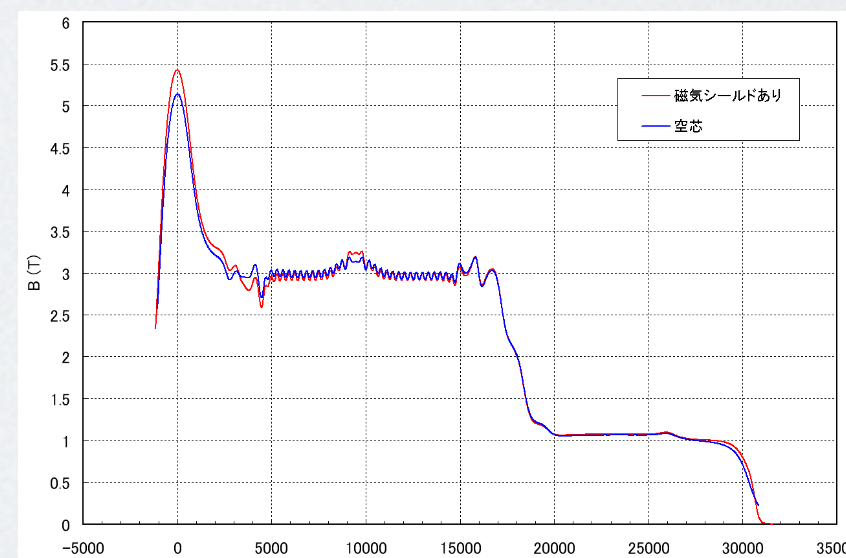


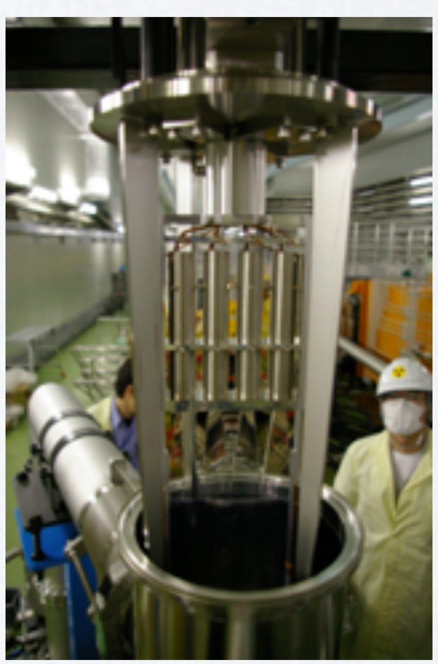

gure.3.2.1: Test Coil with the outer aluminum ring and G-10 lead insulators, installed
the bottom aluminum flange.

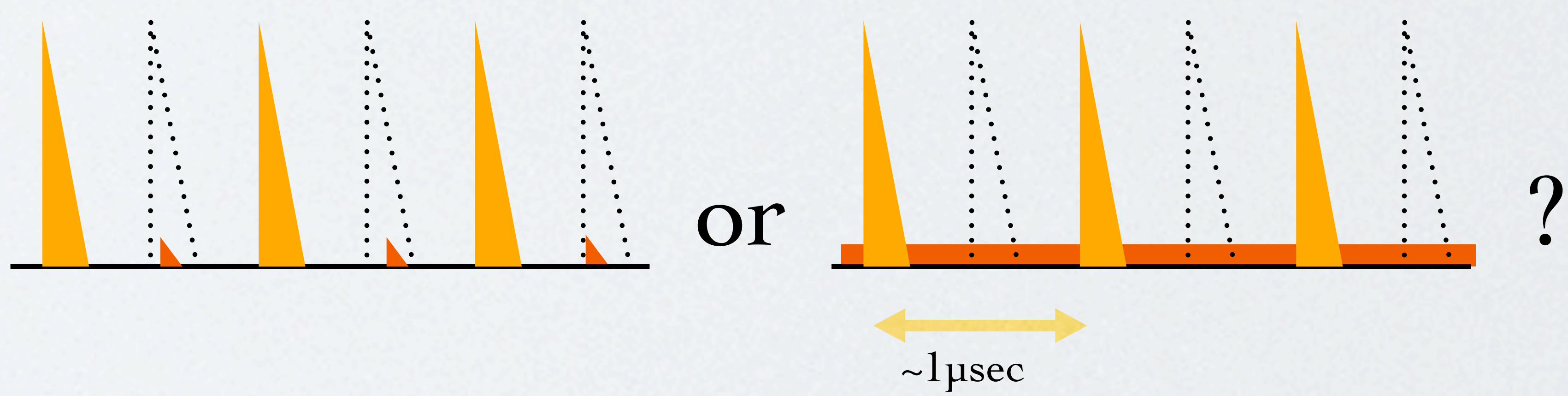


- SC wire R&D
  - Al stabilizer
  - neutron irradiation test
- Magnet design
  - Coil configuration
  - axial force
- Detector R&D
  - tracker
  - calorimeter
  - CR shield
- Extinction Measurement

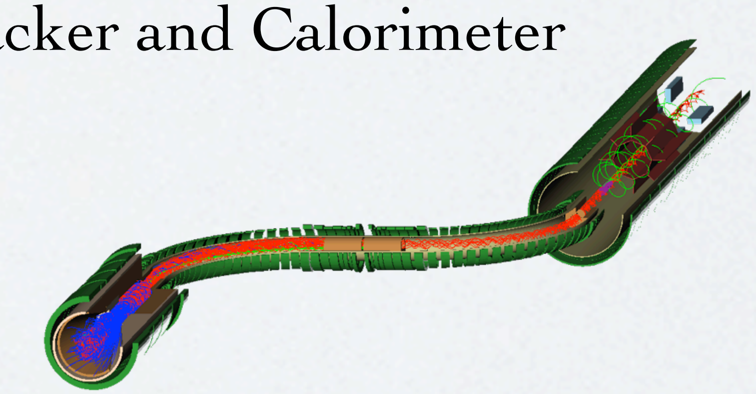
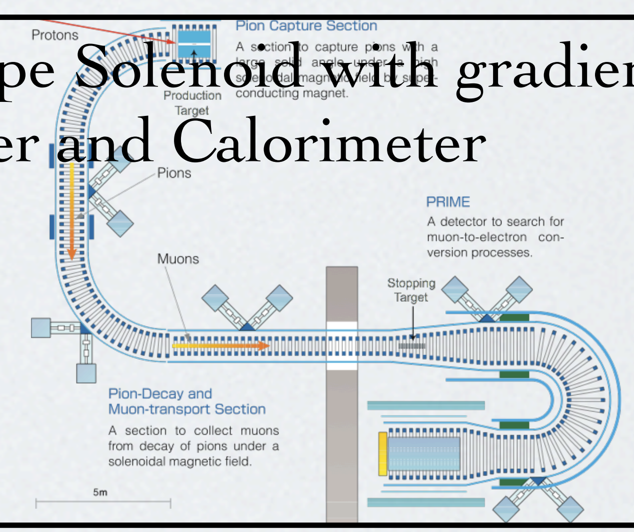








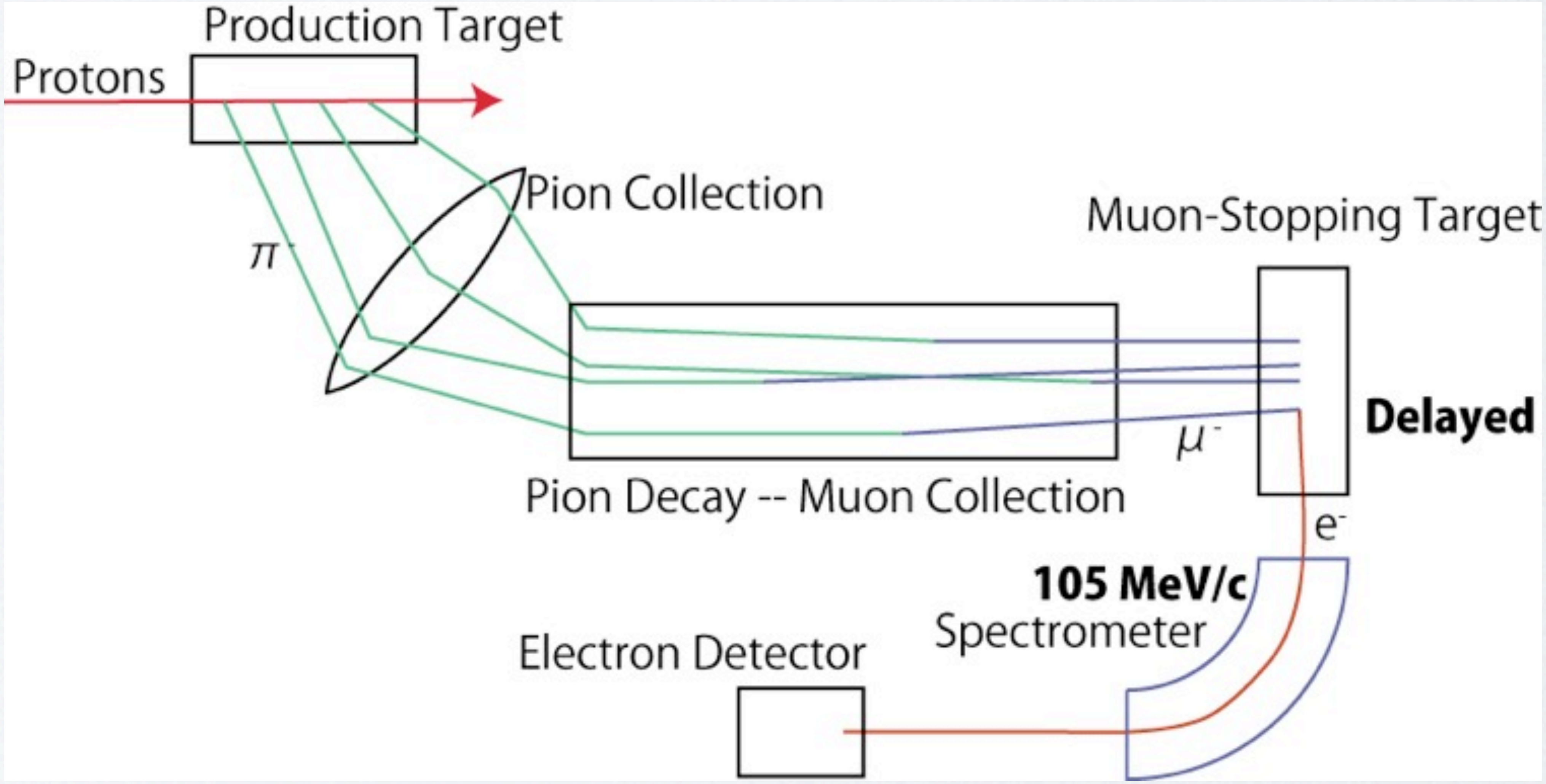
Comparison between Mu2e and COMET

	Mu2e	COMET
Proton Beam	8GeV, 20kW bunch-bunch spacing 1.69 μsec rebunching Extinction: 10^{-9}	8GeV, 50kW bunch-bunch spacing 1.18-1.76 μsec empty buckets Extinction: 10^{-9}
Muon Transport	S-shape Solenoid	U-shape solenoid
Detector	Straight Solenoid with gradient field Tracker and Calorimeter 	U-shape Solenoid with gradient field Tracker and Calorimeter 
Sensitivity	SES: 2.5×10^{-17} 90% CL UL: 6×10^{-17}	SES: 2.6×10^{-17} 90% CL UL: 6×10^{-17}

DeeMe

another mu-e conversion search at J-PARC

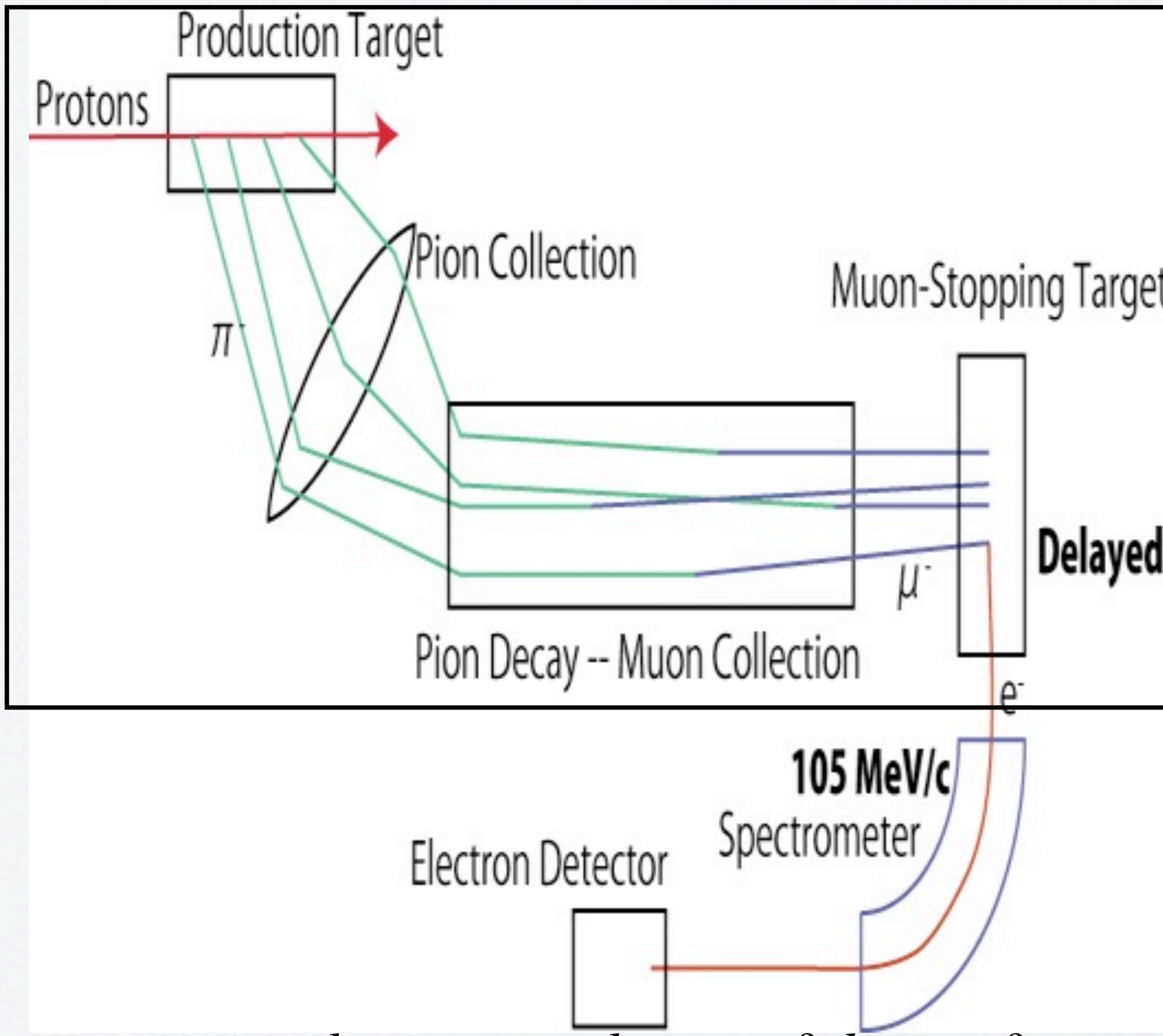
General Idea of μ-e Conversion Setup

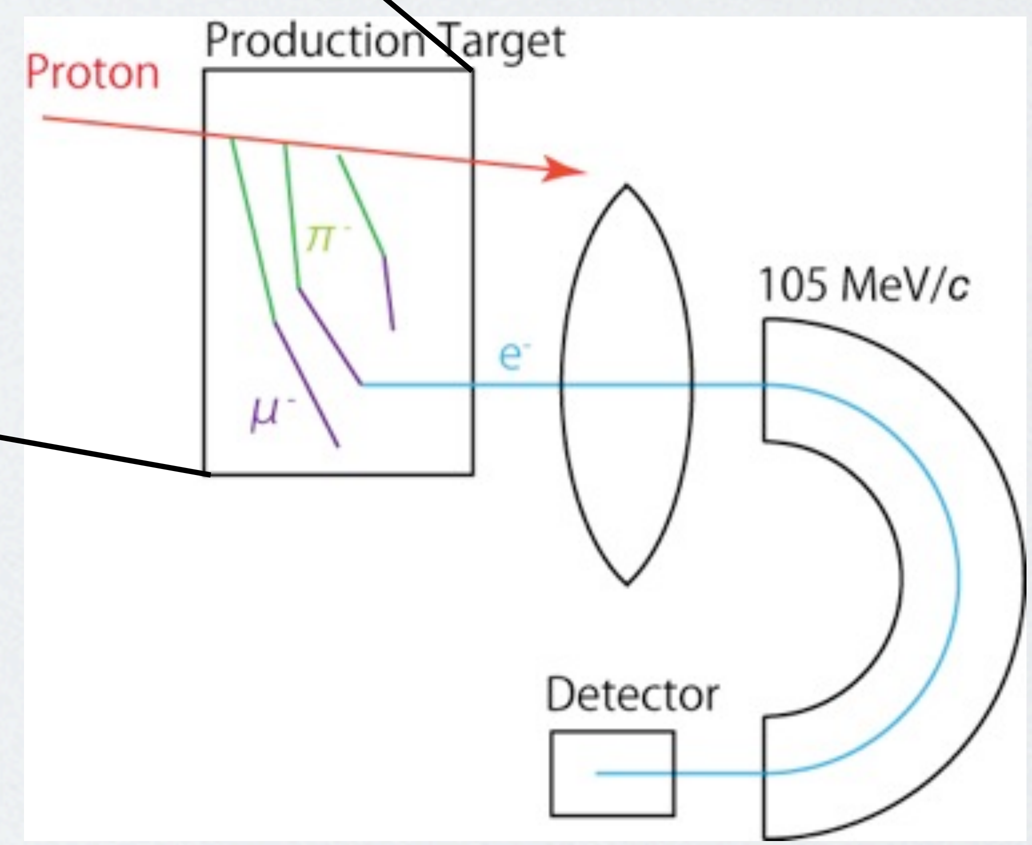


- Sensitivity
  - High μ^- yield
- Background
  - Pulsed Proton
- Detector Rate
  - Momentum Selection before Detector

μ-e electrons may directly coming from a production target

→ DeeMe



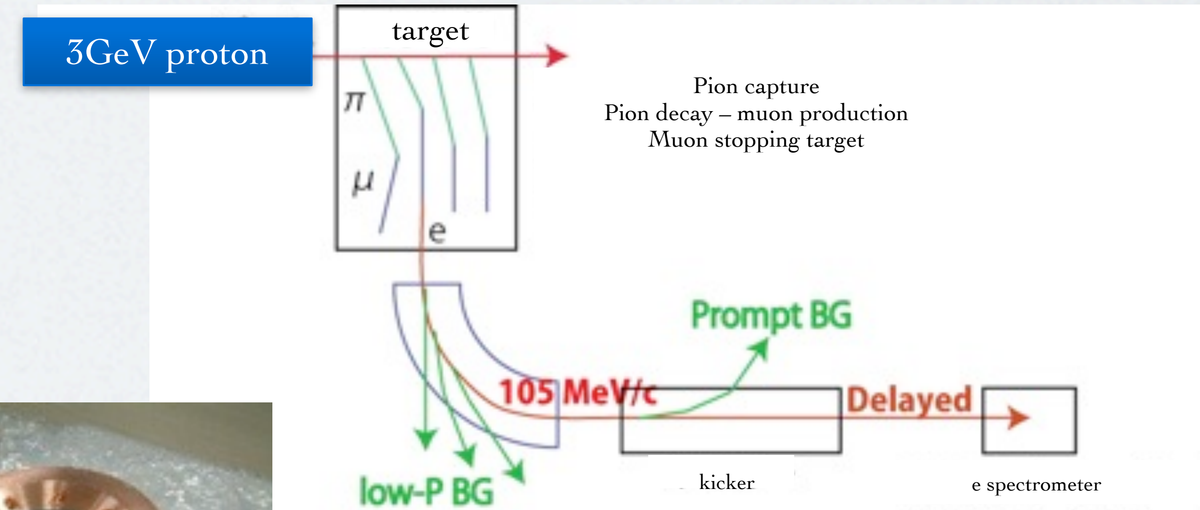


- An electron analogue of the surface muon.
- Experiment could be **very simple, quick and low-cost**.
  - but with lower sensitivity...

DeeMe

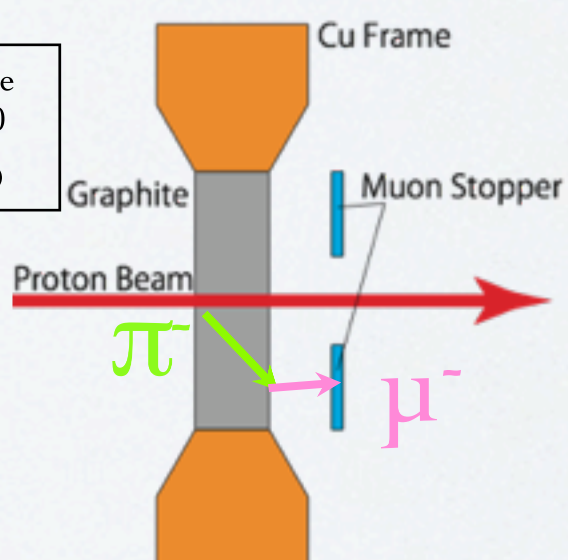
Another m-e conversion search at J-PARC

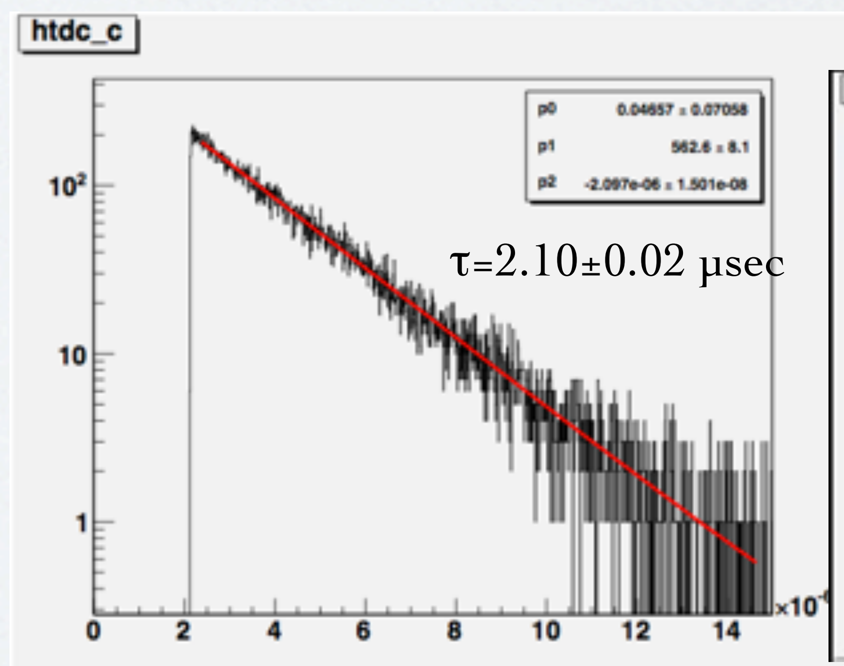
- Mu-e conversion electron directly comes from the target?
- 10^{10} muon stops/sec/MW
- Transport 105MeV/c delayed electrons
- Expected reach (crude)
  - D2 beam line (40msr)
    - 8×10^{-13} for C (10^{7} sec)
    - 2×10^{-13} for Al (10^{7} sec)
  - New beam line (150msr)
    - 10^{-14} for Al (2×10^{7} sec)
  - cf SINDRUM II limit: 7×10^{-13}

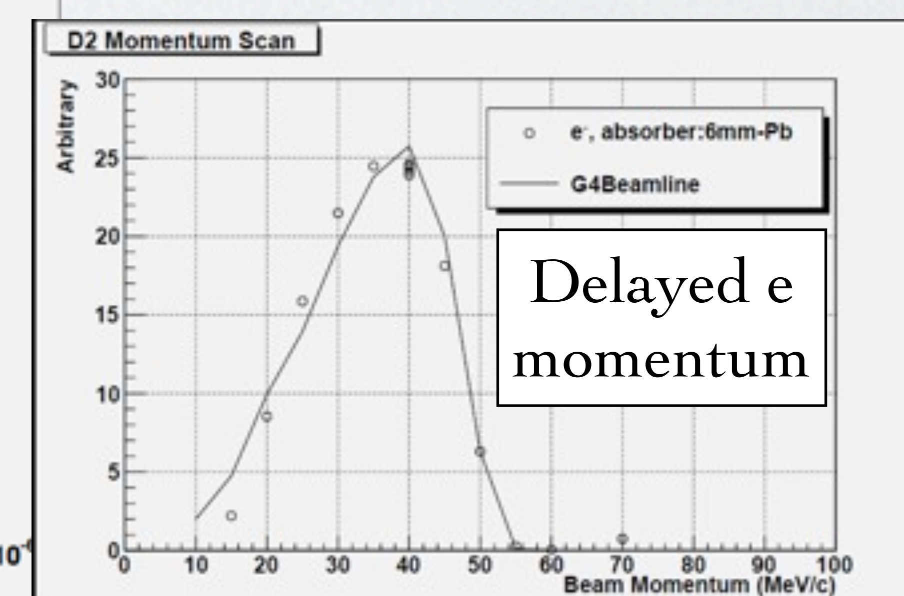


Graphite target with water cooling

Capture rate
0.08 → 0.60
(C) (Al)







Reliable BG estimation is in progress now

Summary

- cLFV search experiment is a powerful tool to investigate new physics beyond the Standard Model
- High intensity muon beam available at high-power proton machines
- $\mu \rightarrow e\gamma$ and mu-e conversion searches
- Mu2e, COMET, DeeME
    - mu-e conversion search at LANL ?