Mu2e: A High-Sensitivity Search for Charged Lepton Flavor at Fermilab

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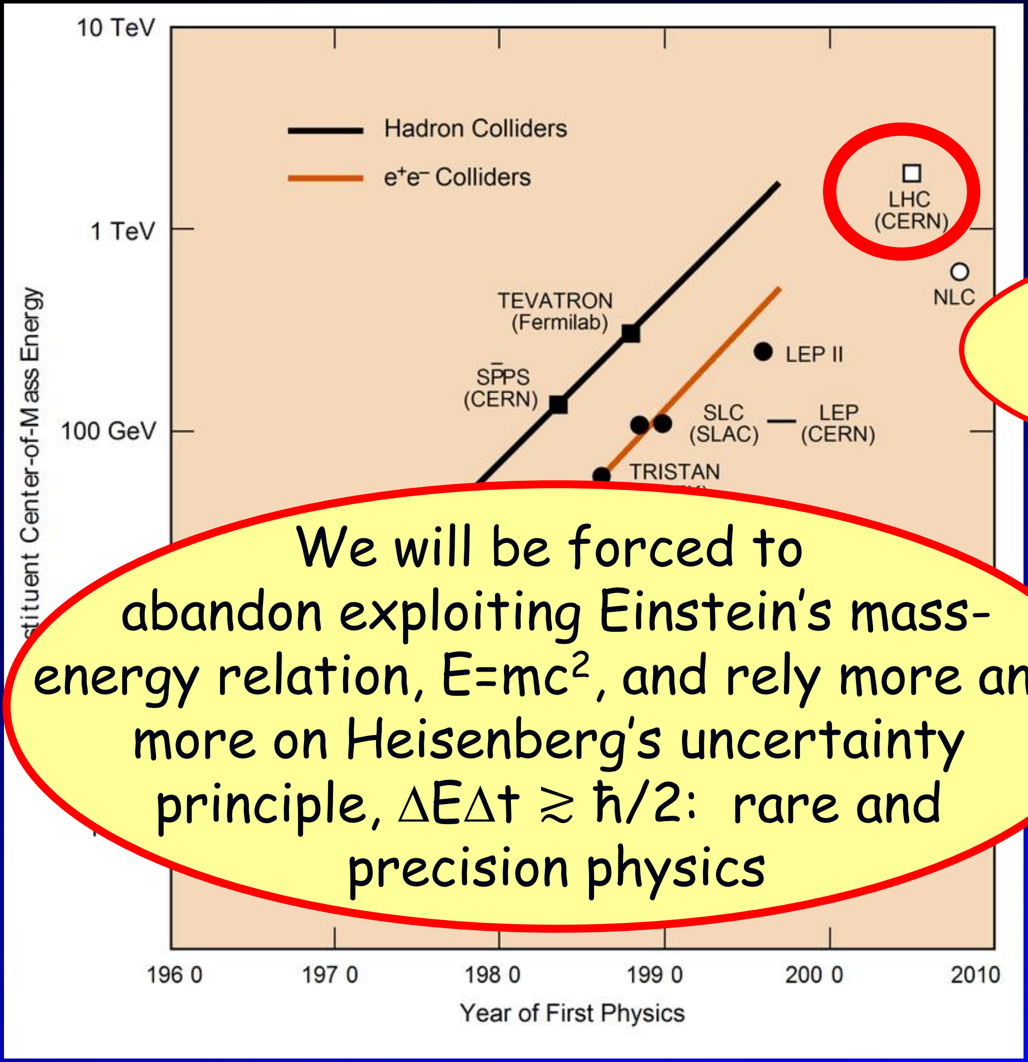
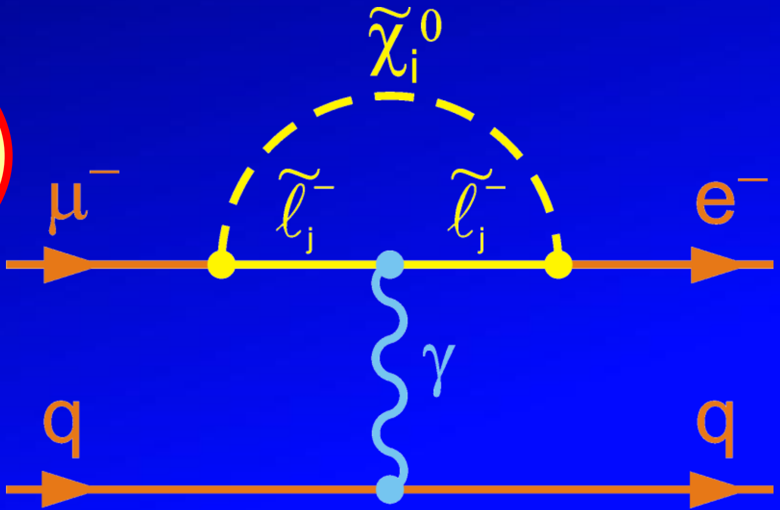
Is the Large Hadron Collider the Last in a Long Line of ever Higher Energy Particle Accelerators?



We will be forced to abandon exploiting Einstein's mass-energy relation, $E=mc^2$, and rely more and more on Heisenberg's uncertainty principle, $\Delta E \Delta t \gtrsim \hbar/2$: rare and precision physics

Presently there are no concrete plans for an accelerator to probe the next energy regime

How are we going go probe higher mass scales without higher energies?

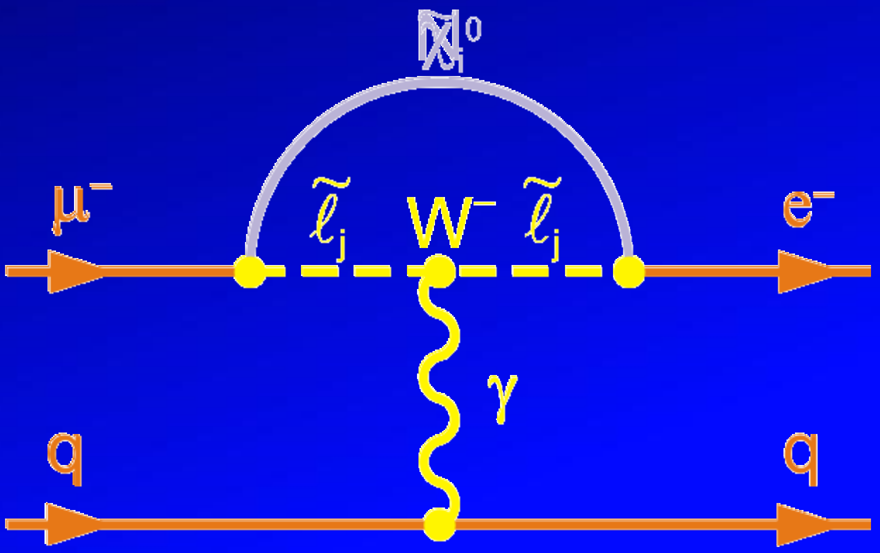


Why Search for Charged Lepton Flavor Violation?

$$\mu^- N \rightarrow e^- N'$$

- In Standard Model not there ⇨ neutrino mass discovery implies an unobservable 10^{-52} rate
- Hence, any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally
  - ⇨sensitivities that allow favored beyond-the-standard-model theories to be tested

Lepton flavor conservation accidental
in the extended Standard Model

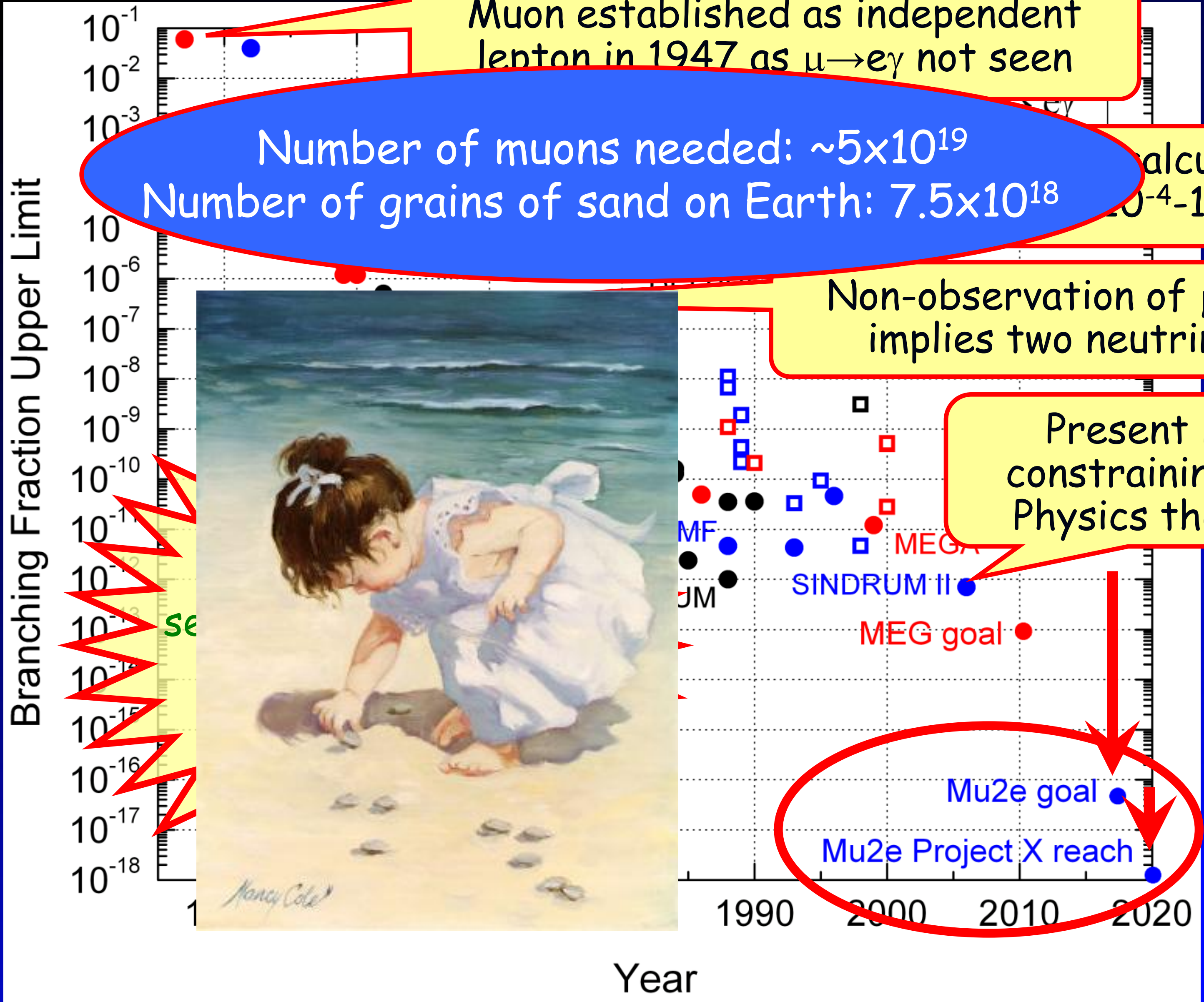


Many models explaining the neutrino mass hierarchy produce $\mu^- N \rightarrow e^- N$ at levels that will be probed by Mu2e

New neutrino

Supersymmetry

History of Lepton Flavor Violation Searches



Muon established as independent lepton in 1947 as μ→eγ not seen

Number of muons needed: ~5x10^{19}
Number of grains of sand on Earth: 7.5x10^{18}

alculation:
0^{-4}-10^{-5}

se

Non-observation of μ→eγ implies two neutrinos

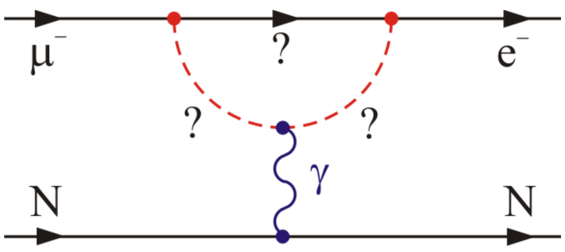
Present limit constraining New Physics theories

CLFV in $\mu^+ \to e^+\gamma$ and $\mu^- N \to e^- N$

Model independent effective CLFV Lagrangian

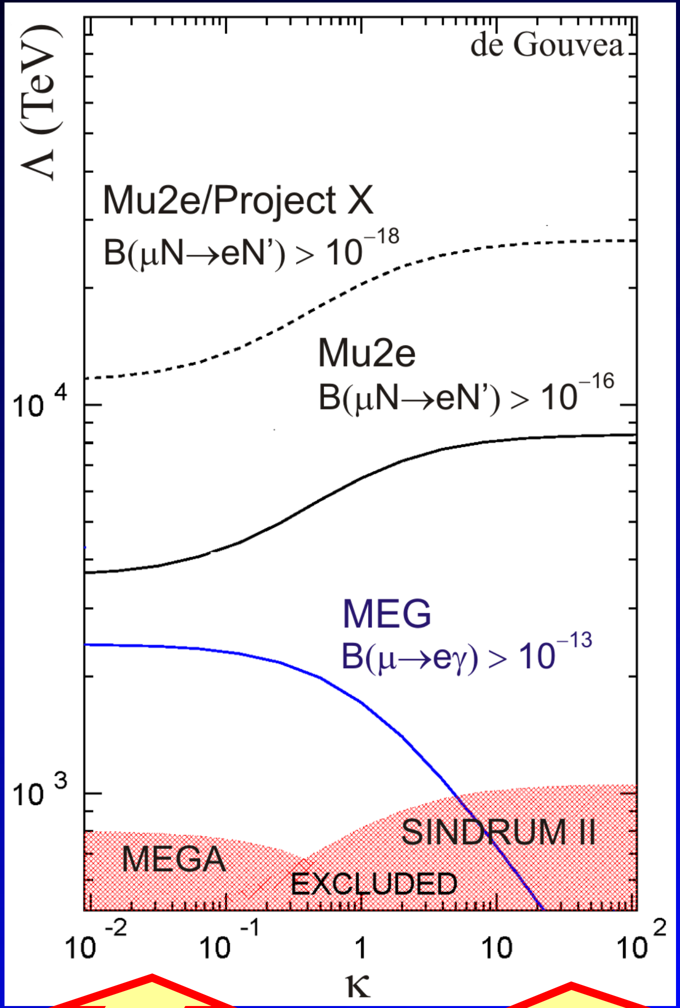
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma$$

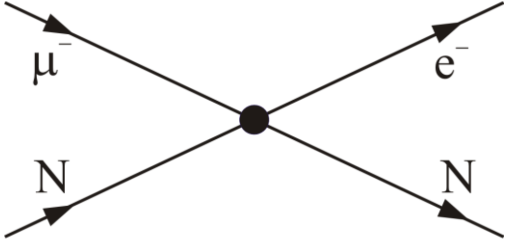
Mass scales probed ~10,000 times that probed directly by LHC



κ << 1
magnetic moment type operator

$\mu \to e\gamma$ rate ~300X $\mu N \to eN$ rate



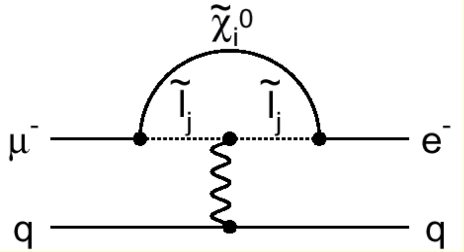


κ >> 1
four-fermion interaction

$\mu N \to eN$ >> $\mu \to e\gamma$ rate

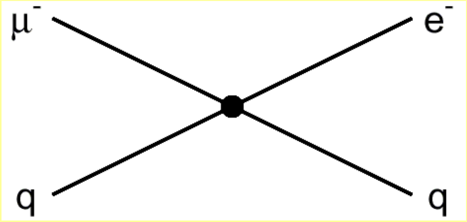
CLFV Sensitive to Many Sources of New Physics

Supersymmetry



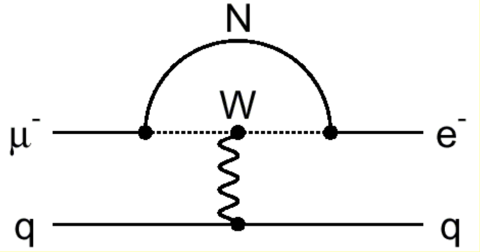
Predictions at 10^{-13}

Compositeness



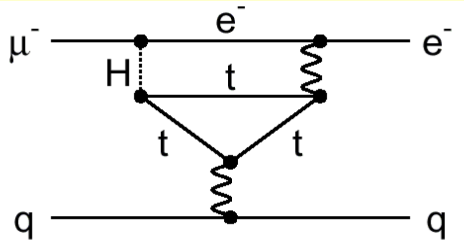
$$\Lambda_c \approx 3000 \text{ TeV}$$

Heavy Neutrinos



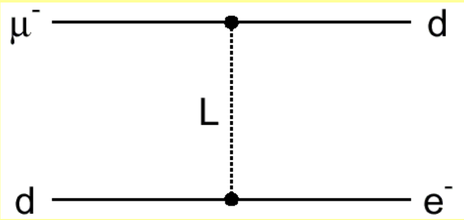
$$\left|U^*_{\mu N} U_{eN}\right|^2 \approx 8 \times 10^{-13}$$

Second Higgs doublet



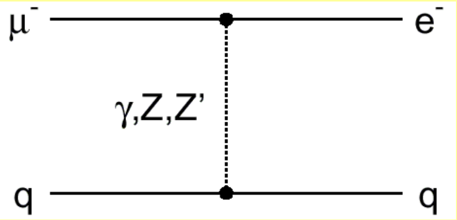
$$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$$

Leptoquarks



$$M_L \approx 3000\sqrt{\lambda_{\mu d}\lambda_{ed}} \text{ TeV/c}^2$$

Heavy Z'
Anomalous Z
coupling



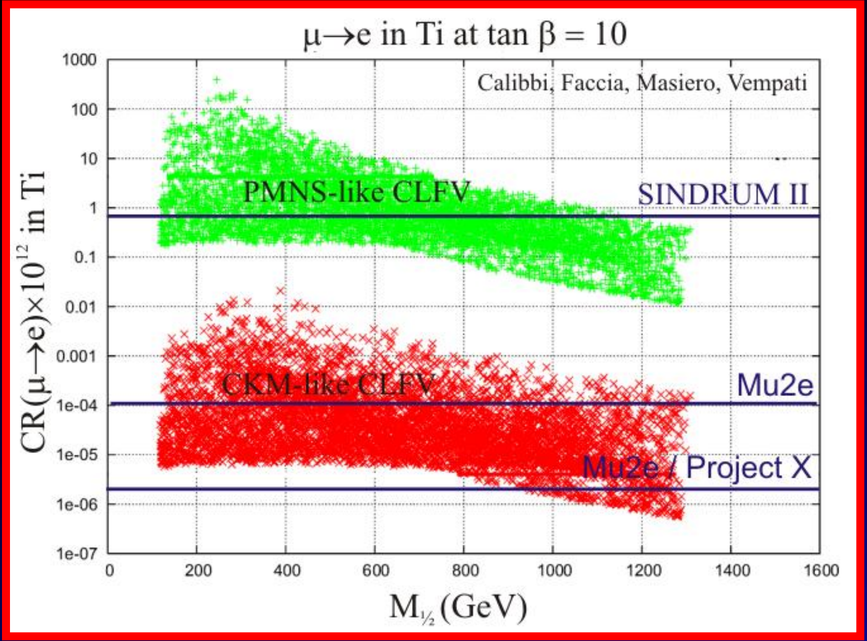
$$M_{Z'} \approx 3000 \text{ TeV}/c^2$$

$$@\ B(Z \to \mu e) < 10^{-17}$$

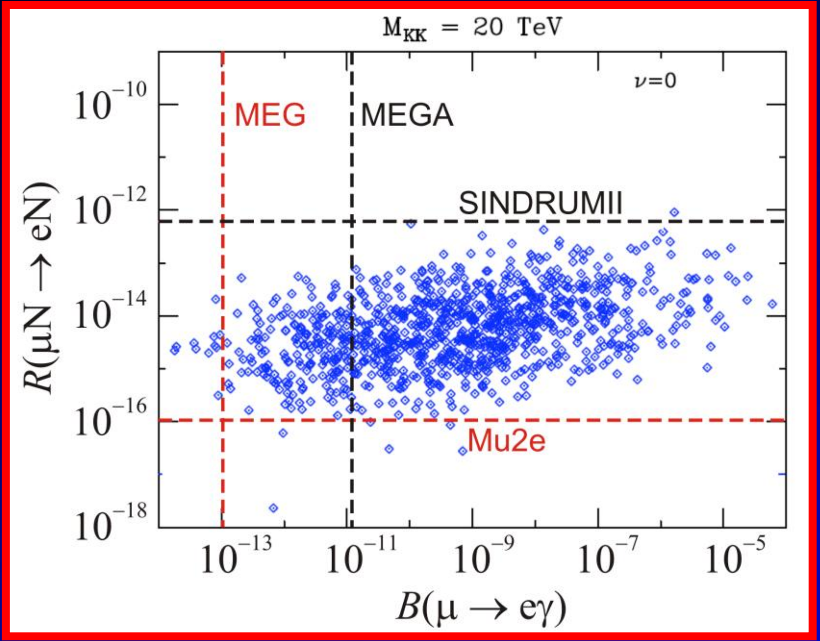
New physics probed by μN→eN (Marciano)

A Few Model Examples

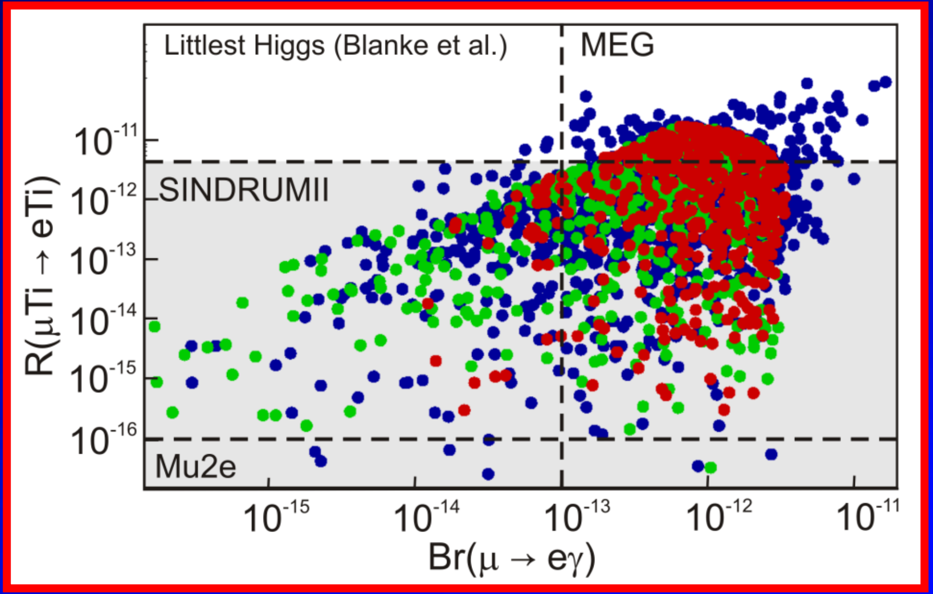
SUSY GUT w Seesaw



Randall-Sundrum



Littlest Higgs w T-parity



If CLFV Seen: Where is it Coming From?

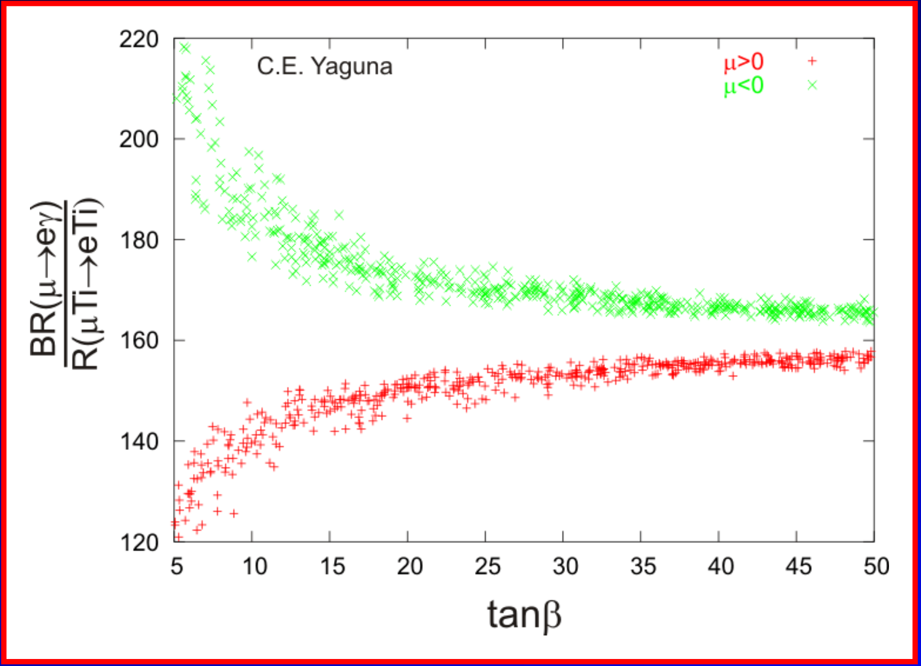
Huge number of models predict CLFV: which is it?

Need:

1. observation of CLFV in more than one channel, and/or
2. evidence from LHC, g-2, or elsewhere

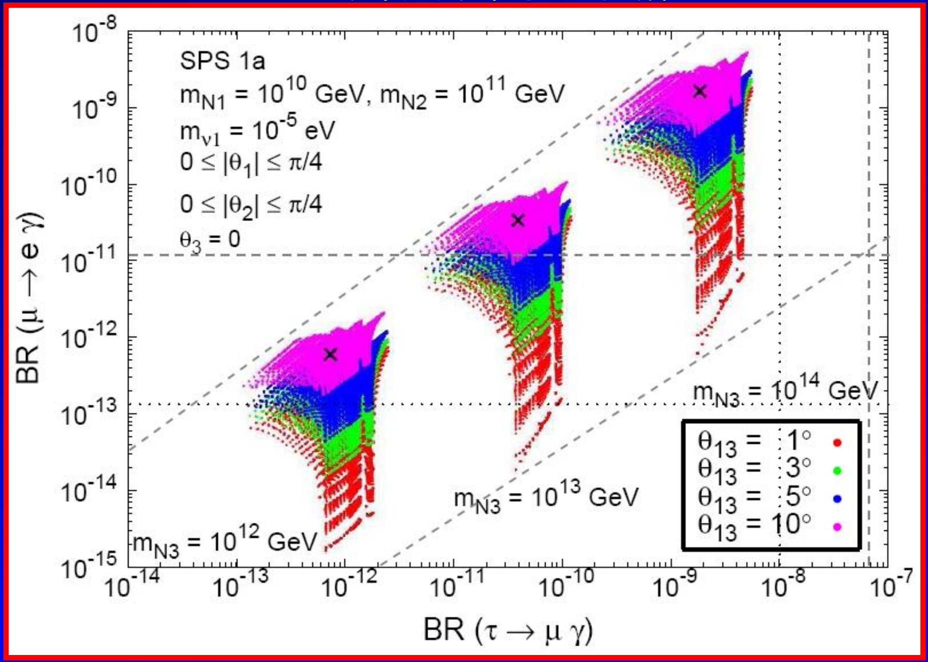
to allow discrimination between different models

MSSM w mSUGRA bc



Yaguma, 2006

CMSSM-seesaw



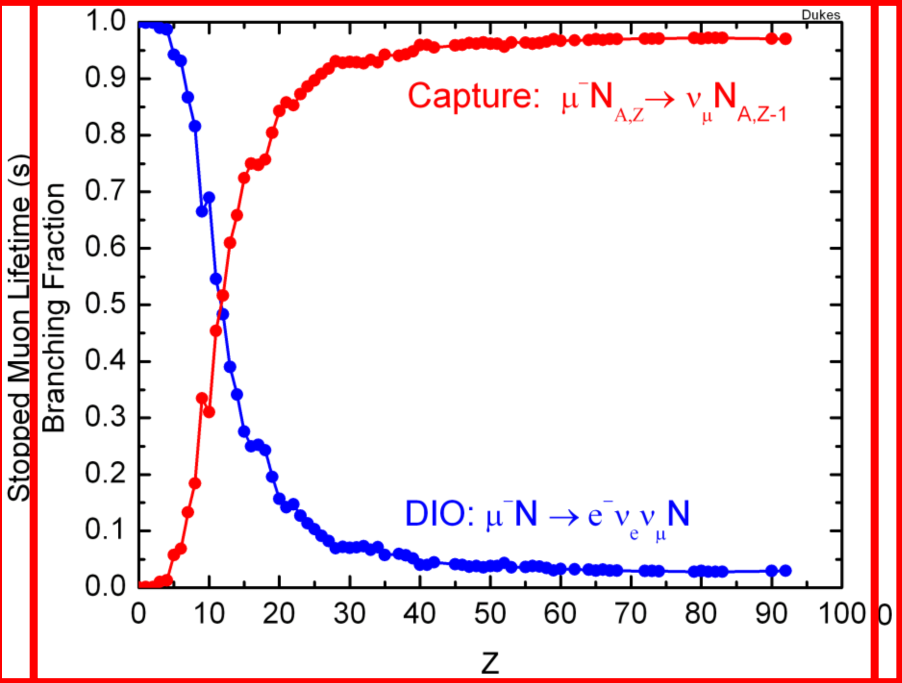
Antusch, Arganda, Herrero, Teixeira, 2006

How to Search for $\mu^-N \rightarrow e^-N$

- Stop muon in atom
- Muon rapidly (10^{-16}s) cascades to 1S state
- Circles the nucleus for up to ~2 μs
- Two things most likely happen:
  1. muon is captured by the nucleus: $\mu^-N_{A,Z} \rightarrow \nu_\mu N_{A,Z-1}$
  2. muon decays in orbit: $\mu^-N_{A,Z} \rightarrow e^-\nu_\mu\nu_e N_{A,Z}$
- In $\mu^-N \rightarrow e^-N$ the muon coherently interacts with nucleus leaving it in ground state
  - signature single isolated electron
  - $E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)

$$R_{\mu e} = \frac{\Gamma(\mu^- Al \rightarrow e^- Al)}{\Gamma(\mu^- Al \rightarrow \nu_\mu Mg)}$$

Measure ratio of conversion rate to capture rate



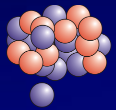
Bunched Beam Technique Needed

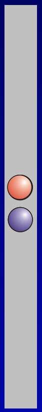
Need ~10^{18} stopped muons

Signal: 105 MeV electron coming from the target, ~1 μs after the μ is stopped in the foils

- Rate too high for continuous beam: need bunched muon beam: 50×10^{9} μ/s
- Need turn off detector for ~ $\tau_{\mu N}$ (~700 ns) while bad stuff (pions, electrons) is around
- Need < 10^{-9} interbunch contamination

bunched beam arrives with μ's, π's, and electrons

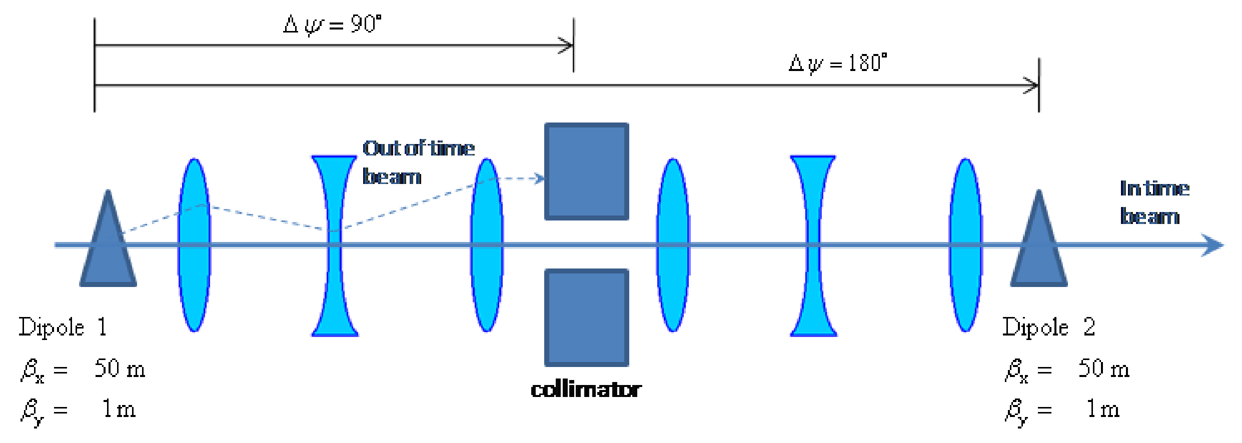




about 50% of the muons stop in the target

a huge amount of stuff comes off the target from scatters, captures etc.

Resonant Dipole Extinction



scattered electron or π

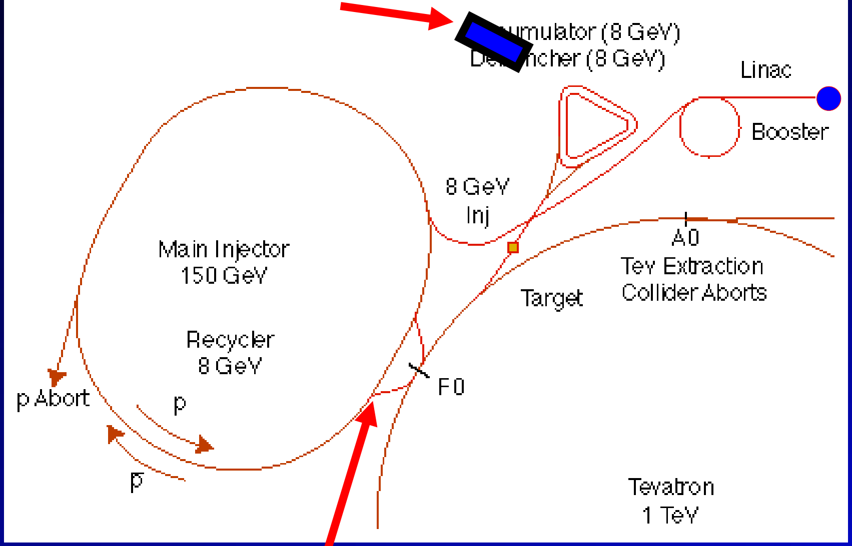
capture electron

105 MeV electron

Producing ~10^{18} Bunched Muons

- Energy: 8 GeV Booster beam optimal
- Structure: need bunch spacing on order of muon lifetime ~1 μs ⇨ orbit period of Accumulator/Debuncher optimal at 1.7 μs
- Use Recycler as a transfer line
- Stack in Accumulator; bunch in Debuncher
- Slow spill extraction: 90% duty factor

new detector hall and beamline



One of several possible schemes

We cannot take any protons away from the Fermilab neutrino program

Mu2e "steals" 6 of 20 booster batches
NOvA cannot use during Main Injector cycle

Backgrounds, backgrounds, backgrounds . . .

1. Stopped Muon Backgrounds

Muon decay in orbit (DIO):

$$\mu^- N_{A,Z} \rightarrow e^- \nu_\mu \nu_e N_{A,Z}$$

- ***defeated by good energy resolution***

Radiative muon capture (RMC):

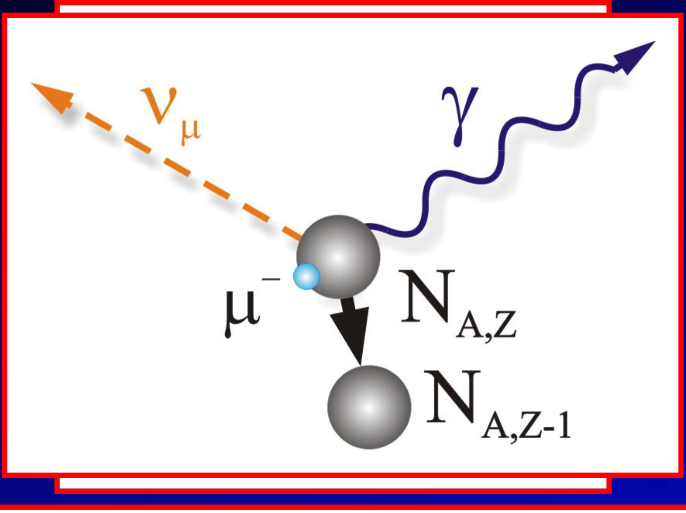
$$\mu^- N_{A,Z} \rightarrow \nu_\mu \gamma N_{A,Z-1},\ \gamma \rightarrow e^+ e^-$$

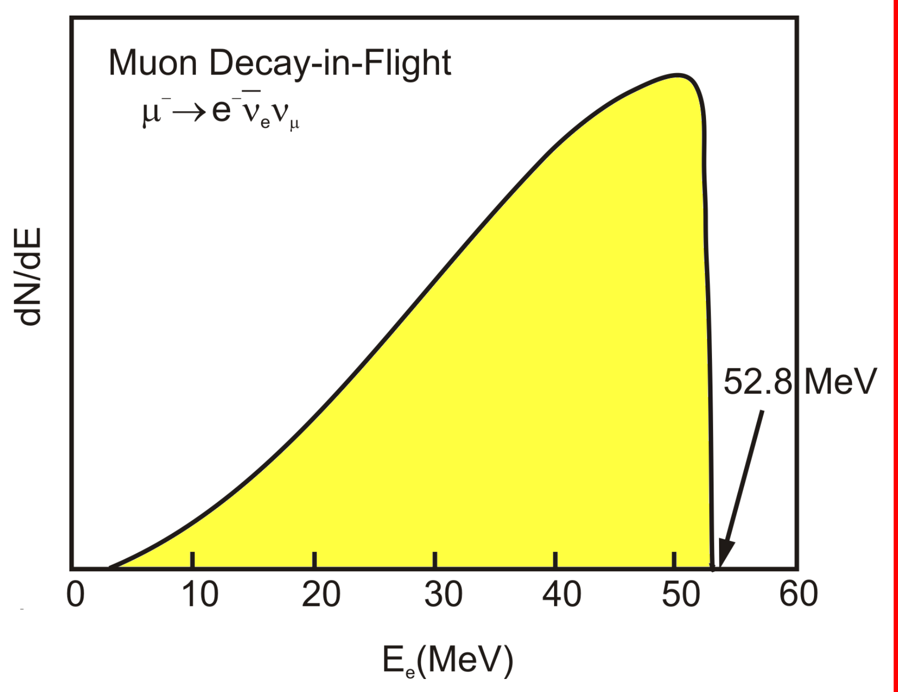
- ***defeated by $m_Z < m_{Z-1}$***
- ***defeated by good energy resolution***

Muon capture:

$$\mu^- N_{A,Z} \rightarrow \nu_\mu N'_{A',Z'} + 2n + 0.1p + 2\gamma$$

- ***defeated by proton absorber***





Backgrounds, Backgrounds, Backgrounds . . .

2. Prompt Beam Related Backgrounds

Radiative pion capture (RPC):

$\pi^- N_{A,Z} \rightarrow \gamma N_{A,Z-1}$, $\gamma \rightarrow e^+e^-$

Note: 1.2% have $E_\gamma > 105$ MeV

Muon decay in flight:

$\mu^- \rightarrow e^- \nu\nu$

Note: $p_\mu > 77$MeV/c

Pion decay in flight:

$\pi^- \rightarrow e^- \nu_e$

Beam electrons scattering in target

- ***Defeated by 10^{-9} interbunch extinction***
- ***Defeated by hard cuts on momentum***

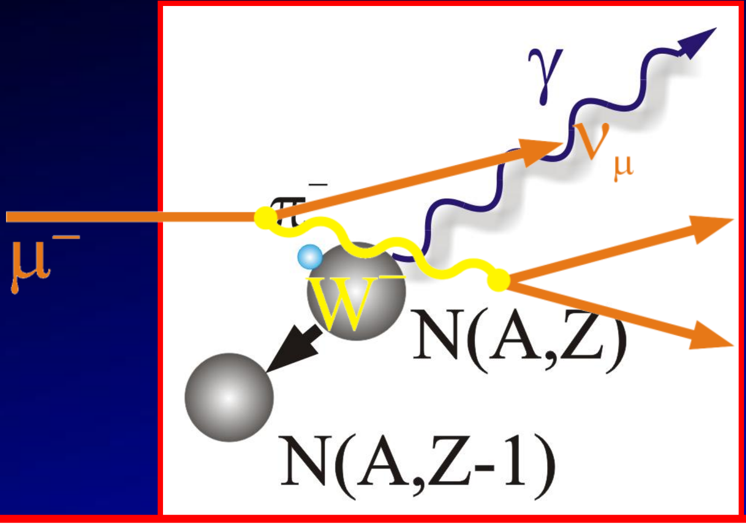
Antiprotons annihilating

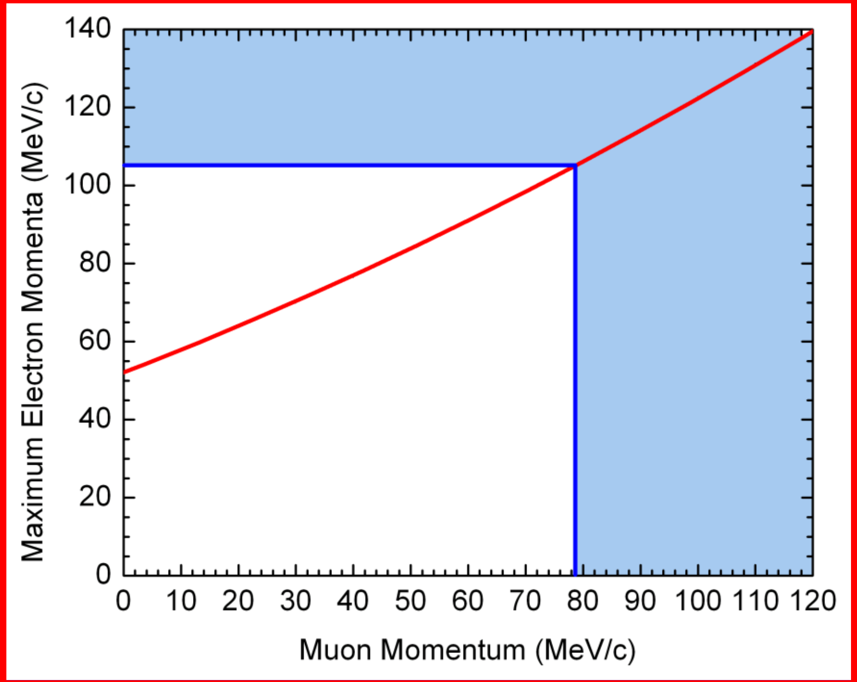
- ***Defeated by thin absorber***

3. Time Dependent Backgrounds

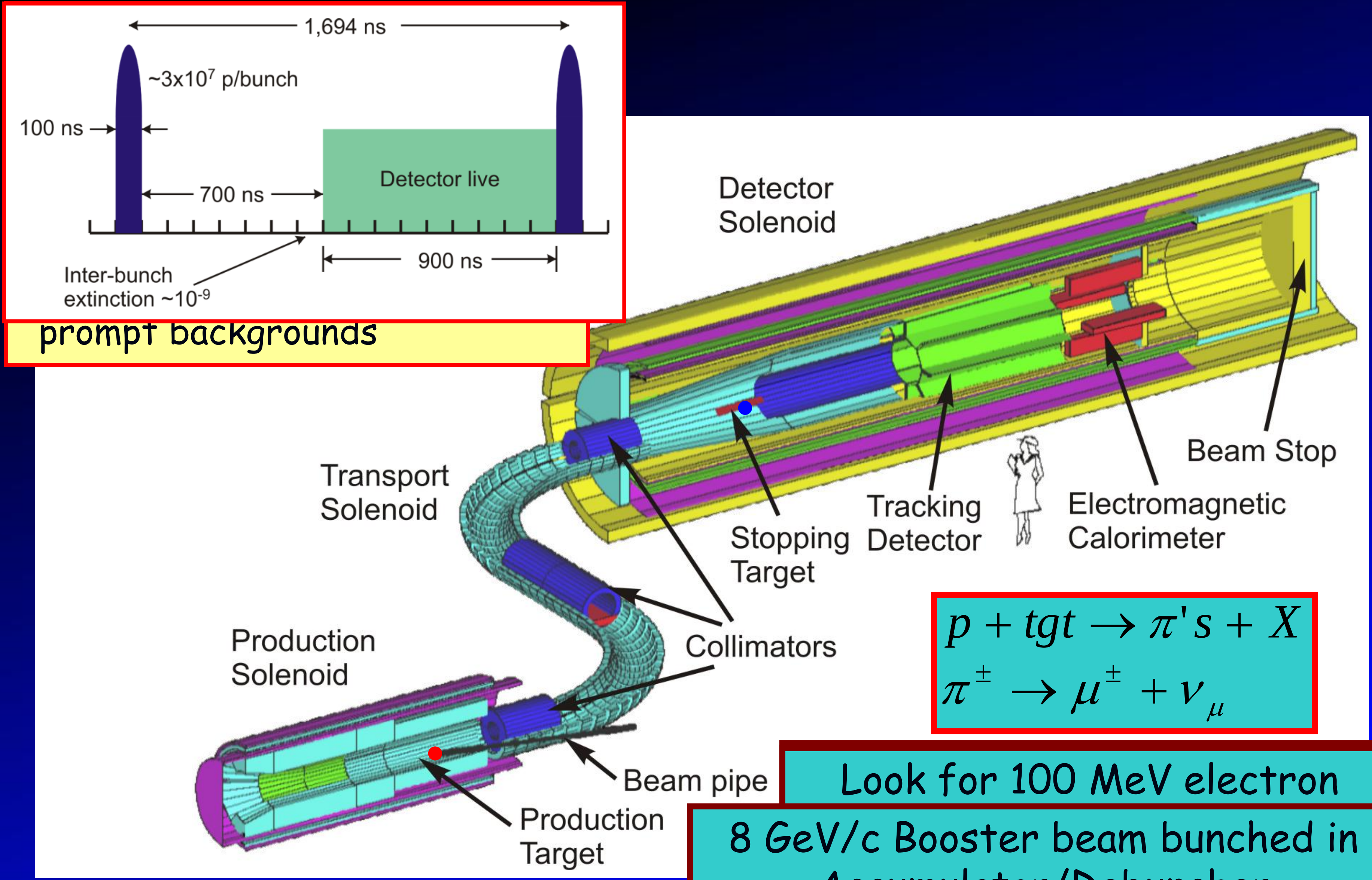
Cosmic Rays

- ***Defeated by active shield***





Mu2e Spectrometer



prompt backgrounds

$$p + tgt \to \pi's + X$$

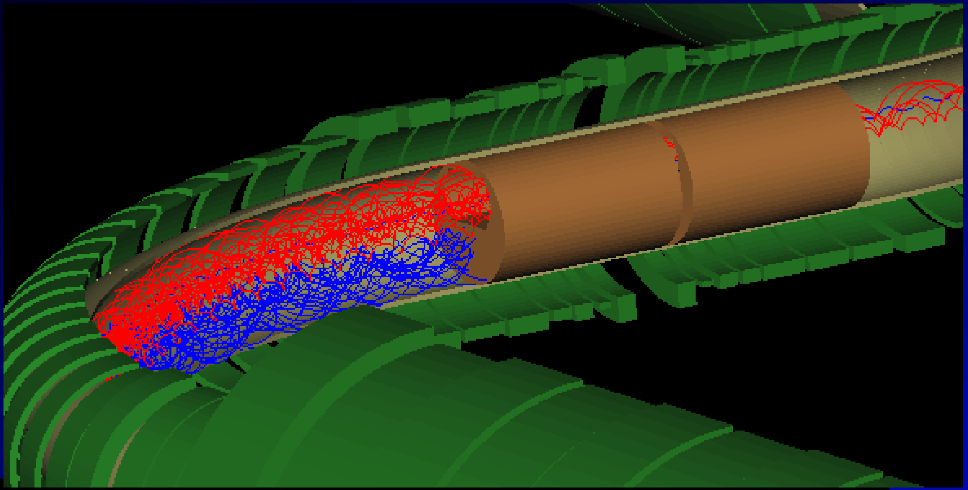
$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}$$

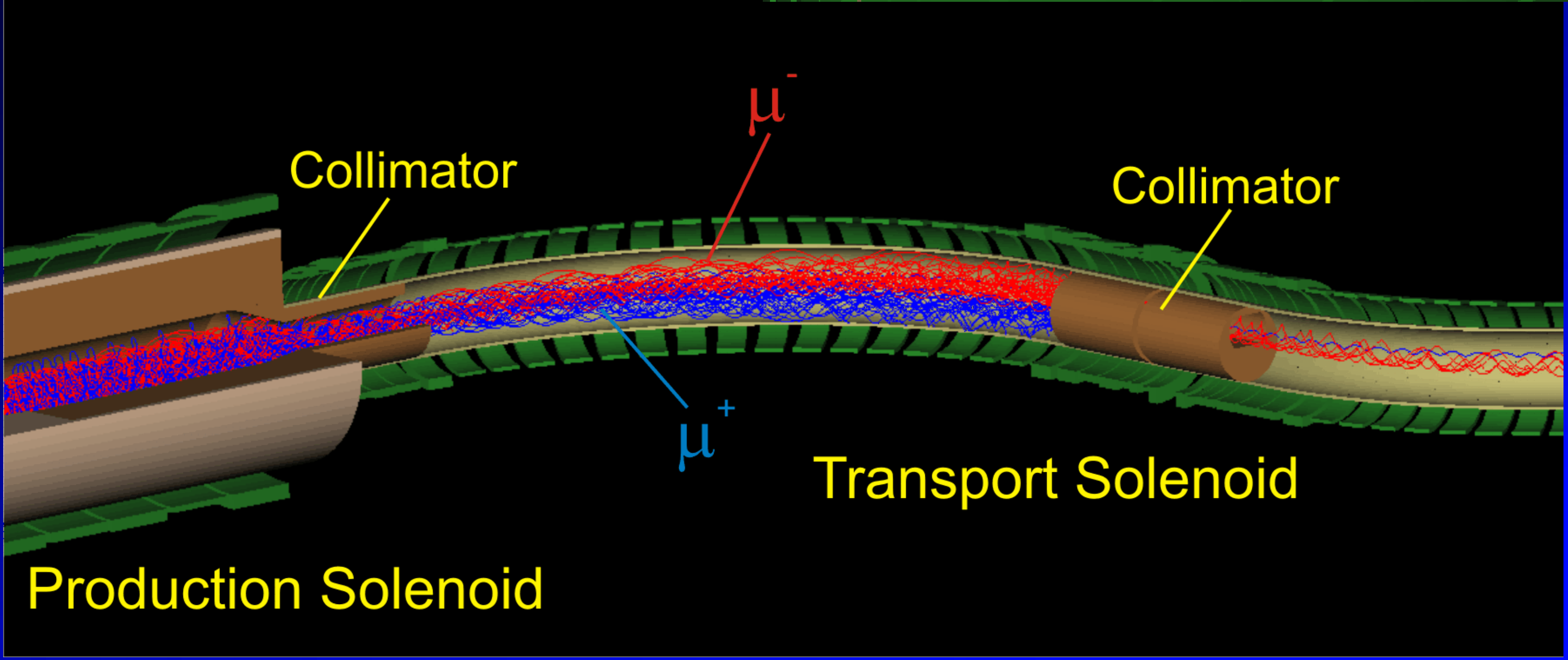
Look for 100 MeV electron

8 GeV/c Booster beam bunched in Accumulator/Debuncher

Transport Solenoidal Magnet

- Curved solenoid:
  1. separates charges by charge sign
  2. reduces line-of-sight transport of neutrals
- Collimators eliminate wrong-sign particles, slow late arriving particles, particles with too large

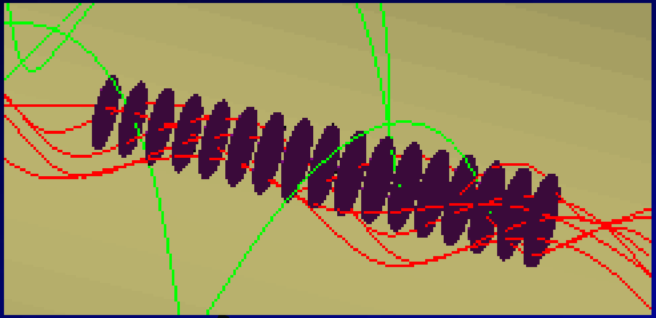


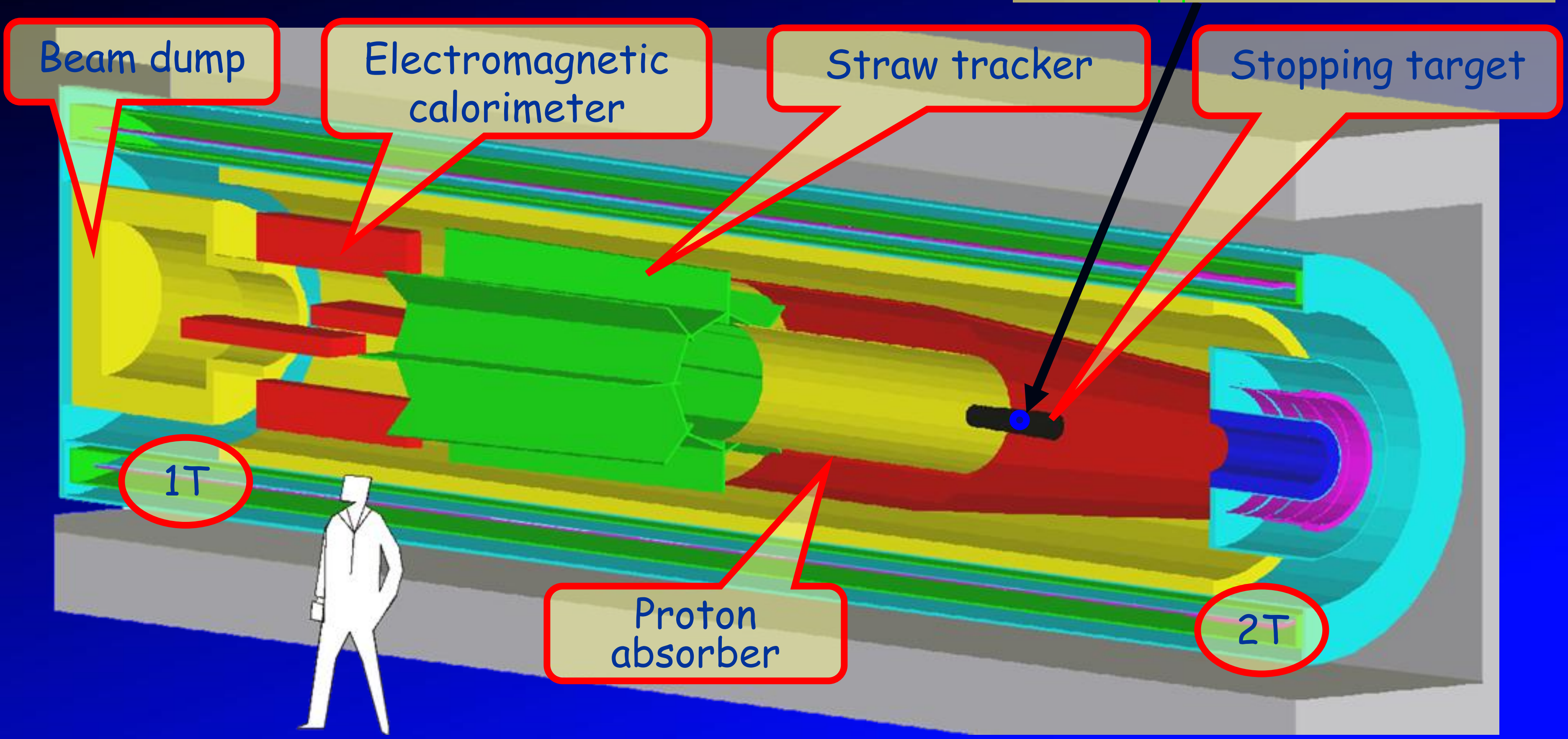


Mu2e Detector

Salient Features

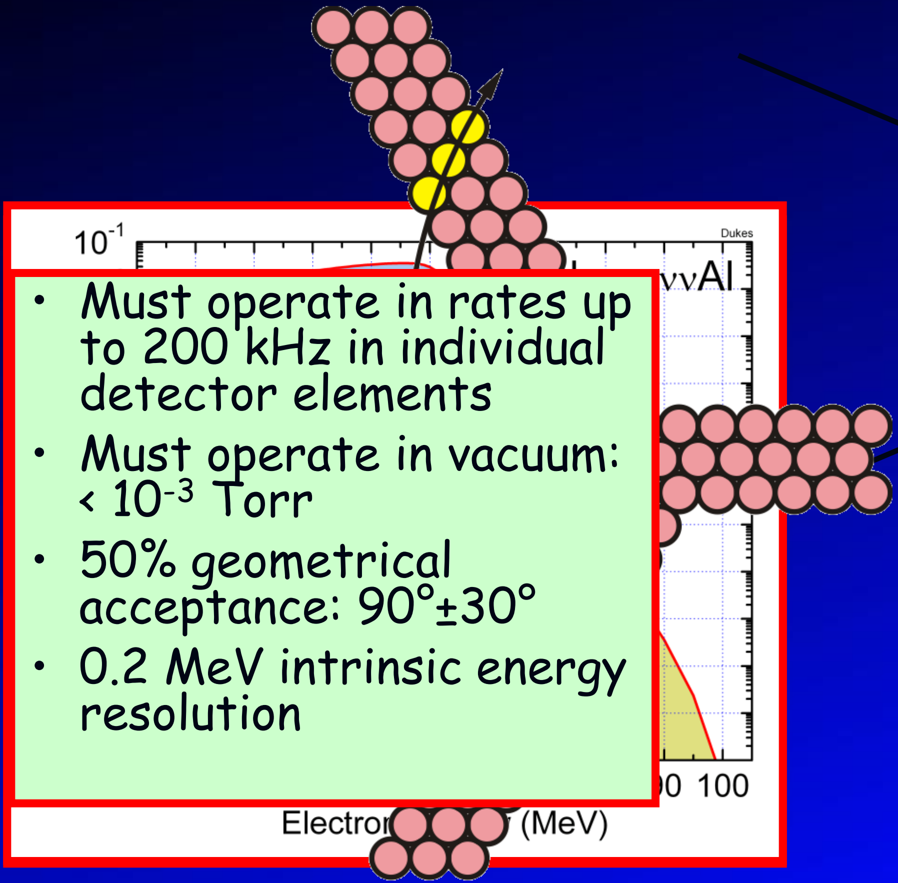
- No detector element in region of transported beam
- Small acceptance for DIO electrons
- Minimal amount of material ⇨ detector elements in vacuum



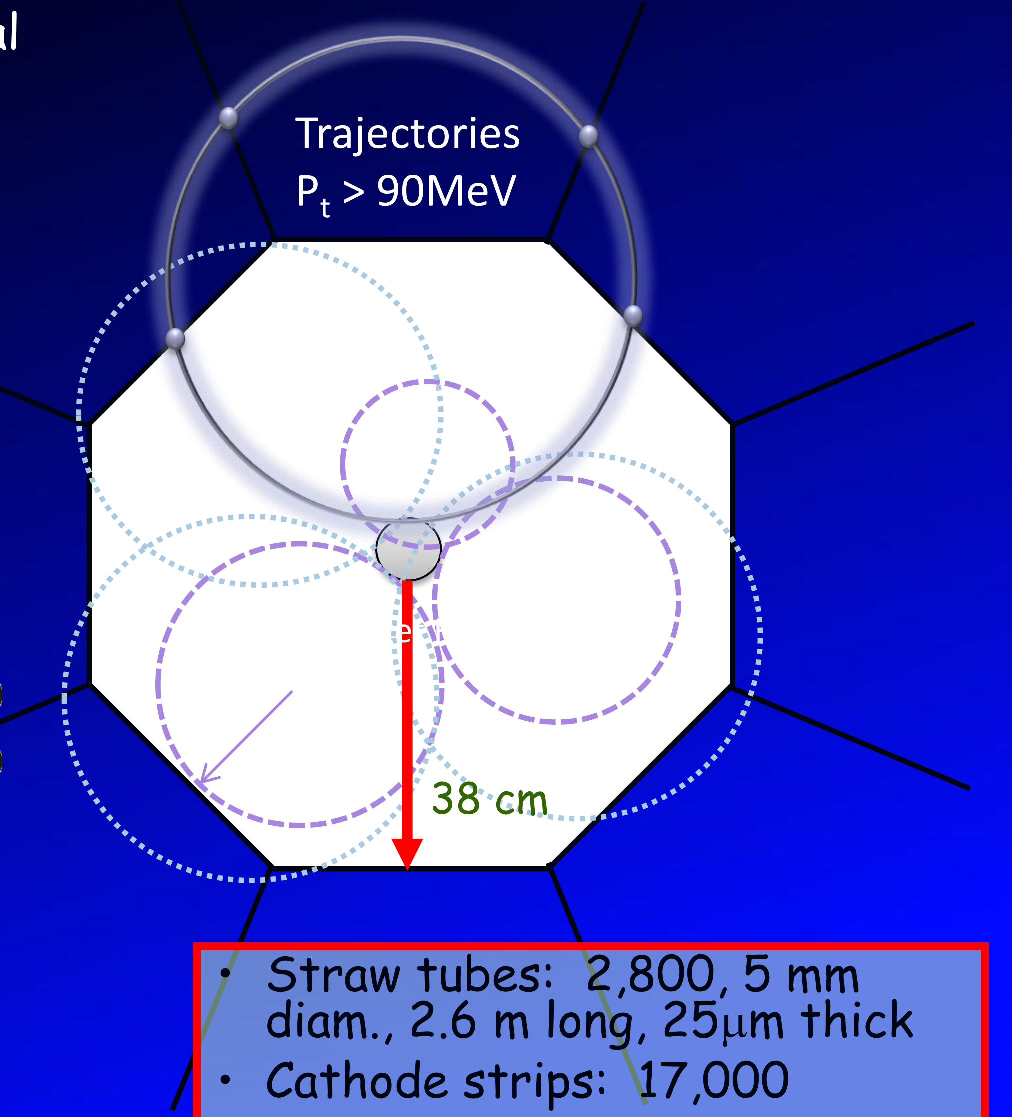


Heart of the Spectrometer: Straw Tracker

- Octagonal vane geometry optimized for reconstruction of 105MeV helical trajectories
- Center beam region empty
- Acceptance for DIO tracks < 10^{-3}



- Must operate in rates up to 200 kHz in individual detector elements
- Must operate in vacuum: < 10^{-3} Torr
- 50% geometrical acceptance: 90°±30°
- 0.2 MeV intrinsic energy resolution



- Straw tubes: 2,800, 5 mm diam., 2.6 m long, 25μm thick
- Cathode strips: 17,000

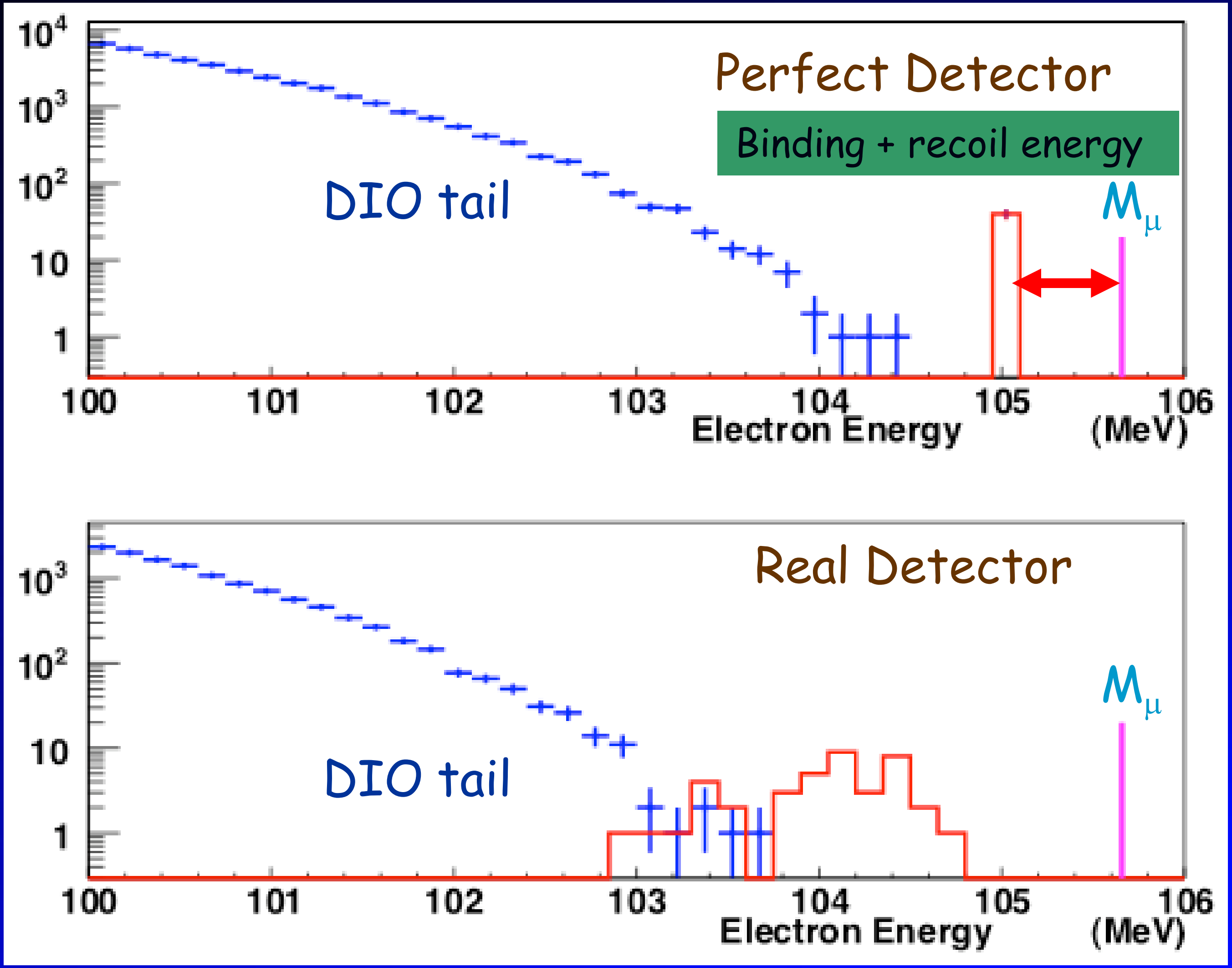
What we Get

Intrinsic tracker energy resolution:

$\sigma(E) \approx 150$ keV

Average energy loss due to spectrometer material:

E(shift) $\approx$ 1 MeV



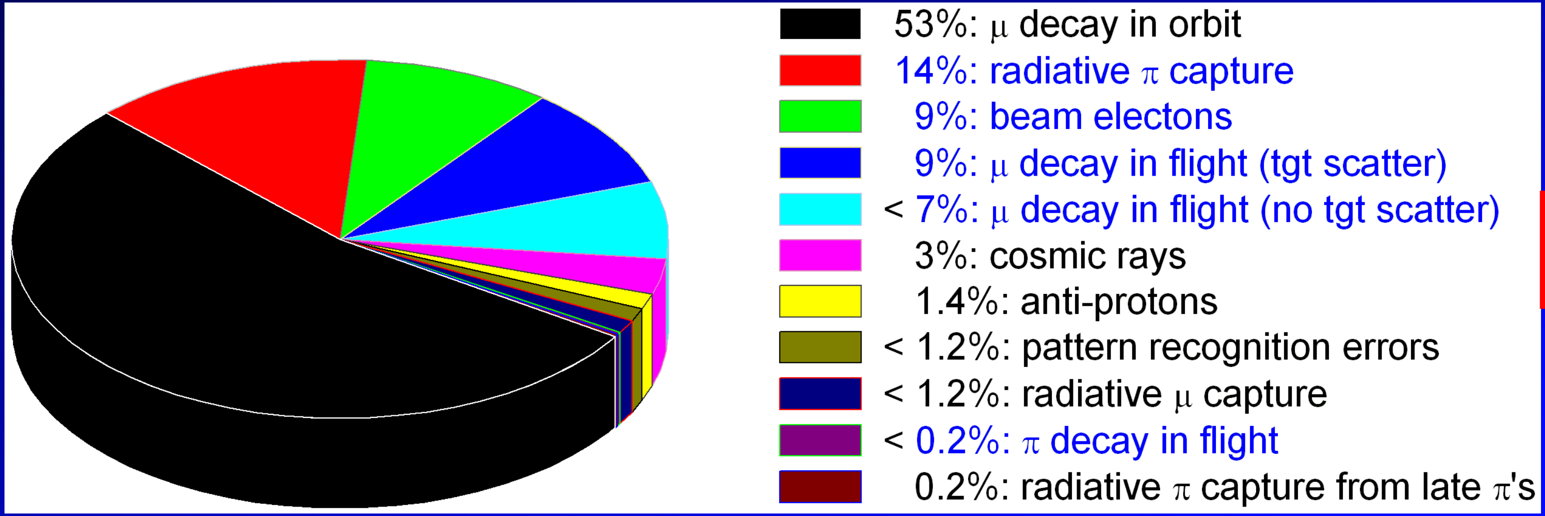
Mu2e Sensitivity

$$R_{\mu e} = \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \nu_{\mu} N^{*})} = \frac{N_{\nu e} / N_{s} \times 1/\varepsilon_{\mu e}}{\Lambda_{\mu\nu} / \Lambda_{tot}\,(= 0.609)}$$

Figure of Merit: $S/\sqrt{B} = 5.5$

for $R_{\mu e} = 1 \times 10^{-16}$

Proton flux	1.8×10^{13} p/s
Running time	2×10^{7} s
Total protons	3.6×10^{20} p
μ^- stops/incident proton	0.0025
μ^- capture probability	0.61
Time window fraction	0.49
Electron trigger eff.	0.80
Reconstruction and selection eff.	0.19
Sensitivity (90% CL)	6×10^{-17}
Detected events for $R_{\mu e} = 10^{-16}$	4
Estimated background events	0.4



Mu2e Collaboration

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College of William & Mary	J. Kane
University of Washington	D. Hertzog, P. Kammel

Currently:

117 scientists

23 institutions

Mu2e Status

1992	Solenoidal collection scheme first pro at Moscow Meson Factory
1997	MECO pro
1998-2005	Intensive at $58M,
July 2005	RSVP canc
2006	Steering c at Fermila
June 2007	Mu2e EOI
October 2007	LOI submitted to Fermilab
May 2008	P5 "recommends pursuing the muon-to experiment, subject to approval by th budget scenarios considered by the panel."
Fall 2008	Proposal submitted to Fermilab and receives Stage I approval. Total project cost estimated at $180M
November 2009	CD-0 status granted ($145M - $205M)
FY2010	Mu2e receives $4M in R&D funding ($10M FY2011, $20M FY2012)
March 2011	CD-1
November 2012	Start of Construction (CD-3)

CD-0 Approve of mission needs
CD-1 Approve preliminary baseline range
CD-2 Approve performance baseline
CD-3 Approve start of construction
CD-4 Approve start of operations

29 May 2008

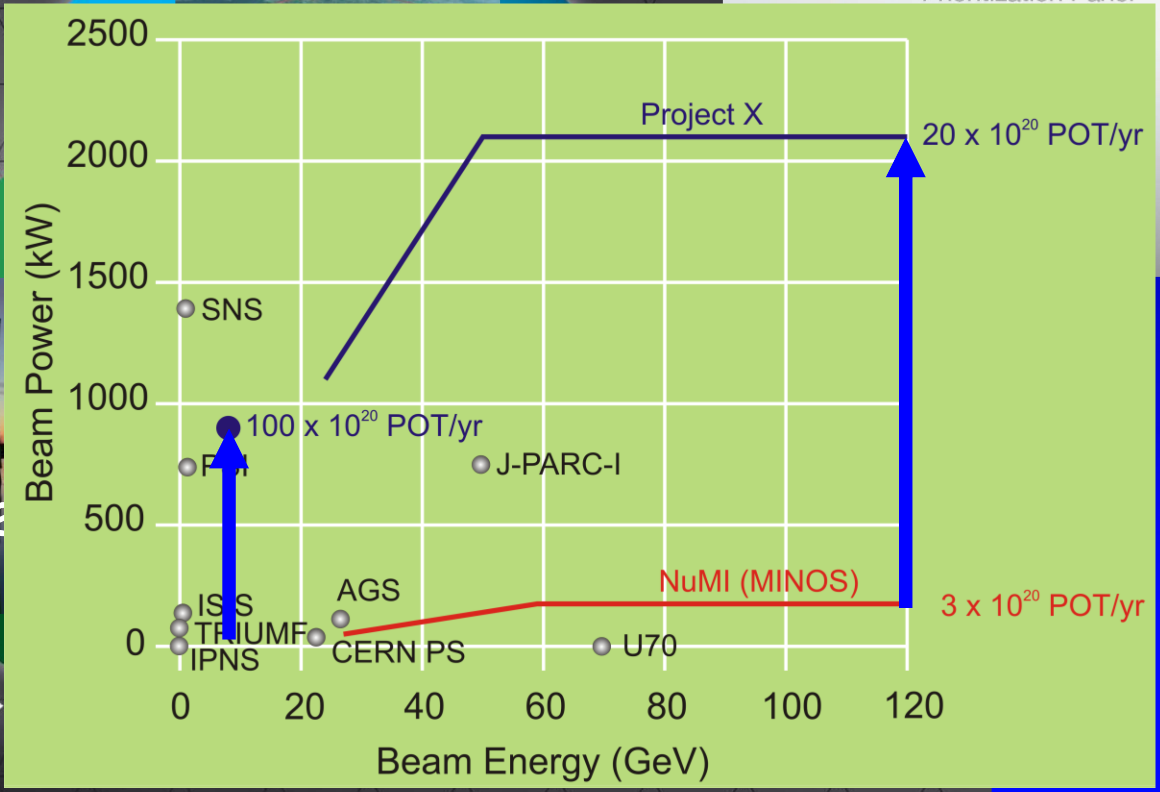
Fermilab Pushing Forward on Intensity Frontier

Strategic Plan for the Next

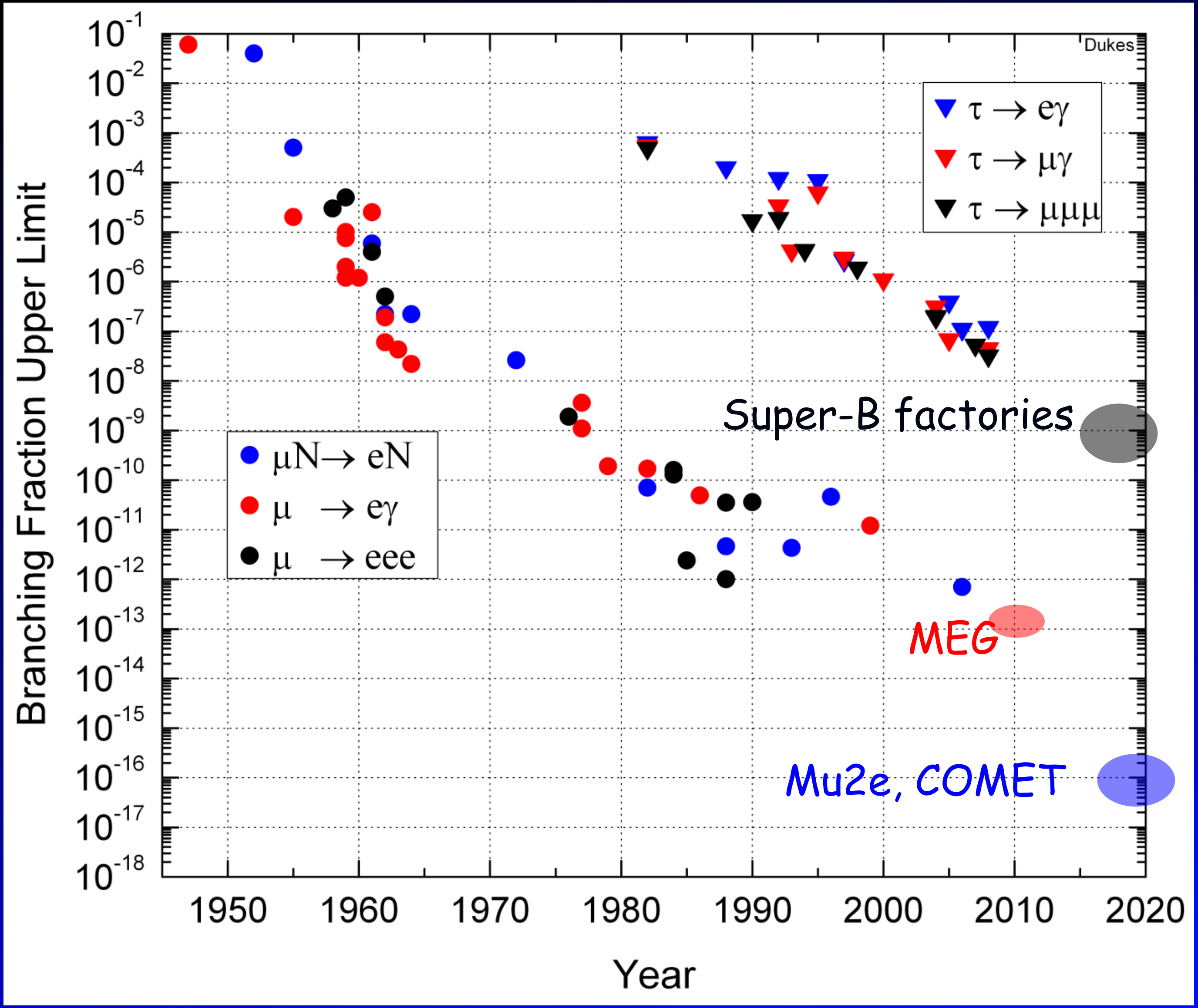
“The panel recommends an R
future to design a multi-meg
Fermilab…”

Project X will allow Mu2e to:

1. If we see nothing: improve sensitivity by another order of magnitude
2. If we see something: confirm it and explore its origin with different targets



Outlook for next Decade Very Exciting!

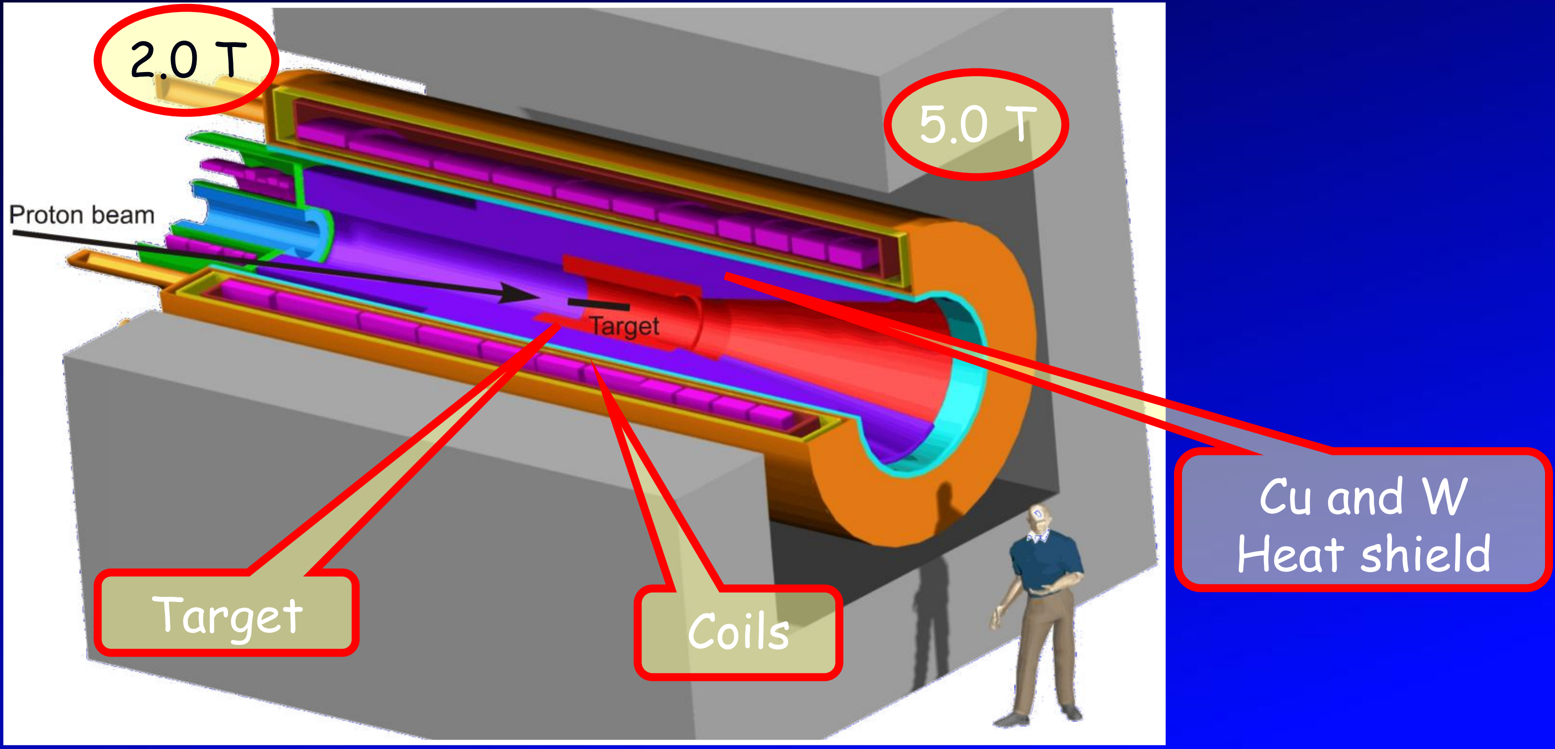


Backup Slides

Production Solenoid

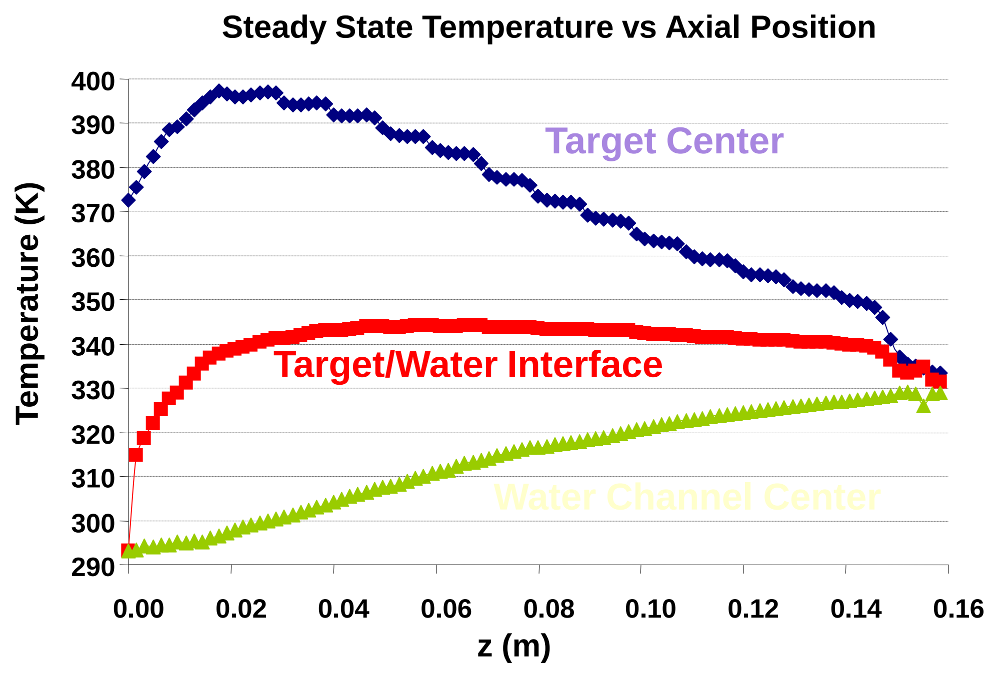
- Graded solenoidal field to maximize pion capture
- 2.5×10^{-3} μ^-/p
  - SINDRUMII: ~10^{-8}
  - MELC: ~10^{-4}
  - Muon collider: ~0.3

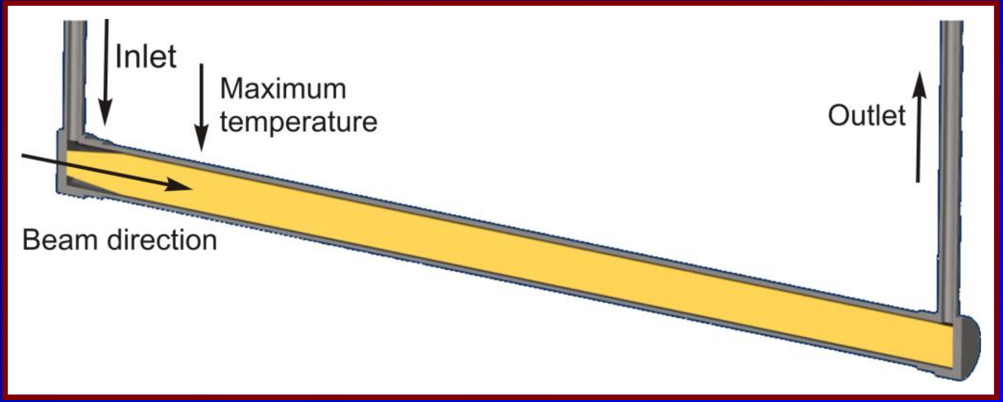
- R = 75 cm
- 23kW beam
- 0.8 mm x 160 mm gold target
- 2.5T – 5.0T graded magnetic field
- Forward moving pions and muons with $\theta > 30°$ and $p_z < 180$ MeV/c reflected back in graded field

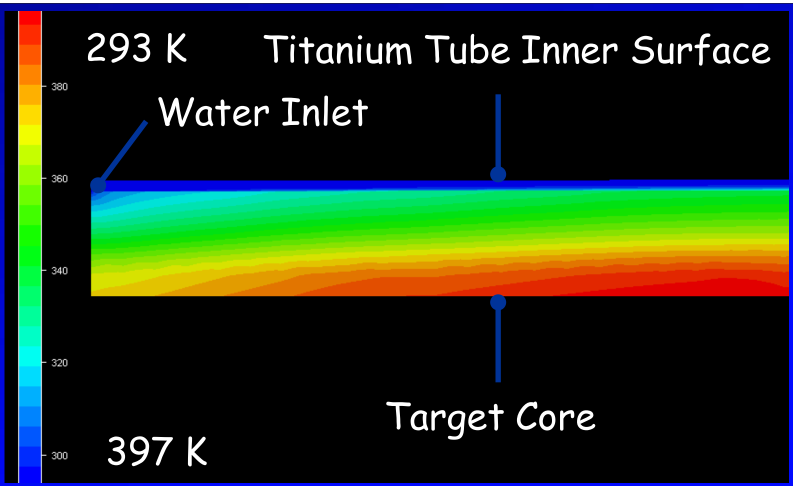


Water-Cooled Target Design

- Average beam power: 23 kW
- Max. beam power:26 kW
- 1.8×10^{13} p/s (90% duty factor)
- W cylinder:
  L = 16.0 cm, R = 3.0 mm
- Water cooled
- Ti coolant cylinder: 0.5 mm wall thickness
- 3.8 liter/min flow rate
- Max. temps:
  - tgt: 124 C
  - water: 71 C

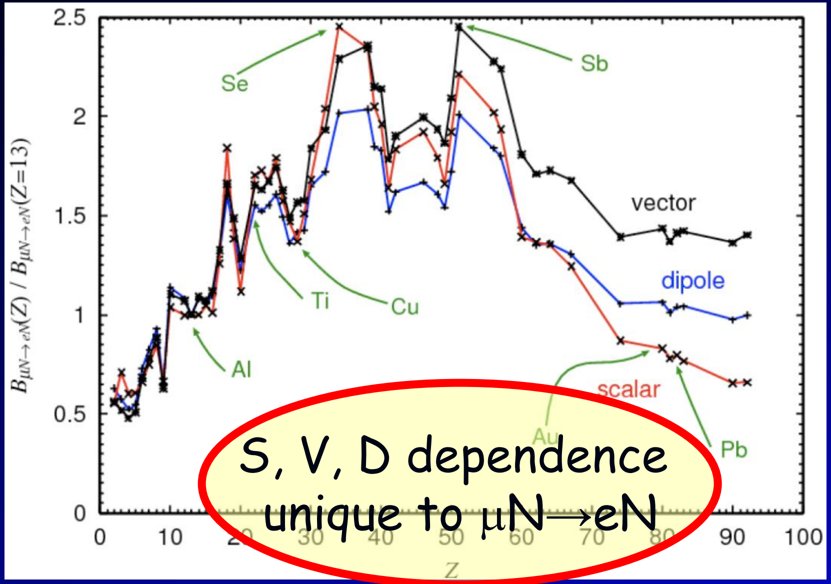




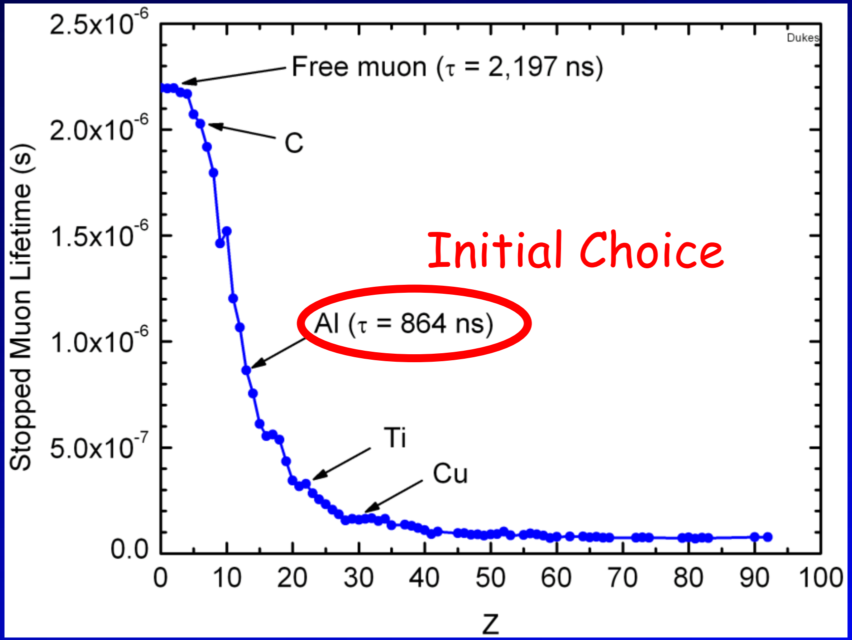


Choice of Stopping Target Material

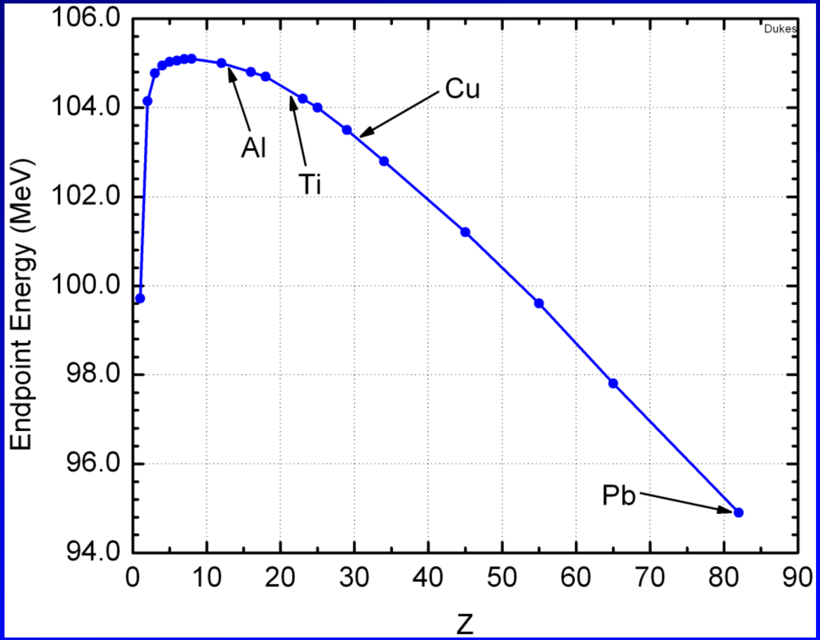
- Large Z:
  - rate ∝Z|F_n|2 (F_n is the form factor)
  - can reveal nature of interaction
- Small Z:
  - longer lifetime
  - higher endpoint energy
- Note: Need $m_{Z-1} > m_Z$ to place max. energy of radiative capture muons below signal electrons



S, V, D dependence unique to μN→eN



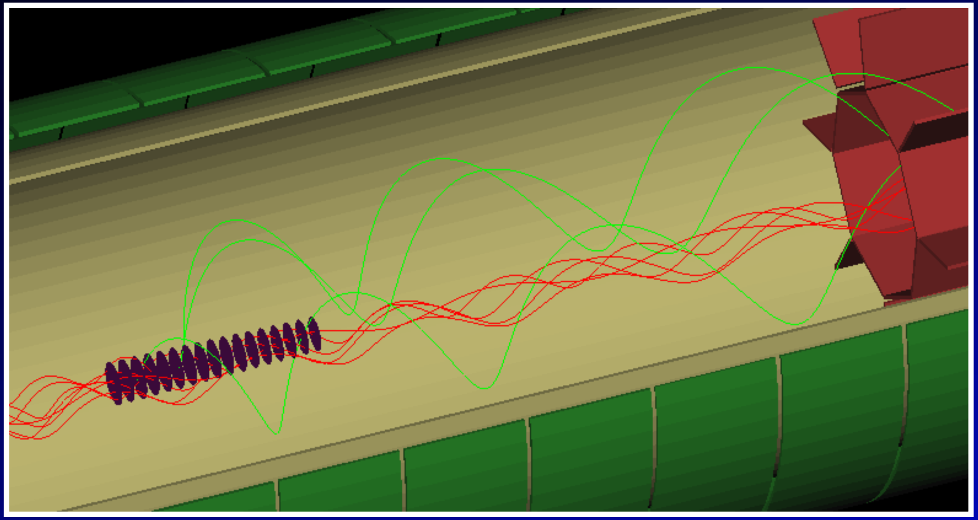
Initial Choice

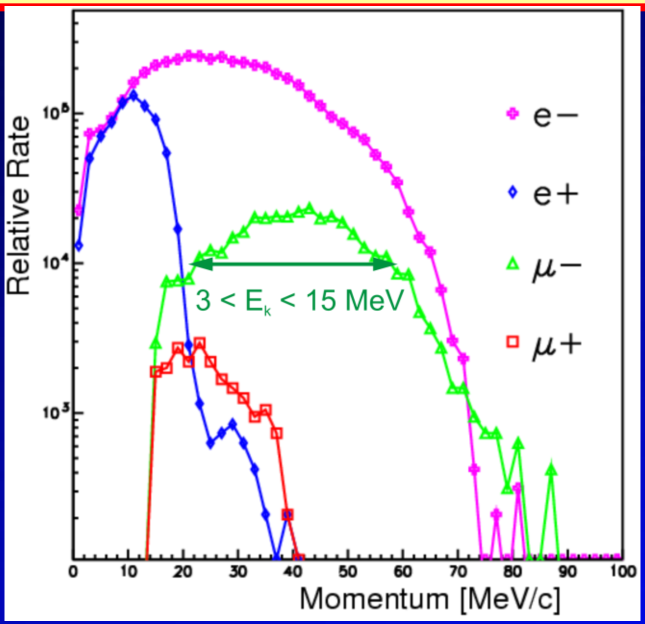


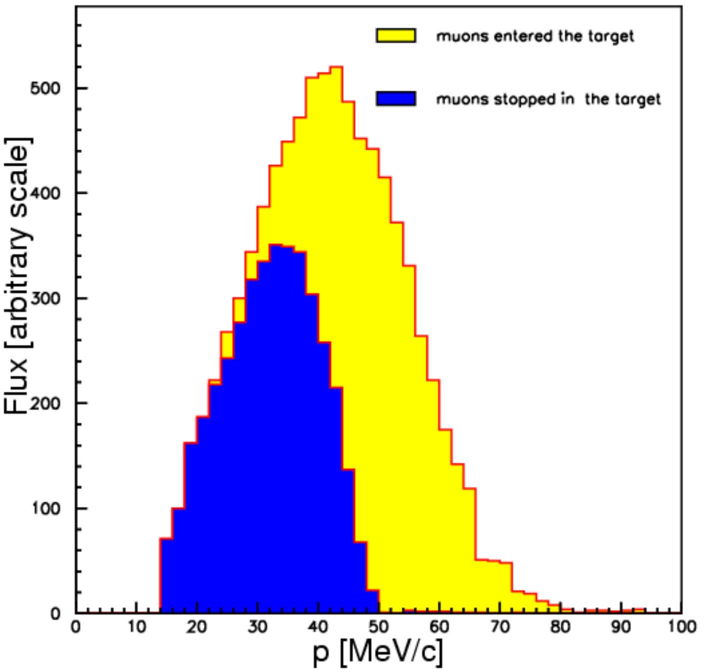
What we get at the Stopping Target

- 17 Al disks
- each 200 μm thick
- 83 mm to 65 mm radius
- in graded magnetic field

- 1/230 incident protons produce a muon at the stopping target
- 58% of muons stop in target
- 50×10^9 μ stops per spill second
- 85,000 μ stops per microbunch

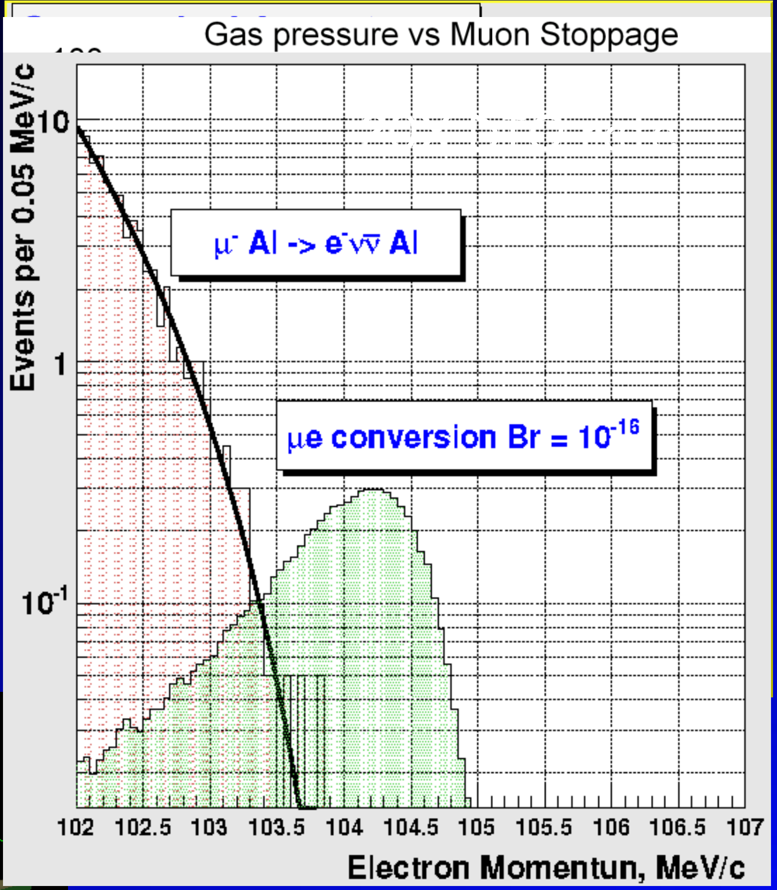


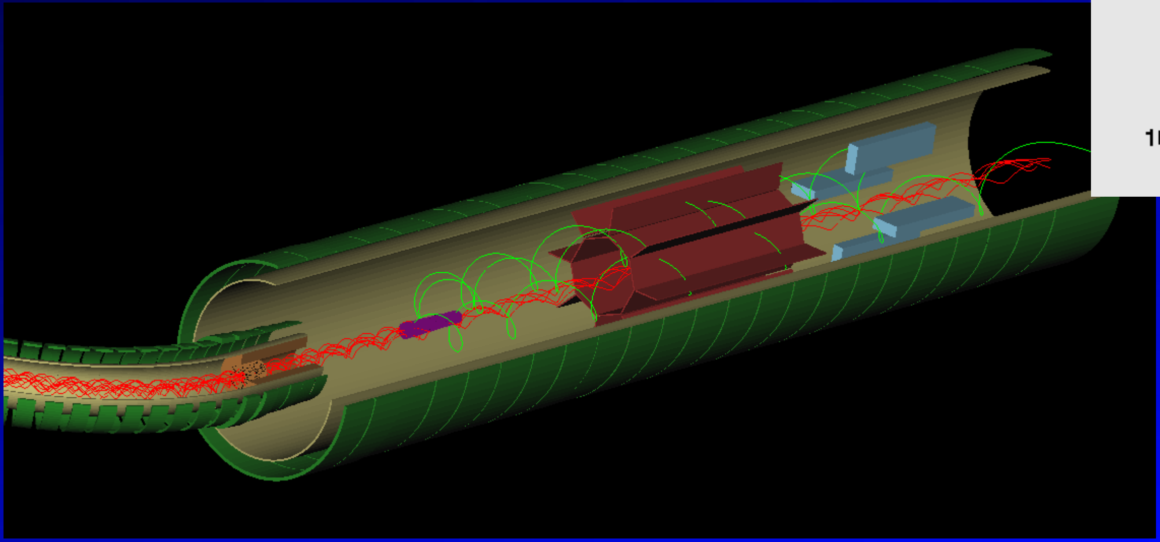




Magnetic Spectrometer

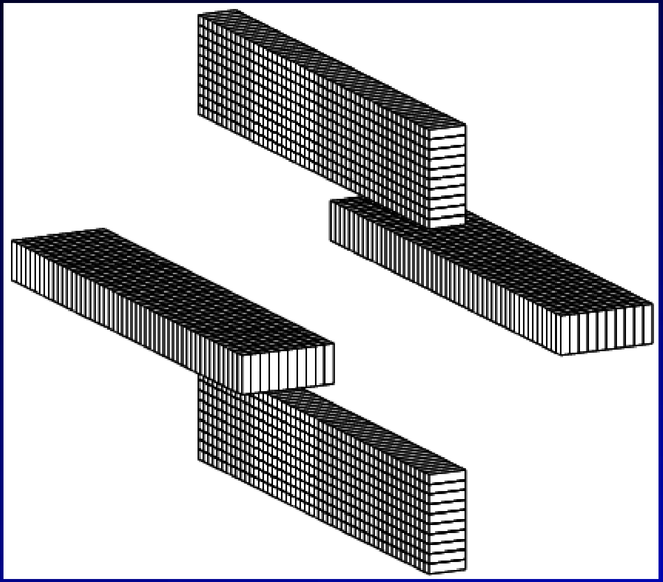
- Must operate in rates up to 200 kHz in individual detector elements
- Must operate in vacuum: < 10^{-3} Torr
- Must have low acceptance for DIO electrons
- Straw tubes: 2,800, 5 mm diam., 2.6 m long, 25μm thick
- Cathode strips: 17,000
- 50% geometrical acceptance: 90°±30°
- 0.2 MeV intrinsic energy resolution
- Resolution dominated by multiple scattering

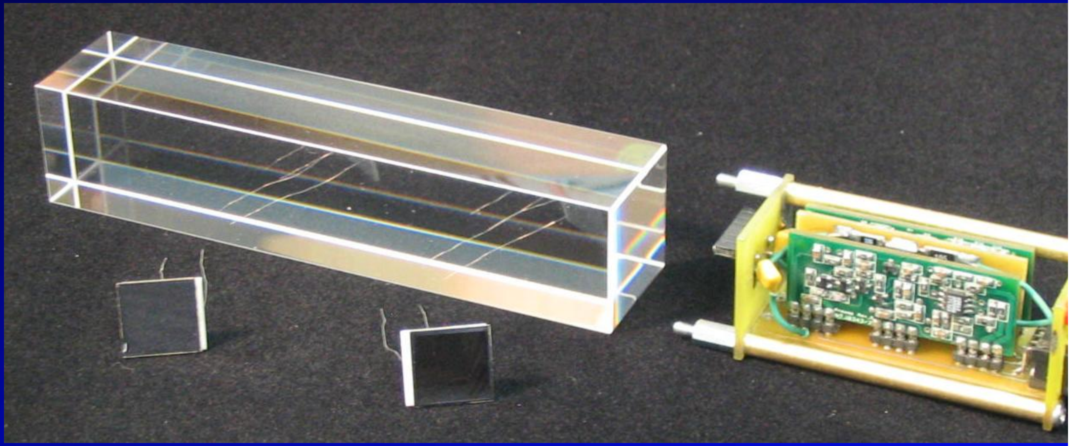




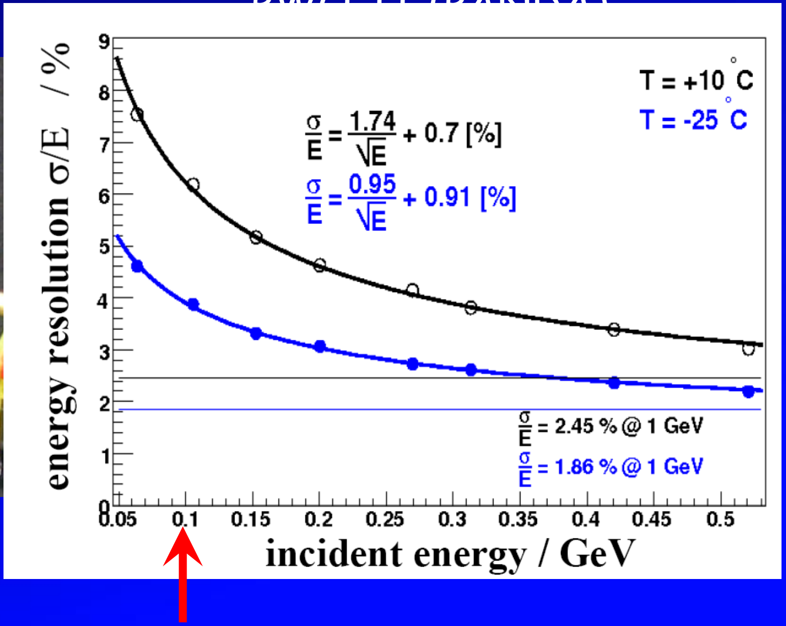
Electromagnetic Calorimeter

- Needed for:
  - trigger: 5% energy resolution → 1,000 triggers/s
  - particle ID
  - confirm the electron position and energy measurements of the straws
- 2000 30x30x120mm^3 PbWO$_4$ crystals
- Dual APD readout





PWO-II (PANDA)



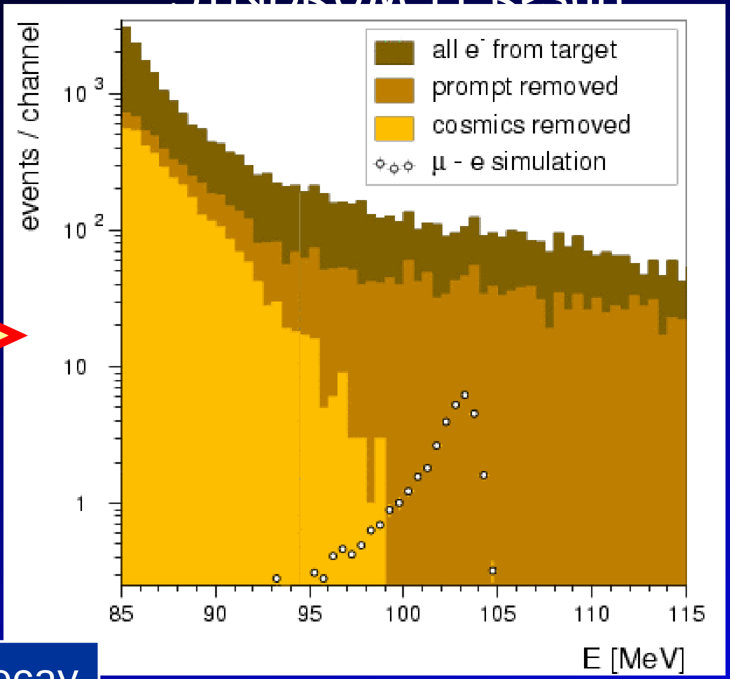
Need for Cosmic Ray Shield

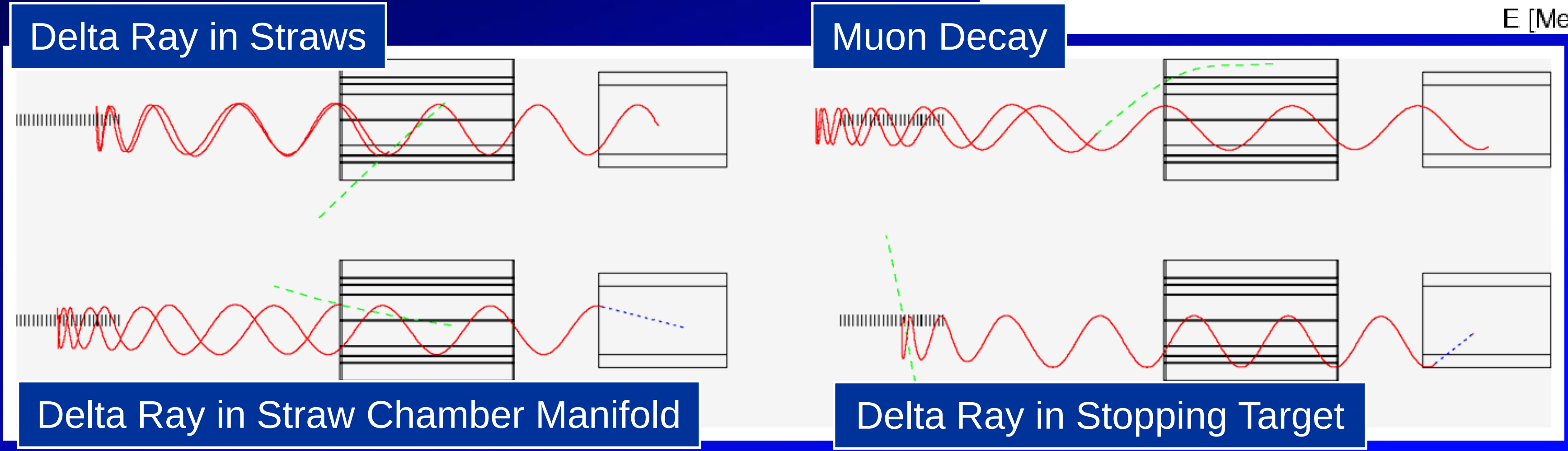
CR Muons cause two types of backgrounds:

1. Muon decay-in-flight
2. Delta electrons from target or tracker

Cosmic ray suppression vital!

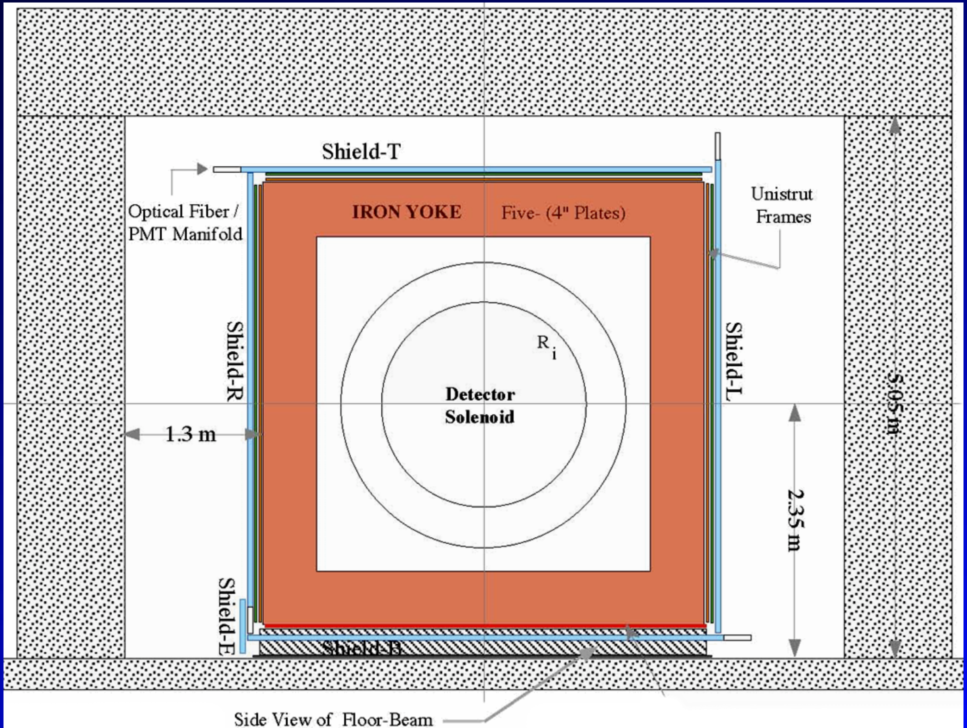
SINDRUM II Result

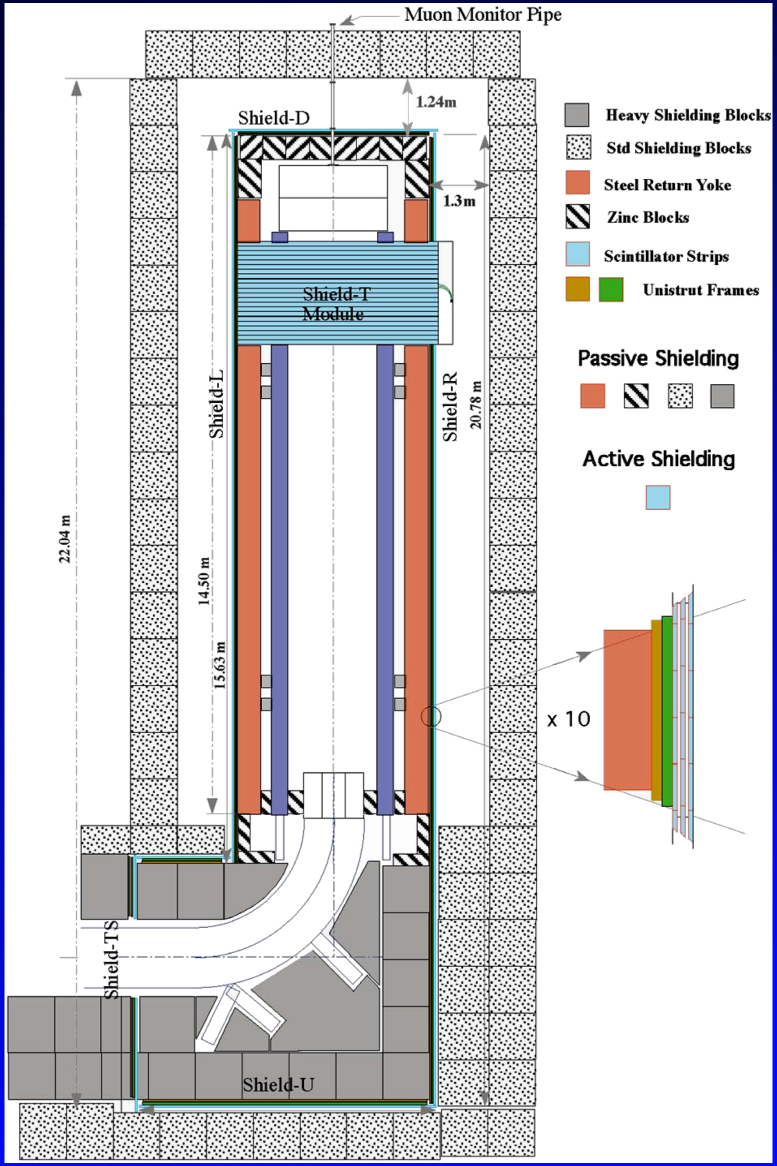




Cosmic Ray Shield Design

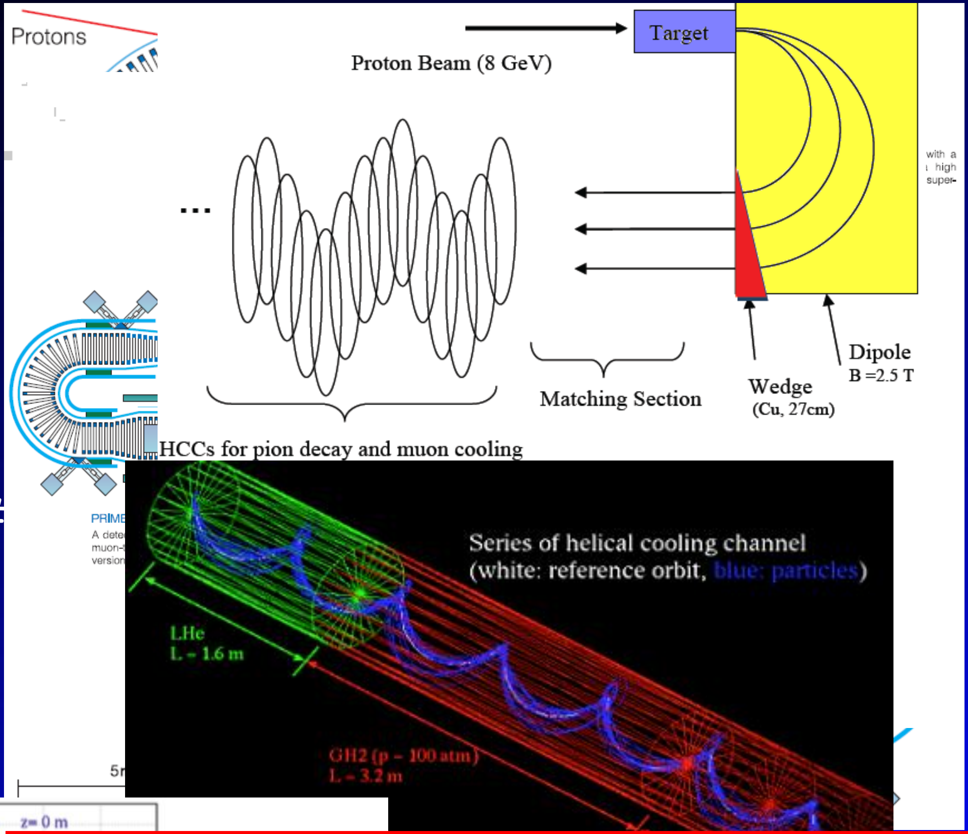
- Passive
  - 1 m thick concrete shielding blocks
  - 0.50 m thick iron return yoke
  - yet-to-be-determined overburden
- Active
  - scintillator strips w embedded fibers
  - three layers with ~99% coverage
  - 10^{-4} inefficiency



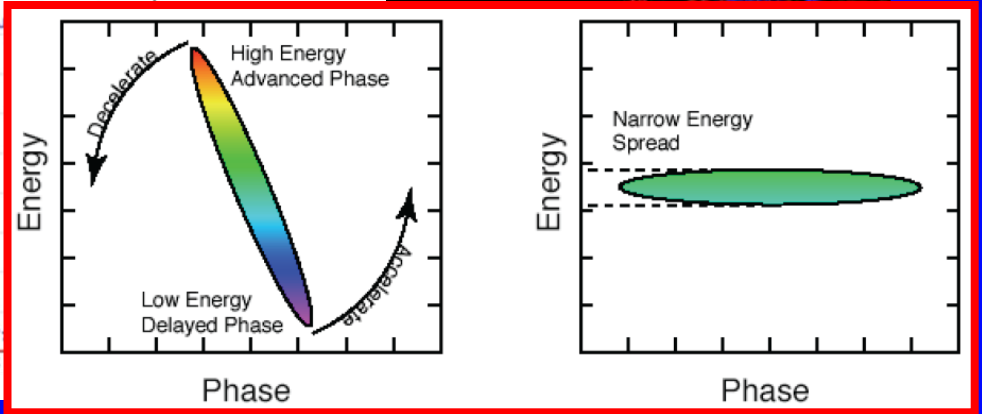


Exploiting the Project X Rates

- Mu2e designed to run at rates 3X possible with Fermilab booster/accumulator/debuncher
- Going beyond 3X will be challenging:
  - A new muon production target and production solenoid are needed
  - Individual straw rates >500 kHz
  - Backgrounds may prove to be insurmountable ⇨ sensitivity scales as square root rather than linearly with # muon captures
- New ideas are needed:
  - COMET
  - PRISM
  - helical cooling channel (Muons Inc)



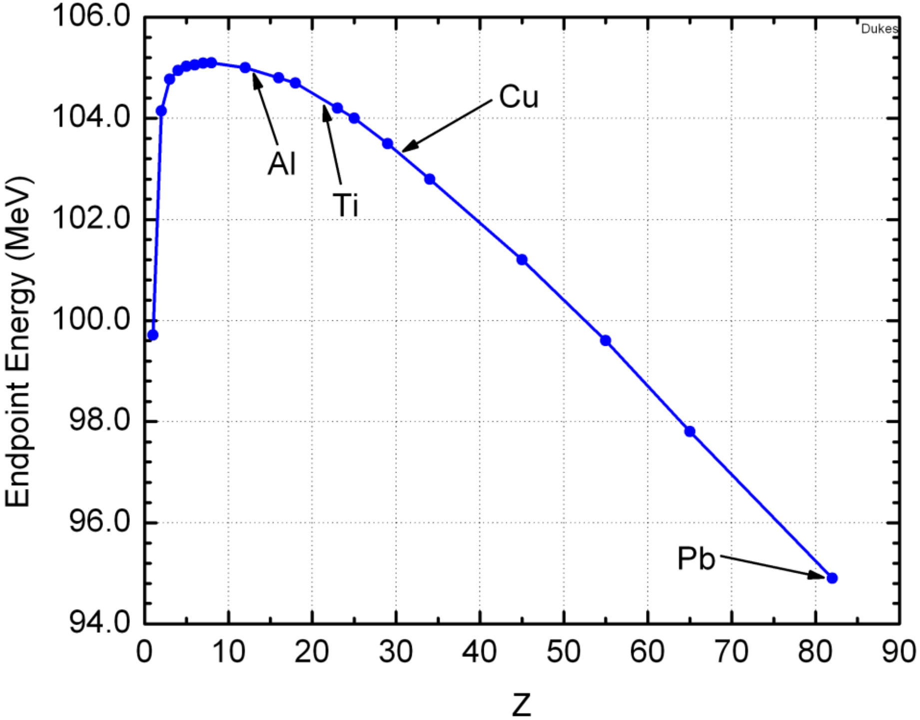
- FFAG as phase rotator
- Intensity: $10^{11} - 10^{12}$ $\mu^{\pm}$/s
- Momentum spread: ±30% ⇨±3%: greater stop %, thinner stopping target
- Pions decay: $<10^{-20}$: less background

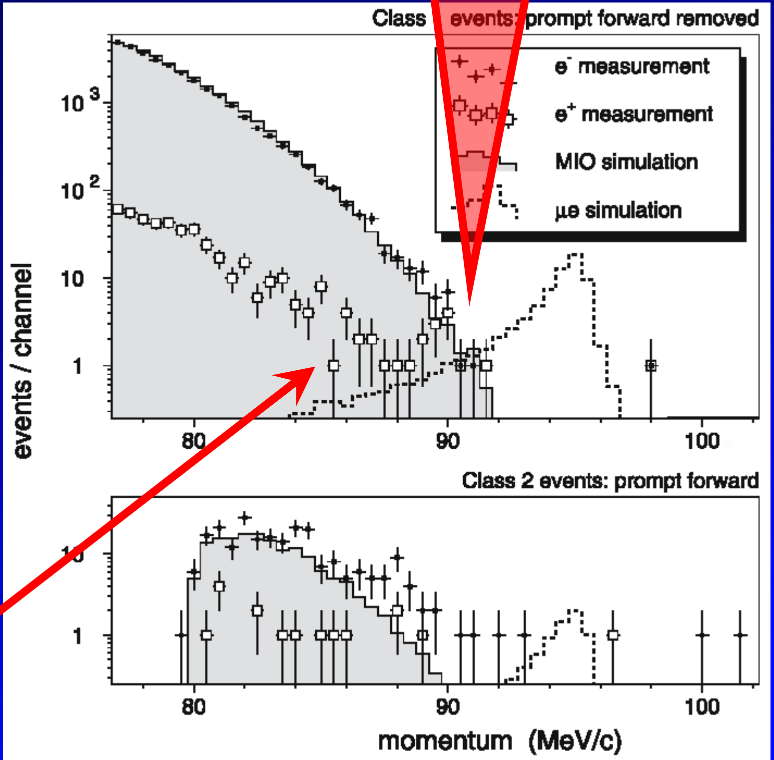


SINDRUM II (PSI) Has Best $\mu^- N \to e^- N$ Limit

- Best limits on:
  - $\mu^+ \to e^+ e^- e^+$: 1.2×10^{-11} (SINDRUM I)
  - $\mu^- N \to e^- N$: 7.3×10^{-13} (SINDRUM II: Au)
- Continuous muon beam: 10^7-10^8 /s
- Muon degrader to remove π background

Note large shift in energy: B_μ=10.08 MeV





High energy tail of coherent Decay-in-orbit (DIO)