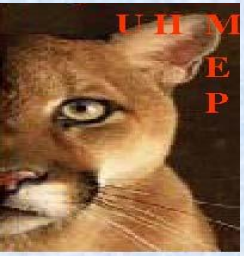
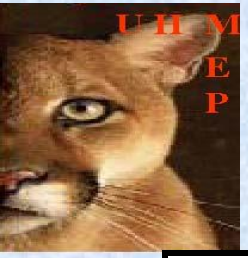


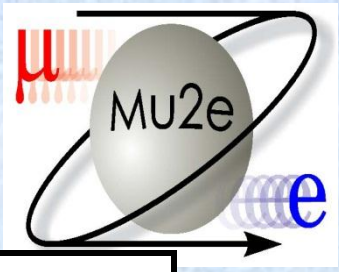
Discovering Charged Lepton Flavor Violation (cLFV)

--Mu2E at FNAL--

Ed V Hungerford
University of Houston



Collaboration



USA

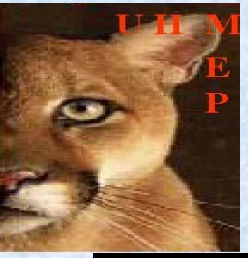
Boston University
Brookhaven National Laboratory
Calif. Institute of Tech.
City University of NY
Duke University
Fermi National Acceleration Lab
Lewis University
Los Alamos National Laboratory
Northern Illinois University
Northwestern University
Rice University
University of Calif./Berkeley/LBL
University of Houston
University of Calif./Irvine
University of Illinois
University of Mass./Amherst
University of Virginia
University of Washington

Italy

Instituto Nazionale di Fisica/ Lecce
Instituto Nazionale di Fisica/ Pisa
Laboratori Nazionali di Frescati

Russia

Institute of Nuclear Research/ Moscow
Institute of Nuclear Research/ Dubna



Acknowledgements

Firstly

- I acknowledge with thanks the Coordinators of NUFACT who extended the offer to talk about our Mu2E experiment

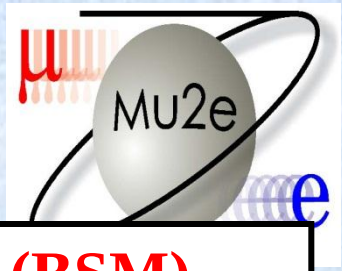
Secondly

- I acknowledge with thanks and appreciation the efforts of my experimental colleagues. A 30 min talk does not due justice to all they have done. However, any errors in this presentation are mine.

Thirdly

- I acknowledge the many authors from whom I have borrowed information and figures. I give credit where I can.

Particle Physics Frontiers



Elucidate TeV-scale physics Beyond the Standard Model (BSM)

- Origin of EW symmetry breaking
- Hierarchy problem (Neutrinos)
- Dark matter in the Universe
- Neutrino mass and mixing issues
- New Models, SUSY, Extra dimensions, various Higgs models

Of relevance to this talk

Charged LFV, cLFV, is sensitive to various BSM and μ→e has the physics reach for discovery, but if new physics is first observed at high energies, cLFV investigations are needed to define the physics

Muons:
A Long-standing tool for precision tests

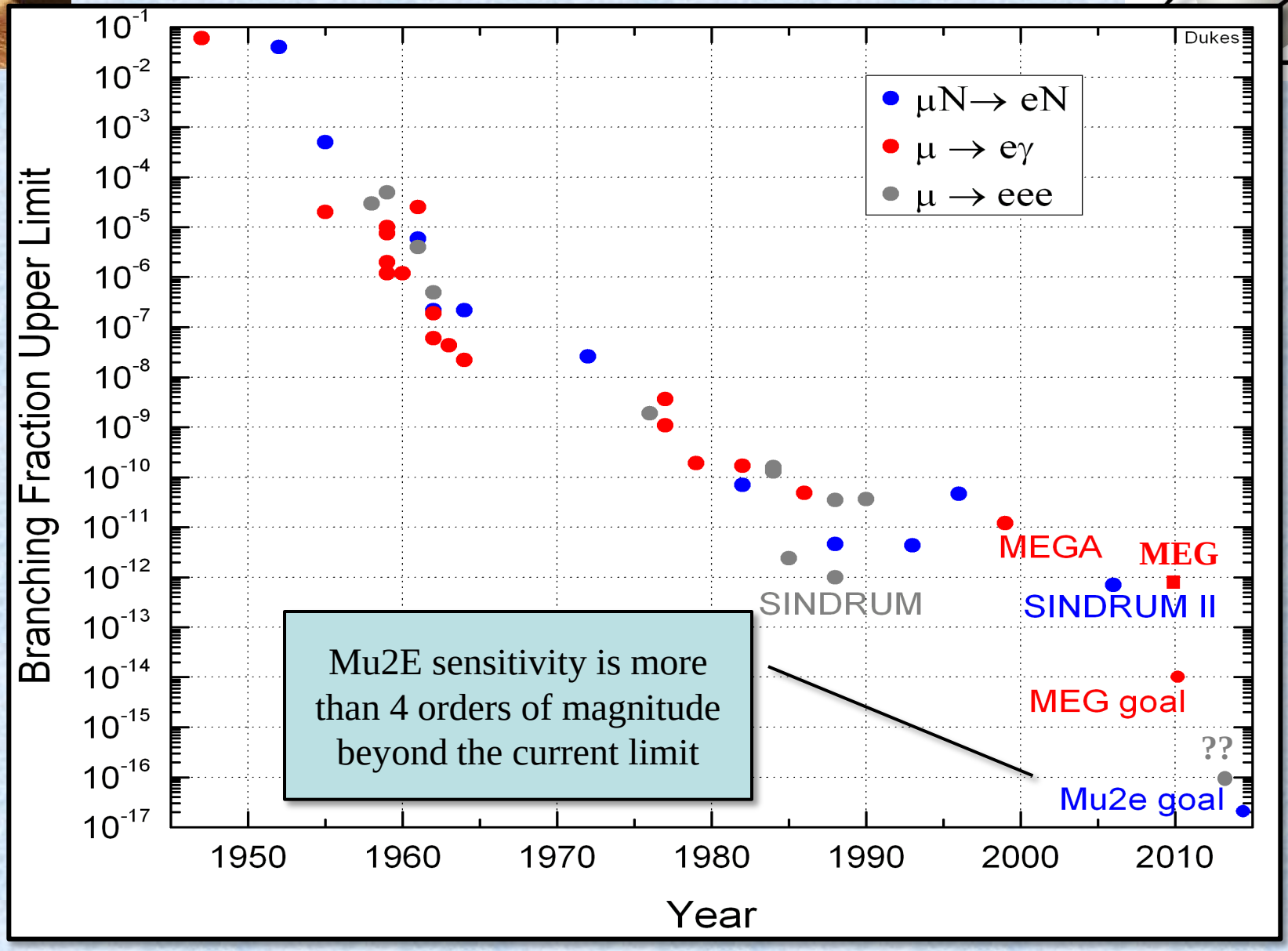
1. Determination of SM parameter
   Lifetime（Fermi constant）
2. Test of SM：
   Muon (g-2)
   Michel parameters in muon decay
   Capture rates
3. Searches for new symmetry breaking：

Possible cLFV	Present Limit	SUSY(GUT)
$\mu^+ \to e^+\gamma$	**2.4 x10^{-12} J. Adam et al, PRL 107(11)171801**	**10^{-14}**
$\mu^+ \to e^+e^+e^-$		
$\mu^- - e^-$Conversion	**7 x10^{-13} W. Bertl et al, EPJ C47(06)337**	**10^{-16}**

muonium-antimuonium

4. Muon EDM

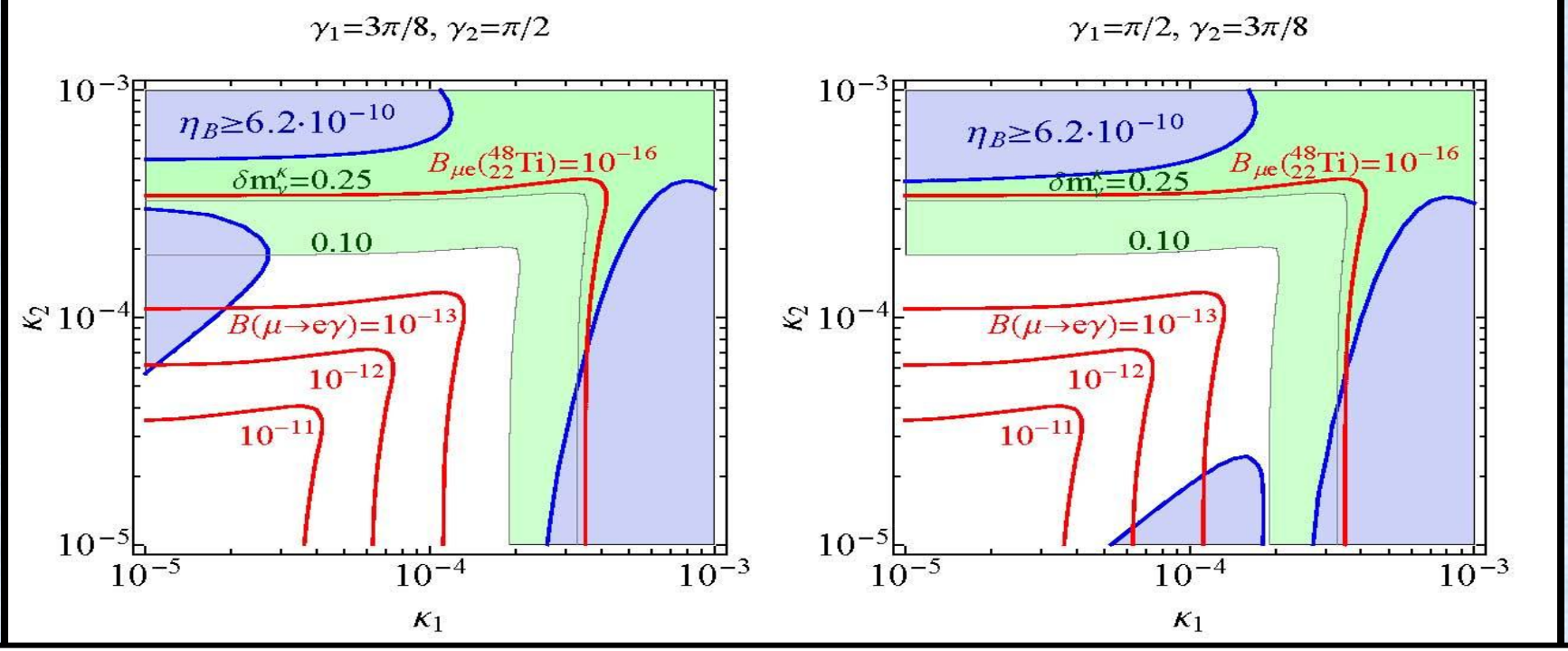
cLFV in muon interactions



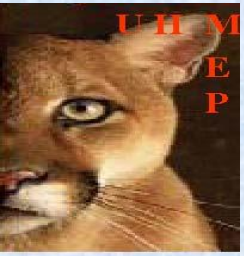
Number of Ways to Justify a cLFV Search
(Connecting the very large to the very small)

One of the more recent advances in physics has been the connection of microscopic particle theory to macroscopic cosmology

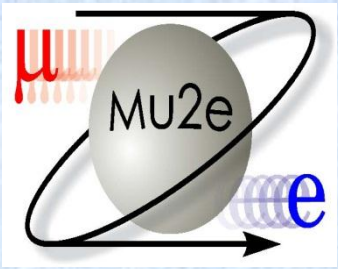
There is no explanation of Barogenesis in the ΛCDM Model. Possibile extensions
-Leptogenesis producing Baryogenesis-

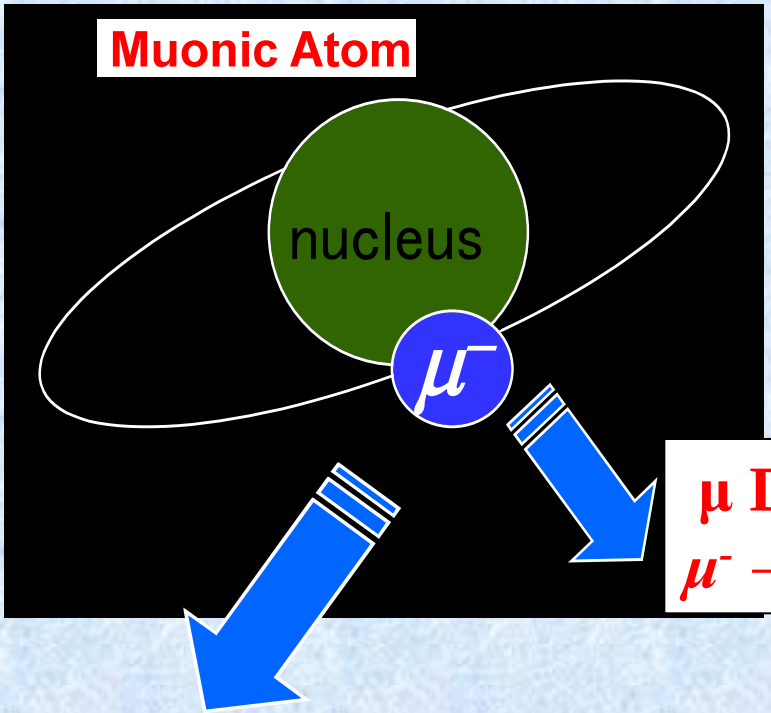


F. Deppisch and A. Pilaftsis arXIV:1012.1834;blue-baryon asymmetry; red -LFV μ→e; κ_1,κ_2 →Yukawa couplings in the RτL model; Heavy Neutrino masses ~120 GeV



Muon-to-Electron (μ-e) (neutrino-less emission)





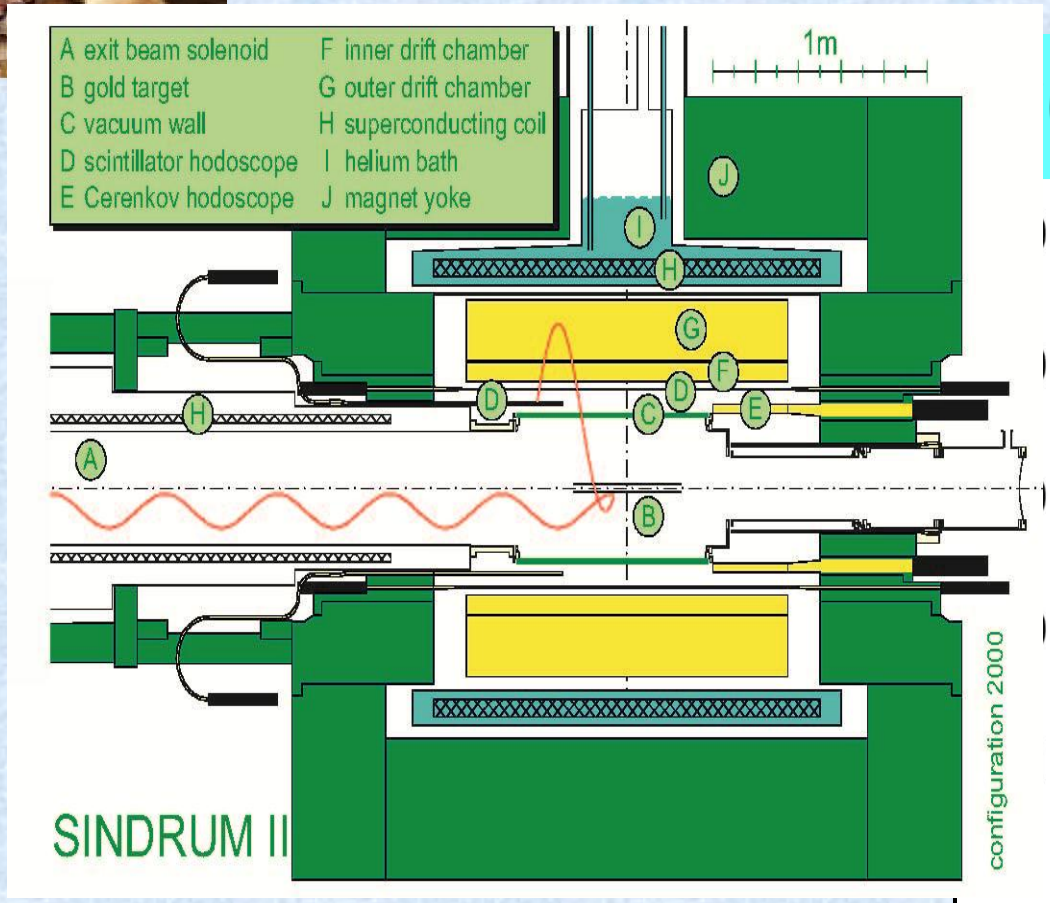
Lepton Flavor changes by one unit
-Coherent Conversion-
$\mu^- + A \rightarrow e^- + A$

μ Decay in Orbit (DIO)
$\mu^- \rightarrow e^- \nu \nu$

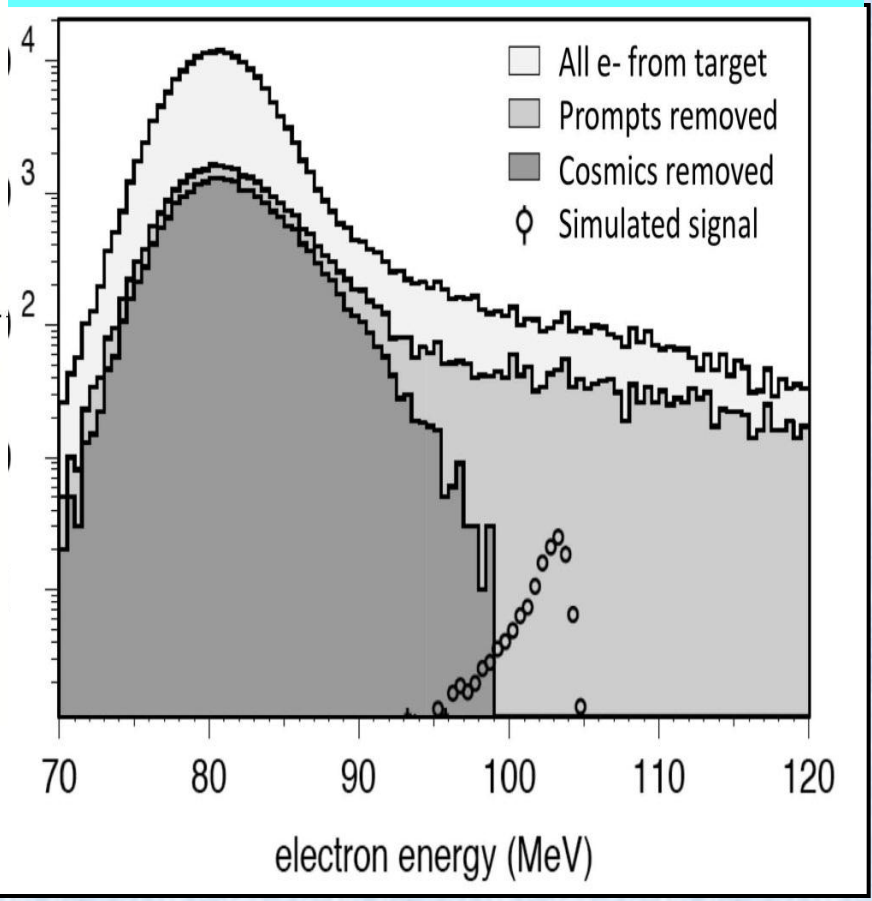
Nuclear Capture
$\mu^- + A \rightarrow \nu + [N + (A-1)]$

Experimental Advantages
- Copious muons
- Long μ lifetime
- No coincident accidentals
- High energy electrons

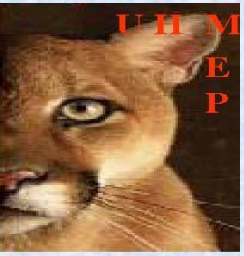
The SINDRUM-II Experiment



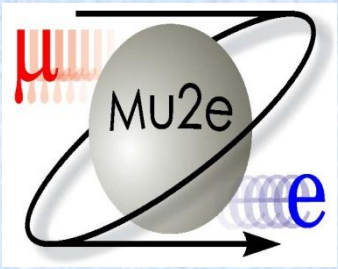
$$(\mu^- + Ti \rightarrow e^- + Ti) < 4.3 \times 10^{-12}$$



SINDRUM-II used a continuous muon beam from the PSI cyclotron. A degrader removes π and scintillator removes e from π decay by timing with respect to beam



To reach Higher Sensitivity



1) Reduce Beam Associated Background

Pulsed beam using advantage of long μ lifetime

2) Increase μ Stopping

High Intensity Pion Production

Capture π, μ, and decay electrons in Continuous Solenoids

3) Improve Electron Energy Resolution and Timing

Better Tracking Detectors

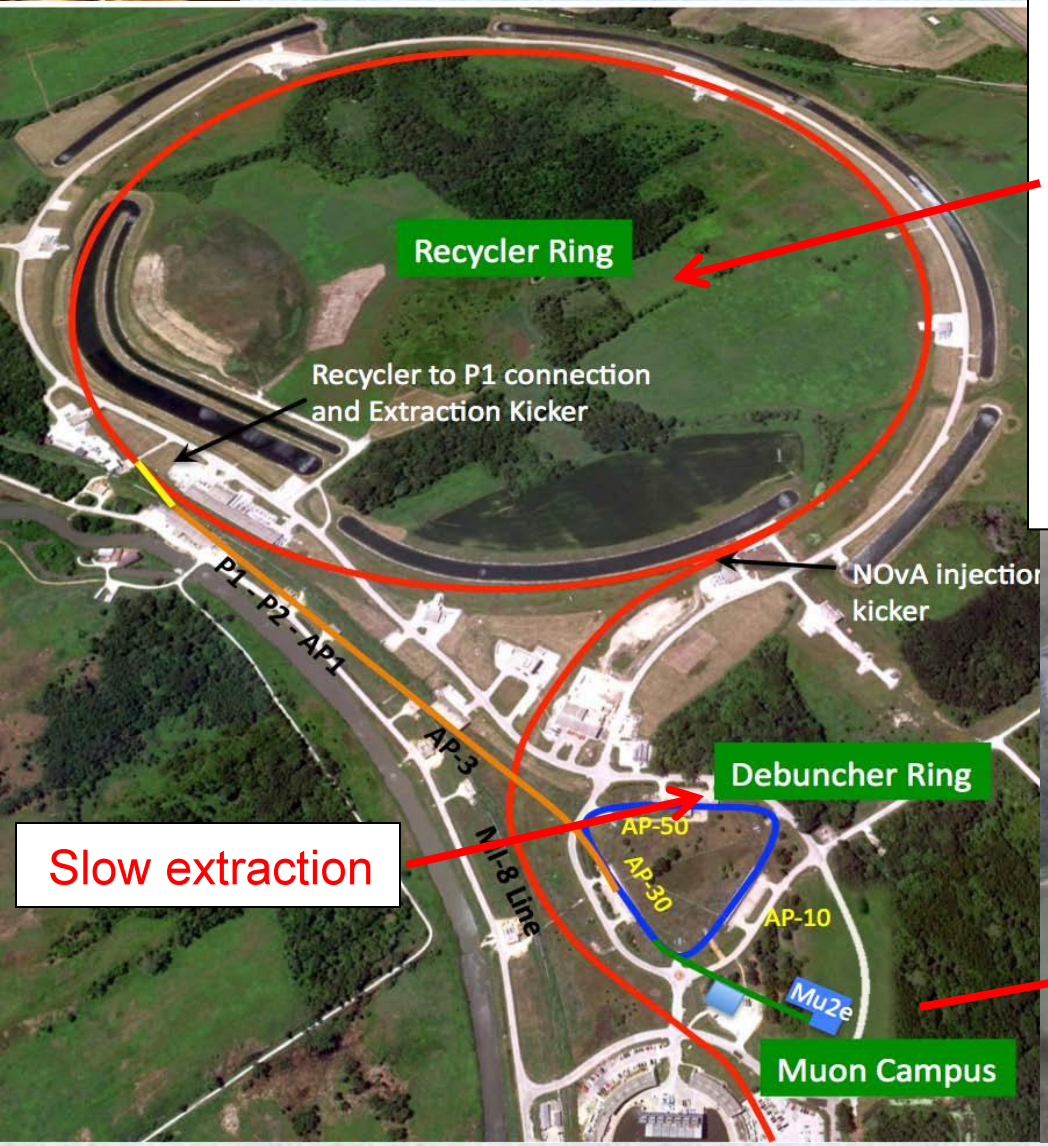
These ideas were contained in MELC (V. Lobashev, 1992)

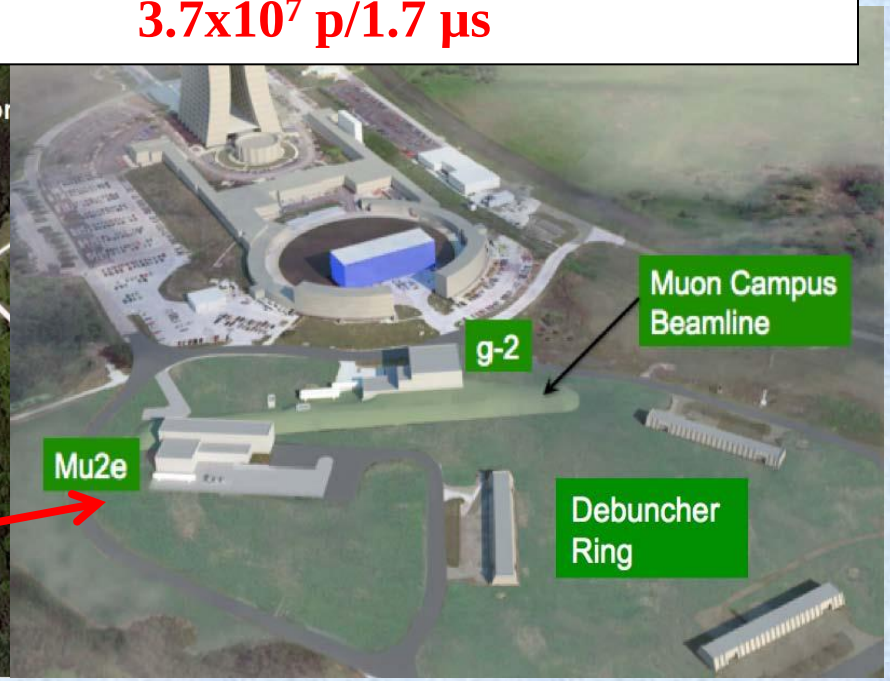
Muon Production at FNAL

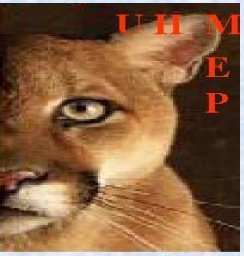
anti-proton complex → μ Campus

G-2, NOVA, Mu2e Share Rec. Ring
Ring Revolution (1694 ns) fits
τ(Al) = 864 ns

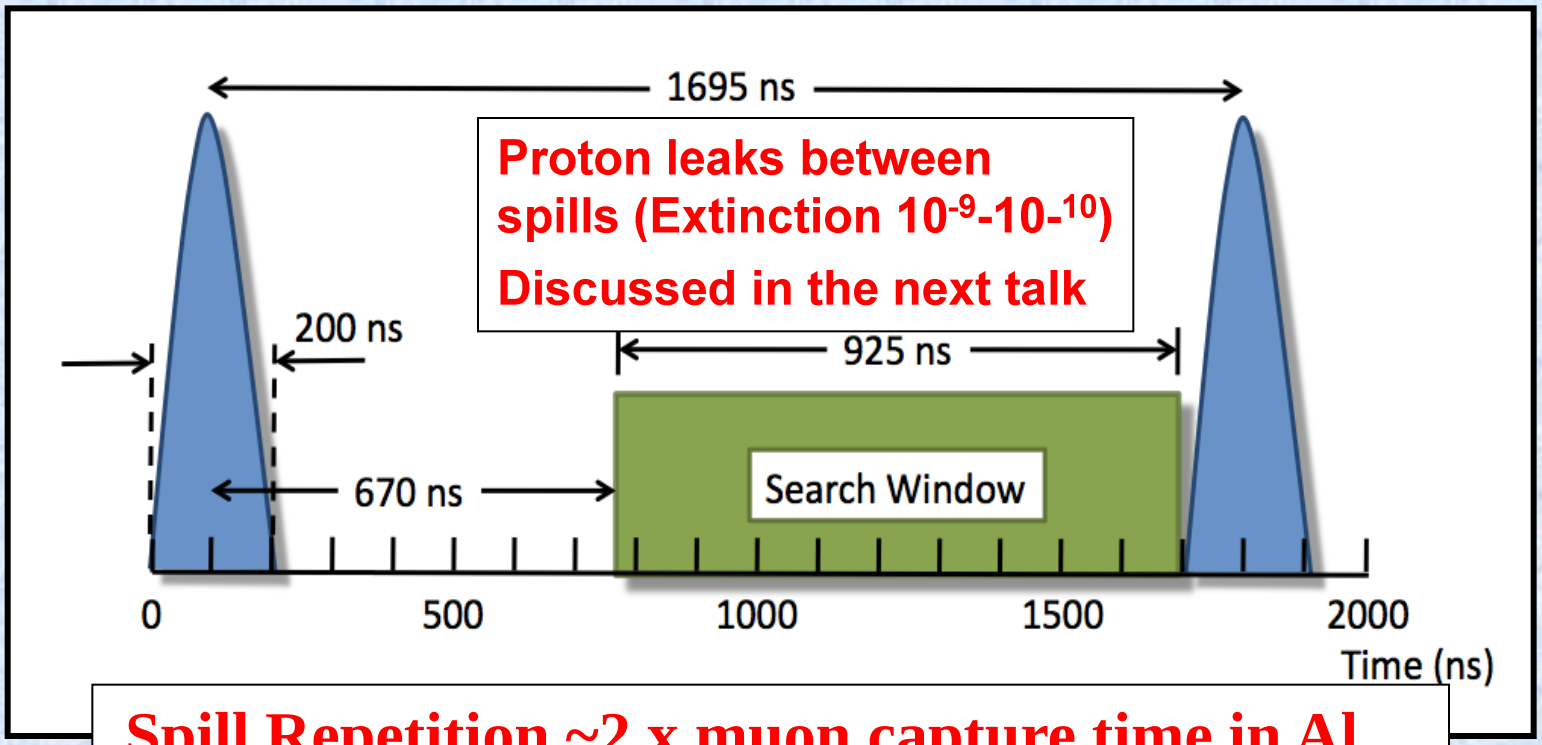
Mu2e Proton Beam
8 GeV - 8 kW
3.7×10^7 p/1.7 μs





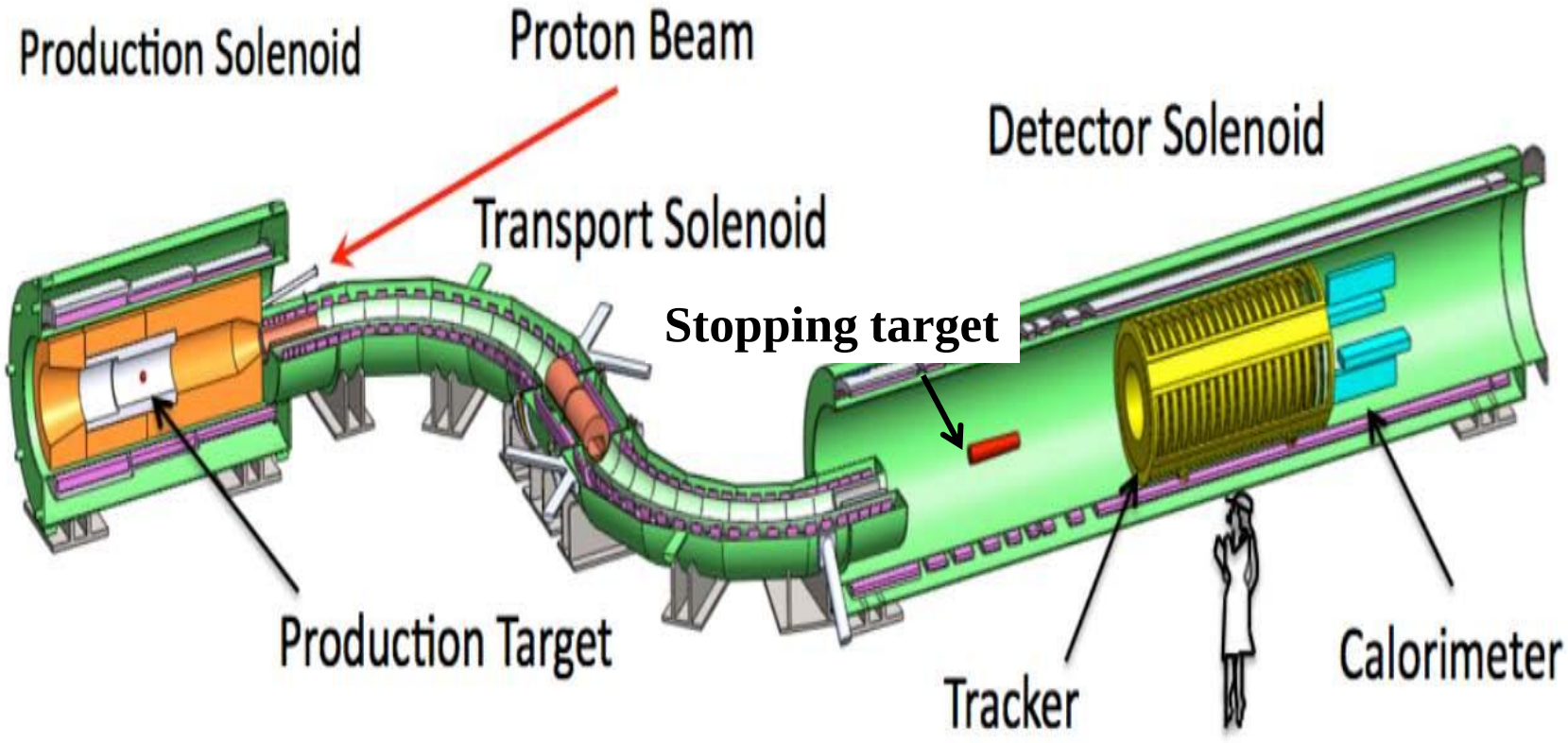


Micro-bunching to remove background



Spill Repetition ~2 x muon capture time in Al

Mu2e Apparatus at FNAL



- **Beam related background reduced by beam pulsing with detector active between spills (MELC)**
- **Continuous Solenoids capture muons, transport them, and analyze decay electrons from a stopping target**

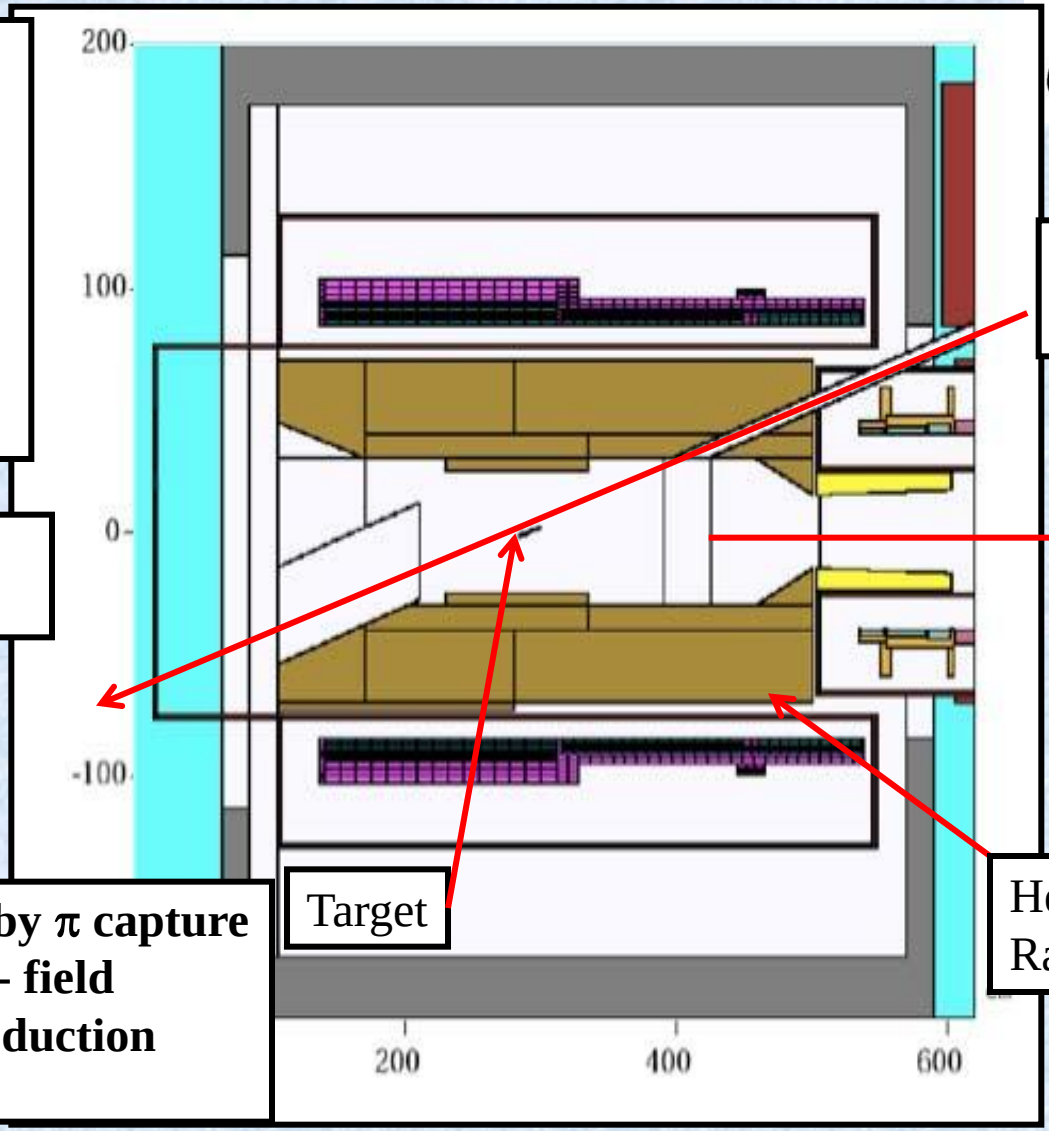
Production Solenoid

Production Target

- **Require high A**
- **Excellent conductivity**
- **High melting temp.**

W rod 16 cm 0.6 cm D

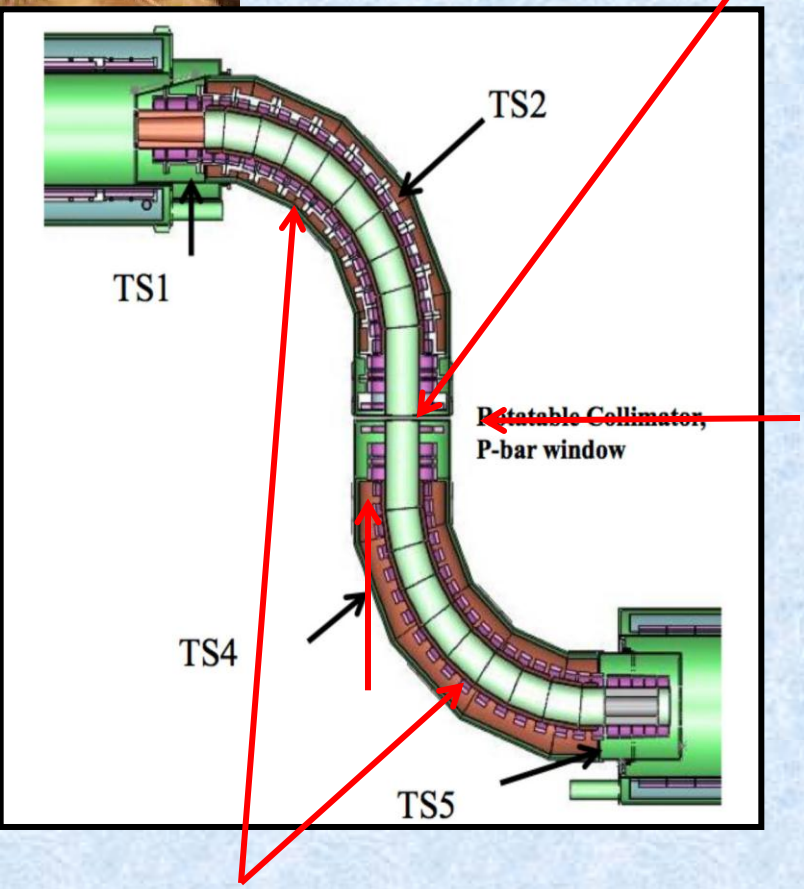
Extinction monitored by viewing target (Next Talk)

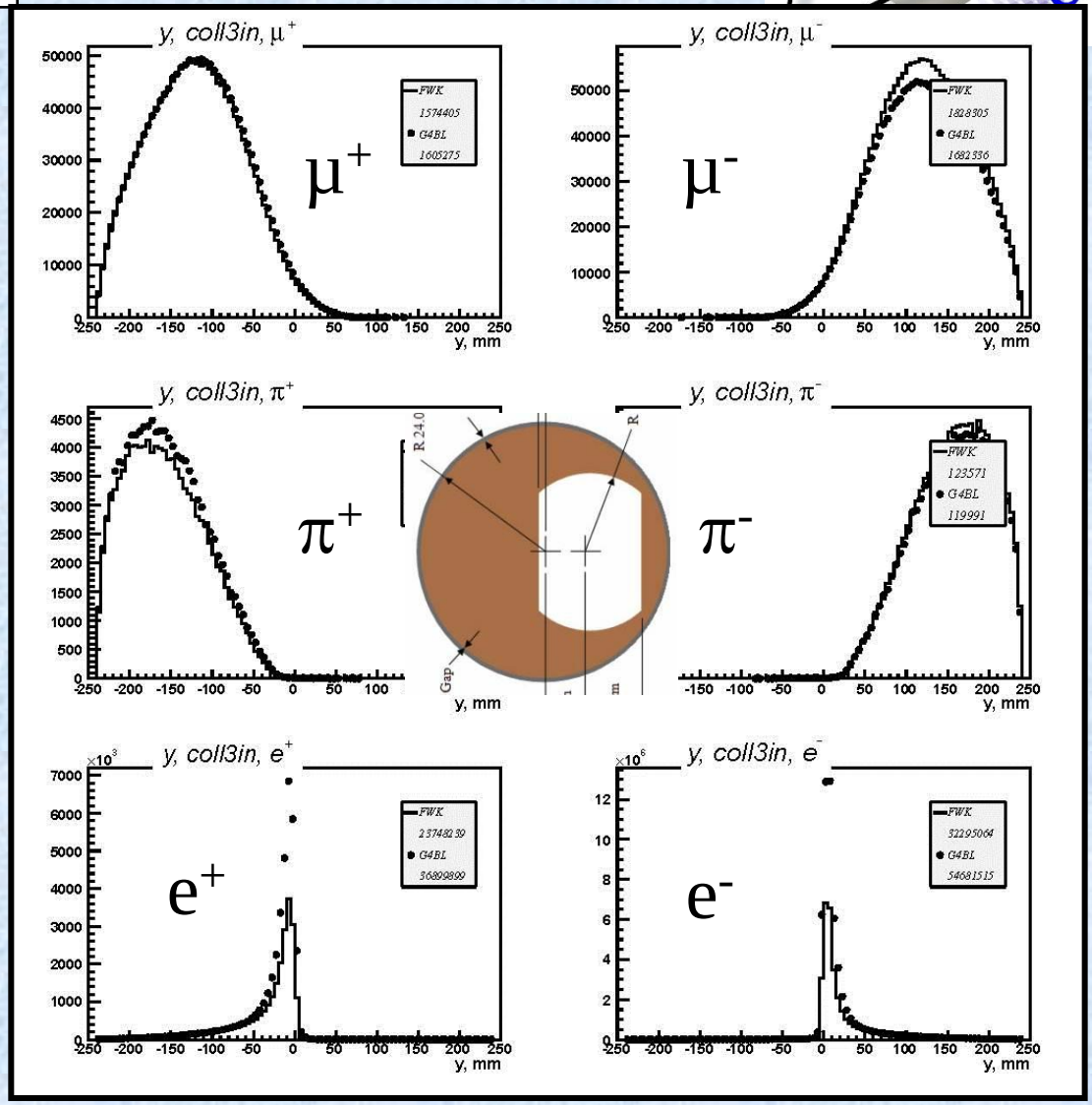


High muon yield achieved by π capture in a large solid angle, high- field solenoid surrounding a production target.

Transport Solenoid

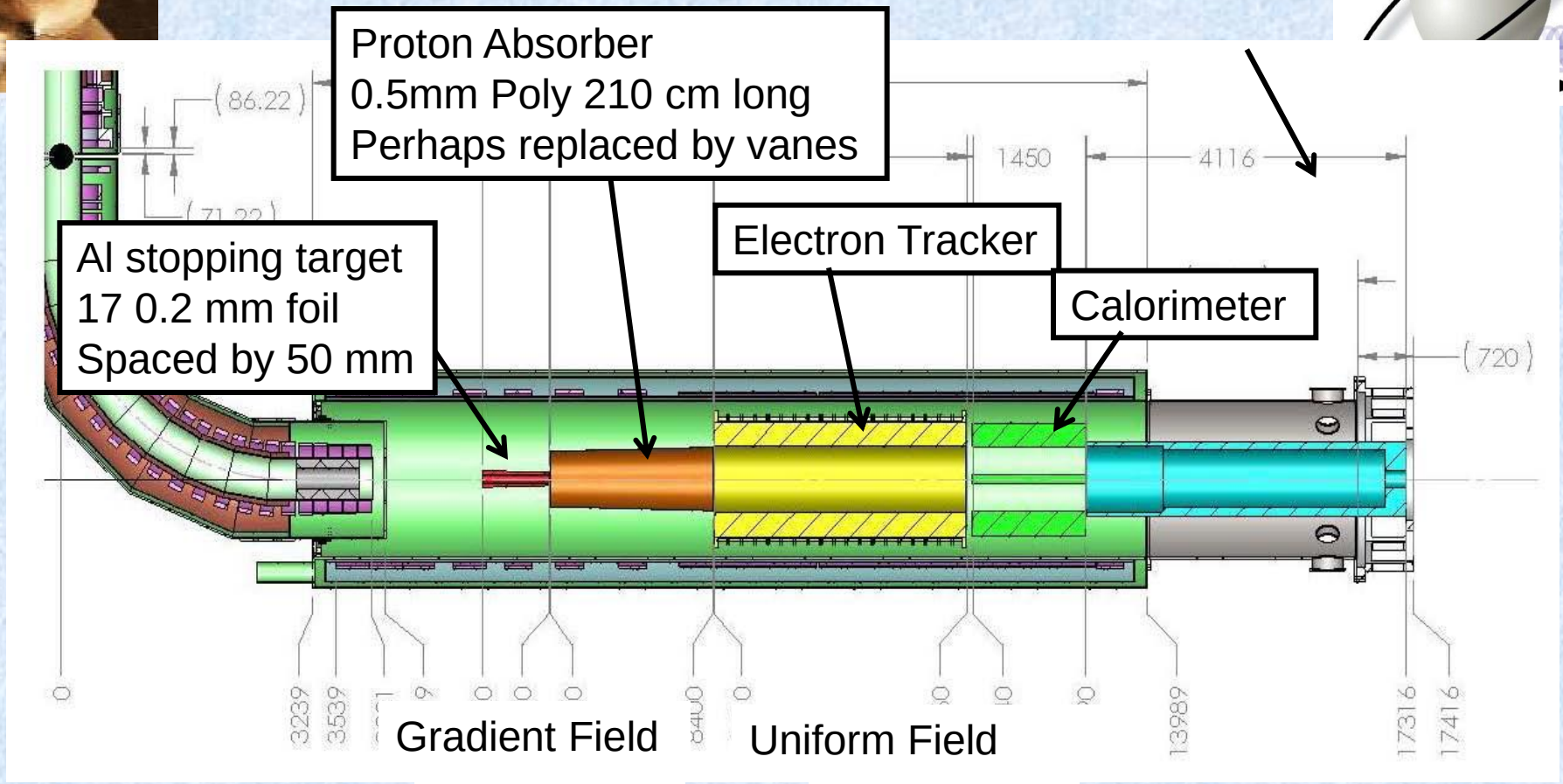
Anti-protons removed by Be foil



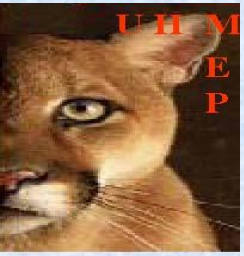


Momentum dependent drift perpendicular to the bend plane
-Particle/Momentum Selection-

Detection Solenoid

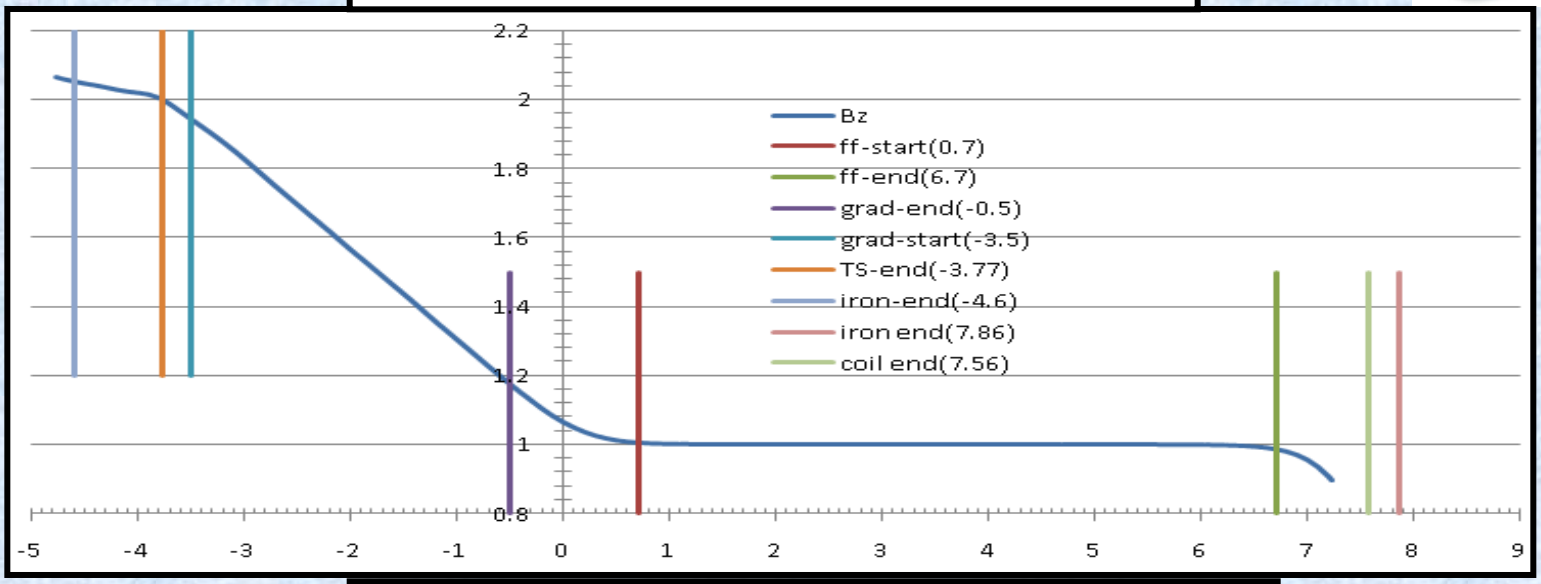


Gradient 2T-> 1T : Uniform Solenoid 1 Tesla for Tracking Detector



Field Gradient

- **Remove magnetic traps**
- **Push particles down stream**



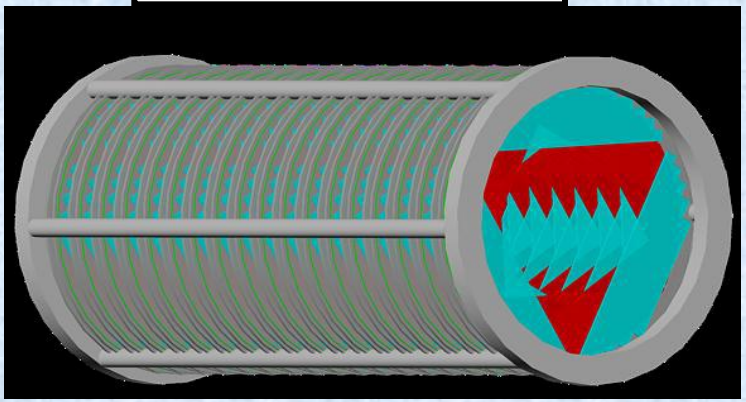
Positive gradient traps pions in a magnetic bottle which decay to muons during the “Detector Active” time window

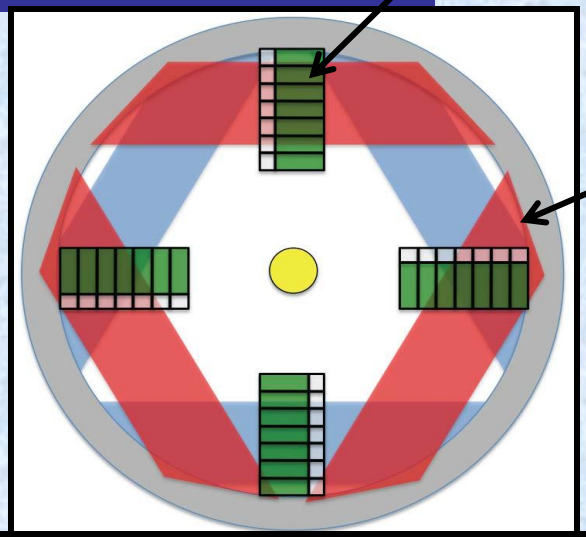
Trap Simulations show this is a potentially serious issue and care has been taken to remove traps using a field gradient

Electron Tracking (Straw Planes)

Calorimeter Vane

2 planes/station
18 stations/detector



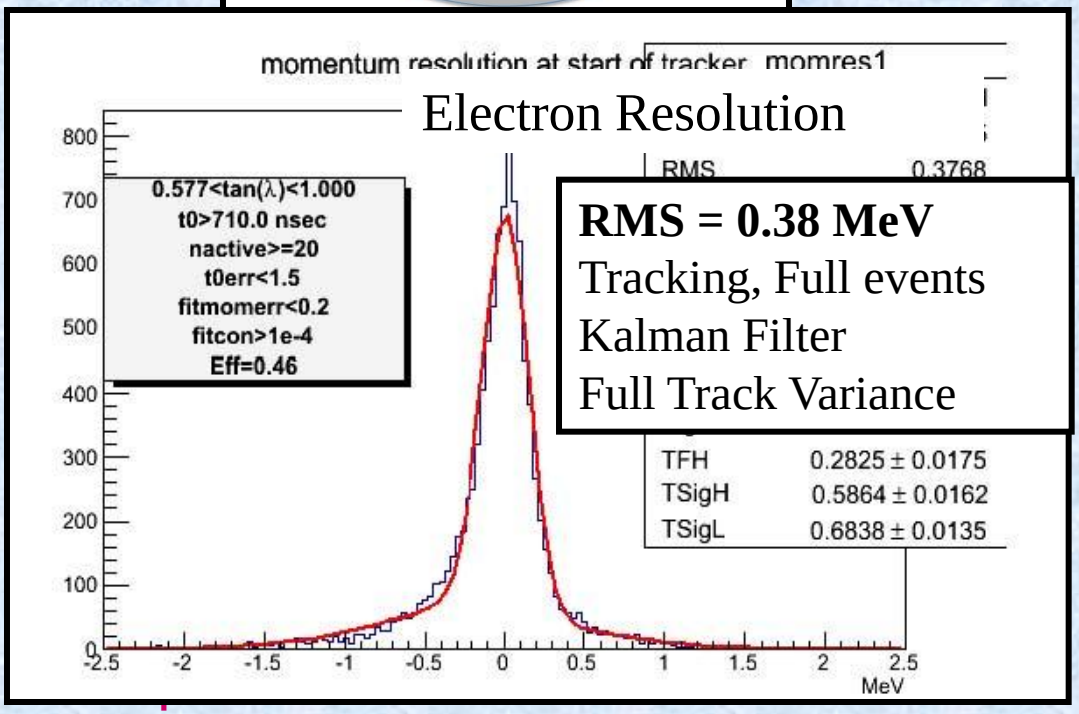


50 straws/layer
2 layers/panel
6 panels/plane
2 planes/station
18 stations/detector
21,600 straws

0.6-1.6m straws
0.5mm diameter
12 μm wall
0.20 μm W sense wire

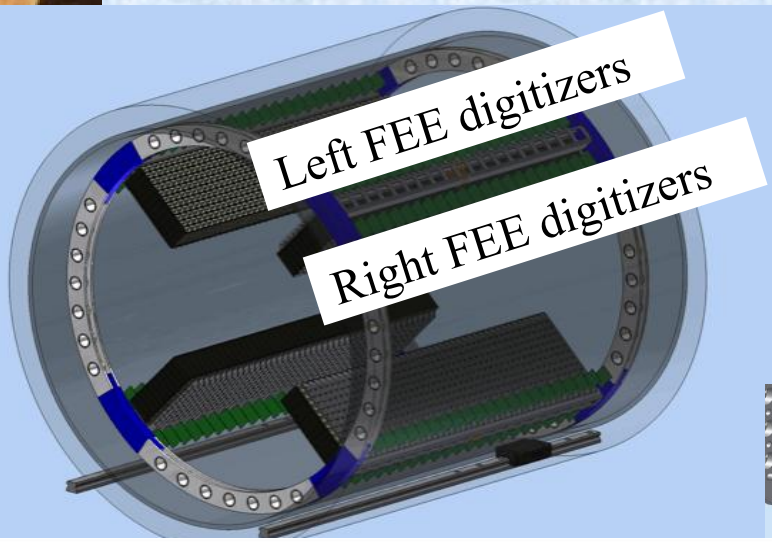
Straw Gas Ar/CO_2: 80/20
100 μm position (trans.)

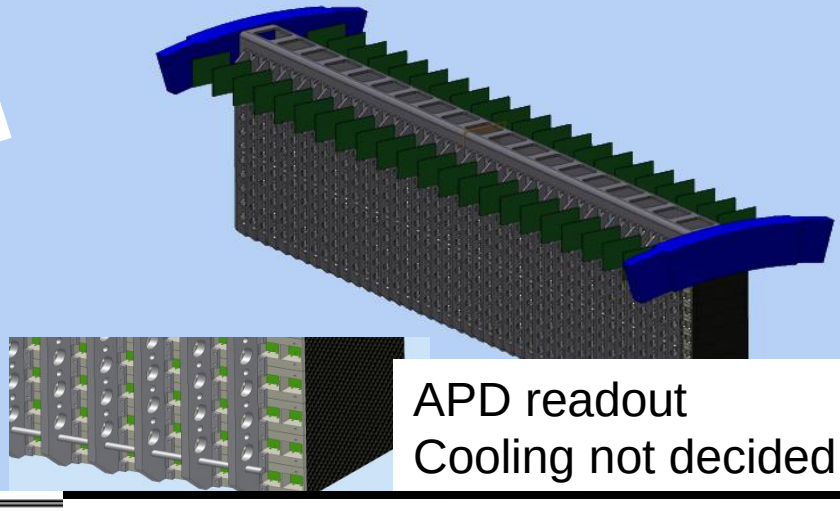
35 ps time resolution
~8cm position (long.)



RMS = 0.38 MeV
Tracking, Full events
Kalman Filter
Full Track Variance

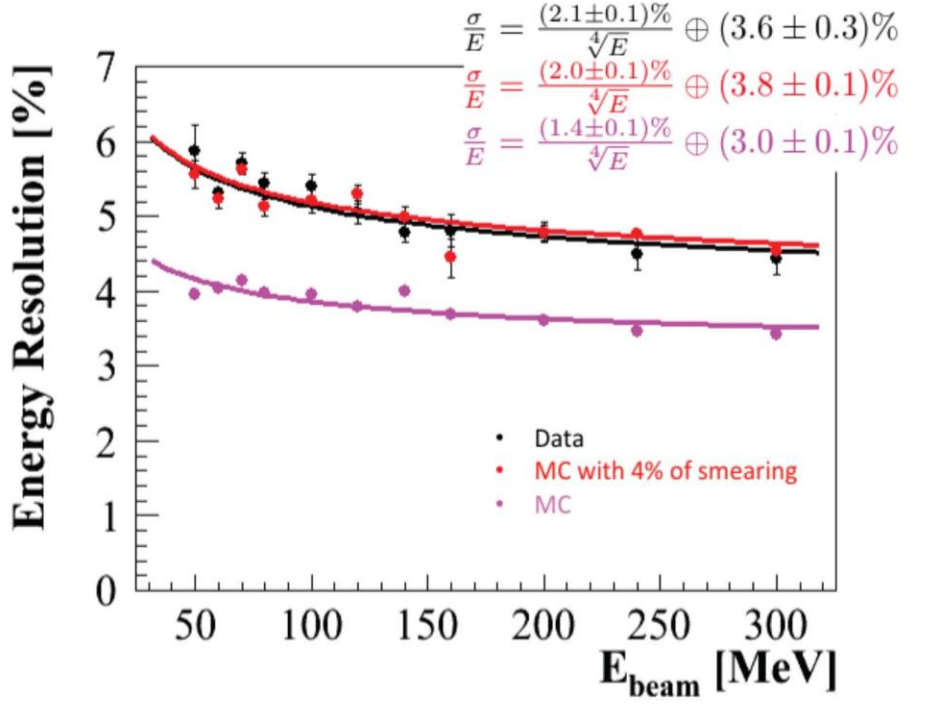
Calorimeter



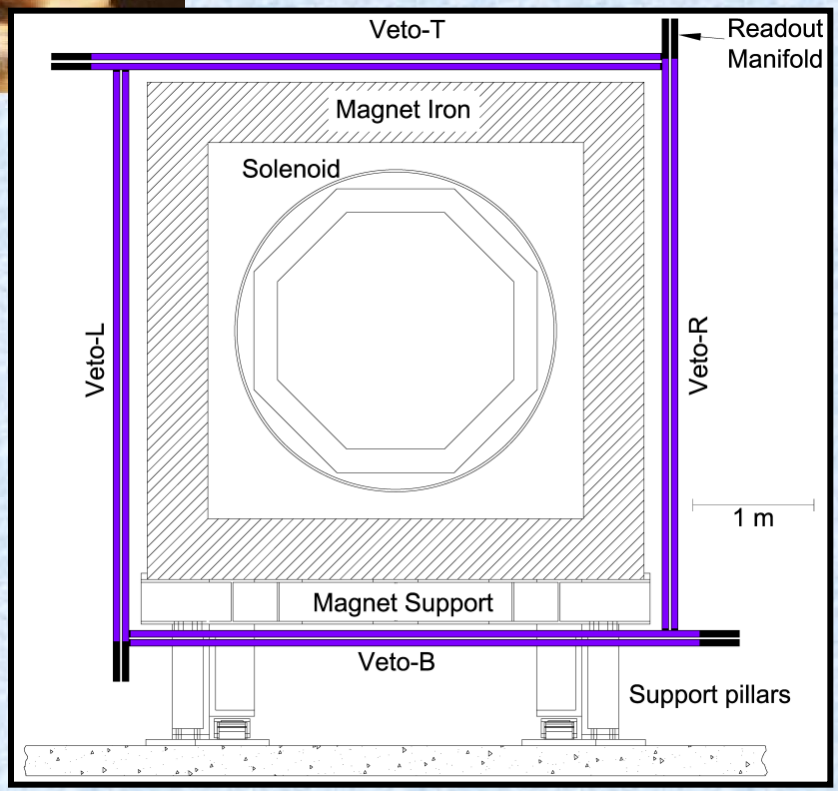


APD readout
Cooling not decided

Crystal	LYSO
Density (g/cm^3)	7.28
Radiation length (cm) X_0	1.14
Molière radius (cm) R_m	2.07
Interaction length (cm)	20.9
dE/dx (MeV/cm)	10.0
Refractive Index at λ_{max}	1.82
Peak luminescence (nm)	402
Decay time τ (ns)	40
Light yield (compared to NaI(Tl)) (%)	85
Light yield variation with temperature(% / °C)	-0.2
Hygroscopicity	None

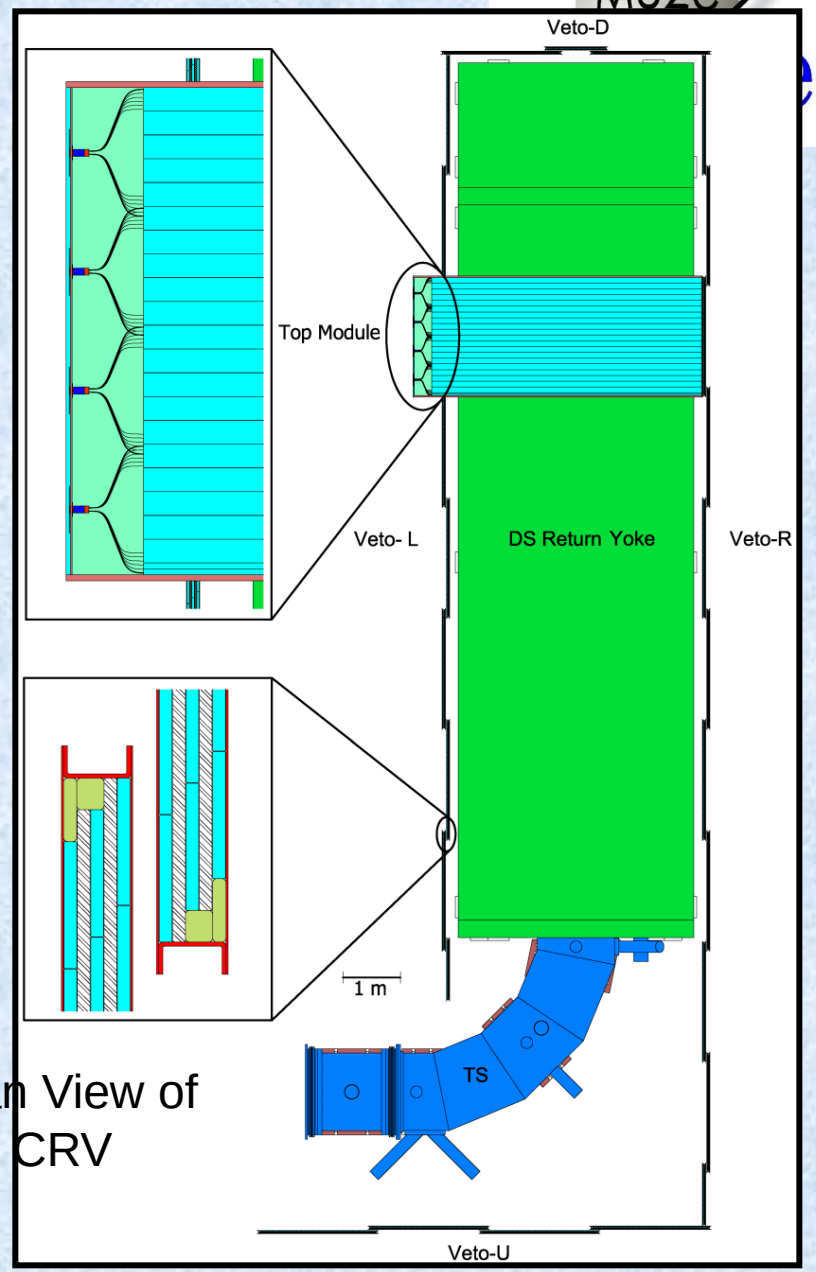


Cosmic Veto

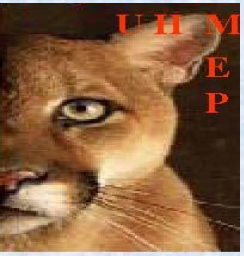


End View of the CRV

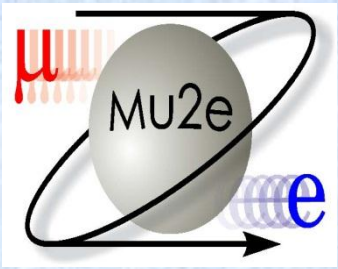
2088 Modules read by fiber connected to SiPM Bottom panel not implemented



Plan View of the CRV



Data Rates



Triggerless DAQ

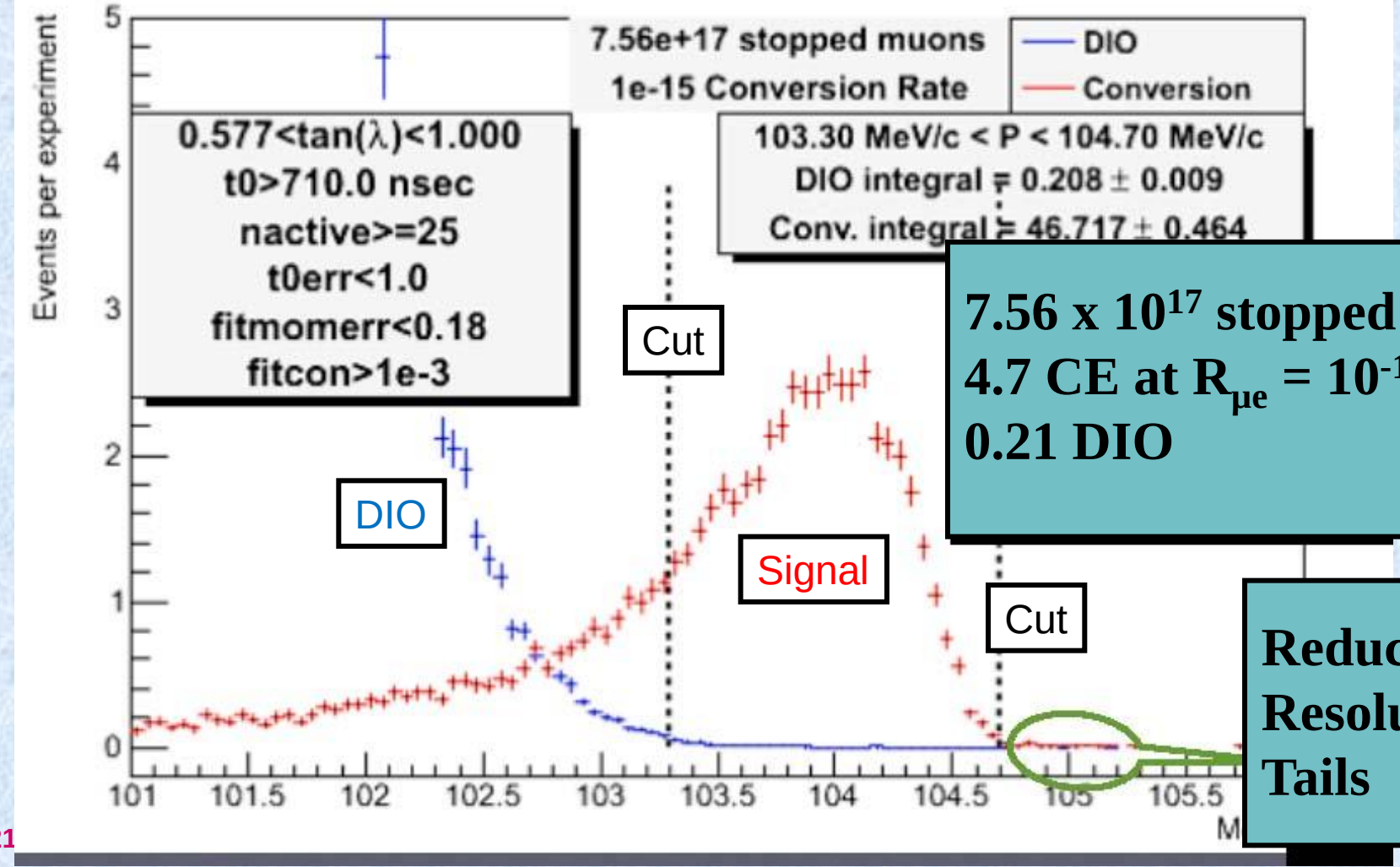
The total DAQ data rate is estimated at 30 GBytes/sec

Tracker	21 GBytes/sec
(Rates are high - 300 Mbyte/s x 218 controllers Pattern recognition is compliated)	
Calorimeter	5 GBytes/sec
CRV	3 GBytes/sec
Extinction Mon, etc	1 GByte/sec

At 155K μBunches/sec, the average μBunch size is estimated at 200 KBytes (~140 KBytes from Tracker).

Example of Endpoint Spectrum showing DIO background and Mu2e signal

Fully Reconstructed Signal (Tracking, backgrounds, Pattern Recognition, "Exact" DIO, Straggling, Timing, etc.)



7.56 x 10^{17} stopped μ^-
4.7 CE at $R_{\mu e} = 10^{-16}$
0.21 DIO

Reduced Resolution Tails

Signal Sensitivity

Single Event Sensitivity

N_μ

number of stopping muons (1yr) 1.9×10^{17}

f_{cap}

fraction of muon captures (0.6 for Al)

A_e

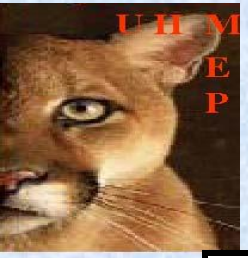
detector acceptance 0.9

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

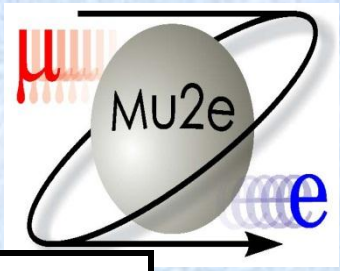
Total Protons/yr	1.2×10^{20}
Muon Transport	0.0016
Muon Capture	0.61
# Muons Captured/yr	1.1×10^{17}

For a 3 year run

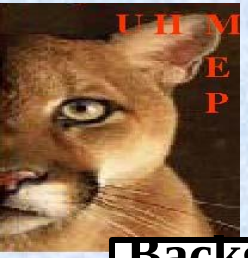
$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{1.2 \times 10^{17} \times 0.09 \times 3} = 3.0 \times 10^{-17}$$



Predicted Sensitivity

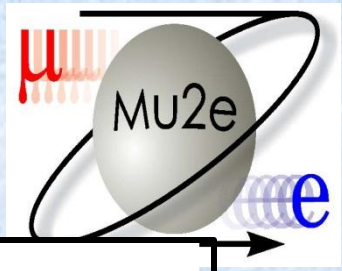


Parameter	Value
Running time @ 2×10^7 s/yr.	3 years
Protons on target per year	1.2×10^{20}
μ^- stops in stopping target per proton on target	0.0016
μ^- capture probability	0.609
Fraction of muon captures in live time window	0.9
Electron Trigger, Selection, and Fitting Efficiency in Live Window	0.10
Single-event sensitivity with Current Algorithms	3.0×10^{-17}

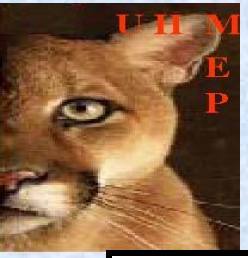


Backgrounds – 3.6x10^{20} protons

(It's what you don't know that bites)



Background	Background Estimate	Error Estimate	Justification
Muon decay-in-orbit	0.22	± 0.06	Acceptance and energy loss modeling, spectrum calculation; reconstruction algorithm
Cosmic Rays	0.05	± 0.013	Statistics of sample
Radiative Pion Capture	0.03	± 0.007	Acceptance and energy loss modeling
Pion decay In-Flight	0.003	± 0.0015	Cross-section, acceptance and modeling
Muon decay In-Flight	0.01	± 0.003	Cross-section, acceptance and modeling
Antiproton Induced	0.10	± 0.05	Cross-section, acceptance and modeling
Beam electrons	0.0006	± 0.0003	Cross-section and acceptance (this is an upper limit)
Radiative muon capture	$< 2 \times 10^{-6}$	–	Calculation
Total	0.41	± 0.08	Add in quadrature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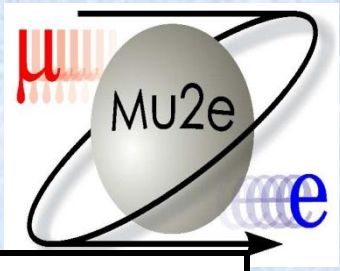
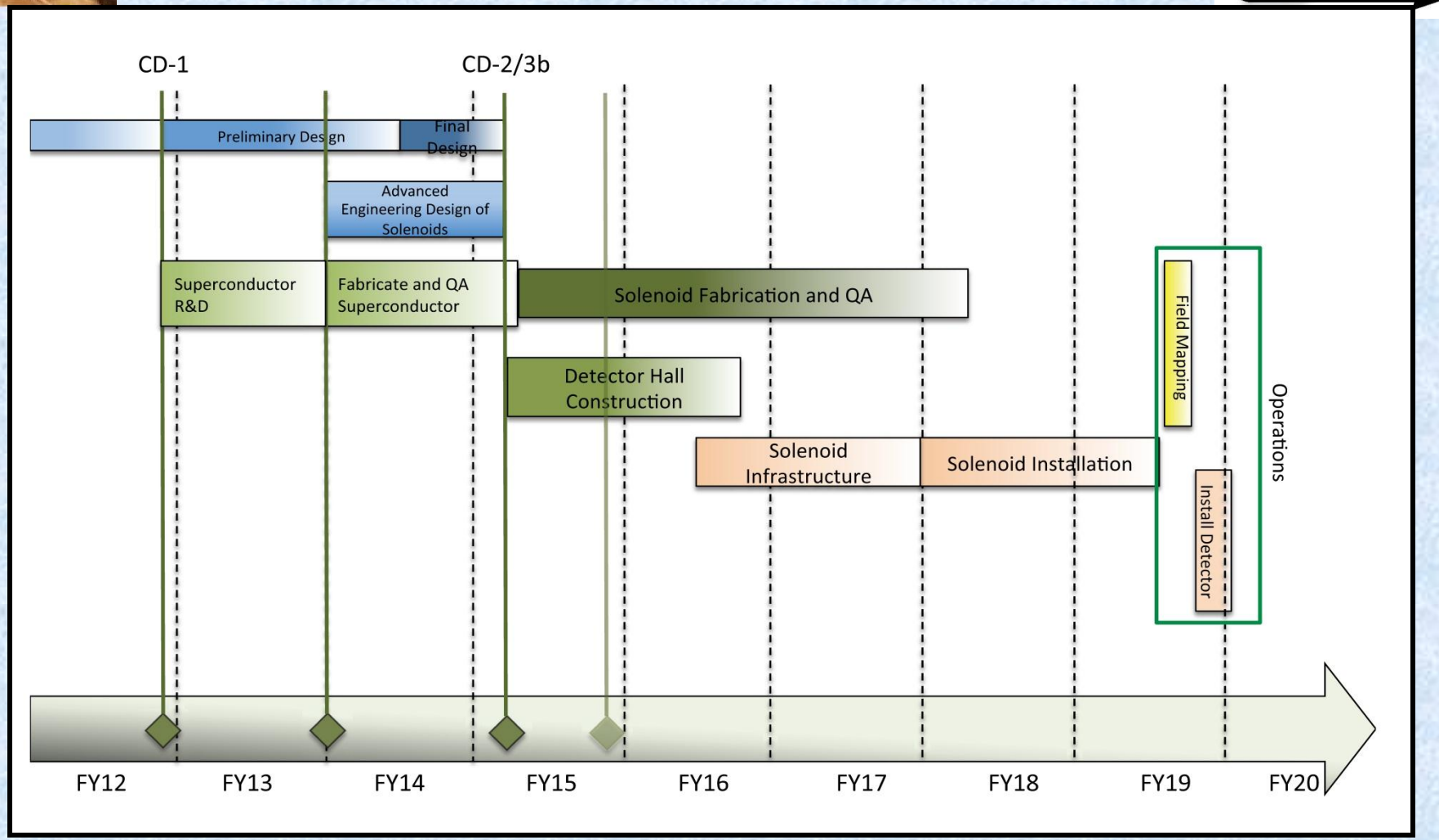
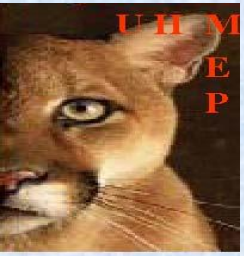
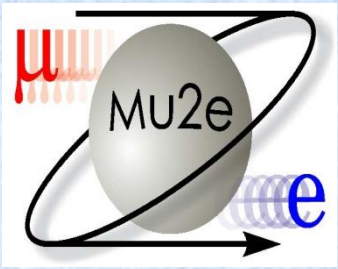
Schedule


Mu2e

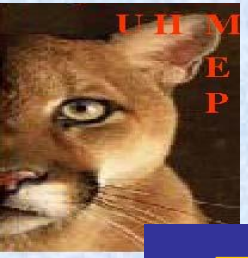

CD-1
CD-2/3b
Preliminary Design
Final Design
Advanced Engineering Design of Solenoids
Superconductor R&D
Fabricate and QA Superconductor
Solenoid Fabrication and QA
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation
Field Mapping
Install Detector
Operations
FY12
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20



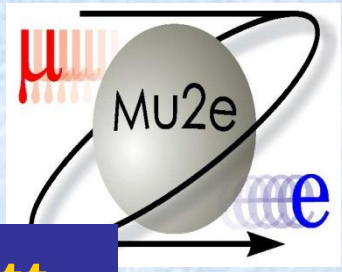
Summary



- Muons are long-standing tools for precision test in particle physics.
- We expect new physics beyond the SM to appear at TeV scale.
- Lepton-flavor is not necessarily conserved in many models, and non-observation of cLFV processes is a puzzle.
- cLFV studies may reveal hidden flavor symmetries or even physics beyond TeV-scale physics.
- Even if new particles are seen at LHC, cLFV can help define the physics
- If SUSY, we may access origin of neutrino mass or SUSY GUTs.
- Cosmological implications



"I Dwell in Possibility"

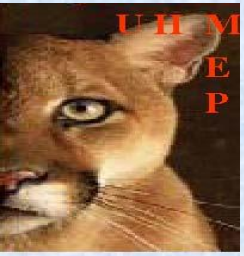


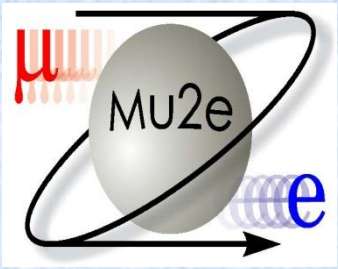
This is a title of a poem by Elizabeth Barrett Browning.

While it was not written to address Subatomic Physics it is a fantastic title that expresses how I feel about the present status of Particle Physics.

We dwell in possibilities

far beyond our imaginations, offering exciting mysteries to explore from the very small to the very large, from the present epoch to the dawn of creation itself.

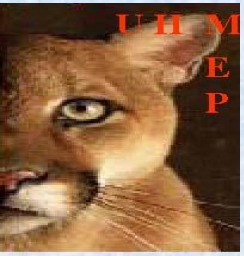




End

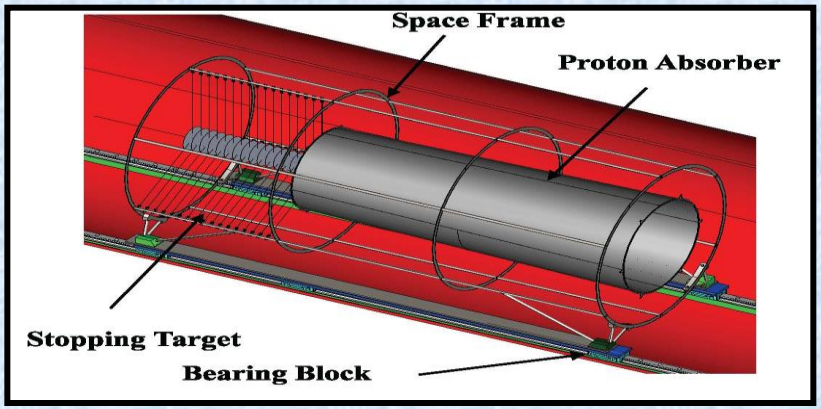
PH^2

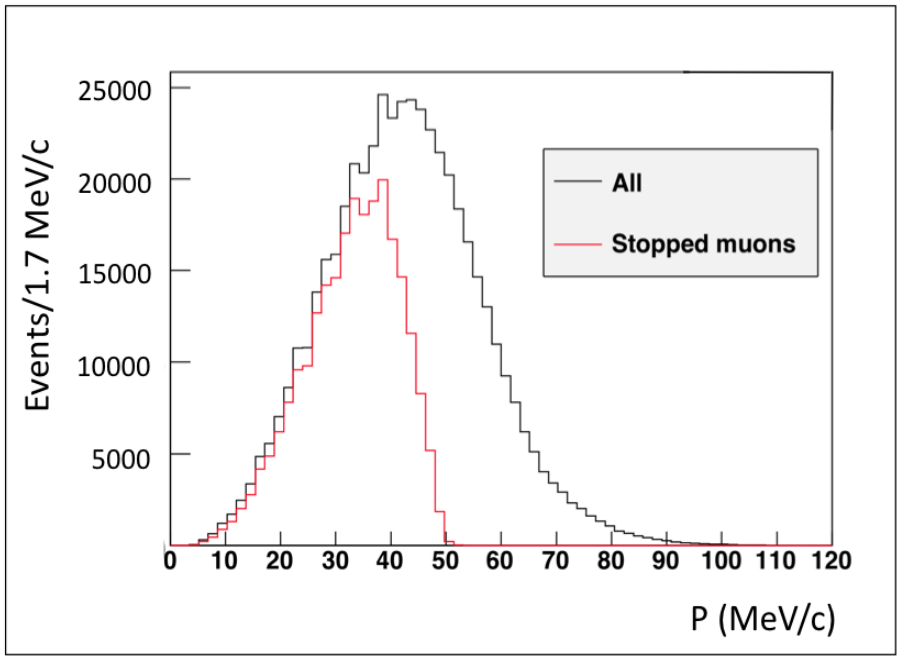
Possible Happy Hunting

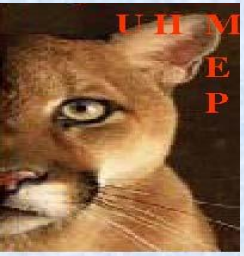


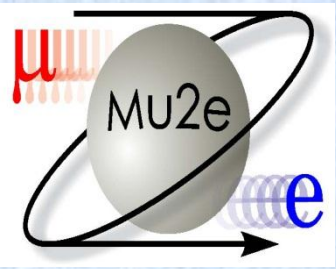
Stopping Target with Proton Shield

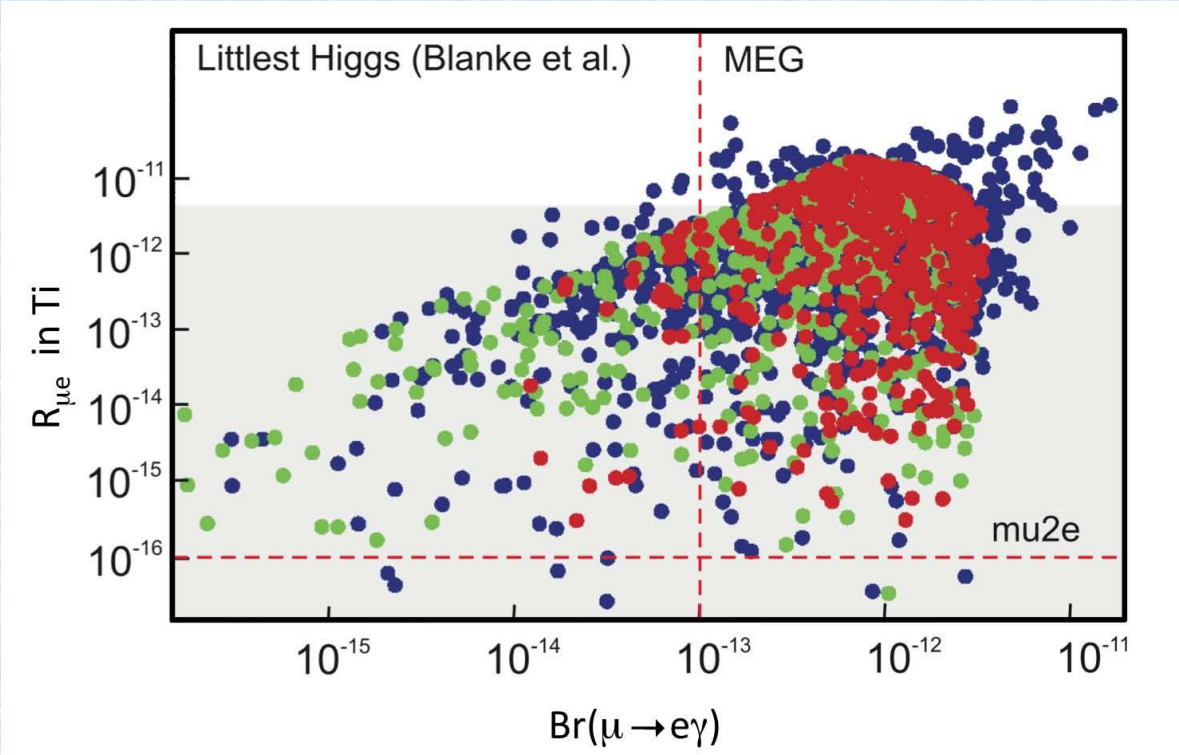
- ~0.15 protons emitted per μ capture
- Energies peaked around 5 MeV.
- Large contribution to background.
- Proton absorber to remove
- Neutron emission also a problem



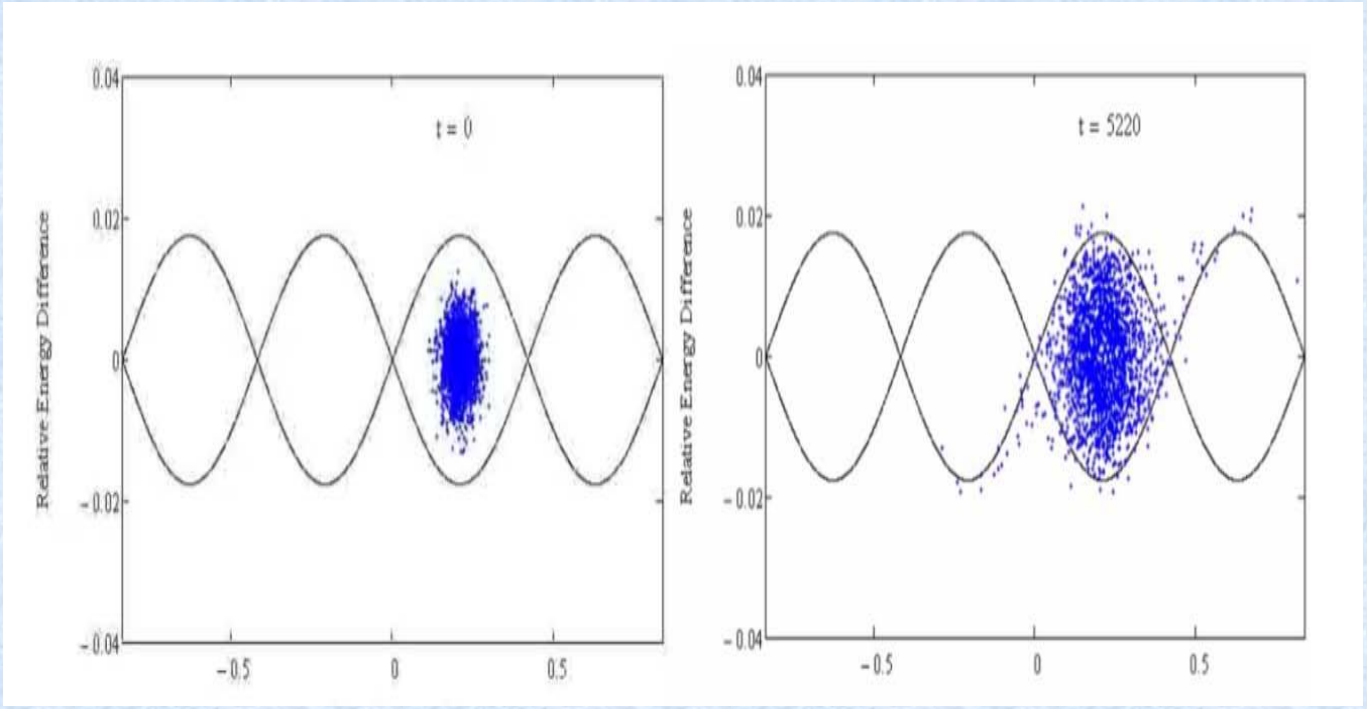


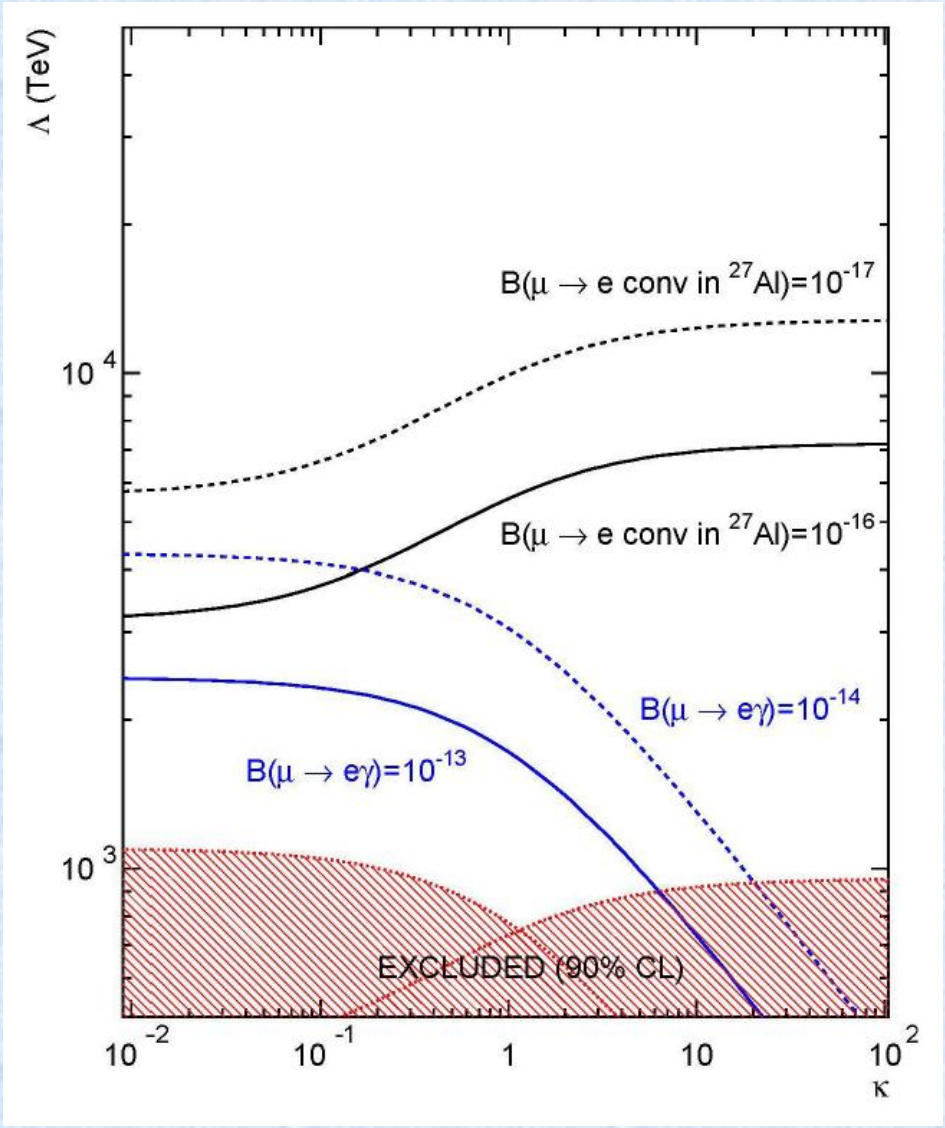

U H M
E
P


μ
Mu2e
e


Littlest Higgs (Blanke et al.)
MEG
mu2e
$R_{\mu e}$ in Ti
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
Br(μ → eγ)

Proton Beam


t = 0
t = 5220
Relative Energy Difference
Relative Energy Difference
0.04
0.02
0
-0.02
-0.04
-0.5
0
0.5


Λ (TeV)
10^4
10^3
B(μ → e conv in ^{27}Al)=10^{-17}
B(μ → e conv in ^{27}Al)=10^{-16}
B(μ → eγ)=10^{-14}
B(μ → eγ)=10^{-13}
EXCLUDED (90% CL)
10^{-2}
10^{-1}
1
10
10^2
κ