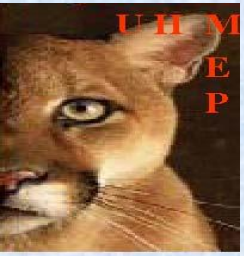
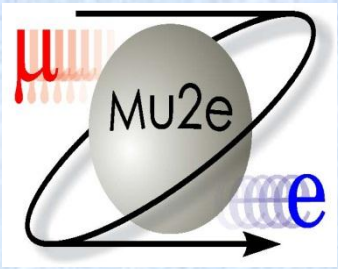


Discovering Lepton Flavor Violation (LFV)

--Mu2E at FNAL--



Ed V Hungerford
University of Houston

Mu2e collaboration: ~ 130 physicists

Boston University

Brookhaven National Laboratory

University of California, Berkeley

Lawrence Berkeley National Laboratory

University of California, Irvine

California Institute of Technology

City University of New York

Duke University

Fermi National Accelerator Laboratory

Lewis University

University of Illinois, Urbana-Champaign

Los Alamos National Laboratory

University of Massachusetts, Amherst

Muons, Inc.

Northwestern University

Northern Illinois University

Rice University

University of Houston

University of Virginia

University of Washington

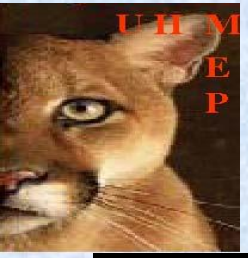
Instituto Nazionale di Fisica Nucleare Pisa

Instituto Nazionale di Fisica Nucleare, Lecce

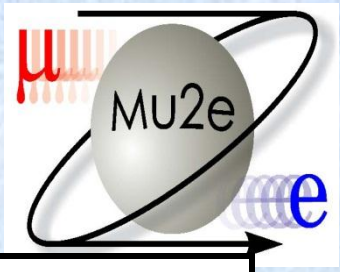
Laboratori Nazionali di Frascati

Institute for Nuclear Research, Moscow

Joint Institute for Nuclear Research, Dubna



Acknowledements



Firstly

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

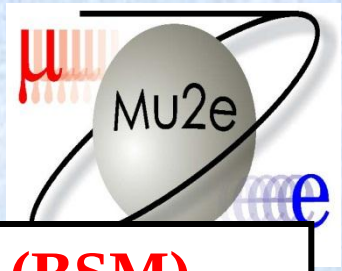
Secondly

- 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

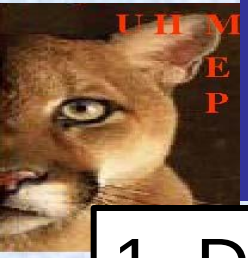


Elucidate TeV-scale physics Beyond the Standard Model (BSM)

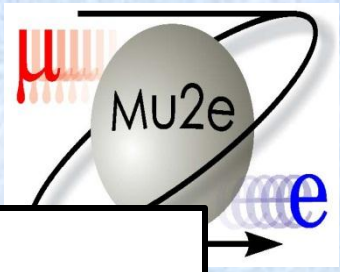
- Origin of EW symmetry breaking
- Hierarchy problem (Neutrinos)
- Dark matter in the Universe
- Neutrino mass and mixing issues
- New Models, SUSY, Extra dimension models, various Higgs models

Of relevance to this talk

Charged LFV, cLFV, is sensitive to various BSM, so even if something is seen at the LHC, investigation of cLFV processes can help 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 processes

   $\mu^+ \rightarrow e^+\gamma$

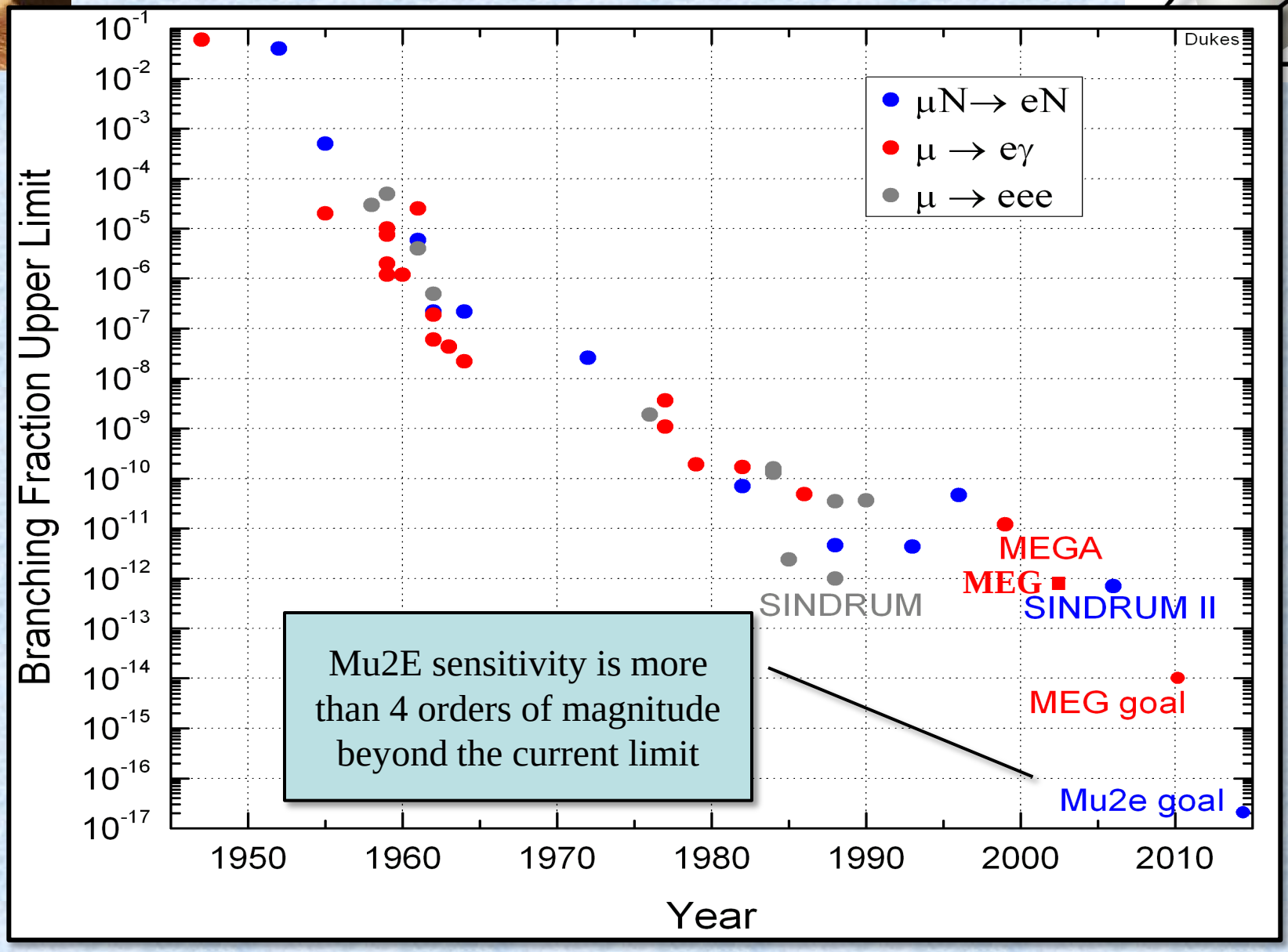
   $\mu^+ \rightarrow e^+e^+e^-$

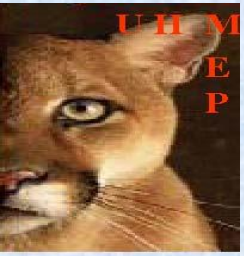
   $\mu^- - e^-$ conversion in nuclei

   muonium-antimuonium conversion

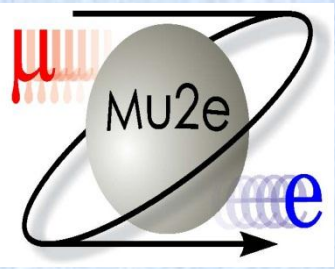
4. Muon EDM

LFV in muon interactions





Muon cLFV Compared to SU(5) SUSY-GUT
(only a few orders of magnitude below experimental limits)

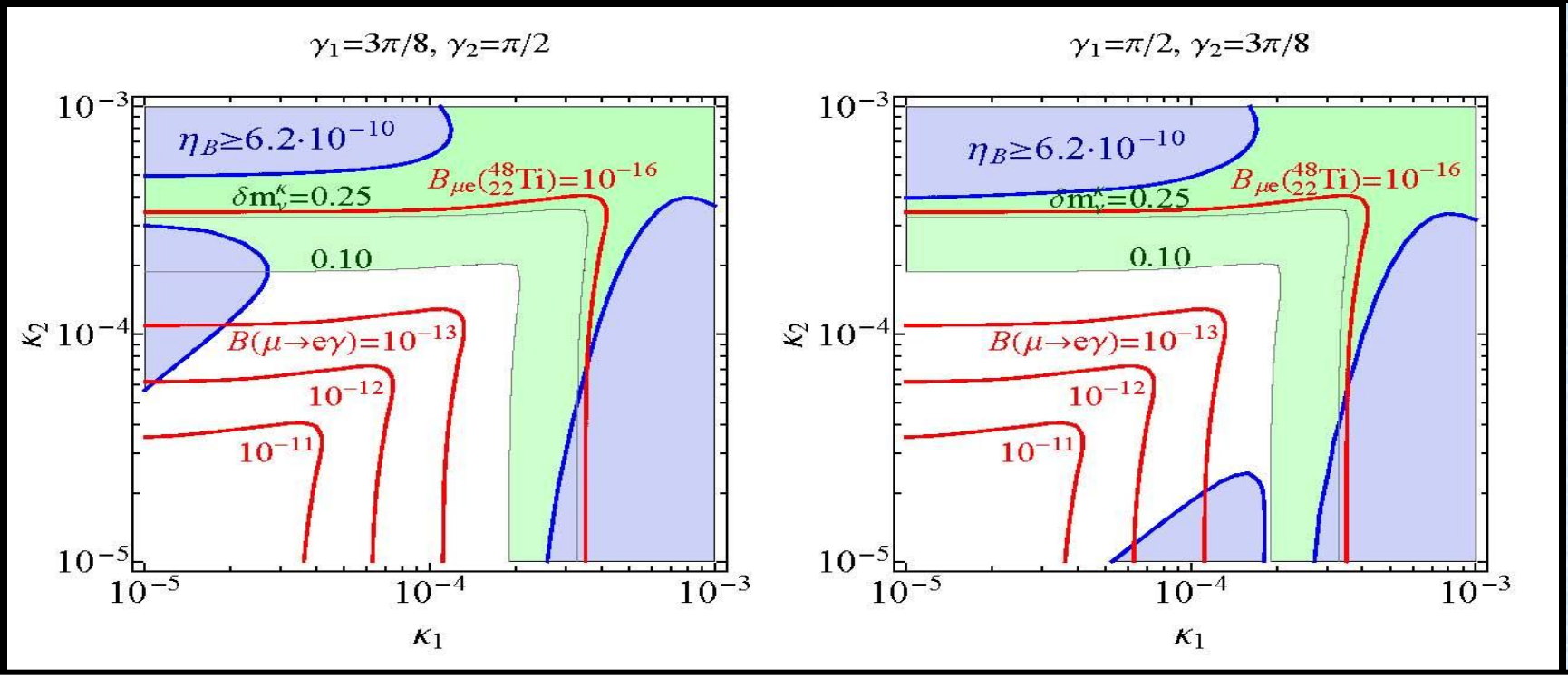


Process	Current Limit	SUSY-GUT level
$\mu N \rightarrow e N$	**7×10^{-13}** W. Bertl, et al EPJ C47(06)337	**10^{-16}**
$\mu \rightarrow e \gamma$	**2.4×10^{-12}** J. Adam, et al PRL 107(11)171801	**10^{-14}**
$\tau \rightarrow \mu \gamma$	**4.5×10^{-8}** K. Hayasaka, et al PL B666(08)16	**10^{-9}**

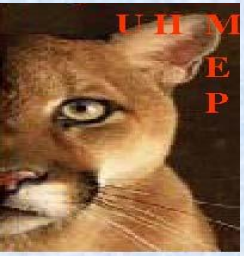
Number of Ways to Justify a cLFV Search
(Connecting the very large to the very small)

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

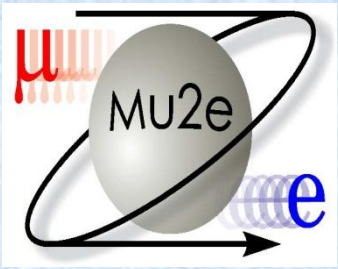
There is no explanation of Barogenesis in the ΛCDM Model. Possibile extensions
-Leptogeneis producing Barogenesis-

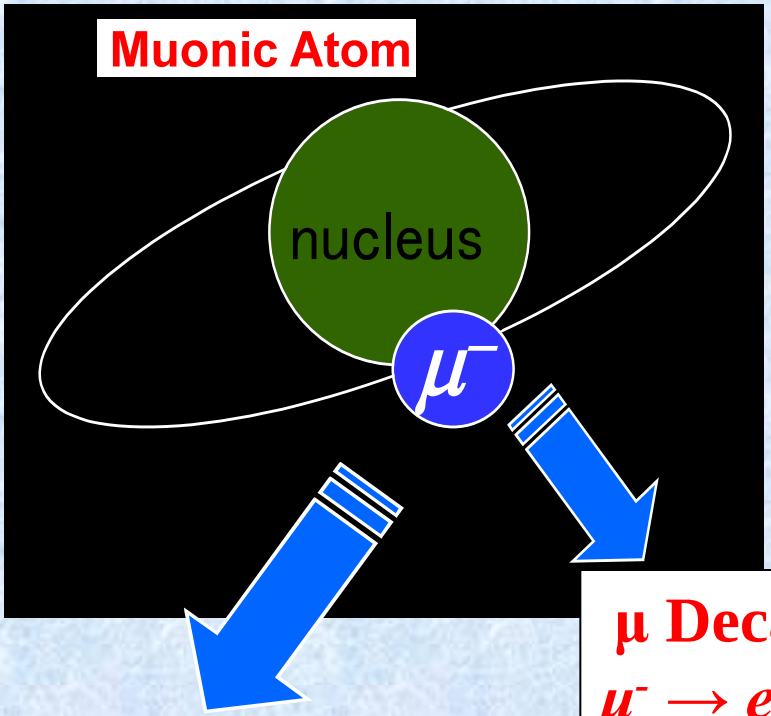


F. Deppisch and A. Pilaftsis arXIV:1012.1834 blue-baryon asymmetry; red -LFV with μ; κ_1,κ_2 in the RτL model with M_n = 120 GeV normal light neutrino hierarchy



Muon-to-Electron (μ-e) Conversion





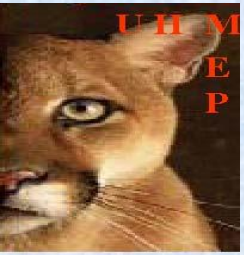
Lepton Flavor changes by one unit
-Coherent Conversion-
$\mu^- + A \rightarrow e^- + A$

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

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

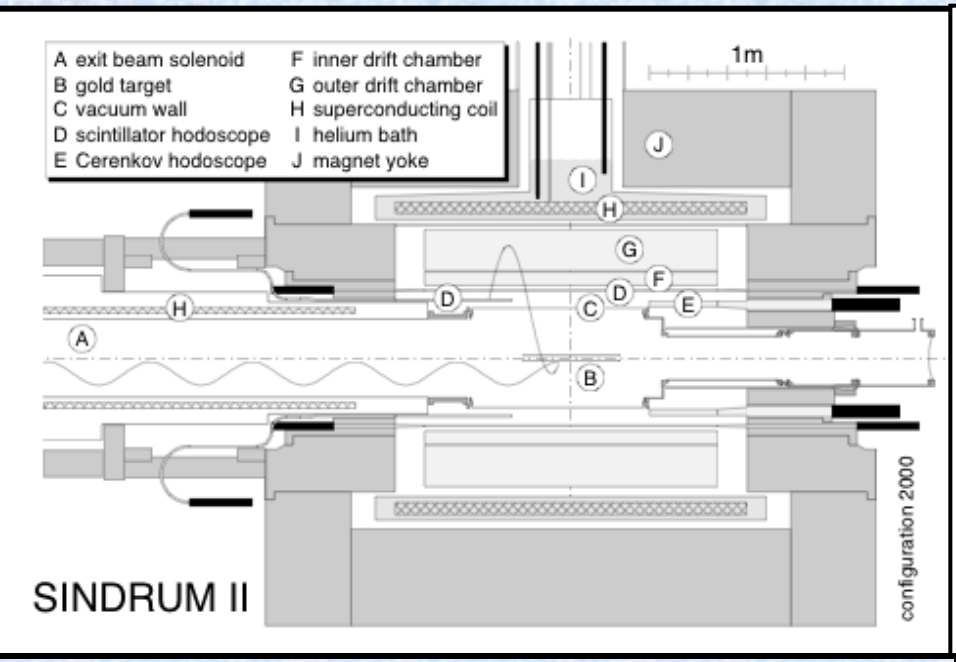
Nuclear Capture
$\mu^- + A \rightarrow \nu + [N + (A-1)]$

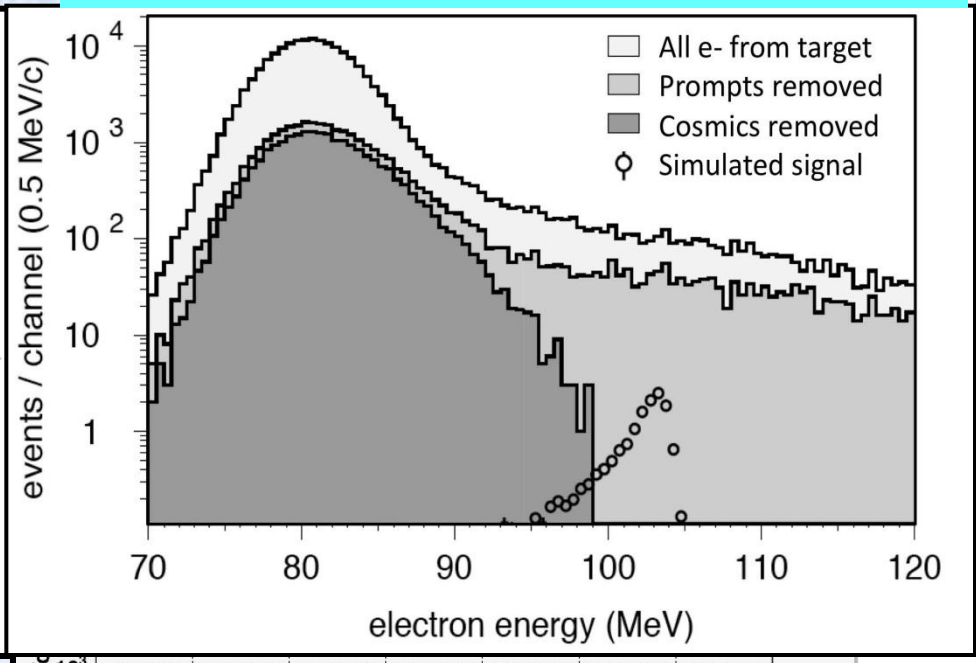
Experimental Advantages
- Copious muons
- Long lifetime
- No coincident accidentals
- High energy electrons
- Redundancy



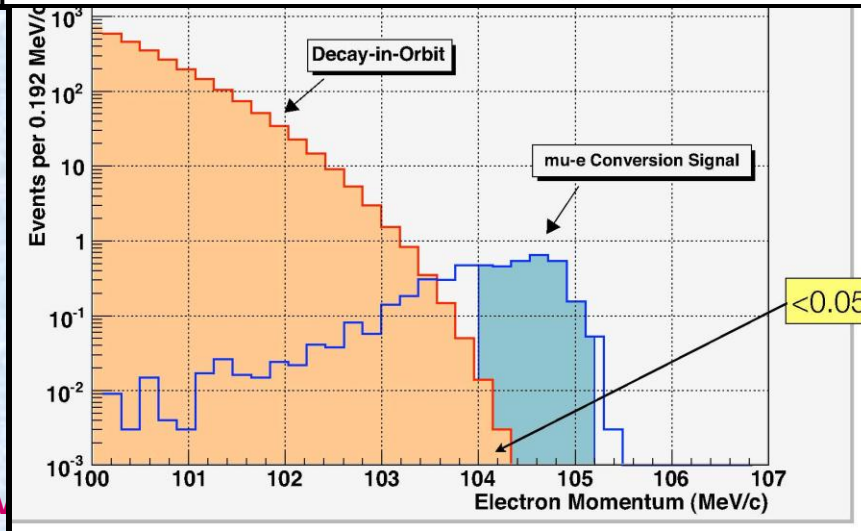
The SINDRUM-II Experiment

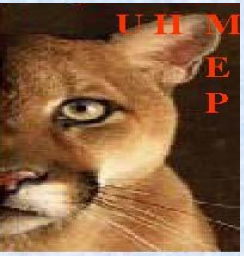
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 4.3 \times 10^{-12}$$



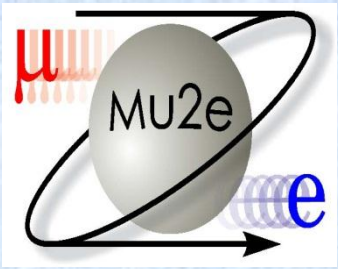


SINDRUM-II used a continuous muon beam from the PSI cyclotron. A beam-veto counter was used to eliminate beam related background. This does not work at high rate.





To reach Higher Sensitivity



1) Reduce Beam Associated Background

Pulsed beam using μ lifetime

2) Increase μ Stopping

High Intensity Pion Production

Trap π, μ, and decay electrons in Continuous Solenoids

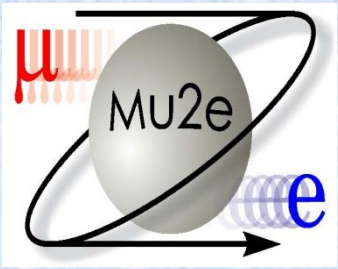
3) Improve Electron Energy Resolution and Timing

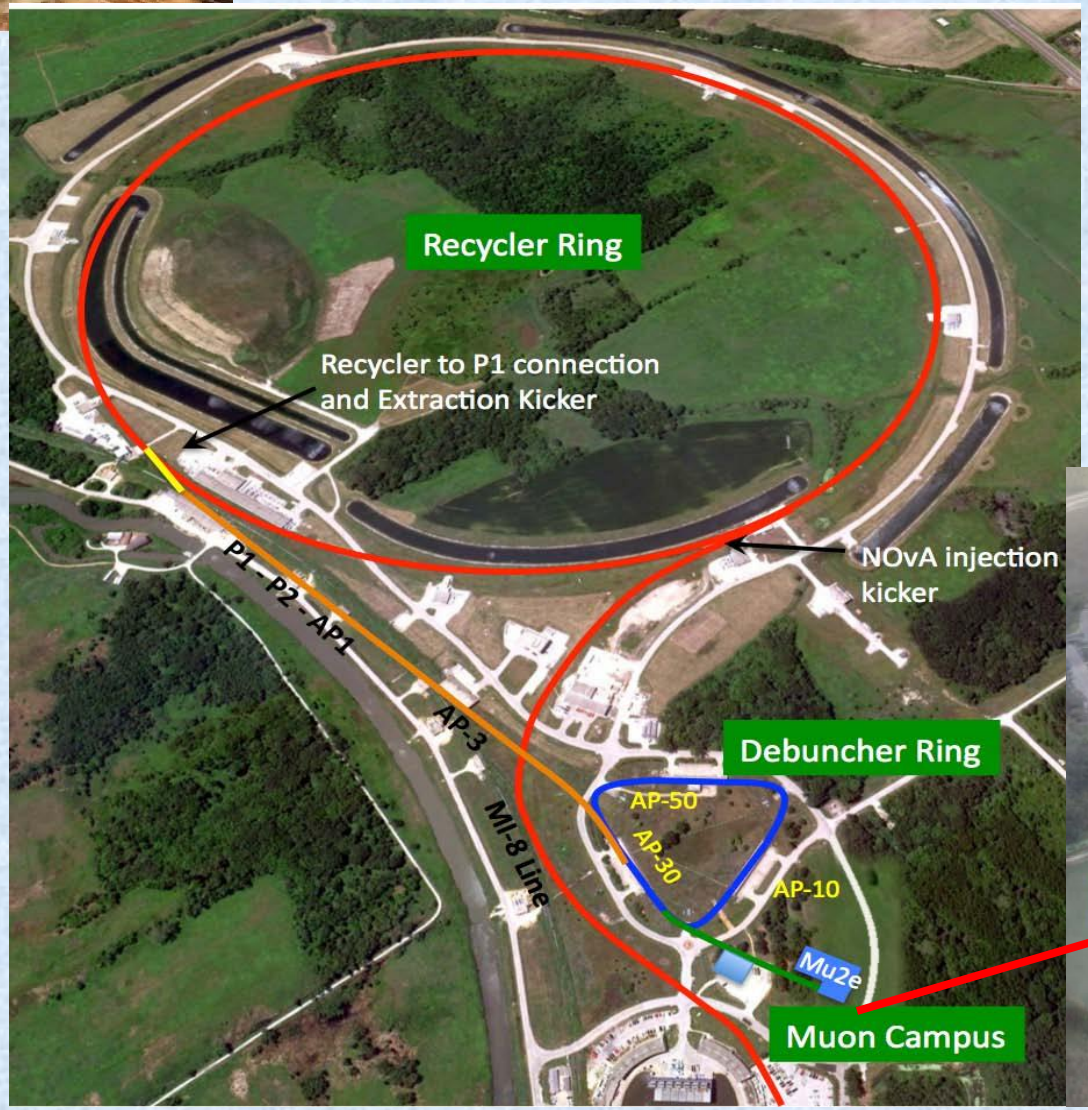
Better Tracking Detectors

4) Redundancy, Redundancy, Redundancy

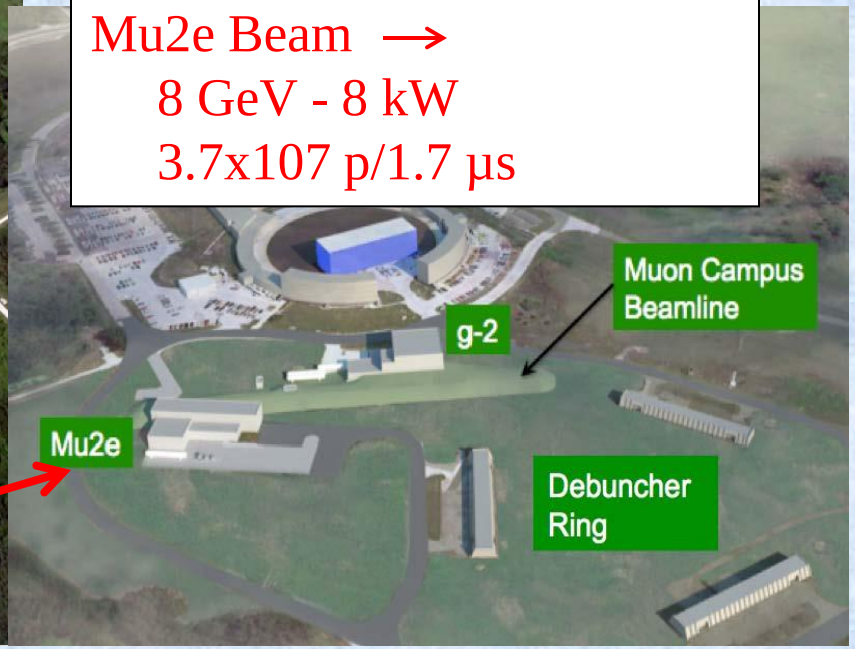
These ideas are obvious and were contained in MELC and MECO

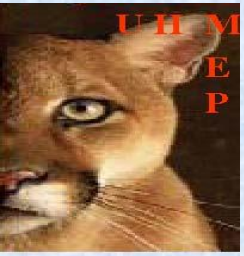
Muon Production at FNAL



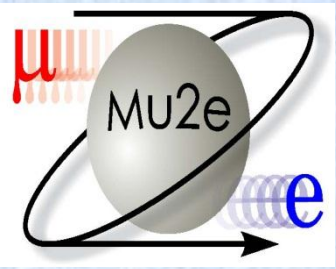


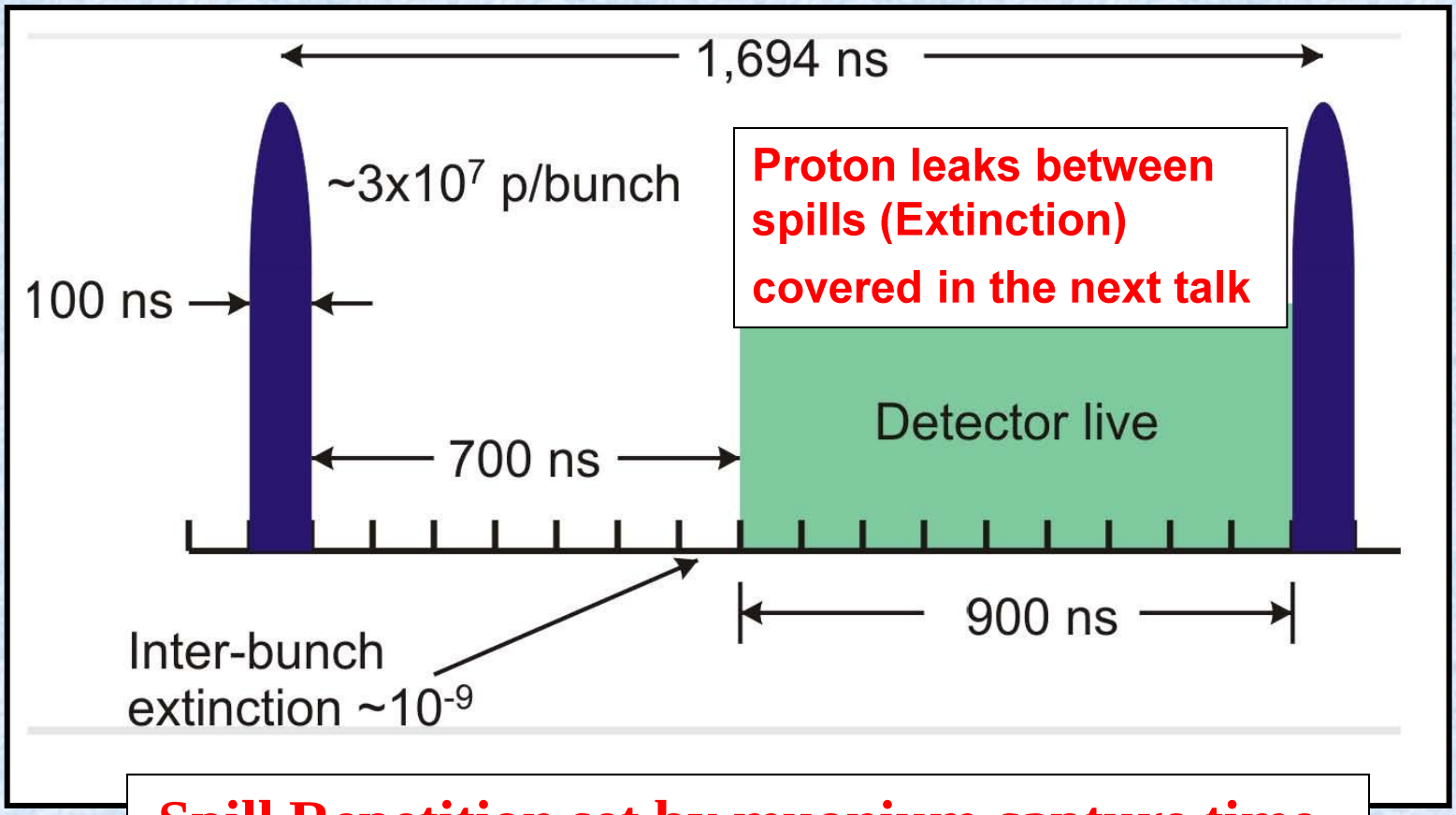
anti-proton complex →
Muon campus
G-2 and NOVA operations
Ring Revolution (1694 ns) →
τ(Al) = 864 ns
Mu2e Beam →
8 GeV - 8 kW
3.7x107 p/1.7 μs





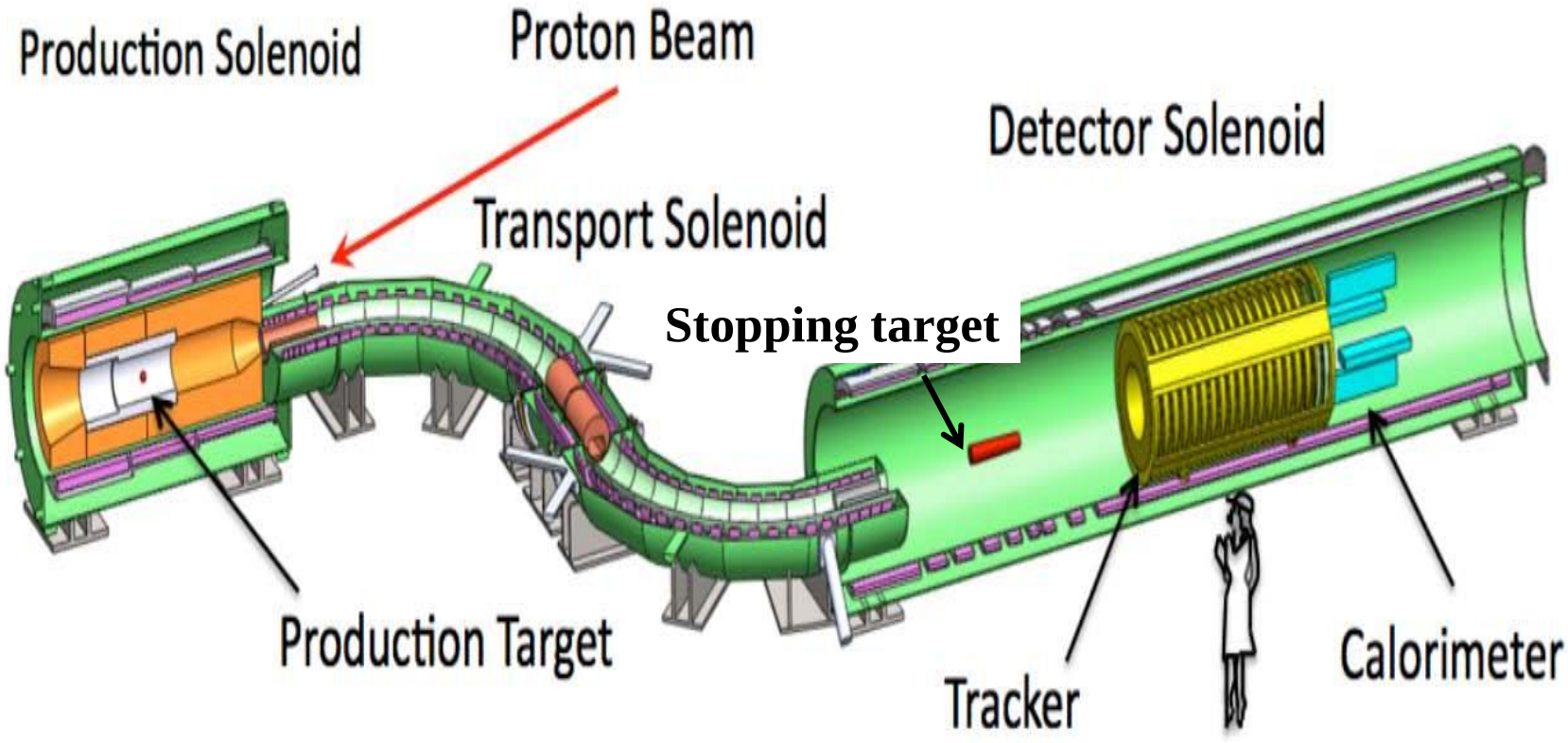
Micro-bunching to remove background





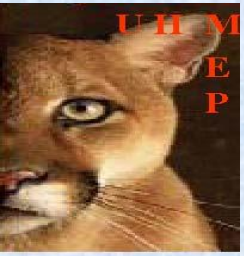
Spill Repetition set by muonium capture time

Mu2e Apparatus at FNAL

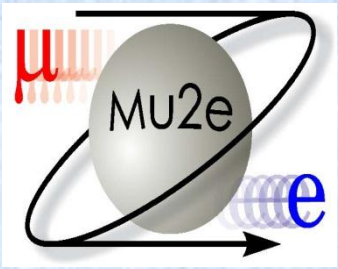


Beam related background reduced by beam pulsing using delayed measurements (MELC; MECO).

Continuous Solenoids capture muons, transport them, and analyze decay electrons

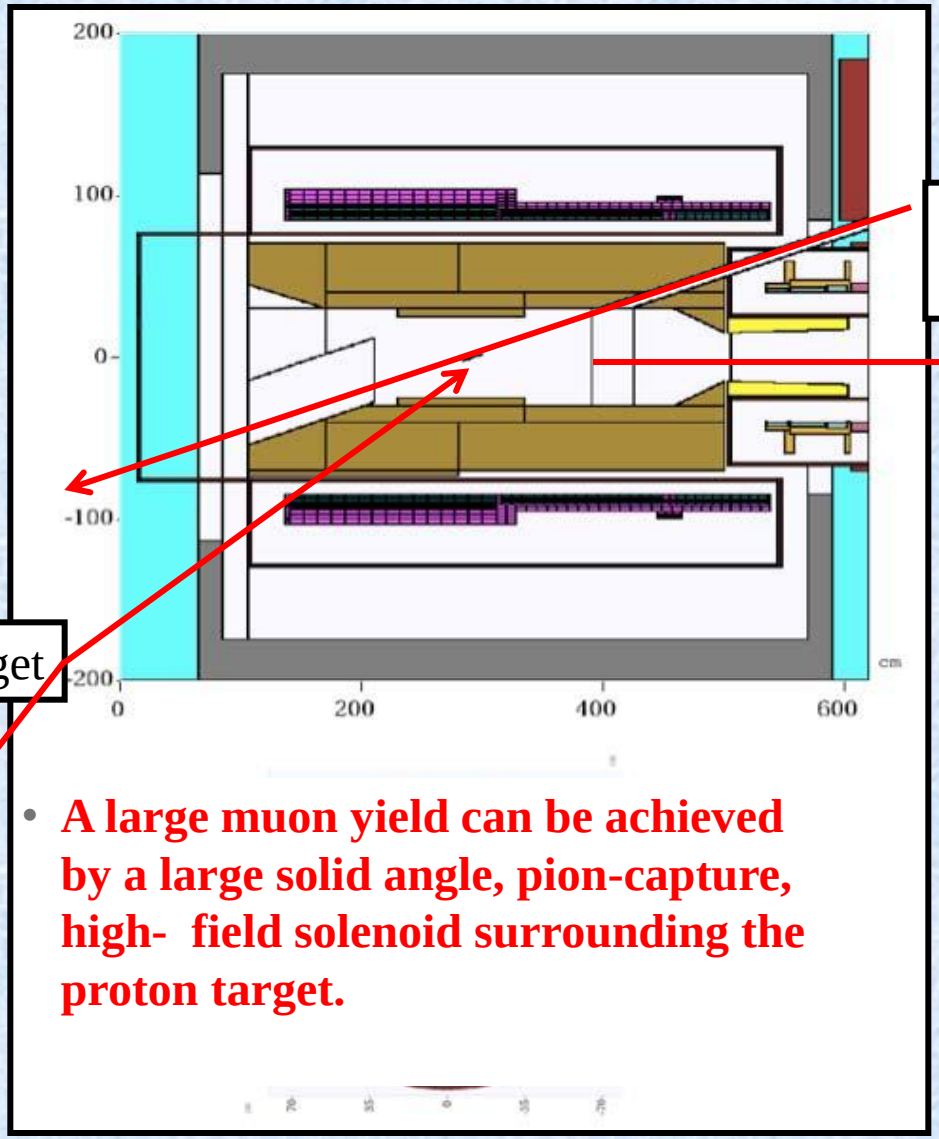


Production Solenoid

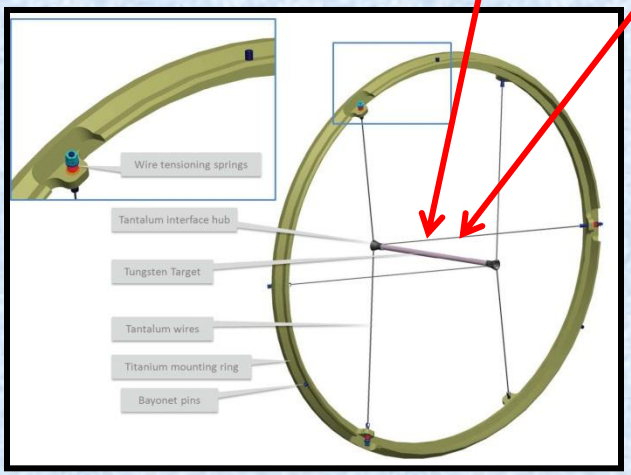


Require high A
Excellent conductivity
High melting temperature

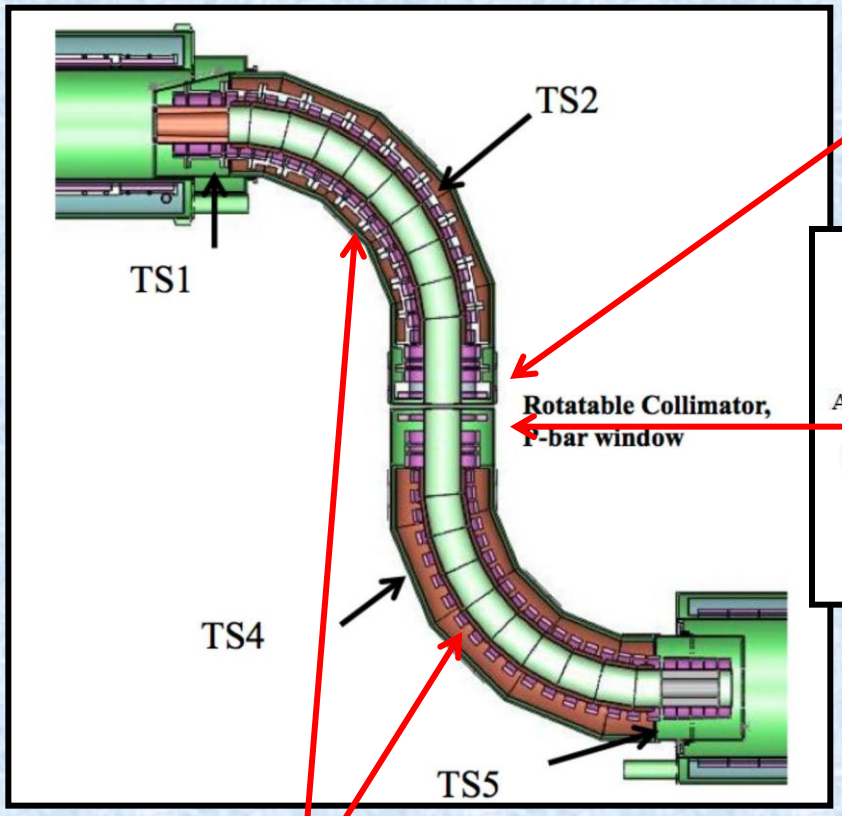
W rod 16 cm 0.6 cm D



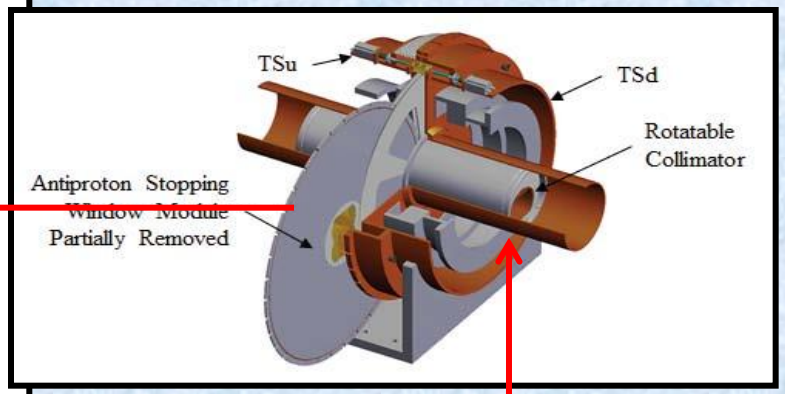
- **A large muon yield can be achieved by a large solid angle, pion-capture, high- field solenoid surrounding the proton target.**

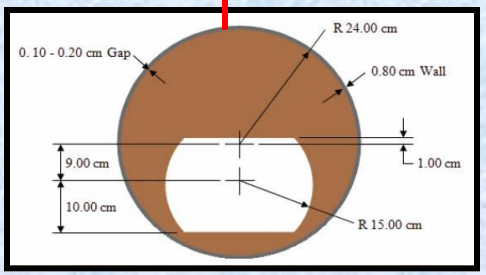


Transport Solenoid



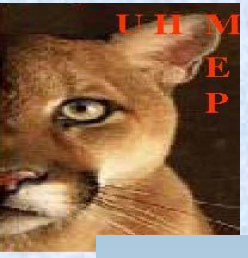
Anti-protons removed by Be foil



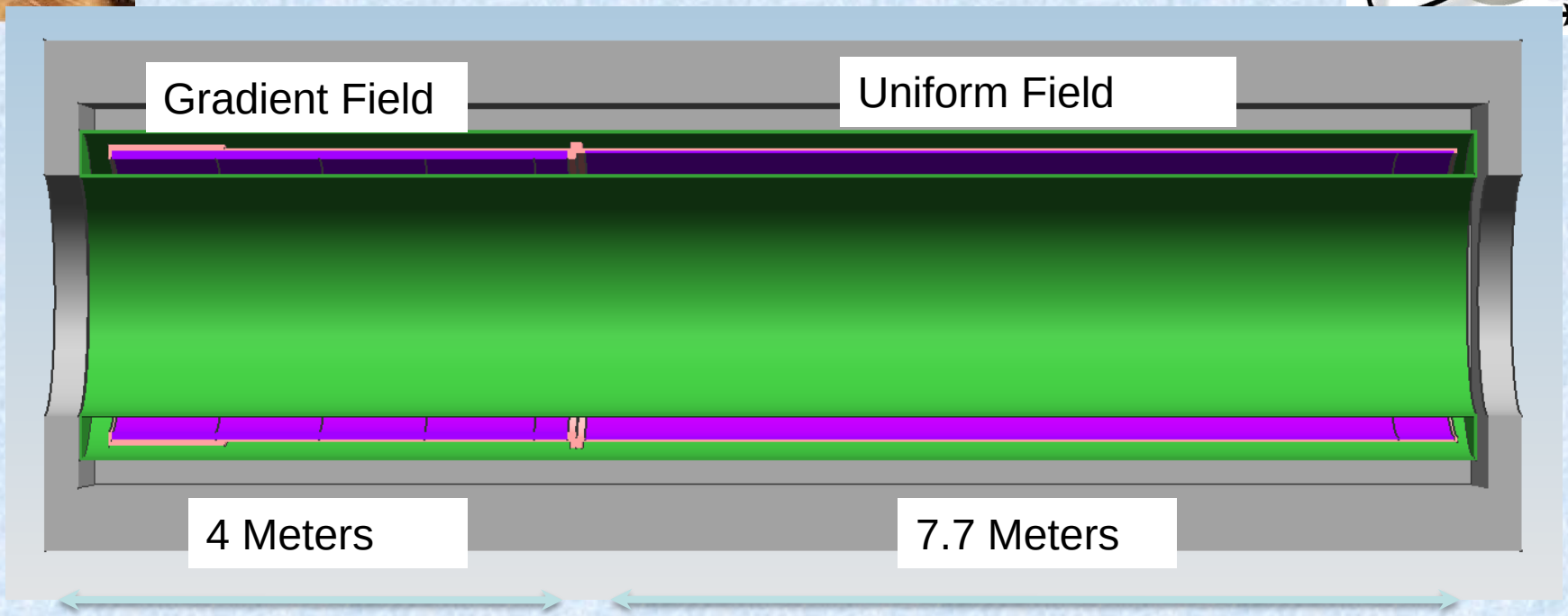


Rotatable Collimator

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



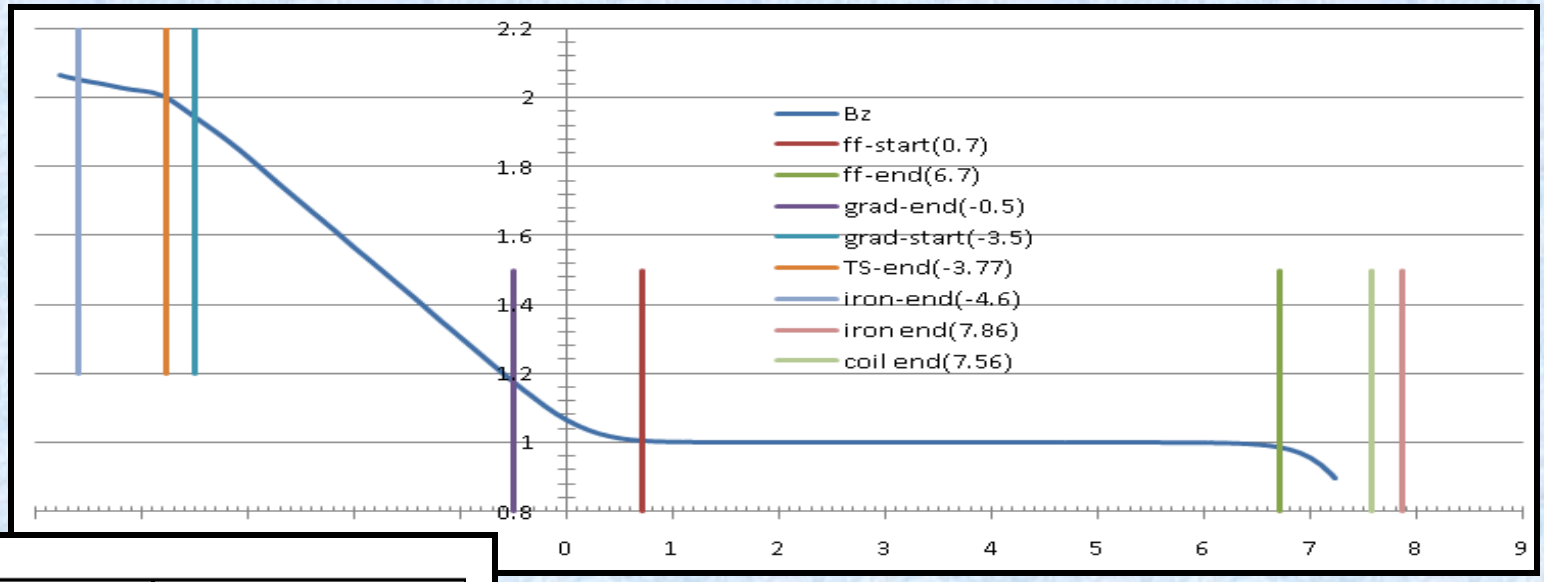
Detection Solenoid

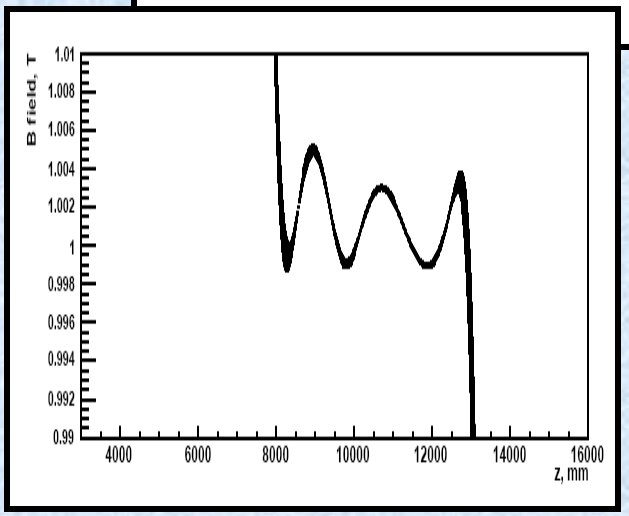


- 2 Solenoids, connected Mechanically and Electrically in Series.
- Gradient 2T-> 1T : Uniform Solenoid 1 Tesla for Tracking Detector.
- Conductor Al stabilized Rutherford NbTi Cables.
- Al outside Support Cylinder. Cold Mass 17 tons & Vacuum Vessel 33 tons
- Iron Yoke ~770 m. tons.

Field Gradient

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



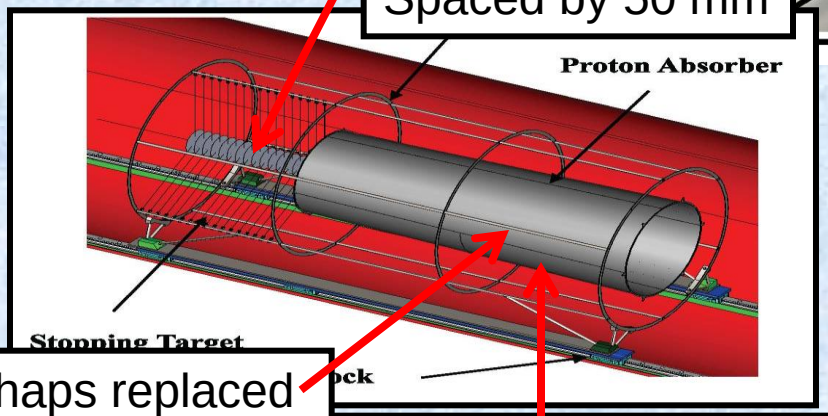


Positive gradient traps pions in a magnetic bottle which decay to muons during the "Detector Active" time window

Simulation shows 2 trapped muons/10^{17} p > 700 ns with p>75 MeV/c yields e ~>105 MeV

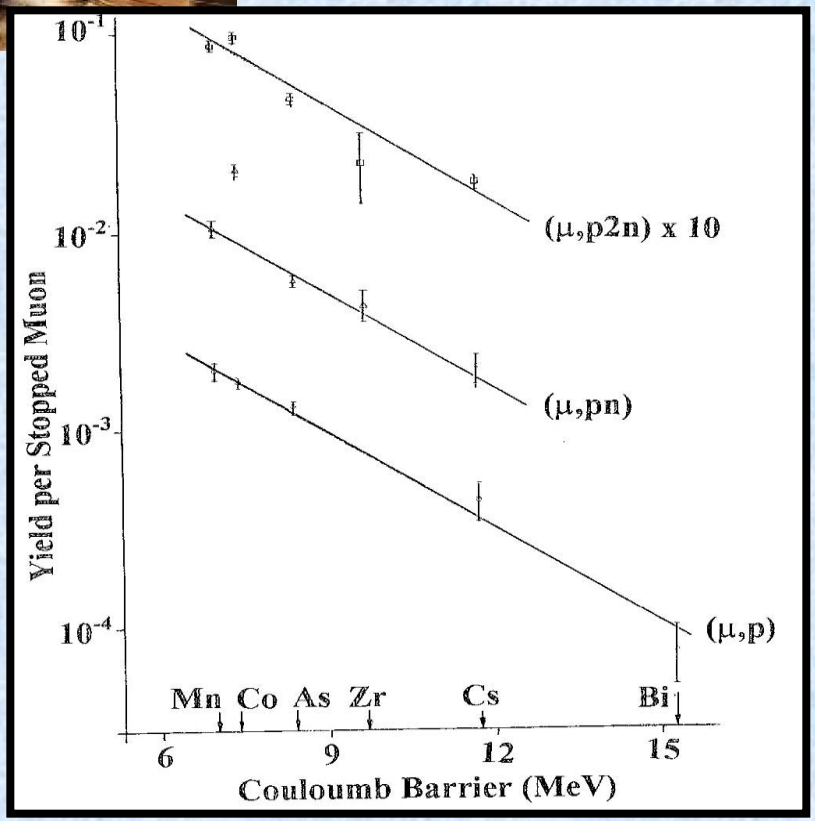
Stopping Target

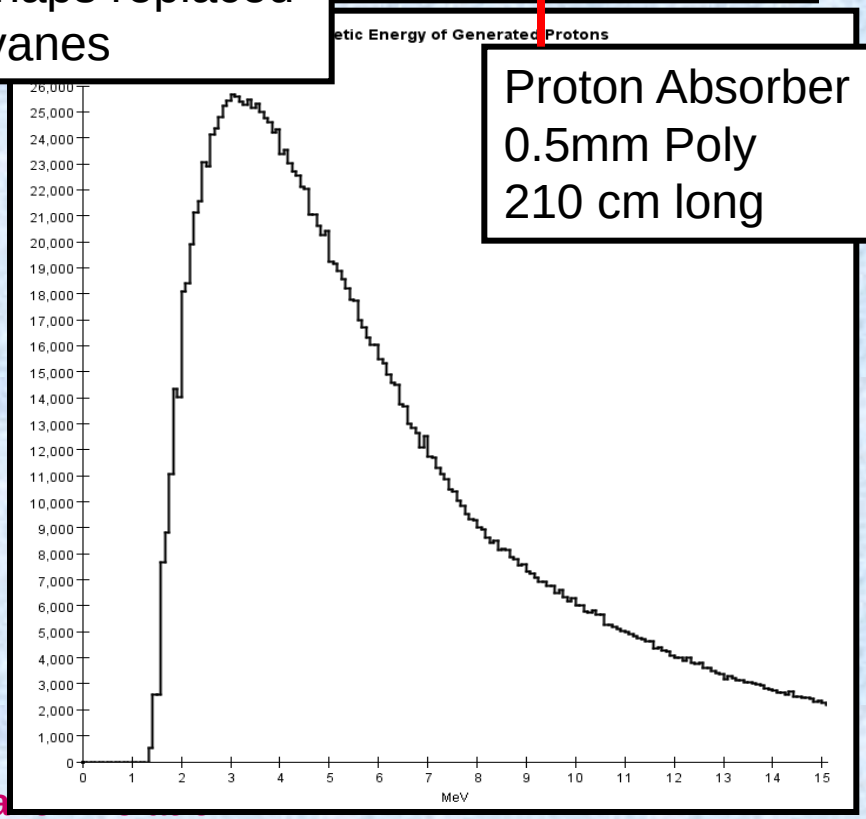
Al stopping target
17 0.2 mm foil
Spaced by 50 mm



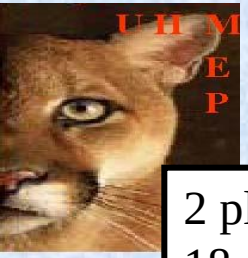
Perhaps replaced by vanes

Proton Absorber
0.5mm Poly
210 cm long



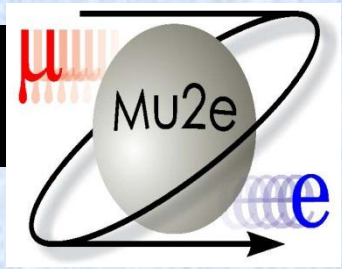


- ~0.15 protons emitted per μ capture
- Energies peaked around 5 MeV.
- Large contribution to background.
- Proton absorber to remove
- Neutron emission also a problem

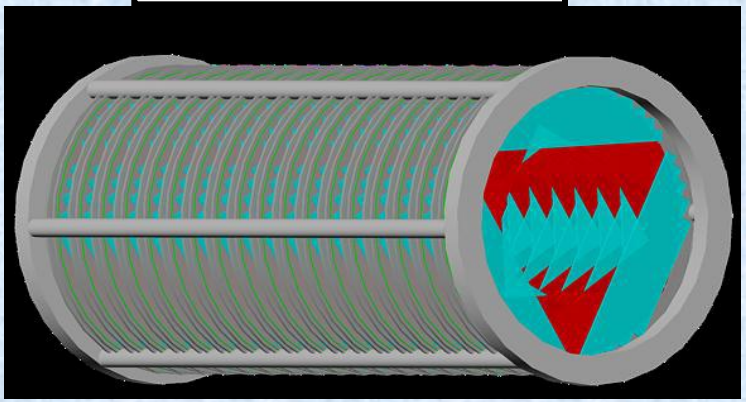


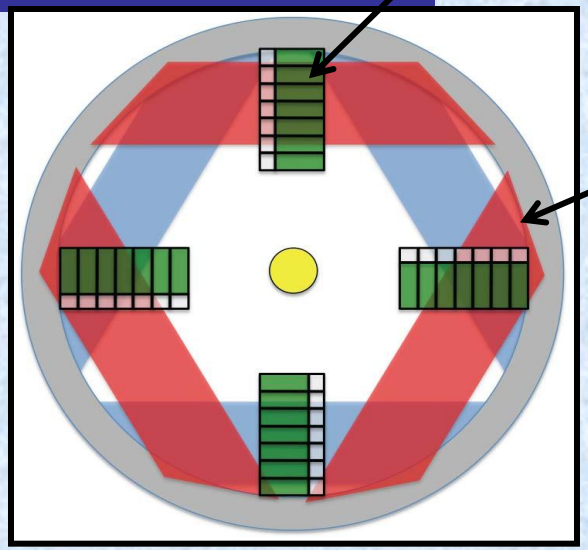
Electron Tracking (Straw Planes)

Calorimeter Vane



2 planes/station
18 stations/detector



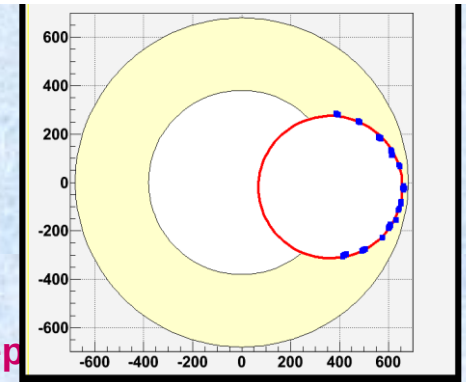


50 straws/layer
2 layers/panel
6 panels/plane
2 planes/station
18 stations/detector
21,600 straws

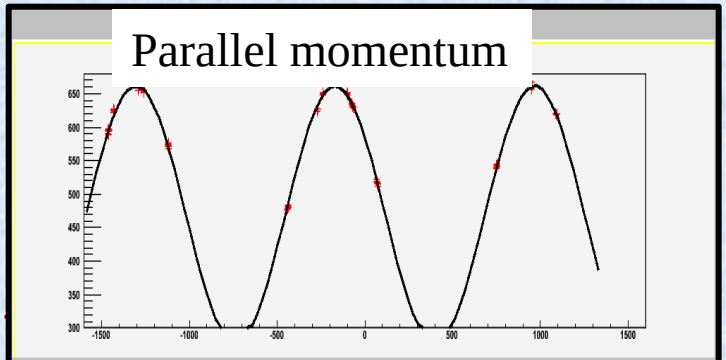
0.6-1.6m straws
0.5mm diameter
12 μm wall
0.20 μm W sense wire

Straw Gas Ar/CO_2: 80/20
100 μm position
35 ns time

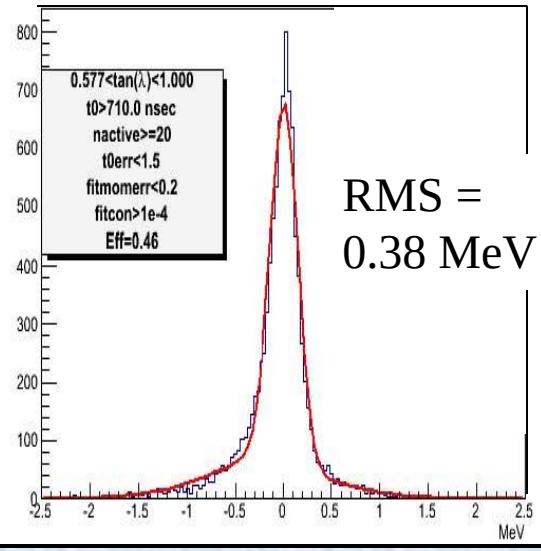
Perpendicular momentum



Parallel momentum

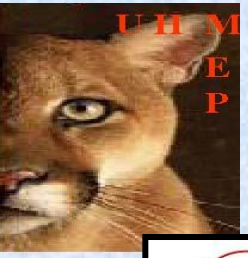


Electron Resolution

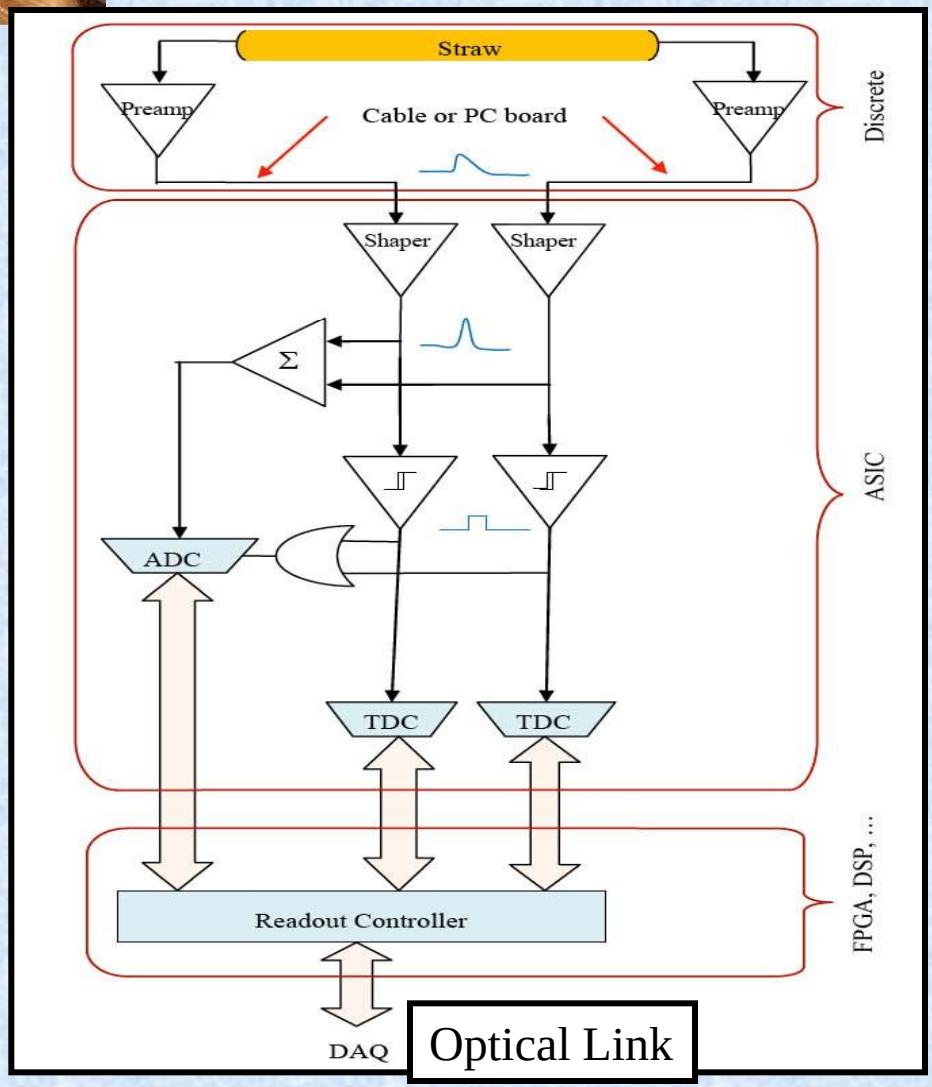


RMS = 0.38 MeV

Lep



Tracking Electronics



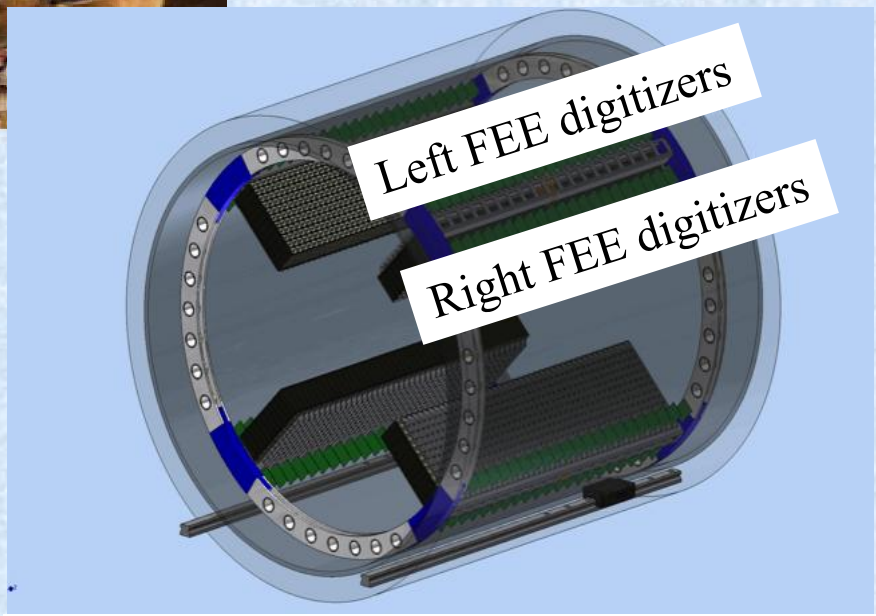
Amplitude 8 bits -
- Select track if a MIP
- zero suppressed

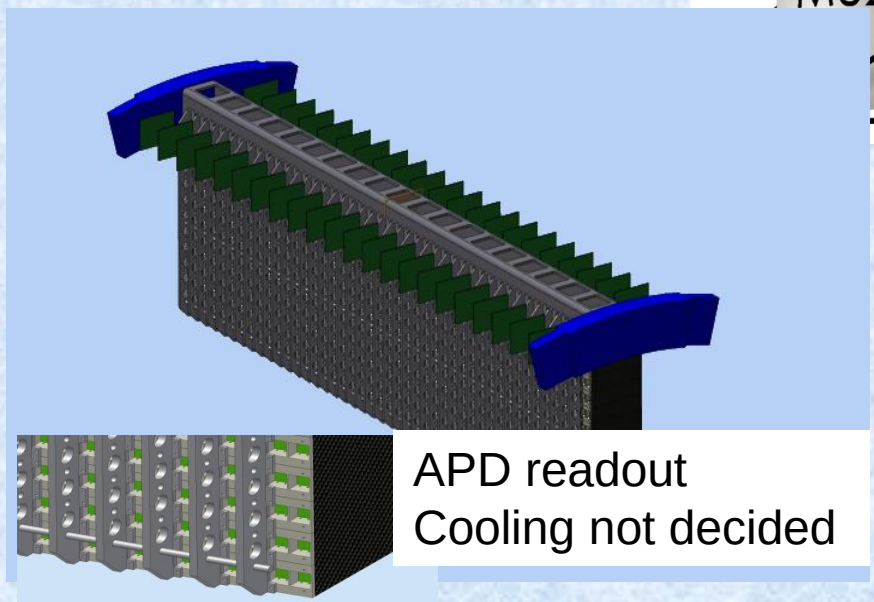
Timing -
- ~σ 35 ps both ends
- position ~1cm

Controller (1 per panel-100straws)
- Time Stamp
- Data buffer
- Sets front end functions
- Data transfer to DAQ

Rates are high - 300 Mbyte/s
218 controllers
Background hits need pattern recognition

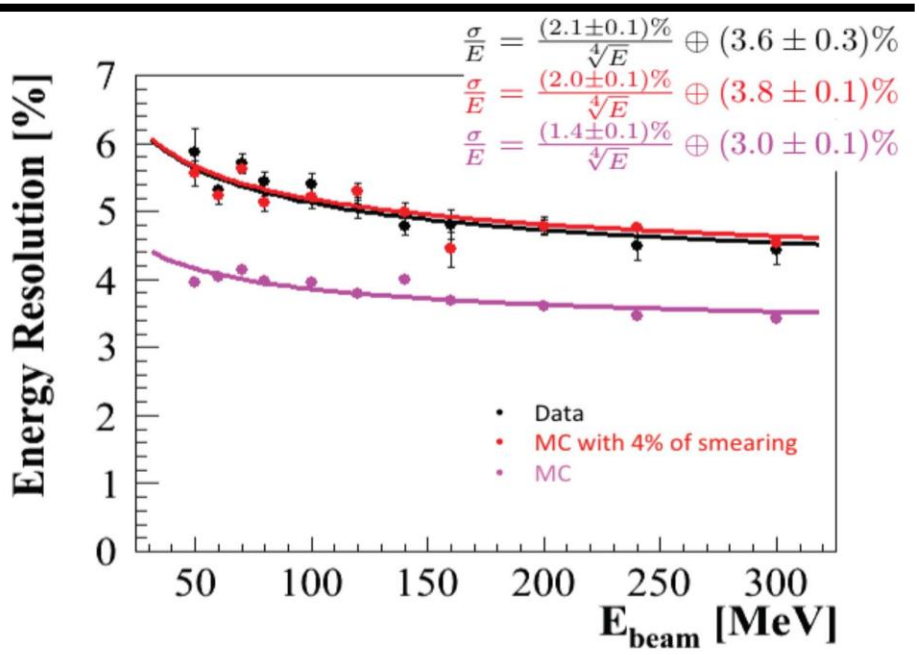
Calorimeter



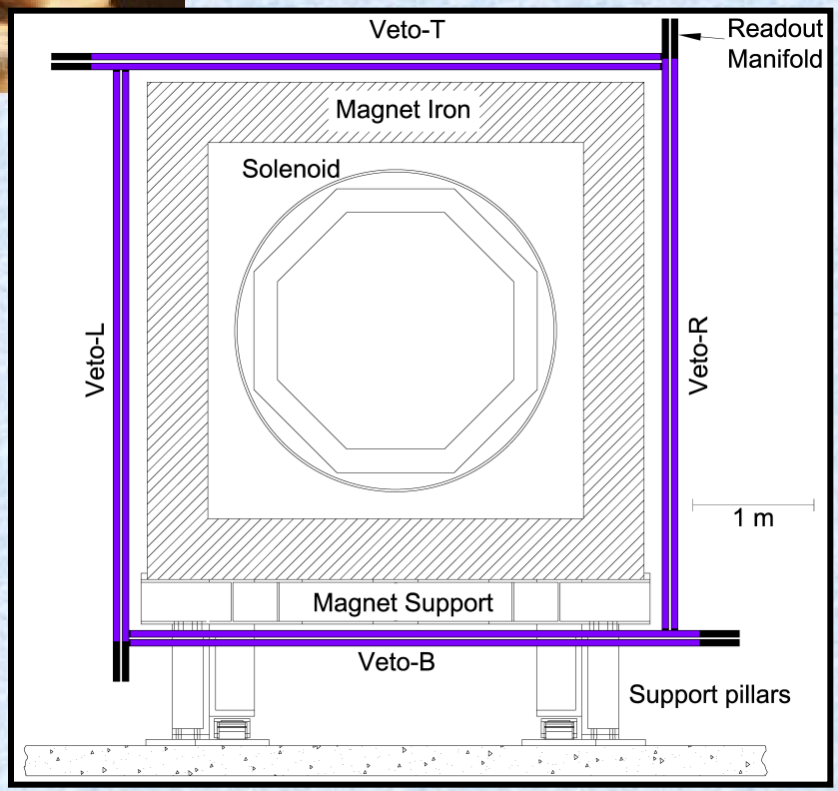


APD readout
Cooling not decided

Crystal	LYSO	$PbWO_4$
Density (g/cm^3)	7.28	8.28
Radiation length (cm) X_0	1.14	0.9
Molière radius (cm) R_m	2.07	2.0
Interaction length (cm)	20.9	20.7
dE/dx (MeV/cm)	10.0	13.0
Refractive Index at λ_{max}	1.82	2.20
Peak luminescence (nm)	402	420
Decay time τ (ns)	40	30, 10
Light yield (compared to NaI(Tl)) (%)	85	0.3, 0.1
Light yield variation with temperature(% / °C)	-0.2	-2.5
Hygroscopicity	None	None

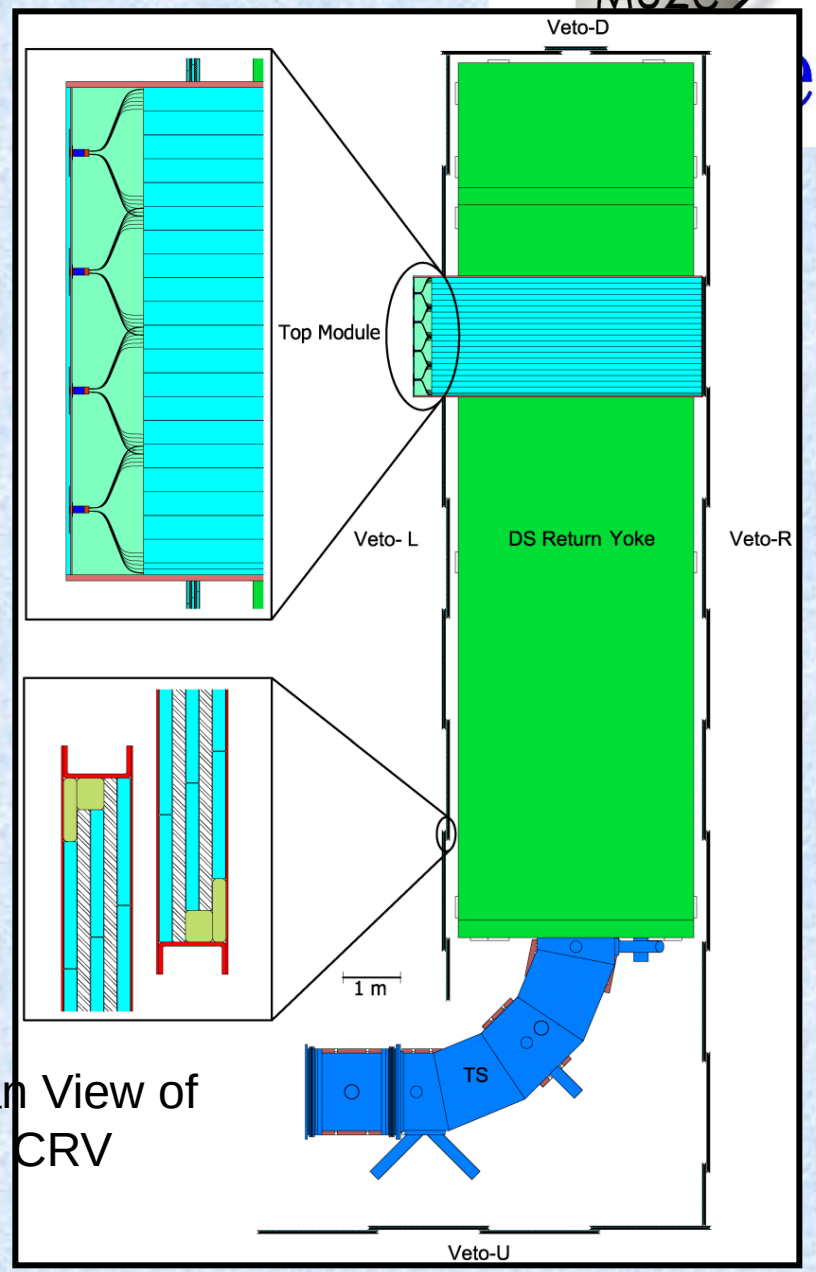


Cosmic Veto



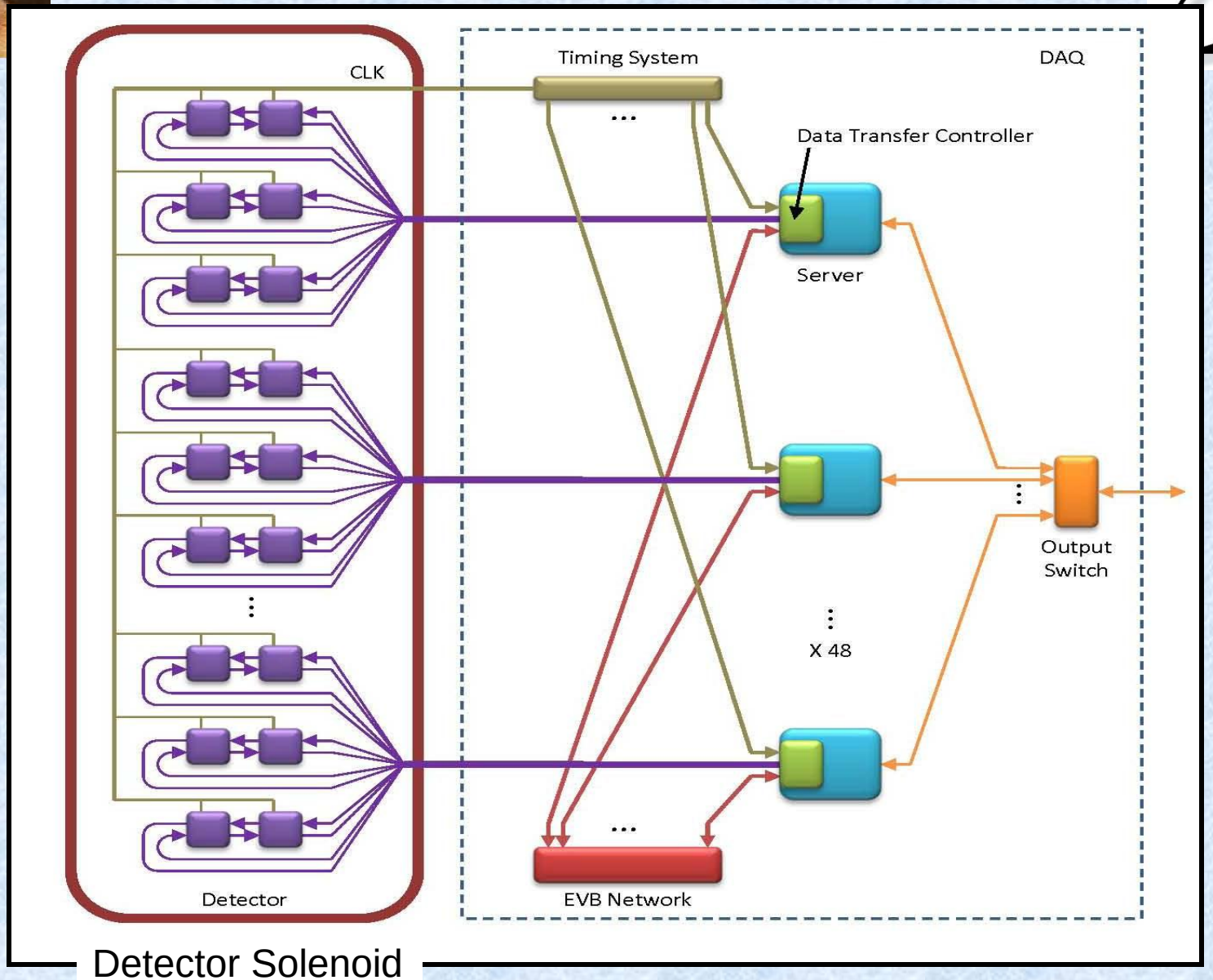
End View of the CRV

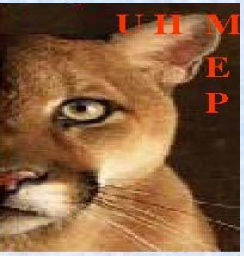
Modules organized into 6 sectors:
Right (R), Left (L), Downstream (D),
Upstream (U), Top (T), Bottom (B)



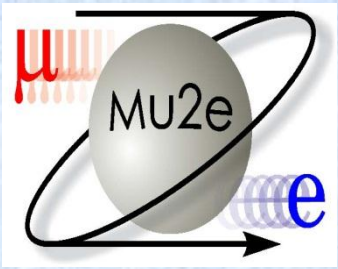
Plan View of the CRV

Triggerless DAQ





Data Rates



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

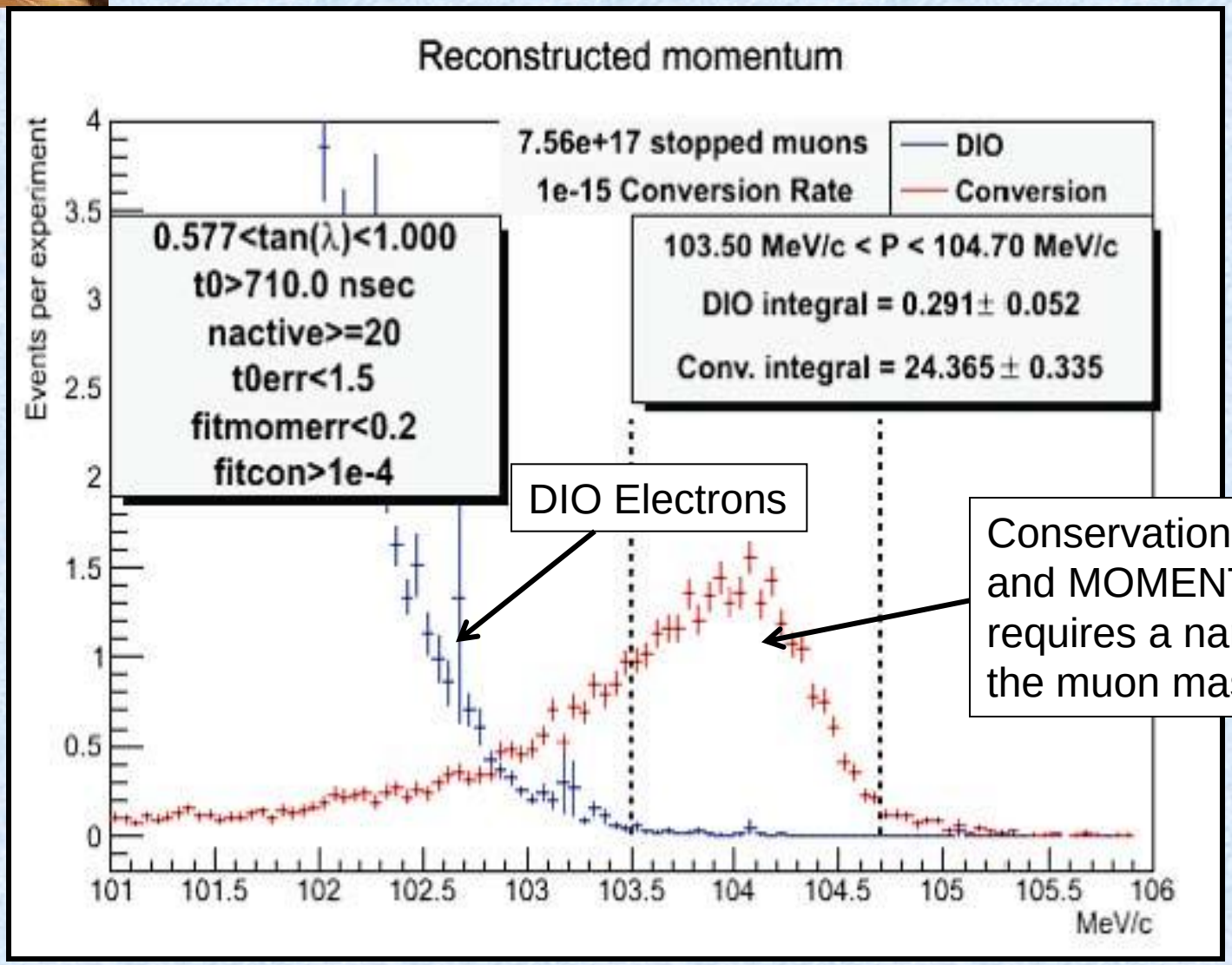
Tracker	21 GBytes/sec
Calorimeter	5 GBytes/sec
CRV	3

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



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

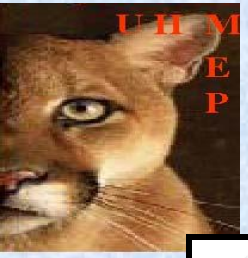
detector acceptance 0.05

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

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

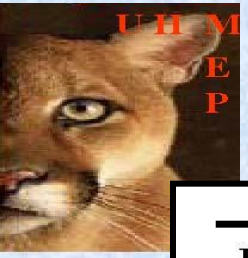
For a 3 year run

$$B(\mu^- + Al \rightarrow e^- + Al) = \frac{1}{1.2\ x\ 10^{17}\ x\ 0.05\ x\ 3} = 5.6 \times 10^{-17}$$



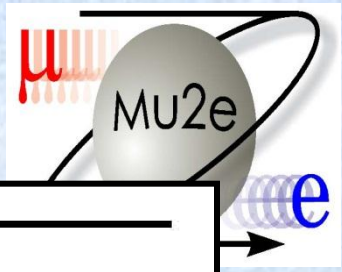
Predicted Sensitivity

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	0.51
Electron Trigger, Selection, and Fitting Efficiency in Live Window	0.10
Single-event sensitivity with Current Algorithms	5.6×10^{-17}
Goal	2.4×10^{-17}

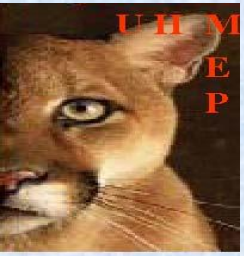


Backgrounds – 3.6x10^{20} protons

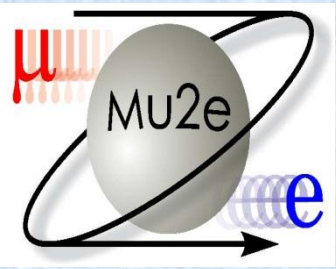
(It's what you don't know that bites)



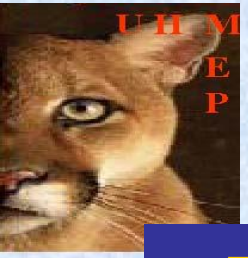
Background	Background Estimate	Error Estimate	Reference	Justification
Muon decay-in-orbit	0.22	± 0.06	2085	Acceptance and energy loss modeling, spectrum calculation; reconstruction algorithm
Cosmic Rays	0.05	± 0.013	CDR	Statistics of sample
Radiative Pion Capture	0.03	± 0.007	2085	Acceptance and energy loss modeling
Pion decay In-Flight	0.003	± 0.0015	2085	Cross-section, acceptance and modeling
Muon decay In-Flight	0.01	± 0.003	2085	Cross-section, acceptance and modeling
Antiproton Induced	0.10	± 0.05	2121	Cross-section, acceptance and modeling
Beam electrons	0.0006	± 0.0003	2085	Cross-section and acceptance (this is an upper limit)
Radiative muon capture	$< 2 \times 10^{-6}$	–	1230	Calculation
Total	**0.41**	**± 0.08**	2085	Add in quadrature



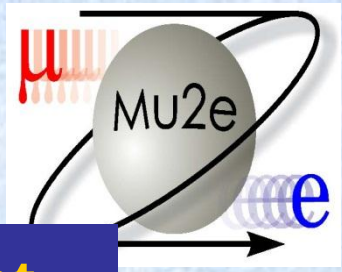
Summary



- 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"

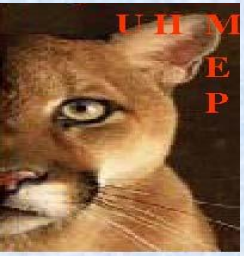


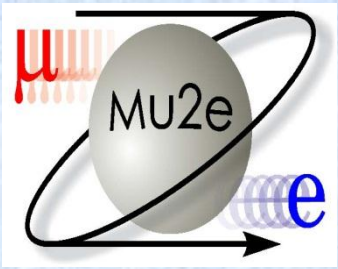
This is a title of a poem by Elizabeth Barret Browning.

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.

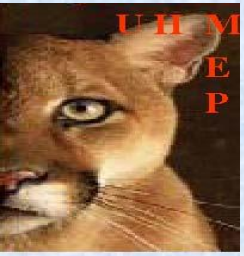


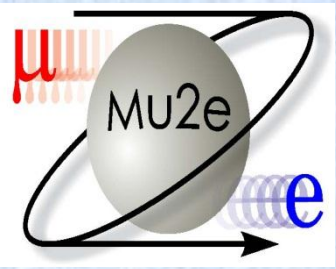


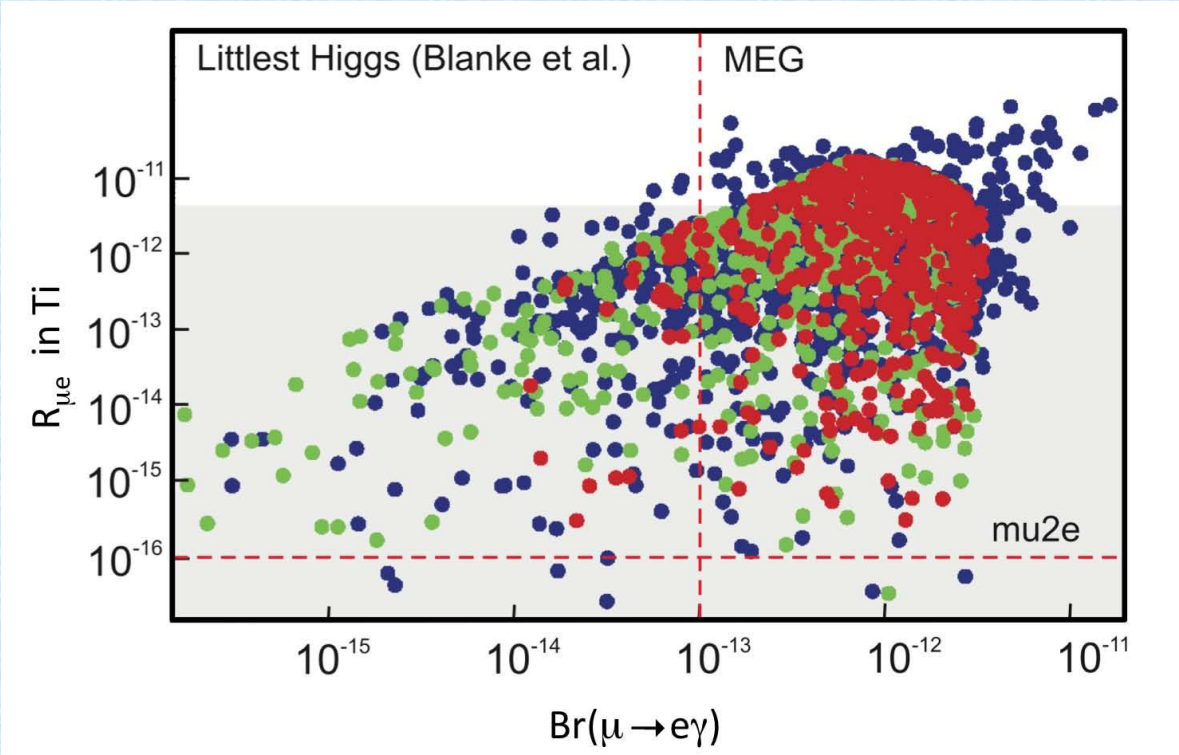
End

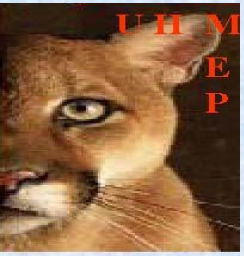
PH^2

Possible Happy Hunting


U H M
E
P

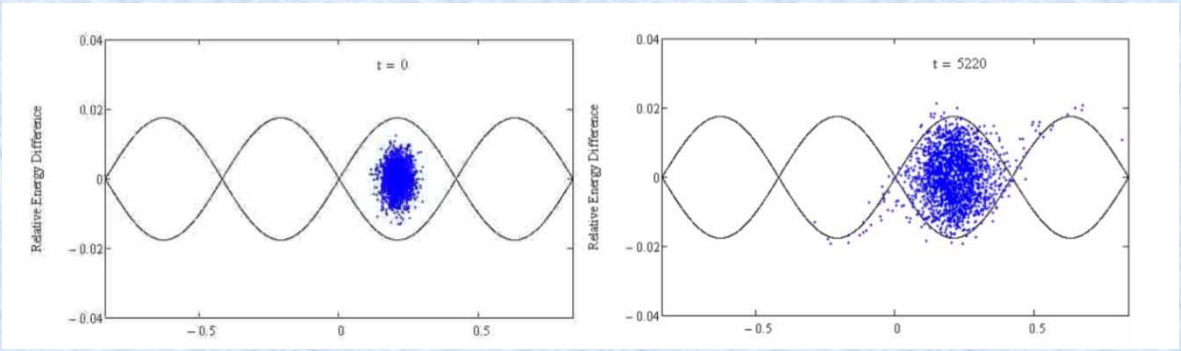

μ
Mu2e
e

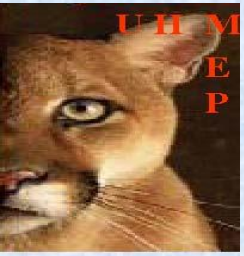

Littlest Higgs (Blanke et al.)
MEG
mu2e
$R_{\mu e}$ in Ti
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
$Br(\mu \rightarrow e\gamma)$

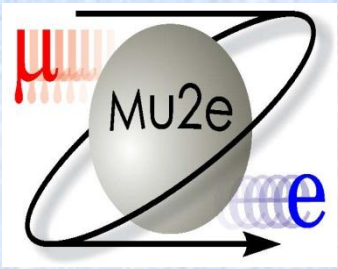

U
H
M
E
P

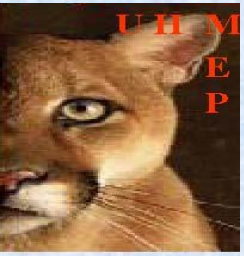
Proton Beam

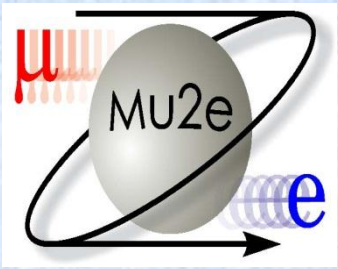
Mu2e

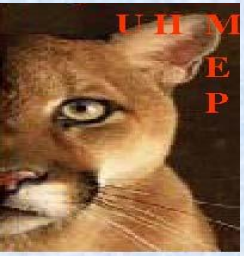

t = 0
t = 5220
Relative Energy Difference
0.04
0.02
0
-0.02
-0.04
-0.5
0
0.5

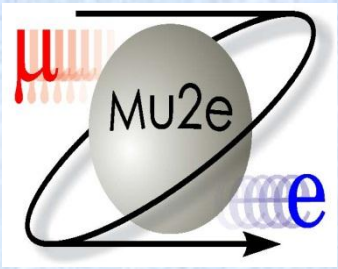

U H M
E
P

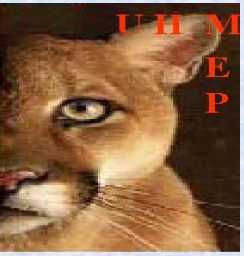

μ
Mu2e
e

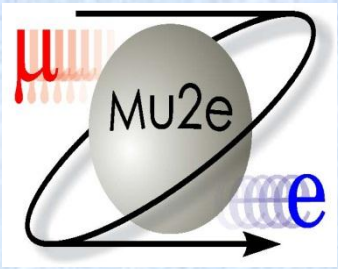

U H M
E
P


μ
Mu2e
e


U H M
E
P


μ
Mu2e
e


U H M
E
P


μ
Mu2e
e