Searching for
Charged Lepton Flavor Violation (cLFV)
--Mu2E at FNAL--

Ed V Hungerford
University of Houston
(for the Mu2E Collaboration)

The Mu2e Collaboration-

200 scientists, 34 institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory University of California, Berkeley, University of California, Irvine, Cal. Tech, City University of New York, JINR Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute For Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

Frontiers in Particle Physics

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

- Origin of EW symmetry breaking
- Hierarchy problem - Neutrino mass and mixing issues
- Dark matter in the Universe - connecting the large and small
- SUSY, extra dimensions, various Higgs models
- Charged Lepton Flavor Violation (cLFV) e.g. Mu2e

Neutrino-less direct conversion of μ→e

Mu2e at FNAL has a single event sensitivity of

$\sim 6\mathrm{x}10^{-17}$ (μ→e / μ→e+ν)

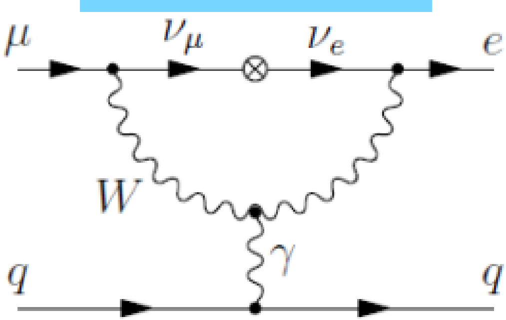
Now 10^{-17} is tiny, tiny, tiny, …

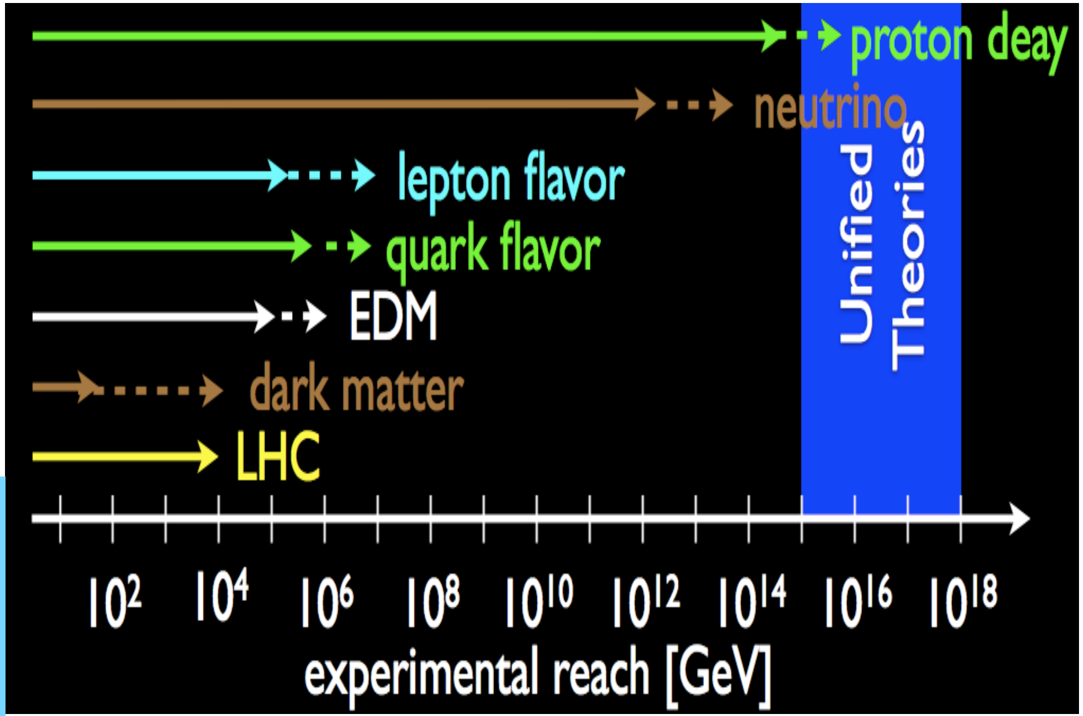
Equivalent to the probability of both lightning and a medeorite striking your house in the same month

Family Mixing (BSM)

- **The CKM matrix mixes Family number in weak decays**
- **Neutrino families mix**
- **In the SM cLFV it is heavily suppressed $\sim(\Delta M_{\nu}/M_{w})^4$**
- **Yet most (BSM) models predict observation in new experiments**

SM branch $\sim 10^{-54}$





Any observation by Mu2e Requires BSM Physics

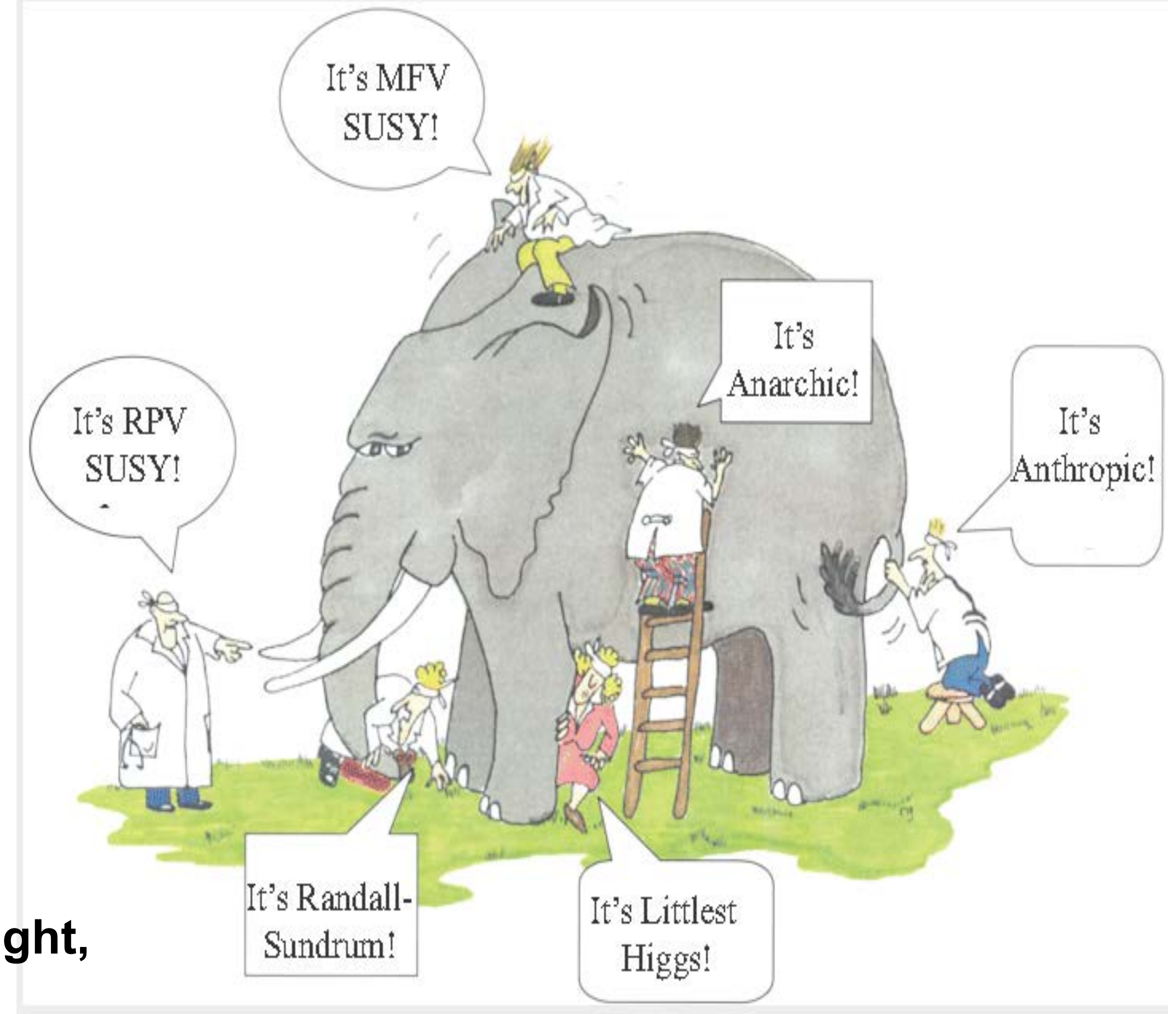
Searching for BSM Physics cLFV is a discovery experiment

The Blind Men and the Elephant
John Godfrey Saxe (1816-1887)

It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.

….

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!



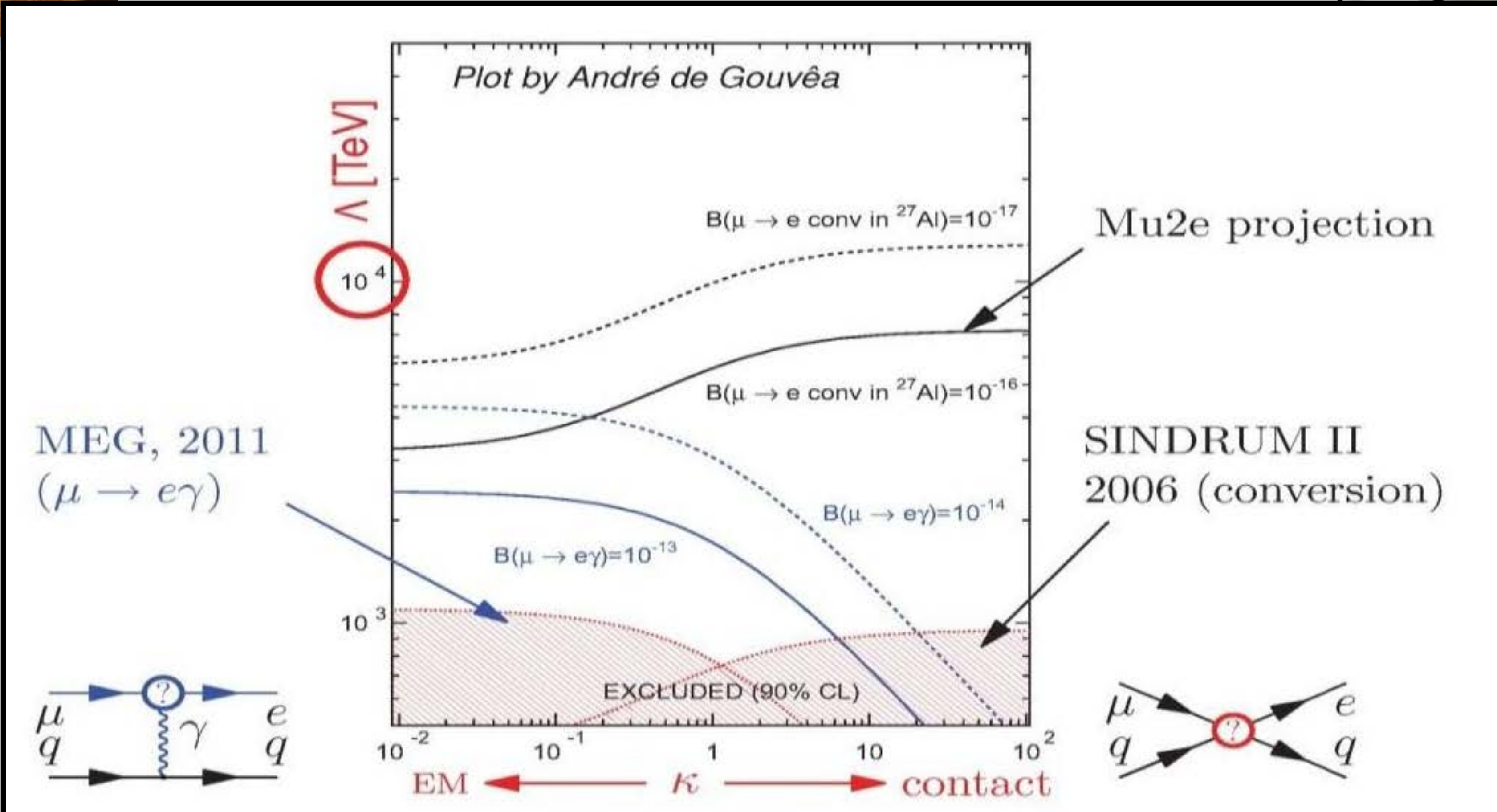
Muons:
An important tool for precision tests

1. **Determination of SM parameters**
   - Muon Lifetime
   - Michel Parameters
   - Muon (g-2)
   - Capture rates
   - Searches for new symmetries or symmetry breaking :

Possible cLFV	Present Limit	SUSY(GUT)
$\mu^+ \to e^+\gamma$	**4.2 x 10^{-14} MEG arXiv 1605.05081**	
$\mu^+ \to e^+e^+e^-$	**1.0 x10^{-12} Sindrum Nucl. Phy. B229(88)1**	**0.007 $\mu \to e\gamma$**
$\mu^- - e^-$ Conversion	**7.0 x10^{-13} W. Bertl et al, EPJ C47(06)337**	**10^{-16}**
Muonium-antimuonium		
Muon EDM		

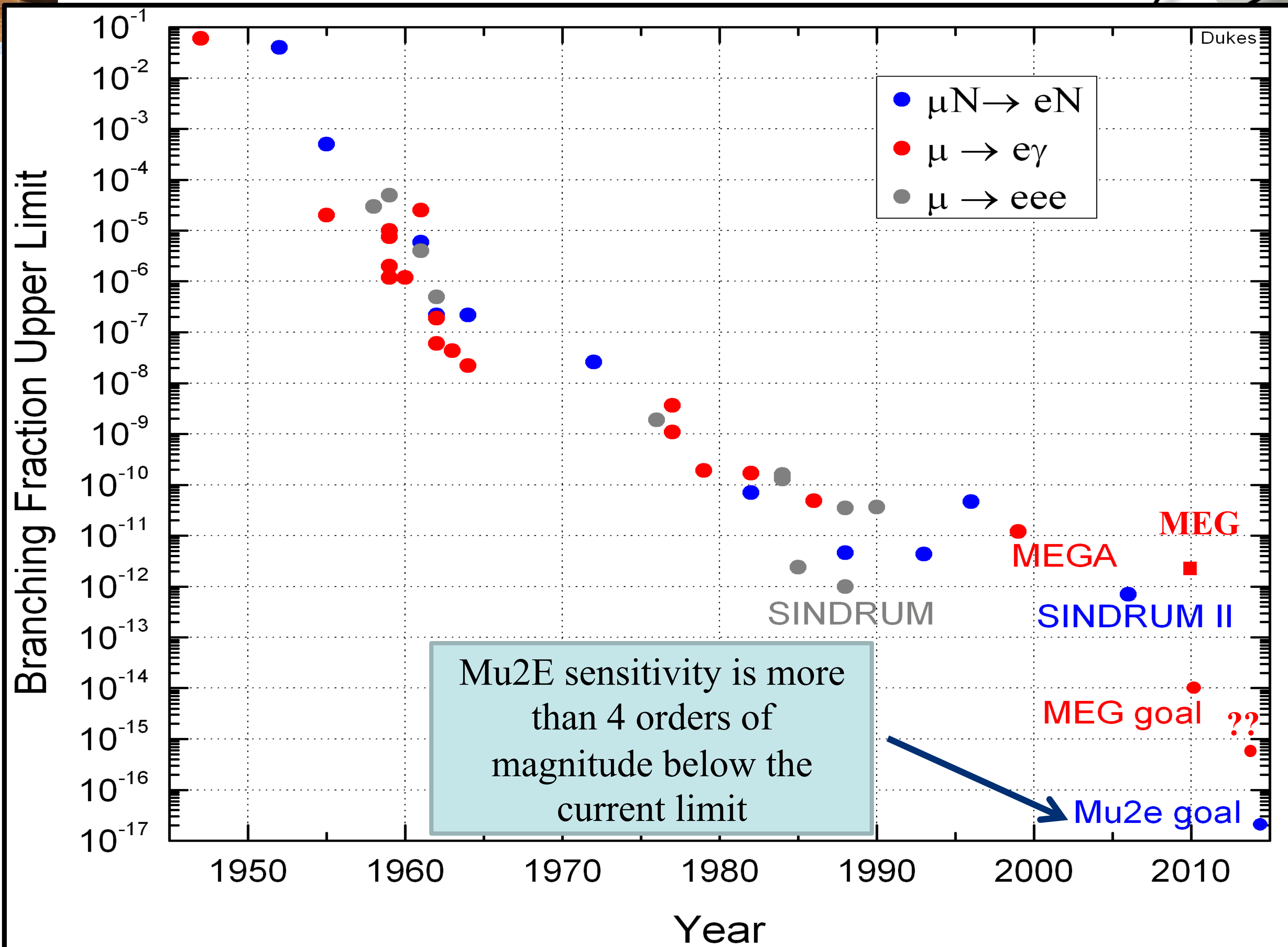
Model Discrimination

Comparison of Contact vs EM Interaction

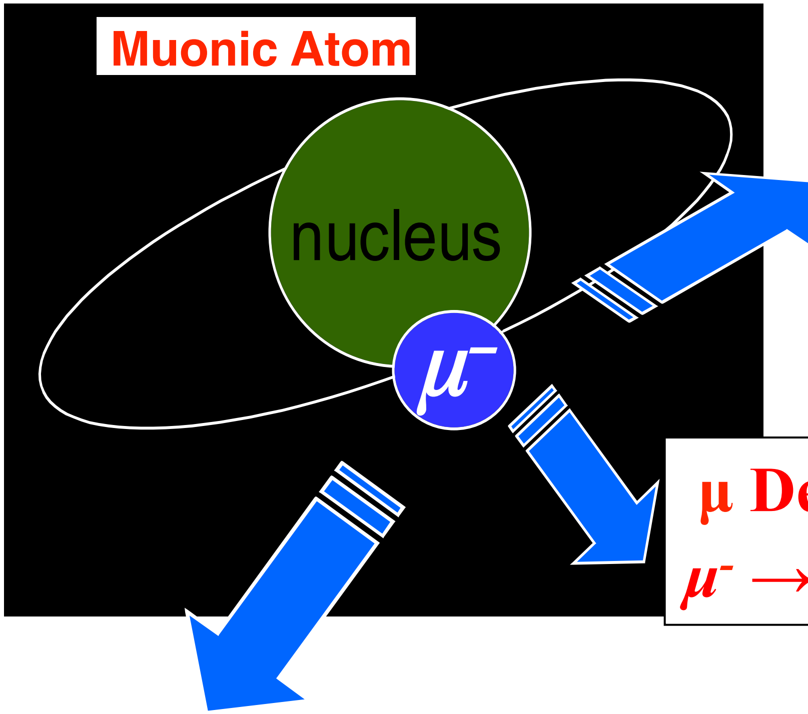


An example of semi-model independent sensitivity between μ→e and μ→eγ. The figure illustrates the reach for new physics processes in mass scale, Λ in TeV. The diagrams on either side of the figure illustrate the leading term in a model representation

cLFV in muon interactions



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



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

energy ~= μ mass

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

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

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

To reach Higher Sensitivity

1) Reduce Beam Associated Background

Pulsed beam and use the long μ lifetime

2) Increase μ Stopping

High Intensity Pion Production (μ from π decay)

Use magnetic solenoids to capture, transport, detect μ

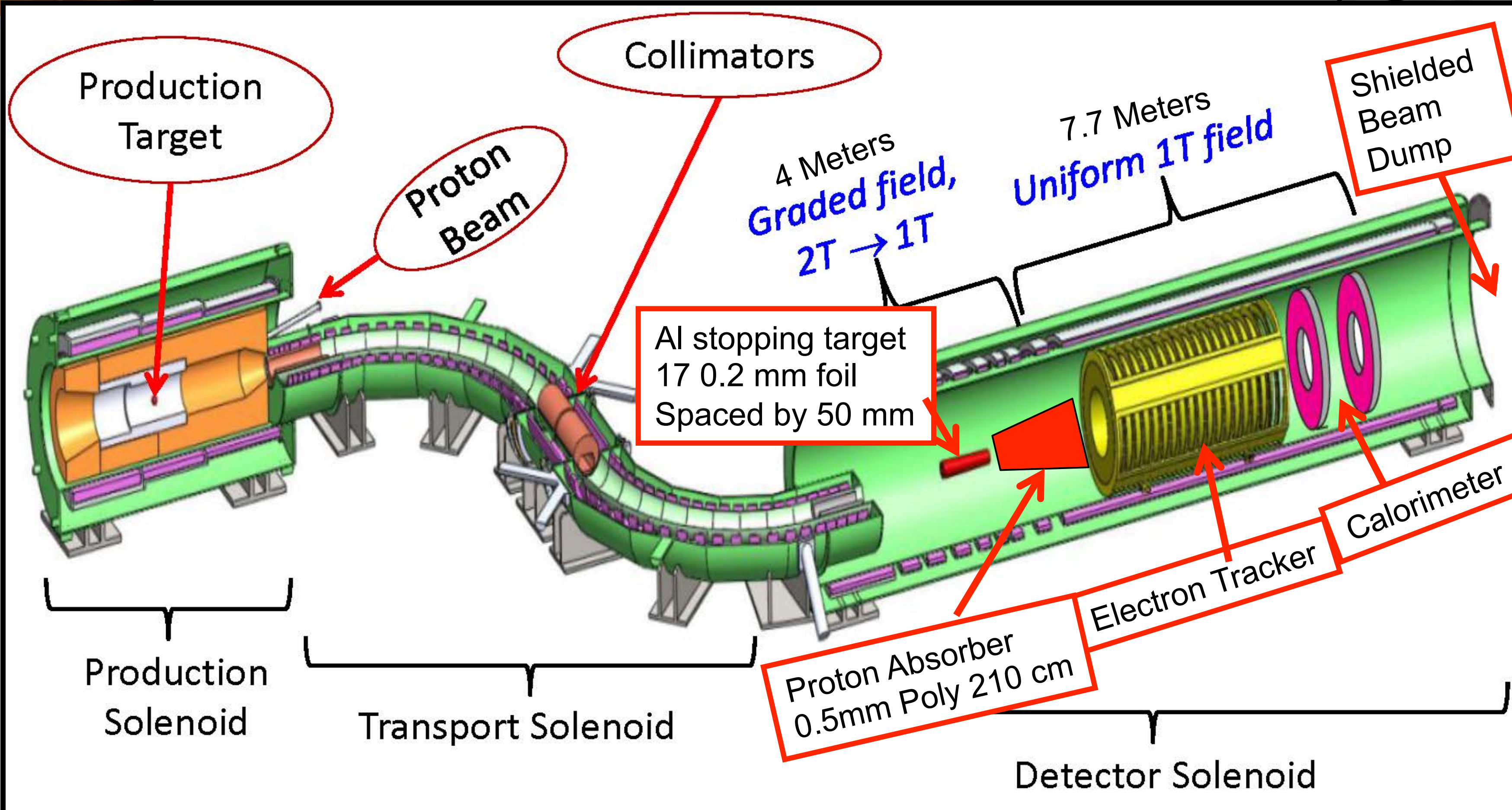
3) Electron Energy Resolution and Timing

Better tracking detectors

Employ new electronic technology to handle higher rates

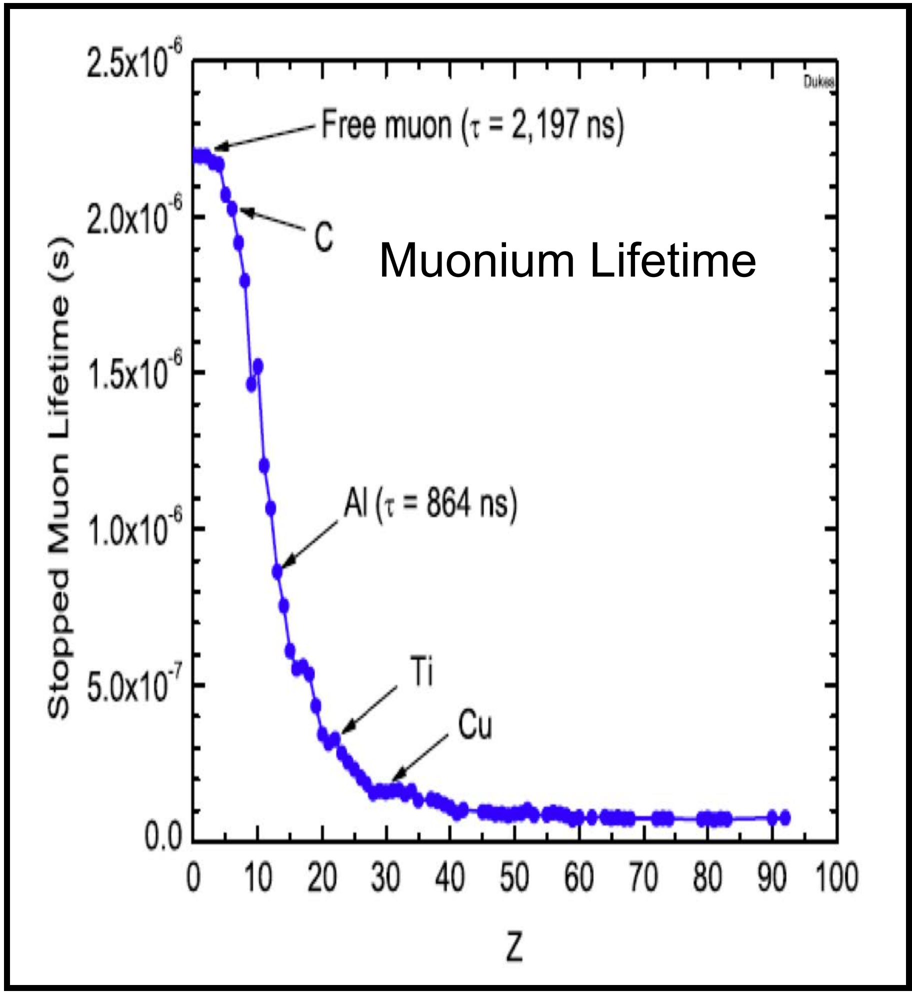
Many of these ideas were contained in MELC (V. Lobashev, 1992)

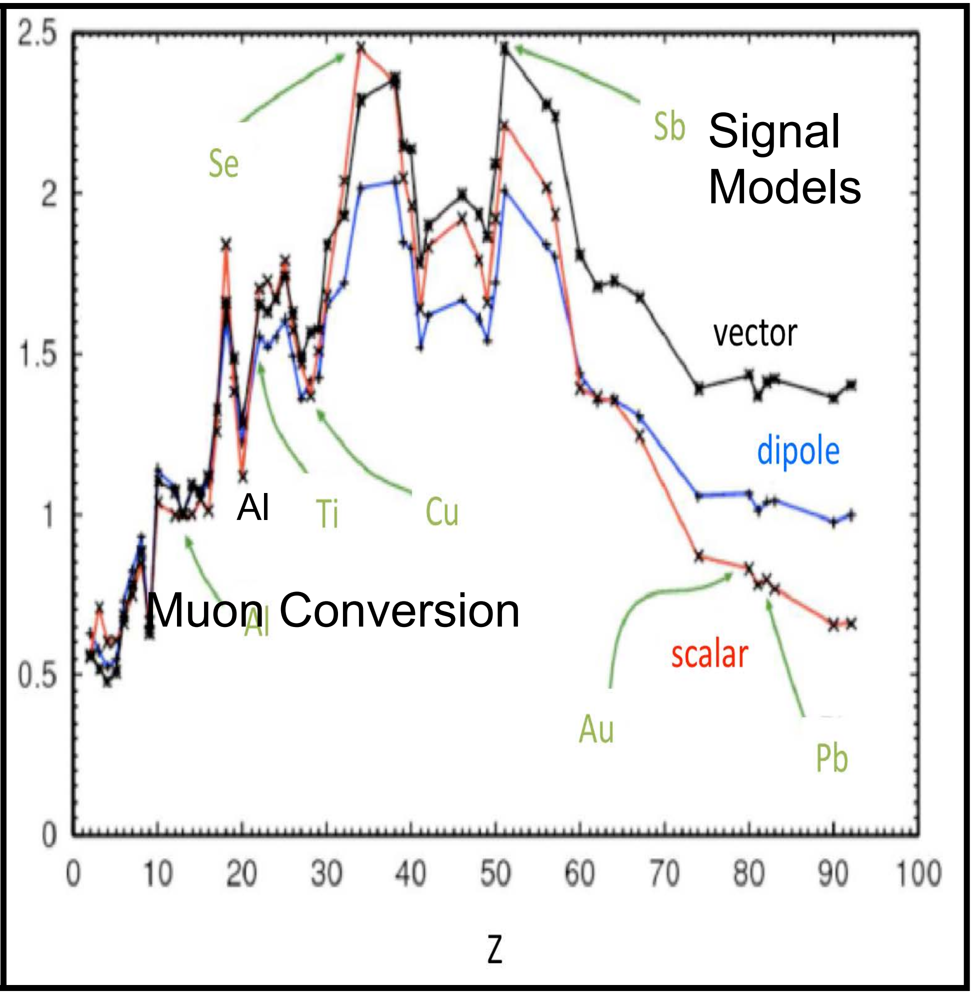
The Mu2E Experimental Apparatus



Gradient field 2T-> 1T : Uniform Solenoid 1T (Tracking Detector)

-Target Selection- Compromise of Lifetime to Signal and accelerator bunching





Muon Production at FNAL

anti-proton complex moved to μ Campus

G-2, NOVA, Mu2e Share Rec-Ring

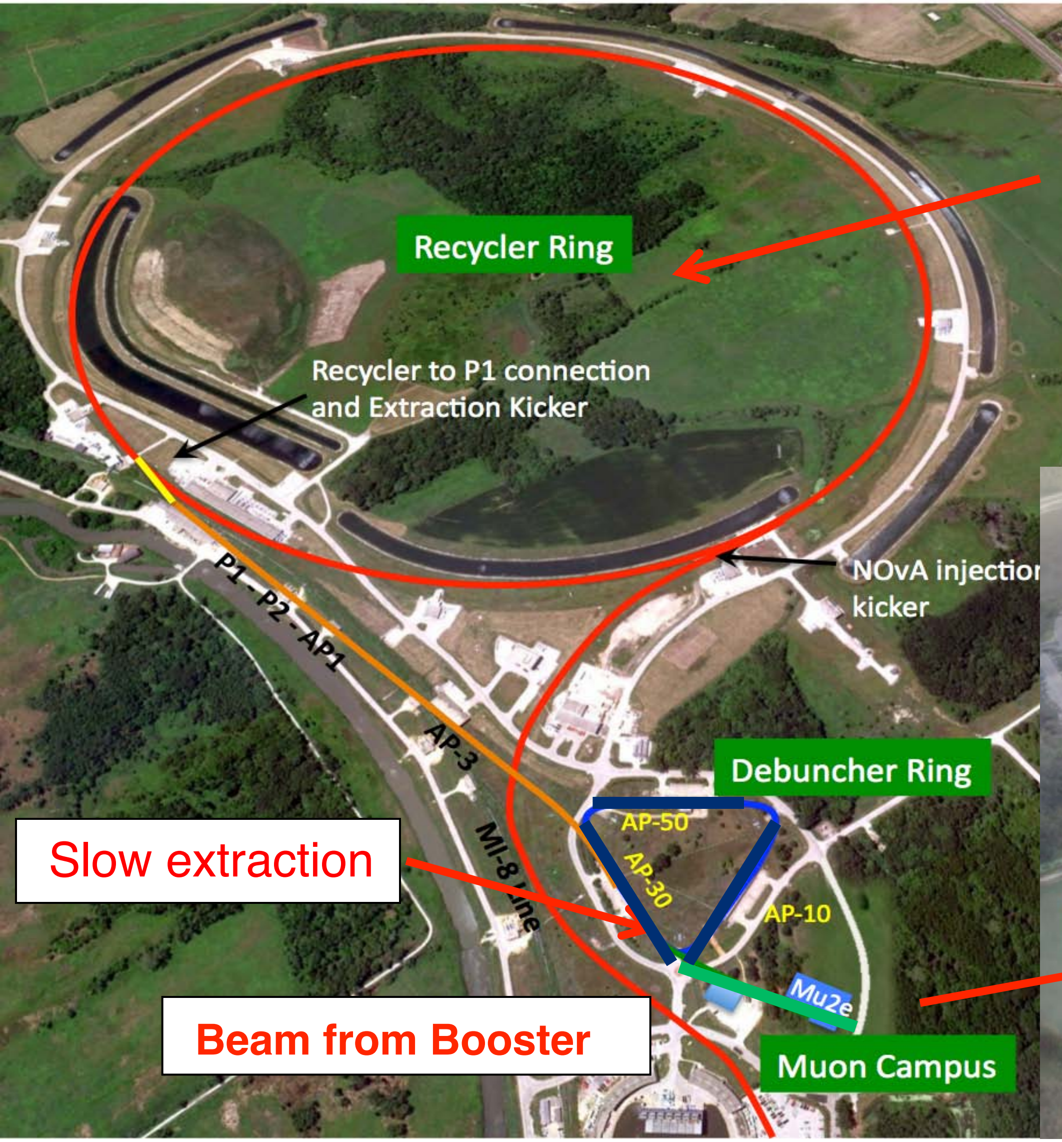
Ring Revolution (1694 ns)

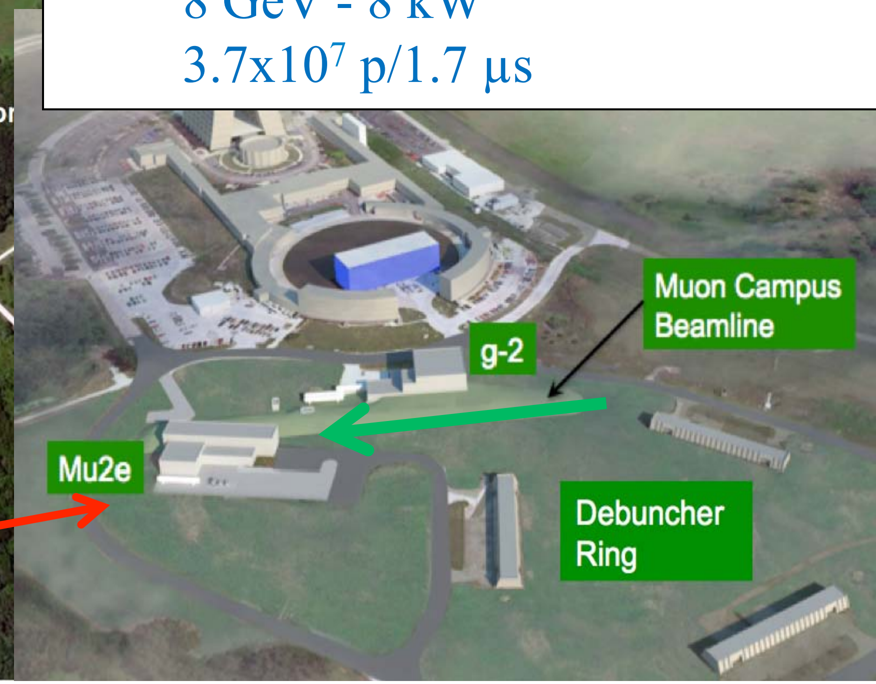
τ(muonicAl) = 864 ns

Mu2e Proton Beam

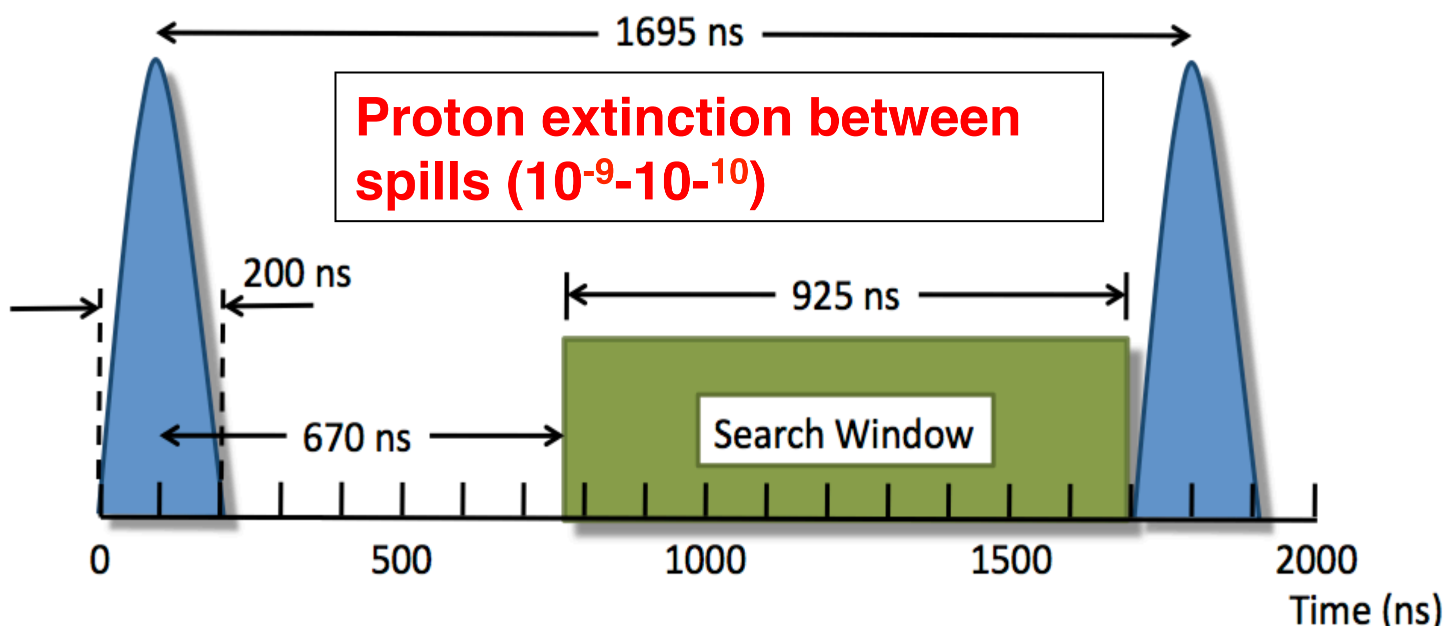
8 GeV - 8 kW

3.7×10^{7} p/1.7 μs





Micro-bunching to remove background



Spill Repetition ~2 x muon capture time in Al

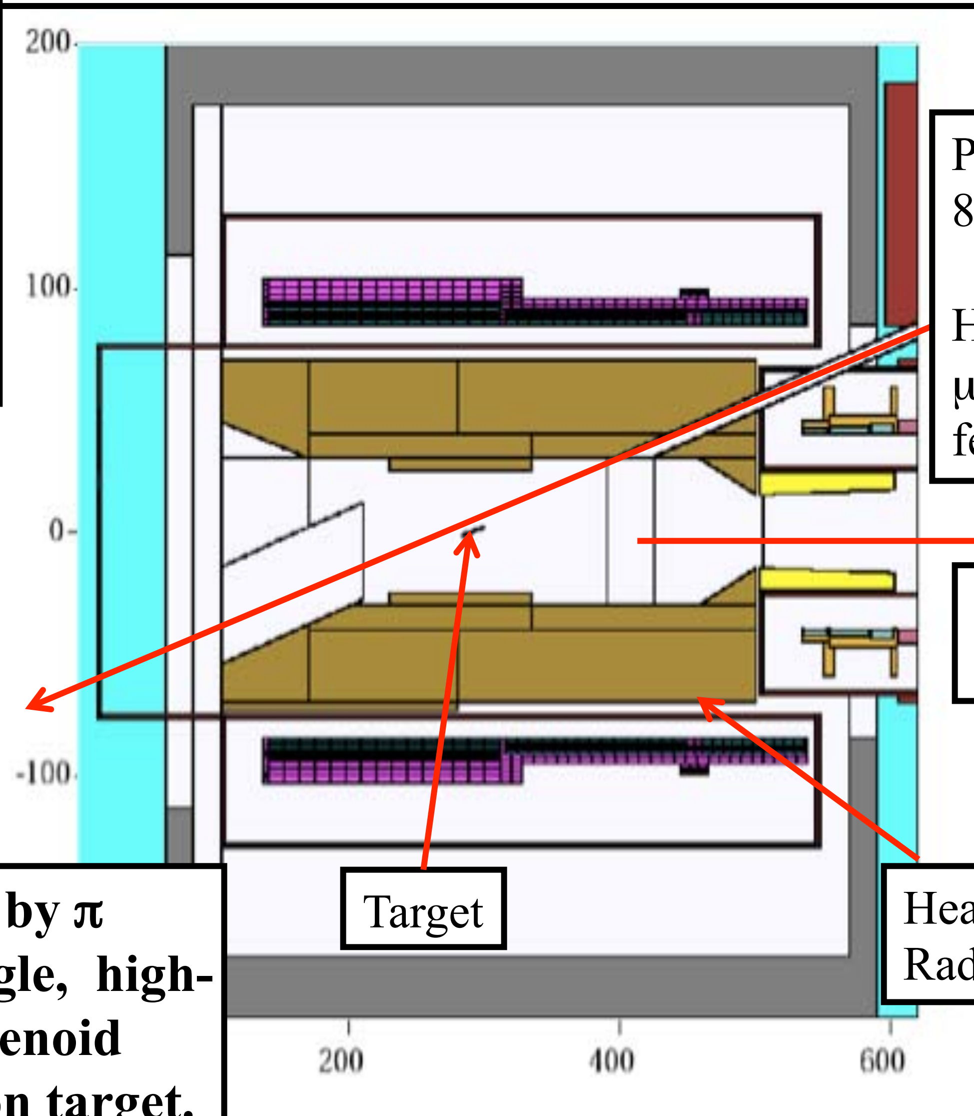
- **Beam related background reduced by beam pulsing with detector active between spills (MELC)**
- **Continuous Solenoids capture muons, transport them, and analyze decay electrons from a stopping target**

Production Solenoid

Production Target

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

W rod 16 cm 0.6 cm D



Proton Beam
8 GeV

High π yield
μ Capture
few antprotons

Beam extinction monitored by viewing target

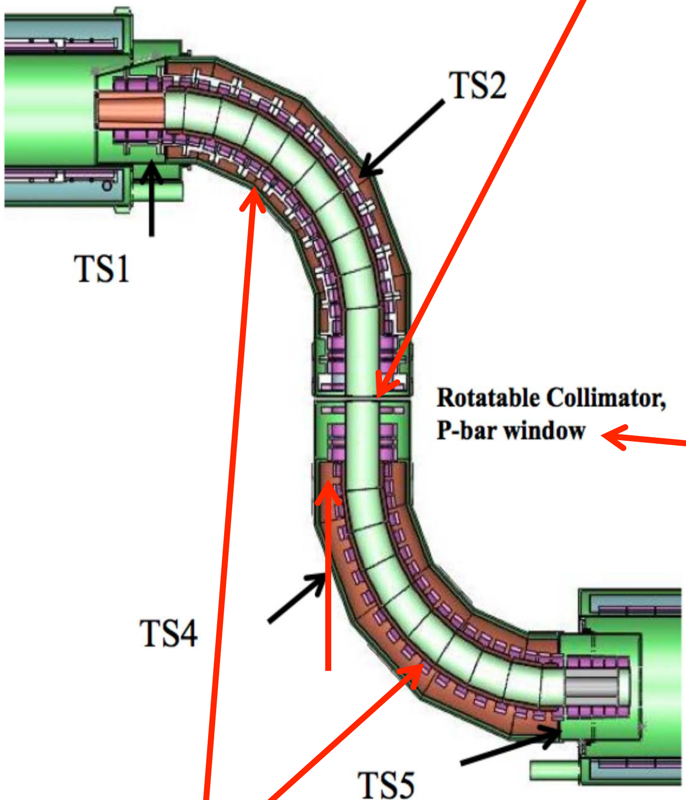
Muons
From π decay

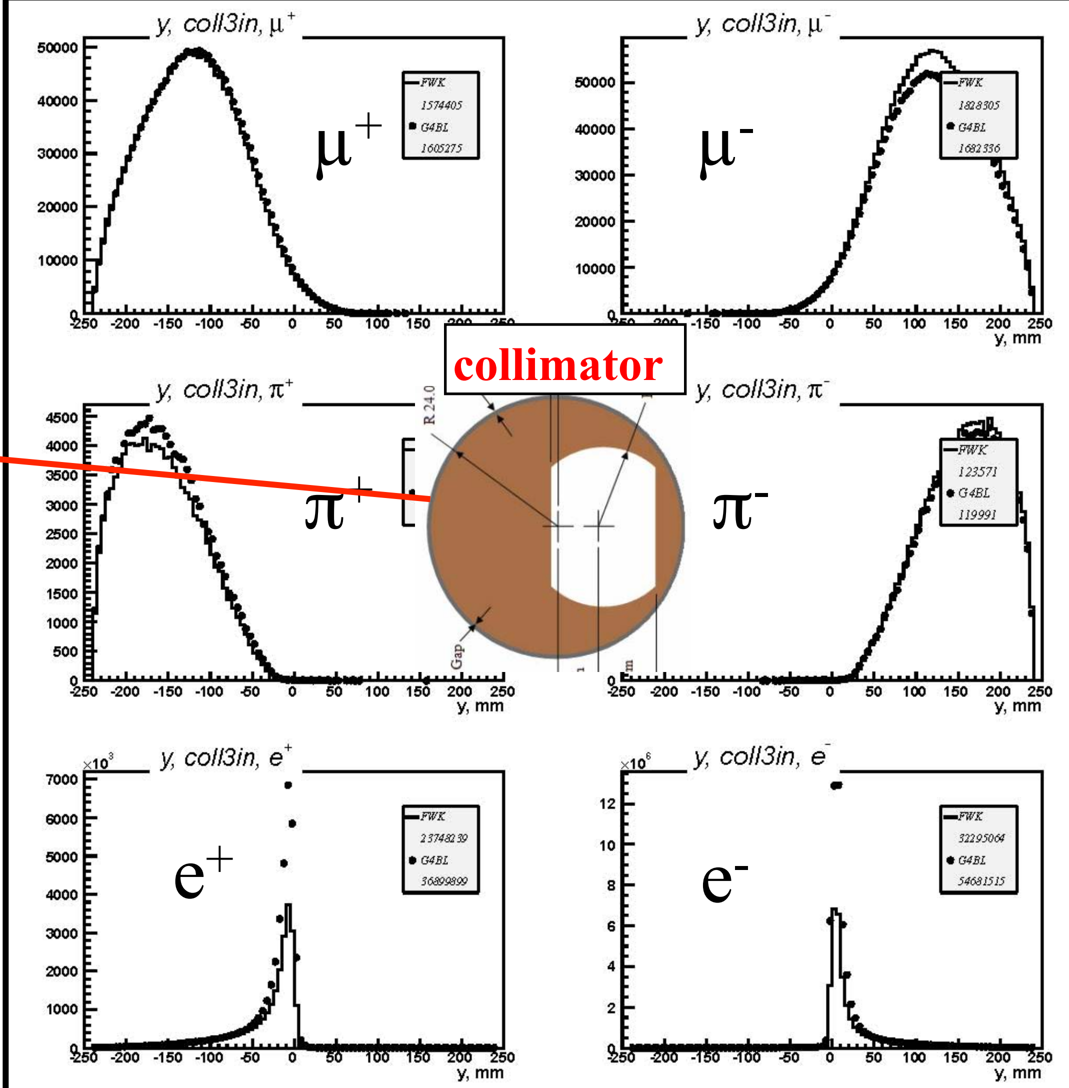
Heat and
Radiation Shield

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

Transport Solenoid

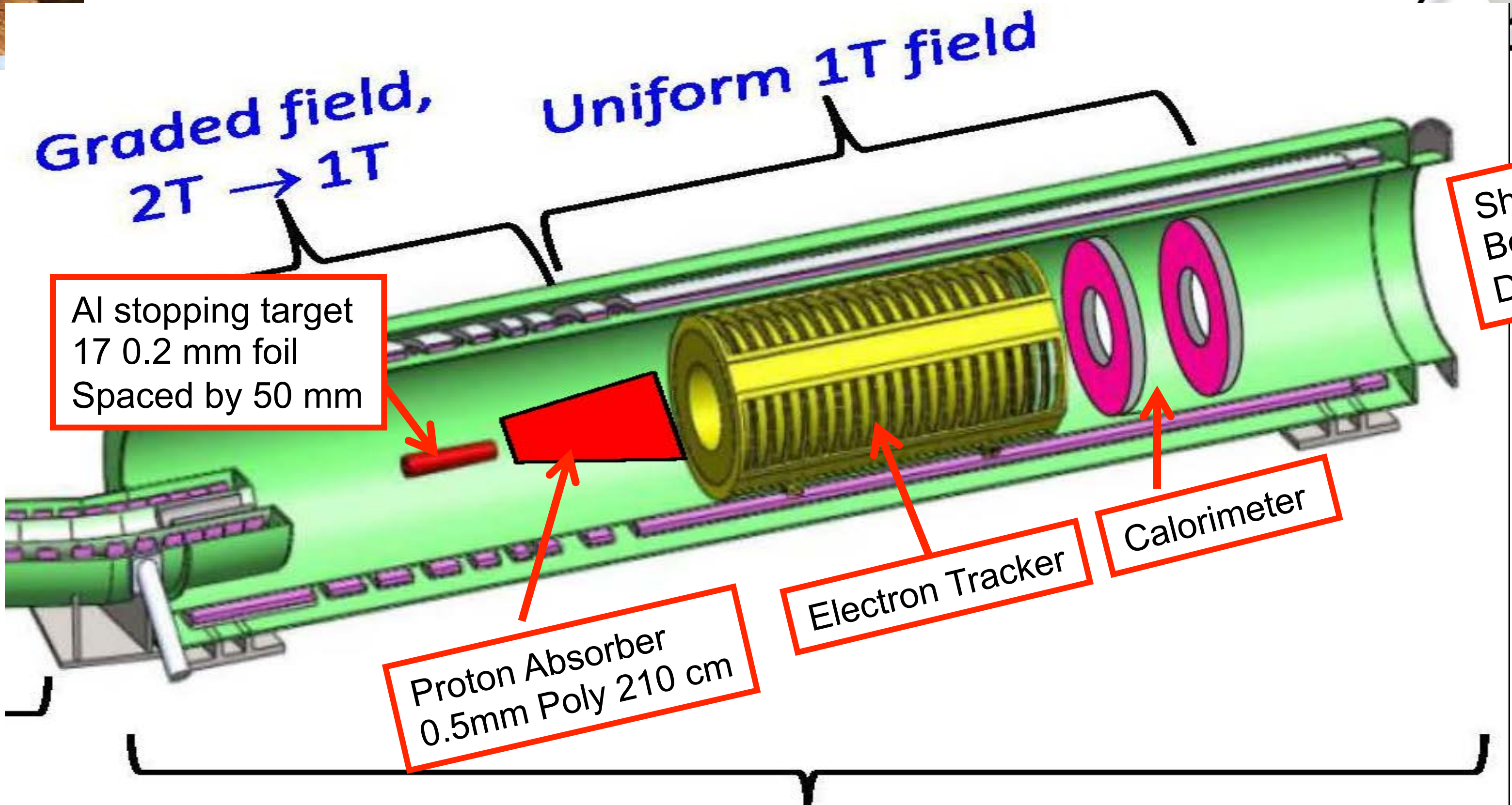
Anti-protons removed by Be foil





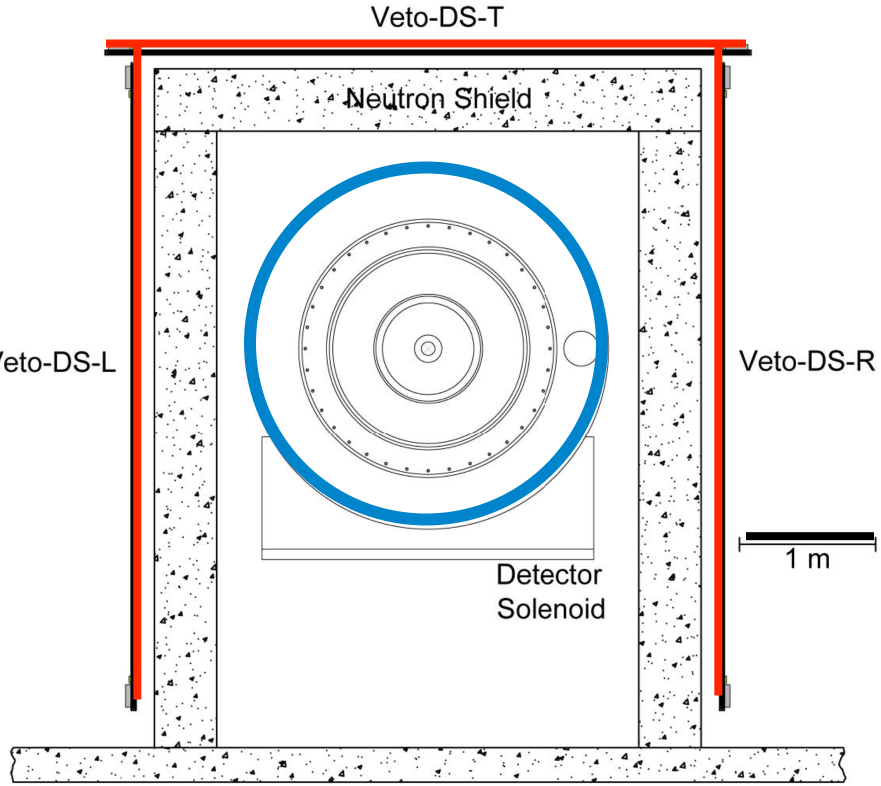
Momentum dependent drift perpendicular to the bend plane
Particle ID and Momentum Selection

Detector Solenoid

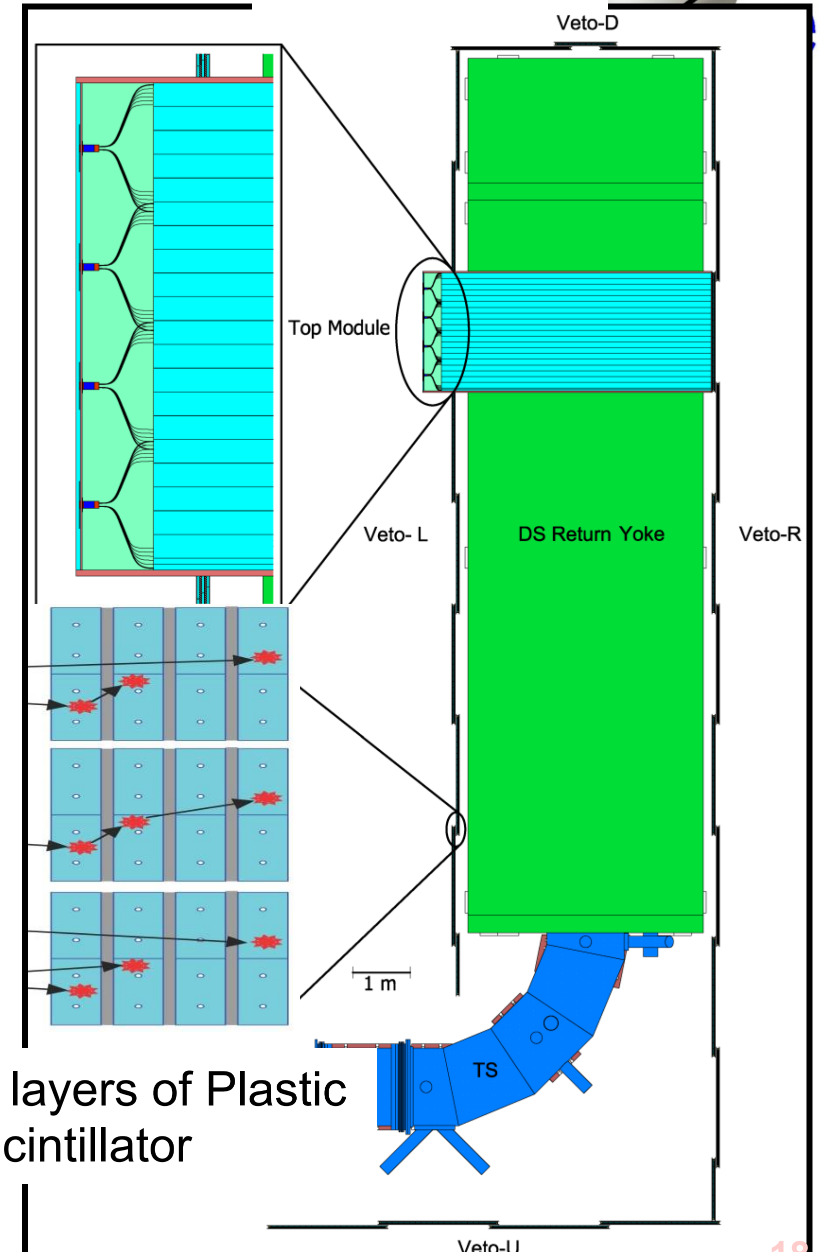


The DS is a superconducting solenoid ~12m long with ~2m bore with a uniform 1T field in the tracking region. The stopping target is a series of 17 Al foils 200 μm thick. The proton absorber removes/degrades protons from the target after μ capture. The beam dump captures the un-stopped beam. Most DIO electrons pass through the central hole in the detectors

Cosmic Veto



End View of the CRV

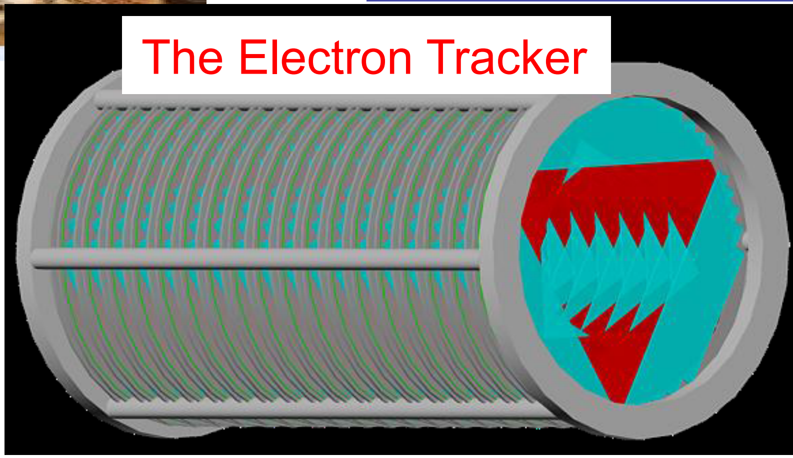


Plan View of the CRV

4 layers of Plastic Scintillator

2088 Modules read by fiber connected to SiPM detetors

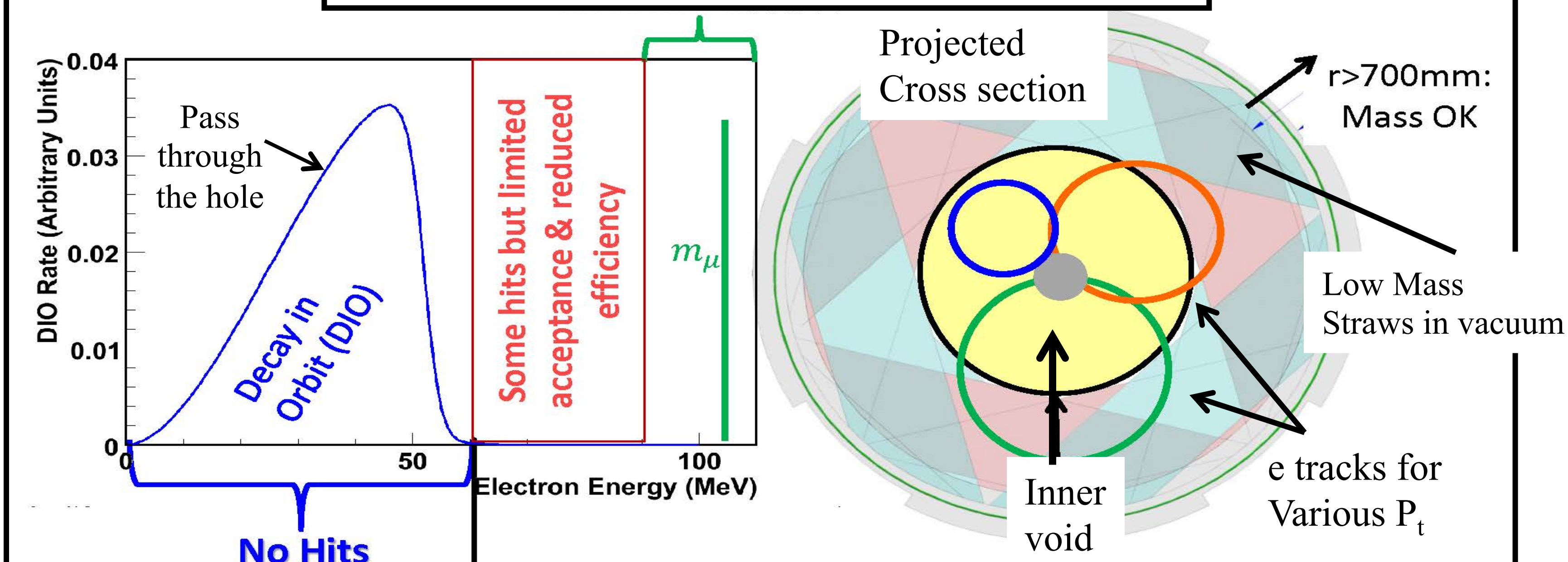
The Experimental Heart (Detector Components)



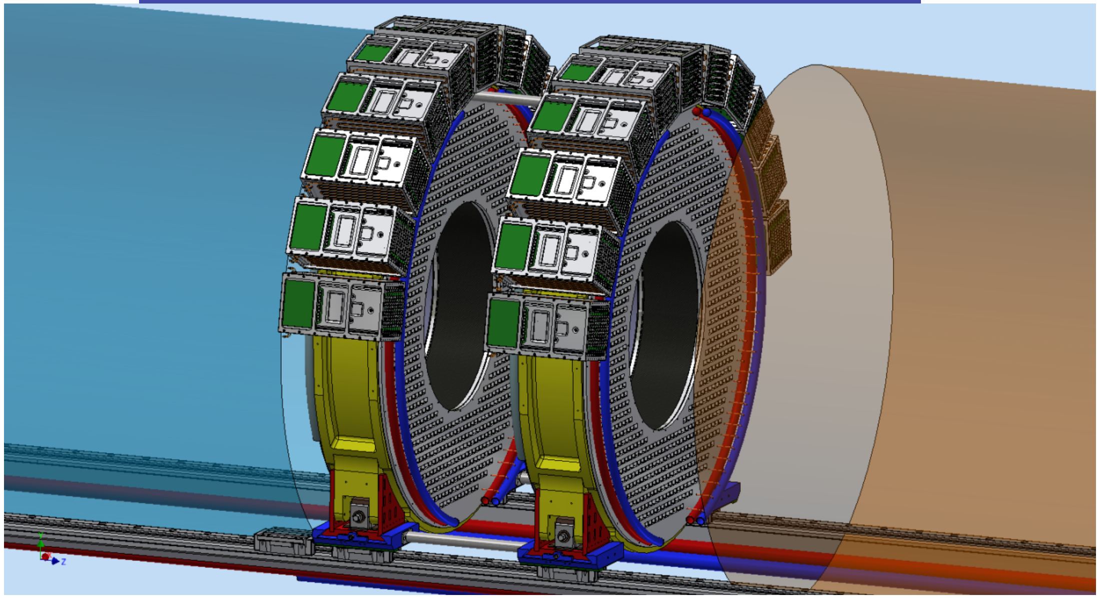
0.6-1.6m straws
0.5mm diameter
12 μm wall
0.20 μm W sense wire

Straw Gas Ar/CO_2: 80/20
100 μm position (trans.)
35 ps time resolution
~8cm position (long.)

Momentum Selection of tracking Detector

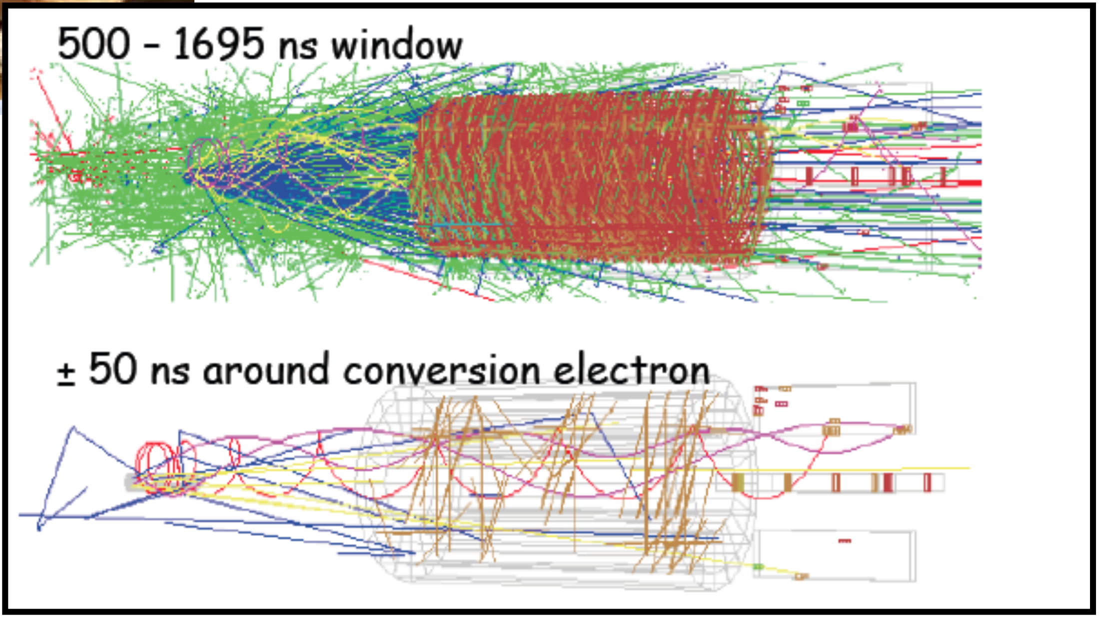


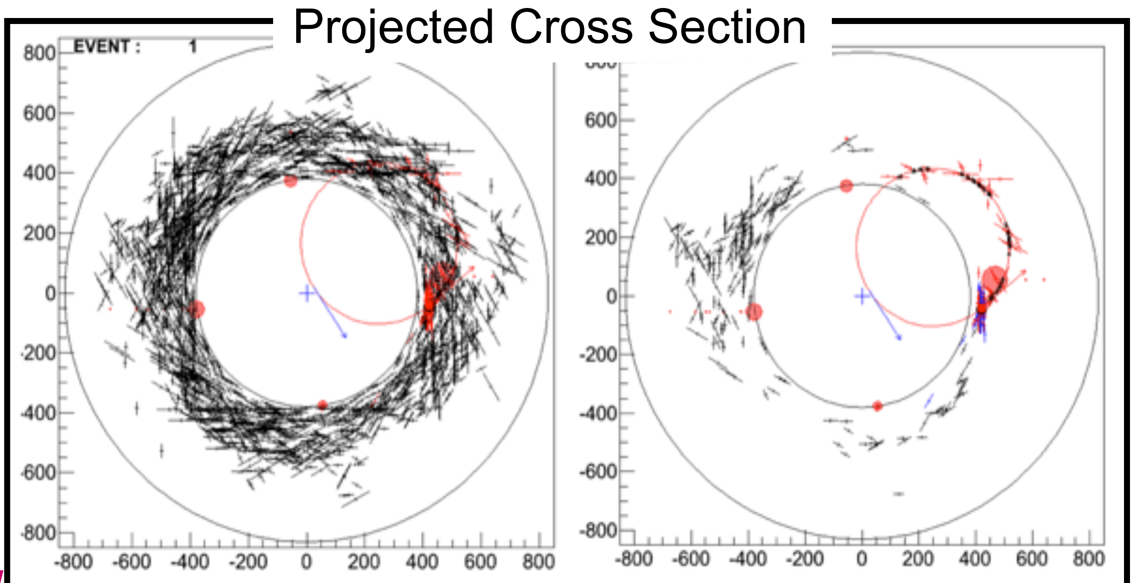
Calorimeter
678 CsI Crystals



- 2 disks; each disk contains 678 undoped CsI crystals 20 x 3.4 x 3.4 cm3
- Disk separation ~ 75 cm ½ average electron orbit
- Inner/outer radii: 37.4/66 cm
- Readout system:
  a)2 custom arrays of 6x6 mm^2 SiPMs/crystal,
  b) 12 bit, 200 Msps waveform digitizer boards

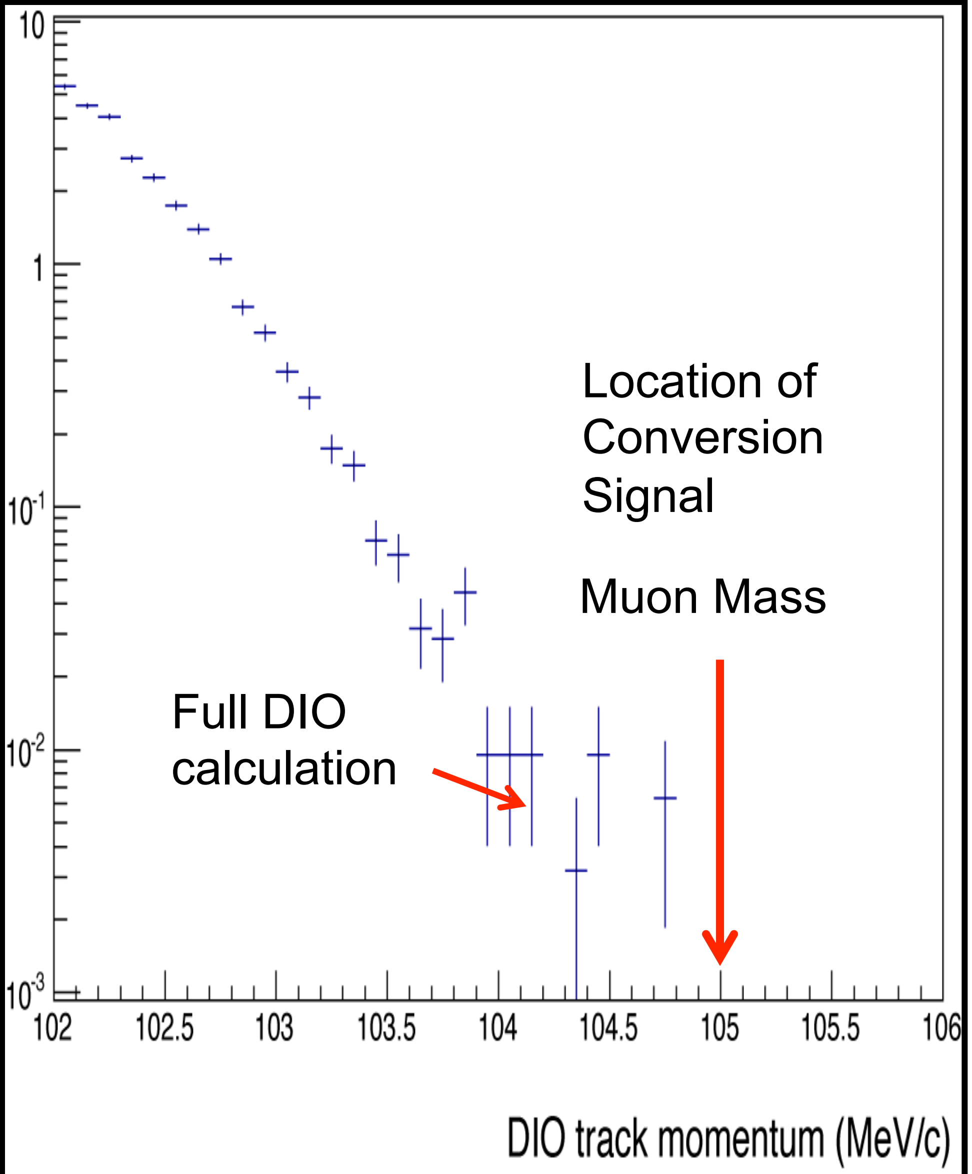
Calorimeter Simulations

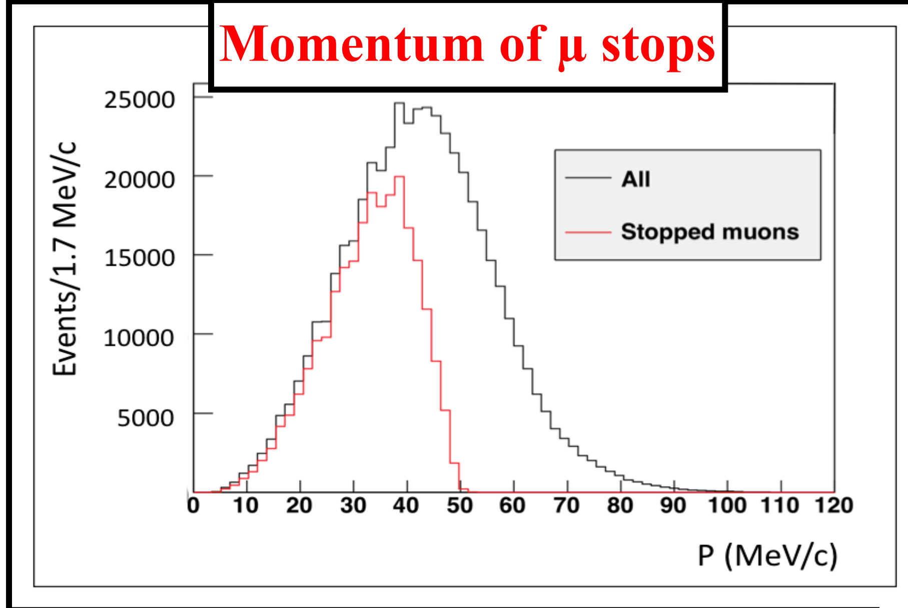




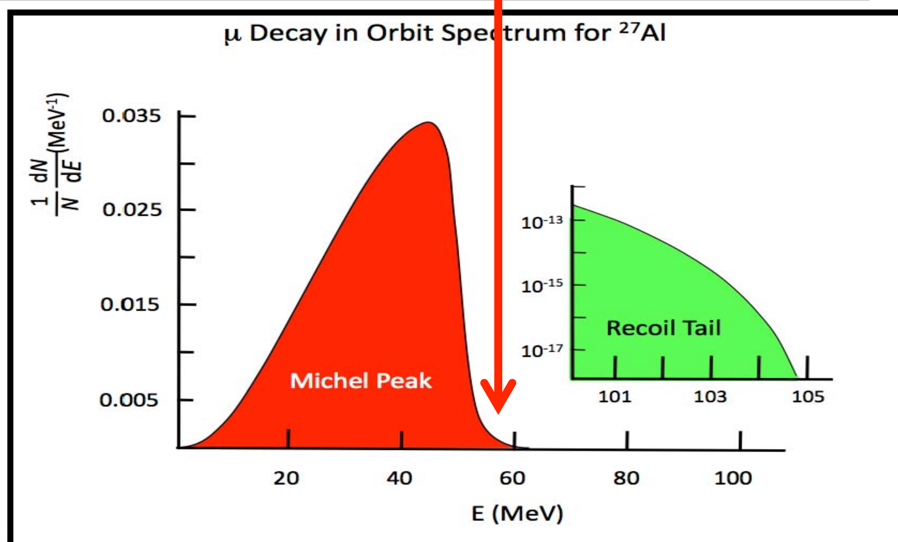
- Cleaning of tracking hits using a time window of +/- 50 ns between tracking hits and Cluster Time
- Improves S/N from ¼ to 1/1 in signal window
- Improves S/N more than a factor 20 over all hit times
- Improve/simplify Pattern Recognition.

Capture and DIO





High spectrum tail falls sharply above the Michel edge. End point slope changes rapidly – usually parameterized as δ^5 but shape is complicated

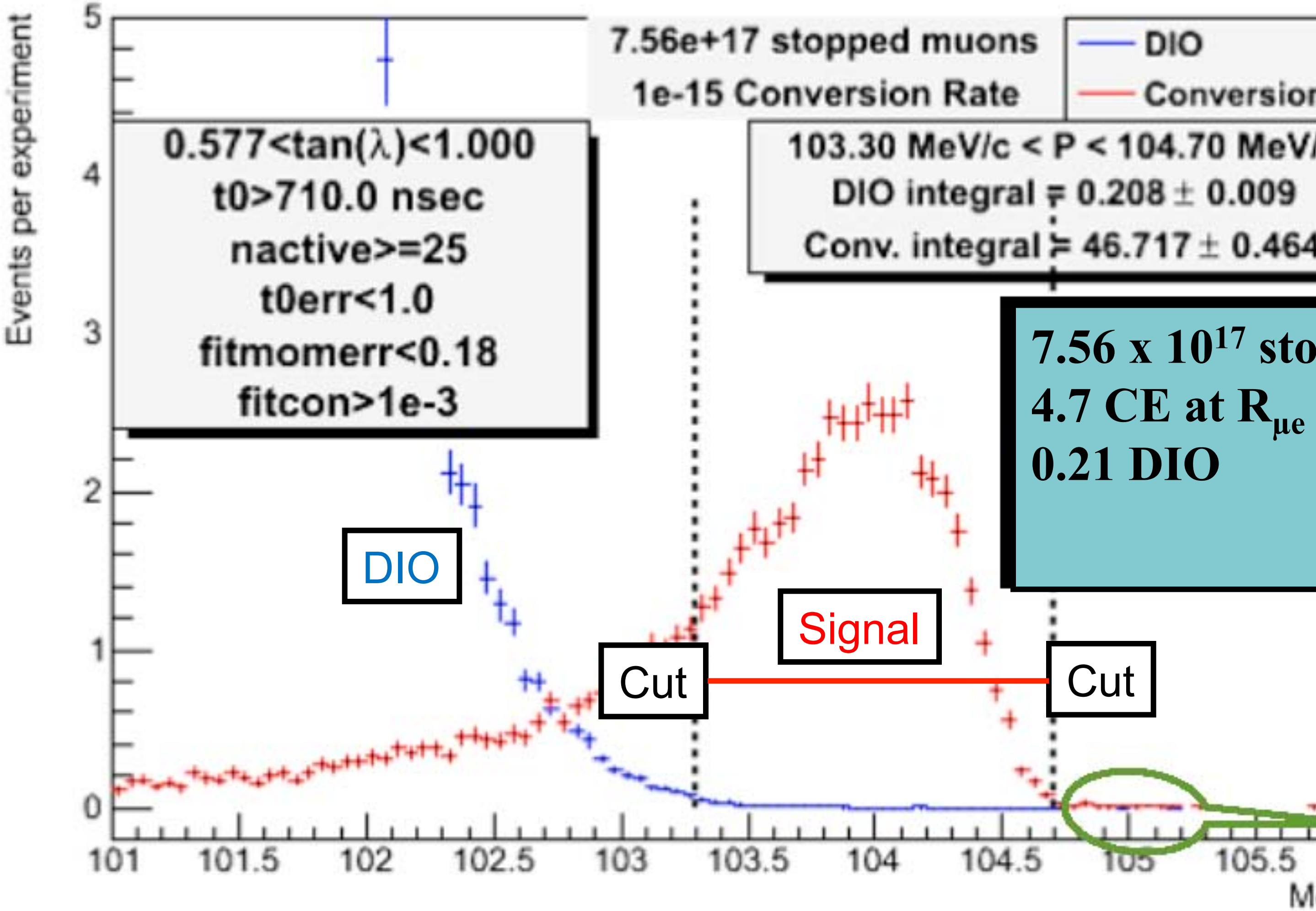


Backgrounds – 3.6×10^{20} protons
(It's what you don't simulate that bites)

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 modeling
Muon decay In-Flight	0.01	± 0.003	Cross-section, acceptance modeling
Antiproton Induced	0.10	± 0.05	Cross-section, acceptance modeling
Beam electrons	0.0006	± 0.0003	Cross-section , acceptance (upper limit)
Radiative muon capture	$< 2 \times 10^{-6}$	–	Calculation
Total	0.41	± 0.08	Add in quadrature

Example of Endpoint Spectrum showing DIO background and Mu2e signal

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



7.56×10^{17} stopped μ^-

4.7 CE at $R_{\mu e} = 10^{-16}$

0.21 DIO

Reduced Resolution Tails

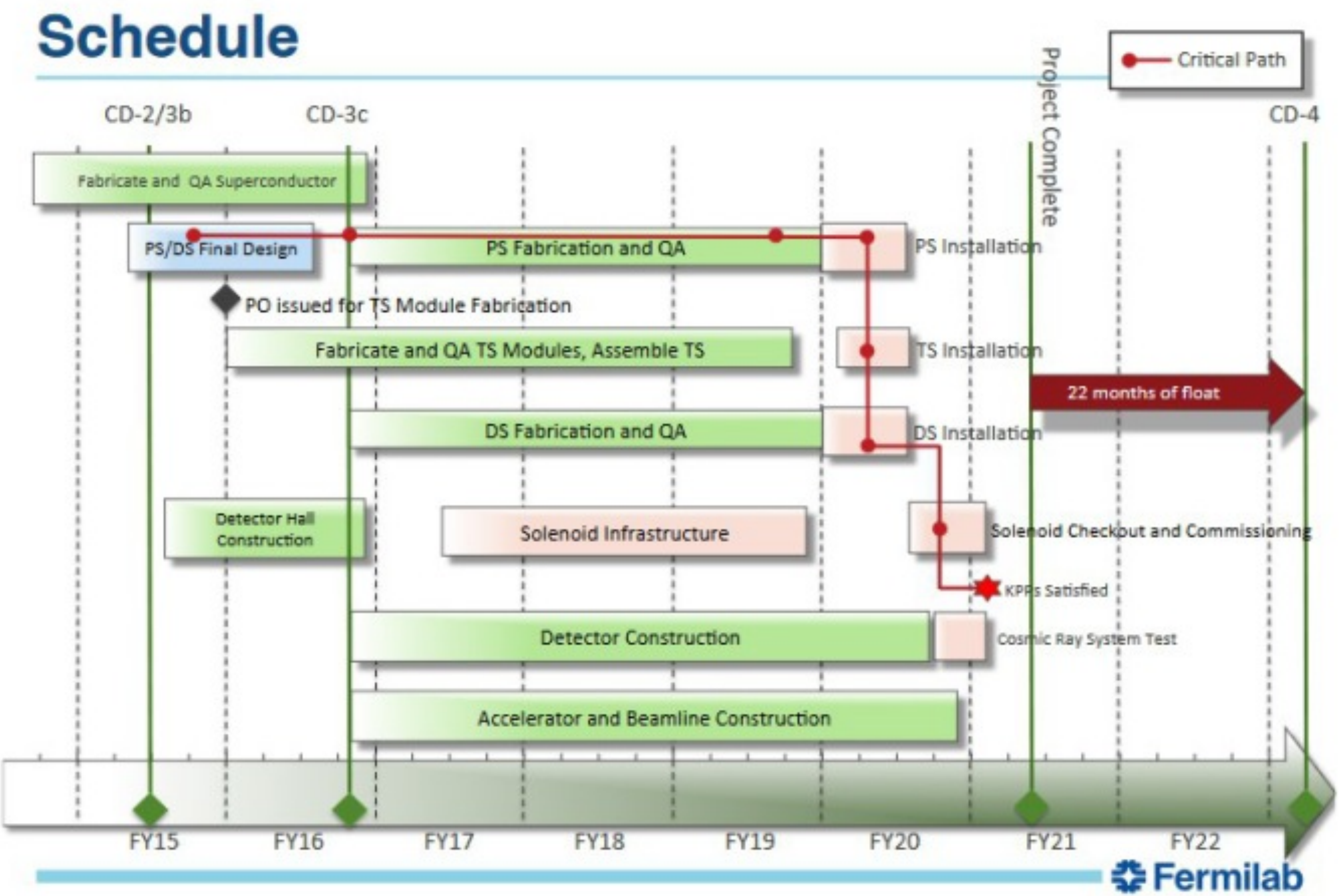
Predicted Sensitivity

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	6.0×10^{-17}

For a 3 year run

$$B(\mu^- + Al \to e^- + Al) = \frac{1}{1.2\text{x}10^{17}\text{x}0.5\text{x}3} = 6.0 \text{ x } 10^{-17}$$

Schedule


Schedule
Critical Path
CD-2/3b
CD-3c
CD-4
Project Complete
Fabricate and QA Superconductor
PS/DS Final Design
PS Fabrication and QA
PS Installation
PO issued for TS Module Fabrication
Fabricate and QA TS Modules, Assemble TS
TS Installation
22 months of float
DS Fabrication and QA
DS Installation
Detector Hall Construction
Solenoid Infrastructure
Solenoid Checkout and Commissioning
KPPs Satisfied
Detector Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
Fermilab

Summary

- Muons are long-standing tools for precision test in particle physics.
- Expect new physics beyond the SM to appear at TeV scale.
- Conservation of cLFV is a puzzle, and flavor is not necessarily conserved
- cLFV studies may reveal hidden flavor symmetries and BSW in TeV-scale physics.
- Even if new particles are seen, cLFV can help define the physics
- Results have cosmological implications

“I Dwell in Possibility”

“I Dwell in Possibility” is a title of a poem by Emily Dickinson.

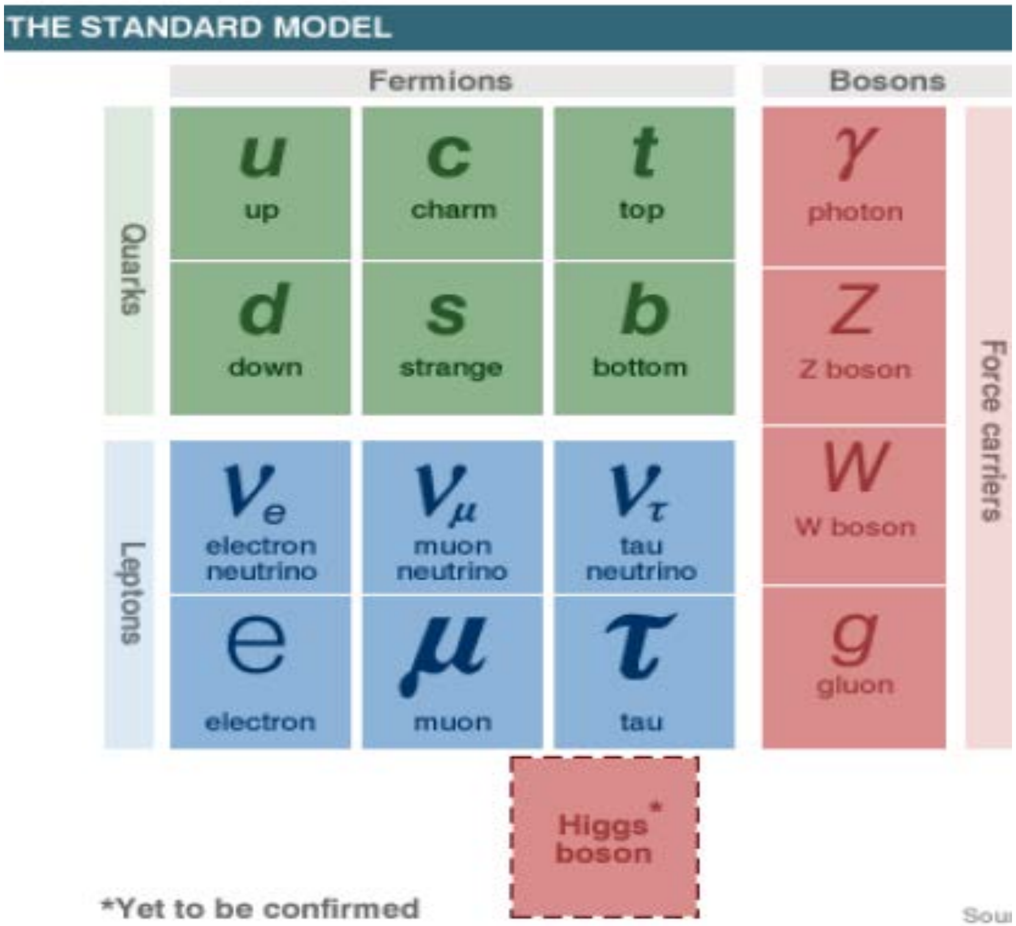
While the poem was not written to address Subatomic Physics it is a fantastic title and expresses how I feel about the present status of Particle Physics.

“I dwell in possibilities”

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.

Backup Slides

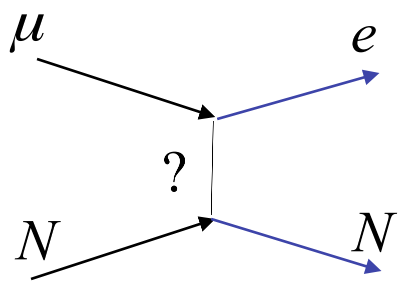
The Standard Model of Particle Physics



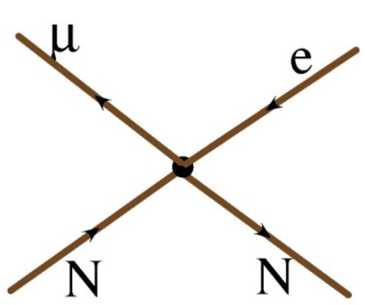
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

Beyond Standard Model Physics

Flavor Changing Neutral Current

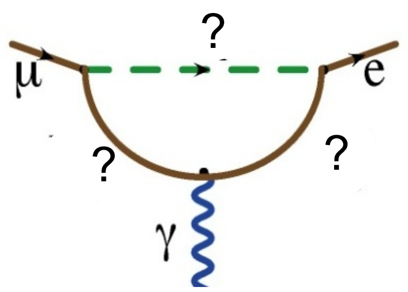


- Mediated by massive neutral Boson, e.g.
  - Leptoquark
  - Z'
  - Composite
- Approximated by "four fermi interaction"

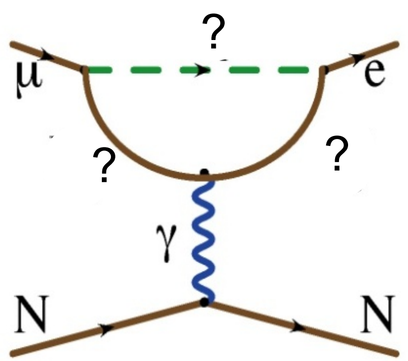


Dipole (penguin)

- Can involve a real photon

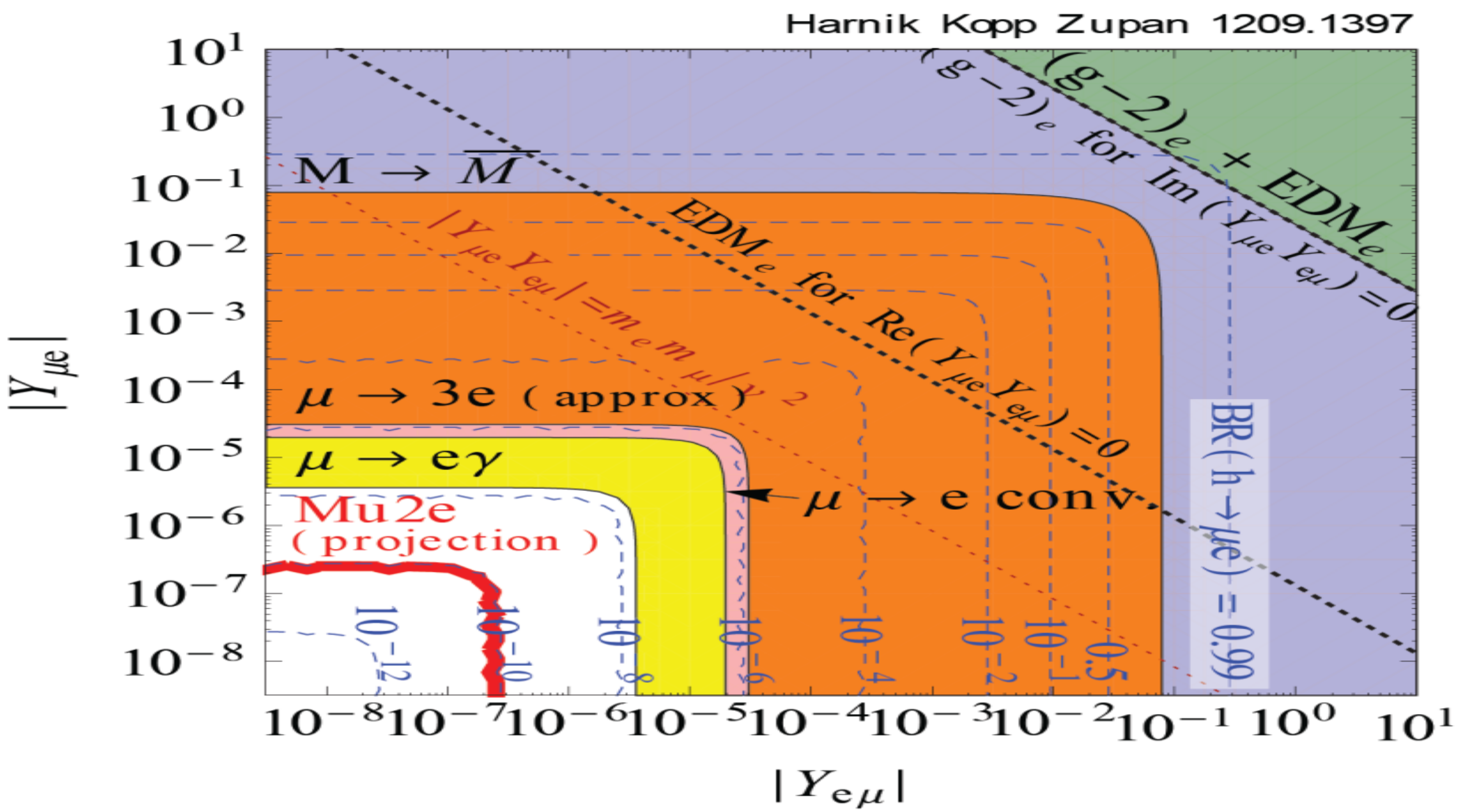


- Or a virtual photon



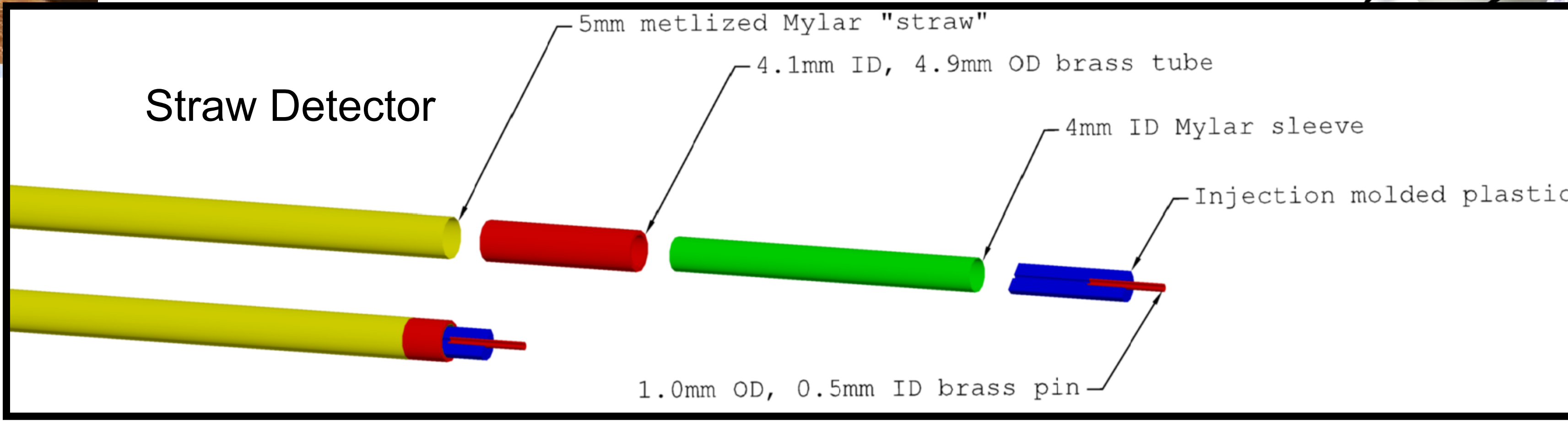
Many Other Ways to Justify a cLFV Search
(Connecting the very large to the very small)

One of the more recent advances in physics has been the connection of microscopic particle theory to macroscopic cosmology . ***e.g.*** **Baryogenesis, and exploring the Higgs field PRL109(12)051302**



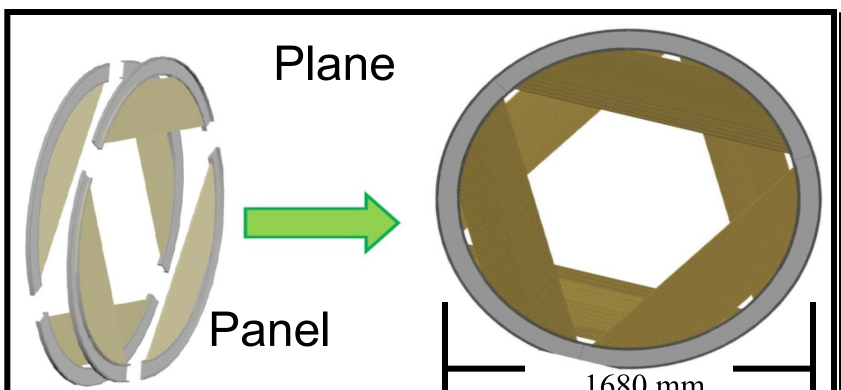
Constraints on the flavor-violating Yukawa couplings $|Y_{e\mu}|$, $|Y_{\mu e}|$ for a 125 GeV Higgs boson [JHEP 3(13)26]. The diagonal Yukawa couplings are approximated by their SM values. Thin blue dashed lines are contours of constant BR for $h \to \mu e$, whereas thick blue lines are the current LHC limits.

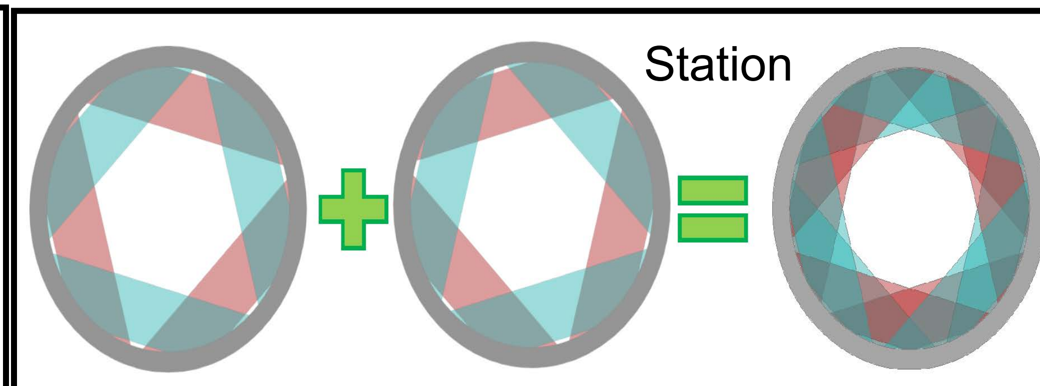
Tracker Components



5mm OD, 15μm thick metalized Mylar tube as cathode
a)Metalized on inner & outer surface
b)400Å Aluminum outer surface
c) 400Å Aluminum + 200Å Gold inner surface
d) 25μm gold-plated tungsten wire as anode

48 straws/layer
2 layers/panel
6 panels/plane
2 planes/station
18-20 stations/detector
21,000-23,000 straws





SEU and Radiation Damage

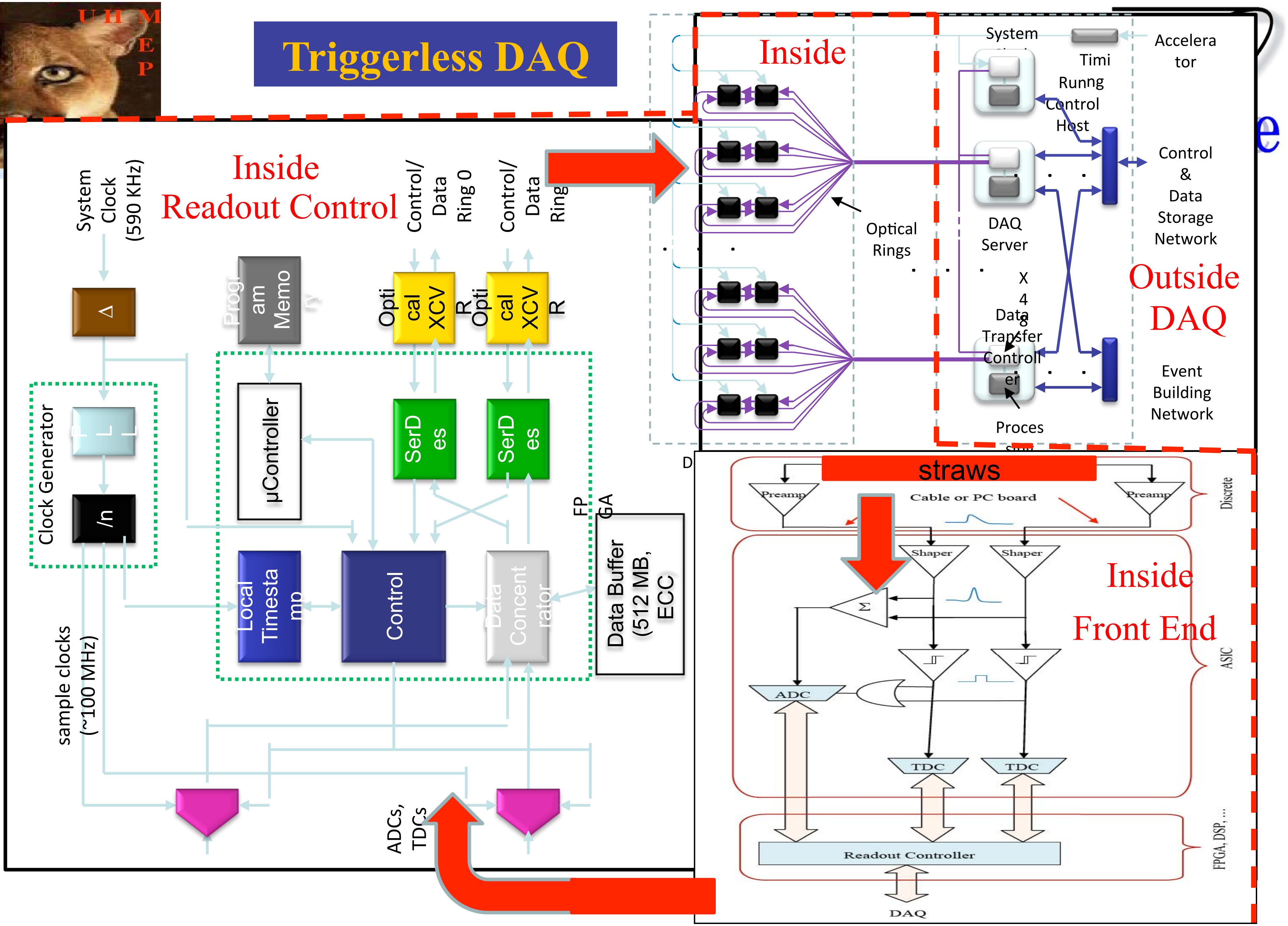
1 FIT = 1 failure in 10^9 hrs → 2.4 x 10^{-8} failure/day

Neutron Background at the standard NYC latitude 40.7^0 N (Sea-Level)→
14 n/hr/cm^2 → 3.9 x10^{-3} n/s/cm^2

Component	Neutron Flux (stopping Target)	Effect (Requires Solid Angle)
ROC FPGA	~2.3 x 10^{10} n/s ~5 x 10^{17} n/yr	0.01 SEU/Day 3.6 - SEU/Day for 300 FPGA
SiPM (CRV)		<1x10^9 n/cm^2
Calorimeter (Crystals)		<3 x 10^9 n/cm^2

Memory and other electronics not included in above. DRAM memory is used and Firmware programming can mitigate SEU problems.

Triggerless DAQ



Data Rates

Triggerless DAQ

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

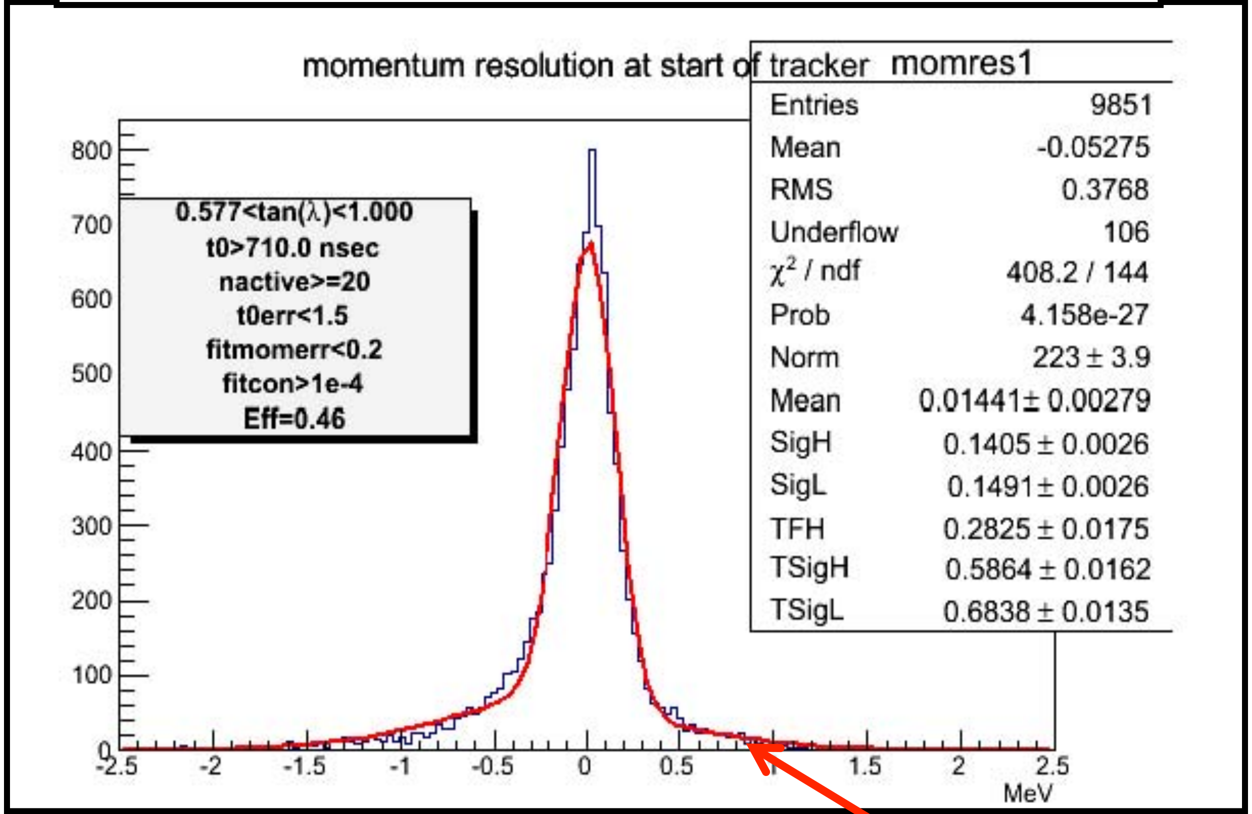
Tracker	22 GBytes/sec
(Rates are high - 300 Mbyte/s x 218 controllers Pattern recognition is compliated)	
Calorimeter	5 GBytes/sec
CRV	3 GBytes/sec
Extinction Mon, etc	1 GByte/sec

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

Energy Resolution

Reconstructed event simulation

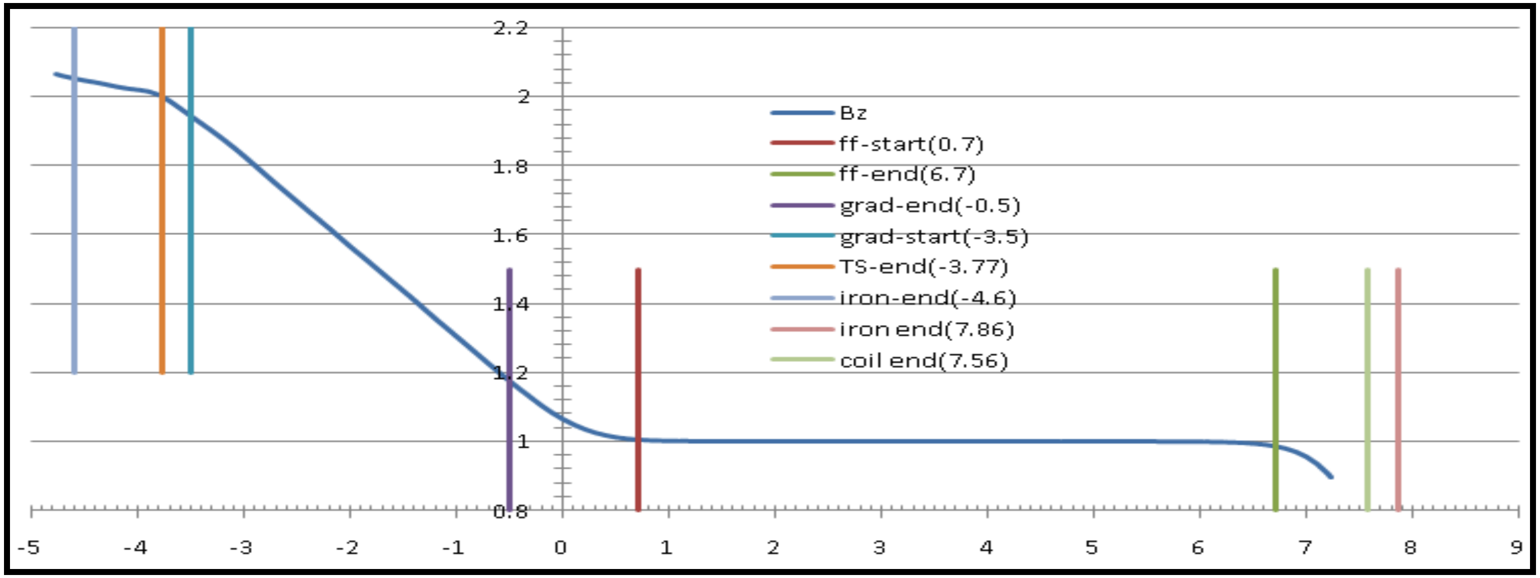
RMS = 0.38 MeV
Tracking; Full events; Kalman Filter reconstruction; Full Variance



High energy tail is most important

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 – Background !!!

Trap Simulations show this is a potentially serious issue (particularly at solenoid boundaries) and care has been taken to remove traps using a field gradient