The Mu2e Experiment

FNAL Users' meeting 2012

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Boston University
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http://mu2e.fnal.gov/

Summary of Talk

- *Charged Lepton Flavor Violation (CLFV)*
- *Observing CLFV.*
- *The physics of muon to electron conversion*
- *The Mu2e experiment*
- *Backgrounds that can limit sensitivity*
- *Current status*

Charged Lepton Flavor violation

$$\mu^- \rightarrow e^- \gamma$$

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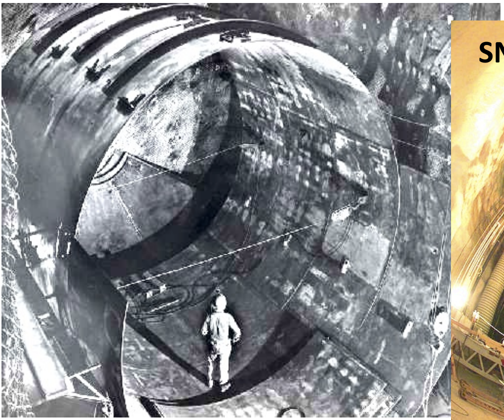
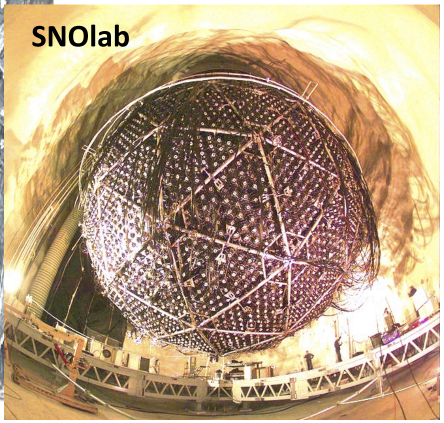


http://jacksonville.com/entertainment/2012-03-20/story/sky-guy-scientists-hold-fast-speed-limit-light#ixzz1v8bLlsN1



http://www.snolab.ca/content/sno-detector

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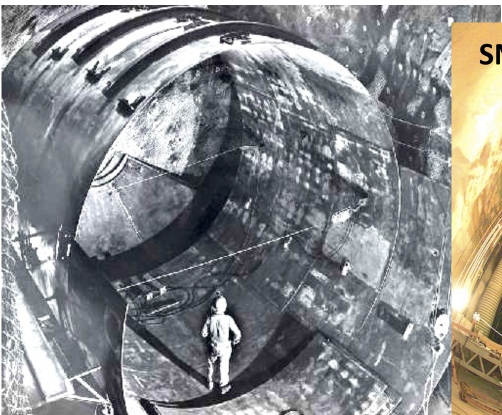

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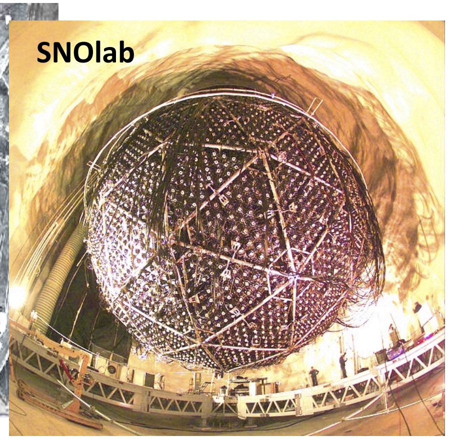

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- The rate depends on the neutrino mass splitting and couplings

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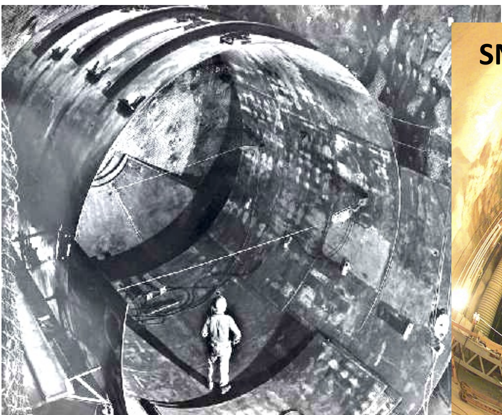

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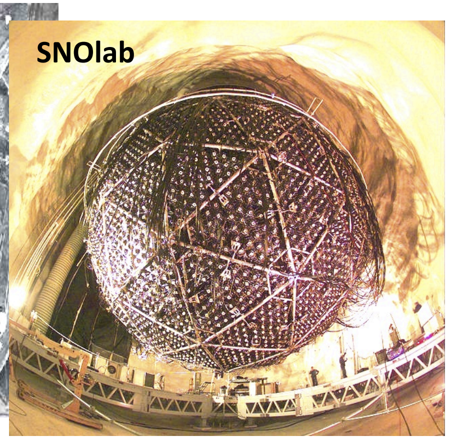

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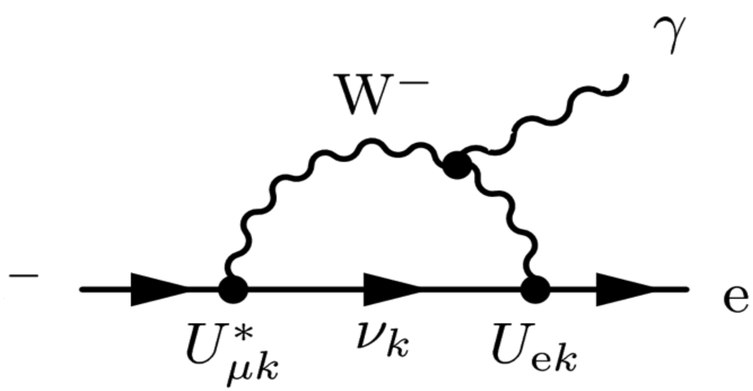

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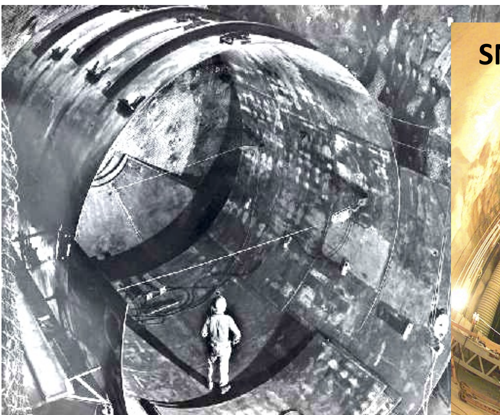

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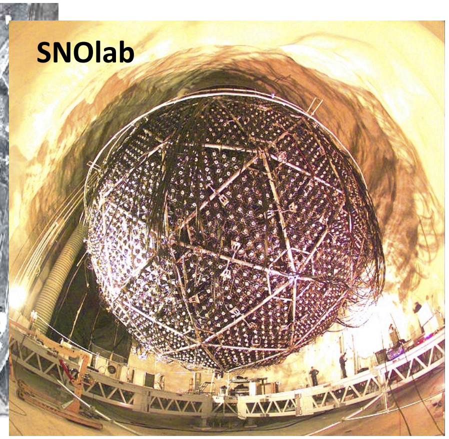

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$$Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 \sim 10^{-54}$$

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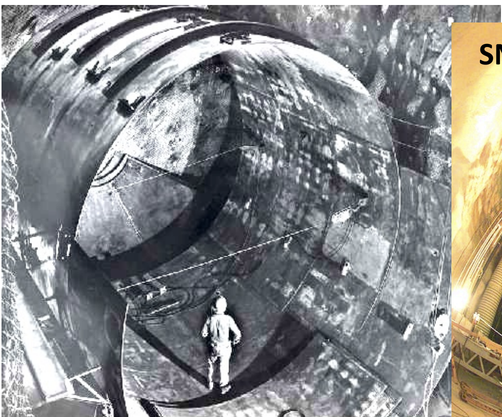

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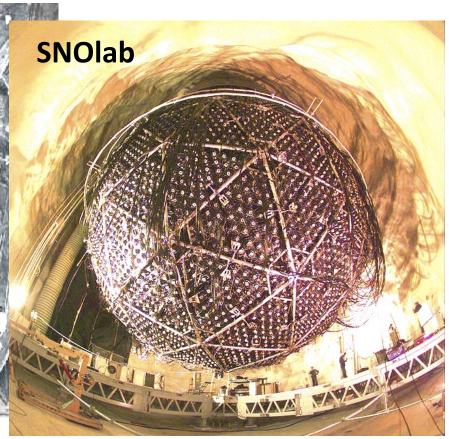

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No Standard model background.

$$Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 \sim 10^{-54}$$

So, if observed it would be unambiguous sign of New Physics

Searching for CLFV

3 rare muon processes stand out

$$\mu^{\pm} \rightarrow e^{\pm}\gamma$$

MEGA, MEG, and others…

$$\mu^{\pm} \rightarrow e^{\pm}e^{+}e^{-}$$

Br($\mu^+ \rightarrow e\gamma$) < 2.4×10^{-12} [MEG 2011]
Br($\mu^+ \rightarrow e^+e^-e^+$) < 1×10^{-12} [SINDRUM-I,1988]

$$\mu^{-}N \rightarrow e^{-}N$$

Mu2e, comet, SINDRUM

$R_{\mu e}$ <7×10^{-13} [SINDRUM-II, 2006]

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- *Accidental coincidences limit usable μ rate*

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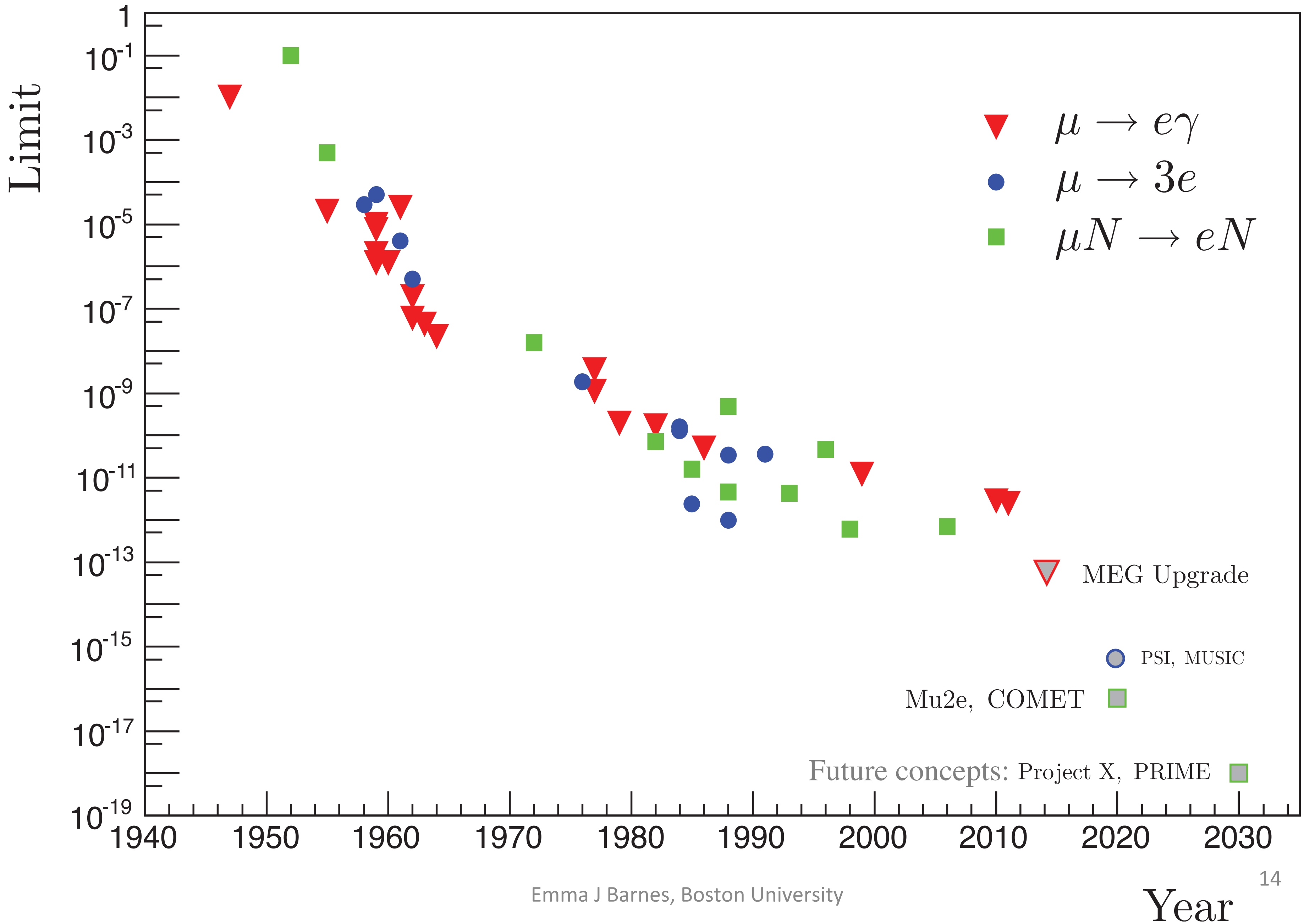
- Signal is a monoenergetic electron.
- Can take more muons/s.

Mu2e, comet, SINDRUM

$R_{\mu e}$ <7×10^{-13} [SINDRUM-II, 2006]

History of CLFV searches



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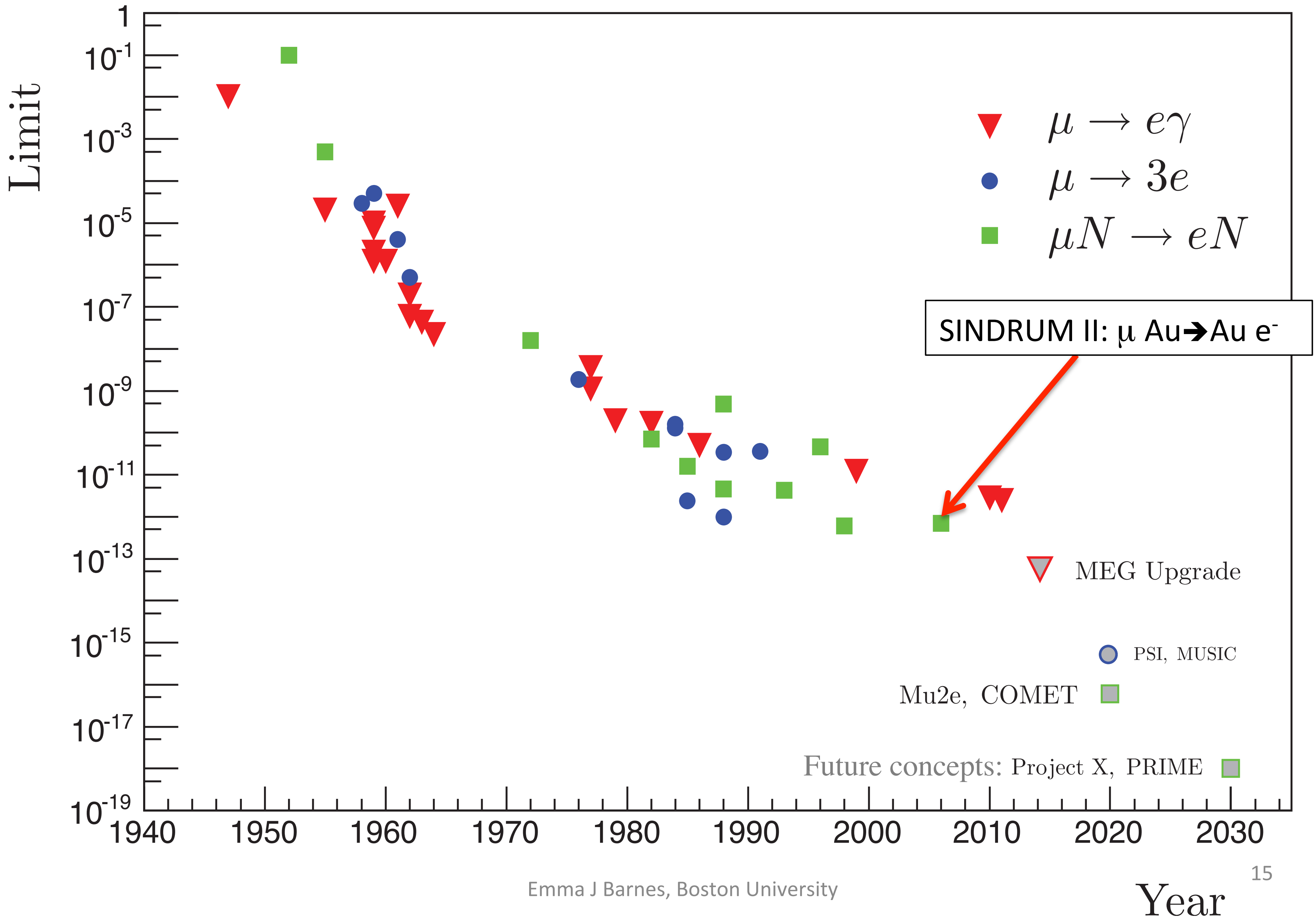

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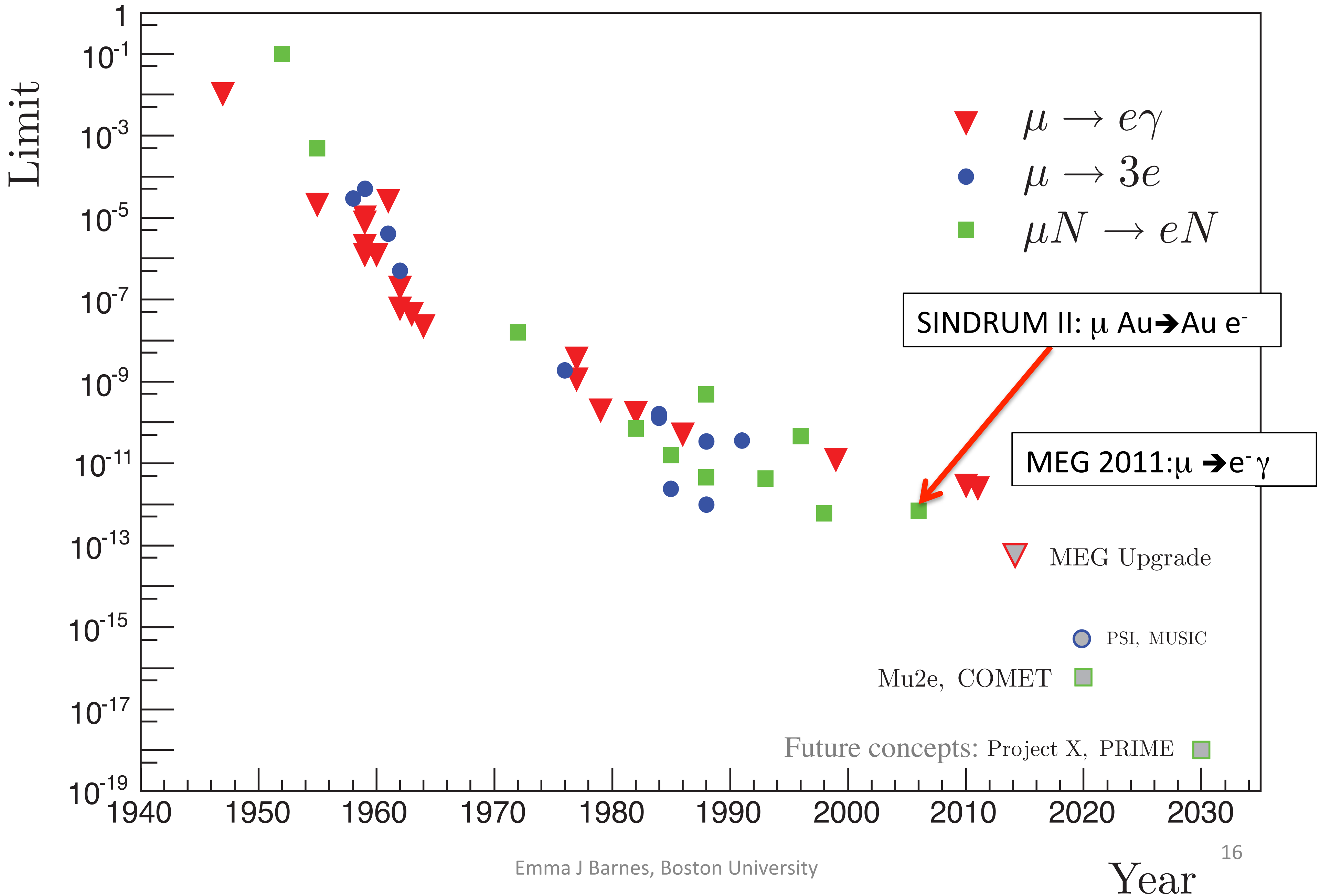

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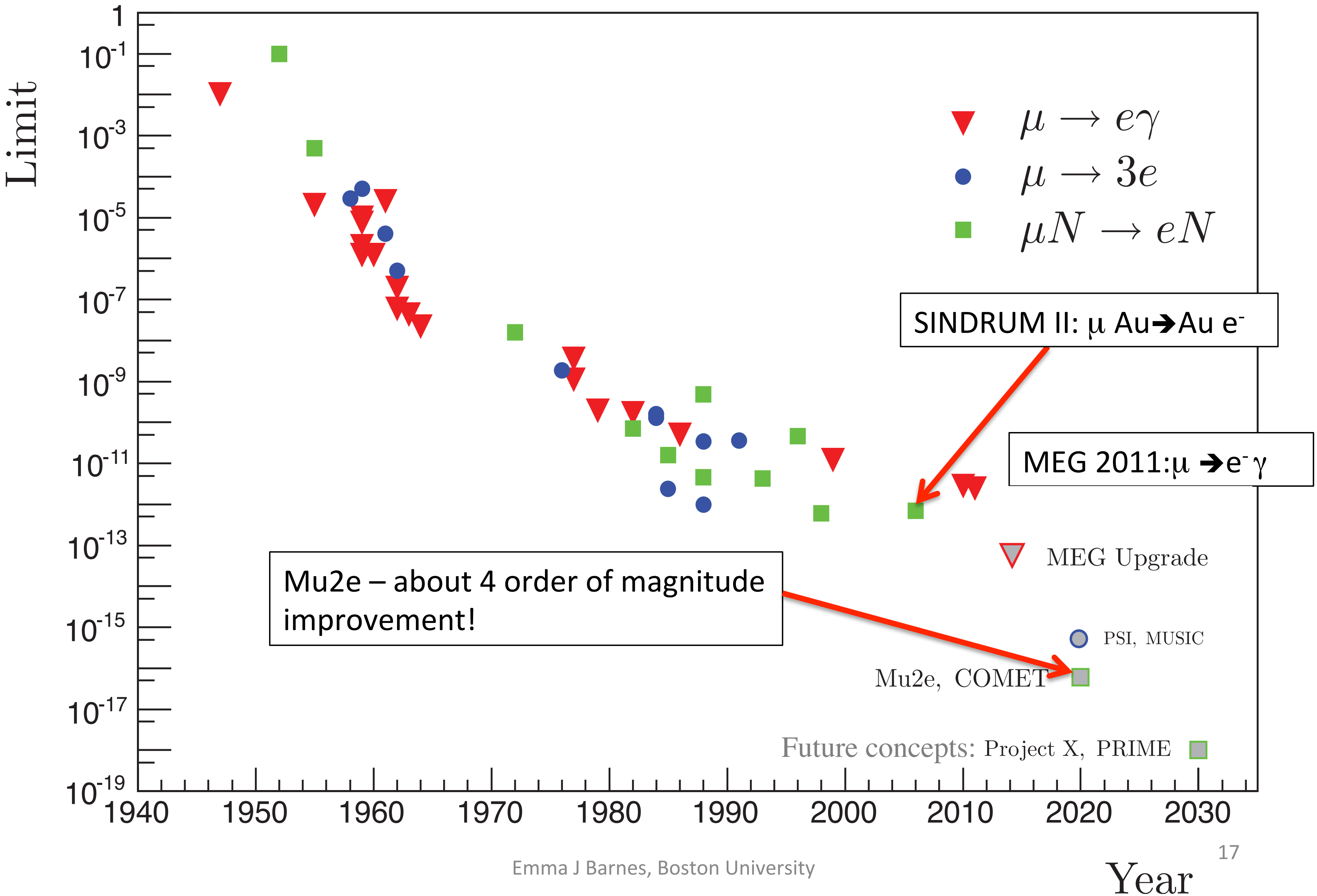
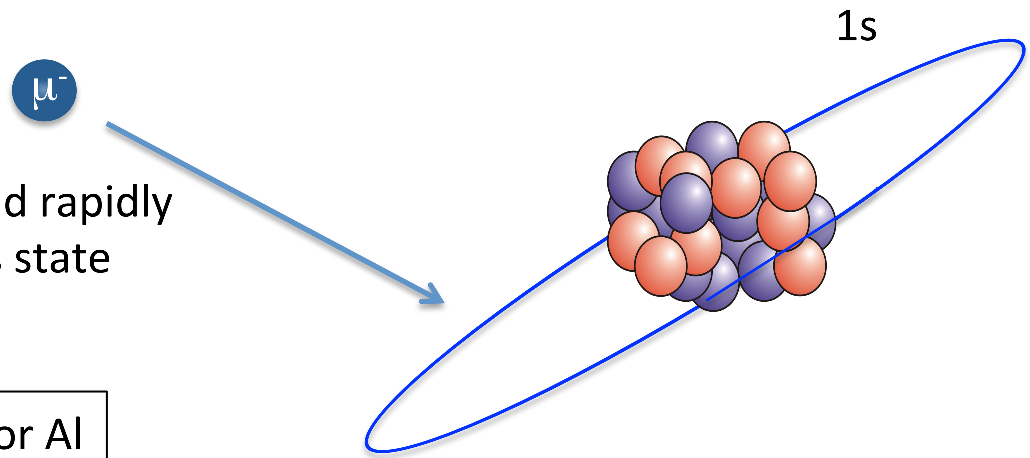


μ-> e conversion



Muon are stopped and rapidly (ps) cascade to the 1s state producing X-Rays.

Transition Energy for Al	
3d→ 2p	66 keV
2p→ 1s	356 keV
3d→ 1s	423 keV
4p→ 1s	446 keV

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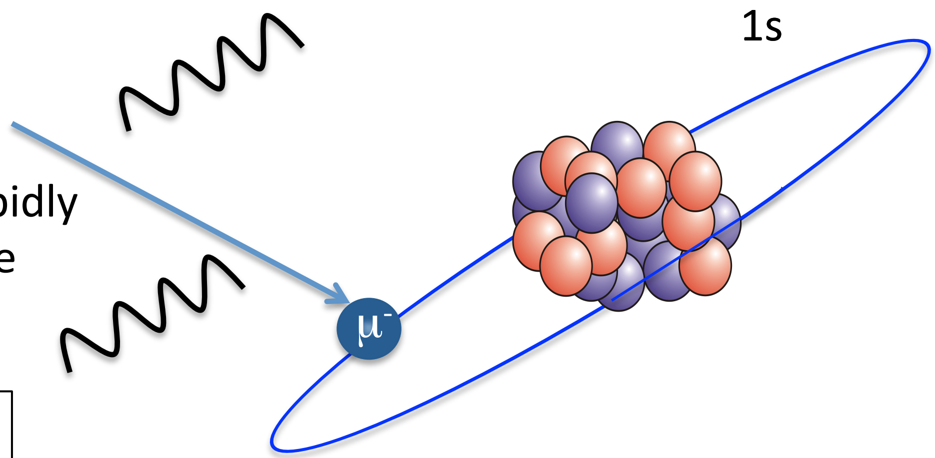

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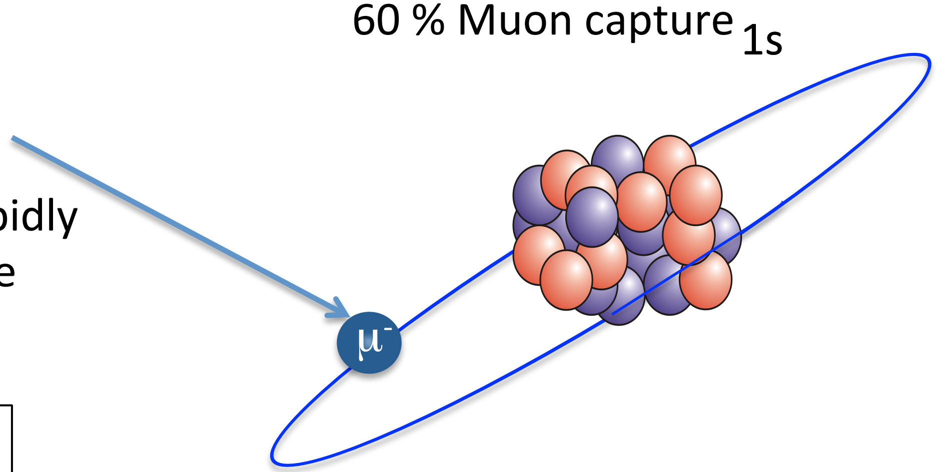
40 % Muon decay in orbit
60 % Muon capture



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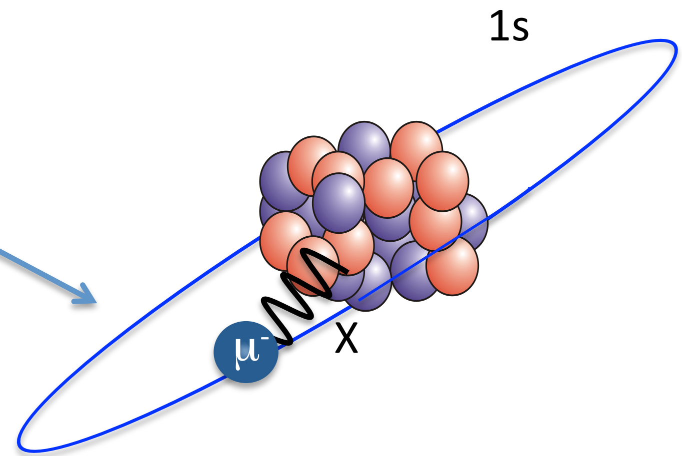

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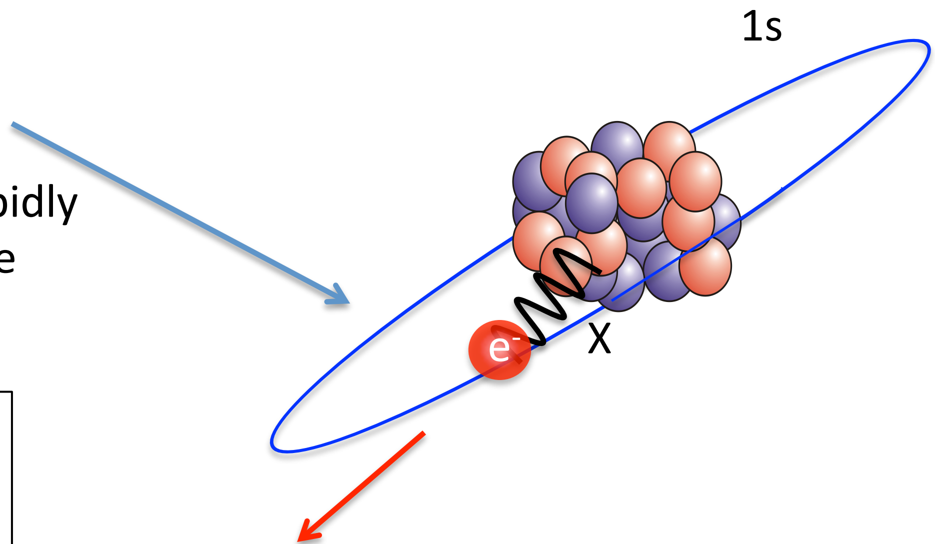

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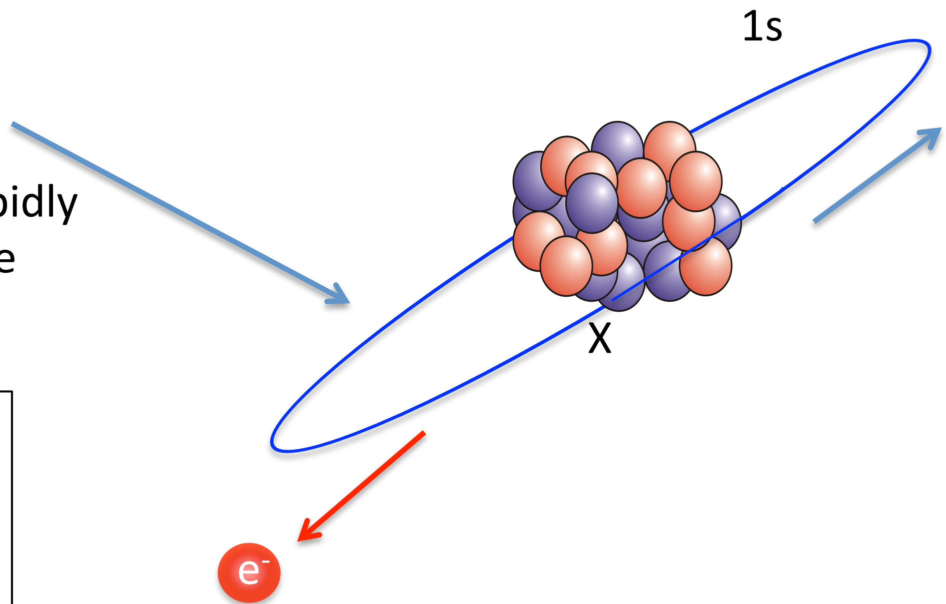

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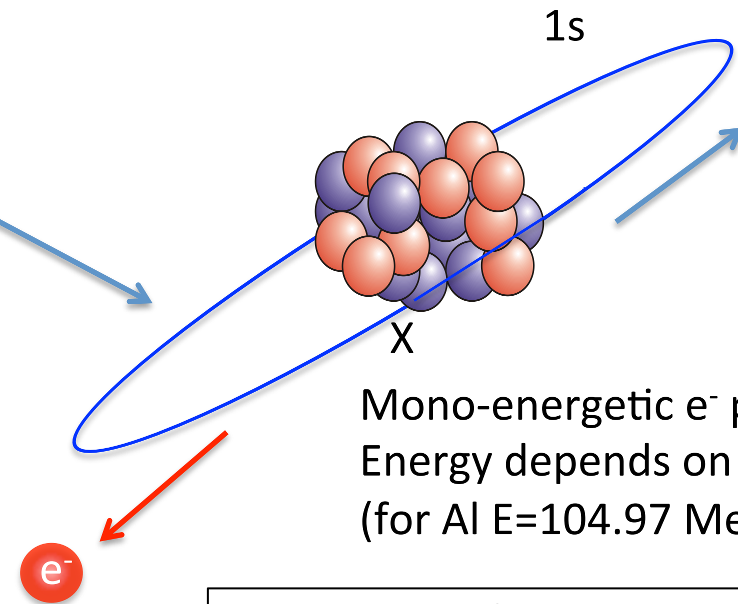

Coherent recoil of nucleus

Mono-energetic e^- produced
Energy depends on the Z of the material
(for Al E=104.97 MeV)

$$E_{e^-} = m_\mu c^2 - BE_\mu(Z) - RE(A)$$

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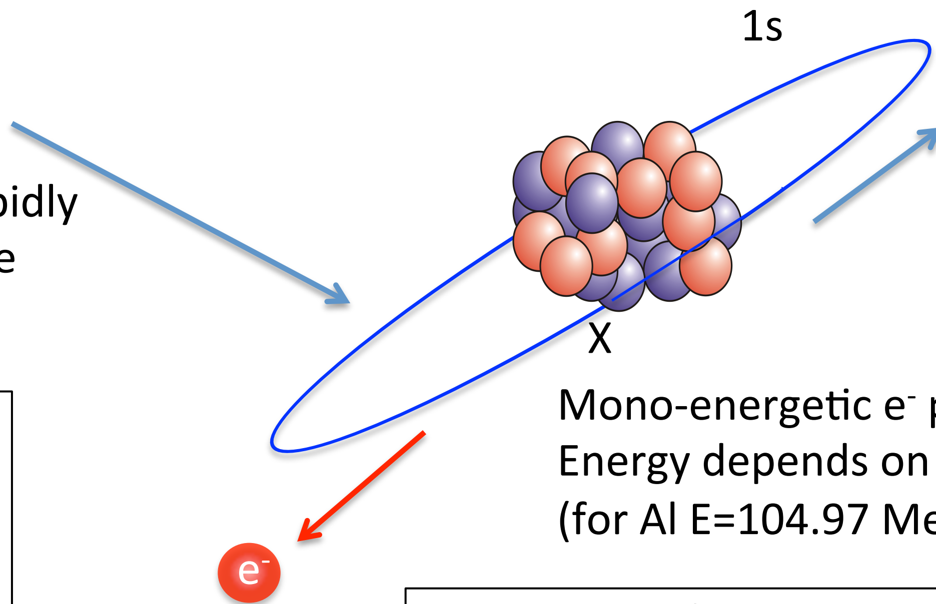

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$$R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to all\ muon\ nuclear\ captures}$$

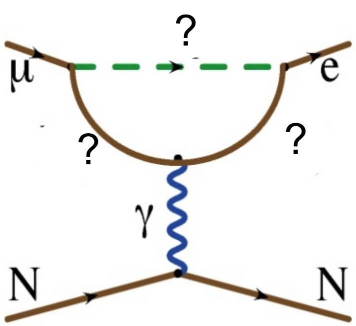
Mu2e Sensitivity

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

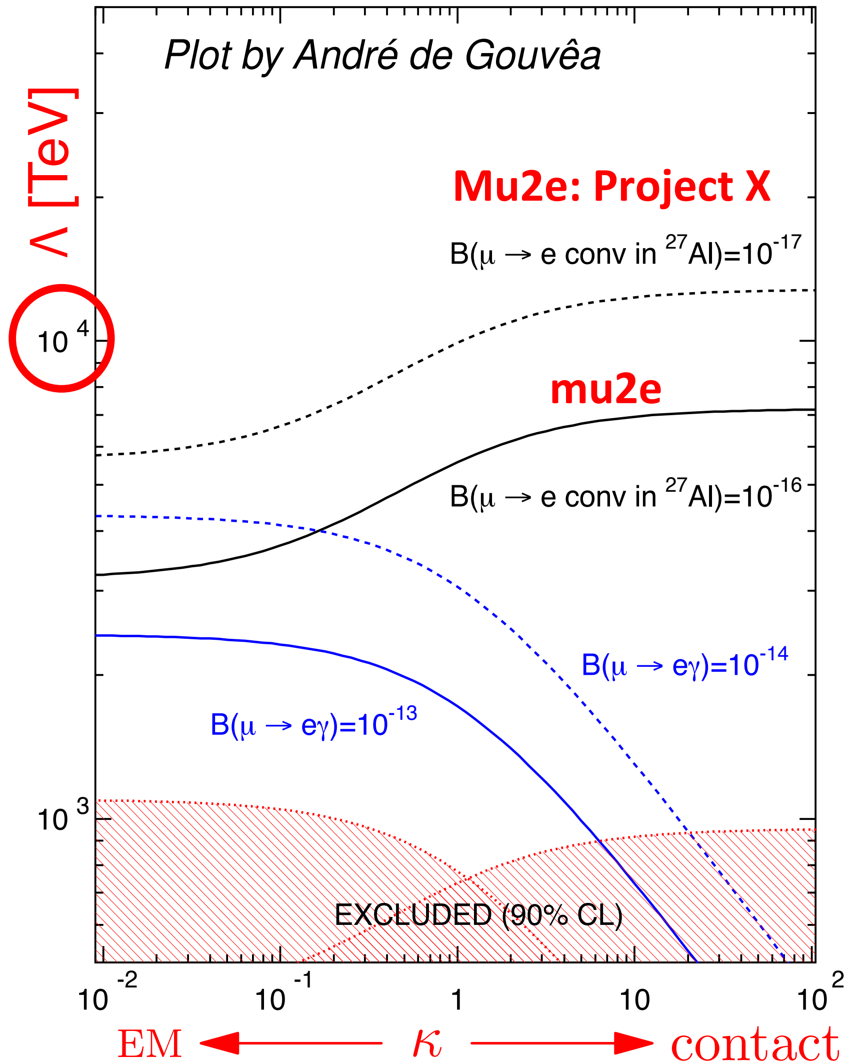
Λ: Energy scale

κ: Importance of contact term

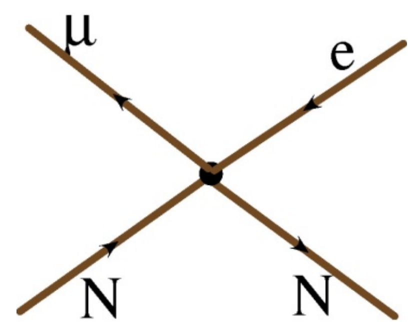
Loops



Supersymmetry and Heavy Neutrinos



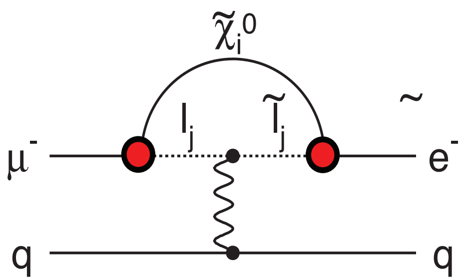
Contact terms



Contributions to μe conversion

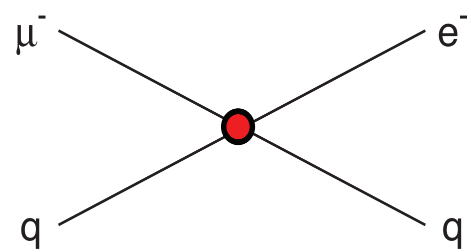
Supersymmetry

Rate ~ 10^{-15}



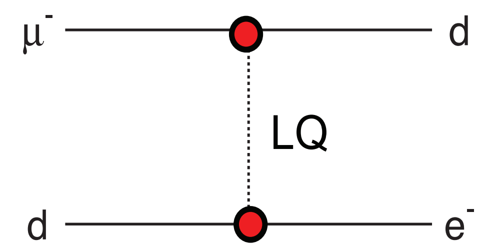
Compositeness

Λ_c ~ 3000 TeV



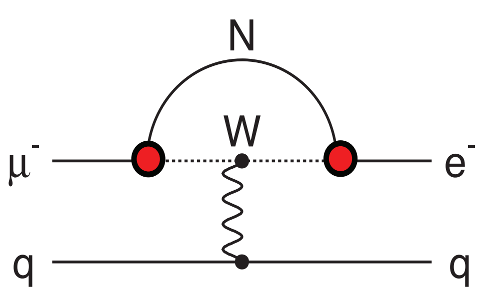
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



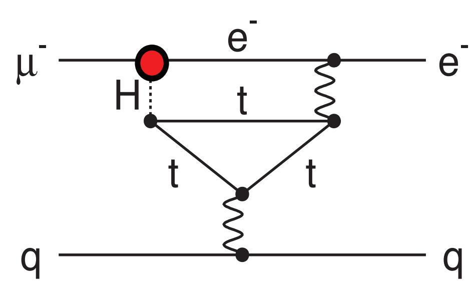
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



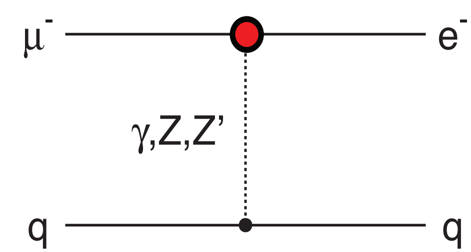
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

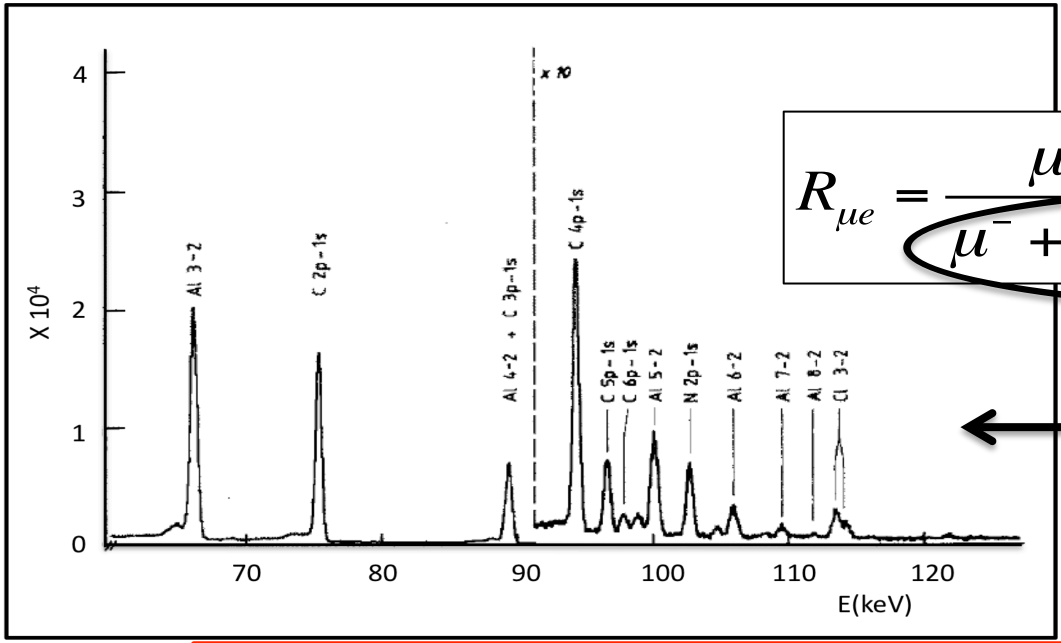
$M_{Z'}$ = 3000 TeV/c^2



Measuring μe conversion

1. Generate pulsed beam of low momentum negative muons.
2. Stop muons in thin foils and form muonic atoms.
   - μ^- in aluminium: $\tau_{1/2}$= 864 ns.
3. Wait for prompt background to decay.
   - Need suitable beam repetition rate.
4. Then measure the electron spectrum.
   - The signal: mono-energetic electrons at 105 MeV

Measuring μe conversion



$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow all\ muon\ captures}$$

With sensitivity to R at 90% C.L. < 5×10^{-17}

- 4 orders of magnitude better than current limits
- Need more than 10^{17} stopped muons!
- -- 3.6×10^{20} protons on target (3 year run)

Need to reduce any background that could affect our sensitivity.

Needle in a haystack?

- Muon decay in orbit (DIOs)
- Radiative muon/pion capture

$$\pi^- N \rightarrow \gamma N^* \qquad \pi^- N \rightarrow e^+ e^- N^*$$

- Long transit time backgrounds (pbars, pions)
- Cosmic ray induced electrons
- Muon/pion decay in flight
- Beam electrons that can scatter into the target

Need to reduce any background that could affect our sensitivity.

Mu2e has been designed with this in mind.

Fermilab

Reider Hahn


Recycler Ring
Recycler to P1 connection
and Extraction Kicker
NOvA injection
kicker
P1 - P2 - AP1
AP-3
MI-8 Line
Delivery Ring
AP-50
AP-30
AP-10
Mu2e
Muon Campus


Recycler Ring
Recycler to P1 connection
and Extraction Kicker
NOvA injection
kicker
P1 - P2 - AP1
AP-3
MI-8 Line
Delivery Ring
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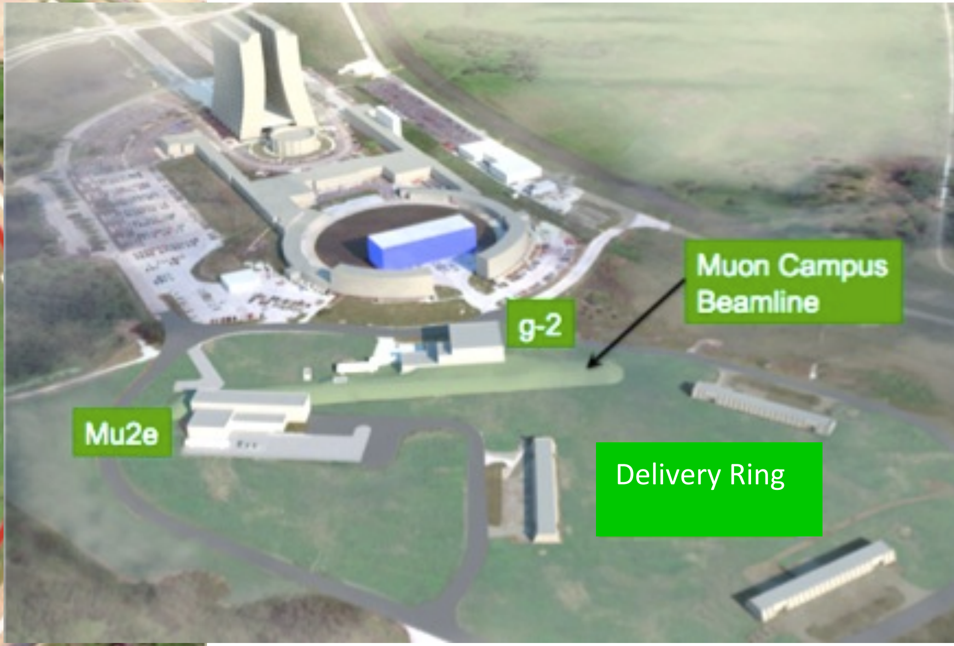
Muon Campus
Beamline
g-2
Mu2e
Delivery Ring

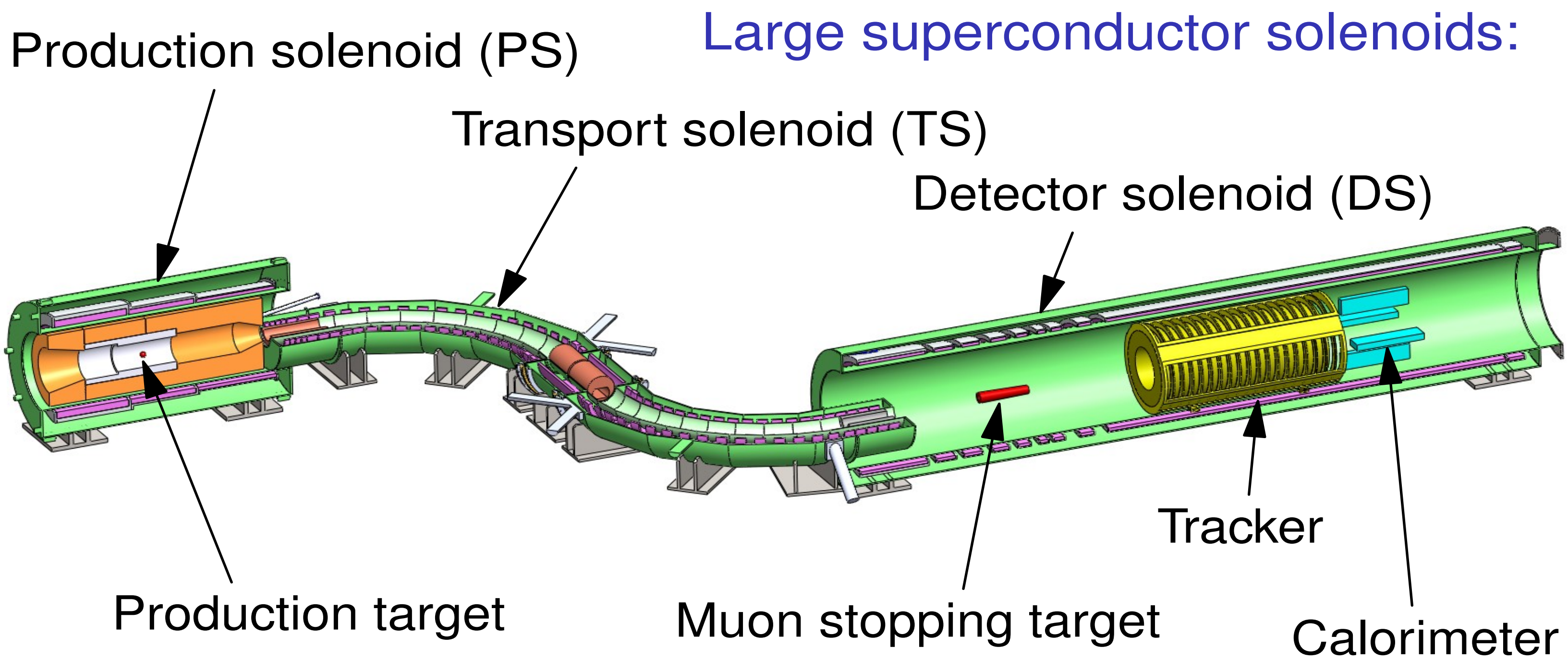

Recycler Ring
Recycler to P1 connection and Extraction Kicker
NOvA injection kicker
P1 - P2 - AP1
AP-3
MI-8 Line
AP-50
AP-30

Muon Campus Beamline
g-2
Mu2e
Delivery Ring

Mu2e

The mu2e Detector System

Transport: S-curve removes line of sight background and also sign-selects.

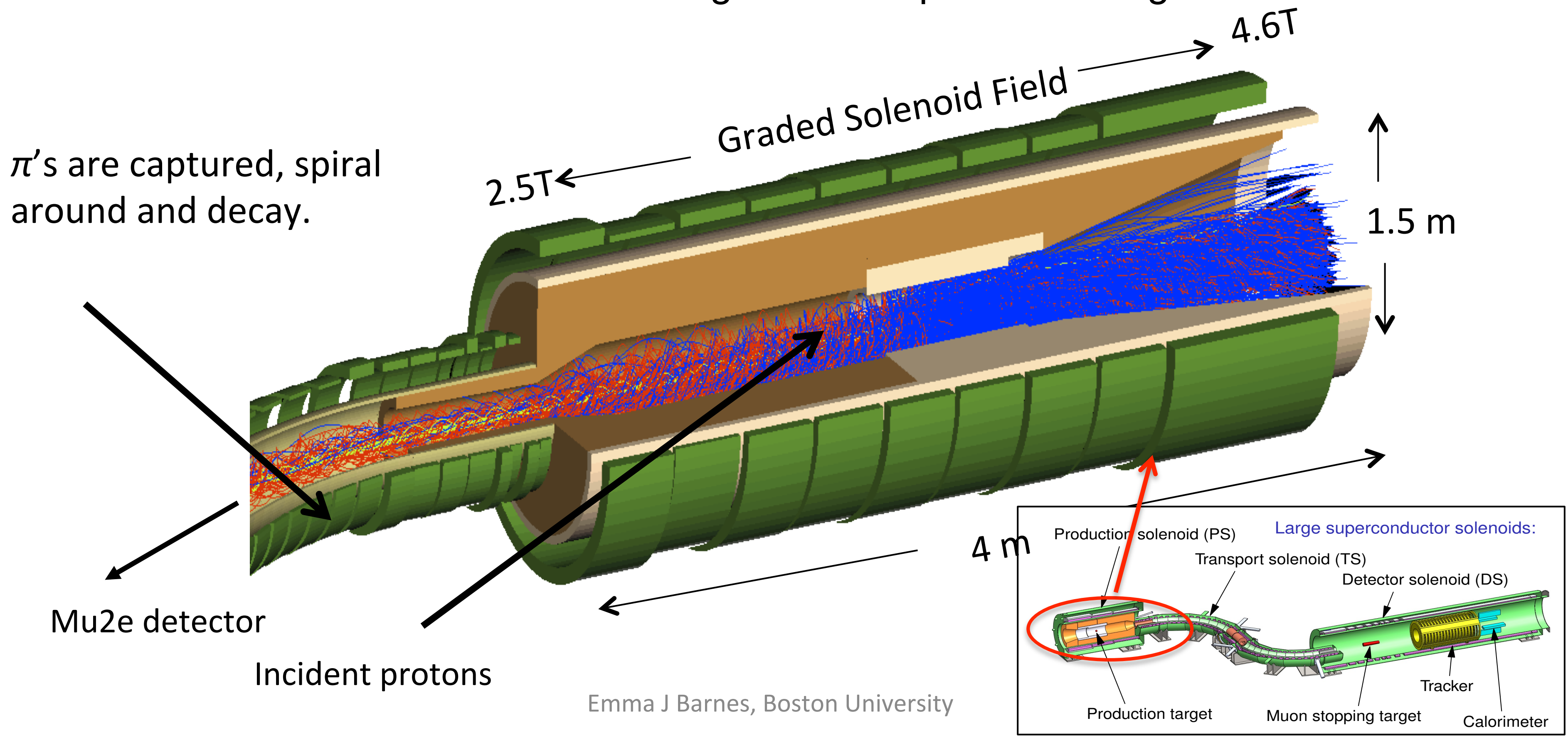
Detector: Stopping Target, Tracking and Calorimeter



Production: 8 GeV protons enter the PS and encounter a tungsten target.
Up to 8 kW beam power (6x10^{12} Protons/s)
π's are then produced which decay into accepted μ's

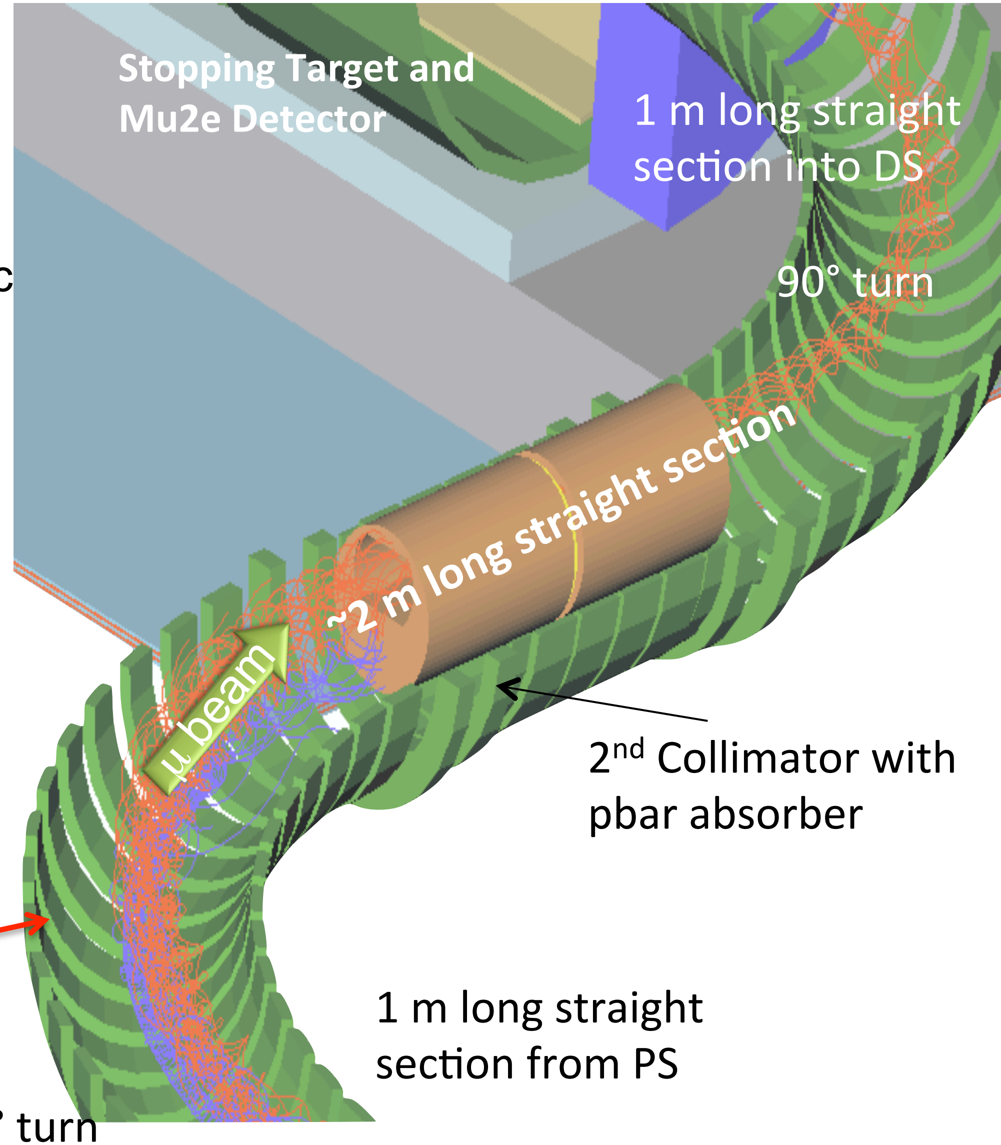
The production Solenoid (PS)

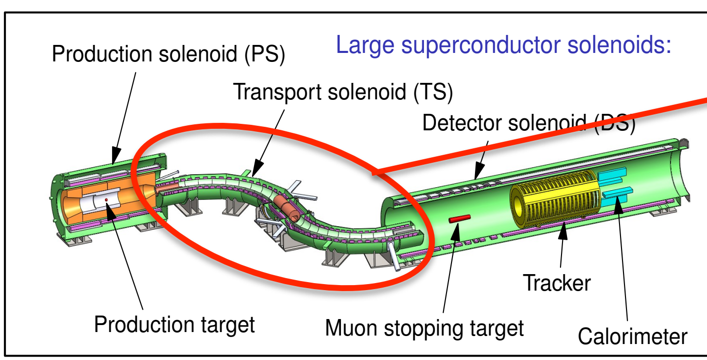
- 8 GeV protons strike a tungsten production target near the center of the Production Solenoid.
- The PS is a high field magnet with a graded (4.6 T -> 2.5 T) solenoidal field.
- The PS will be used to capture pions which can then decay into muons.
- A heat and radiation shield, constructed from bronze, will line the inside of the PS to limit the heat load and radiation damage to the superconducting cable.



The Transport Solenoid (TS)

- S-shaped to reduced any line-of-sight photons and neutrons.
- It consists of a set of superconducting solenoids and toroids that form a magnetic channel that transmits low energy negatively charged muons from the PS.
- High energy negatively charged particles, positively charged particles and line-of-sight neutral particles will nearly all be eliminated by the two 90° bends combined with a series of absorbers and collimators.

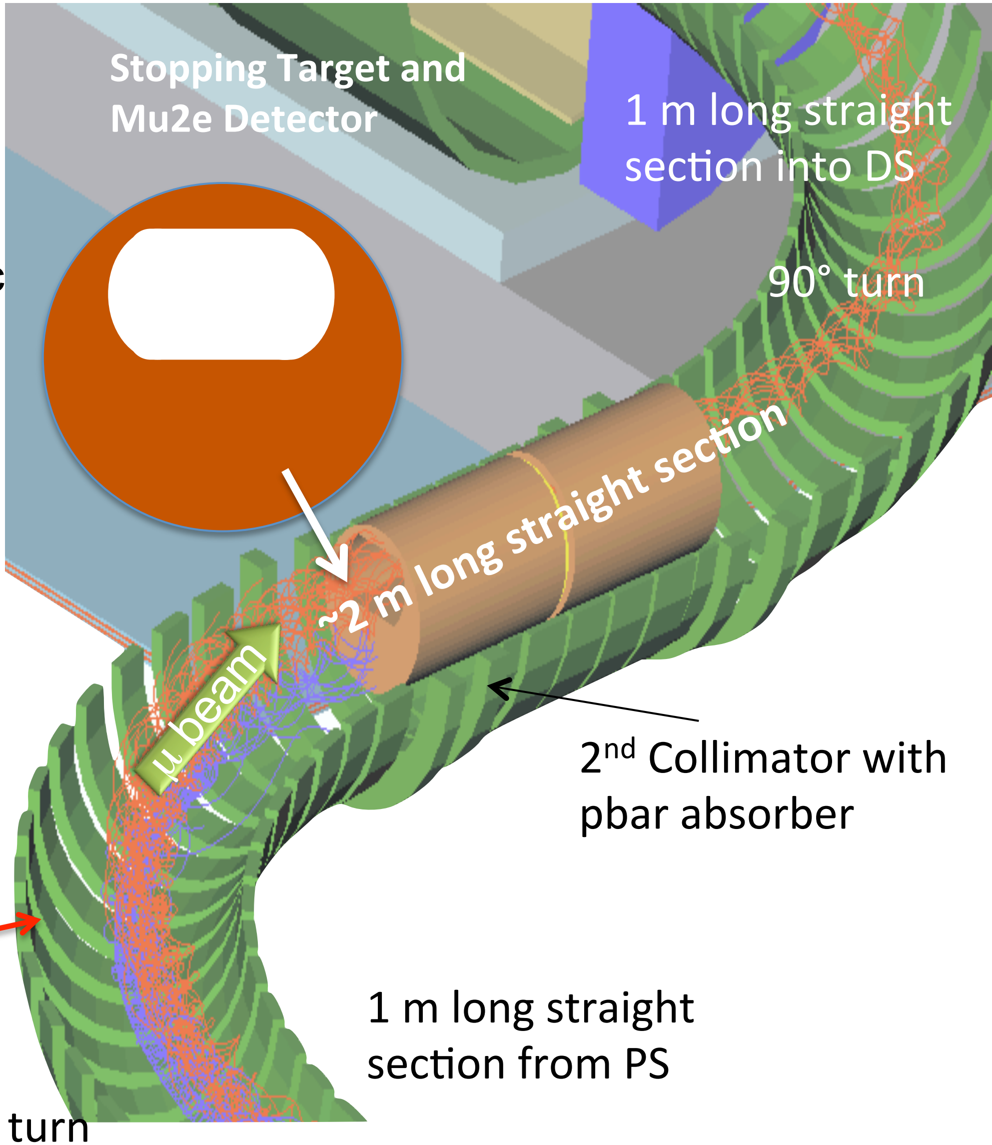


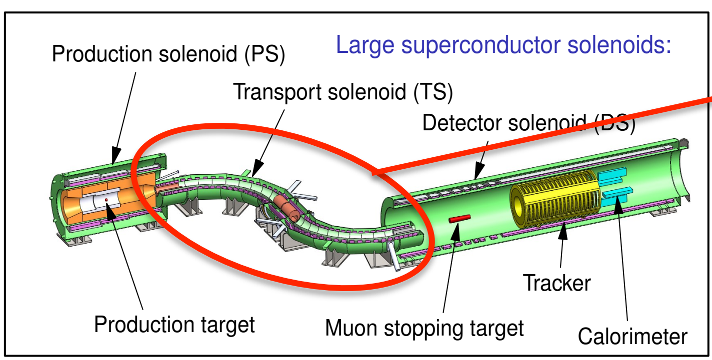


The Transport Solenoid (TS)

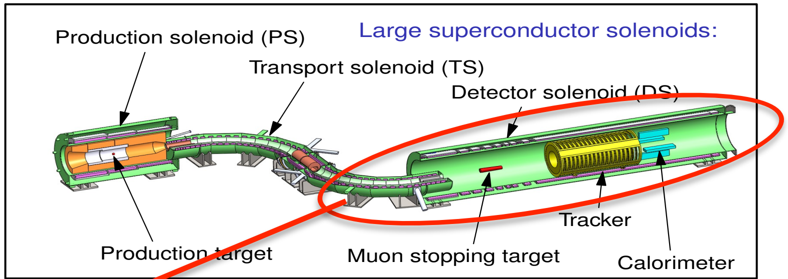
BOSTON UNIVERSITY

- S-shaped to reduced any line-of-sight photons and neutrons.
- It consists of a set of superconducting solenoids and toroids that form a magnetic channel that transmits low energy negatively charged muons from the PS.
- High energy negatively charged particles, positively charged particles and line-of-sight neutral particles will nearly all be eliminated by the two 90° bends combined with a series of absorbers and collimators.

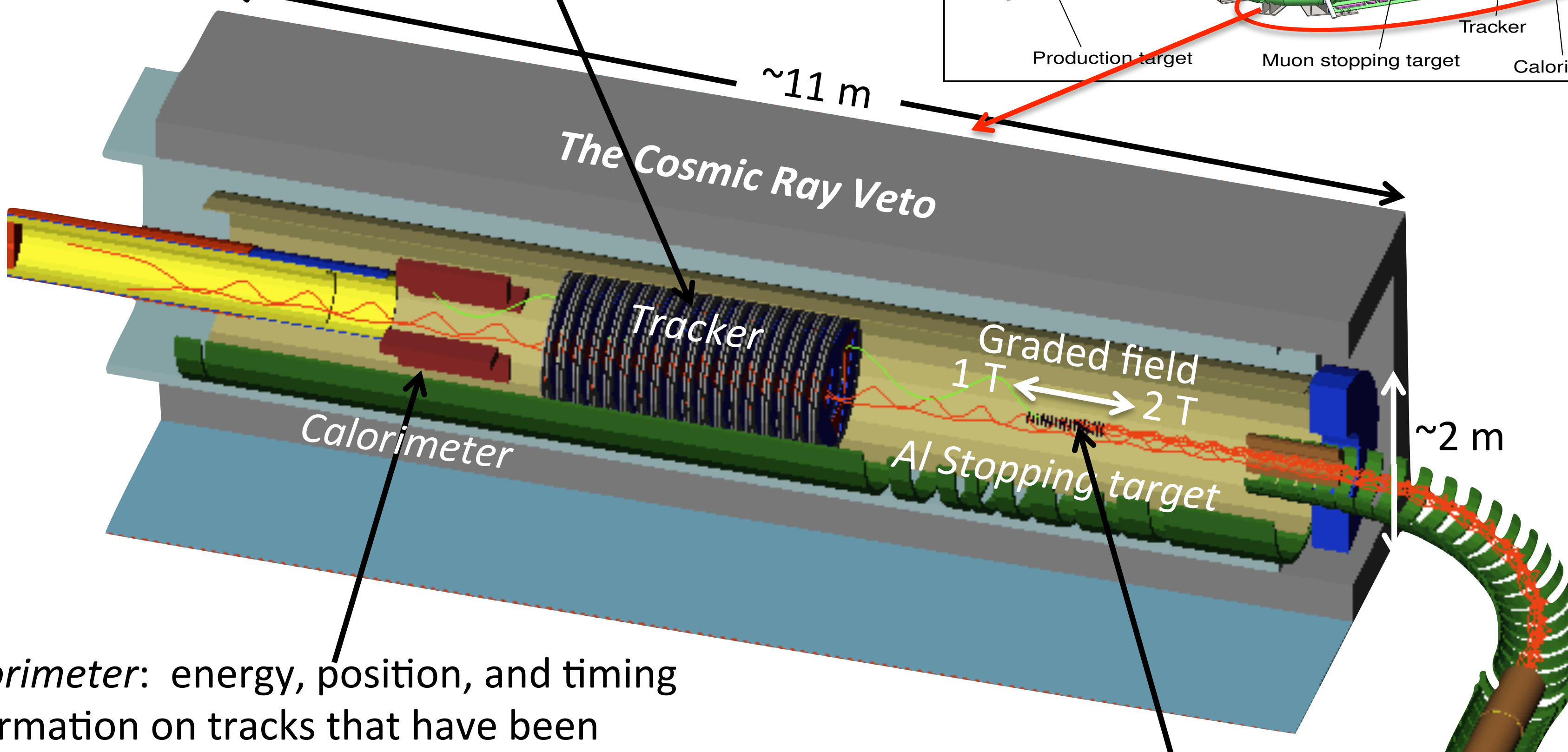




The Detector Solenoid (DS)



Signal events pass *through* tracker and produce hits, then stop in calorimeter



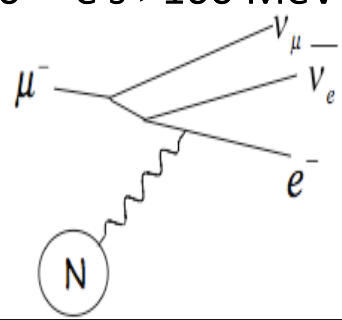
Calorimeter: energy, position, and timing information on tracks that have been reconstructed by the tracker.
1936 LYSO crystals arranged in four vanes

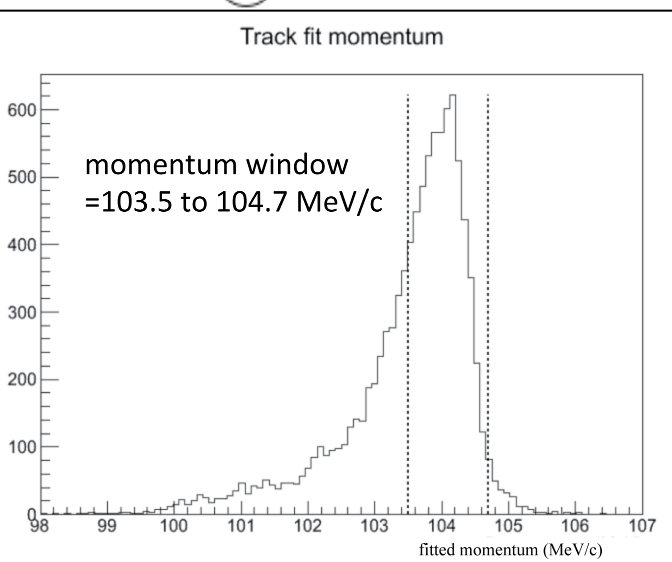
17 thin Al disks. Radii decreases from 8.3 cm upstream to 6.53 cm downstream.

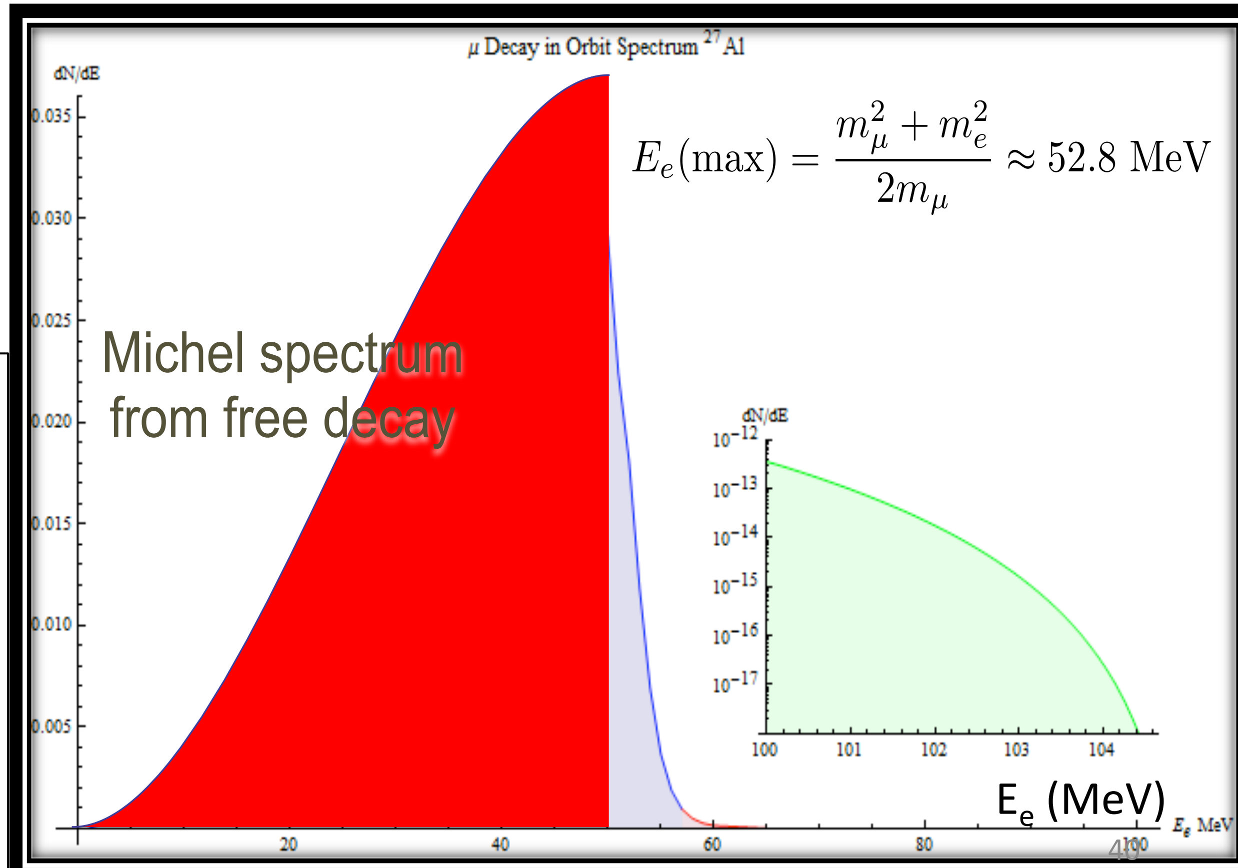
Decay In Orbit (DIO)

$$\mu^- + A(Z,N) \rightarrow A(Z,N) + e^- + \bar{\nu}_e + \nu_\mu$$

- DIOs contribute ~50% background in the signal energy region.
- Most DIO e^-s have energies below 52.8 MeV, the kinematic limit for for decay of a free muon.
- For decay off a bound muon the outgoing e^- can recoil off the nucleus.
- If the neutrinos are at rest the e^- can have exactly the conversion energy E_{CE}=104.97 MeV.
- Small rate $\propto (E_{ce} - E_{electron})^5$
- ~$3\text{x}10^{-13}$ e^-s >100 MeV







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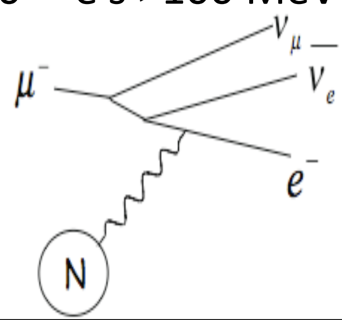
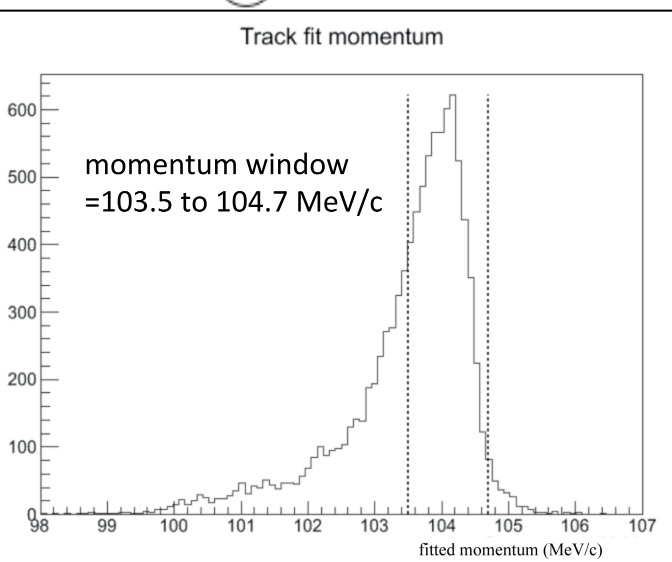
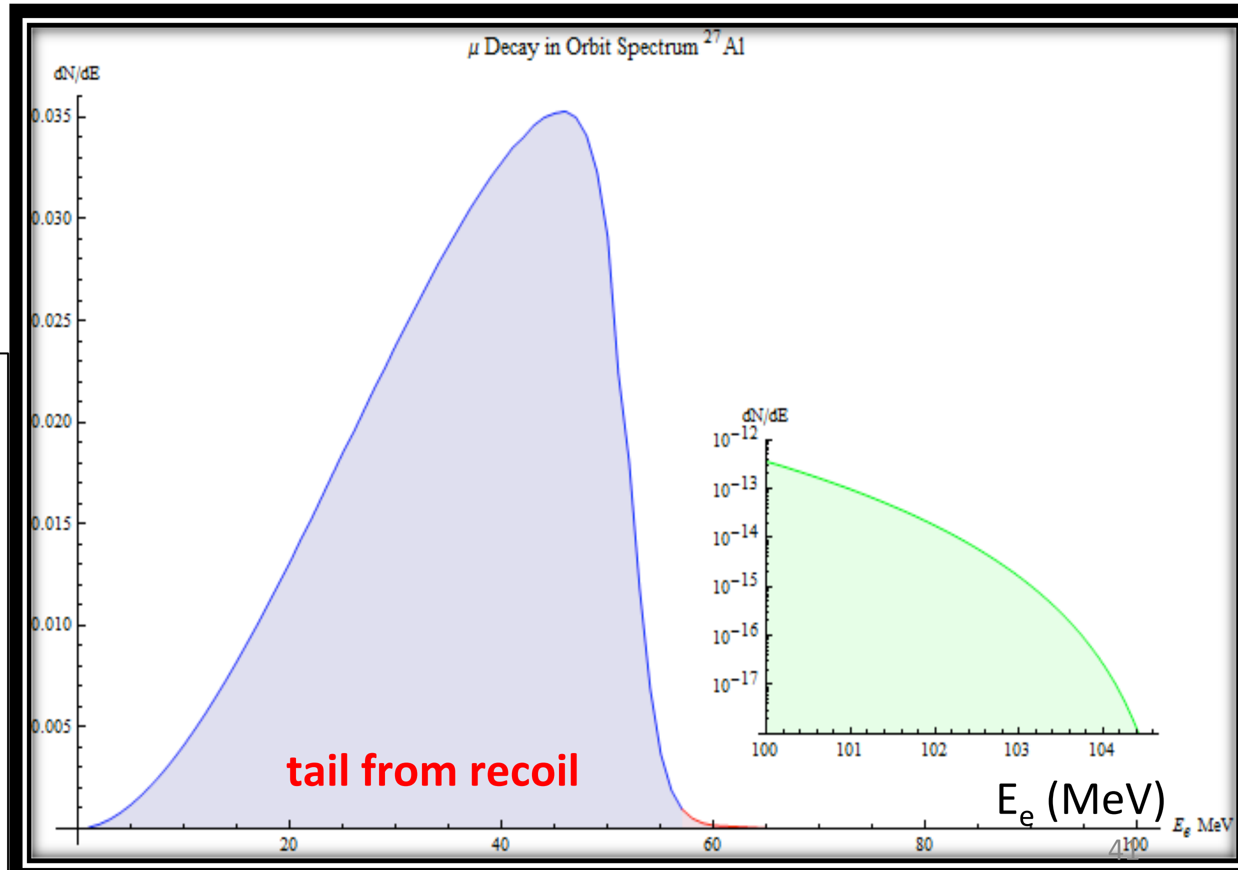
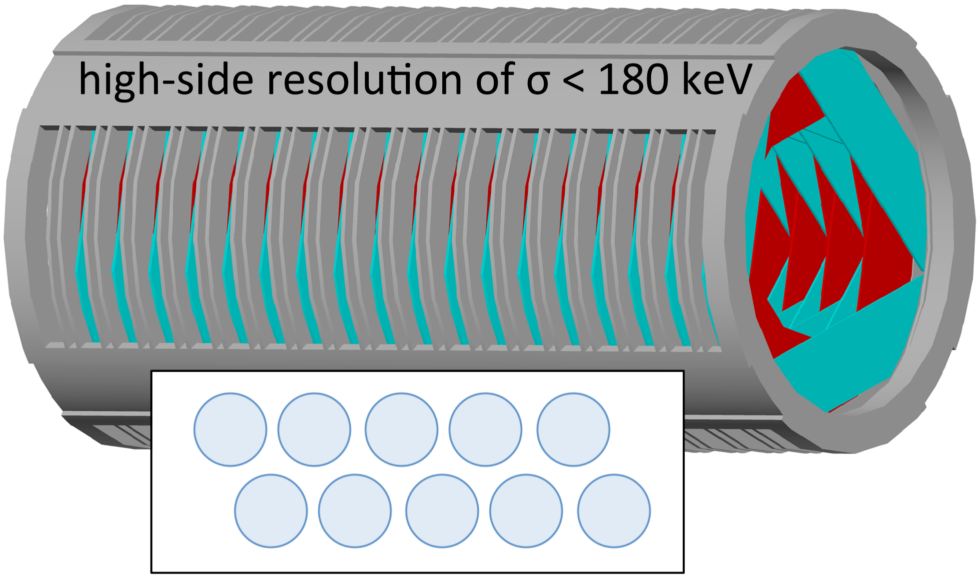


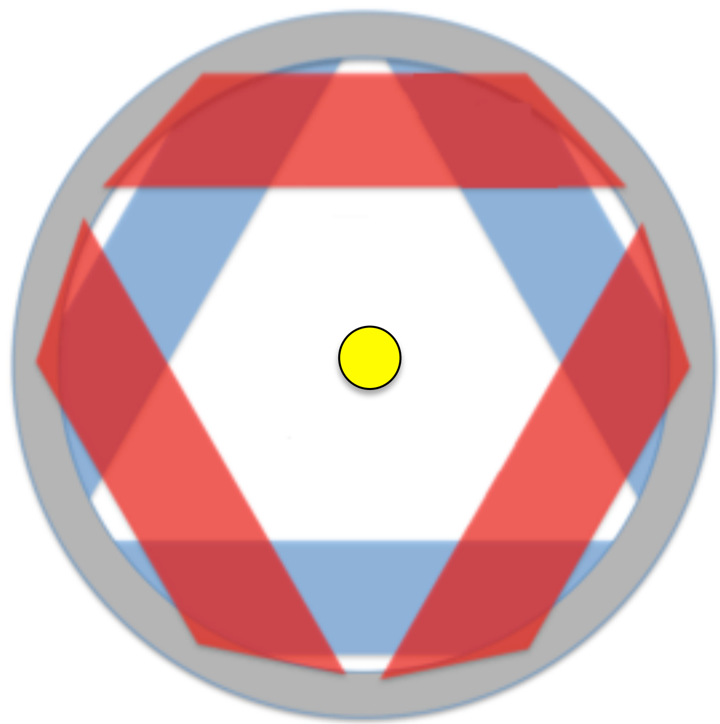




The Tracker

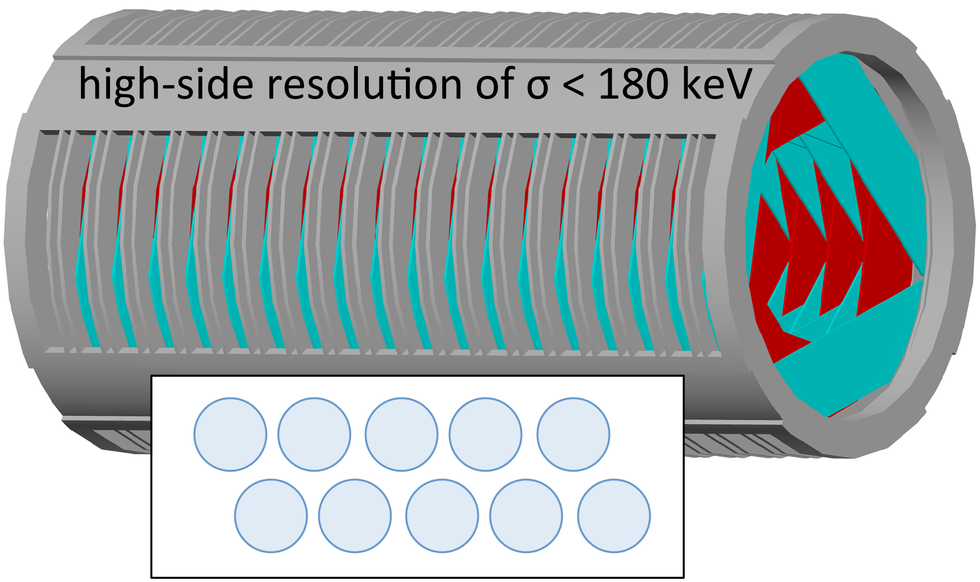


20 µm sense wire inside a 5 mm diameter tube made of 15 µm thick metalized Mylar®. ~22,000 straws distributed into 18 measurement stations across a ~3 m length. Planes are constructed from two layers of straws and are operated in a vacuum.



- The tracker is designed to intercept only a small fraction of the significant flux of electrons from muon decays-in-orbit (DIO) (energies < 60MeV).

The Tracker



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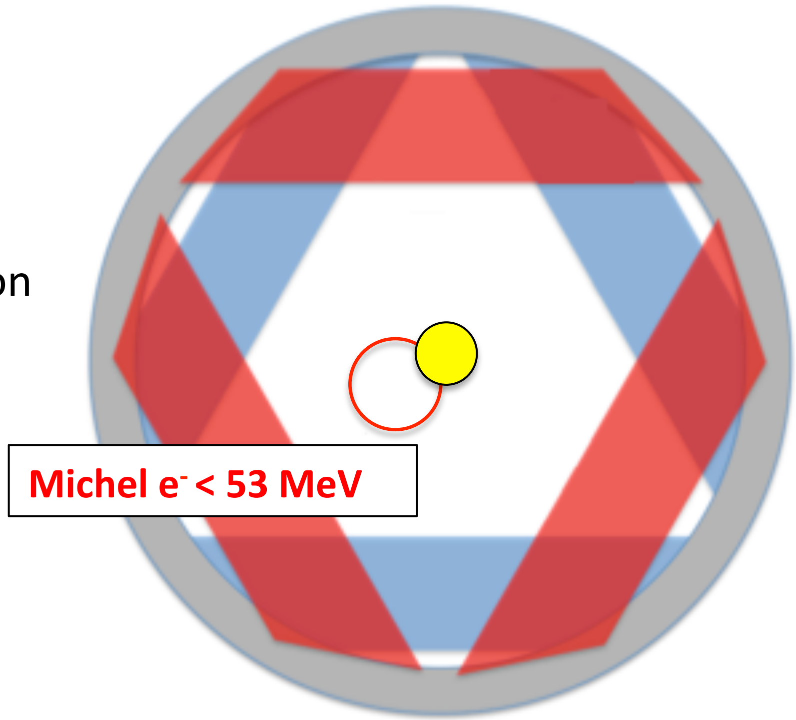
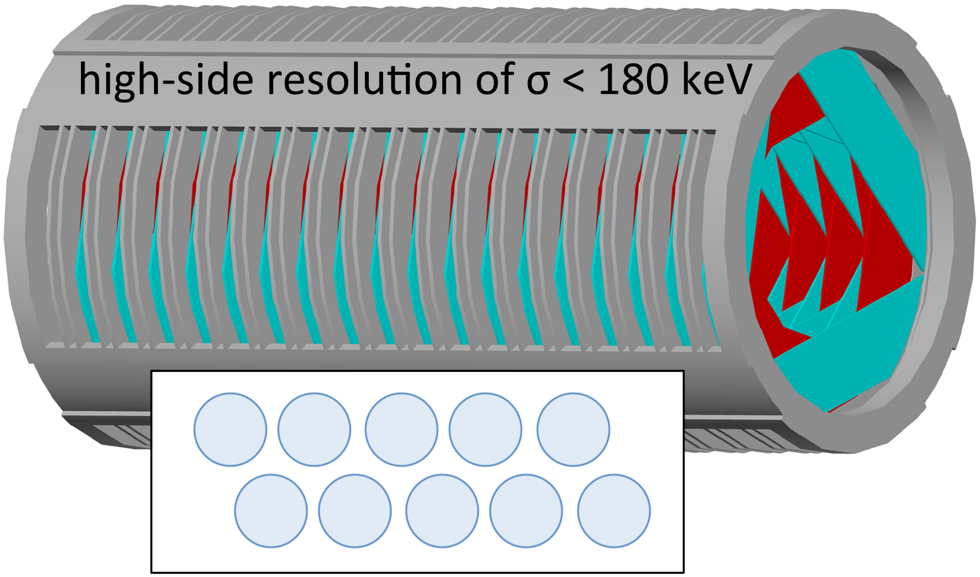
- e^- with energies < 53 MeV will curl in the field of the DS and pass unobstructed through the hole in the center of the tracker.



The Tracker



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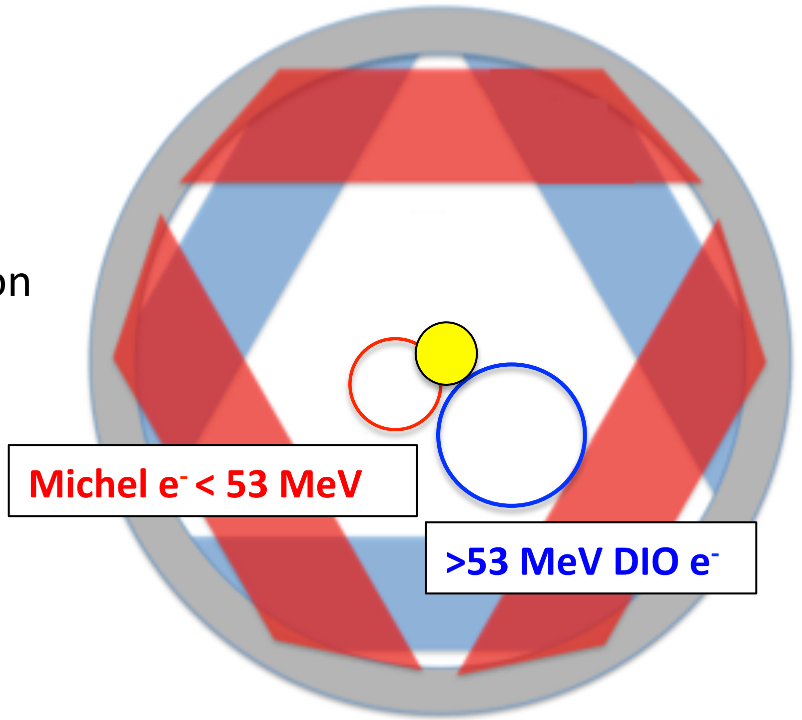

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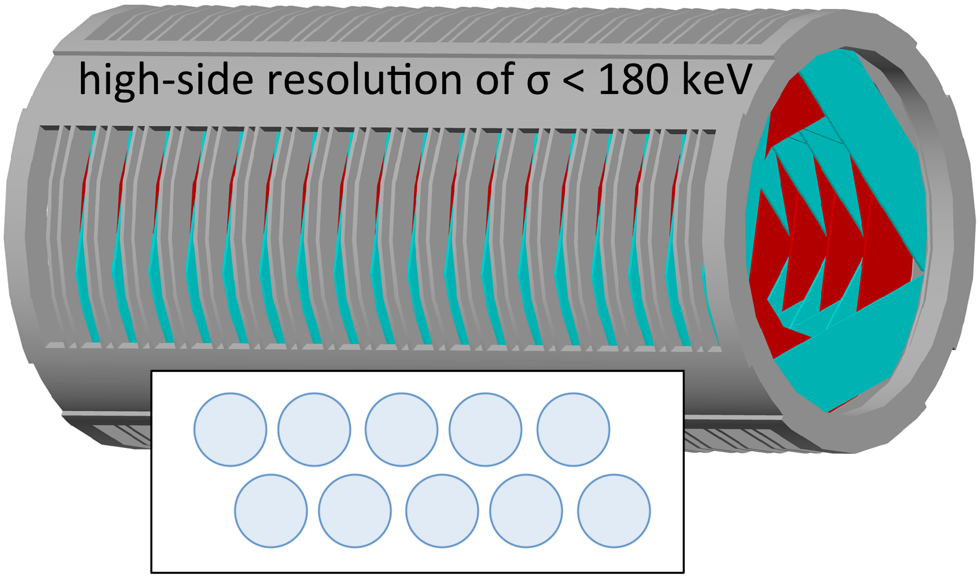

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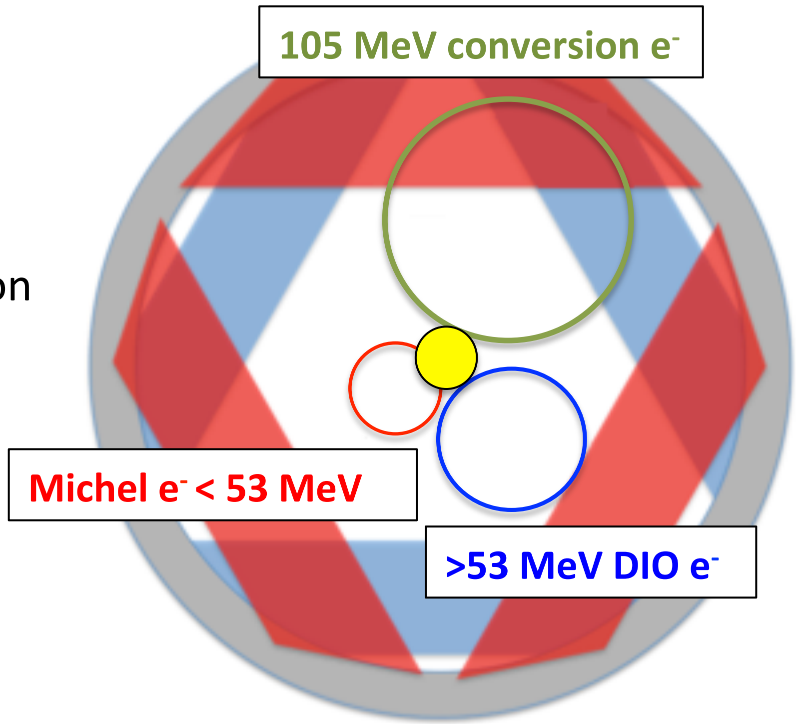

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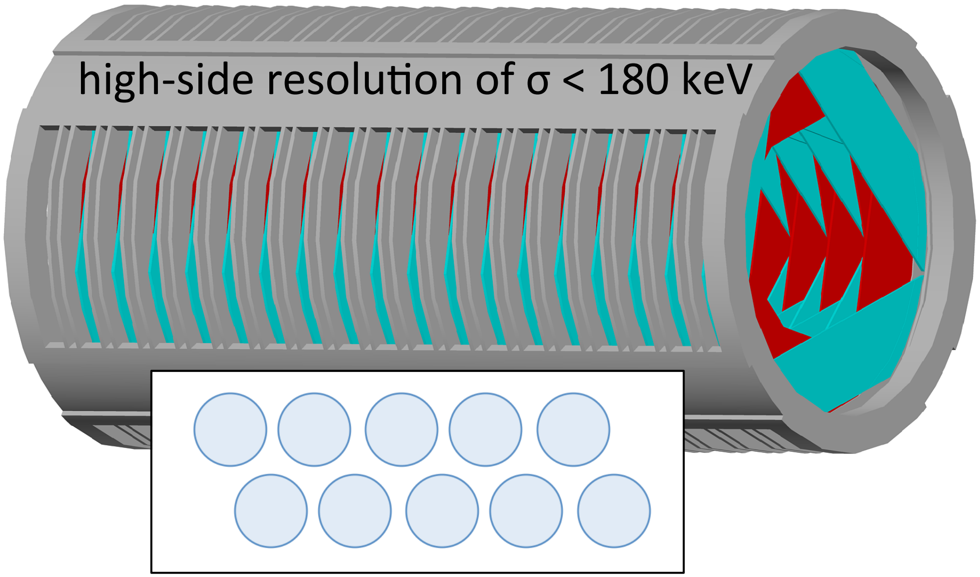

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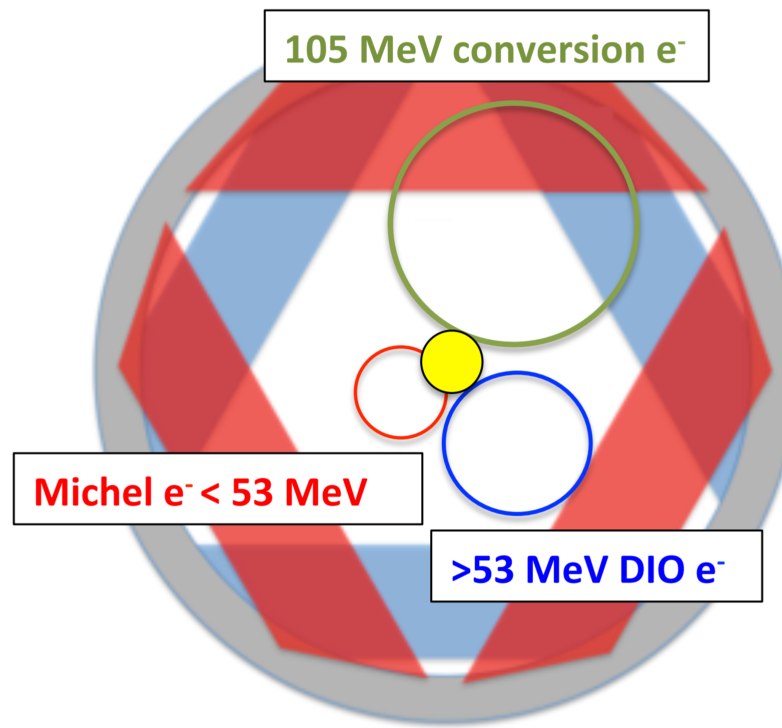
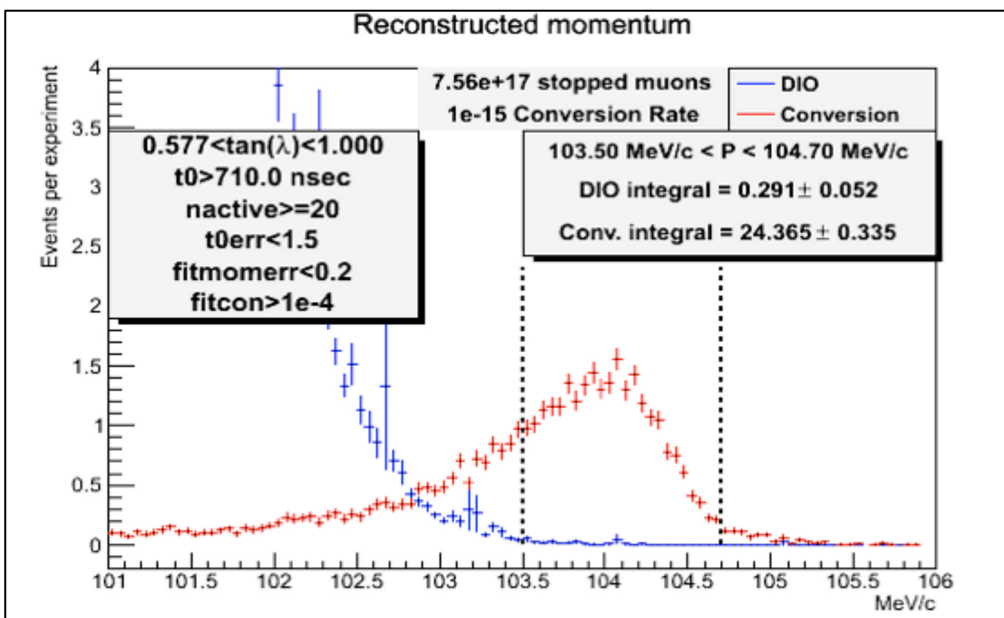
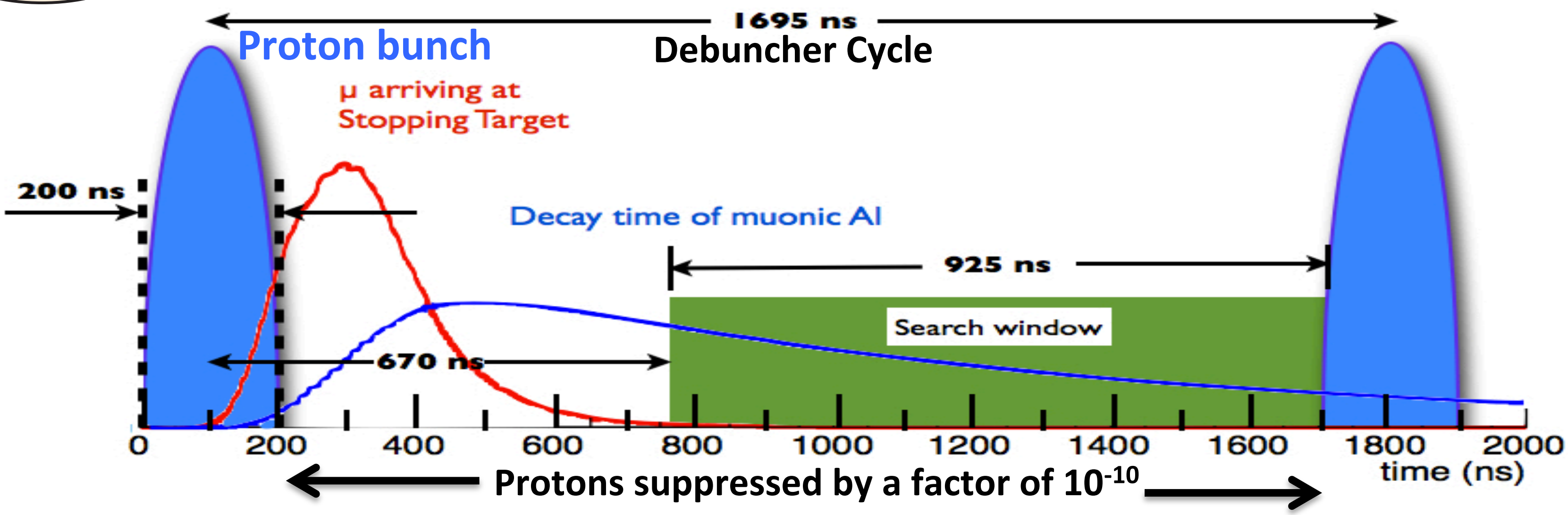




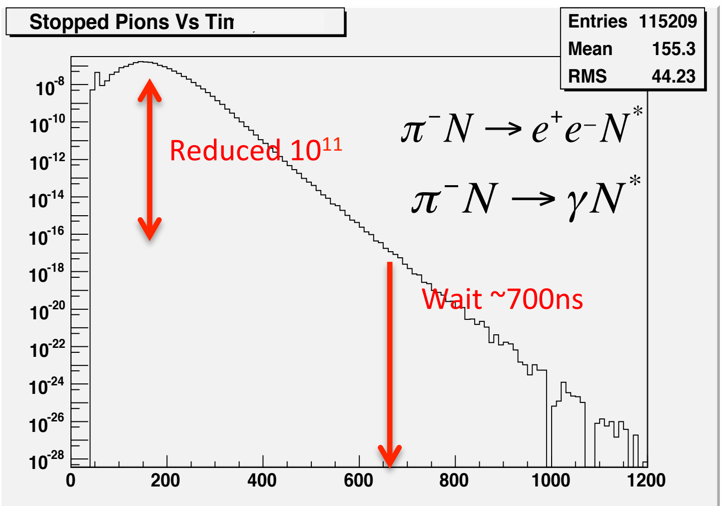
Pulsed beam structure



- Delivery ring supplies a single circulating bunch where protons are resonantly extracted to the beamline.
- Pulsed beam to Mu2e every cyclotron period of 1695 ns (2x muons lifetime) for 8 GeV protons.
- Muon lifetime in Al is long (864 ns) the loss of muons is acceptable if the time between pulses is not much longer than the muon lifetime and one simply waits for the pions to decay (21 ns).

Extinction level of 10^{-10} between bunches is crucial!

$$\text{Extinction} = \frac{\text{number of protons striking the PT between spills}}{n\text{umber striking it during the spills.}}$$



Backgrounds and sensitivities

3 years of 1.2 x10^{20} protons/year (8 kW beam power)

Background	Background Estimate
Muon decay-in-orbit	0.22 ± 0.06
Cosmic Rays	0.05 ± 0.013
Radiative Pion Capture	0.03 ± 0.007
Pion decay In-Flight	0.003 ± 0.0015
Muon decay In-Flight	0.01 ± 0.003
Antiproton Induced	0.10 ± 0.05
Beam electrons	0.0006 ± 0.0003
Radiative muon capture	< 2 x 10^{-6}
Total (Add in quadrature)	**0.41 ± 0.08**

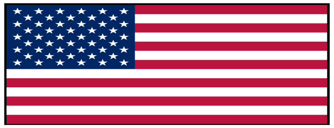
GOAL < 2.4× 10^{-17} single event sensitivity

$R_{\mu e}$~10^{-15} 40 signal events

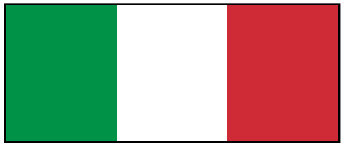
Road Map

- Aim for a 4 orders of magnitude improvement compared to SINDRUM II which achieved $R_{\mu e} < 7\times10^{-13}$.
- CD-0 approval.
- Lehman review for CD-1 last week!
- Start taking data in 2019
- 3 year running time

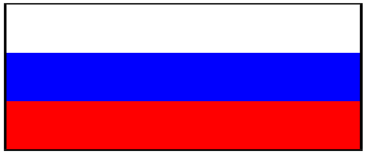
The Mu2e Collaboration



- 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



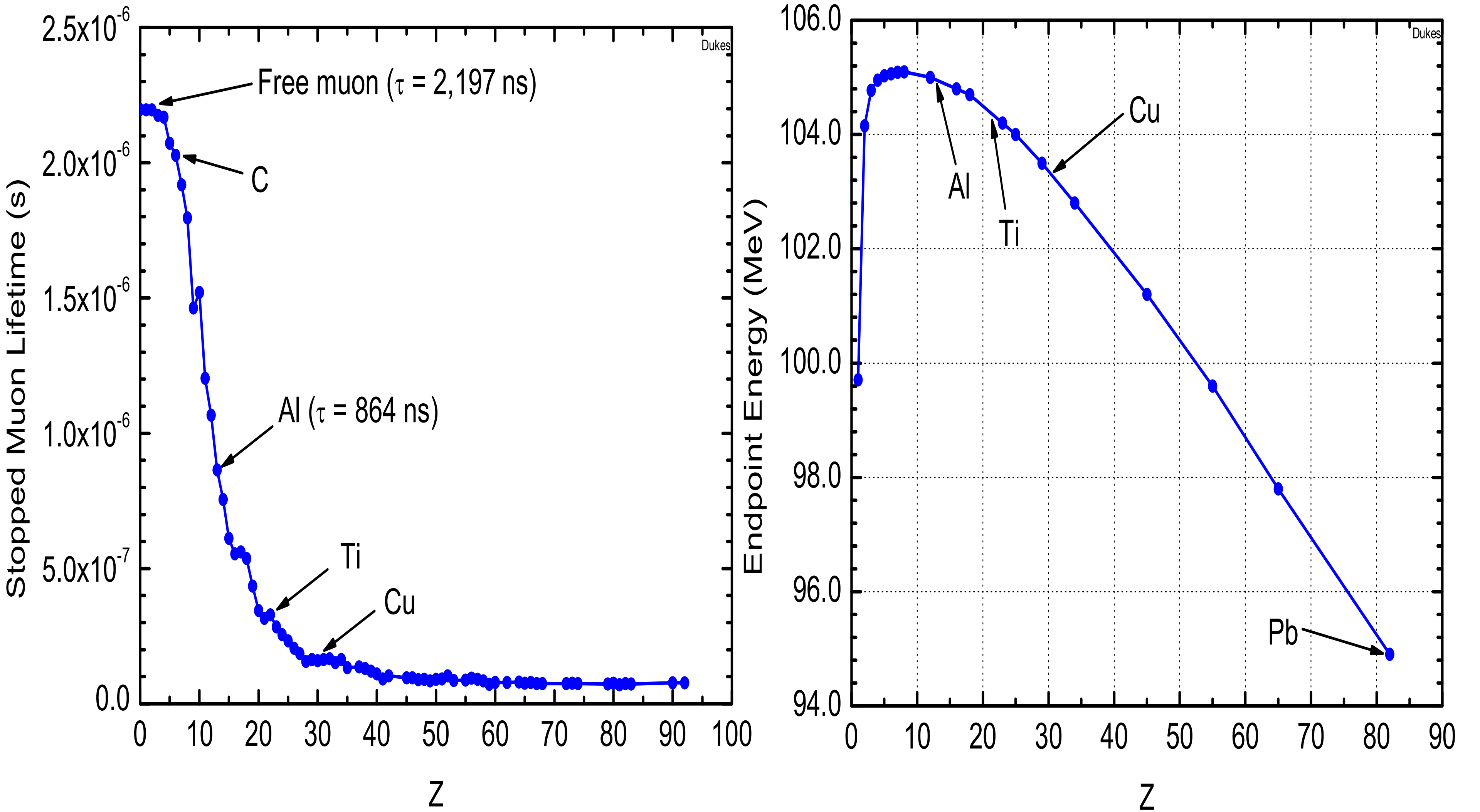
- Institute for Nuclear Research, Moscow
- Joint Institute for Nuclear Research, Dubna

~130 collaborators

http://mu2e.fnal.gov/

Thanks for listening!

Backup Slides

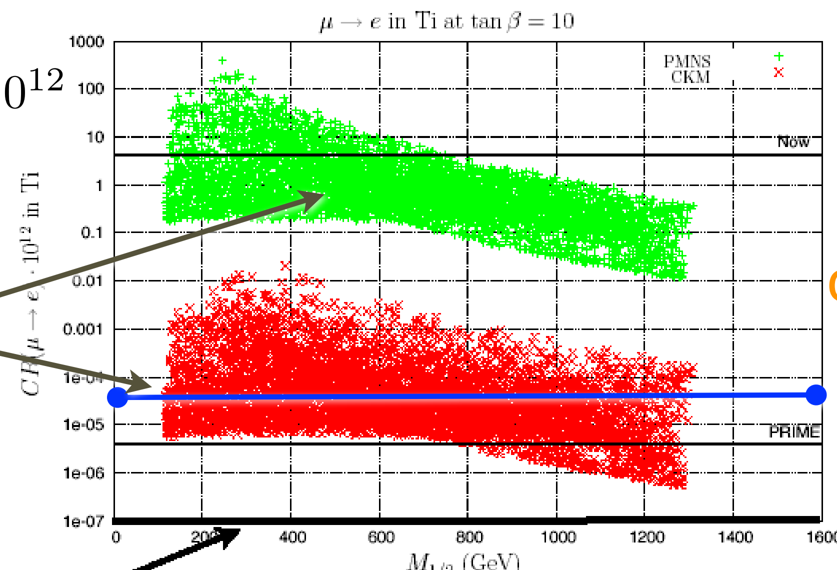


Stopped Muon Lifetime (s)
Free muon (τ = 2,197 ns)
C
Al (τ = 864 ns)
Ti
Cu
Dukes
2.5x10-6
2.0x10-6
1.5x10-6
1.0x10-6
5.0x10-7
0.0
0
10
20
30
40
50
60
70
80
90
100
Z
Endpoint Energy (MeV)
106.0
104.0
102.0
100.0
98.0
96.0
94.0
Al
Ti
Cu
Pb
Dukes
0
10
20
30
40
50
60
70
80
90
Z

Mu2e and the LHC

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

$\mathrm{BR}(\mu \to e) \times 10^{12}$



Current μe conversion

Mu2e

measurement can distinguish between PMNS and MFV

Project X reach

$M_{1/2}$ (GeV)

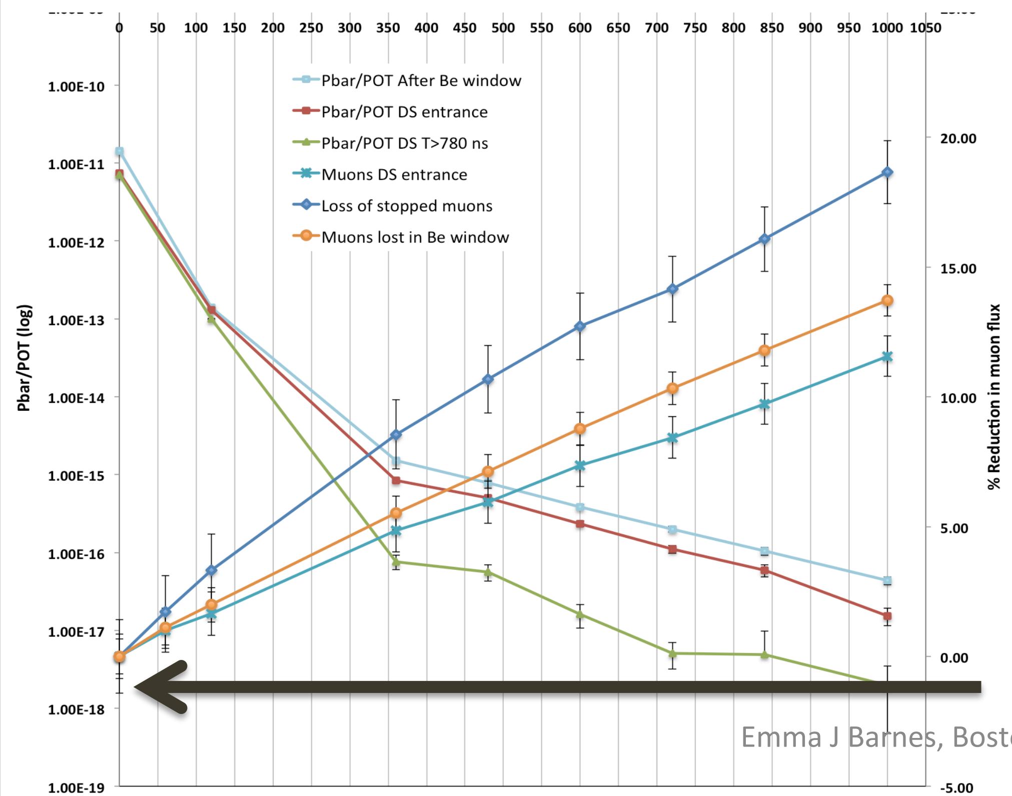
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

complementarity between Lepton Flavor Violation (LFV) and LHC experiments

Antiprotons

- The 8 GeV K.E proton beam can produce antiprotons in sufficient numbers to be a serious background.
- Spiral slowly through the TS entering the DS.
- They do not decay (well not that we know of!)
- Annihilate on nuclei (such as in the stopping target) releasing a large number of secondaries (energetic π, γ, n and p.)

Can reduce the Pbar flux to 533±124 Pbars throughout entire mu2e run



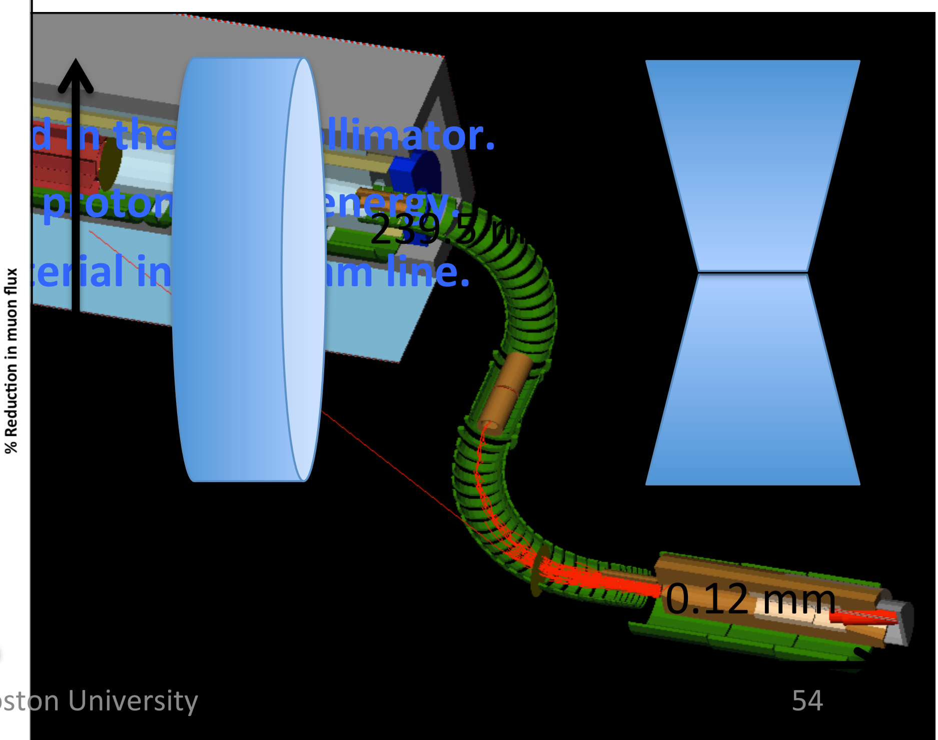


Table 3.1: The table gives the total $\bar{p}$ induced backgrounds for different incident proton momenta.

p momentum (GeV/c)	Number of $\bar{p}/p$ produced	Number of $\bar{p}/p$ entering transport	Background events
5	3.9×10^{-10}	7.4×10^{-15}	7×10^{-7}
6	5.3×10^{-8}	8.0×10^{-13}	8×10^{-5}
7	1.4×10^{-6}	1.2×10^{-11}	1.2×10^{-3}
8	8.5×10^{-6}	6.8×10^{-11}	7×10^{-3}

Beam requirements

Parameter	Design Value	Requirement	Unit
Booster synchrotron repetition rate	15	> 10.5 [2]	Hz
Booster synchrotron beam intensity	4.0×10^{12}	4.0×10^{12}	Protons/batch
Time between beam pulses	1685	> 864	nsec
Out of time extinction factor	10^{-10}	$\leq 10^{-10}$	
Pulse full width	±100	≤ ±130	nsec
Pulse rms width	40	≤ 50	nsec
Duration of spill	54	> 20	msec
Beam Power on Target	8	-----	kW
Average proton intensity per pulse	31	< 50	Mp/pulse
Pulse to Pulse intensity variation	50	< 50	%
Minimum Target rms spot size[3]	1	0.5	mm
Maximum Target rms spot size[3]	1	2.0	mm
Target rms beam divergence	0.5	< 20	mrad

Table 5.1. Summary of the Mu2e Proton Beam Requirements

Accelerator timeline

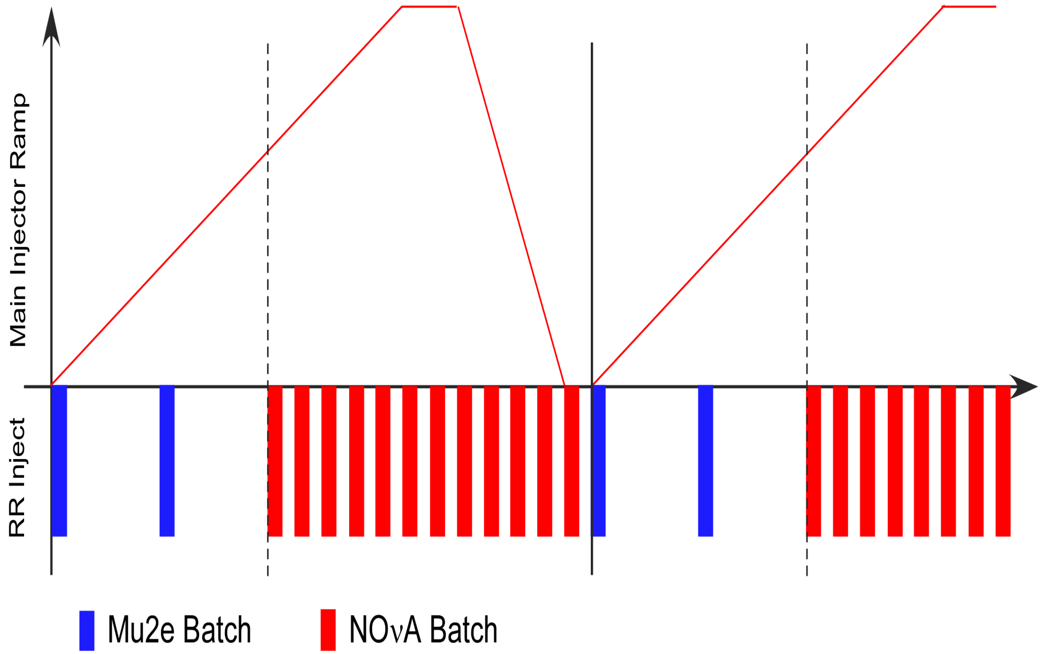


Figure 5.2. The accelerator timeline is shared between Mu2e and NOνA. The blue and red bars represent Mu2e and NOνA proton batch injections respectively. Mu2e Recycler Ring beam manipulations occur in the first eight 15 Hz ticks. NOνA proton batches are slip-stacked during the remaining twelve 15 Hz ticks. The total length of a cycle is 20 ticks = 1.333 sec.