Search for new physics in Mu2e experiment

JINR team

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Mu2e

Search for neutrinoless conversion of a muon into an electron in the field of a nucleus

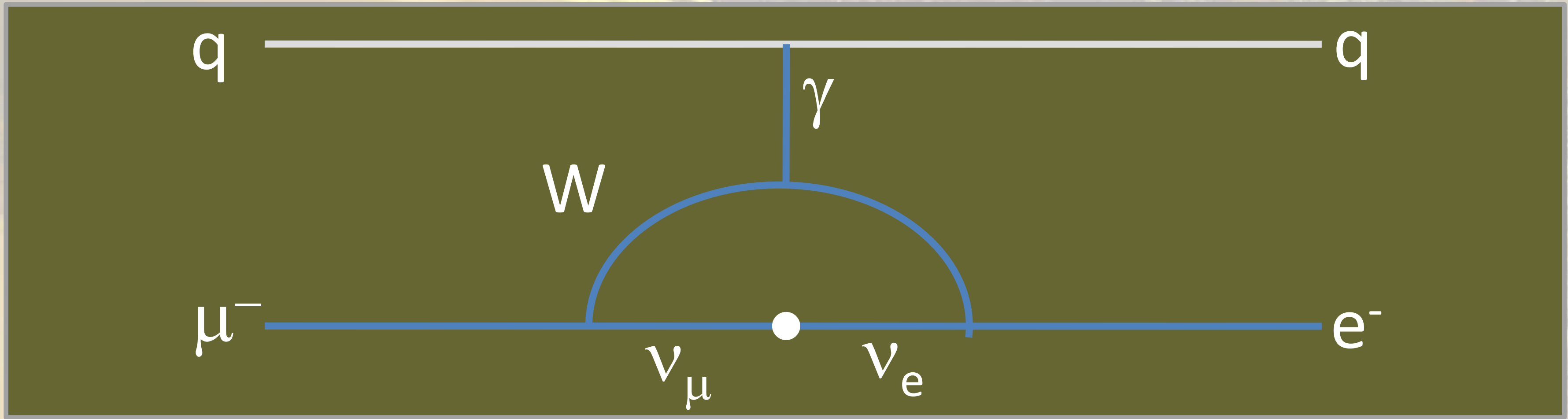
$$\mu^- N \rightarrow e^- N$$

Charged Lepton Flavor Violation

Flavor Violation

- We've known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by CKM matrix
- In last 15 years we've come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)

CLFV in the Standard Model

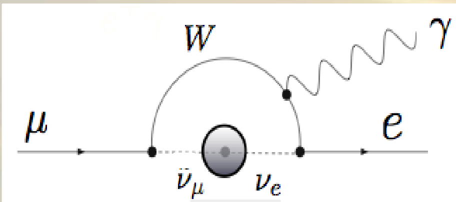


- Strictly speaking, forbidden in the SM
- Even in ν-SM, extremely suppressed

  (rate ~ $\Delta m_\nu^2 / M_w^2 < 10^{-50}$)
- However, most all NP models predict rates observable at next generation CLFV experiments

Mu2e : SM prediction and New Physics

The BR of CLFV processes in the Standard Model

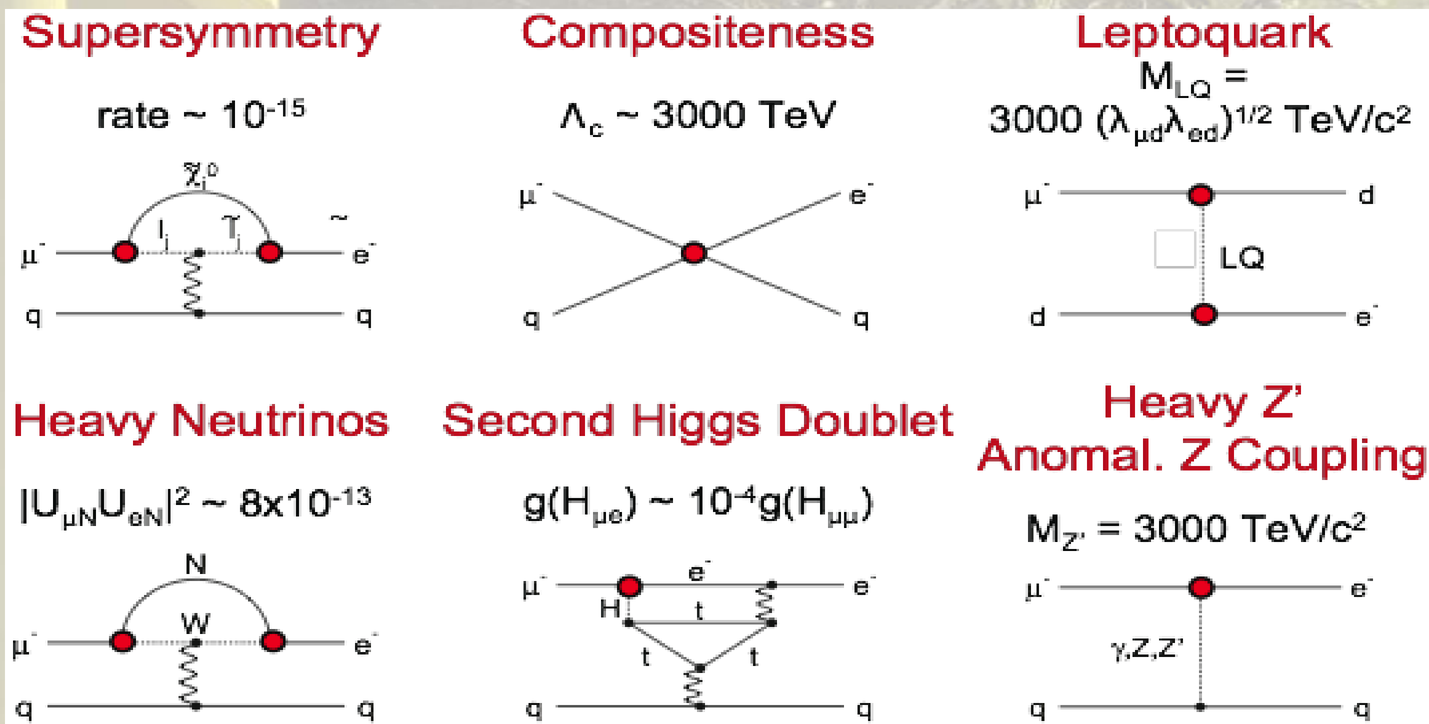


$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Mu2e sensitivity is $6*10^{-17}$

NP

Sensitive to mass scales up to O(10,000 TeV)



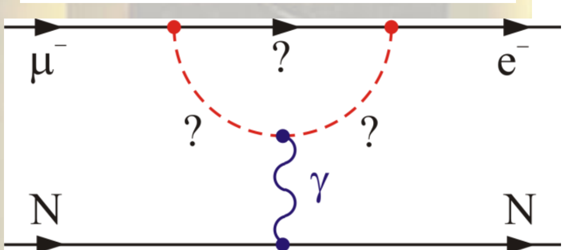
$$\mathrm{L_{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J.C57:13-182,2008

Mu2e : Sensitivity to High Mass Scales

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

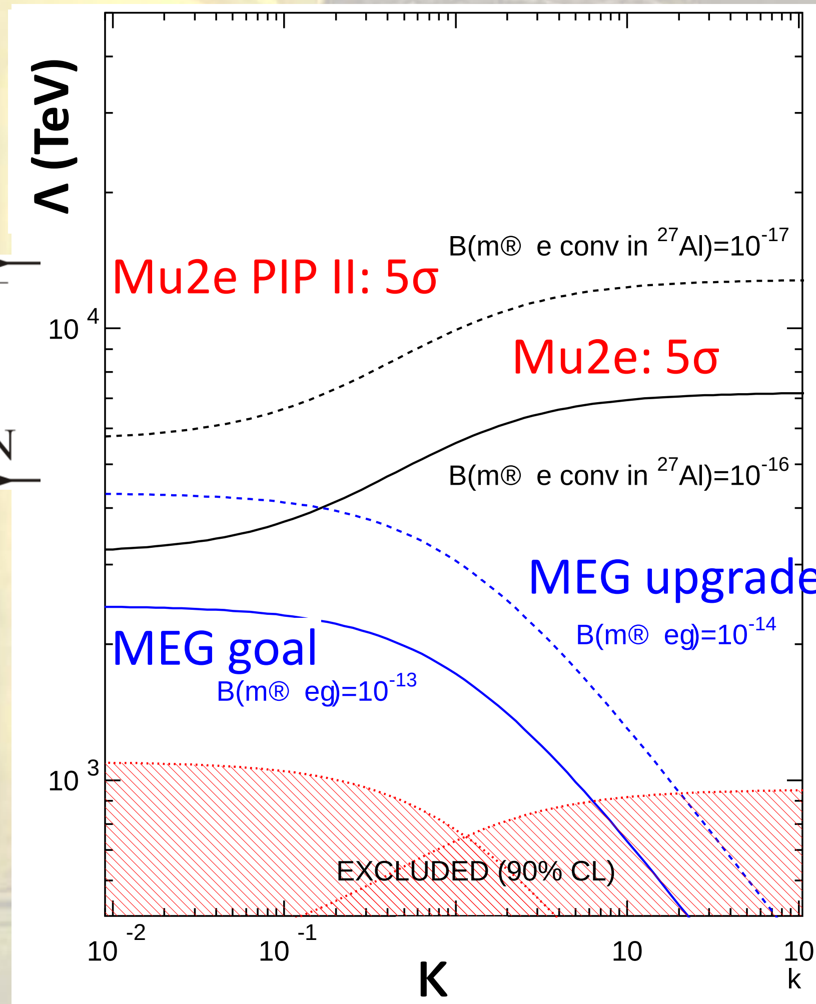
Loops dominate for κ << 1



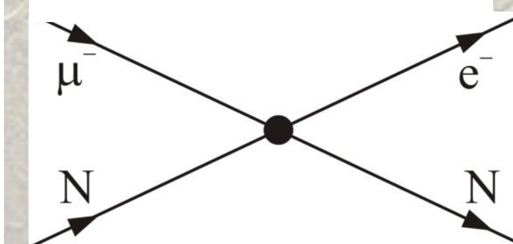
μ→eγ

μN→eN

μ→eee



Contact terms dominate for κ >> 1



μ→eγ

μN→eN

μ→eee

The great-grandparents of the Mu2e
(MELC, 1992; MECO, 1997)
are INR scientists
V.M. Lobashev and R.M. Djilkibaev

Владимир Михайлович Лобашёв
(29.07.1934–03.08.2011)

Mu2e Muon-to Electron Conversion

Mu2e will measure the ratio of the coherent neutrinoless muon-to-electron conversion rate to muon capture rate

muon converts to electron in the field of a nucleus

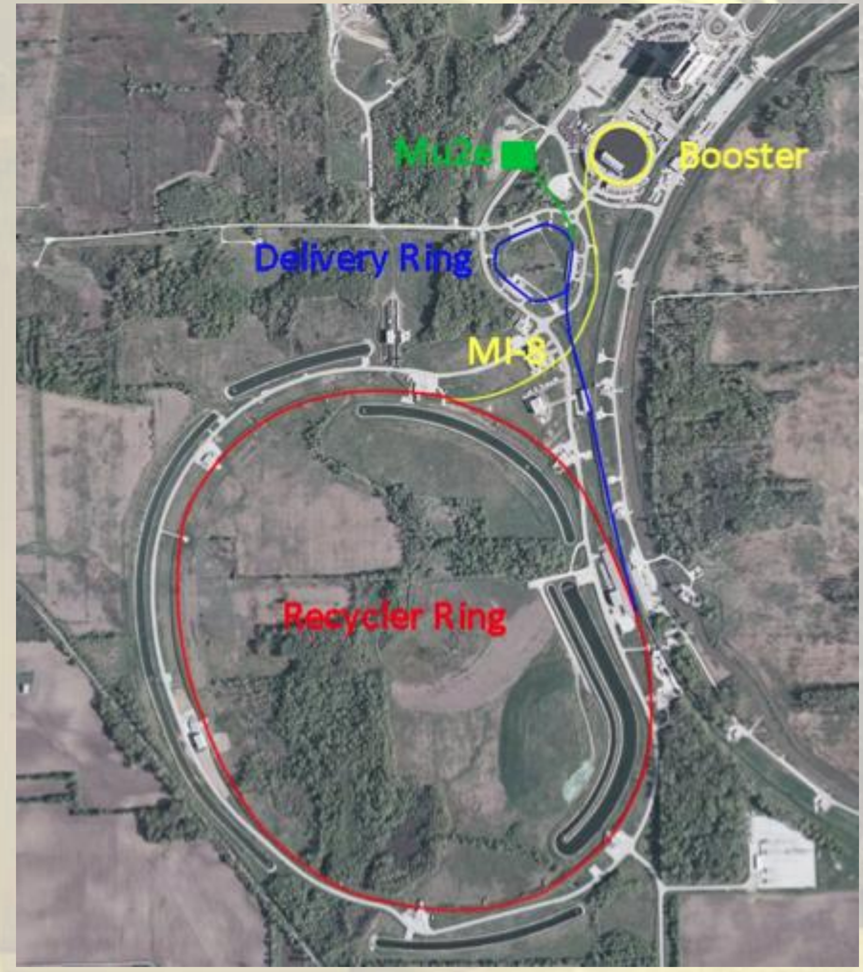
$$\mu^- N \rightarrow e^- N$$

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

- Charged Lepton Flavor Violation (CLFV)
  - manifest Beyond-Standard-Model physics
  - SES of 2.3×10^{-17}, 0.4 evt bkg; 6×10^{-17} at 90% CL

Requires about 10^{18} stopped muons; about 10^{20} protons on target

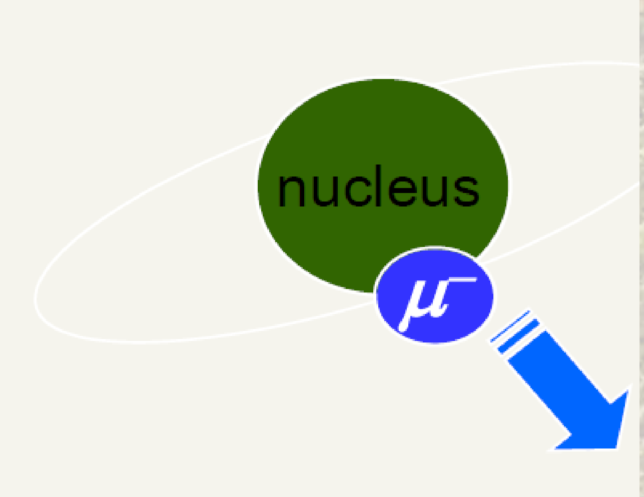
The Mu2e Proton Beam



- Mu2e begins by using protons to produce pions
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Mu2e can (and will) run simultaneously with NOvA.

The Measurement Method

- Stop negative muons in an aluminum target
- The stopped muons form muonic atoms
  - 207x smaller radius than inner e^- in Al–>
  - well inside electron orbits →
    muon forms a hydrogen-like atom, unaffected by e's
  - hydrogenic 1S : Bohr radius ~20 fm, BE~500 keV
  - Nuclear radius ~ 4 fm →
    muon and nuclear wavefunctions overlap significantly



- Three main things can happen (numbers for case of Al):
  - Muon decays (40%): $\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$
  - Muon captures on the nucleus (60%): $\mu^- + {}^{27}_{13}Al \rightarrow X + \nu_\mu (capture)$

  (capture is roughly sum of reactions with protons in nucleus: $\mu^- + p \rightarrow \nu_\mu + n$)
  - Muon to electron conversion: $\mu^- + {}^{27}_{13}Al \rightarrow {}^{27}_{13}Al + e^-$
- Muon lifetime in 1S orbit of aluminum ~864 ns

  (40% decay, 60% nuclear capture), compared to 2.2 μsec in vacuum
- Look for 105 MeV conversion electron signal $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$ E_e=104.96 MeV

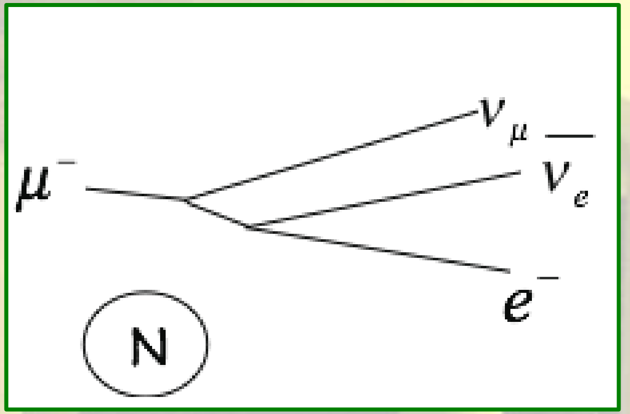
Backgrounds

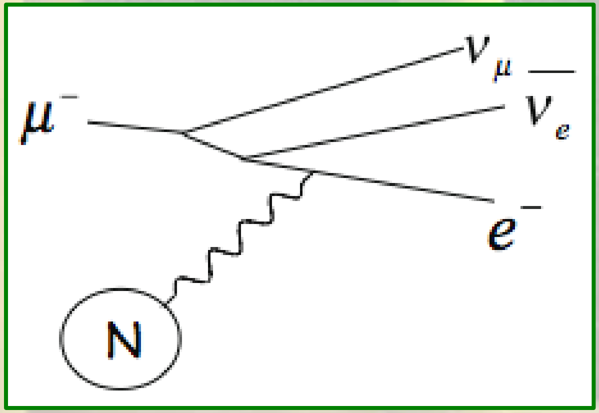
- Stopped Muon induced
  - Muon decay in orbit (DIO)
- Out of time protons or long transit-time secondaries
  - Radiative pion capture; Muon decay in flight
  - Pion decay in flight; Beam electrons
  - Anti-protons
- Secondaries from cosmic rays

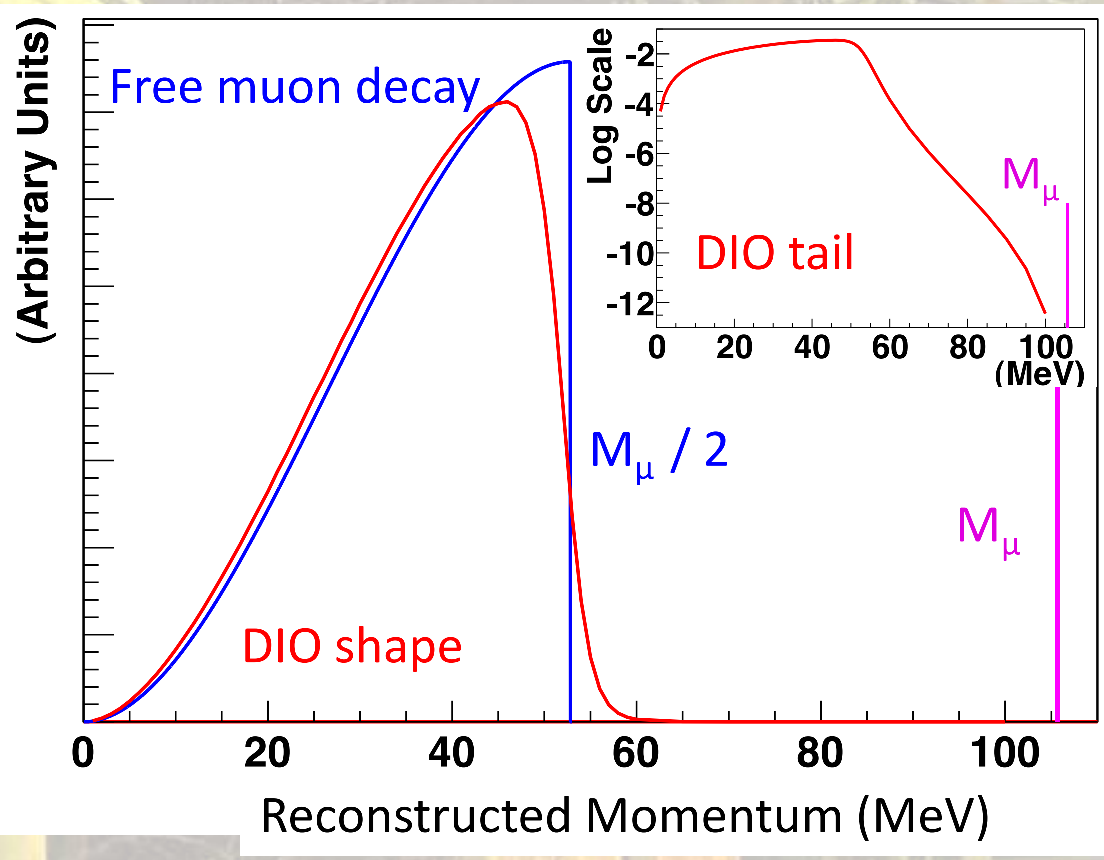
- Mitigation:
  - Excellent momentum resolution
  - Excellent extinction plus delayed measurement window
  - Thin window at center of TS absorbs anti-protons
  - Shielding and veto

Decay–in-Orbit: Dominant Background

DIO: Decay in orbit

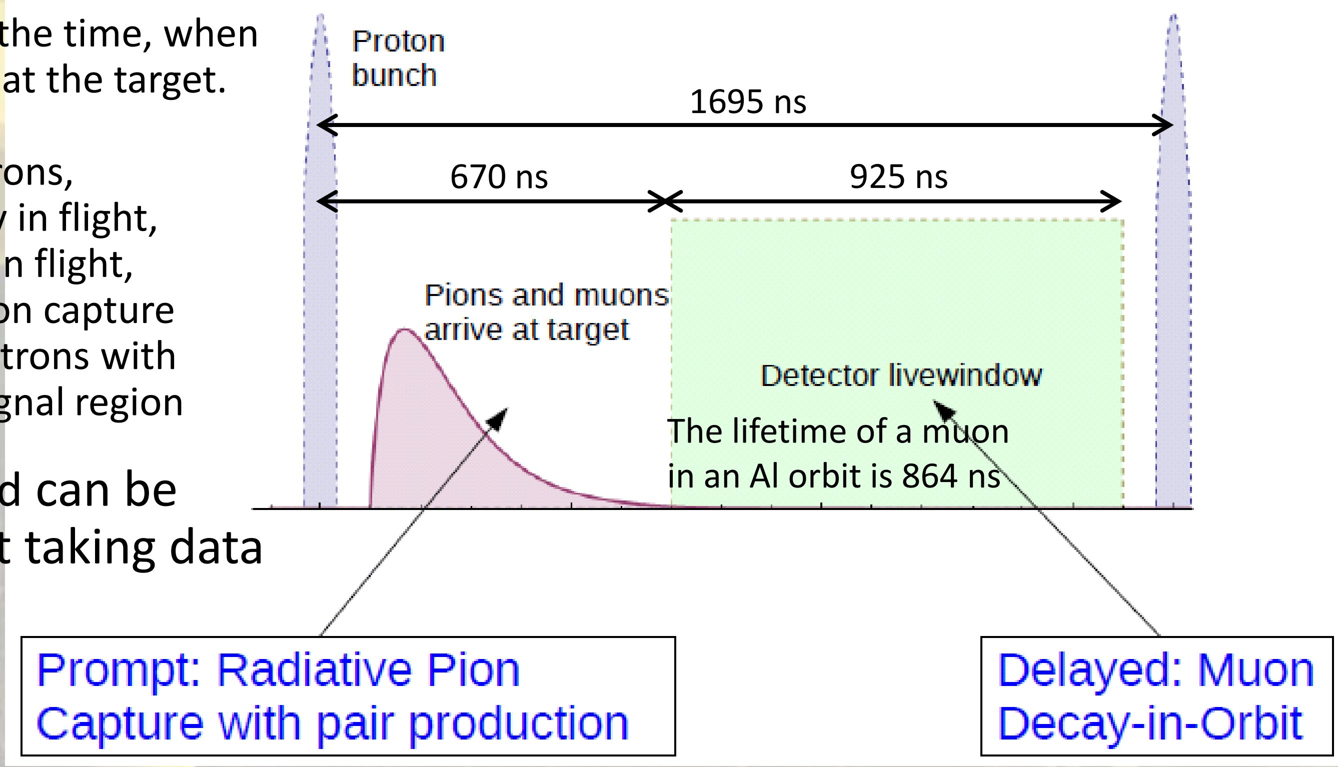






Prompt Background Suppression

- Prompt background
  - Happens around the time, when the beam arrives at the target.
  - Sources
    - beam electrons,
    - muon decay in flight,
    - pion decay in flight,
    - radiative pion capture
  - May creaste electrons with energies in the signal region



- Prompt background can be suppressed by not taking data during the first 670 ns after the peak of the proton pulse.

- However, this prompt background cannot be eliminated entirely, since some of the protons arrive “out of time”.
  - A ratio of 10^{-10} is required for the beam between pulses vs. the beam contained in a pulse.

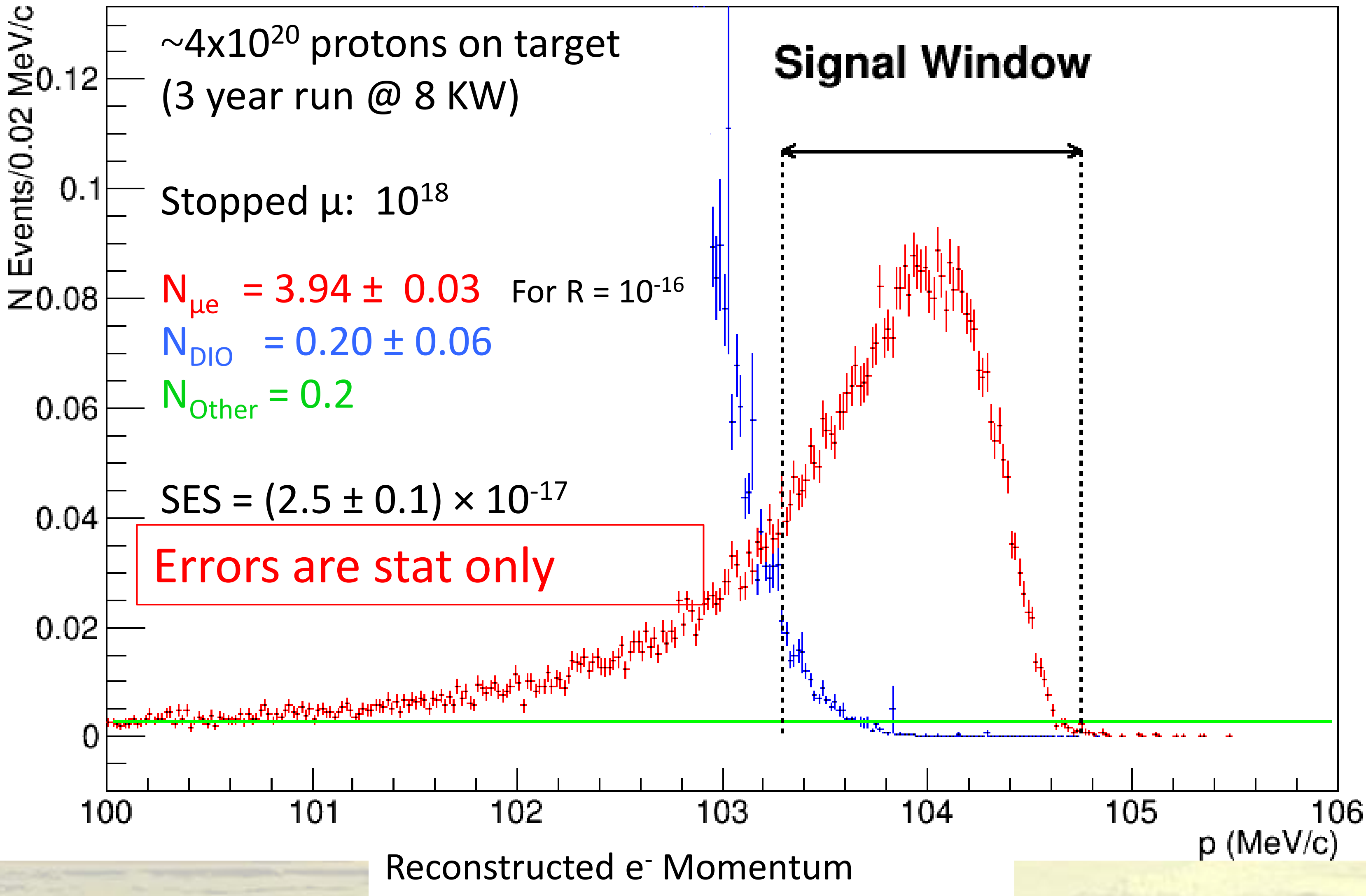
Backgrounds for 3 Year Run

Source	Events	Comment
μ decay in orbit (DIO)	0.20 ± 0.06	
Anti-proton capture	0.10 ± 0.06	
Radiative π^- capture*	0.04 ± 0.02	From protons during detection time
Beam electrons*	0.001 ± 0.001	
μ decay in flight*	0.010 ± 0.005	With e^- scatter in target
Cosmic ray induced	0.050 ± 0.013	Assumes 10^{-4} veto inefficiency
Total	**0.4 ± 0.1**	

All values preliminary; some are stat error only.

- * scales with extinction: values in table assume extinction = 10^{-10}

Signal Sensitivity for 3 Year Run



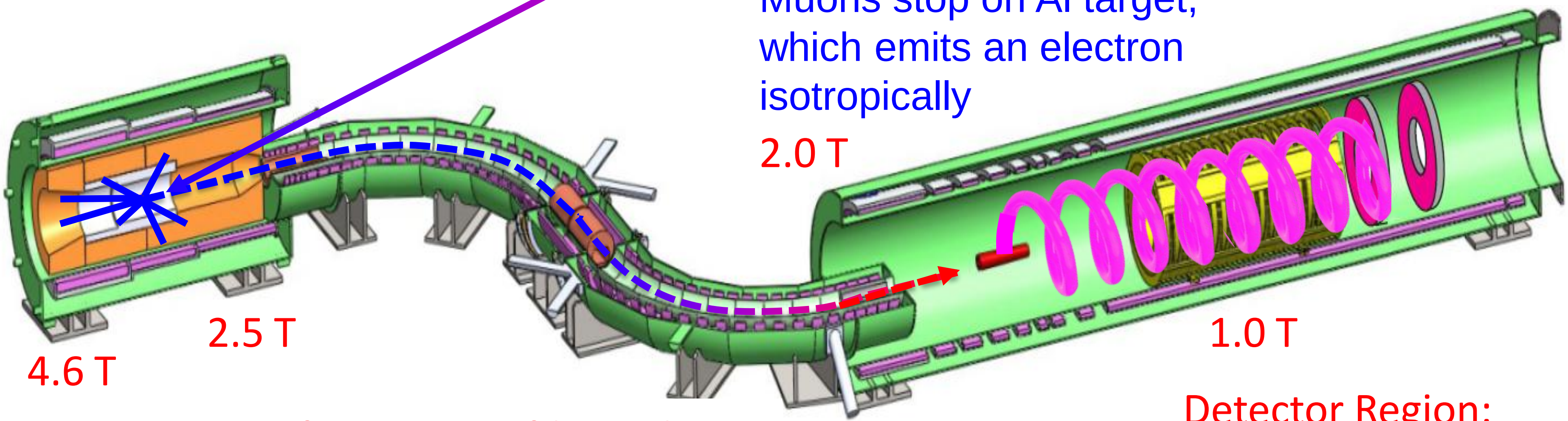
Baseline Mu2e Apparatus

8-GeV protons from delivery ring

about 25 meters end-to-end

Particles produced from tungsten target

Muons stop on Al target, which emits an electron isotropically



Graded B for most of length

Detector Region: Uniform Field 1T

S-shaped solenoid:

- transports particles to detector area, and
- allows remaining pions to decay to muons
- collimator selects negatively-charged particles

Tracker/calorimeter detect electron signature

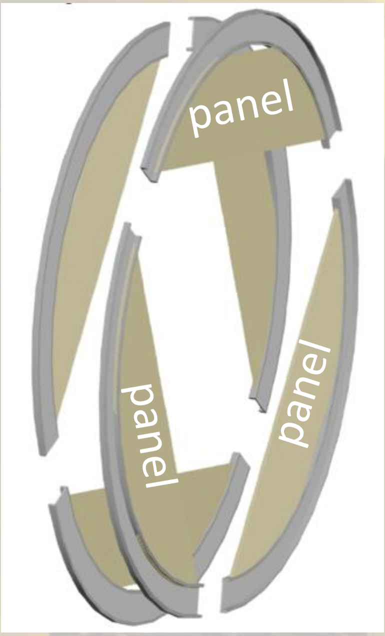
The Mu2e Tracker

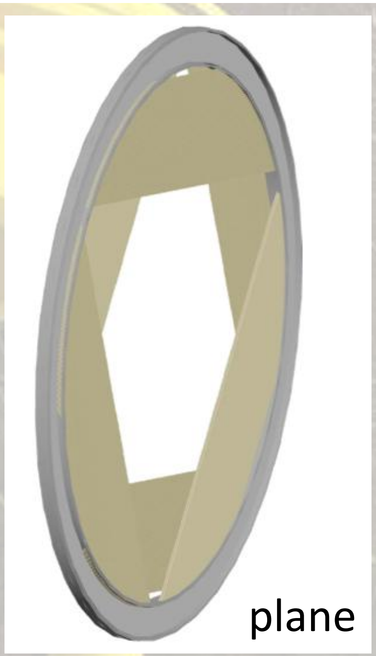
- Will employ straw technology
  - Low mass
  - Can reliably operate in vacuum
  - Robust against single-wire failures

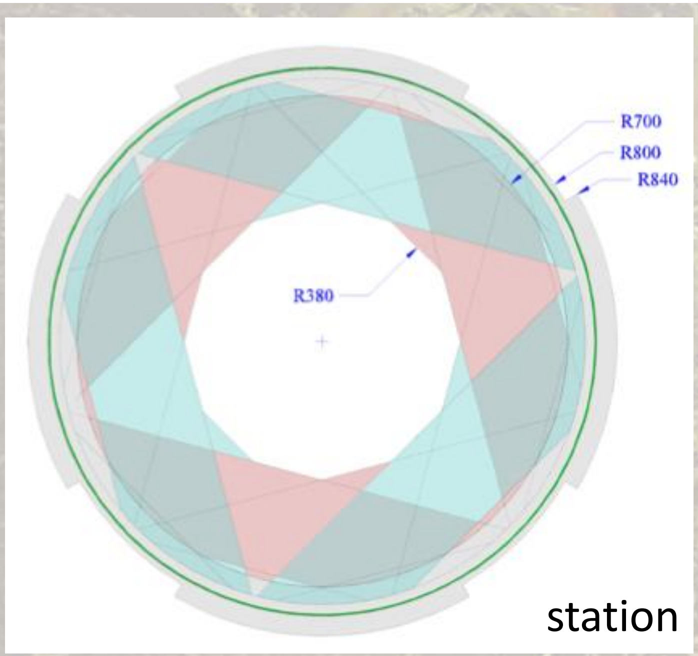
5 mm diameter straw

- **Spiral wound**
- **Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al**
- **25 μm Au-plated W sense wire**
- **33 – 117 cm in length**
- **80/20 Ar/CO2 with HV < 1500 V**

The Mu2e Tracker



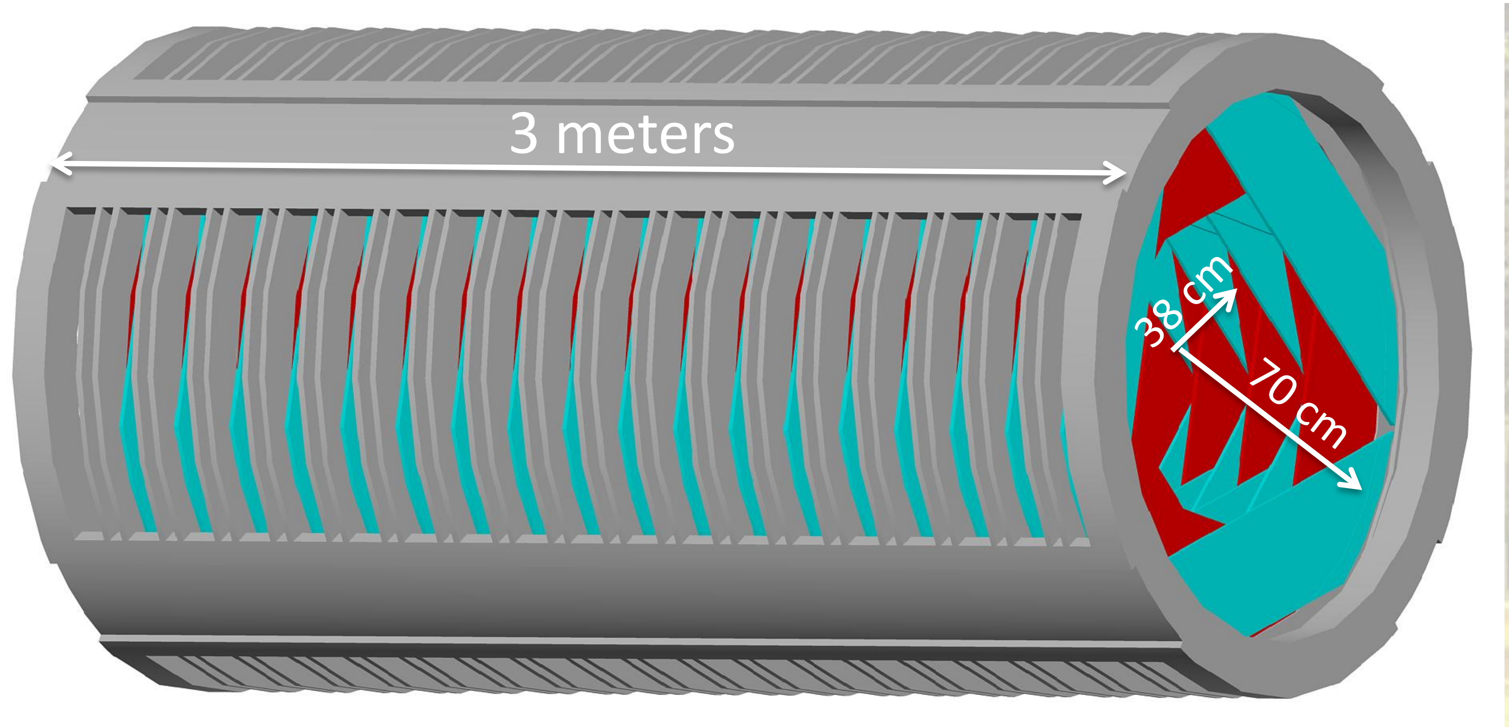




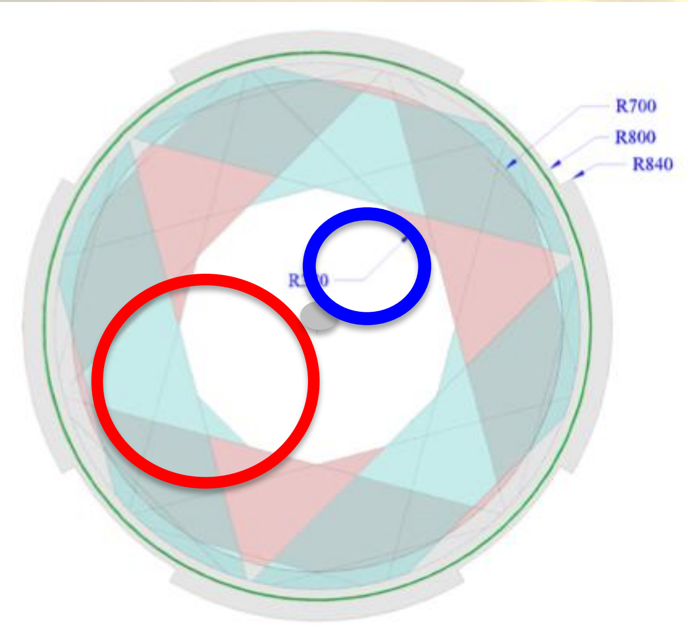
- Self-supporting “panel” consists of 100 straws
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- >20k straws total

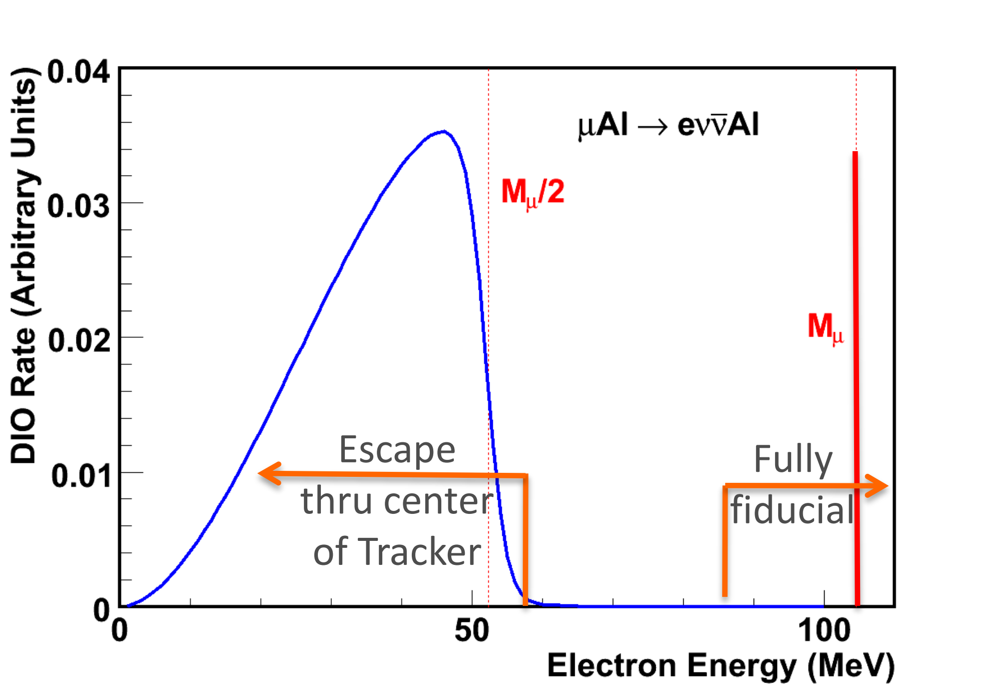
The Mu2e Tracker

- 18-20 “stations” with straws transverse to beam
- Naturally moves readout and support to large radii, out of active volume



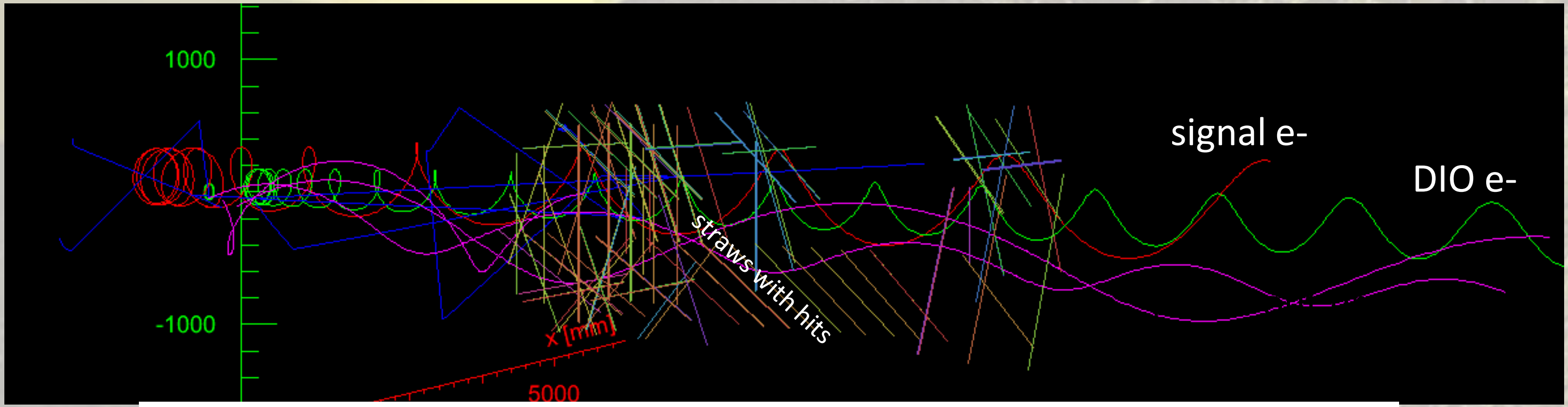
The Mu2e Tracker





- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

Mu2e Pattern Recognition



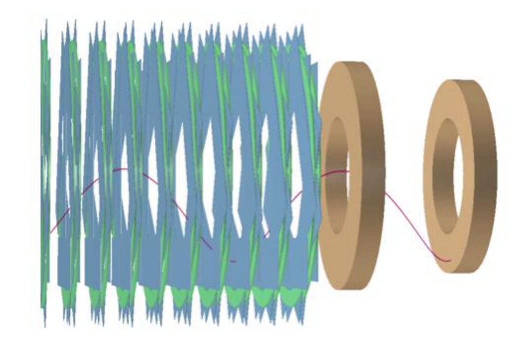
(particles with hits within +/-50 ns of signal electron t_{mean})

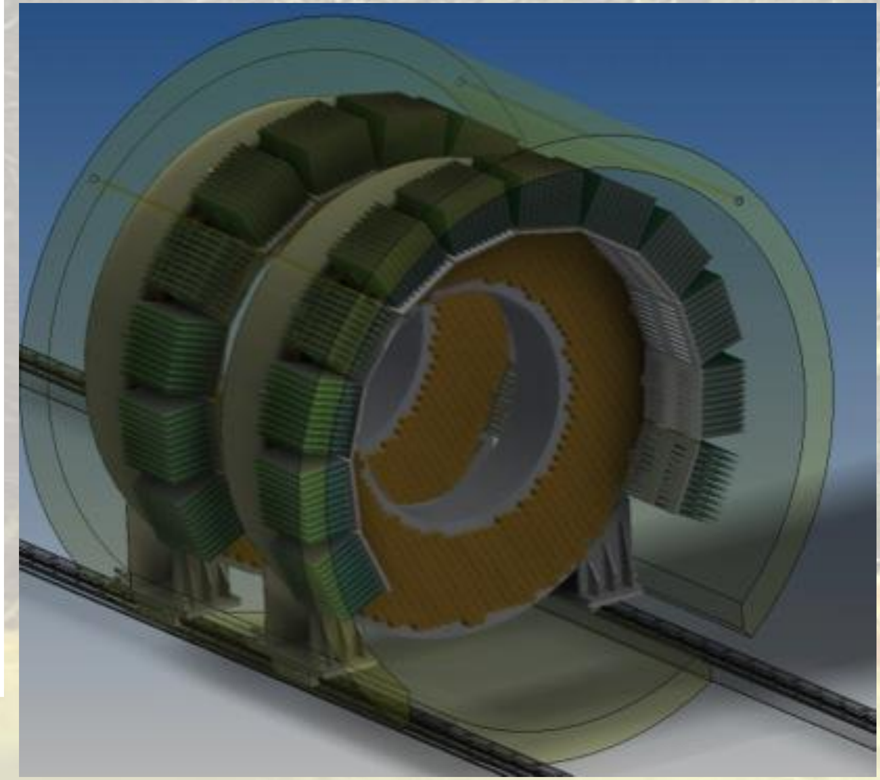
- We use timing information to look in +/- 50 ns windows – significant reduction in occupancy and significant simplification for Patt. Rec.

Mu2e Calorimeter

The Calorimeter consists of two disks with 1650 BaF_2 hexagonal crystals (30 mm x 200 mm):

- → R_{inner} = 351 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)
- → The distance between disks is optimized at ½ wavelength (70 cm)
- → Each crystal is readout by two large area APD's (9x9 mm^2) (3300 total)
- → Analog FEE and digital electronics are located in near-by electronics crates
- → Radioactive source and laser systems provide absolute calibration as well as fast and reliable monitoring capability





Mu2e Calorimeter

	LSO:Ce/LYSO:Ce	BaF_2	CsI
Density (g/cm^3)	7.40	4.89	4.51
Melting point (°C)	2050	1280	621
Radiation Length (cm)	1.14	2.03	1.86
Molière Radius (cm)	2.07	3.10	3.57
Interaction Length (cm)	20.9	30.7	39.3
Z_{eff}	64.8	51.6	54.0
dE/dX (MeV/cm)	9.55	6.52	5.56
Emission Peak[a] (nm)	420	300 220	310
Refractive Index[b]	1.82	1.50	1.95
Relative Light Yield[a]	100	42 4.8	4.2
LY in 1st ns (photons)	740	960	100
Decay Time[a] (ns)	40	650 0.9	26
d(LY)/dT [c] (%/°C)	-0.2	-1.9 0.1	-1.4

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C)

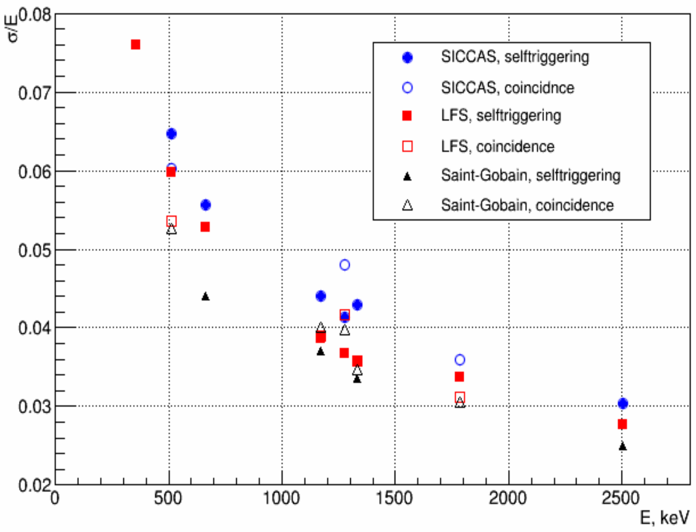
Mu2e Calorimeter

Barium Fluoride (BaF_2)

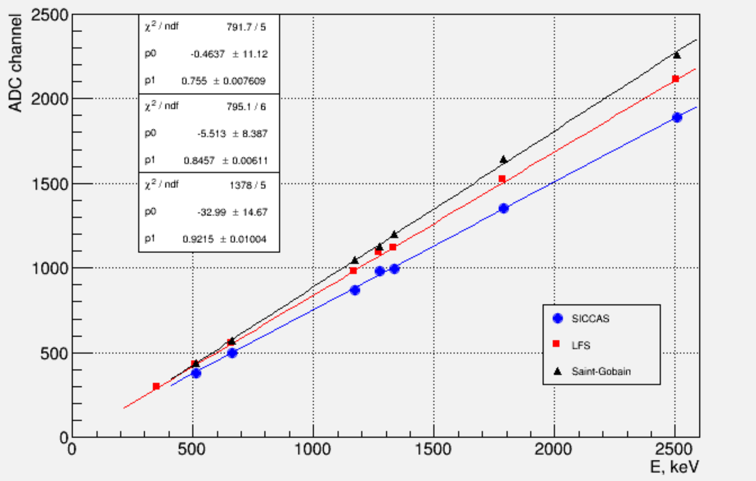
- Radiation hard, non-hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be “solar”-blind
- Crystal dimension: hexagonal faces of 33 mm across flats, 200 mm length (10 X_0)

	BaF_2
Density (g/cm^3)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.29)% / °C

JINR R&D



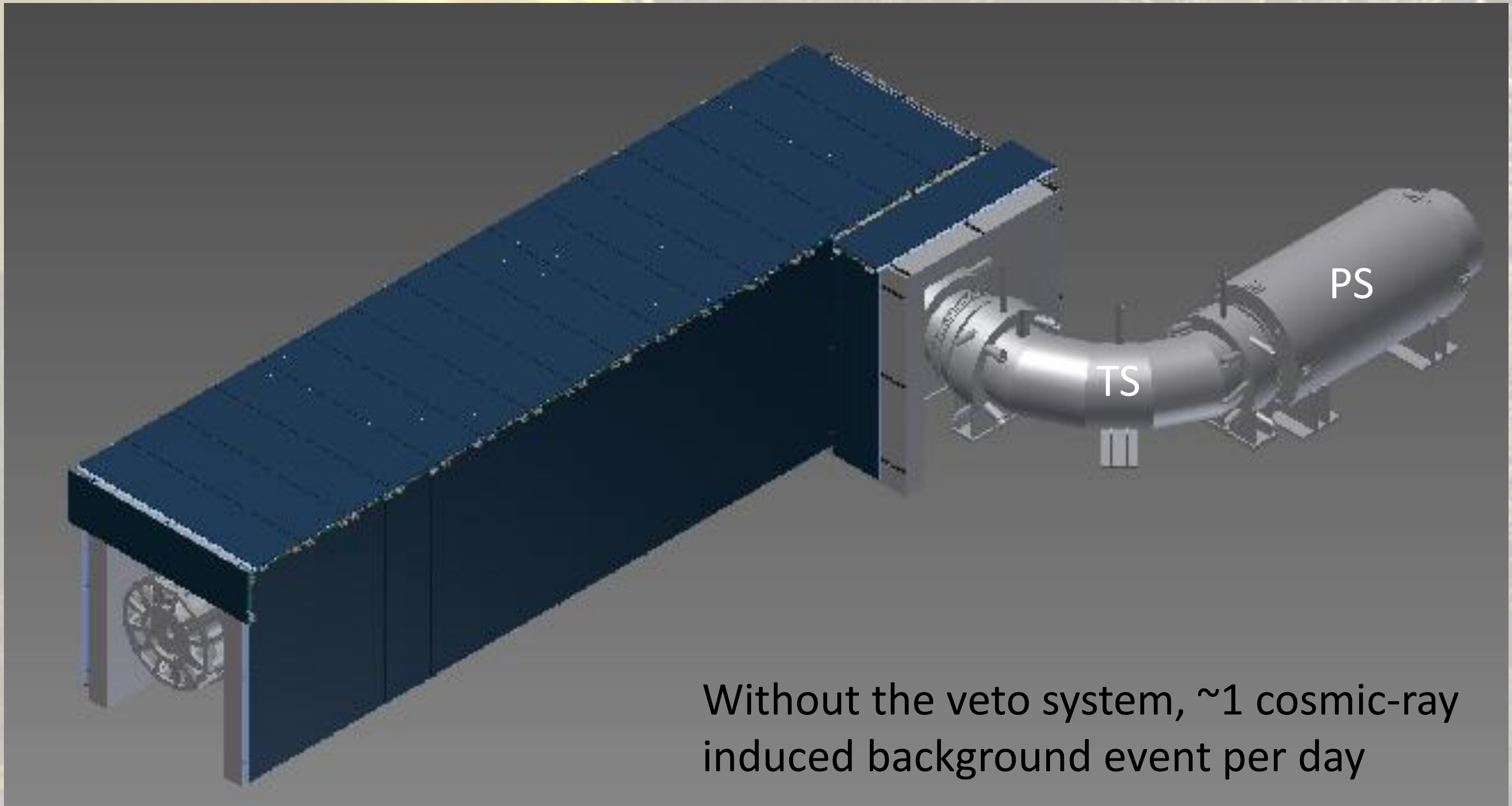
Energy resolutions of LYSO:Ce crystals from Saint-Gobain and SICCAS and LFS crystal from Zecotek.



Energy response linearity of the same three crystals in the 511-2500 keV energy range.

- **R.J. Abrams et al., “Mu2e Conceptual Design Report”, arXiv:1211.7019 (2012).**
- **J. Budagov et al., “The calorimeter project for the Mu2e experiment”, Nucl. Instr.&Meth. A718(2013) 56-59.**
- **O. Sidletskiy et al., “Evaluation of LGSO:Ce scintillator for high energy physics experiments”, Nucl. Instr.&Meth. A735(2014) 620-623.**
- **K. Afanaciev et al., “Response of LYSO:Ce scintillation crystals to low energy gamma-rays”, JINR preprint E13-2013-141, Dubna, 2013. Submitted to Nucl. Instr.&Meth. A.**
- **Z. Usubov, “Electromagnetic calorimeter simulation for future μ→e conversion experiments”, arXiv:1212.4322 (2012).**
- **Z. Usubov, “Light output simulation of LYSO single crystal”, arXiv:1305.3010 (2013).**

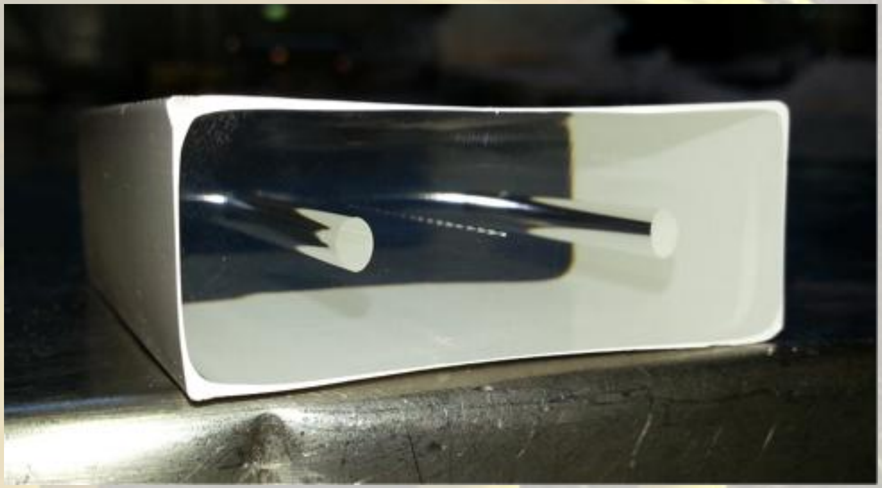
Mu2e Cosmic-Ray Veto

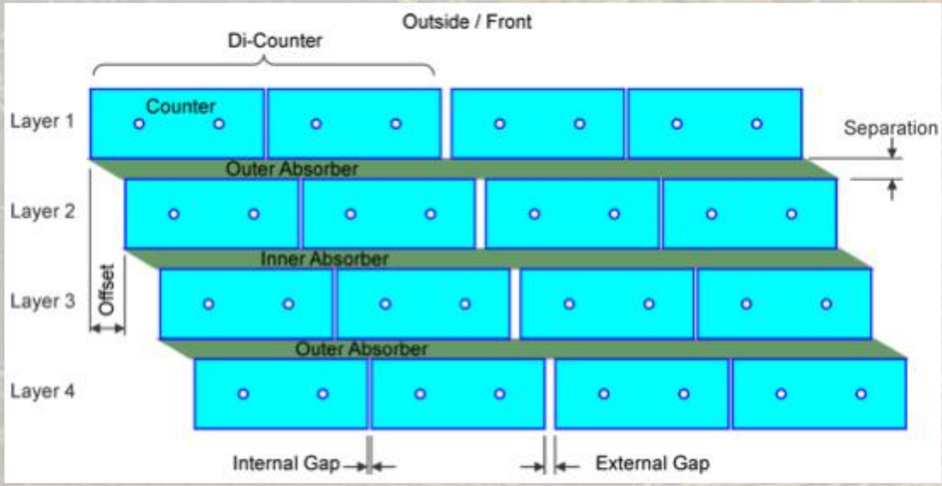


Without the veto system, ~1 cosmic-ray induced background event per day

- Veto system covers entire DS and half TS

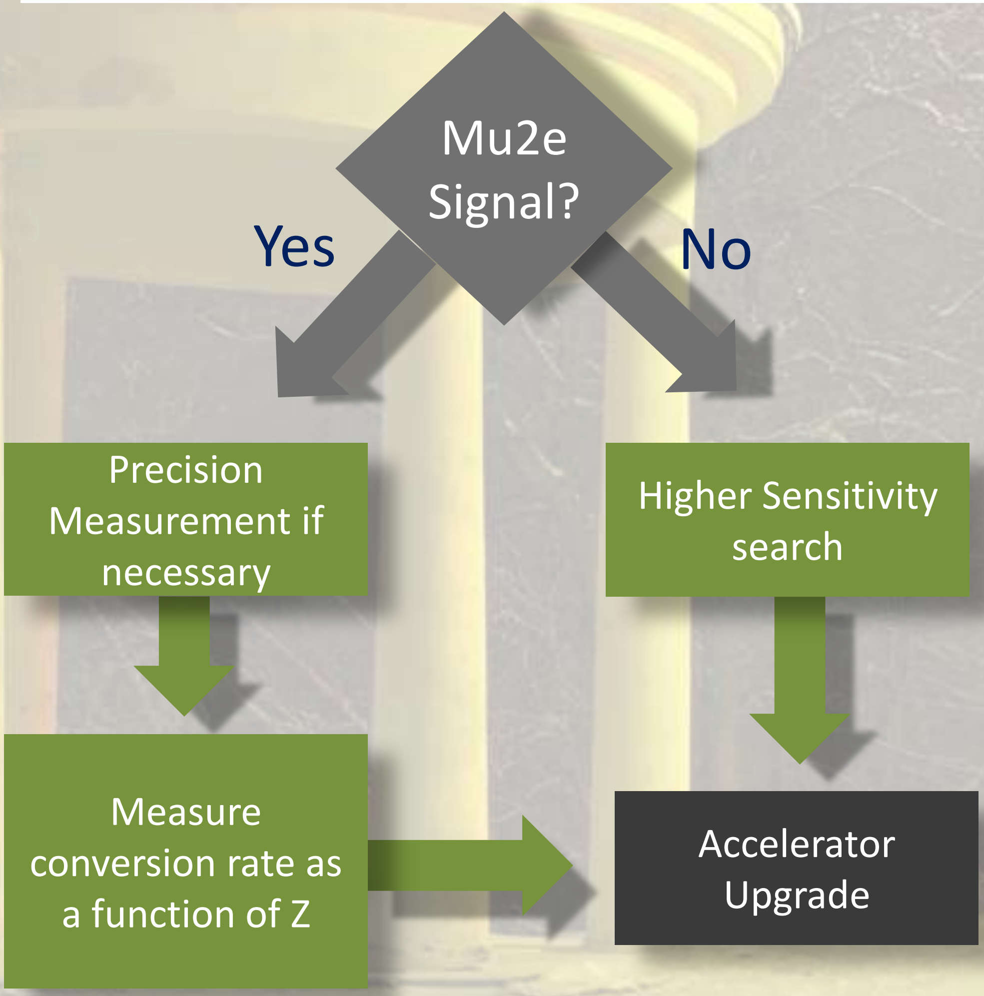
Mu2e Cosmic-Ray Veto





- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam

What next?



- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons → upgrade accelerator

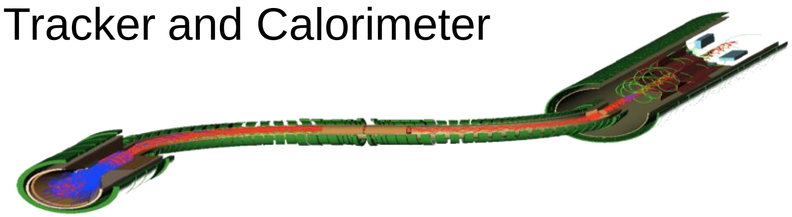
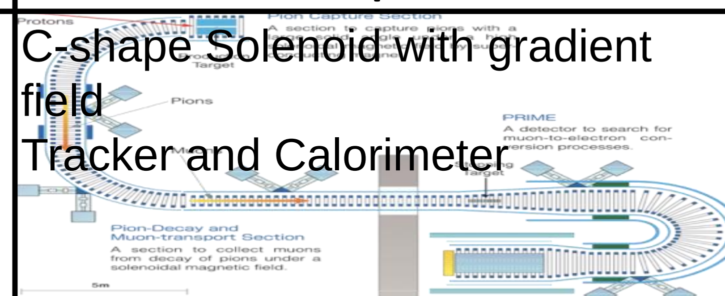
Summary

The Mu2e experiment:

- Improves sensitivity by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- Is complementary to LHC, heavy-flavor, and neutrino experiments

BACKUP

Mu2e / COMET comparison

	Mu2e	COMET
approval/ funding	**ranked among the very top priorities for the U.S. HEP program** P5 Report 2014 "Complete the Mu2e and g-2 projects." Mu2e is *fully funded in all budget scenarios* The DOE is committed to completing Mu2e	**COMET phase-II funding has not been identified** and Japan has clearly stated that their top priorities are Belle-II, long baseline neutrinos, and ILC
Operation Condition	**Mu2e will run simultaneously with NOvA and the short-baseline neutrino program at Fermilab**	**COMET cannot run simultaneously with the JPARC neutrino program. It forces COMET to plan for higher beam power in order to minimize the amount of required beam time**
Detector	Straight Solenoid with gradient field Tracker and Calorimeter 	C-shape Solenoid with gradient field Tracker and Calorimeter 

Mu2e is equally sensitive to e- and e+ and thus have an additional physics channel $\mu^- N \rightarrow e^+ N'$ and will be able to measure in situ some background components (e.g. $\pi^- N \rightarrow \gamma N' \rightarrow e^- e^+ N'$)

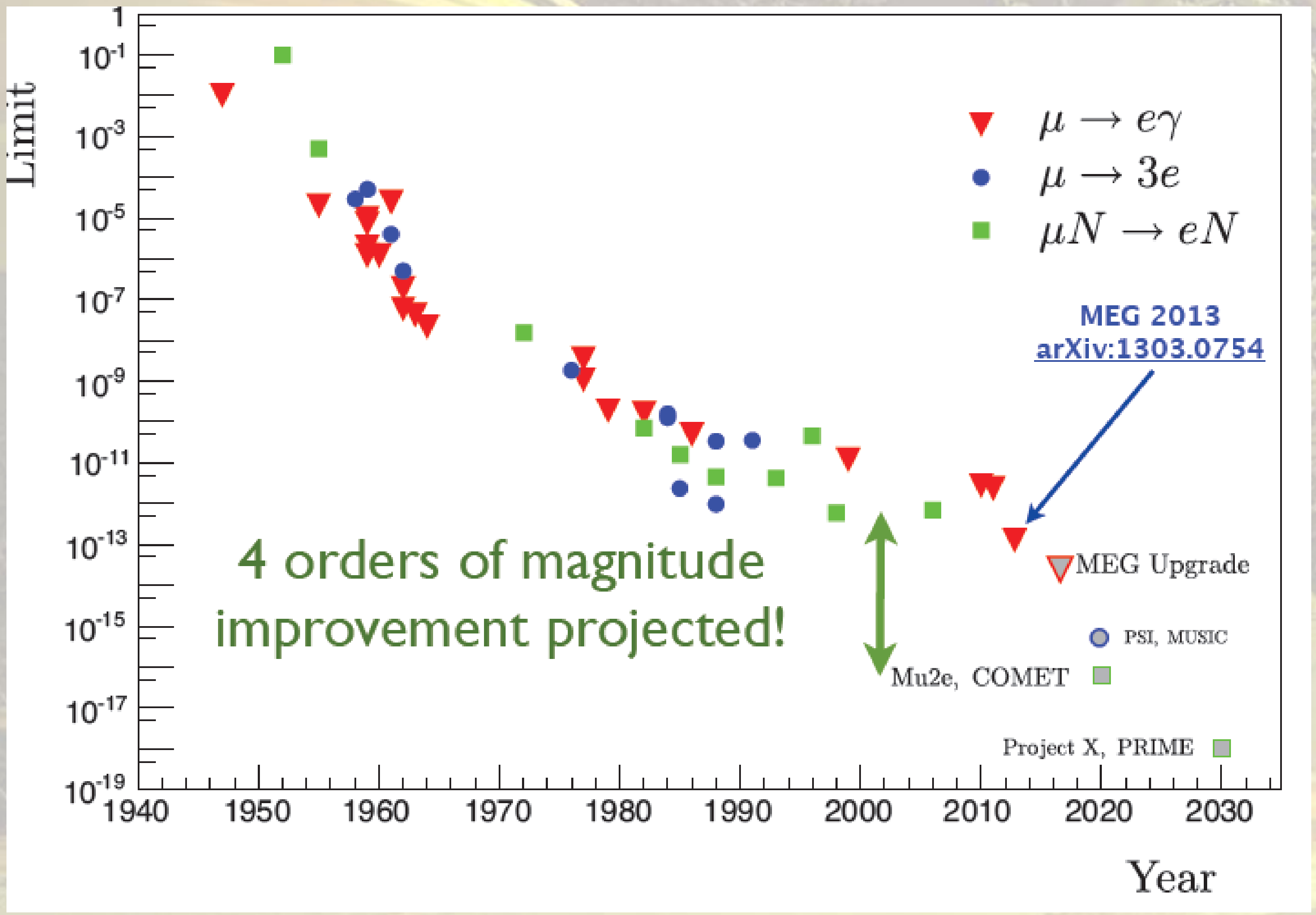
the COMET solenoids, particularly their production solenoid, is more technically risky (e.g. they will use a 9 (!) layer coil, Mu2e is 3 layer).

Comparison of COMET Phase-I / Phase-II and Mu2e

90% C.L. upper limit is 7×10^{-13} (SINDRUM)

	S.E. sensitivity	BG events at aimed sensitivity	running time (sec)	Year	Comments
COMET Phase-I	3×10^{-15}	0.03	1.5×10^{6}	~2016	Proposal (2012)
COMET Phase-II	3×10^{-17}	0.34	2×10^{7}	~2019	CDR (2009)
Mu2e	3×10^{-17}	0.4	3x (2×10^{7})	~2019	J. Miller's talk at SSP2012

Status of CLFV Searches



Mu2e / COMET comparison

- Mu2e employs Booster batches left unused by the Fermilab neutrino program
  - **Mu2e will run simultaneously with NOvA and the short-baseline neutrino program at Fermilab**
  - All these program can simultaneously get the protons they need to meet their physics goals
  - **Mu2e can run at lower beam power**
    - **Saves significant money, reduces detector rates, simplifies solenoids, strengthens physics program**

- **COMET cannot run simultaneously with the JPARC neutrino program**
  - Either one or the other can take data
  - **Forces COMET to plan for higher beam power in order to minimize the amount of required beam time**
    - More complicated solenoid system, need to mitigate detector rates with a C-shaped detector solenoid, which significantly reduces their acceptance for e+

Mu2e and Muon g-2 work together

Example:

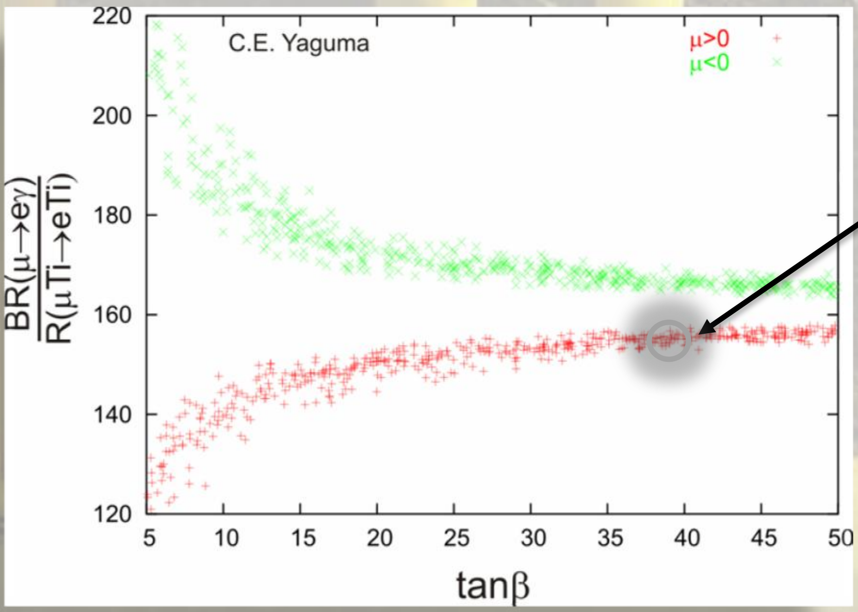
SUSY contributes to a_μ= (g-2)/2

- From g-2 we know tan β
- From g-2 we know also know μ>0
- From Mu2e we measure

  R(μ N → e N) and take the ratio to the MEG result

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\text{GeV}}{M_{SUSY}}\right)^2 \tan\beta \ \text{sign}(\mu)$$

We use this match to prediction as a way to disentangle, or validate, or interpret manifestations of SUSY



MSSM/msugra/seesaw

g-2 selects which curve we should be on, and gives us the value of tan β

tan β - the ratio of the vacuum expectation values of the two Higgs doublets

Sign(μ) - the sign of the higgsino mass parameter

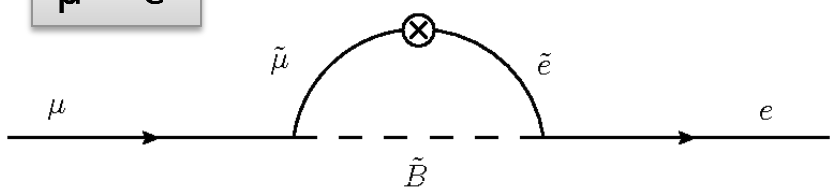
Mu2e and Muon g-2 work together

Gives us access to Slepton Mixing Matrix elements

Slepton Mixing Matrix

$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{e}\tilde{\mu}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

μ→ e



g-2