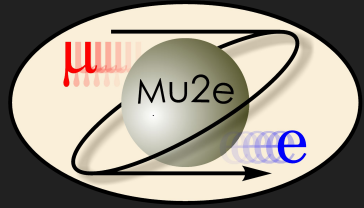


The Mu2e Experiment

Cole Kampa
Northwestern University
for the Mu2e Collaboration

New Perspectives 2021
August 19, 2021

Conceptual Overview of Mu2e

- Muon converts to electron in the field of a nucleus
- Does not conserve muon number or electron number -- Charged Lepton Flavor Violation (CLFV)
- (Very) rare process
- An observation of the Mu2e signal process is unambiguous evidence of physics Beyond the Standard Model.
- Discovery experiment capable of improving current limit by factor 10,000
  - Pulsed proton beam
  - High intensity muon beam
  - Accurate momentum measurement

Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.23E-13
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

Current limit

Mu2e goal

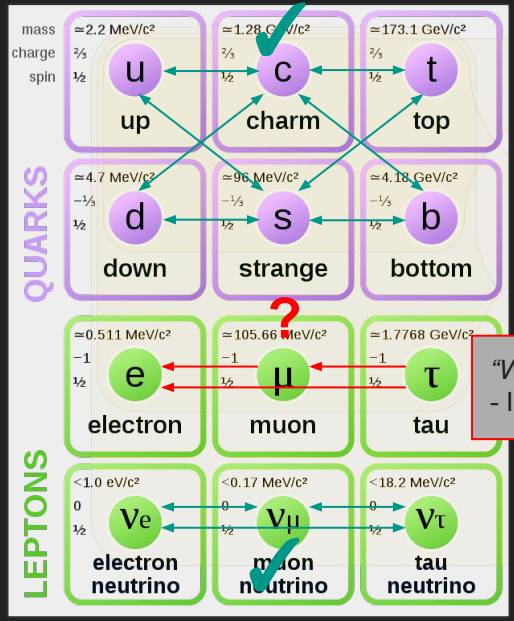
The Mu2e Experiment at Fermilab

- An international collaboration of 237 members from 38 institutions
- Strong early-career presence
  - Young Mu2e group advocates for early-career members (≥30% of collaboration in Young Mu2e)

- US DOE flagship experiment at Fermilab
- Part of the cutting-edge muon campus

Charged Lepton Flavor Violation (CLFV)

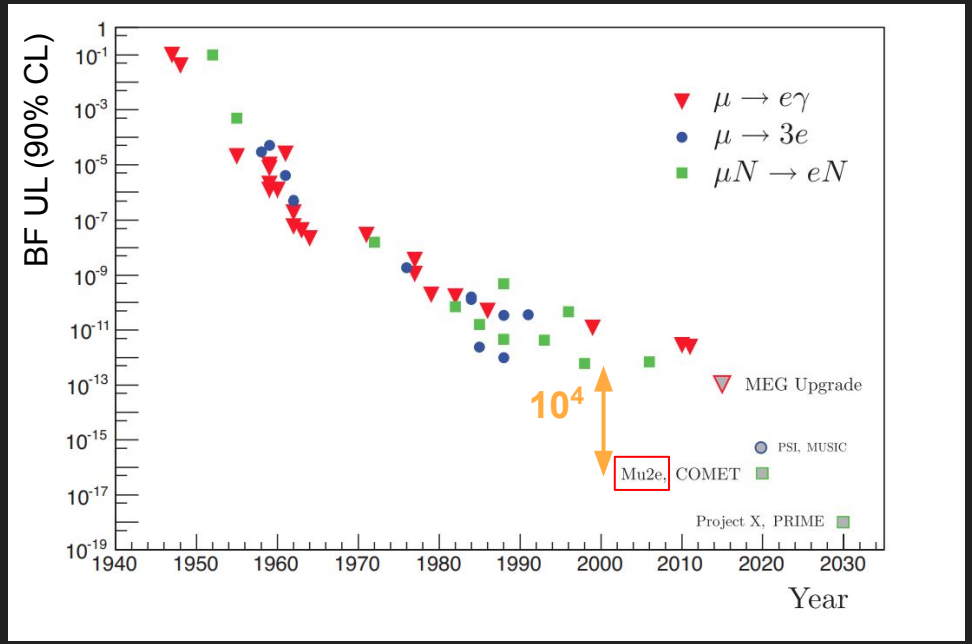
- Flavor conservation is interesting
  - Quark mixing ✓
  - Uncharged leptons (neutrino oscillation) ✓
  - Charged leptons ?
- **Do charged leptons conserve flavor?**
- Many models beyond the Standard Model speculate CLFV within reach of current generation of experiments



"Who ordered that?"
- I. I. Rabi

CLFV Landscape: Muons

- Parameterize with EFT terms added to the Lagrangian
  - Loop term
  - Contact term
- Λ mass scale -- Mu2e will probe $\Lambda \sim 10^4$ TeV
- κ tunes relative contribution from each term



[Bernstein and Cooper; arXiv:1307.5787]

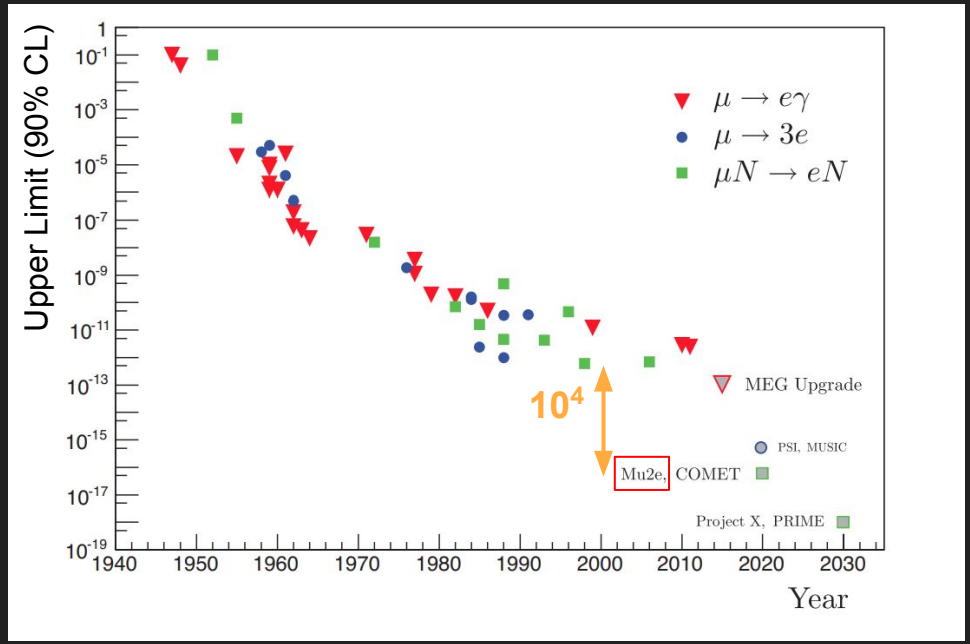
Loop term Contact term

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L\right)$$

[de Gouvêa and Vogel; arXiv:1303.4097]

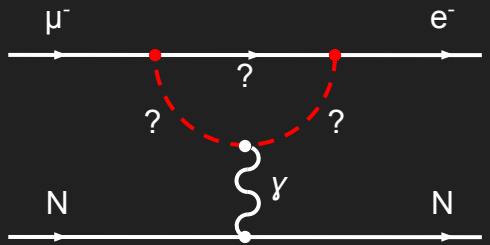
CLFV Landscape: Muons

- Parameterize with dimension six EFT terms added to the SM Lagrangian ($\propto 1 / \Lambda^2$)
  - Loop term: e.g. SUSY, heavy ν's ...
  - Contact term: e.g. leptoquarks, heavy Z ...
- **Mu2e sensitive to both types of terms**
- Λ mass scale -- **Mu2e will probe $\Lambda \sim 10^4$ TeV**

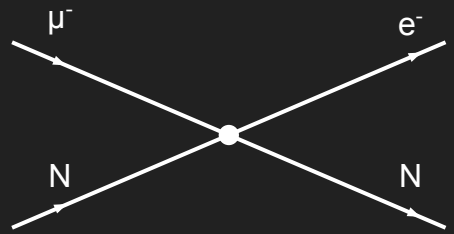


[Bernstein and Cooper; arXiv:1307.5787]

Loop term



Contact term



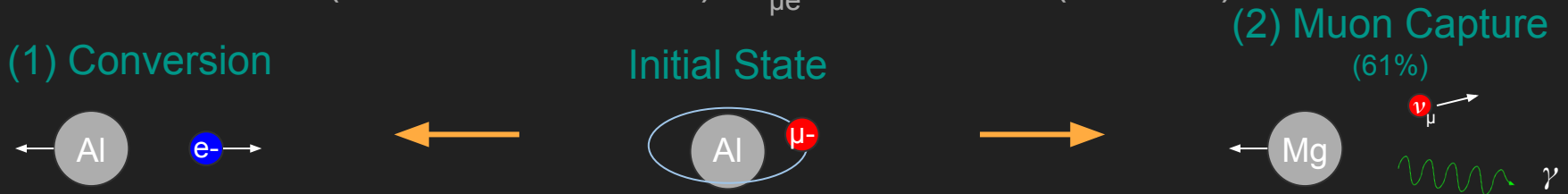
[see e.g. de Gouvêa and Vogel; arXiv:1303.4097]

Characterizing the Mu2e Signal

- Initial state is a muon in the Coulomb field of an Al nucleus
- The muon interacts coherently with the nucleus
- Final state is a mono-energetic electron with $p \cong m_{\mu}$
- Measure ratio of signal events to muon capture on the nucleus:

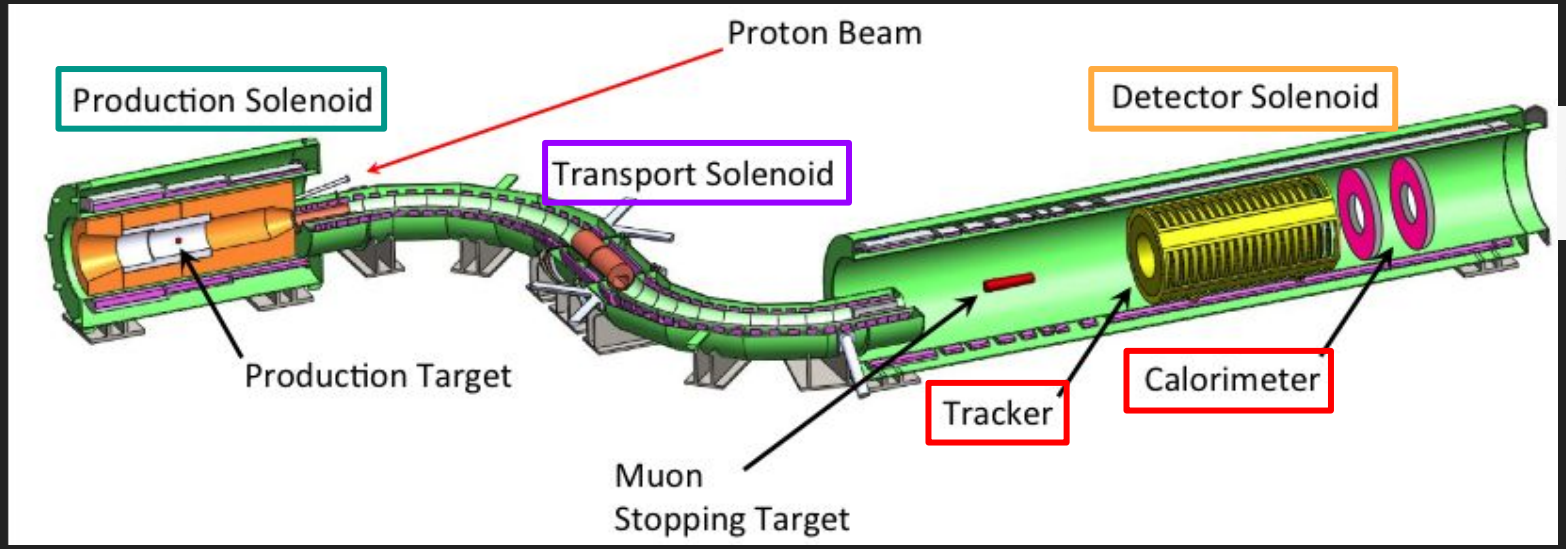
$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)} \quad \begin{matrix}(1)\\(2)\end{matrix}$$

- Current limit (SINDRUM-II on Au): $R_{\mu e} < 7 \times 10^{-13}$ (90% CL)



Experimental Design

- Two superconducting solenoids create and manipulate the muon beam, while the third is designed to stop muons and direct electrons to detectors
- Detectors measure the momentum and energy of outgoing electrons



Transport Solenoid Critical Lift (August 2021)

https://twitter.com/Mu2eExperiment/status/1423045896305053703

Backgrounds Overview

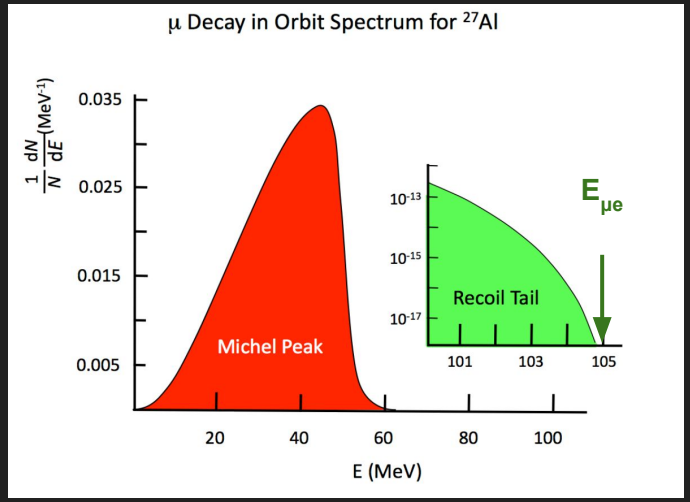
1. Intrinsic backgrounds -- scale with the number of stopped muons
   a. Muons
      i. Decay-in-Orbit (DIO)

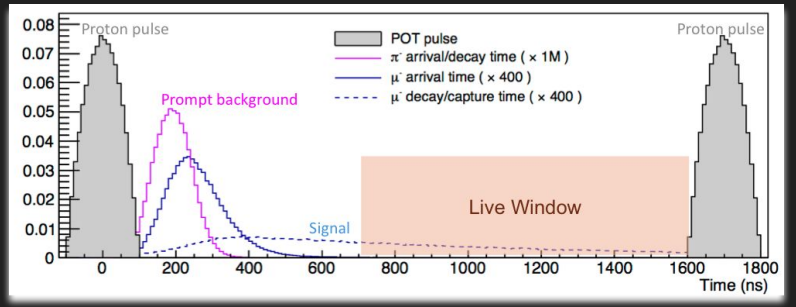
         ⇨ Motivates detector design

      ii. Radiative Muon Capture (RMC)
2. Beam-related backgrounds (formation of muon beam) / prompt backgrounds
   a. Pions
      i. Radiative Pion Capture (RPC)

         ⇨ Motivates beam design (pulsed)

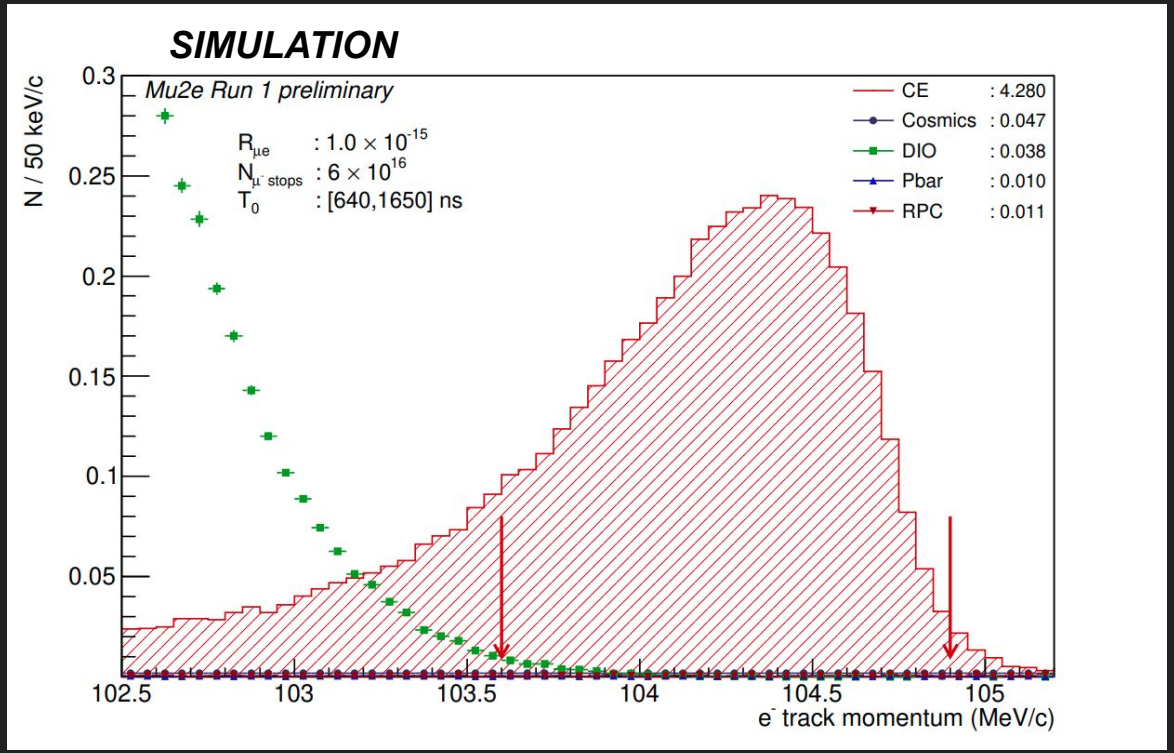
   b. Antiprotons
3. Cosmic ray muons -- scale with detector live-time





Electron Momentum Spectrum

- Run 1 = ~10% of full dataset
- Analysis cuts optimized for mean 5σ discovery



Sensitivity Estimate for Run 1 (10% Data)

Single Event Sensitivity (signal):

SES = 2.7×10^{-16}

Median Discovery:

$R_{\mu e} = 1.1 \times 10^{-15}$

≥ 5 signal events for a discovery

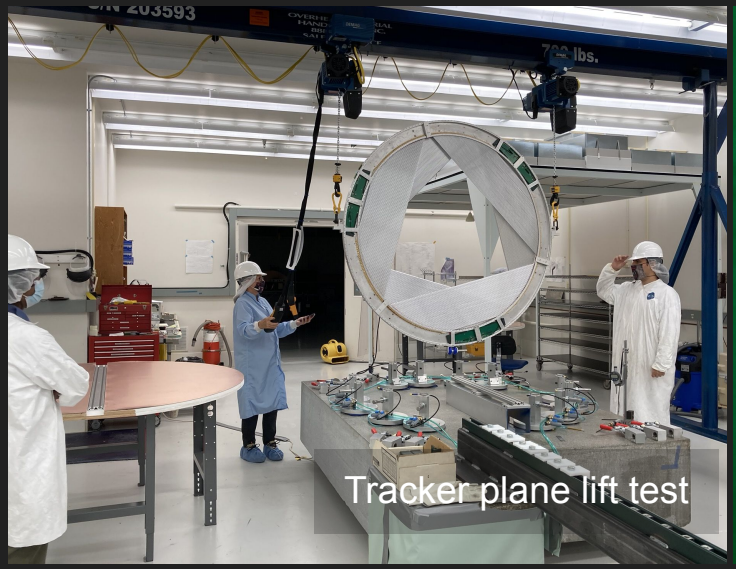
Upper Limit (90% CL):

$R_{\mu e} < 5.9 \times 10^{-16}$

Run 2 will improve discovery potential by x10

Channel	Mu2e Run 1 Background Expectation
Cosmics	$0.047 \pm 0.010\ (\text{stat}) \pm 0.009(\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})^{+0.026}_{-0.016}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat})\ ^{+0.010}_{-0.004}\ (\text{syst})$
RPC in-time	$0.011 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.003}\ (\text{syst})$
RPC out-of-time	negligibly small
RMC	negligibly small
Beam electrons	negligibly small
Total	$0.106 \pm 0.032\ (\text{stat} \oplus \text{syst})$


PS Coil


Tracker plane lift test


Production target + mounting ring


TS Thermal Shield and Cold Mass Coil

- Great progress in construction efforts
- Lots of areas to contribute
- Now is a great time to join Mu2e!

Summary and Outlook

- Mu2e is a flagship discovery experiment under construction at Fermilab.
- Run 1 in 2025-2026 and will improve current limit by x1,000
- Run 2 after LBNF/PIP-II shutdown will improve current limit by x10,000

It is an exciting time for Mu2e. Join us to help answer:

“Who ordered that?”

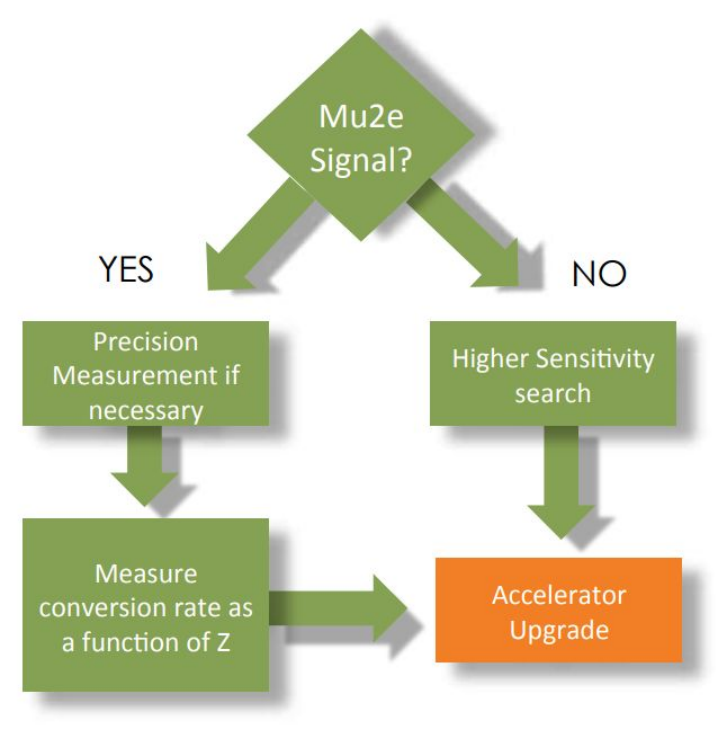
 [@Mu2eExperiment](#)

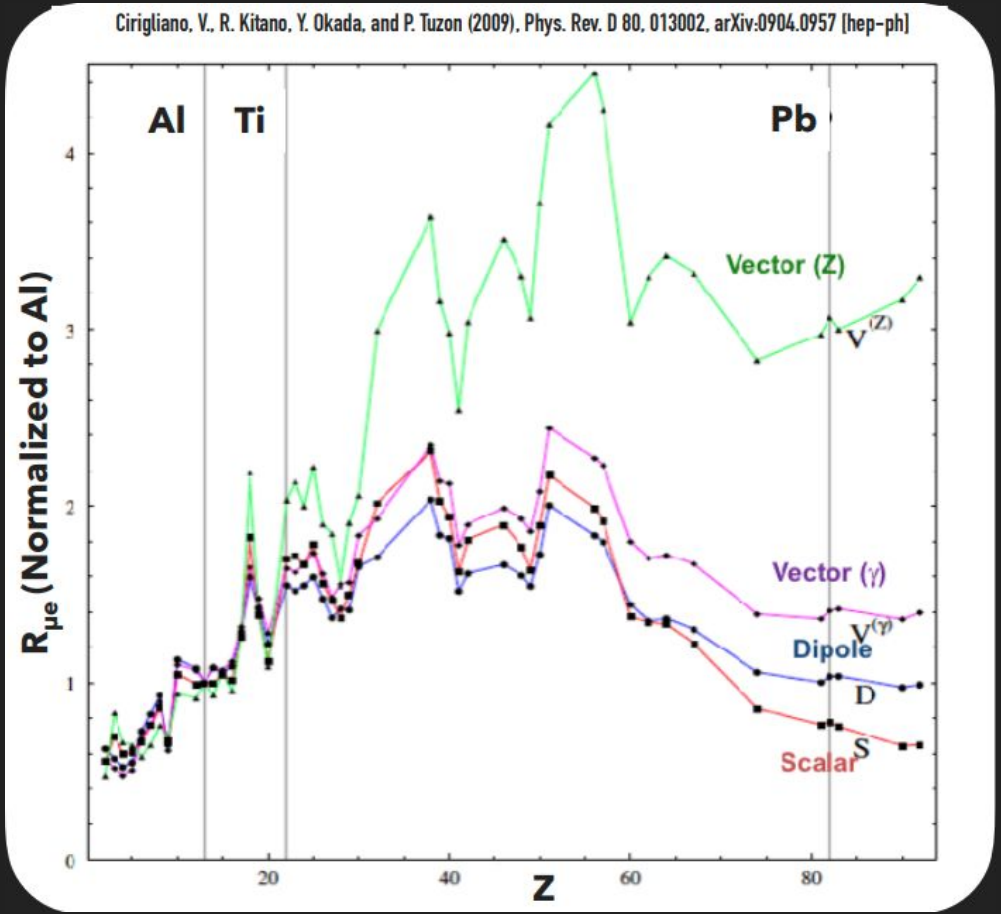
 [@mu2eexperiment](#)

 [https://mu2ewiki.fnal.gov](#)

Backups

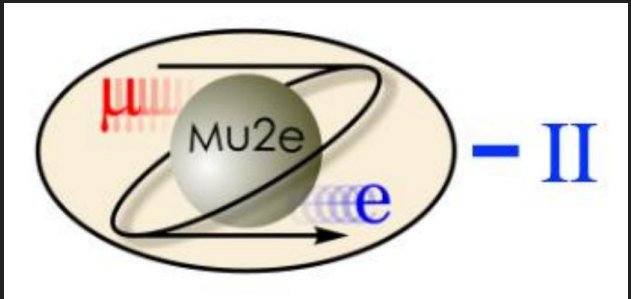
What happens next?





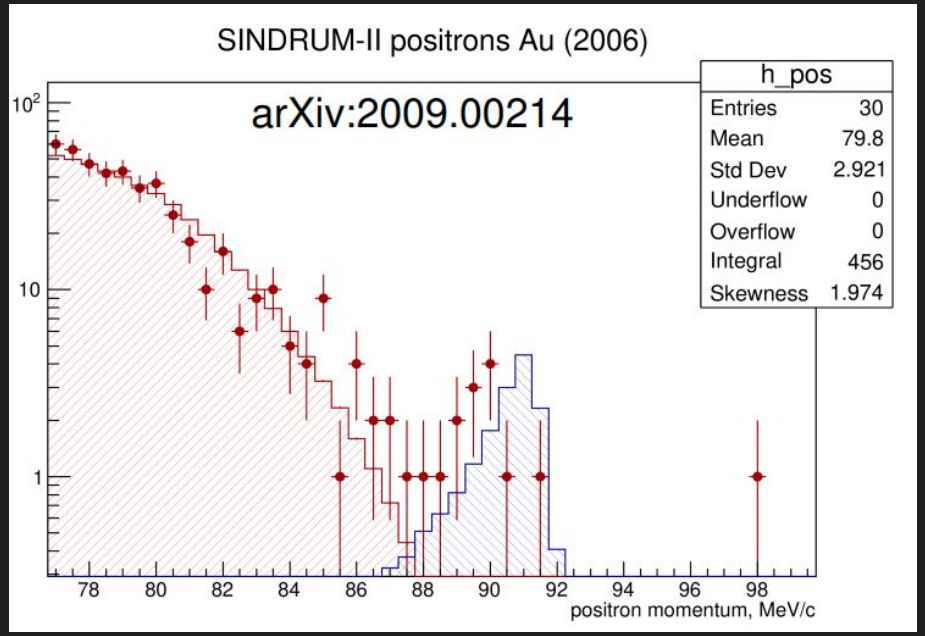
Mu2e II

- Next-generation of Mu2e -- goal of another x10 improvement in discovery potential
- Active in Snowmass 2021
- Expression of Interest: [arxiv:1802.02599]



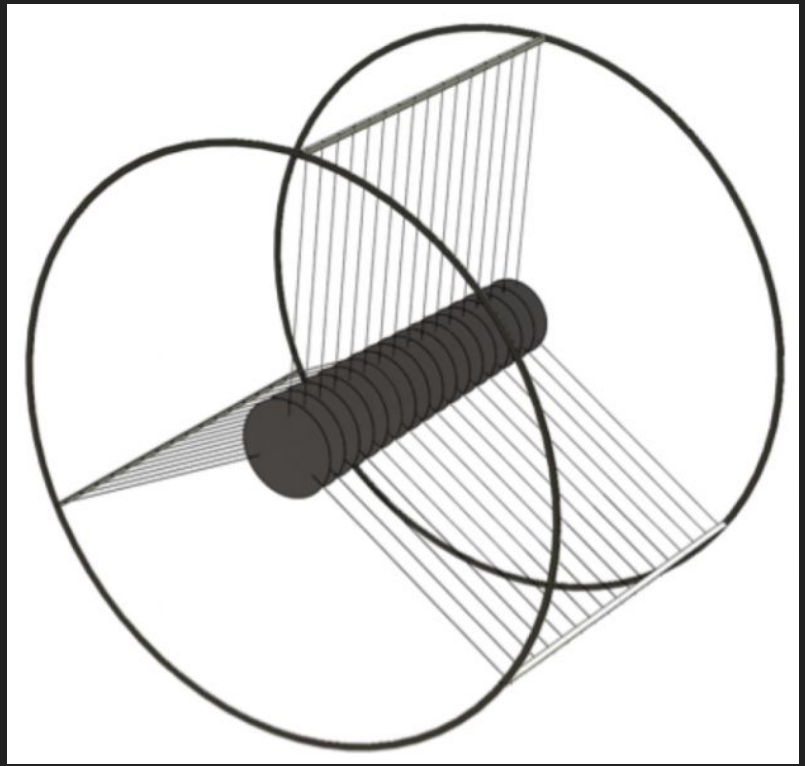
Additional Mu2e Measurement: $\mu^- \rightarrow e^+$

- Violates lepton flavor and lepton number
- Primary background is RMC
  - Experimental data on RMC is sparse
- Mu2e will make a world-leading measurement in tandem with $\mu^- \rightarrow e^-$



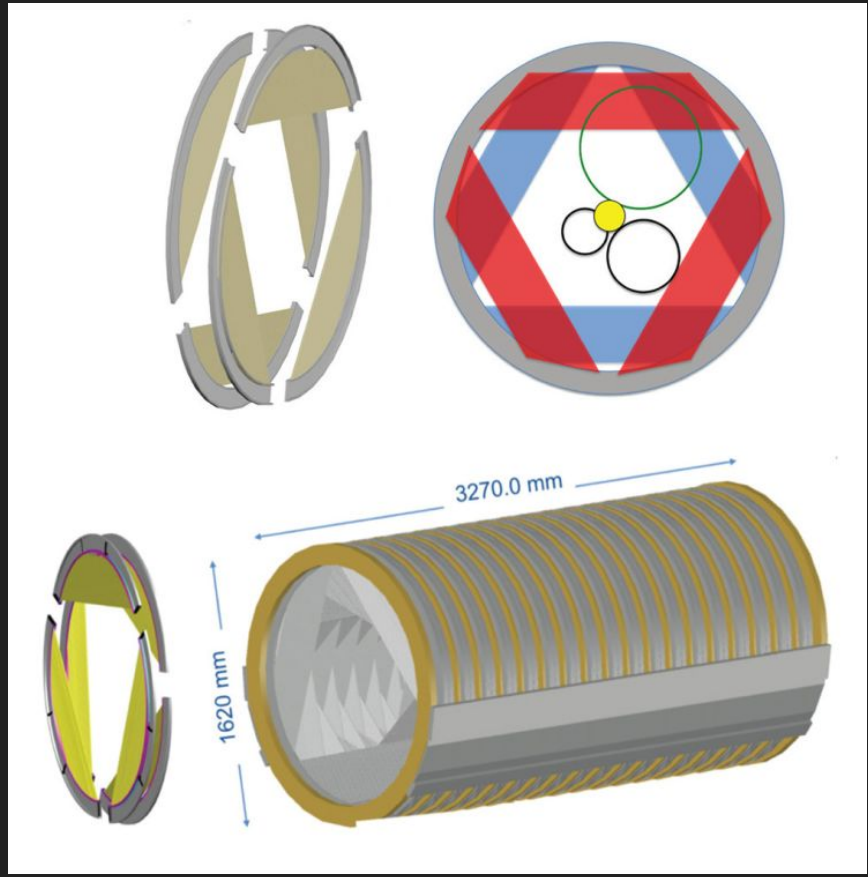
Stopping Target

- Annular Al foils
- Optimized to maximize stopped muons and minimize energy loss of outgoing electrons

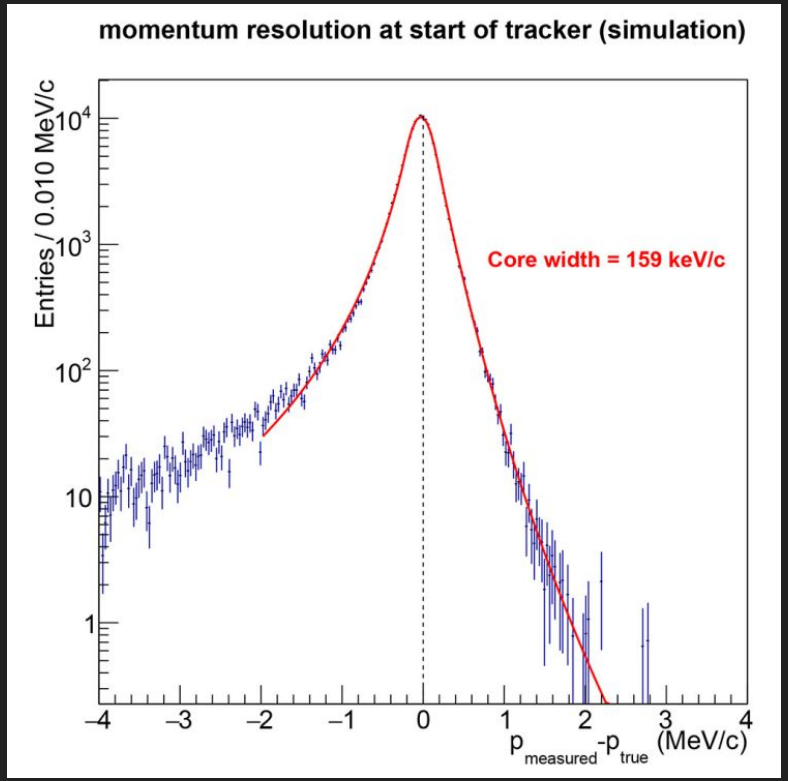


Tracker

- Metallized mylar straws (>20,000)
- 5 mm diameter
- 15 micron thick walls
- Tungsten sense wire as anode
- ArCO2 gas through straw tubes



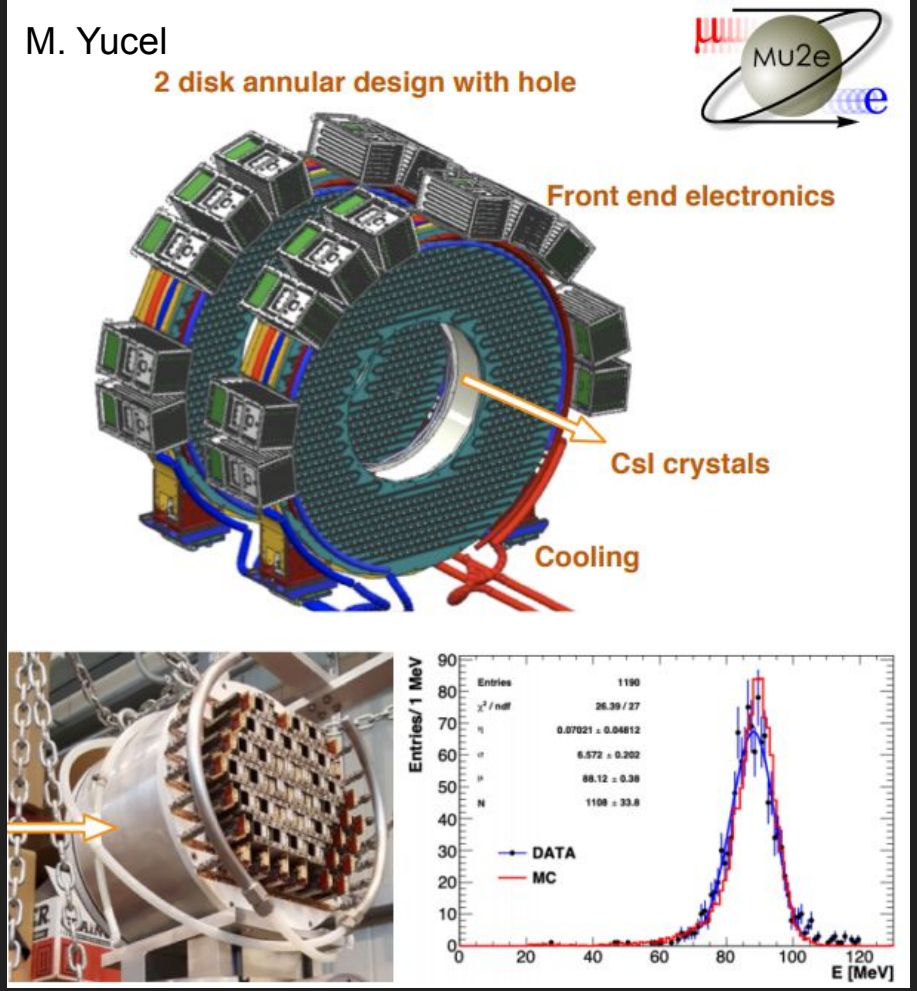
Tracker Resolution



Calorimeter

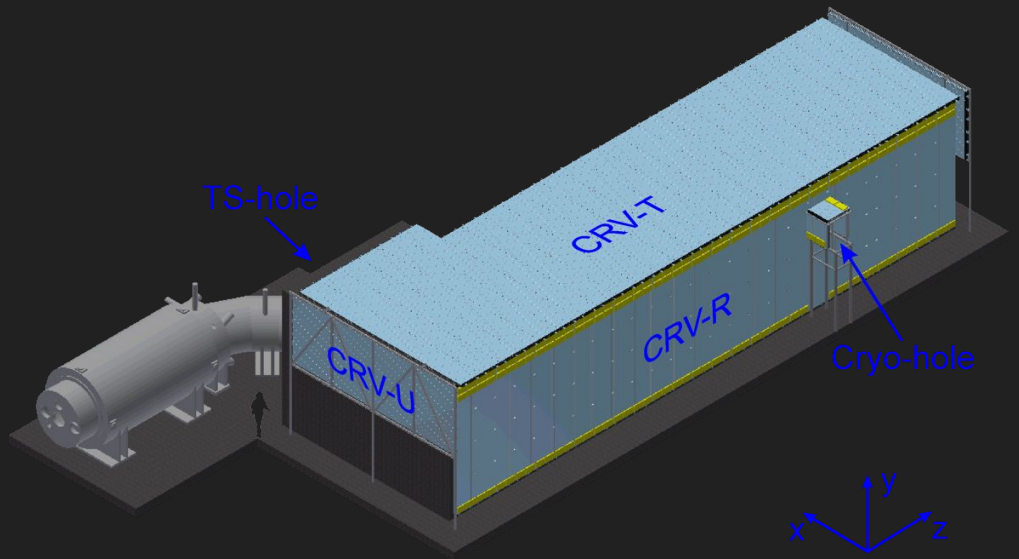
- 1348 CsI crystals (fabrication complete)
- SiPMs for readout
- Aids in Particle ID (momentum + energy measurements)
- Track seeding

M. Yucel



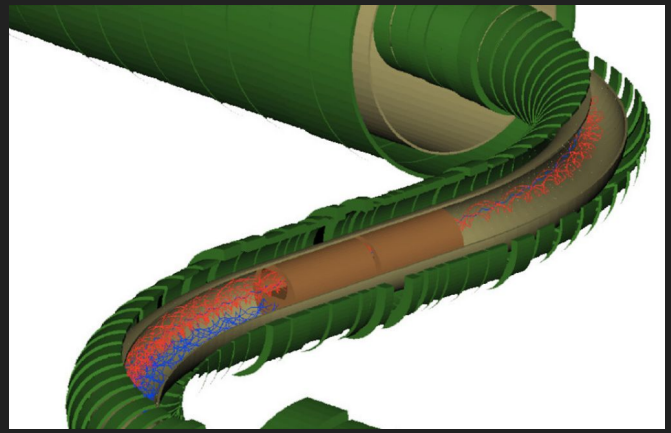
Cosmic Ray Muons

- Cosmic ray muons interact in detector material to produce signal-like e^-,
- Active vetoing detector encapsulates Detector Solenoid and half of Transport Solenoid
- Software veto
- Without Cosmic Ray Veto, we would see approx. 1 signal-like event per day

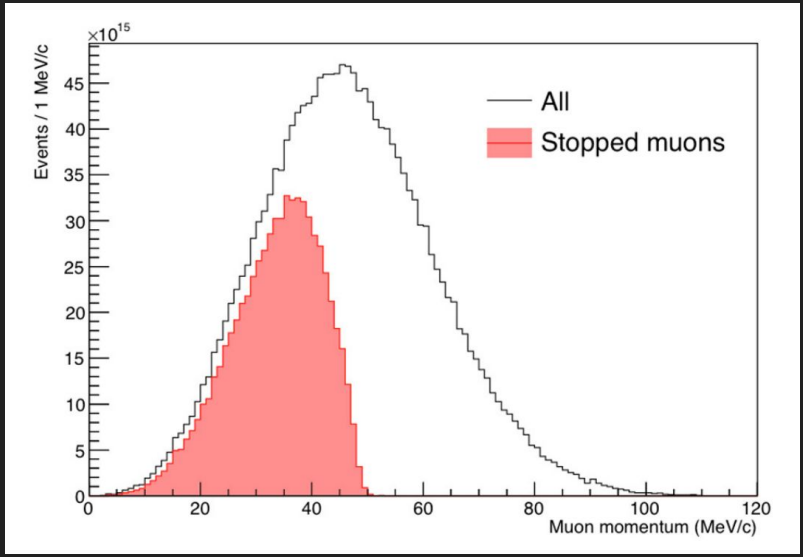


Magnetic Field (TS)

- Charge and momentum selection yields low energy negative muons
- Collimator in middle of TS can be rotated 180° to pass positive muons for calibrations



Muons at Stopping Target

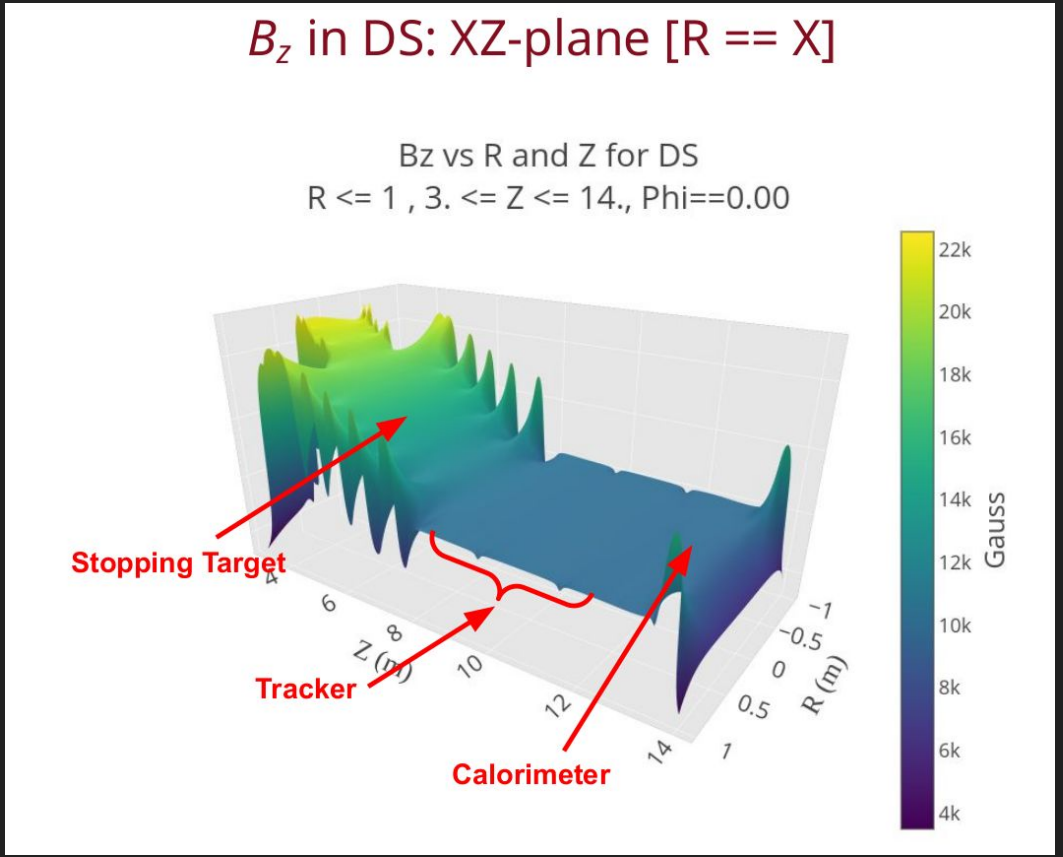


Vertical Drifts at TS Middle

$$D[m] = -\frac{Q}{e}\frac{\pi}{0.6B[T]}\frac{P_L^2 + 0.5P_T^2}{P_L[GeV/c]}$$

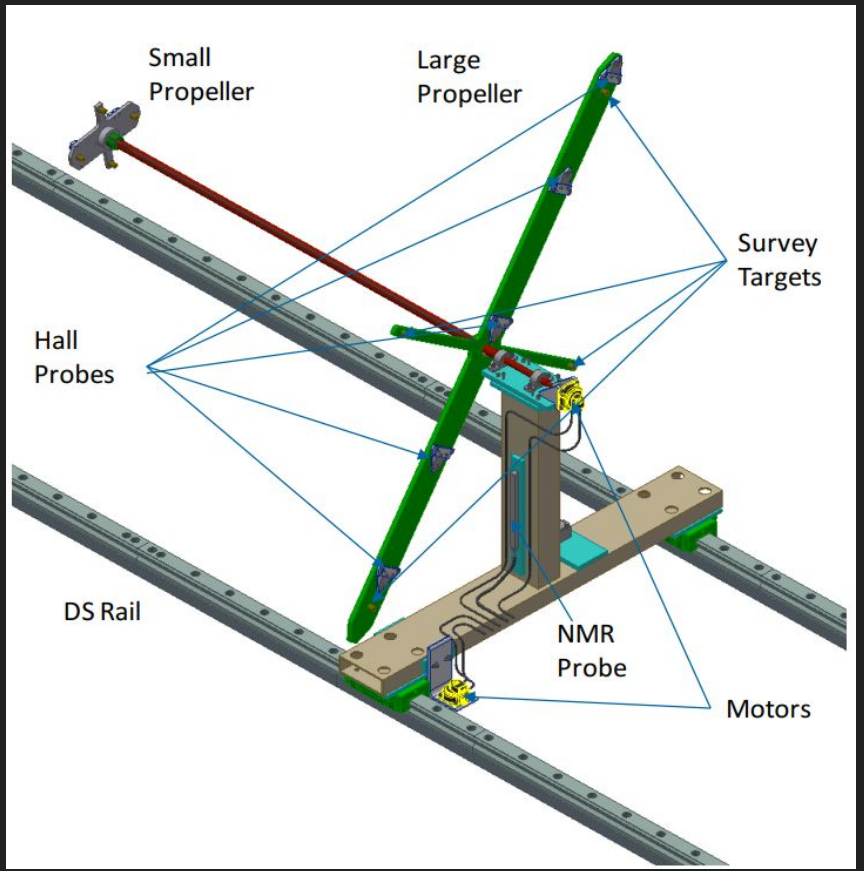
Magnetic Field (DS)

- Gradient region to direct electrons from Stopping Target to detectors
- Flat field in Tracker region for momentum measurement (1 T)



Field Mapping System

- DS field measured on discrete cylindrical grid of points
- Model function is fit to data
- 10^{-4} accuracy requirement



Time Window From RPC

- RPC drives live window start time
- End of time window set based on when the next proton pulse arrives