

Oct 3, 2026

Muons at Fermilab

Karie Badgley

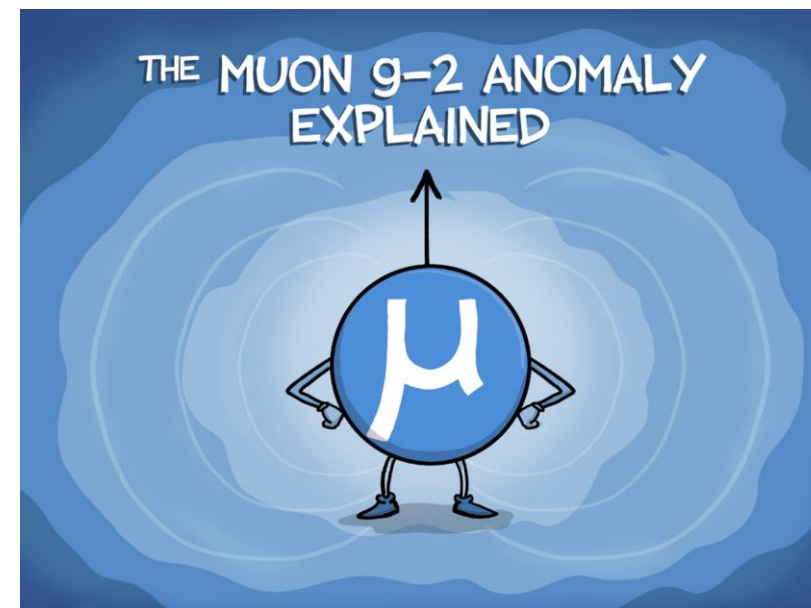


U.S. DEPARTMENT
of **ENERGY**

Fermi National Accelerator Laboratory is managed by
FermiForward for the U.S. Department of Energy Office of Science

Outline

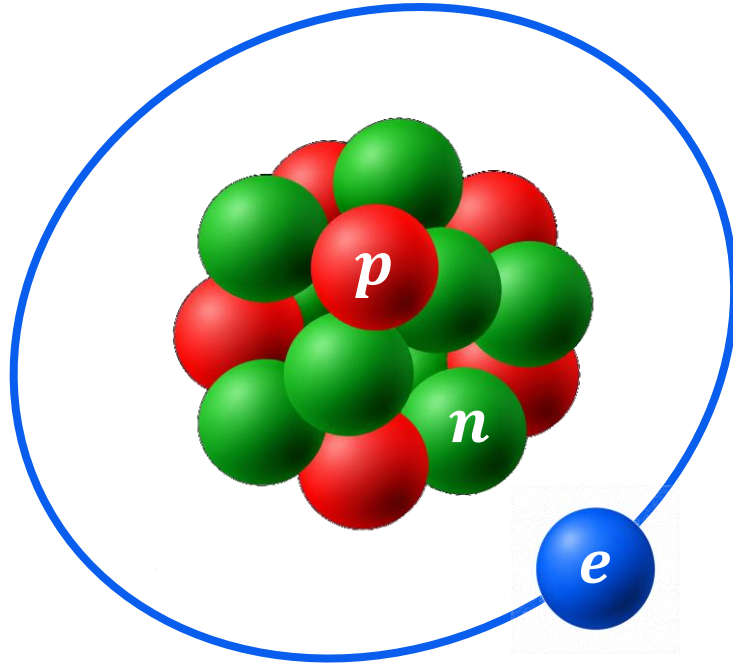
- What is a muon?
 - Fundamental particles
- How do we use muons at Fermilab?
 - Muon $g-2$
 - Mu2e



Recommended reading:
Jorge Cham's PHD Comics
<https://physics.aps.org/articles/v14/47>



Fundamental Particles



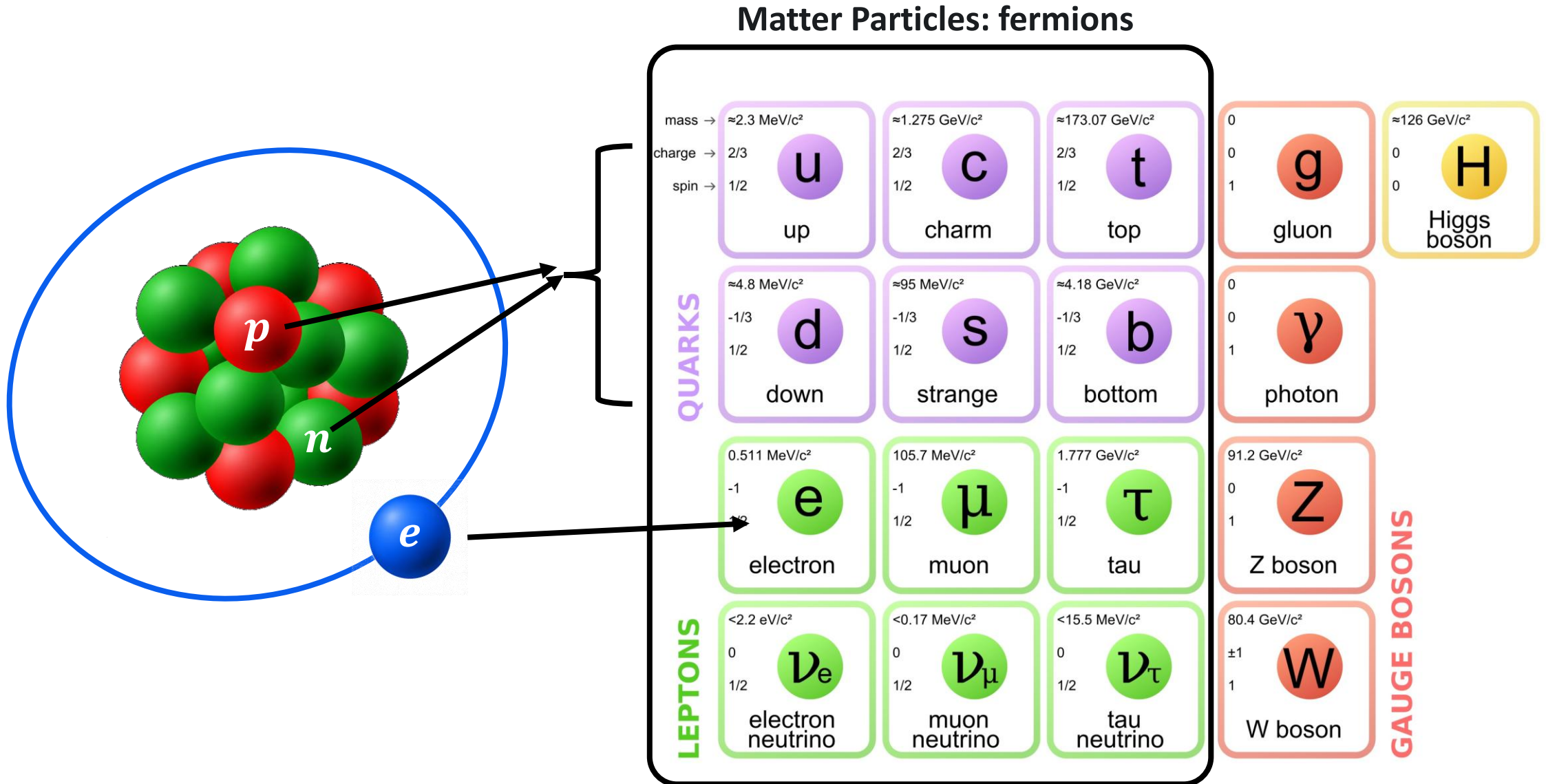
Atoms are made of protons, neutrons, and electrons, but these are not all fundamental particles

Matter Particles: fermions

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$	0	0
	d down	s strange	b bottom	γ photon	
				1	
	$0.511 \text{ MeV}/c^2$ -1 $1/2$	$105.7 \text{ MeV}/c^2$ -1 $1/2$	$1.777 \text{ GeV}/c^2$ -1 $1/2$	$91.2 \text{ GeV}/c^2$ 0	Z Z boson
	e electron	μ muon	τ tau	1	
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $1/2$	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$	$80.4 \text{ GeV}/c^2$ ± 1 1	W W boson
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino		
				GAUGE BOSONS	

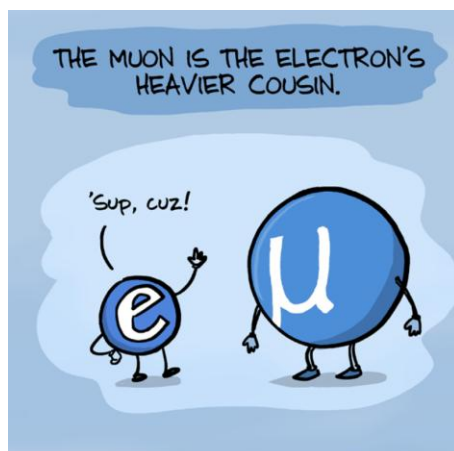


Fundamental Particles

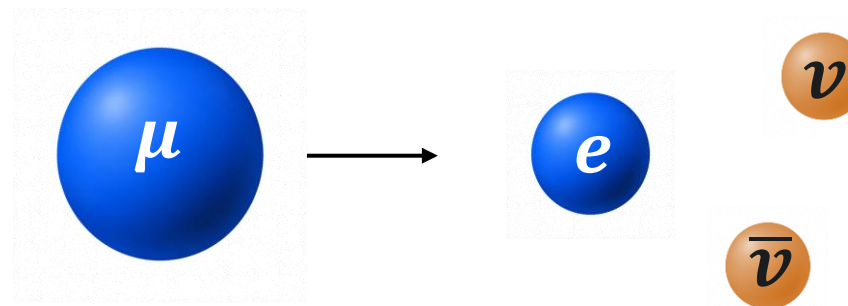


Muon

LEPTONS	mass →	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²
	charge →	-1	-1	-1
	spin →	1/2	1/2	1/2
				
		electron	muon	tau
		<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²
		0	0	0
		1/2	1/2	1/2
				
		electron neutrino	muon neutrino	tau neutrino

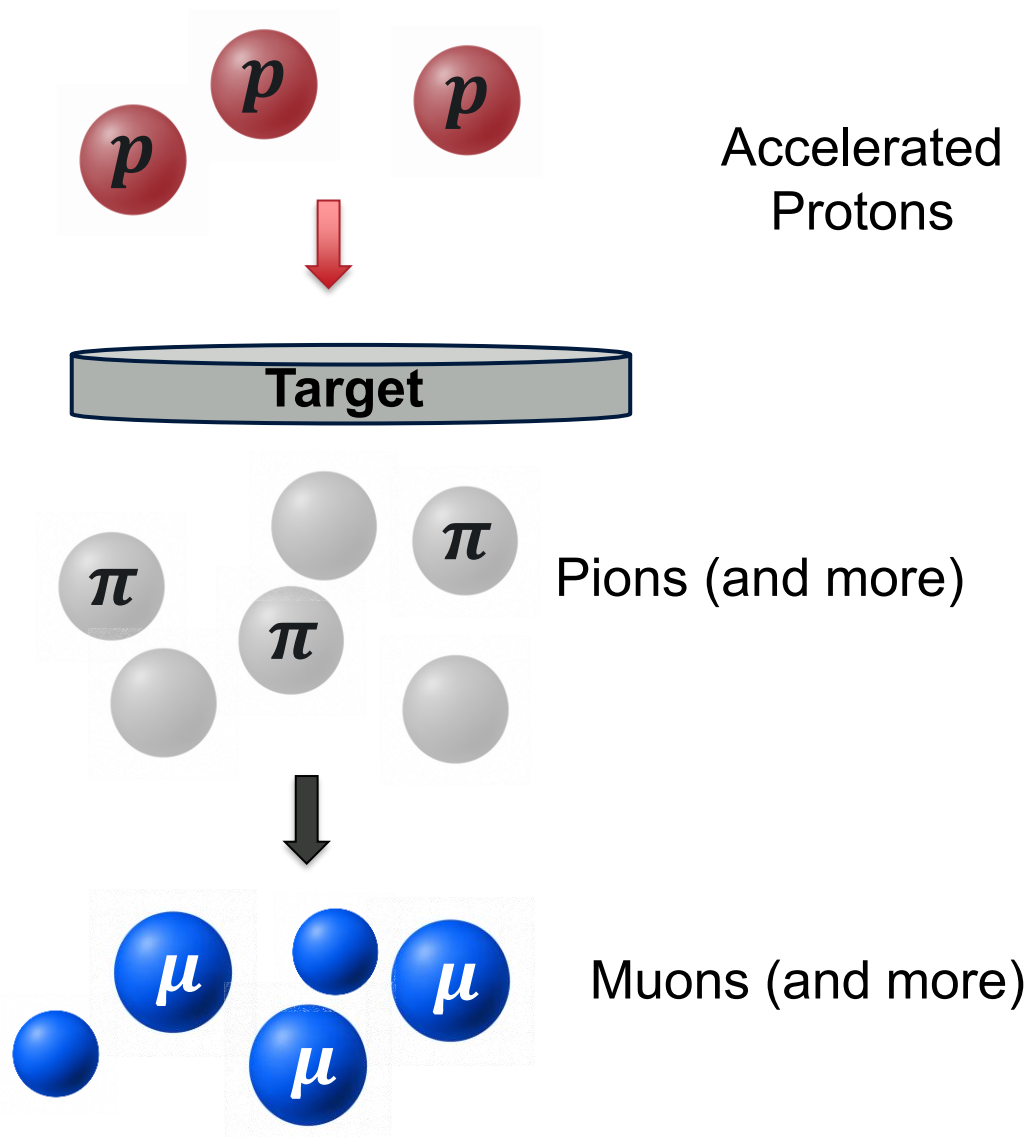


- Same charge and spin as electron
- 207 x more massive than electron
- Muons are unstable – they decay into different particles
- Muon lifetime: only 2.2 microseconds! (2.2×10^{-6} s)
- Muons are not found in normal atoms, we create them in high energy collisions
- $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

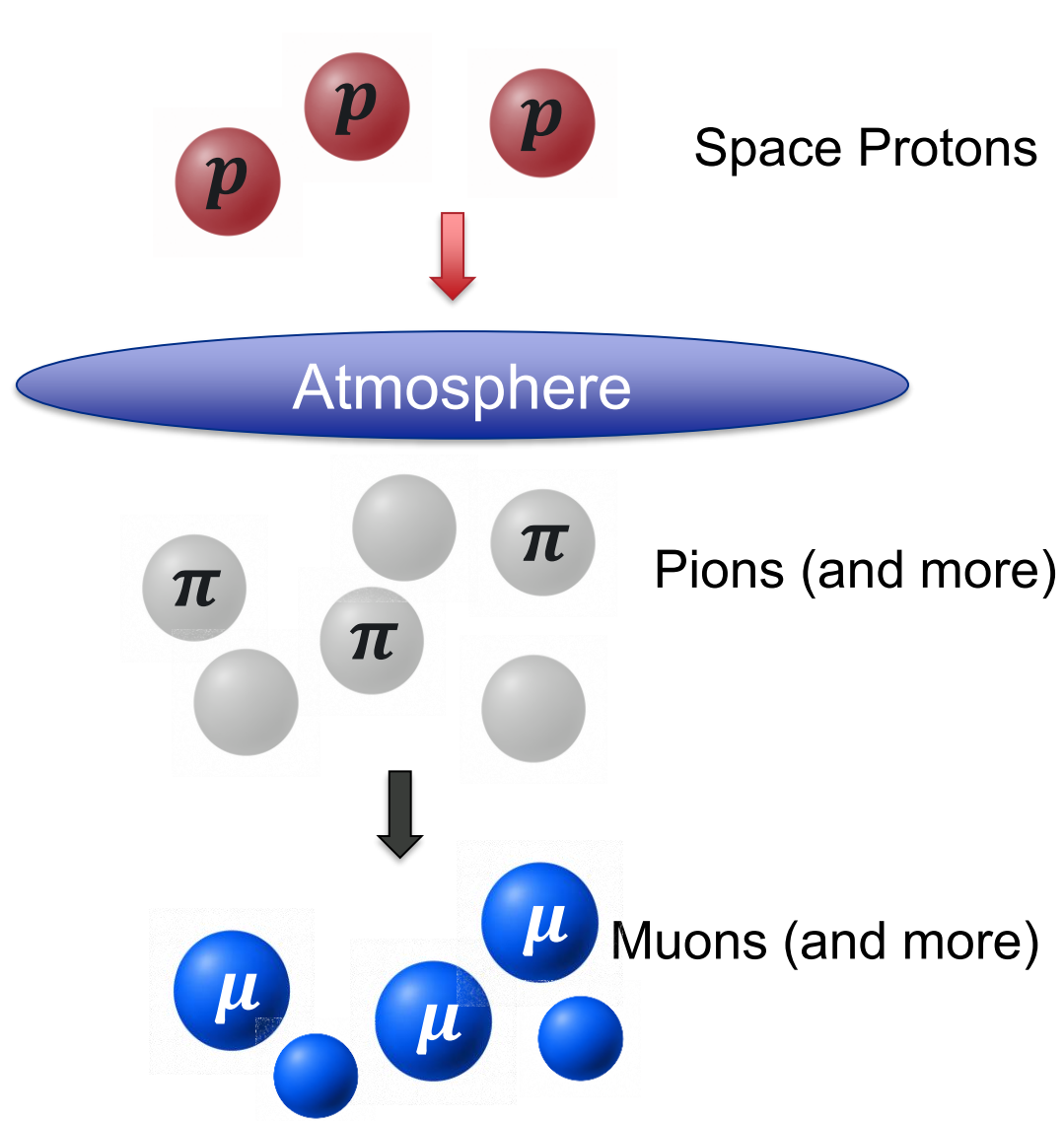


Muon Production

Accelerator Muons



Natural Muons





Why are muons useful for physics experiments?



Precision

A muon's magnetic properties can be measured extremely precisely. Small differences between experiment and theory can reveal missing physics. Due to its larger mass, the muon's **anomalous magnetic moment** is highly sensitive to interactions with virtual particles in the quantum vacuum, making it a premier probe for physics beyond the **Standard Model**.



Penetrating

Muons travel through much more material than electrons of the same energy. Muons lose energy primarily through ionization rather than bremsstrahlung, allowing them to **penetrate deeply** into matter. This enables applications like **muography** to image volcanoes, pyramids, and nuclear reactors.



Short but useful lifetime

A muon lives about $2.2 \mu\text{s}$ at rest. That is long enough to produce, transport, stop, and study large samples of muons.



Rare processes

Experiments can search for extremely rare muon decays. Seeing a forbidden or unexpectedly frequent process could point beyond the Standard Model.

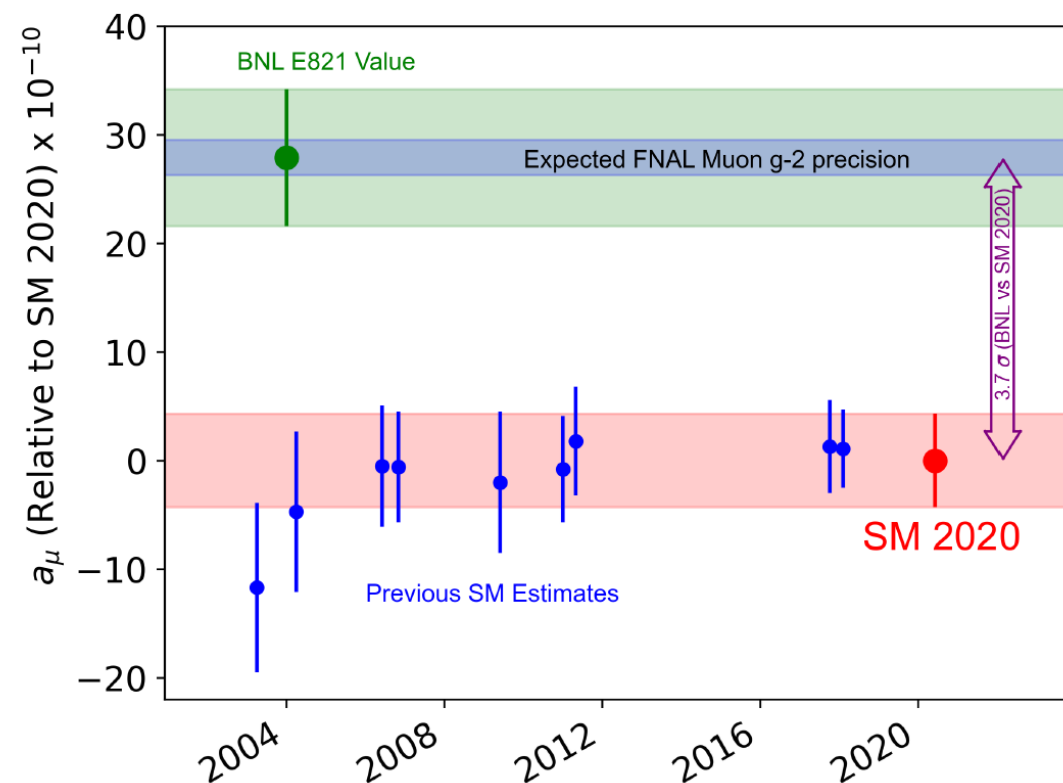
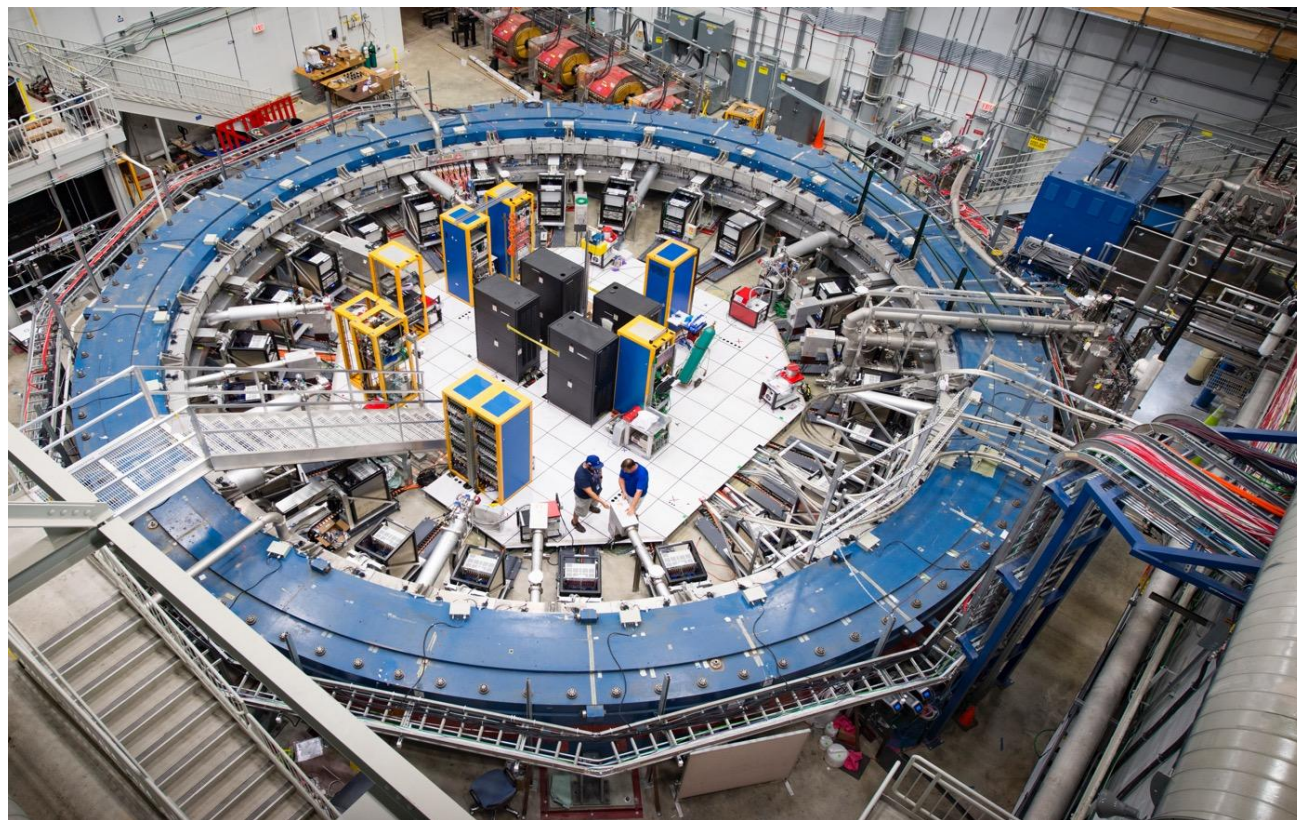


Precision Science at Fermilab

Fermilab's Muon campus was built to host **two muon experiments** that test predictions to the **highest accuracy** and search for phenomena that are either **extremely rare or forbidden**

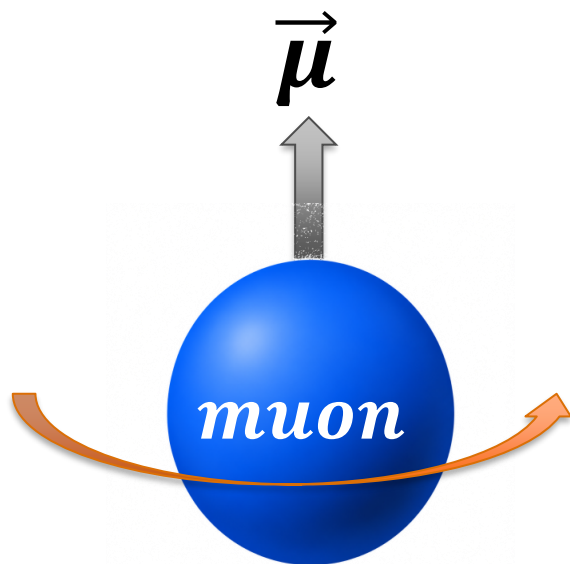


Muon g-2



- Measure muon's magnetic moment to 140 parts per billion precision
- g-2 experiment at Brookhaven indicated new particles may be interacting with the muon
- Fermilab experiment allows us to probe if new particles interact with the muon

Magnetic Moment



Things with charge and spin are magnetic.

Magnetic moment $\vec{\mu}$ describes how strongly muons respond to magnetic fields.

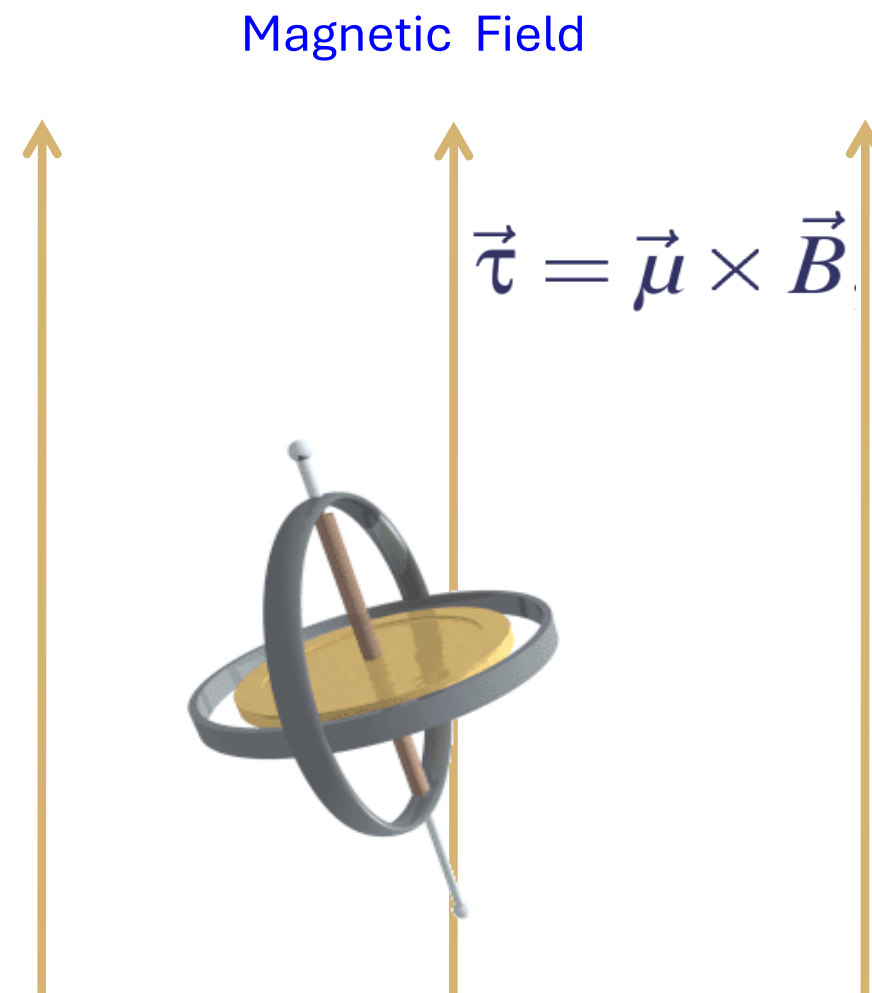
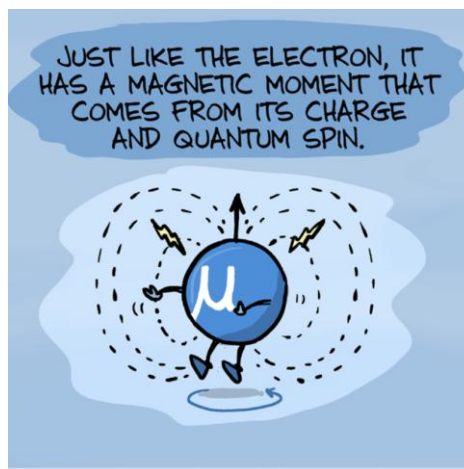
$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

Charge

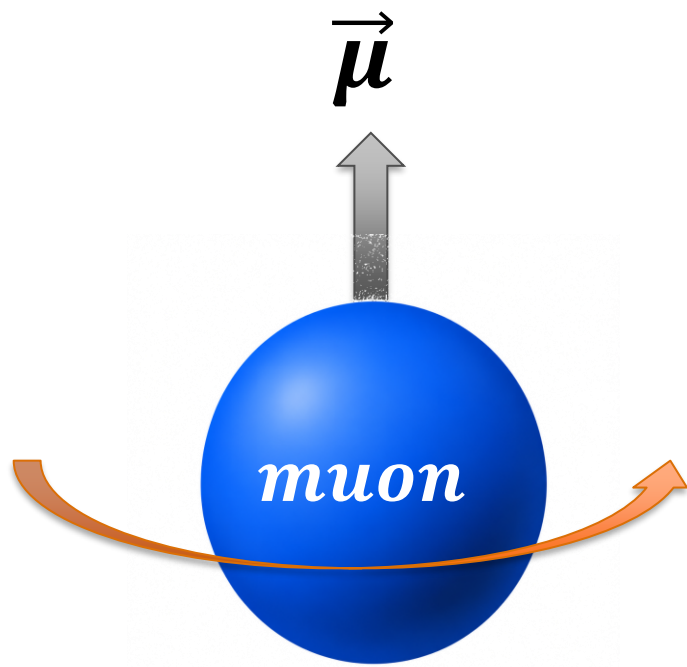
Spin

Mass

$g?$



Muons precess in magnetic field, similar to spinning top



Muon Magnetic Moment $\vec{\mu}$:

$$\vec{\mu} = g * \left(\frac{q}{2m} \right) * \vec{S}$$

The quantum correction factor “g” is what we are trying to measure
(It’s the “g” in “Muon g-2”)

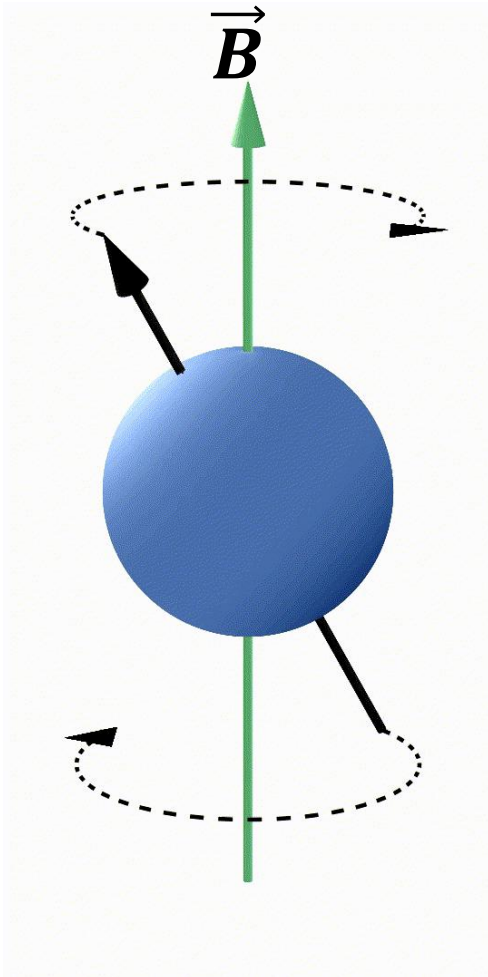
But a_μ makes equations nicer,
so we usually end up writing a_μ
instead.

$$a_\mu = \frac{g - 2}{2}$$



Precession Frequency, w_s

- In external B fields, muons “**precess**”: Spin axis swivels around field axis
- Precession frequency is proportional to muon magnetic moment, and to external B



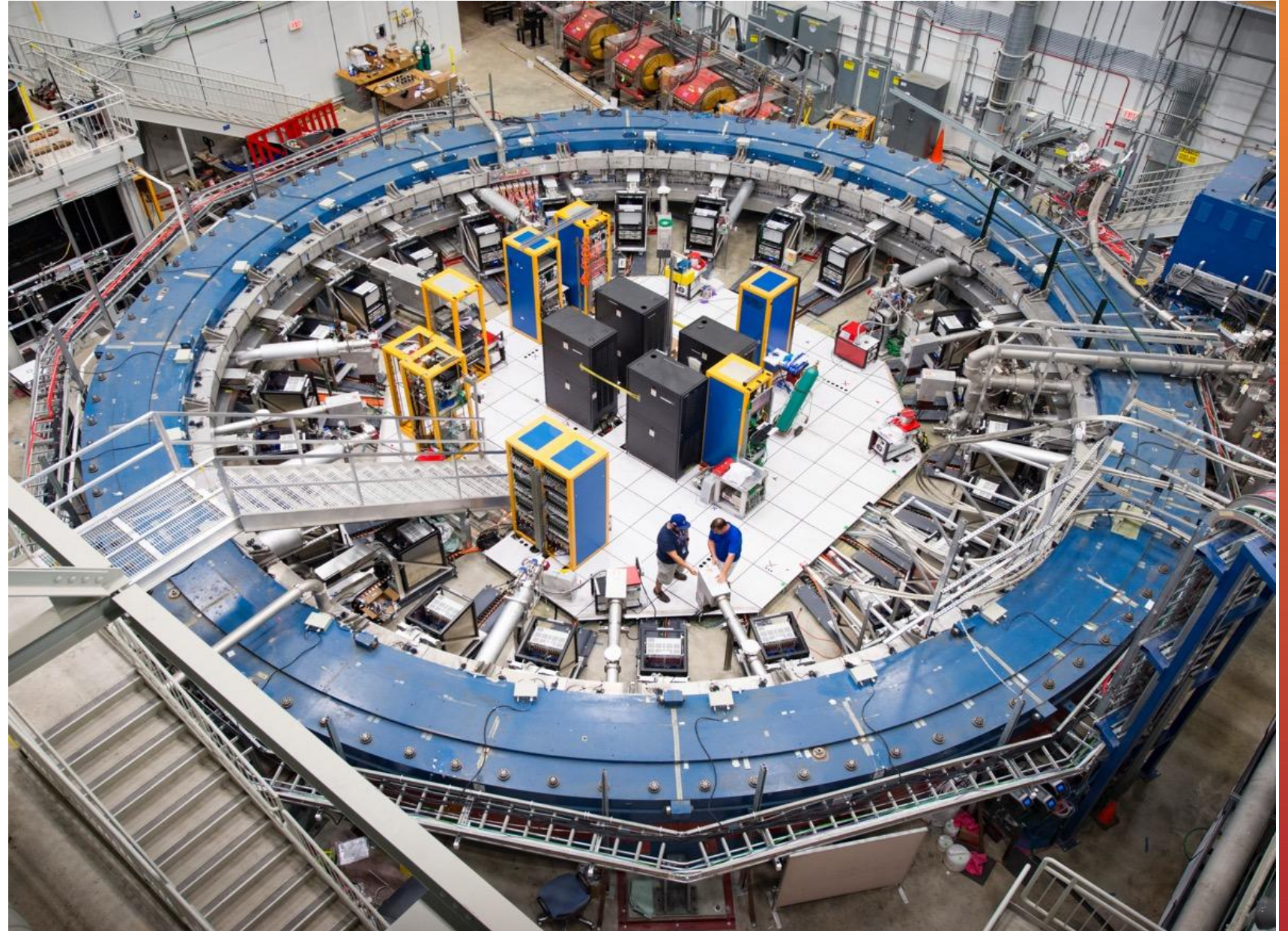
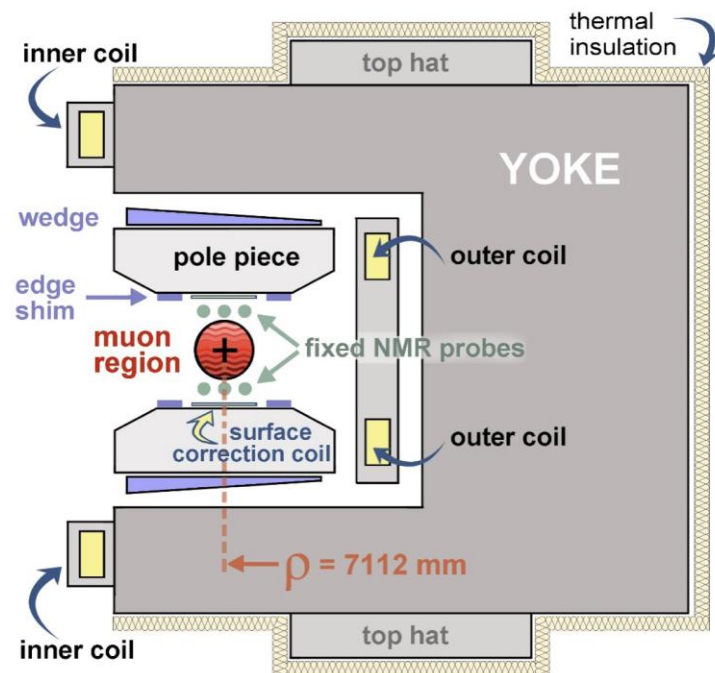
$$w_s = g * \left(\frac{-q}{2m} \right) * B \quad (\text{Non-relativistic})$$

$$w_s = \left(g - 2 + \frac{2}{\gamma} \right) * \left(\frac{-q}{2m} \right) * B \quad (\text{Relativistic})$$

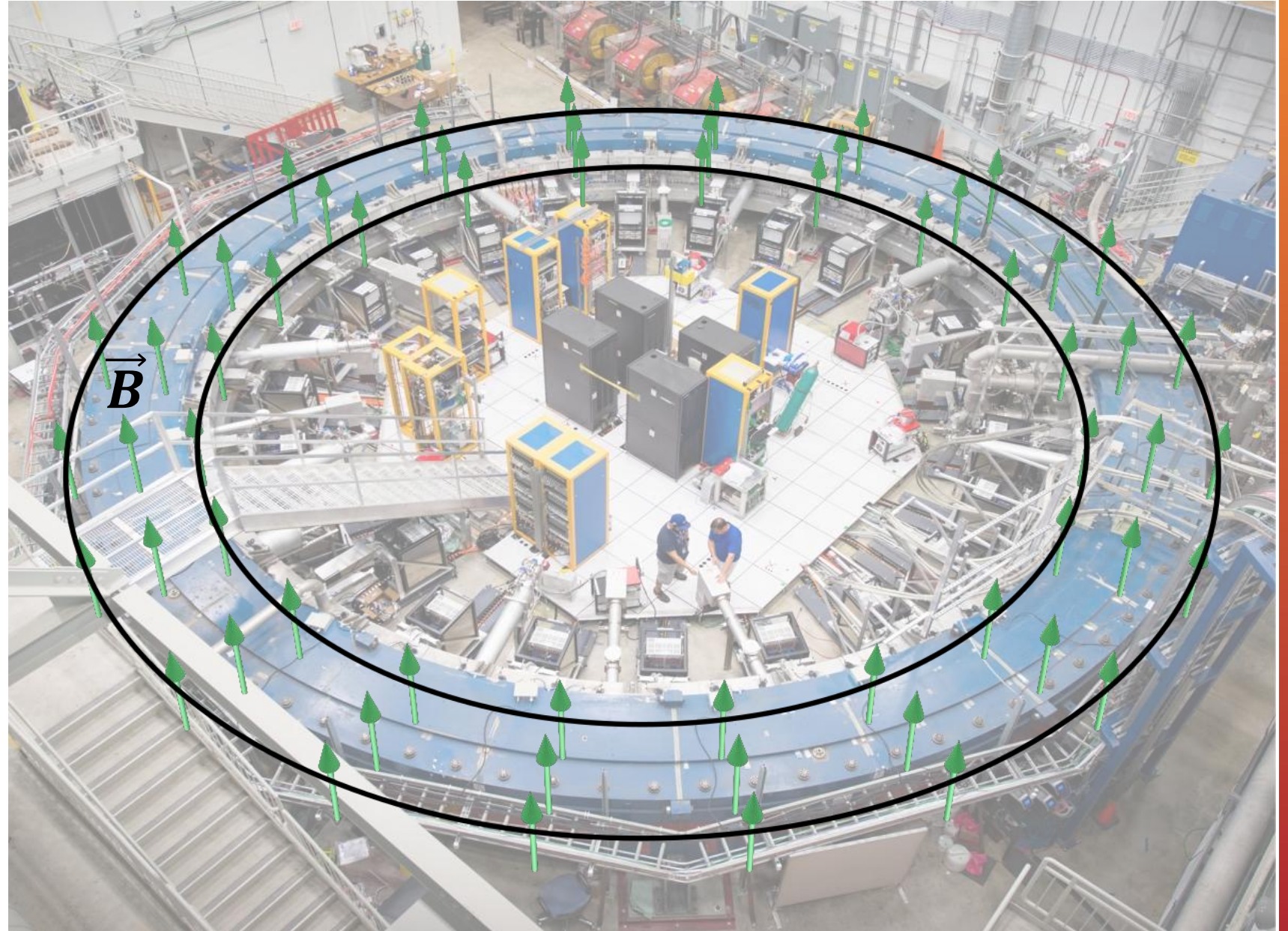
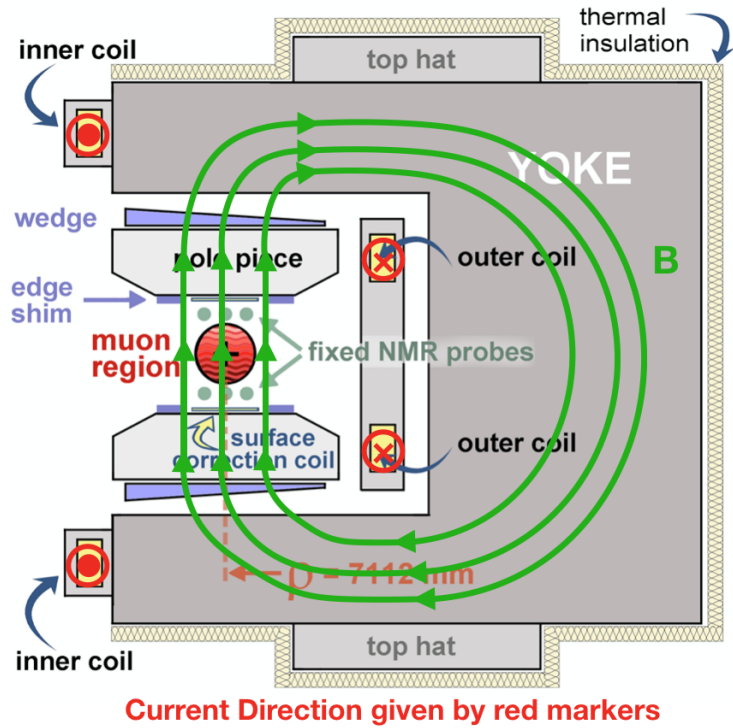
Need to measure precession frequency and field strength

g-2 Experimental Layout

- Superconducting magnet produces 1.45 T field
- Designed and optimized for homogeneity



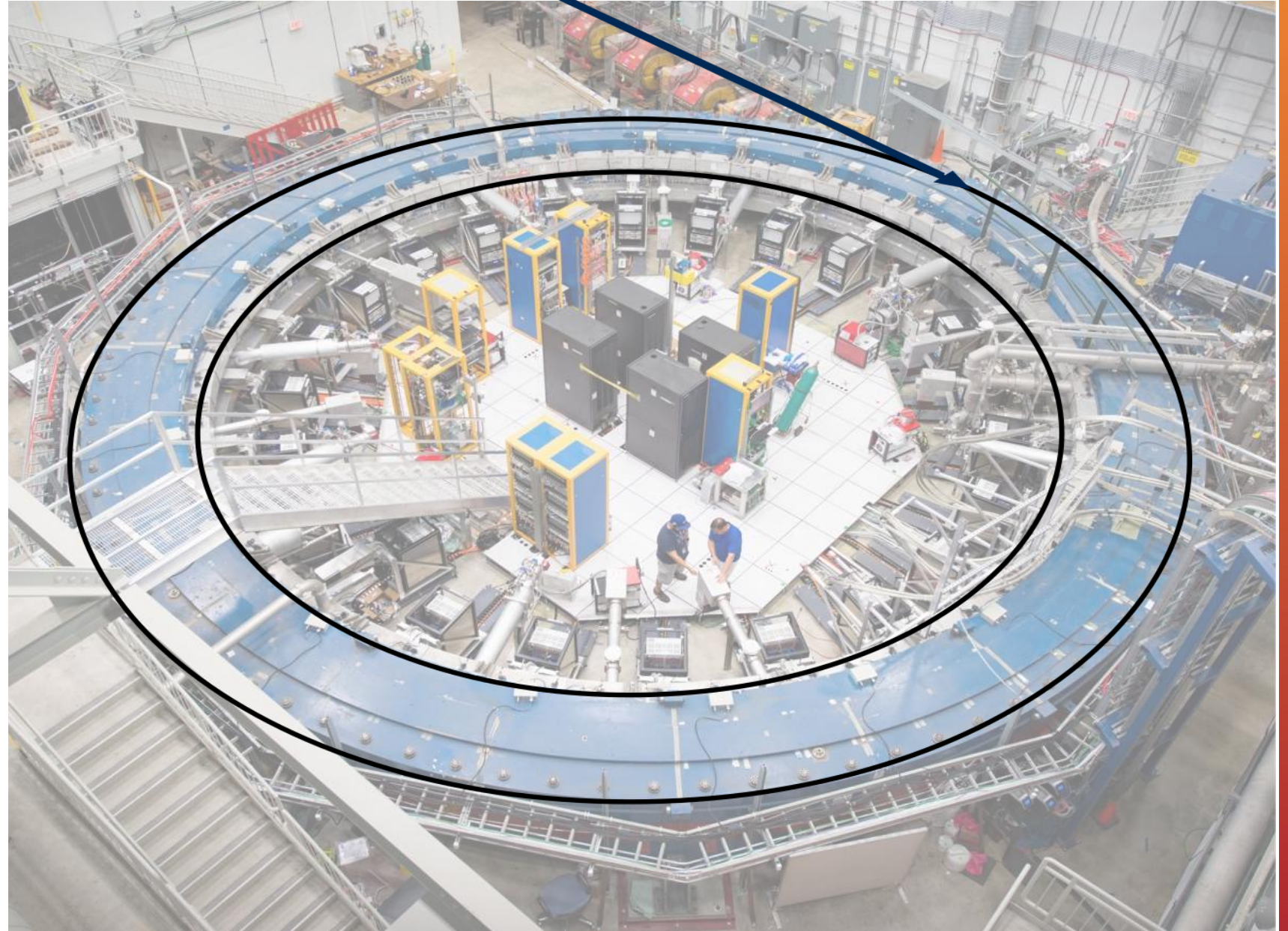
Magnetic Field



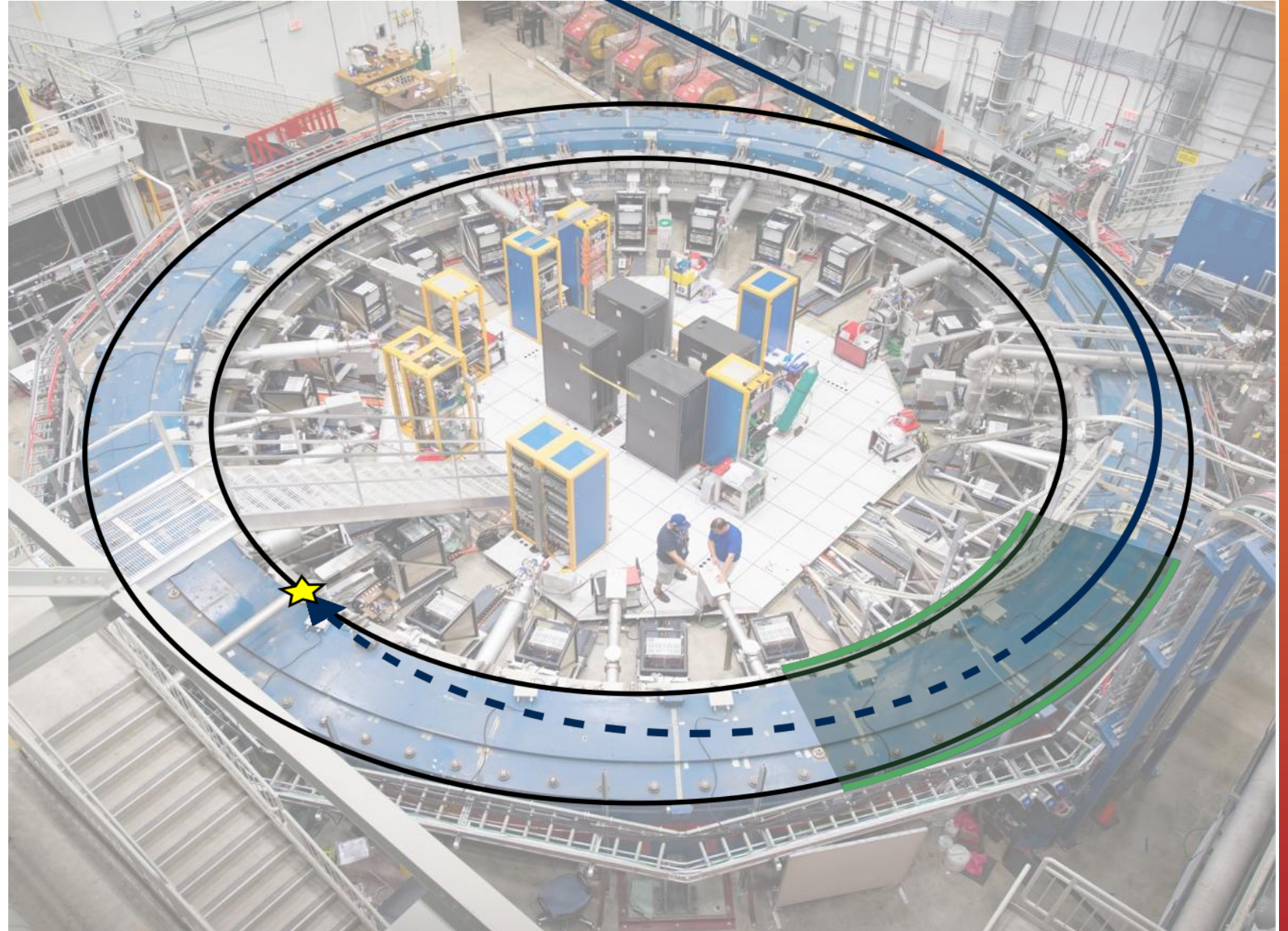
Injection

- Muons produced upstream from protons on target
- Travel down a beamline and enter the ring through a field free hole in the magnet
- Actually another magnet inside the hole to cancel out the B field

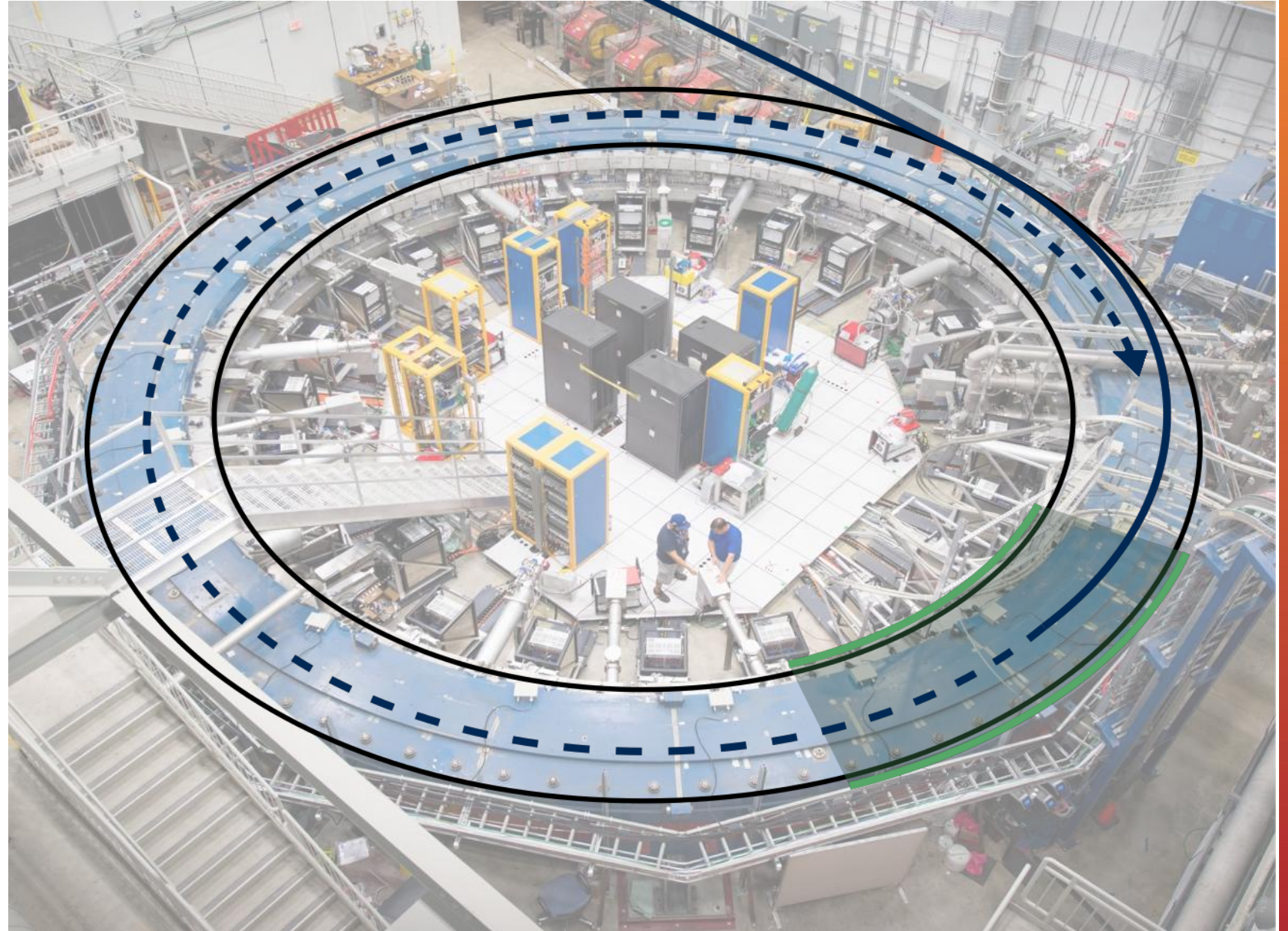
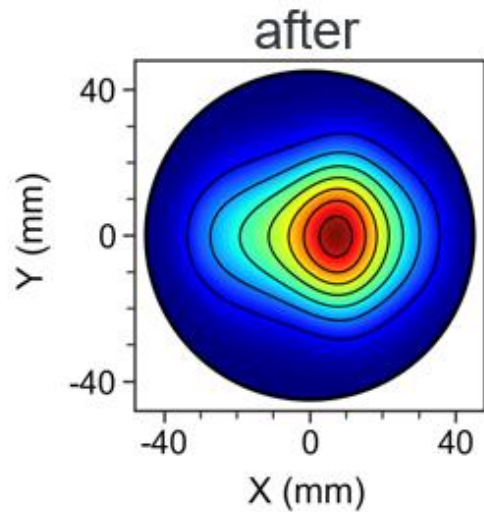
Muons



- Geometry of injection puts the beam offset 8 cm from storage center
- Pulsed kicker magnet used to “kick” muons on correct path

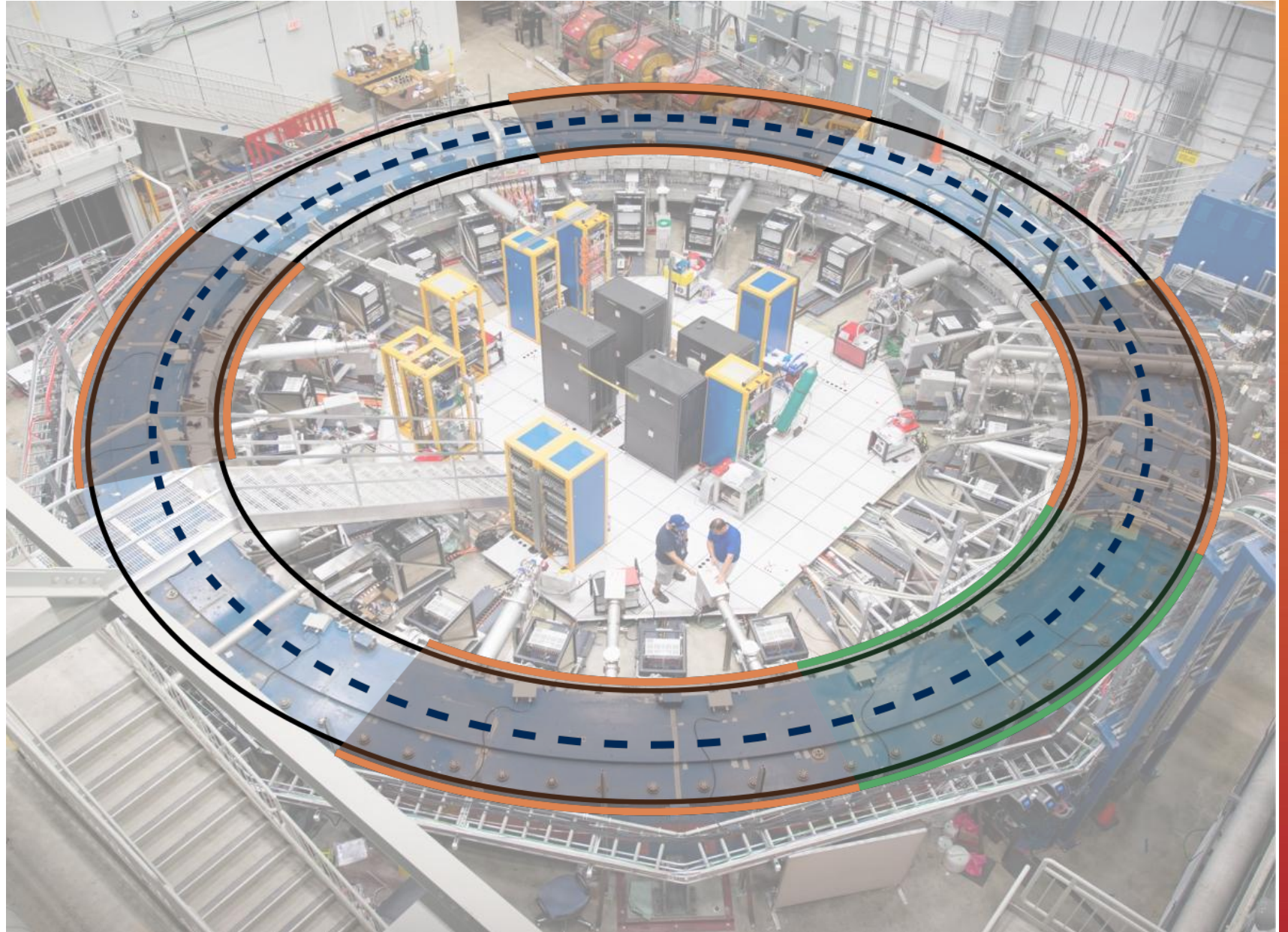
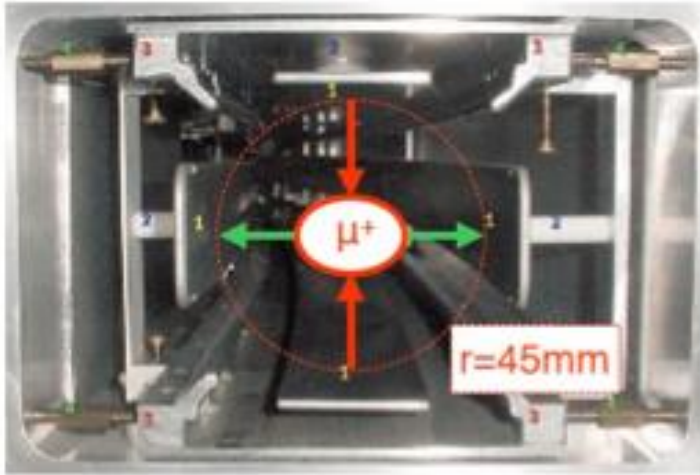


- Steer muons onto orbit in the first pass
- After kick muons roughly centered in the storage ring



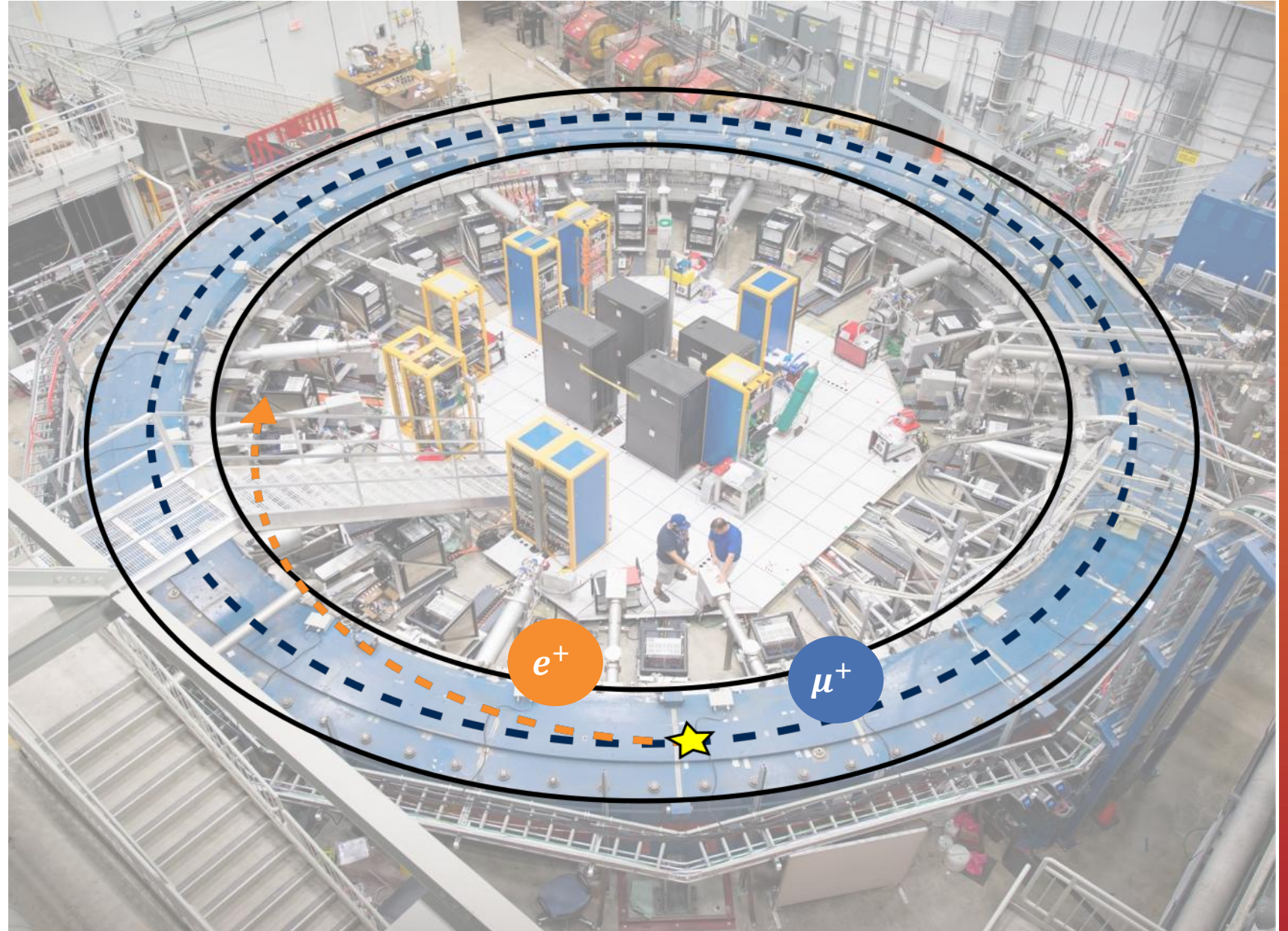
Electrostatic Quadrupoles

- Electric fields provide vertical focusing



Muon Decay

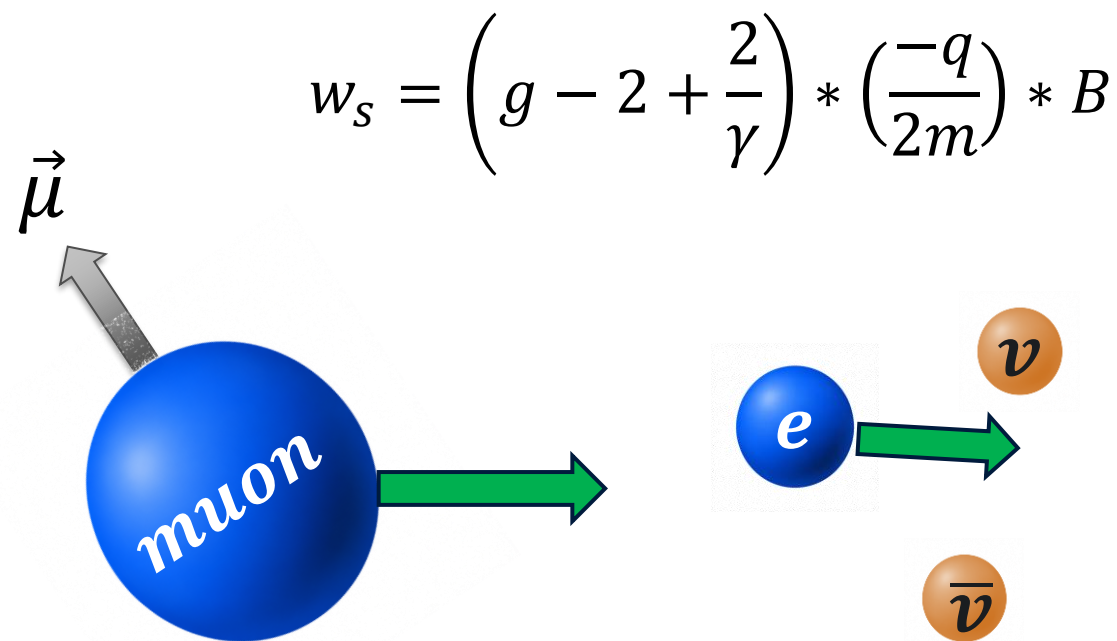
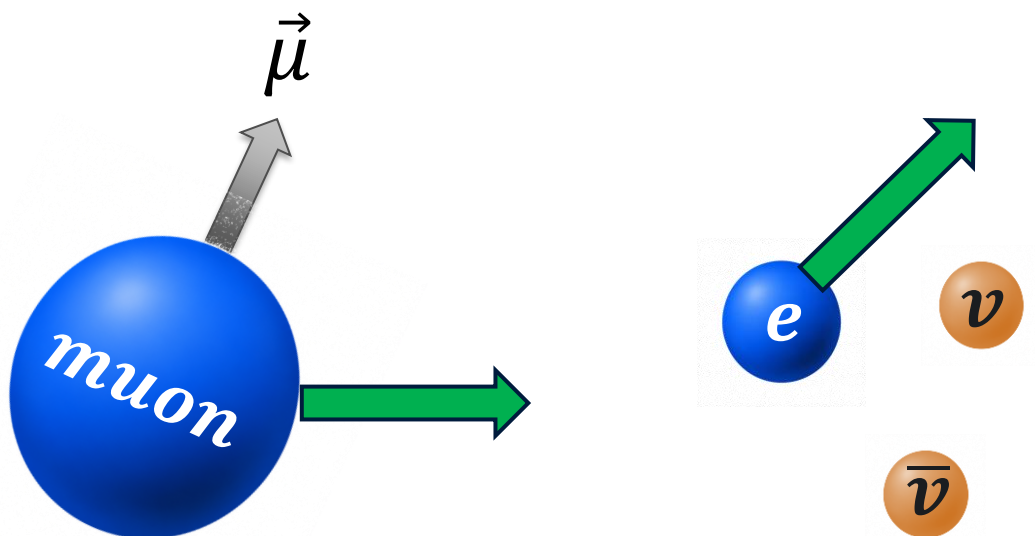
- Muons travel around the ring a few hundred times before decaying
- $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- μ^+ **spin** information encoded in e^+ **energy**
- Lighter e^+ bends inward in the field



Muon Decay

Muons have special decay property

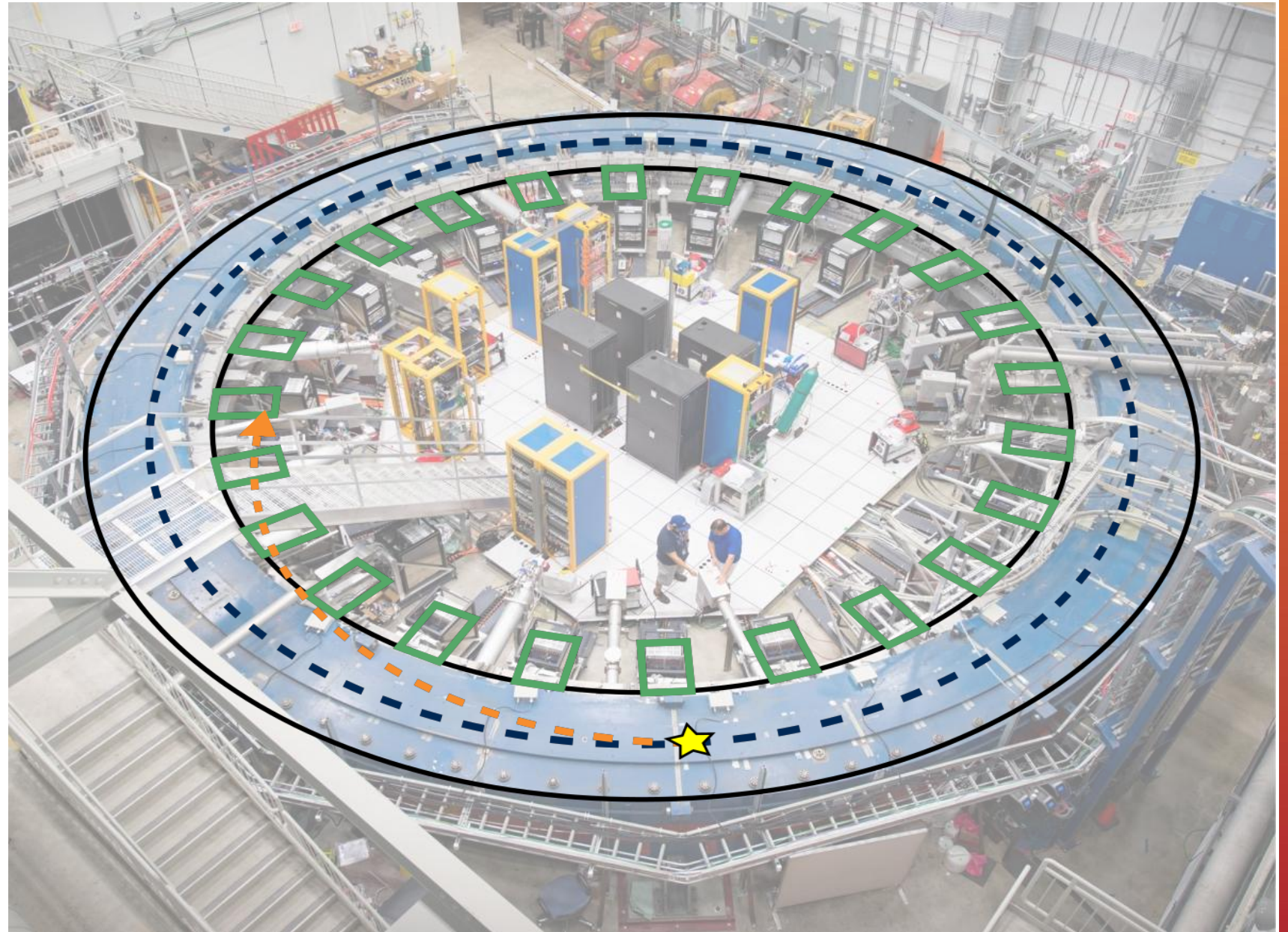
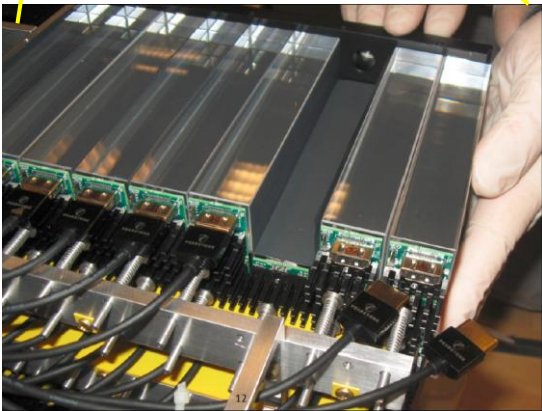
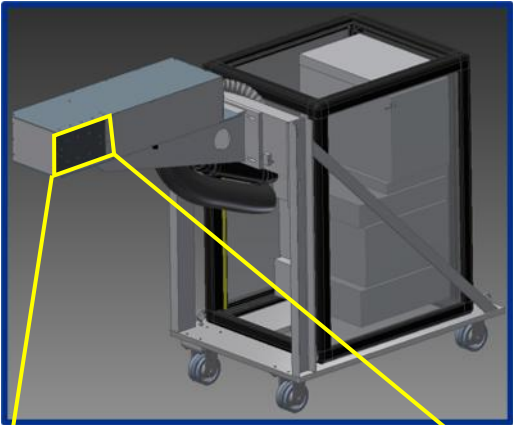
- Energy of emitted positrons is higher when spin is aligned with linear momentum
- And it's lower (on average) when spin is counter-aligned with linear momentum
- Positrons are preferentially emitted in the direction of the muon's spin



$$w_s = \left(g - 2 + \frac{2}{\gamma} \right) * \left(\frac{-q}{2m} \right) * B$$

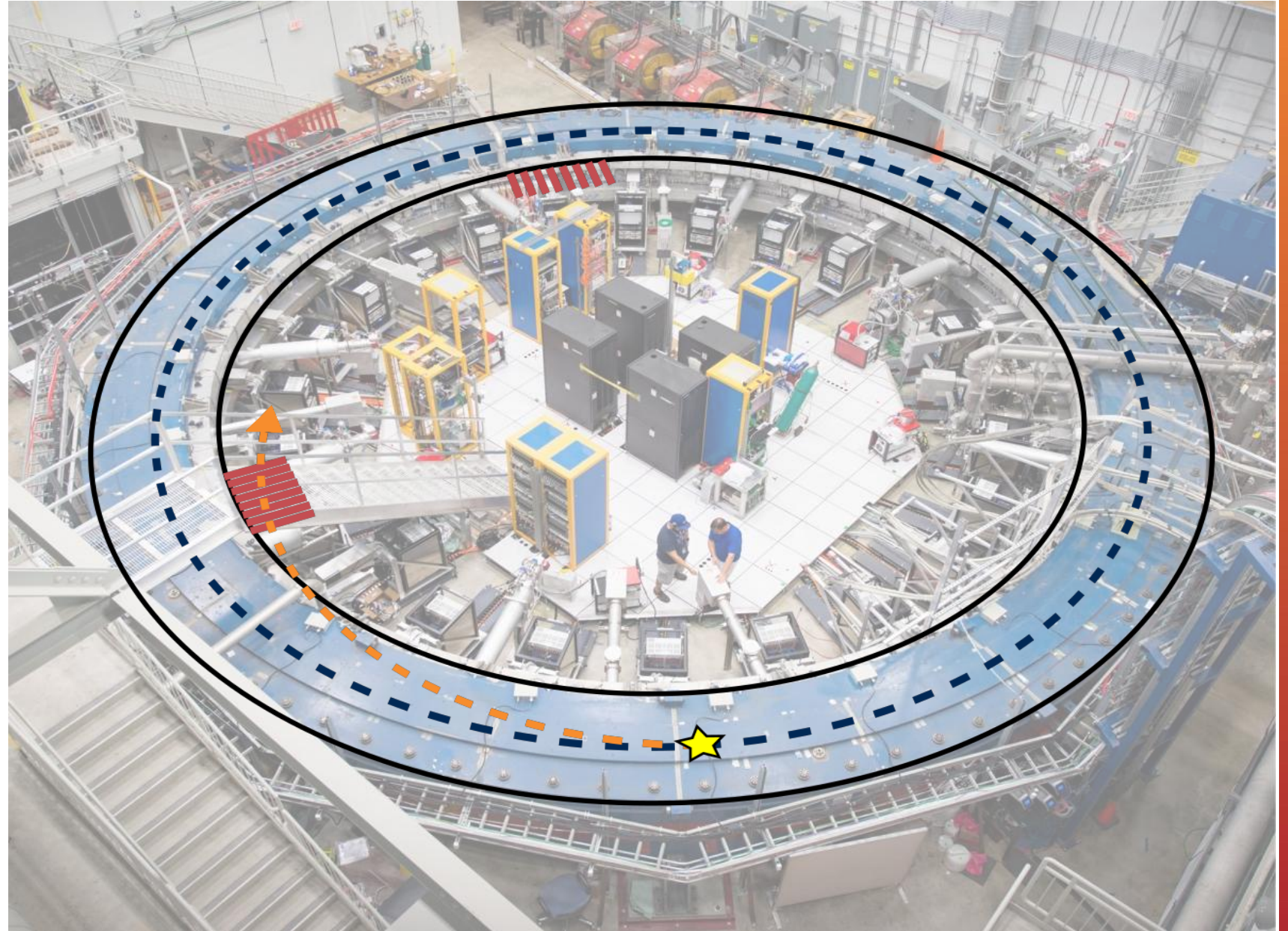
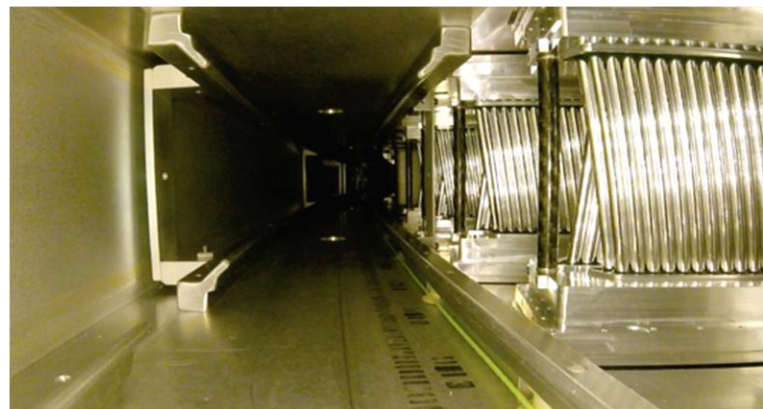
Calorimeters

- 24 Calorimeters with 54 (9x6) Cherenkov PbF_2 crystals



Straw Tracker

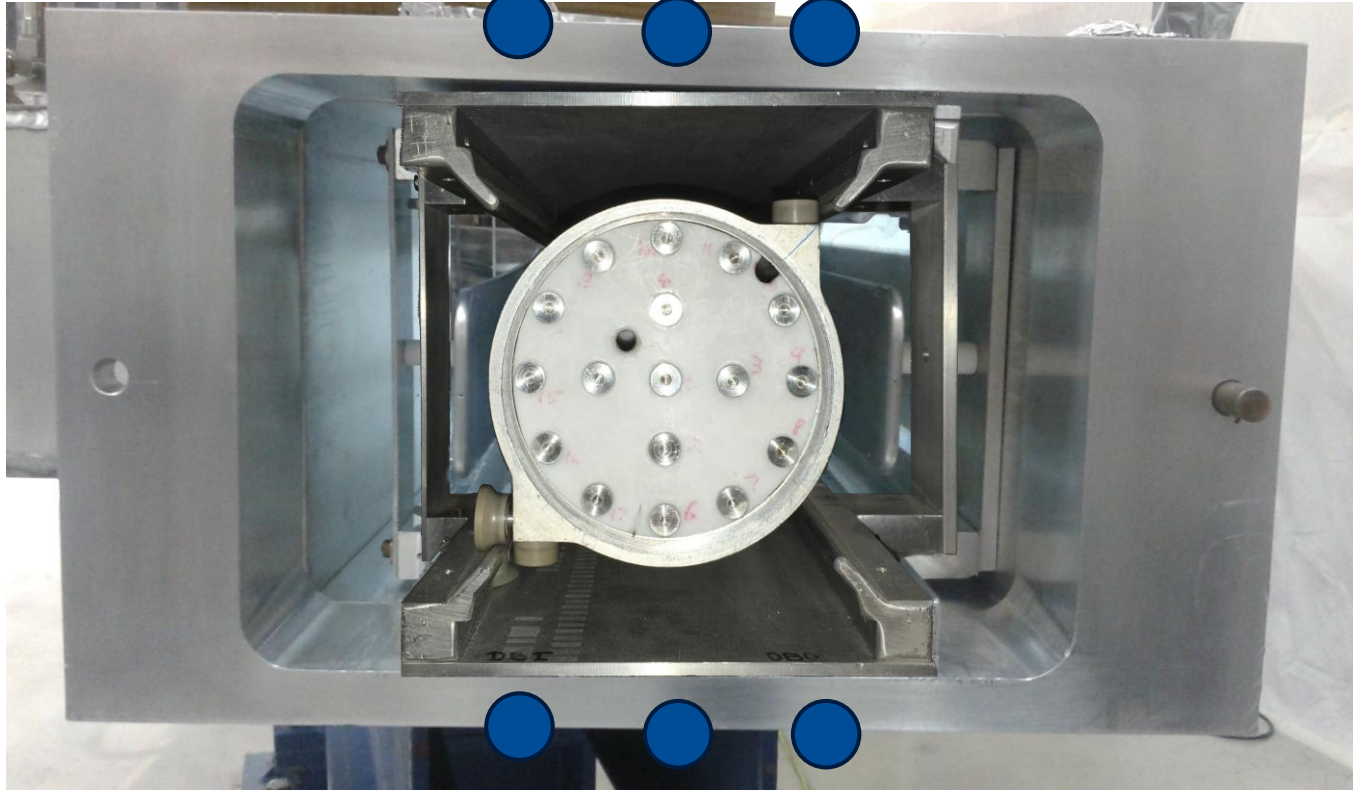
- 2 straw-tracker stations each 8 modules, 4 layers of 32 straws
- Enable tracking of the electron produced in muon decay
- Can study trajectories, track back to decay point and help reconstruct muon distribution





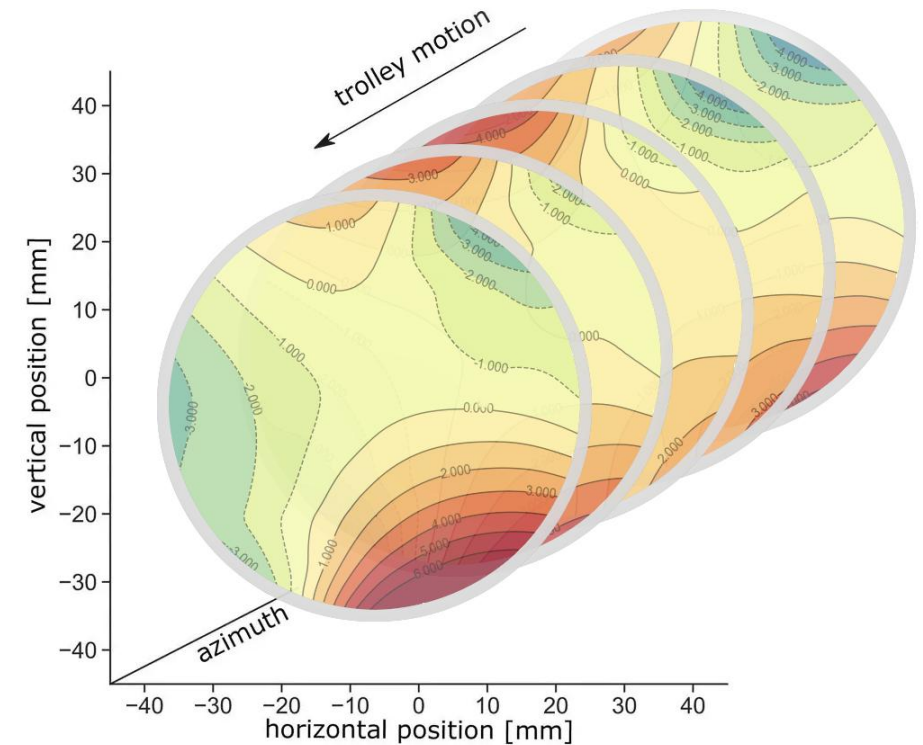
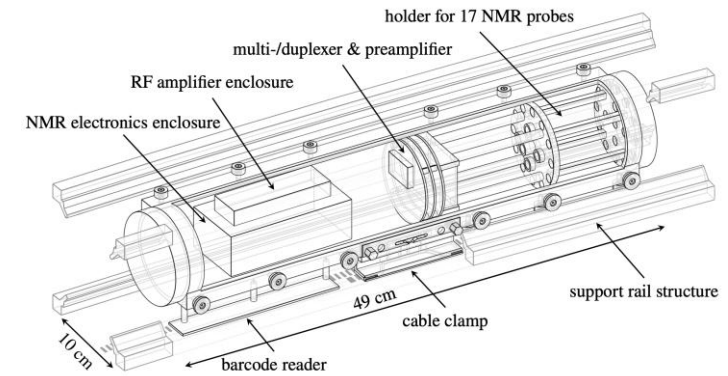
Magnetic Field Mapping

Field Monitor: Fix installed NMR probes
at 72 azimuthal locations around the ring



Trolley: Field Mapper

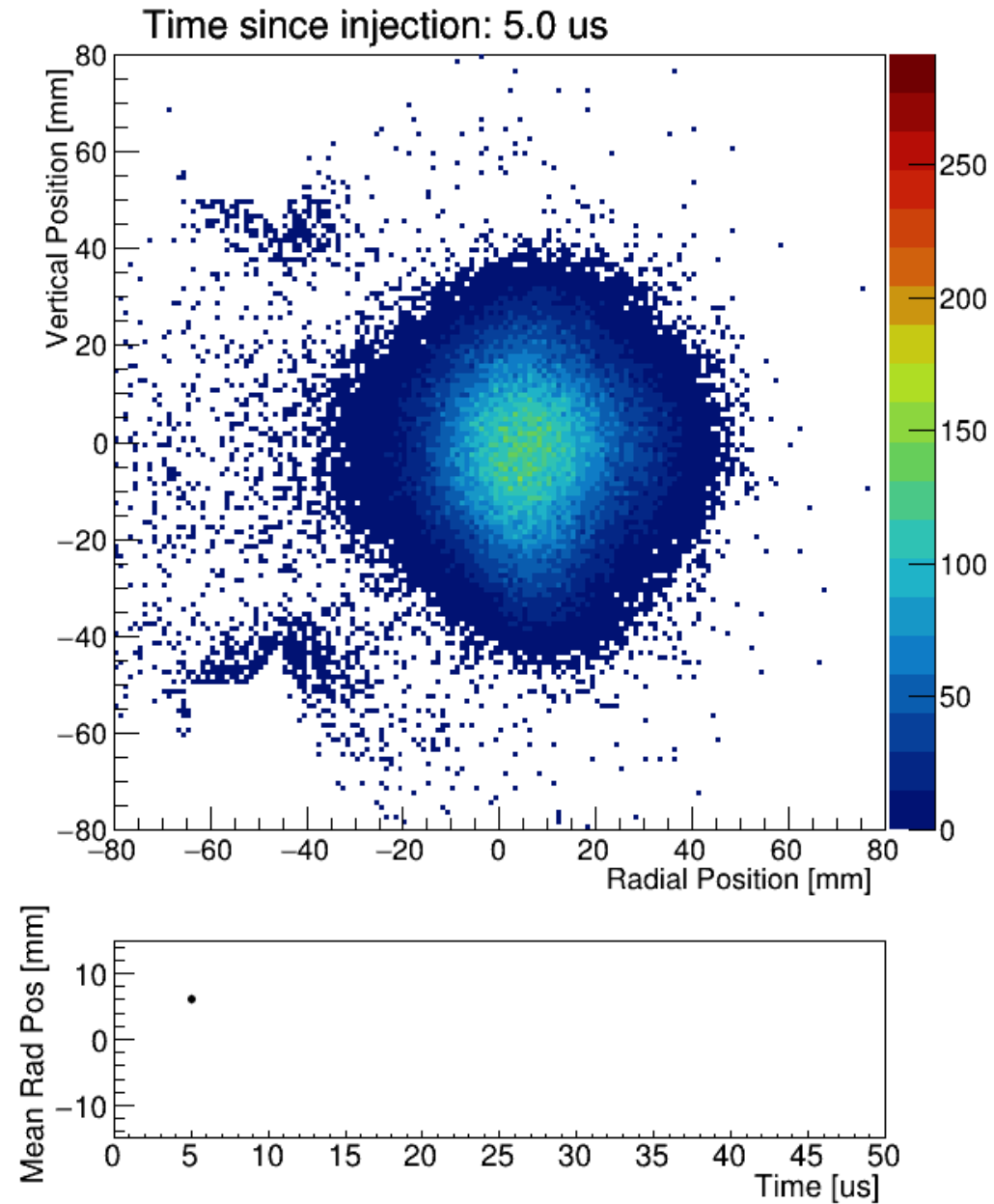
The field between field maps (trolley runs) is tracked by the fixed NMR probes.





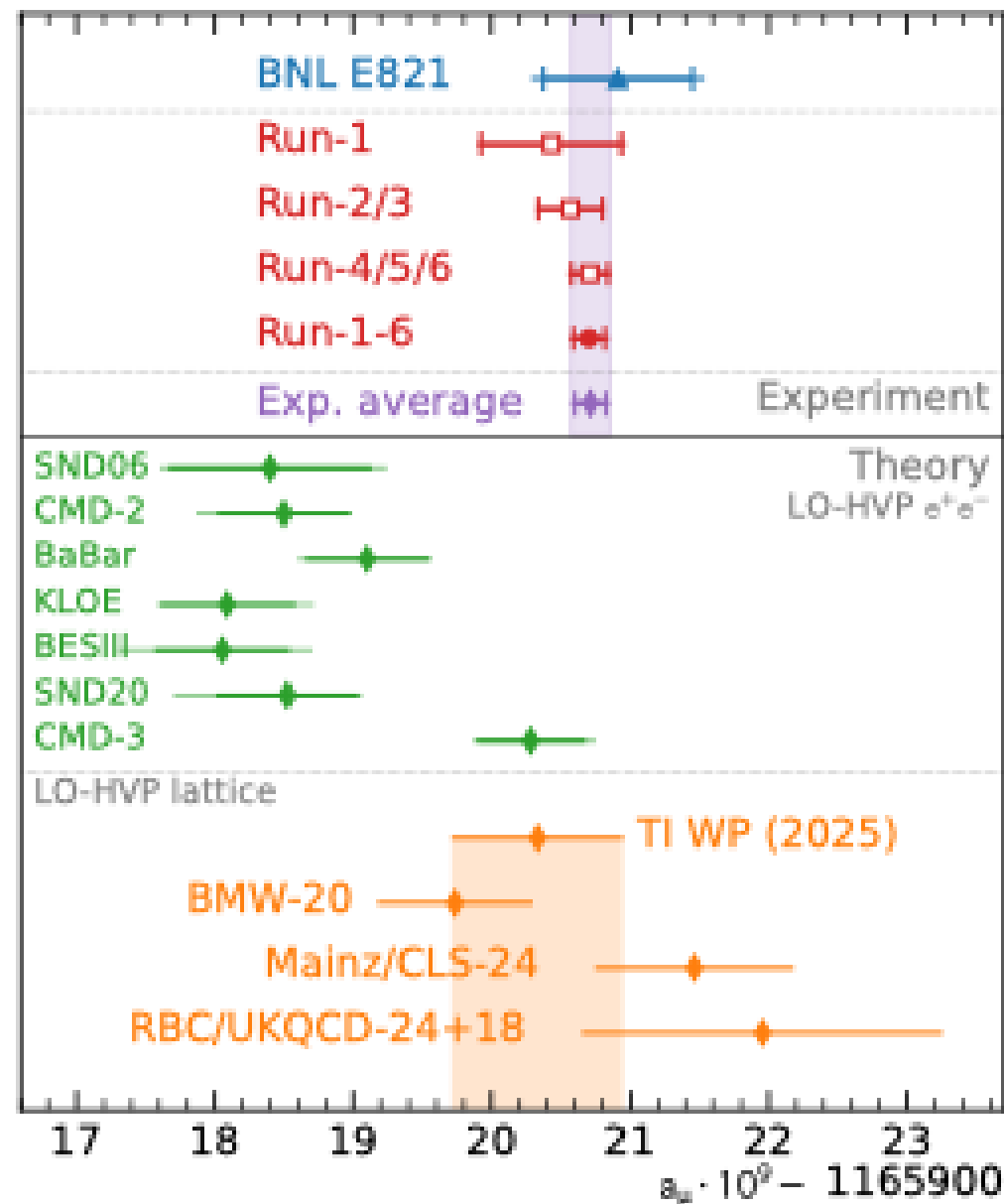


Muon Beam Motion

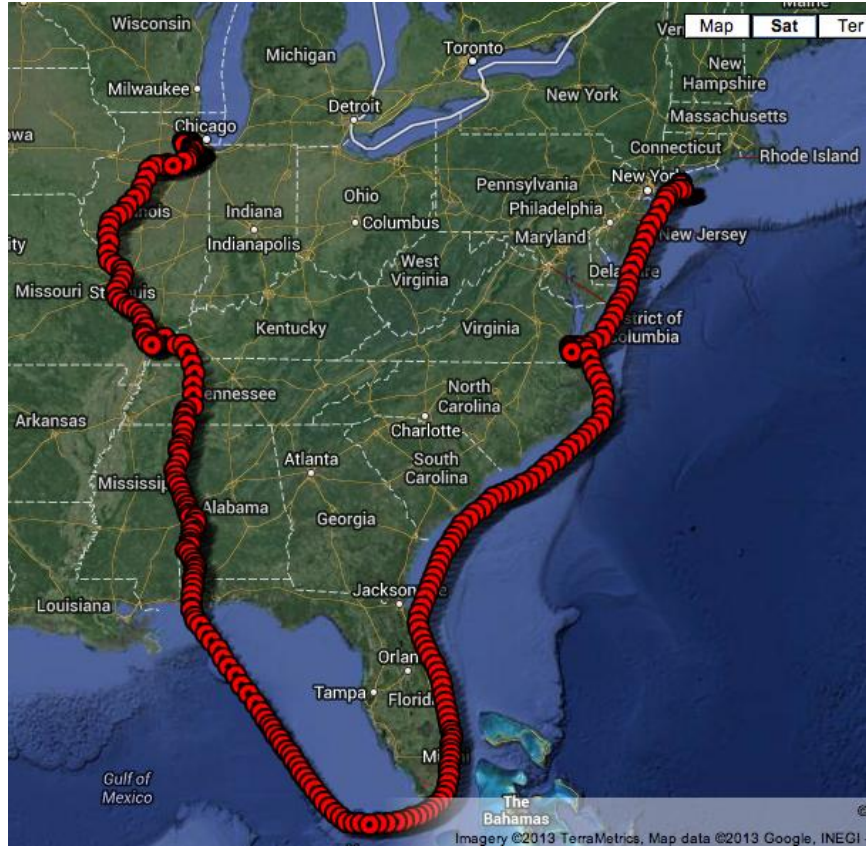


Final Result

- As the g-2 experiment collected more data, the BNL result was verified
- g-2 theory groups were also making progress
 - Some tension still in the theory values
- Successful experiment!



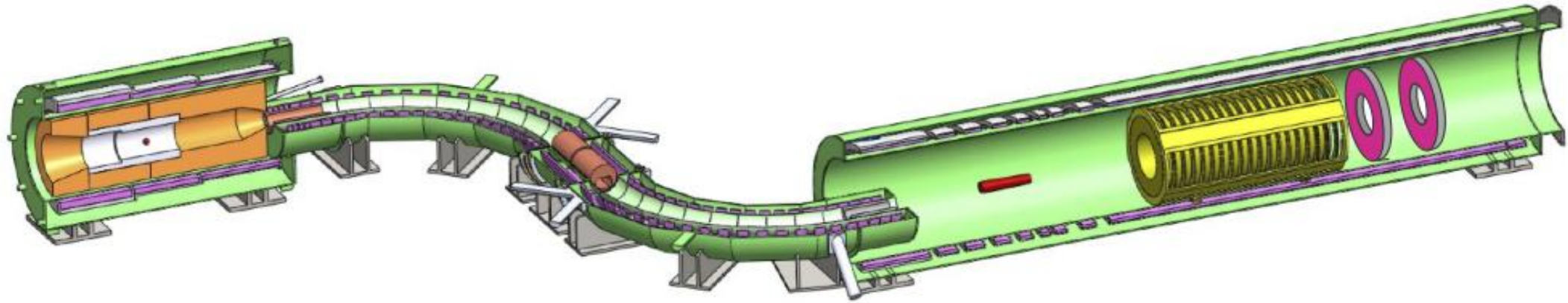
The Big Move



2026 Breakthrough Prize!

Muon g-2 collaboration awarded Breakthrough Prize

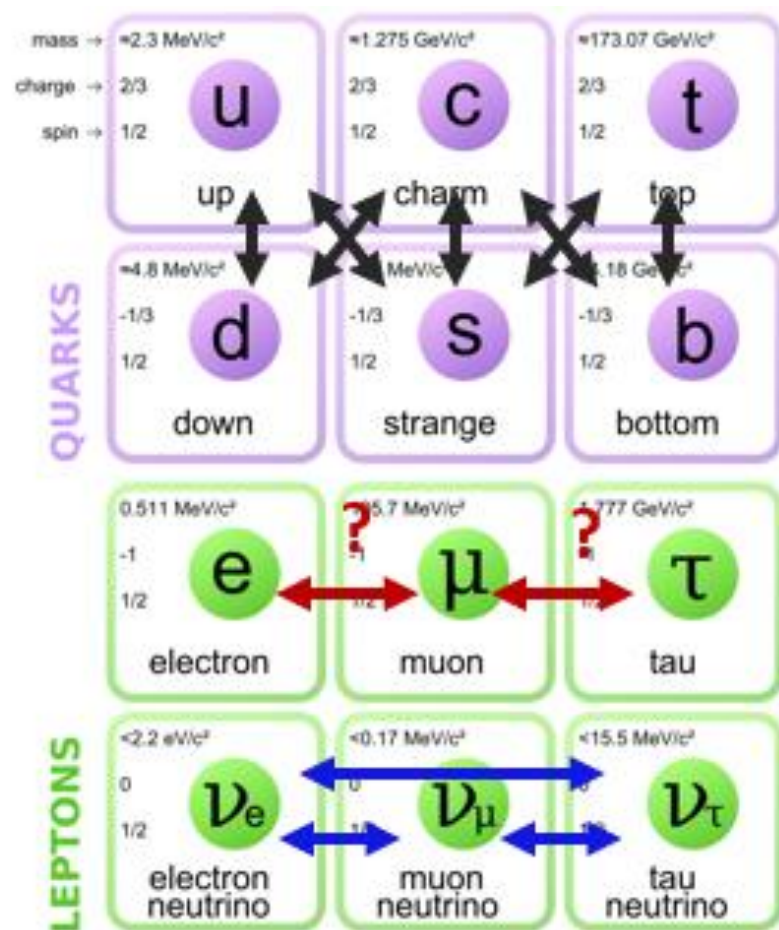




- Search for an extremely rare interaction (charged lepton flavor violation) of the muon with a nucleus: $\mu N \rightarrow e N$
- Each second, fire 1 trillion protons at the experiment to make 10 billion muons
- Look for one out of a billion billion muons that spontaneously converts into an electron (1 billion billion number of grains of sand on all the earth's beaches)
- Four orders of magnitude improvement over the previous experiment



Charged Lepton Flavor Violation

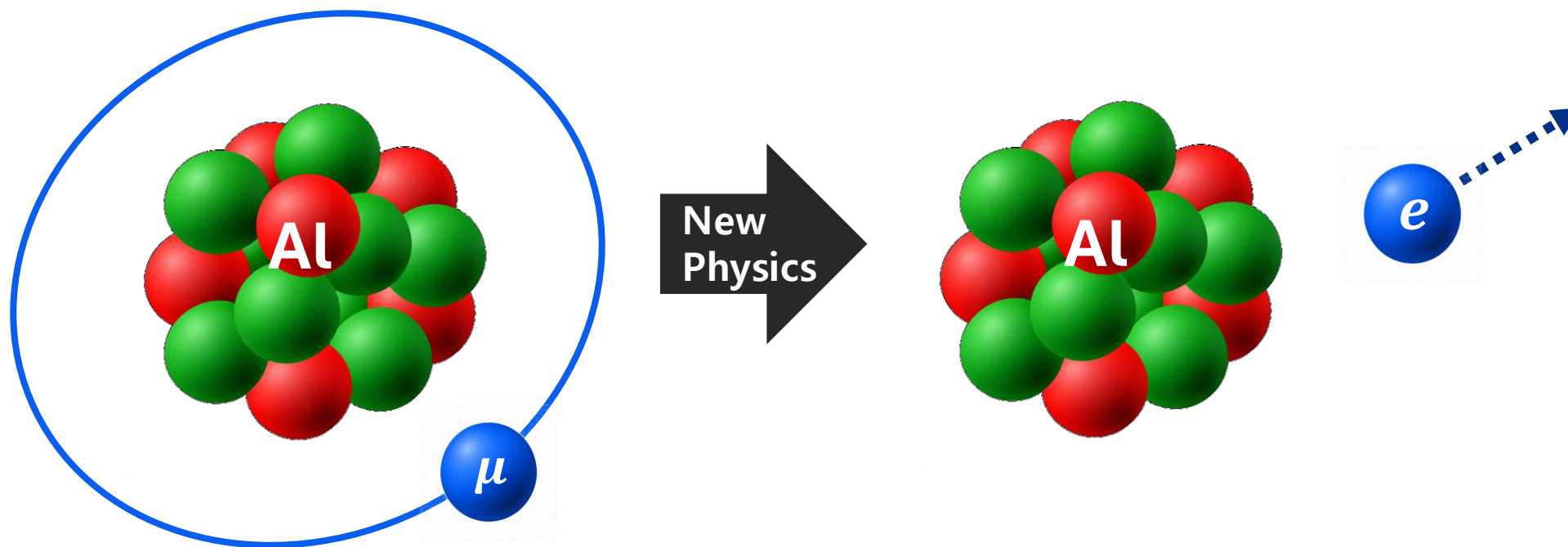


- Quarks mix $\rightarrow$ (Quark) Flavor Violation
- Recently ($\sim$ last 20 years) found the neutrinos mix $\rightarrow$ **Lepton Flavor Violation (LFV)**
- Why not the charged leptons?
 - **CLFV**

What is Mu2e?

Search for Charged-Lepton Flavor Violation (CLFV)

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

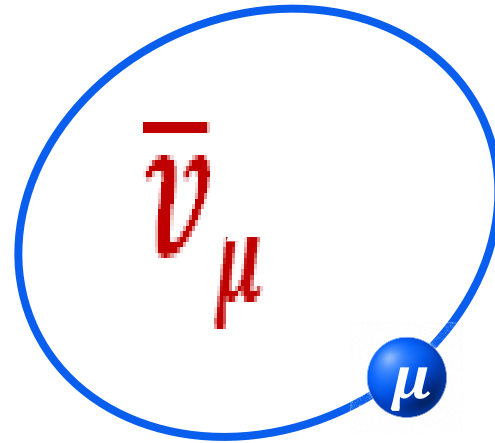


Looking for **M**uon converting **t**o an **E**lectron

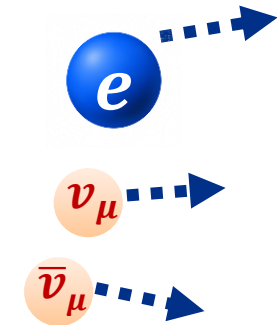
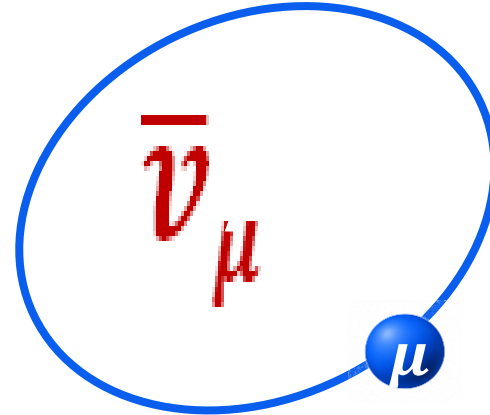
What is Mu2e Measuring?

Muonic Al

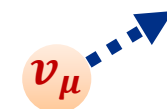
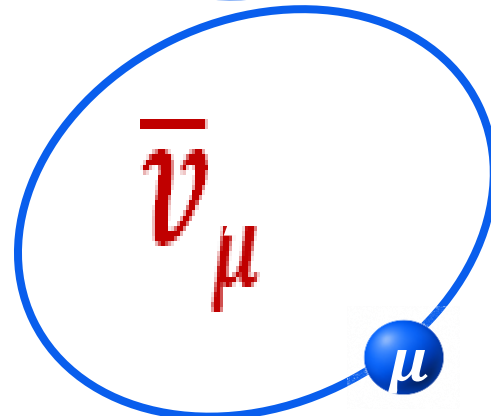
Conversion $< 10^{-12}$



Decay In Orbit $\sim 39\%$

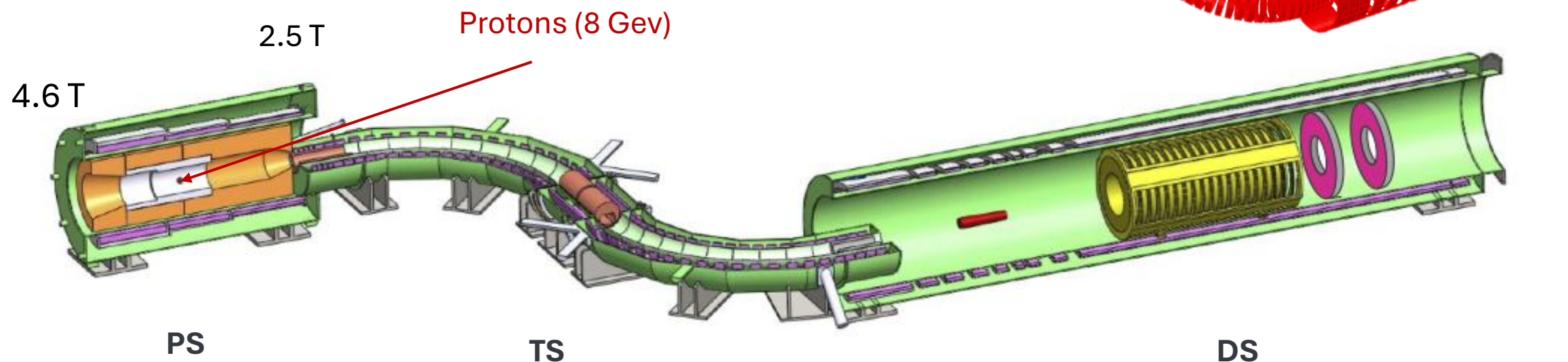


Nuclear Capture $\sim 61\%$





Mu2e Experimental Layout



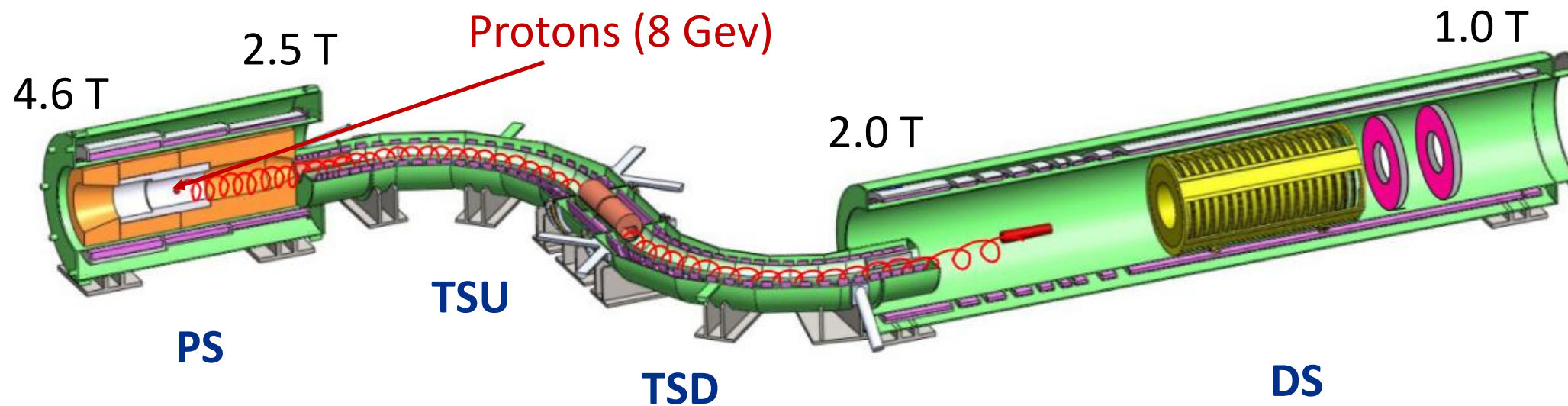
Experiment consists of 3 solenoid systems

Production Solenoid (PS)

- 8 GeV protons interact with a tungsten target to produce, among other things, μ^- (from pion decay)
- Magnetic field gradient encourages pions and muons to travel toward the stopping target

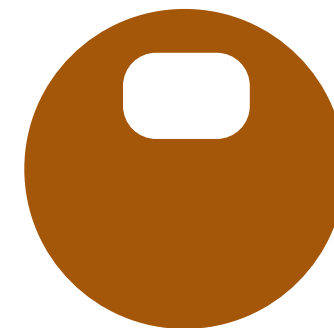


Mu2e Experimental Layout



Transport Solenoid (TS)

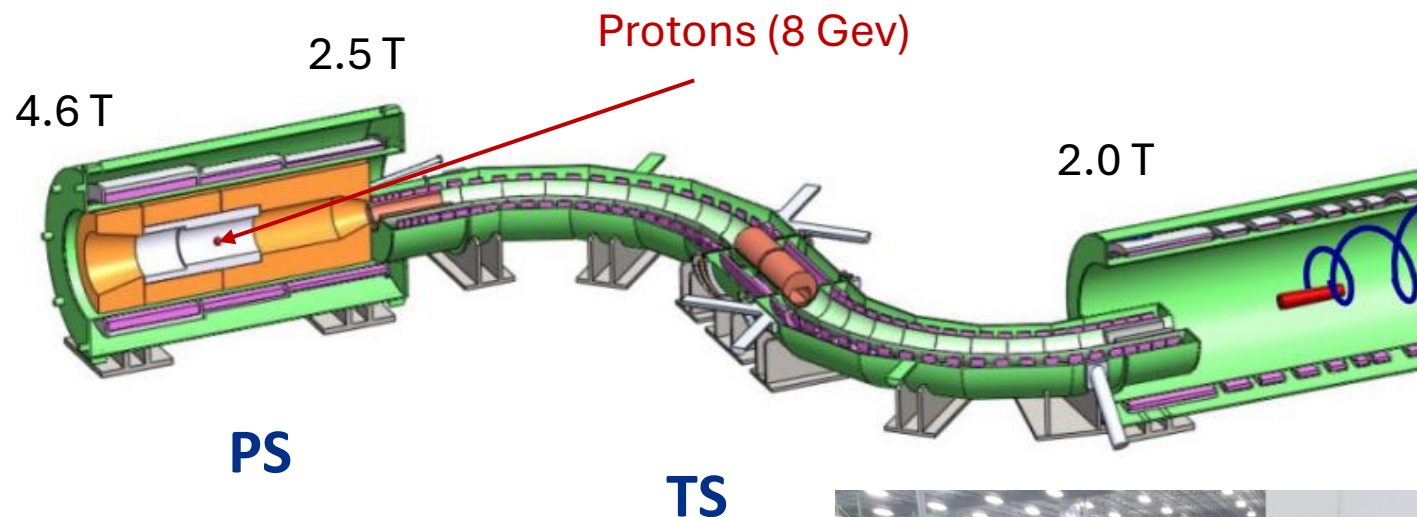
- Magnetic field gradient encourages pions and muons to travel toward the stopping target
- S-shape
 - Eliminates line of sight
 - Minimize positive and neutral particles
 - Allows for momentum and sign filtering
- Absorb anti-protons in a thin window



Rotatable Collimator
between TSU and TSD



Mu2e Experimental Layout



Detector Solenoid (DS)

- Aluminum stopping target
- Magnetic field gradient in the target toward the detector
- Uniform field in detector region
 - Tracker
 - Calorimeter



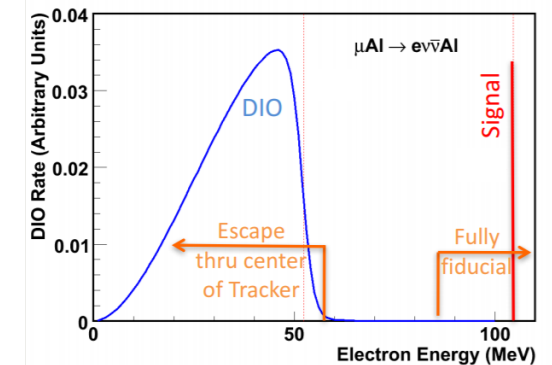
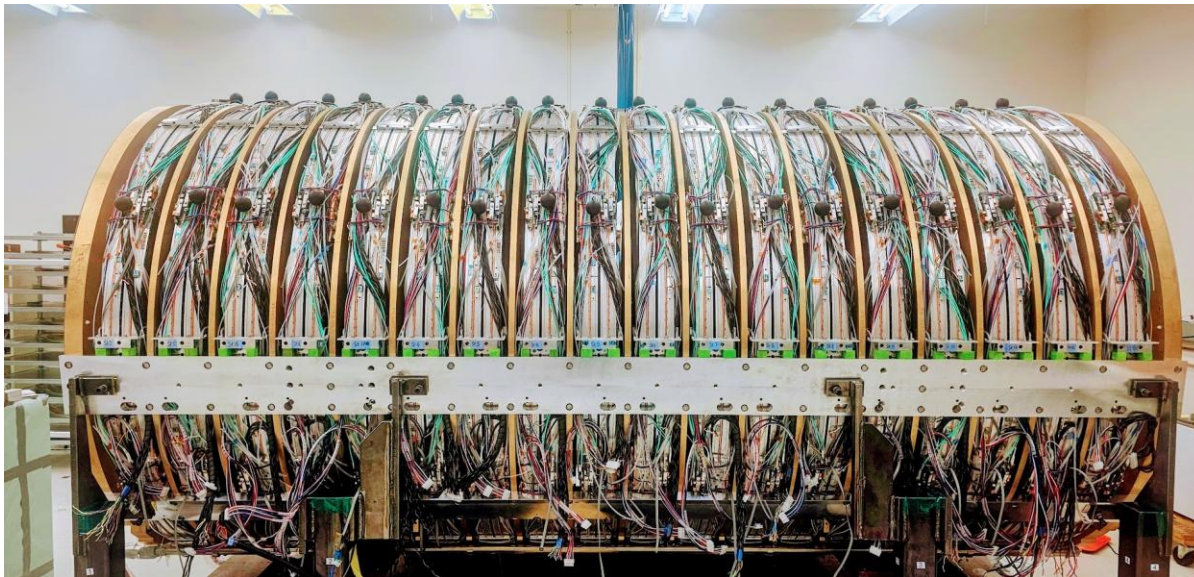
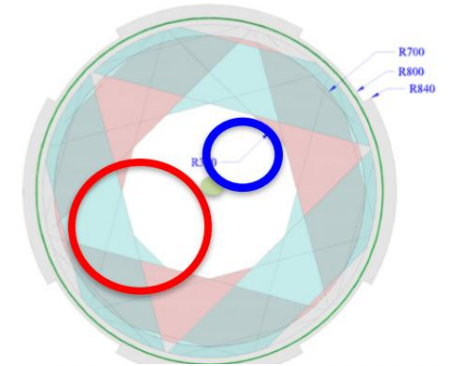
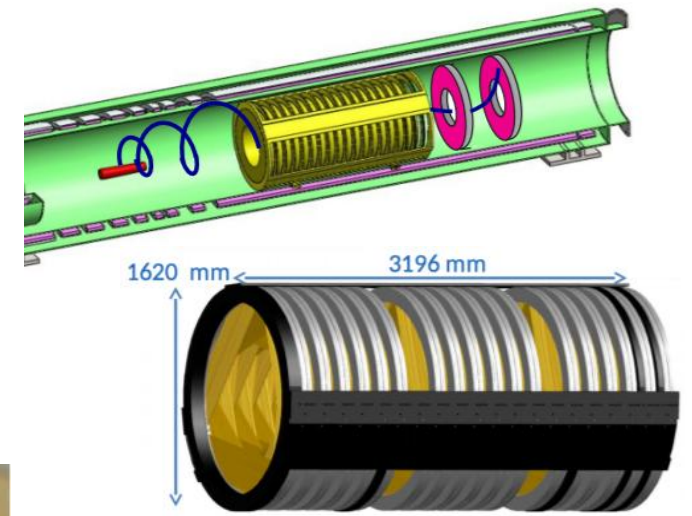
PS bore tube



DS

Detector – Straw Tracker

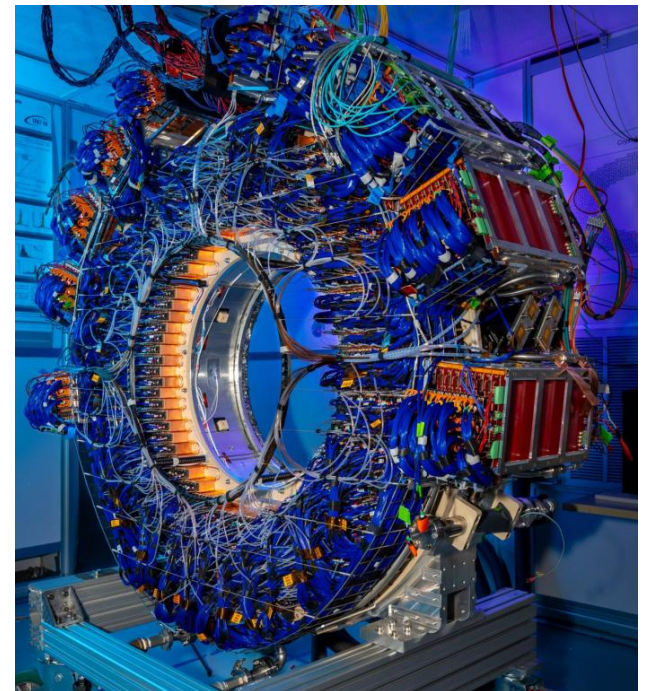
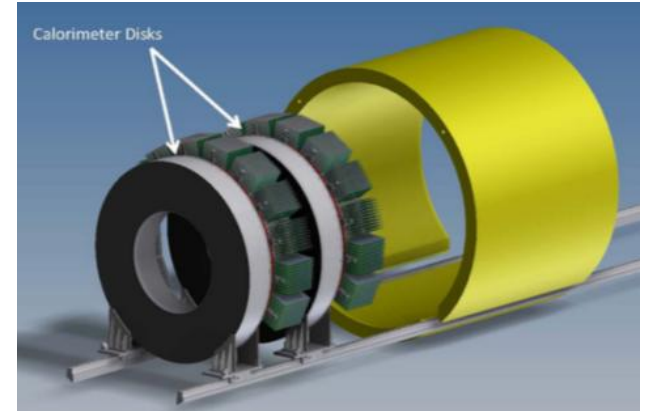
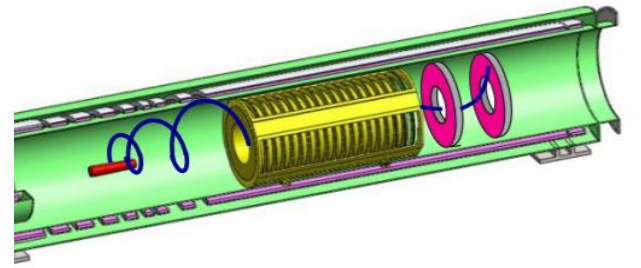
- 5 mm diameter mylar straws, 15 μm wall thickness, ~ 1.2 m to ~ 0.5 m in length
- 25 μm gold plated tungsten wire at ~ 1450 V
- Filled with Ar/CO₂ 80:20
- 96 straws per “panel,”
- 6 panels per “plane”
- 36 planes total





Detector - Calorimeter

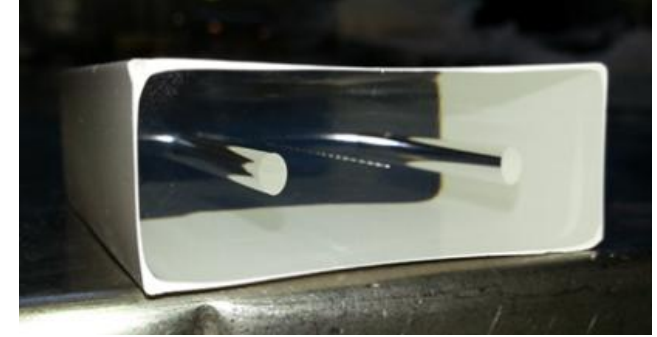
- Used to cross check the measurement taken by the tracker, distinguish muons from electrons
- Two annuli with inner radius 35.1 cm and outer radius 66 cm
- Disks separated by 70 cm (1/2 wavelength)
- ~800 pure Cesium Iodide crystals per disk
- Two 9x9 mm² avalanche photodiodes per crystal
- Under 500 ps timing resolution, ~1 cm position resolution



Cosmic Ray Veto

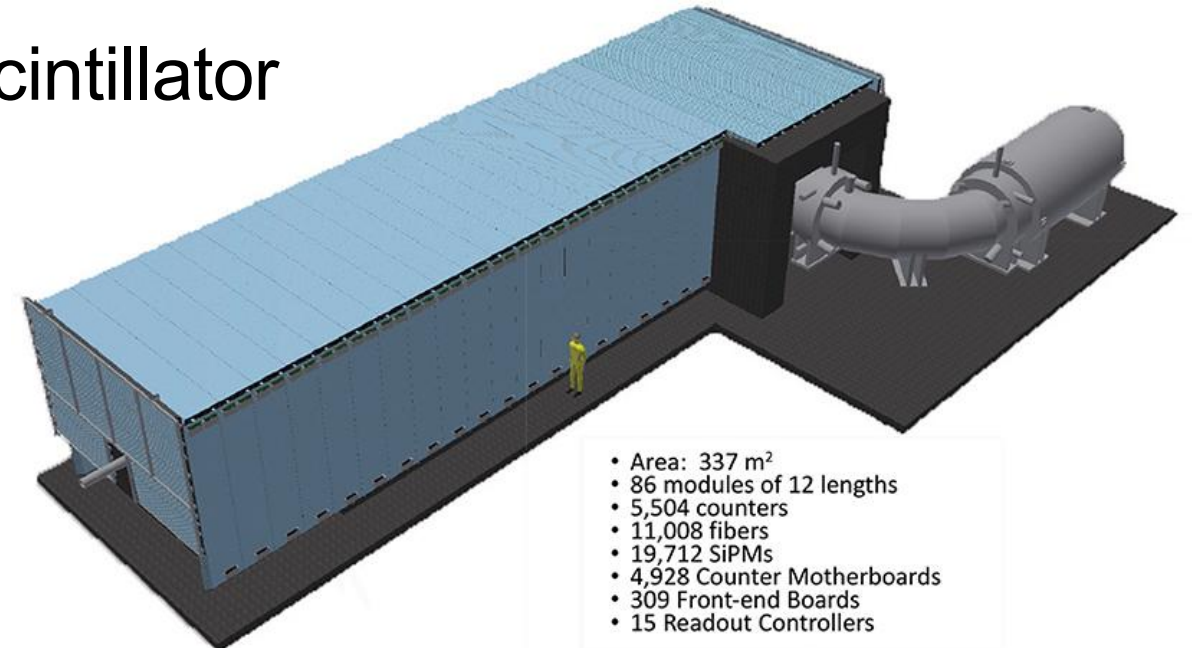
Cosmic background

- 10^9 cosmic rays/day
- **~1 background event/day !**

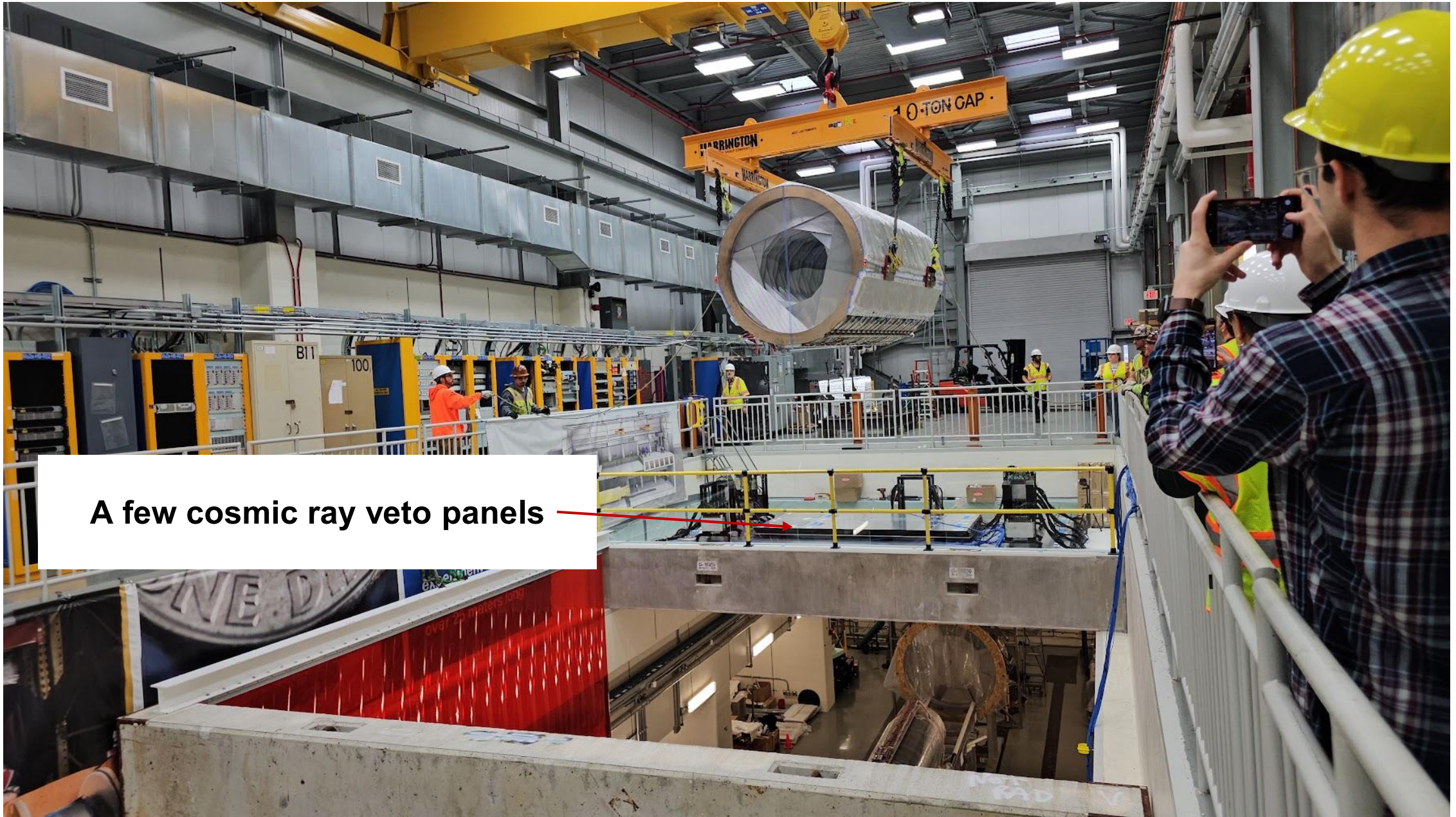


Requires 99.99% efficient cosmic ray veto system

- 4 layers of extruded polystyrene scintillator counter
- 5,000 total counters

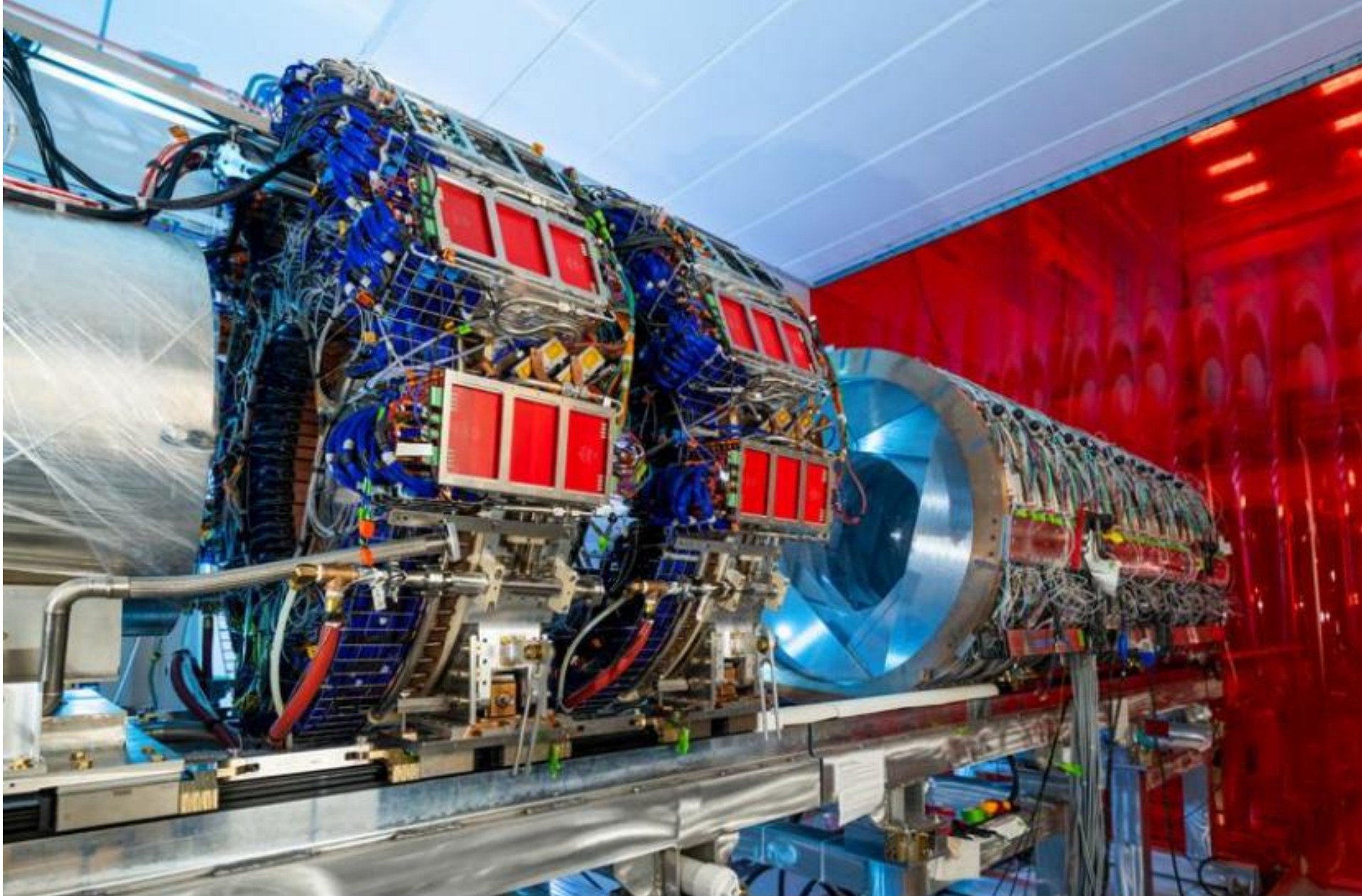


Tracker Installation



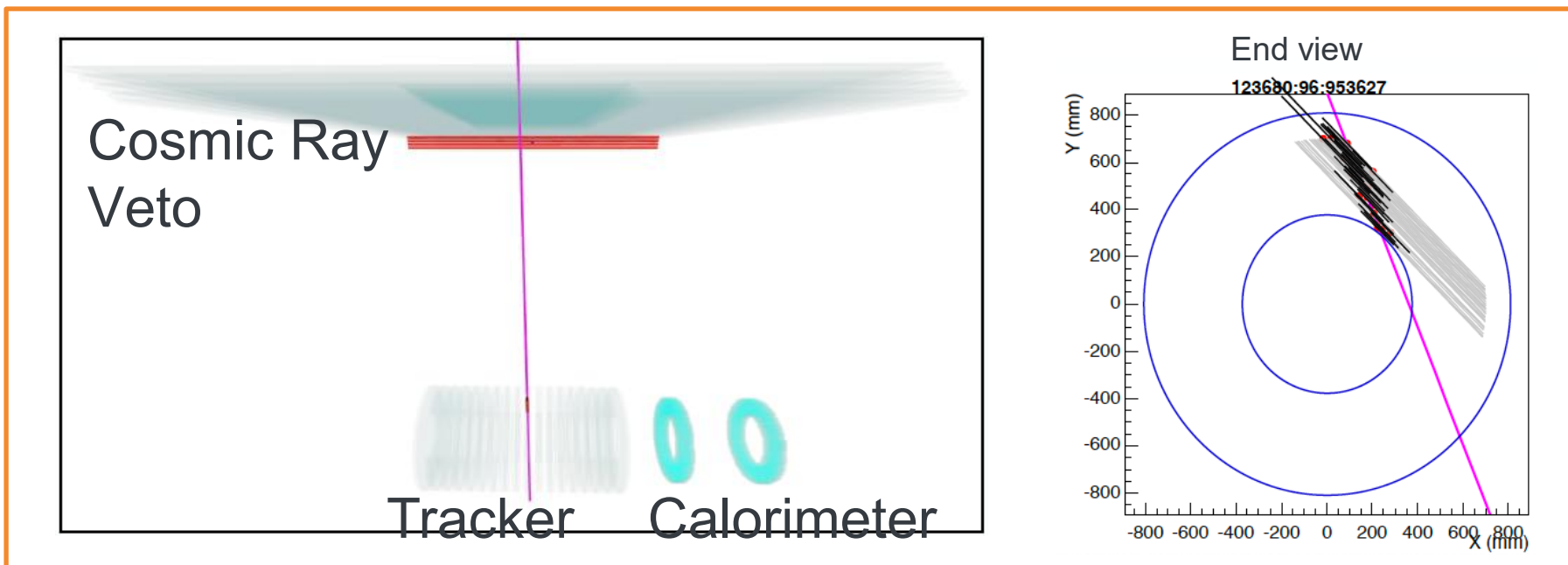


Detector Train Installed

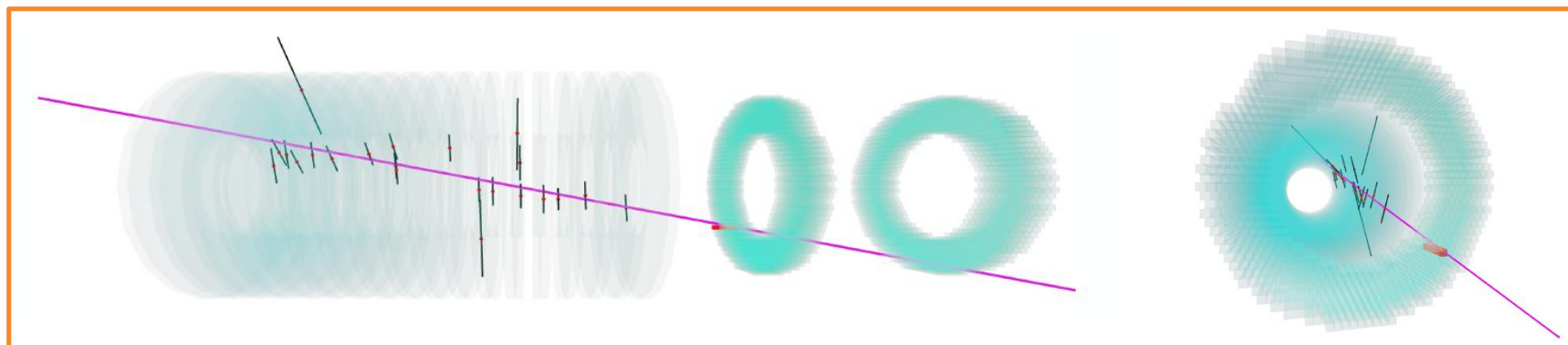


Mu2e Detector System Commissioning

Mu2e has successfully reconstructed its first cosmic ray coincidences across three systems



Vertically-oriented cosmic ray event



Horizontally-oriented cosmic ray event



Magnet Installation: TSu and TSd





Magnet Installation: PS & DS-Installed Yesterday!



Mu2e Results

- Still in construction phase but hoping to take beam in late 2027!
- Stay tuned..

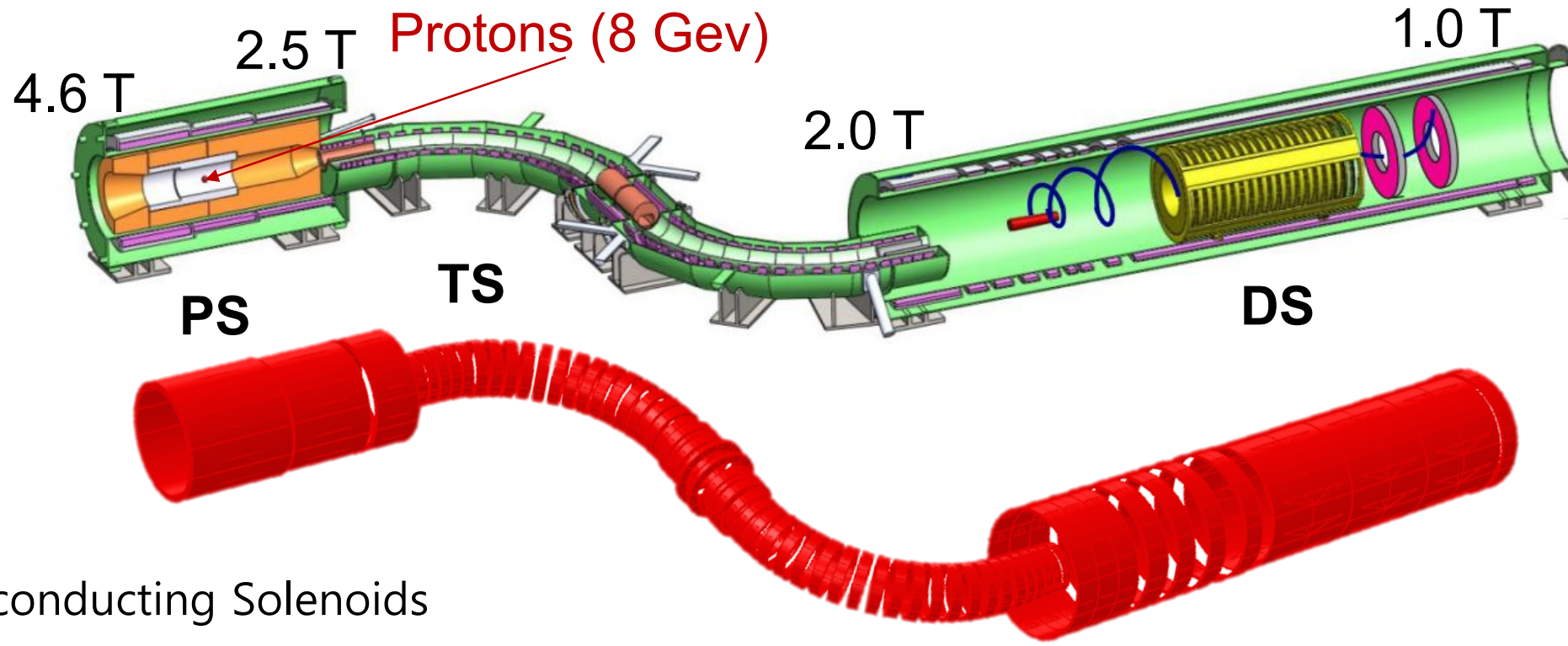


Fermi *FORWARD*

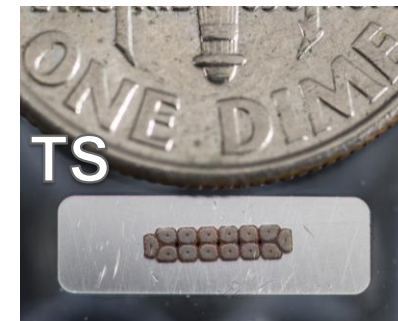
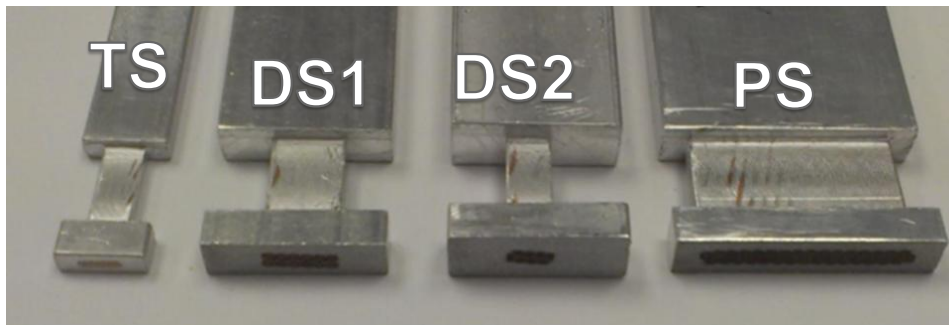


U.S. DEPARTMENT
of ENERGY

Mu2e Solenoids



- 66 Superconducting Solenoids
- Aluminum stabilized NbTi



Rutherford Cable

