Muons and Magnets: The Mu2e Experiment at Fermilab

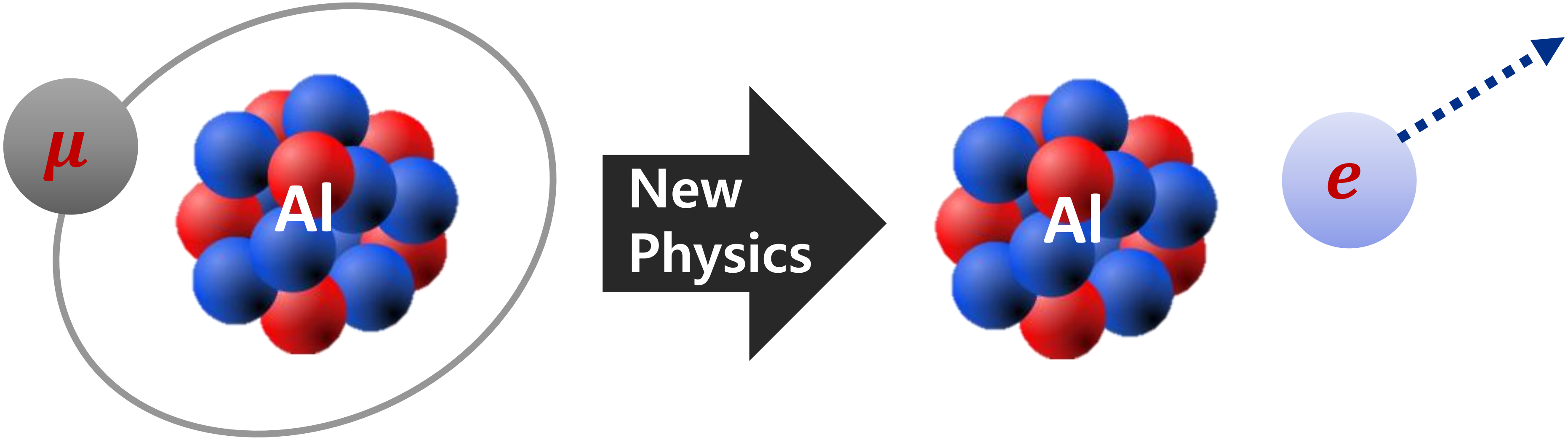
Karie Badgley

ASP 2022- South Africa

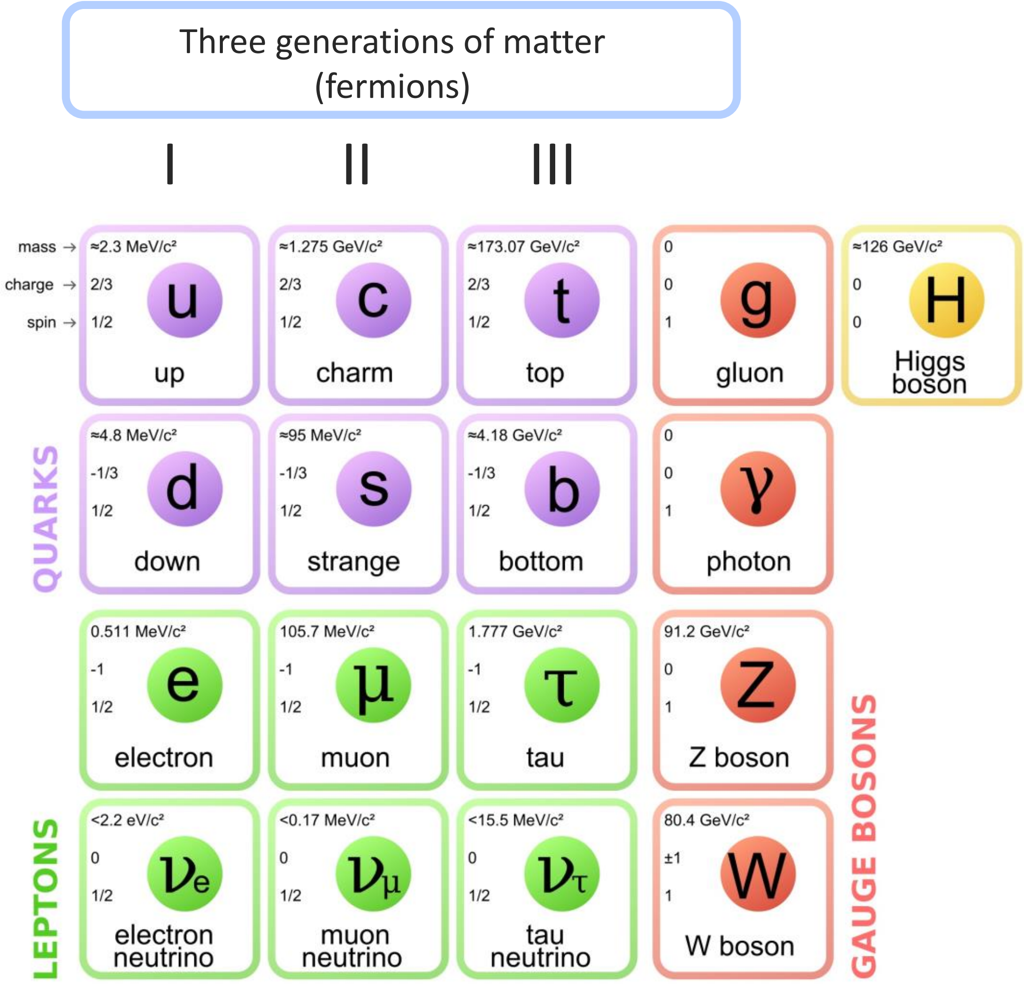
What is Mu2e?

Search for Charged-Lepton Flavor Violation (CLFV)

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

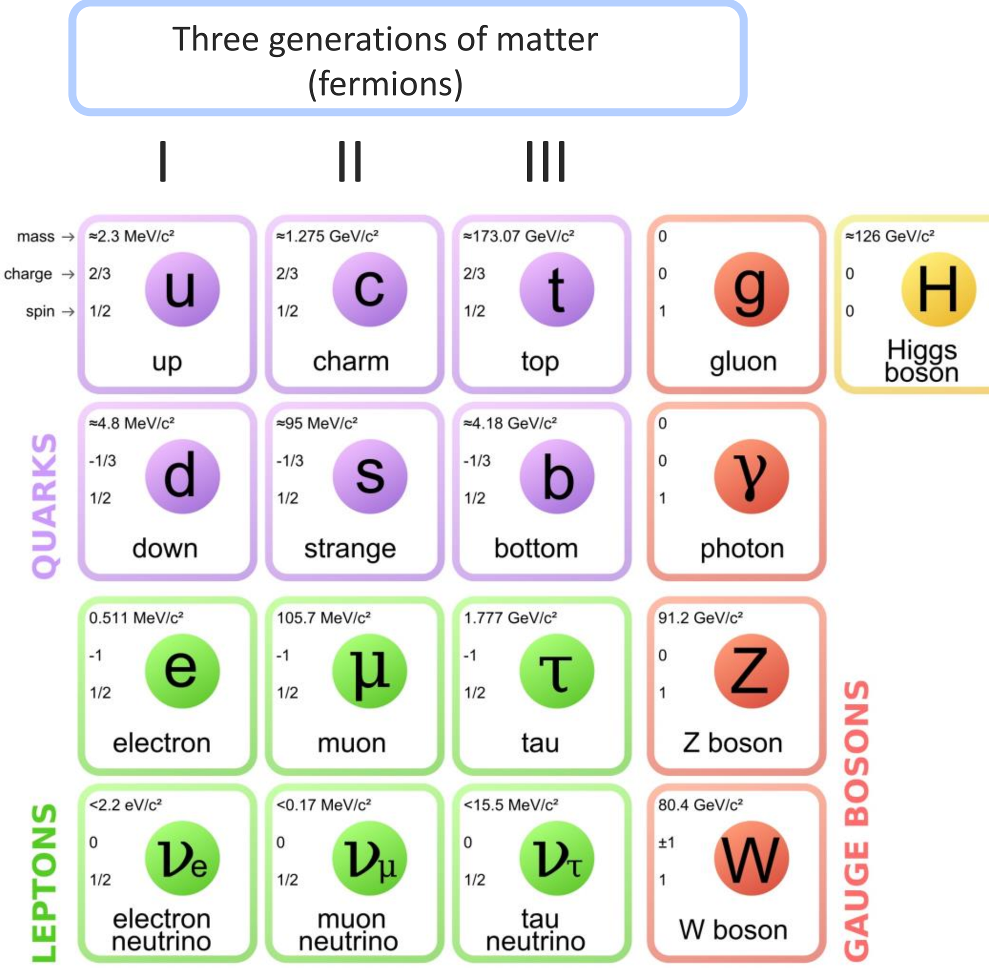


Standard Model



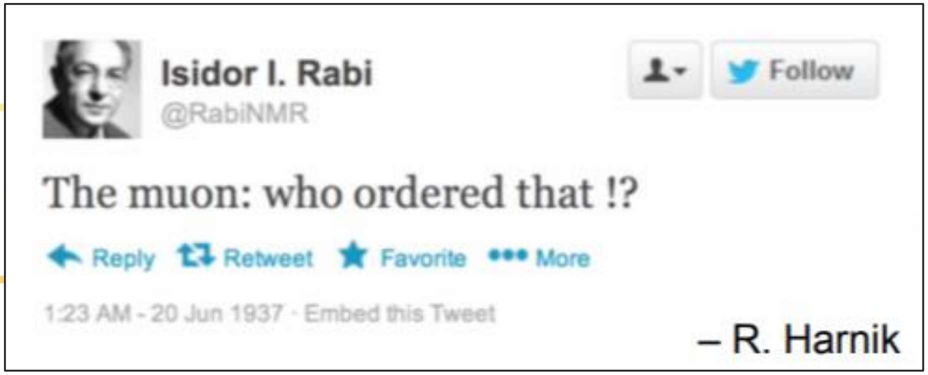
- **Successful theory**
  - Discovery of SM-like Higgs particle
- Incomplete!
  - Gravity, Dark matter, Neutrino oscillations…
- Motivates a search for physics beyond the SM

Standard Model



SM Flavor Puzzle

- Why are there 3 generation of matter?



Isidor I. Rabi
@RabiNMR

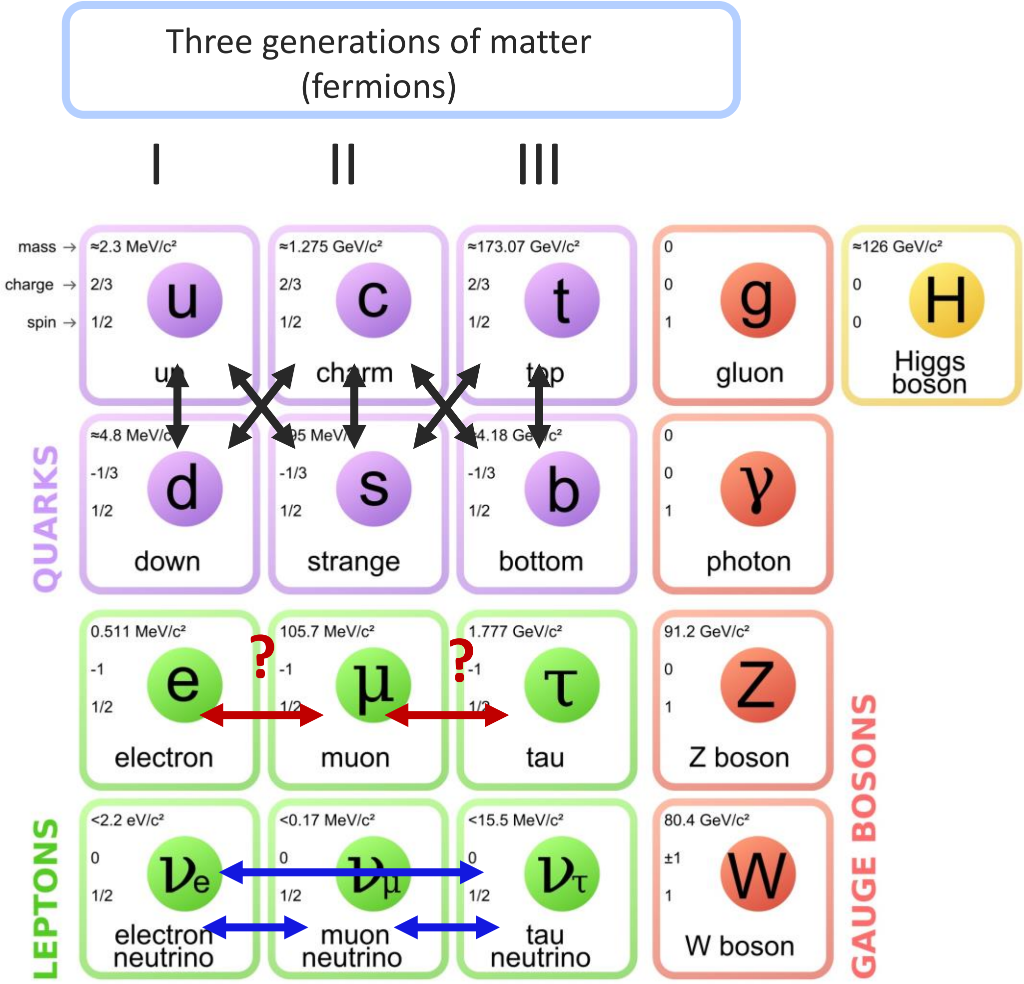
The muon: who ordered that !?

1:23 AM - 20 Jun 1937 · Embed this Tweet

– R. Harnik

- What defines fermion masses?
- What is the origin of lepton asymmetry in the universe?
- Is mixing allowed between generations/flavors?
- ……?

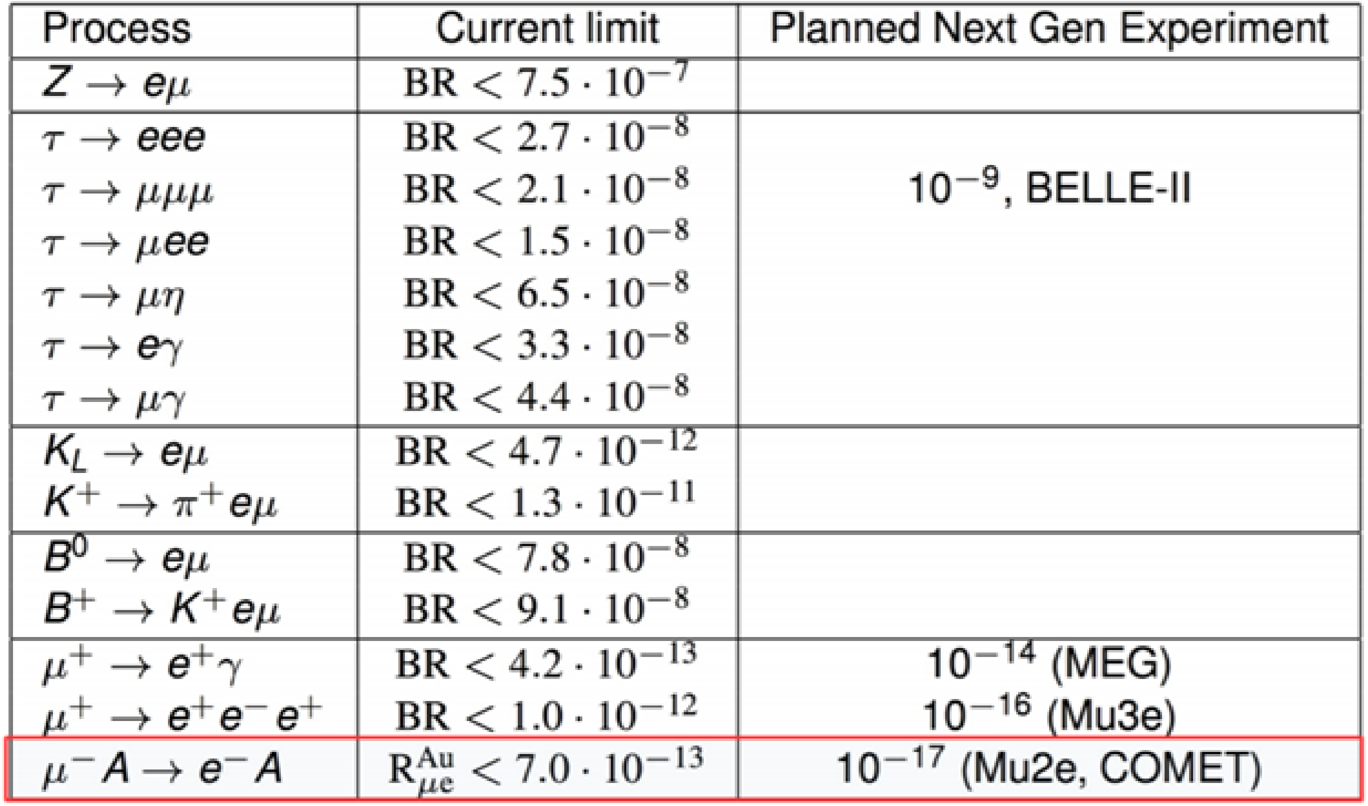
“Forbidden” Search



- Quarks mix → (Quark) Flavor Violation
- Recently (~last 15 years) found the neutrinos mix → Lepton Flavor Violation (LFV)
- Why not the charged leptons?
  - CLFV

Global interest in CLFV

Some of the CLFV Processes

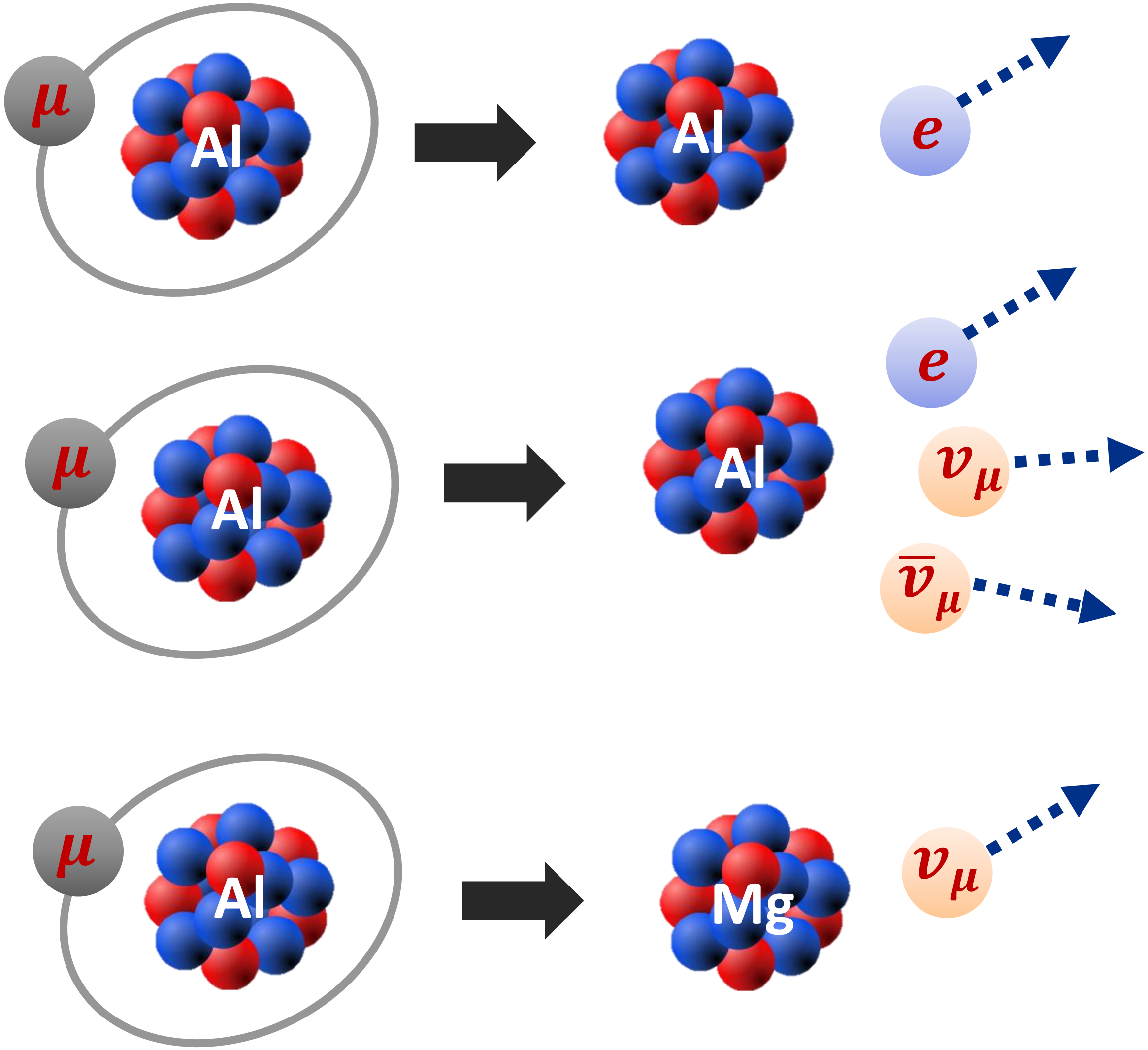


Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \cdot 10^{-8}$	
$\tau \to e\gamma$	$\mathrm{BR} < 3.3 \cdot 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 4.4 \cdot 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \to \pi^+ e\mu$	$\mathrm{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \to e^+e^-e^+$	$\mathrm{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \to e^- A$	$\mathrm{R}^{\mathrm{Au}}_{\mu e} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

Most sensitive CLFV measurements use μ

What is Mu2e measuring?

Muonic Al



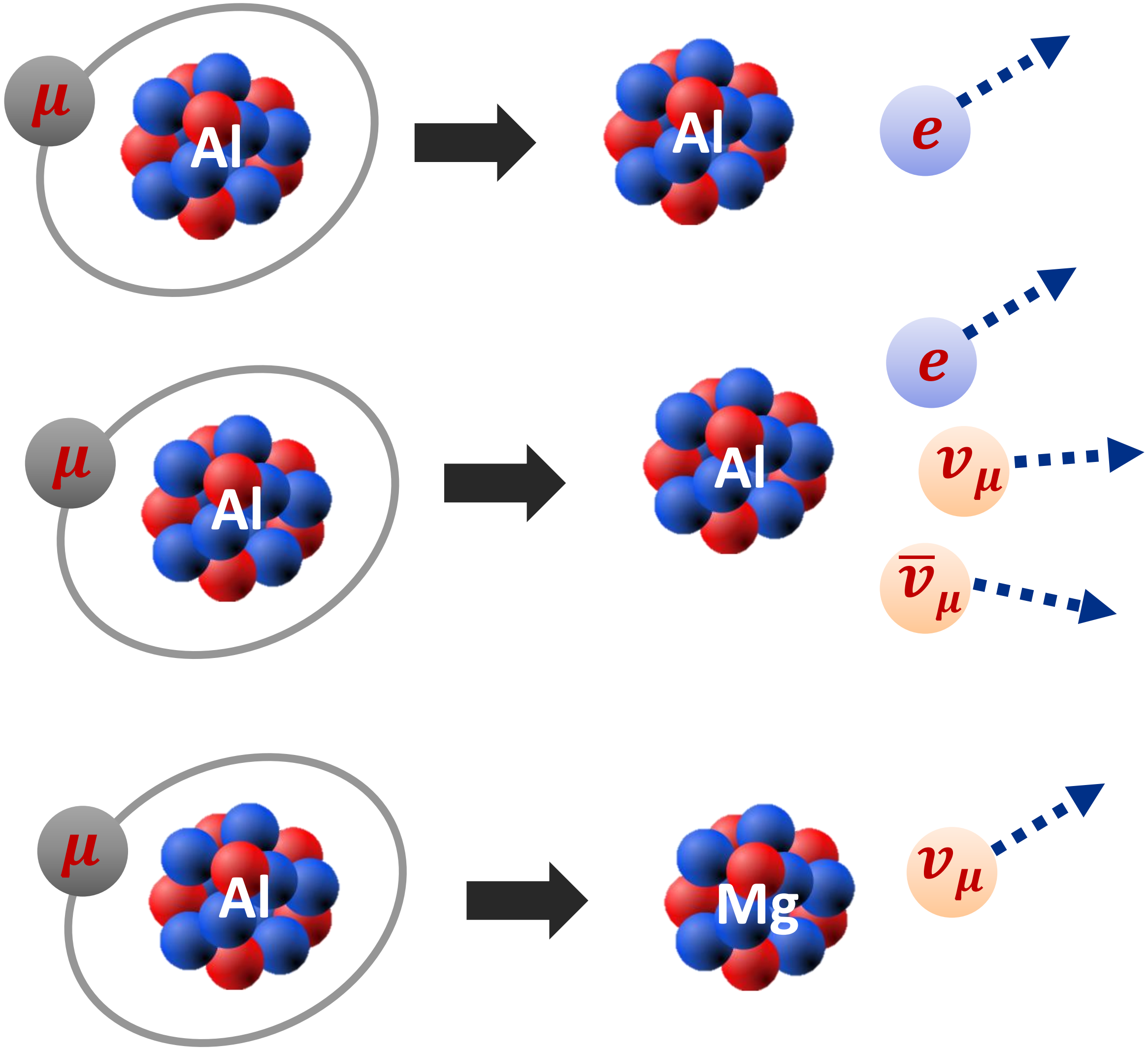
Conversion < 10^{-12}

Decay In Orbit ~39%

Nuclear Capture ~61%

What is Mu2e measuring?

Muonic Al



Conversion < 10^{-12}

-Signal

Decay In Orbit ~39%

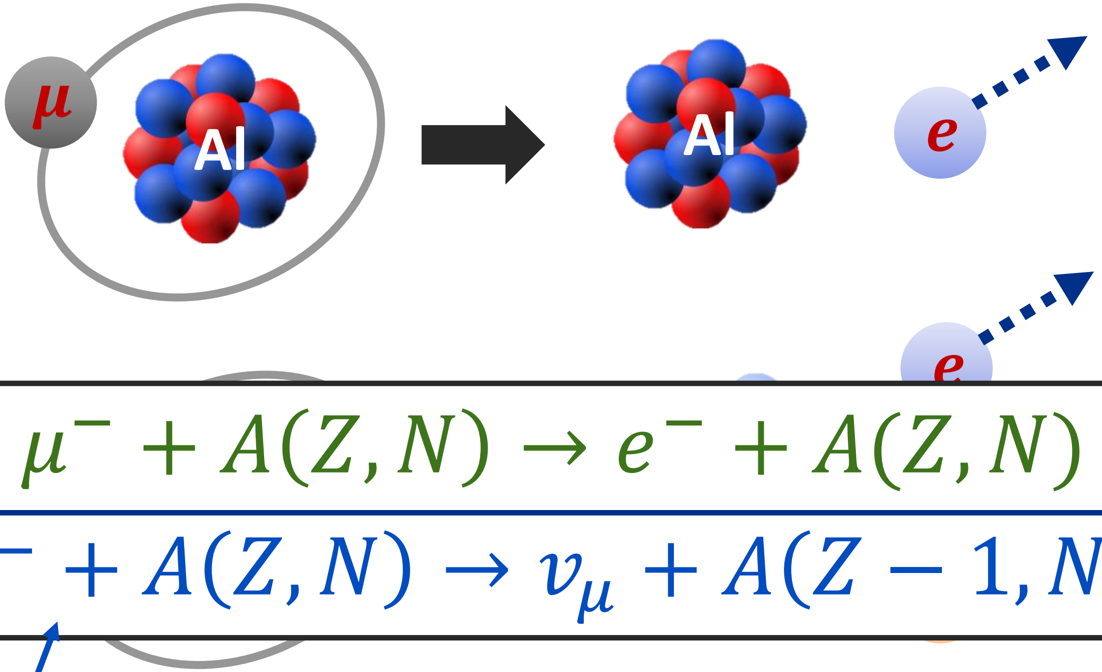
-Dominant Background

Nuclear Capture ~61%

-Normalization Factor

What is Mu2e measuring?

Muonic Al



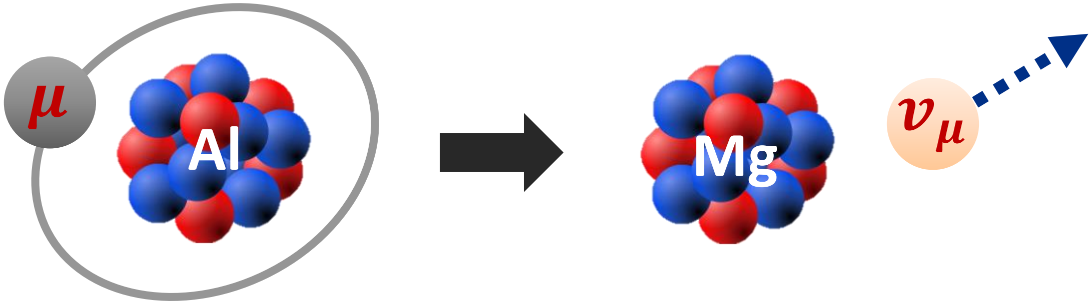
Conversion < 10^{-12}

-Signal

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

Decay In Or

-Dominant Ba



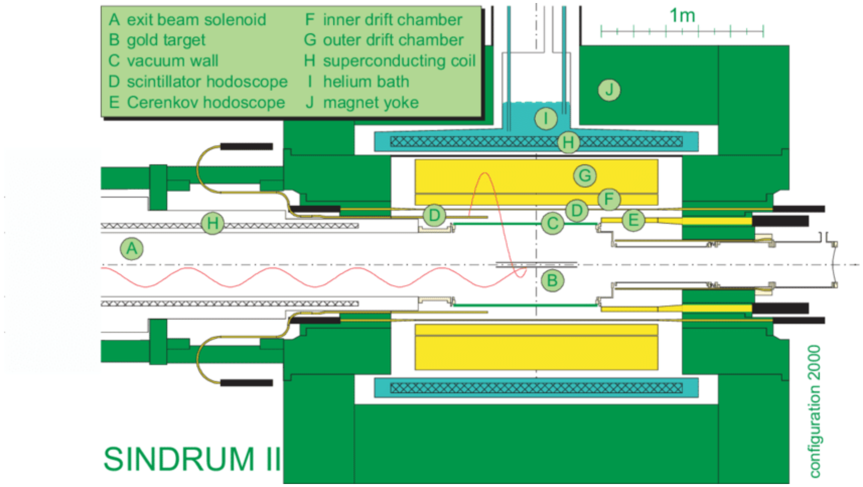
Nuclear Capture ~61%

-Normalization Factor

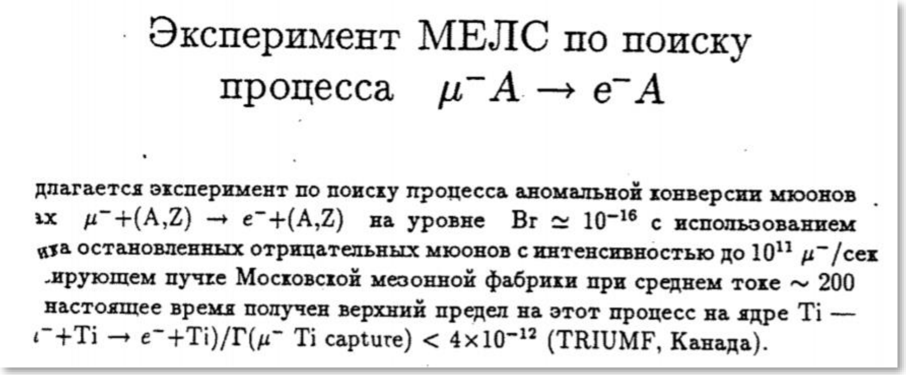
Improving on the previous experiment

- Current world's best limit on $\mu N \rightarrow eN$
  - $R_{\mu e}(\mu N_{Au} \rightarrow eN_{Au}) < 7\times10^{-13}$ at 90% CL
  - Sindrum-II Collaboration, 2006

- The previous measurement was limited by
  - Backgrounds from prompt pions
  - Stopped μ rate (10^{7} μ/s with 1 MW beam)



A Clever Idea



Эксперимент МЕЛС по поиску
процесса $\mu^- A \rightarrow e^- A$

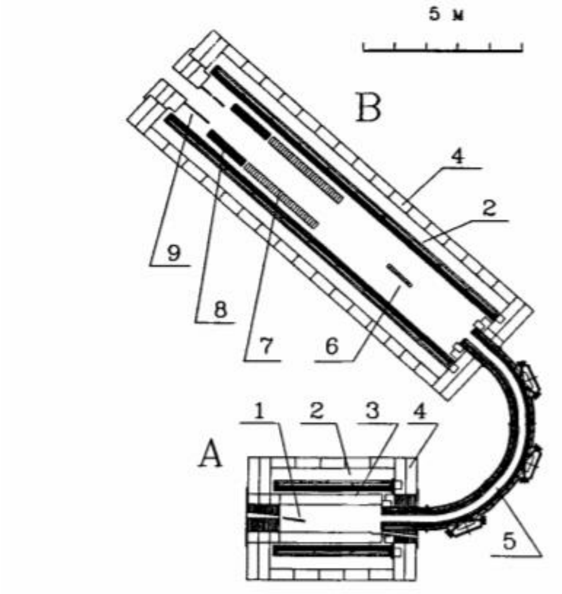
длагается эксперимент по поиску процесса аномальной конверсии мюонов ах $\mu^-+(\mathrm{A,Z}) \rightarrow e^-+(\mathrm{A,Z})$ на уровне $\mathrm{Br} \simeq 10^{-16}$ с использованием ка остановленных отрицательных мюонов с интенсивностью до $10^{11}\ \mu^-/$сек ирующем пучке Московской мезонной фабрики при среднем токе ~ 200 настоящее время получен верхний предел на этот процесс на ядре Ti — $^-+\mathrm{Ti} \rightarrow e^-+\mathrm{Ti})/\Gamma(\mu^-$ Ti capture$) < 4\times10^{-12}$ (TRIUMF, Канада).

The Solenoid Muon Capture System
for the MELC Experiment

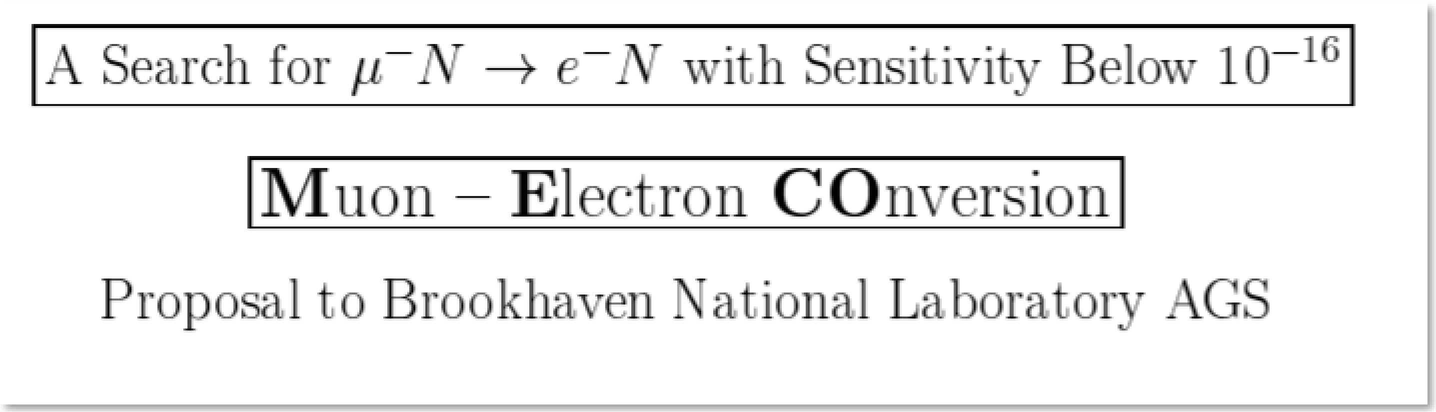
Rashid M. Djilkibaev and Vladimir M. Lobashev

Institute for Nuclear Research, Russian Academy of Sciences,
60-th Oct. Ann. 7a, Moscow 117312, Russia

- Proposed in a 1989 by V. Lobashev & R. Djilkibaev in the Soviet Journal of Nuclear Physics
  - – Pulsed proton beam
  - – Solenoids to capture muons



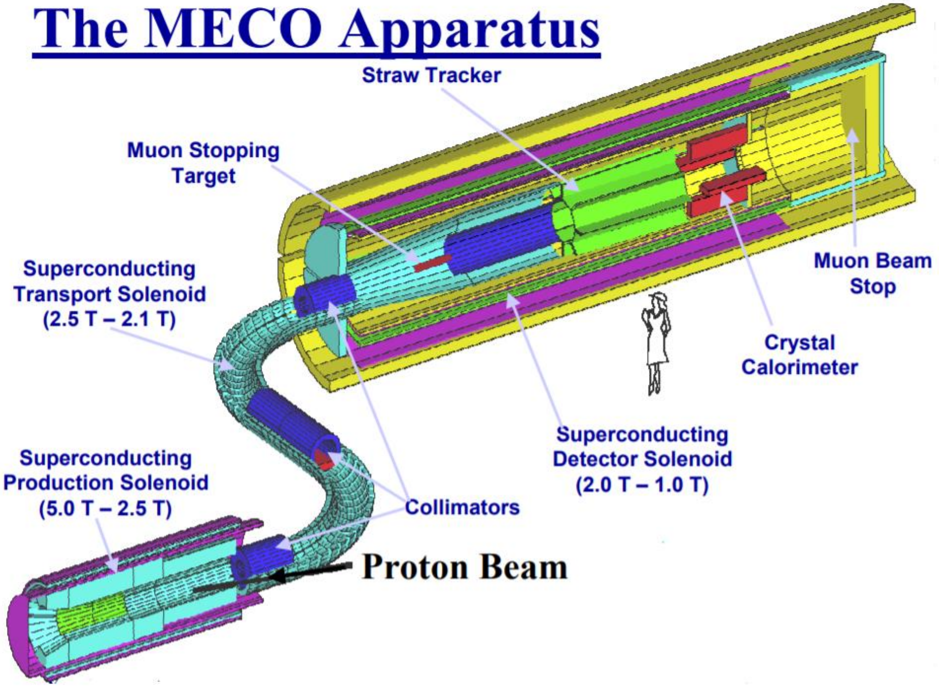
A Clever Idea…proposed at BNL



A Search for $\mu^- N \rightarrow e^- N$ with Sensitivity Below 10^{-16}

Muon – **E**lectron **CO**nversion

Proposal to Brookhaven National Laboratory AGS

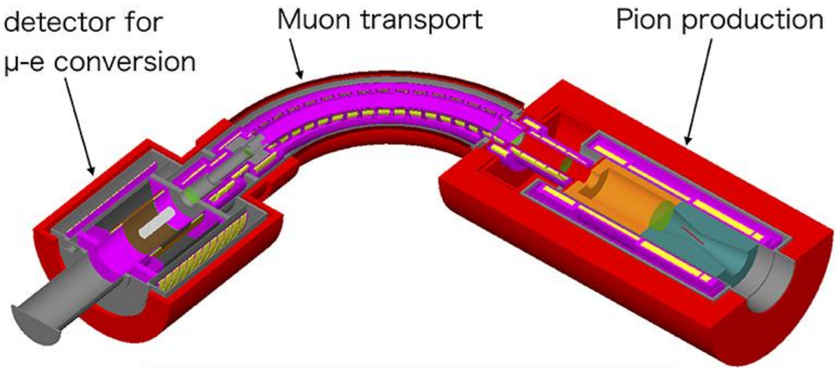


The MECO Apparatus

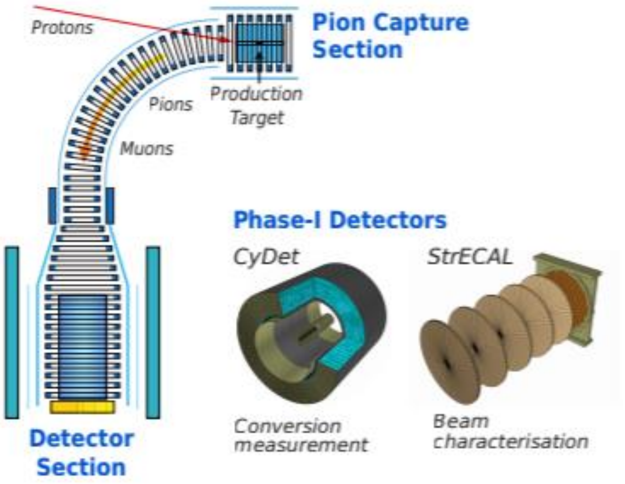
- Proposed at Brookhaven in 1997
- Mu2e is essentially the MECO experiment moved to Fermilab to take advantage of the accelerator complex

A Clever Idea…also in Japan

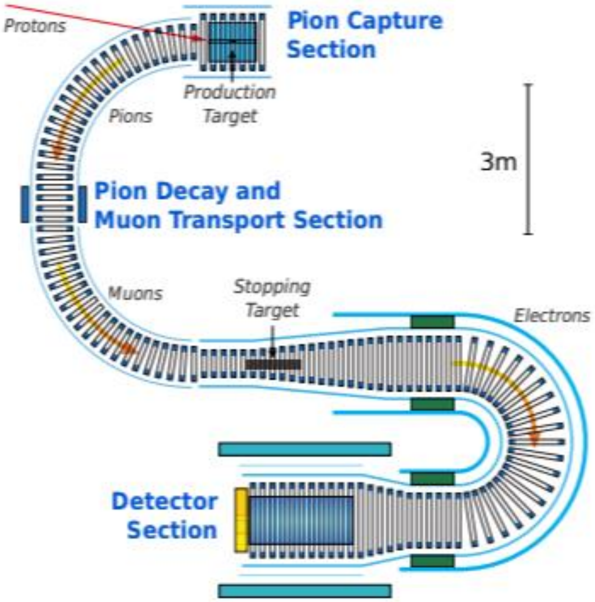
- COMET is currently under construction at J-Parc in Japan
- Phase-II will provide the same sensitivity as Mu2e



COMET Phase-I Layout



Phase I



Phase II

Searching for a rare process

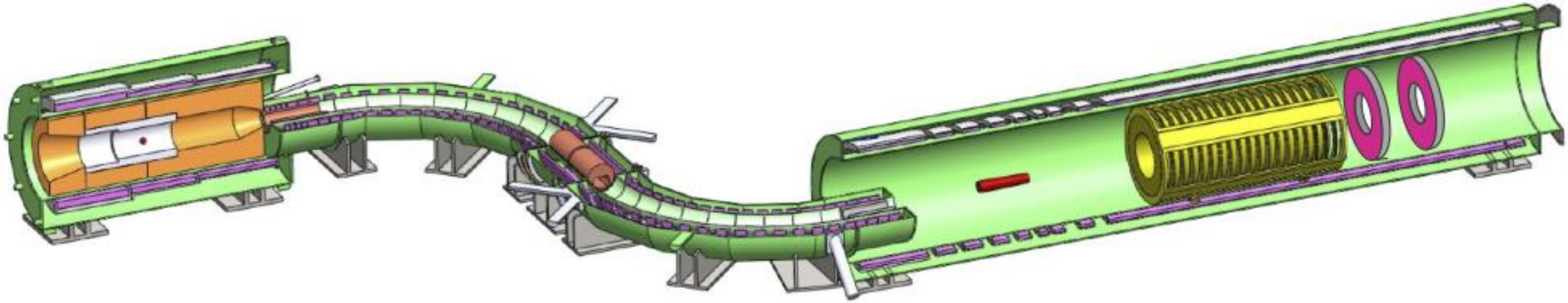
Mu2e Sensitivity:

- If $R_{\mu e}$~ 10^{-15}, will see about 40 events
- If $R_{\mu e}$~ 3×10^{-17}, will see 1 event (Single Event Sensitivity)
- The Mu2e experiment will probe $R_{\mu e}$ at the level of < 3×10^{-17}

Four orders of magnitude improvement over the previous experiment

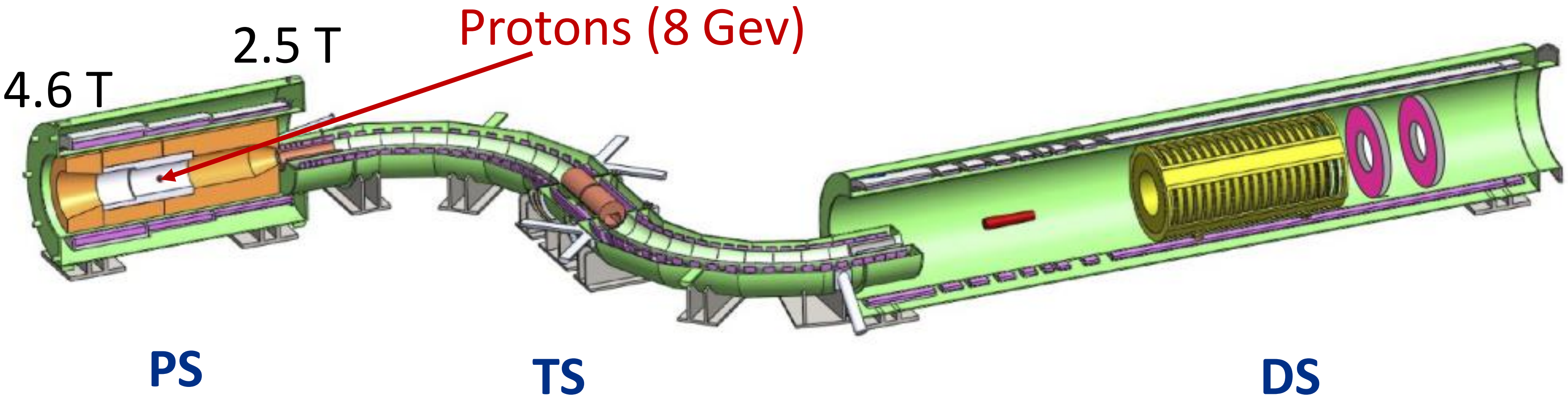
Mu2e: 4 orders of magnitude, who ordered

Mu2e Goals



- Produce 10^{18} Muonic Al atoms
  - This is on the order of the number of grains of sand on all the world's beaches!
- Suppress Backgrounds
- Detection system with tracking and calorimetry
  - Conversion electrons of 104.96 Mev

Mu2e Experimental Layout

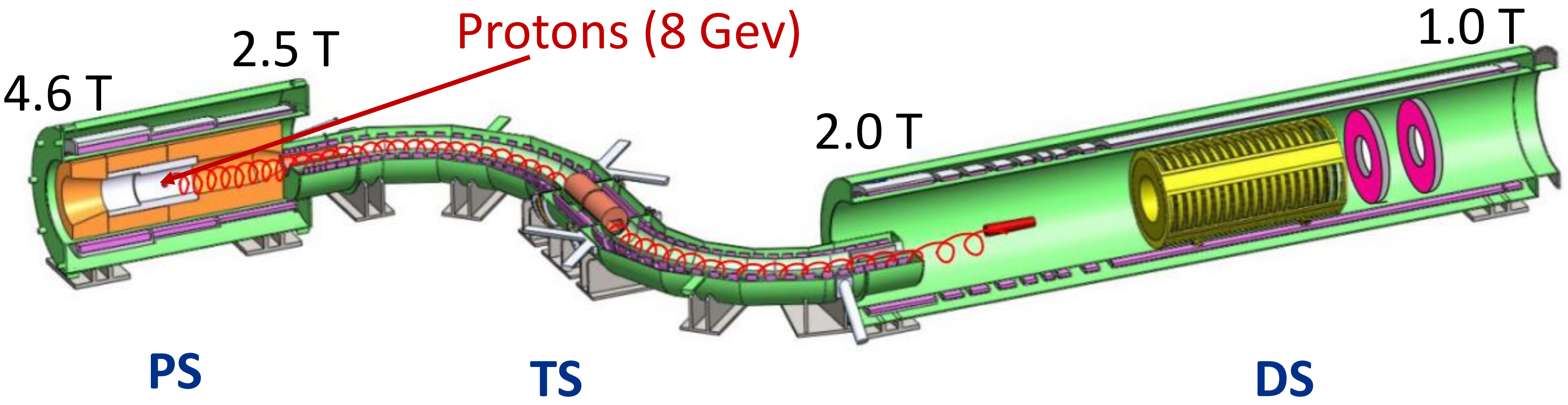


Experiment consists of 3 solenoid systems

Production Solenoid (PS)

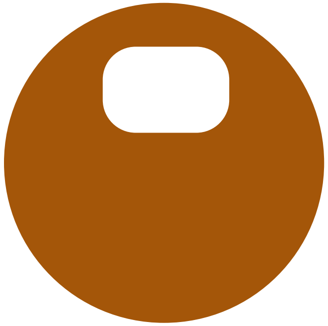
- 8 GeV protons interact with a tungsten target to produce, among other things, μ^-(from pion decay)
- Magnetic field gradient encourages pions and muons to travel toward the stopping target

Mu2e Experimental Layout



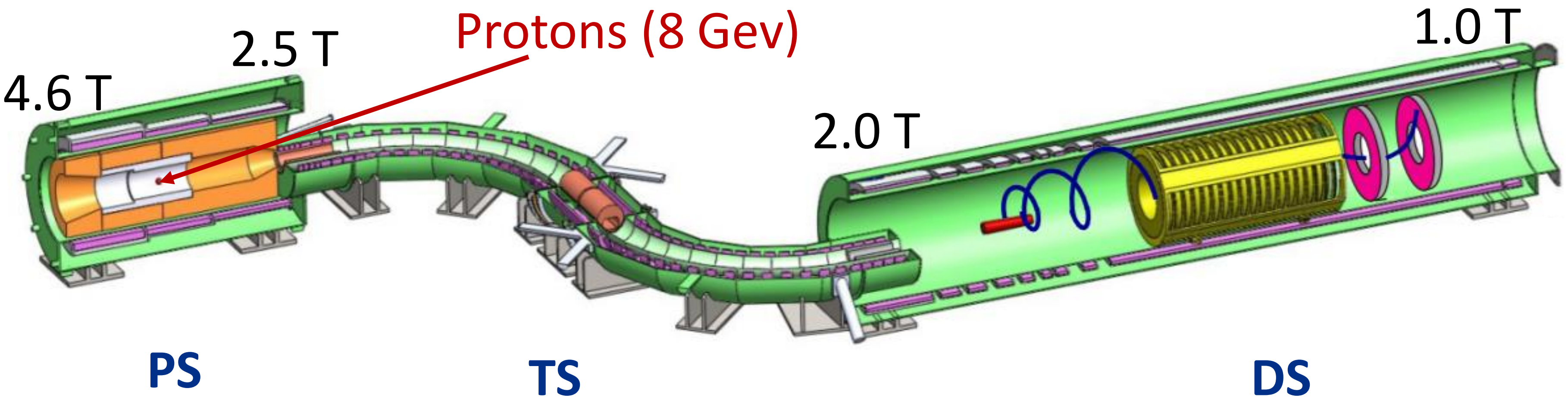
Transport Solenoid (TS)

- 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



Collimator between TSU and TSD

Mu2e Experimental Layout



Detector Solenoid (DS)

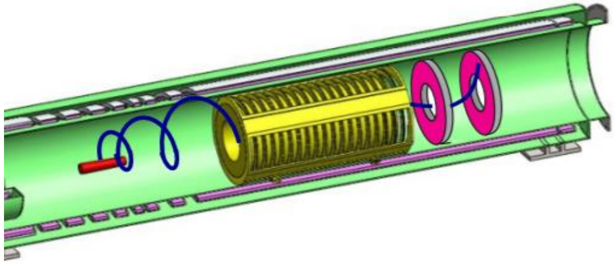
- Aluminum stopping target
- Magnetic field gradient in the ta co pions and muons to travel towa
- Uniform field in detector region
  - Tracker
  - Calorimeter

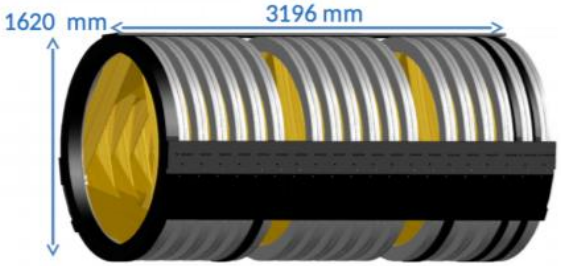
PS bore tube

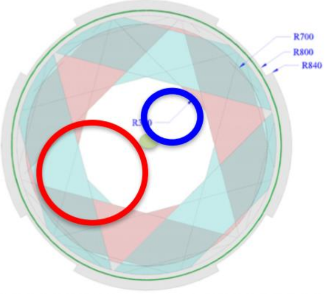
DS bore tube

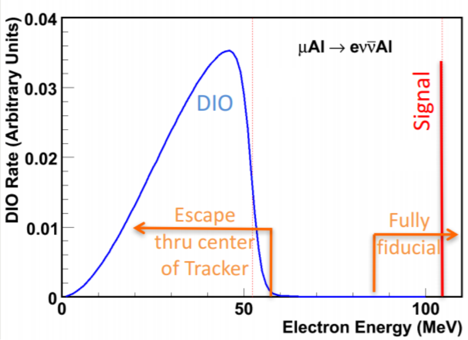
Detector- Straw Tracker

- 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



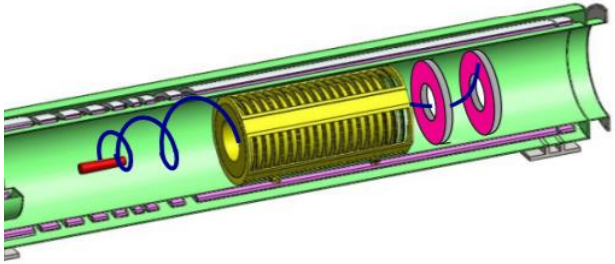


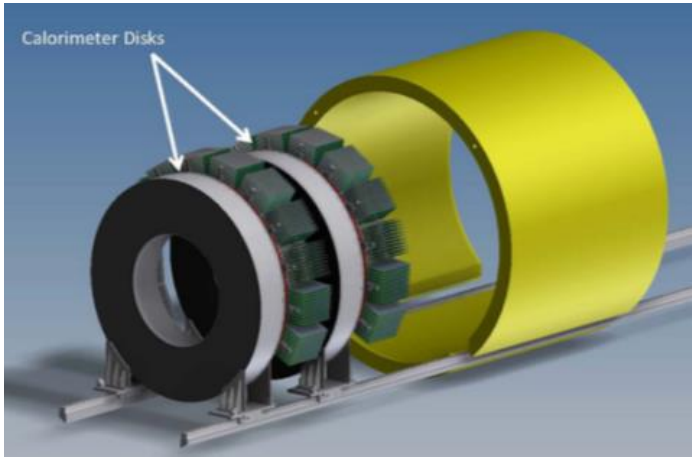


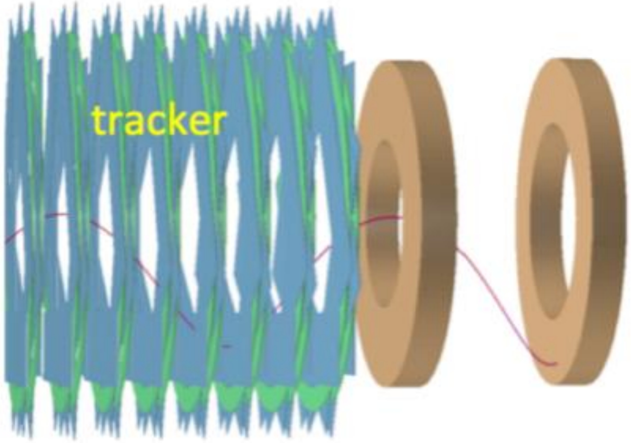


Detector- Calorimeter

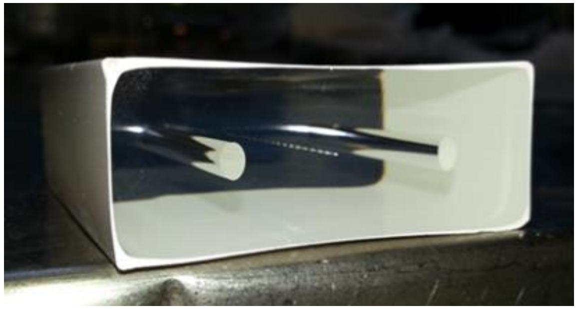
- Used to cross check the measurement taken by the tracker, distinguish muons from electrons
- Two annuli with inner radius 35.1 cm and outer radius 66 cm
- Disks separated by 70 cm (1/2 wavelength)
- ~800 pure Cesium Iodide crystals per disk
- Two 9x9 mm2 avalanche photodiodes per crystal
- Under 500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







Cosmic Ray Veto

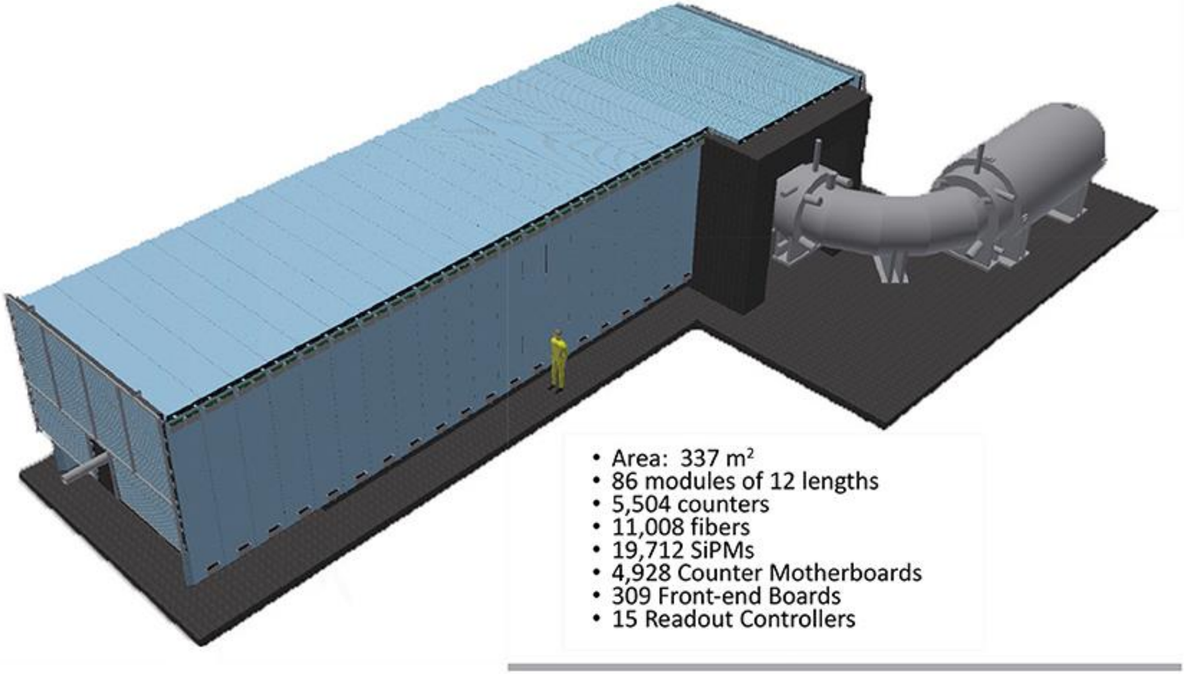


Cosmic background

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

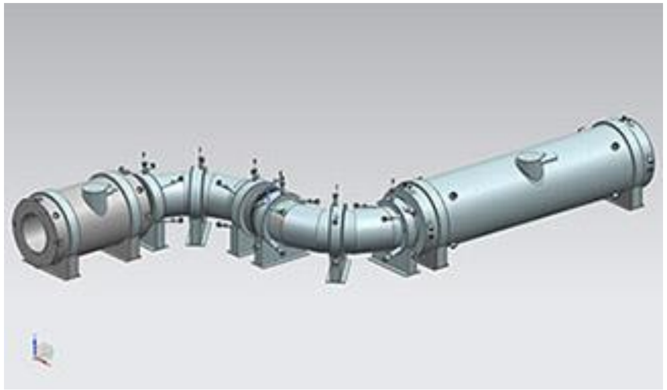
Requires 99.99% efficient cosmic ray veto system

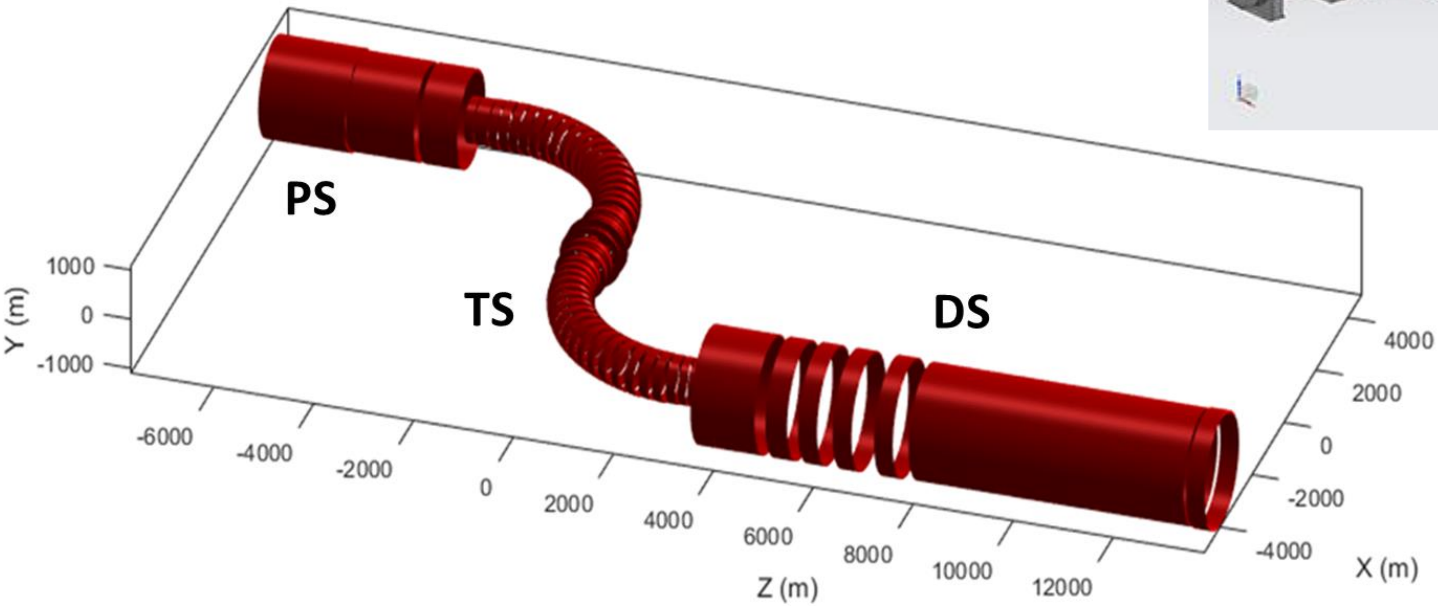
- 4 layers of extruded polystyrene scintillator counter
- 5,000 total counters



- Area: 337 m^2
- 86 modules of 12 lengths
- 5,504 counters
- 11,008 fibers
- 19,712 SiPMs
- 4,928 Counter Motherboards
- 309 Front-end Boards
- 15 Readout Controllers

Mu2e Magnet System

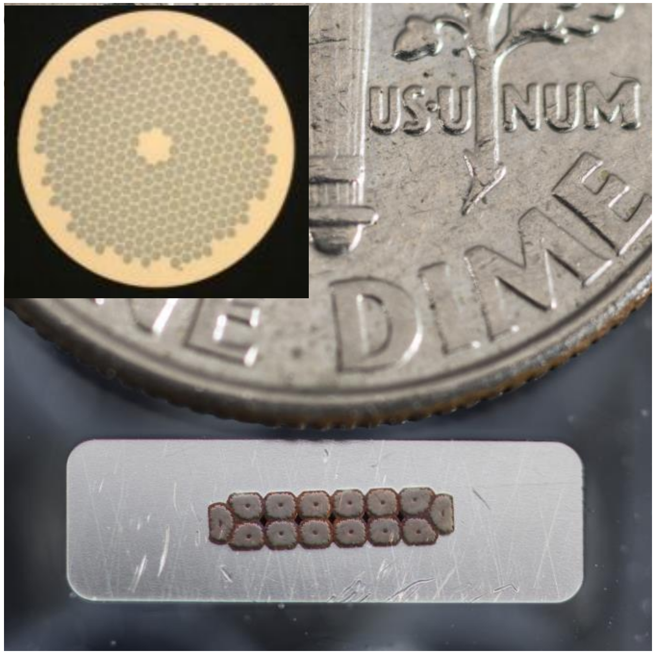


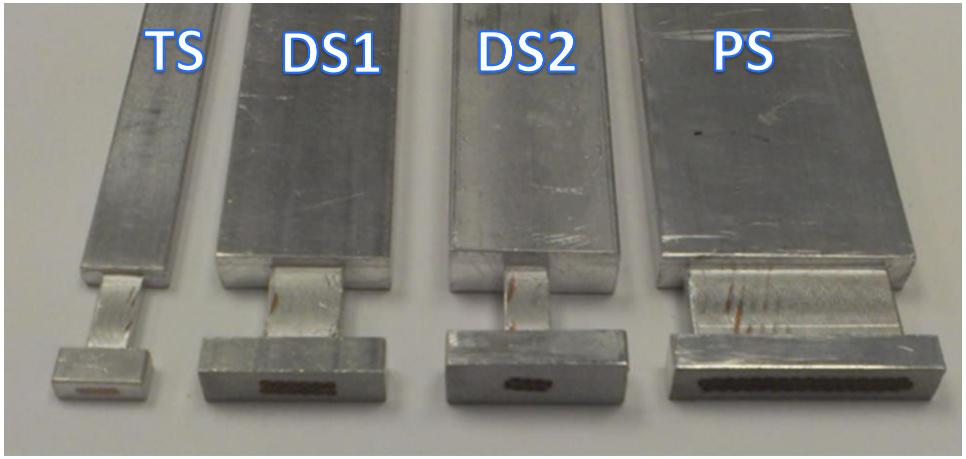


- 66 superconducting solenoids
  - PS 3, TS 52, DS 11
- TS is divided into an upstream(TSU) and downstream(TSD)
- Each magnet has its own cryostat and is individually cooled and powered

NbTi Superconductor

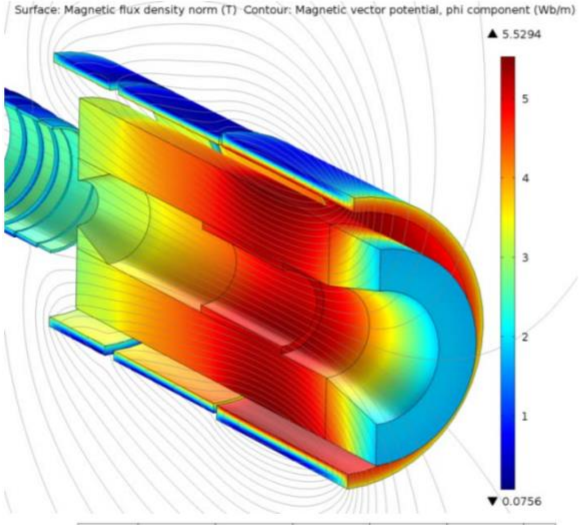
- All coils are made of Al-stabilized NbTi superconductor
- DS and TS used 99.998% pure Al (5N)
- PS uses 5N doped with 0.1wt% Ni
- ~ 75 km of cable required
- Coils are cooled using liquid He
  - NbTi critical temperature ~10 K in zero magnetic field





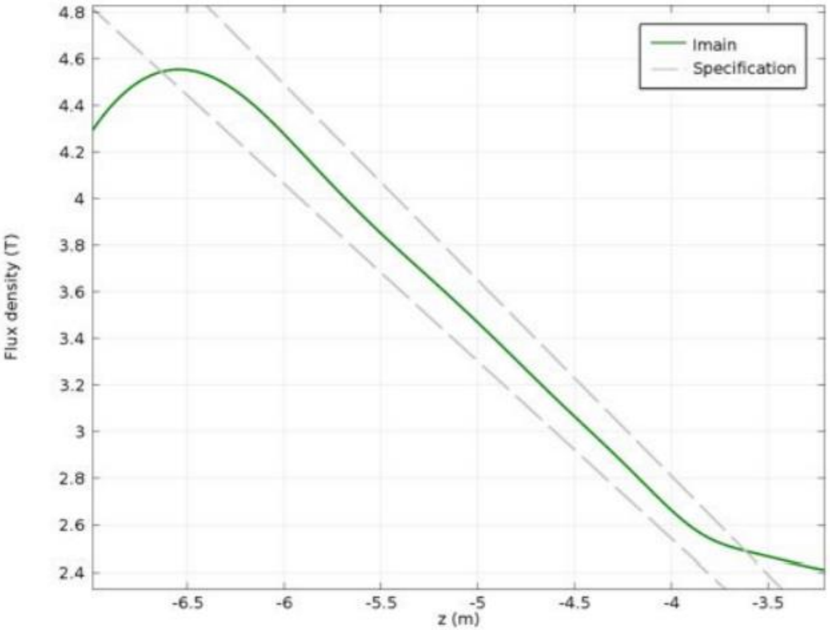
Production Solenoid

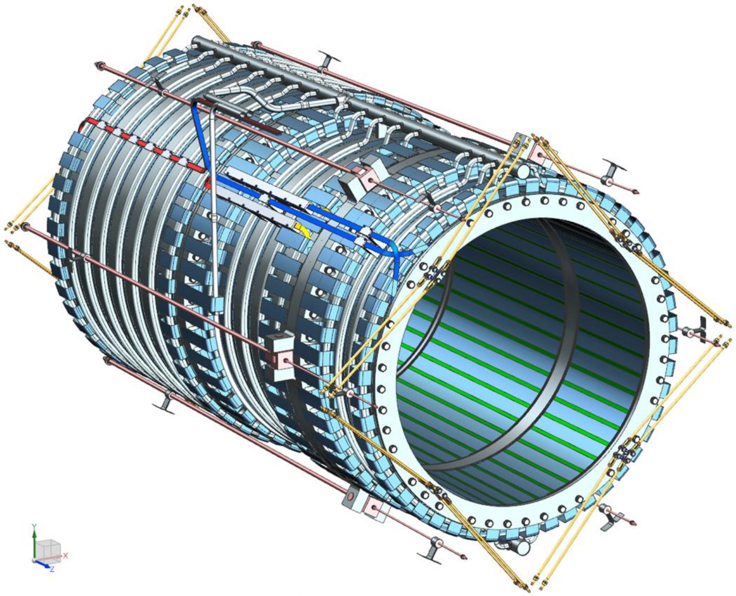
- Highest magnetic field region, ~4.5 T down to 2.6 T, 9200 A
- Being fabricated in industry, will be delivered fully cryostated and ready to install



V. Kashikhin et al., IEEE Trans on Applied Superconductivity, Vol 3, No 3

PS Magnetic Field Requirement



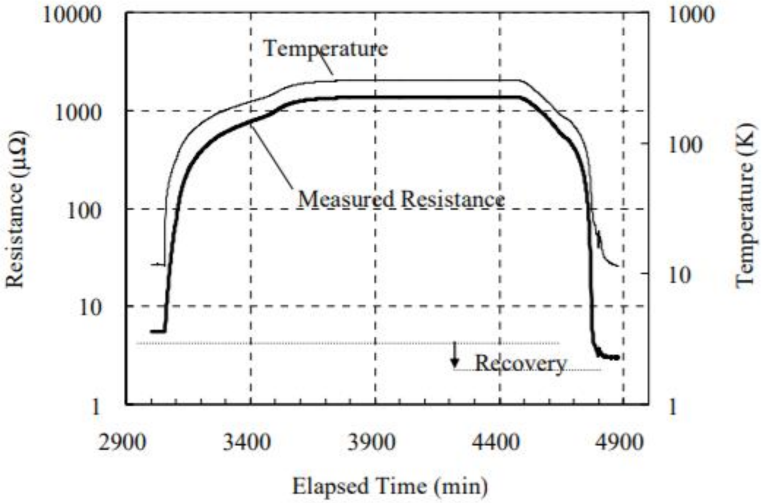


PS Cold Mass Design

Production Solenoid

- Large heat and radiation environment
  - Mitigated by heat and radiation shield
  - Heat conductively removed through Al stabilizer and thermal straps
  - Radiation reduces the thermal conductivity over time (~2.5x10^{-5} /year DPA)
  - In metals, measure of resistance can give an idea of thermal performance
    - relationship between electrical and thermal conductivity
  - Room temperature thermal cycle to anneal Al ~1/year

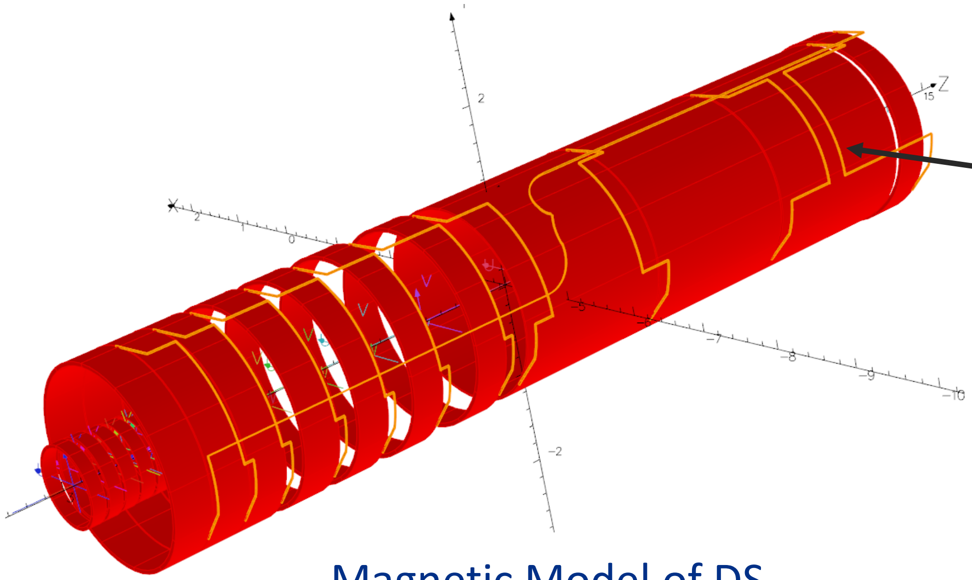
PS3 Wound, VPI, Inserted



M. Yoshida et al., AIP Conference Proc. 1345, 167

Detector Solenoid

- Field gradient 2 T down to a uniform 1 T in the detector region to transport electrons from the target to the detector, ~6 kA
- Two conductor cross sections were required to meet the field requirements while operating at the same current
- The DS is also being fabricated in industry, will be delivered fully cryostated and ready to install

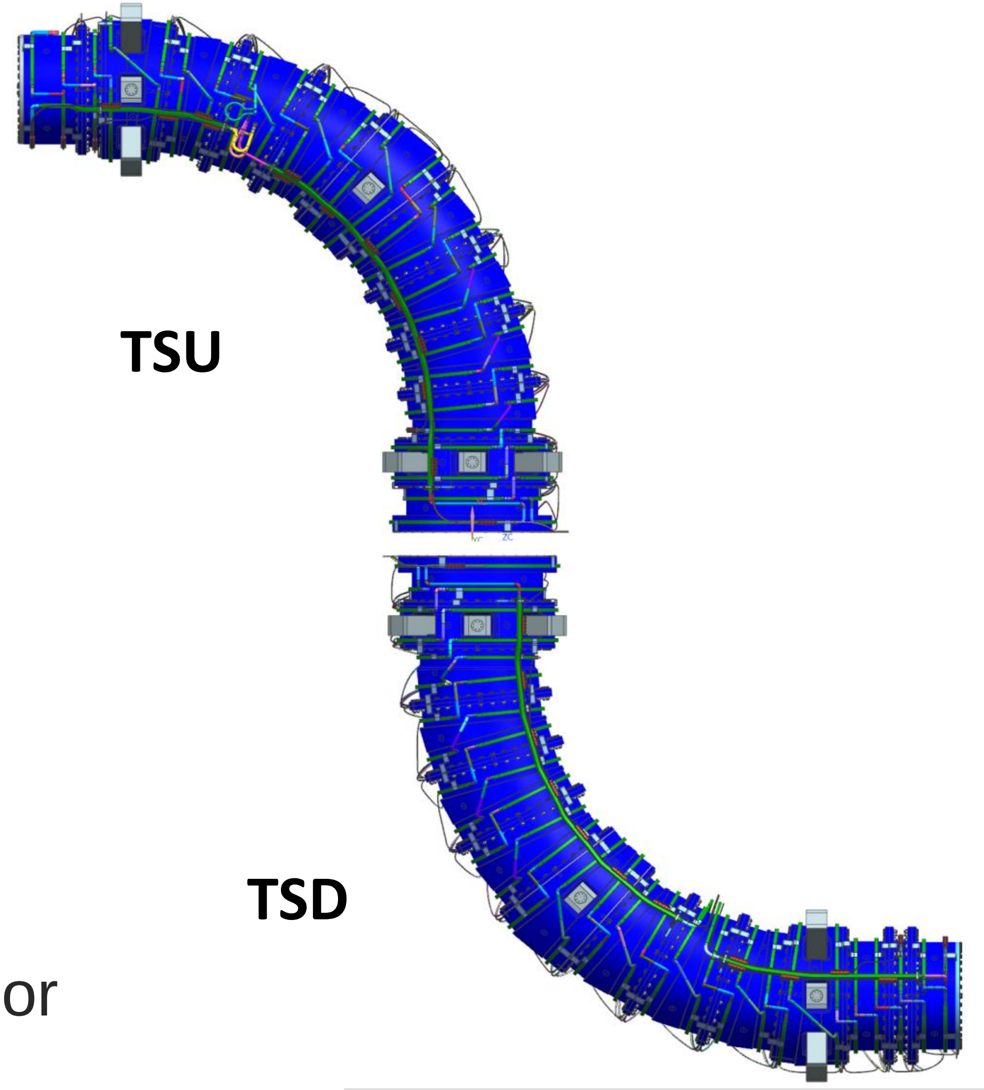


Magnetic Model of DS

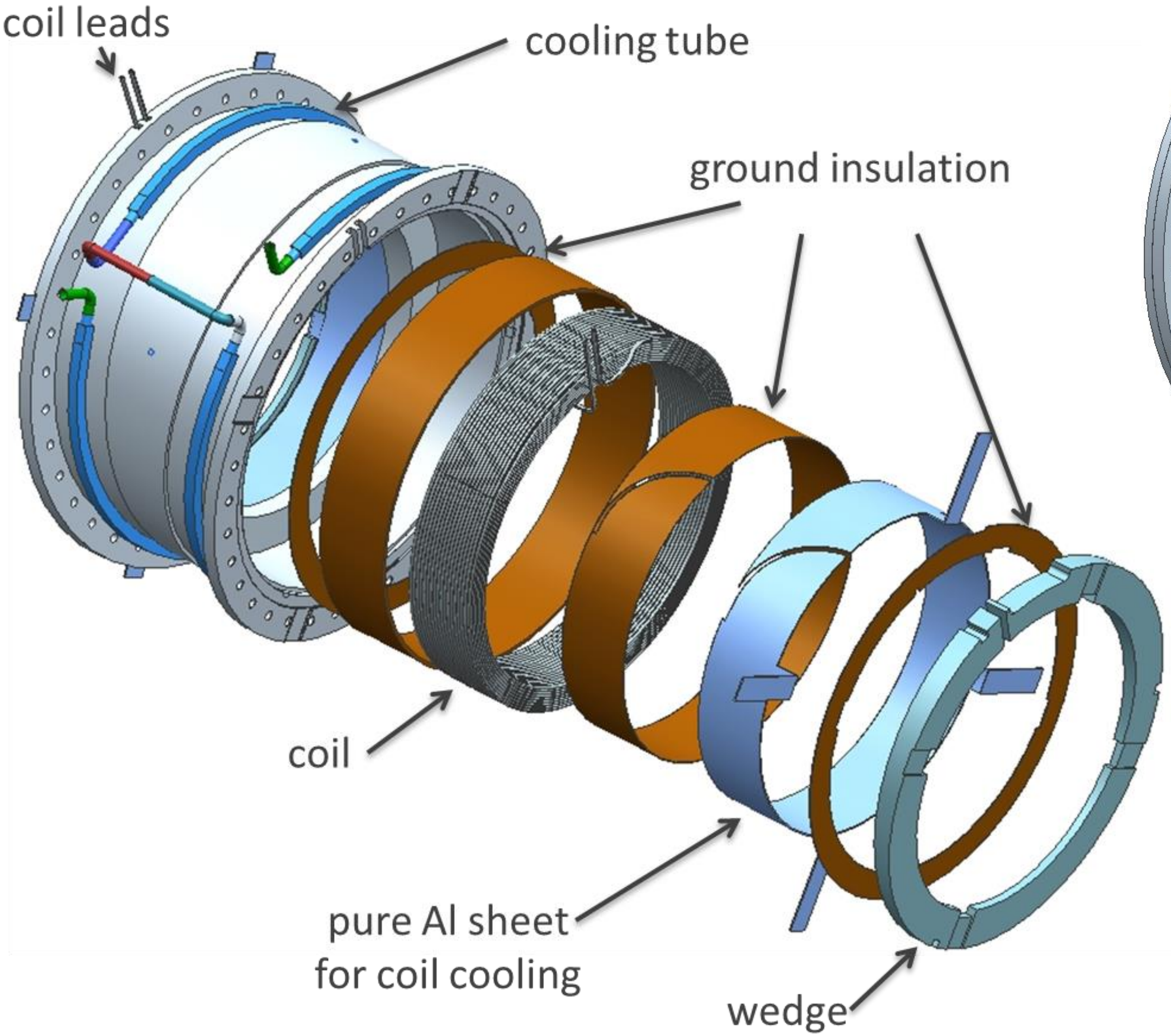
DS10 Wound and epoxied

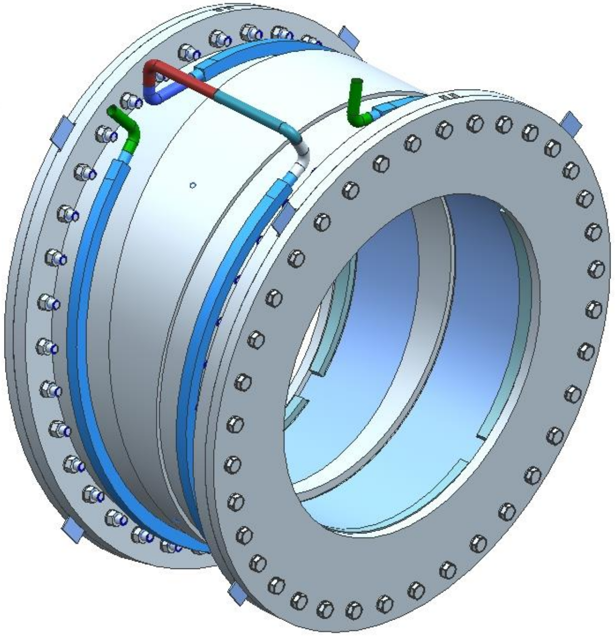
Transport Solenoid

- Consists of 52 coils grouped into the TSU(25) and the TSD(27)
- The coils are housed in Al shells to form a module
  - There are 27 Coil modules, TSU(13), TSD(14)
- Modules are assembled together to form a unit
  - There are 14 test units, TSU(7), TSD(7)
- Units are fabricated at a vendor and shipped to Fermilab for testing and assembly



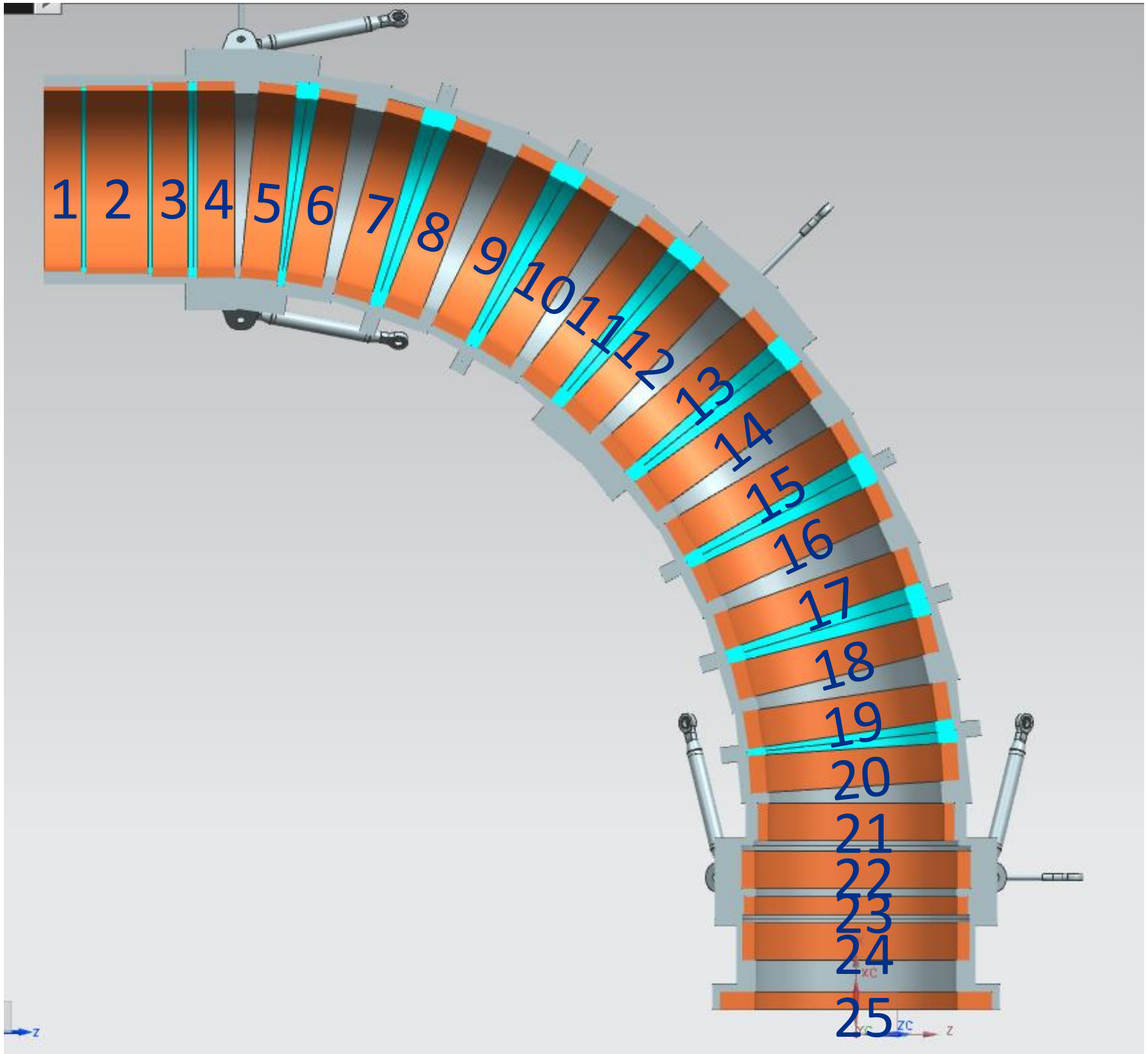
Transport Solenoid Module





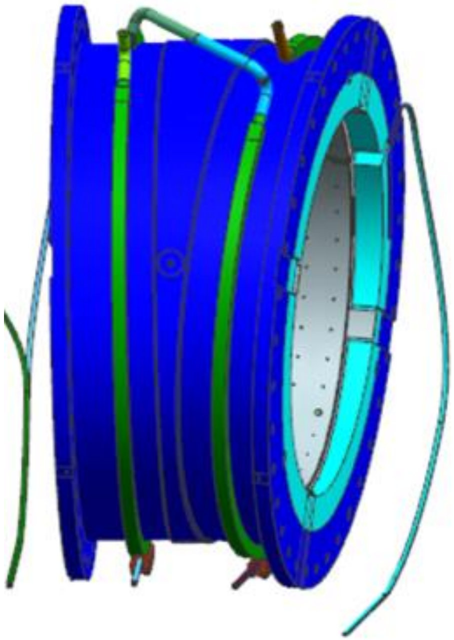
Coils inserted through shrink fit process

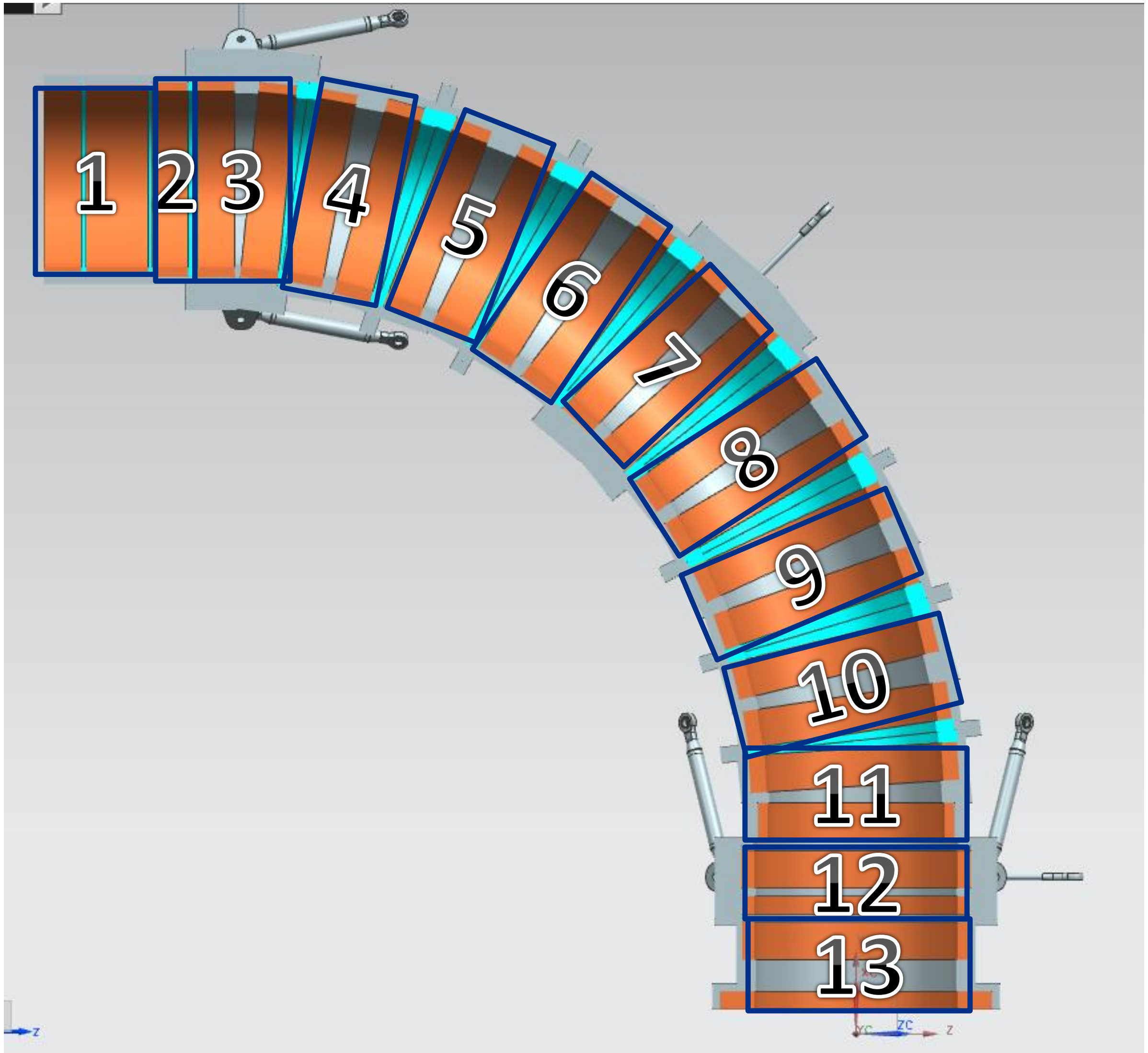
Transport Solenoid-TSU Coils



Transport Solenoid – TSU Modules

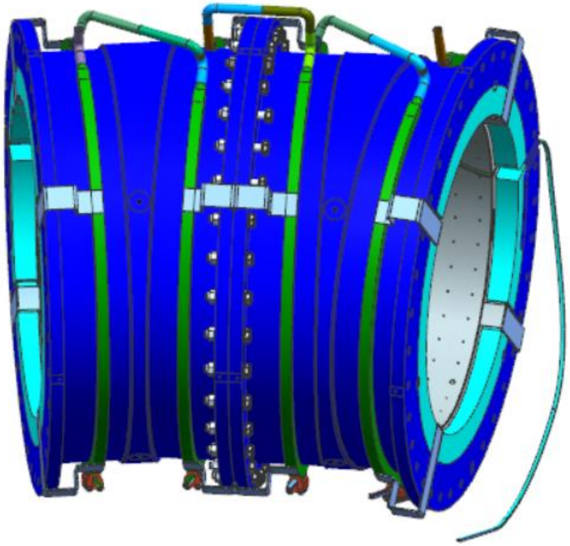
Typically 2 coils per module

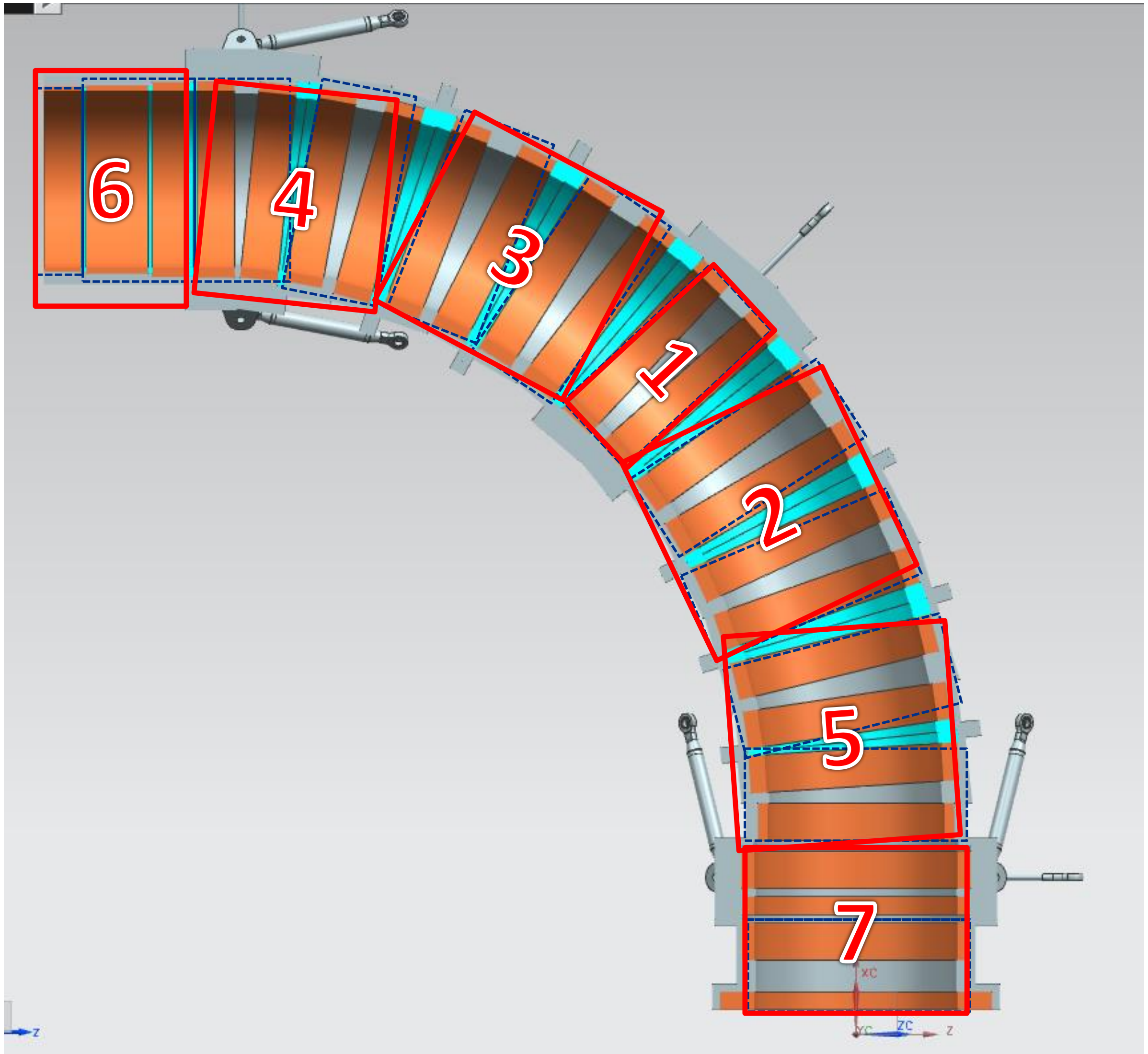




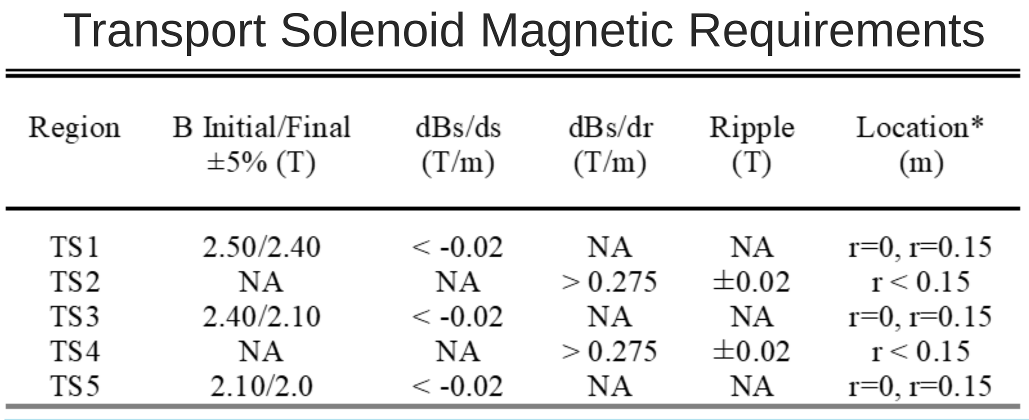
Transport Solenoid – TSU Units

1-3 modules per unit





Transport Solenoid

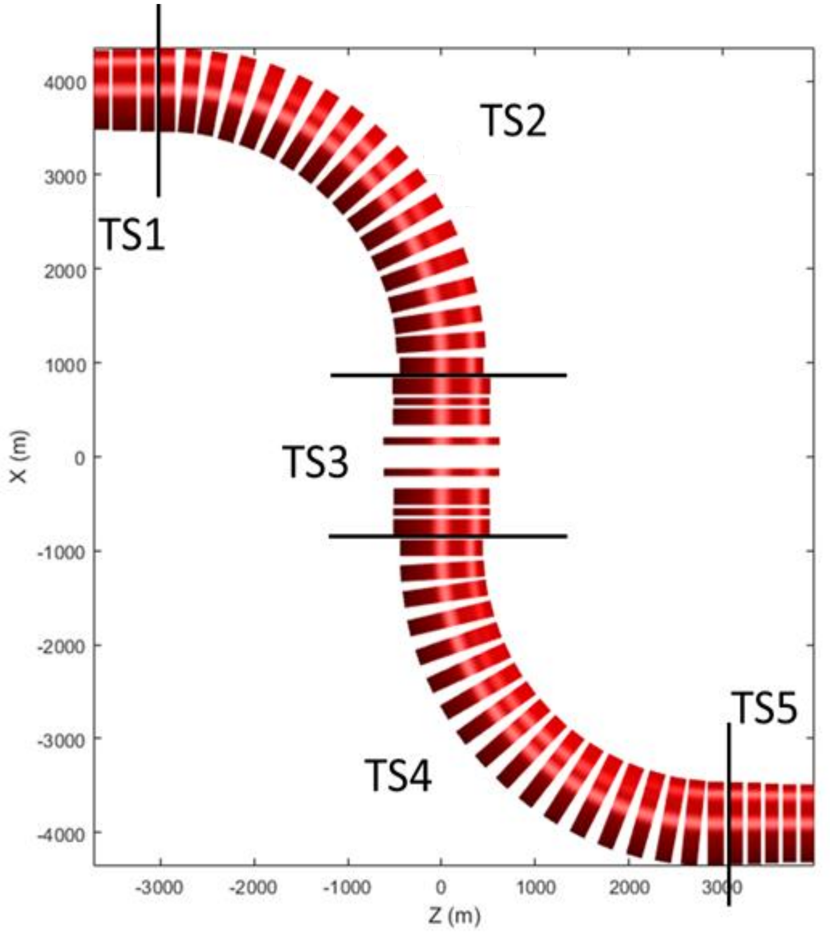


Transport Solenoid Magnetic Requirements

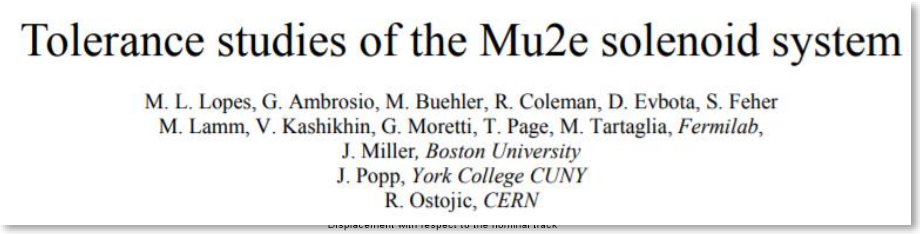
Region	B Initial/Final ±5% (T)	dBs/ds (T/m)	dBs/dr (T/m)	Ripple (T)	Location* (m)
TS1	2.50/2.40	< -0.02	NA	NA	r=0, r=0.15
TS2	NA	NA	> 0.275	±0.02	r < 0.15
TS3	2.40/2.10	< -0.02	NA	NA	r=0, r=0.15
TS4	NA	NA	> 0.275	±0.02	r < 0.15
TS5	2.10/2.0	< -0.02	NA	NA	r=0, r=0.15

- The straight sections require a gradient to prevent trapped particles and direct muons toward the detector solenoid

- The curved sections have a limit on the radial gradient and the ripple due to the coil spacing

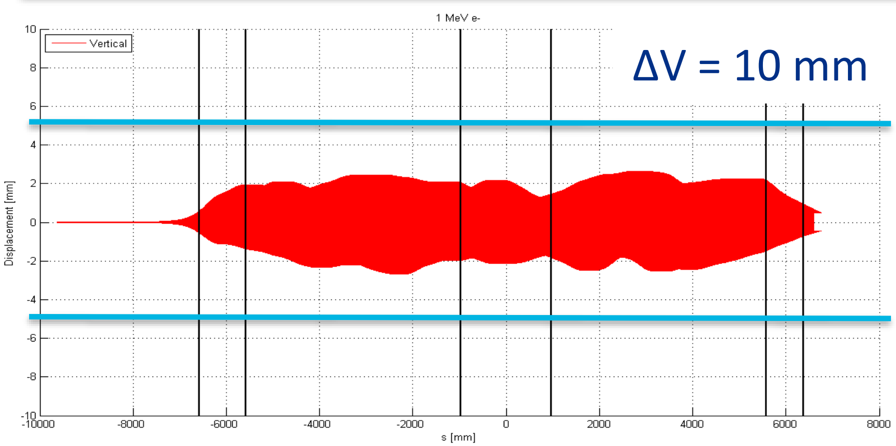


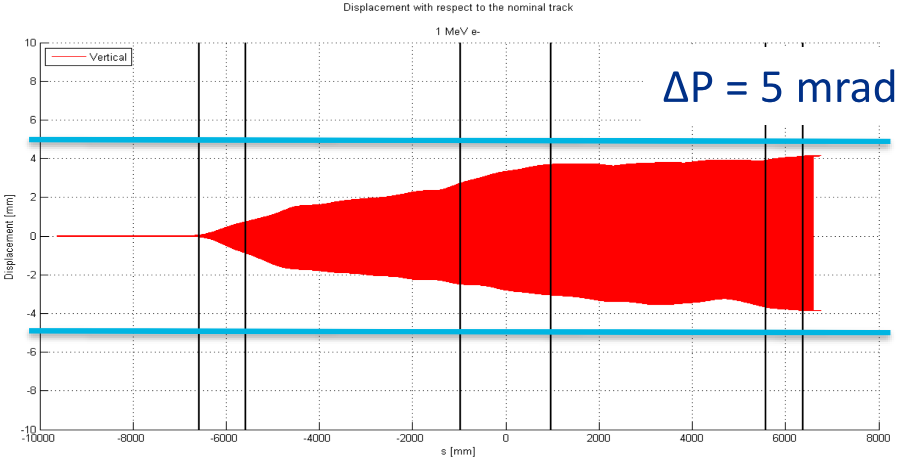
Tolerance



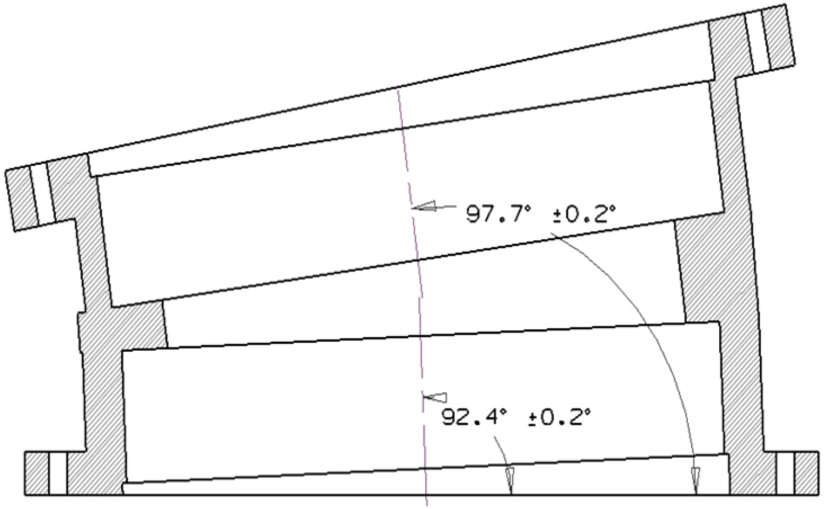
Tolerance studies of the Mu2e solenoid system

M. L. Lopes, G. Ambrosio, M. Buehler, R. Coleman, D. Evbota, S. Feher
M. Lamm, V. Kashikhin, G. Moretti, T. Page, M. Tartaglia, *Fermilab*,
J. Miller, *Boston University*
J. Popp, *York College CUNY*
R. Ostojic, *CERN*



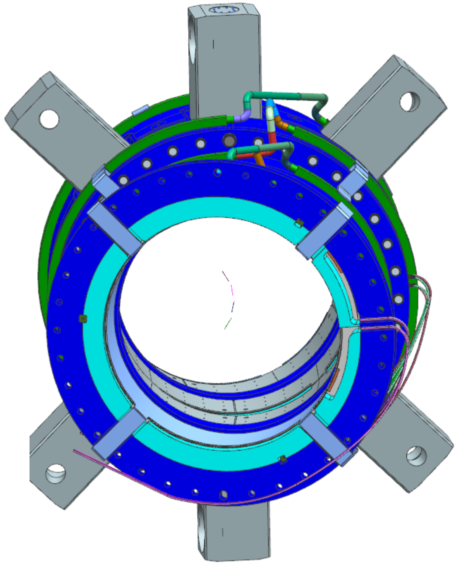


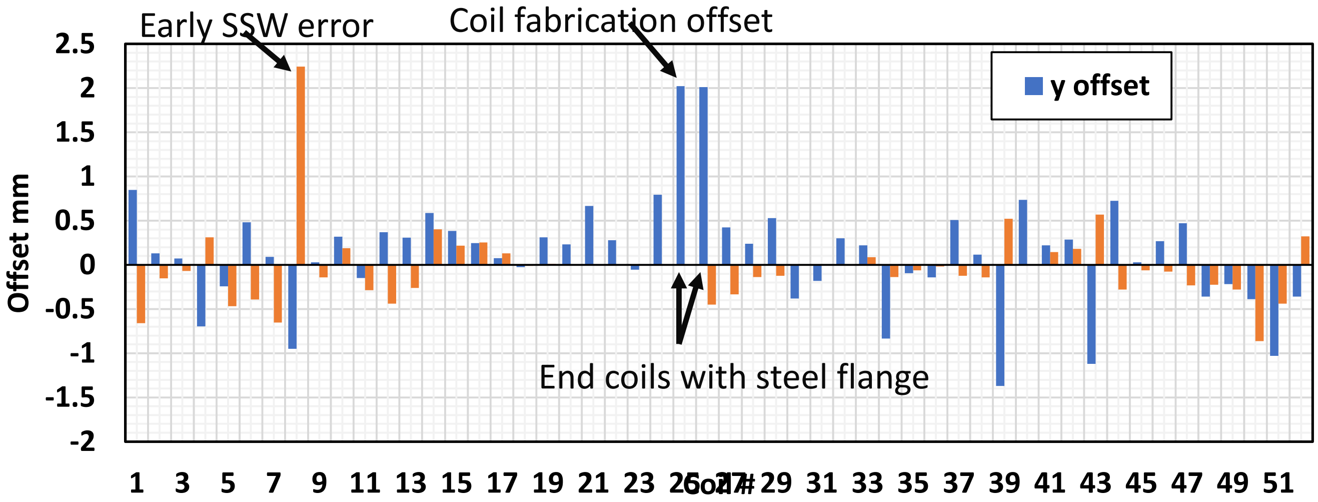
- Mu2e requires efficient muon transmission and no trapped particles
- Error studies helped set the tolerances for fabrication and assembly
- Transmission was found to be sensitive to the angle between coils



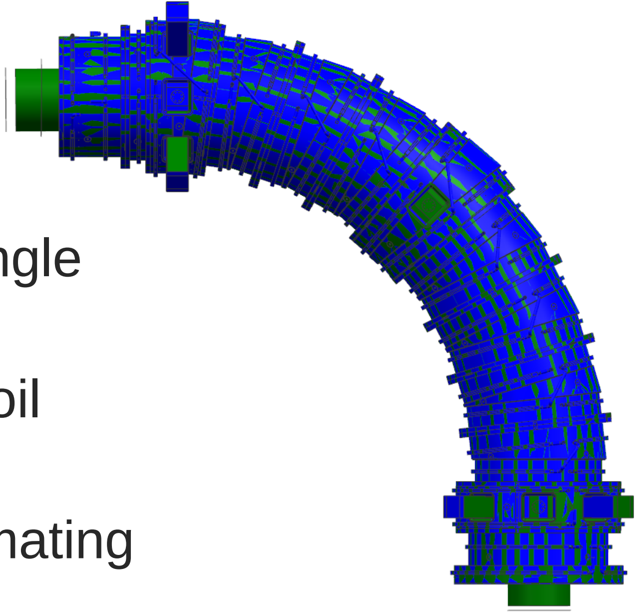
Magnetic Axis

- Vibrating stretched wire measurement made to find the magnetic axis for each coil
- Position measured with respect to fiducials on the shell and wire system, translated to the Mu2e coordinate system
- Acceptance tolerance on coil position <1 mm, but tolerance was tighter than needed, can tolerate up to about 10 mm offset



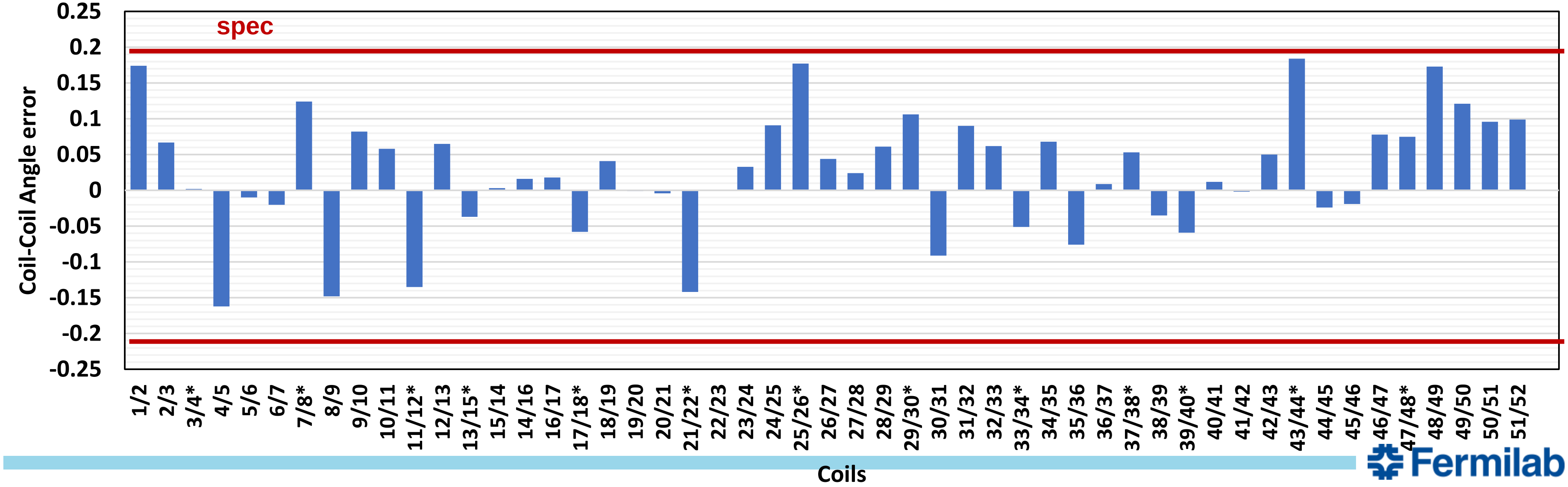


TS Magnetic Measurements



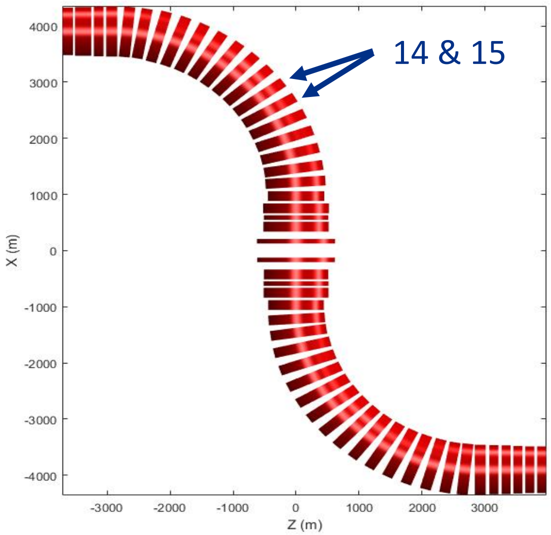
CAD compare.
Designed vs as-built.

- Previous tolerance studies showed muon transmission was most sensitive to coil-to-coil angle errors
- A strict fabrication tolerance was set on coil-to-coil angle of < 0.2 degrees
- This also set tight fabrication tolerances on the mating module surfaces
- Very good agreement between model and as-built assembly

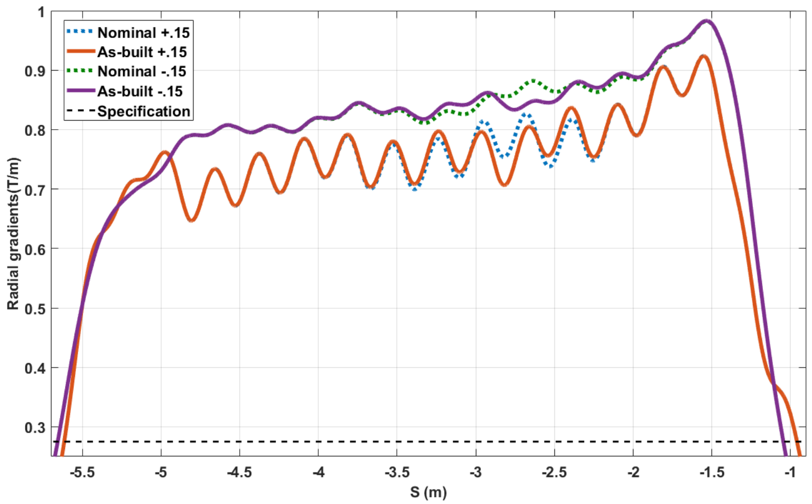


Swapped Coils 14 & 15

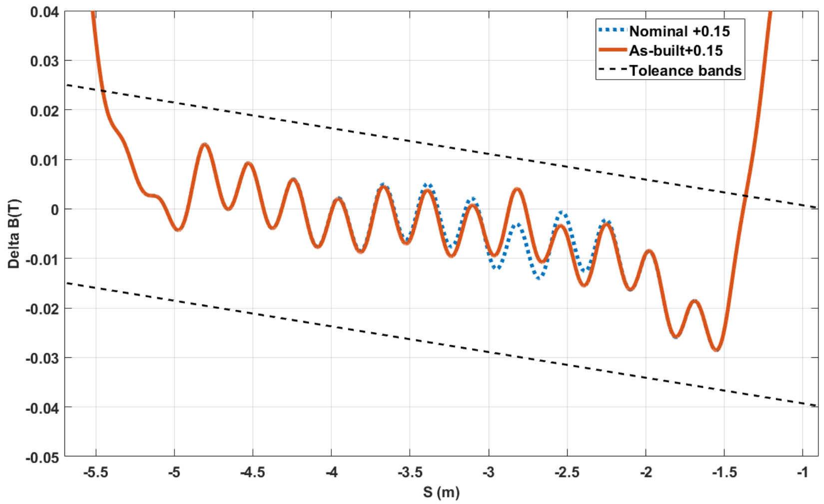
- Due to a fabrication error, we investigated the feasibility of swapping coils 14 and 15
- The coil lengths and inner diameter are the same, so the coil center position and angles remained at nominal
- Coil 15 has one additional layer of conductor, this increases the axial field at 14 and decreases at 15


14 & 15

TS2 Radial Gradient

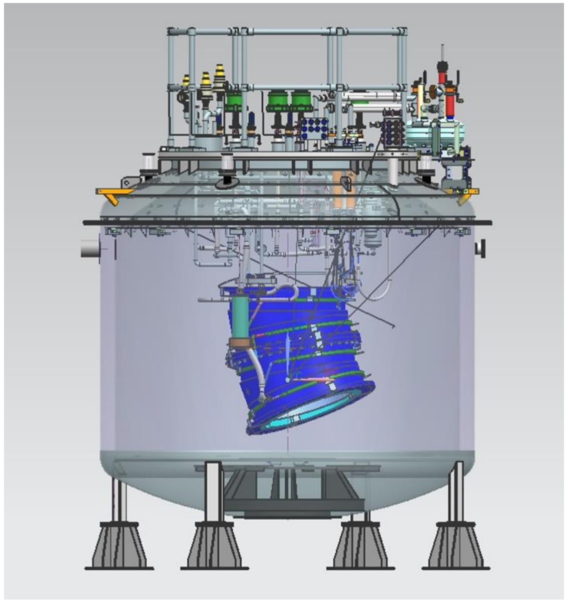


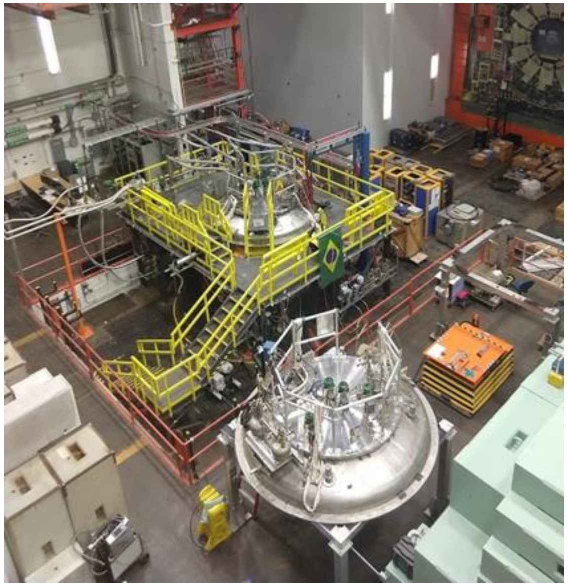
TS2 Ripple



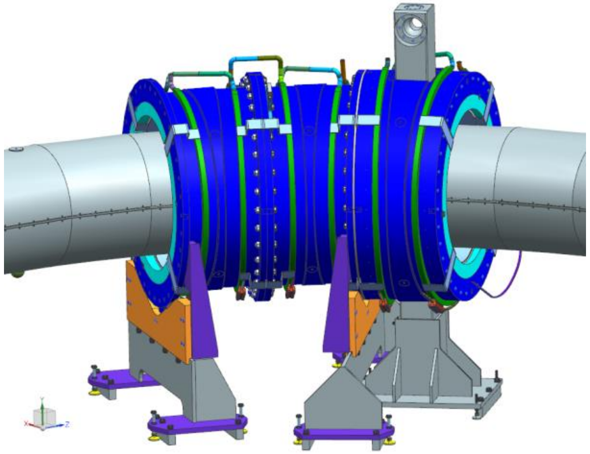
Cold Testing

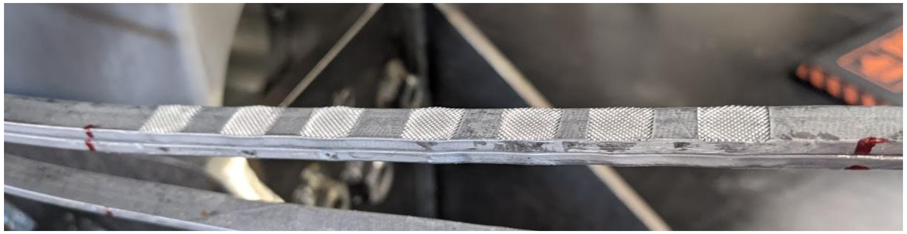
- Each unit is cooled to ~5 K
- Powered to 2100 A (120% of operating current) to produce fields seen in the experiment





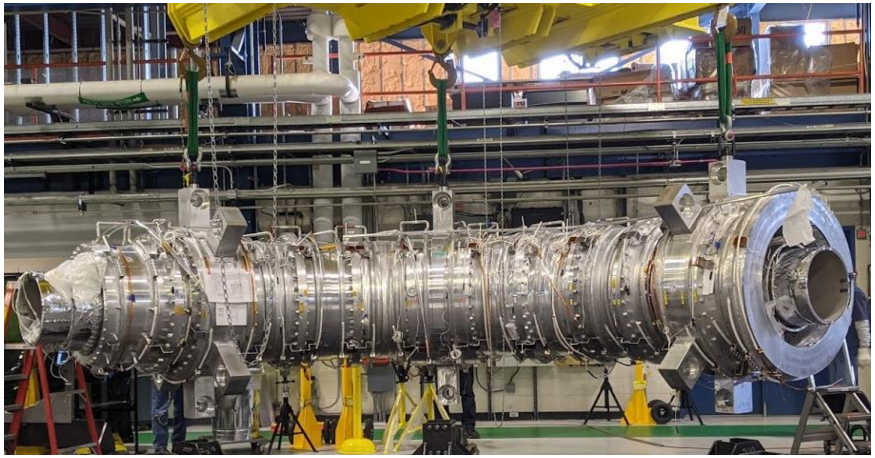
Transport Solenoid Assembly



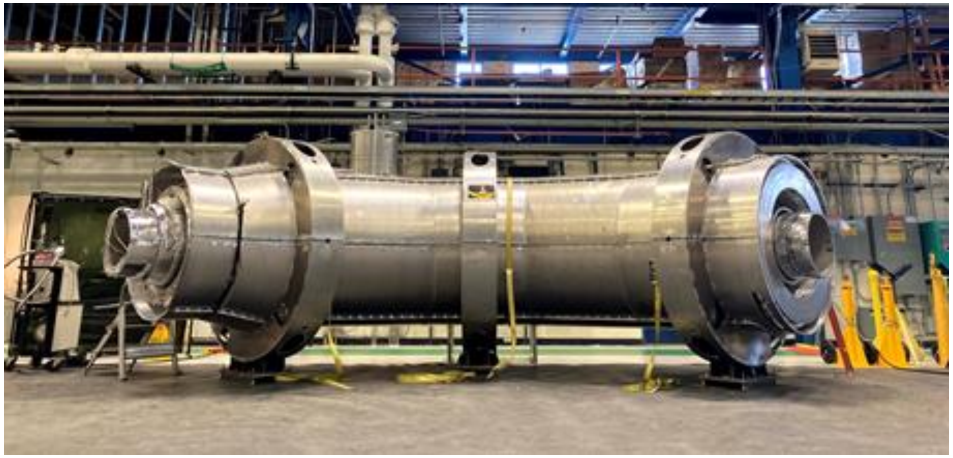


Ultrasonic splice

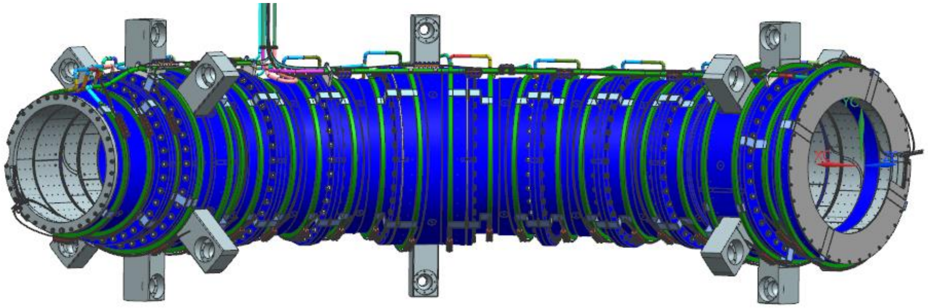
Transport Solenoid Assembly



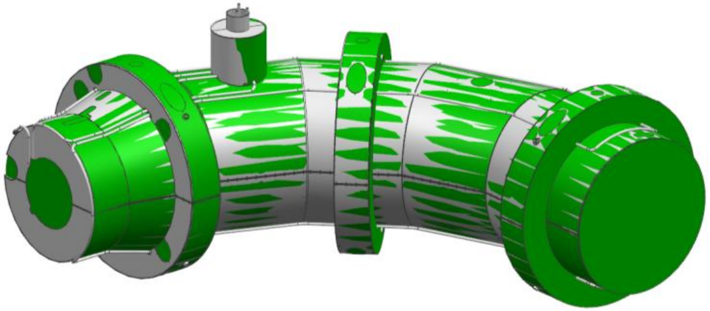
Assembled TSU coldmass



TSU thermal shield

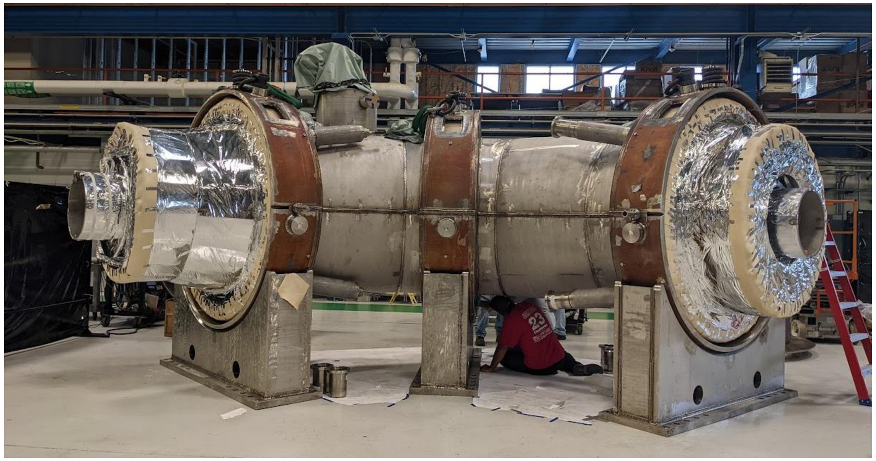


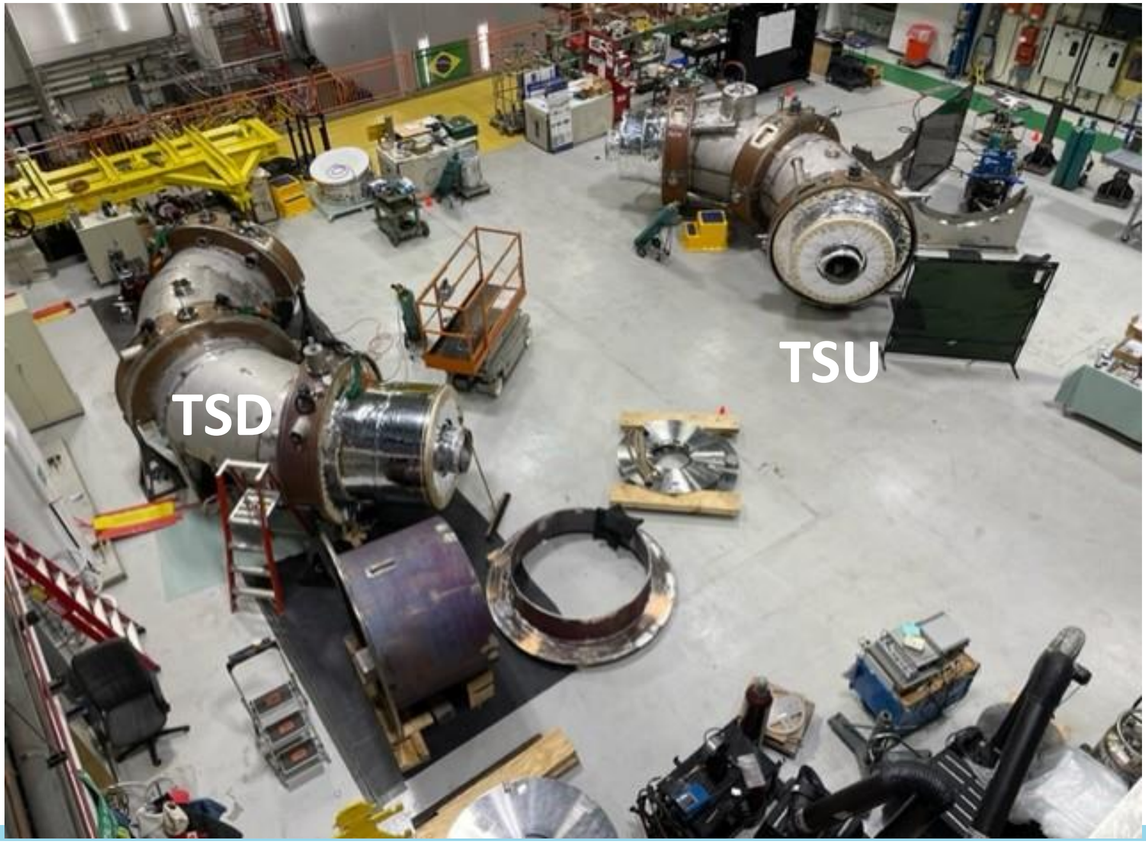
TSU coldmass model



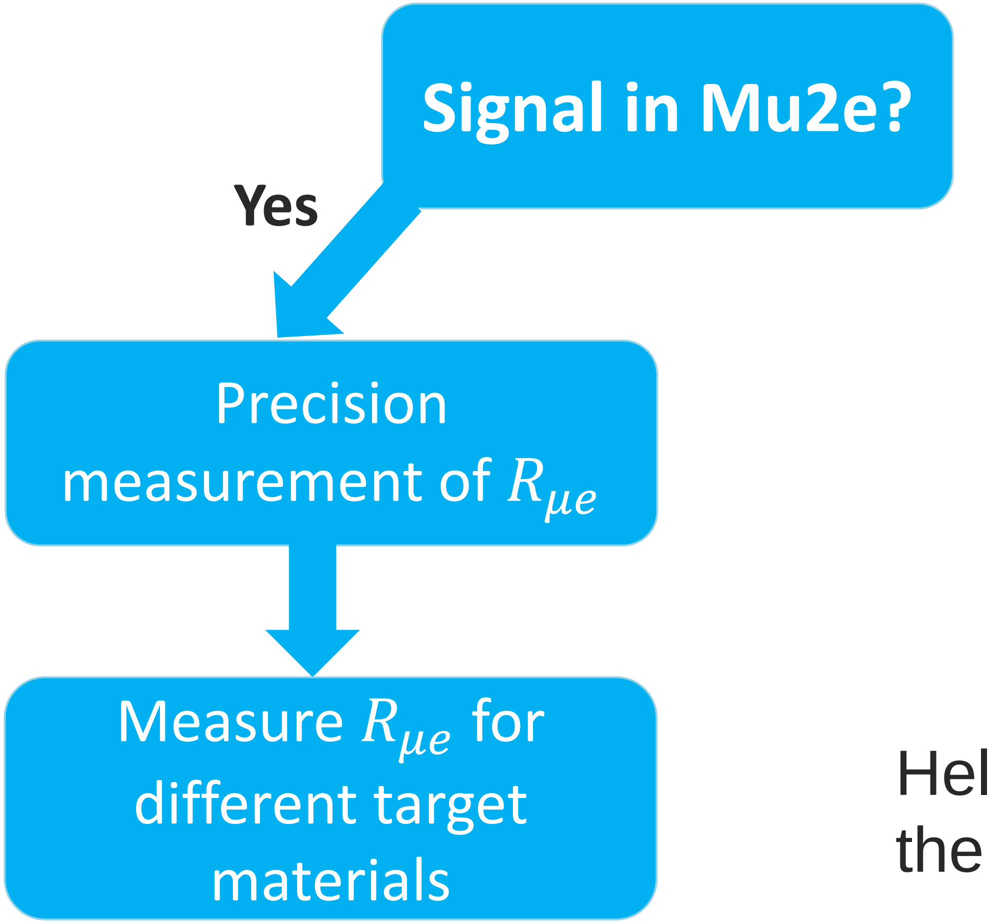
Good agreement between designed and as-built thermal shield

TS Status





The Future



Signal in Mu2e?

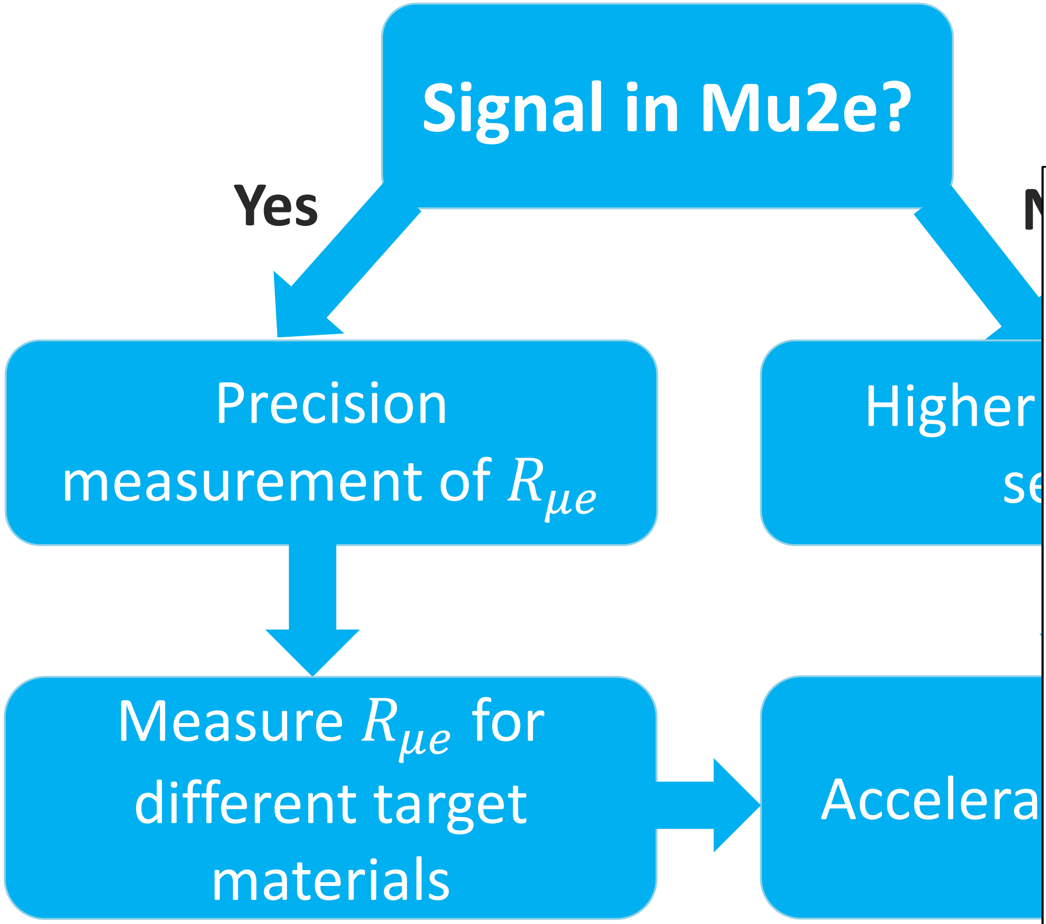
Yes

Precision measurement of $R_{\mu e}$

Measure $R_{\mu e}$ for different target materials

Help discriminate between the different models

The Future



Signal in Mu2e?

Yes

N

Precision measurement of $R_{\mu e}$

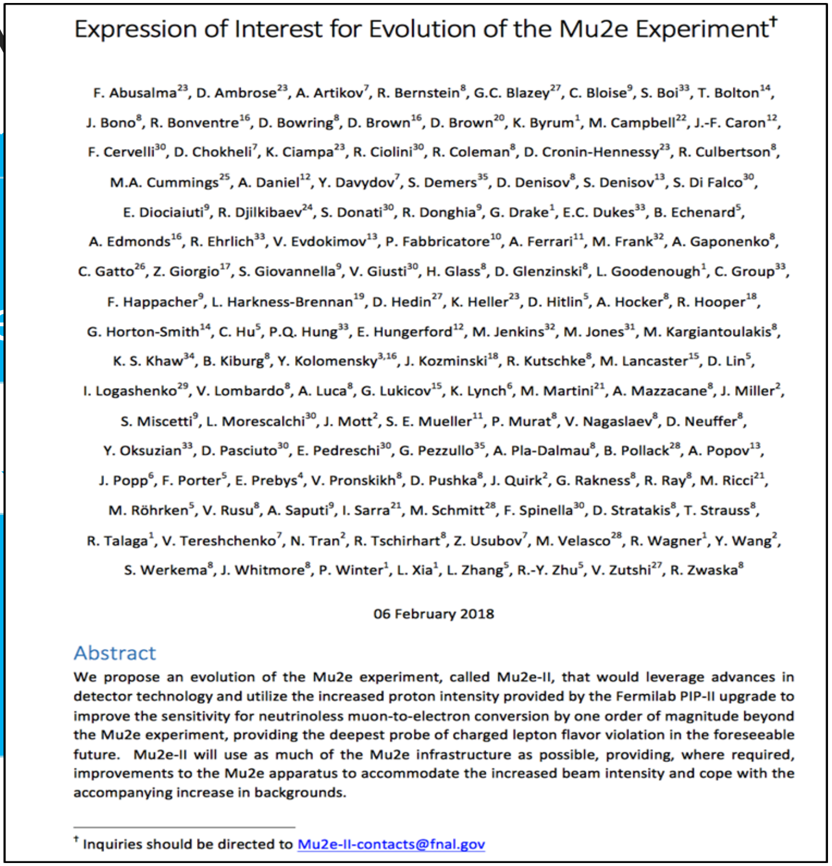
Measure $R_{\mu e}$ for different target materials

Higher

se

Accelera

Mu2e-II



Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

---

† Inquiries should be directed to Mu2e-II-contacts@fnal.gov

arXiv:1802.02599

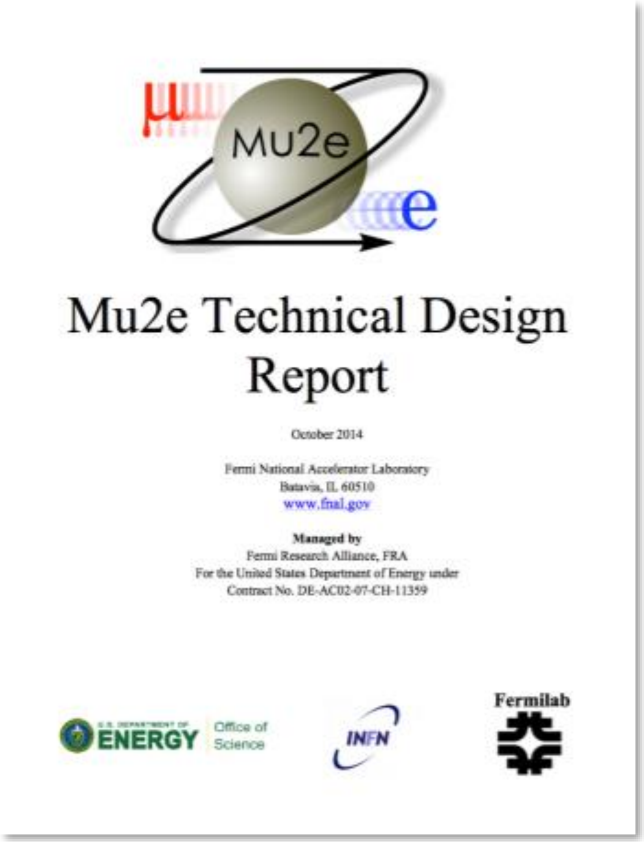
Muon Campus

Mu2e Collaboration

- > 240 collaborators, 6 countries, and 40 institutions
- ..and growing

Concluding Remarks

- Exciting time to be part of Mu2e!
- Project is currently under construction, pushing to take data before the long shut down
- Interested in learning more?
  - Technical Design Report
    - http://arXiv.org/abs/1501.05241
  - Experiment Website
    - Mu2e.fnal.gov



Mu2e Technical Design Report

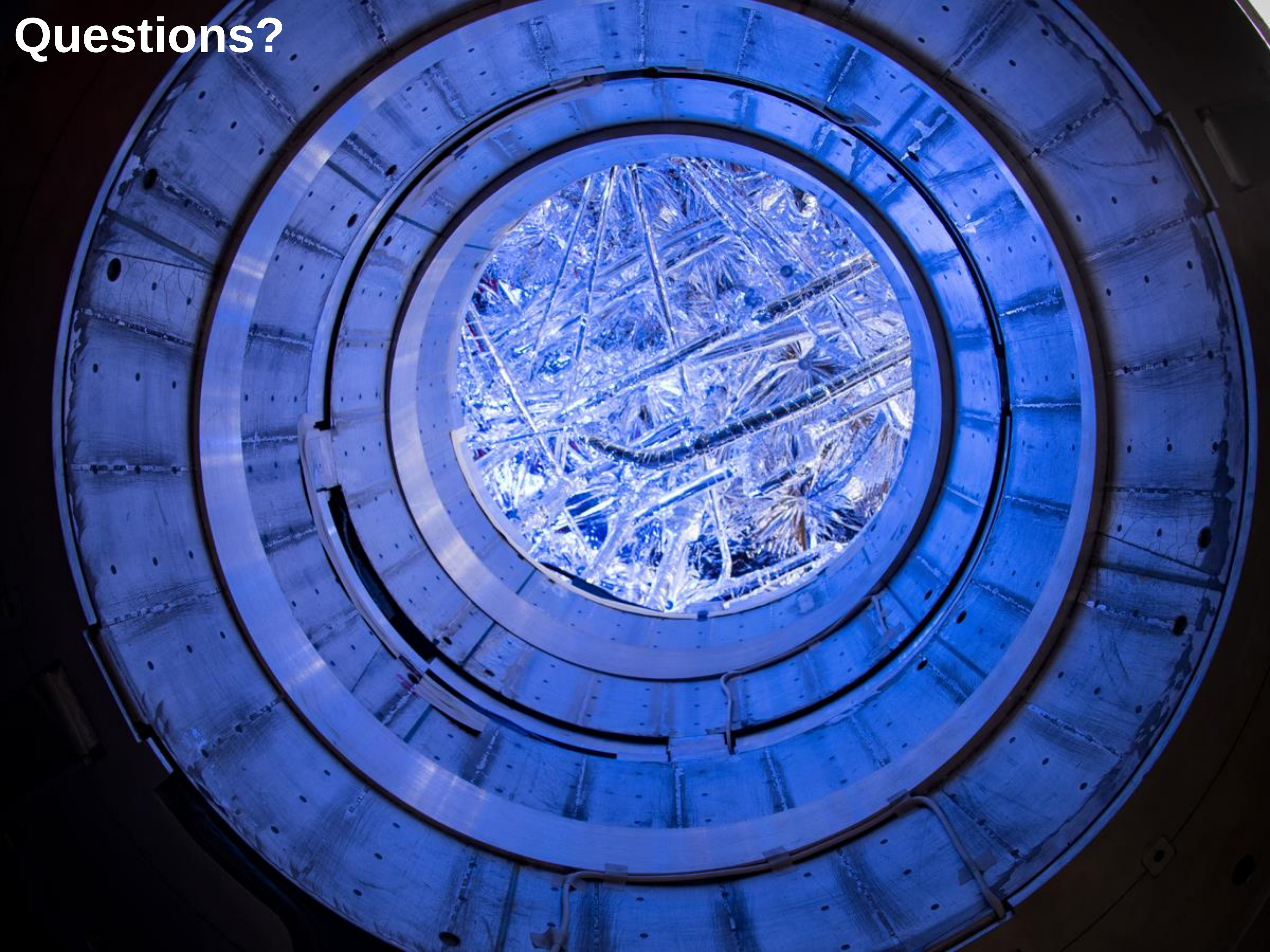
October 2014

Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

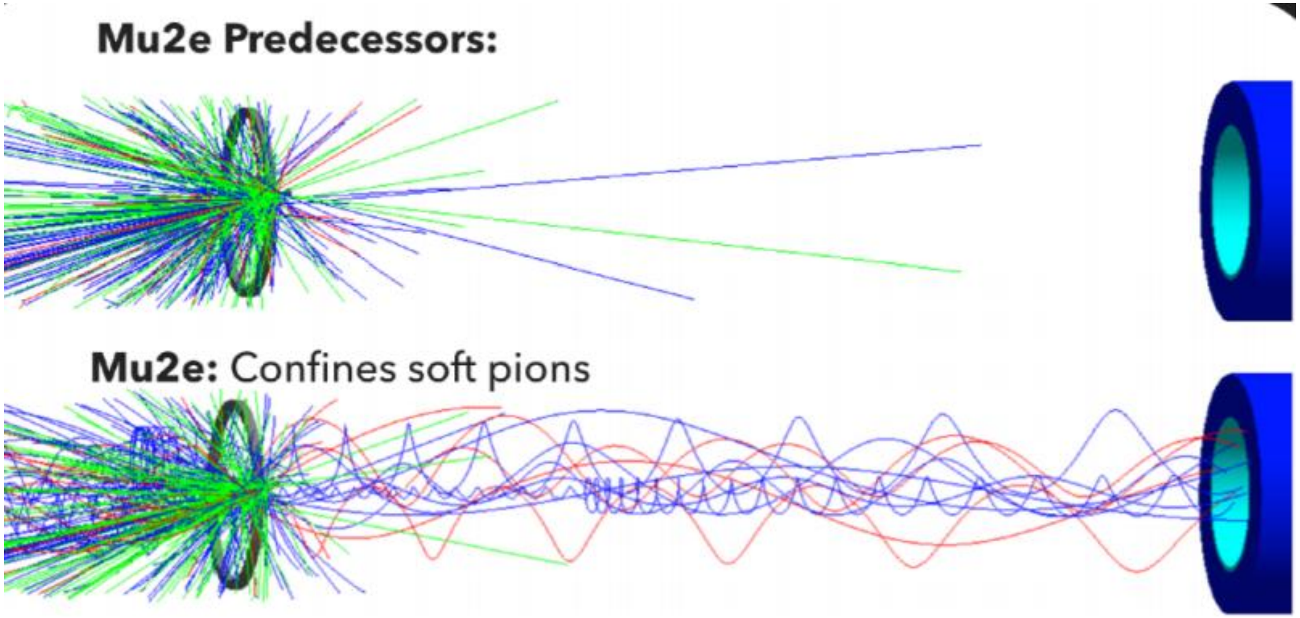
Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

Fermilab

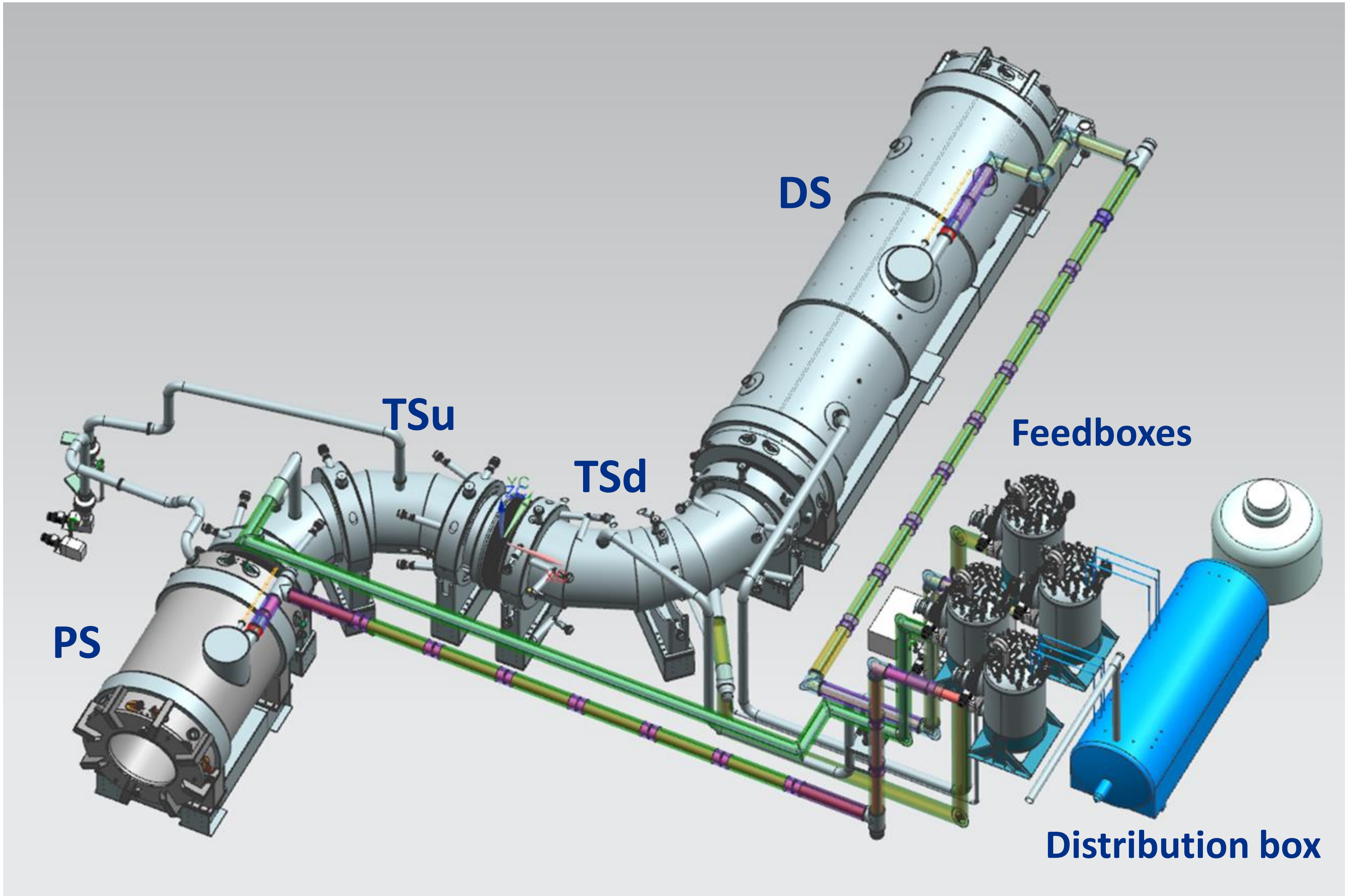
Questions?



Bonus Slides



Experiment	SINDRUM-II	COMET Phase-I	COMET Phase-II	Mu2e
Location	PSI (Switzerland)	J-PARC (Japan)	J-PARC (Japan)	Fermilab (USA)
Proton energy	590 MeV	8 GeV	8 GeV	8 GeV
Proton beam power		3.2 kW	56 kW	7.7 kW
N (proton)		3.2×10^{19}	6.8×10^{20}	3.6×10^{20}
N (stopped muon)	4.37×10^{13}	1.5×10^{16}	1.1×10^{18}	6.7×10^{17}
Transport solenoid shape	Linear	Half C-shape	Full C-shape	S-shape
Muon target material	Au	Al	Al	Al
Sensitivity (90% C.L.)	7×10^{-13}	7×10^{-15}	2.6×10^{-17}	2.6×10^{-17}
Total DAQ time	81 days	~150 days	~180 days	~690 days
DAQ start year	2000	2019 -	After Phase-I completion	2021 -


DS
TSu
TSd
Feedboxes
PS
Distribution box