Status of the Mu2e experiment

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For the Mu2e Collaboration

Outline

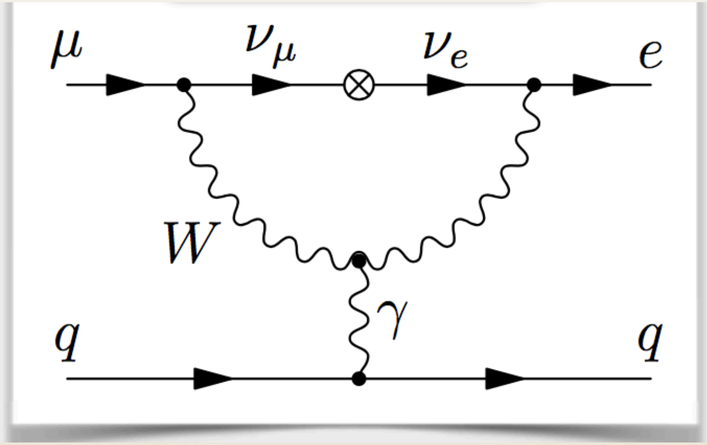
- Quick reminder
- Mu2e apparatus
- Status and plan
- Summary

Quick reminder

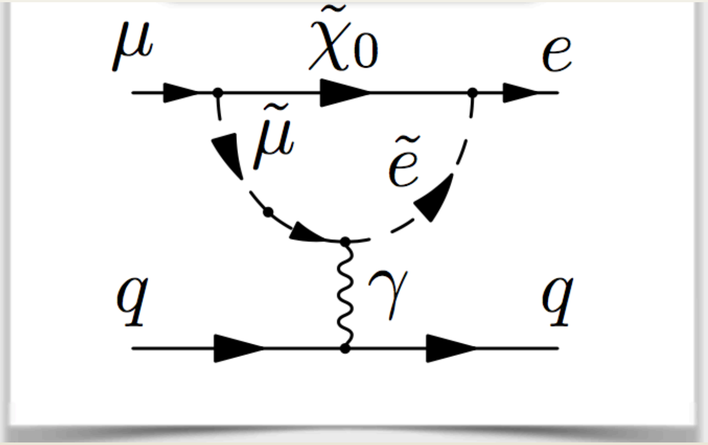
- Mu2e will look for coherent muon conversion into electron in a muonic atom

$$\mu^- + {}^{27}_{13}\mathrm{Al} \rightarrow e^- + {}^{27}_{13}\mathrm{Al}$$

  - Charge lepton flavor violation (CLFV) process
  - clear signal: mono-energetic electrons at 104.96 MeV
- Will be unambiguous sign of new physics beyond the Standard Model



Standard Model with neutrino mass
< 10^{-50}



Beyond Standard Model
~ 10^{-15}

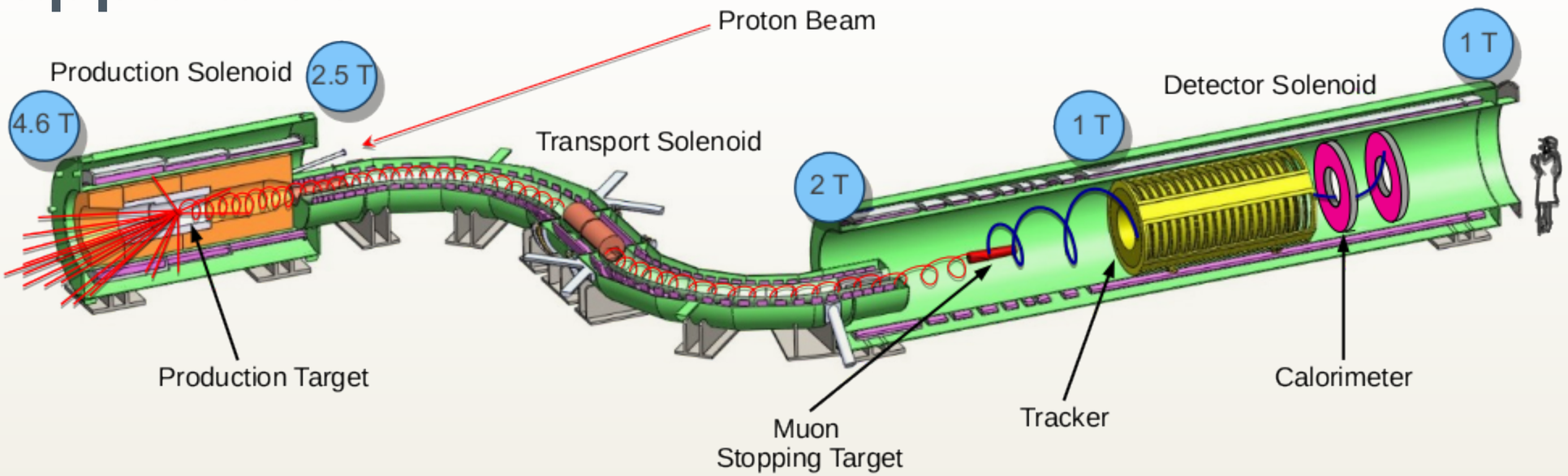
What does Mu2e measure?

- μ-e conversion branching ratio:

$$R_{\mu e} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \text{all captures})}$$

- Number of stopped muons in Mu2e: 6.8×10^{17}
  - Single event sensitivity: 3.0×10^{-17}, and background less than 1 count
  - Requires 7 events for 5σ discovery sensitivity at $R_{\mu e} = 2 \times 10^{-16}$
- If no signal found, new limit: $R_{\mu e} < 8 \times 10^{-17}$@ 90% CL
  - 4 order of magnitude improvement from SINDRUM II (2006) limit: $R_{\mu e} < 7 \times 10^{-13}$

Mu2e apparatus



- Produce lots of μ^-: protons hit Production Target, giving π^-
  - Magnetic mirror to increase pion collection efficiency
- π^-, μ^- are collected in Production Solenoid, transferred to curved Transport Solenoid, there are collimators allow selecting low momentum μ^-
- Stop μ^- in a Muon Stopping Target (Al), inside Detector Solenoid
- Wait for 104.96 MeV e^-: tracker and calorimeter
  - Hollow design to avoid particles from beam flash and Michel electrons

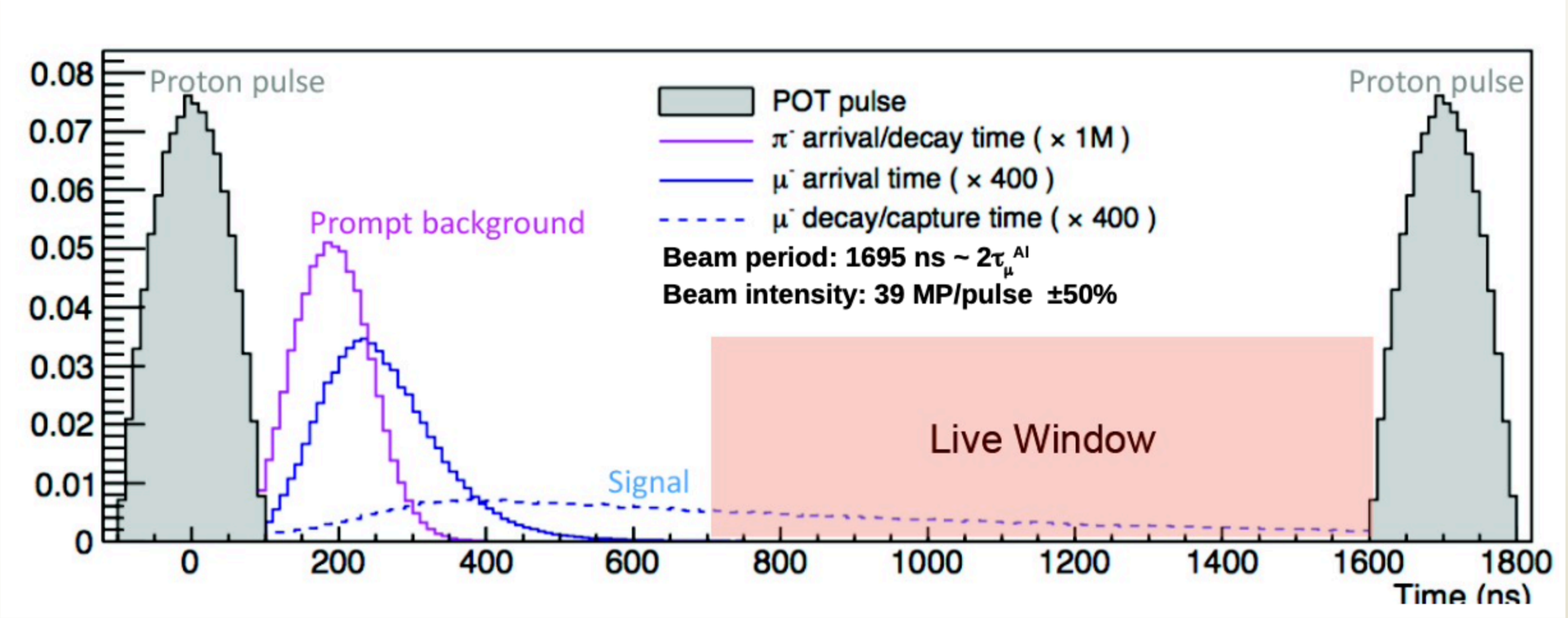
The Muon campus at Fermilab

Mu2e proton beam line

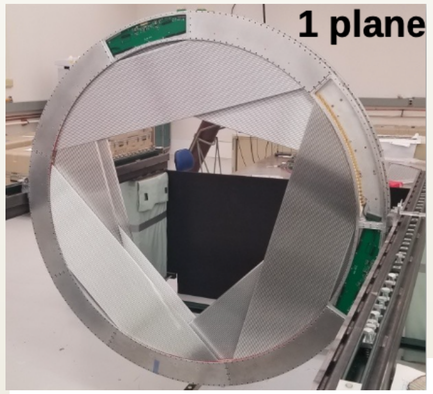
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons
- 8 GeV protons are produced in the Booster
- Recycler forms 8 proton bunches
- Delivery ring gets 1 bunch at a time
- Slow extraction to Mu2e occurs once every 1695 ns
- Mu2e will collect data simultaneously with NOvA and short baseline program
  - small impact on NOvA

Pulsed proton beam

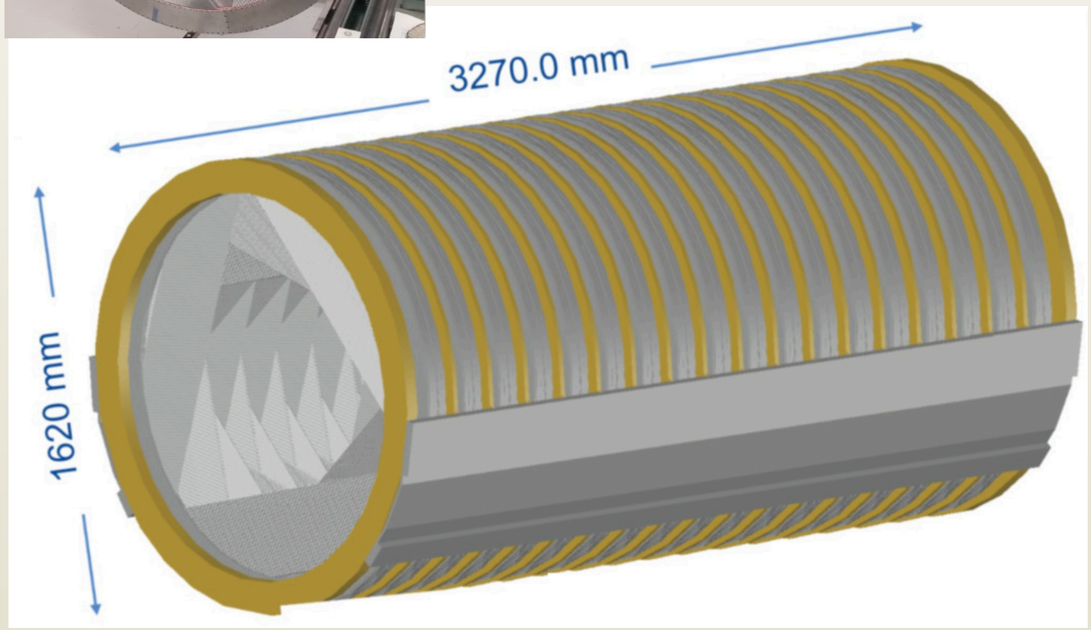
- Beam period: 1659 ns ~ 2 x $\tau_{\mu^-}^{Al}$
- Beam intensity: 39 x 10^6 proton/pulse
- Analysis starts from 700 ns to suppress prompt background
- out-of-time protons / in-time protons < 10^{-10}

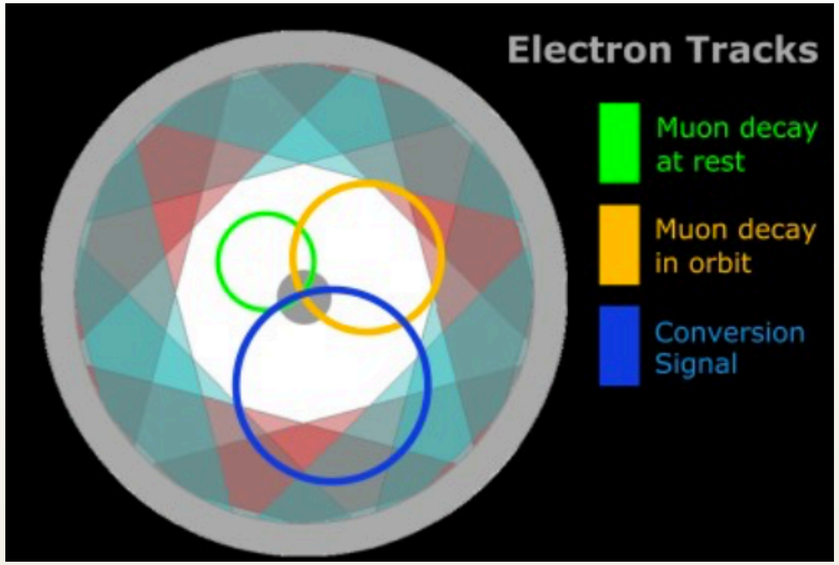


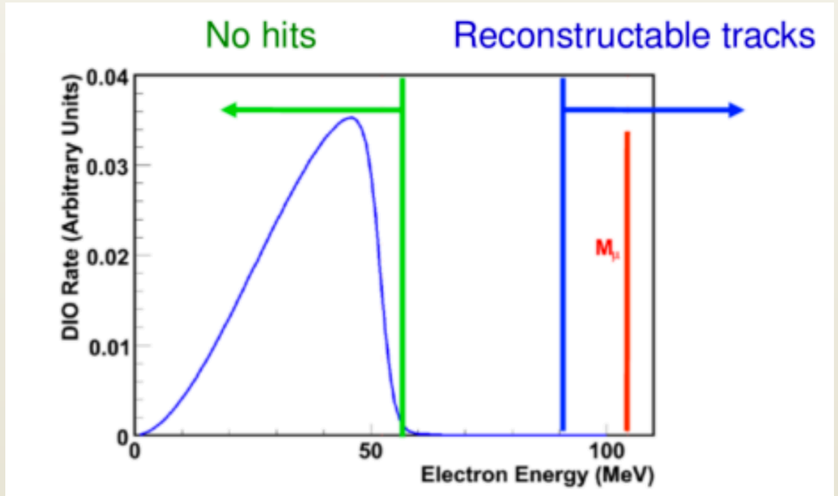
Tracker design



- Straw technology employed:
  - 5 mm diameter, 12 μm Mylar walls
  - 25 μm Au-plated W sense wire
  - 80/20 Ar/CO2 with HV ~ 1450 V
- 18 stations equally spaced, each containing 12x 120° panels for stereo measurement
- Inner 38 cm un-instrumented, blinded to beam flash and low pT particles

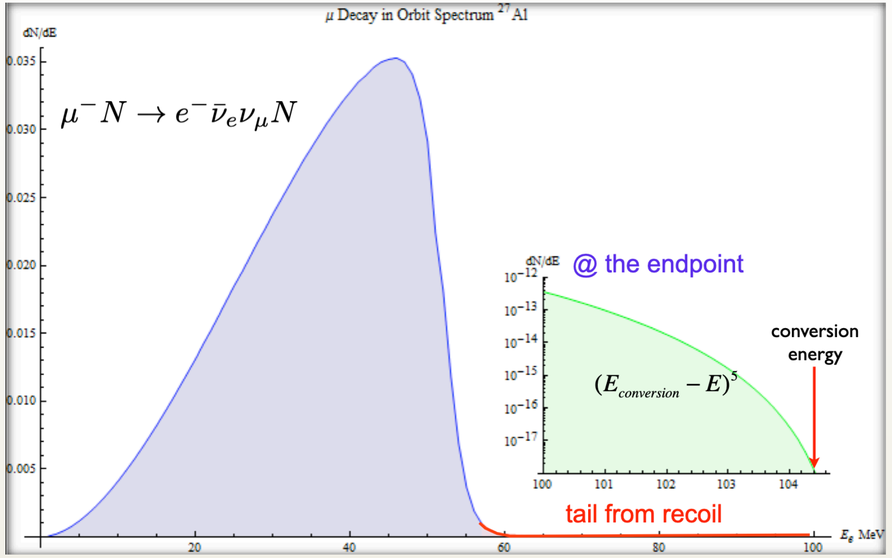


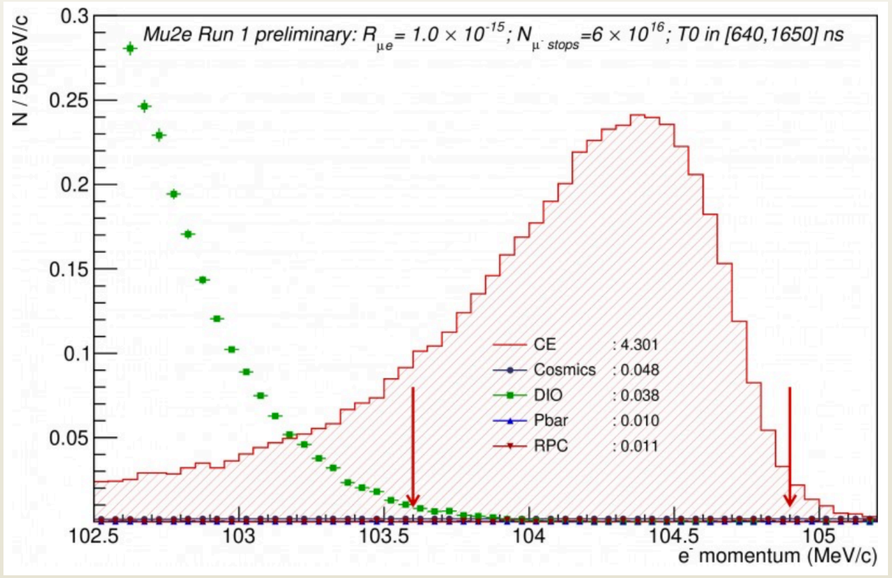


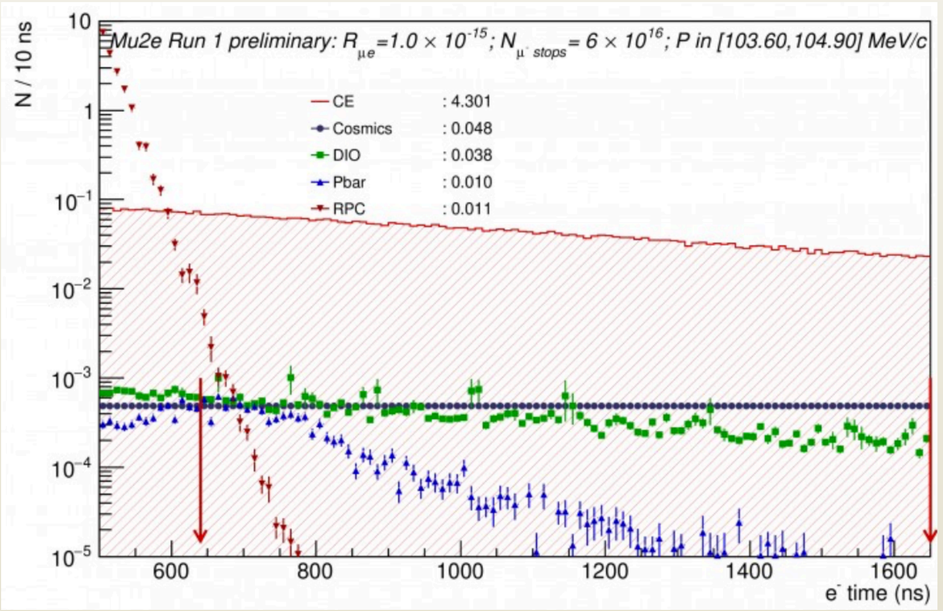


Backgrounds of the μ-e search

- Muon decay in orbit:
  - Electrons from normal decay, but with the presence of aluminum atom
  - Falls rapidly as $(E_{conversion} - E)^5$
  - Can be suppressed by momentum window cut
- Cosmic induced background: suppressed by cosmic ray veto
- Other background can be dealt with by timing cut



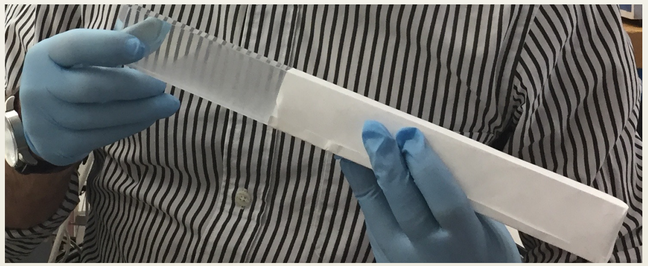




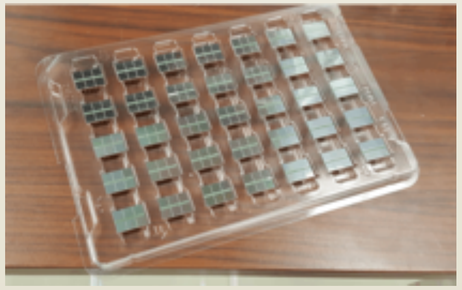
Calorimeter design

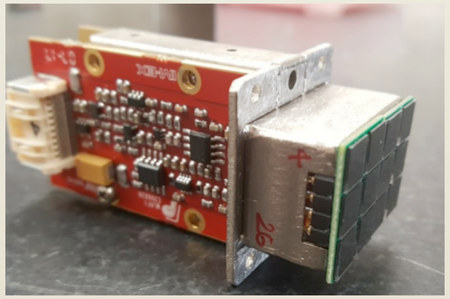
- 2 disks, each disk contains 630 undoped CsI crystals 20 x 3.4 x 3.4 cm3
- Inner/outer radii: 35.1/66 cm
- Disk separation ~ 75 cm
- Readout system:
  - 2 large area SiPM-array/crystal
  - 12 bit, 200 MHz waveform-based digitizer boards

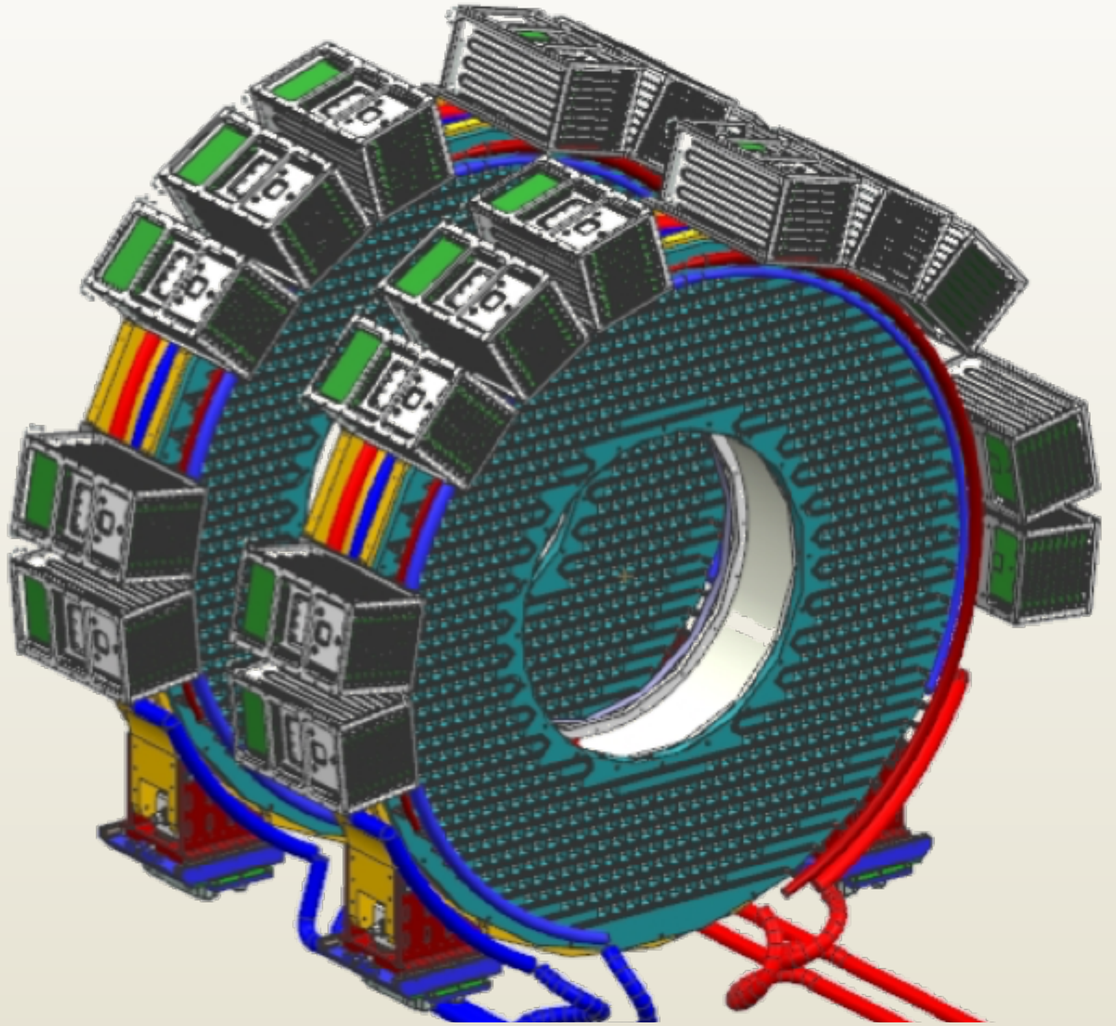
undoped CsI



SiPM array

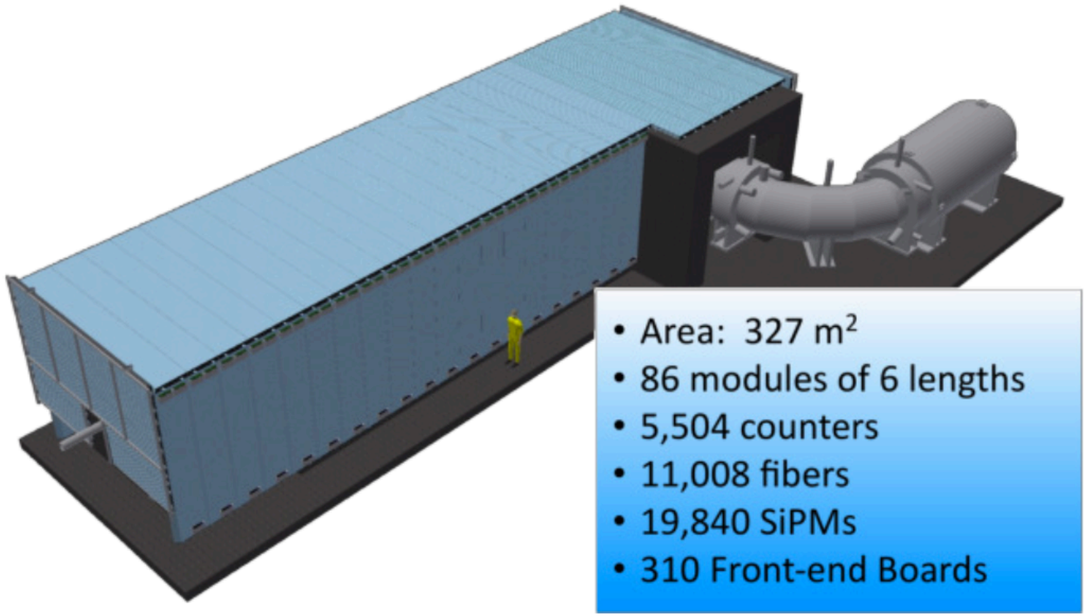




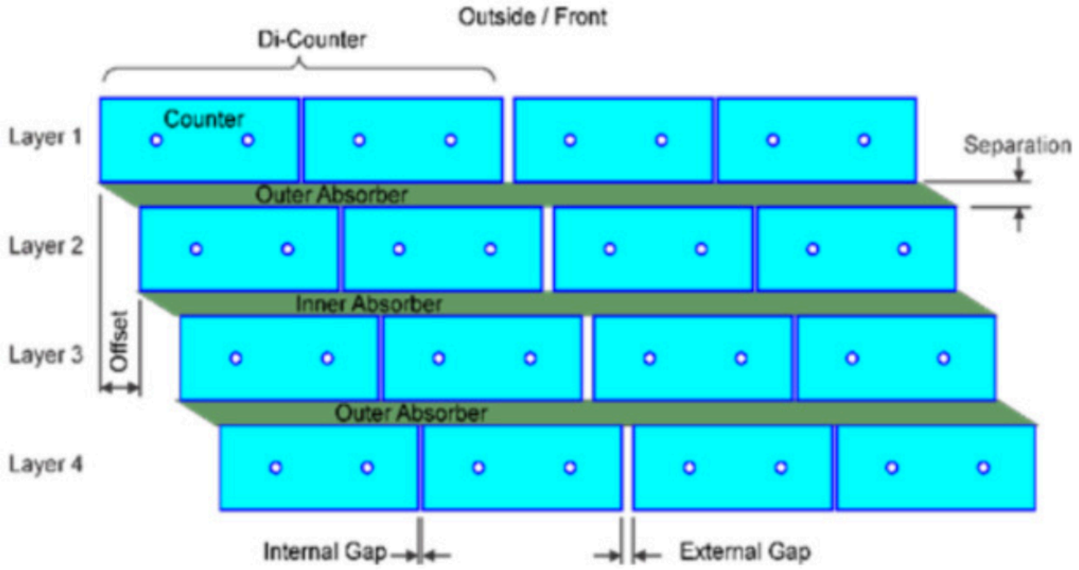


Cosmic ray veto

- Needed to reject 105 MeV/c electrons induced by cosmic rays
  - 1 fake μ-e event per day!
- 4 overlapping layers of scintillator with wavelength shifting fibers, read out on both ends with SiPMs
  - Veto on 3-fold coincidence
- will reduce the rate to 0.1 fake event in 3 years.



- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards



Background estimation for the entire experiment

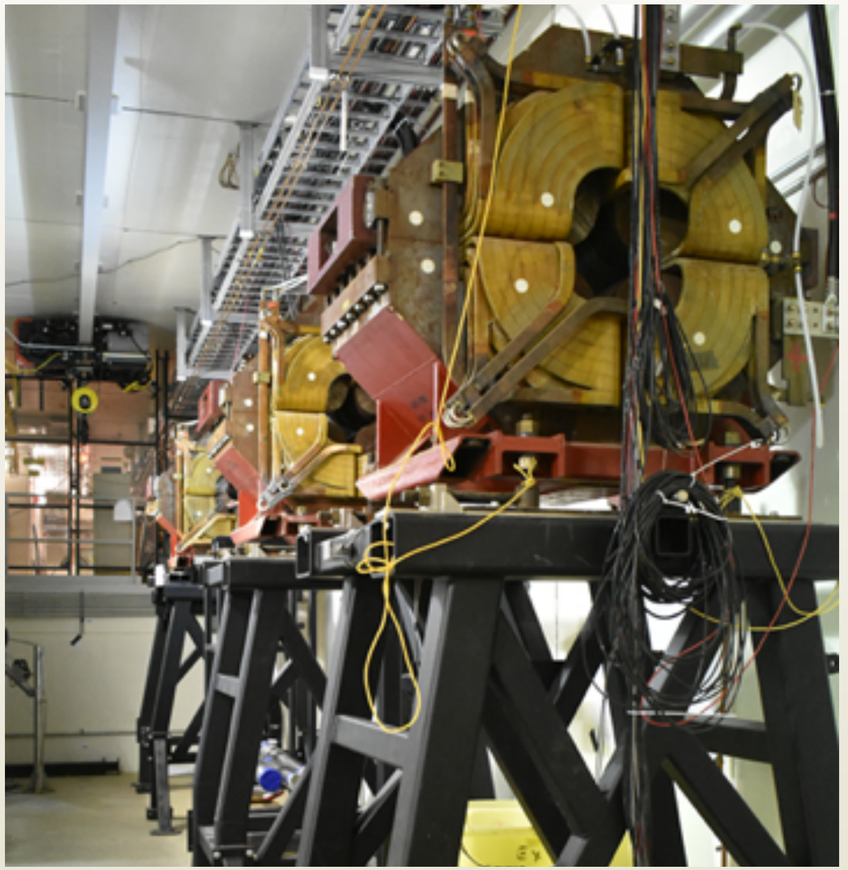
Process	Expected event yield
Cosmic ray muons	0.21± 0.02(stat) ± 0.06(syst)
Decay-in-orbit electrons	0.14 ± 0.03(stat) ± 0.11(syst)
Antiprotons	0.040 ± 0.001(stat) ± 0.020(syst)
Pion capture	0.021 ± 0.001(stat) ± 0.002(syst)
Muon decay-in-flight	<0.003
Pion decay-in-flight	0.001 ± <0.001
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Radiative muon capture	$0.000^{+0.004}_{-0.000}$
Total	**0.41 ± 0.13(stat+syst)**

Status of Mu2e: beam line

- Mu2e beam line is well underway

Magnets installed along M4 beamline

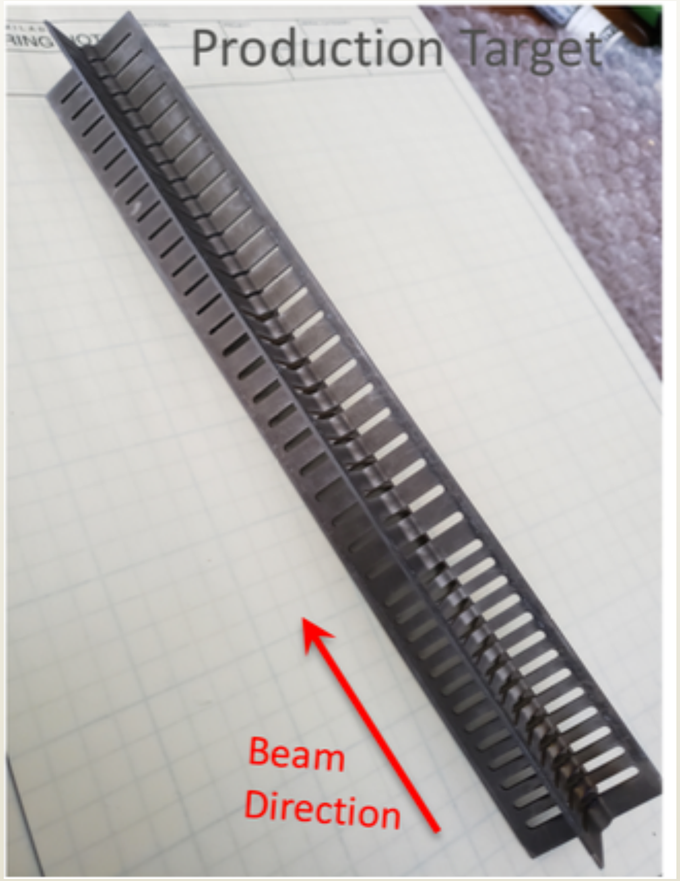
Quadrupole in Delivery Ring used for resonant extraction

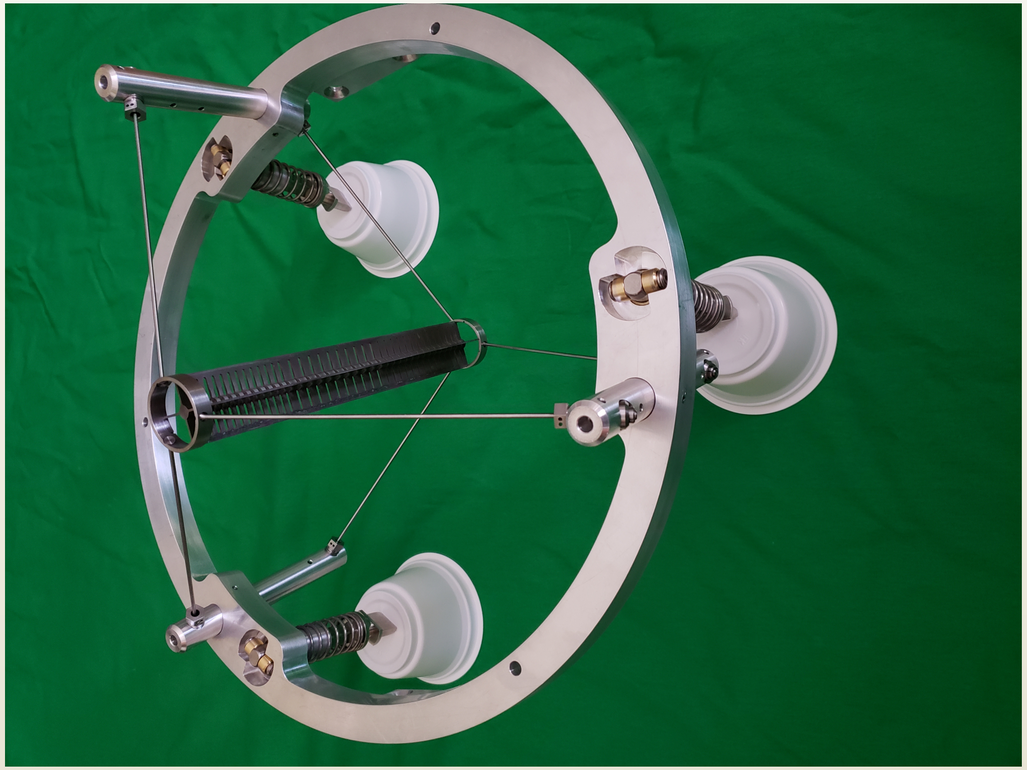


Final Focus magnets are in place

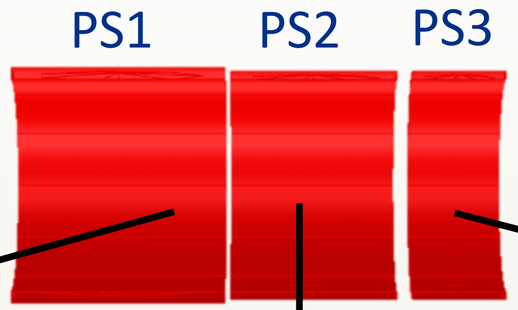
Mu2e status: Production target

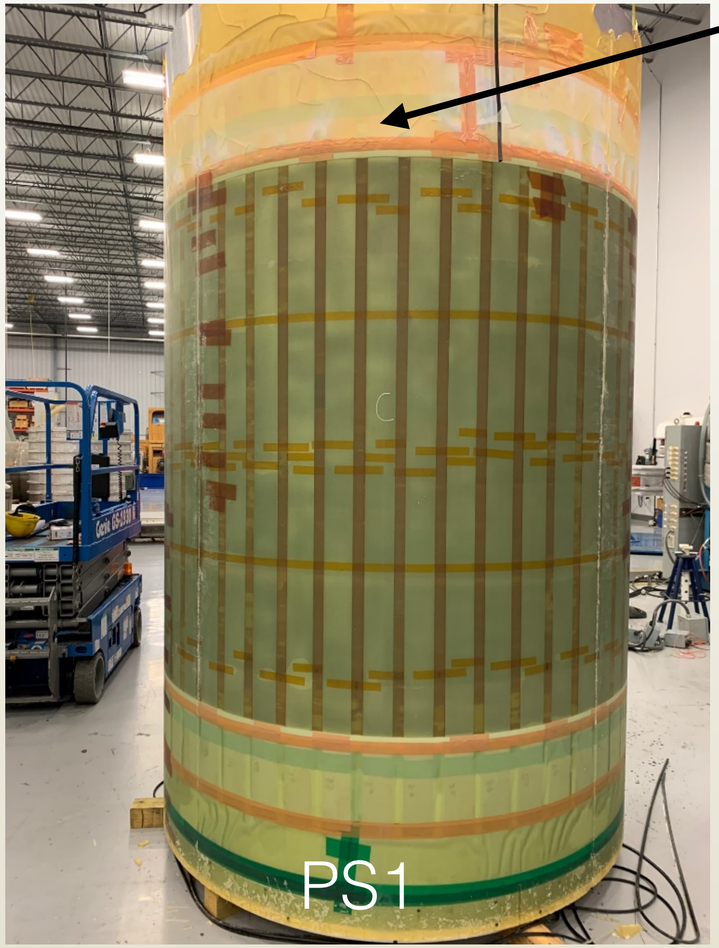
- Made of tungsten, completed in April 2021
- 10% of beam power into the target
  - heats up to 1700 °C (~3100 F), average power density ~150 MW/m^3





Mu2e status: Production solenoid





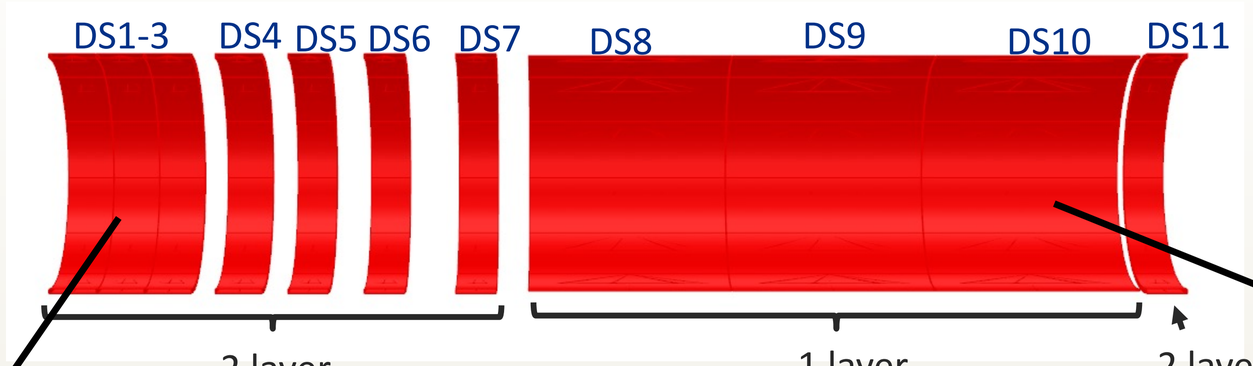
Mu2e status: Transport solenoid

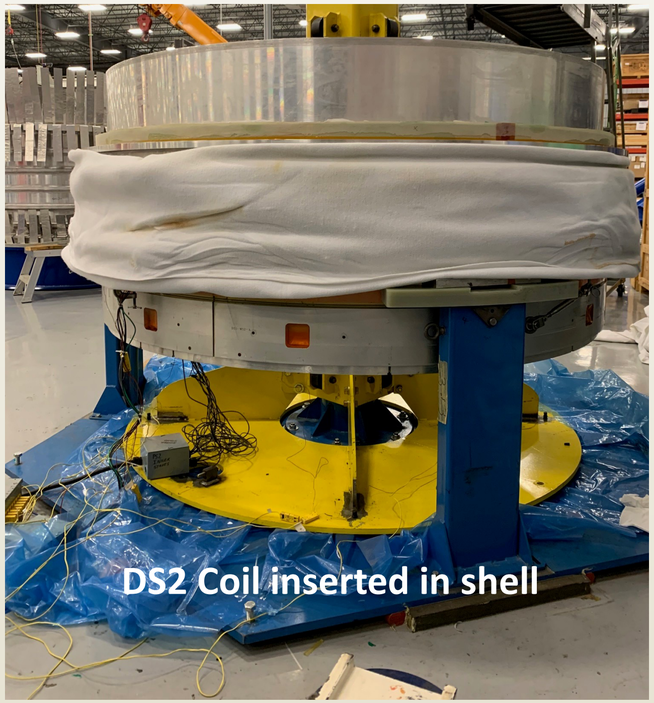
- Transport solenoid cold masses assembled
- Cooled down with liquid helium, power tested 120% full power

Fermilab test facility

Upper transport solenoid (TSu) mass and thermal shield

Mu2e status: Detector solenoid

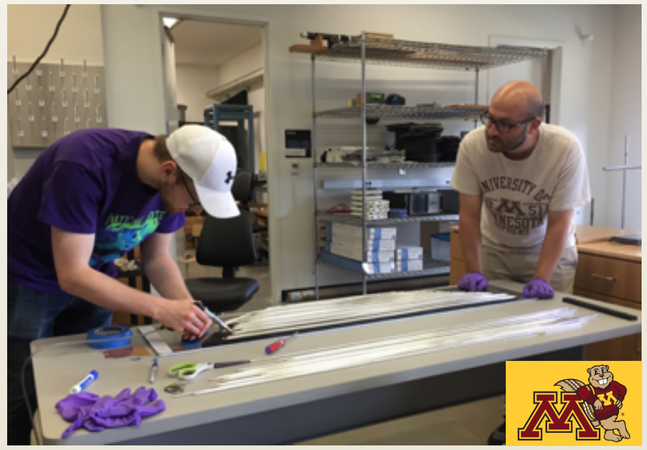




Mu2e status: Tracker construction

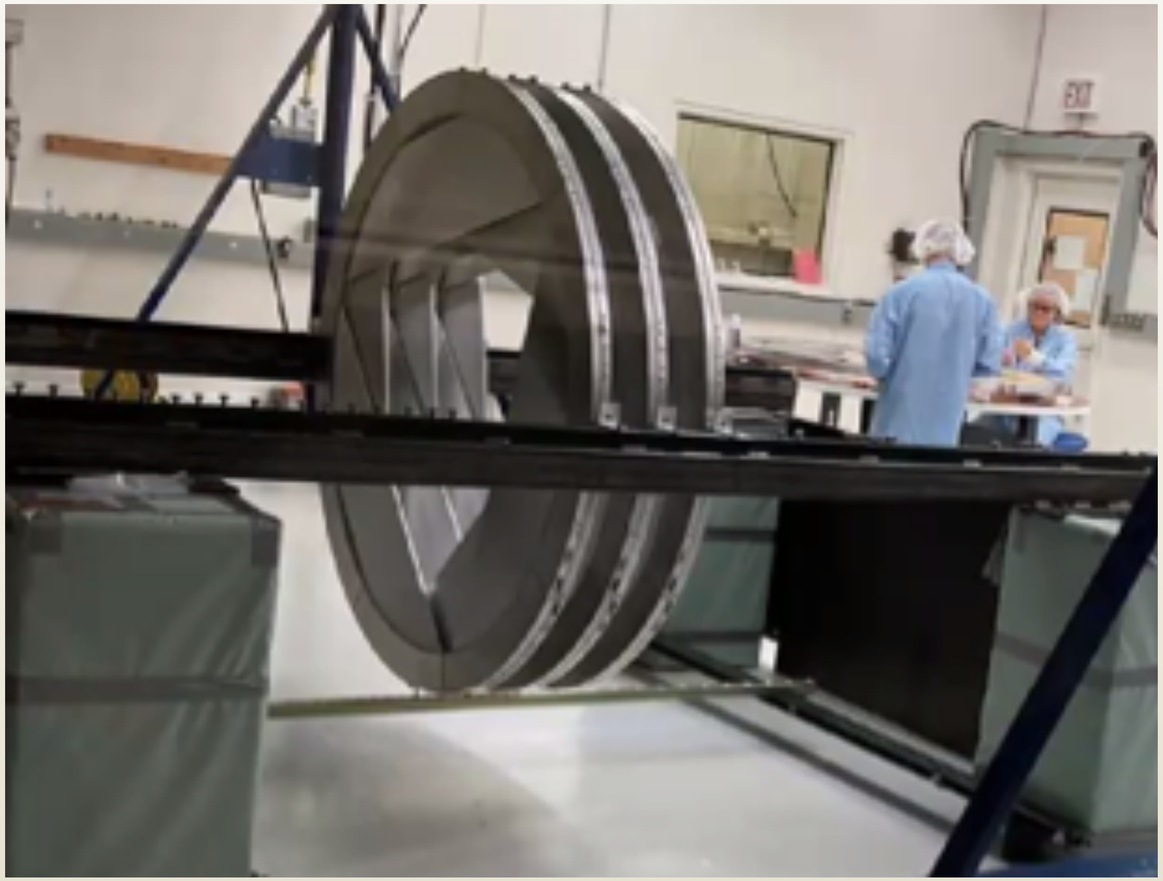
- Straw-tubes and panel assembly is proceeding steadily at Univ of Minnesota
- 7/36 planes already assembled at Fermilab
- Vertical slice test is underway with full DAQ chain

panel assembly & test @ Univ of Minnesota



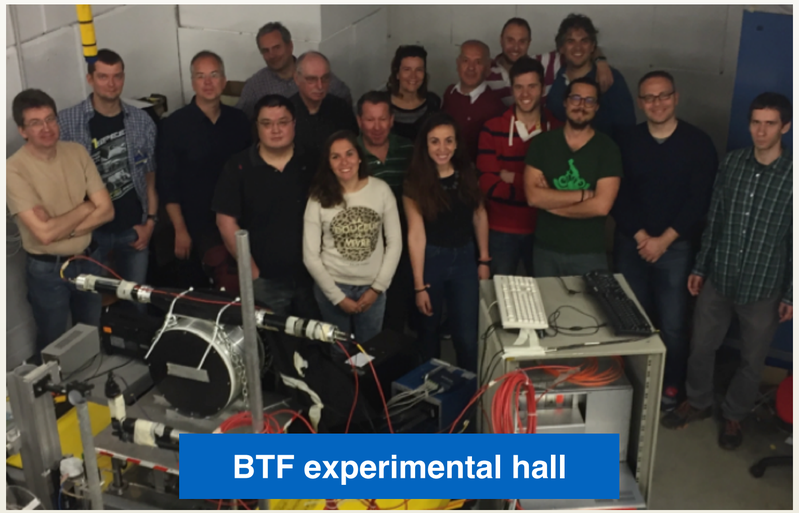
vacuum test @ Fermilab

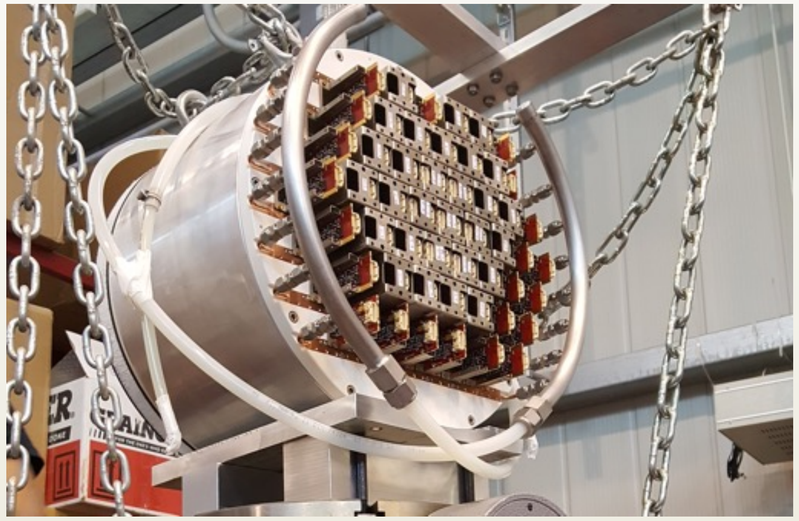
Tracker assembly @ Fermilab

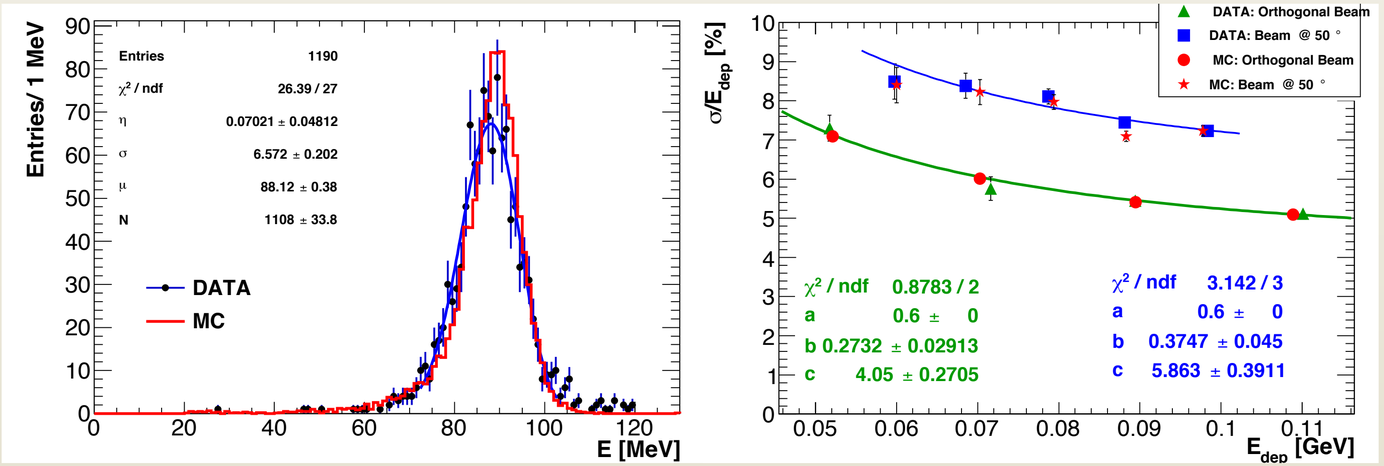


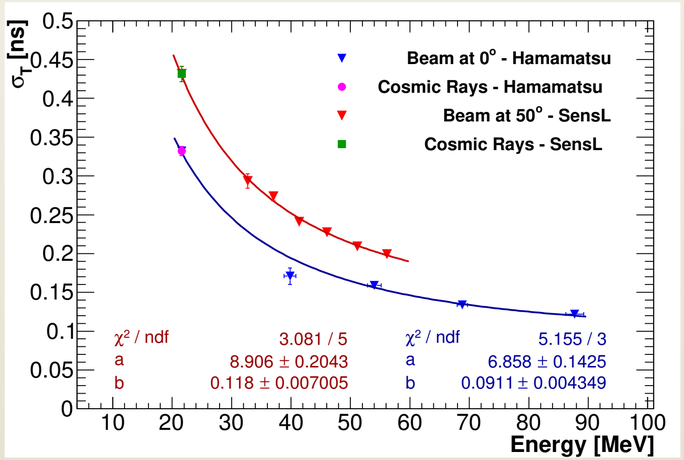
Mu2e status: Calorimeter R&D

- Large prototype: 51crystals + 102 SiPM + 102 FEE boards
- Beam test successfully performed @ BTF in Frascati using electron beam





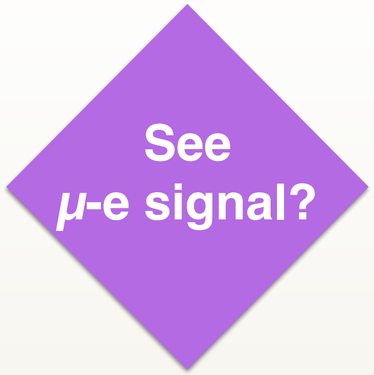




Plan

- Installation and commissioning begins this year
- Data taking starts early 2025
  - Run 1 in two years 2025-2026: 1000 times improvement in sensitivity
  - LBNF shut down at Fermilab
  - Run 2: 2-3 more years to achieve 10,000 times improvement in sensitivity
- Anticipate 4-5 years of run time for full data set

What’s next?



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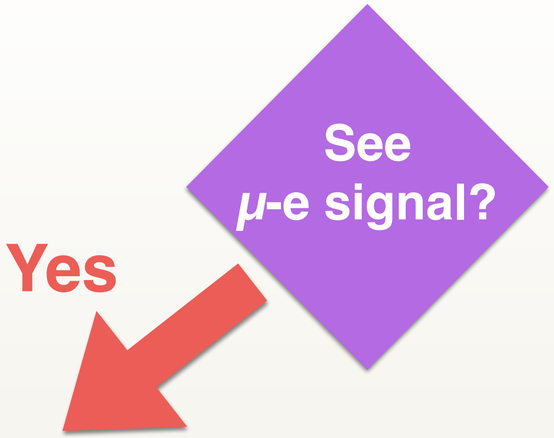

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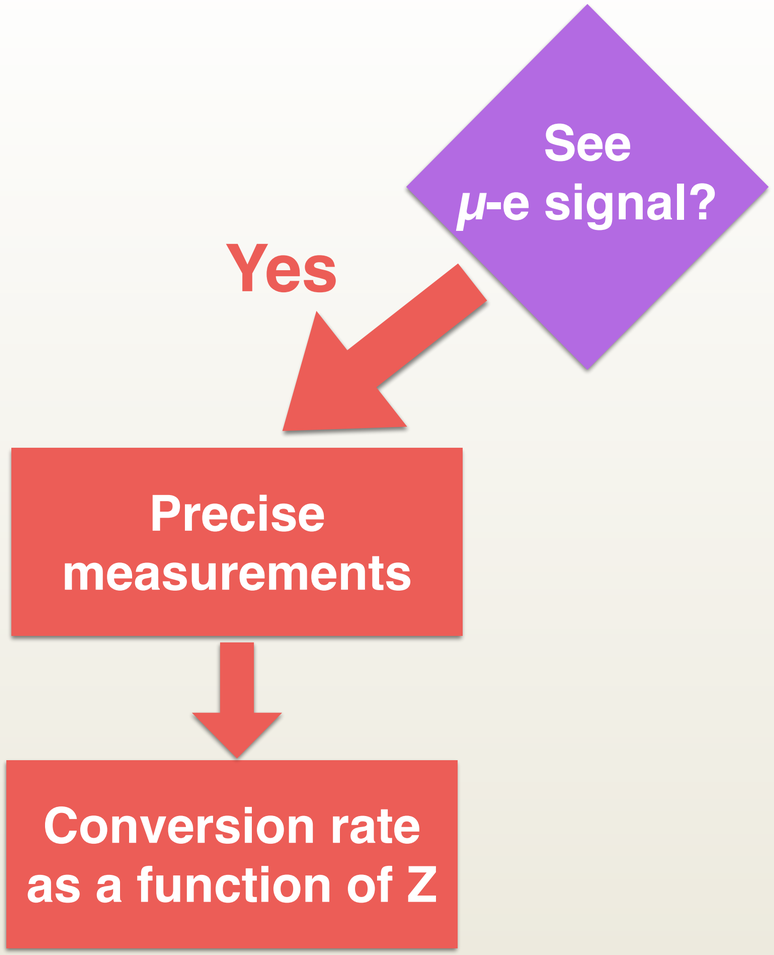
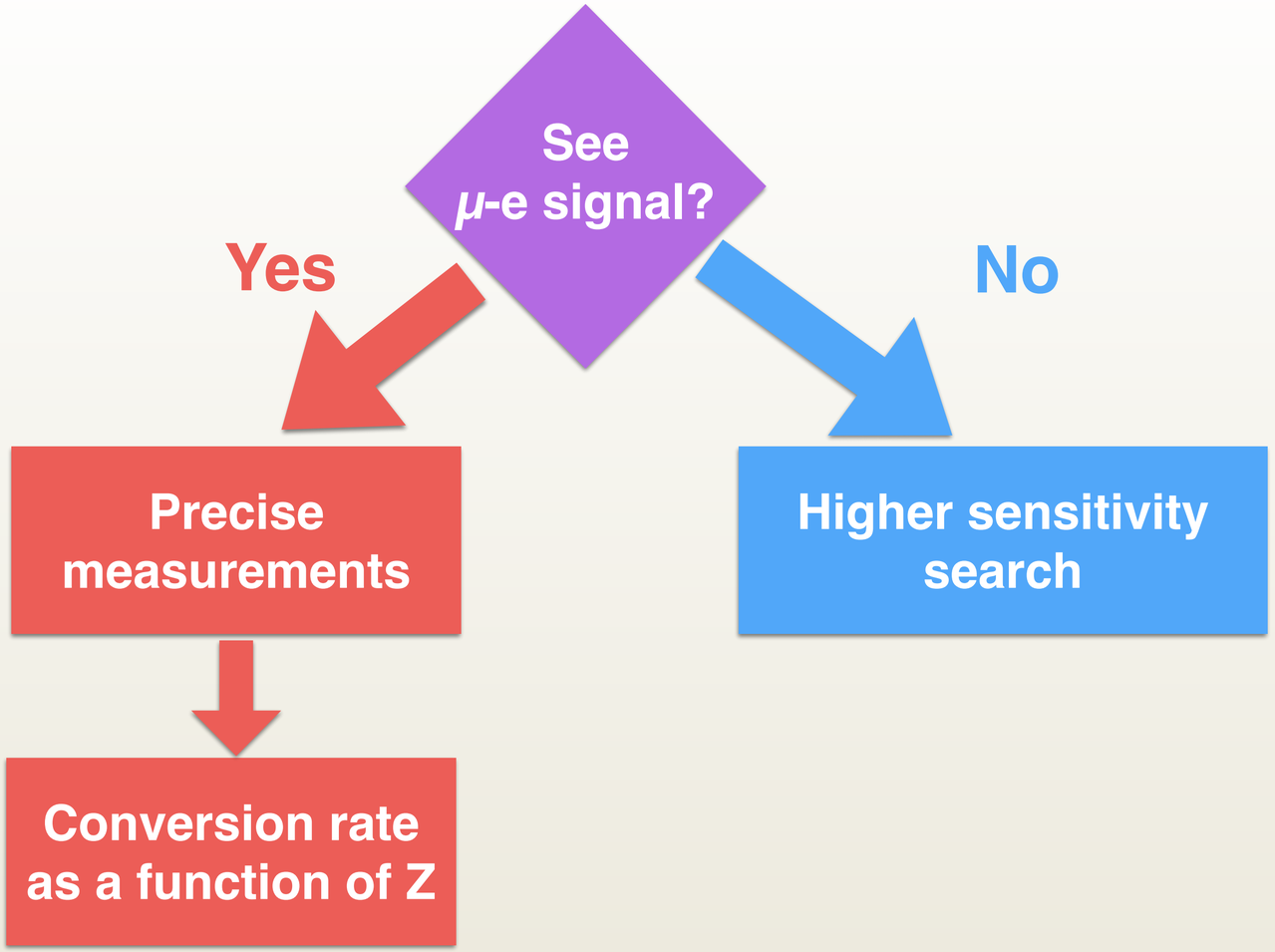
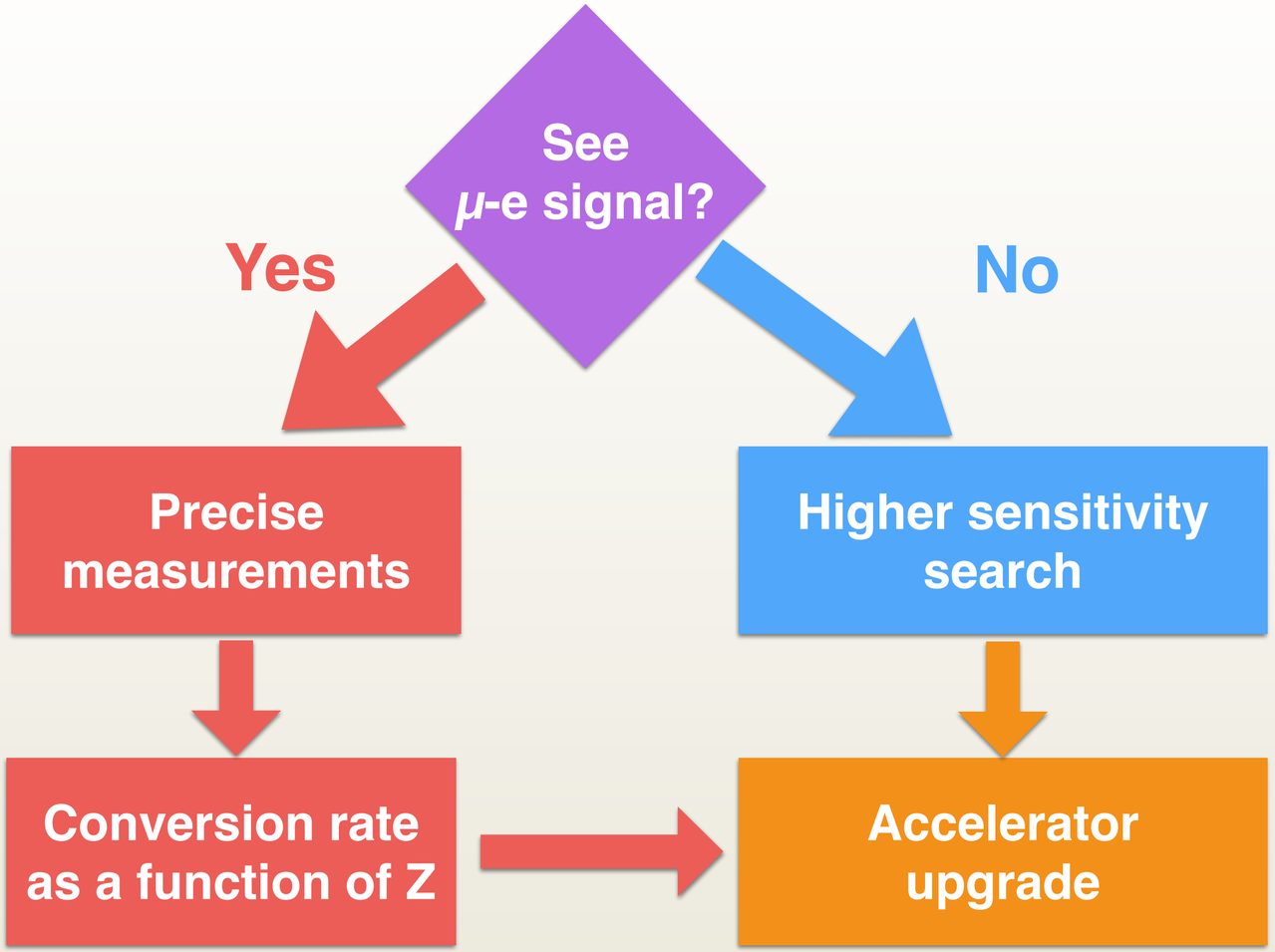

See
μ-e signal?
Yes
Precise
measurements
Conversion rate
as a function of Z

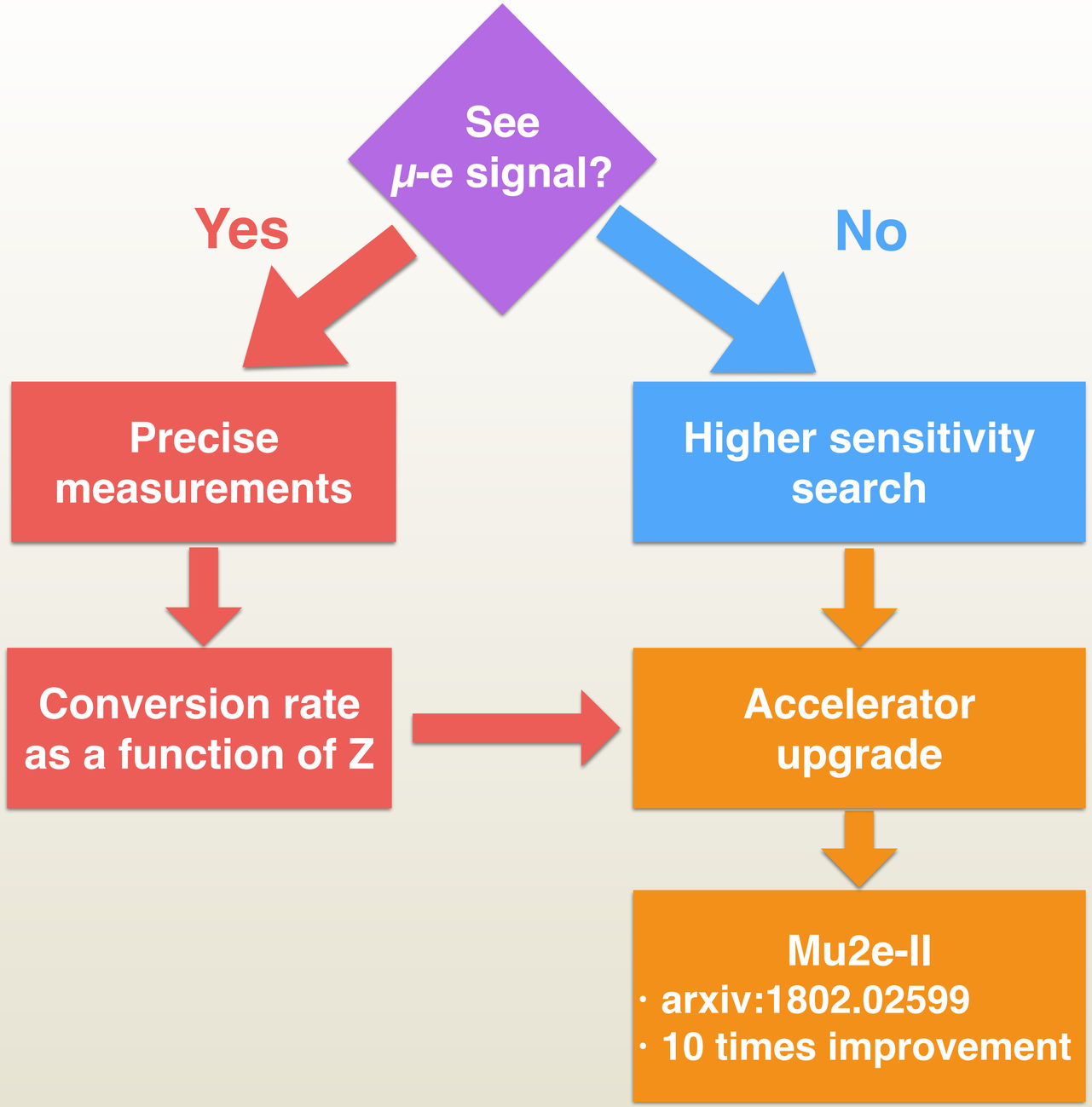
What's next?


See
μ-e signal?
Yes
No
Precise
measurements
Higher sensitivity
search
Conversion rate
as a function of Z

What's next?


See
μ-e signal?
Yes
No
Precise
measurements
Higher sensitivity
search
Conversion rate
as a function of Z
Accelerator
upgrade

What's next?


See
μ-e signal?
Yes
No
Precise measurements
Higher sensitivity search
Conversion rate as a function of Z
Accelerator upgrade
Mu2e-II
· arxiv:1802.02599
· 10 times improvement

Summary

- Mu2e will improve sensitivity on μ-e conversion experiment by a factor of 10,000
  - provides discovery capability over wide range of New Physics models
- In construction phase:
  - begin commissioning in 2021
  - First physics run expected in 2025-2026, 1000 times improvement in sensitivity
  - Full dataset from 4-5 years of running
- Start discussing about next phase, Mu2e-II
  - Increase sensitivity by another order of magnitude (see Giani's talk on Oct 1)

Z-dependence of μ-e conversion rate