Mu2e in 10 Minutes

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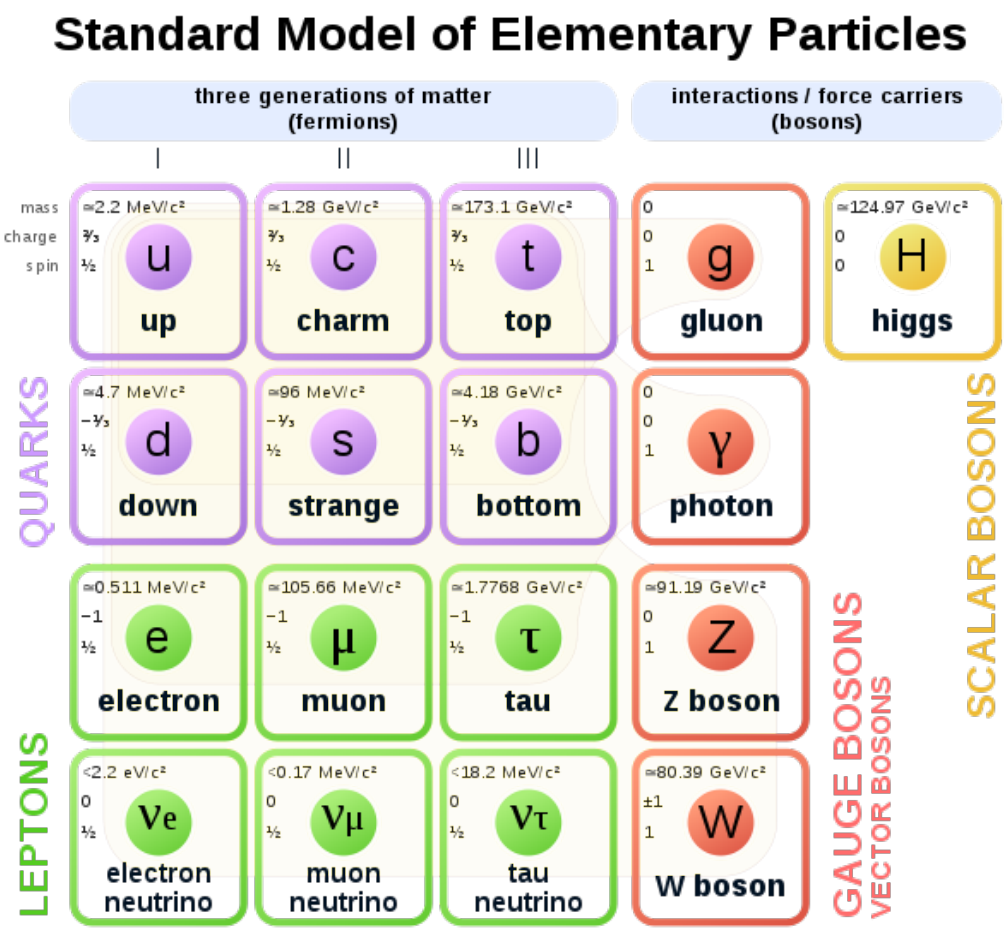
New Perspectives at Fermilab

06/11/2019

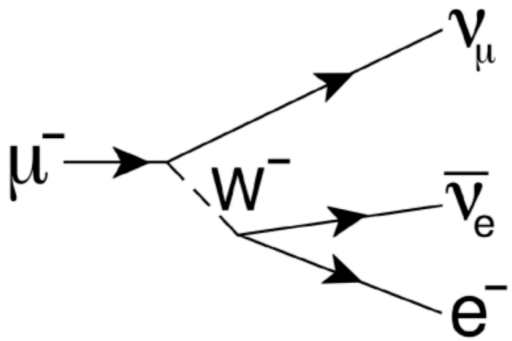
Standard Model

- Quark mixing (CKM)
- Neutrino oscillation (lepton flavor violated)
- Mixing among charged leptons (Never observed)
- Charged Lepton Flavor Violation?
  - ✓ A single observation would be evidence of New Physics



Charged Lepton Flavor Violation

- Ordinary muon decay

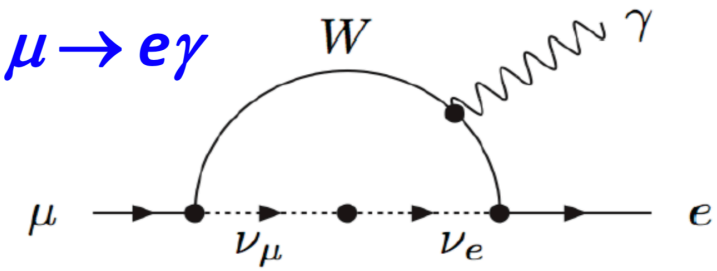


- Lepton flavor conserved

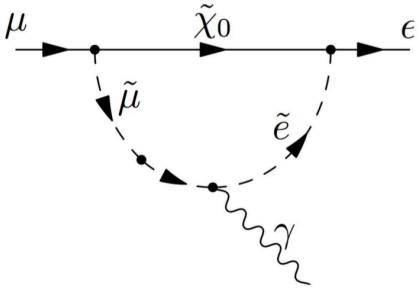
	$\mu^- \rightarrow$	e^-	$\bar{\nu}_e$	ν_μ
L_μ	1	0	0	1
L_e	0	1	-1	0

- CLFV is not complete forbidden in SM, but tiny

$\mu \rightarrow e\gamma$



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



- Any observation would be evidence of the rate enhanced by new physics

CLFV Processes & History

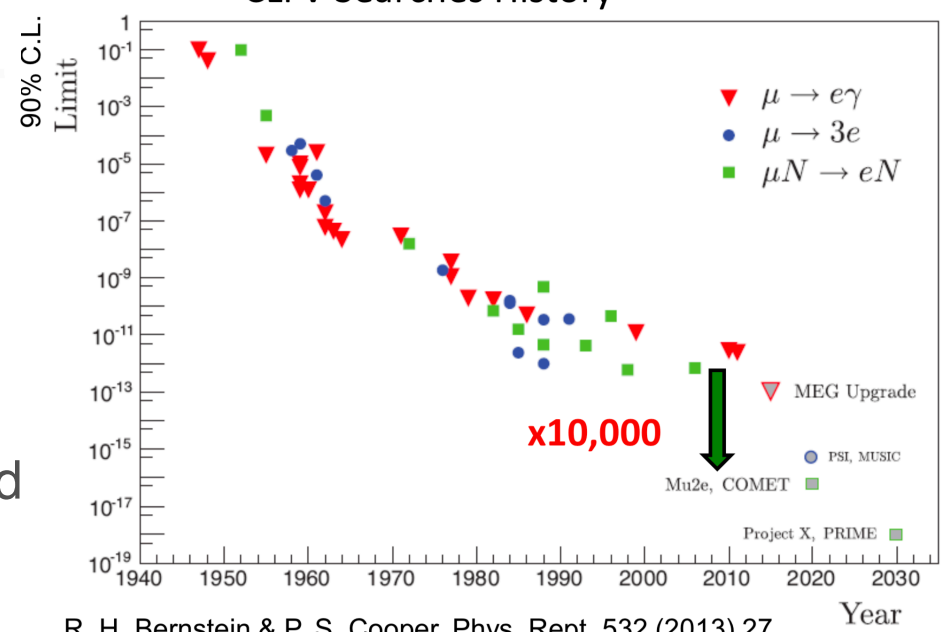
Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR}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

- Muon sector gives the most stringent limits
- One of the most effective channels

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

- Current best limit
  - ✓ MEG<4.2x10^{-13} (90% C.L.)
  - ✓ Mu2e's goal ~10^{-17}
- 10000 improvement, exploring unconstrained phase space favored by many new physics models

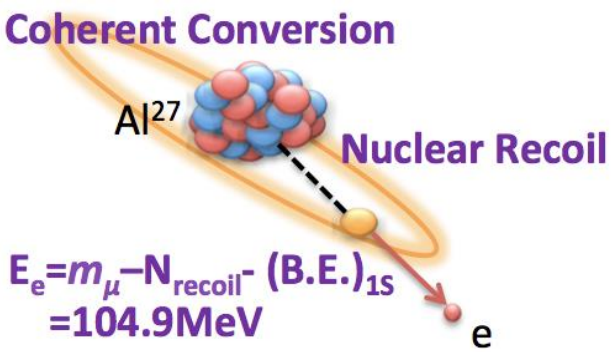
CLFV Searches History

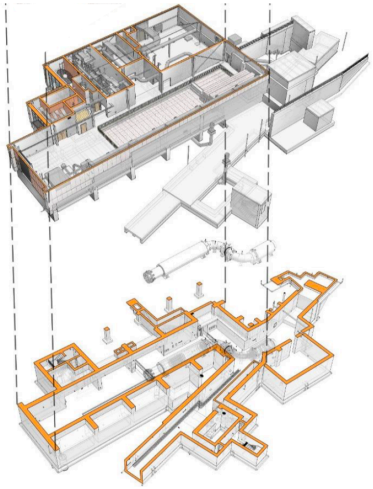


R. H. Bernstein & P. S. Cooper, Phys. Rept. 532 (2013) 27

Mu2e Experiment

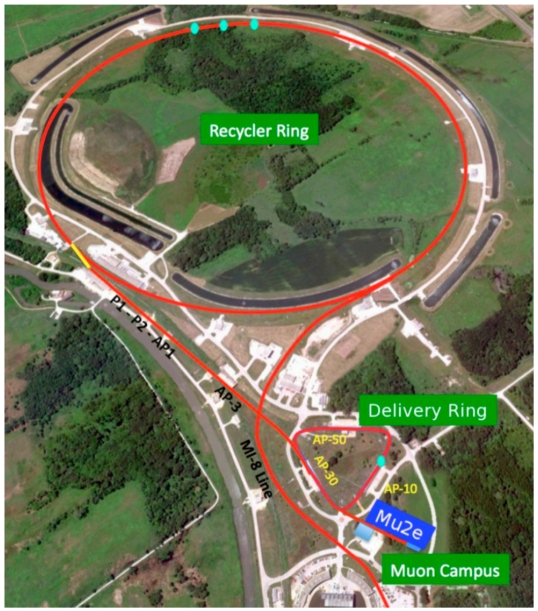
- Lacated at Fermilab Muon Campus
- One of the U.S. Intensity Frontier top priority projects
- Cost $270M
- Civil construction completed (2017/3)

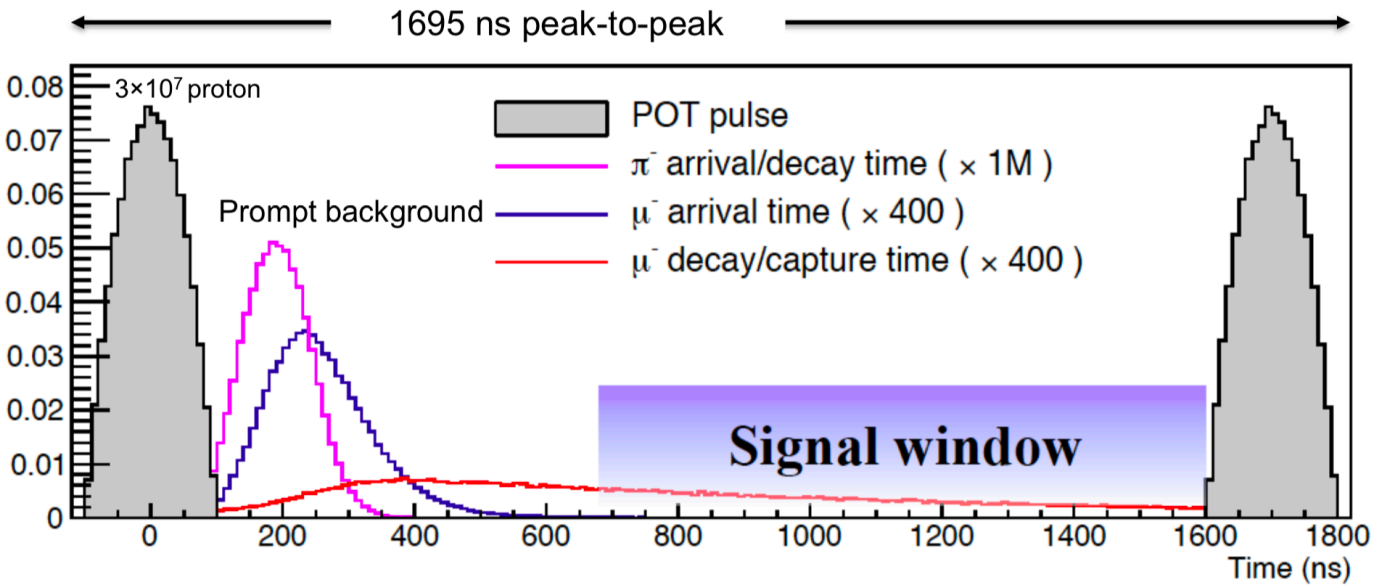




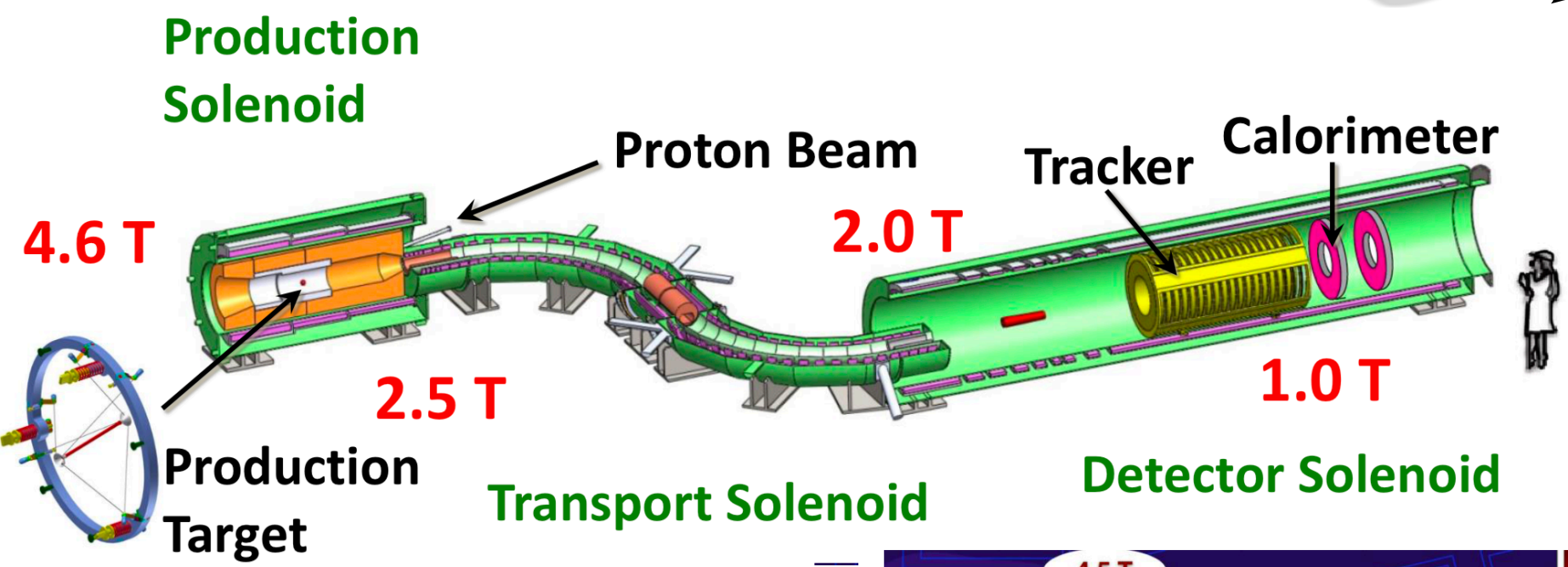
The Proton Beam

- 3×10^7 8GeV protons per bunch, bunch spacing 1695 ns
- 700 ns delay before 1 μs live gate
- Extinction $<10^{-10}$

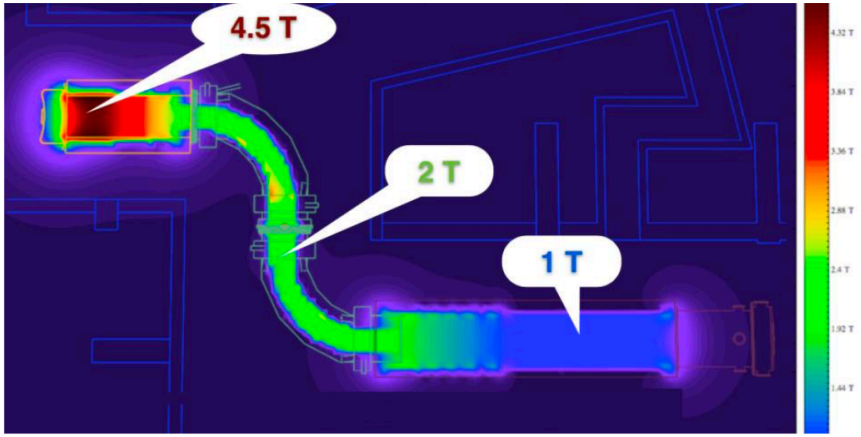




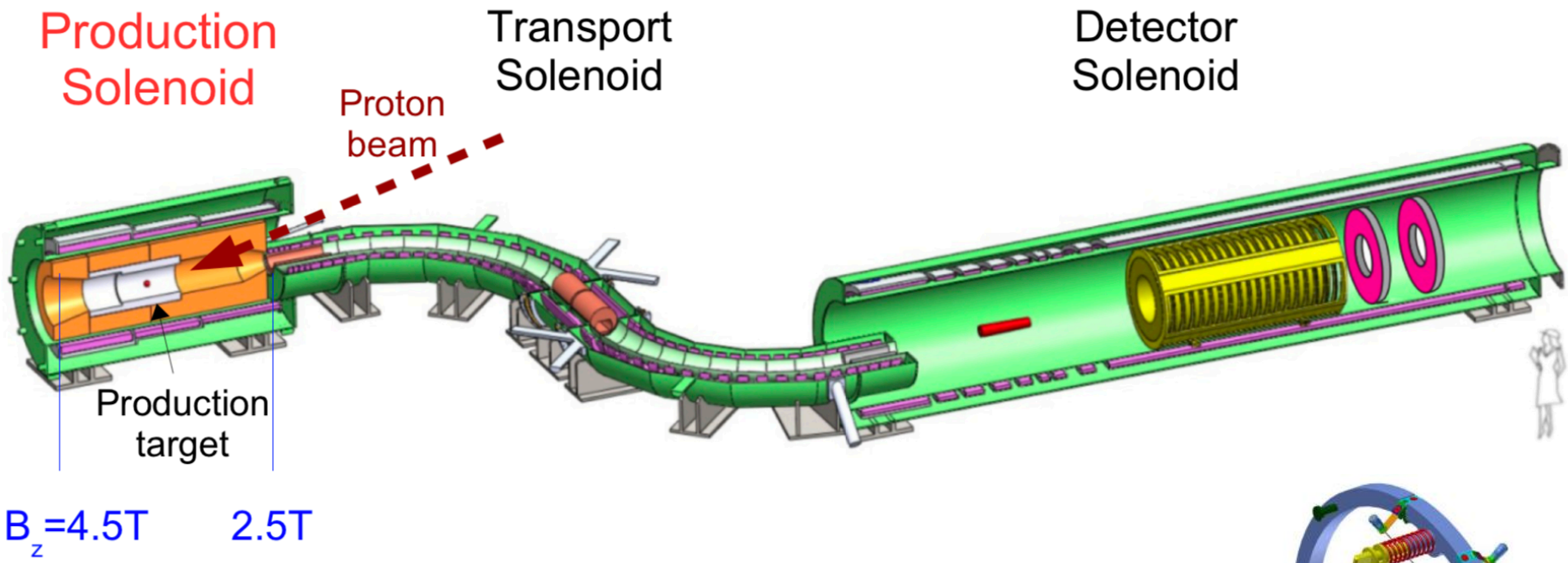
Mu2e Apparatus

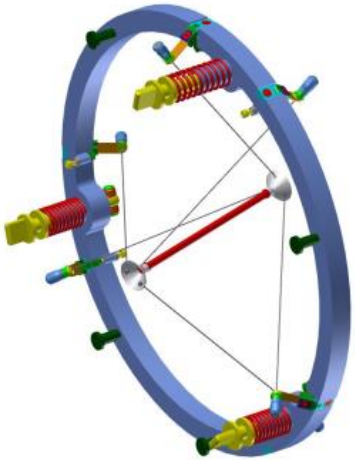


- Three functional solenoids with graded magnetic fields (4.5T – 1T)
- Increase collection efficiency, sweep particles from production to detector



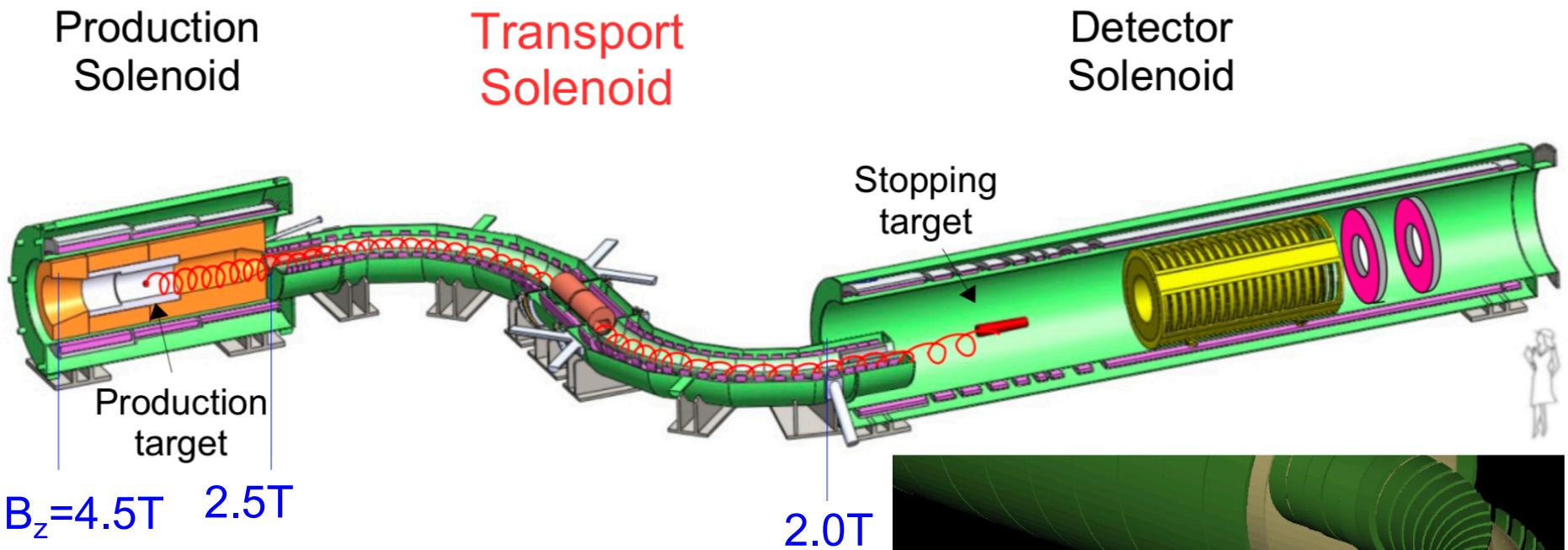
Production Solenoid



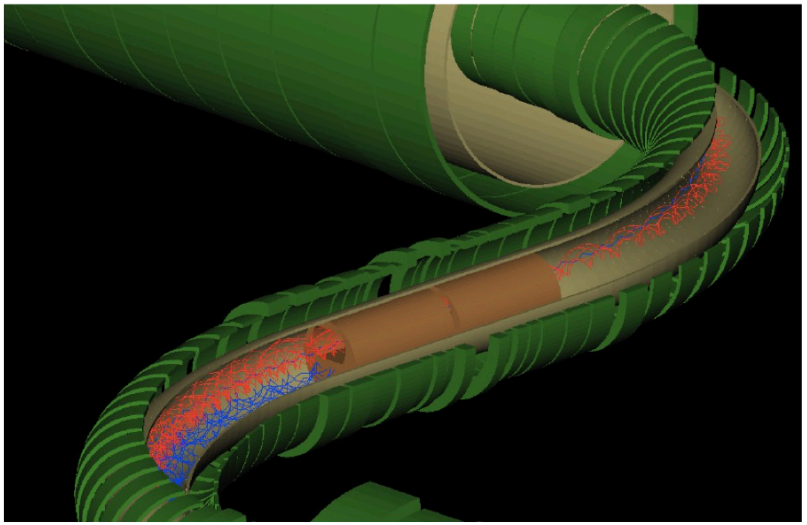


- 8 GeV protons on target to produce πs which decay into muons
- High A and high density material Tungsten to maximize muons production
- 25 tons of Bronze shield to limit the heat load and radiation damage

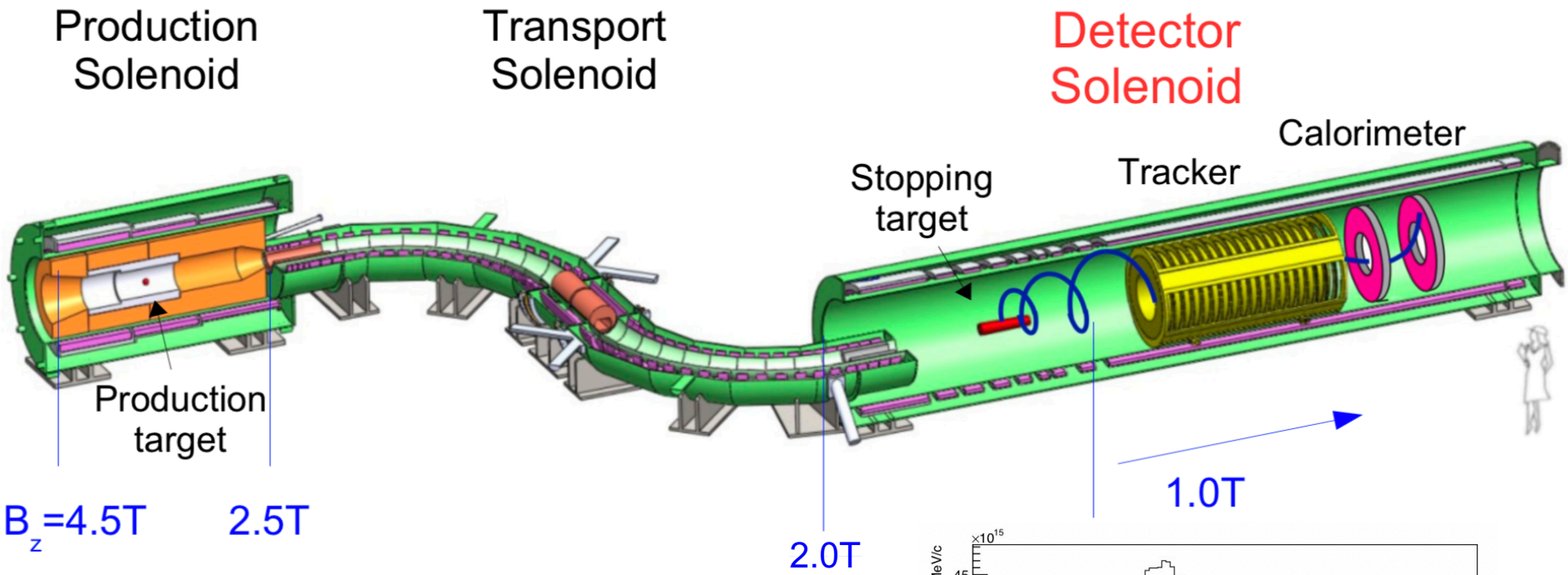
Transport Solenoid



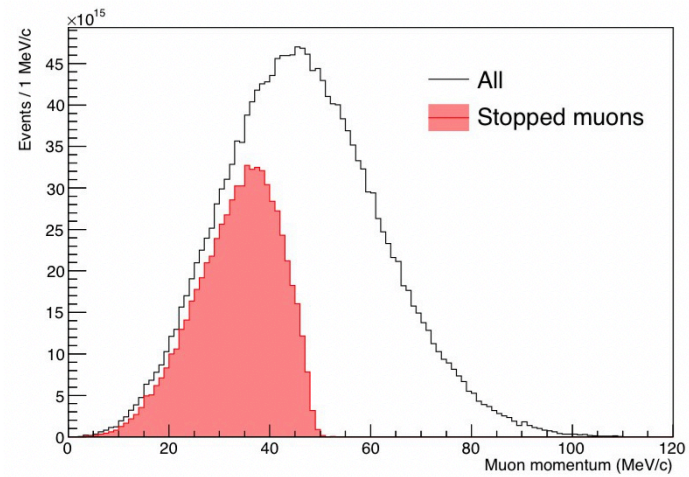
- S-shaped magnetic channel to transmit low-momentum negatively charged particles in helical trajectories
- Curvature drift and collimators select sign and momentum of muon beam, transport to stopping target
- S-shape solenoid eliminates neutral background particles



Detector Solenoid

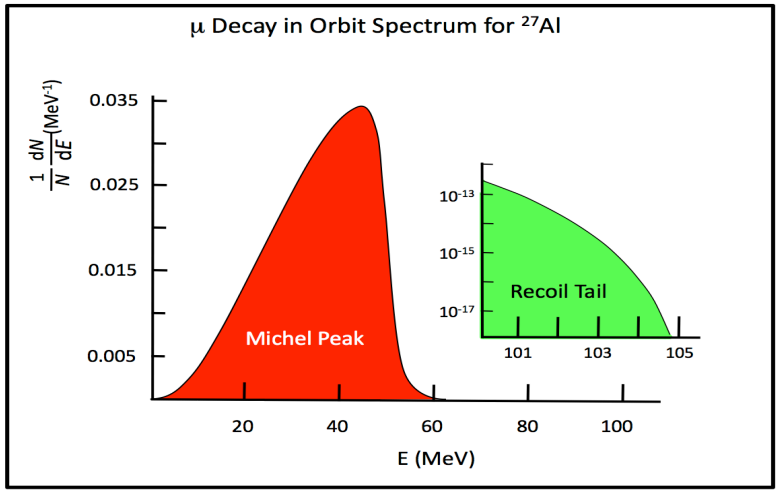


- Slow muons stopped at Al target
- 10^{10} stopped μ/s, ~10^{18} total over 3 years
- World's most intense muon beam
- Detector system must identify and reconstruct a 105 MeV conversion electron, while rejecting backgrounds from conventional processes

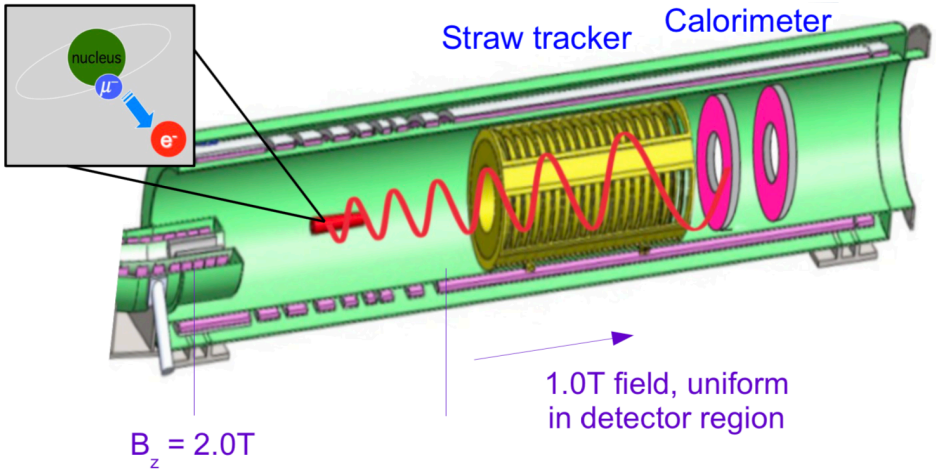


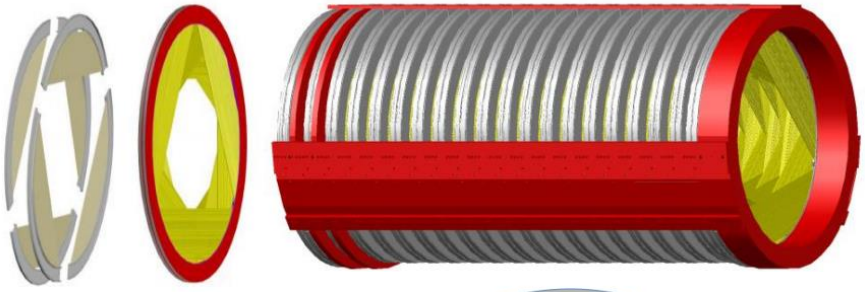
Processes at the Stopping Target

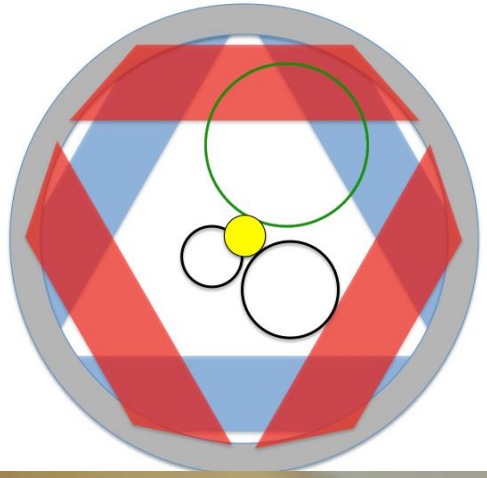
- Neutrinoless conversion of a muon to mono-energetic ~105 MeV electron expected rate < ~10^{-13}
- Muon capture in Al, $\mu + Al \rightarrow \nu_\mu + Mg$, de-excitation X-rays used for rate normalization 60%
- Decay in orbit (DIO): $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ Background process 40% occurrence



Tracker







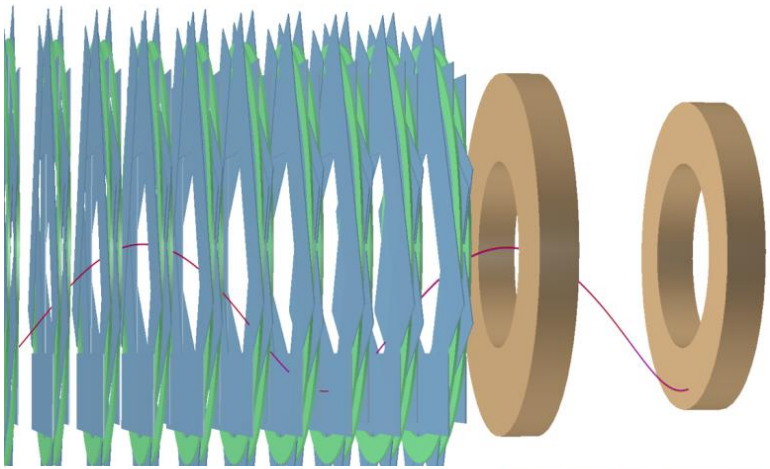
- Straw tracker: low-mass straw drift tubes, transverse to axis, main detector element, ultra low mass, minimize multiple scattering, highly segmented, handle high rates, excellent fit to tracker requirements

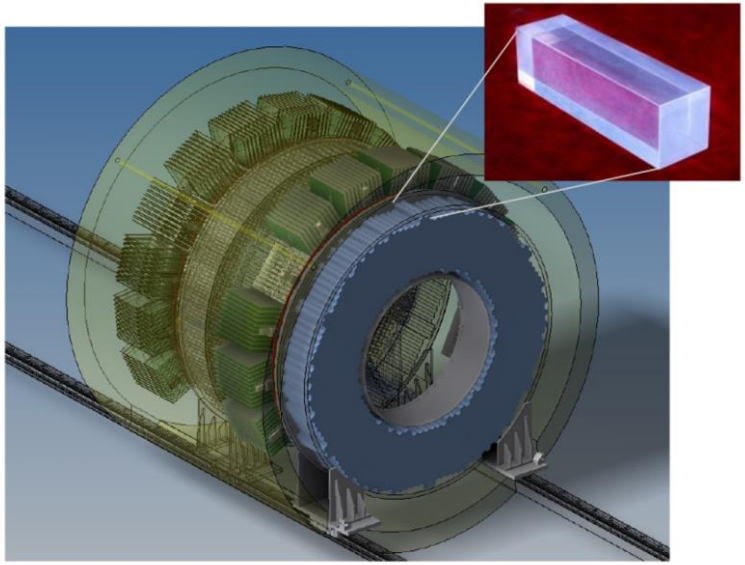
- Straw: 5mm diameter filled with 80/20 Ar/CO_2 gas
- Straw Wall: 12μm mylar + 3μm epoxy + 200Å Au + 500Å Al
- Wire: 25μm gold-plated tungsten wire at 1450V

- 18 stations, 2 planes/station, 6 panels /plane
- Blind to beam flash and >97% DIO
- Position resolution 100 μm
- High precision momentum resolution < 180 keV/c (@105MeV/c)

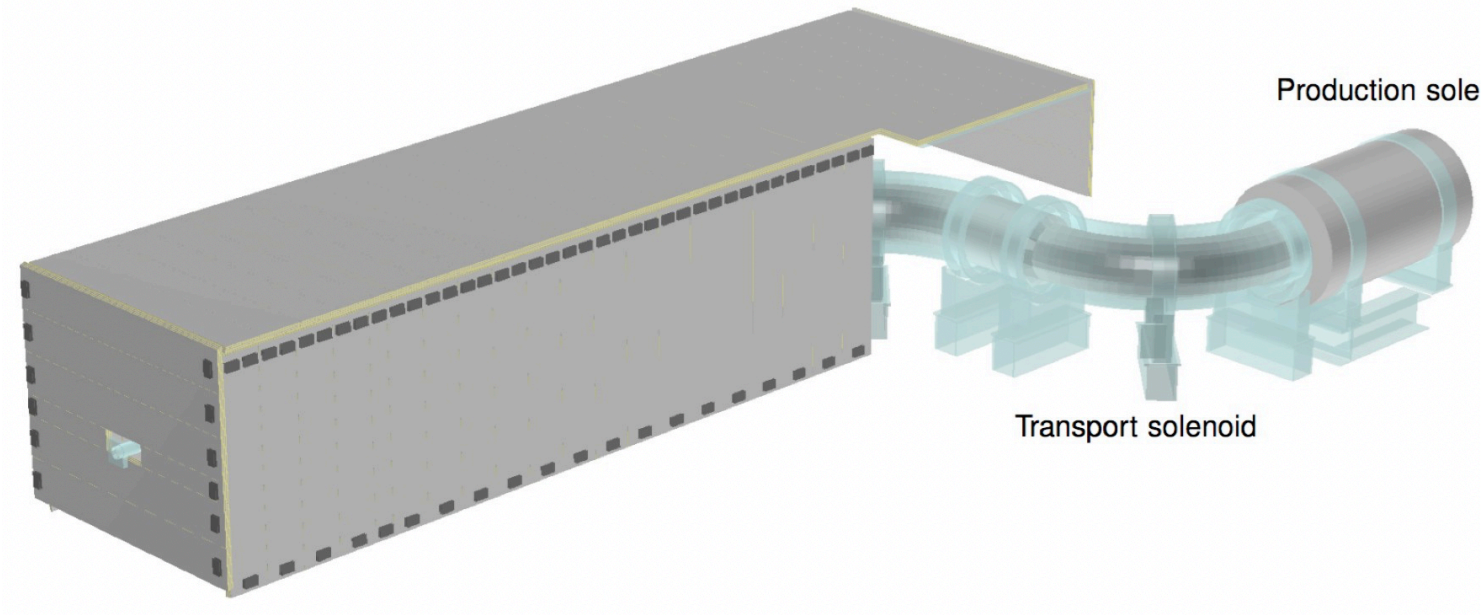
Calorimeter

- Two disks separated by 70 cm (1/2 λ) following the tracker, ~674 CsI crystals/disc
- Further reject the background by: particle ID, cosmic ray rejection, tracking seed
- Provides independent energy, time and position measurements
  - ✓ $\sigma_E/E < 5\%$
  - ✓ $\sigma_t < 0.5$ns
  - ✓ σ_{pos} ~1cm
  - ✓ Independent trigger
- Dr. Raffaella DONGHIA will talk about the Calorimeter into more details

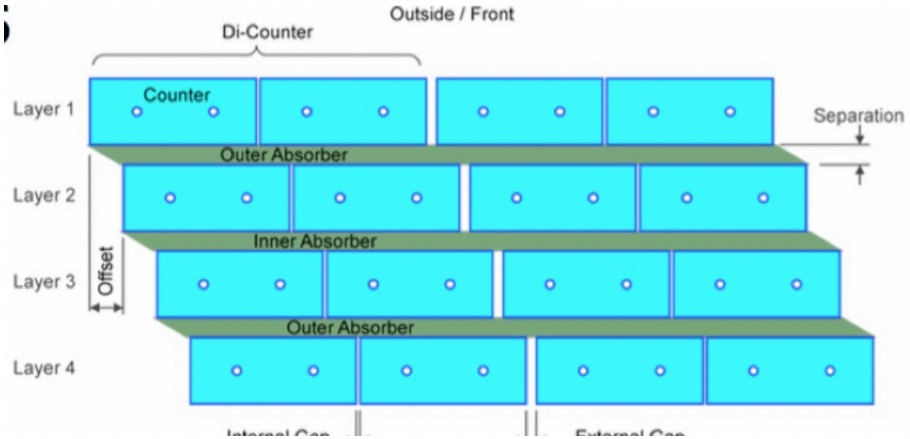




Cosmic Ray Veto (CRV)



- Covers half of transport solenoid and detector solenoid
- 4 stacked layers of scintillation counters
- 99.99% efficiency requirement
- Cosmic ray background ~1 event / day
- Requires <10^{-4} inefficiency → 0.1 event in 3 years



Backgrounds

3 years at 1.2×10^{20} protons/year (8 kW beam power)

Category	Background	Expected events
Intrinsic	Muon decay in orbit	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late arriving	Pion capture	0.023 ± 0.006
	Muon decay in flight	< 0.003
	Pion decay in flight	$0.001 \pm\ < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic rays	0.082 ± 0.018
Total		0.36 ± 0.10

Expect <0.5 background event in 3 years

Any observation will be evidence of CLFV

Mu2e II

- Next-generation Mu2e-II will be powerful even if no signal is observed in Mu2e to conduct a higher sensitivity search

- If a signal *is* observed in Mu2e. Mu2e-II will be able to do precision measurement to discriminate between new physics models

Summary

- CLFV has never been observed, any observation of a conversion electron in Mu2e will be sign of new physics which will shape future directions in physics research
- Mu2e will improve the sensitivity by 4 orders of magnitude
- Expected commissioning in 2021, Single event sensitivity $R_{\mu e} = 3 \times 10^{-17}$
- Next-generation Mu2e-II well motivated in any scenario