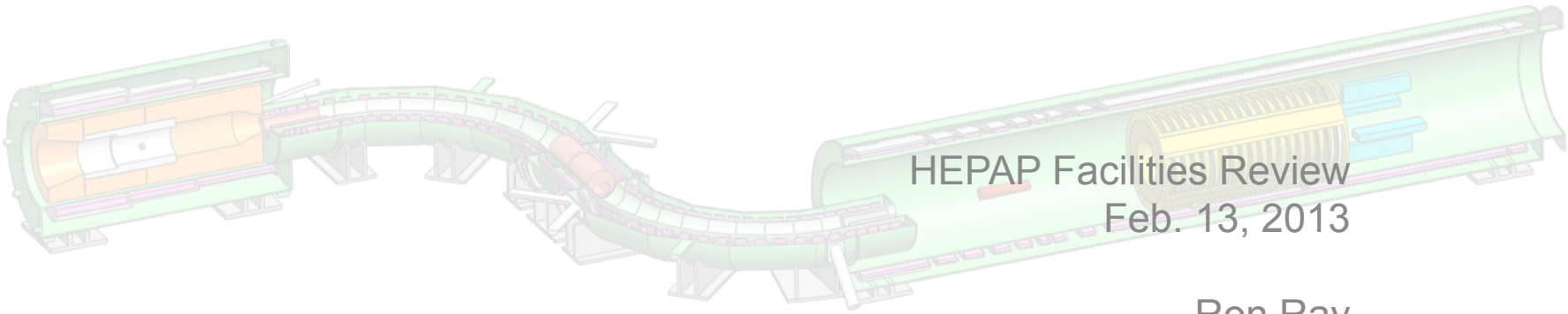
Mu2e



HEPAP Facilities Review
Feb. 13, 2013

Ron Ray
Mu2e Project Manager

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

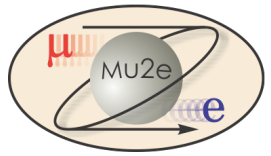
US-Japan

INFN

Introduction

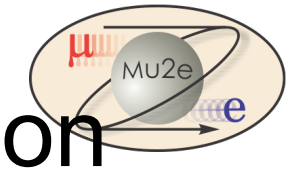
- Mu2e is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \rightarrow e^- N$
- Mu2e will repurpose the Fermilab antiproton source into an intense source of low energy muons to achieve world's best sensitivity.
- Target sensitivity has great discovery potential
  - Goal: <0.5 events background
  - Goal: Single-event-sensitivity of 2×10^{-17} (relative to ordinary μ capture)
    - Yields Discovery Sensitivity for all rates > few 10^{-16}
- Factor of 10^4 improvement over world's previous best results

Flavor Physics is Important



- In the 2008 P5 *Strategic Plan for the next 10 years*, the role played by flavor physics in developing the Standard Model was highlighted along with its importance moving forward.
  - Prediction of charm quark, CP violation, CKM model, Neutrino mass, etc.
- Most new physics models so far postulated provide new sources of flavor phenomena.
- Quark flavor is violated. Neutrino flavor is violated.
  - Both implied something profound about the underlying physics
  - Both garnered Nobel Prizes
- What about charged lepton flavor?

Charged Lepton Flavor Violation



- Significant worldwide interest from Energy and Intensity Frontiers and the theoretical community
  - Rare CLFV decays of μ, τ, K, B-mesons
- Rates negligible in νSM but wide array of new physics models predict rates that are measurable in next generation experiments.
  - Sensitive to new physics well above the TeV scale (10^3 – 10^4 TeV).
- Rates of CLFV processes are model dependent and vary widely depending on the underlying physics.
  - CLFV processes are powerful discriminators.
- The most stringent limits on CLFV come from muons because of the relative "ease" of producing an intense source.
- Muon-to-electron conversion offers excellent discovery potential across a breadth of models and will explore impressive mass scales.

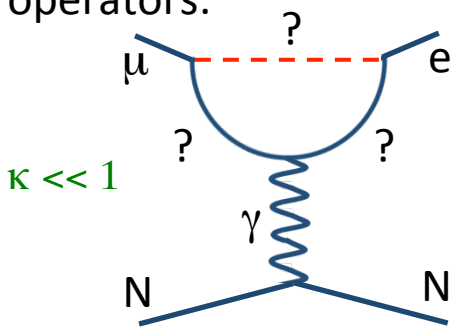
Model Independent Evaluation

Add CLFV operators to SM Lagrangian.

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

Λ is mass scale of new physics

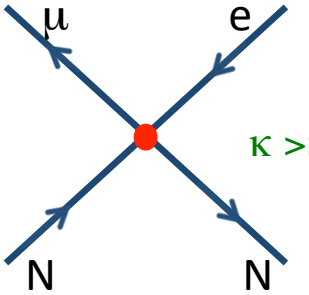
κ controls relative contribution of two classes of operators:



$\kappa << 1$

Loops

Contributes to $\mu \rightarrow e\gamma$



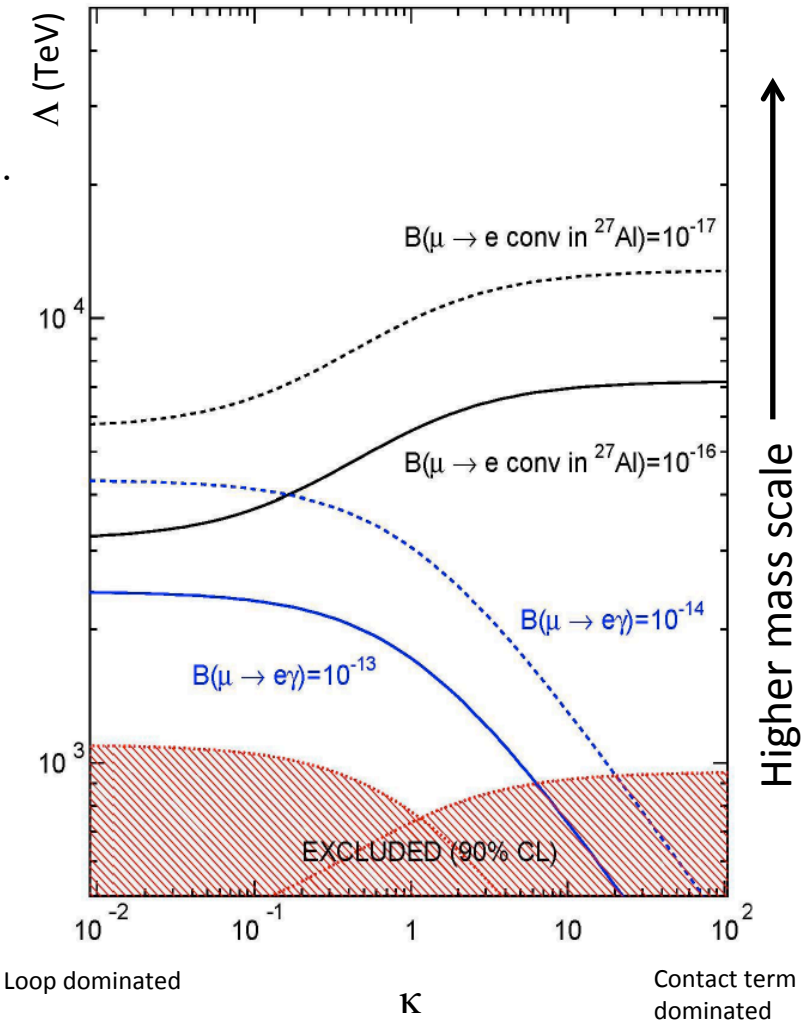
$\kappa >> 1$

Contact Terms

Does not contribute to $\mu \rightarrow e\gamma$

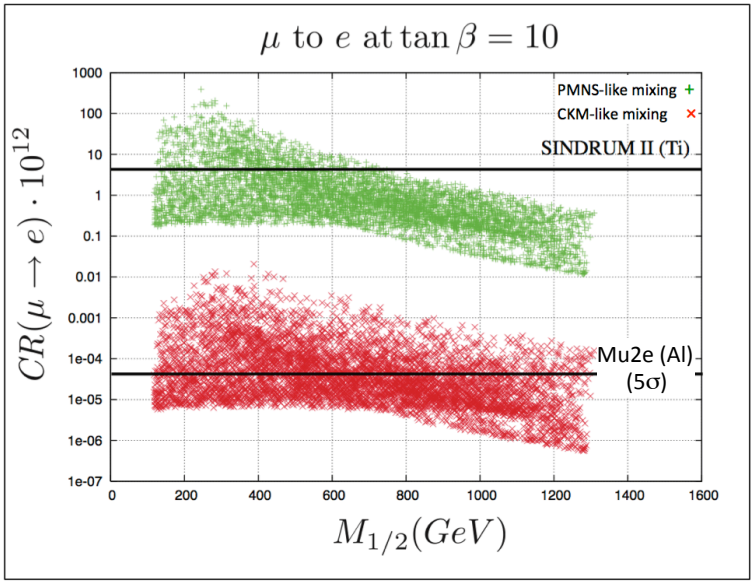
Both contribute to muon-to-electron conversion

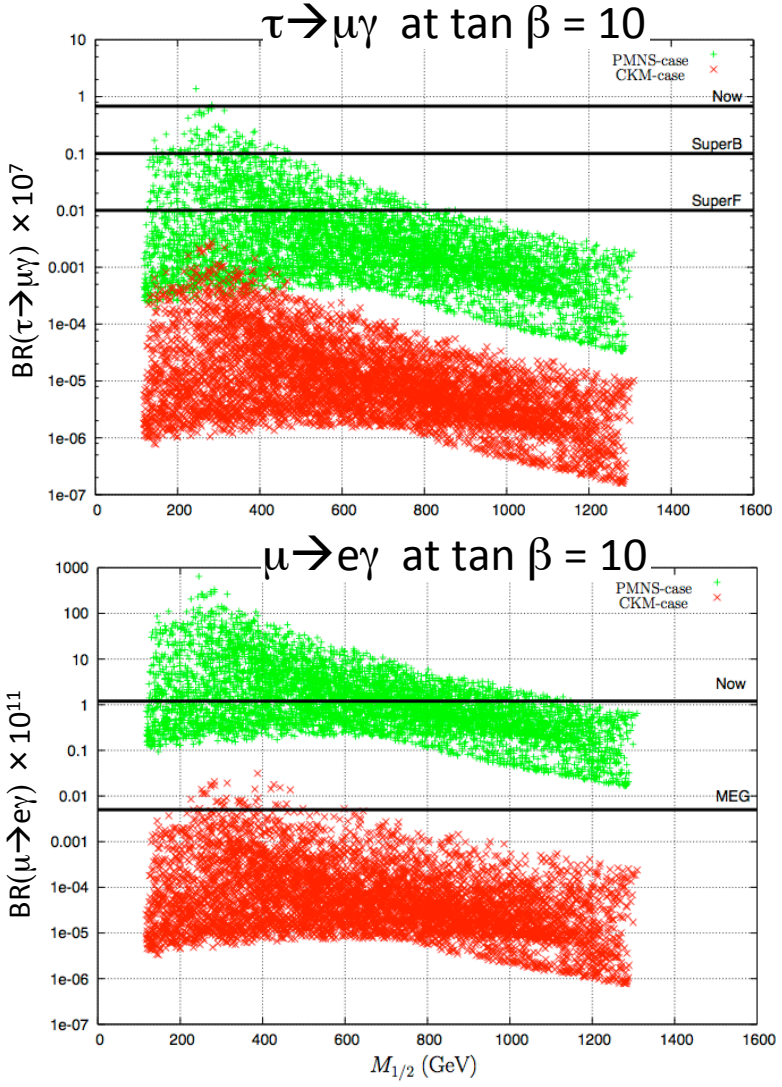
A. De Gouvea
Project X Golden Book



A Specific Model

- CLFV rates as a function of gaugino mass at the GUT scale for an SO(10) SUSY GUT model.
- Colors indicate different assumptions about neutrino Yukawa couplings.
- Muon-to-electron conversion has the greatest sensitivity.

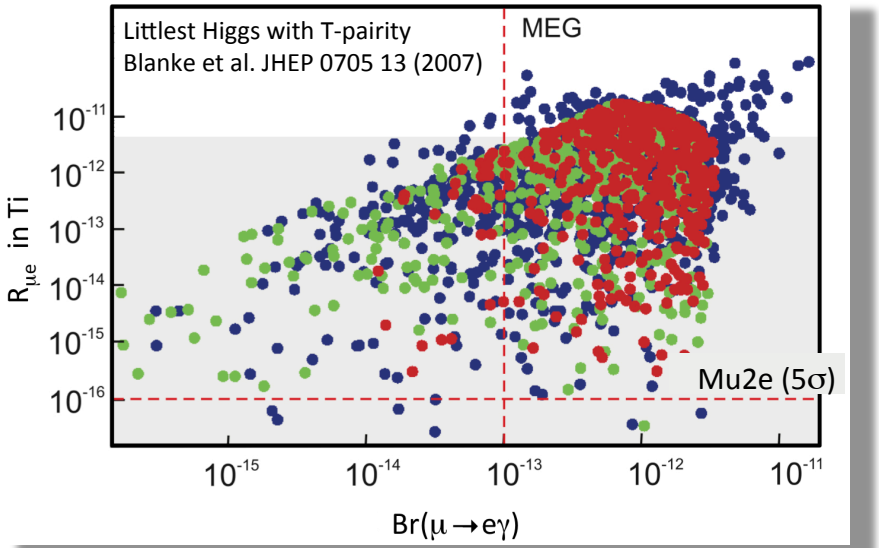




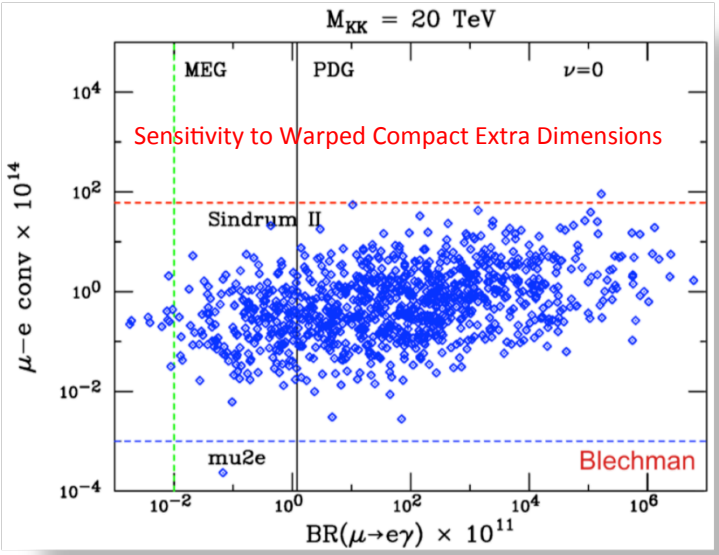
L. Calibbi et al. PRD **74** (2006) 116002

More Models

- Mu2e has sensitivity over this entire parameter space.
- Many examples illustrate the power of combined results.
- Rates and correlations of CLFV processes vary widely for different models.
- More measurements lead to greater discrimination power.

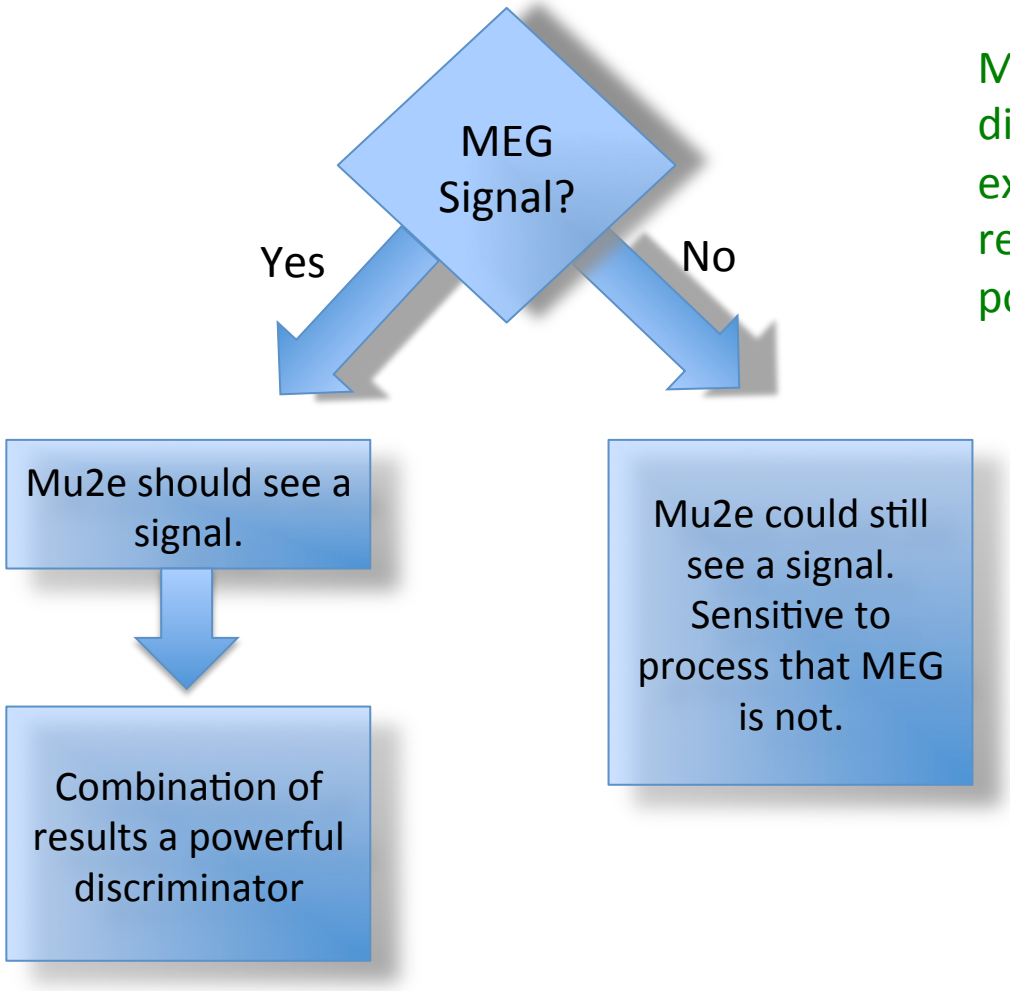


Littlest Higgs Model. The different colored points refer to different choices for the structure of the mirror-lepton mixing matrix that gives rise to the CLFV effects.



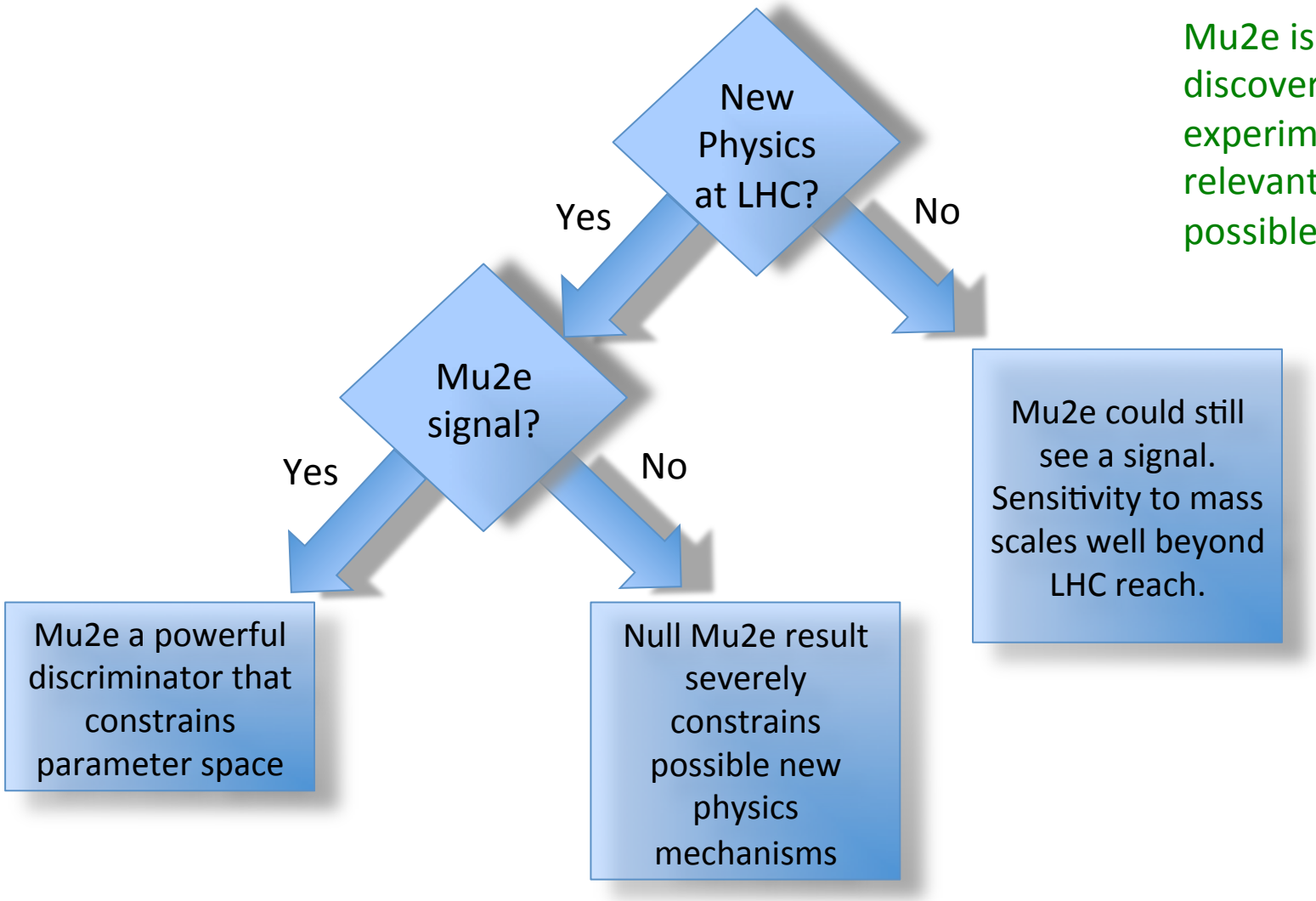
Scan of Randall-Sundrum Parameter space

Mu2e and MEG



Mu2e is a potential discovery experiment that is relevant in all possible scenarios.

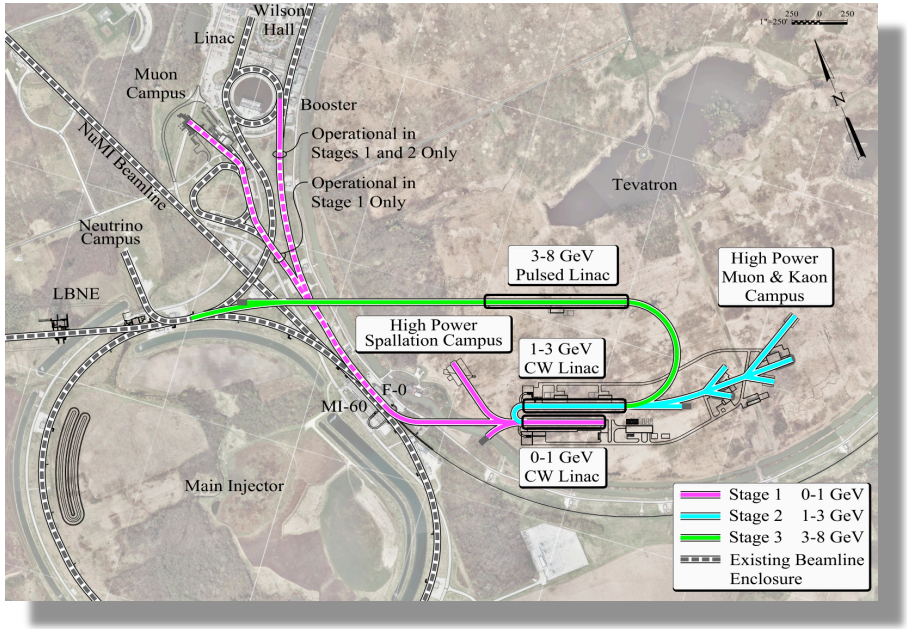
Mu2e and the LHC



Mu2e is a potential discovery experiment that is relevant in all possible scenarios.

Solidifying the Intensity Frontier with Project X

- Mu2e uses 8 kW proton beam from Booster
- First stage of Project X could provide up to x10 more beam power.
  - Narrower proton pulses
  - No pbar background
  - Flexible beam structure
  - Requires some modest upgrades to Mu2e apparatus to handle higher beam power.
  - Important physics goals regardless of results from first phase of Mu2e.
    - Flexible time structure of Project X beam allows access to different stopping target nuclei where model dependent effects vary by factor of 2.
    - Investigating possibility of $\mu \rightarrow eee$ for Snowmass



- Later stage of Project X could provide ~ 100X the beam power
  - Significant redesign of Mu2e apparatus required to handle increased beam power.

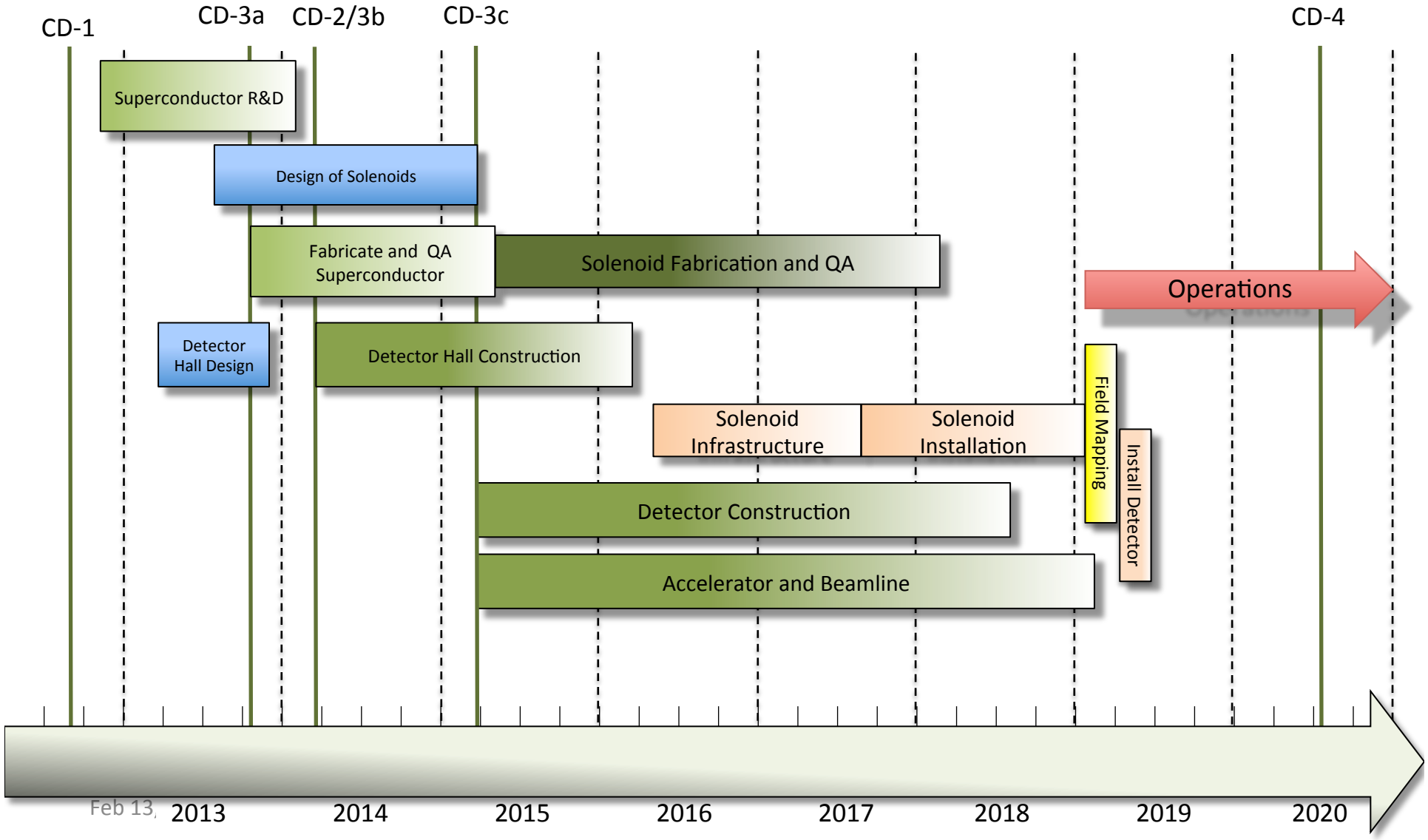
Mu2e - Absolutely Central

- Mu2e is *absolutely central* to the goals of HEP in the US over the next decade.
- Provides broad discovery potential, excellent reach and access to highest mass scales.
  - Real chance to see new physics, not just set a better limit.
- Complementary with other Energy and Intensity Frontier programs. Adds significant value to existing international program.
- A Critical step that helps to establish a world class Intensity Frontier Program in the US in this decade.
- Second phase of Mu2e is a "day 1" experiment for first stage of Project X.

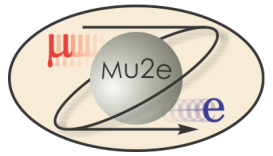
Mu2e - Ready to Construct

- Mu2e – Ready to construct.
- Mu2e will *initiate construction* in 2014.
  - Procure production conductor for solenoids
  - Break ground for detector hall
- No development of new technologies required.
  - R&D now focused on validation of construction techniques.
  - Solenoids are complicated but rely on conventional technology.
  - Detector components are familiar technologies.
  - Accelerator work similar to other upgrades.
- By FY15 all detector systems will have constructed and tested pre-production prototypes. All systems will have passed construction readiness reviews and be ready for construction.

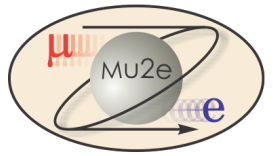
Schedule (CY)


CD-1
CD-3a
CD-2/3b
CD-3c
CD-4
Superconductor R&D
Design of Solenoids
Fabricate and QA Superconductor
Solenoid Fabrication and QA
Operations
Detector Hall Design
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation
Field Mapping
Install Detector
Detector Construction
Accelerator and Beamline
2013
2014
2015
2016
2017
2018
2019
2020

Summary



- Mu2e has discovery sensitivity over a wide array of physics models and probes the underlying physics in ways that are complementary to the Energy, Cosmic and remaining Intensity Frontier program.
- Second phase of Mu2e is a “day 1” experiment for first stage of Project X.
- Mu2e is *absolutely central* to the goals of particle physics in the US over the next decade.
  - Consistent with P5 evaluation.
- Mu2e will *initiate construction* in FY14.



Backup Slides

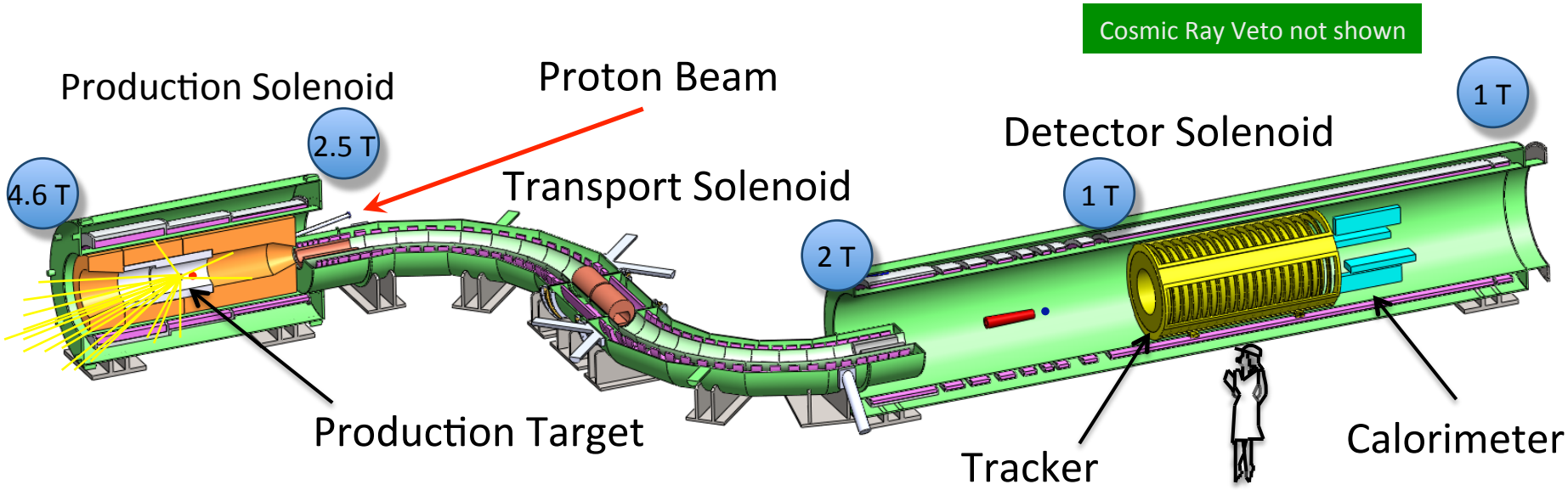
Mu2e Apparatus

Production Solenoid
- Production target
- Graded field

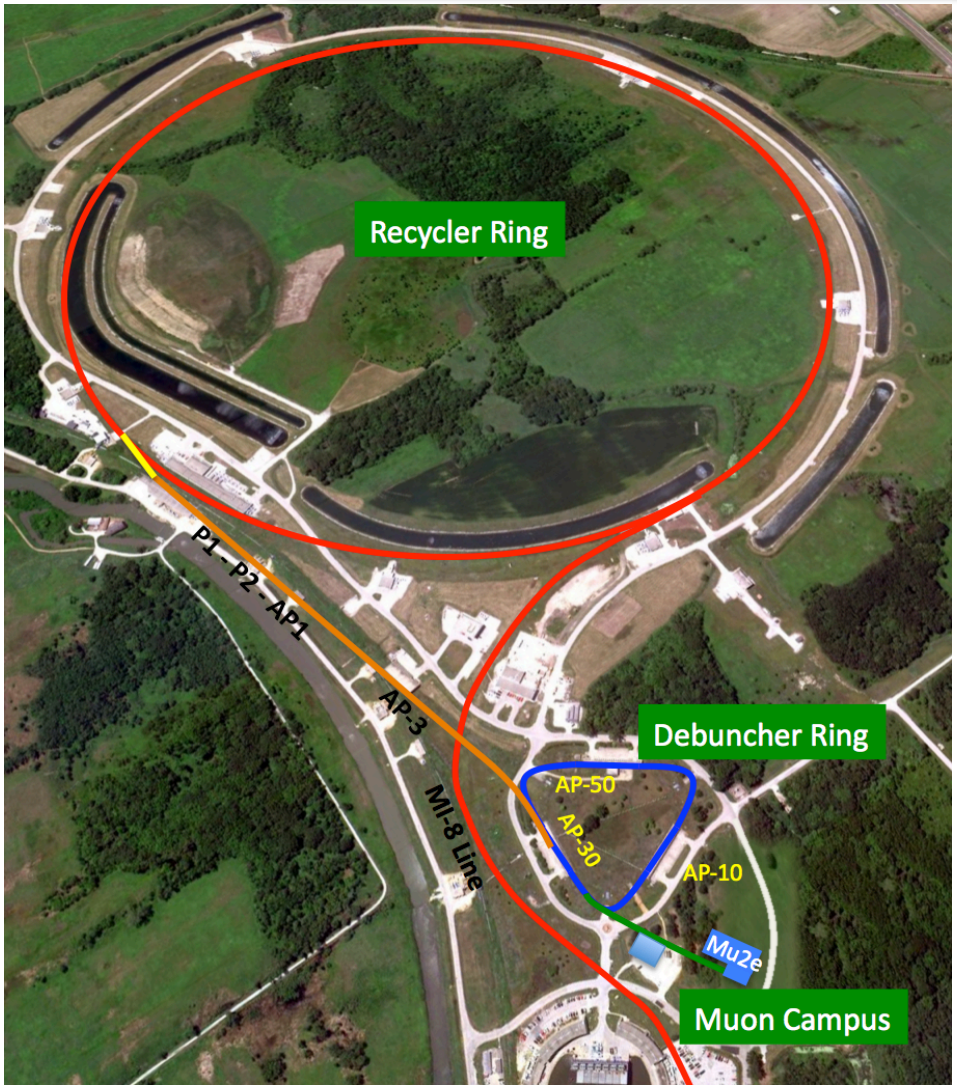
Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

- Delivers ~ 0.0016 stopped μ^- per incident proton
- 10^{10} Hz of stopped muons

Detector Solenoid
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr



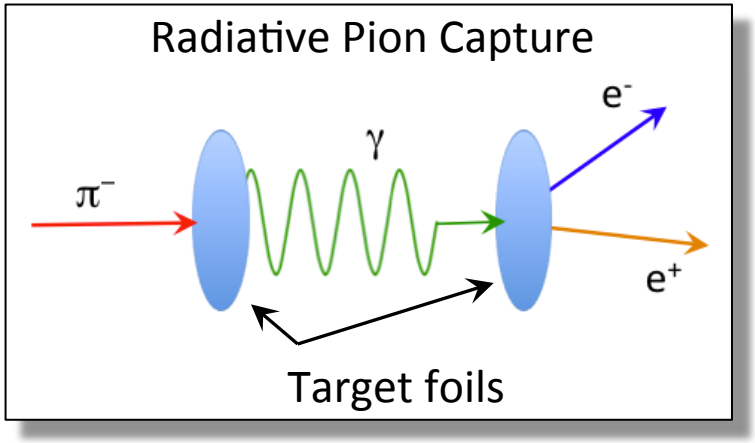
Beam Delivery

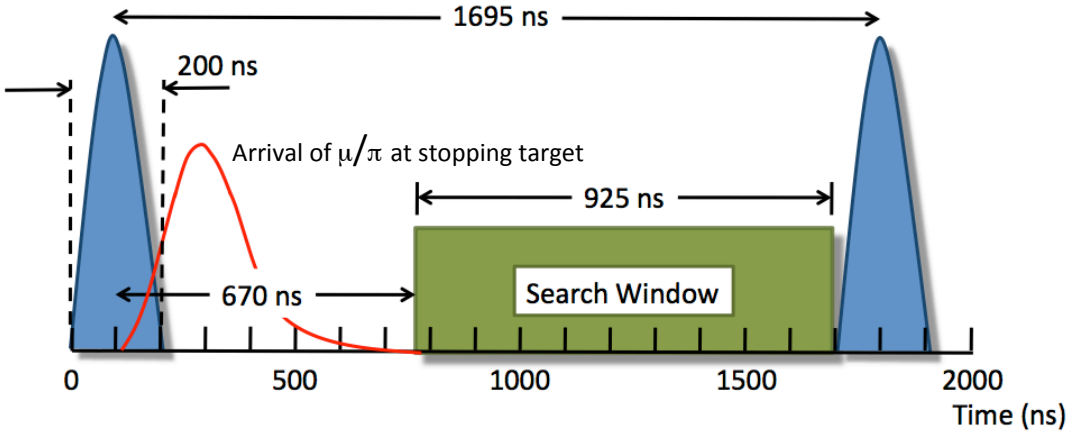


- We make muons by slamming 8 GeV protons into a target.
- Batches of protons from the Booster are transported through existing beamlines to the Recycler Ring where they are re-bunched and transported to the Delivery Ring through existing transport lines.
- Beam is slow extracted from Delivery Ring in microbunches of ~ 10^7 protons every 1695 ns through a new external beamline to the Mu2e production target.
- Run simultaneously with NOvA
- We are repurposing the pbar facilities to make muons.

Beam Structure

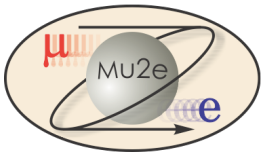
Prompt background:
Processes where the detected background electron is nearly coincident in time with the arrival of a beam particle at the muon stopping target.





Pulsed beam combined with extinction of beam between pulses and delayed search window reduces prompt backgrounds like Radiative Pion Capture.

Thesis Topics



- In Conventional HEP/Nuclear Physics:
  - Mu2e Conversion with different reconstruction techniques
  - $\mu^- N(A,Z) \rightarrow e^+ N(A,Z-2)$ ($\Delta L=2$ process)
  - Precision measurement of muon Decay in Orbit spectrum
  - Mu2e Normalization mode (nuclear capture)
  - Radiative pion capture spectrum
  - Radiative muon capture spectrum
  - Beam related backgrounds
    - Electrons
    - Antiprotons
  - Calibration Measurements
    - $\pi^+ \rightarrow e^+ \nu$ (monoenergetic line)
    - Spallation muons
    - Michel edge
- Detector Development
  - Good at foreign institutions

Thesis Topics

- In Accelerator PhD Program:
  - Extinction Method
  - Extinction Measurement
  - Slow Extraction
- Mu2e @ Project X
  - All measurements with higher sensitivity and different target nuclei
    - Flexible time structure of Project X beam allows access to different stopping target nuclei where model dependent effects vary by factor of 2.
  - Investigating possibility of $\mu \rightarrow eee$ for Snowmass

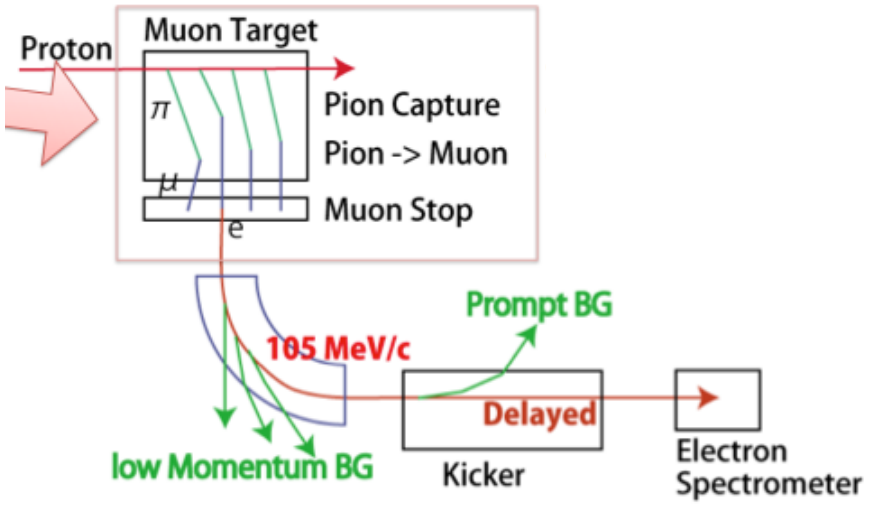
World Competition

Significant interest in this physics on 3 continents

- PSI
  - MEG upgrade recently approved.
    - Estimated Sensitivity of 6×10^{-14} (90% C.L.)
    - Comparable to Mu2e for loop physics but no sensitivity to other sources
    - Resume data taking in 2016.
  - $\mu^+ \rightarrow e^+e^+e^-$
    - Proposal recently approved.
    - Broader reach than $\mu \rightarrow e\gamma$ but does not access the mass scales available to Mu2e.
    - Data possibly available by the end of the decade. Competes with MEG.
  - PSI program and Mu2e are complementary. Combination with Mu2e is a powerful discriminator.

World Competition

- J-PARC
  - DeeMe – Muon Conversion
    - Look for muon conversion directly from production target
    - Fast and cheap way to get to sensitivity of 10^{-14}
    - Requires extraordinary extinction ~ 10^{-17}
    - Backgrounds still under study
    - Still in design phase.
    - Physics result in 5 year, before Mu2e or COMET.



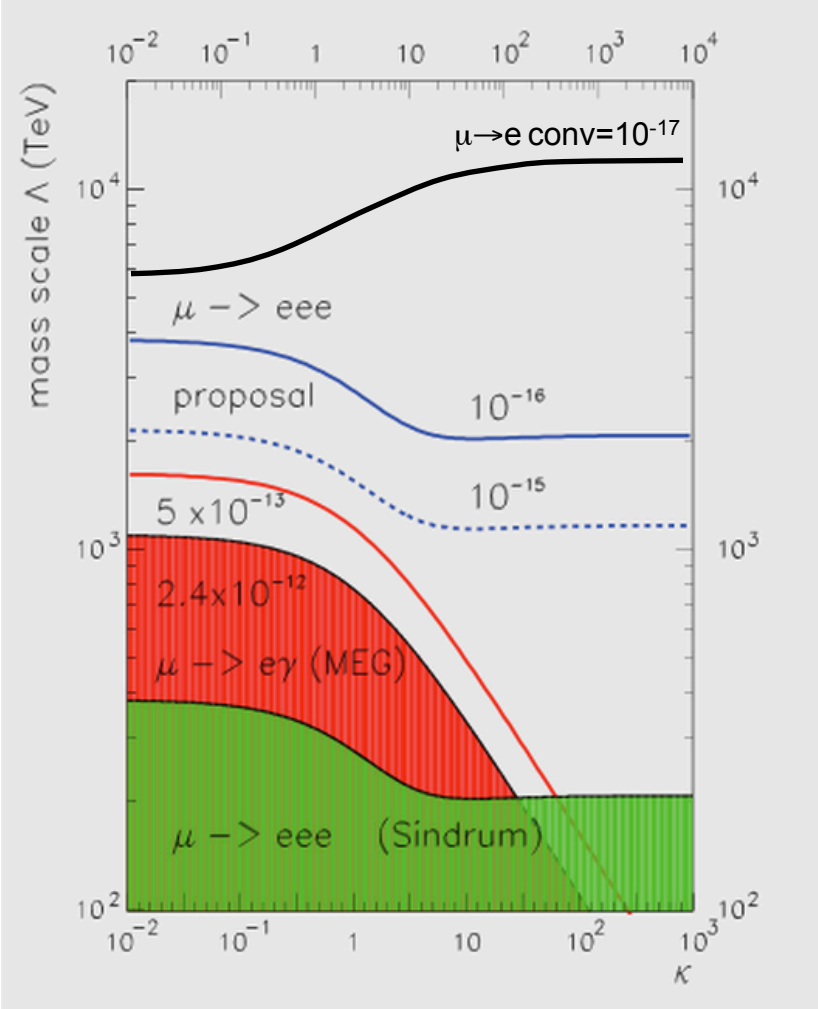
World Competition

- COMET
  - Recently broken into 2 phases.
  - Phase II reaches similar sensitivity to Mu2e
  - Advertised schedules similar.

	SES	Background	Year
COMET Phase-I	3×10^{-15}	0.03	~2016
COMET PHASE-II	3×10^{-17}	0.4	~2019
Mu2e	2×10^{-17}	0.5	~2019

- Competition is indicative of compelling physics
- Confirmation of significant results by competing experiments generally considered important in our field.

μ→eee


mass scale Λ (TeV)
μ→e conv=10-17
μ −> eee
proposal
10−16
10−15
5 x10−13
2.4x10−12
μ −> eγ (MEG)
μ −> eee (Sindrum)
κ