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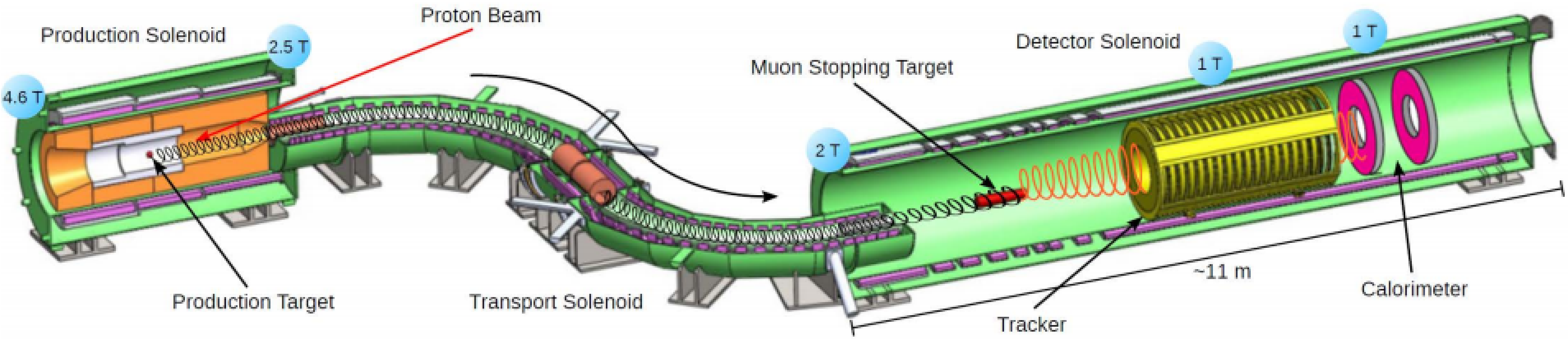

The Mu2e Experiment: A Search for Charged Lepton Flavor Violation

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Lake Louise Winter Institute 2019

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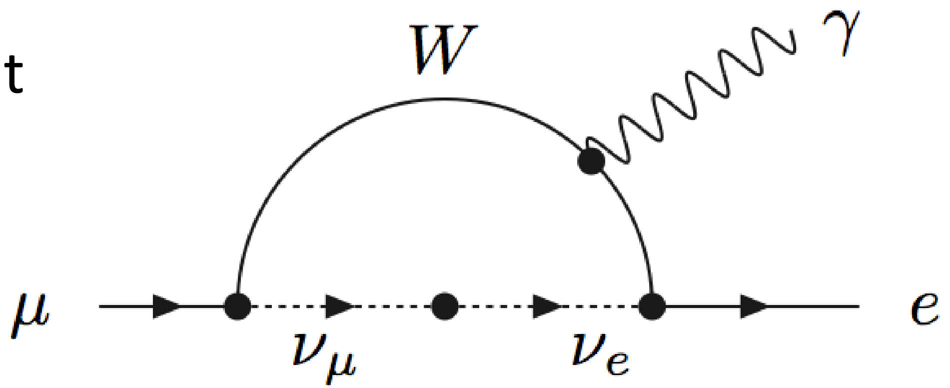
Charged Lepton Flavor Violation (CLFV)

With neutrino mass, we know that lepton flavor is not conserved.
The SM CLFV process would be :

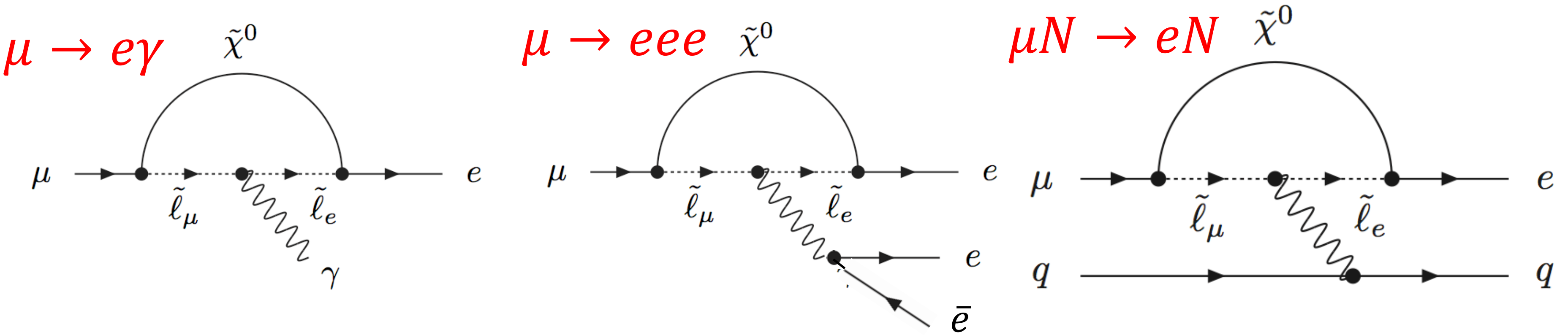


$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

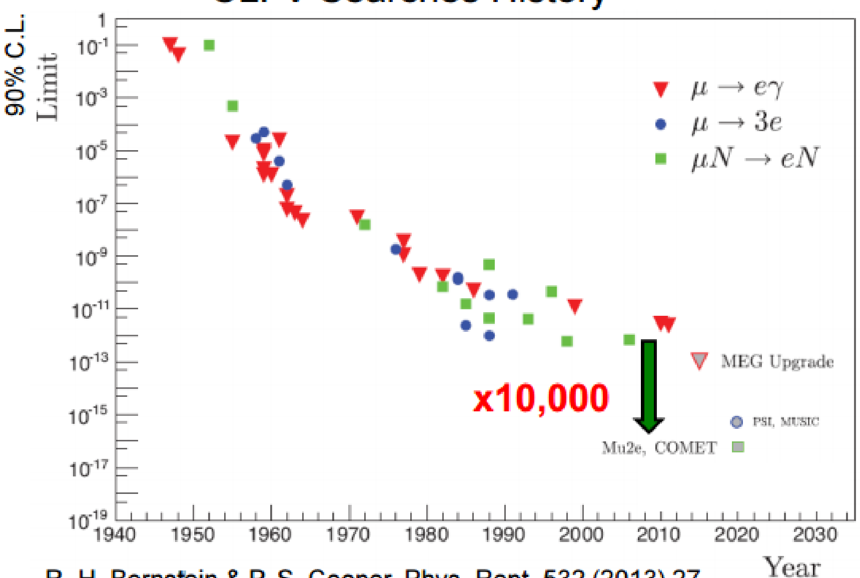
*Physically unobservable

Any observation of CLFV must be new physics!

Searching for CLFV



CLFV Searches History



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

Currents experimental limits:

MEG: $\mathcal{B}(\mu \to e\gamma) < 5.7\times10^{-13}$ [1]

SINDRUM-I: $\mathcal{B}(\mu \to 3e) < 1\times10^{-12}$ [2]

SINDRUM-II: $R_{\mu e}(\mu N \to eN \text{ on } Au) < 7\times10^{-13}$ [3]

Mu2e will increase precision by an incredible 4 orders of magnitude.

Mu2e's single event sensitivity will be $2.5\text{x}10^{-17}$, sensitive to many BSM models and probing mass scales between 2000 and 7000 TeV.

[1]PRL **110**, 201801 (2013)
[2]Nucl. Phys., B **299**, 1 (1988)
[3]EPJ C **47**, 337 (2006)

Mu2e's Concept

- Use Fermilab's proton beam to create a beam of low momentum muons
- Stop the muons in an Aluminum target (10^{18} over 3 yrs)
- Detectors which look for mono-energetic electrons consistent with $\mu N \rightarrow eN$ and differentiate background
- We measure :

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

Numerator:

Muon to electron conversion in the presence of a nucleus

Denominator:

Nuclear captures of muonic Al atoms

Creating and Decaying Muonic Atom

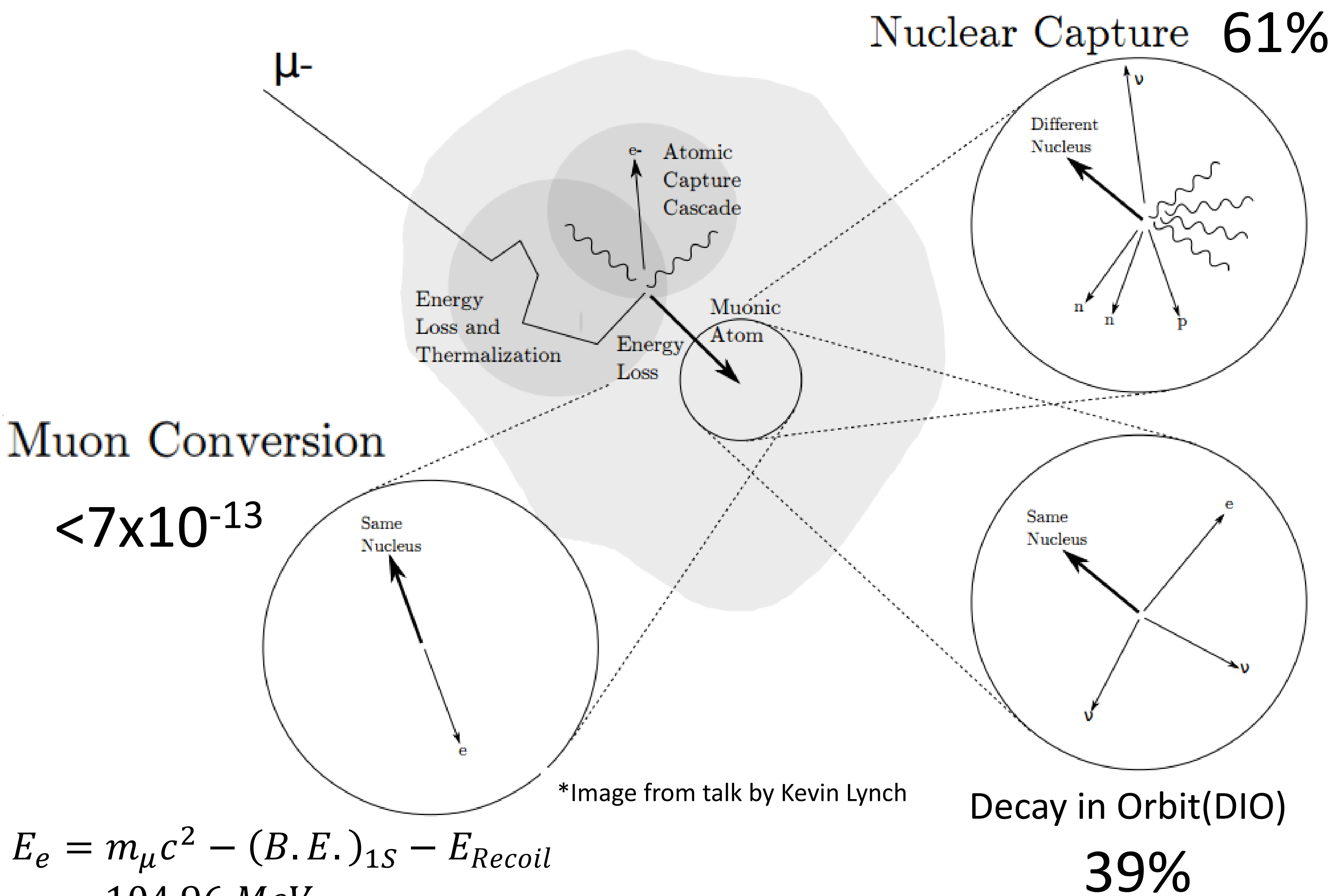
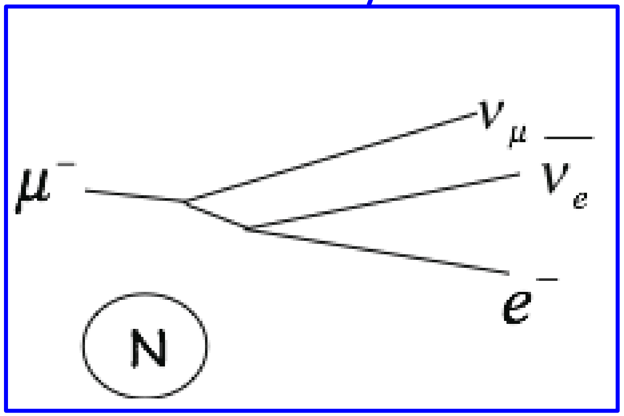


*Image from talk by Kevin Lynch

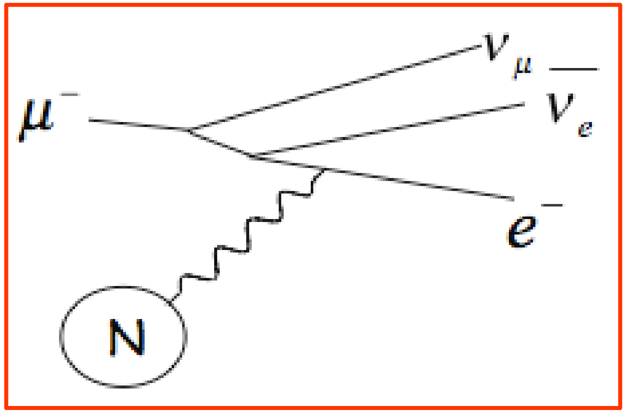
$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{Recoil}$$
$$= 104.96\ MeV$$

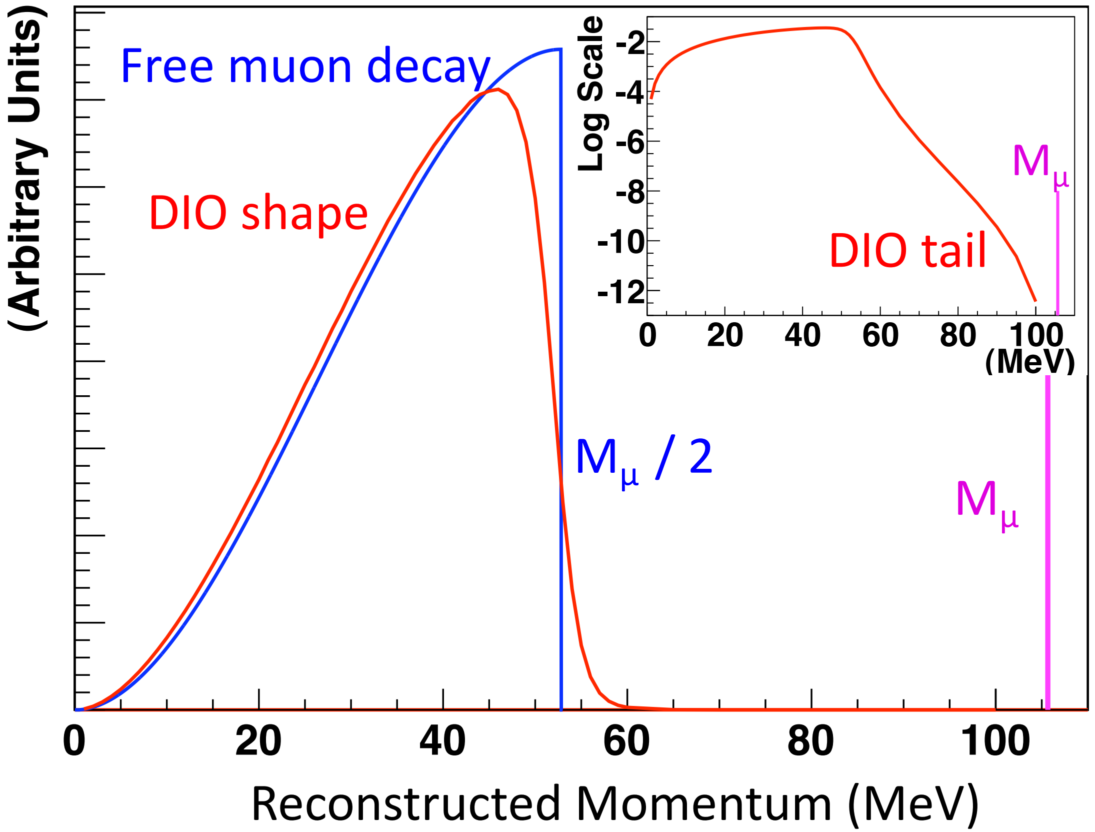
Comparing DIO to conversion electrons

Free muon decay



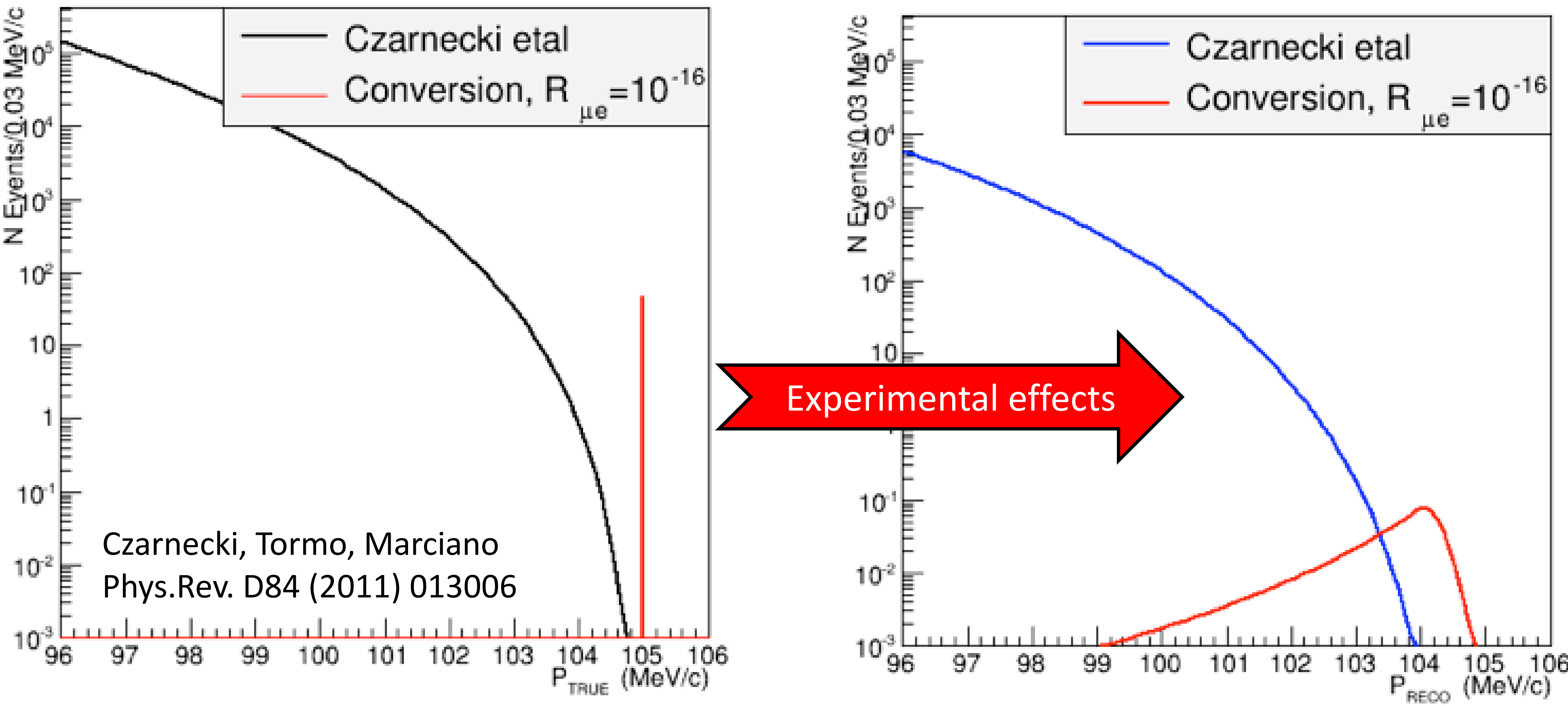
Nucleus affected DIO shape



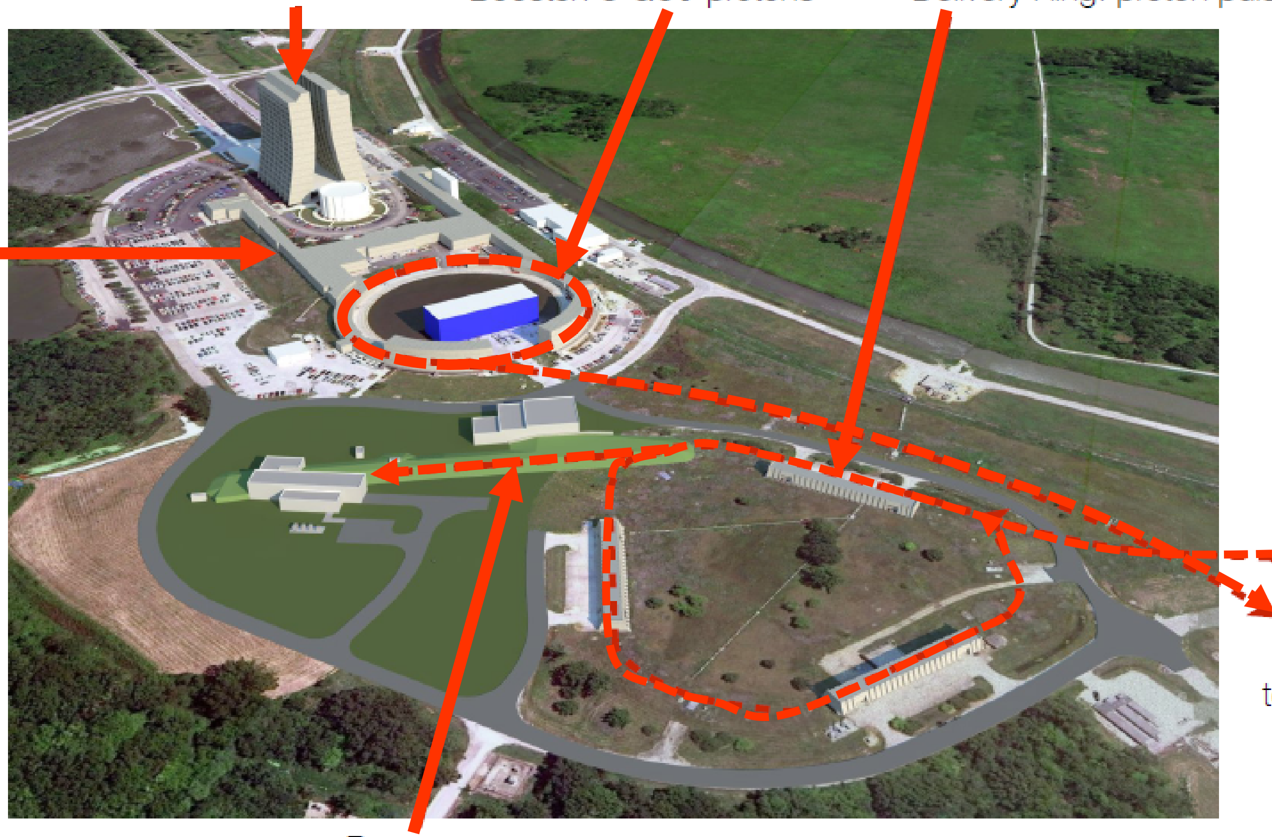


Experimental effects on DIO to conversion electrons

- Tail of DIO falls as $(E_{Endpoint} – E_e)^5$
- A window of a few hundred keV, where Signal >> DIO for $R_{\mu e} = 10^{-16}$

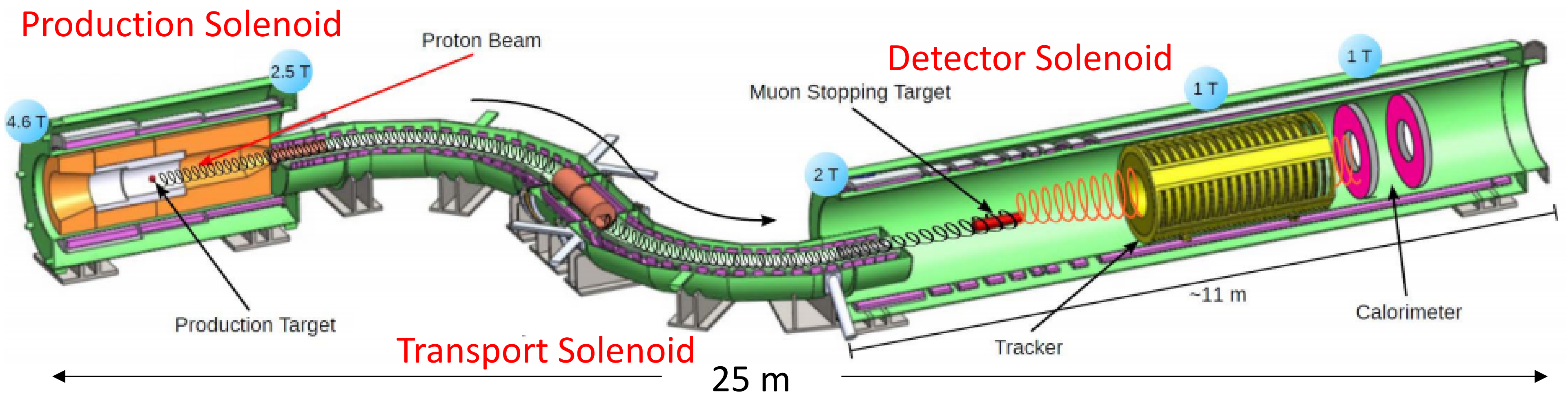


Fermilab Facility : The Proton's Path



3.6×10^{20} total protons on target
3.1×10^{7} protons per bunch
Sharing the beam with NOvA

The Mu2e Experiment



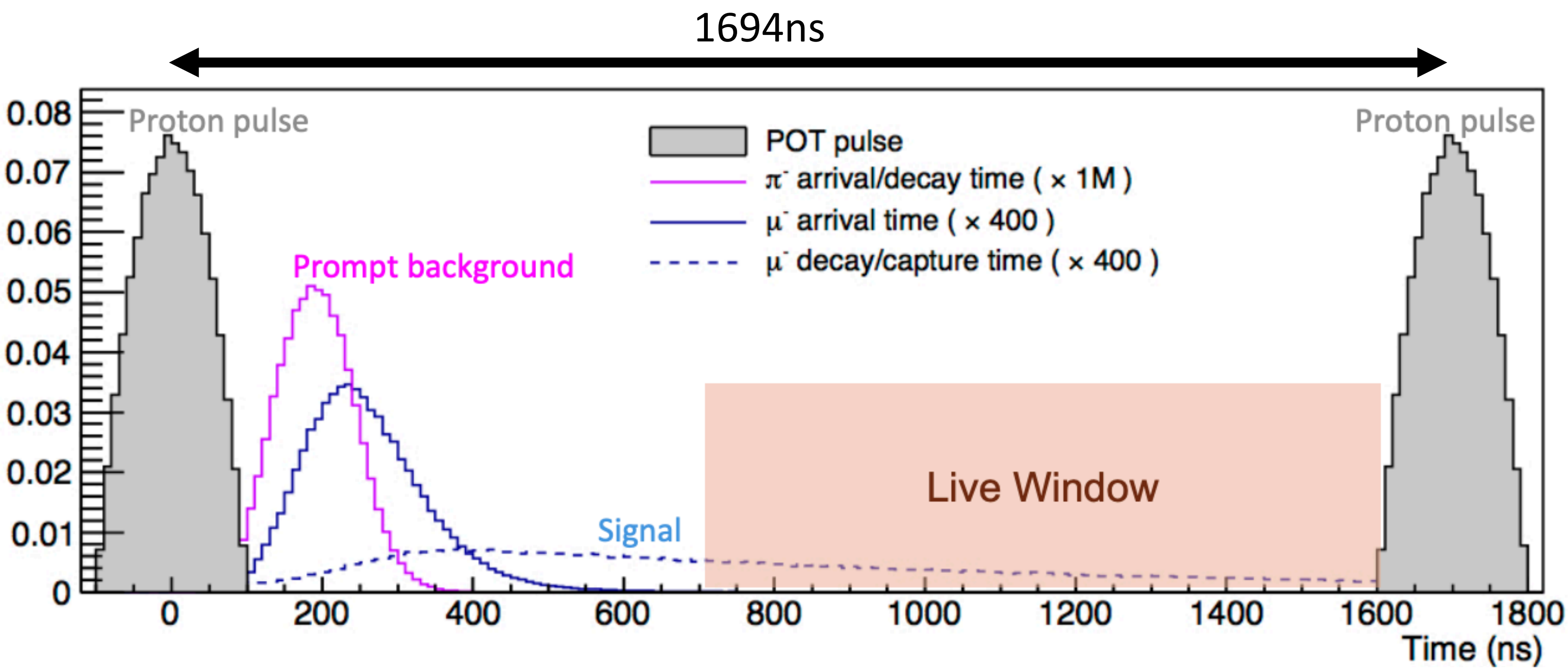
Mu2e's significant improvement over past experiments relies on its high intensity pulsed muon beam.

3 main components: Production Solenoid (PS), Transport Solenoid (TS), and Detector Solenoid (DS)
Experimental setup contained within vacuum space
Gradient magnetic field (4.6 T → 1 T) moves charged particles downstream
Step 1:
- 8 GeV proton beam hits tungsten target and produces Pions in PS
- Pions decaying into muons are pushed downstream towards TS

Step 2:
- TS selects particles based on charge and momentum
- TS collimators eliminate backgrounds

Step 3:
- Muons are captured in Aluminum target foils
- Conversion electron trajectories measured and validated in tracker and calorimeter

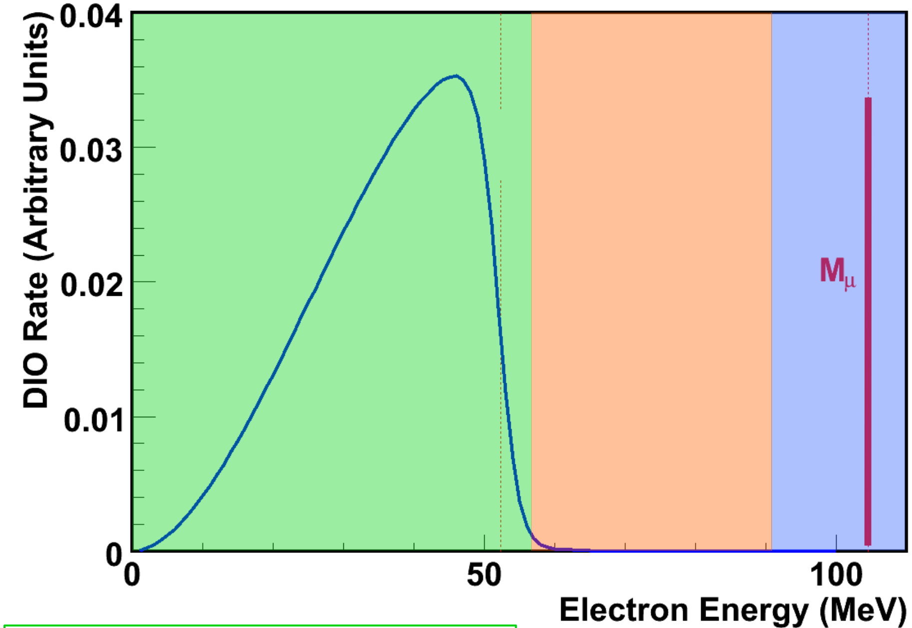
Beam Time



- ~20,000 muons per bunch
- 10^{10} muons per second

Almost all protons, unstopped muons, stopped and unstopped pions will have passed through the detector before observation window.

Annular Detector Geometry

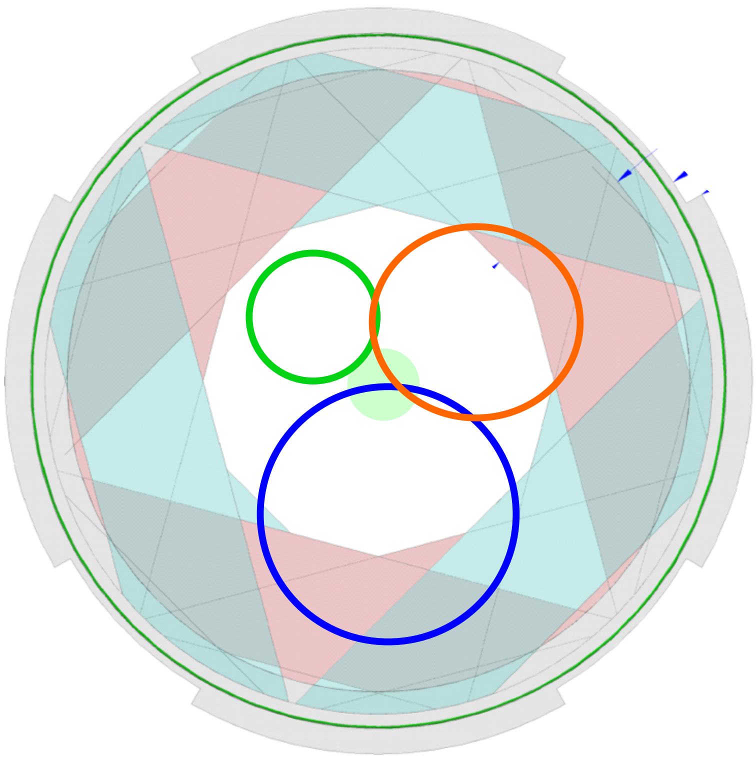


No hits in detector

Some hits in detector.
Tracks not reconstructable.

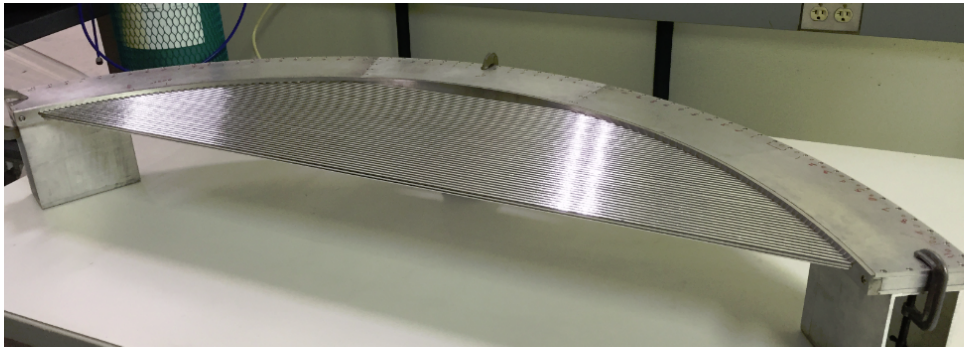
Reconstructable tracks
Momentum resolution σ < 180 keV/c

$$p = qBr$$

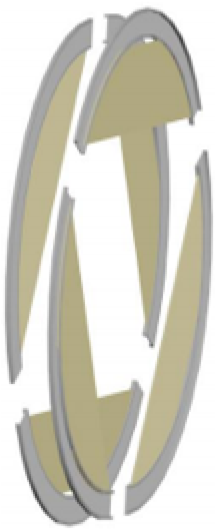


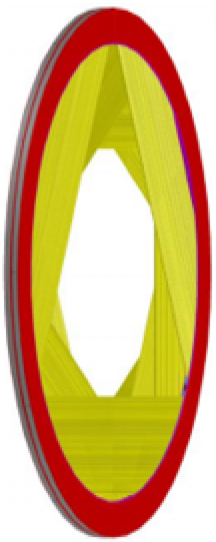
Beam's-eye view of Tracker

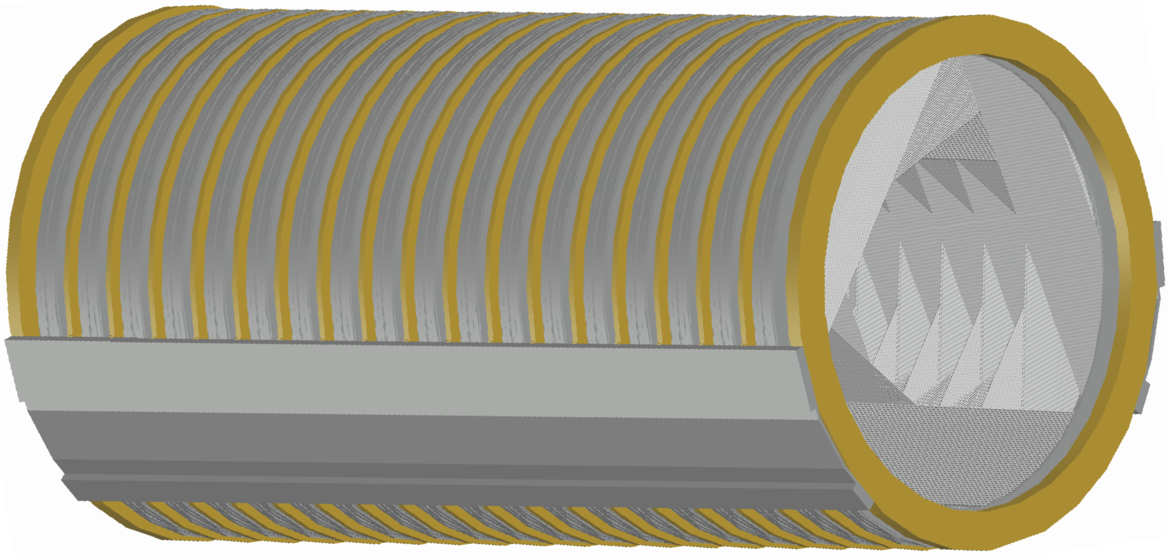
Low Mass Tracker Design



- Excellent momentum resolution better than 180 KeV/c
- 15 micron thick Mylar straws provide for a very low mass detector

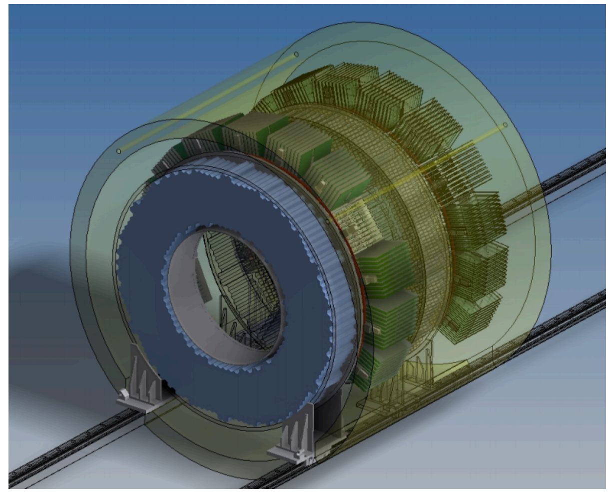


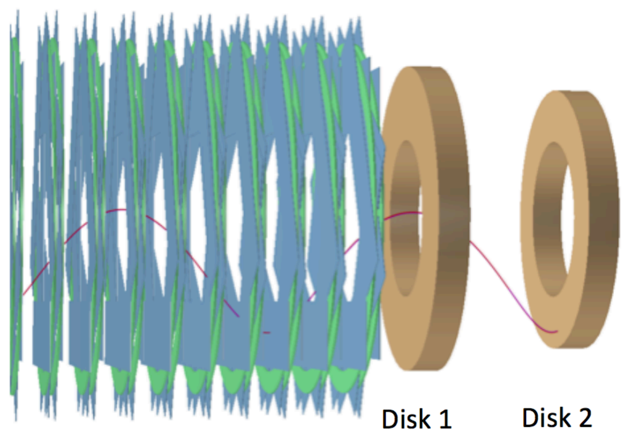




Calorimeter

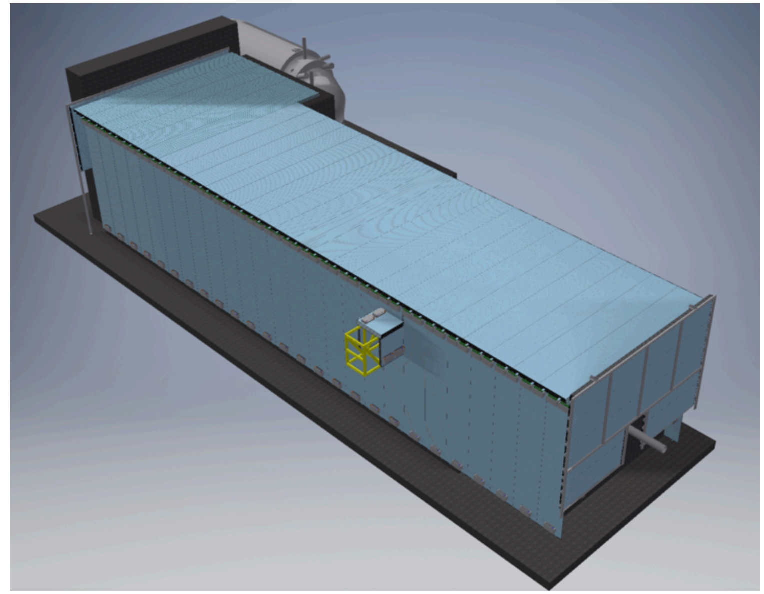
- Provides precise timing, PID, seed for tracking and triggering
- Will employ 2 disks (radius = 37-66 cm)
- ~1400 CsI crystals with square cross-section – ~3 cm diameter, ~20 cm long (10 X0)
- Calorimeter properties have been measured in beam tests

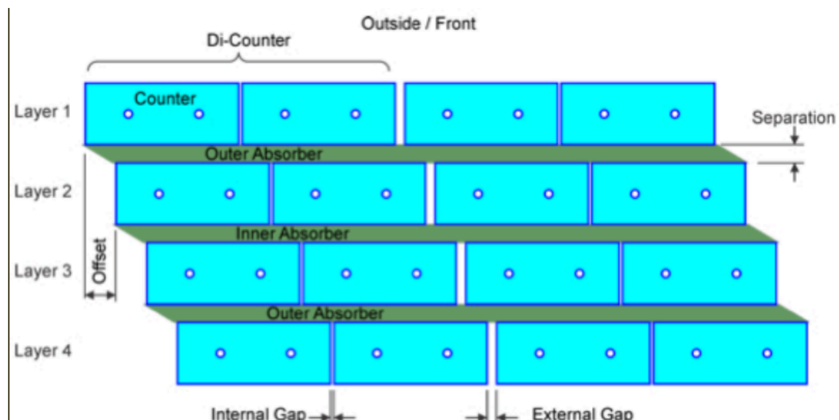




Cosmic Ray Veto (CRV)

- The CRV covers all of DS and half of TS
- Without CRV, expect ~1 cosmic-ray-induced background event per day (99.99% net efficiency)
- The CRV consists of 4 overlapping layers of scintillator strips with wavelength shifter and aluminum absorber
- Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam



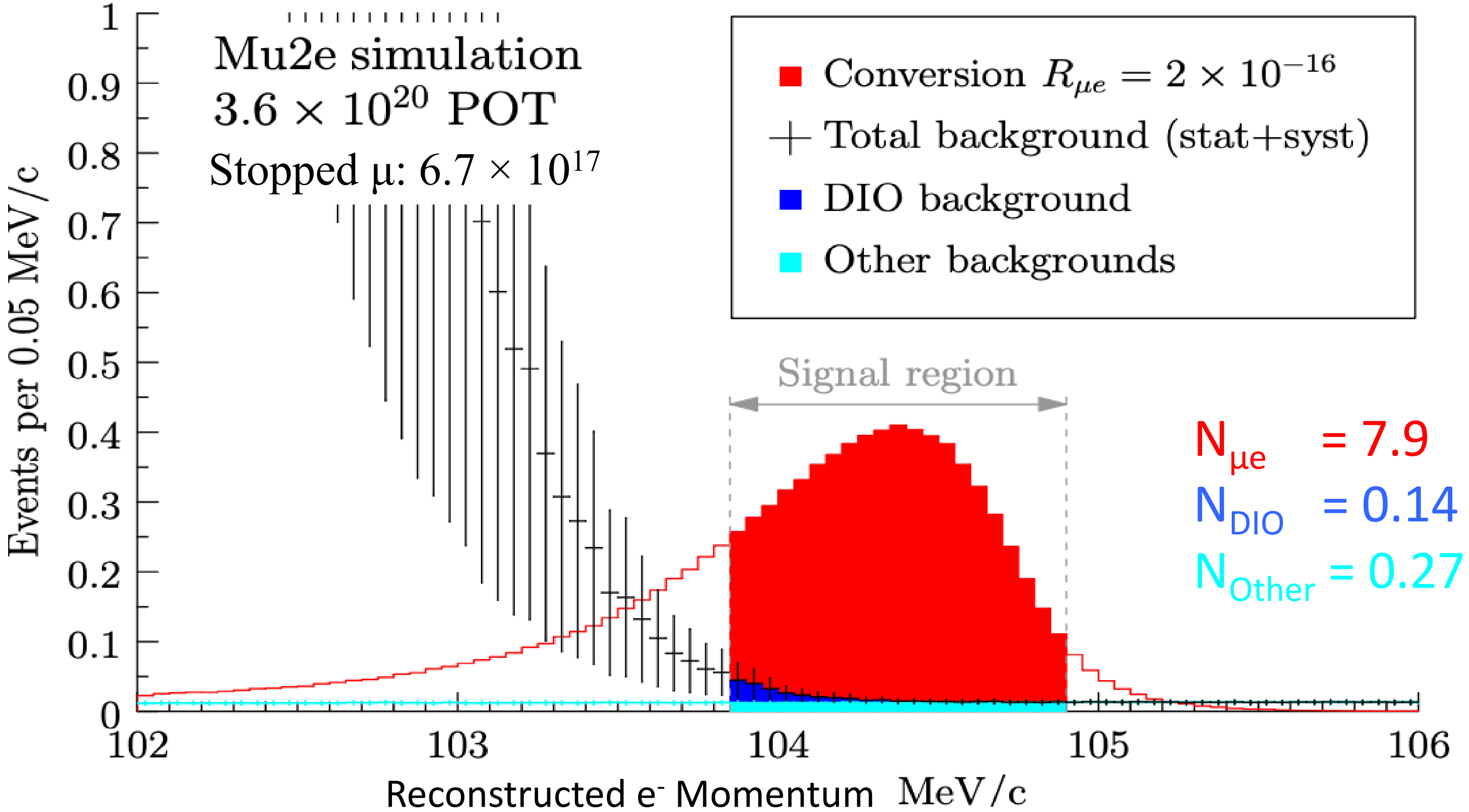


Estimated background yields

Category	Background process	Estimated yield (events)
Intrinsic *	Muon decay-in-orbit (DIO)	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving+	Pion capture (RPC)	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
	Muon decay-in-flight (μ-DIF)	< 0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm < 0.001$
	Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Antiproton induced	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
	Cosmic ray induced	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
	Total	$0.41 \pm 0.13(\text{stat+syst})$

*Assuming $6\text{x}10^{17}$ stopped muons in $6\text{x}10^{7}$ sec of beam time
+Assuming an proton beam extinction of 10^{-10}, a cosmic ray veto inefficiency of 10^{-4}, PID muon-rejection of 200.

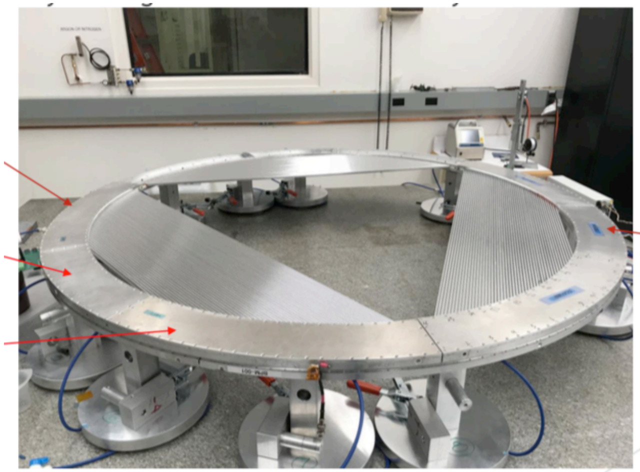
Reconstruction Simulation

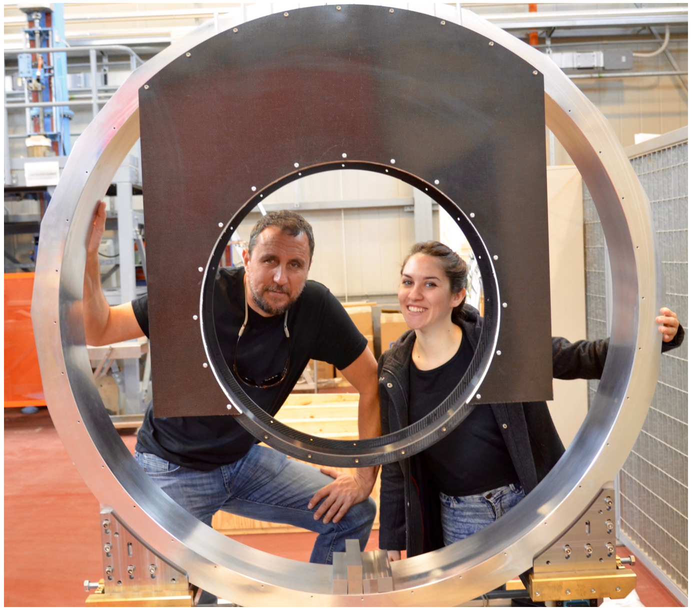


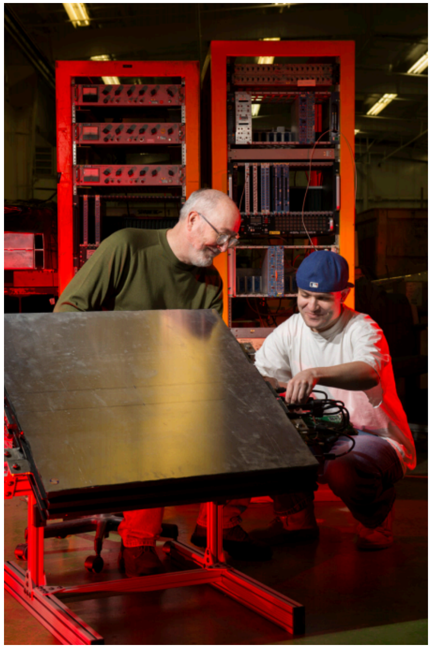
This simulation includes measured properties of prototype detectors.

At $R_{\mu e} = 2 \times 10^{-16}$, we would expect to see 7.9 events which is a 5σ discovery!

Production is underway!



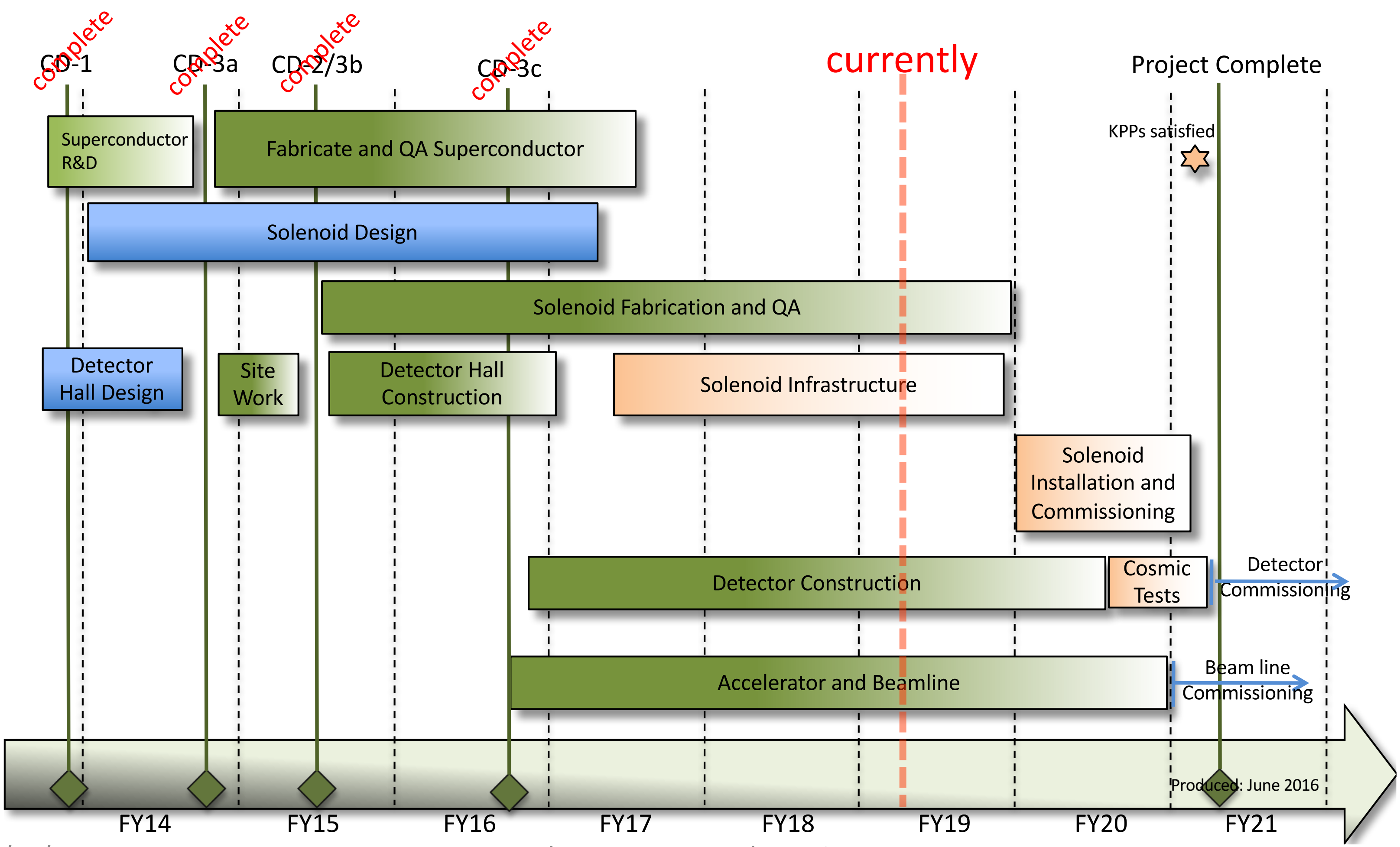




New Building completed in 2016

Schedule

Mu2e is on schedule.
We expect to be commissioning in 2020.



The Mu2e Collaboration

200 scientists, 37 institutions

Summary

- There is a lot of excitement about theoretical model discrimination afforded by a 4 order of magnitude improvement on muon conversion sensitivity.
- The Mu2e project has a design which will allow for a single event sensitivity of 2.5×10^{-17}.
- The experimental design is mature and on schedule for commissioning in 2020 and taking production data starting in 2021.

  For more detailed information ask or check out :

Summary of Experiment	http://arxiv.org/pdf/1901.11099.pdf
Technical Design Report	http://arXiv.org/abs/1501.05241
Experiment web site	http://mu2e.fnal.gov

- A plan for the upgrade, Mu2e-II, has also progressed

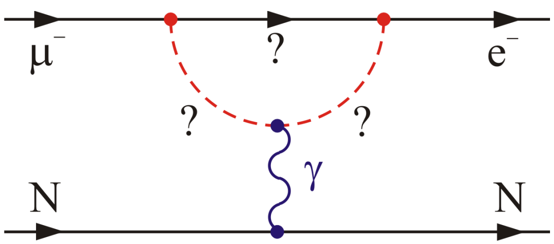
  Expression of Interest http://arxiv.org/pdf/1802.02599.pdf

Thank you

Sensitivity to High Mass Scales

$$L_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

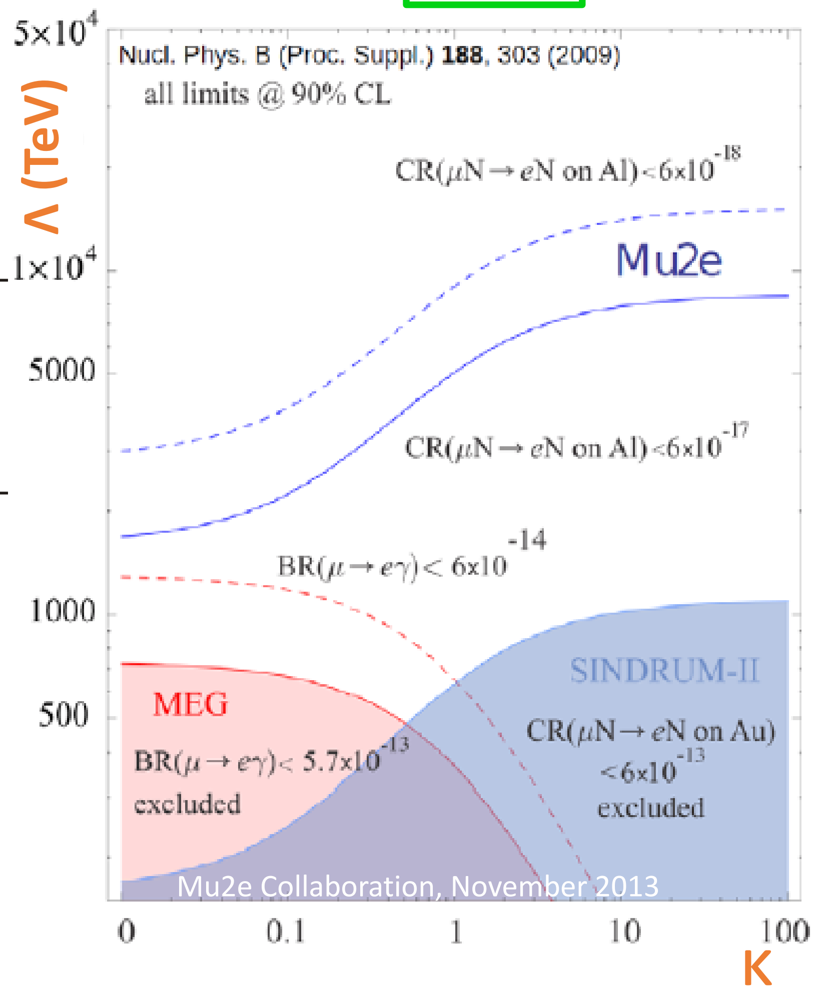
Loops dominate for κ << 1



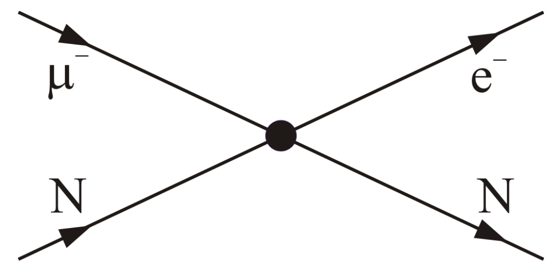
μ→eγ

μN→eN

μ→eee



Contact terms dominate for κ >> 1



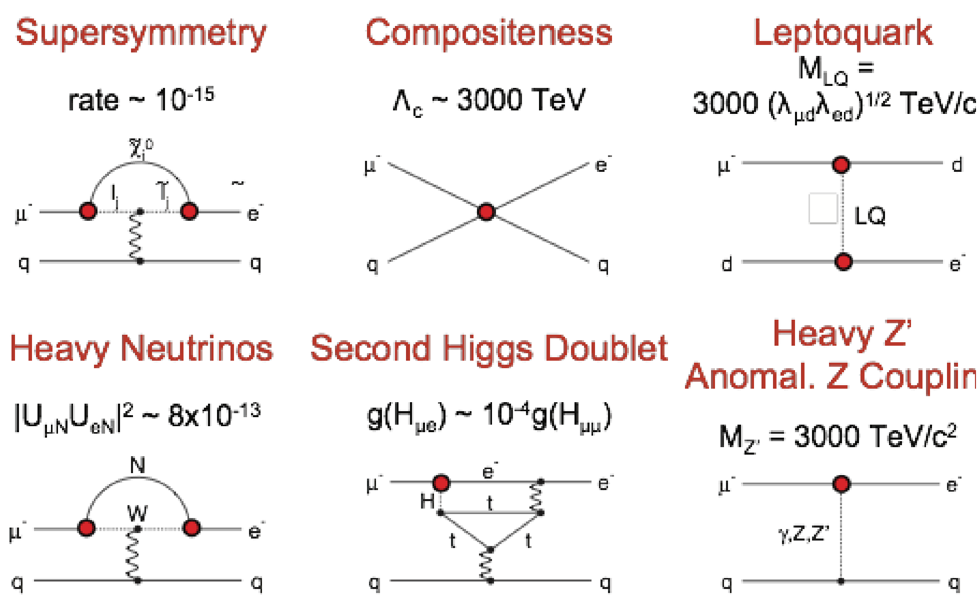
μ→eγ

μN→eN

μ→eee

Sensitive to many models

Λ_c between 2000 to 7000 TeV



W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Estimates from Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J.C57:13-182,2008

The Comet Experiment

The Comet experiment is another muon to electron conversion experiment which will run at J-PARC.

Phase 1 will be a 100x sensitivity improvement is scheduled to begin in 2020. Phase 2 has a similar sensitivity to Mu2e (10^4x sensitivity improvement) and is scheduled to begin after Mu2e begins.

For more information on the technical design of Comet : http://arxiv.org/pdf/1812.09018.pdf