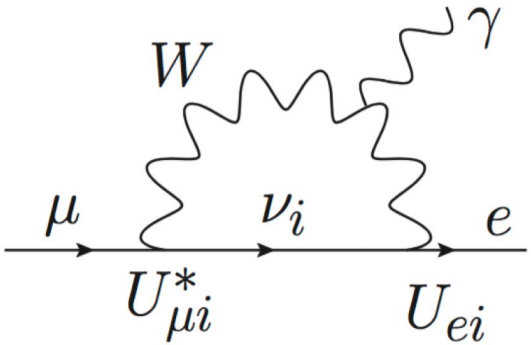
# Design and Fabrication of the Cosmic Ray Veto for Mu2e

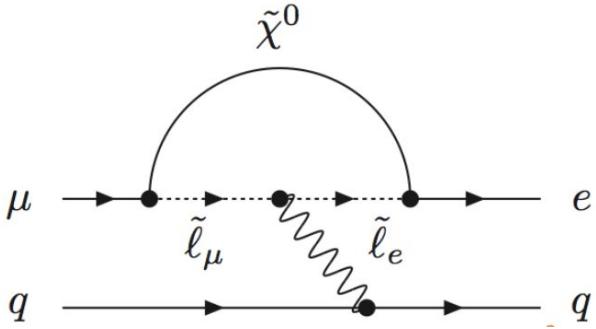
June 17, 2022
Fermilab New Perspectives
Matt Solt

# Charged Lepton Flavor Violation (CLFV)

- CLFV is predicted by the SM, but at unobservable rates μ → eγ < 1e-54
- An observation of CLFV would be an **unambiguous sign of new physics**
- Mu2e searches for CLFV through a neutrino-less conversion of a muon to an electron in the presence of a (aluminum) nuclei μN → eN
- Mu2e's goal is **4 orders of magnitude improvement** over current limits!



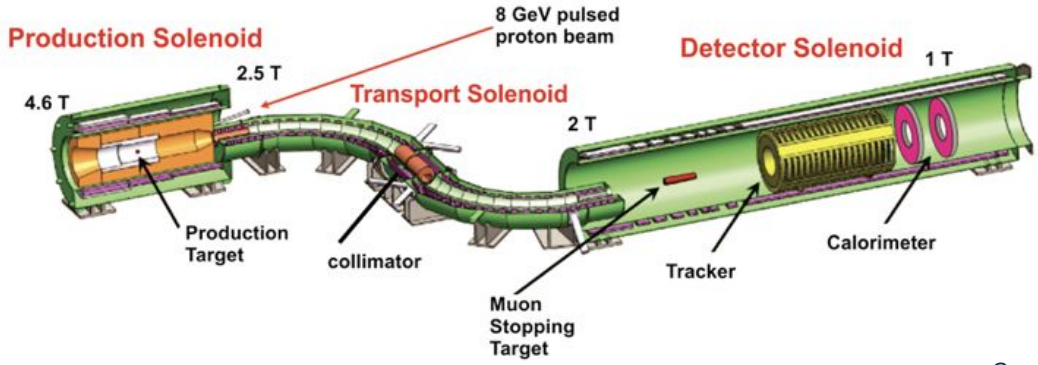

SM CLFV



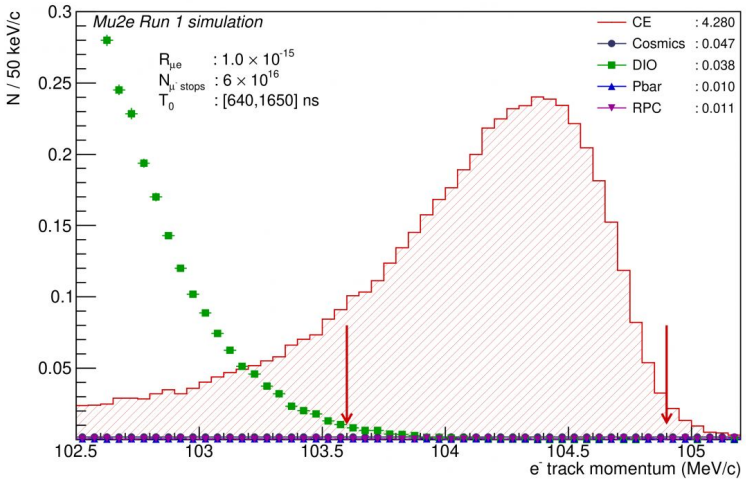

BSM CLFV: conversion via SUSY

# The Mu2e Apparatus

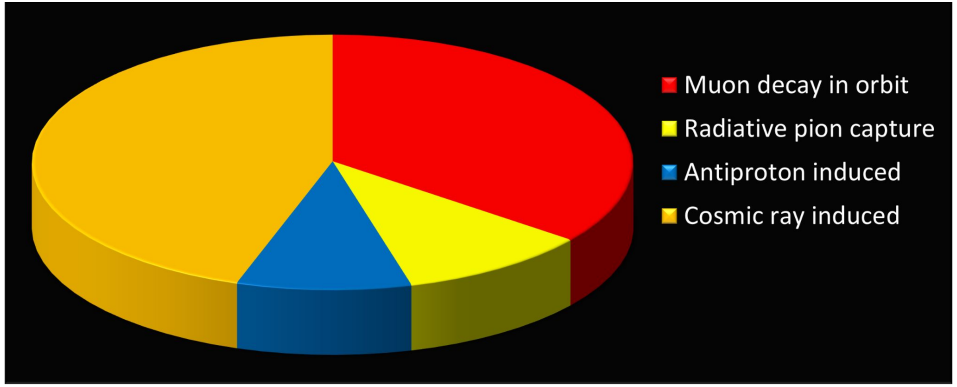
- Fermilab provides high-intensity bunched proton beam on production target
- Produces pions -> muons at production target, momentum and charge selected in the transport solenoid
- Muons stopped in Al stopping target; delayed muon decay to electron
- **Delayed signal is a monoenergetic electron** of 104.4 MeV μN → eN



# Mu2 Backgrounds




**Backgrounds must be kept < 1 event** over the 3 year lifetime of the experiment (for 3.6e20 PoT)

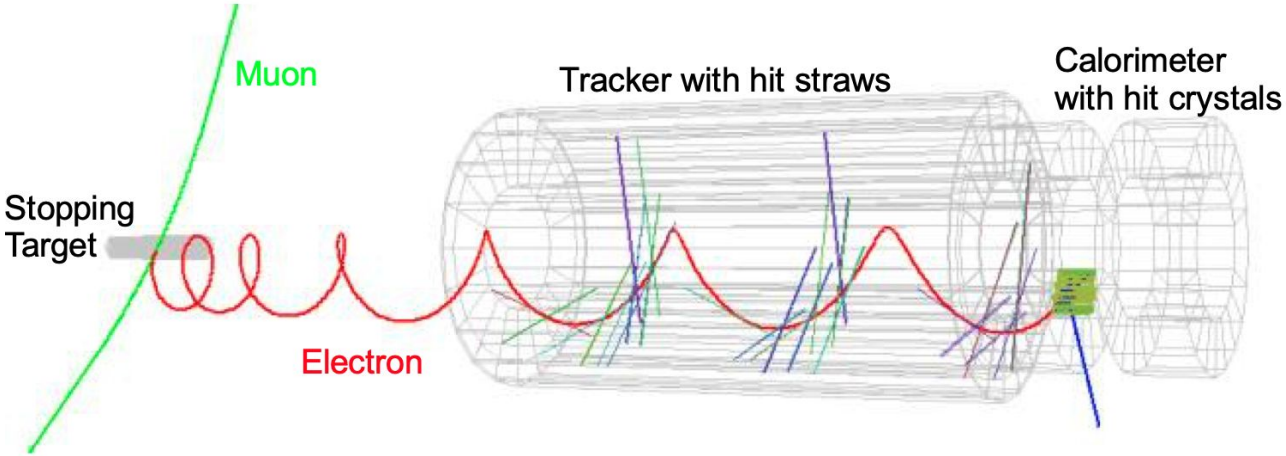



**Largest background are due to cosmic rays**

| Channel | Mu2e Run 1 Background Expectation |
|---|---|
| Cosmics | $0.048 \pm 0.010$ (stat) $\pm 0.010$(syst) |
| DIO | $0.038 \pm 0.002$ (stat)$^{+0.026}_{-0.016}$ (syst) |
| Antiprotons | $0.010 \pm 0.003$ (stat) $^{+0.010}_{-0.004}$ (syst) |
| RPC in-time | $0.011 \pm 0.002$ (stat) $^{+0.001}_{-0.002}$ (syst) |
| RPC out-of-time | negligibly small |
| RMC | negligibly small |
| Beam electrons | negligibly small |
| Total | $0.107 \pm 0.032$ (stat$\oplus$syst) |

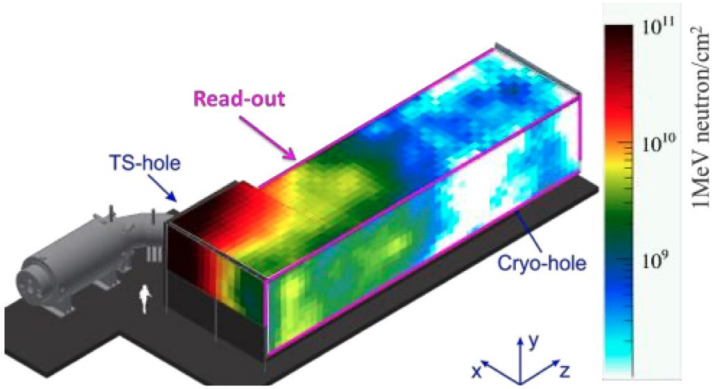
# Cosmic Ray Backgrounds

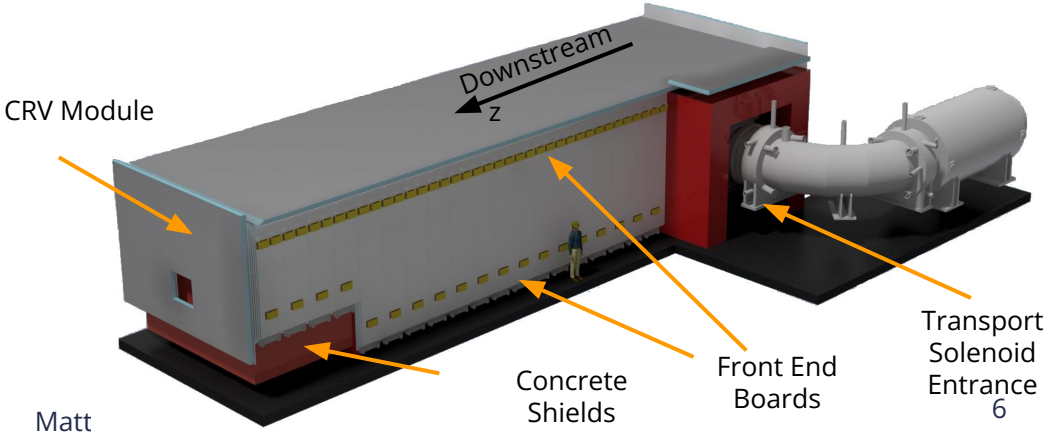
- A cosmic ray muon entering the experimental hall and striking material can eject an electron at the expected signal energy
  - **This is indistinguishable from signal,** example muon striking the stopping target below
  - Expect 1 signal-like event/day -> ~1000 events over the lifetime of the experiment
  - **Cosmic rays must be vetoed with high efficiency** -> need a Cosmic Ray Veto (CRV)



# The Cosmic Ray Veto (CRV)

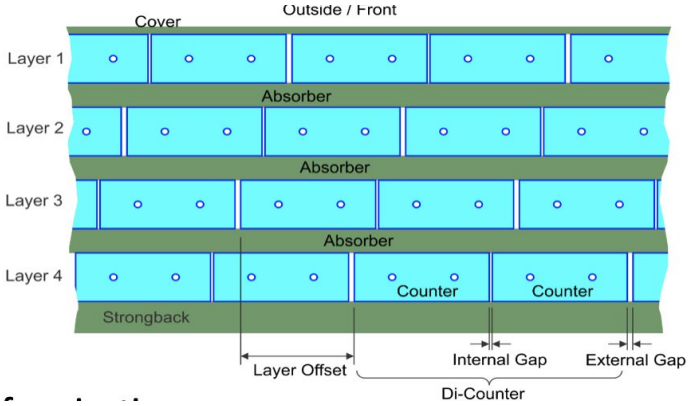
- A CRV will surround much of the Mu2e apparatus. It will detect cosmic rays entering the hall and reject them (offline)
- Two Basic requirements:
  - **99.99% cosmic ray rejection efficiency**
  - **Low dead time in a high radiation environment**

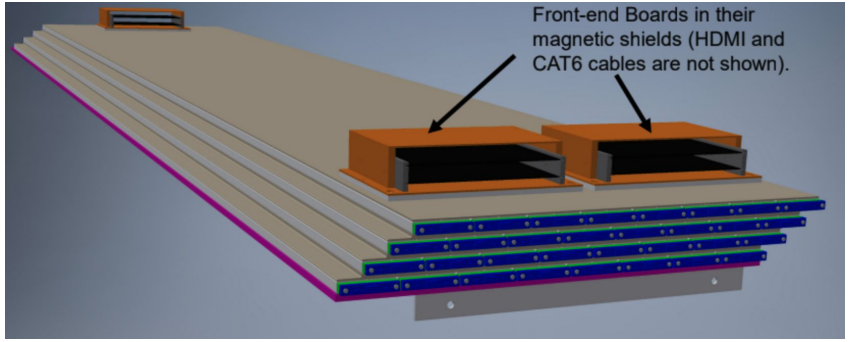


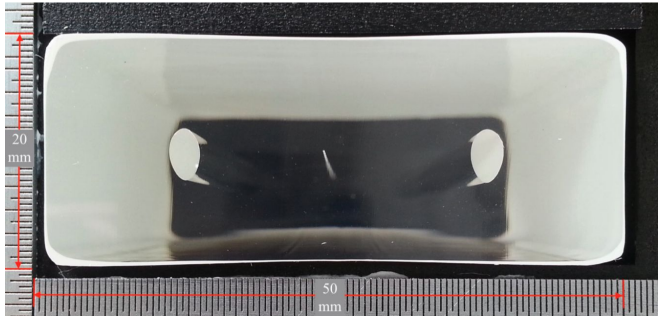
# CRV Design

- CRV is divided into 83 modules, each containing 4 layers of scintillator counters (16/layer). Aluminum absorbers between each layer
- 42 mm offset between layers is optimized to minimize projective gaps
- Require 3 out of 4 layer hits within time coincidence (reduced fake hits)



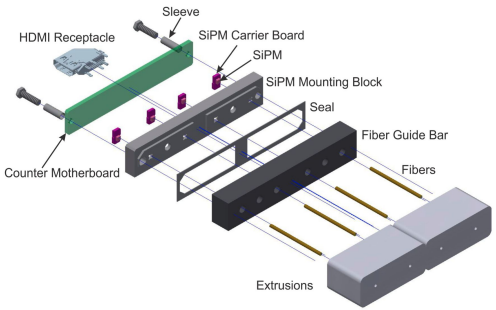



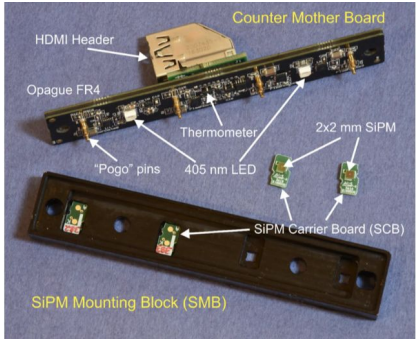
# CRV Module Design




- Extrusions manufactured at **FNAL-NICADD Extrusion Line Facility**
- Two embedded wavelength-shifting fibers from Kuraray in each counter
- Fiber ends are readout by Silicon Photomultipliers (SiPMs) from Hamamatsu

| |
|---|
| 83 Modules |
| 6 Module lengths |
| 64 Counters/Module |
| 5,344 counters |
| 10,688 fibers |
| 19,392 SiPMs |
| Area 335 m^2 |

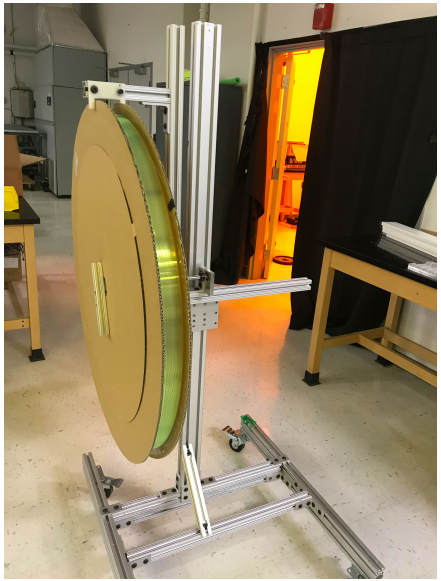



Matt Solt

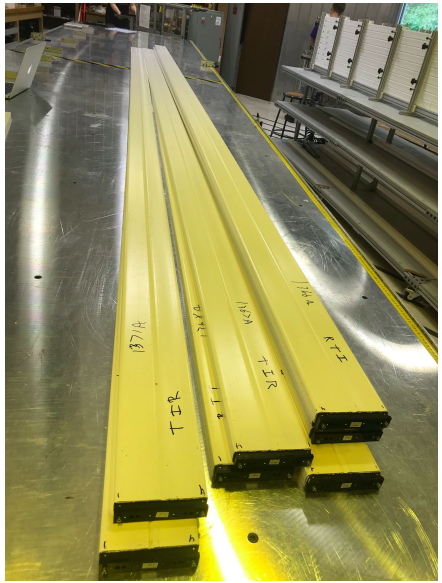
# Di-Counter Fabrication

Counters arrive from Fermilab



WLS Fibers from Kuraray

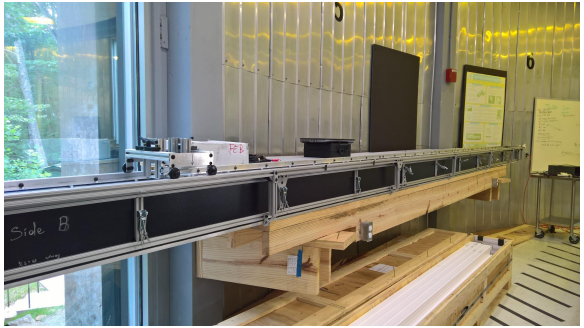
Counters epoxied to form di-counters

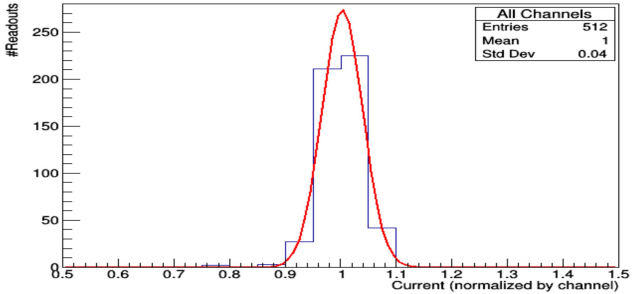


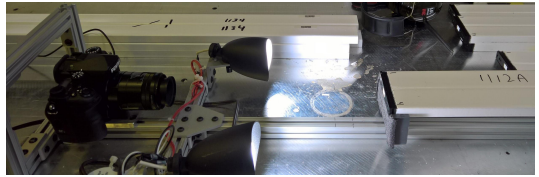
Di-counter assembly

# Di-Counter QA

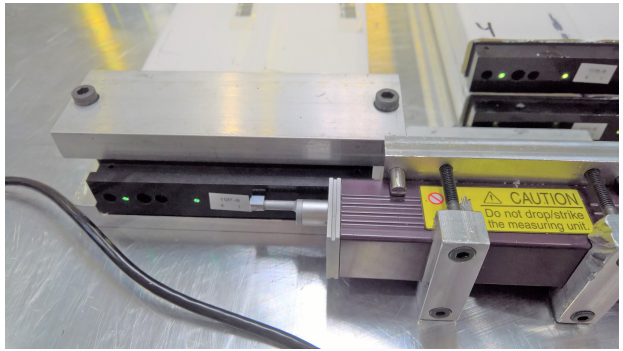
Source tested before module assembly





Fiber guide bar imaging

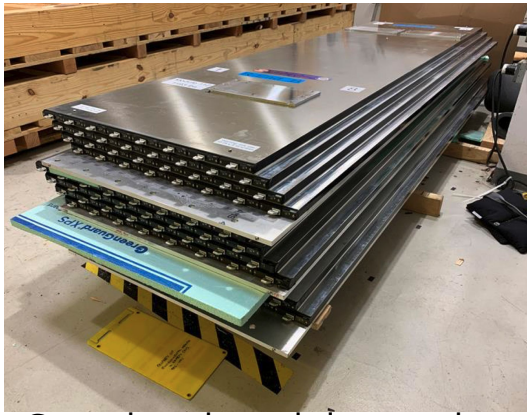



Roughness testing of fiber guide bars

# Module Fabrication

Al and Scintillator layers are epoxied together

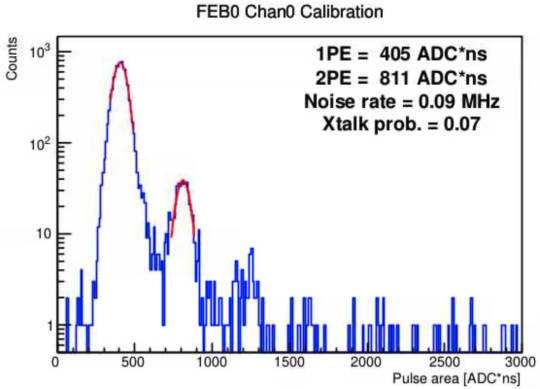
Completed module is vacuum bagged for 24 hours



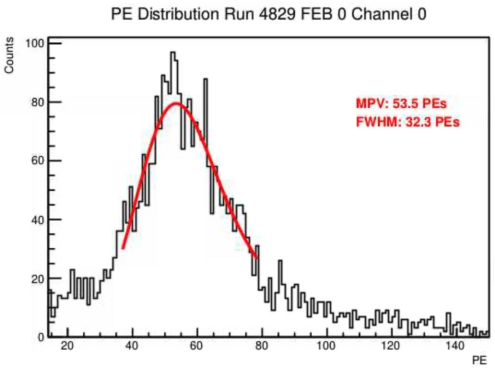
Completed modules ready for storage

Crated and shipped to Fermilab (Wideband)

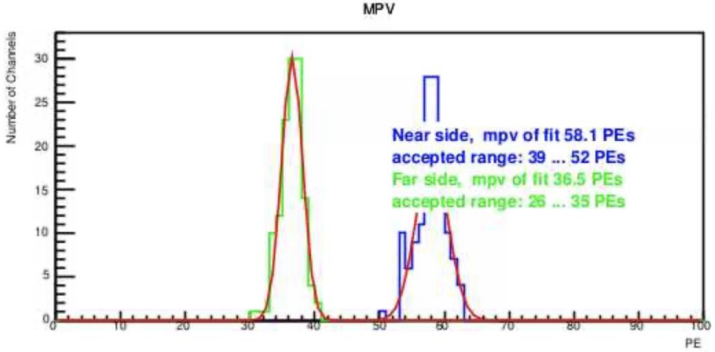
# Module QA

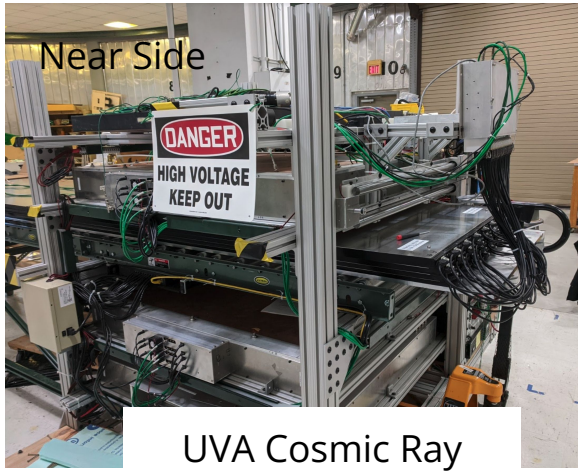



Sample calibration via dark counts from photo-electrons

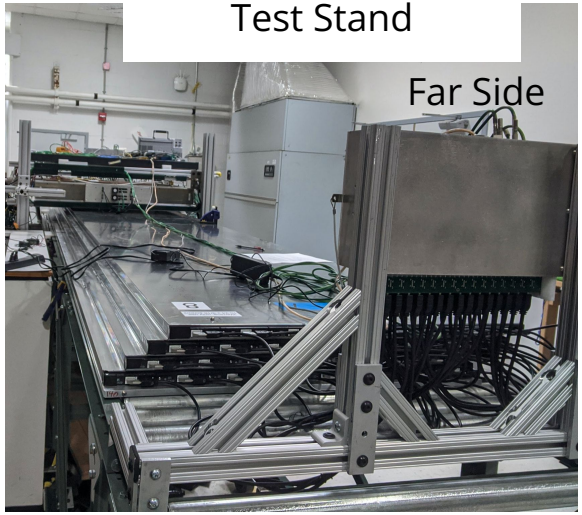



Sample light yield outputs for single channel (above) and Module 167 (below)



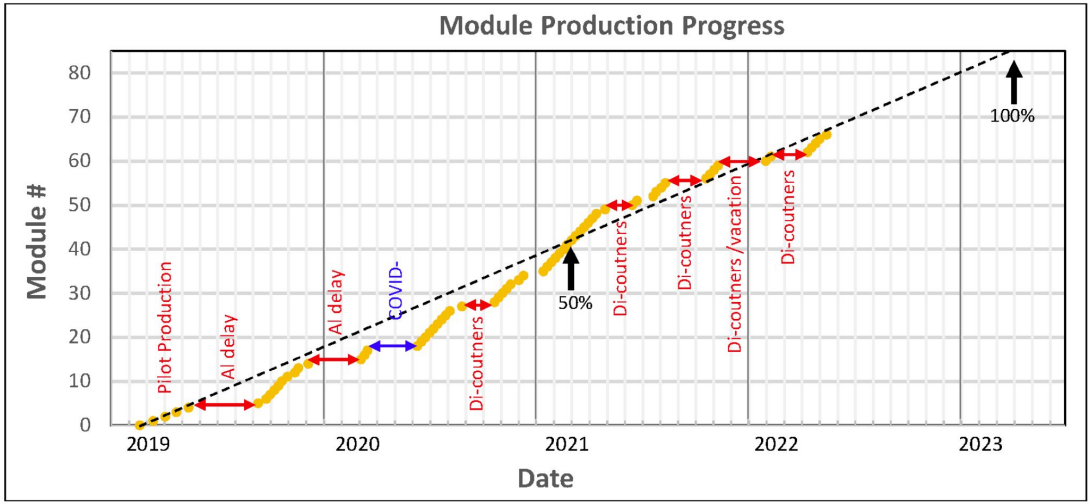



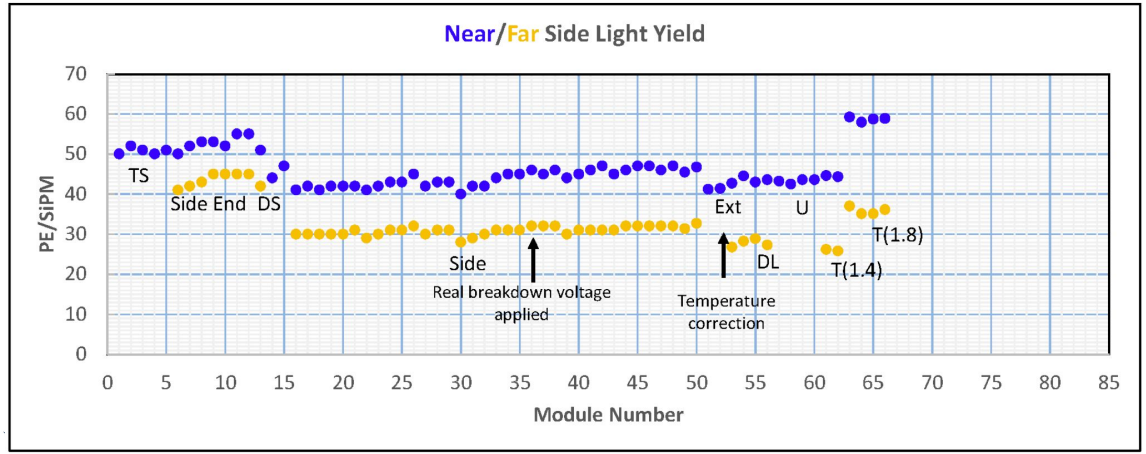

UVA Cosmic Ray Test Stand



# Current CRV Status

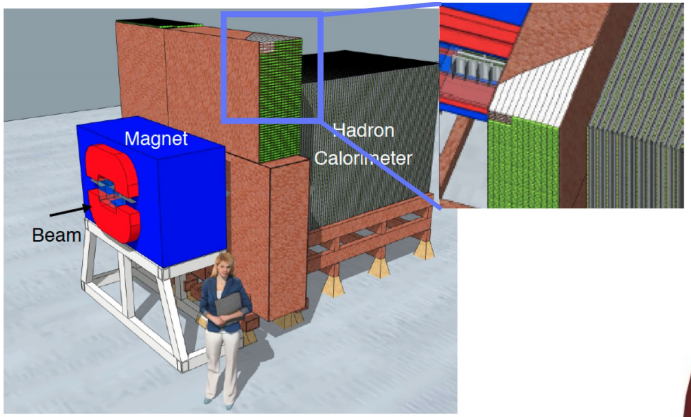
**68 of 83 modules are completed.** Expected to be completed early 2023




Light yield QA measured in UVA's cosmic ray test stand meets Mu2e CRV requirements

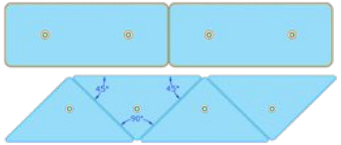
# Other Uses for Mu2e-like Counters




**The Light Dark Matter eXperiment** (LDMX) Hcal as a high efficiency neutral hadron veto

arXiv:1808.05219

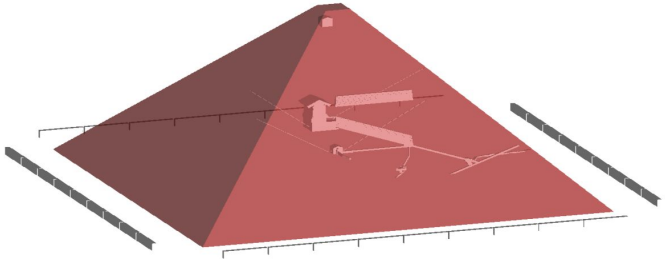
Mu2e Di-counter



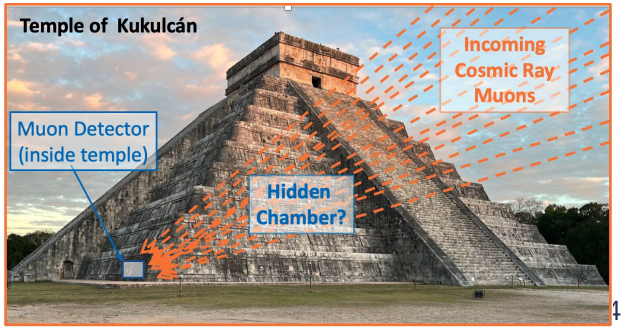
Mu2e-II/Pyramid Project
Triangular Quad-counter

Proposed **DUNE** Near Detector

**The Pyramid Project**



Triangular counters minimize gaps for higher efficiency and improve hit resolution



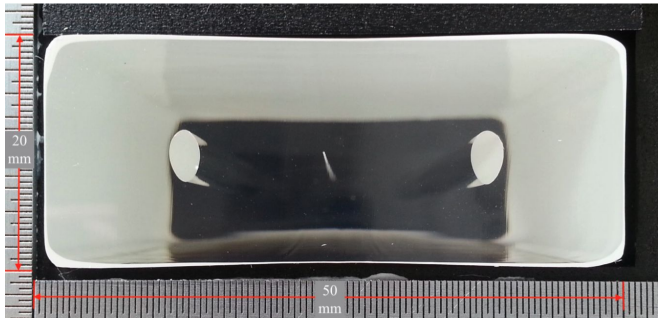
# Conclusion

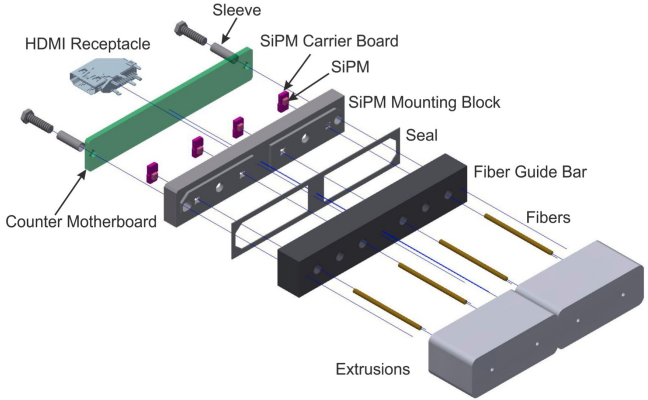
- An observation of CLFV would be a **clear indication of BSM physics**
- Mu2e attempts to observe a direct conversion of a muon to electron in the presence of a nucleus μN → eN - a clear sign of CLFV
- The largest background to the monoenergetic electron signal are cosmics rays. **The CRV is designed to mitigate this with 99.99% efficiency**
- **To date, the CRV is on track to complete fabrication at UVA in early 2023 and meets QA requirements**

**Thanks to my Mu2e Collaborators!**

# Backup

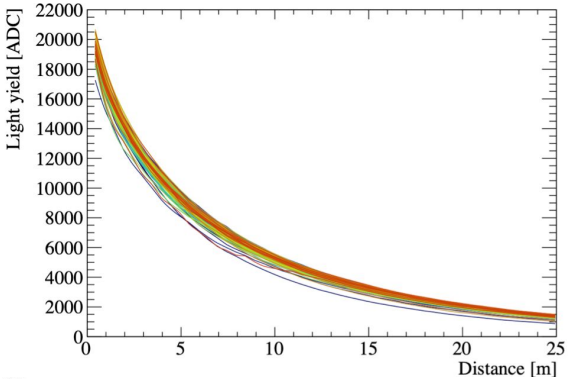
- Extrusions manufactured at FNAL-NICADD Extrusion Line Facility
  - Polystyrene doped with 1% PPO and 0.03% POPOP
  - Coated with 0.25 thuch reflective mixture of 30% TiO2 and 70% polystyrene
- Two embedded wavelength-shifting fibers from Kuraray
  - Double-clad Y11 dopen with 175 ppm K27 dye, non-S-type. 1.4 mm or 1.8 mm
- SiPMs from Hamamatsu
  - 1684 pixels
  - 2 mm x 2 mm (S13360-2050VE)
  - Pixel size: 50 um

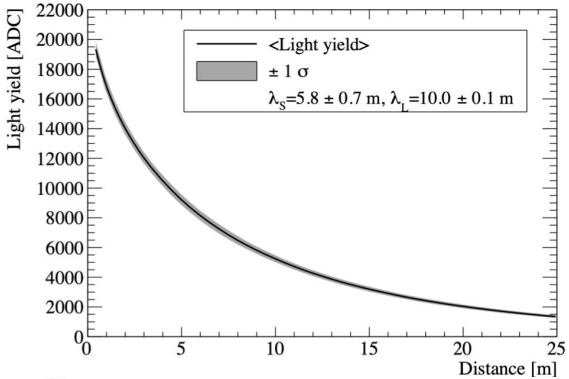


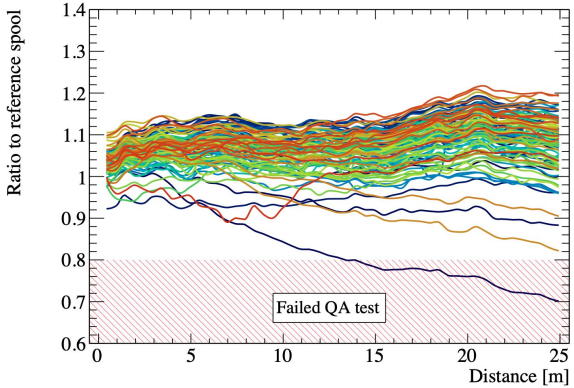



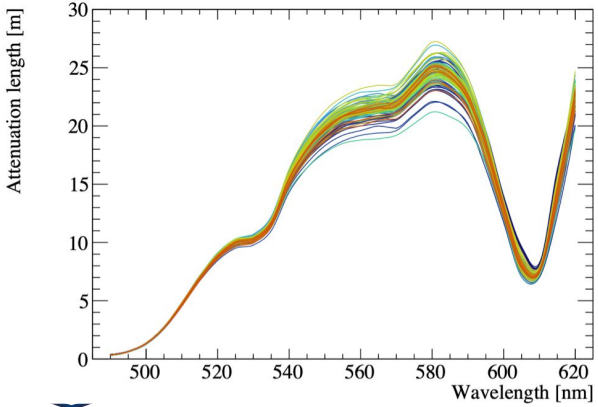
# Backup

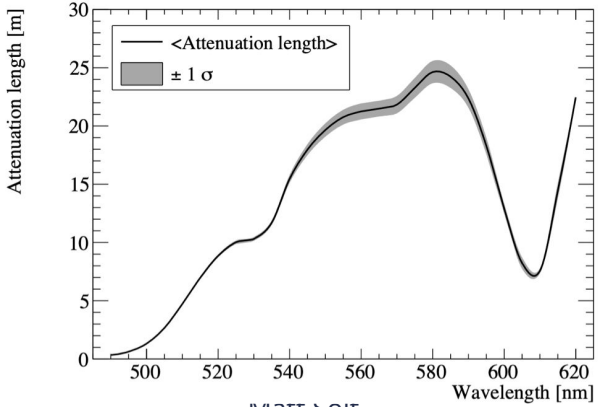
arXiv:1811.04874v1

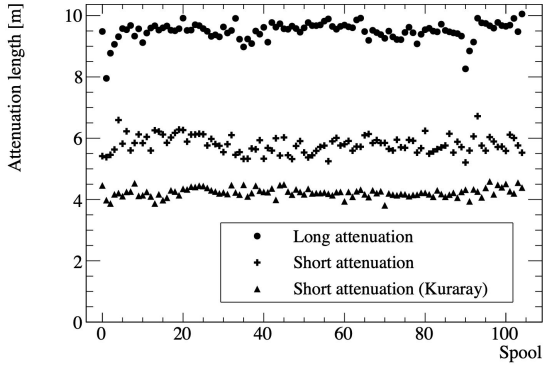


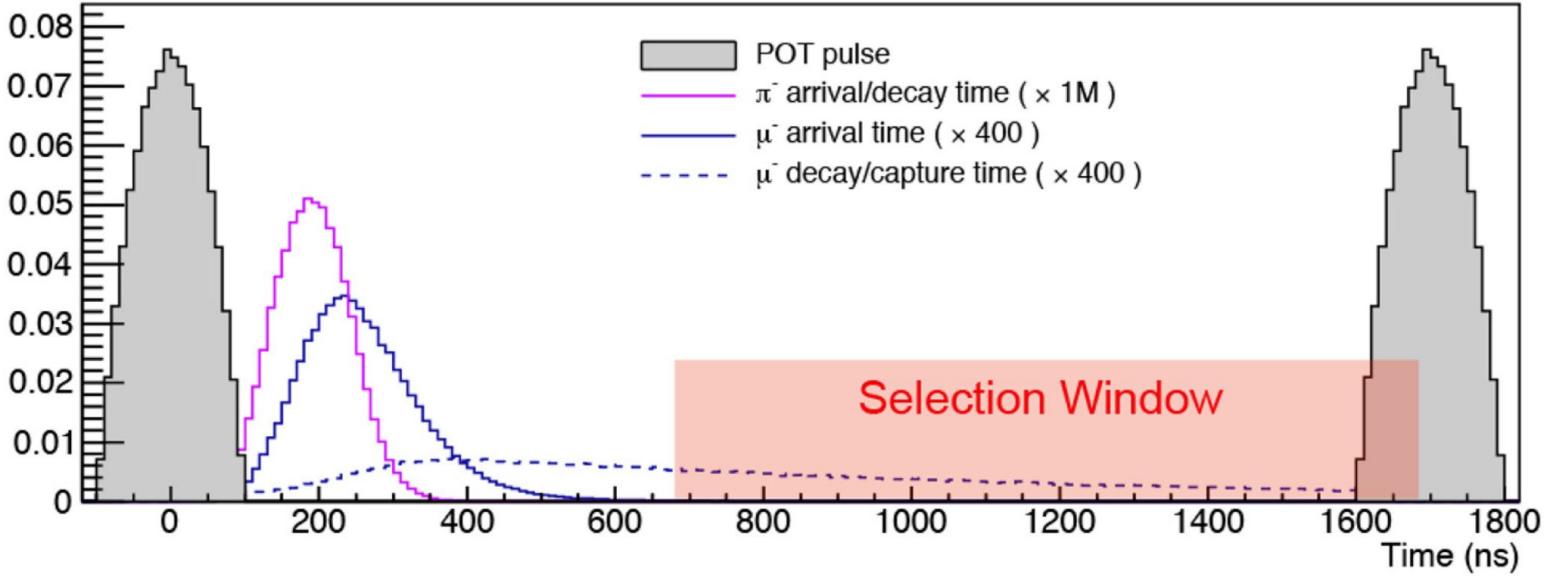



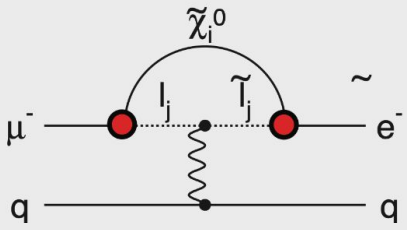
# Backup


POT pulse
π⁻ arrival/decay time ( × 1M )
μ⁻ arrival time ( × 400 )
μ⁻ decay/capture time ( × 400 )
Selection Window
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)

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

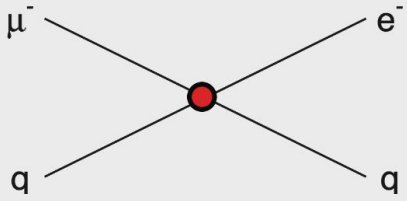
## Supersymmetry

rate ~ $10^{-15}$



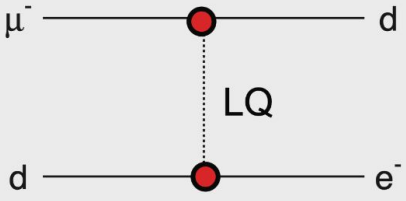

## Compositeness

$\Lambda_c$ ~ 3000 TeV



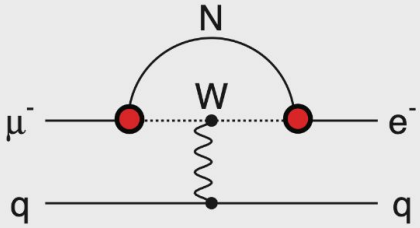

## Leptoquark

$M_{LQ}$ = 3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/$c^2$



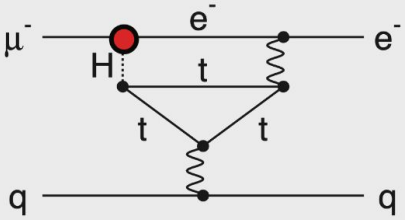

## Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ $8\times10^{-13}$



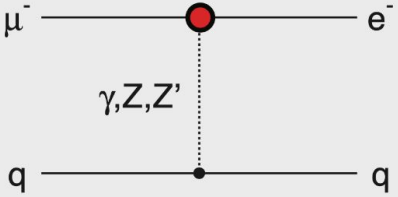

## Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$

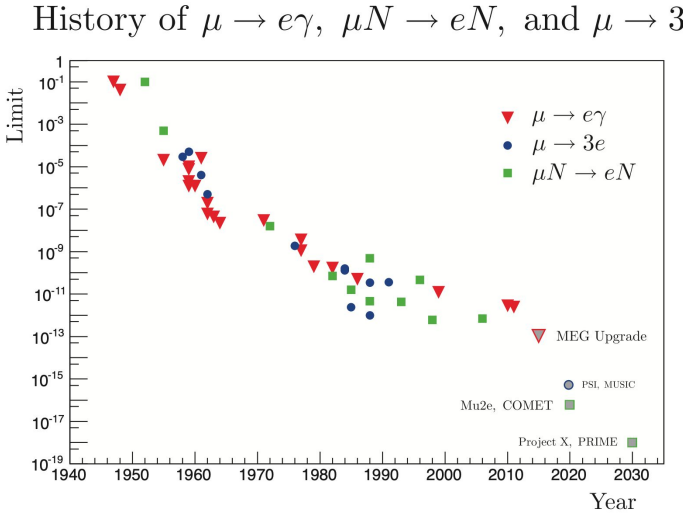


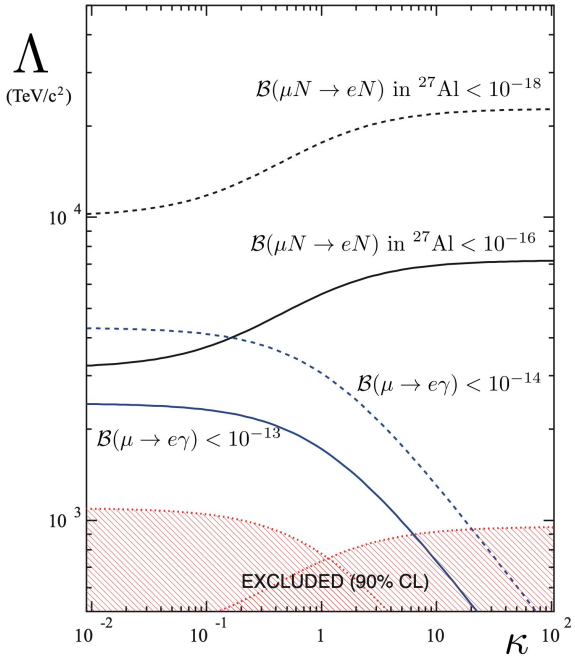

## Heavy Z' Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/$c^2$



# Backup




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

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.