ICHEP2018 SEOUL

XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS

JULY 4 - 11, 2018
COEX, SEOUL

The Mu2e Tracker

Gianantonio Pezzullo
Yale University

on behalf of the Mu2e tracker group

The Mu2e collaboration

Argonne National Laboratory, Boston University, Brookhaven National Laboratory University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York, Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

What is μ→e conversion

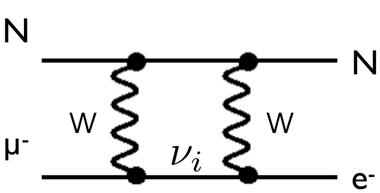
- μ converts to an electron in the presence of a nucleus $\mu^- N \to e^- N$

$$E_e = m_\mu c^2 - B_\mu(Z) - C(A) = 104.973 \text{ MeV}$$

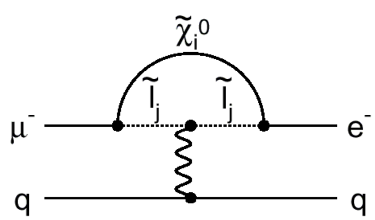
- for Aluminum: $\begin{cases} B_\mu(Z) \text{ is the muon binding energy } (0.48 \text{ MeV}) \\ C(A) \text{ is the nuclear recoil energy } (0.21 \text{ MeV}) \end{cases}$

- μ conversion in the SM is induced by **neutrino masses and mixing** at a negligible level ~ 10^{-52}

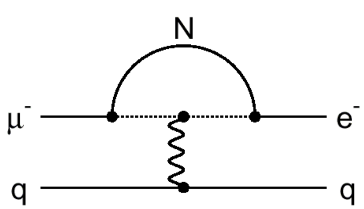
- Many **SM extensions enhance the rate** through mixing in the high energy sector of the theory (other particles in the loop…)



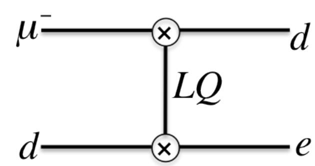
nuMSM Muon conversion: R≈10^{-52}



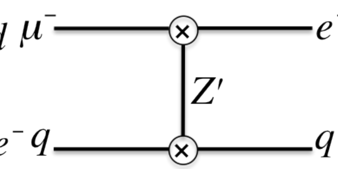
Supersymmetry : R ≤10^{-13}



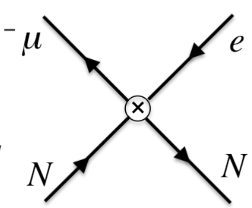
Heavy neutrino



Lepto-quark exchange

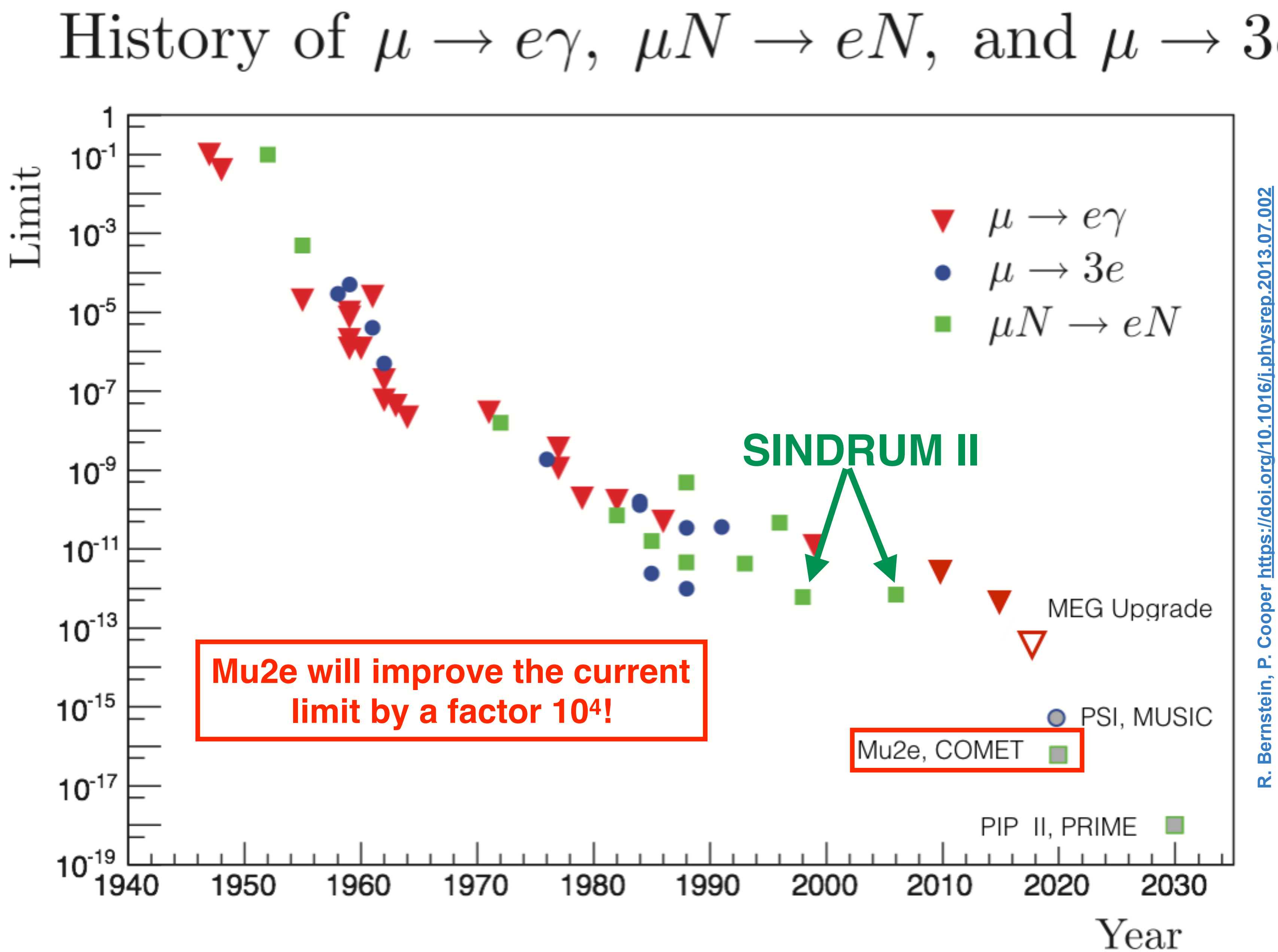


Z' exchange



Eff contact interaction

History of μ→e search



Experimental setup

(1) Production Solenoid:

➡ Proton beam strikes target, producing mostly pions

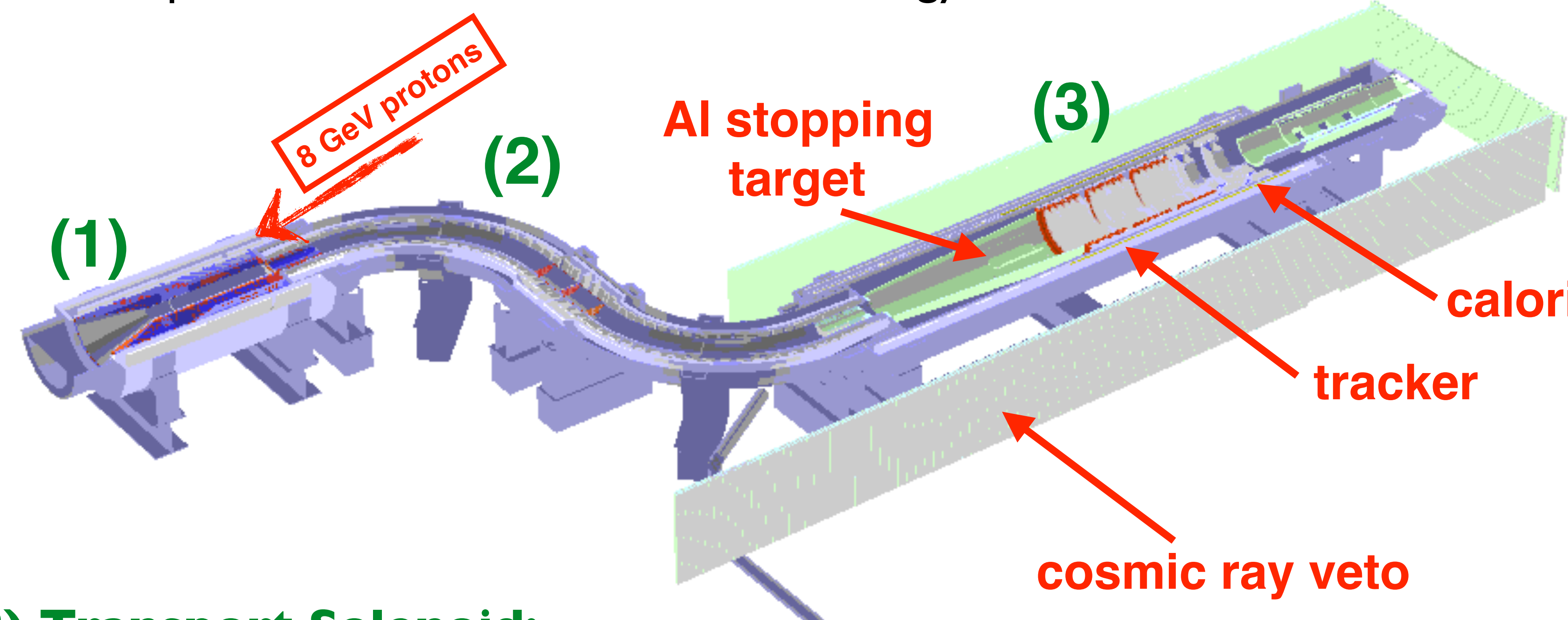
➡ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

(3) Detector Solenoid:

➡ Capture muons on Al target

➡ Graded field "focuses" e^- in tracker fiducial

➡ Measure momentum in tracker and energy in calorimeter



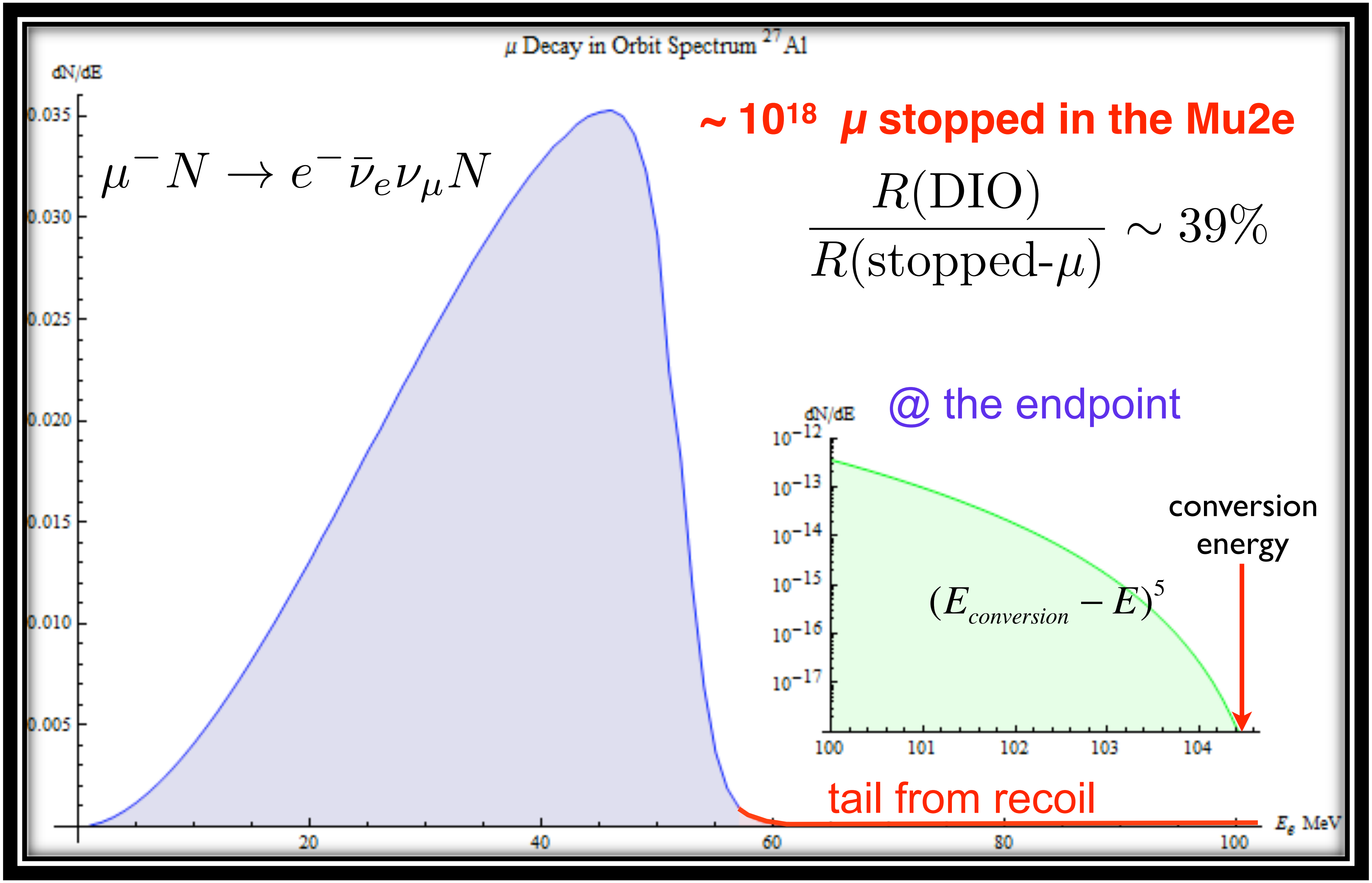
(2) Transport Solenoid:

➡ Select low momentum, negative muons

Backgrounds & design

	Source	Scale with	Solution
Intrinsic	**decay-in-orbit**	**# of stopped-μ**	**Tracker resolution**
Beam	radiative π capture	closeness to beam pulse	pulsed beam
Running time	Cosmic ray	live time	veto system & PID

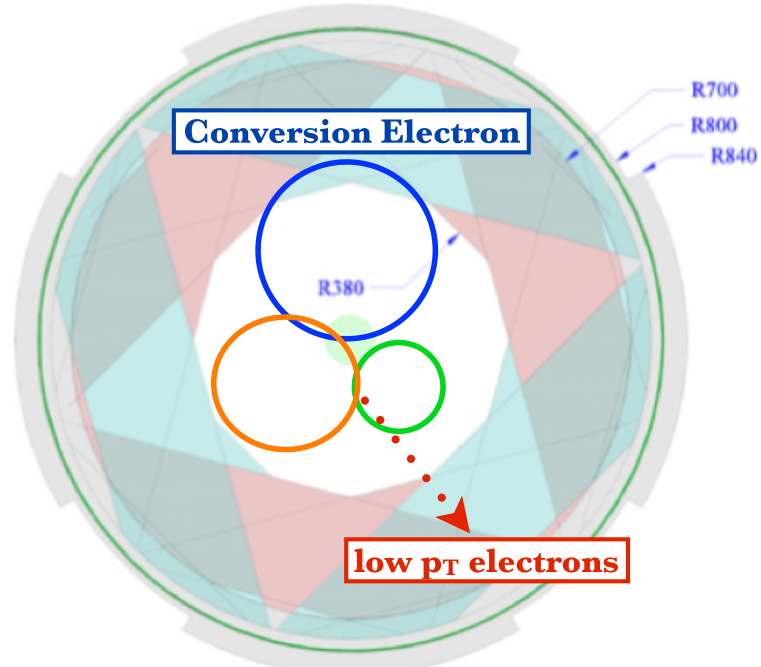
μ decay-in-orbit (DIO)

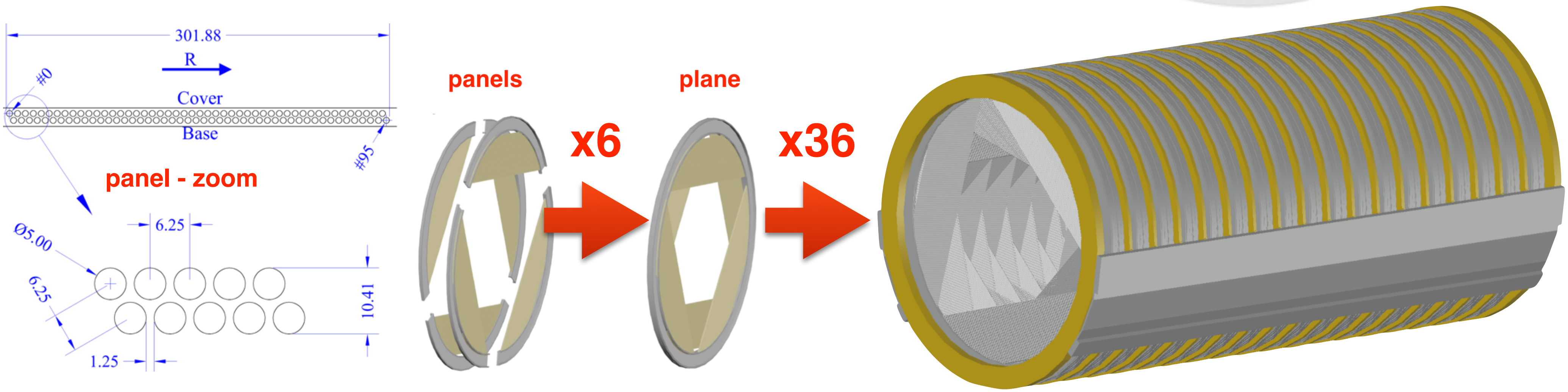


R. Szafron, A. Czarnecki https://doi.org/10.1016/j.physletb.2015.12.008

Tracker design

- 36 double-layer planes equally spaced with straws transverse to the beam
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to >99% of the DIO spectrum
- Expected resolution:
  - ✓ ~ 200 keV/c @ 105 MeV





Straw technology

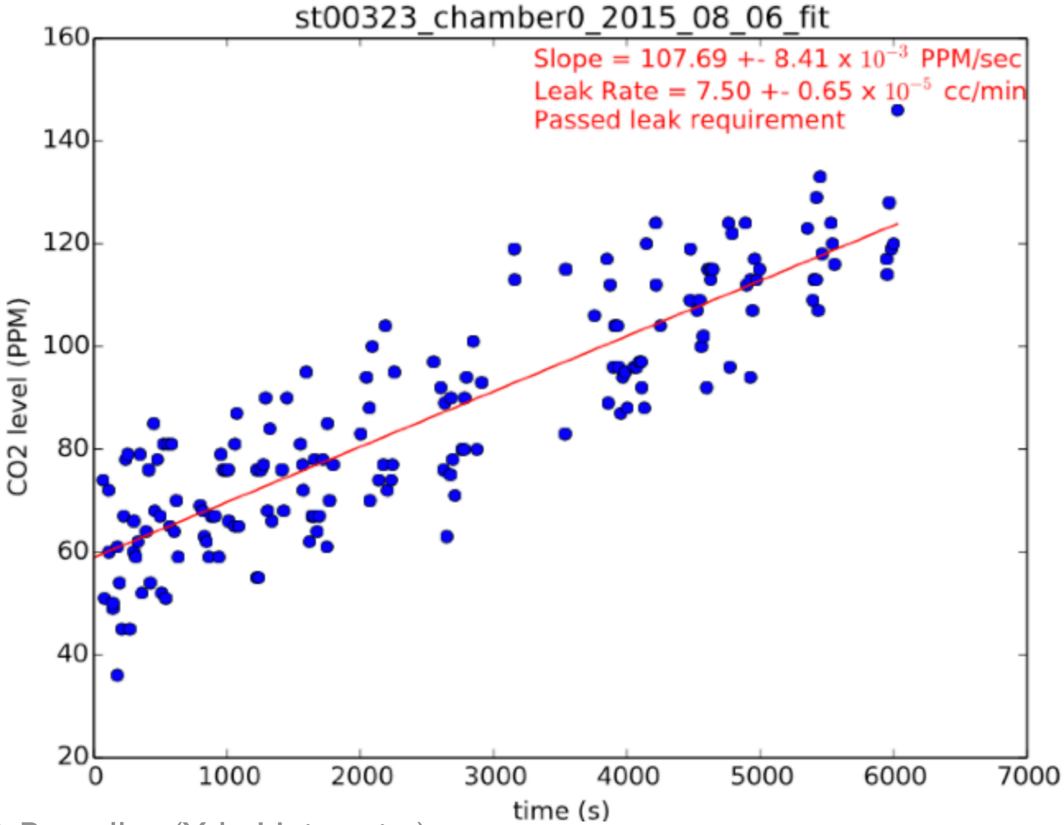
- ~ 20k straws employed in the tracker
- Multiple scattering is the major contributor to dp
  - ✓ straw material budget is comparable to the gas
- Straw specs:
  - ✓ 5 mm diameter, 2x6.25 μm Mylar walls Au and Al coated
  - ✓ 25 μm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Straw length varies from 44 to 114 cm

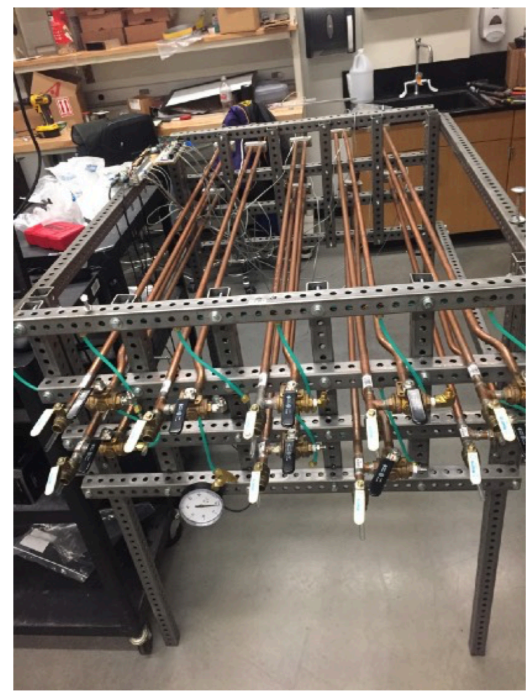
Mylar roll

straw tube

Vacuum requirements

- There are ~ 20k straws that collectively must leak less than 6 cm^3/min
  - ✓ total surface > 3e6 cm^2 with ~ 1 atm differential pressure Ar:CO_2
  - ✓ straw are delicate and we need to test all of them!
- CO2 permeates Mylar at least x10 faster than Argon
- We measure the CO_2 leak rate for each straw with custom chambers

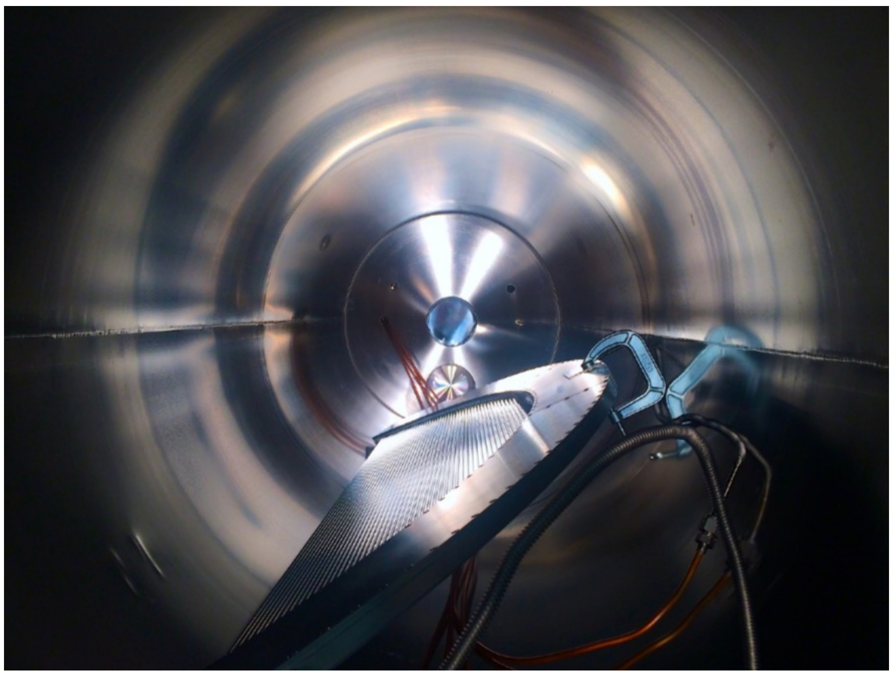




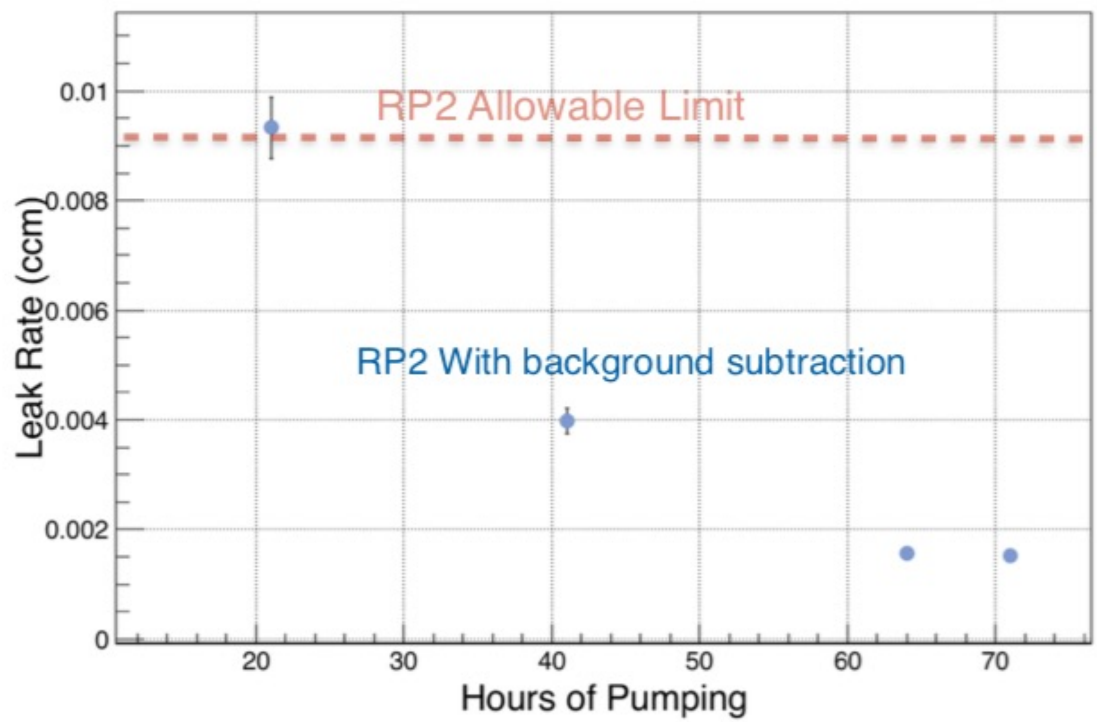
chamber @ UMN

Vacuum requirements

- Vacuum test on each panel to check
  - ✓ gas manifold leak + outgassing

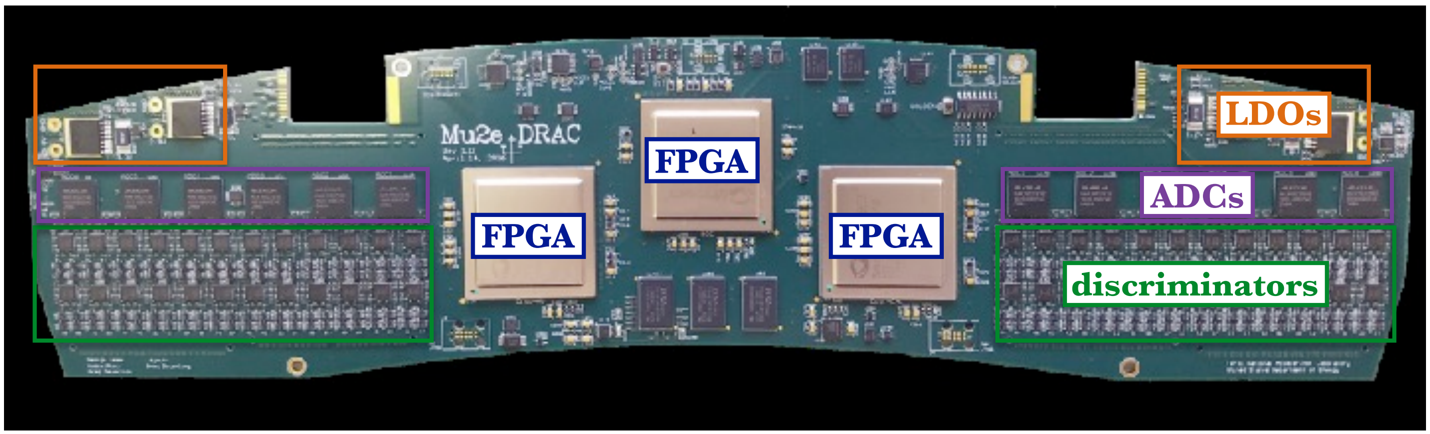


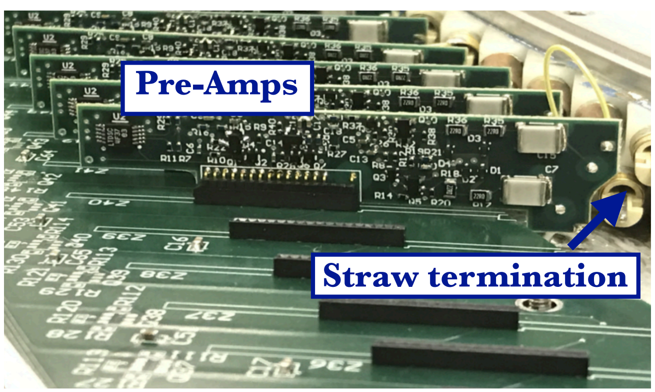
panel vacuum test @ Fermilab

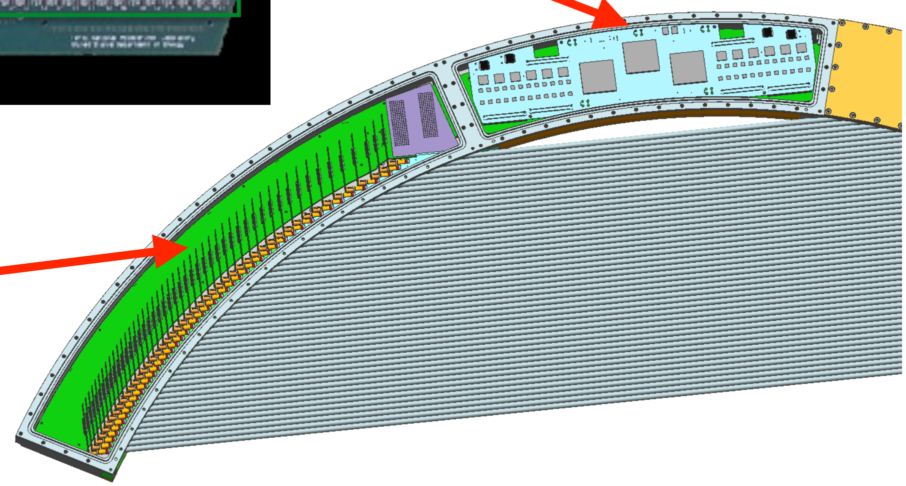


Electronics

- Outer part of the panel houses the FEE and Digitizer Readout & Assembler Controller (DRAC)
- High hit rate sustainability: 15 kHz/cm²



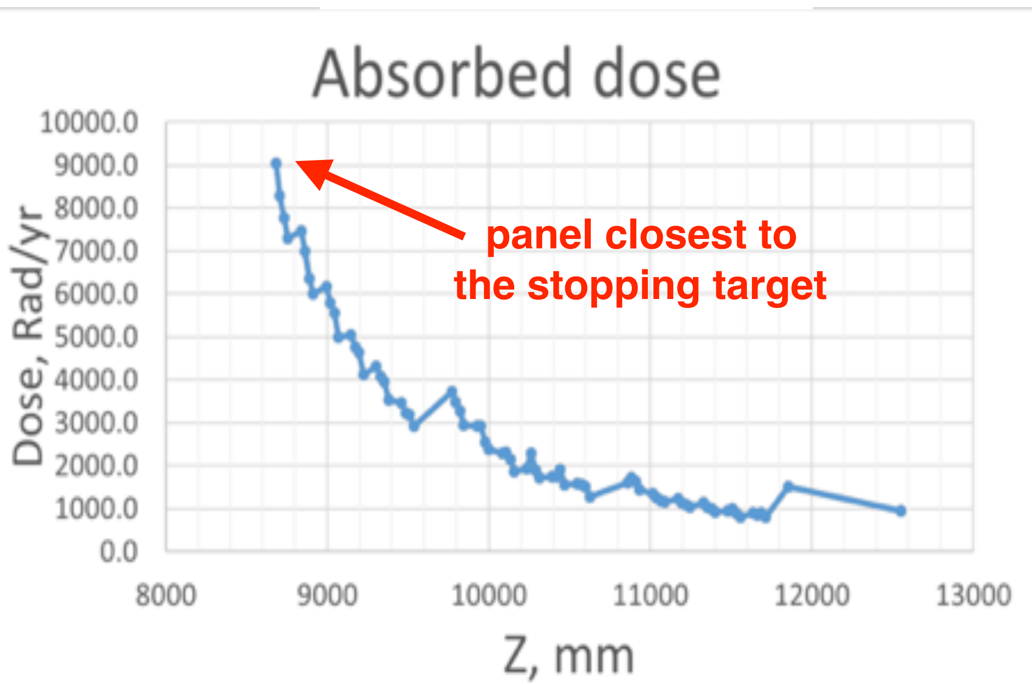




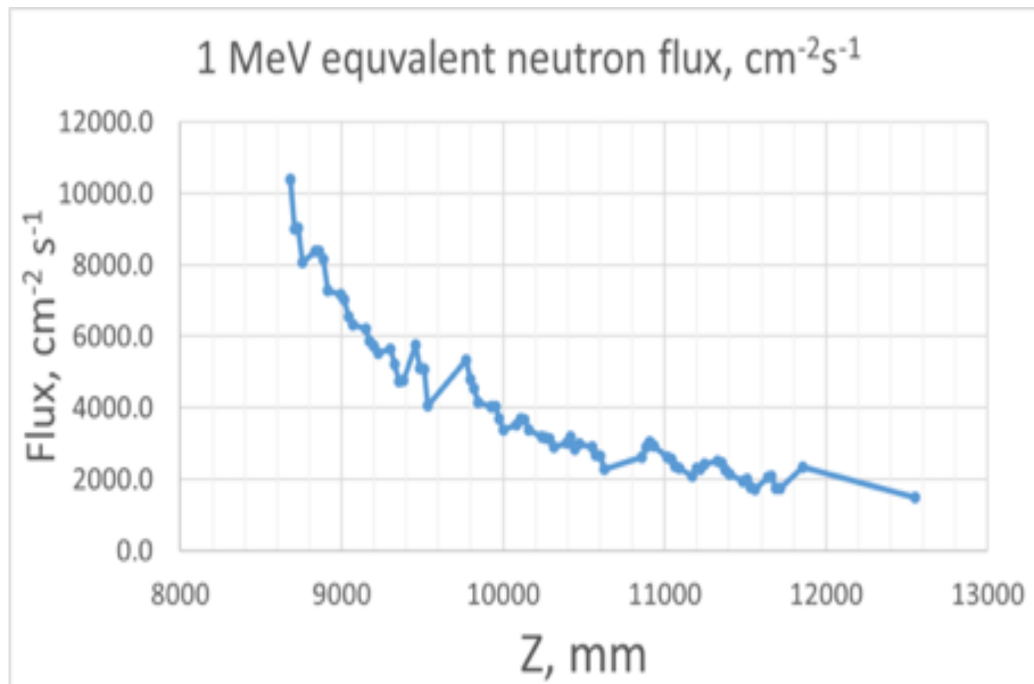
Radiation Environment

- Detailed Monte Carlo simulations with MARS and GEANT4
- peak dose ~ 9 krad/year in the first plane
- Neutron flux up to 2e11 $n_{1MeVeq}/cm^2/year$

Total Ionizing Dose (TID)

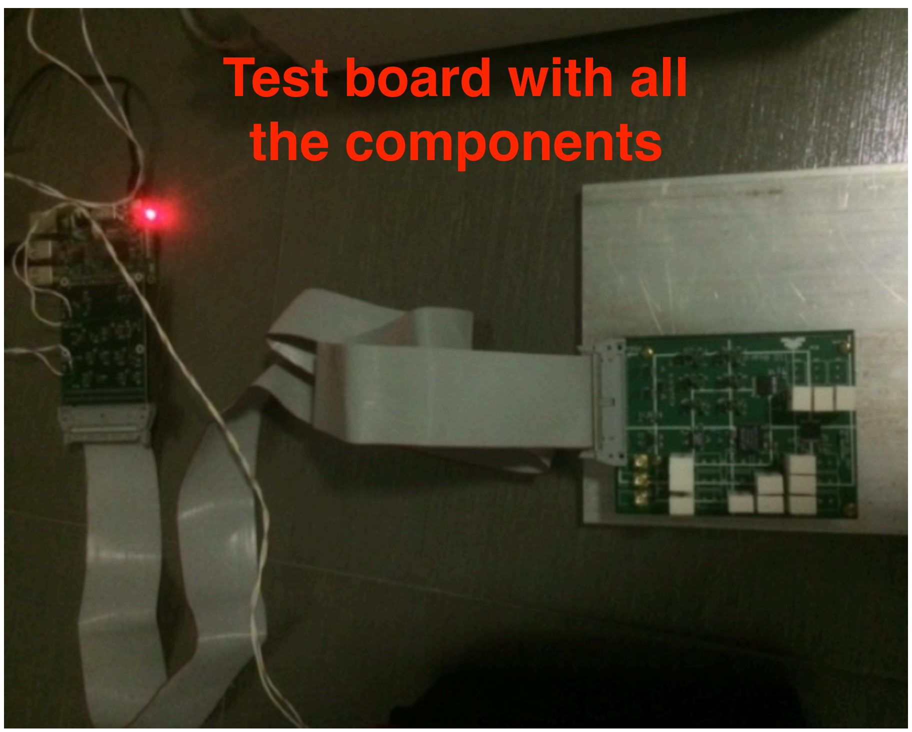


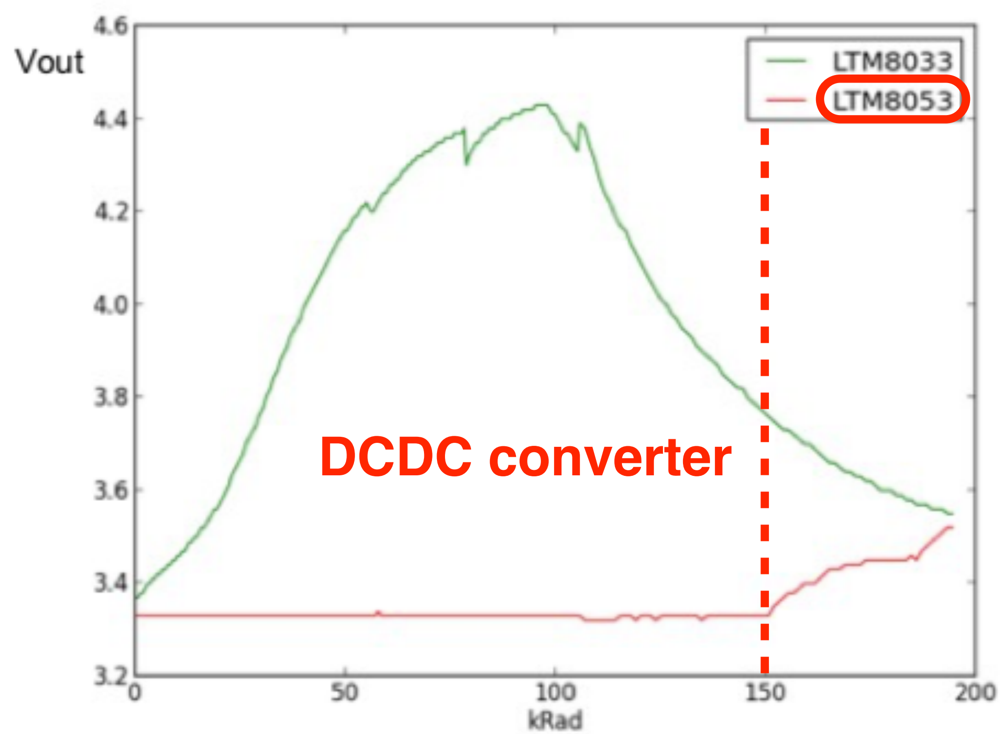
Non Ionizing Energy Loss (NIEL)



Electronics vs radiation

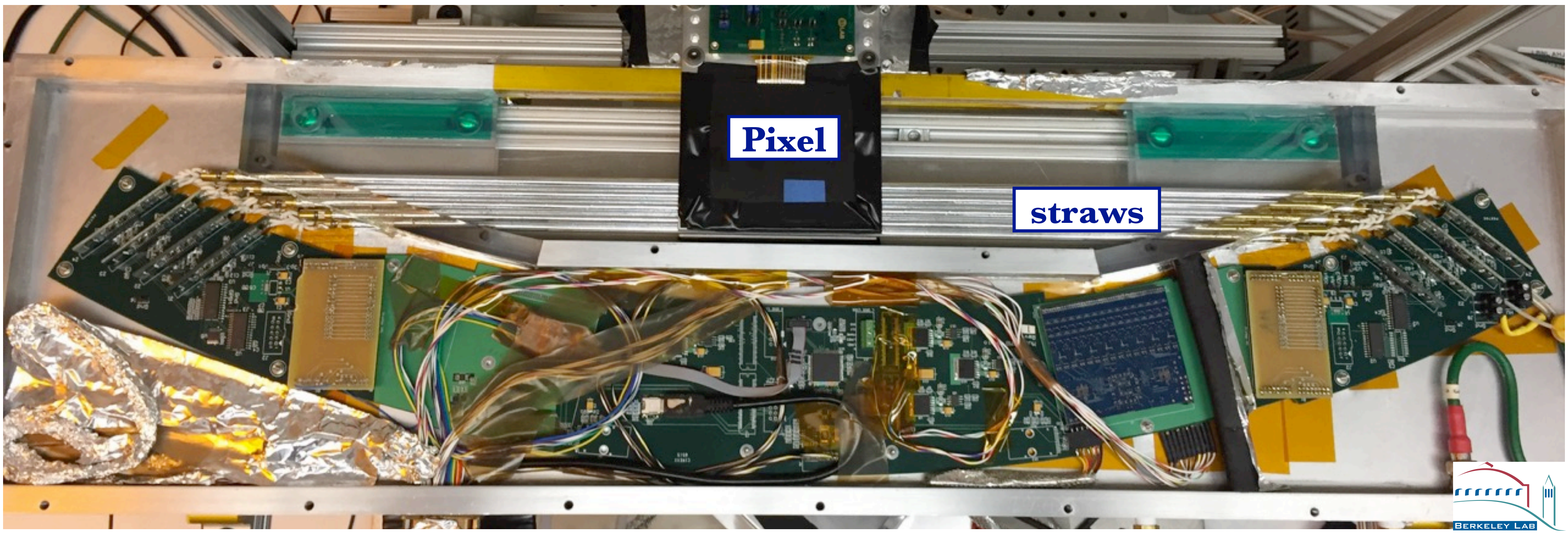
- PolarFire FPGA from Microsemi (tested up to 500 krad)
- rad hard Optical transceiver VTRx from CERN (tested up to 1 Mrad)
- tests campaign to qualify other major components:
  - ✓ TID tests @ local radiotherapy clinic up to 200 krad
  - ✓ NIEL tests @ UC Davis McClellan reactor up tp 2e14 n_{1MeVeq}/cm^2





Prototype

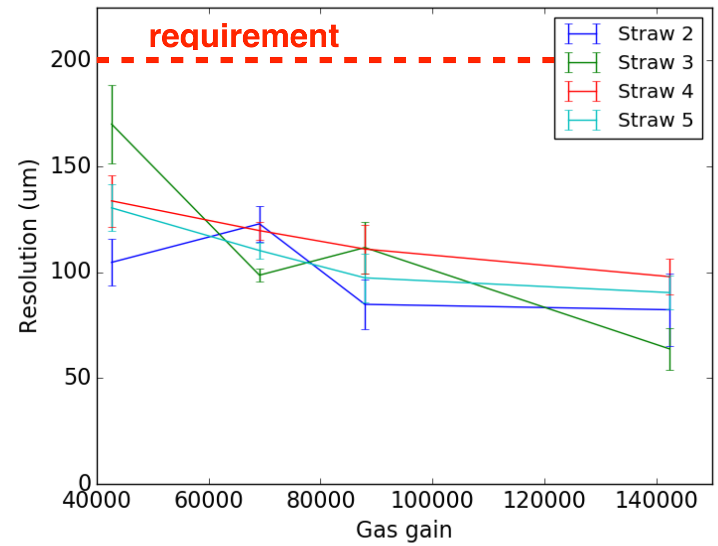
- Small panel prototype with 8 straws used to test performance @ LBL
- Test for cross talk using LBL 88″ cyclotron
- Test with Cosmic rays and radioactive sources to measure performance



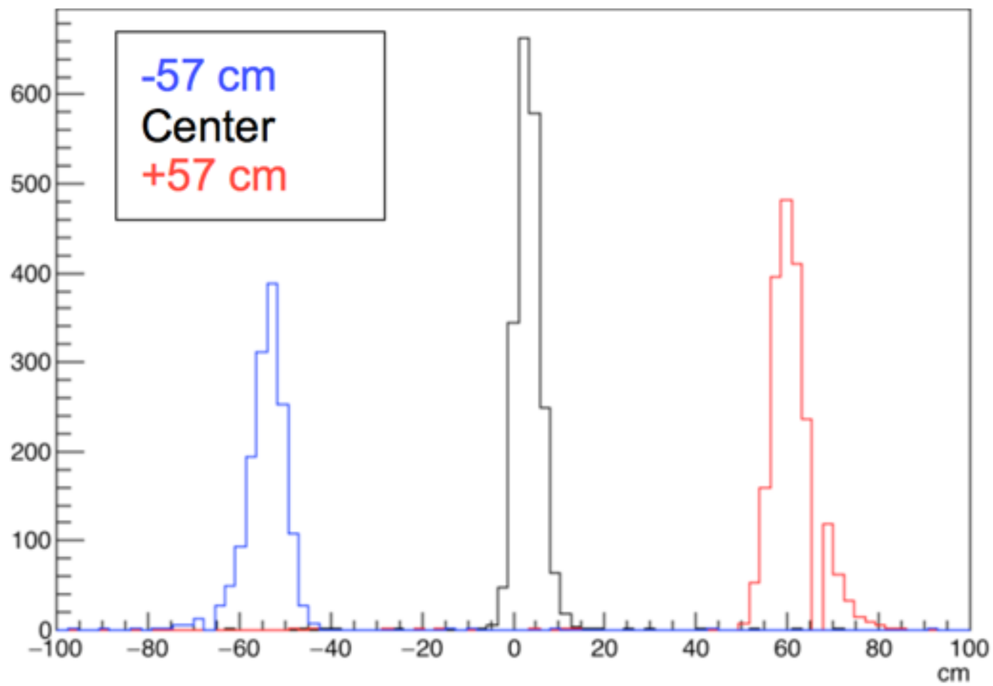
Prototype - Results

- Single hit efficiency and resolution meet requirements

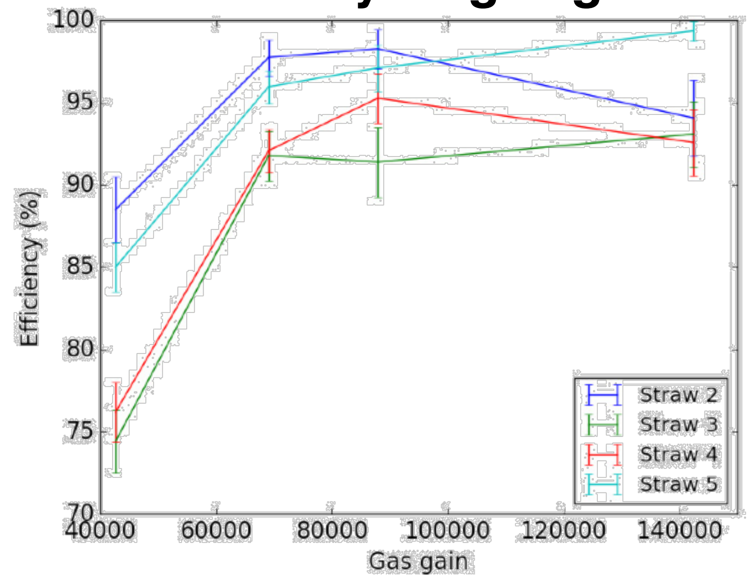
Drift resolution vs gas gain



Position measurement vs source location

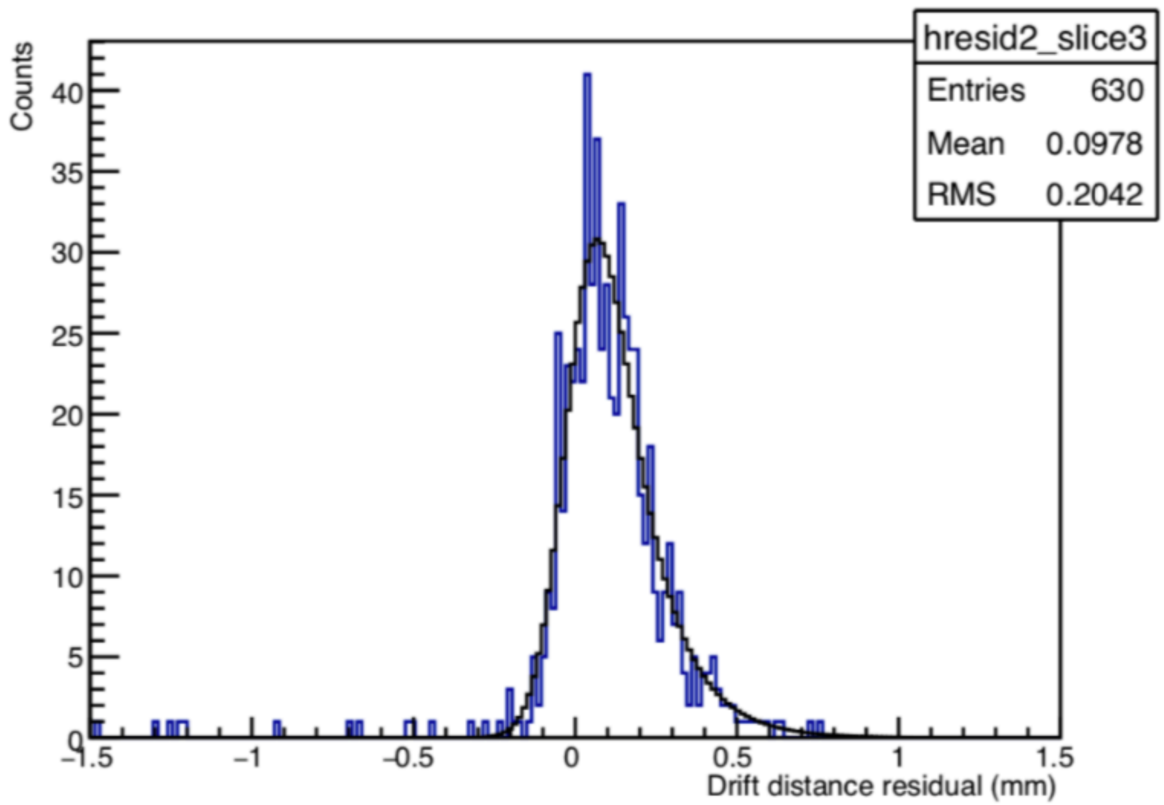


Efficiency vs gas gain

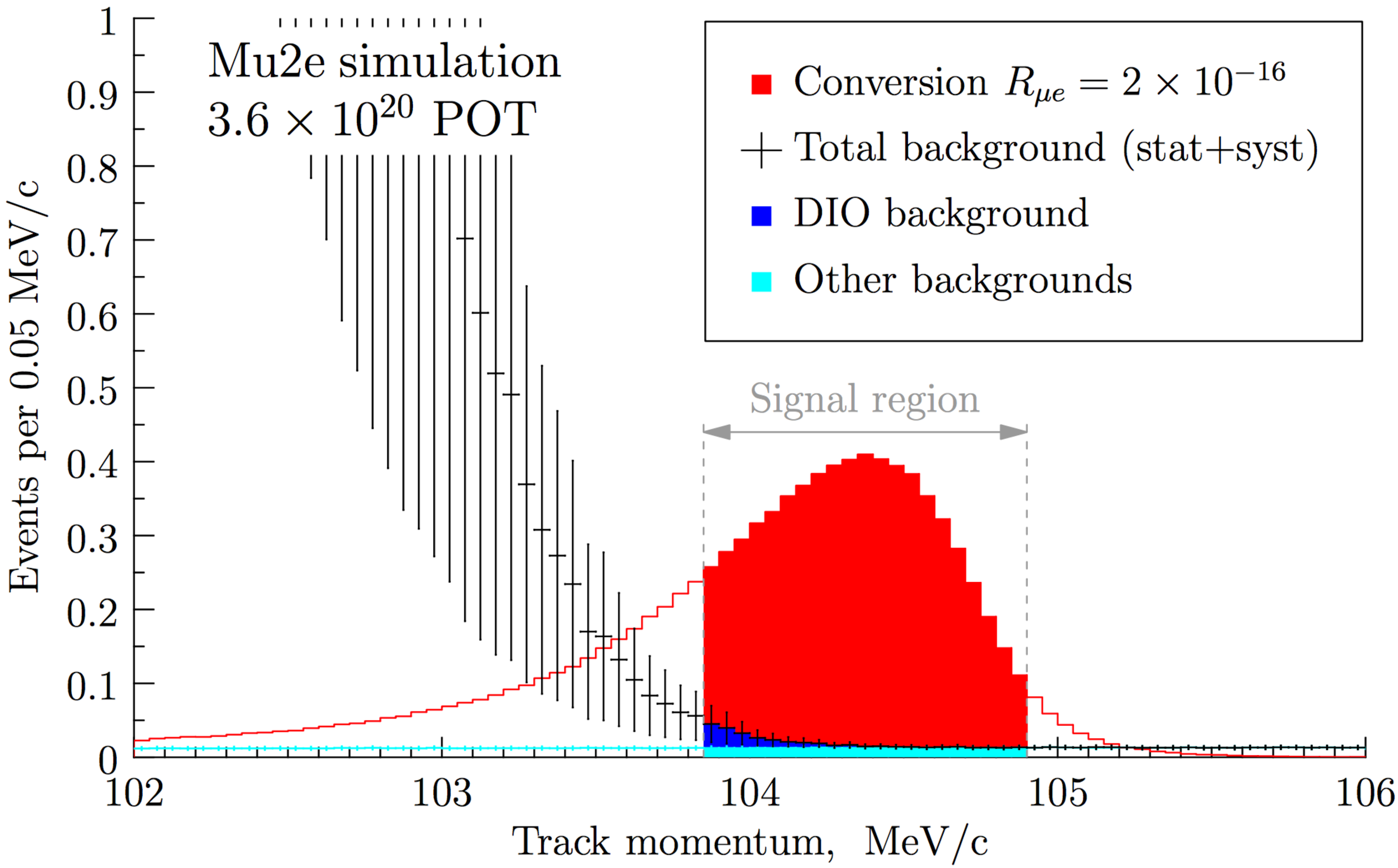


Prototypes

- straw resolution measured for each of the 8 straws using cosmic rays
- Simulation implements detailed model of physical and electronics reposes to G4 energy deposition
  - ✓ Clusters→Drift→Current pulse→Voltage waveform→Digitization
  - ✓ Tuned to literature and prototype

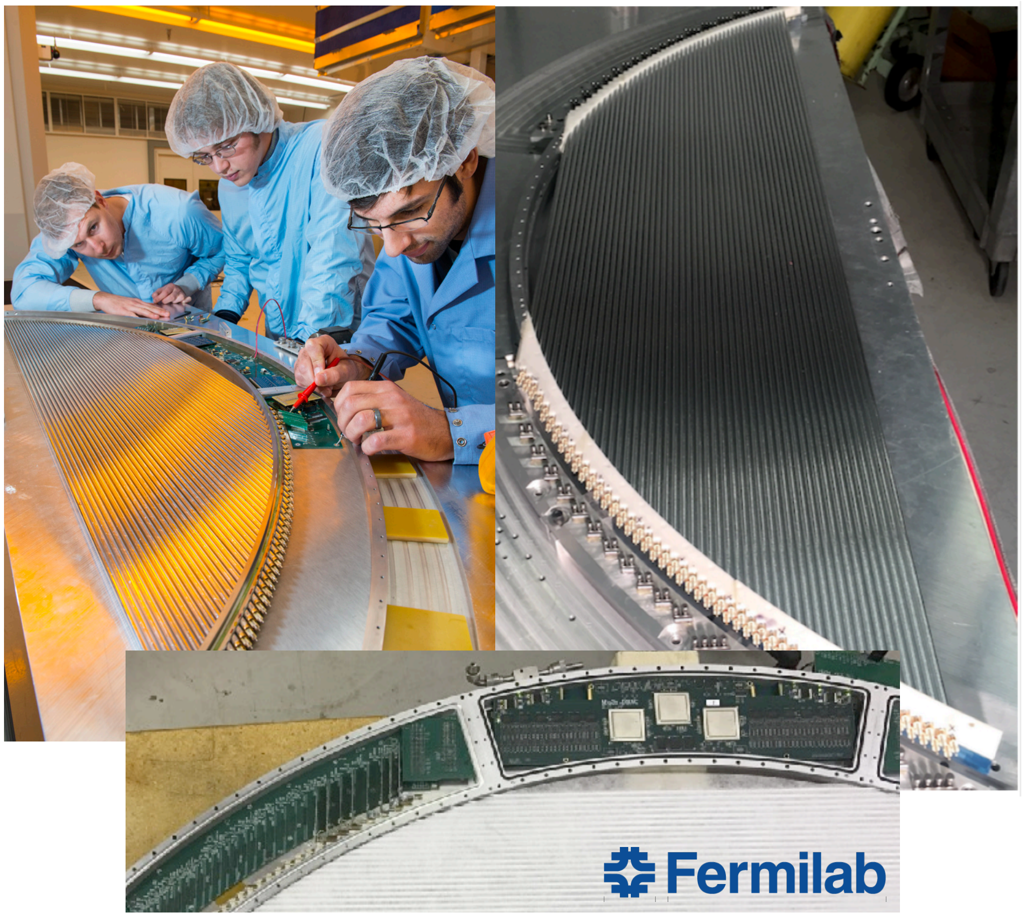


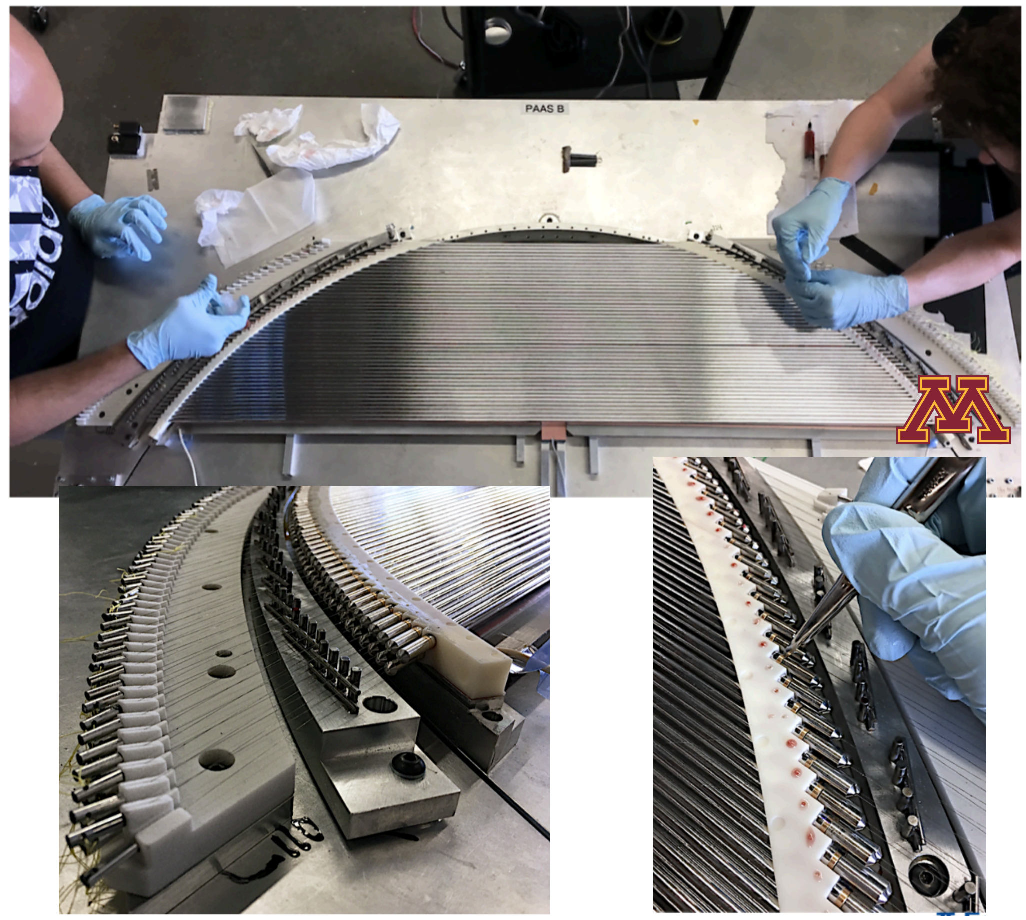
Mu2e sensitivity



Panel production

- Panel assembly @ Univ of Minnesota (with Fermilab and U. Houston)
- Full plane assembled at Fermilab
- QA of panel components @ CUNY, Duke and LBL/UC Berkeley





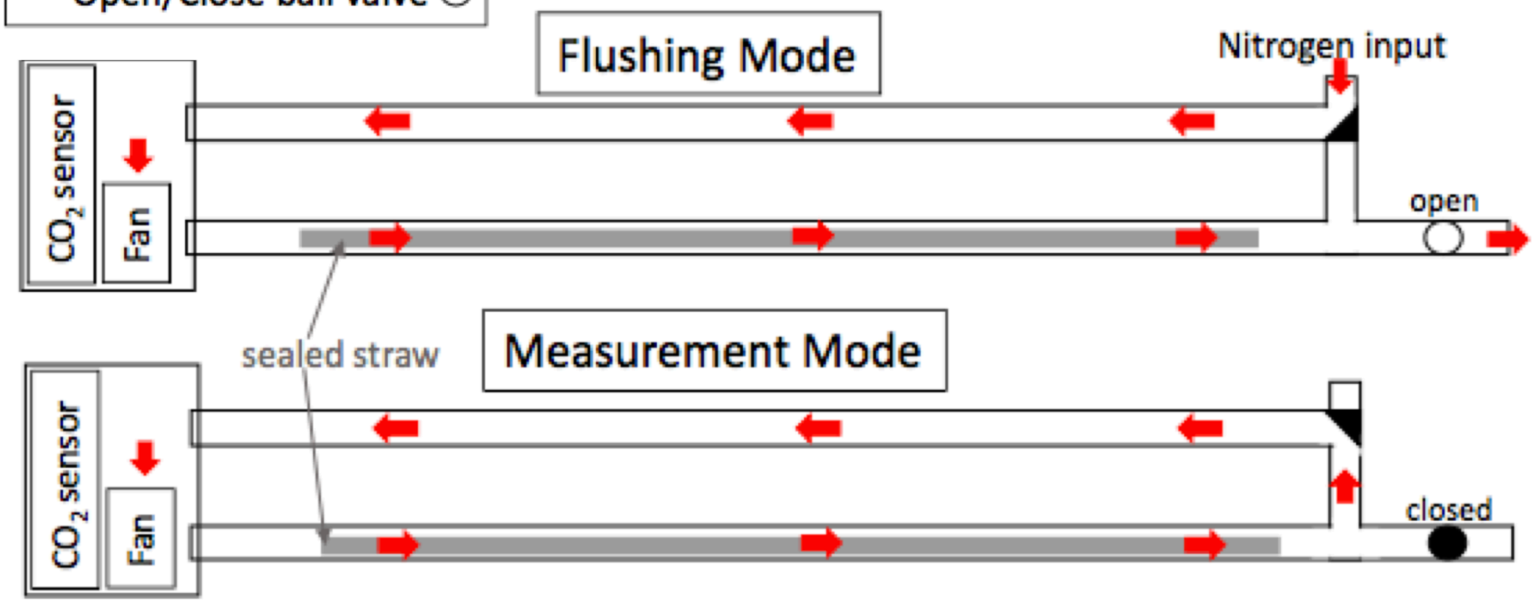
Summary

- Mu2e will improve the sensitivity by four orders of magnitude
- The Mu2e tracker has been designed to:
  - ✓ provide accurate reconstruction of e^- momentum
  - ✓ operate in a very harsh environment (high γ and neutron dose)
- First 3 panels built and already under test:
  - ✓ good agreement of data with our Monte Carlo simulation
- QA process and plane assembly started

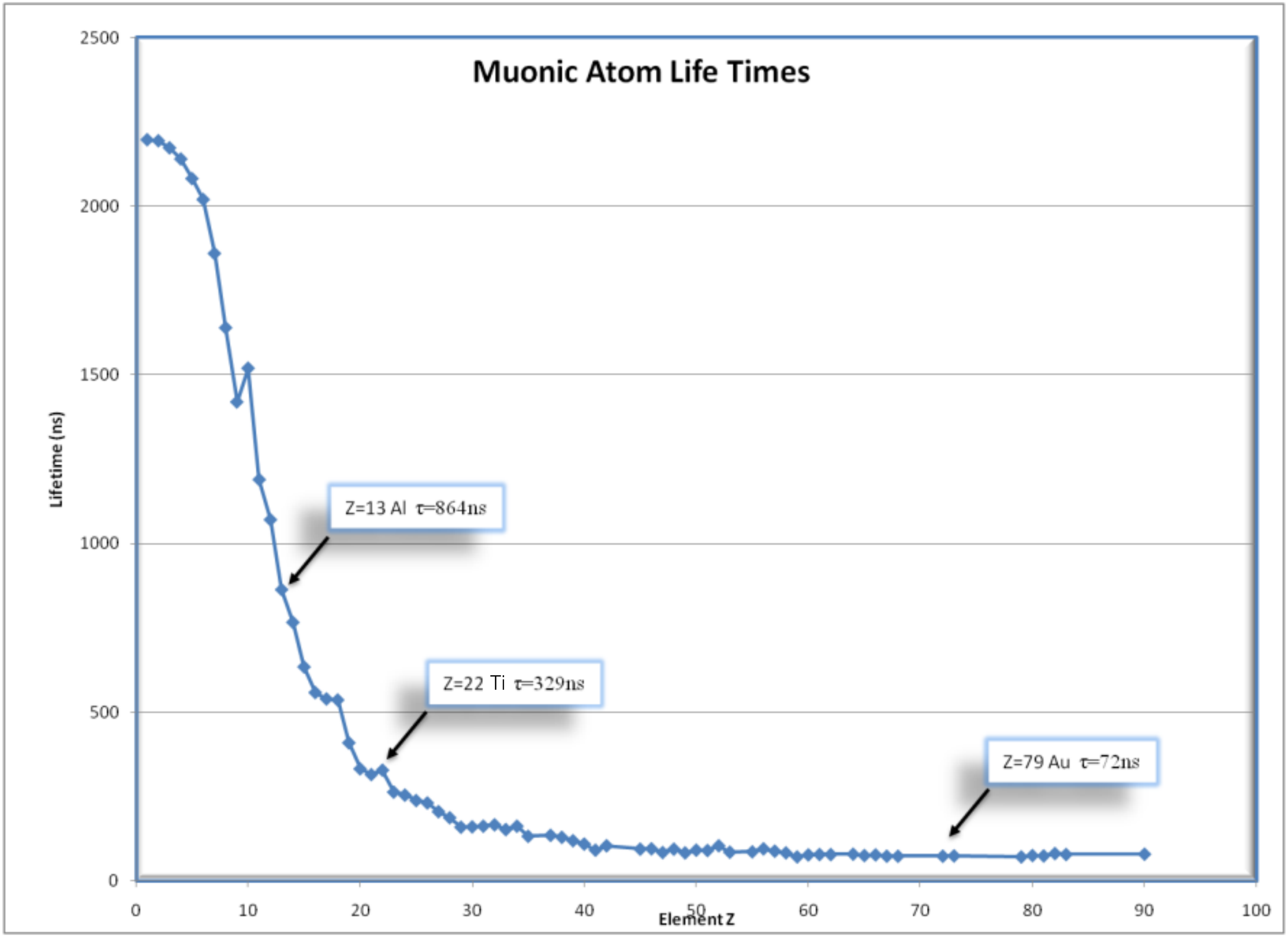
backup slides

Straw leak chamber

Test Chamber parts:
- CO_2 sensor
- Fan
- ½" copper pipe
- 3 way ball valve ◢
- Open/Close ball valve ○

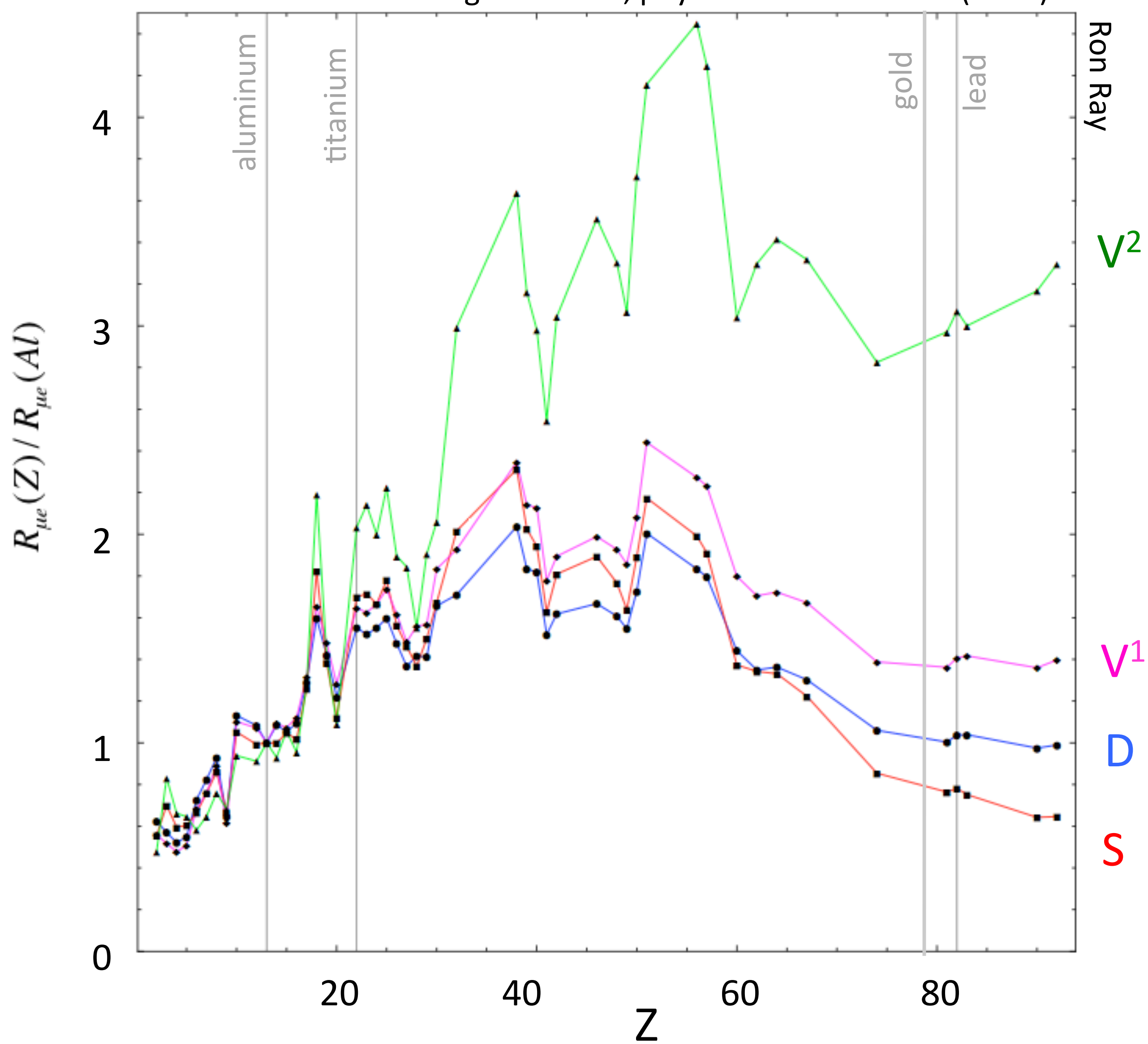


Muonic atom life times



$R_{\mu e}$ rate vs Z

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



Mu2e sensitivity

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

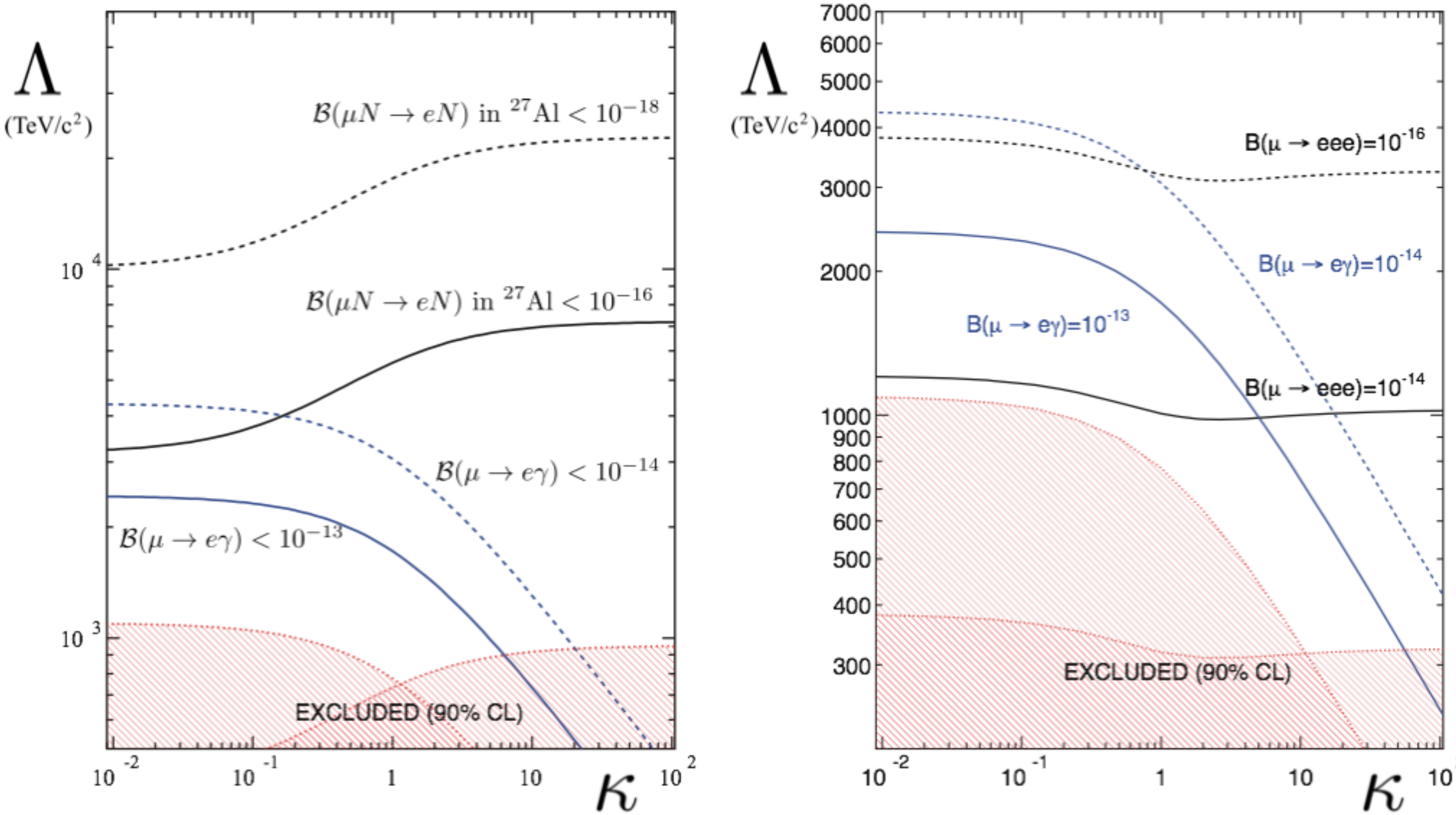
★★★ = Discovery Sensitivity

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

arXiv:0909.1333[hep-ph]

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.

Model independent Lagrangian



$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right)$$

"dipole term" **"contact term"**

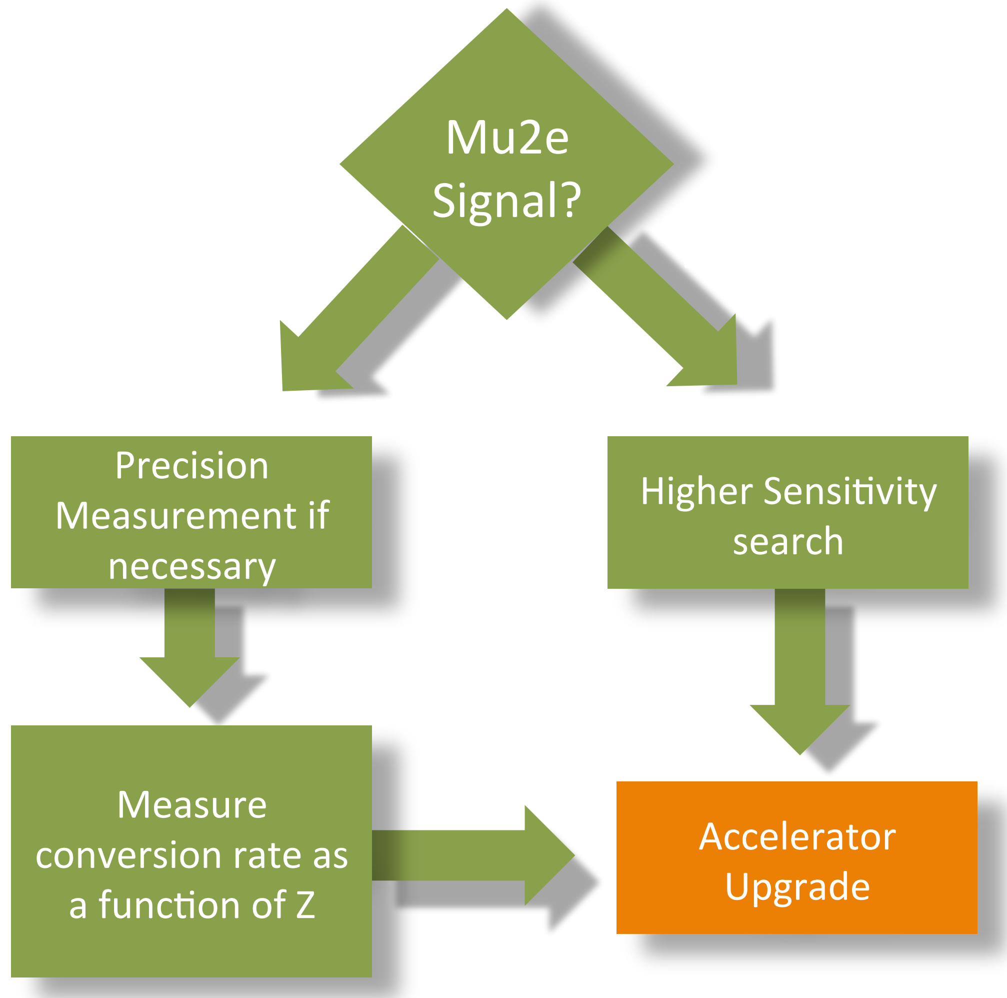
CLFV limits I

Process	Upper limit
$\mu^+ \to e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$< 1.7 \times 10^{-12}$
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 3.0 \times 10^{-13}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to e^-e^+e^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-\mu^+\mu^-$	$< 2.1 \times 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$< 1.8 \times 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$< 1.7 \times 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$< 1.5 \times 10^{-8}$

CLFV limits 2

Process	**Upper limit**
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$
$K^0_L \to \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \to \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$
$K^0_L \to \pi^0 \mu^+ e^-$	$< 4.4 \times 10^{-10}$
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \to \tau \mu$	$< 1.2 \times 10^{-6}$

Mu2e signal?



- A next-generation Mu2e experiment makes sense in all scenarios:
  - ✓ Push sensitivity or
  - ✓ Study underlying new physics
  - ✓ Will need more protons upgrade accelerator
  - ✓ **Snowmass** white paper, arXiv:1802.02599

Mu2e detector hall

put solenoid pictures here!!!