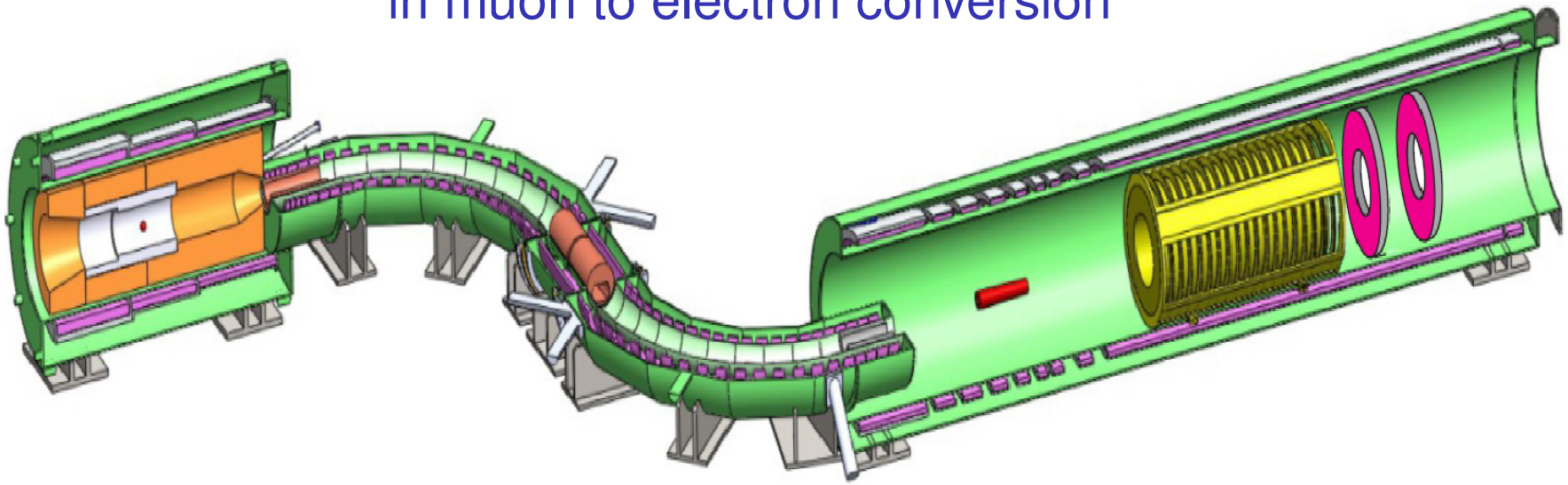
The Mu2e experiment

A search for charged lepton flavor violation in muon to electron conversion



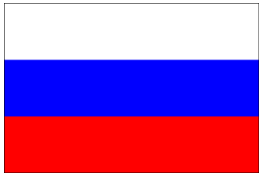
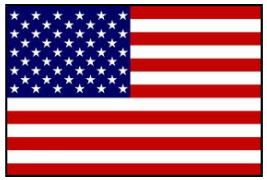
Andrei Gaponenko (Fermilab)
on behalf of the Mu2e Collaboration

http://mu2e.fnal.gov/collaboration.shtml

PSI2016

Mu2e collaboration

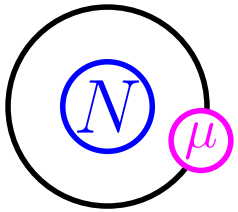


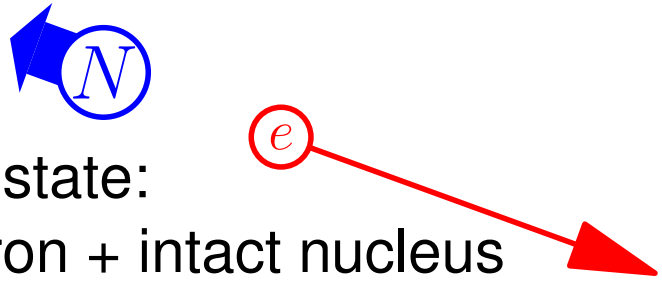
Over 200 scientists from 34 institutions

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, 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

$\mu \to e$ conversion:



Initial state:
muonic atom at rest



Final state:
electron + intact nucleus

Conventional normalization: $R_{\mu e} = \Gamma(\text{conversion})/\Gamma(\text{capture})$

Theoretical features

- SM: $R_{\mu e} \sim 10^{-52}$: no theory uncertainty
- Sensitivity to broad range of BSM models

Experimental features

- Signal: electron at 104.97 MeV (Al)
- Single particle—scales well with μ rate

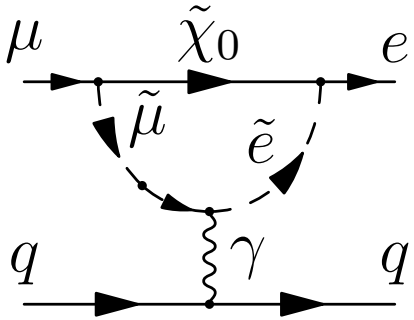
Extremely powerful probe of BSM

Mu2e goals

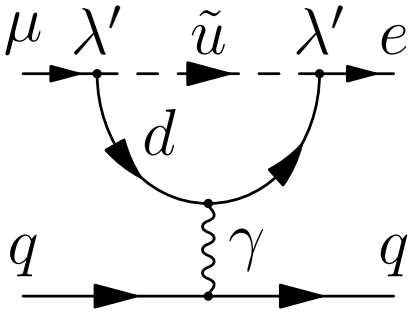
- Aim for a factor of 10 increase in the mass reach
  - Think Tevatron to LHC change
- Best previous measurement (SINDRUM II, gold nucleus):
  Single event sensitivity: $S^1_{\mu e} = 2.5 \times 10^{-13}$
  $R_{\mu e} < 7 \times 10^{-13}$ 90% CL [Eur.Phys.J C47(2006)]
- Indirect search: must improve sensitivity by 10^4
  - Single event sensitivity goal 2.5×10^{-17}
- Leading New Physics models predict $\mu N \to eN$ signal in this range!

Mu2e can discover

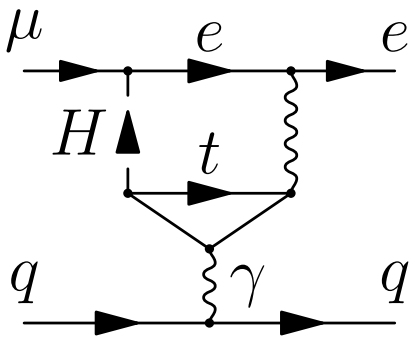
SUSY



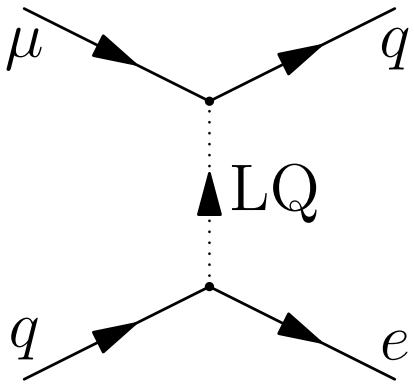
RPV SUSY



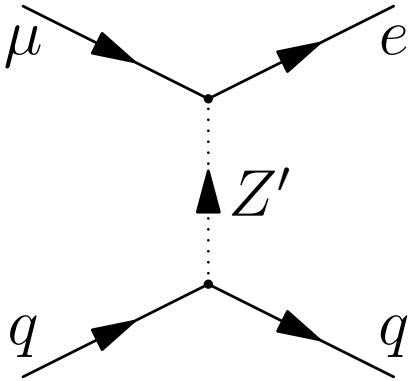
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

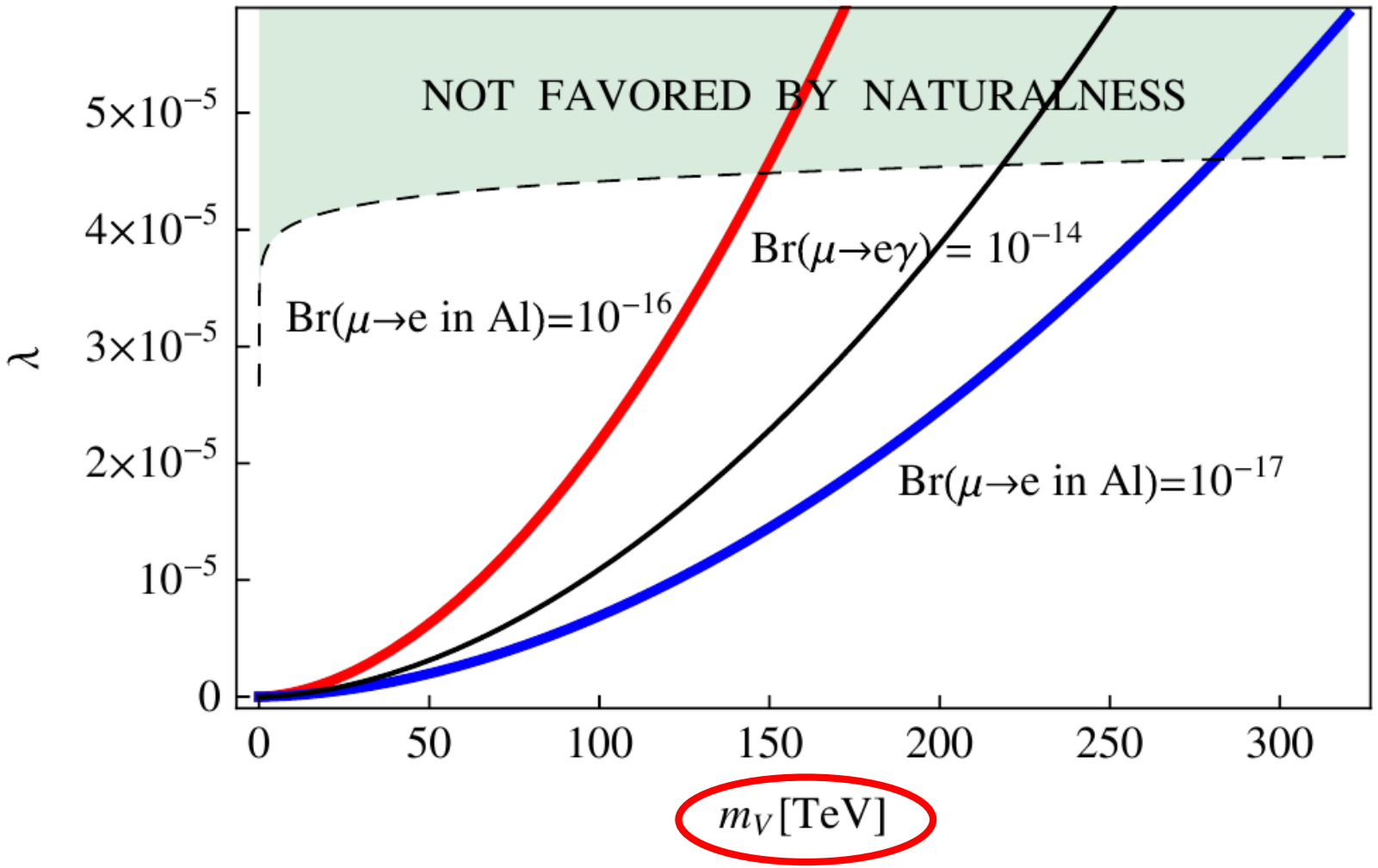
Y. Kuno, Y. Okada, 2001

M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013

Mu2e mass scale reach example

Combination of couplings vs scalar leptoquark mass



J.M. Arnold, B. Fornal, M.B. Wise
*Phys.Rev.**D88**(2013)035009*

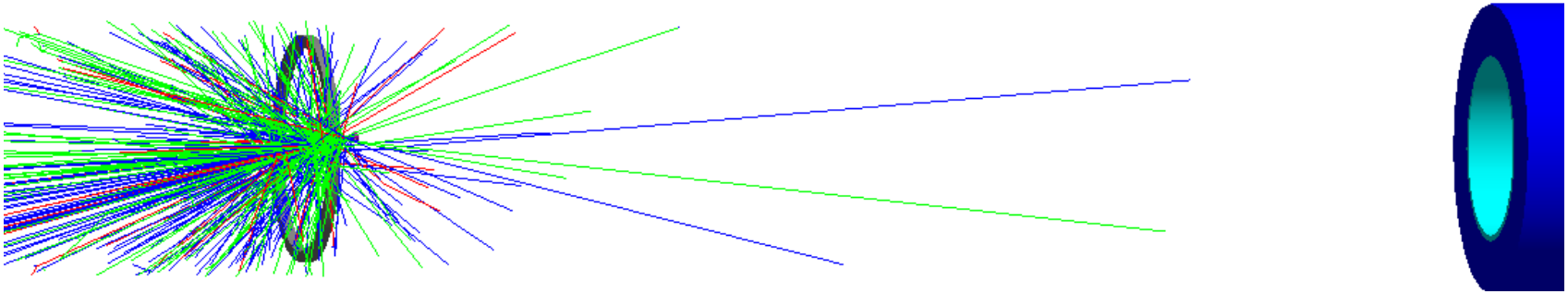
From SINDRUM II to Mu2e

- SINDRUM II:
  - $\mathcal{O}(10^7)$ muon stops per second
  - with $\mathcal{O}(1\ \text{MW})$ proton beam
- Mu2e single event sensitivity goal 2.5×10^{-17}
- Need $\mathcal{O}(10^{18})$ muon stops
  - thousands years of data taking?
  - GW proton beam is not an option...

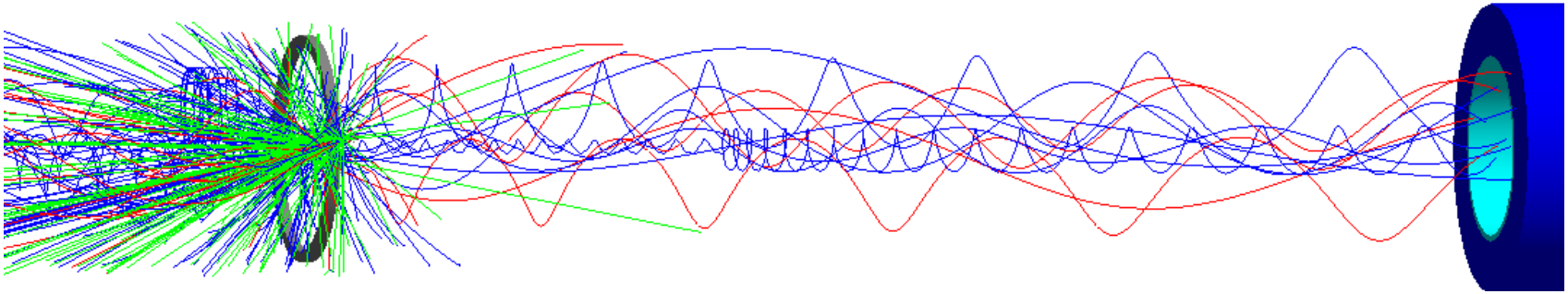
A more energy efficient way to get the rate

R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys **49**, 384 (1989)

Instead of this



Do this



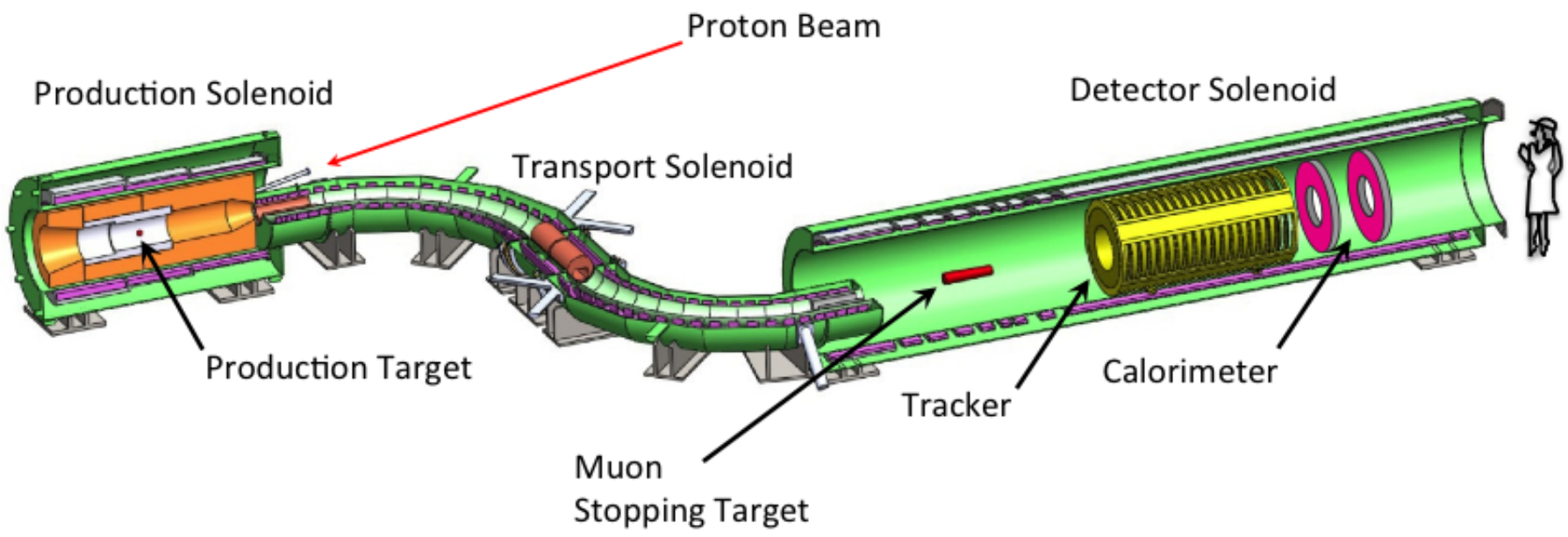
Solenoidal *B* field confines soft pions. Collect their muons.

Mu2e: $> 10^{10}$ μ^-/s from only 8 kW of protons!

The concept of the measurement

- Make muons
- Collect and stop them
- Wait for prompt backgrounds to decay
  - Mu2e beam pulse spacing: 1695 ns
  - Muonic Al lifetime: 864 ns
- Look for electrons at conversion energy

Mu2e setup

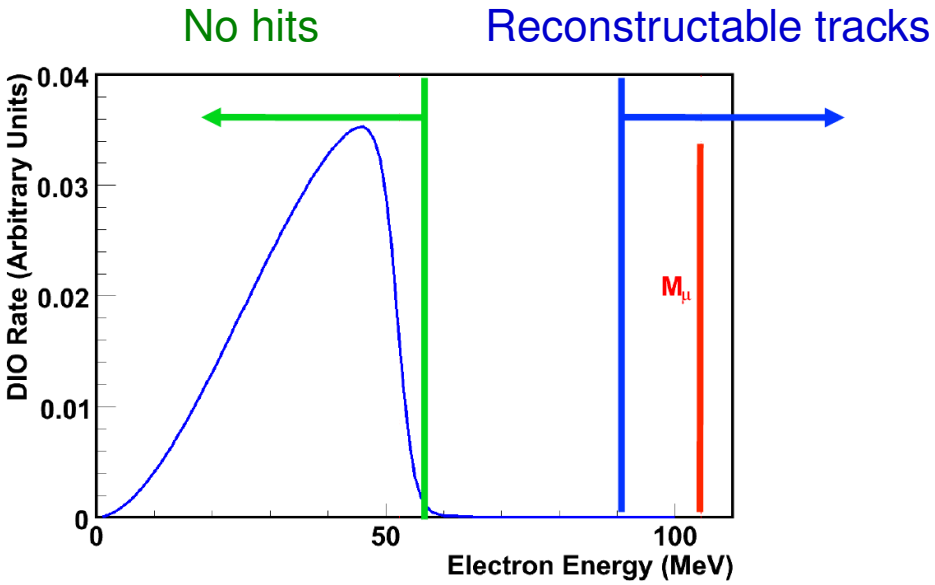


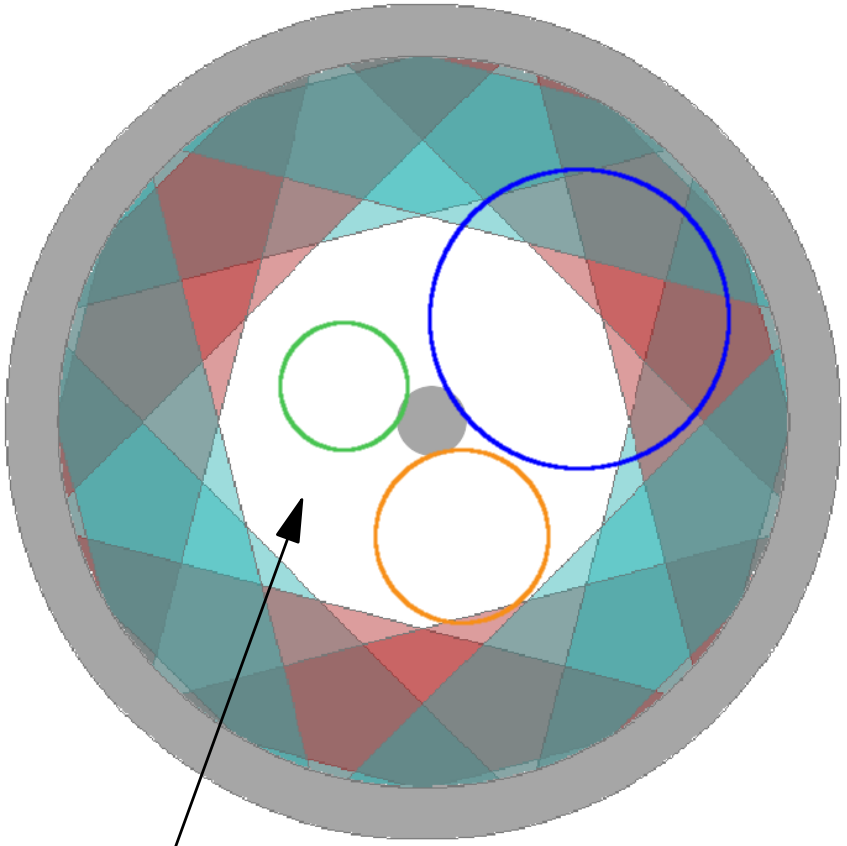
Muon beamline: B 4.6 $\longrightarrow$ 1 T, negative gradient
Tracker+calo region: uniform $B = 1$ T
Charge selection using a rotating collimator
Symmetric detectors: measure e^- and e^+

Not shown: Cosmic Ray Veto, beam Extinction Monitor, Stopping Target Monitor

How to measure 2.5×10^{-17}

Be blind to most tracks: annular design

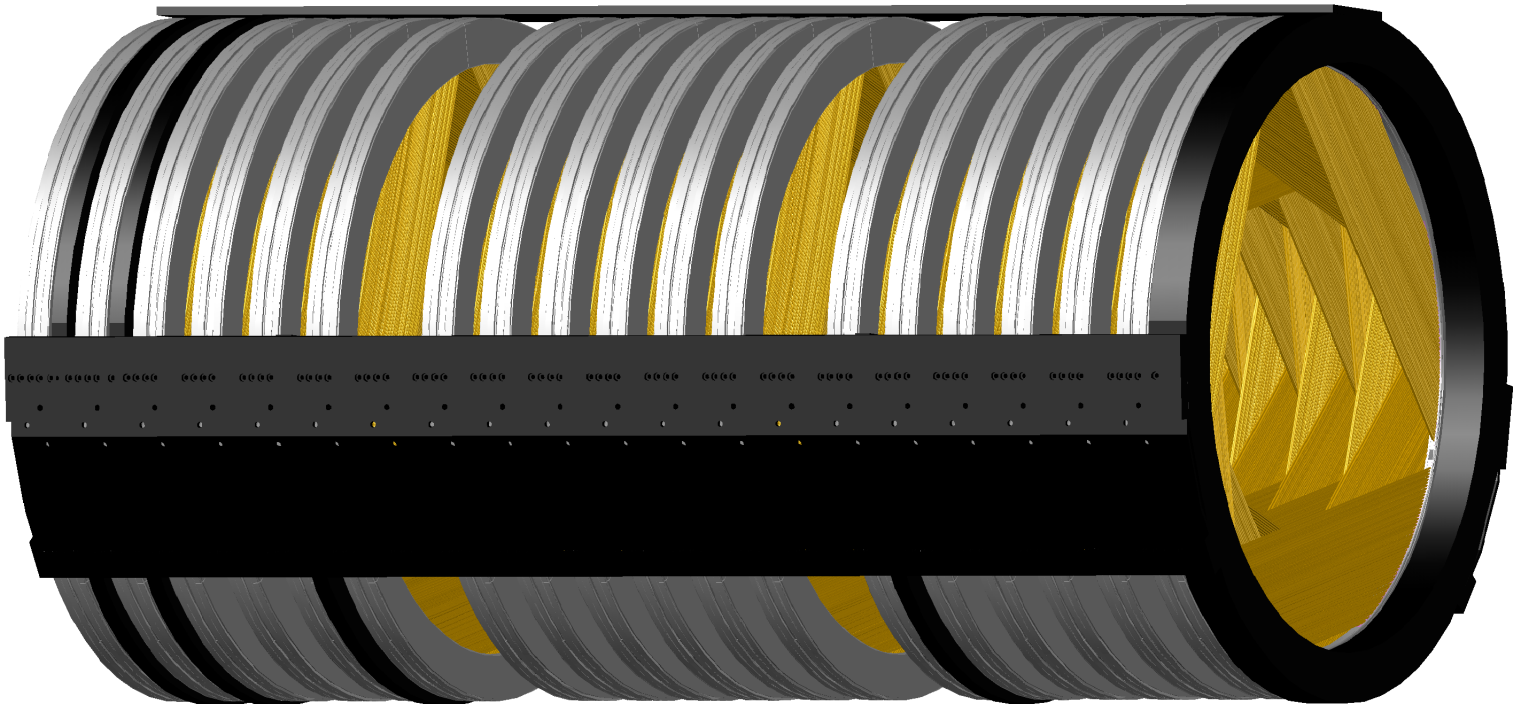




Vacuum: no scattering

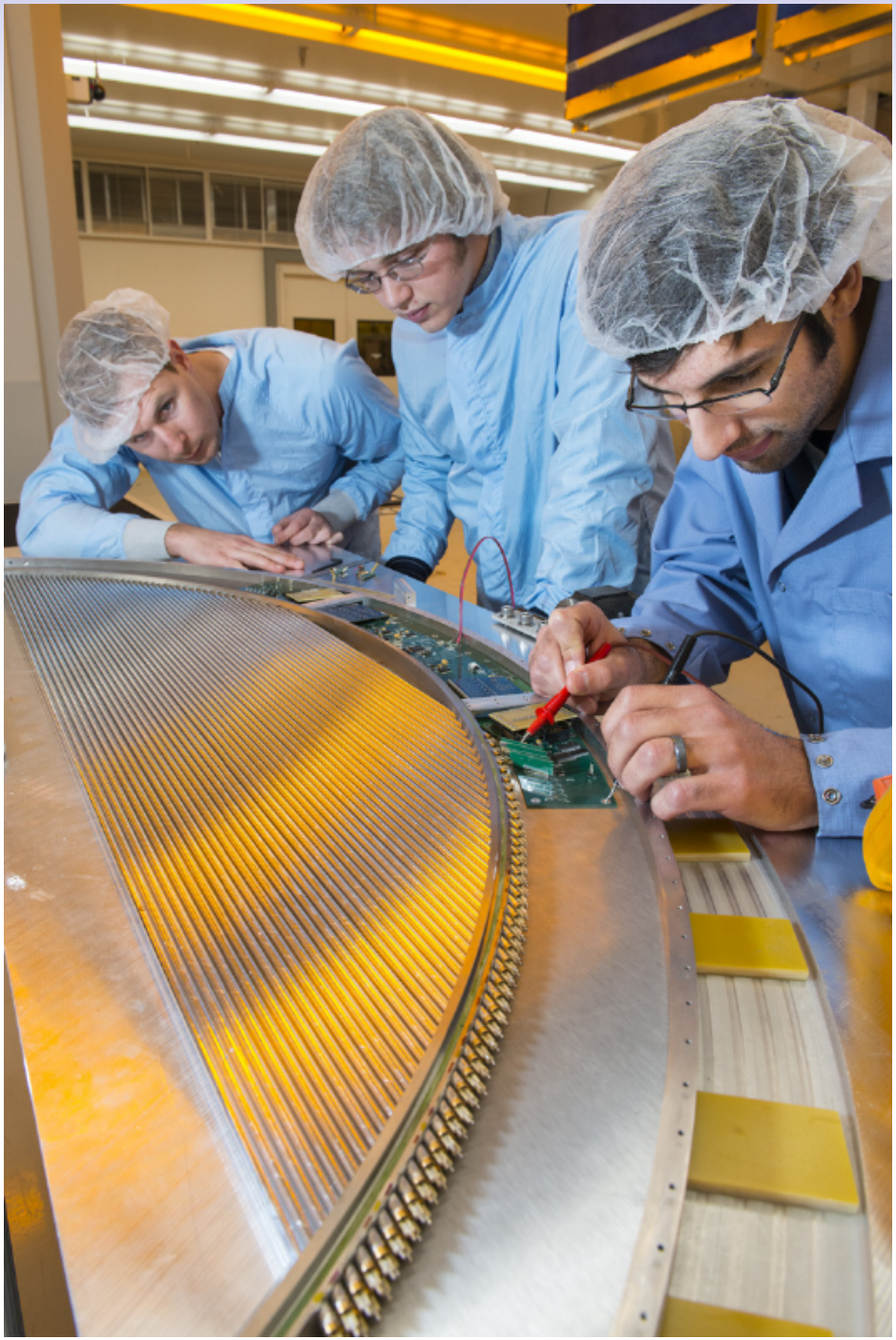
Tracker

Precise momentum measurement



- about 3 m long
- 1 T B field
- “Good” tracks make 1.5–2 turns

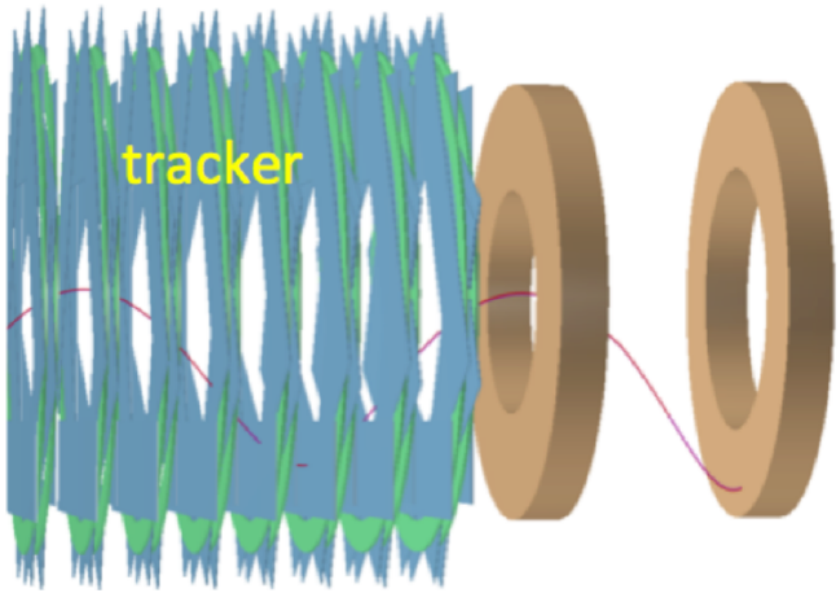
Work on prototype tracker panel



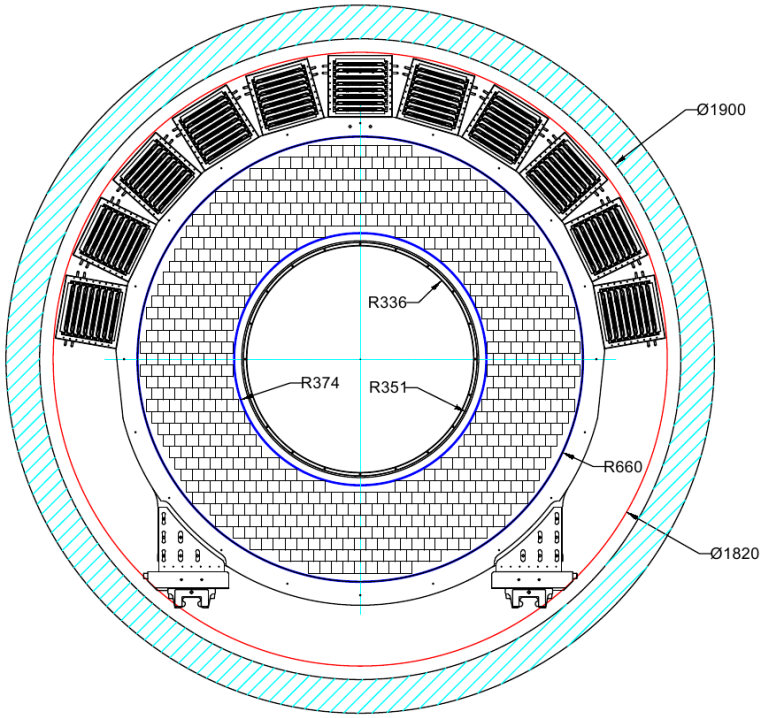
Calorimeter

Particle ID to suppress some backgrounds

Two disk geometry



CsI crystals



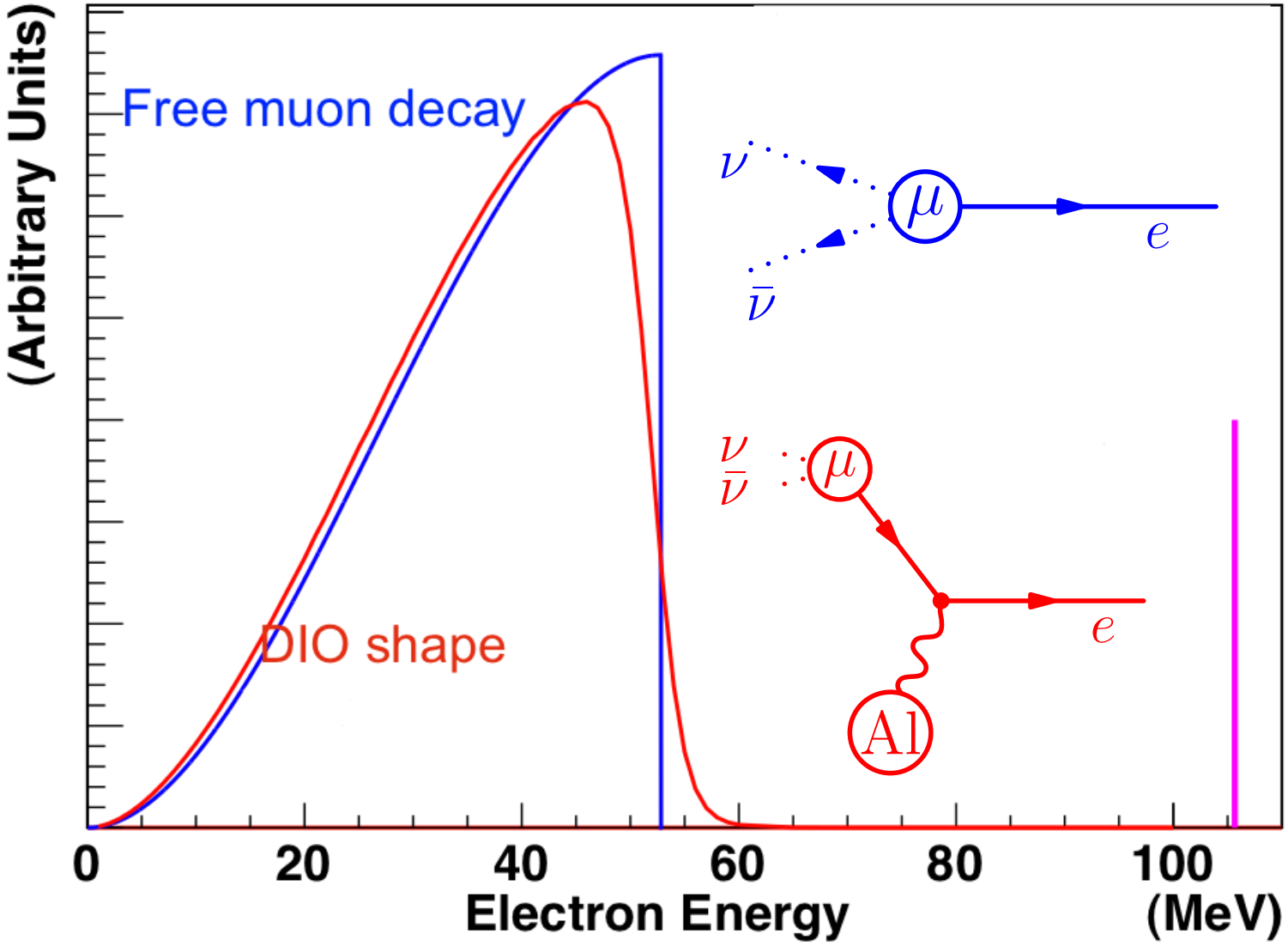
Also provides precise timing, alternate track seed.

Calorimeter: testing the crystals

Types of backgrounds

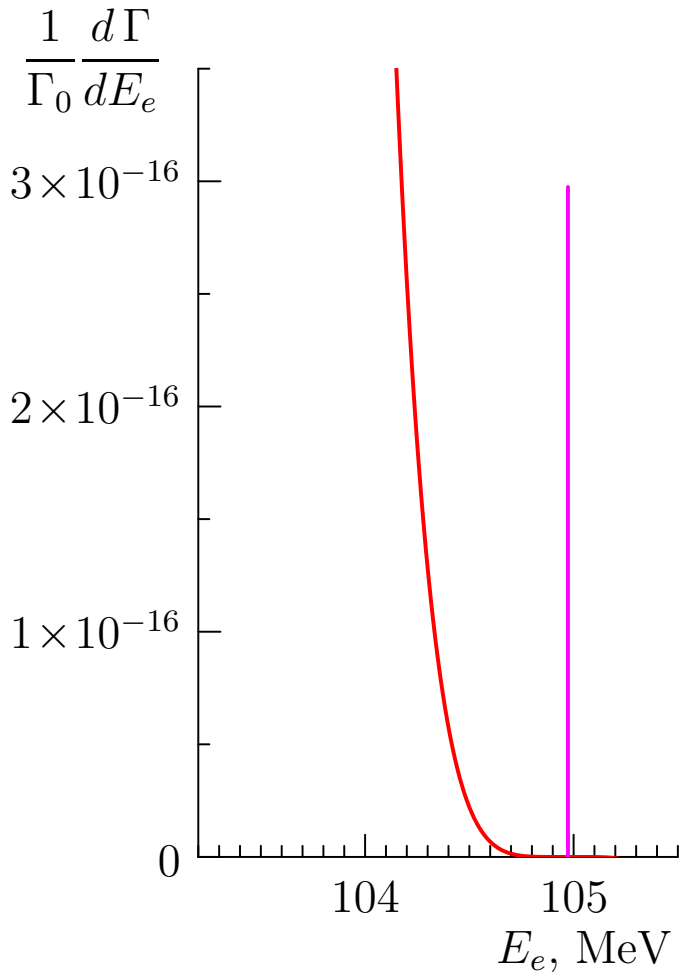
- Muon induced
  - Muon decay in orbit (DIO)
- Protons arriving out of time
  - Radiative pion capture
  - Muon decay in flight
  - Pion decay in flight
  - Beam electrons
- Long transit through muon beamline
  - Antiprotons
- Cosmic rays

Decay electron spectra



Decay in orbit

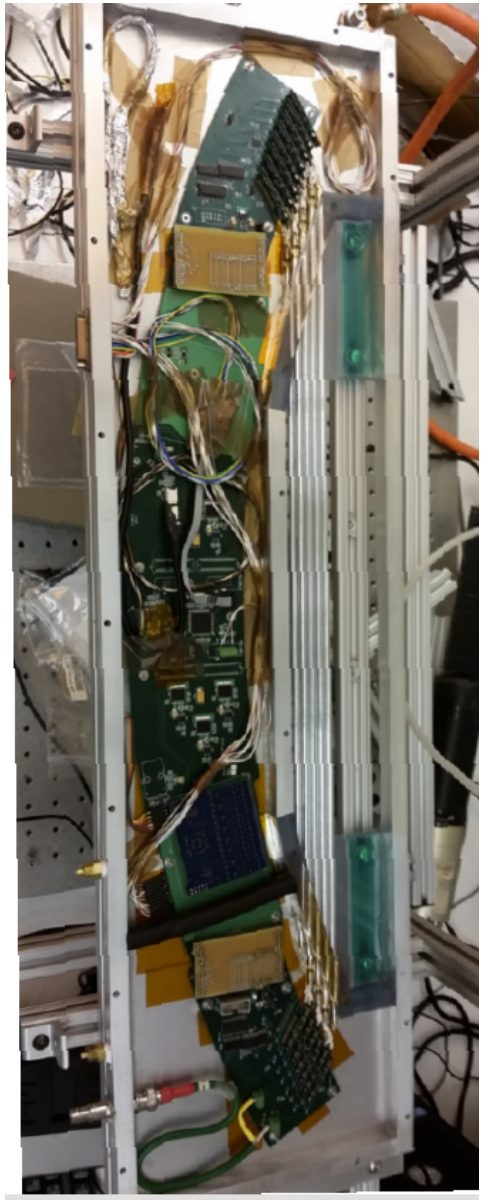
- Small, but steep tail
- Theory prediction: R. Szafron, A .Czarnecki, Phys. Rev. D**94**(2016)051301
- DIO electron differs from signal only by its momentum
- High tail of detector resolution pushes DIO “wall” into signal window
- Must understand resolution in detail!



Understanding the tracker

First principle hit simulation

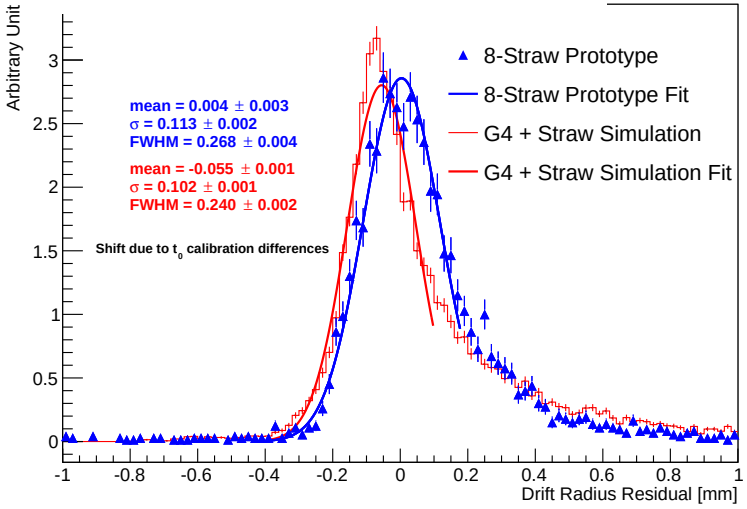
- Gas cluster formation
- Drift
- Avalanche amplification
- Signal propagation along the wire
- Analog and digital electronics response
  - Saturation, deadtime, cross-talk, bandwidth, electronics noise...
- Detector-like output hits
- Resolution and efficiency are emergent effects



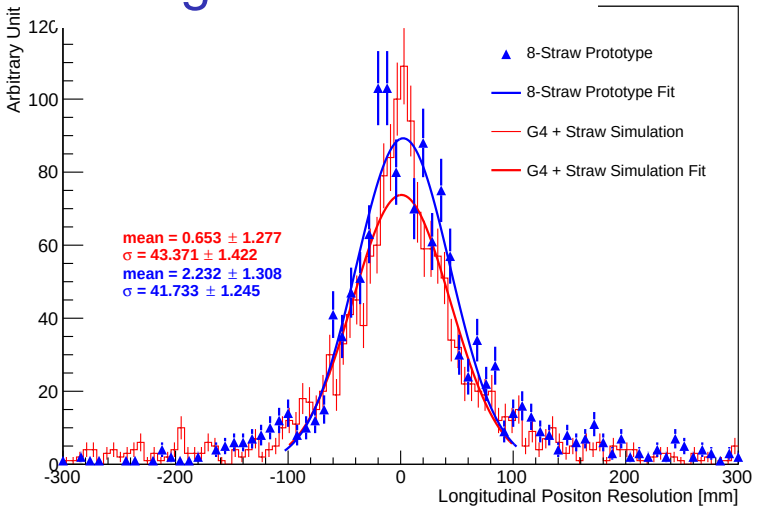
Functional 8-straw prototype

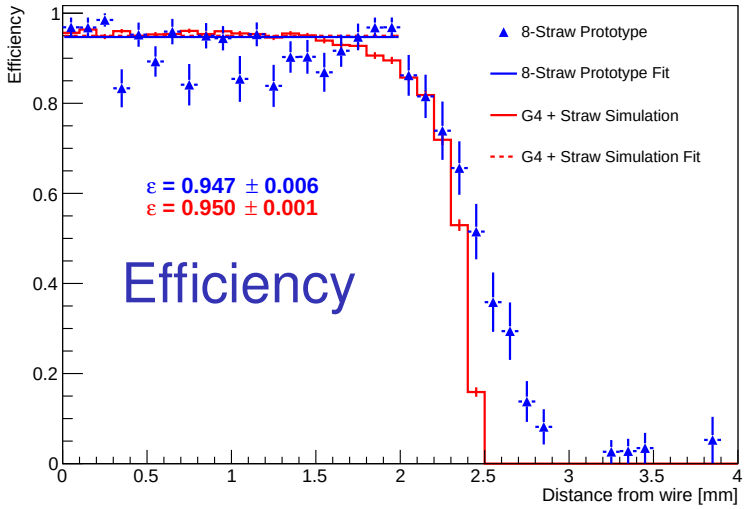
Tracker *hit* simulation vs prototype

Transverse resolution



Along wire resolution

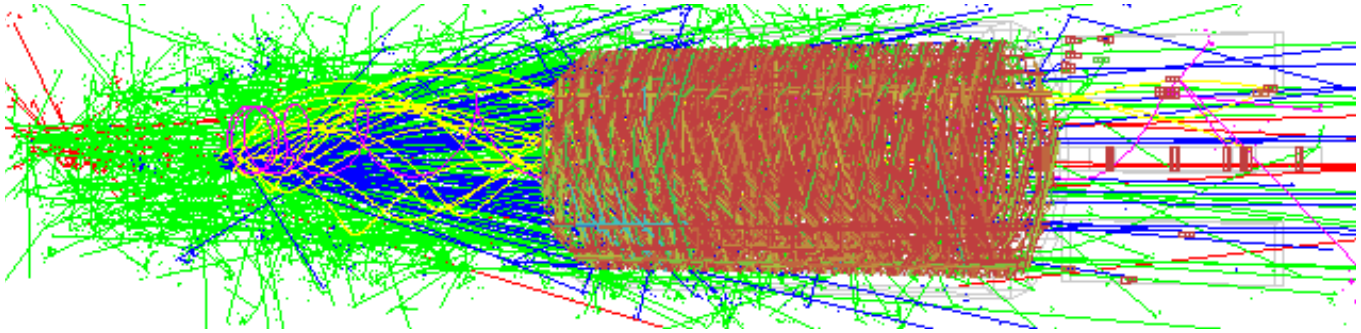




Compare PROTOTYPE measurements to SIMULATION

Mu2e *event* simulation (pile-up)

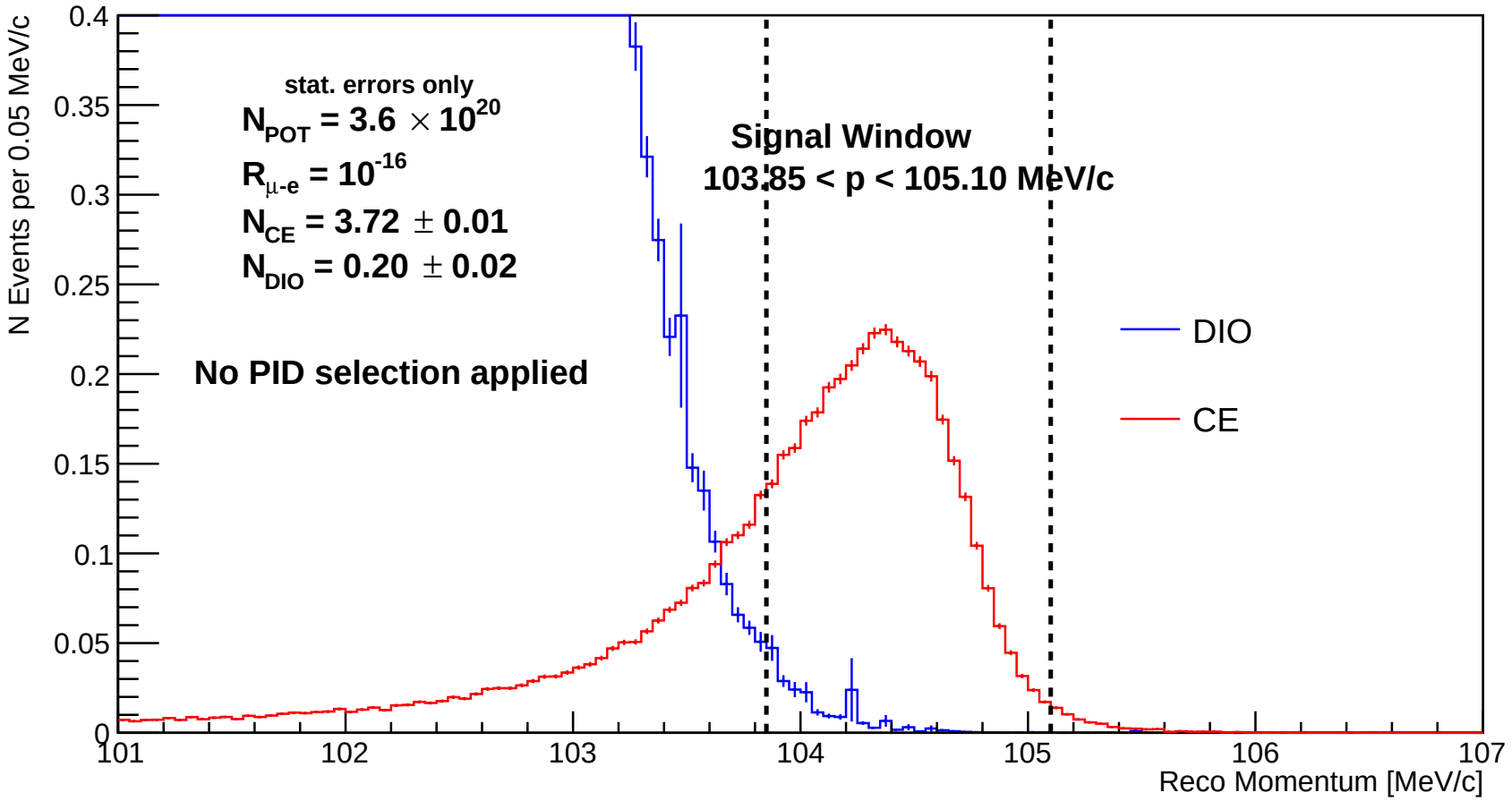
- Hit digitization is validated
- Beam pulse: 39M $\pm$ 50% protons
- Combine charge depositions and digitize



Particles and hits in 500–1695 ns time window

- Find and fit conversion tracks in mock data

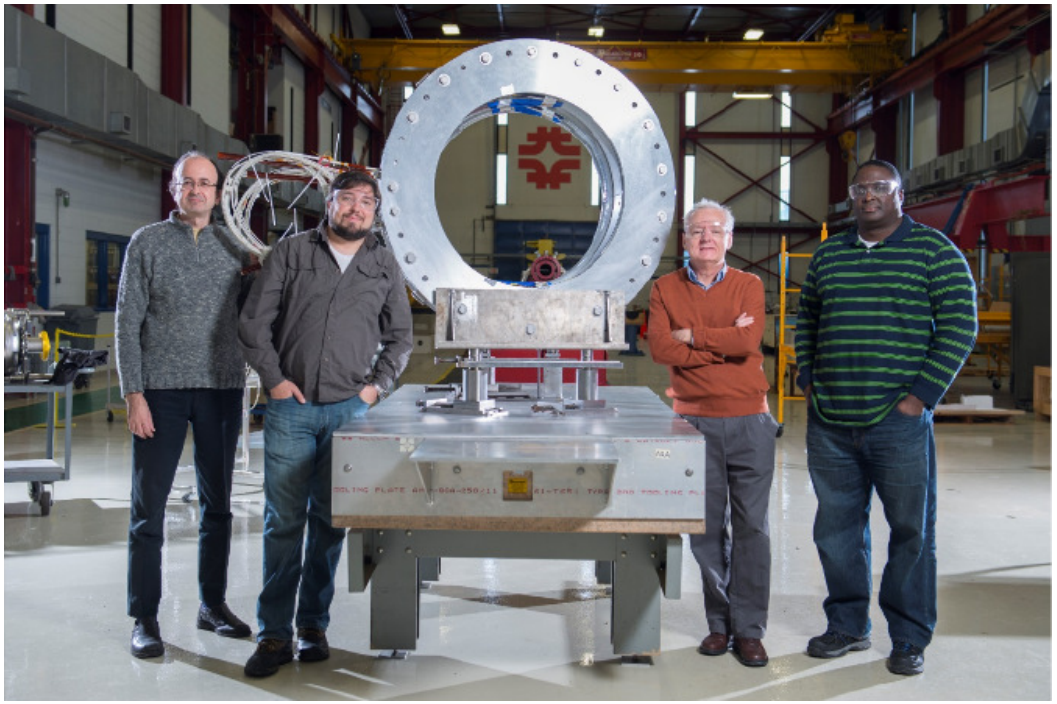
Separation of signal and DIO background



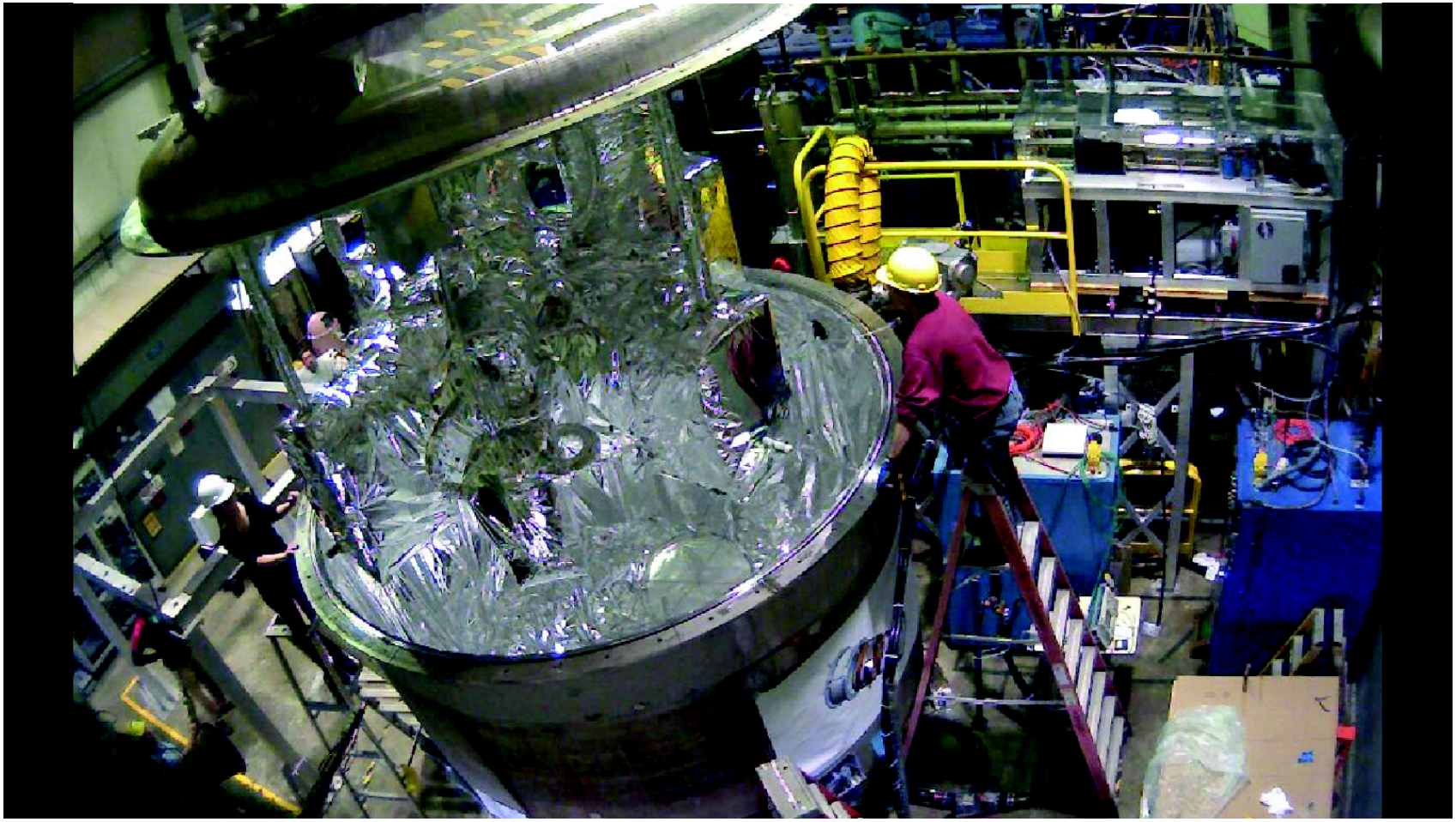
More Mu2e prototypes. . .

Cosmic ray veto

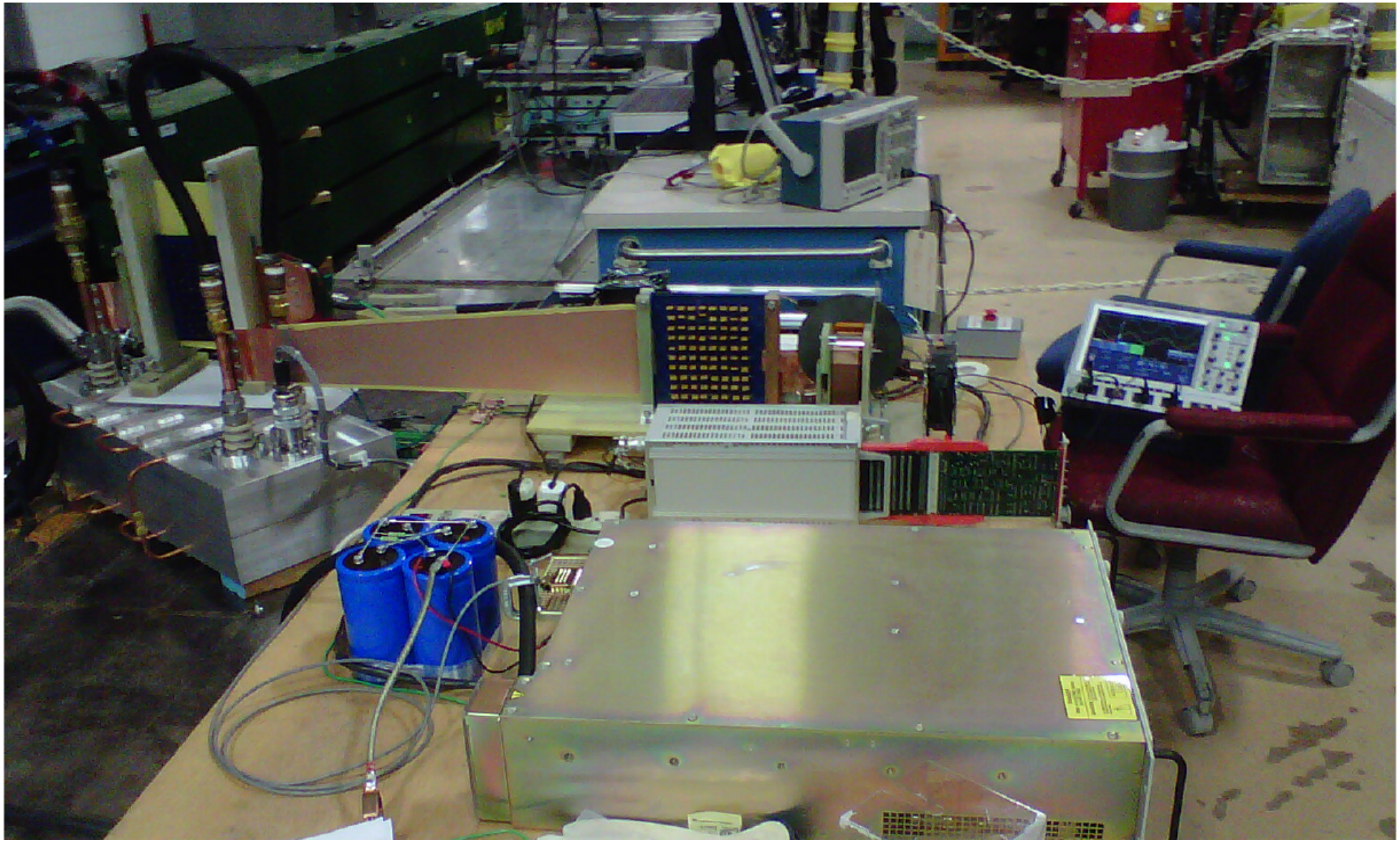
Transport solenoid



Cold test of a TS module



Testing extinction dipoles



Mu2e slide at PSI2013

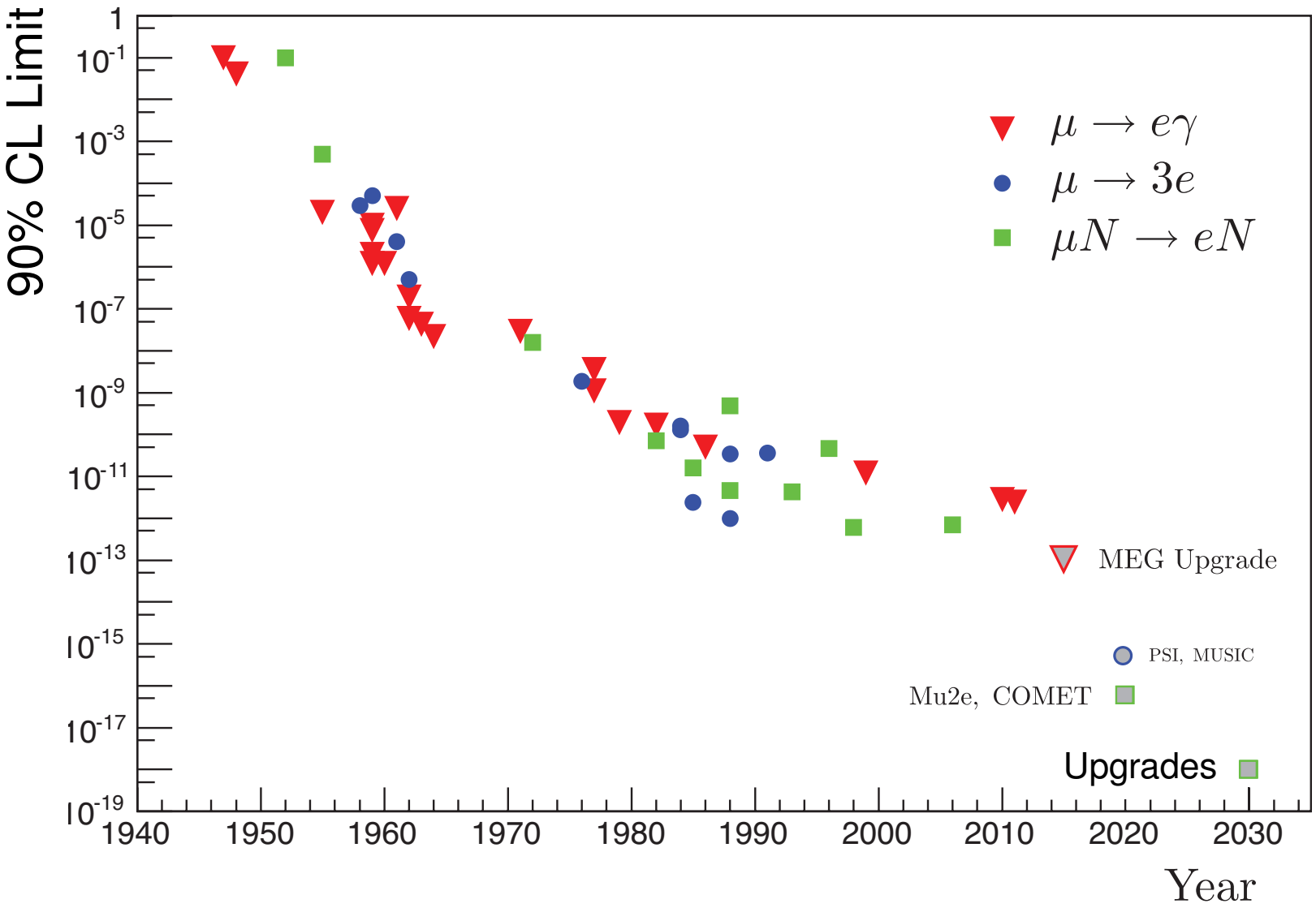
Mu2e building last week

Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aims for $\times$ 10 mass scale reach improvement
  - 4 orders of magnitude advance on the conversion rate: $R_{\mu e} \approx 2.5 \times 10^{-17}$ single event sensitivity at ≈ 0.5 events background
- The project is fully funded
- Building construction is almost finished
- Starting to construct the detector
- Solenoids are on schedule for commissioning in 2020
- More information: `http://mu2e.fnal.gov`

Extra slides

History of muon CLFV searches...



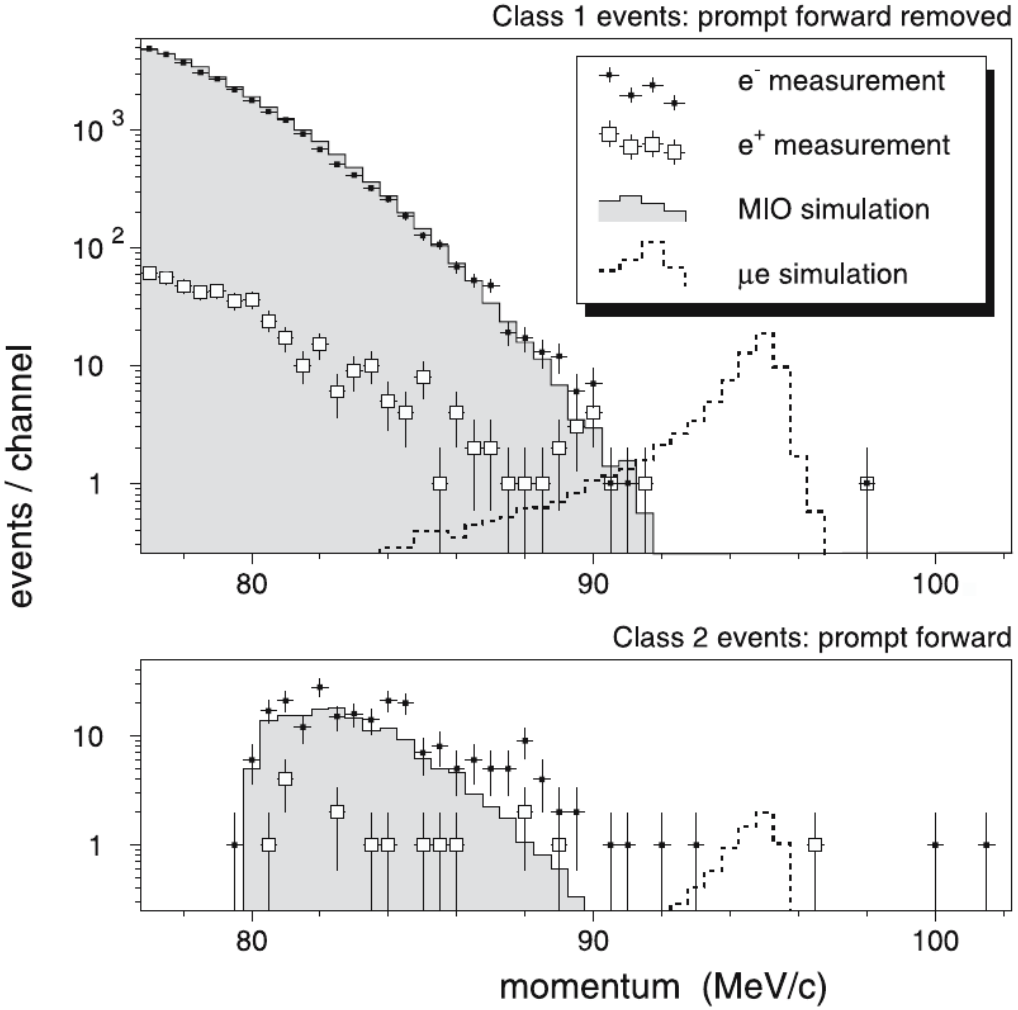
R. H. Bernstein, P. S. Cooper
Phys.Rept.532(2013)27

Current best $\mu N \to eN$ limit

SINDRUM II experiment at PSI

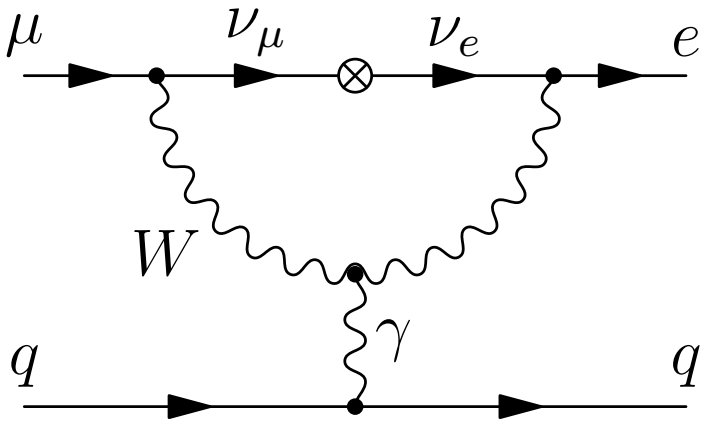
Conversion on gold:
$R_{\mu e} < 7 \times 10^{-13}$ 90% CL
[Eur.Phys.J C47(2006)]

Single event sensitivity
$S^1_{\mu e} = 2.5 \times 10^{-13}$



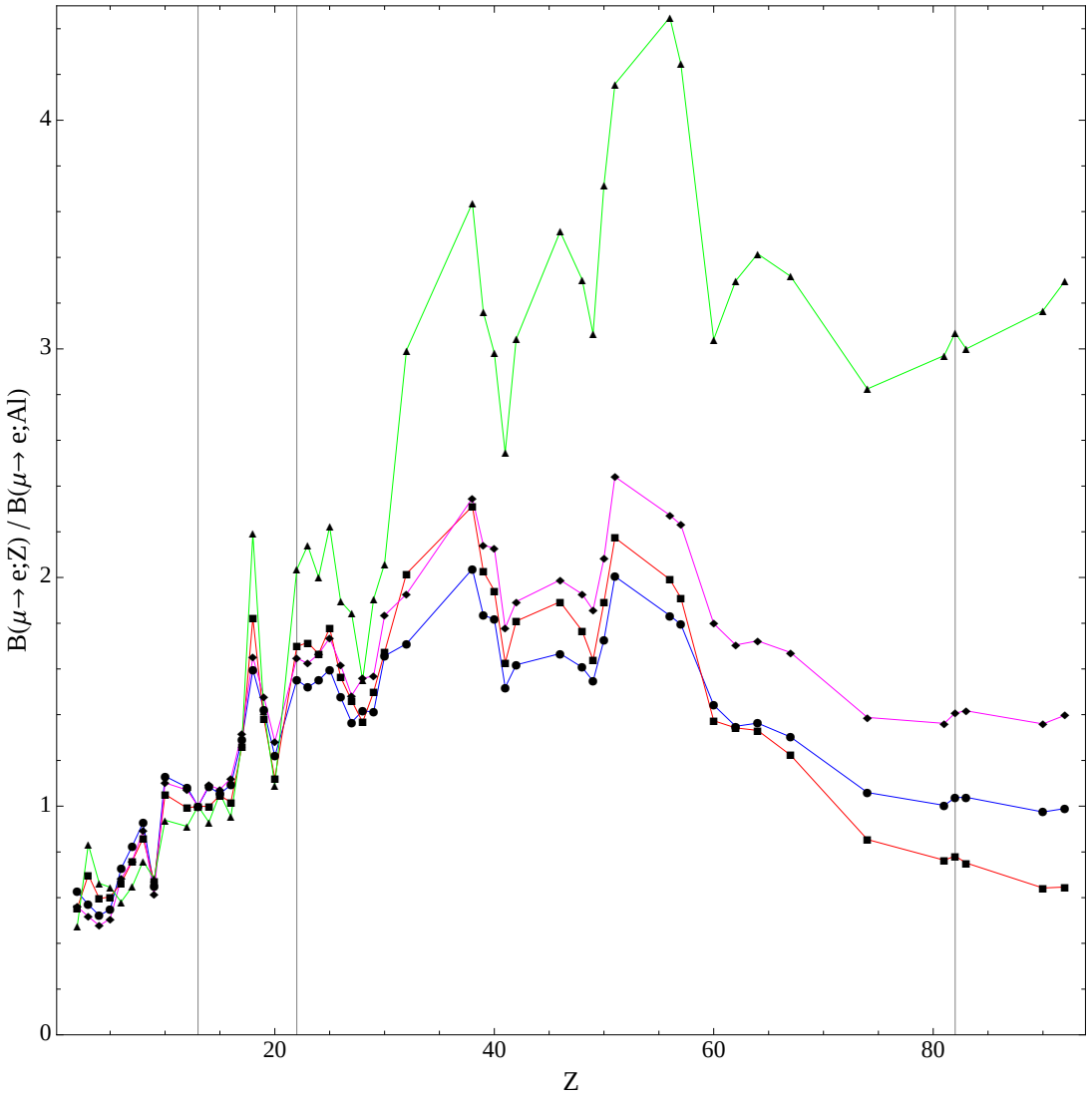
Expected rates

- SM: $R_{\mu e} = 0$
- νSM:
  $R_{\mu e} \propto (\Delta m_\nu^2 / M_W^2)^2 \approx 10^{-52}$



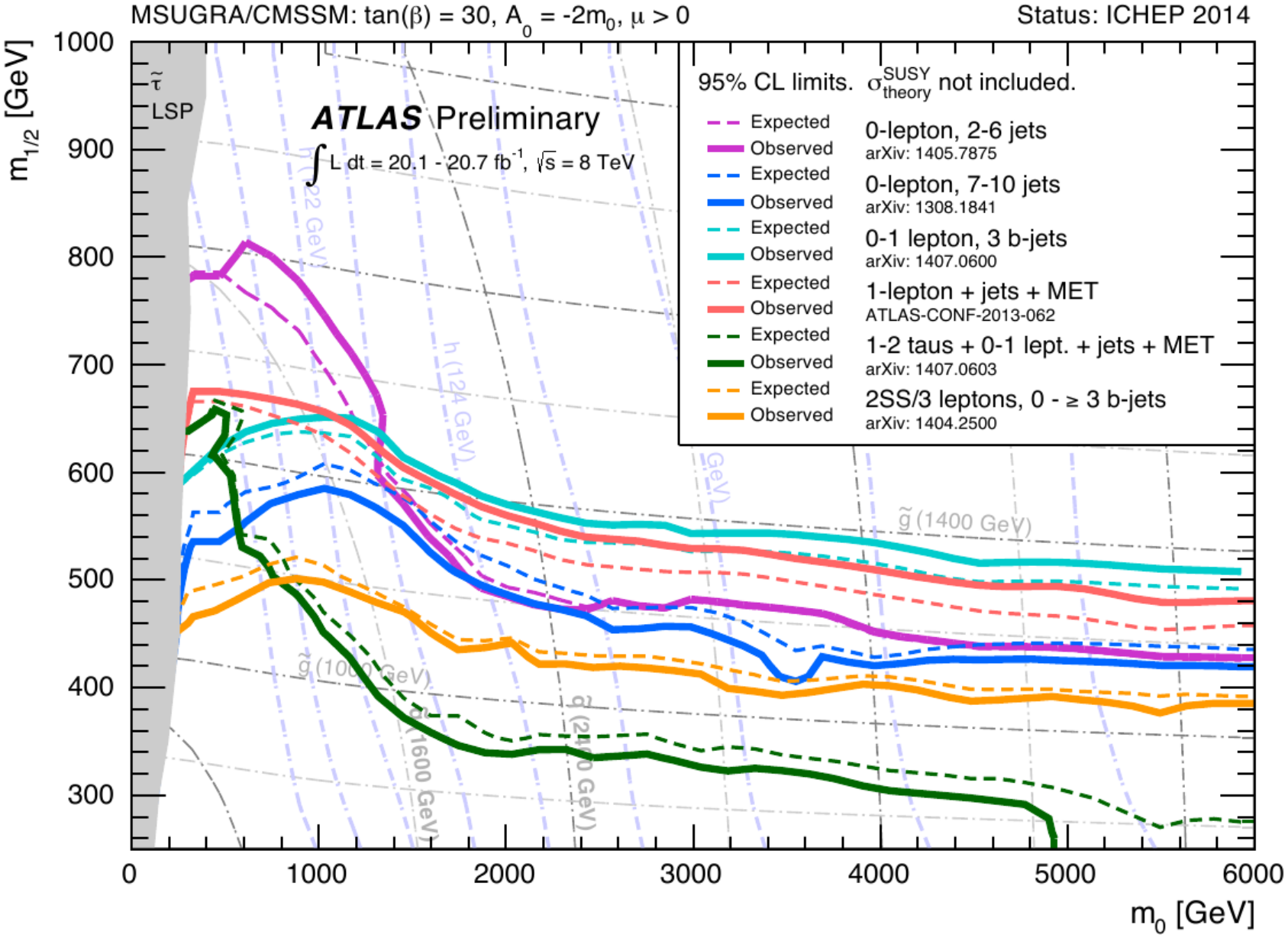
- Observation of $\mu \to e$ conversion would be an unambiguous signal of New Physics

Target Z dependence



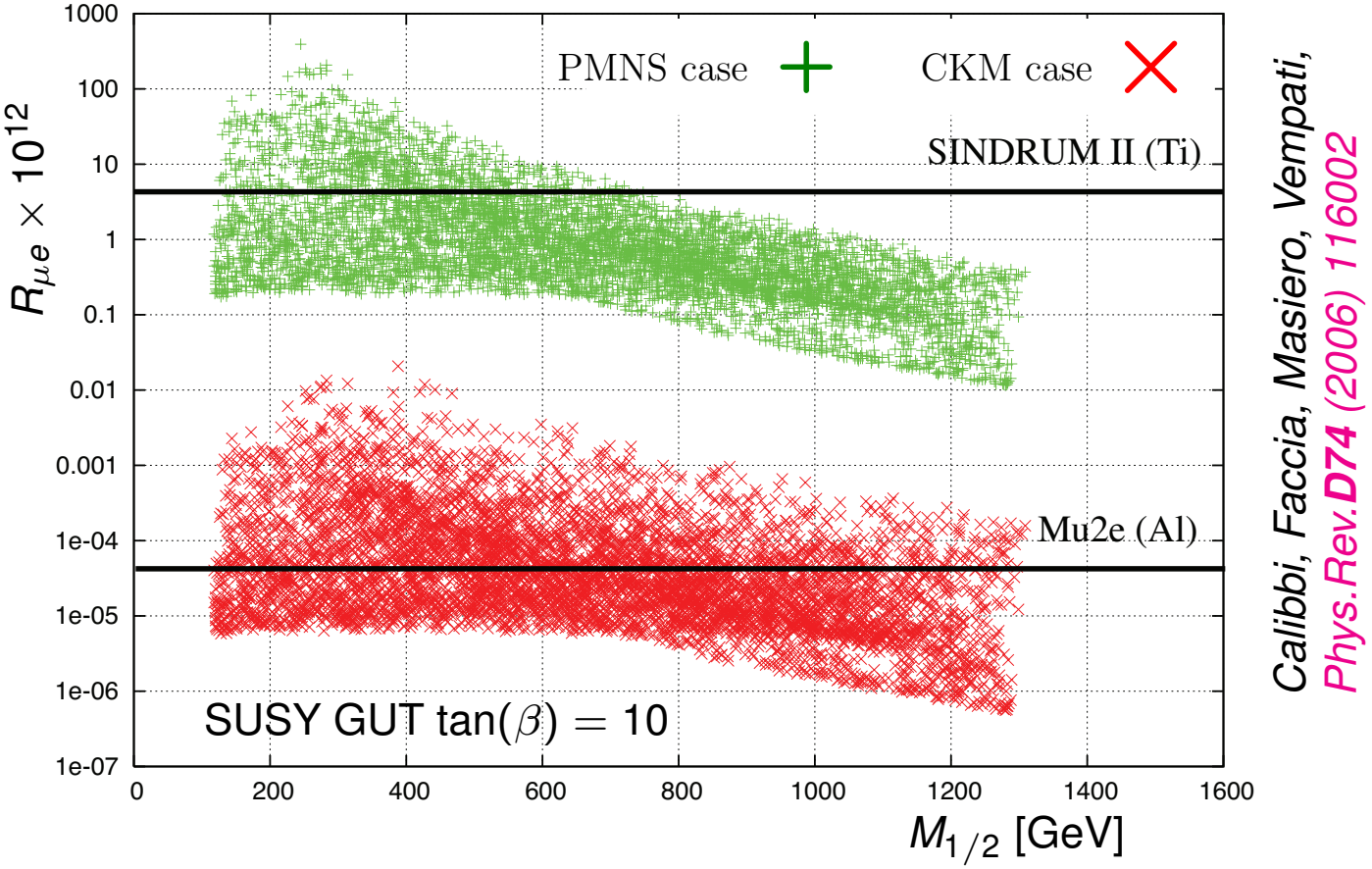
V. Cirigliano et al., Phys. Rev. D **80**, *013002 (2009)*

ATLAS SUSY exclusion



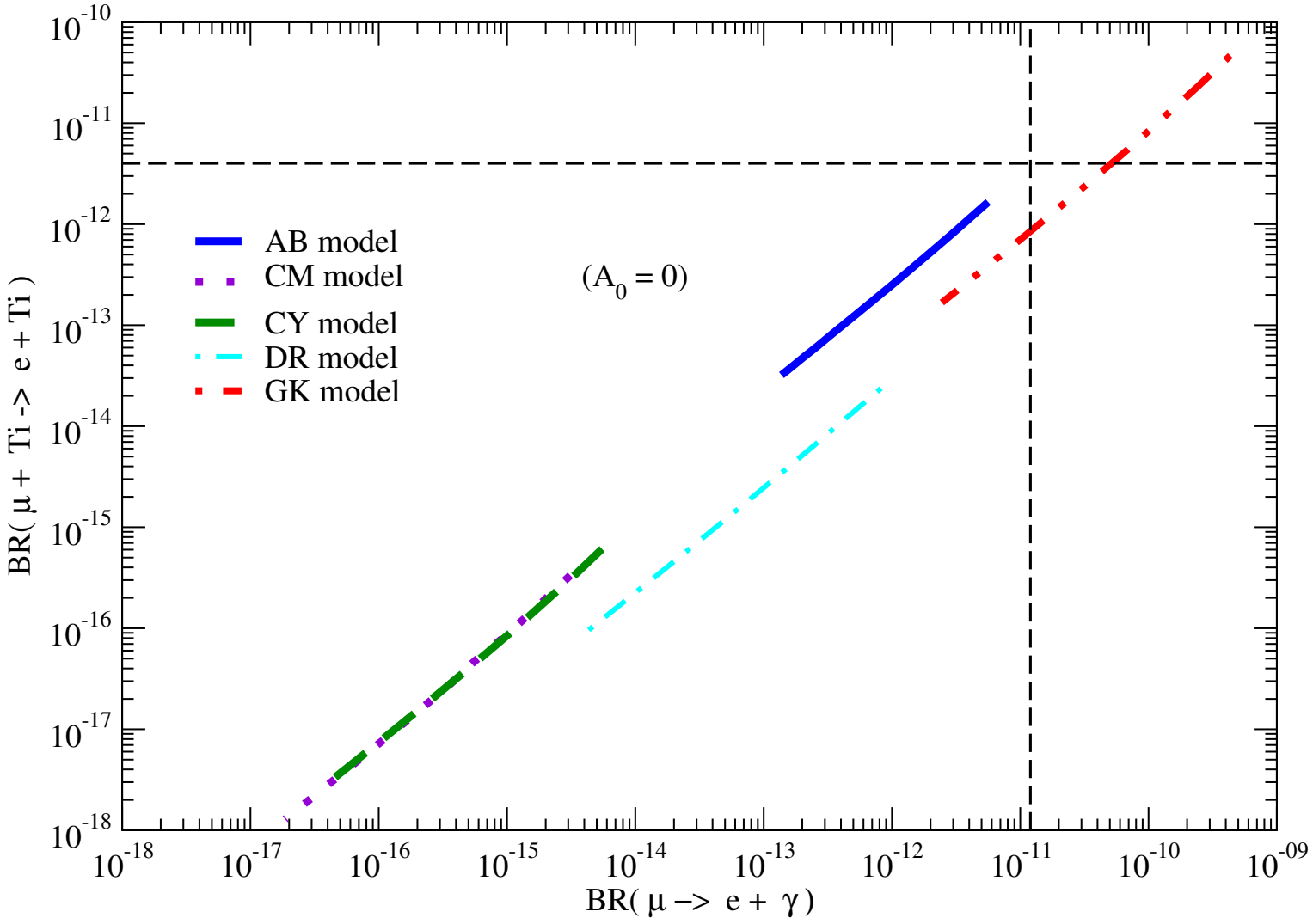
$\mu N \to eN$ and the LHC

Scan of "LHC accessible" SUSY parameter space



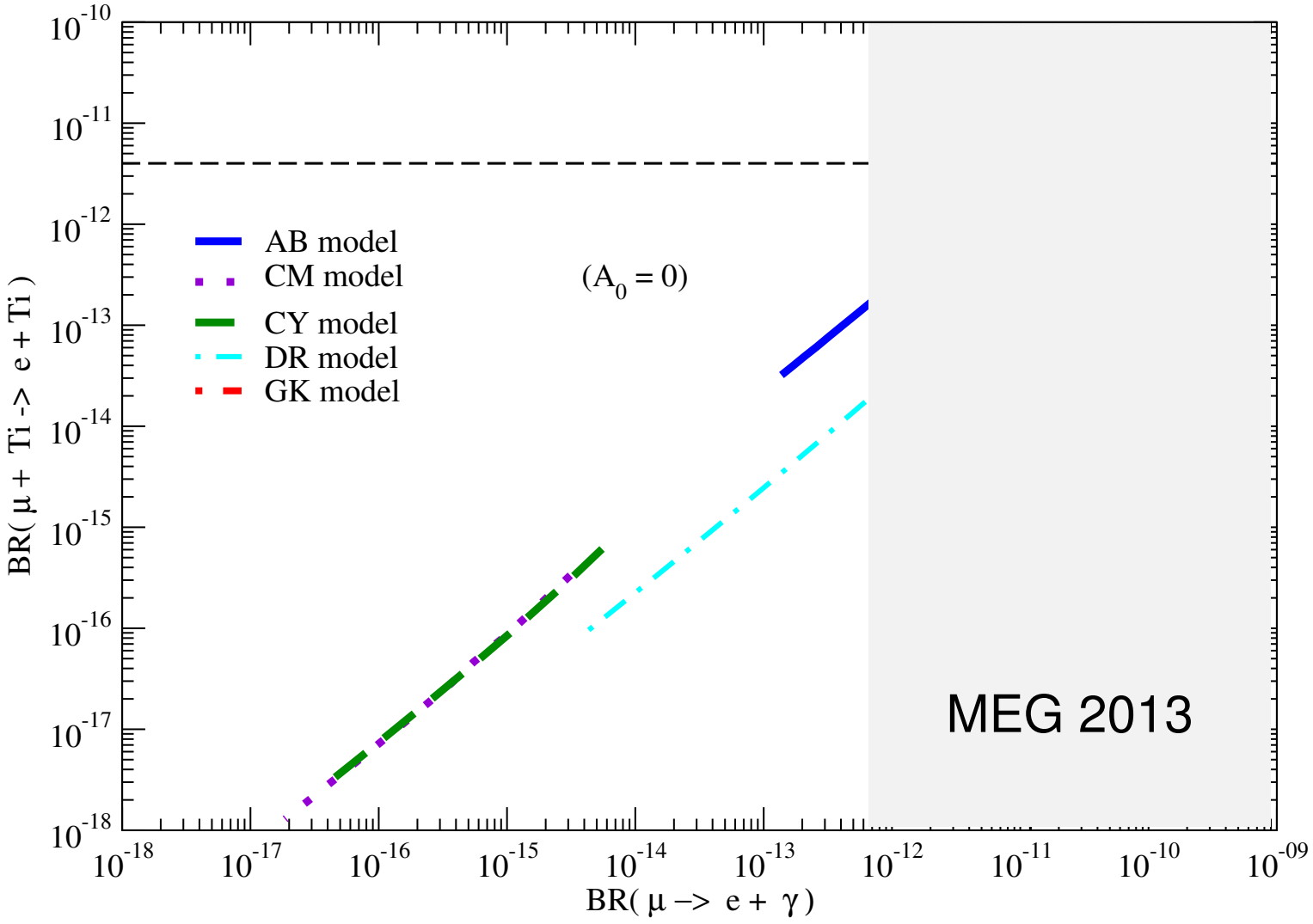
Signal in Mu2e if LHC sees this SUSY. Or if it does not.

Mu2e and $\mu \to e\gamma$: SO(10) SUSY GUT



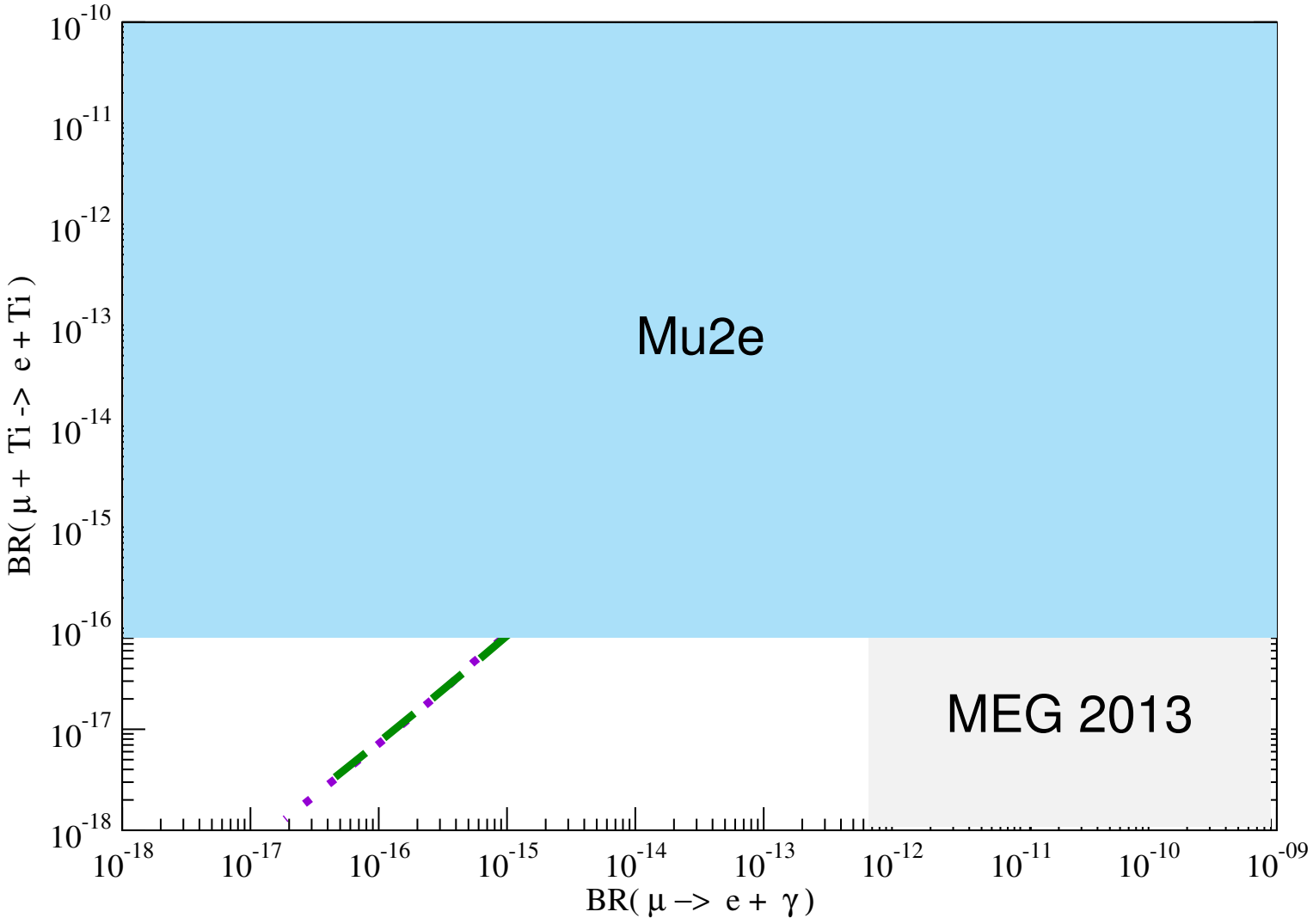
C.H. Albright, M.-C. Chen, 2008

Mu2e and $\mu \to e\gamma$: SO(10) SUSY GUT



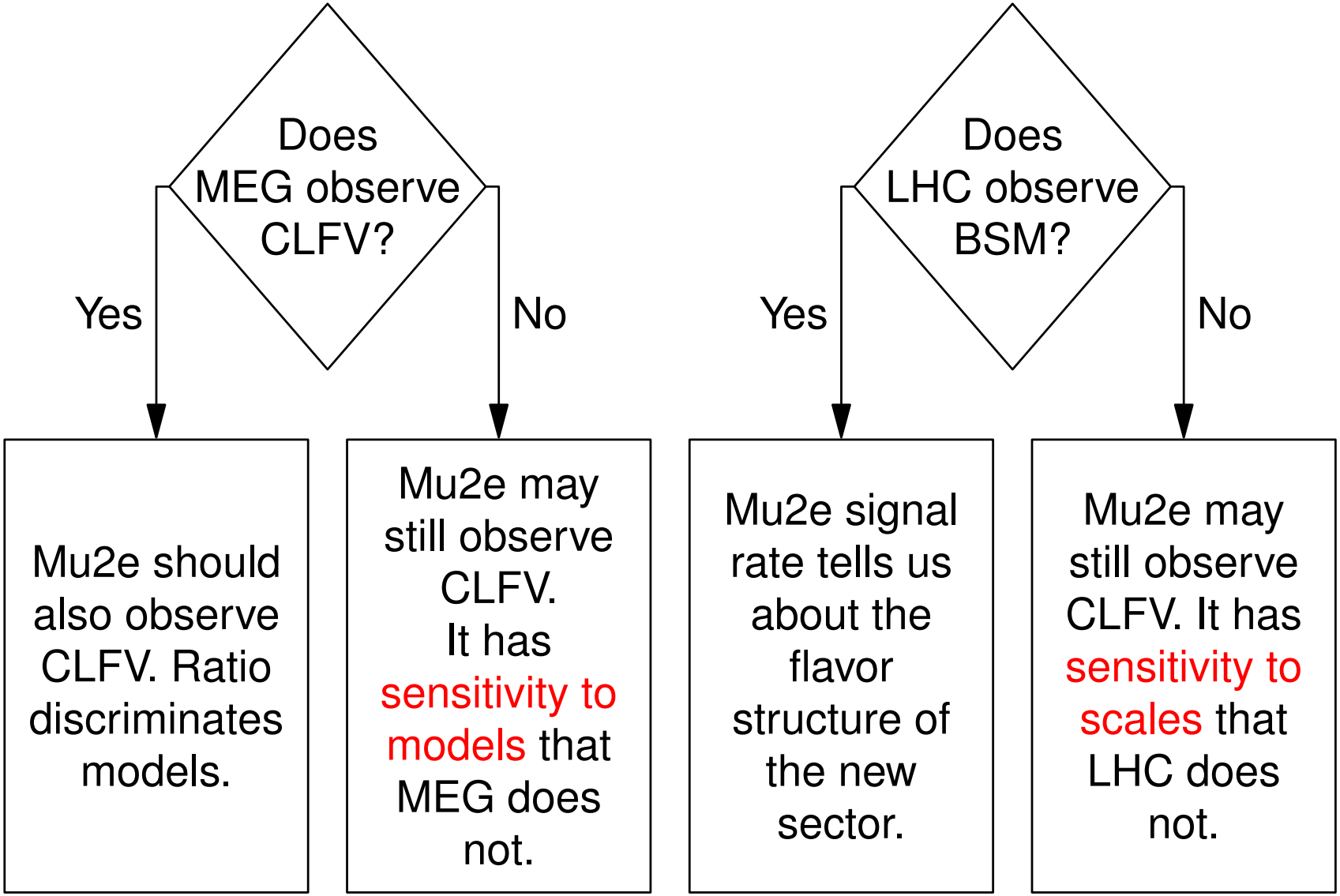
C.H. Albright, M.-C. Chen, 2008

Mu2e and $\mu \to e\gamma$: SO(10) SUSY GUT



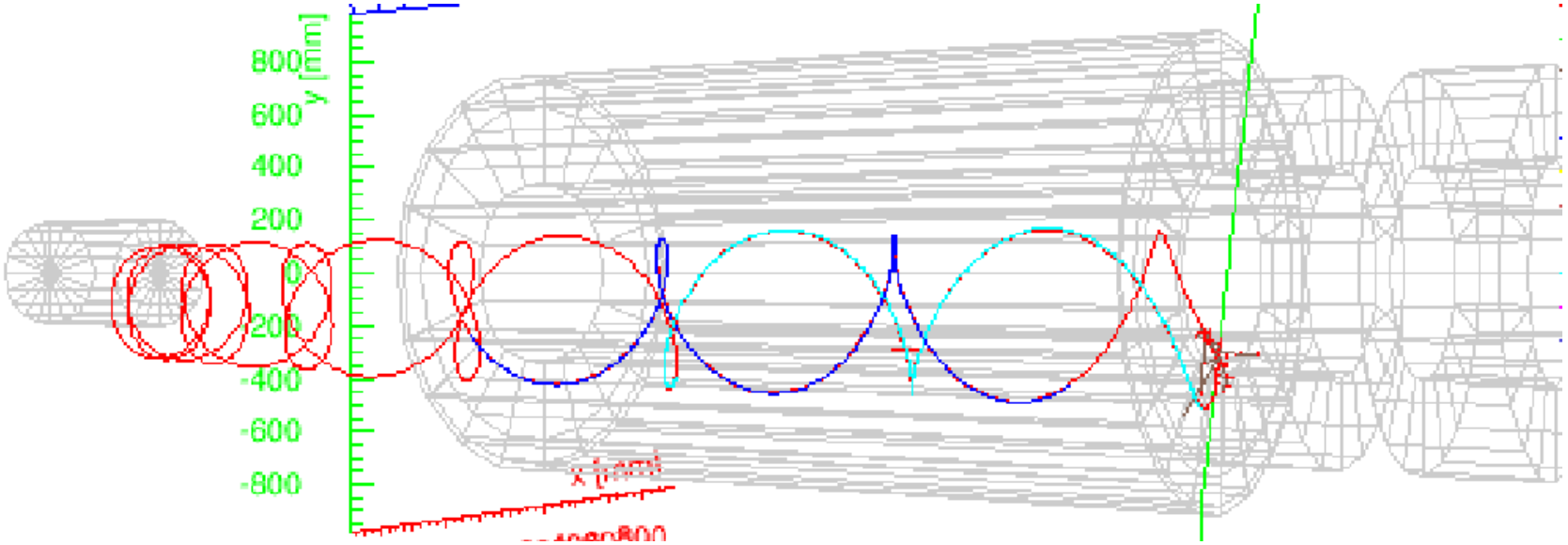
C.H. Albright, M.-C. Chen, 2008

Mu2e in different scenarios



Tracker energy loss calibration

Double-pass cosmic rays



The breadth of the physics reach

"Flavor physics DNA matrix":

Models →

Observables ↓

	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Altmannshofer, Buras, Gori, Paradisi, Straub Nucl. Phys. B **830**, *17 (2010)*

$\mu \to e$: broad discovery sensitivity!

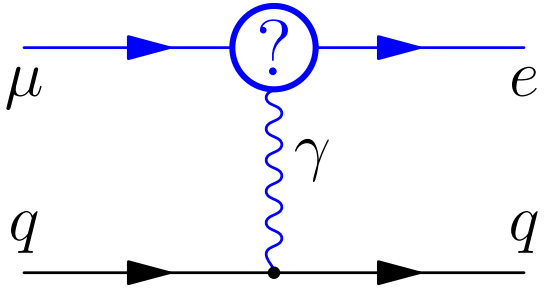
Effective theory

Parametrization: $\mathcal{L}_{CLFV} =$

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

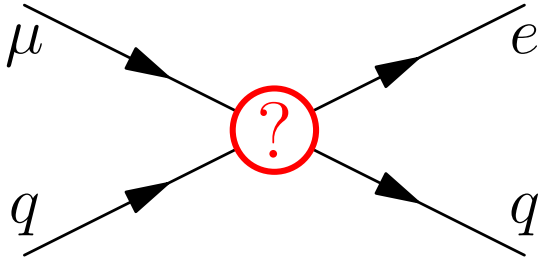
Λ: mass scale, κ: relative importance of contact term

Dipole: $\kappa = 0$



Often gives large $Br(\mu \to e\gamma)$

Contact: $\kappa = \infty$

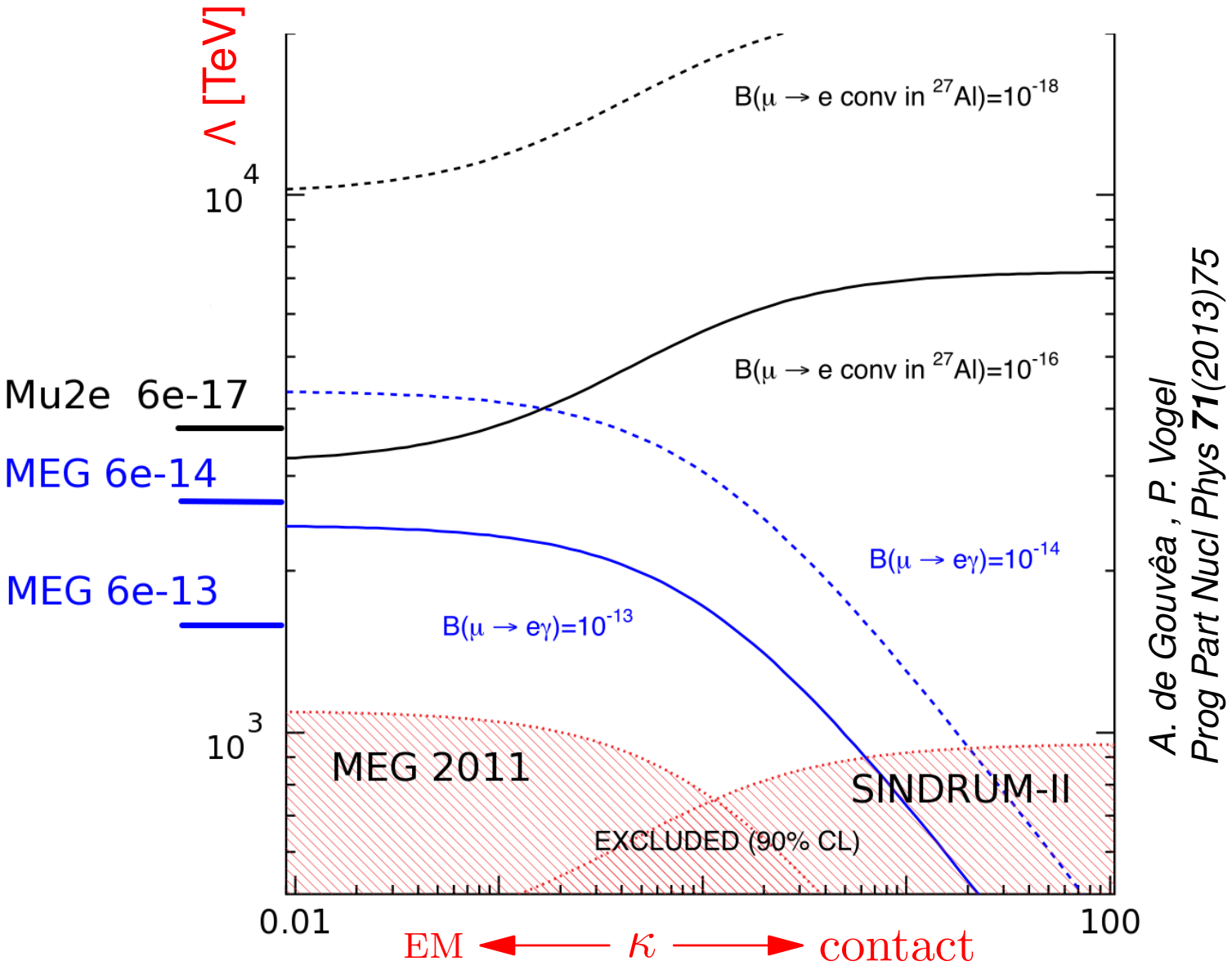


May be no $\mu \to e\gamma$ signal

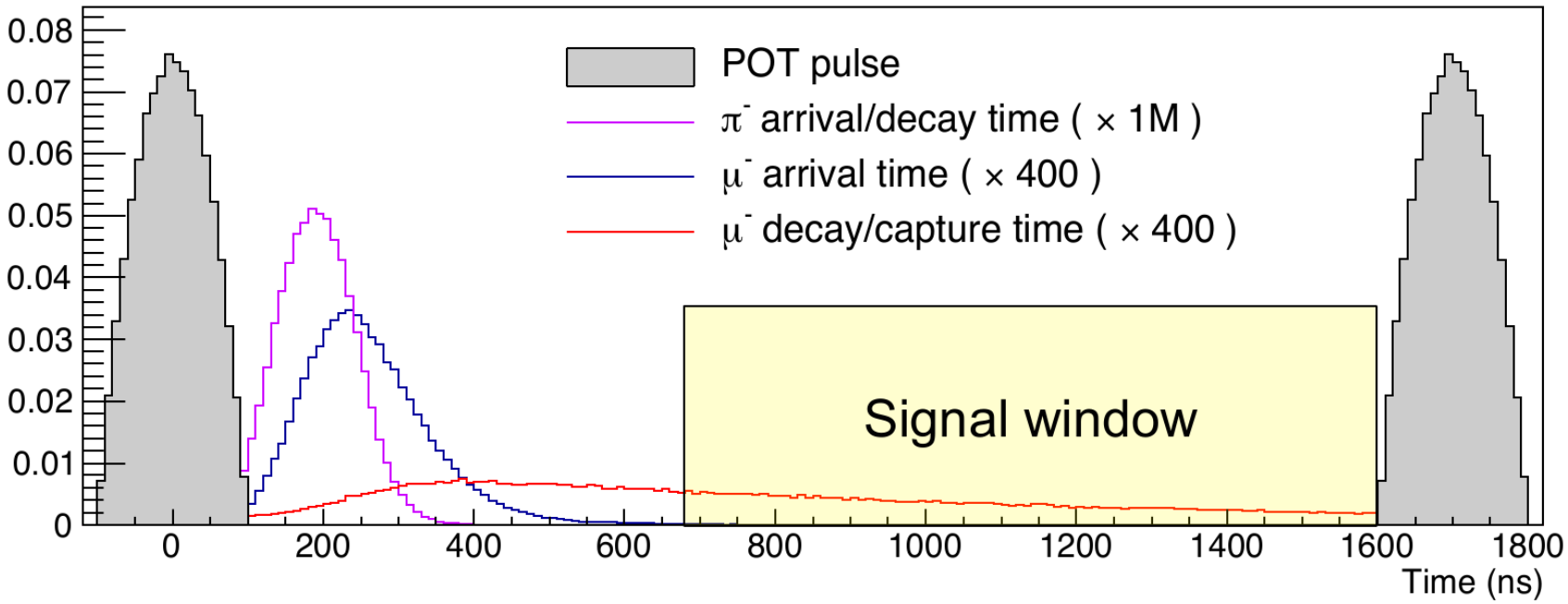
Relative rates of conversion and $\mu \to e\gamma$ are model dependent

Handle to discriminate New Physics models

Muon LVF physics reach

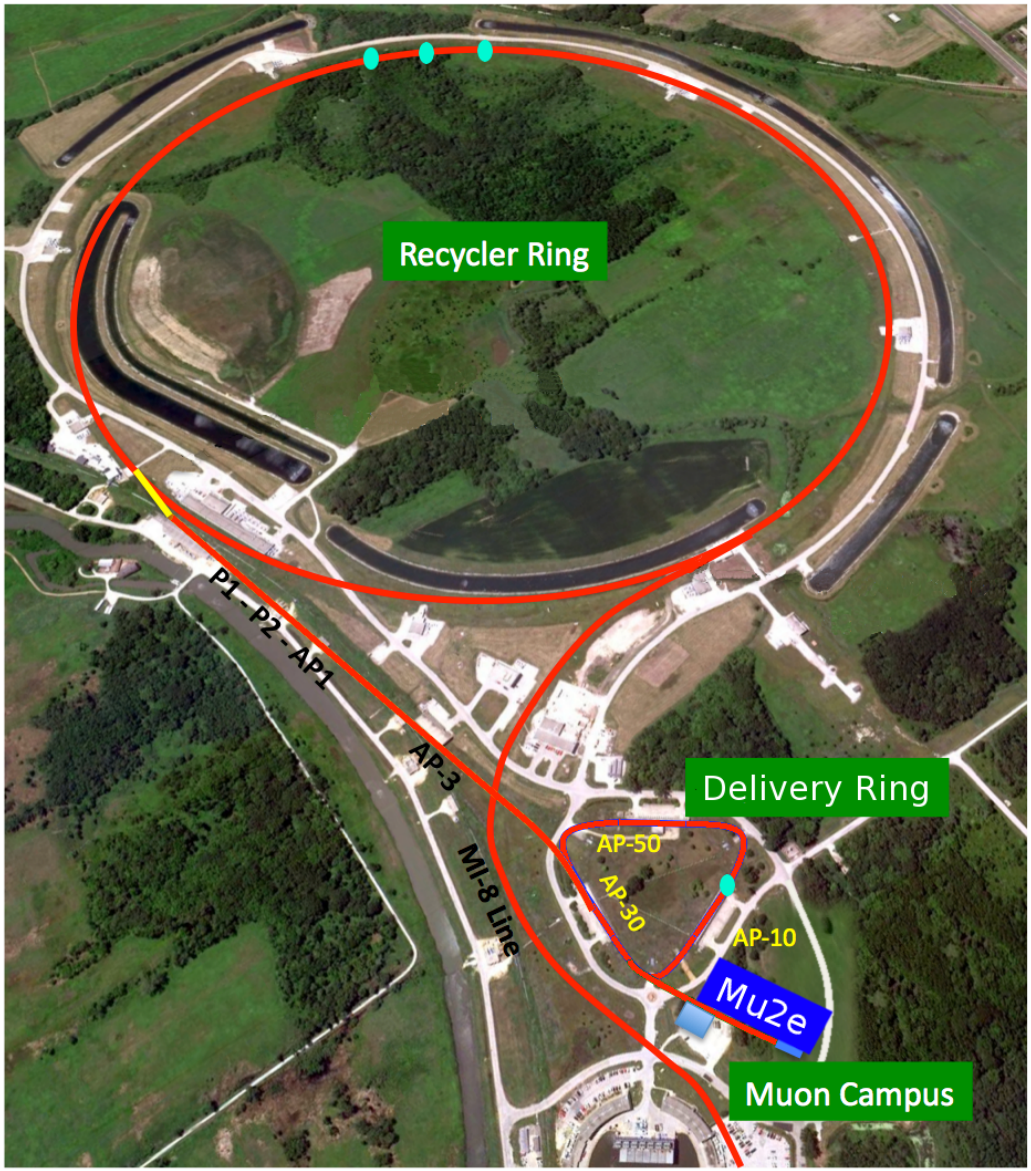


Mu2e beam time structure



Beam extinction (fraction of protons between pulses):
Mu2e requires $\epsilon < 10^{-10}$

Mu2e beam delivery

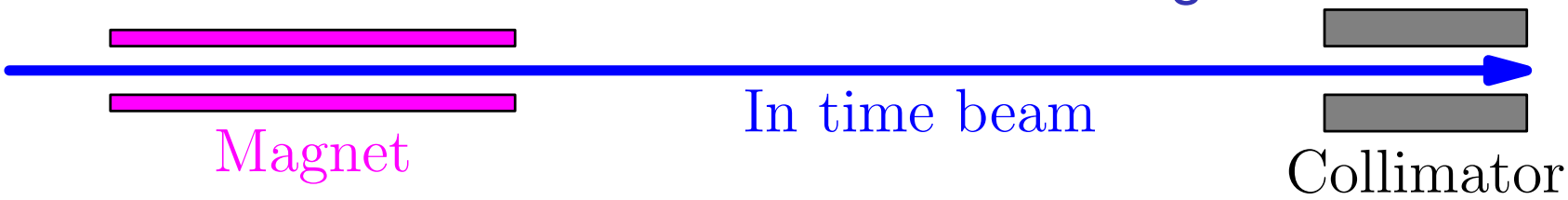


- A single beam bunch in the delivery ring at a time
- Revolution period is 1695 ns
- Resonant extractions "peels" a fraction of the bunch each turn
- Extracted beam: $\epsilon \approx 2 \times 10^{-5}$

How to get $\epsilon = 10^{-10}$

Start with $\epsilon = 2 \times 10^{-5}$ from the delivery ring

Deflect out of time beam with extinction magnets



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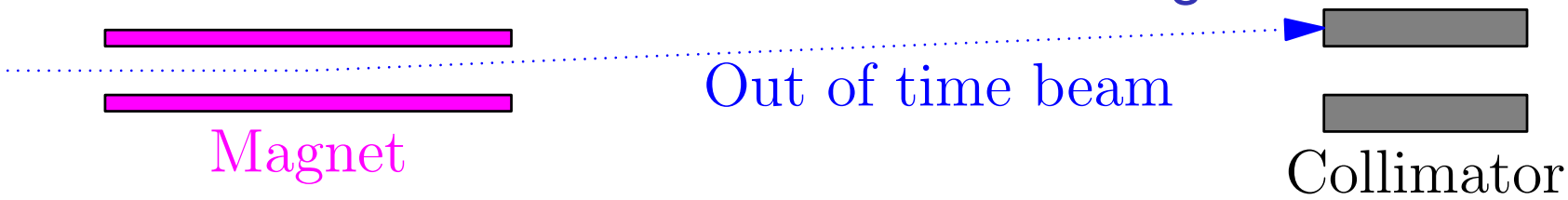
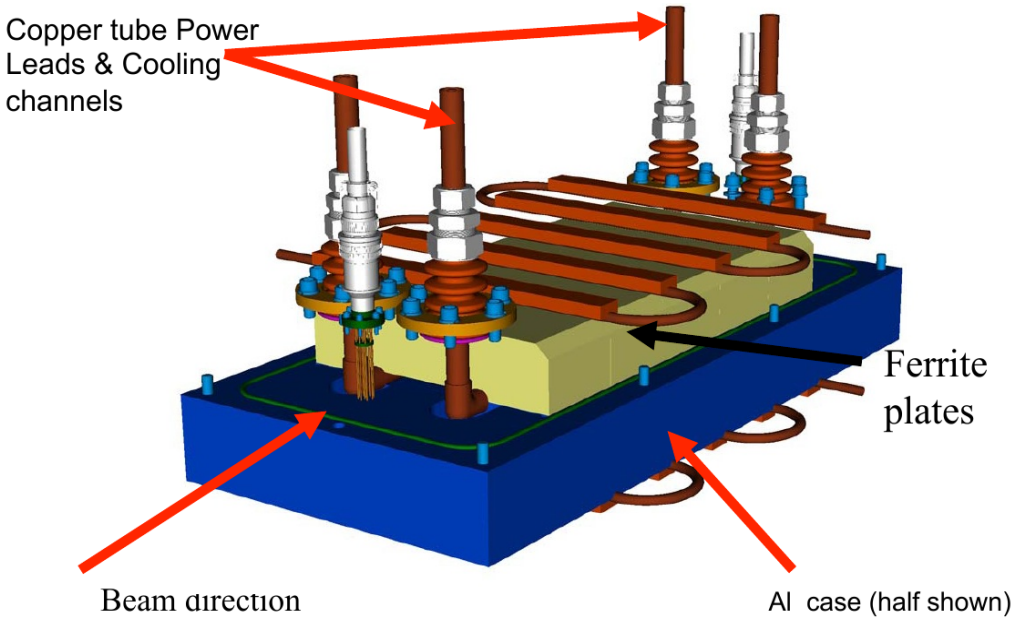


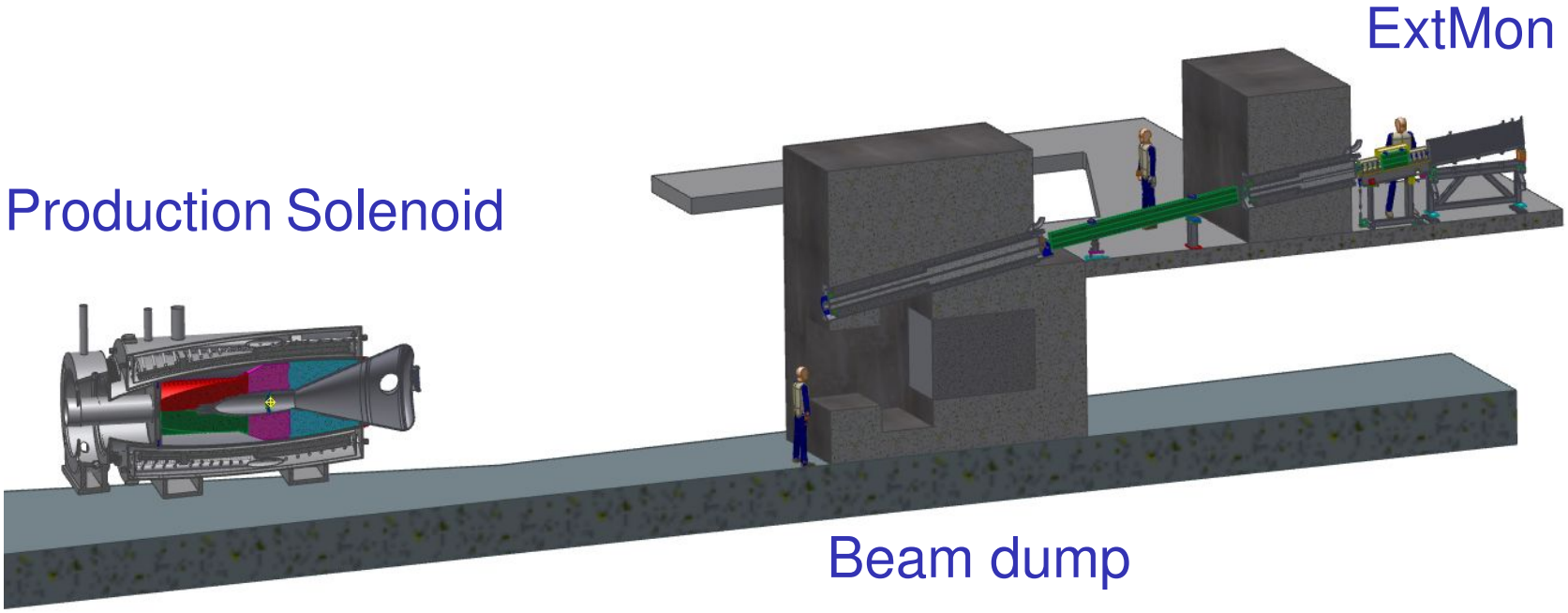
Achieving the extinction

- 0.6 MHz beam pulses
- Use resonant dipoles
- Optimized waveform and collimators
- 99.5% in-time transmission
- 5×10^{-8} extinction factor
- Final $\epsilon = 1.1 \times 10^{-12}$



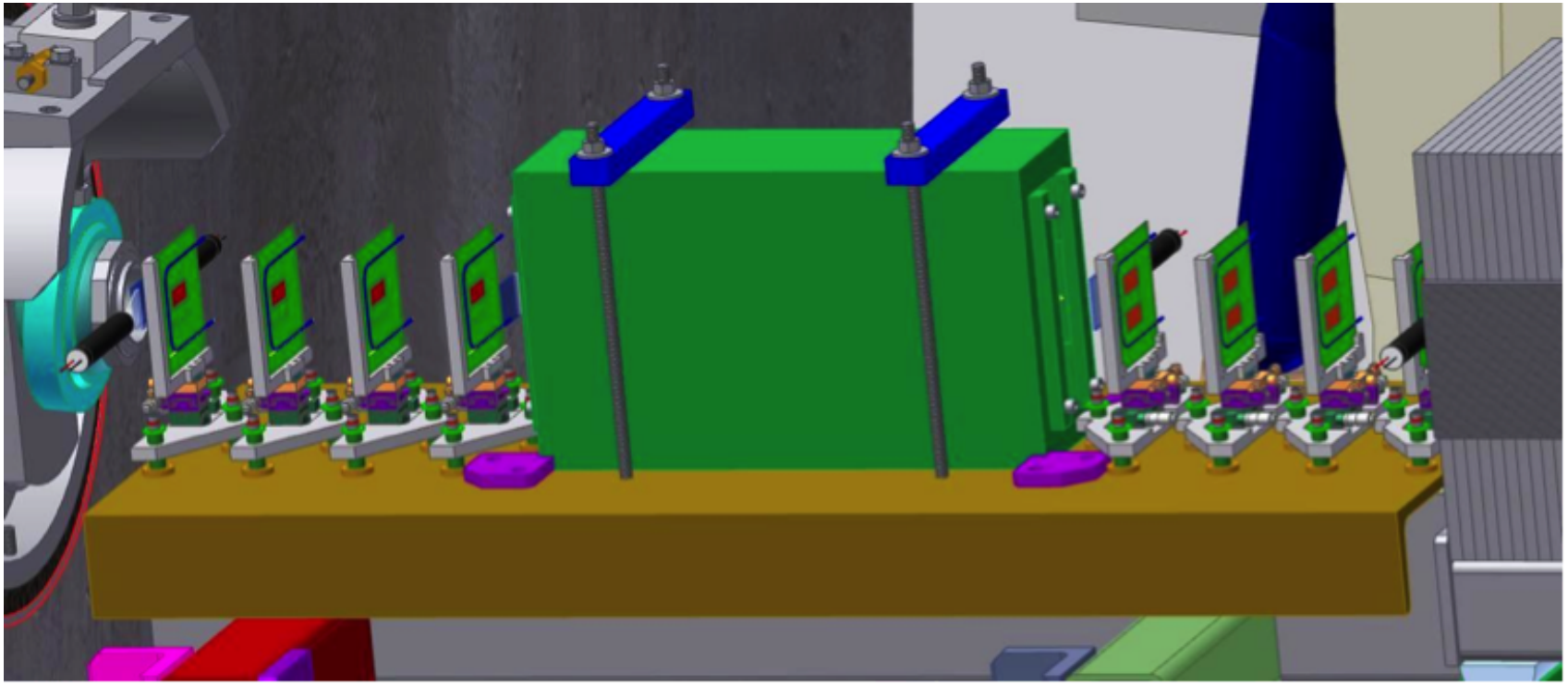
Monitoring beam extinction

- Must measure extinction directly to prove conversion signal
- Approach
  - observe charged secondaries from production target
  - Accumulate time profile of the beam
- Continuous monitoring with 10^{-10} sensitivity

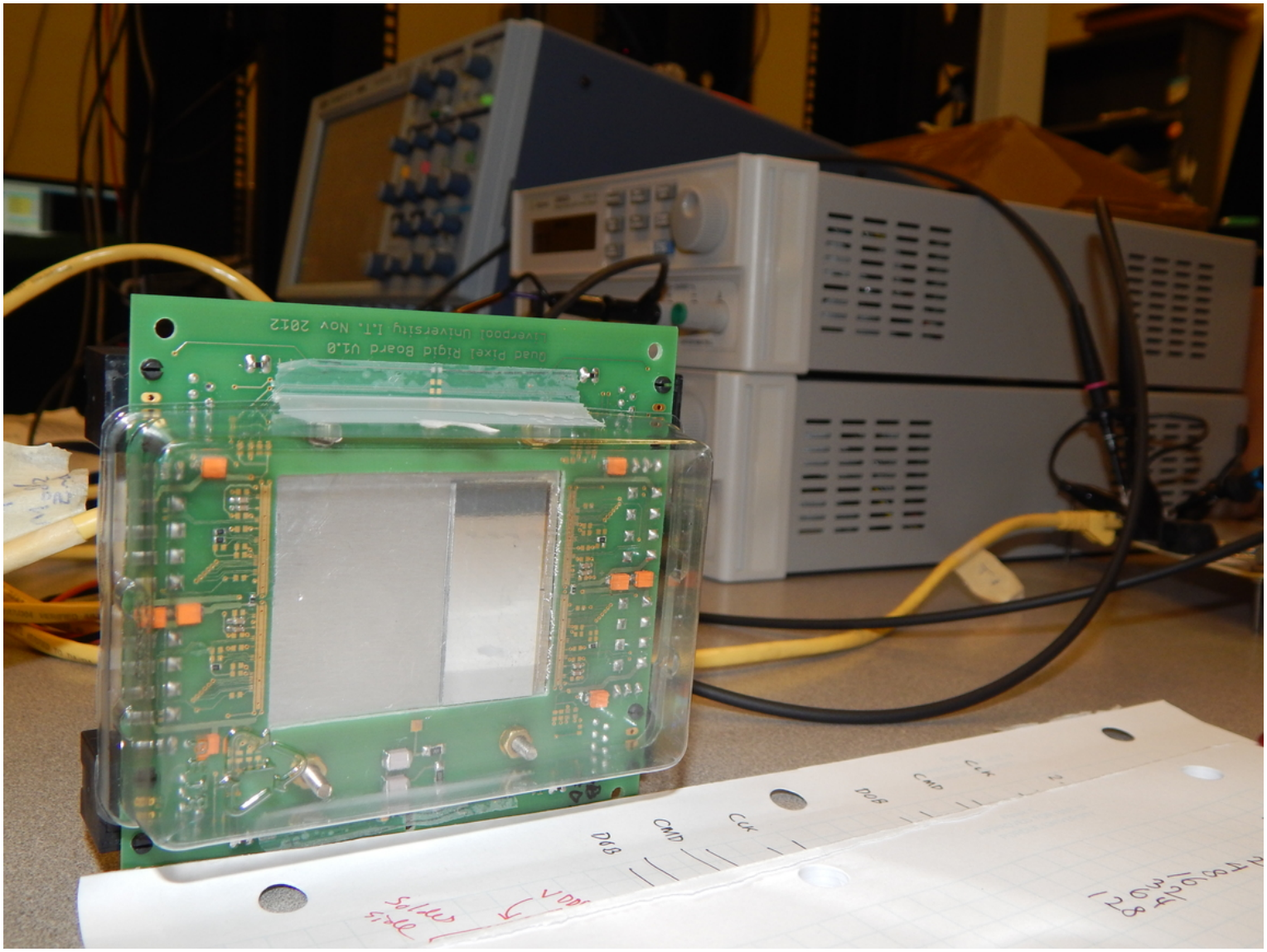


Extinction monitor

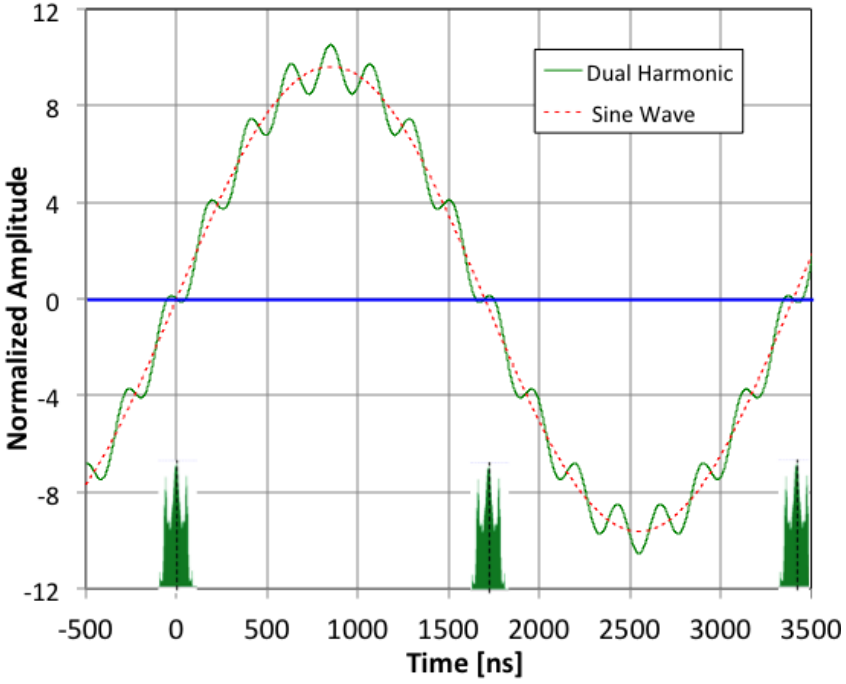
- Permanent magnet spectrometer
- Based on ATLAS silicon pixel chips
- Simulations show excellent performance, negligible background

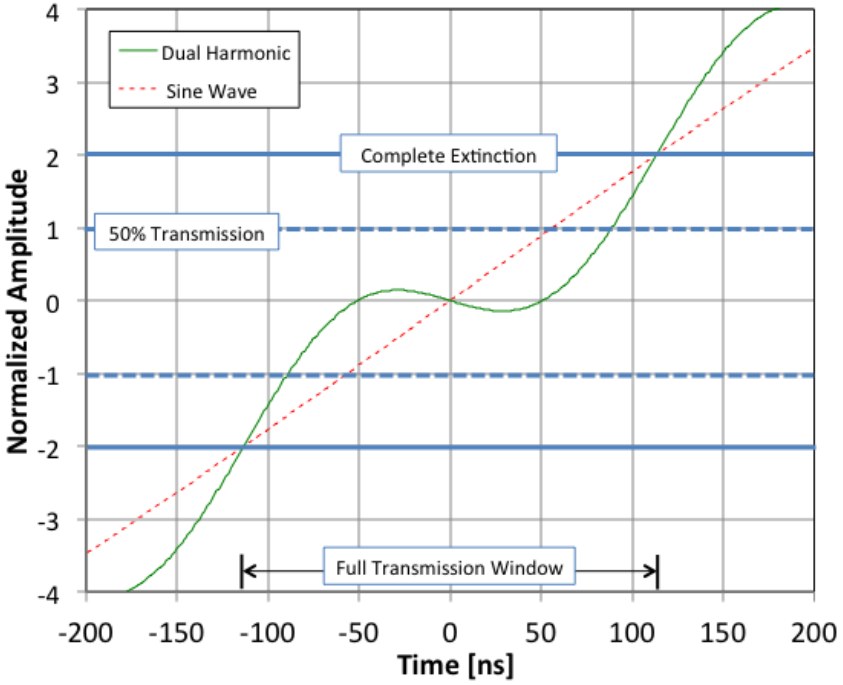


ExtMon: Pixel readout test

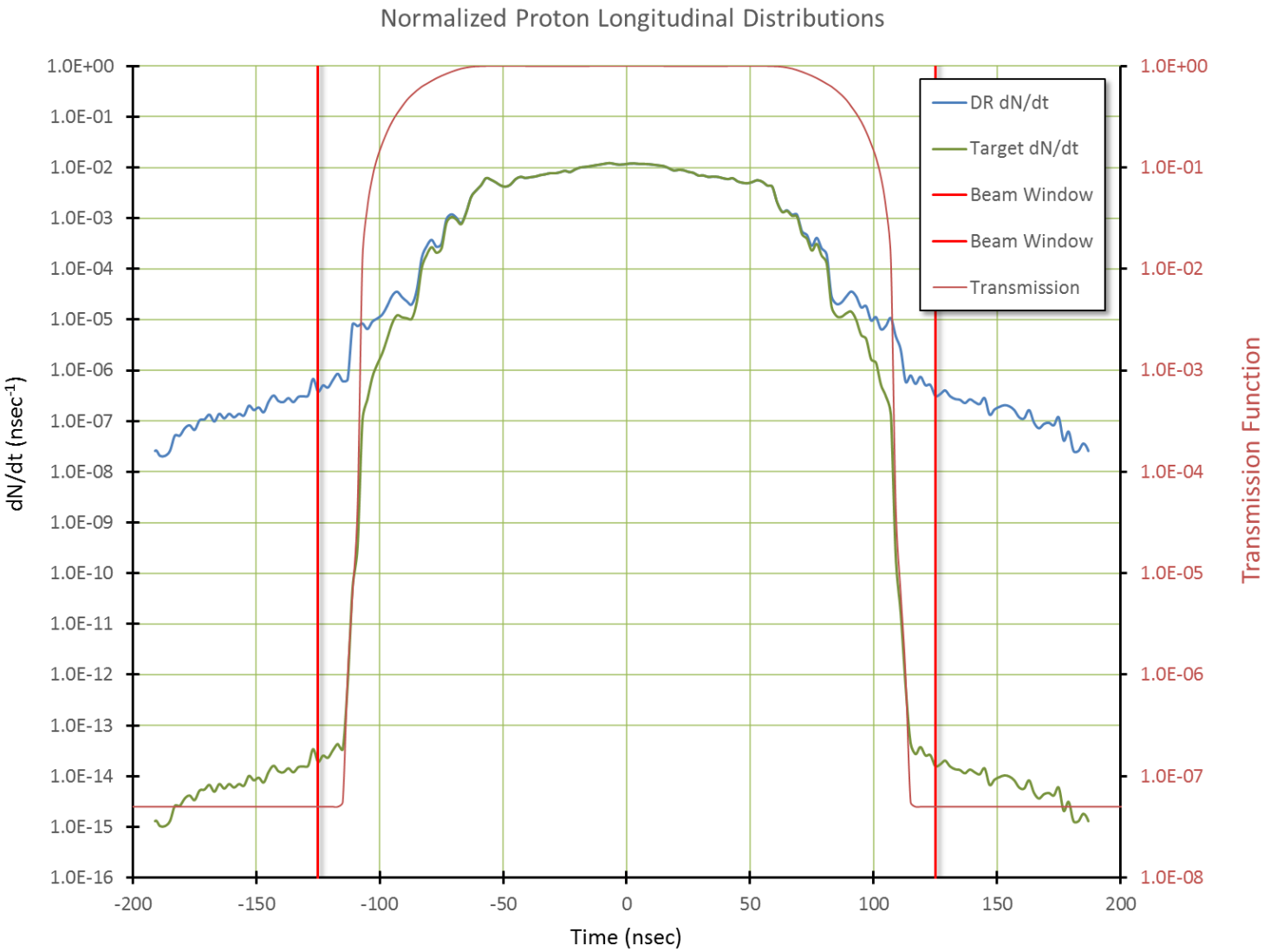


External extinction waveform



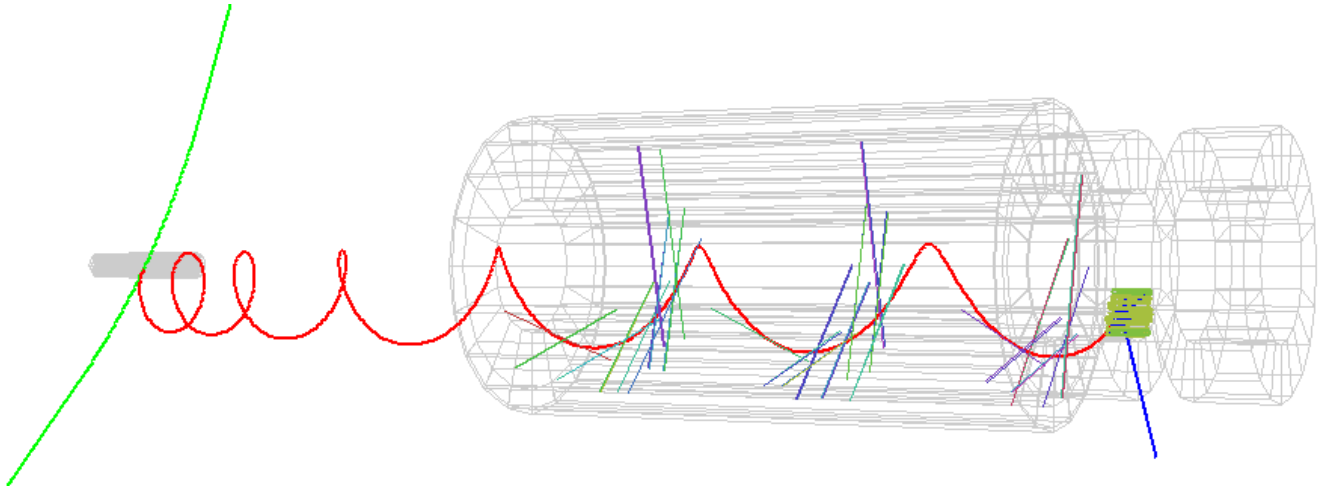


External extinction result



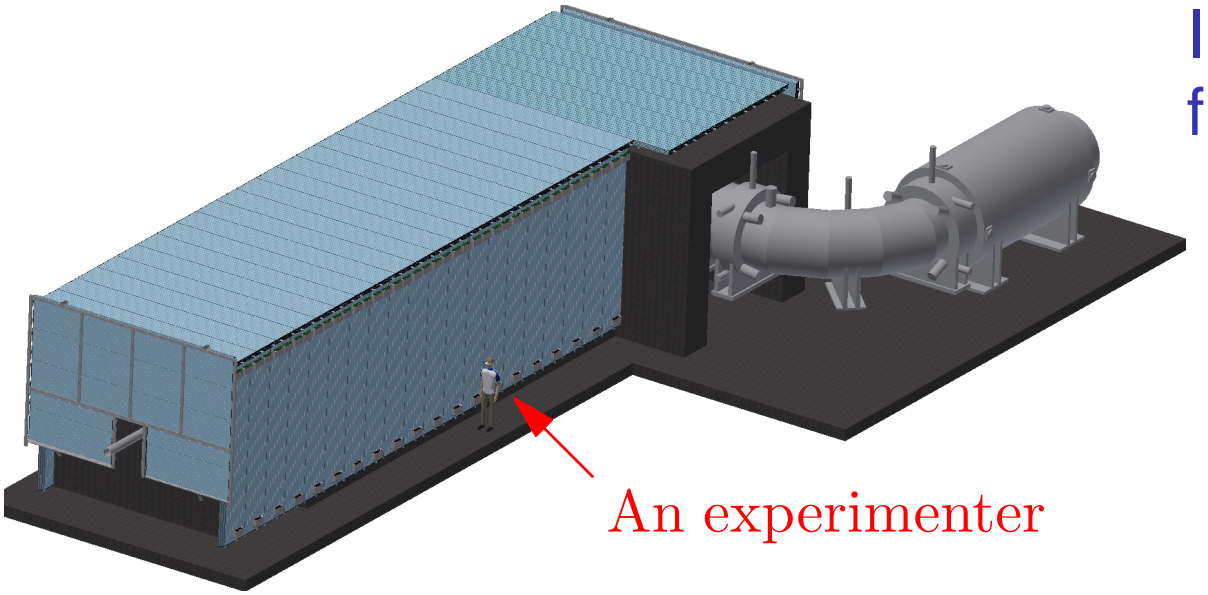
Cosmic background introduction

- A cosmic muon track can look like a 105 MeV/c electron track
- A cosmic muon can decay, or knock out an electron from detector material



- 1 event per day without counter-measures
- Vetoing cosmic muons is crucial
- Aim for as much coverage as possible

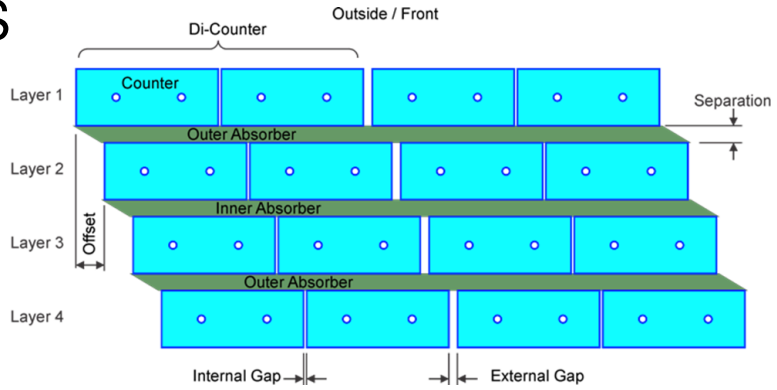
Cosmic Ray Veto



Intense radiation field

- proton target
- $\mathcal{O}(10^{10})$ muon captures per second: n, γ, ...
- false vetoes (dead time)

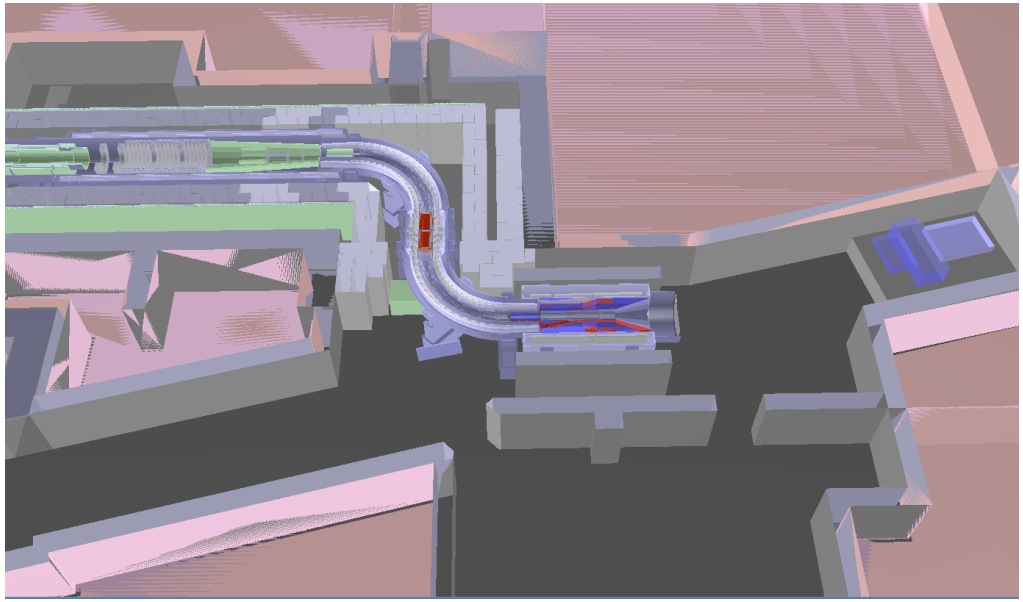
- Optimized counter and shielding design using massive G4 and MARS simulations
- Four layers of scintillator counters
- Aluminum absorbers
- Veto will be applied offline



Cosmic background simulations

Detailed GEANT4 model

- Detectors
- Mechanical supports, services
- Individual shielding blocks
- Civil infrastructure
- Dirt overburden, . . .



Simulation statistics

0.5×10^{12} events, $4 \times$ livetime (1 livetime = 3 year run)

4 additional samples targeting areas that lack CRV coverage:

$> 255 \times$ livetime each

Summary of backgrounds

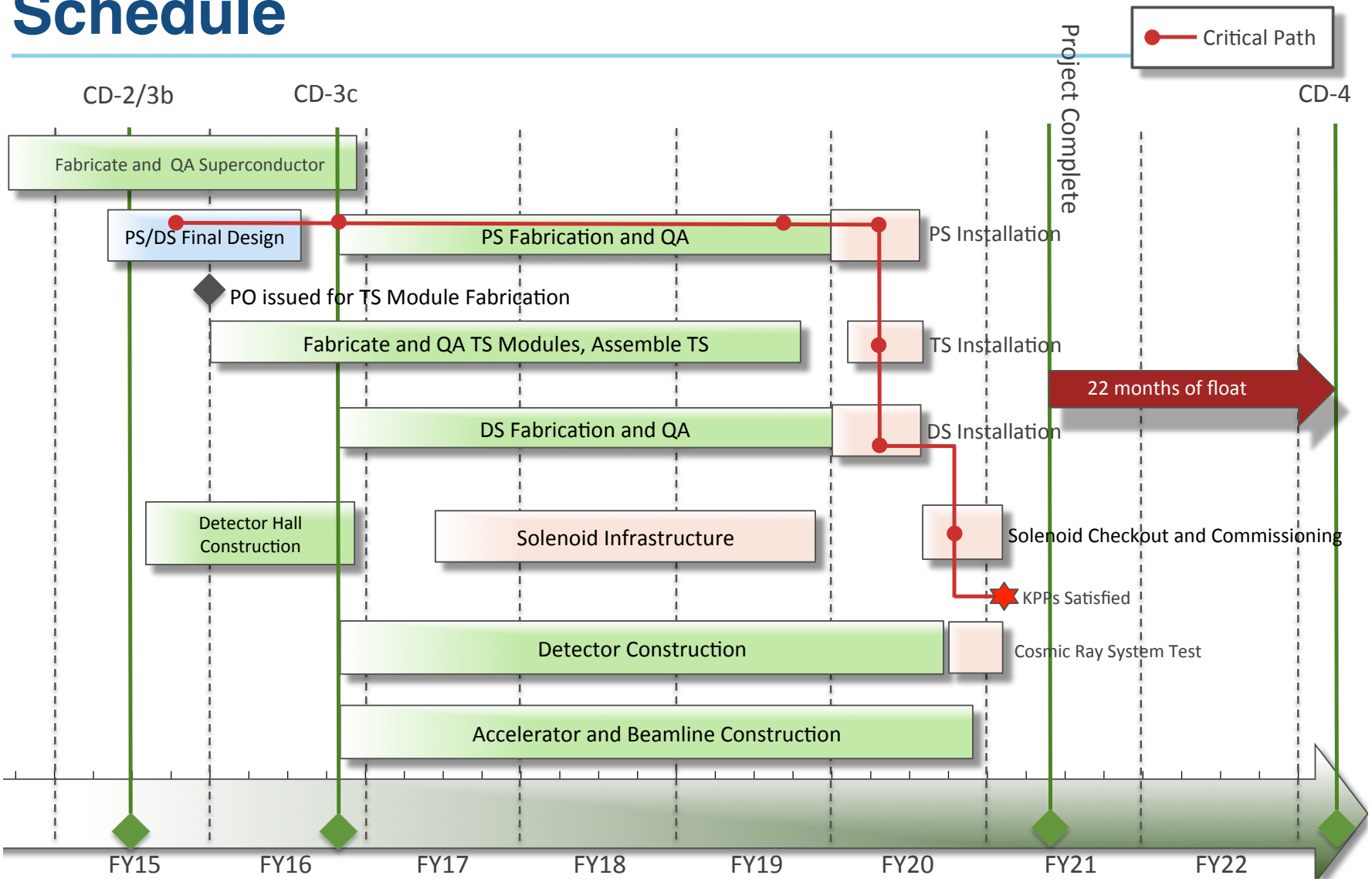
arXiv:1501.05241

3 years of 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

Assuming 10^{-10} beam extinction, 10^{-4} CRV inefficiency, and PID muon rejection of 200.

Schedule


Critical Path
CD-2/3b
CD-3c
Project Complete
CD-4
Fabricate and QA Superconductor
PS/DS Final Design
PS Fabrication and QA
PS Installation
PO issued for TS Module Fabrication
Fabricate and QA TS Modules, Assemble TS
TS Installation
22 months of float
DS Fabrication and QA
DS Installation
Detector Hall Construction
Solenoid Infrastructure
Solenoid Checkout and Commissioning
KPPs Satisfied
Detector Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22