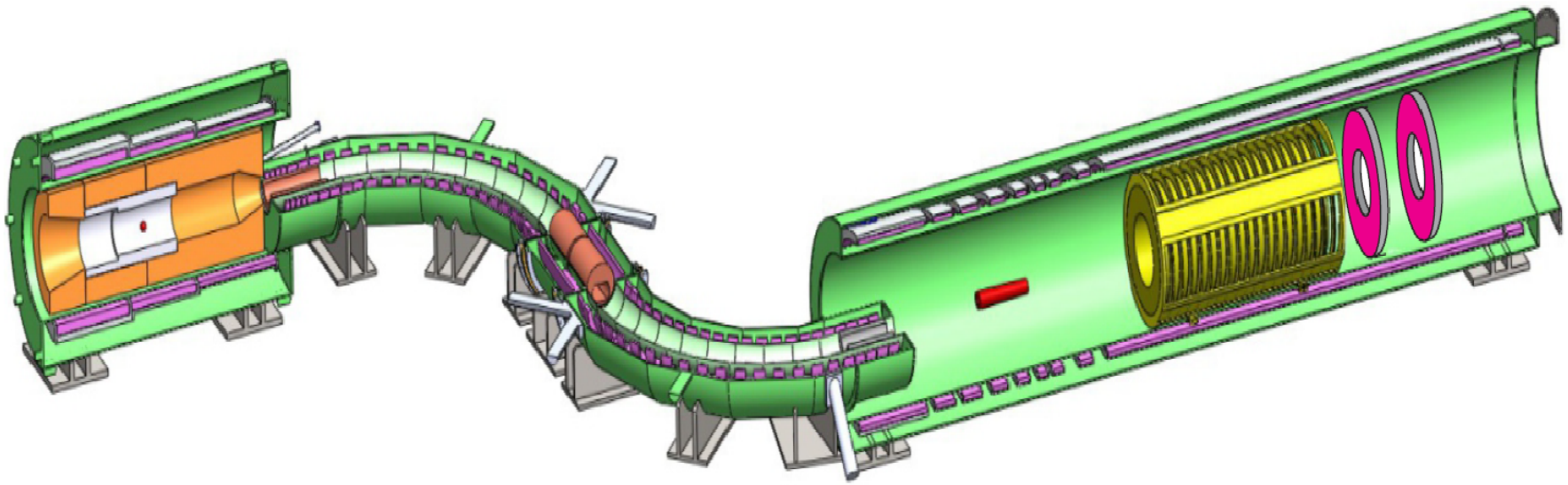
The Mu2e experiment at Fermilab

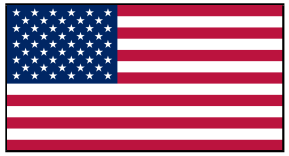
A search for charged lepton flavor violation in muon to electron conversion



Andrei Gaponenko (Fermilab)

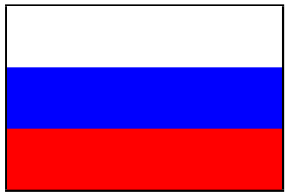
Lattice QCD meets experiment 2014

Mu2e collaboration: more than 150 physicists



Boston University
Brookhaven National Laboratory
LBL/UC Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Lewis University
University of Massachusetts, Amherst
Muons, Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Purdue University
Rice University
University of Virginia
University of Washington

Laboratori Nazionali di Frascati
INFN Genova
INFN Lecce and Università del Salento
INFN Lecce and Università Marconi Roma
INFN Pisa
Università Udine and INFN Trieste/Udine



Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna

Our search: $\mu N \to e + N$

- Initial state: muonic atom
- Final state: electron + intact nucleus
  - signal is monoenergetic electron
- CLFV process
- Conventional signal normalization

$$R_{\mu e} = \frac{\Gamma[\mu^- + N \to e^- + N]}{\Gamma[\mu^- + N \to \text{all captures}]}$$

- What we know: $R_{\mu e} < 7 \times 10^{-13}$ 90% CL
  SINDRUM II at PSI, gold nucleus, [Eur.Phys.J C47(2006)]
- Mu2e goal SES is 2.5×10^{-17}: 4 orders of magnitude!

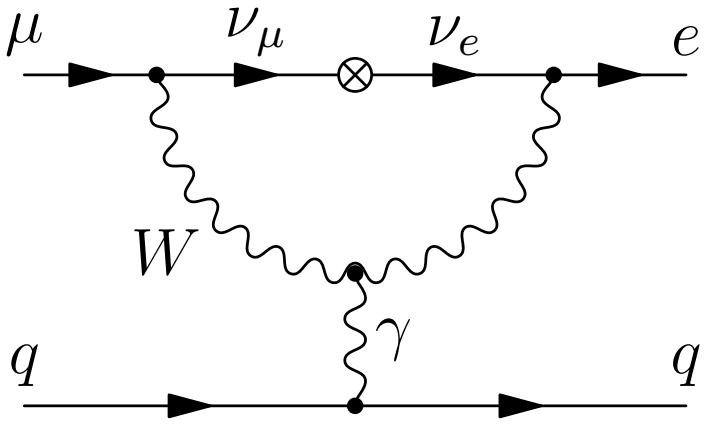
Expected rates

- SM: $R_{\mu e} = 0$

- νSM:

  $R_{\mu e} \propto (\Delta m_\nu / M_W)^4 \approx 10^{-54}$

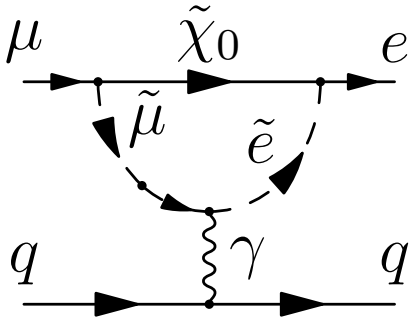
  40 orders of magnitude
  below experimental limits



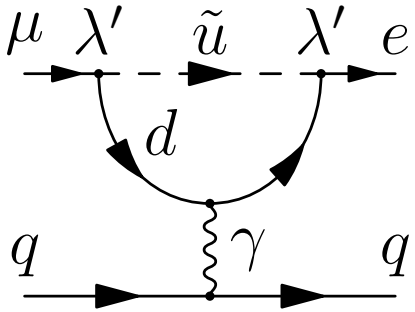
- CLFV observation would be an unambiguous signal of New Physics

Mu2e can discover

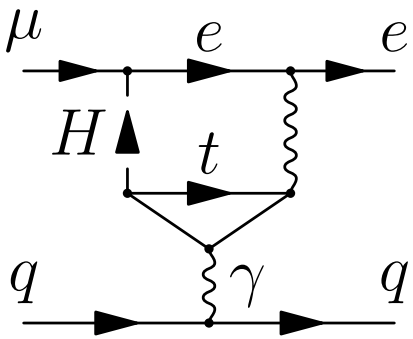
SUSY



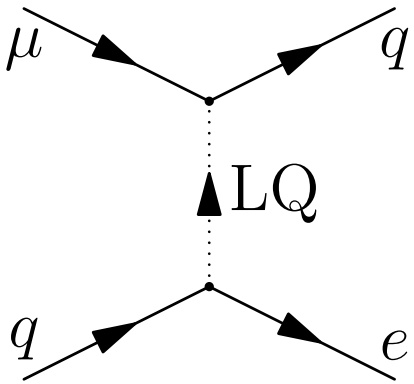
RPV SUSY



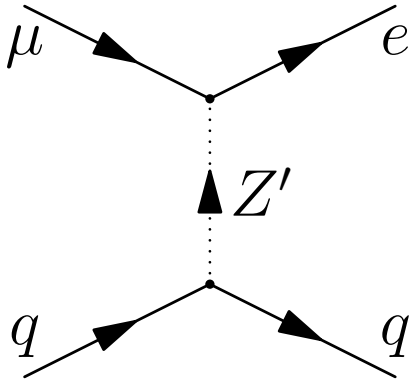
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

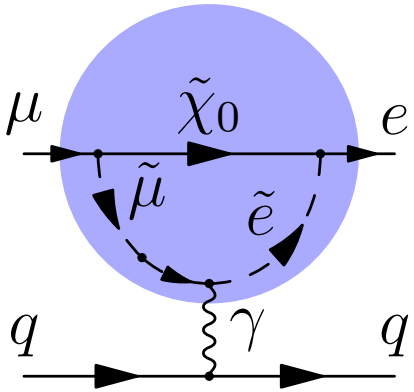
Y. Kuno, Y. Okada, 2001

M. Raidal *et al.*, 2008

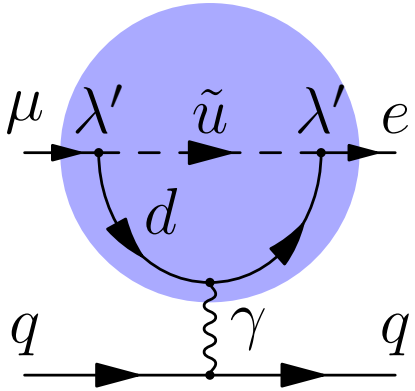
A. deGouvea, P. Vogel, 2013

Mu2e can discover

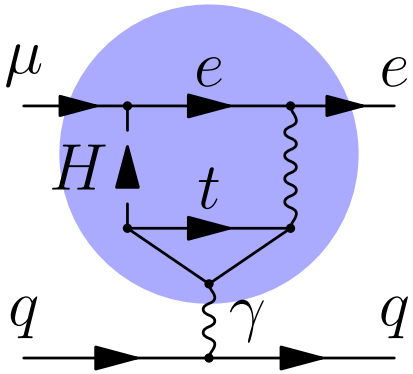
SUSY



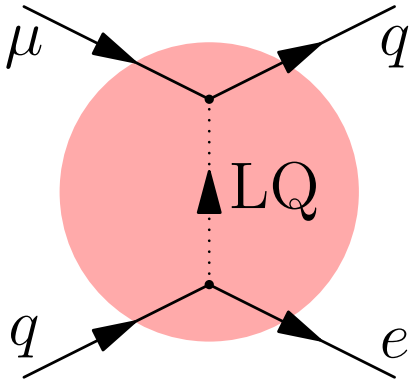
RPV SUSY



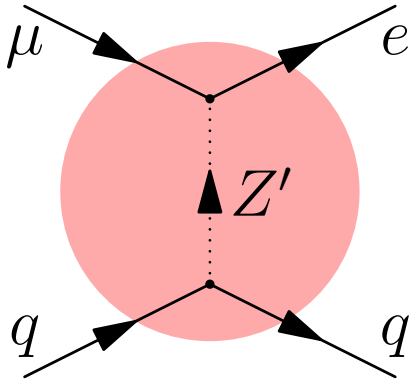
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

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Effective theory

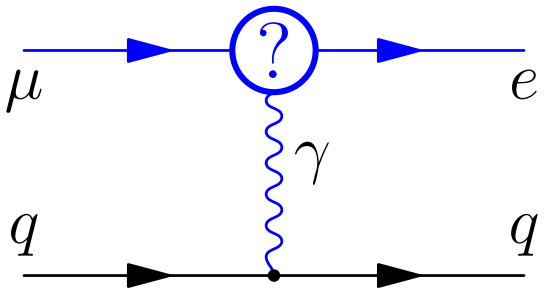
Parametrization: $\mathcal{L}_{CLFV} =$

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

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

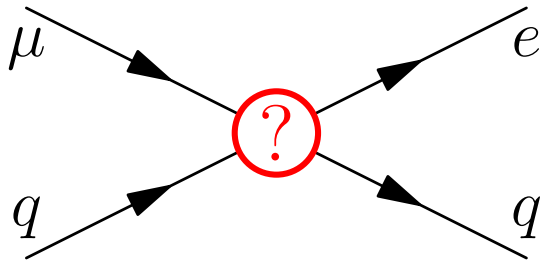
right: matrix element terms: connection to lattice QCD

Dipole: $\kappa = 0$



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

Contact: $\kappa = \infty$

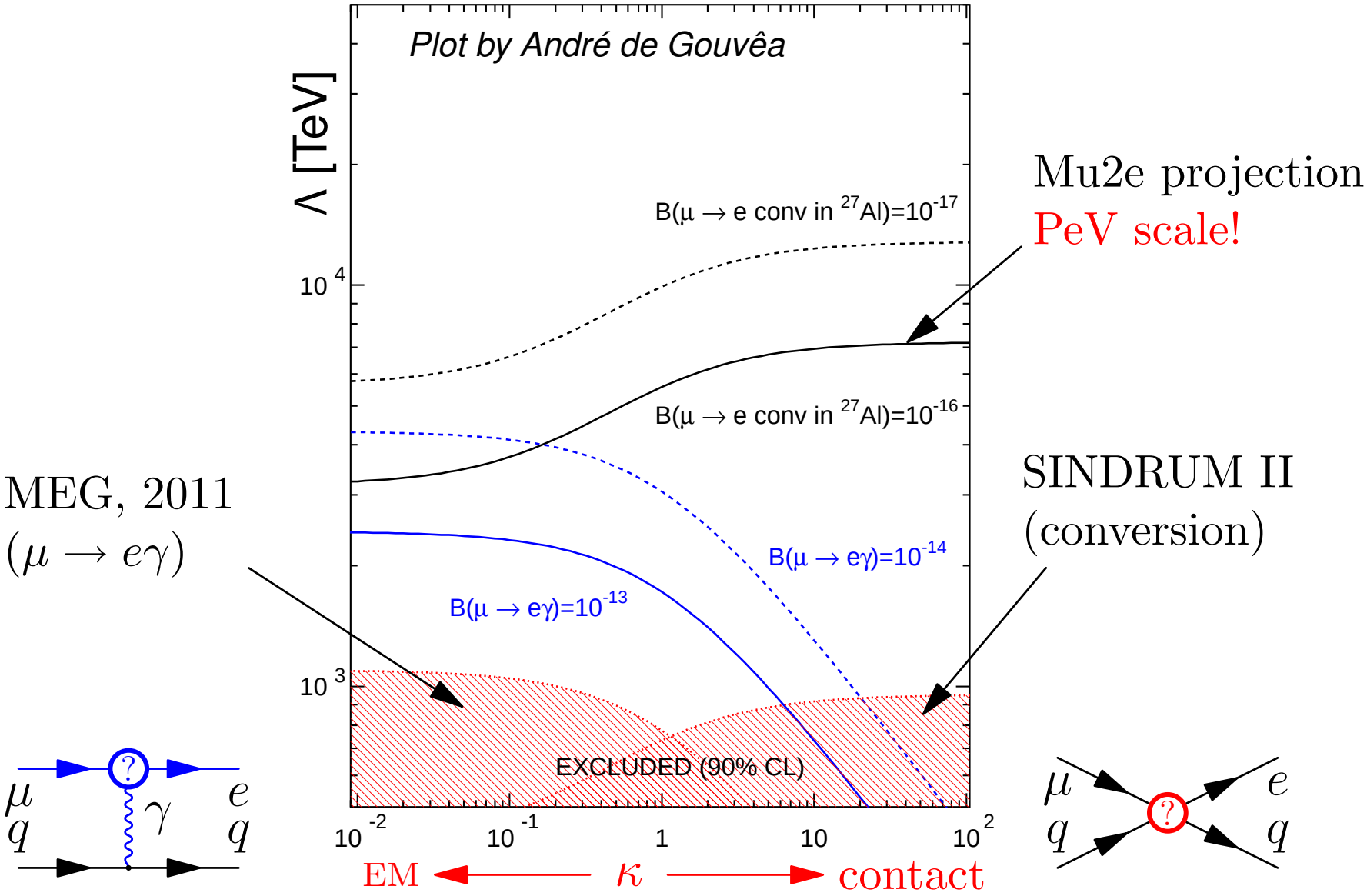


May be no $\mu \to e\gamma$ signal

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

Handle to discriminate New Physics models

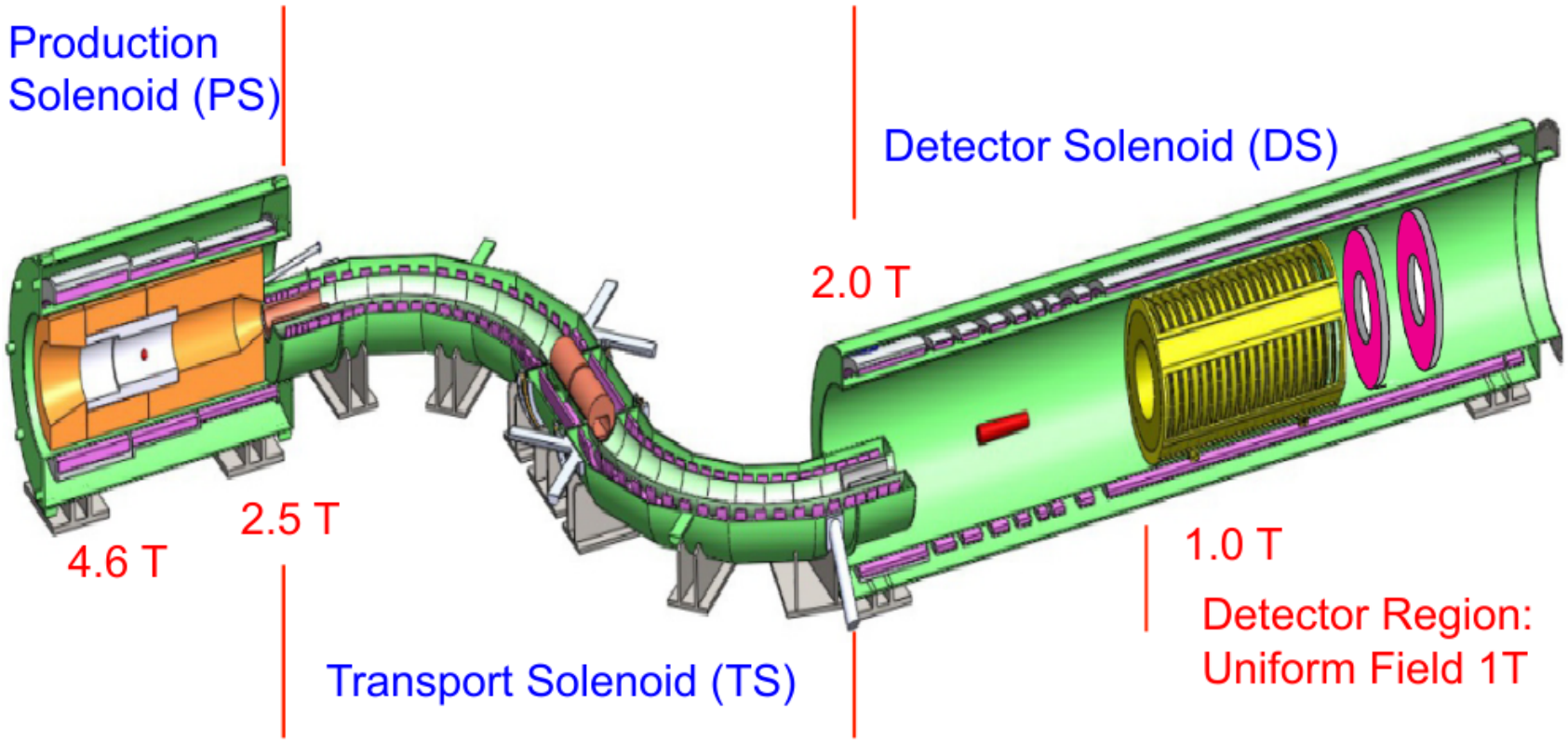
Muon LVF physics reach



The concept of Mu2e measurement

- Generate pulsed beam of low momentum negative muons
- Stop muons in thin foils and form muonic atoms
- Wait for prompt backgrounds to decay
- Then measure electron spectrum
    - The signal: mono-energetic electrons at 105 MeV

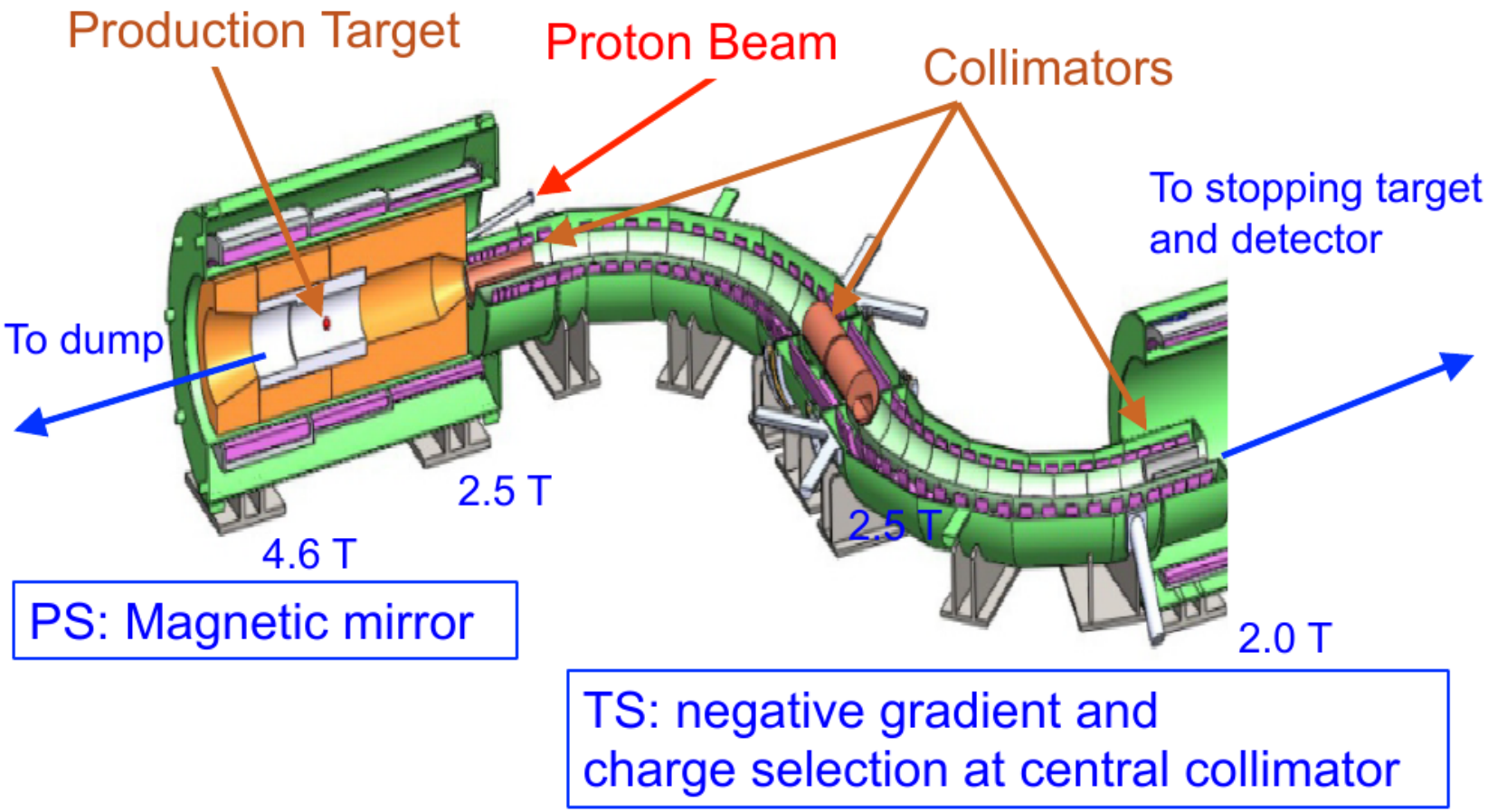
Overview of Mu2e setup



Graded B for most of length

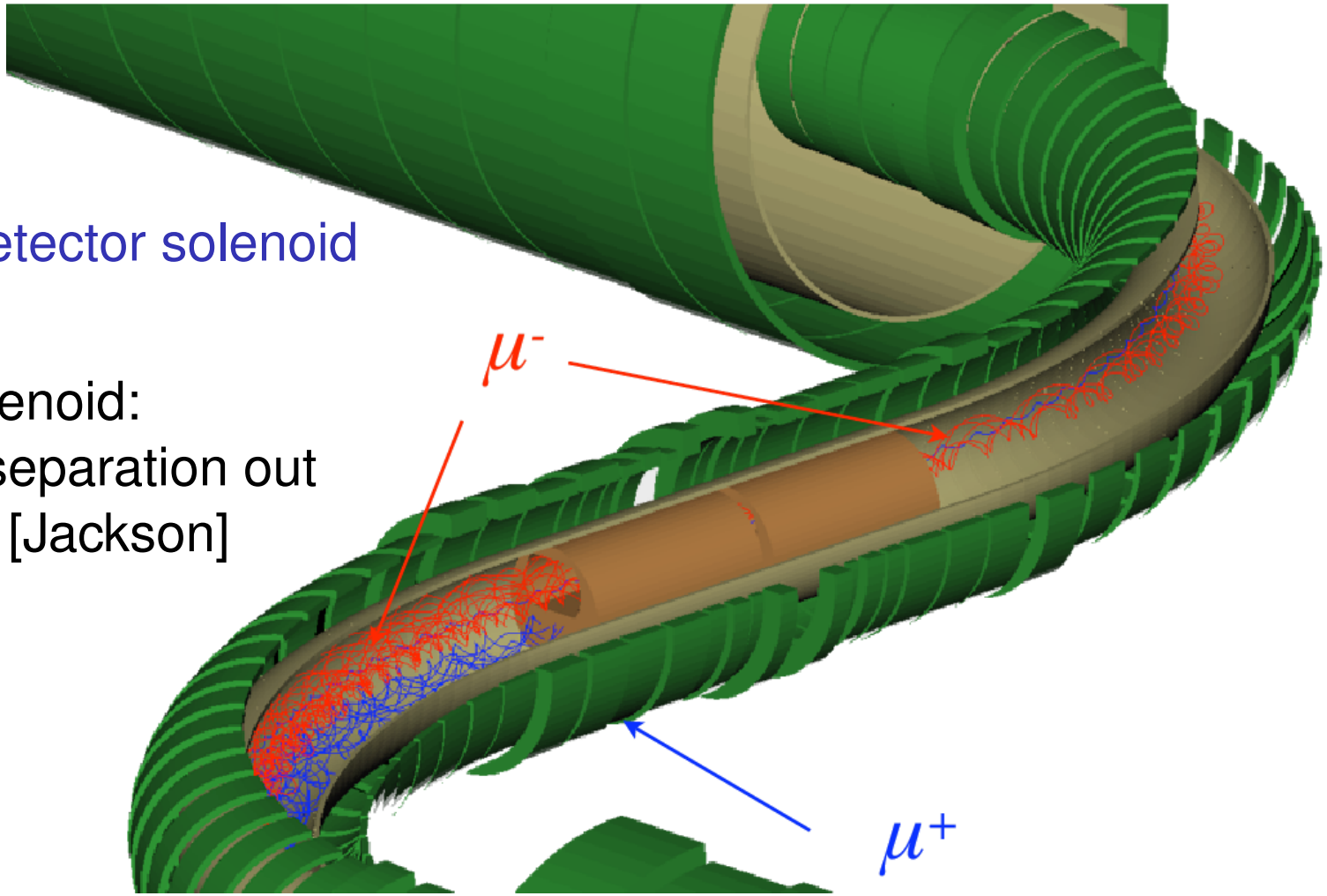
Not shown: Cosmic Ray Veto, Extinction Monitor

Muon production and delivery

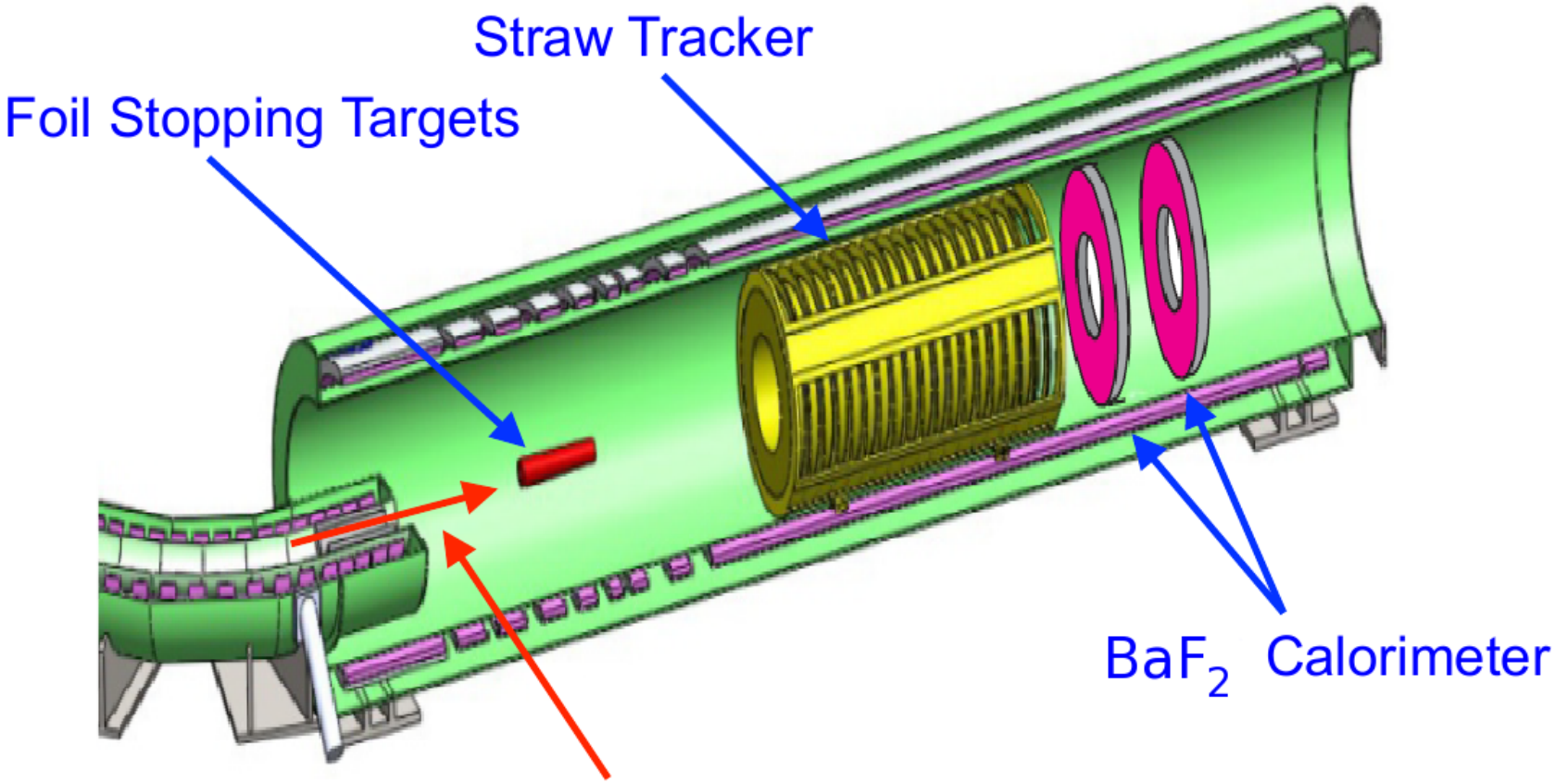


Charge selection

Bent solenoid:
charge separation out
of plane [Jackson]

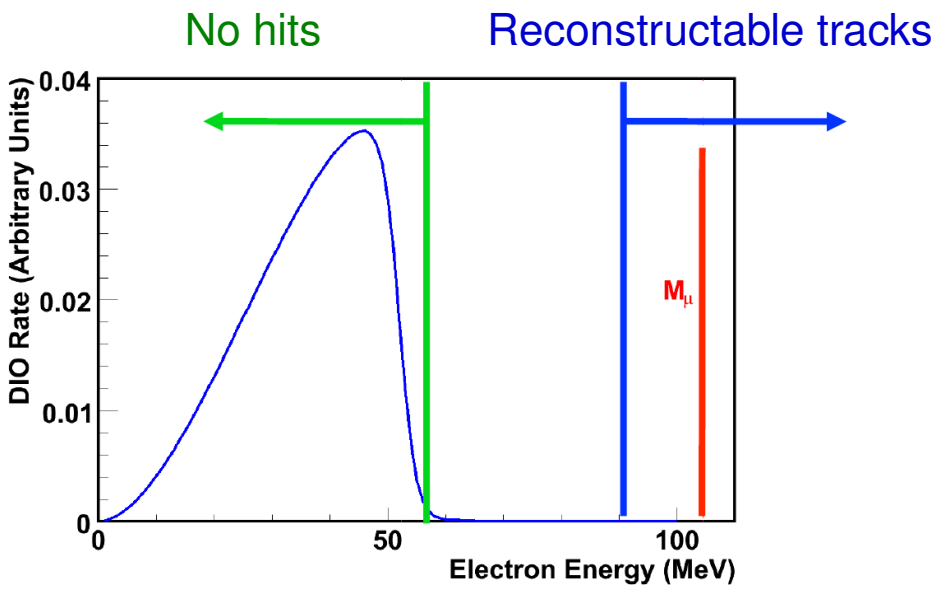


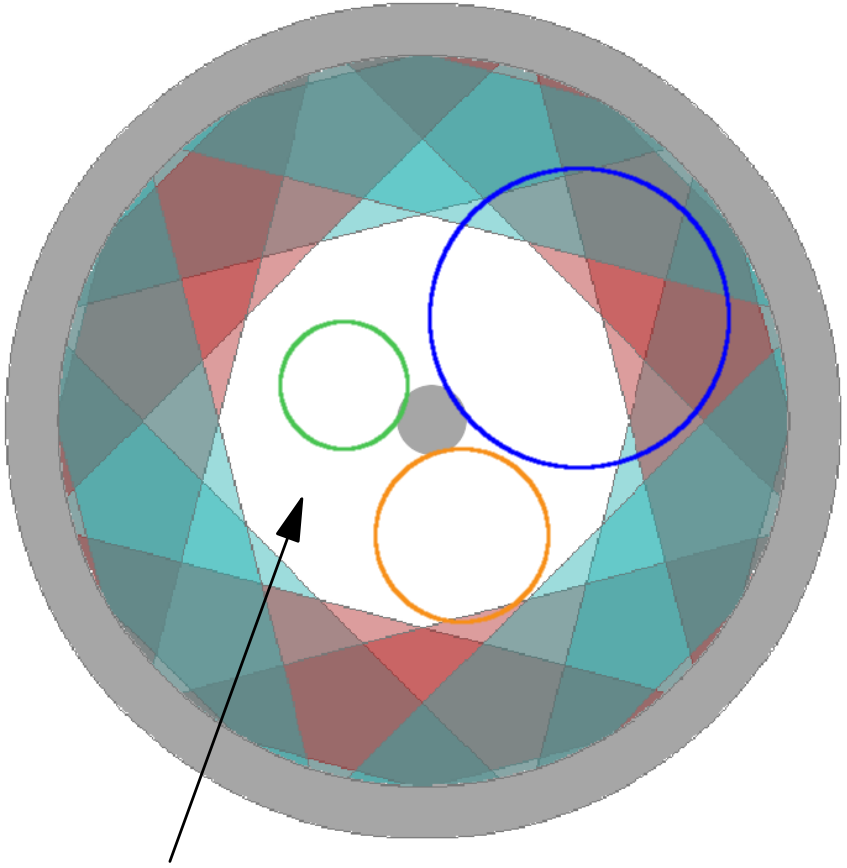
Stopping target and detectors



FIXME: BaF_2

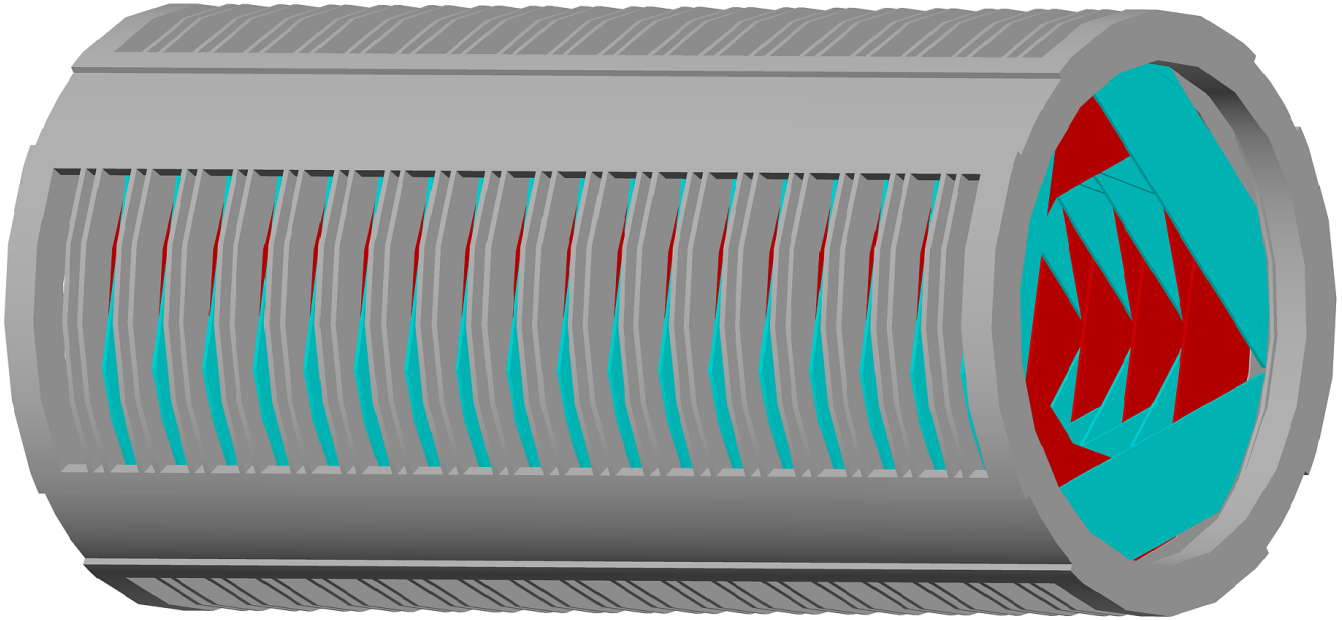
How to measure 2.5×10^{-17}





Vacuum: no scattering

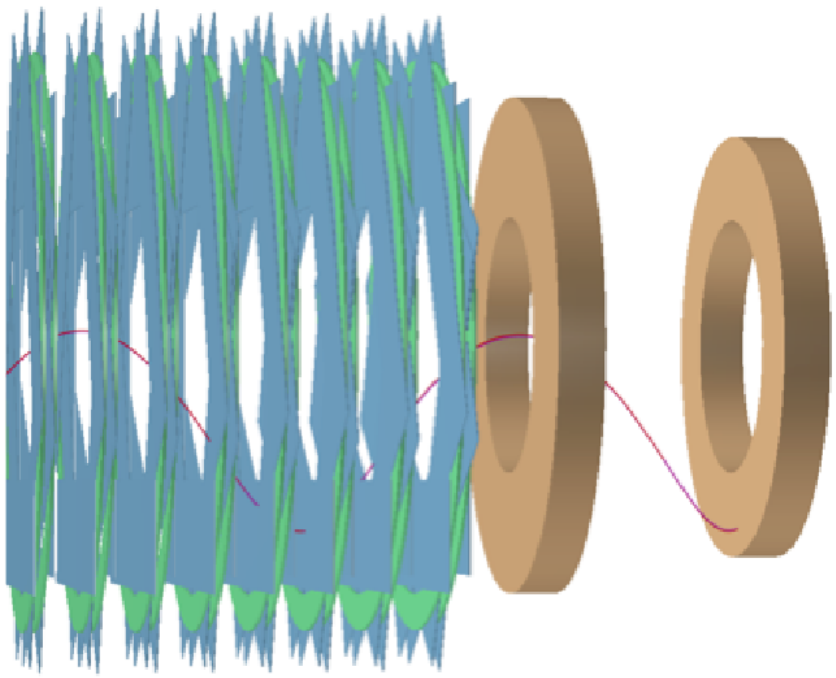
Tracker



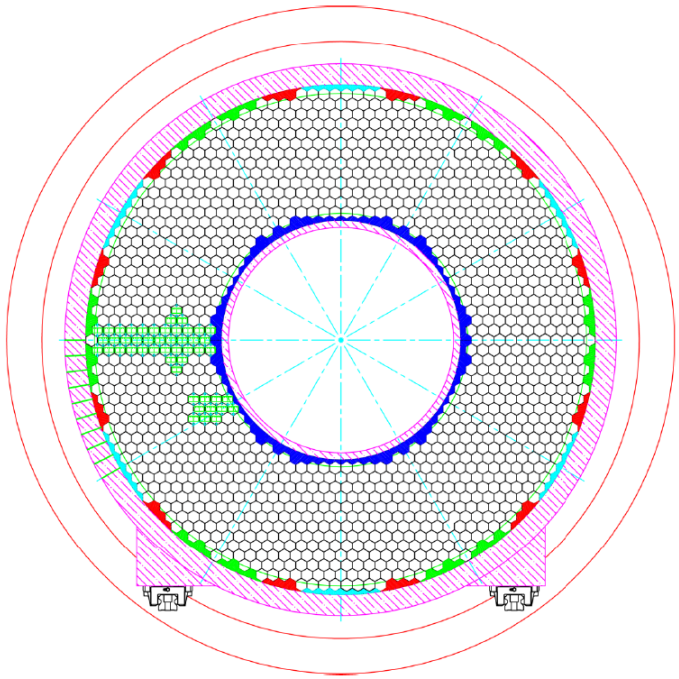
- Measures electron spectrum
- about 3 m long
- 1 T uniform B field
- “Good” tracks make 2–3 turns

Calorimeter

Two disk geometry



Hex BaF_2 crystals

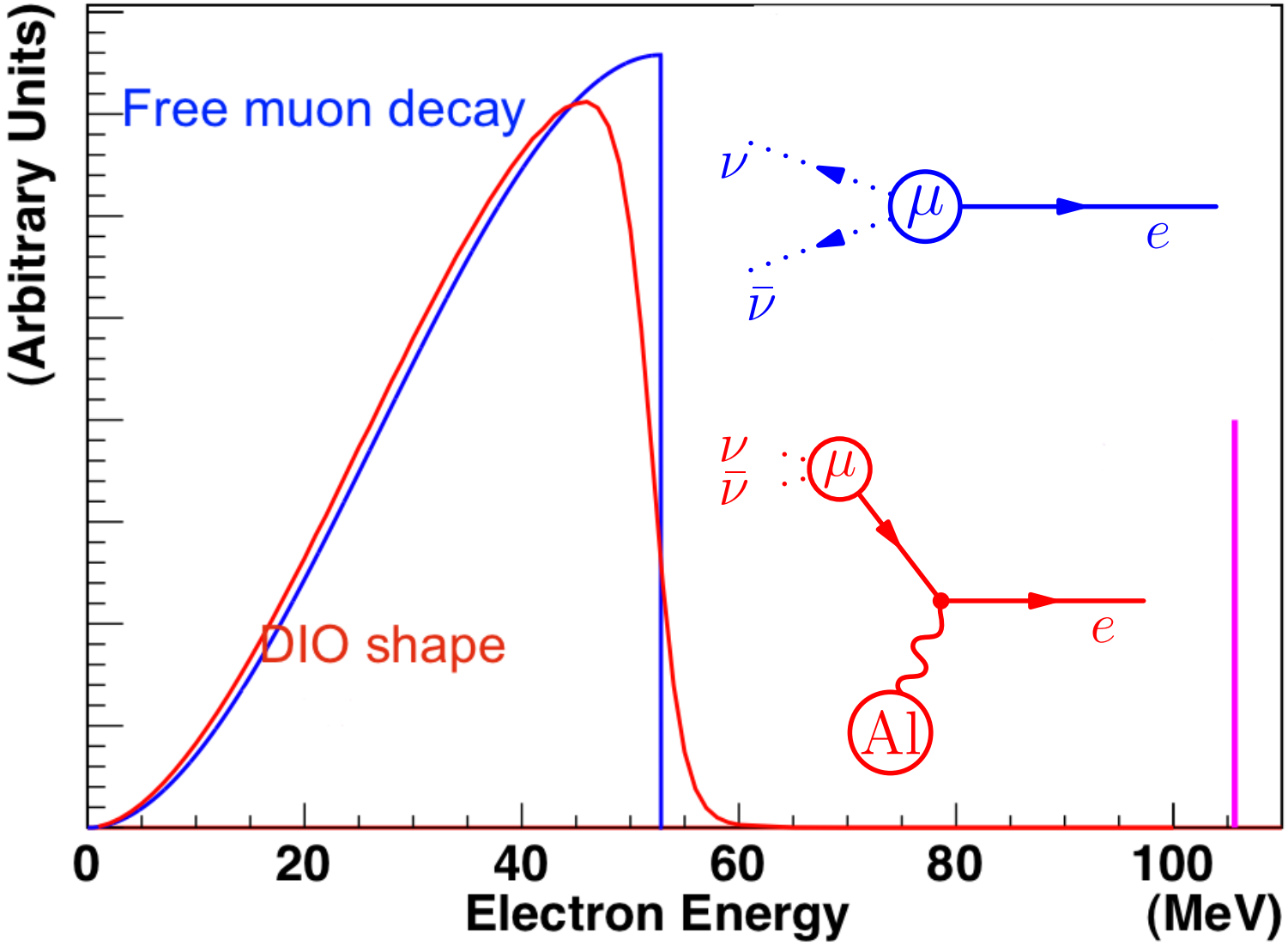


Makes sure signal candidates are not catastrophic misreconstructions.

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



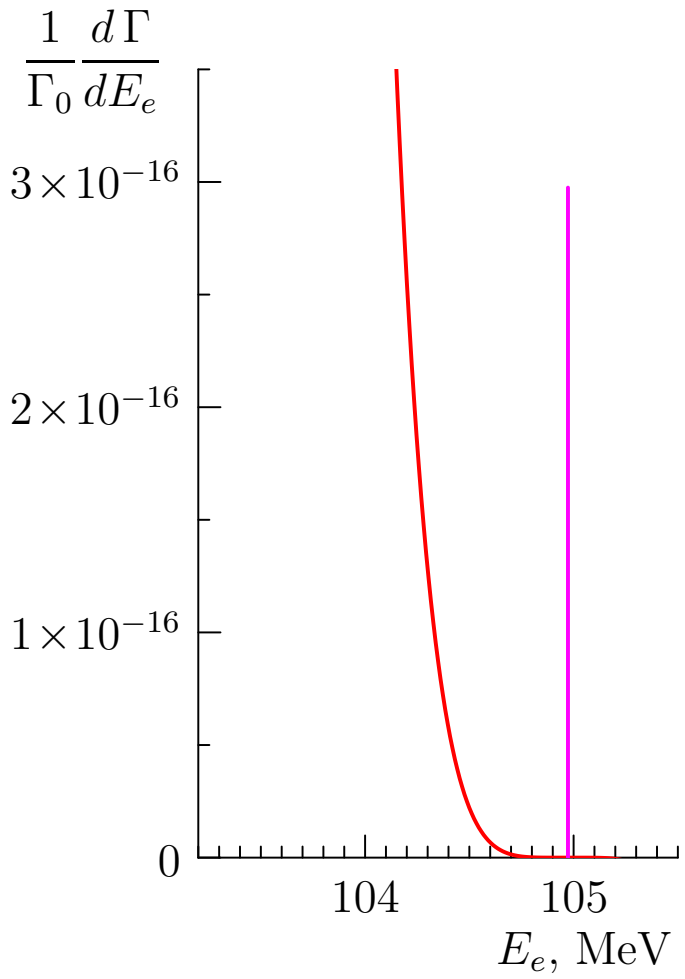
Decays in orbit

- Latest spectrum computation: Czarnecki, Tormo, Marciano (2011)
- End point expansion

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e} = B\left(E_\mu - E_e - \frac{E_e^2}{2m_N}\right)^5$$

— small but steep tail!

- DIO electron differs from signal only by its p
- Momentum resolution is important!
  - Especially the high side tail: pushes DIOs into the signal region



Prompt backgrounds

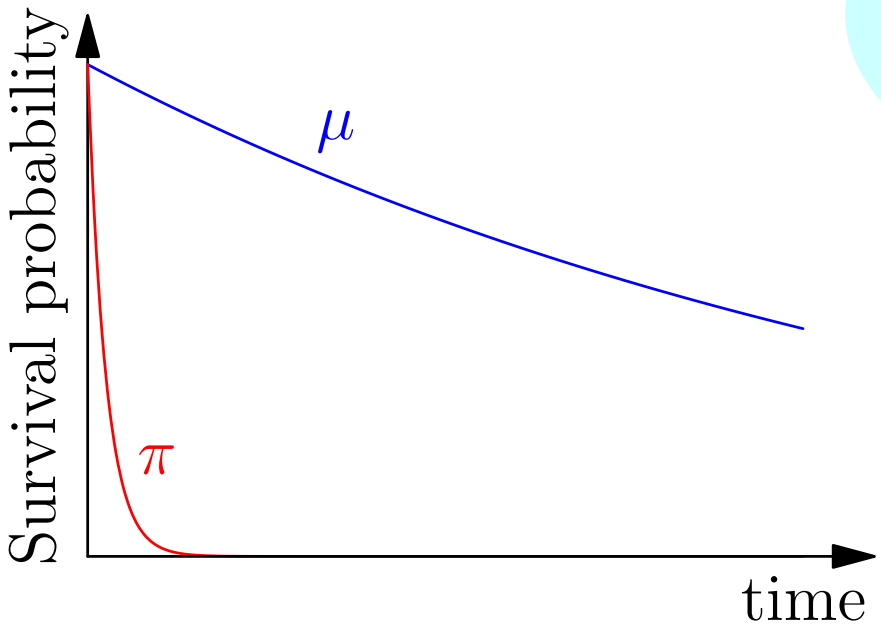
- Signal is a 105 MeV electron
- Many ways for 8 GeV protons to make those
- Example: Radiative Pion Capture

$$pN \longrightarrow \pi^- X$$

$$\pi^- N \xrightarrow{\text{radiative capture}} \gamma N'$$

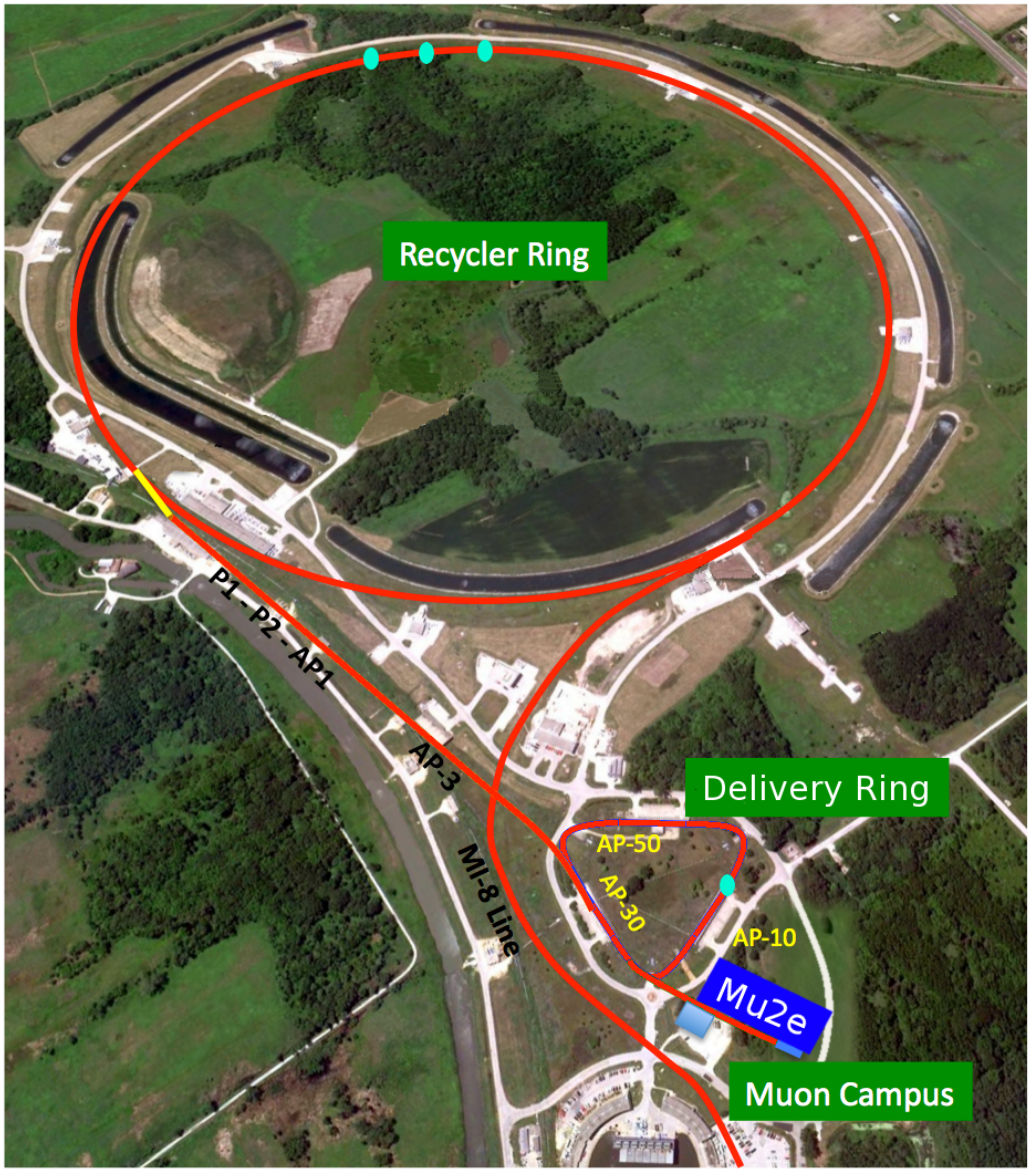
$$\gamma N \xrightarrow{\text{conversion}} e^- e^+ N$$

Processes in Al target



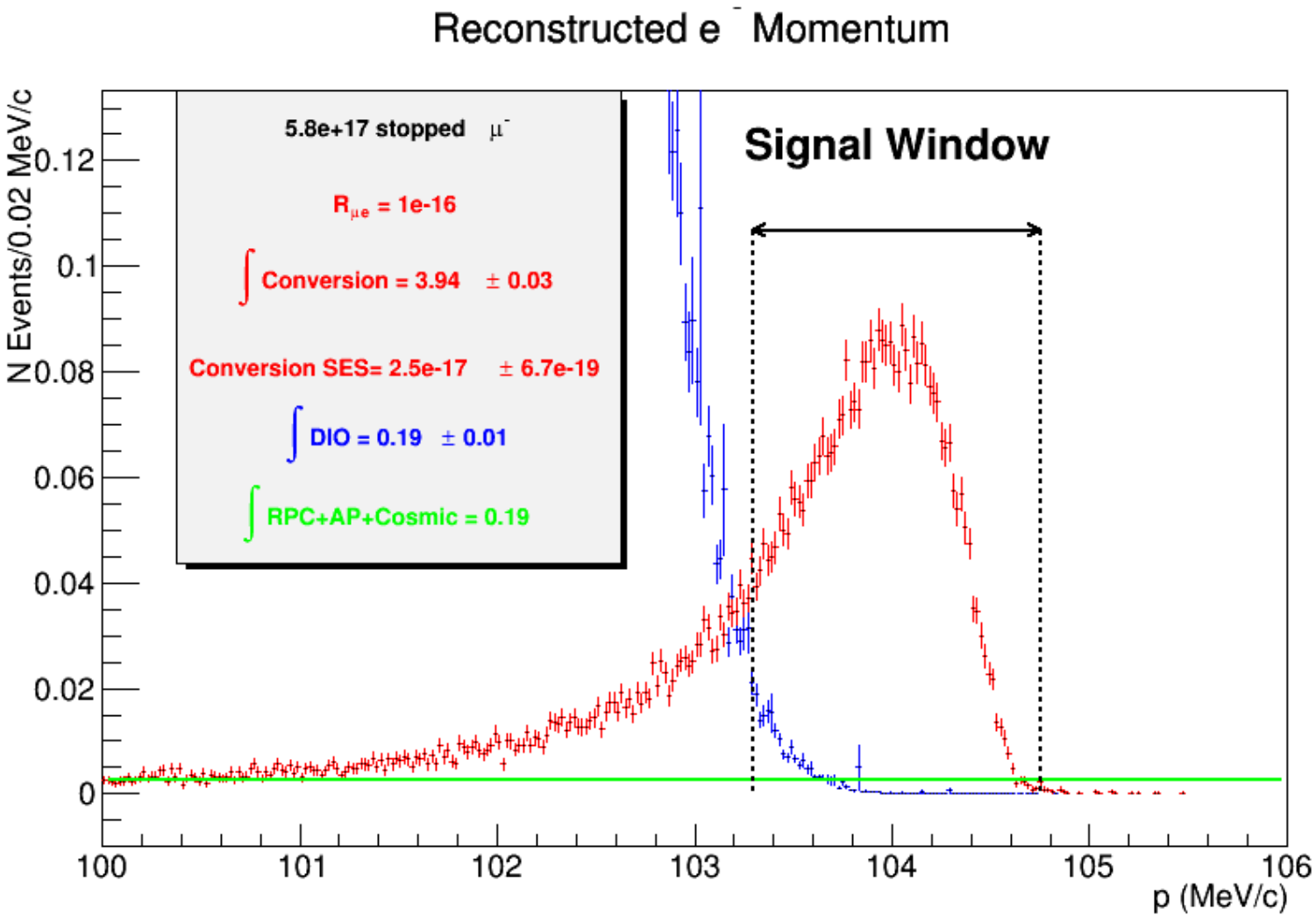
$\Longleftarrow$ Mitigation: wait

Why aluminum



- Desired proton pulse timing $\approx 2 \times \tau_\mu$
- Making pulses: slowly extract a single circulating bunch
- Existing accelerator complex
- Delivery ring revolution period is 1694 ns:
- good match to $\tau^{\mathrm{Al}} = 864$ ns

Mu2e signal sensitivity for 3 year run



$\approx$ 4 signal for $R_{\mu e} = 10^{-16}$ over 0.4 background

Theory desiderata

A major strength of Mu2e:

- Discovery claim will not be sensitive to theory uncertainties

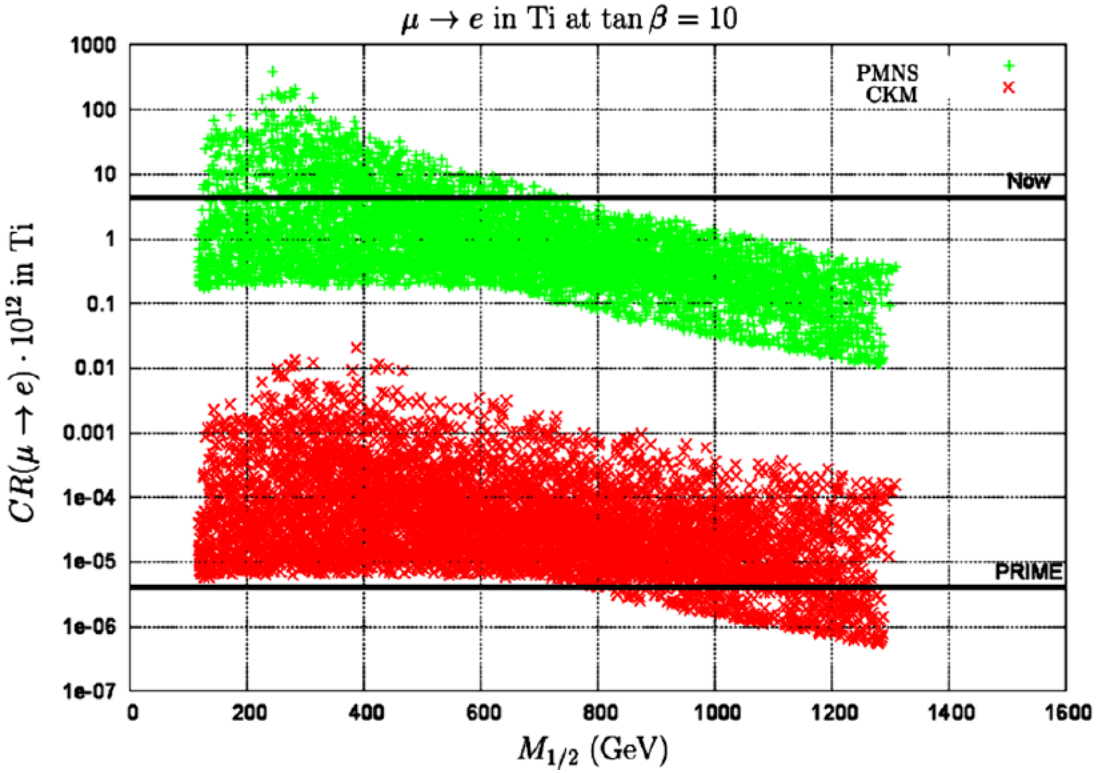
Of course we still need theory inputs

- From proposal to result interpretation:
  BSM model predictions
- Experiment design stage:
  Backgrounds
- After discovery
  BSM interpretations, target nucleus dependence

Theory desiderata: always needed

- BSM model predictions for conversion on Al
- Studies placing conversion in the same model parameter space as other measurements (LHC, other flavor, g-2,. . .)
- Similar for $\mu^- \to e^+$ process

SUSY GUT $\tan(\beta) = 10$



L. Calibbi et al., *Phys.Rev.**D74** (2006) 116002*

Theory desiderata: design stage

- Most backgrounds will be derived from data
- Theory inputs can be very useful for optimization of experiment

Needed now

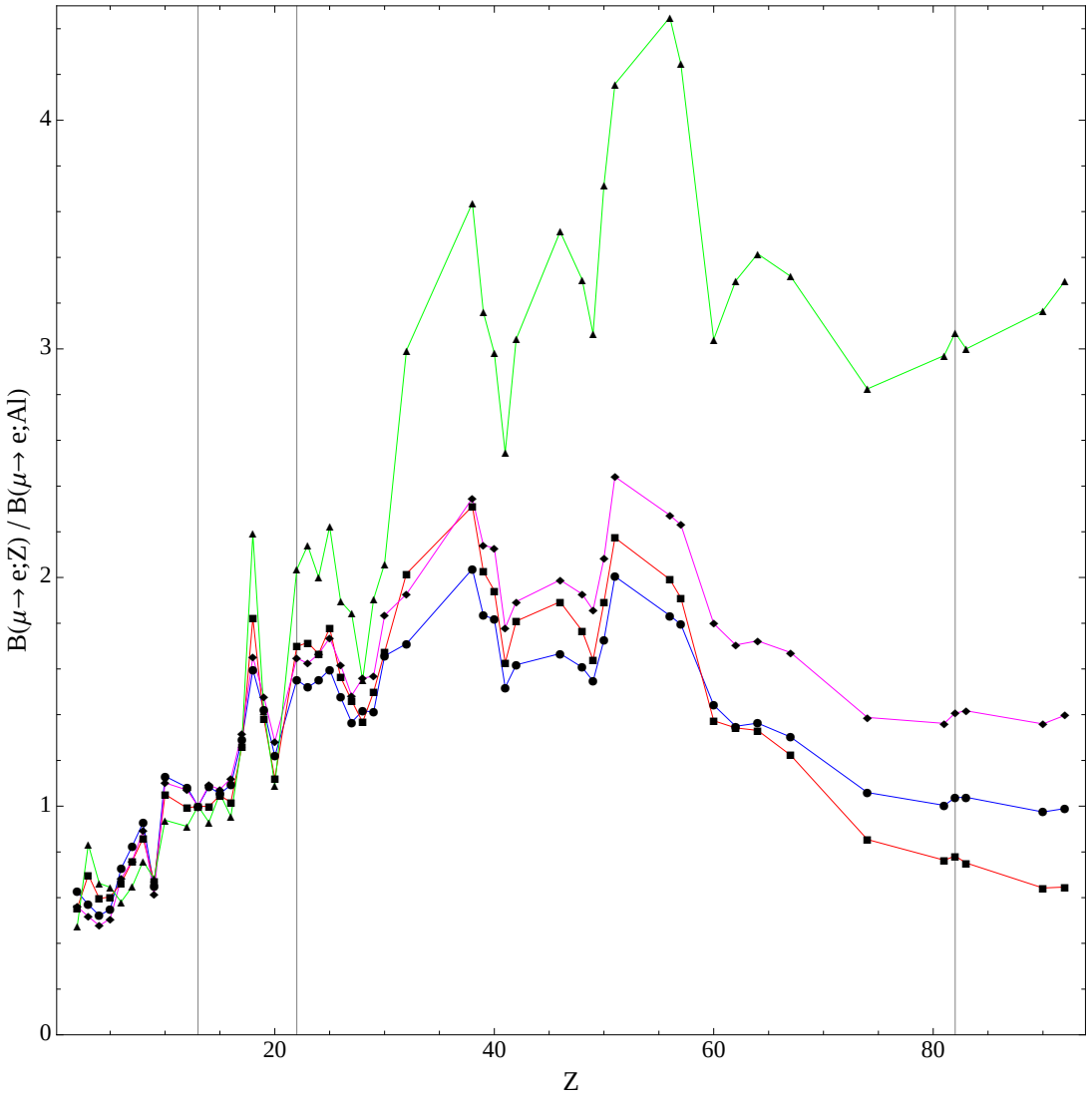
- antiproton production by 8 GeV protons on tungsten
- antiproton cross sections on materials (0 to few GeV energies)
- production of low energy backward going pions by 8 GeV protons
- Radiative pion capture: γ spectrum
- RPC with internal conversion: electron spectrum
- Decay in orbit with rad corrections
- Photon spectrum from radiative DIO (for $\mu^+ \to e^-$)

Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aims for 4 orders of magnitude improvement: $R_{\mu e} \approx 2.5 \times 10^{-17}$ single event sensitivity
  - New physics reach: Λ_{eff} up to thousands of TeV
- Conceptual design complete: Mu2e CDR arXiv:1211.7019
- Working towards technical design
- Data taking: about 2019
- Theory inputs needed before and after data
- More information: `http://mu2e.fnal.gov`

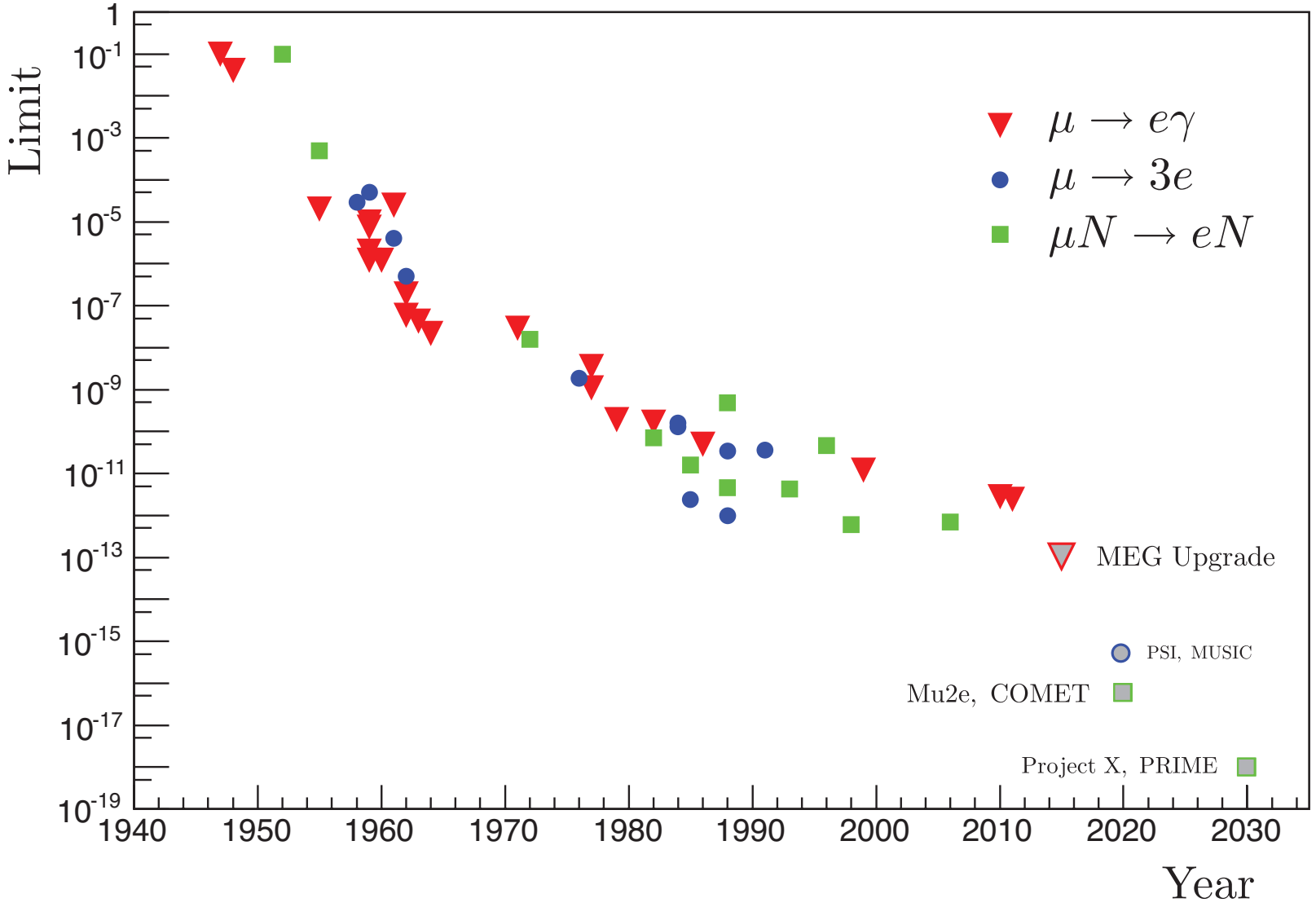
Extra slides

Target Z dependence



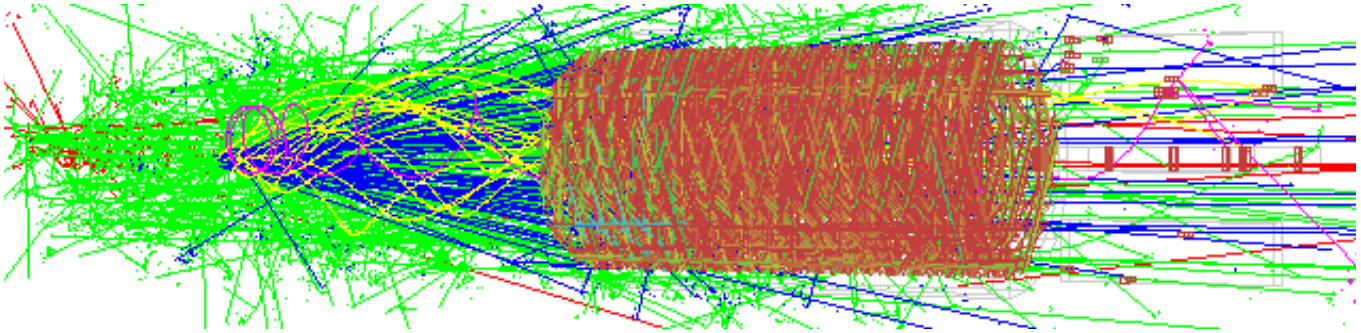
V. Cirigliano et al., Phys. Rev. D **80**, *013002 (2009)*

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



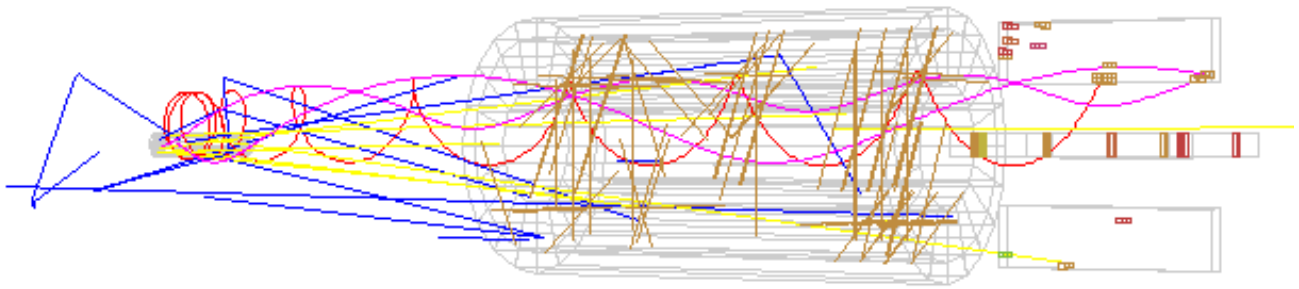
R. H. Bernstein, P. S. Cooper
arXiv:1307.5787

Pattern recognition



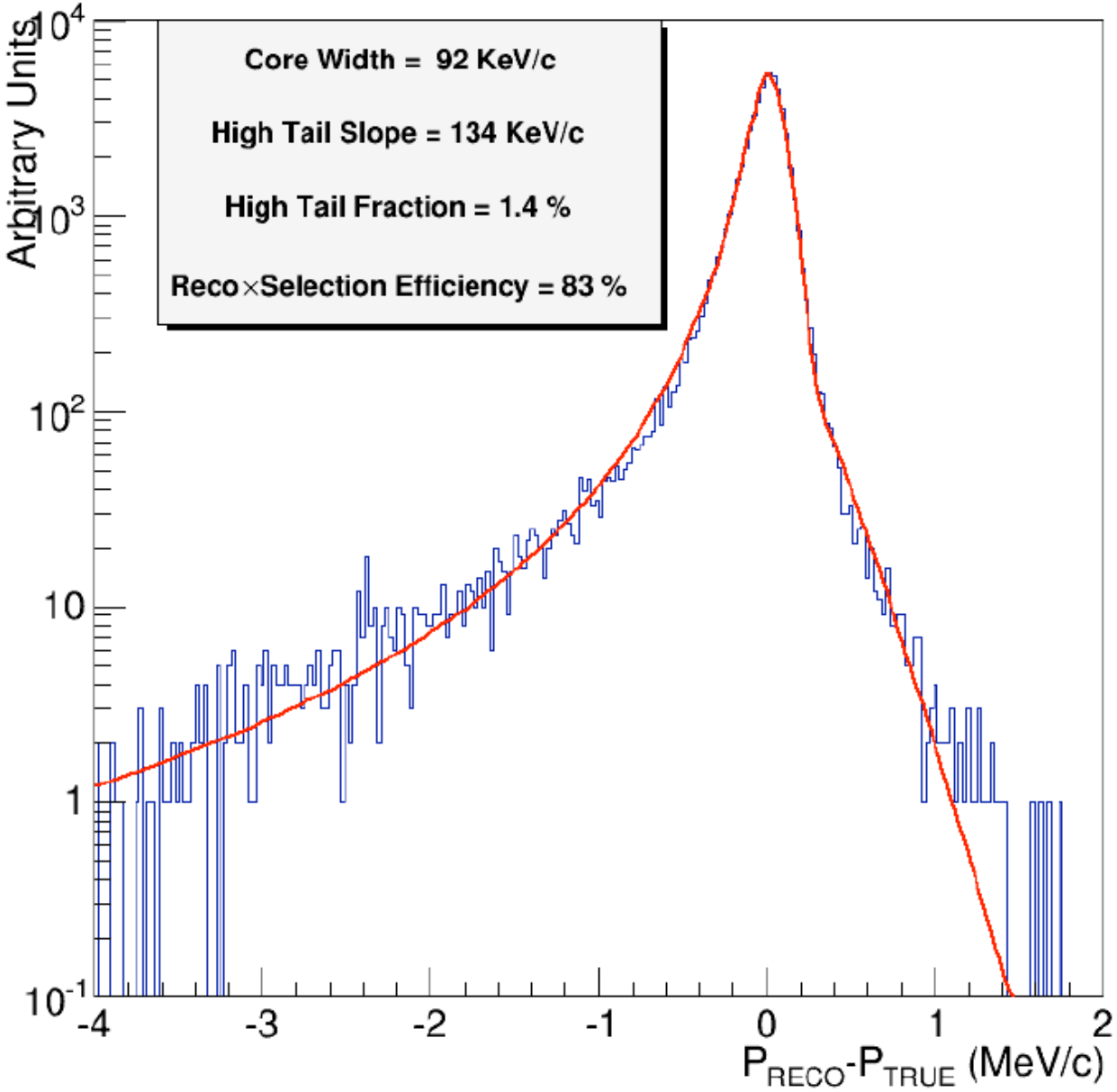
Single proton pulse: particles and hits in 500–1694 ns

Pattern recognition



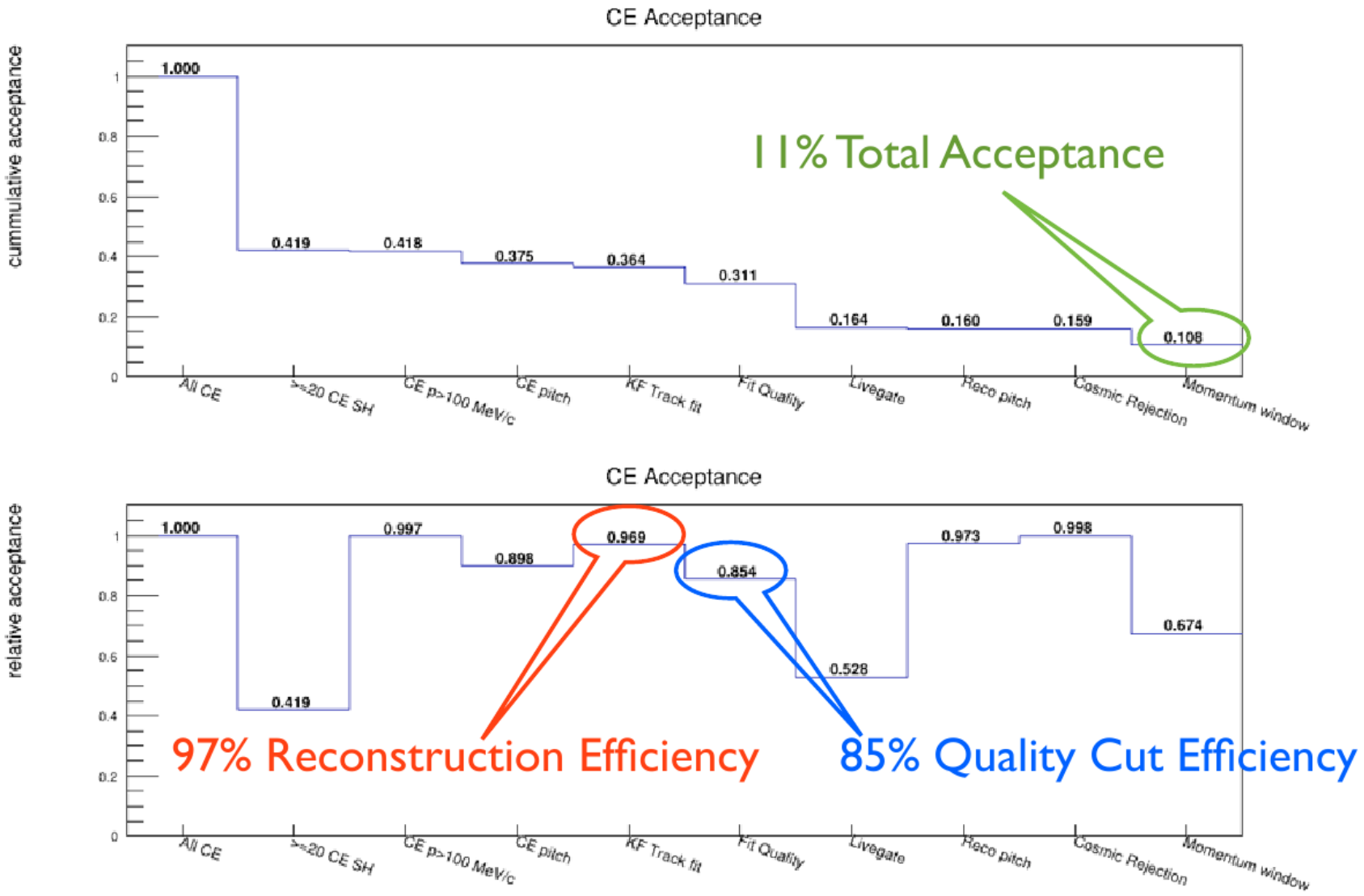
Single proton pulse: particles and hits in ± 50 ns around conversion

Tracker momentum resolution



Dave Brown, CLFV2013 (Lecce)

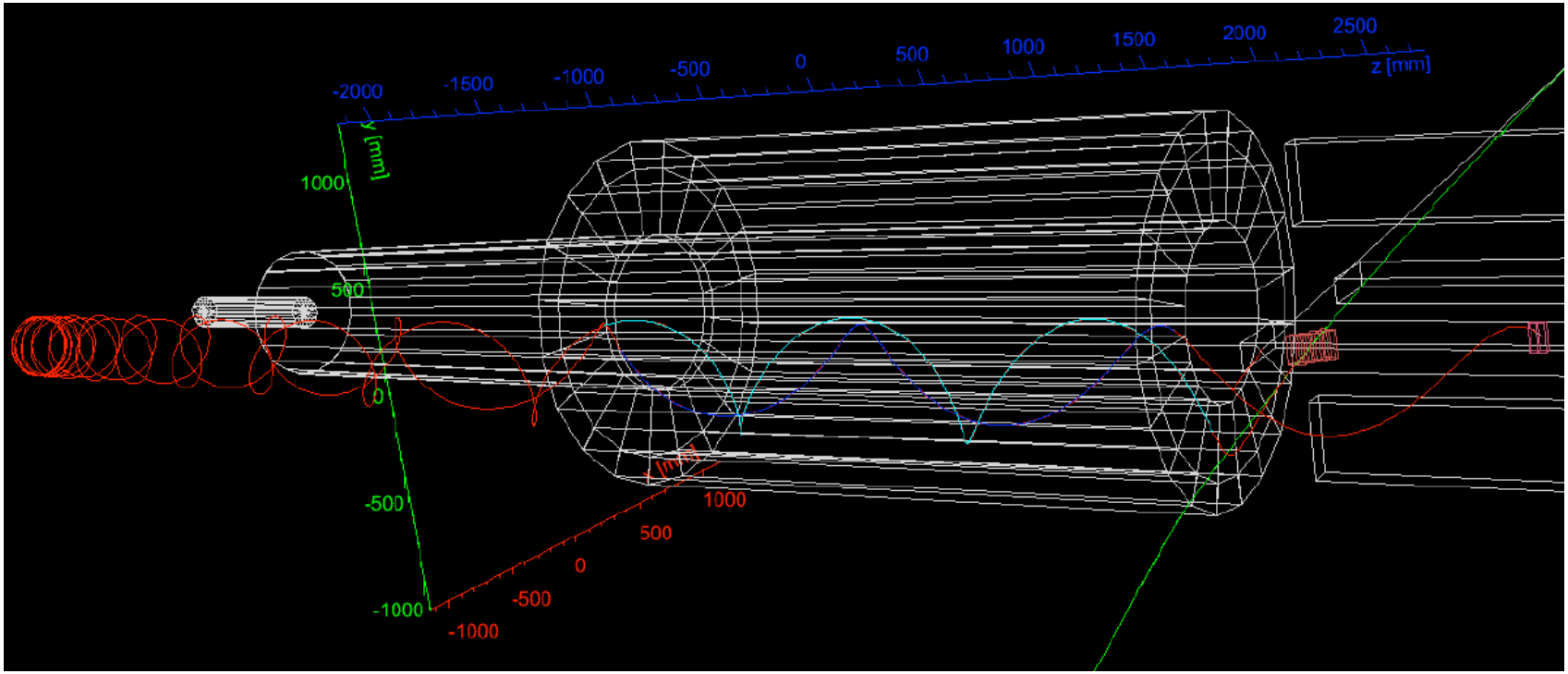
Signal reconstruction efficiency



Dave Brown, CLFV2013 (Lecce)

Tracker energy loss calibration

Double-pass of cosmic produced electrons [Dave Brown]



Preliminary backgrounds

3 years of 1.2×10^{20} protons/year (8 kW beam power)

Background description	Expected events
Muon decay in orbit	0.20 ± 0.06
Antiproton induced	0.10 ± 0.06
Radiative pion capture*	0.04 ± 0.02
Beam electrons*	0.001 ± 0.001
Muon decay in flight*	0.010 ± 0.005
Cosmic rays**	0.050 ± 0.013
Total	0.4 ± 0.1

* Assuming 10^{-10} beam extinction
** For 10^{-4} cosmic ray veto inefficiency