Searching for muon to electron conversion: the Mu2e experiment at FERMILAB

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LNF Theory Seminars – 28 November 2017

Outline

- The Physics
  →CLFV processes in muon sector
  →BSM: Conversion exp. vs MEG-II/mu3e
- Description of Muonic Atom processes
- Experimental technique
- Detector Layout
- Status of Mu2e experiment
- Conclusions

The Mu2e Collaboration

~230 Scientists from 37 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 of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Institute for High Energy Physics Protvino, Kansas State University, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

Physics Program

CLFV processes

- Muon-to-electron conversion is a charged lepton flavor violating process (CLFV)

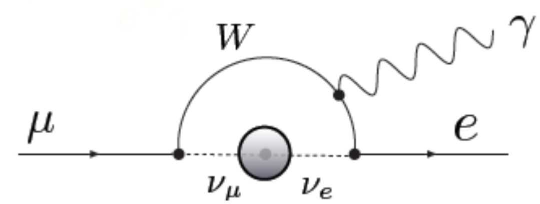
  similar but complementary to other CLFV processes as μ→ eγ and μ → 3e.

- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \rightarrow e^- Al$

- **CLFV processes are forbidden in the Standard Model**

  → Assuming neutrino oscillations they are allowed but ..

  in practice BR($\mu \rightarrow e\gamma$) ~ 10^{-54} …. they are negligible



- **New Physics could enhance CLFV rates to observable values**

- Various NP models allow for it, at levels just beyond current CLFV upper limits.
  - SO(10) SUSY
    - L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.*, JHEP **1211**, 40 (2012).
  - Scalar leptoquarks
    - J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
  - Left-right symmetric model
    - C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

Observation of CLFV is New Physics

An overview of some CLFV Processes

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

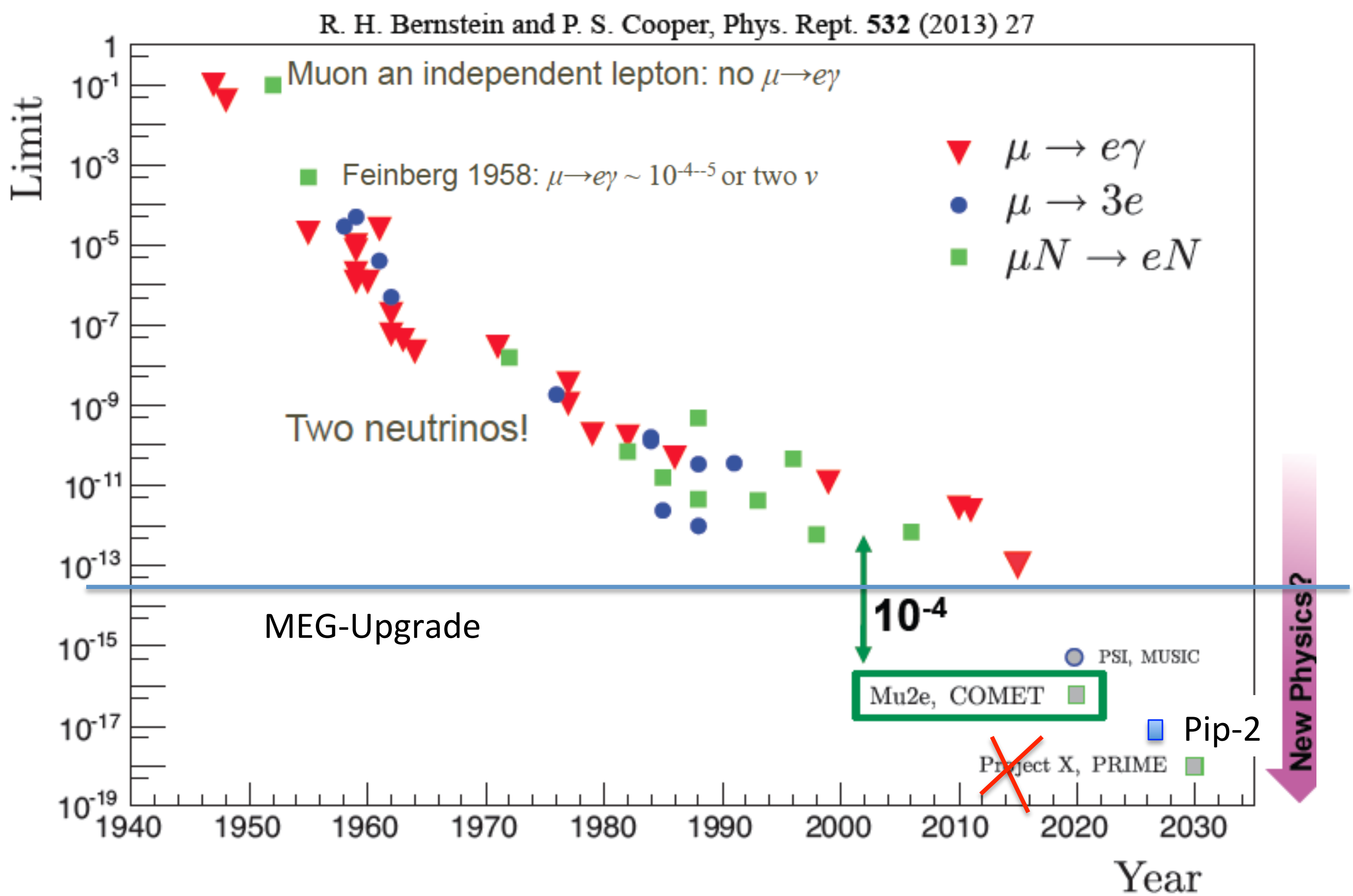
Most promising CLFV measurements use μ

→ **large rates available for the beams**

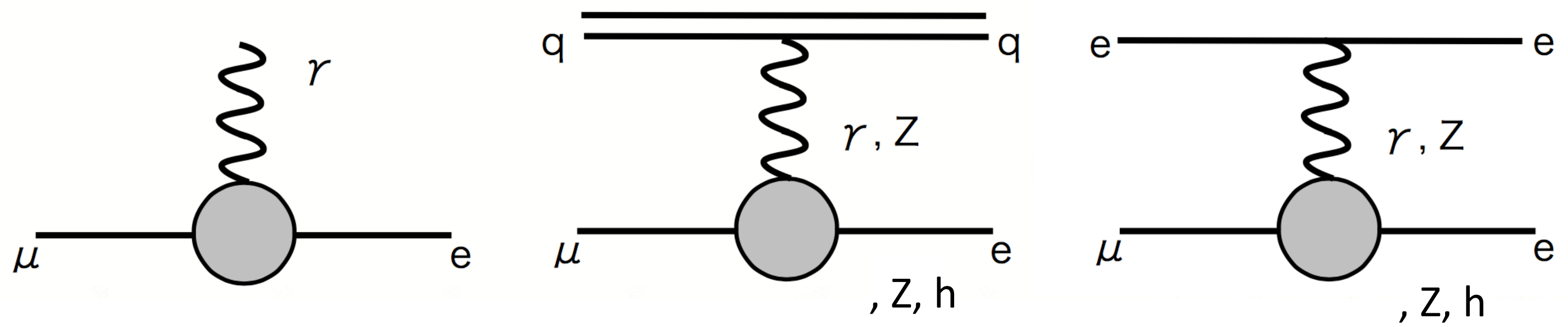
→ **no needs of hadronic corrections in final states**

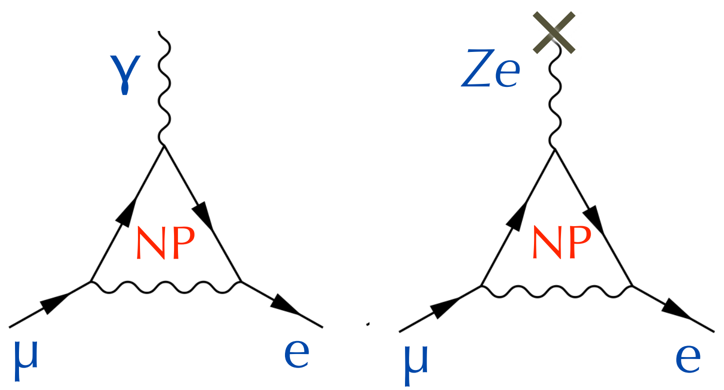
→ **Colliders/factories win when 3rd generation is involved, $\tau \to \mu\gamma$ H → $\tau\,\mu$**

CLFV history for muons

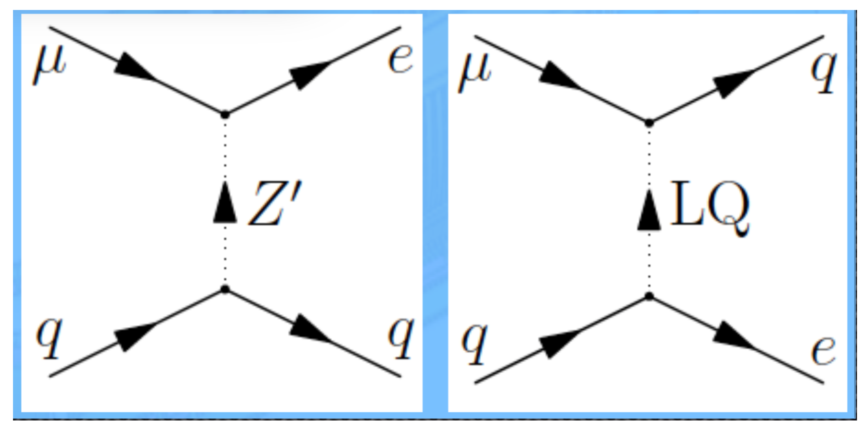


Diagrams for CLFV muon processes





$\mu \rightarrow e\gamma \qquad \mu^- \mathcal{N} \rightarrow e^- \mathcal{N}$



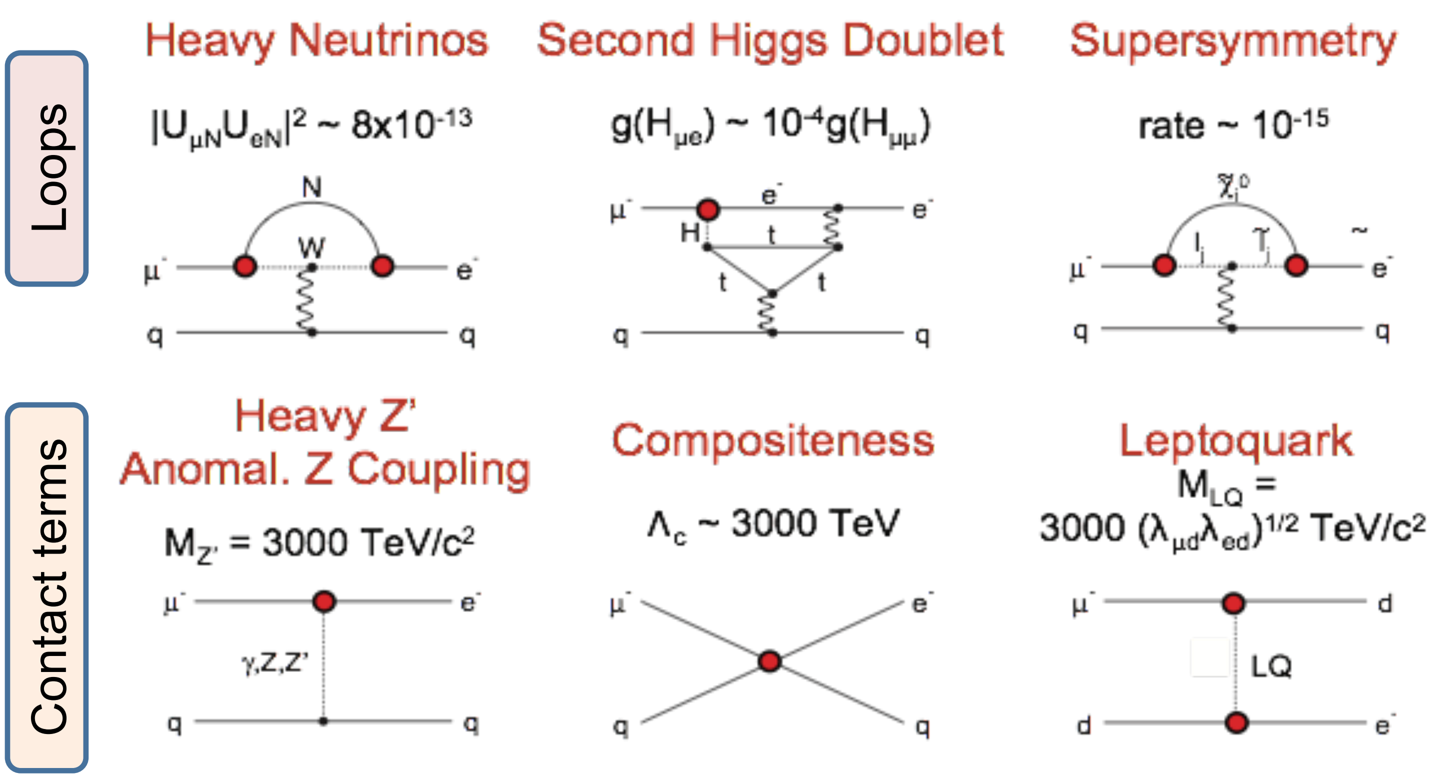
Loop terms

Contact or 4-lepton terms

CLFV rates and ratios are sensitive probes of underlying model

CLFV General Lagrangian

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



Models which can be probed also by μ→eγ searches

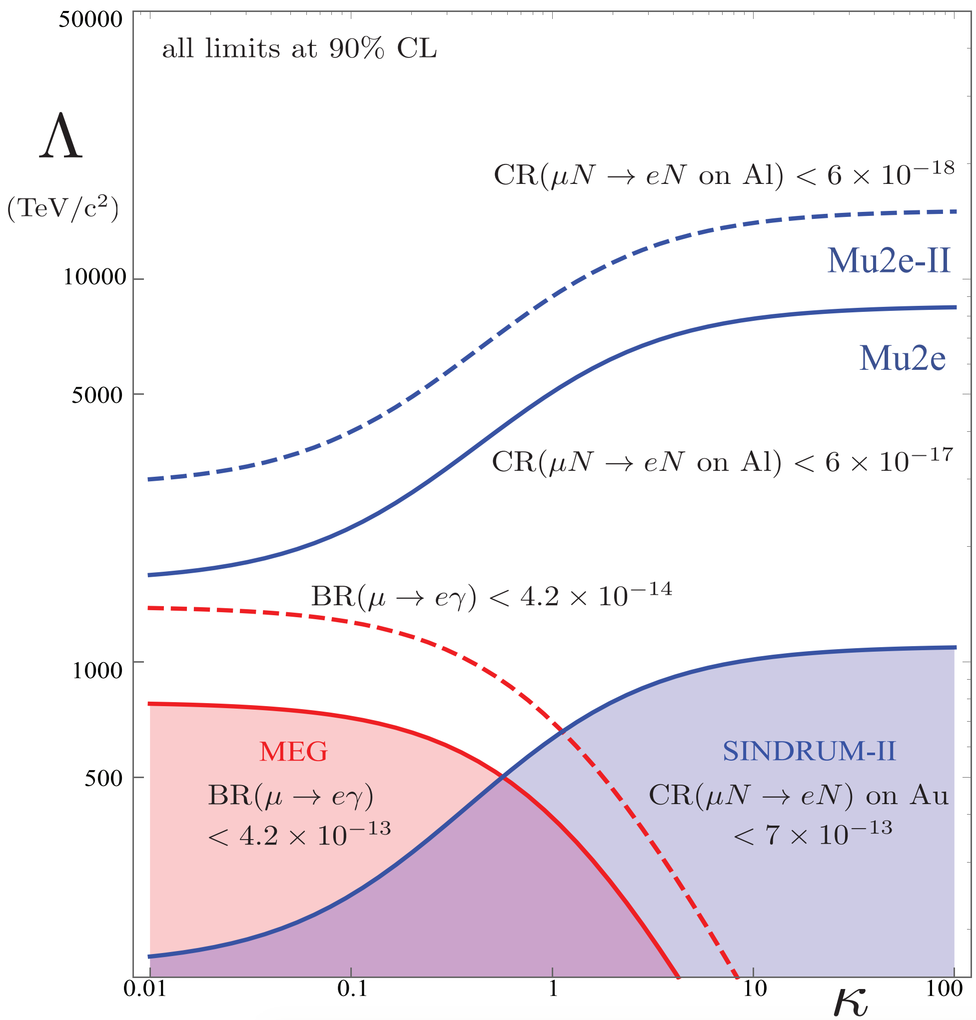
Direct coupling between quarks and leptons, better accessed by *μN→eN*

Test of Physics BSM: Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

μN → eN sensitive to wide array of New Physics models

Lambda-k plane for CLFV in muon sector

κ <<1: LOOP DOMINATED **κ >>1: CONTACT DOMINATED**



Mass scale discovery up to ~10k TeV, significantly above the direct reach of LHC

Slightly better than MEG upgrade in loop-dominated physics

If SUSY seen at LHC → rate ~10^{-15}

Implies O(40) reconstructed signal events with negligible background in Mu2e for many SUSY models.

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 8 \times 10^{-17} \text{ (@90\%CL)}$$

Are CLFV processes relevant ?

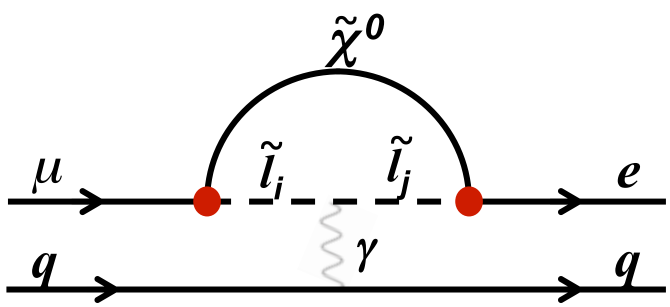
W. Altmannshofer, *et al*, `arXiv:0909.1333 [hep-ph]`

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

Specific Example: SUSY

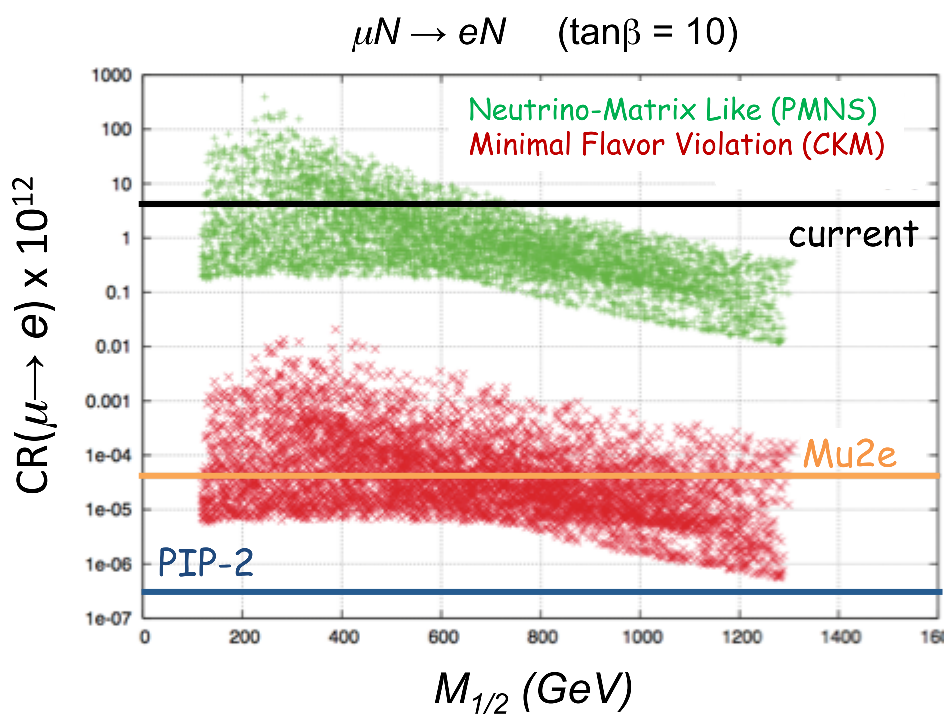
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies **~ 40-50 signal events** with **negligible background** in Mu2e for many SUSY models.

SUSY GUT in an SO(10) framework



L. Calibbi et al., hep-ph/0605139

Complementary with the LHC experiments while providing models' discrimination

SUSY benchmark points vs LHC

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		**SPS 1b**		**SPS 2**		**SPS 3**		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
$BR(\mu \to e\,\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$BR(\mu \to e\,e\,e)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$CR(\mu \to e \text{ in Ti})$	$\mathit{2.0 \cdot 10^{-15}}$	$\mathit{2.4 \cdot 10^{-14}}$	$\mathit{2.6 \cdot 10^{-15}}$	$\mathit{7.6 \cdot 10^{-14}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{6.7 \cdot 10^{-16}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{8.4 \cdot 10^{-16}}$	$\mathcal{O}(10^{-18})$
$BR(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$BR(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$BR(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	$\mathit{7.8 \cdot 10^{-10}}$	$2.7 \cdot 10^{-12}$	$\mathit{6.0 \cdot 10^{-10}}$	$\mathcal{O}(10^{-9})$
$BR(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG-upgrade/Belle-2
- **All of these will be clearly observable by Mu2e**

Other CLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

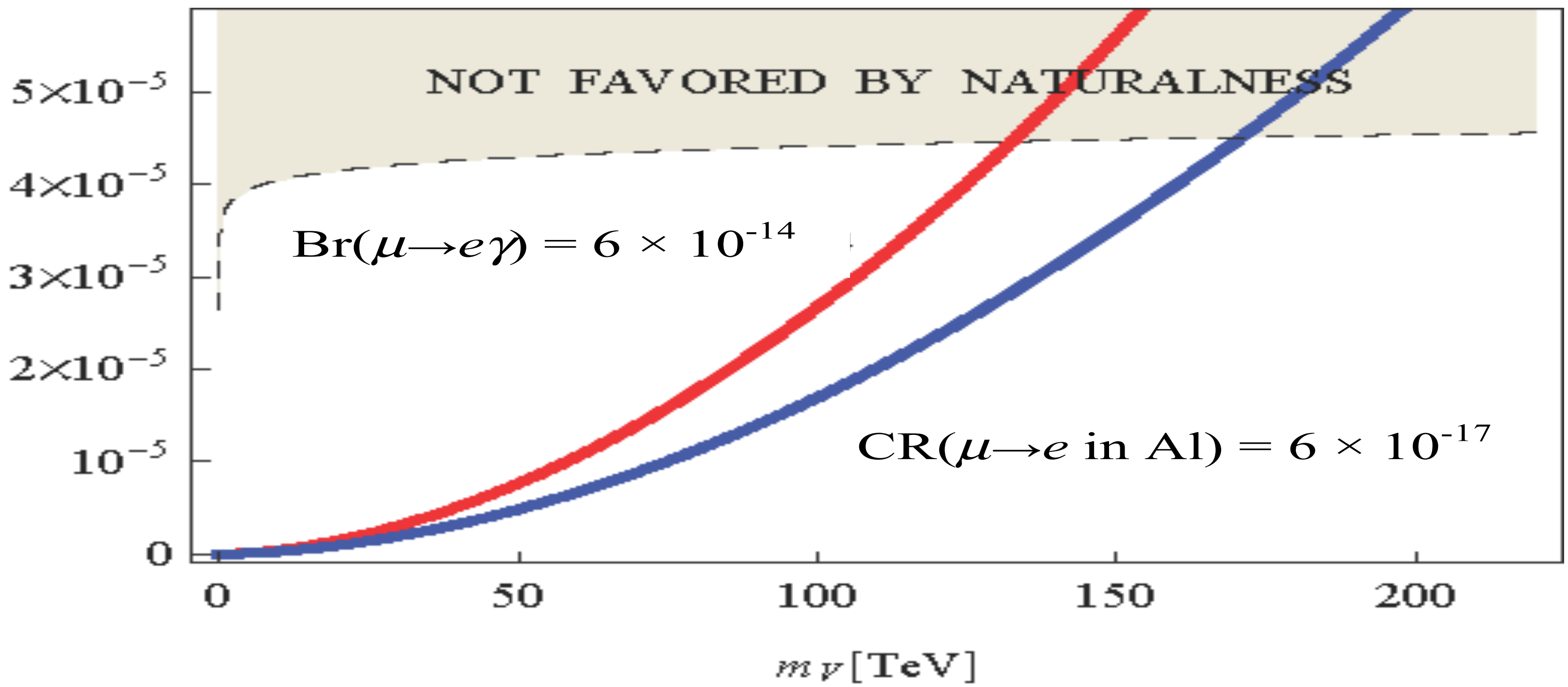
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02\ldots1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04\ldots0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2 \cdot 10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04\ldots0.3$	$\sim 2 \cdot 10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08\ldots0.15$

arXiv:0909.5454v2[hep-ph]

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

- **Relative rates Conversions/MEG/mu3e are model dependent**
  - **Measure ratios will pin-down theory details**

Specific example: Leptoquarks

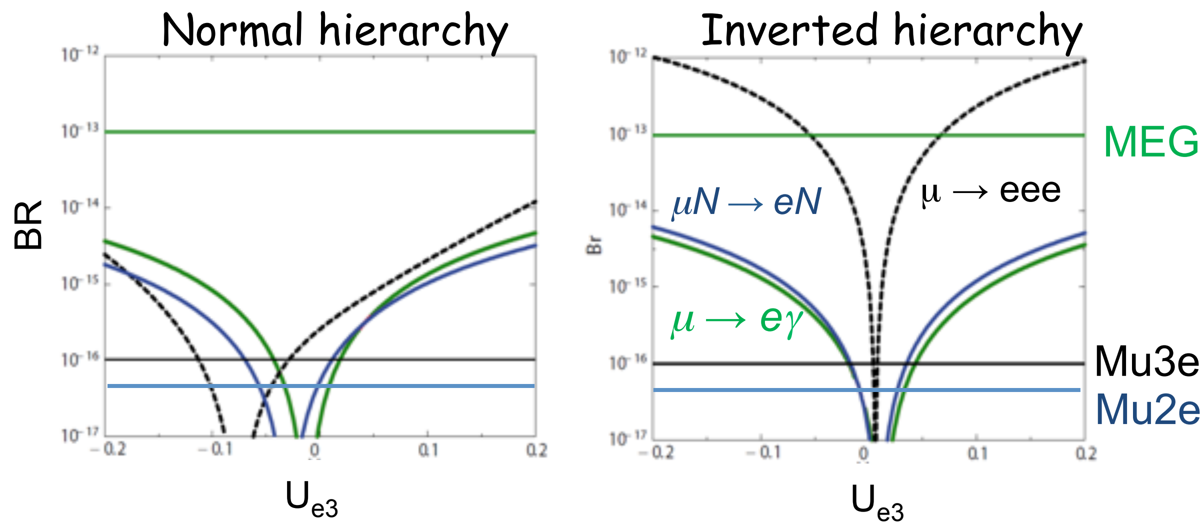


Specific example: Higgs Triplet e LHT

Higgs triplet model

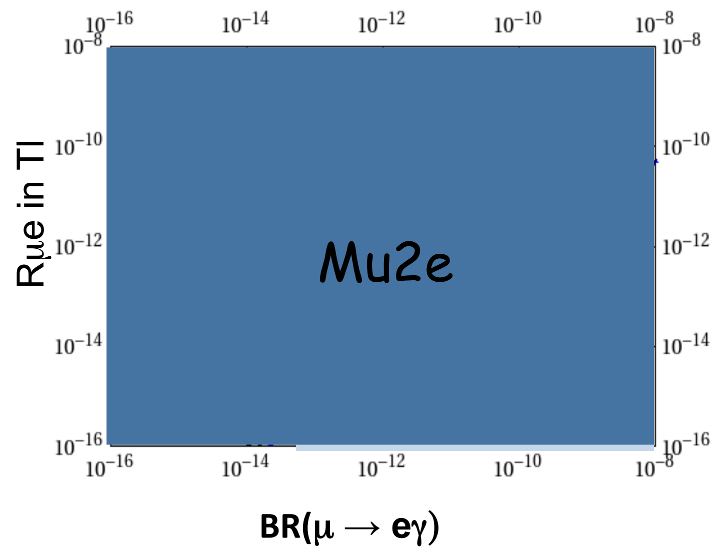
Dependence on neutrino mass hierarchy and θ_{13}

M. Kakizaki et al., PLB566 (2003) 210



Littlest Higgs with T-parity

M. Blanke et al., Acta Phys.Polon.B41:657,2010



Muon to electron conversion is unique

Muon to electron conversion is a unique probe for BSM:

- **Broad discovery sensitivity across all models:**

  → Sensitivity to the same physics of MEG/Mu3e but with better mass reach

  → Sensitivity to physics that MEG/Mu3e are not

  → If MEG/Mu3e observe a signal, Mu2e/COMET do it with improved statistics.
  Ratio of the BR allows to pin-down physics model

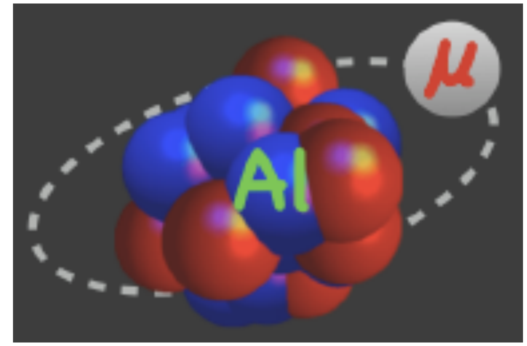
  → If MEG/Mu3e do not observe a signal, Mu2e/COMET have still a reach to do so.
  In a long run, it can also improve further (Mu2e-II) with the proton improvement plan (PIP-2)

- **Sensitivity to Λ (mass scale) up to thousands of TeV beyond any current existing accelerator**

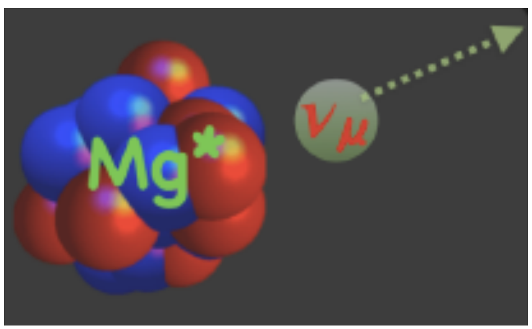
Primer of processes and experimental technique

Experimental Technique

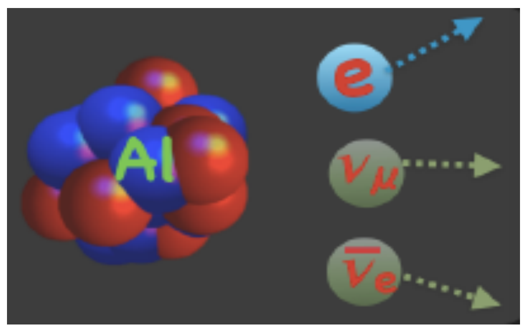
- ❑ Low momentum μ beam (< 100 MeV/c)
- ❑ High intensity "pulsed" rate
  - → 10^{10}/s muon stop on Al. target
  - → 1.7 μsec micro-bunch
- ❑ Formation of muonic atoms that can make a:



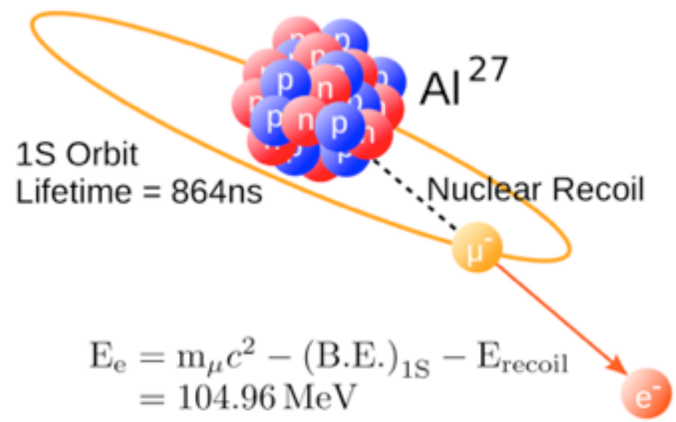
Nuclear capture ~ 61%



Decay In Orbit (DIO) ~ 39%



Conversion Process



The conversion process results in a clear signature of a single electron, CE, with a mono-energetic spectrum close to the muon rest mass

Mu2e Sensitivity

- **Design goal: single-event-sensitivity of 3×10^{-17}**
  - Requires about 10^{18} stopped muons
  - Requires about 10^{20} protons on target
  - Requires extreme suppression of backgrounds

in 3 years running

- **Expected limit: $R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL**
  - Factor 10^4 improvement
- **Discovery sensitivity (5 SIGMA) : all $R_{\mu e} > 1.9 \times 10^{-16}$**
  - Covers broad range of new physics theories

Mu2e backgrounds

- **Intrinsic – scale with number of stopped muons**
  - μ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)

- **Late arriving – scale with number of late protons**
  - **Radiative pion capture (RPC)**

    $\pi^- N \to \gamma N', \gamma \to e^+e^-$ **and** $\pi^- N \to e^+e^- N'$
  - **μ and π decay-in-flight (DIF)**

- **Miscellaneous**
  - **Anti-proton induced**

    produce pions when they annihilate in the target ..

    antiprotons are negative and they can be slow!
  - **Cosmic-ray induced**

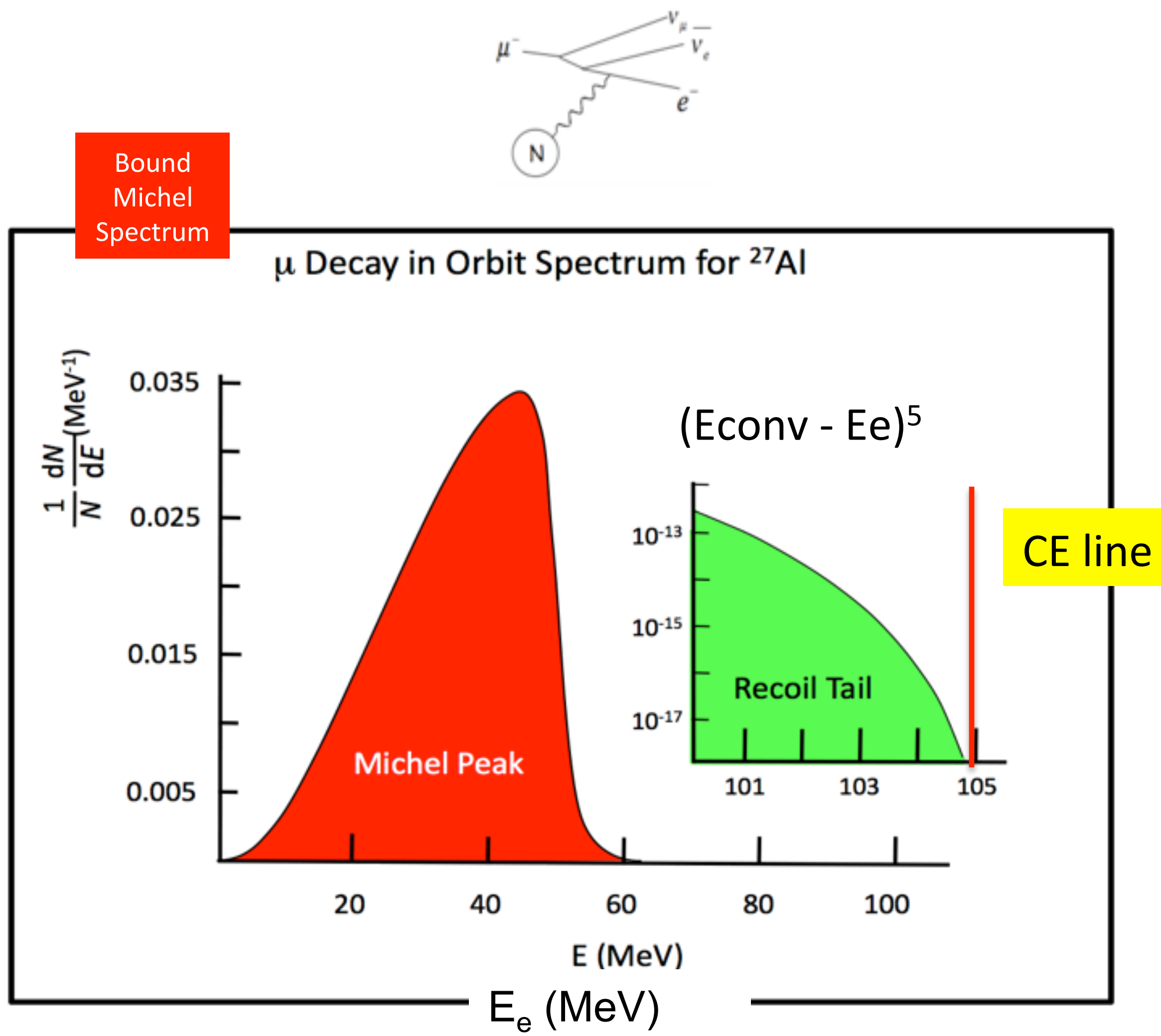
DIO background

❑ **The DIO background is the most difficult one.**

❑ Electron energy distribution from the decay of bound muons is a (modified) Michel spectrum:

→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

→ **To separate DIO endpoint from CE line we need a high Resolution Spectrometer**

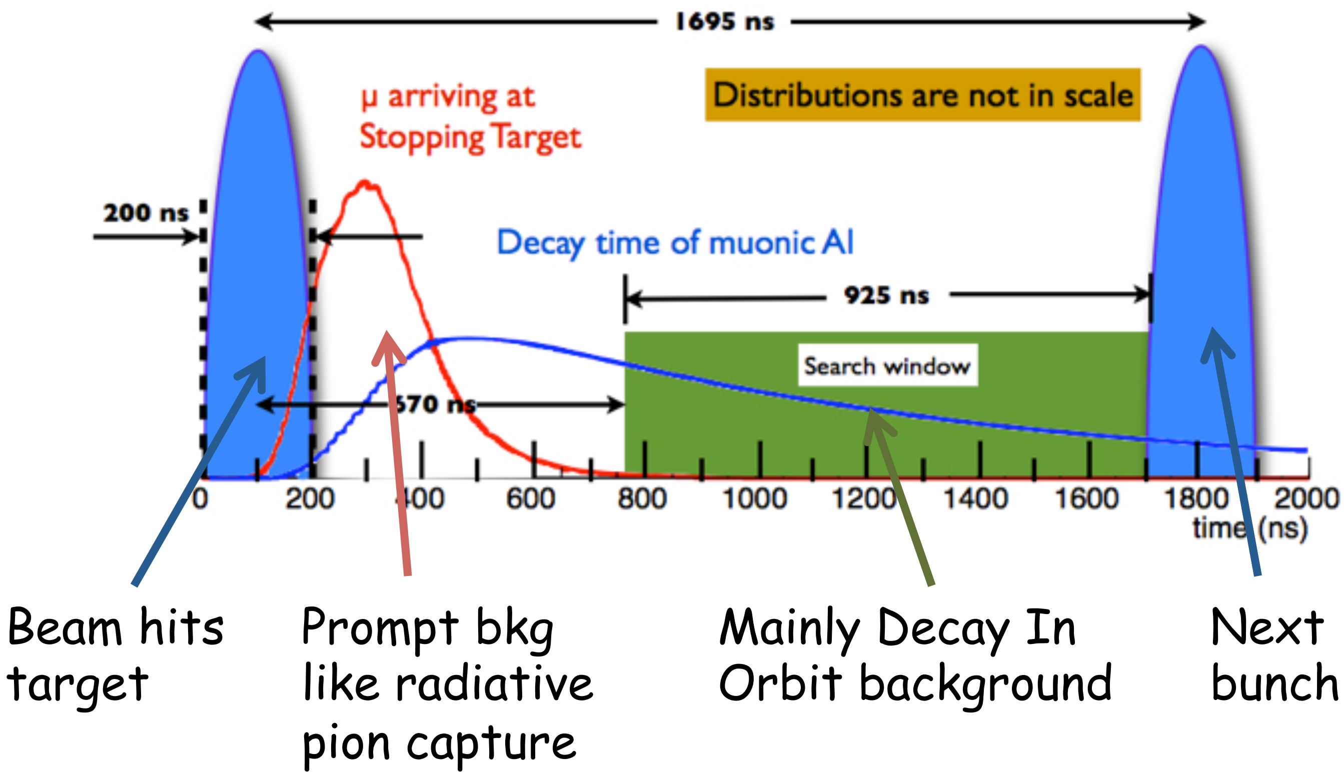


Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv:1106.4756v2

Mu2e: Late Arriving Backgrounds

- **Backgrounds arising from all the other interactions which occur at the production target**
  - Overwhelmingly produce a prompt background when compared to $\tau_\mu^{Al} = 864$ ns
  - **Eliminated by defining a signal timing window starting 700 ns after the initial proton pulse**
  - **Must eliminate out-of-time ("late") protons, which would otherwise generate these backgrounds in time with the signal window**

Beam structure → prompt background



The trick is … muonic atomic lifetime >> prompt background

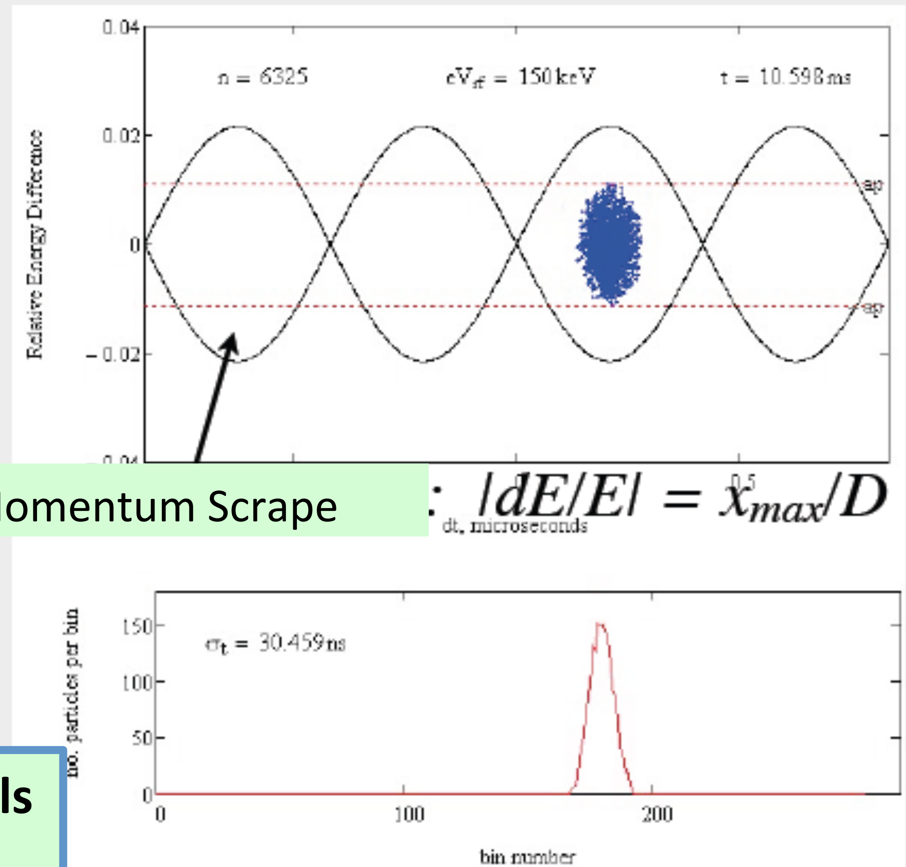
Need a pulsed beam to wait for prompt background to reach acceptable levels!
Fermilab provides the beam we need !

Out of Time proton → Extinction Method

Proton extinction between pulses → # protons out of beam/# protons in pulse

achieving 10^{-10} is hard; normally get $10^{-2} – 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators



Calculations based on accelerator models that take into account collective effects Shows that this combination gets ~ 10^{-12}

Summary: keys to Mu2e Success

- **High intensity Pulsed proton beam**
  - Narrow proton pulses (< +/- 125 ns)
  - Delayed window to eliminate prompt background
  - Very few out-of-time protons (< 10^{-10})

- **Excellent detector**

  → High CR veto efficiency (>99.99%)

  → Excellent momentum resolution (120 keV core)

  → Calorimetry for PID and track seeding

  → Thin anti-proton annihilation window(s)

Experiment Layout

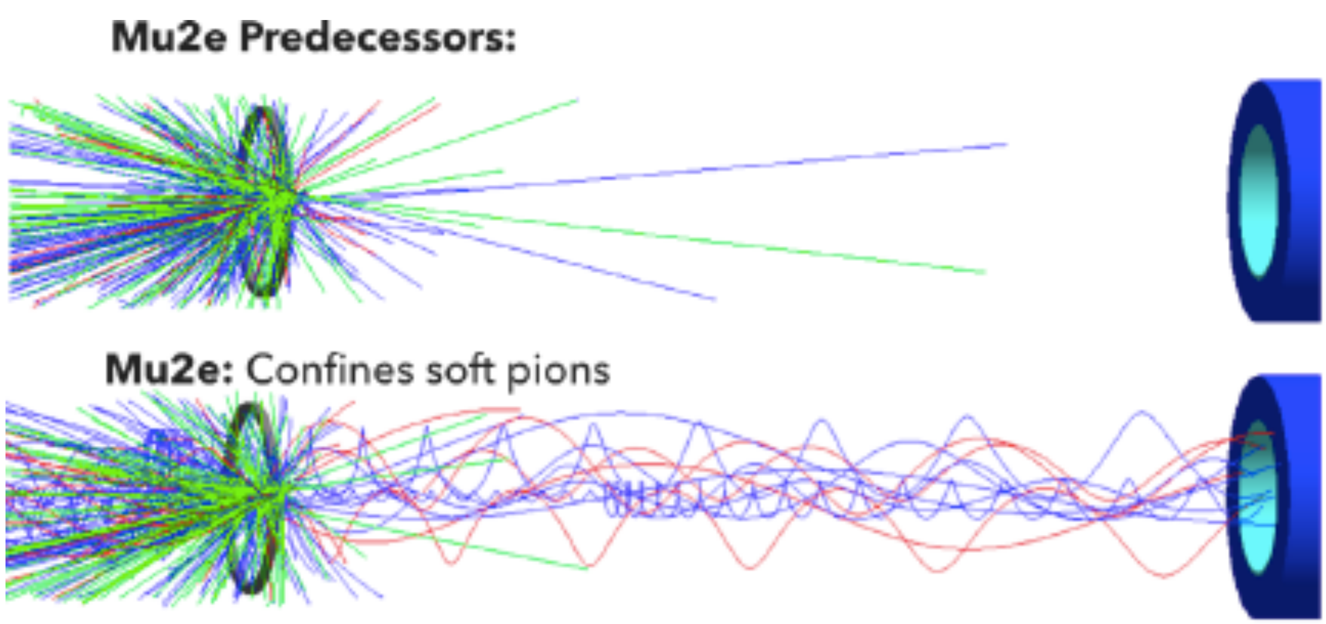
Maximizing Muon Flux

✗ World's hottest muon source by using low power:

→ 8 GeV, 8 kW proton beam on a tungsten target

→ Soft pions confined with a solenoidal B field

→ Strong gradient to increase the yield through magnetic reflection



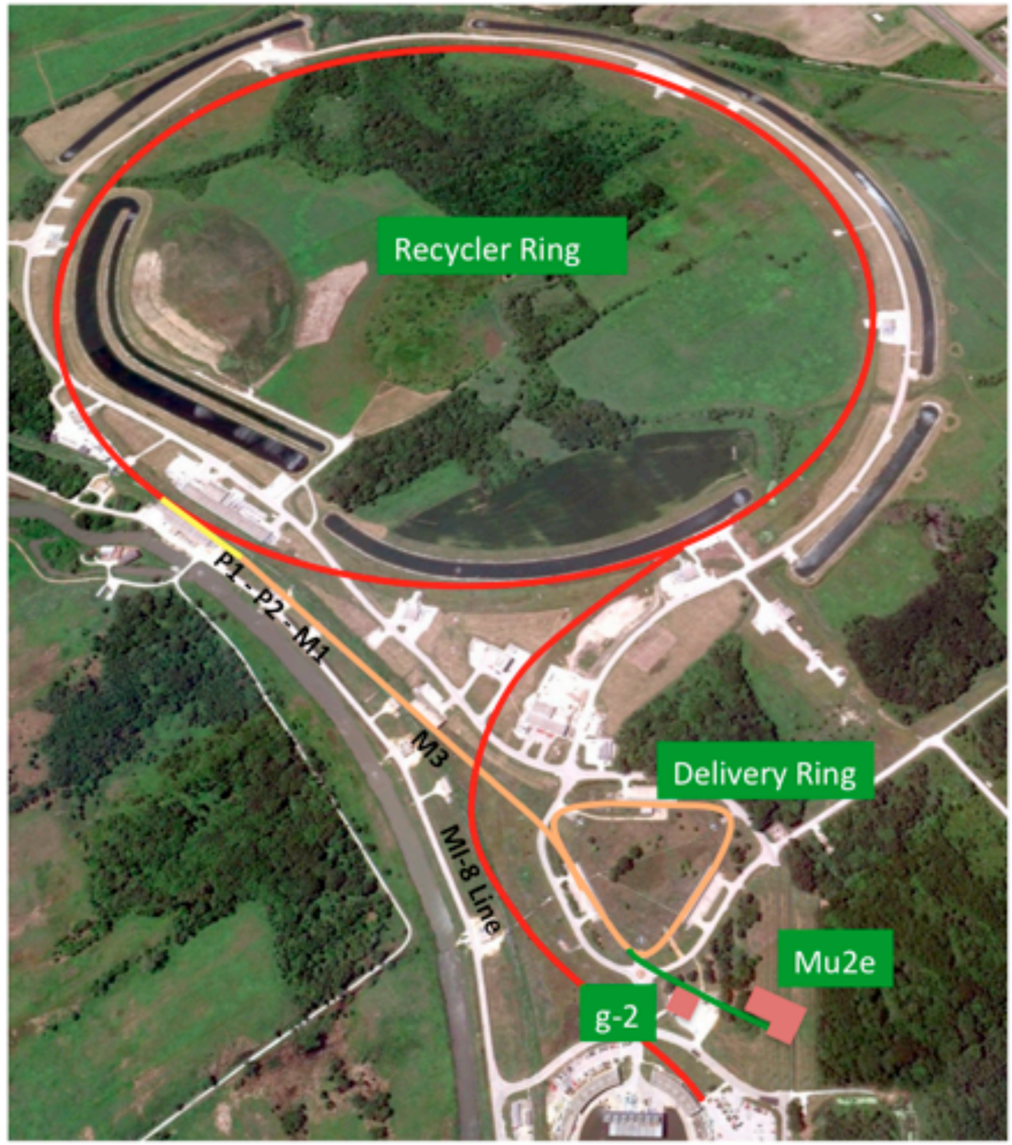
Concept by Lobashev and Djilkibaev

Sov.J.Nucl.Phys. 49, 384 (1989)

Accelerator Scheme

Mu2e will reuse much of the Tevatron anti-proton complex to produce muons:

- 8 GeV protons from the **Booster (4x10^{12} each 1/15 s)**
- **Recycler** divides proton batches into 4 smaller bunches
- **Delivery ring** gets 1 out of 4 bunches from recycler
- **Mu2e** gets the proton beam in bunches of 3x10^{7} protons every 1695 ns



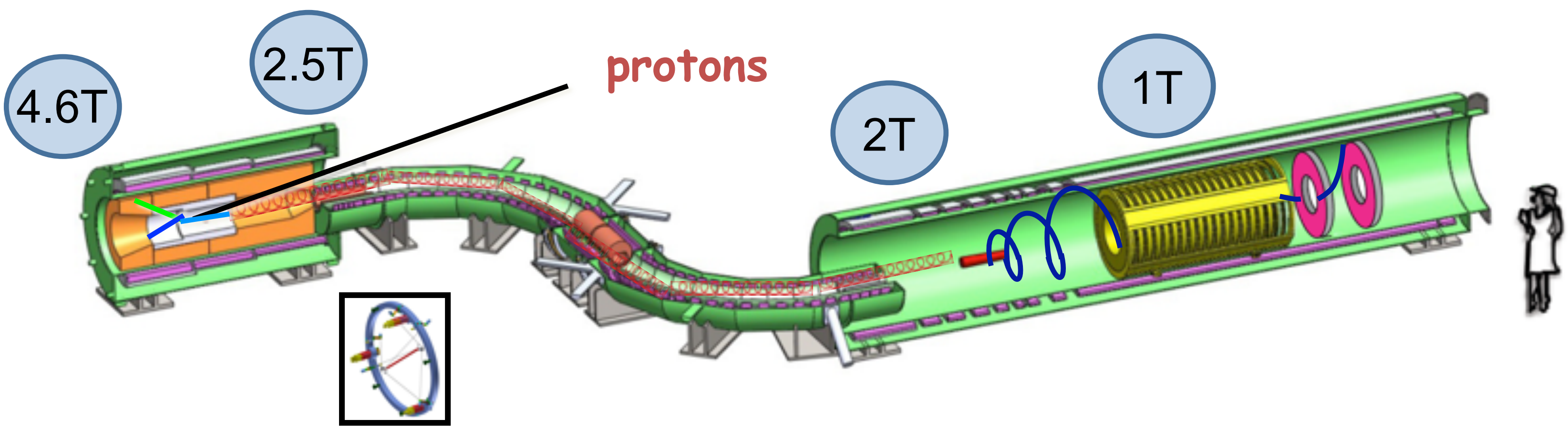
Muon campus: g-2/Mu2e → rendering

Muon campus: g-2/Mu2e → reality

Muon Beam-line

Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons



→ Heat and radiation shielding
→ Tungsten target.

Transport Solenoid (TS)

Selects low momentum, negative muons
Antiproton absorber in the mid-section

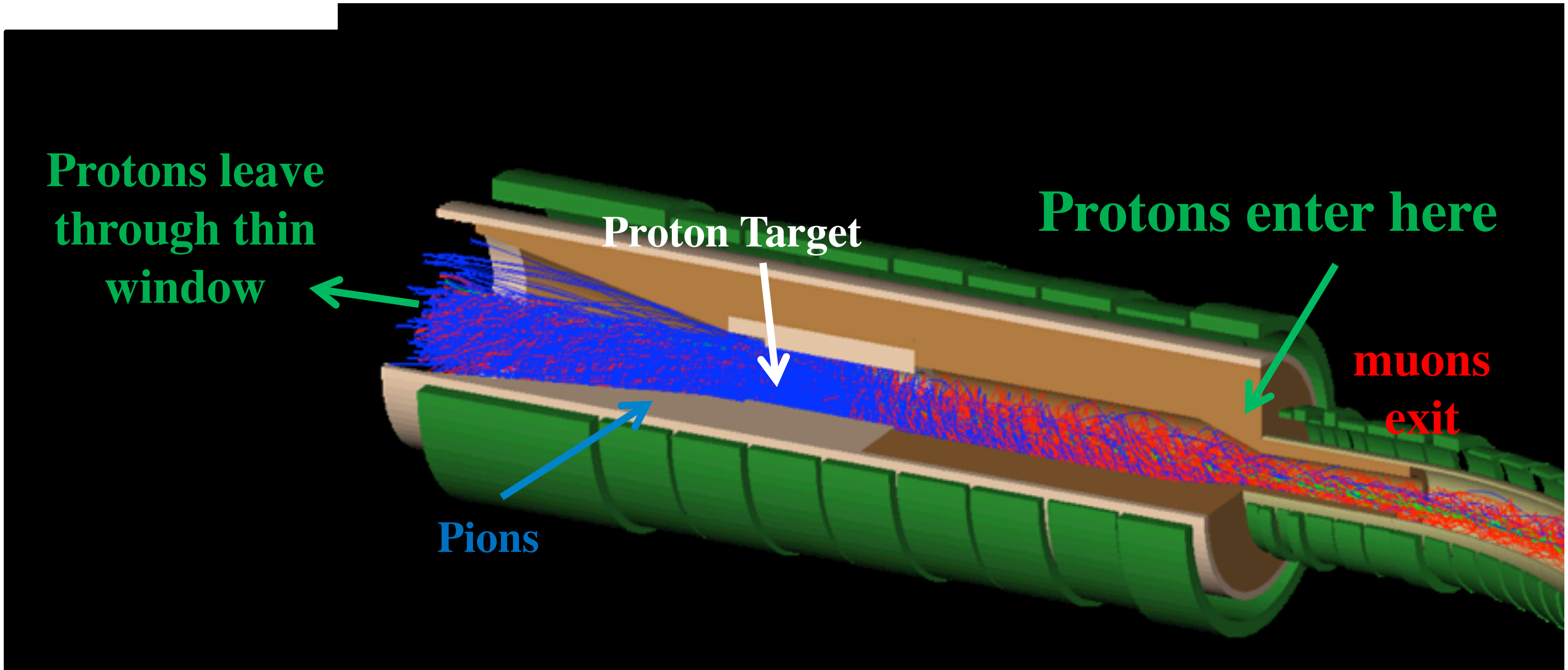
Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Production Solenoid

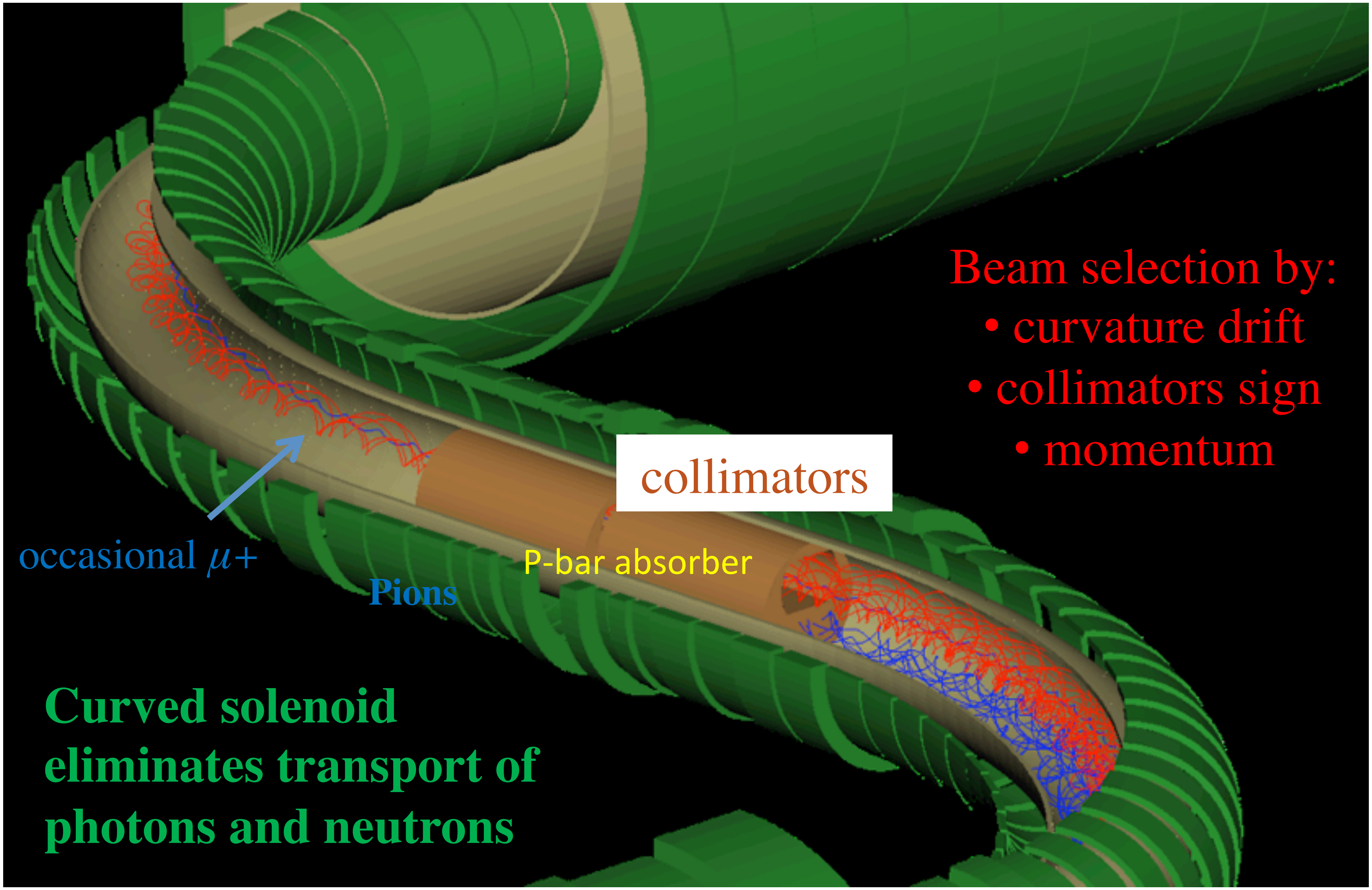
Protons enter opposite to outgoing muons:

This is a central idea to remove prompt background



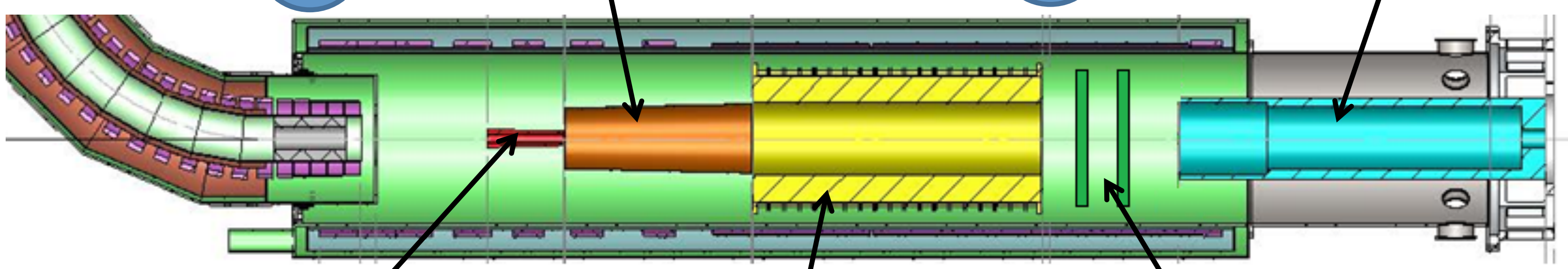
The magnetic field is graded from approximately 5.0 Tesla on the upstream side down to 2.5 Tesla at the entrance to the Transport Solenoid. This graded field captures pions, which spiral around in the field and decay into muons.

Transport Solenoid



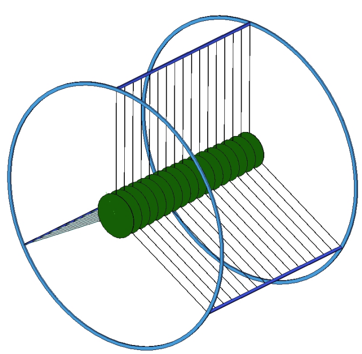
Detector Solenoid

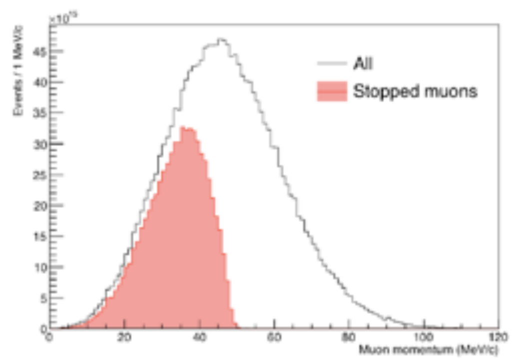
Graded field "reflects" downstream a fraction of conversion electrons emitted upstream



17 Al foils; Aluminum selected mainly for the muon lifetime (**864 ns**) that matches beam structure.

Sensitivity goal → ~ 6 x 10^{17} stopped muons





3 year runs , 6 x 10^7 sec →
10^{10} stopped muon/sec

Mu2e Solenoid Summary (1)

	PS	TS	DS
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	52	11
Conductor (km)	14	44	17
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

- PS, DS is being built by General Atomics (USA)
- TS is being built by ASG Superconducting (Italy) + Fermilab

Mu2e Solenoid Summary (2)

- ✗ 75 km of superconducting cable procured and tested
- ✗ Solenoid design completed
- ✗ TS fabrication has begun at ASG Superconducting in Genova (Italy)
- ✗ PS, DS fabrication started at General Atomic (USA)

The Mu2e Tracker (1)

Detector requirements:

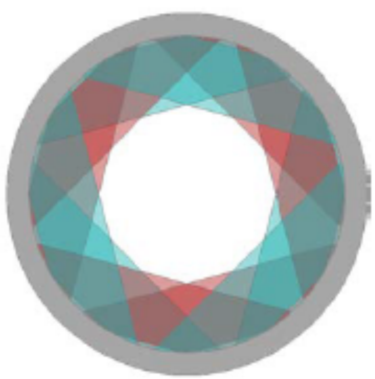
1. Small amount of X_0
2. σ_p < 180 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm^2 in live window
   - Beam flash of 3 MHz/cm^2
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

Low mass straw drift tubes design:

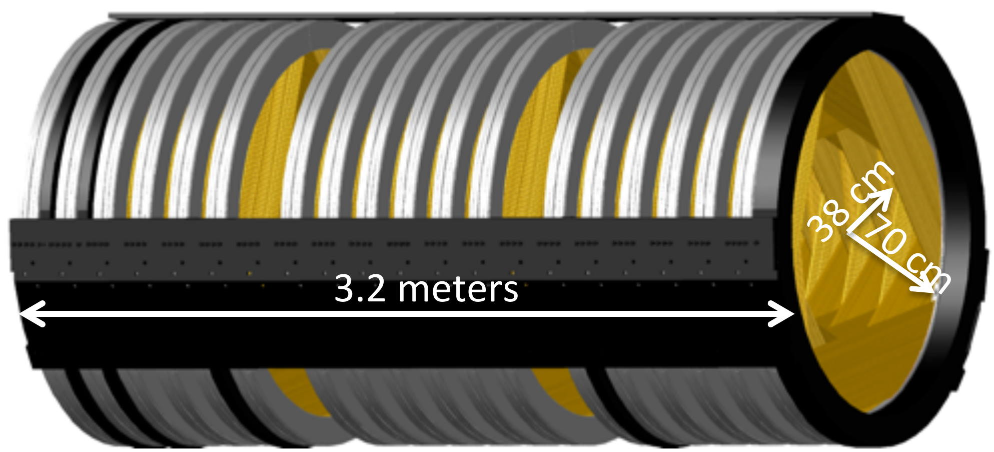
- 5 mm diameter, 33 – 117 cm length
- 15 μm Mylar wall, 25 μm Au-plated W wire
- 80:20 Ar:CO_2 @ 1 atm
- Dual-ended readout

Tracker Plane

Tracker Station: 2 rotated planes

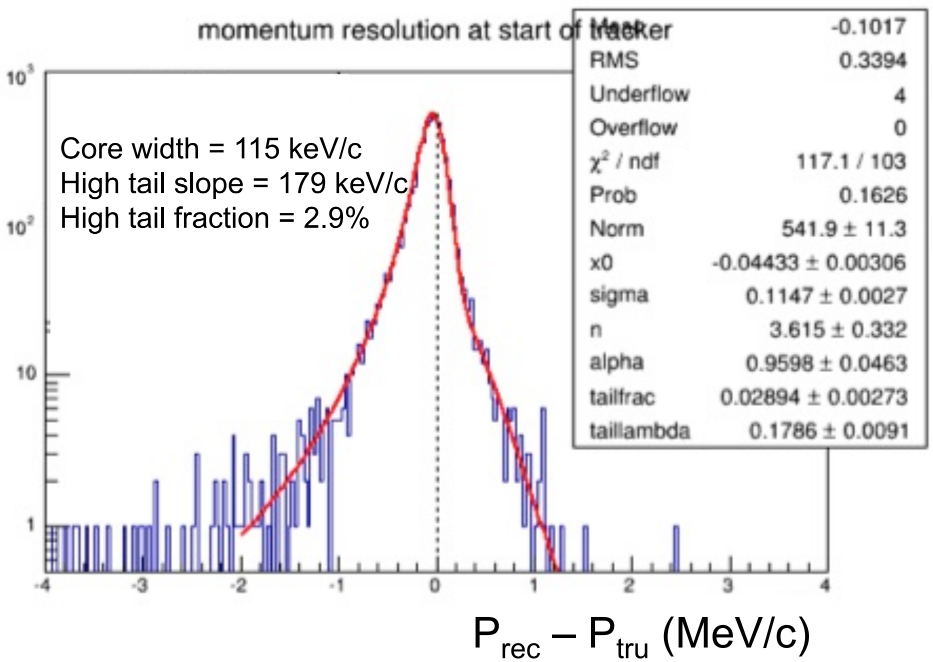


Tracker:18 stations (>20k tubes)



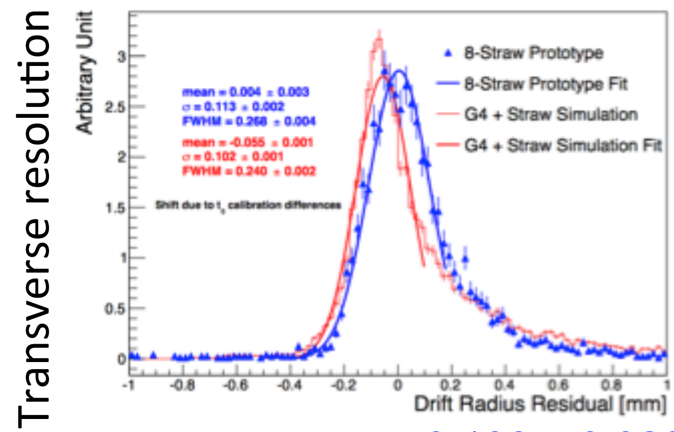
The Mu2e Tracker (2)

Full simulation



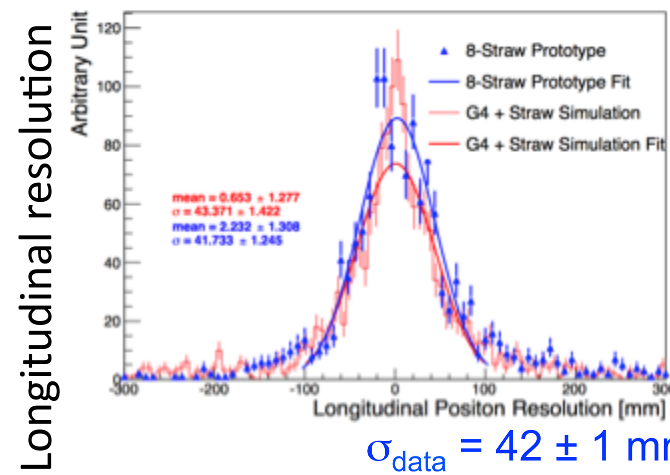
- ✗ Well within physics requirements
- ✗ Robust against increases in rate
- ✗ Inefficiency dominated by geometric acceptance

Cosmics, 8 channel prototype



σ_{data} = 0.133 ± 0.022 mm

σ_{MC} = 0.102 ± 0.001 mm

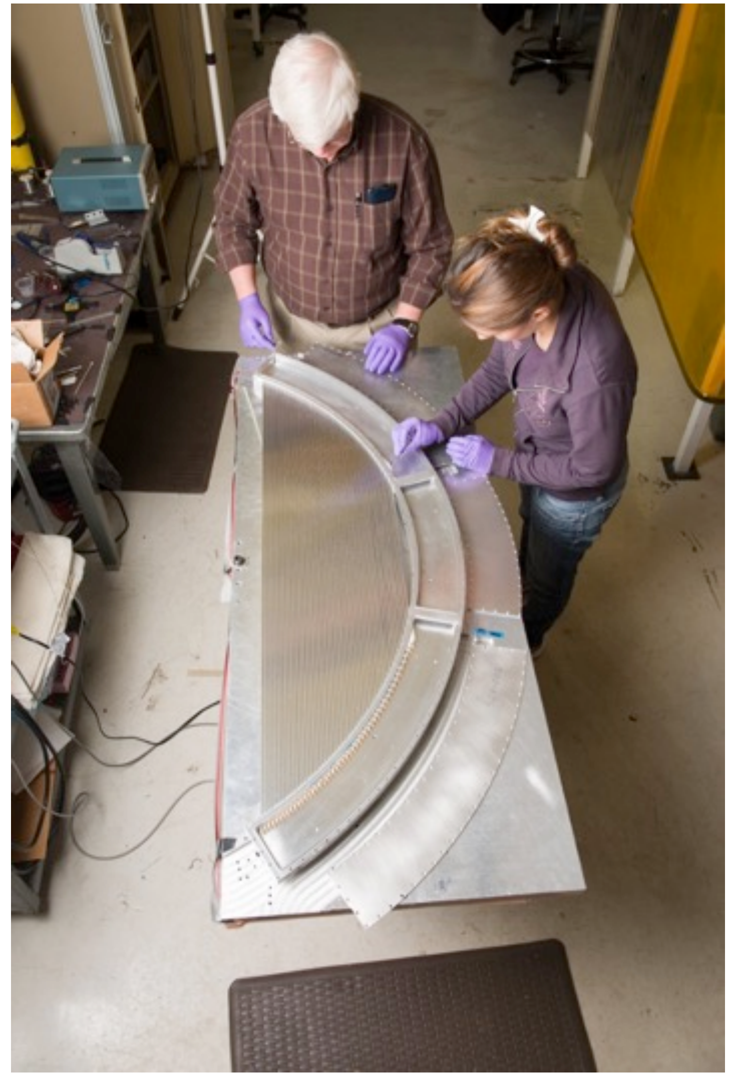


σ_{data} = 42 ± 1 mm

σ_{MC} = 43 ± 1 mm

The Mu2e Tracker (3)

- ✗ First pre-production prototype, with final design, recently built and being tested
- ✗ Orders placed for final production
- ✗ FEE prototypes tested successfully
- ✗ Vertical slice test to be performed on fully instrumented panels with entire FEE chain



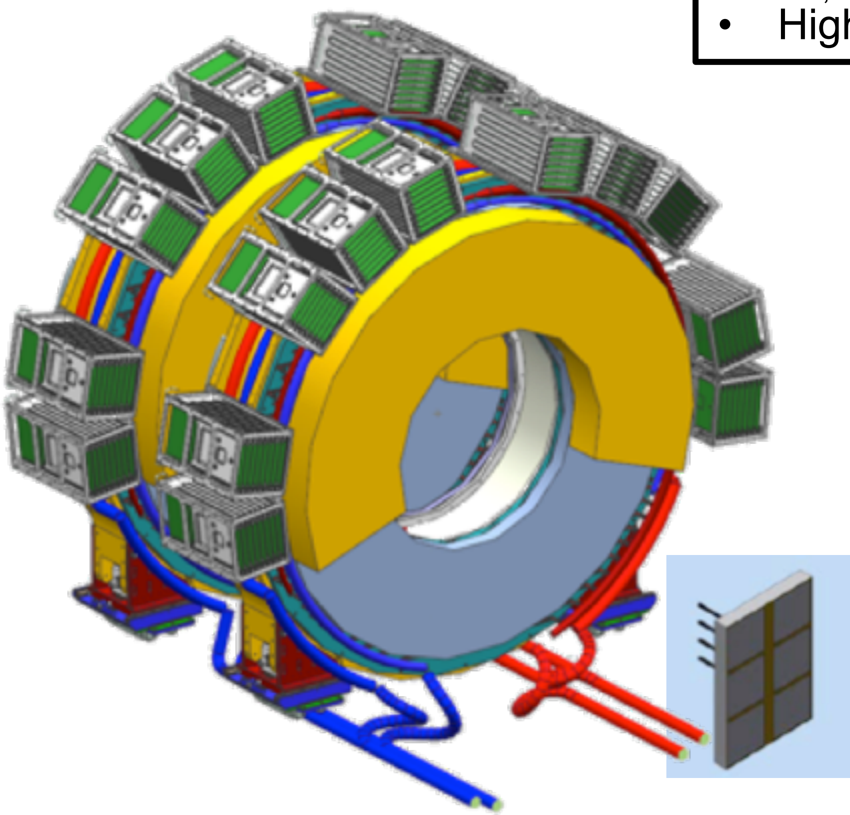
The Mu2e Calorimeter (1)

Calorimeter provides confirmation for CE and other crucial functions:

- ✗ PID: e/μ separation
- ✗ EMC seeded track finder
- ✗ Standalone trigger

Requirements:

- $\sigma_E/E = \mathcal{O}(5\%)$ for CE
- $\sigma_T < 500$ ps for CE
- $\sigma_{X,Y} \leq 1$ cm
- High acceptance for CE
- Fast (τ<40 ns)
- Operate in 1T and 10^{-4} Torr
- Redundancy in readout
- Radiation hard: 90 krad photons and 3×10^{12} n/cm^2

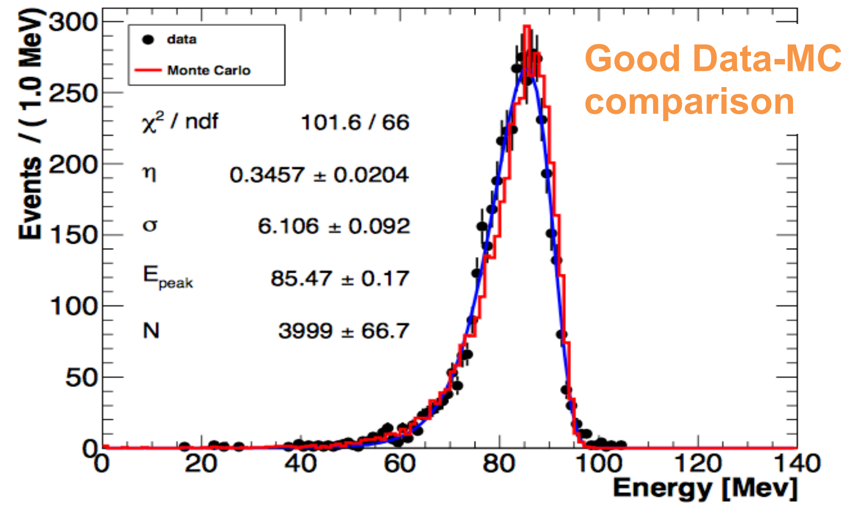


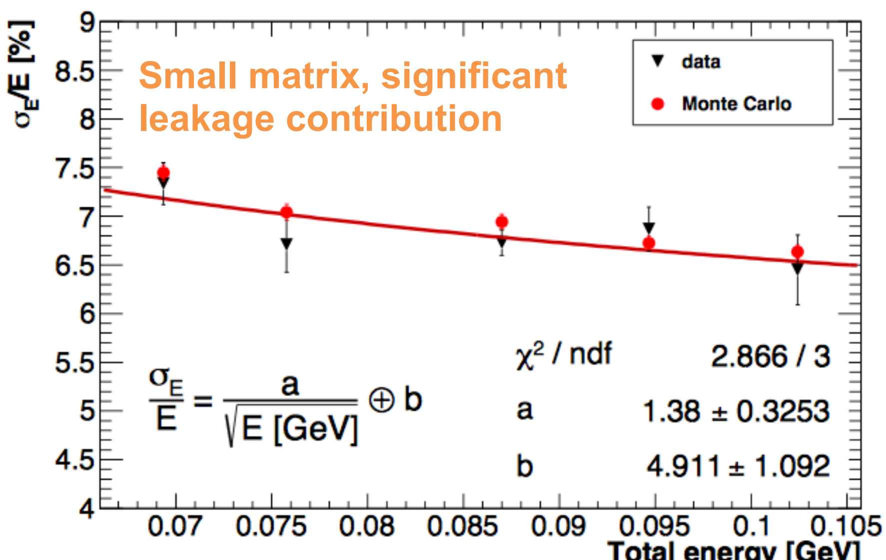
EMC Design:

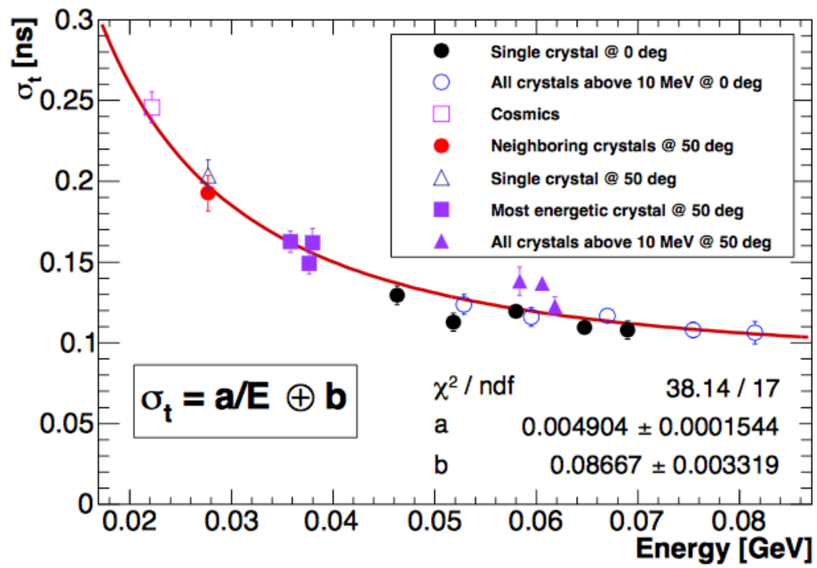
- ✗ Two disks, R_{in}=374 mm, R_{out}=660 mm, $10X_0$ length, ~ 75 cm separation
- ✗ 674+674 square x-sec **pure CsI crystals**, (34×34×200) mm^3
- ✗ For each crystal, two custom array (2×3 of 6×6 mm^2) **large area UV-extended SiPMs**
- ✗ Analog FEE directly mounted on SiPM
- ✗ Calibration/Monitoring with 6 MeV radioactive source and a laser system

The Mu2e Calorimeter (2)

- ✗ Small prototype tested @ BTF (Frascati) in April 2015, 80−120 MeV e^-
- ✗ 3×3 array of (30×30×200) mm^2 undoped CsI crystals coupled to Hamamatsu MPPC
- ✗ DAQ readout: 250 Msps CAEN V1720 Wave Form Digitizer







σ_E ~ 6.5% at 100 MeV

σ_T ~ 110 ps at 100 MeV

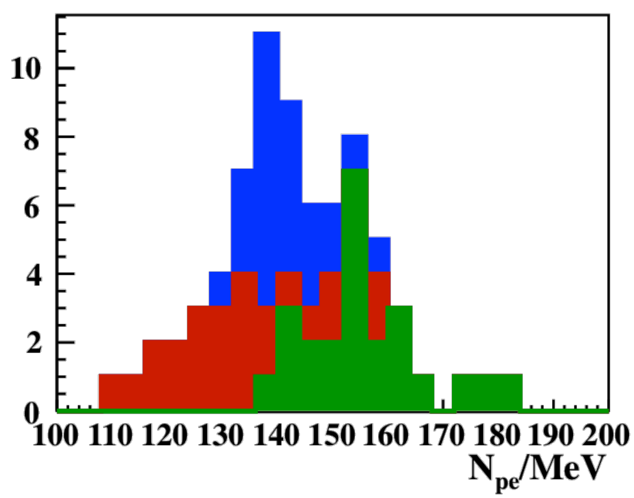
The Mu2e Calorimeter (3)

- ✗ 3×24 pre-production crystals tested → QA and Rad Hard OK → Production started

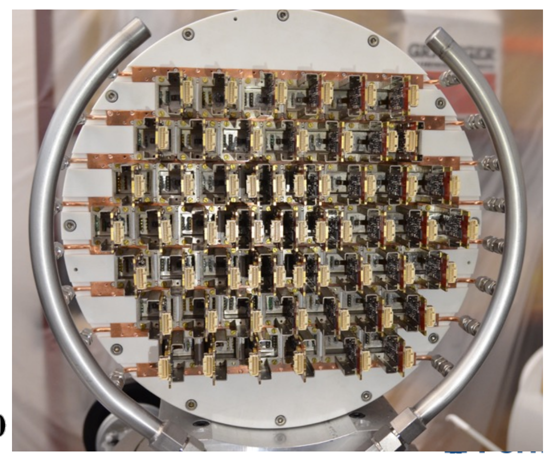
- ✗ 3×50 pre-production SiPMs tested → Production started
  3×35 characterized, irradiation test up to 8.5×10^{11} n_{1MeVeq}/cm^2, MTTF ≥ 6×10^5 hours

- ✗ Module0 built: Large EMC prototype (51 crystals, 102 SiPMs, 102 FEE boards) with pre-productions and mechanics cooling systems similar to the final ones
  - ➢ **Test of integration and assembly procedures, test beam with 60-120 MeV e^-**

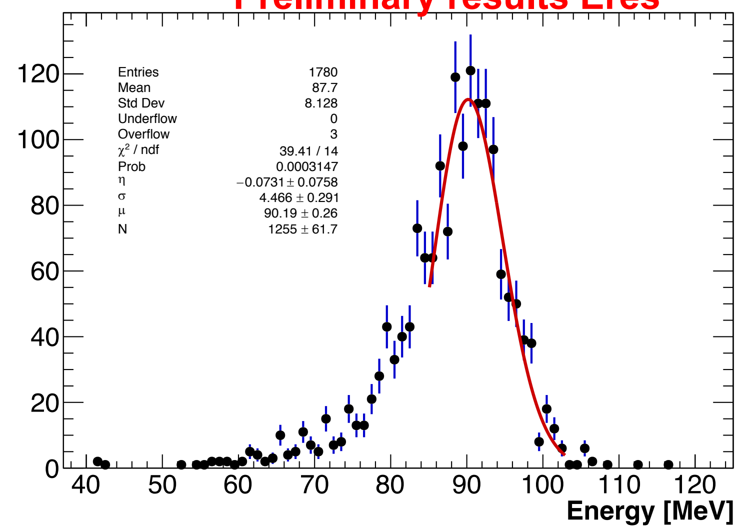
CsI Light Output



Module-0

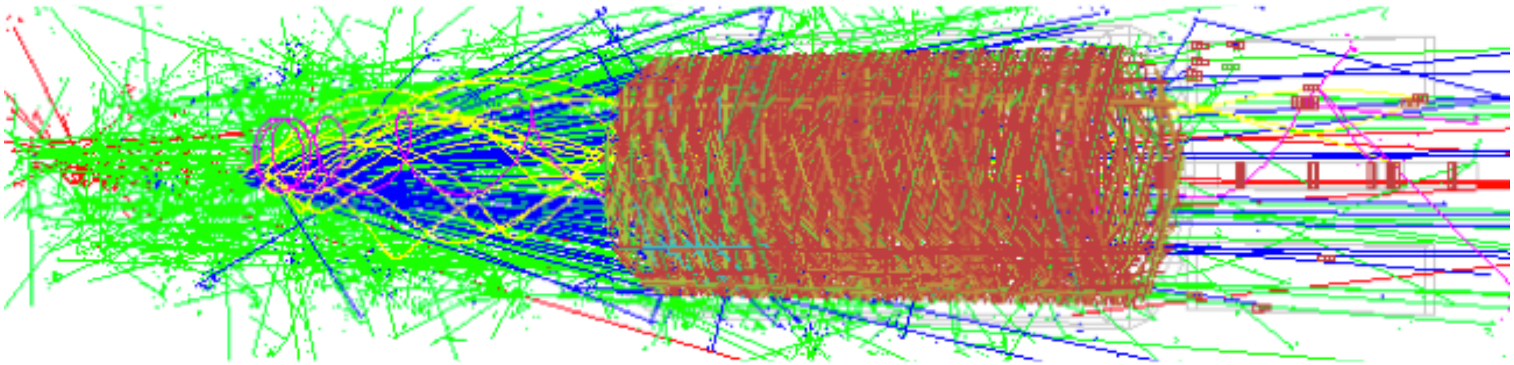


Preliminary results Eres

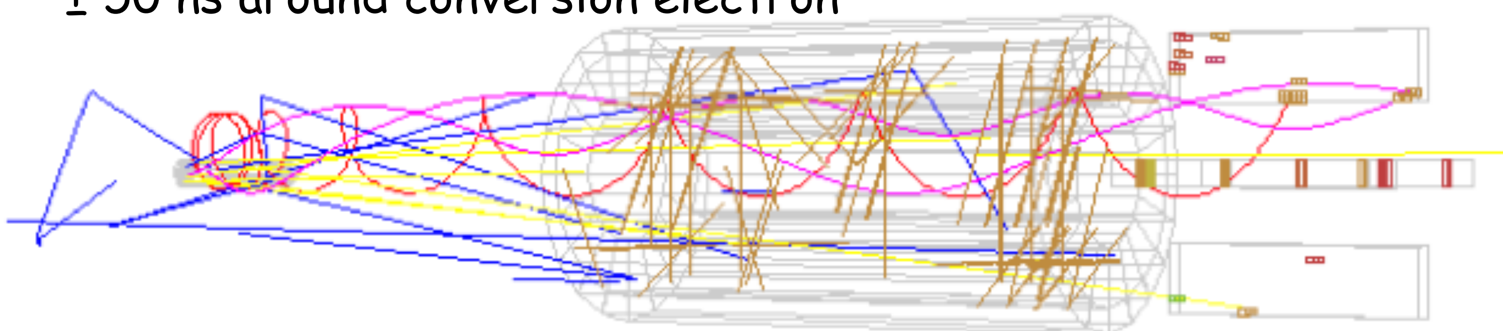


A typical Mu2e event: Calo track seeding

500 – 1695 ns window



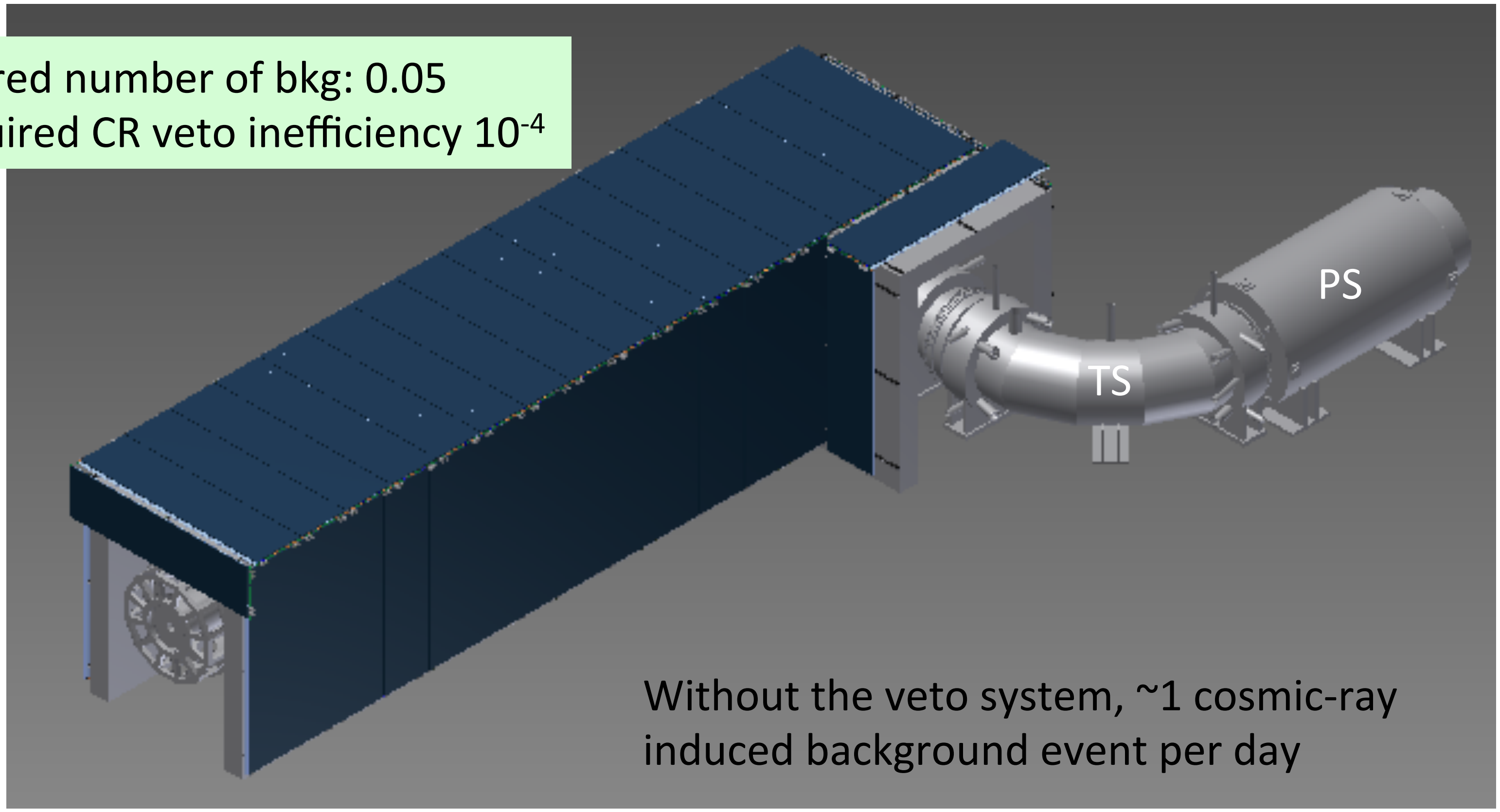
± 50 ns around conversion electron



Search for tracking hits with time and azimuthal angle compatible with the calo clusters (|ΔT| < 50 ns) → **simpler pattern recognition + higher efficiency**

Mu2e Cosmic-Ray Veto (1)

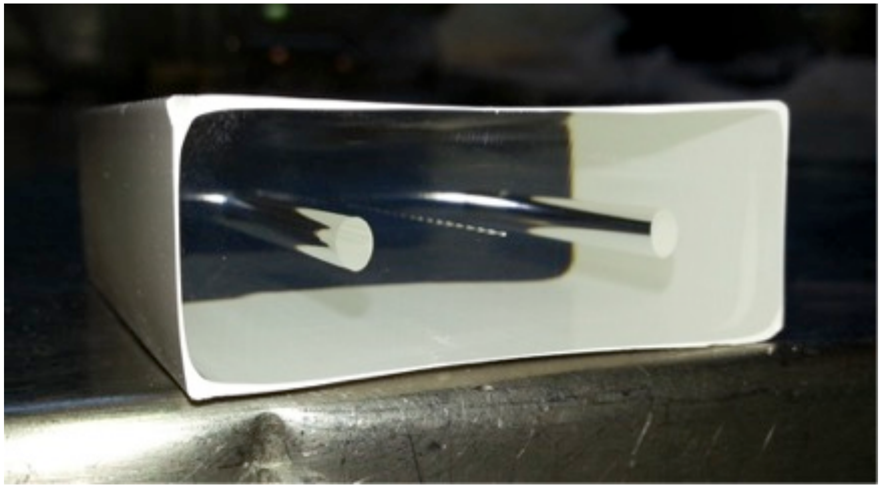
Desired number of bkg: 0.05
Required CR veto inefficiency 10^{-4}

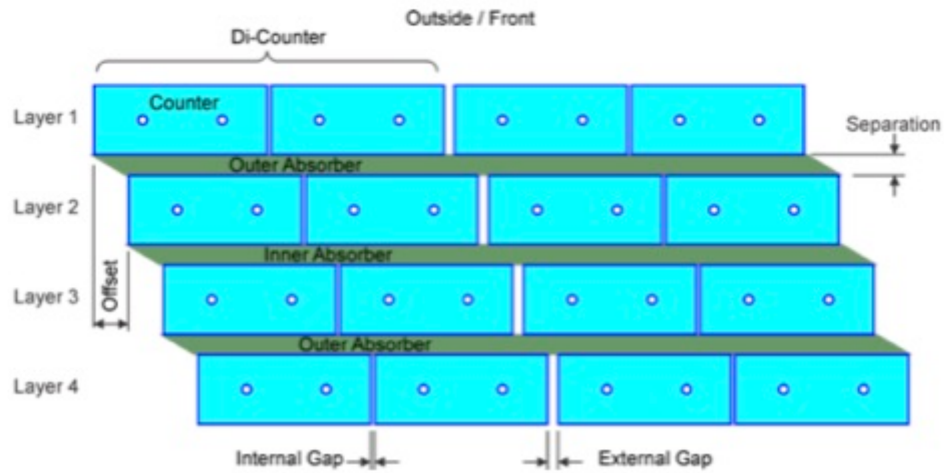


Without the veto system, ~1 cosmic-ray induced background event per day

- Veto system covers entire DS and half TS

Mu2e Cosmic-Ray Veto (2)



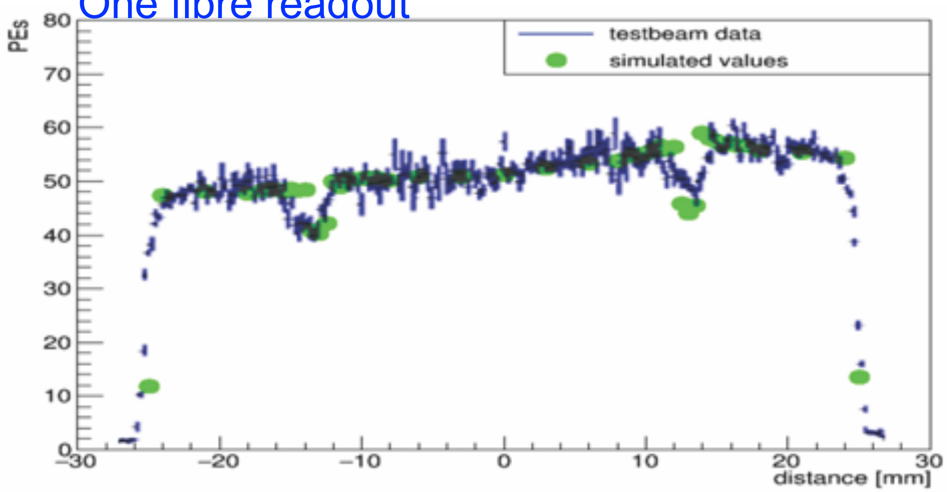


- Will use 4 overlapping layers of scintillator bars
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved ε > 99.4% (per layer) in test beam

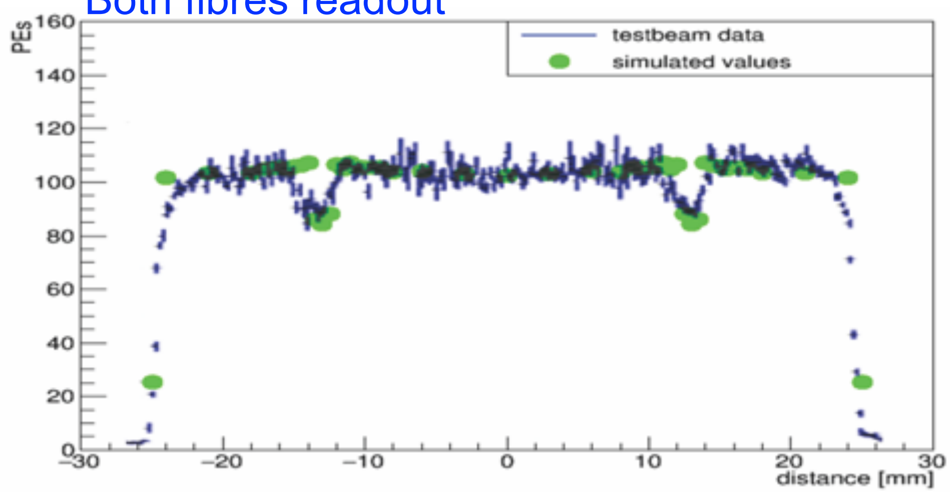
Mu2e Cosmic-Ray Veto (3)

MC well describes test beam data

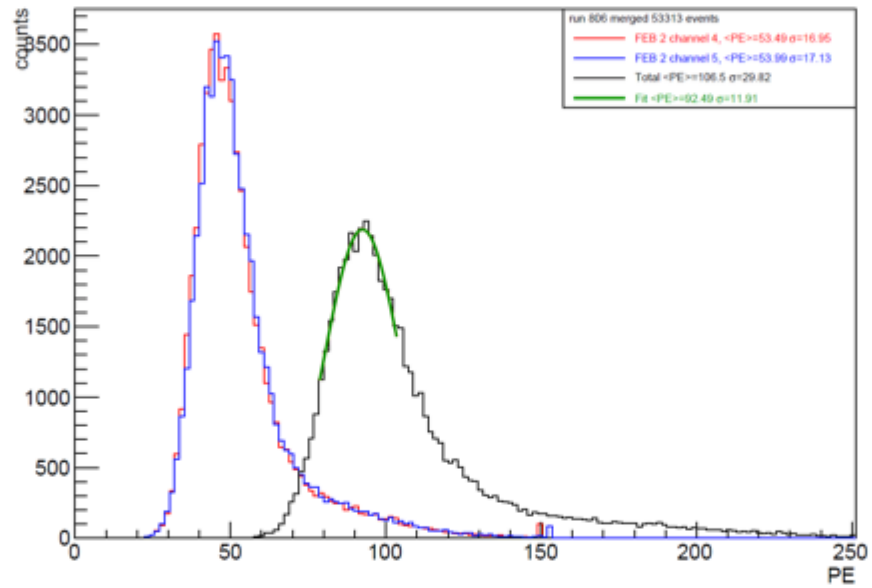
One fibre readout



Both fibres readout



Test beam results with beam centered on counter 1 m from readout end



✗ The single-plane requirement is ε > 99.5%

➪ yield of **66 photo-electrons** at 1 m from readout end

✗ Test beam results give **92 photo-electrons**: safety factor of ~ 40%.

Mu2e Neutron Shielding

- **Several copious sources of neutrons**
  - Production target, stopping target, collimators

- **Lots of neutrons and subsequent photons (from n- capture and activation processes)**
  - Generate false vetoes in CRV… if rate high enough becomes a source of significant dead-time
  - Cause radiation damage to the read-out sensors and electronics (i.e. digitizers and SiPMs)

→ Using HZDR P-ELBE for neutron damage characterization of EMDSiPMs.

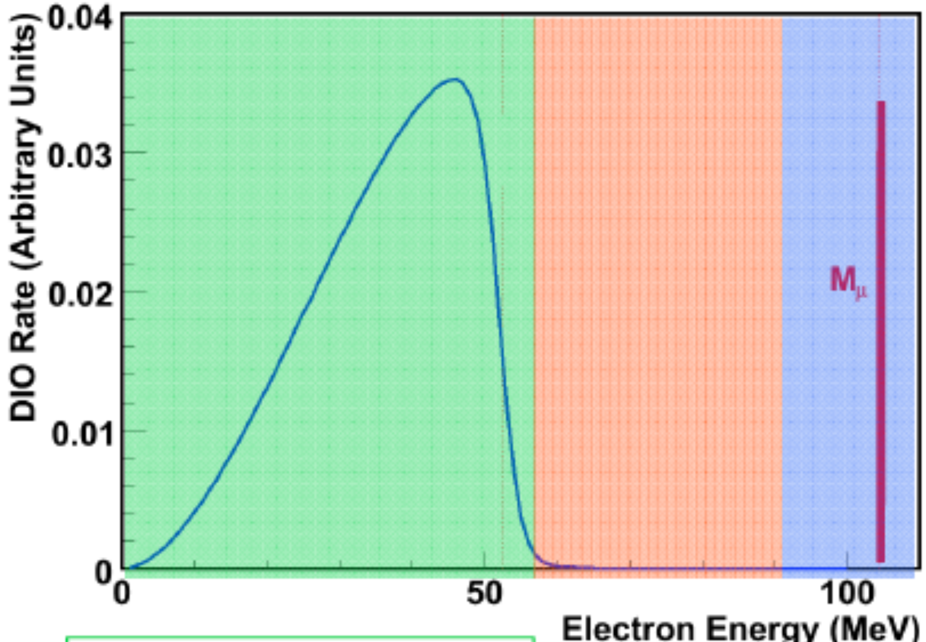
→ Radiation damage effort will continue with g-ELBE for dose irradiation and characterization of FEE/Digitizer electronics, SiPMs and Stopping Target Monitor detectors (HPGE)

→ Other irradiation tests at medical facility in Chicago for neutrons

→ Planned for SEU with charged hadrons ..

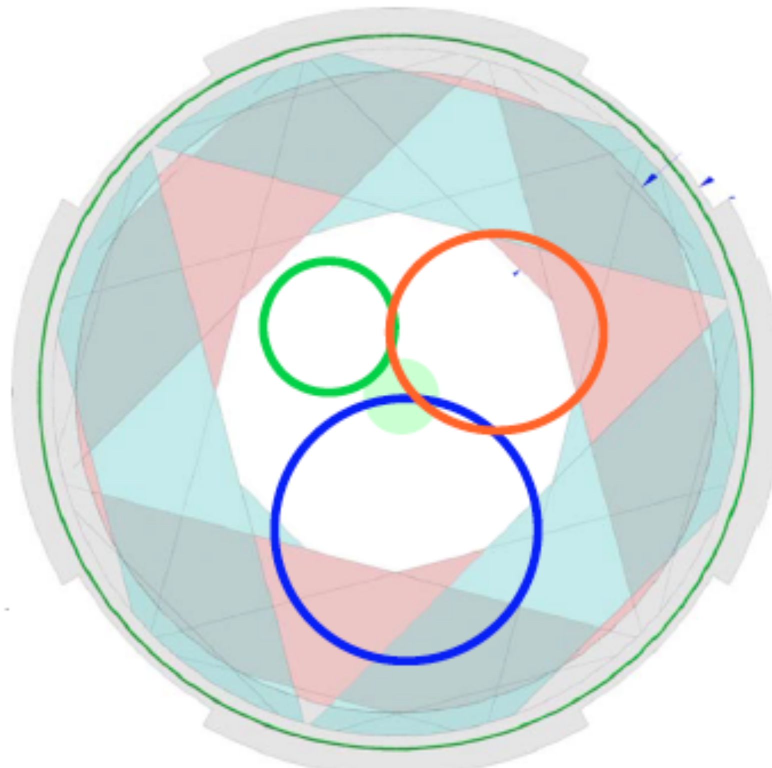
Basic reconstruction scheme

reconstructable tracks



no hits in tracker

some hits tracker, tracks not reconstructable.



beam's-eye view of the tracker

BLIND TO Beam Flash and > 99% DIO

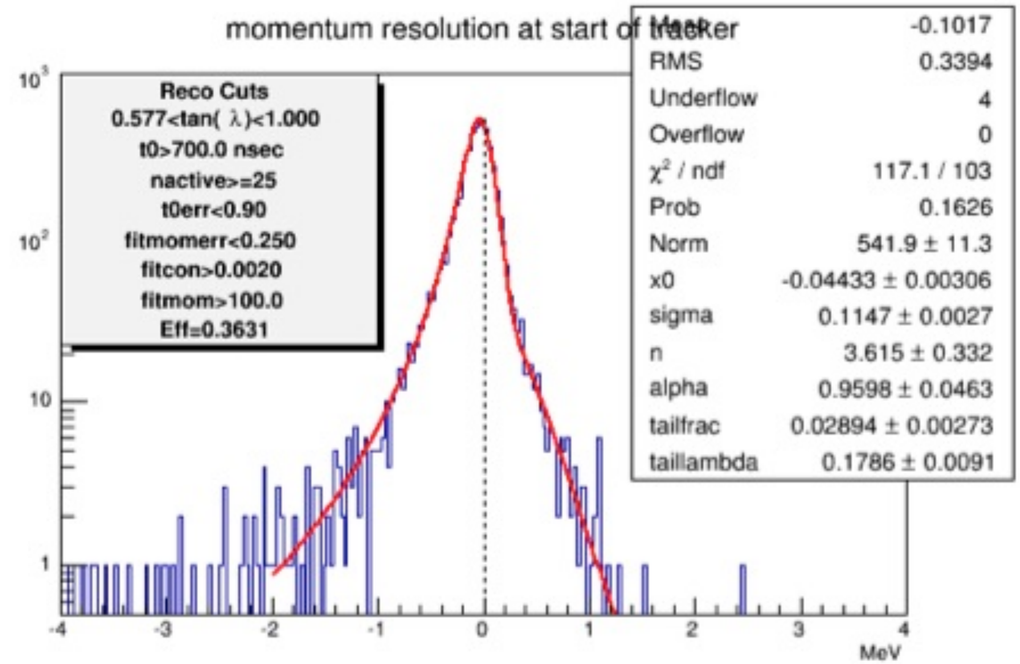
Simulation results on tracker

Pattern Recognition based on
***BABAR* Kalman Filter algorithm**

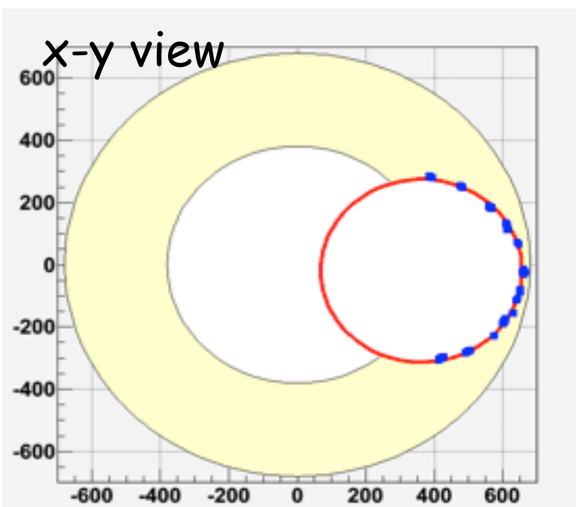
No significant contribution of
mis-reconstructed background

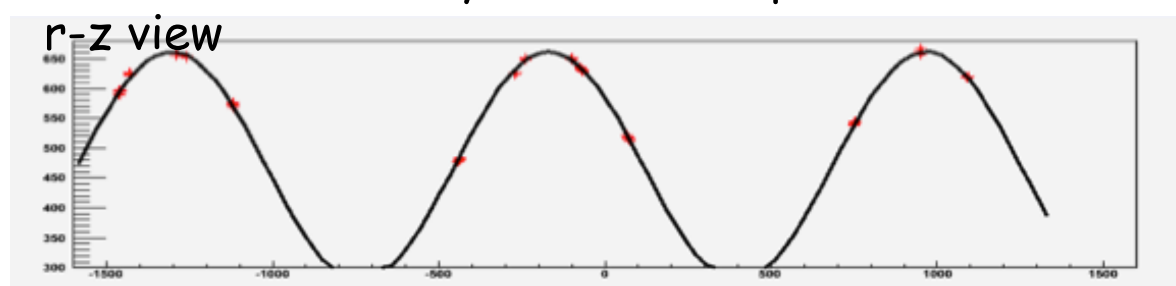
Momentum resolution

core σ~120 keV
tail σ~180 keV (2.5%)

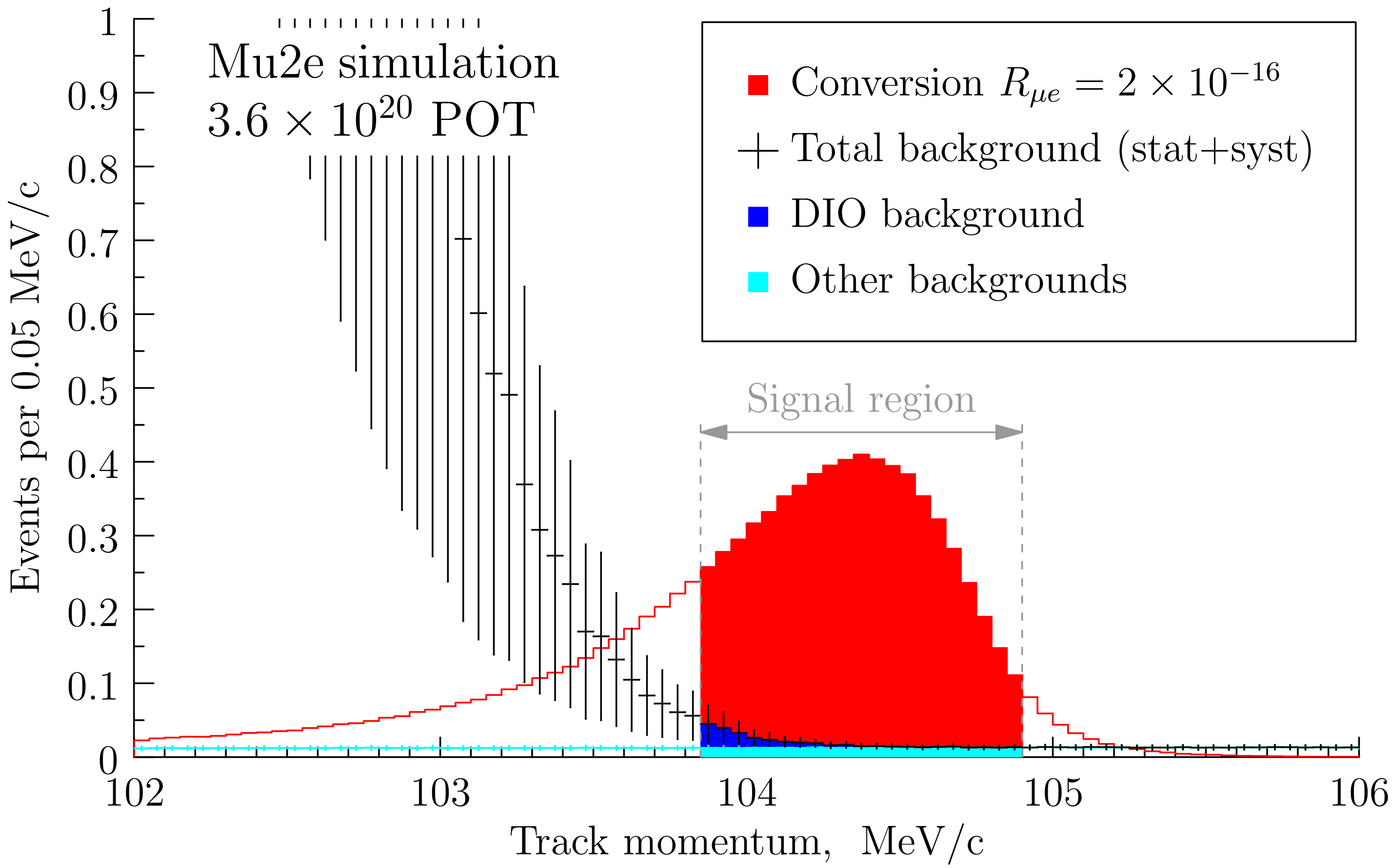


Fit: Crystal Ball + exponential





DIO/CE final count with simulation



Discovery sensitivity accomplished with three years of running and suppressing backgrounds to < 0.4 event total (50% cosmics, 35% DIOs)

$R_{\mu e} < 8 \times 10^{-17}$ @ 90% C.L.

Mu2e Expected Background

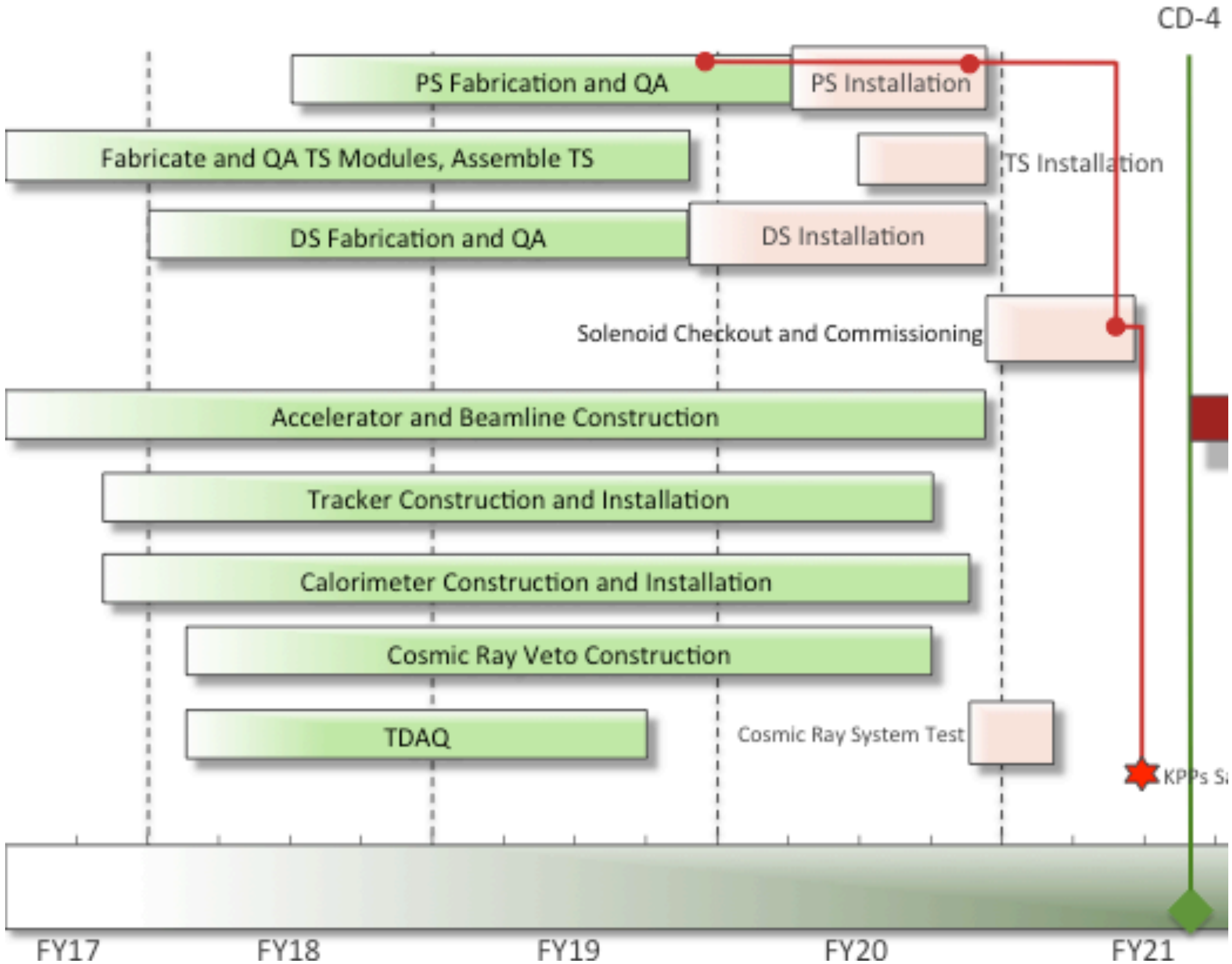
Category	Background Process	Estimated Yield
Intrinsic	Decay In Orbit (DIO)	0.144 ± 0.028(stat) ± 0.11(syst)
	Muon Capture (RMC)	0
Late Arriving	Pion Capture (RPC)	0.021 ± 0.001(stat) ± 0.002(syst)
	Muon Decay in Flight	< 0.003
	Pion Decay in Flight	0.001 ± <0.001
	Beam Electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Cosmic Ray Induced	0.209 ± 0.022(stat) ± 0.055(syst)
	Antiproton Induced	0.040 ± 0.001(stat) ± 0.020(syst)
Total		**0.41 ± 0.13(stat + syst)**

(scale with number of stopped muons)

(scale with number of late protons)

Upper Limit on Rue < 8×10^{-17} @ 90% C.L.

Mu2e Schedule



Three years run expected 2022-2025

(What-Next?) Mu2e → Mu2e-II

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:

→ 1 MW at LNBF at start (2025)
→ 2 MW at regime at LNBF
→ **It can be used to deliver a x 10 muons at Mu2e**

Snowmass →Arxiv.1311.5278
Mu2e-2 → Arxiv.1307.1168v2.pdf

2) **Depending on the beam Structure available:**
→ study Z dependence if signal is observed

3) If no signal is observed
Use x 10 events in Mu2e-II

Some modifications of the detector → **BR < 6 x 10^{-18}**

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-p
Phys.Rev. D80 (2009) 013002

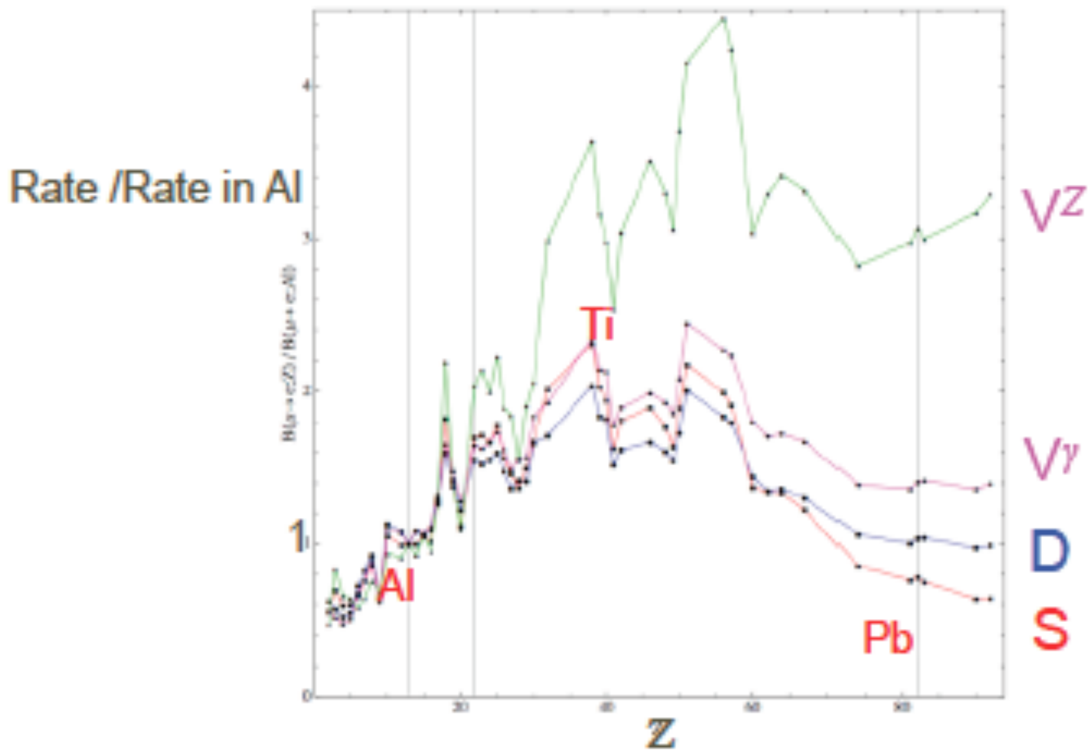


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

MU2E-II workshop at Argonne : 8 Dec 2017
EOI in preparation → PAC FNAL summer 2018

Summary

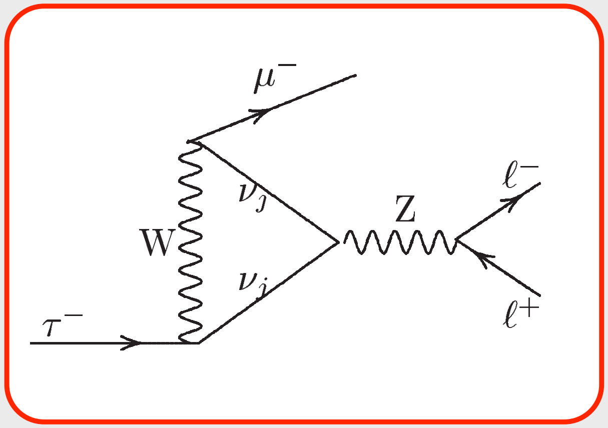
The Mu2e experiment:

- Improves sensitivity on u-e conversion by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- Is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments ….
- Is progressing on schedule. It will begin commissioning at the end of 2020
- Start discussing about Mu2e-II

Additional Material

CLFV and Tau Processes

- Advantage:
  - Beyond SM rates can be orders of magnitude higher than in the corresponding muon channel
- Disadvantage
  - τ's hard to produce:
    - ~10^{11} τ/*yr* vs ~10^{11} μ/*sec* in muon experiments



SM ~ 10^{-14} ?

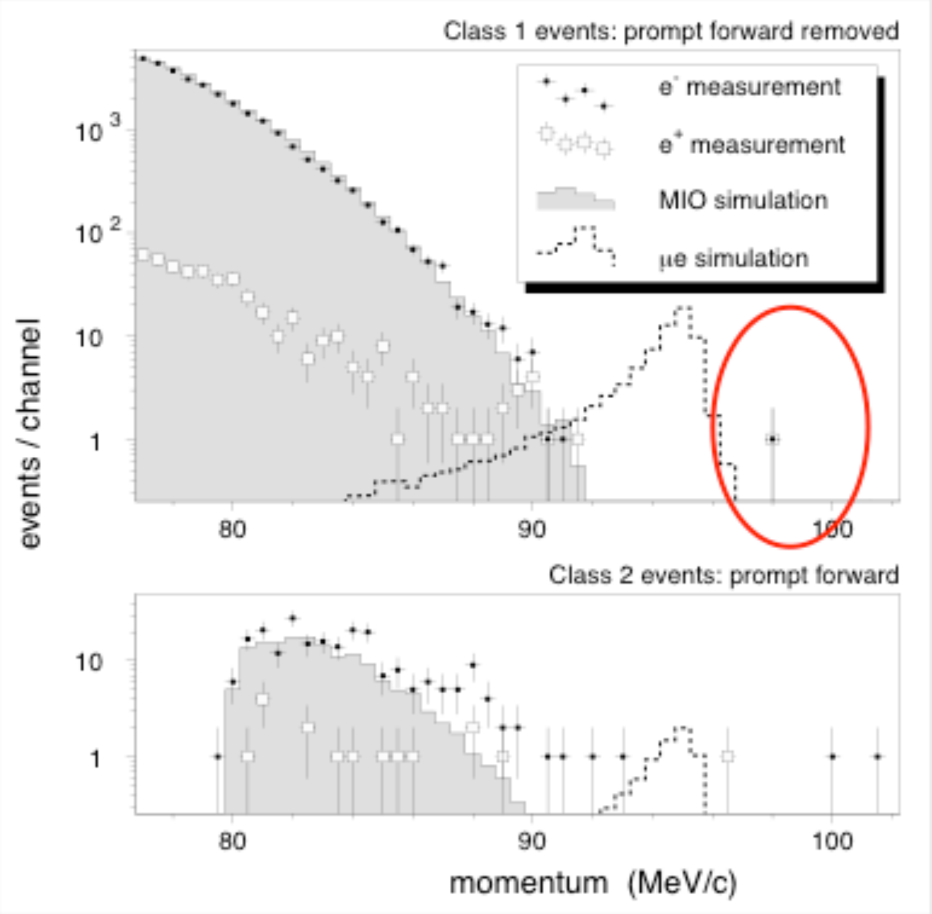
τ's help pin down models; e.g. Cheng-Sher Ansatz $\sqrt{m_i m_j}$

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

SINDRUM-II Results

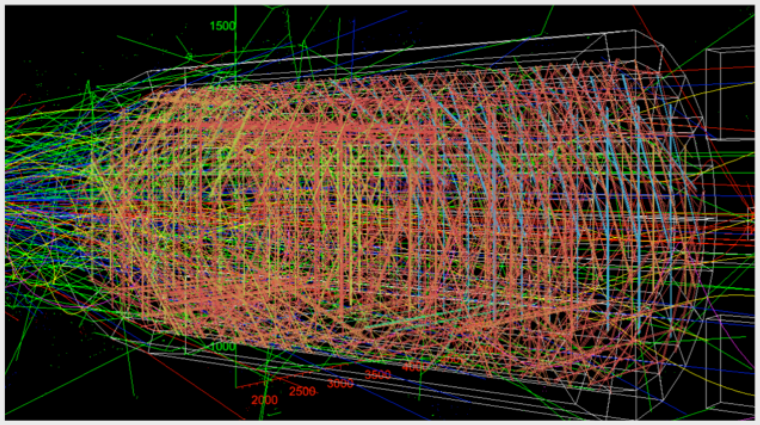
- Effectively constant beam
  - 51 MHz (~20 nsec) repetition rate, ~0.3 nsec pulse
- Small time separation between signal and prompt pion backgrounds
  - bottom plot is first half of 20 nsec, top plot is 2nd half
  - time lowers background

$$B_{\mu e}^{\mathrm{Au}} < 7 \times 10^{-13} \text{ @ } 90\% \text{ CL}$$



Choice of Z for Upgrade

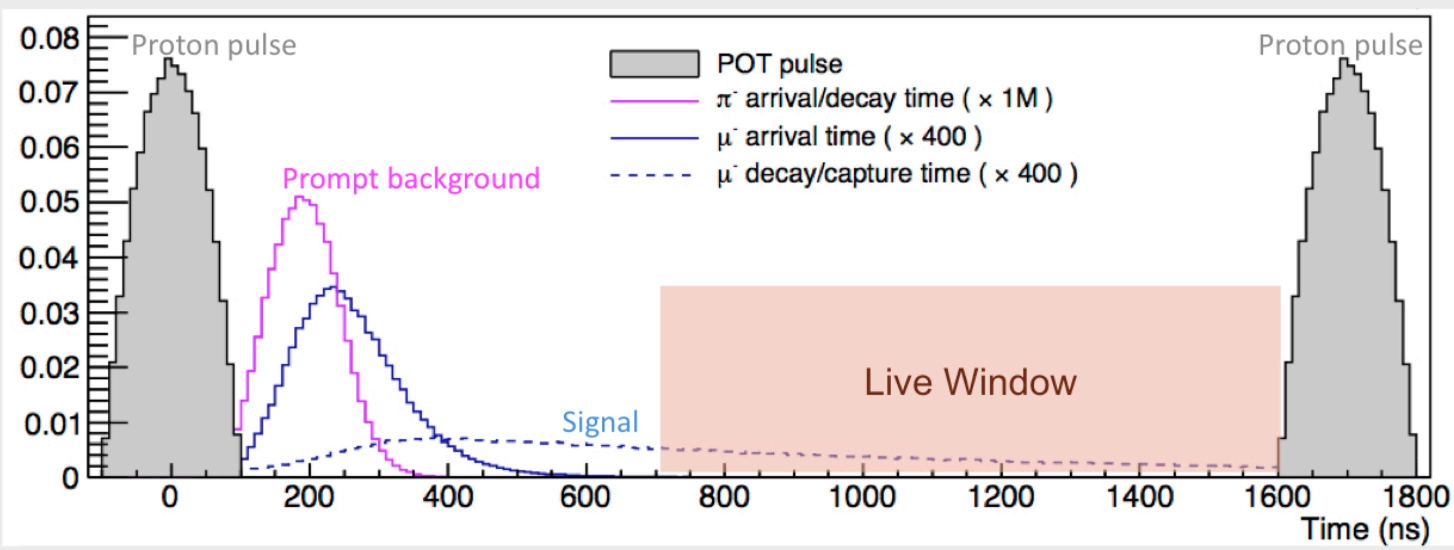
- What Sets Material Choice? Lifetime:



$$\tau_\mu(\mathrm{Al}) = 864 \text{ ns}$$

$$\tau_\mu(\mathrm{Ti}) = 338 \text{ ns}$$

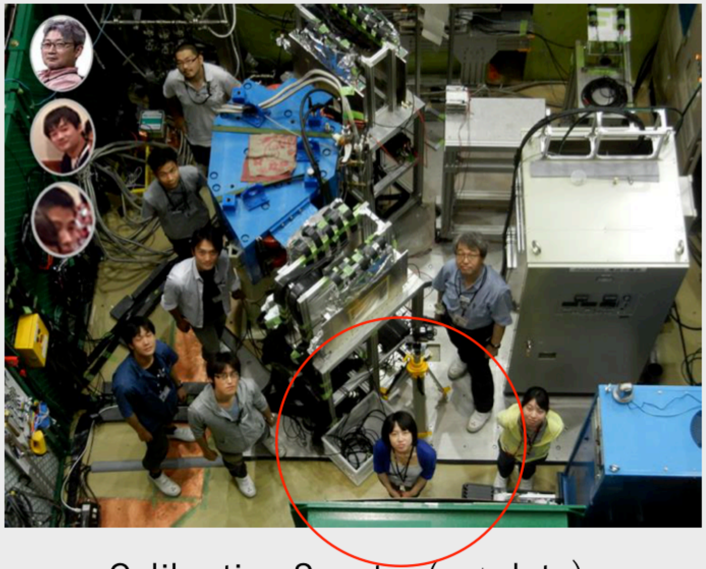
$$\tau_\mu(\mathrm{Au}) = 74 \text{ ns}$$

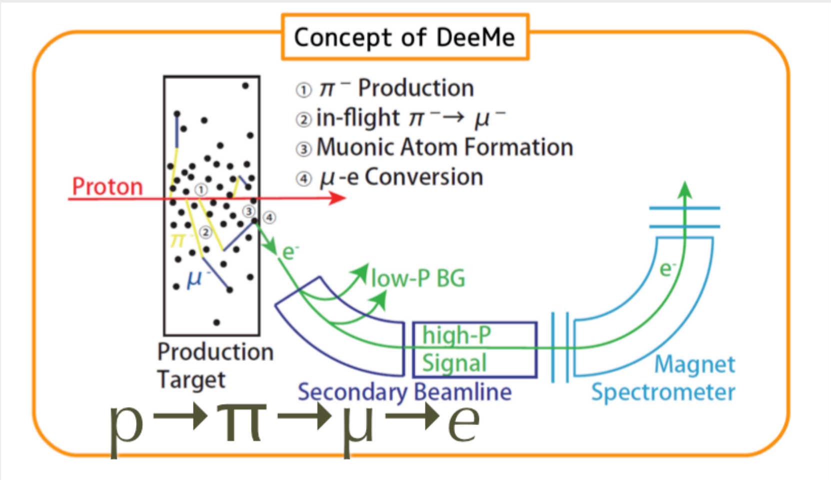


DeeMe

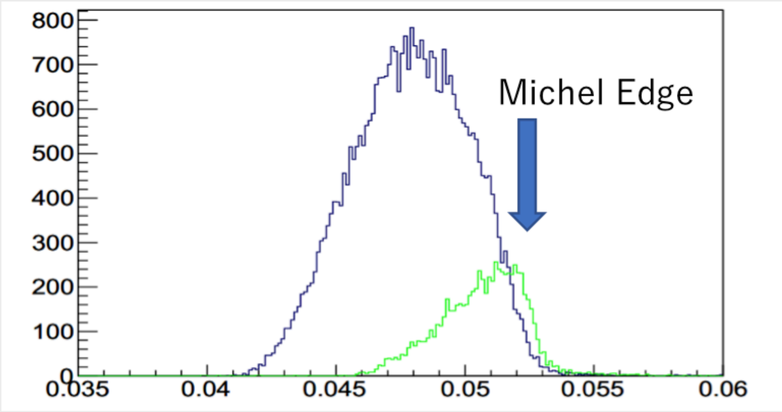
- DeeMe at J-PARC $\mu N \rightarrow eN$ with a 2 x 10^{-14} SES, x10 better than existing

- ***production target and conversion target are the same: not like Mu2e or COMET***





Calibration Spectra (μ⁺ data)



Teshima, WG4

COMET vs Mu2e

- ❑ Similar capabilities in physics reach

- ❑ **COMET designed to operate at 56 kW, Mu2e 8 kW**
  → COMET will use all JPARC beam
  → Mu2e runs simultaneously with neutrino beam

- ❑ Final bend after COMET stopping target efficiently transmits conversion e- and provides rate suppression in detector.

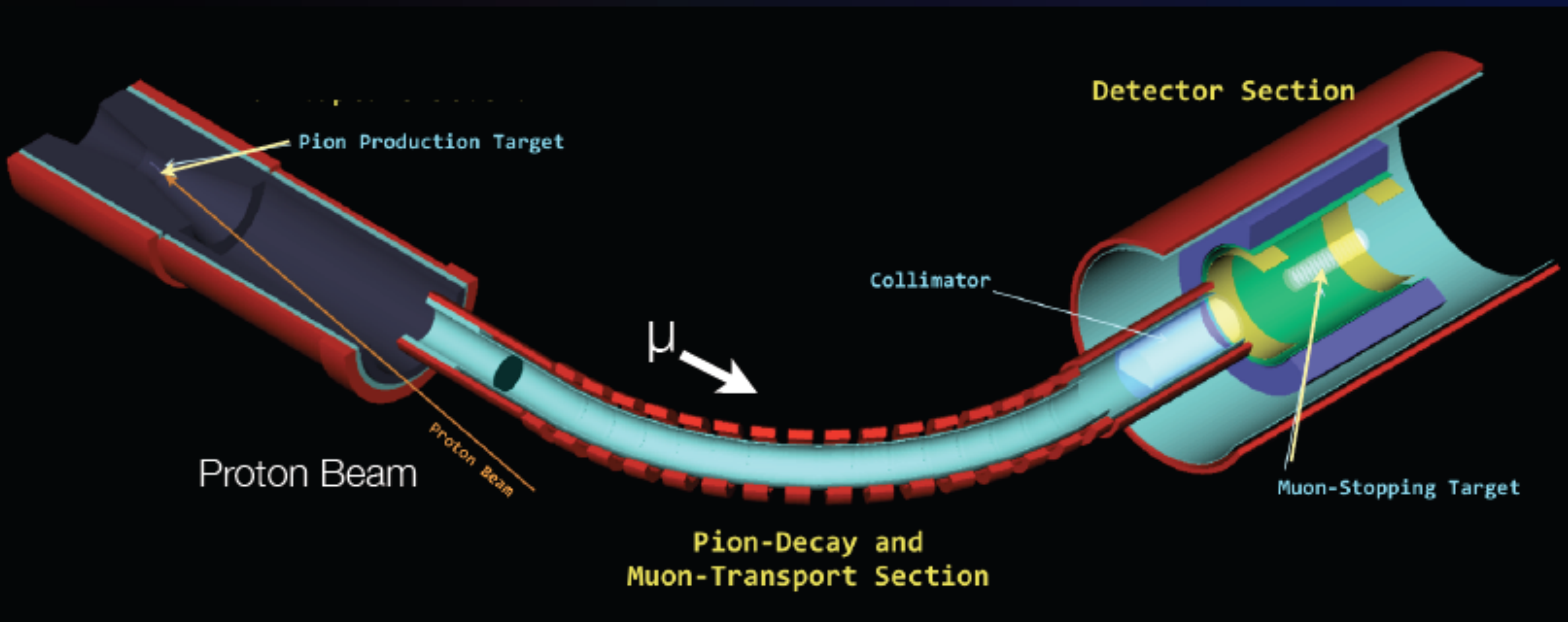
- ❑ **It does not transmit positrons (no $\mu^- N \rightarrow e^+ N$)**
- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam → higher cost (solenoid shieldling, neutron shielding)
- Longer solenoids carry "cost" in operation

COMET Phase-1 could be useful if successful to study background rate
COMET Phase-2 schedule …not yet official
Mu2e is fully approved → now looking for Mu2e-II (Next @ PAC 2018)

- ❑ Great competition/collaboration → ALCAP @ PSI physics case coupled with the explicit scope of the experiment

COMET Phase-I Experimental Layout

Osaka University



COMET muon beam-line :

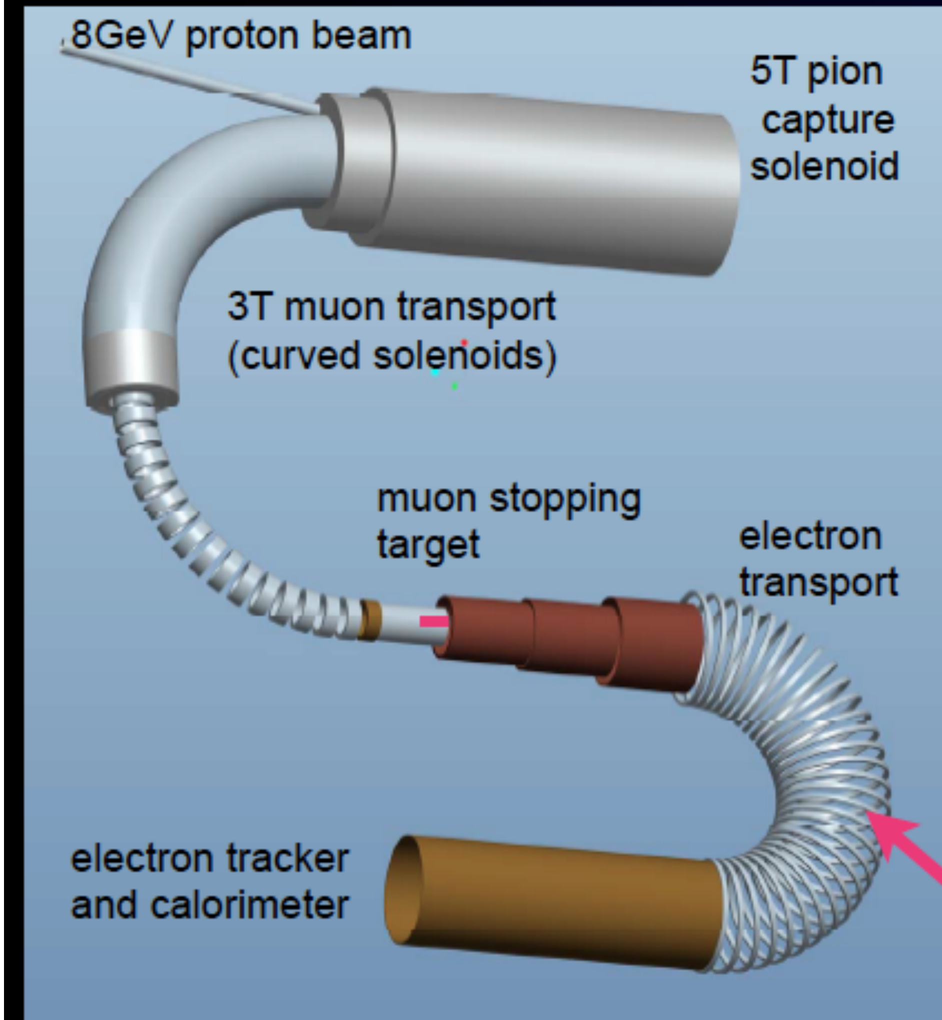
(1~3)x10^9 muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I detector :

Cylindrical drift chamber (CDC) for μ-e conversion is used. Straw chamber and ECAL are for beam studies.

Q:physics case coupled with the explicit scope of the experiment

What is COMET (E21) at J-PARC



Experimental Goal of COMET

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- 2×10^{7} running time (~1 year)
- C-shape muon beam line
- C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

SINDRUM-II Results

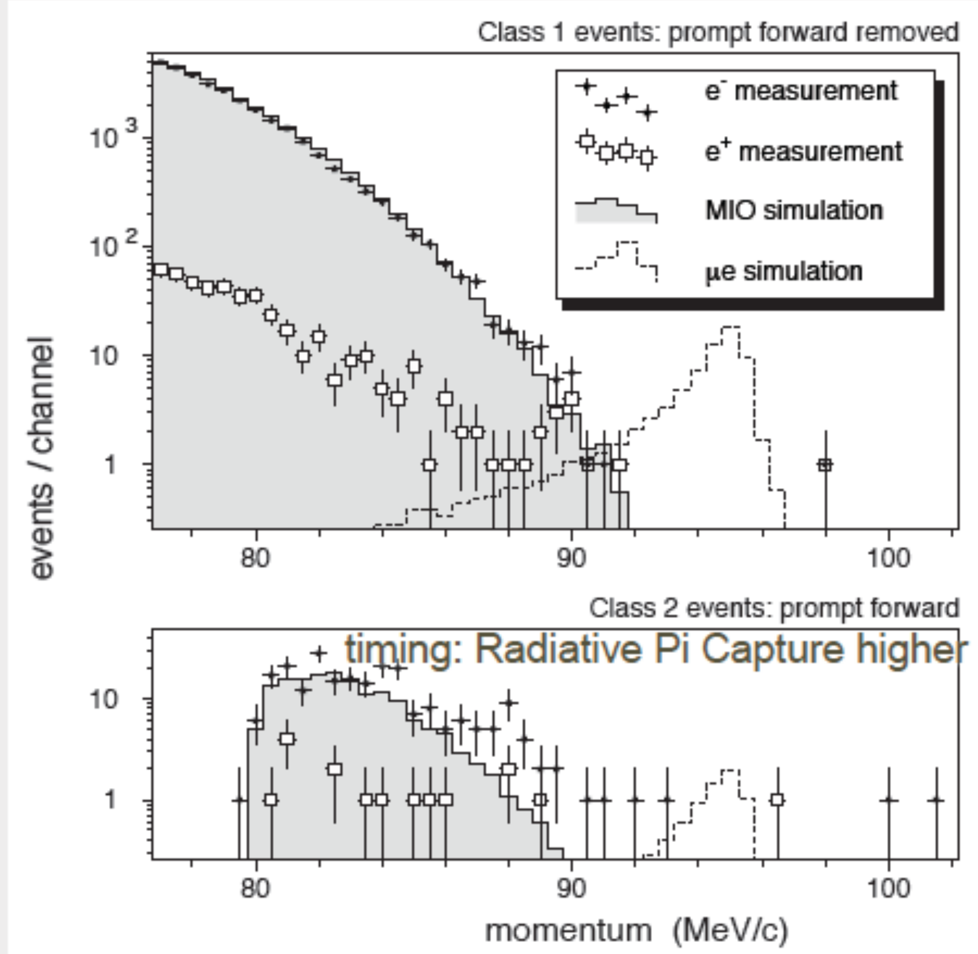
- Final Results on Au:

$$B_{\mu e}^{\mathrm{Au}} < 7 \times 10^{-13} \text{ @ } 90\% \text{ CL}$$

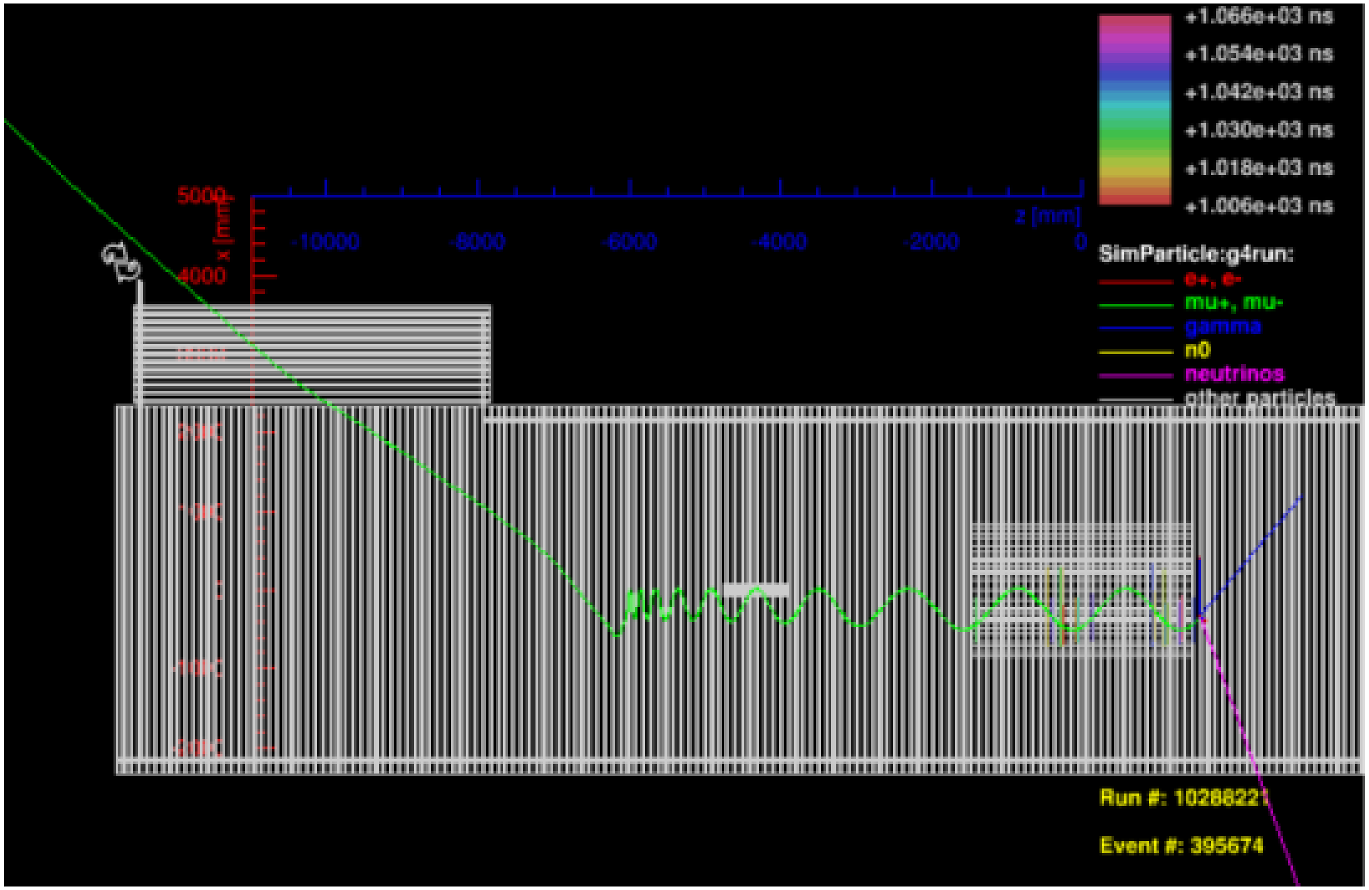
51 MHz (20 nsec) repetition rate, width of pulse ~0.3 nsec

little time separation between signal and prompt background

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

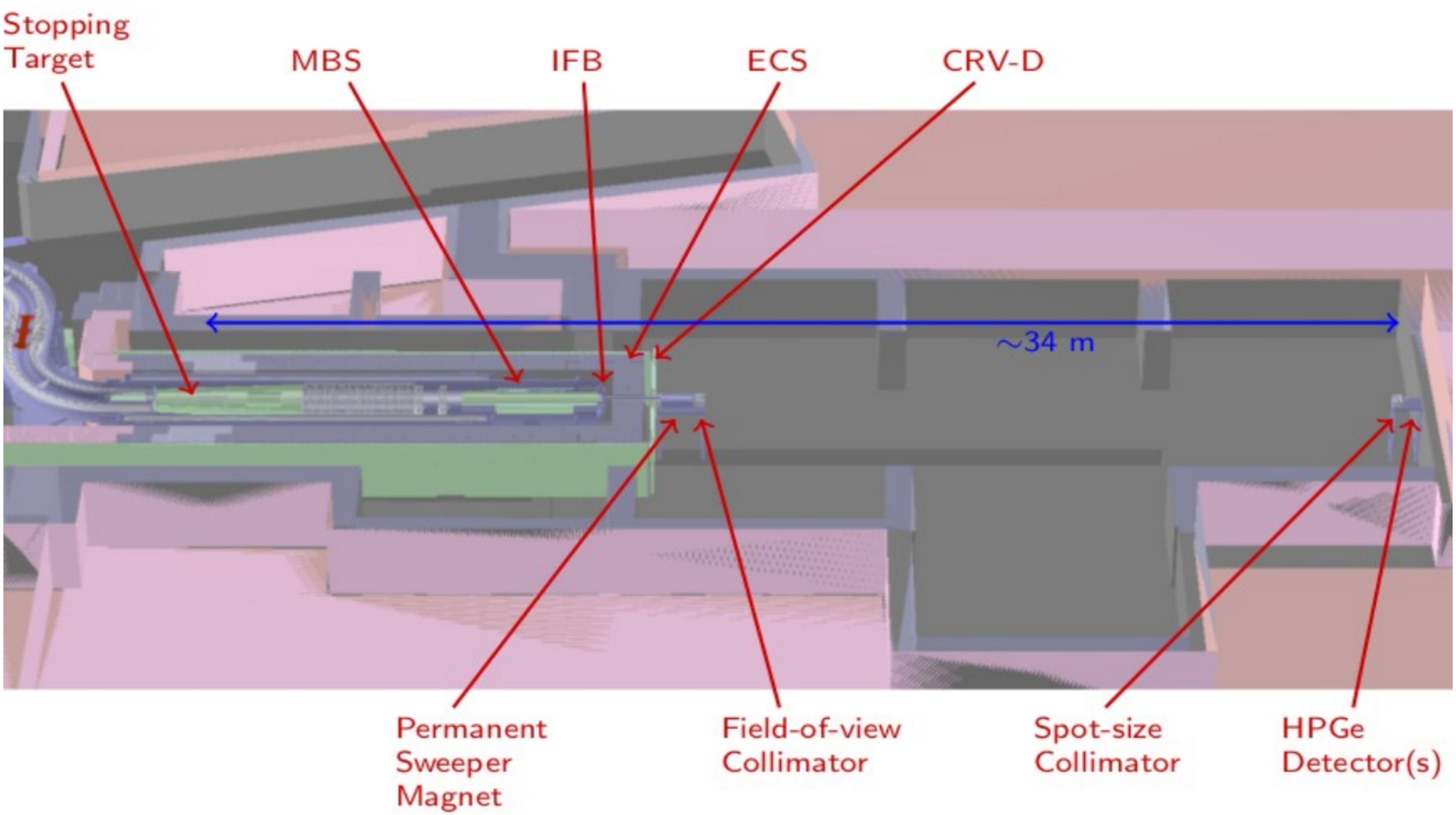


Mu2e: “fake” CE from CR events



- ❑ A long MC production used to optimize the CRV geometry by generating the same amount of cosmics that will cross the detector in MU2E running period.
- ❑ **few events evaded the CRV**, passing closely enough to the target, were tracked by the tracker and passed all reconstruction tracking criteria. They were all μ^- → **rejected due to the combination of Calorimeter and tracking information : timing and *E*/*p***

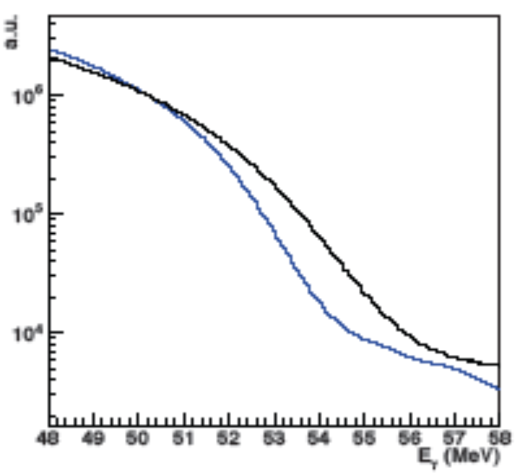
Mu2e: Stopping Monitor

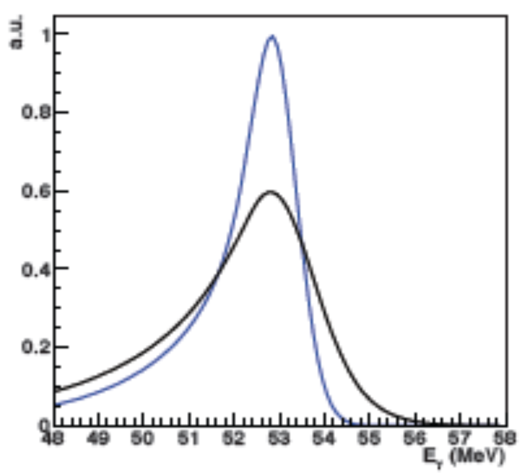


The STM will measure a variety of well understood gamma ray lines … under a high-rate brehmstrahlung background

MEG UPGRADE parameters

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88





The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

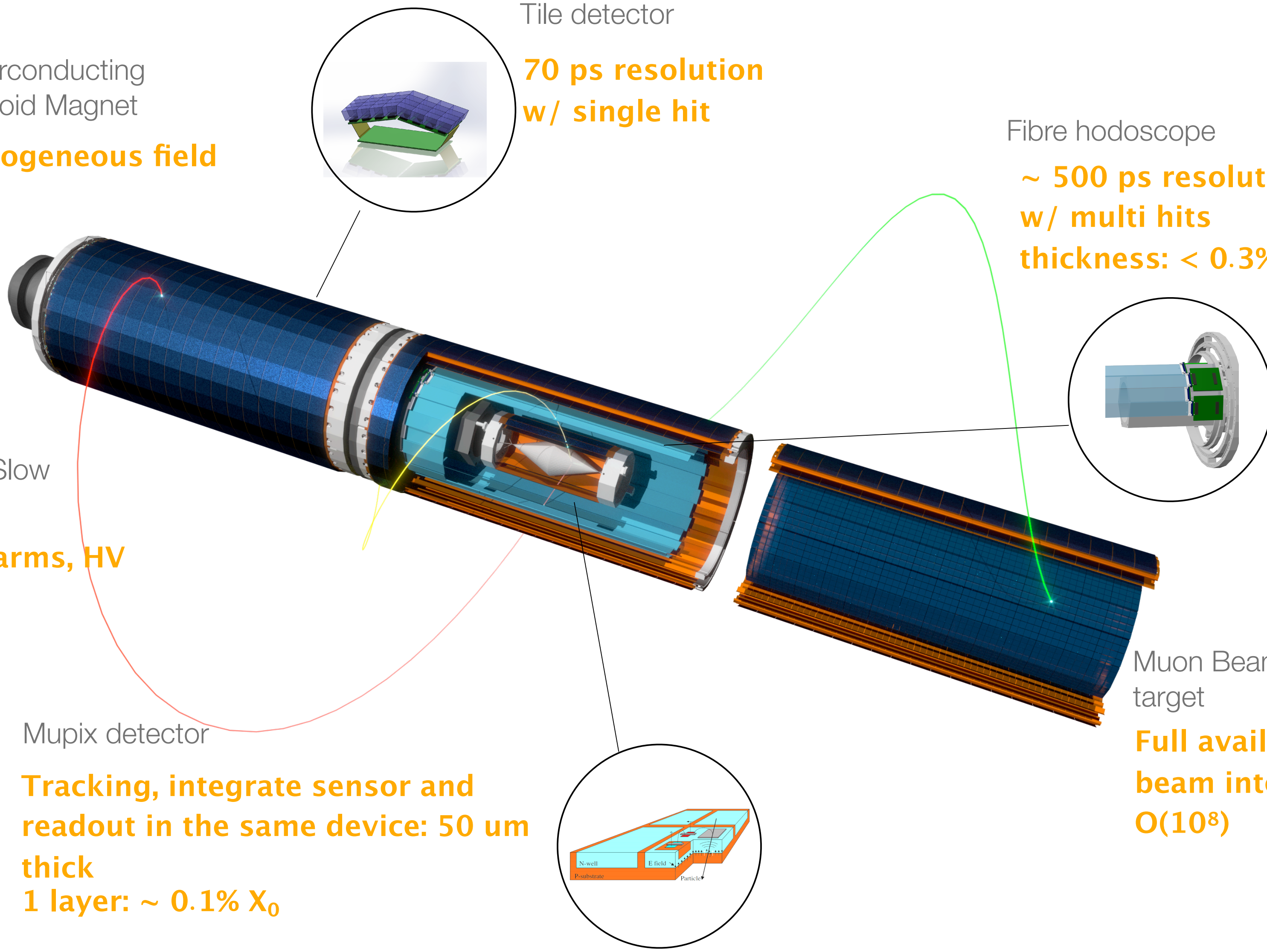
Homogeneous field 1T

Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

~ 500 ps resolution w/ multi hits thickness: < 0.3% X_0



MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Muon Beam and target

Full available beam intensity O(10^8)

Mupix detector

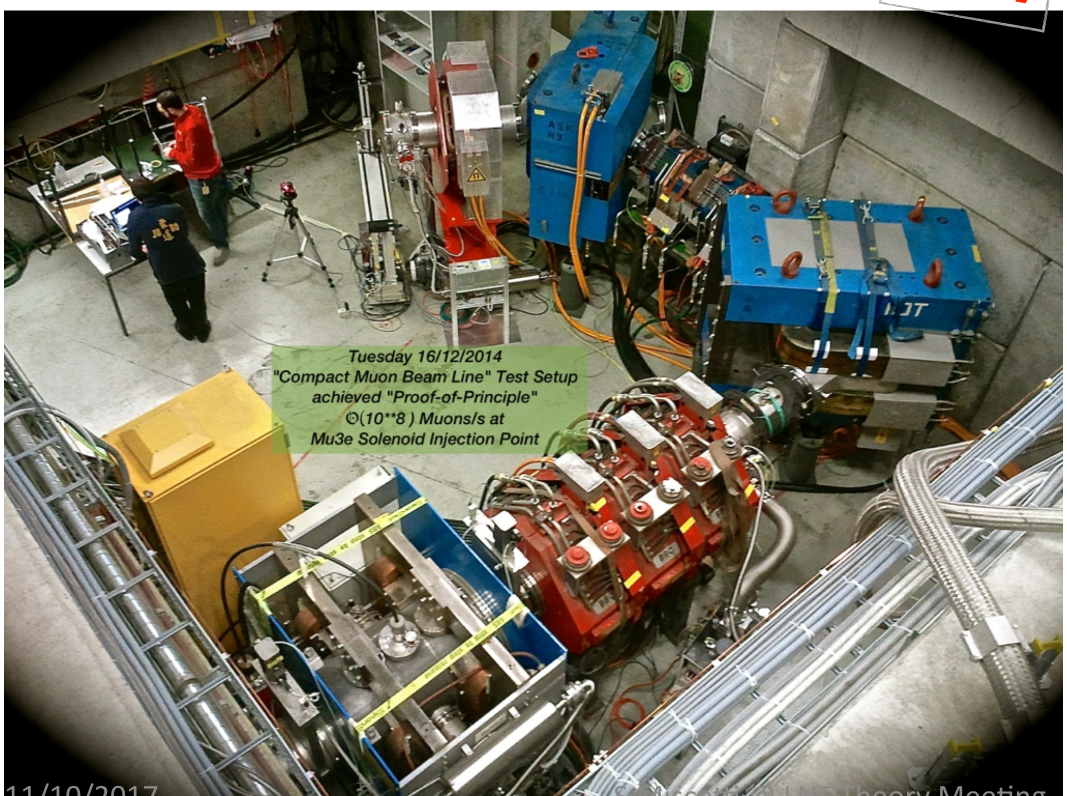
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0

The compact beam line: Results

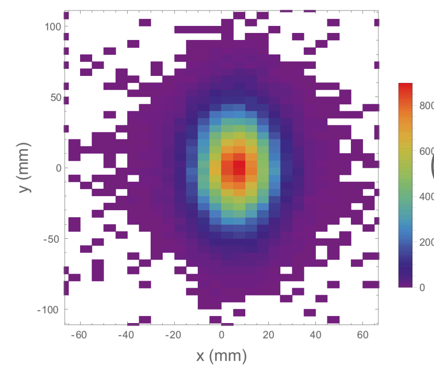
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8.4 10^7 muon/s during 2016 test beam

New

The CMBL

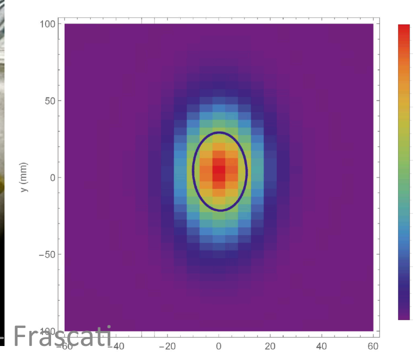


Beam at the injection Mu3e solenoid point



Simulation

$$(\sigma_x, \sigma_y) = (10.6, 24.3)[\mathrm{mm}]$$



Data

$$(\sigma_x, \sigma_y) = (10.4, 25.4)[\mathrm{mm}]$$

MEG vs Mu3e

- Mu3e decays test also values of K larger than MEG but with different (reduced) sensitivity al large K with respect to Mu2e
- Phase 1 Mu3e at PSI aims to 10^{-15} (approved)
- Next phase aims to few 10^{-16} .. Schedule is not yet clear