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

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Outline

- The Physics
  - →CLFV processes
  - →BSM Reach: Conversion exp. vs MEG-II
- Description of Muonic Atom processes
- Experimental technique
- Accelerator Complex
- 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)

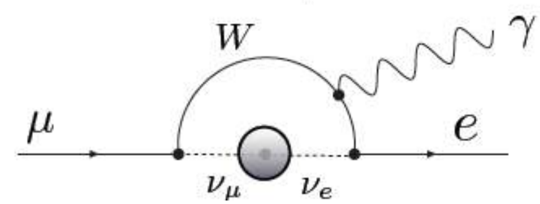
  similar but complementary to other CLFV processes as $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$.

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

- CLFV processes are strongly suppressed in the Standard Model

  → In principle, not forbidden due to neutrino oscillations

  → In practice $BR(\mu \rightarrow e\gamma) \sim 10^{-54}$ is negligible in the SM!

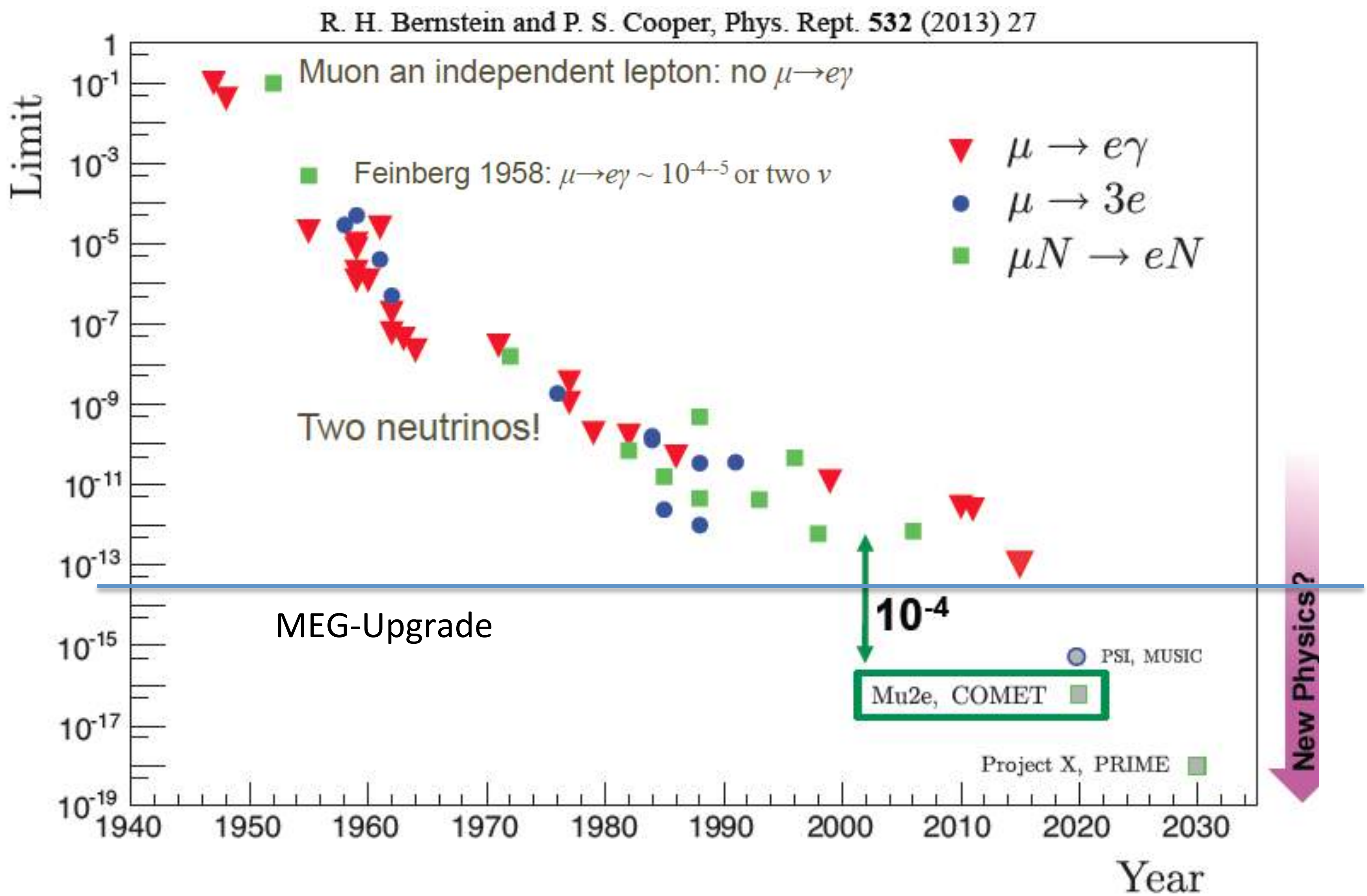


- New Physics could enhance CLFV rates to observable values

- 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

CLFV history for muons

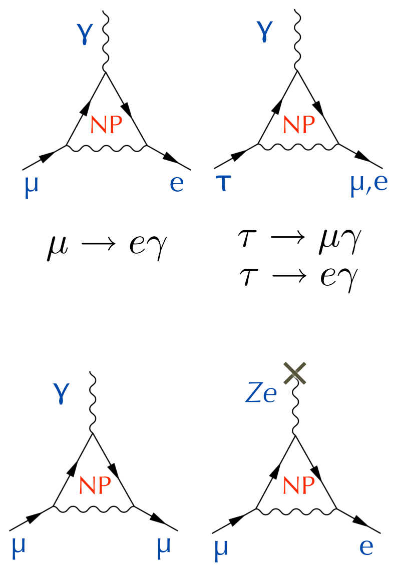


Mu2e vs MEG/MEG upgrade

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

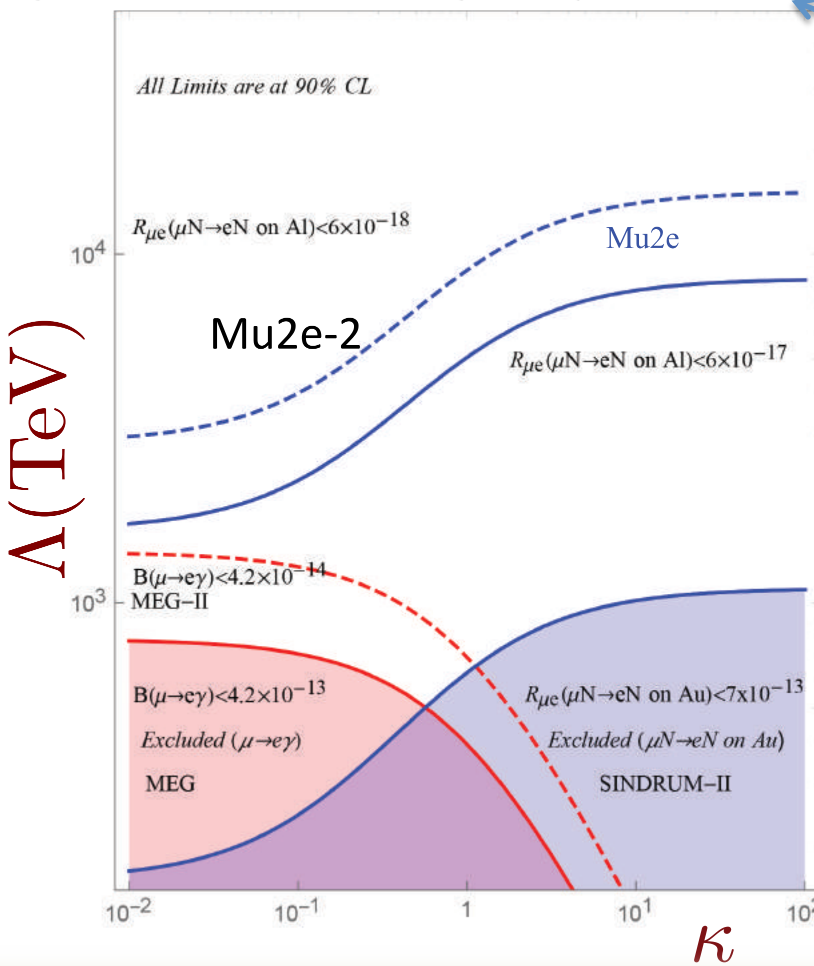
LOOP TERM

$\kappa \ll 1$



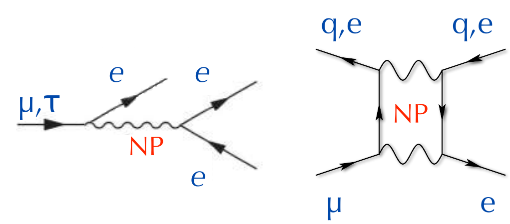
$\mu \to e\gamma$ $\quad \tau \to \mu\gamma$, $\tau \to e\gamma$

$(g-2)_\mu$ $\quad \mu^- \mathcal{N} \to e^- \mathcal{N}$



CONTACT TERM

$\kappa \gg 1$

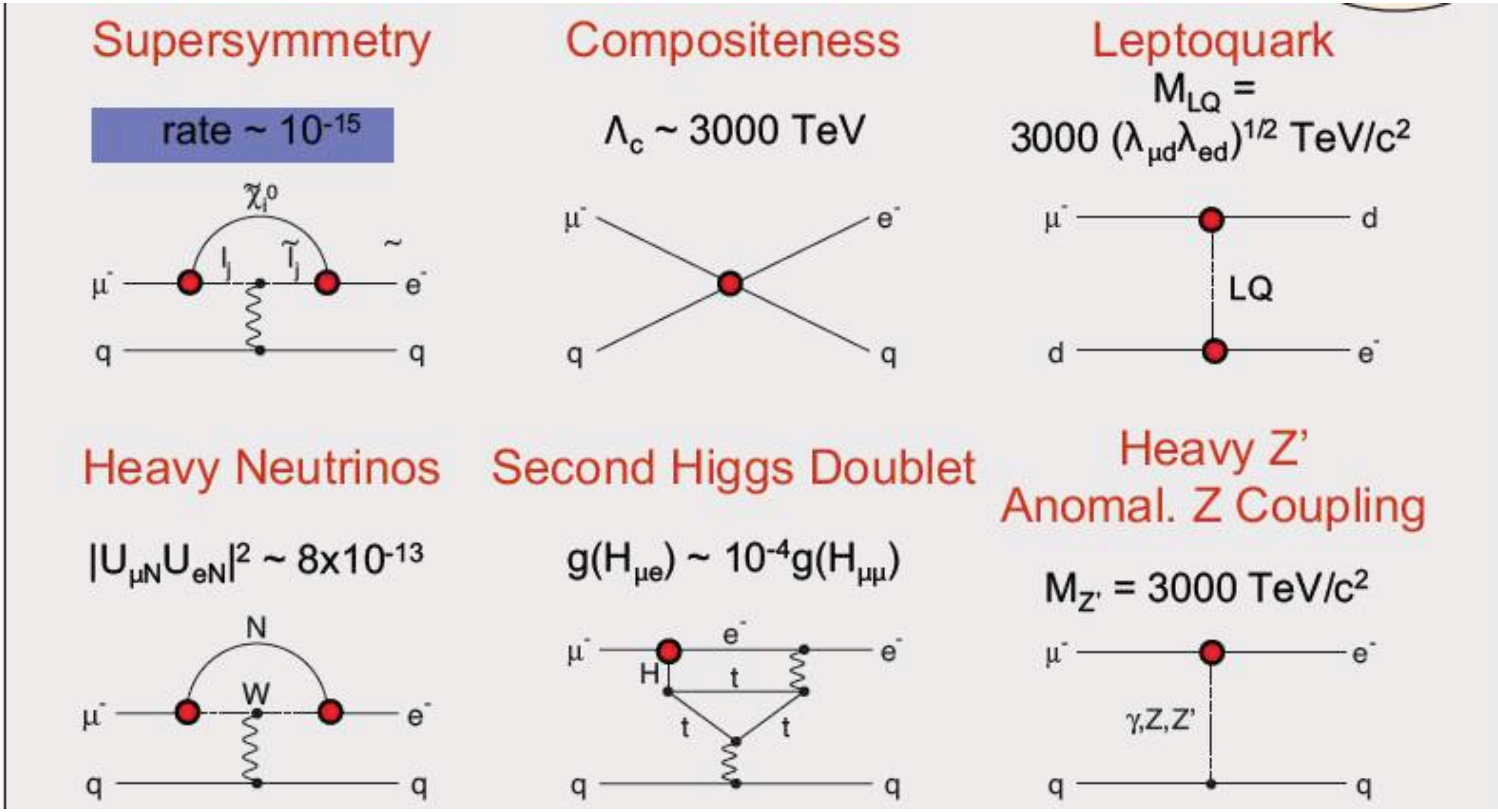


$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 6\times 10^{-17} \text{ (@90\%CL)}$$

Mu2e physics reach & goal

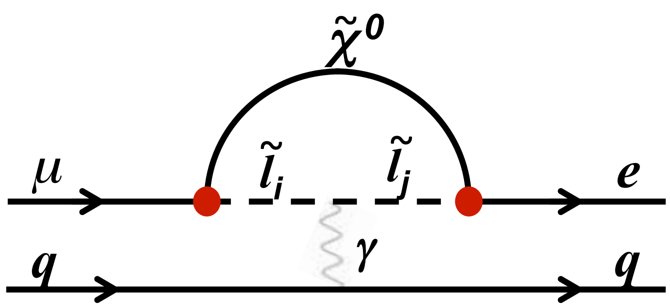


Sensitivity reach:
10^4 improvement with respect to previous muon to electron
conversion experiment (Sindrum-II)

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

Specific Example: SUSY

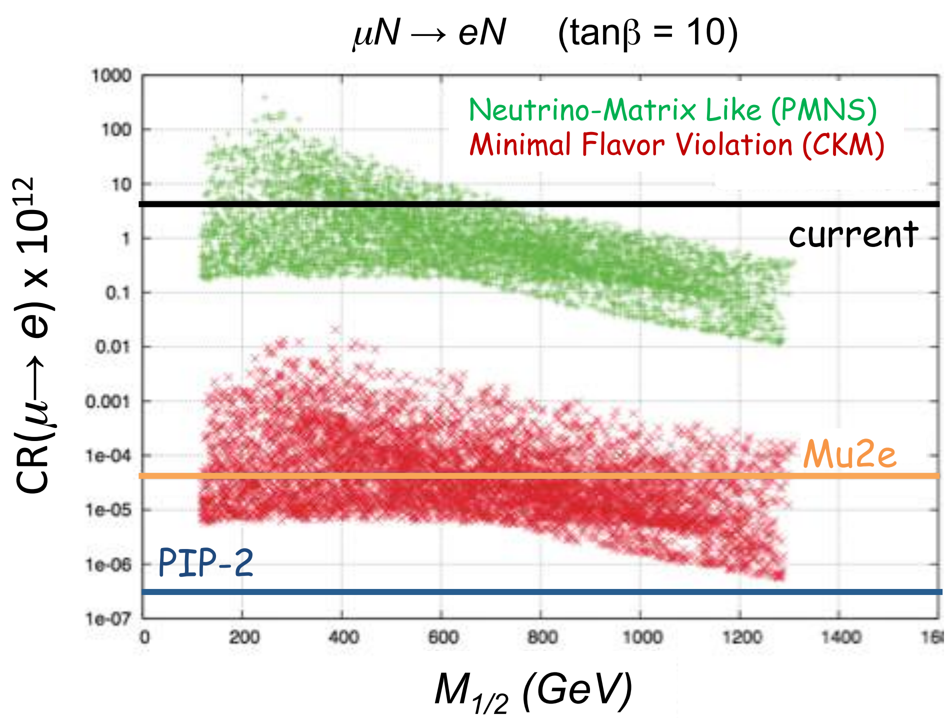
Probe SUSY through loops



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

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**

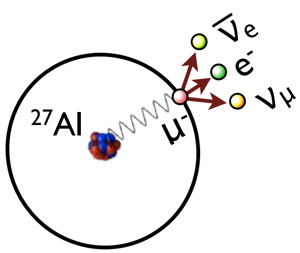
Primer of processes and experimental technique

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:

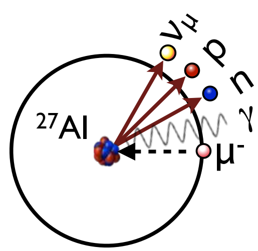
Decay in Orbit (DIO)

(BR=39%)

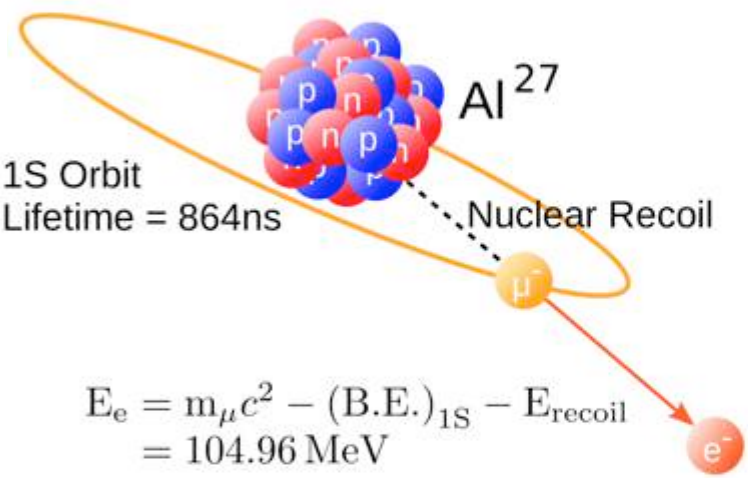


Muon Capture Process

(BR=61%)



Conversion Process



$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,\mathrm{MeV}$$

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 2.4×10^{-17}**
  - Requires about 10^{18} stopped muons
  - Requires about 10^{20} protons on target
  - Requires extreme suppression of backgrounds
- **Expected limit: $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL**
  - Factor 10^{4} improvement
- **Discovery sensitivity: all $R_{\mu e} >$ few $\times 10^{-16}$**
  - 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)**

    $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$ and $\pi^- N \rightarrow e^+e^- N'$
  - **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**

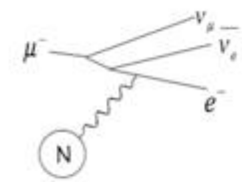
DIO background

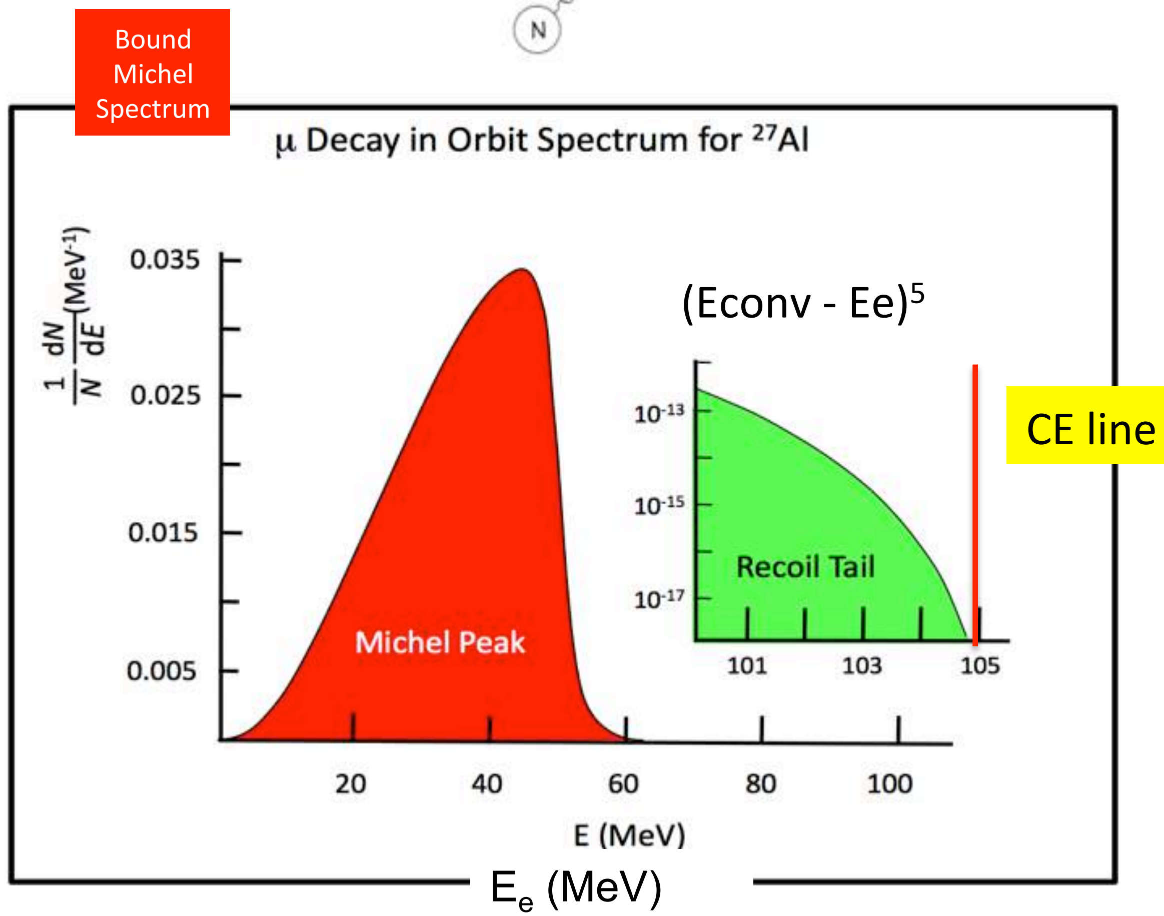
- ❑ **The DIO background is the most difficult one.**

- ❑ 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



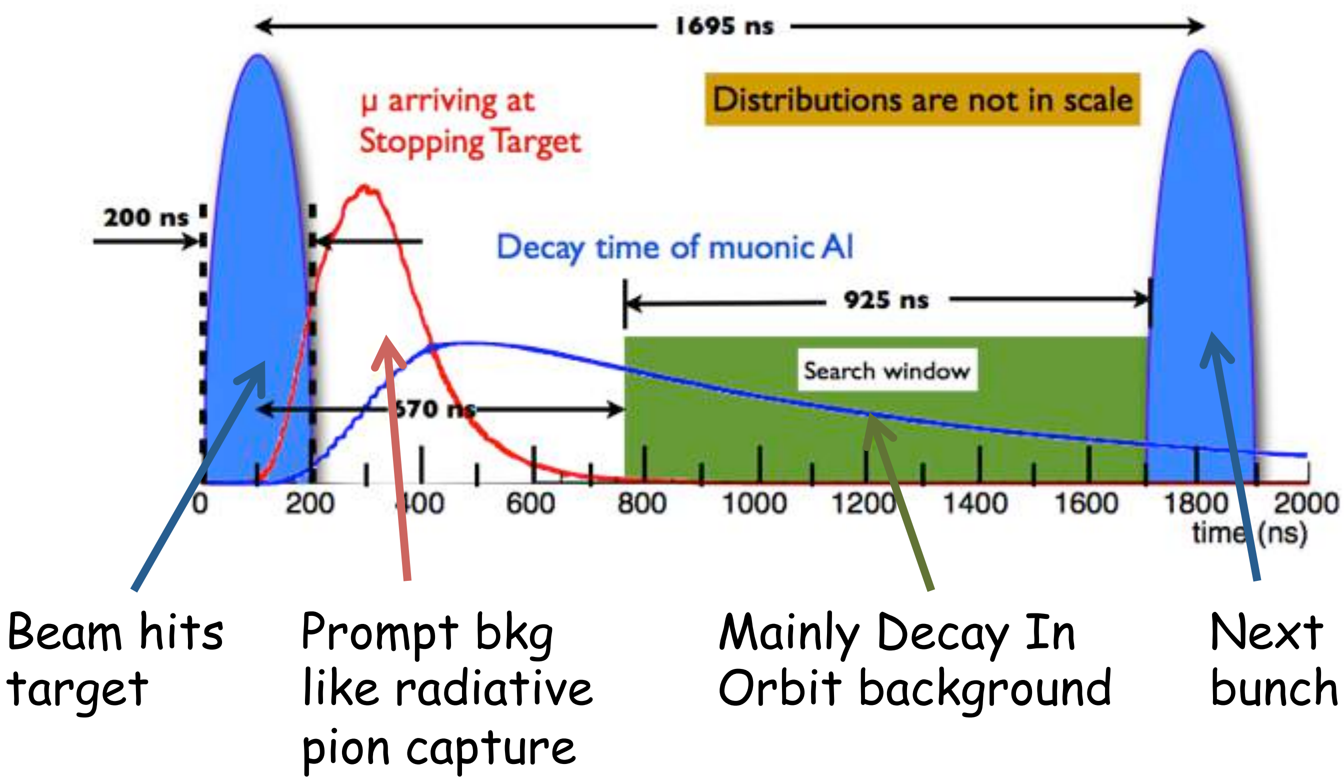


Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv: 1106.4756v2

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

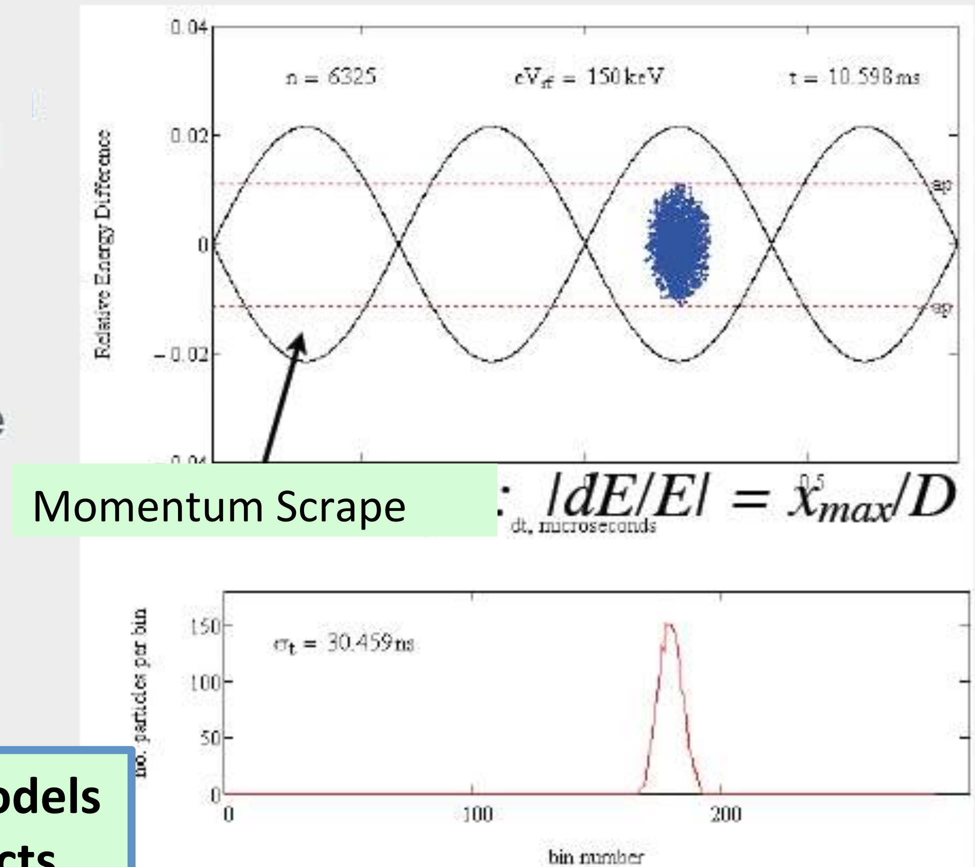
Need a pulsed beam to wait for prompt background to reach acceptable levels!
Fermilab provides the beam we need !

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

- **Pulsed proton beam**
  - Narrow proton pulses (< +/- 125 ns)
  - Very few out-of-time protons (< 10^{-10})

- **Avoid trapping particles… B-field requirements**
  - Further mitigates beam-related backgrounds

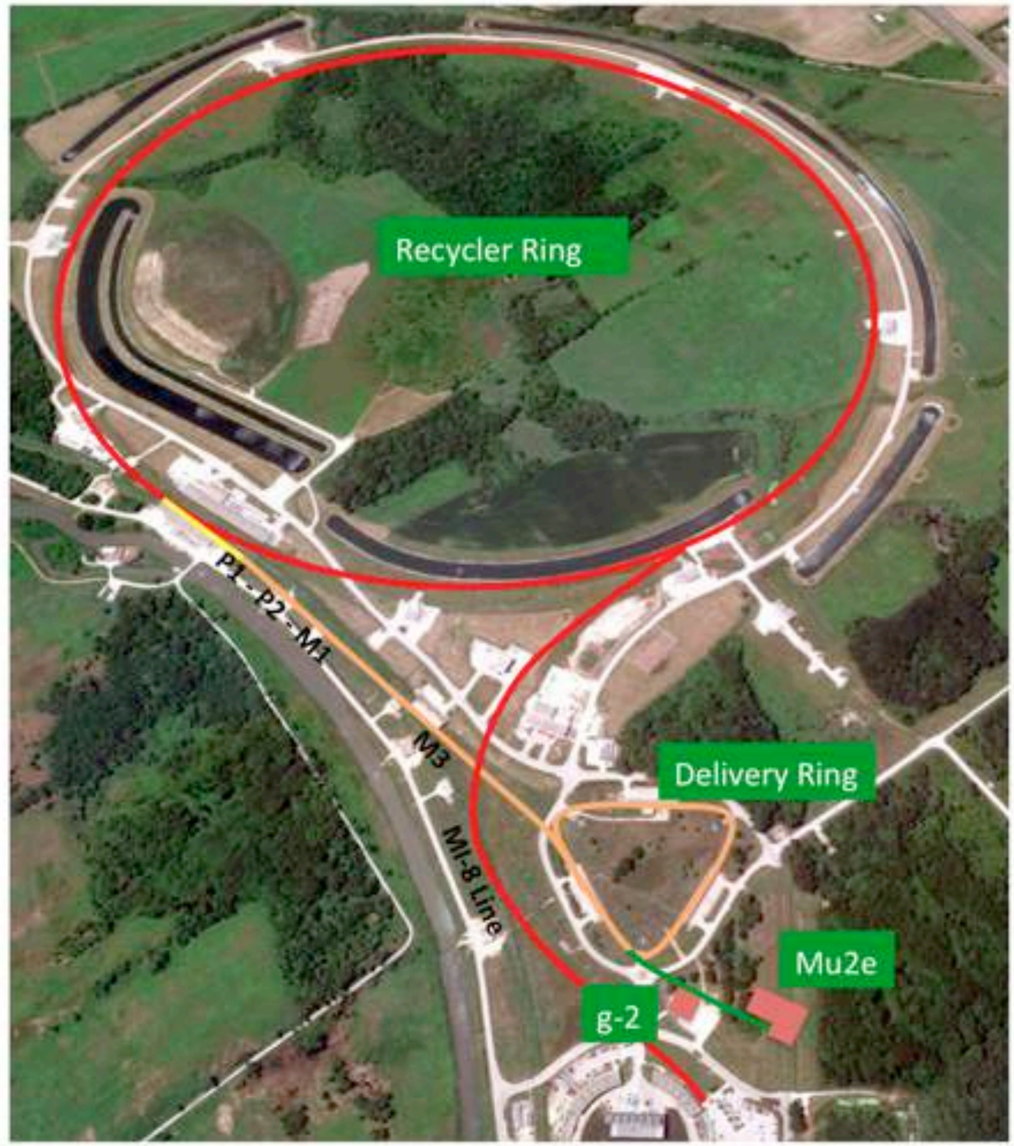
- **Excellent detector**

→ High CR veto efficiency (>99.99%)
→ Excellent momentum resolution (< 200 keV core)
→ Calorimetry for PID and track seeding
→ Thin anti-proton annihilation window(s)

Experiment Layout

Accelerator Scheme

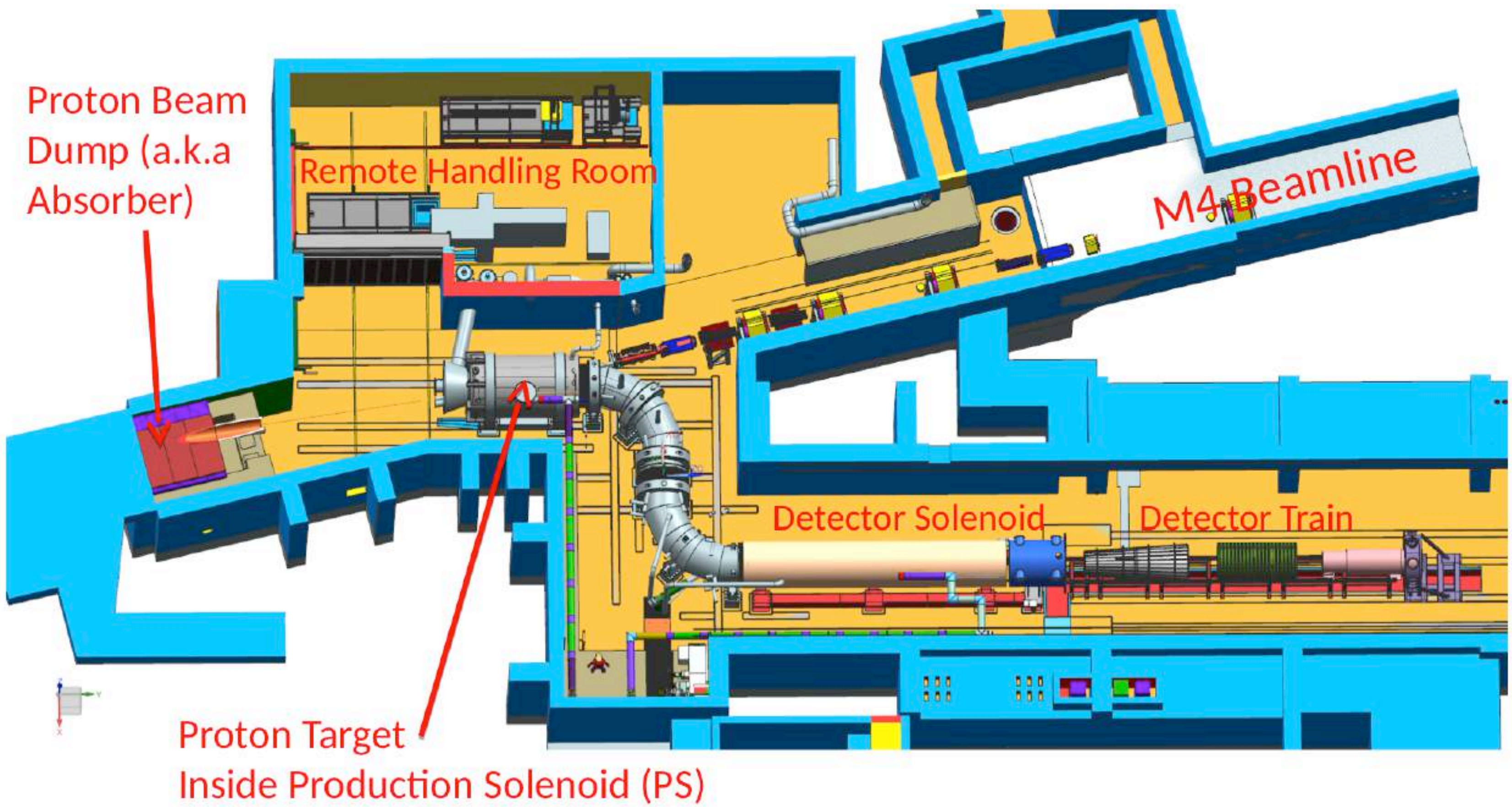
- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring
- Batch is re-bunched into 4 bunches
- These are extracted one at a time to the Debuncher/Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure
- **Produces bunches of ~$3\text{x}10^7$ protons each, separated by 1.7 μs (debuncher ring period)**



Muon campus: g-2/Mu2e → rendering

Muon campus: g-2/Mu2e → reality

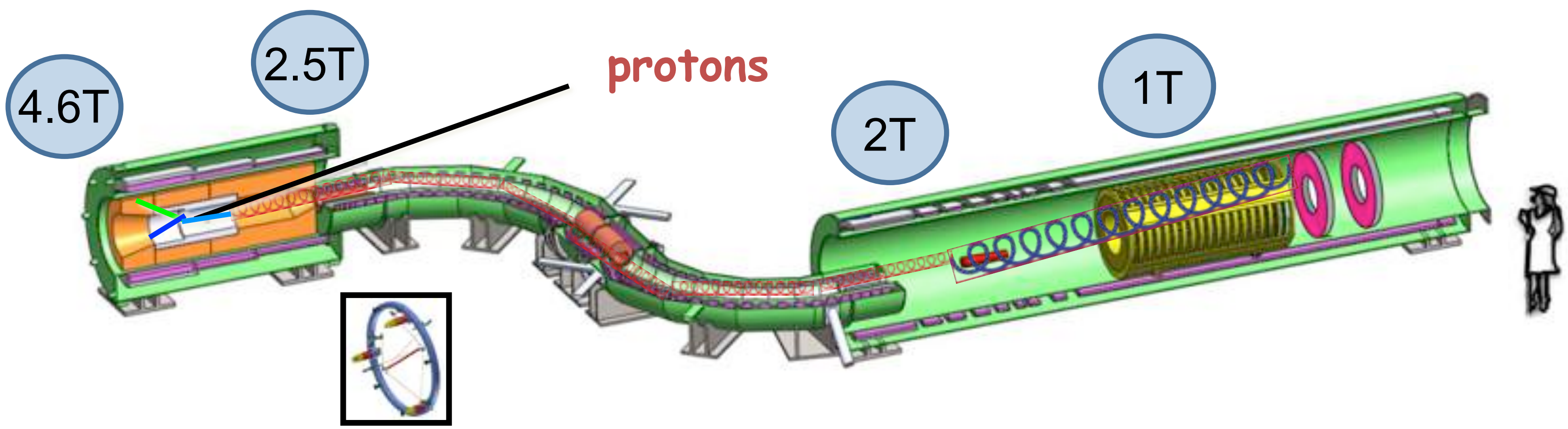
Mu2e – experiment layout



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.

Target, Detector and Solenoid (DS)

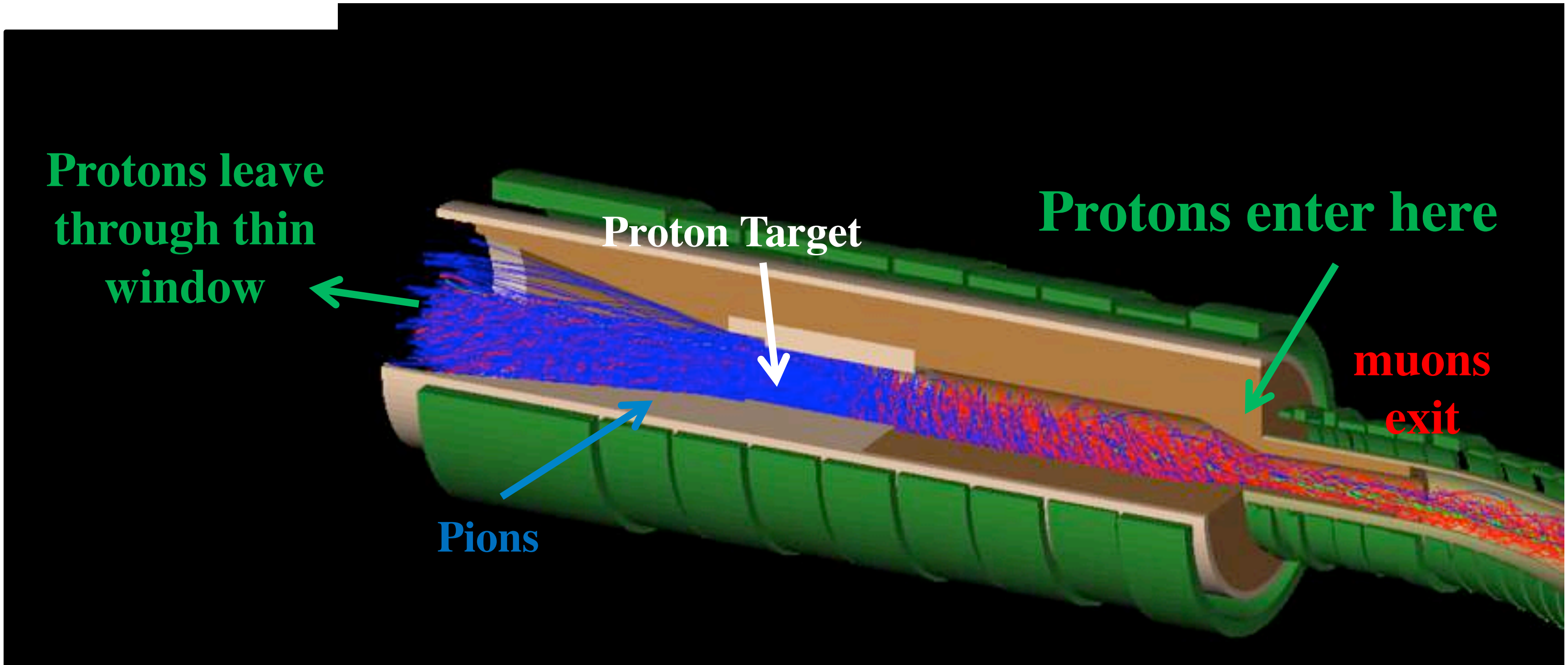
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Transport Solenoid (TS)

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

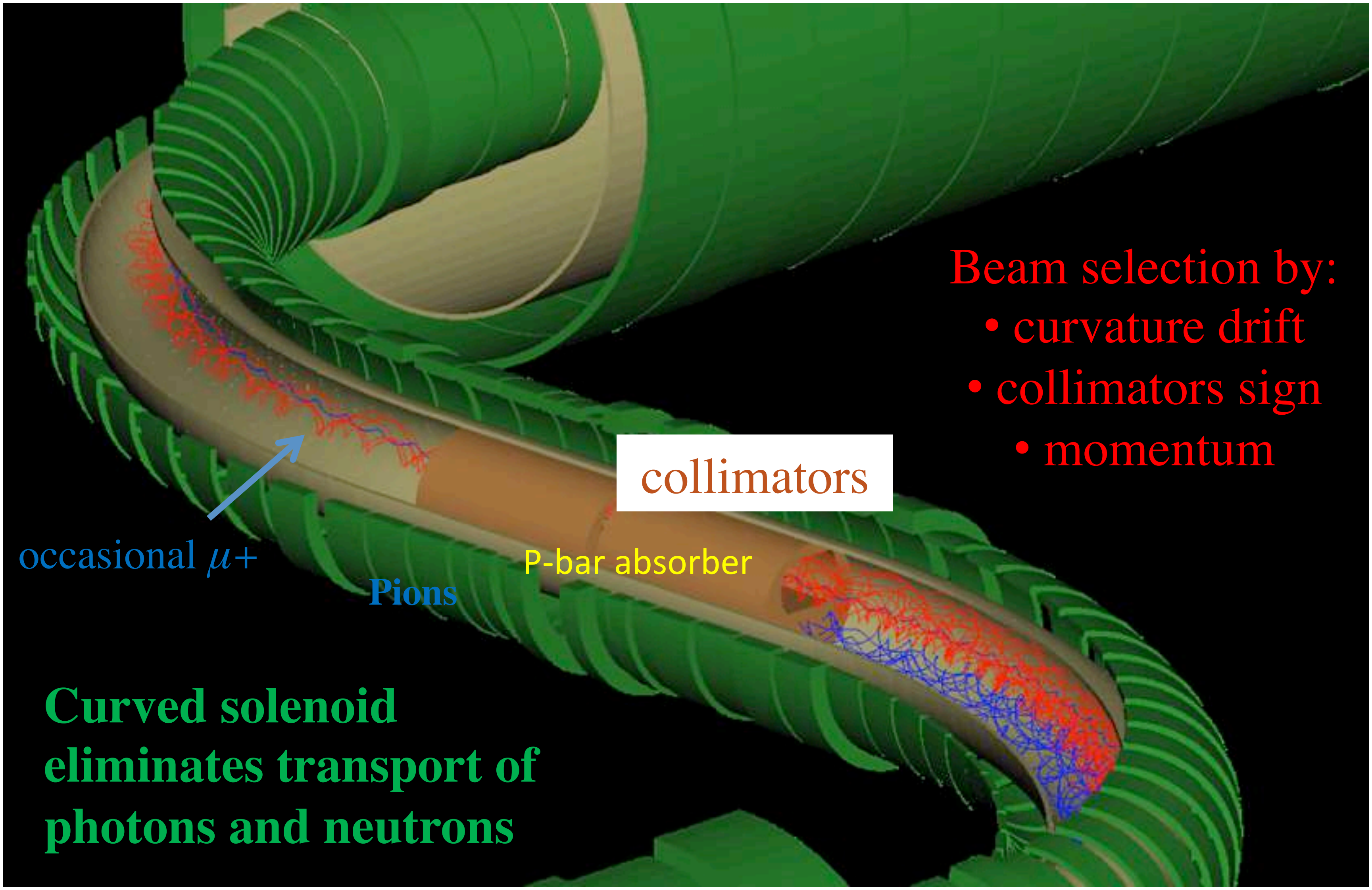
Production Solenoid

Protons enter opposite to outgoing muons:
This is a central idea to remove prompt background



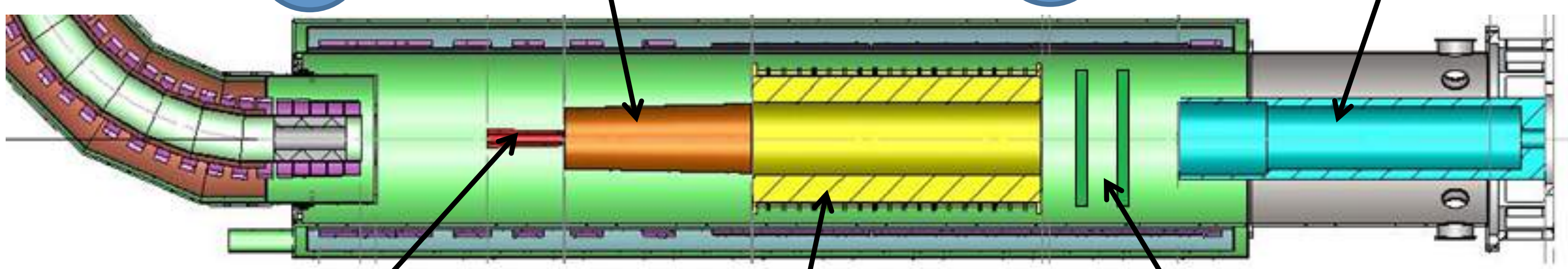
The magnetic field is graded from approximately 5.0 Tesla on the upstream side down to 2.5 Tesla at the entrance to the Transport Solenoid. This graded field captures pions, which spiral around in the field and decay into muons.

Transport Solenoid

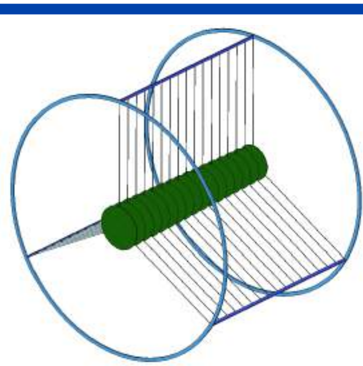


Detector Solenoid

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



17 Al foils; Aluminum selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the prompt separation in the Mu2e 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 will be built by General Atomics
- TS will be built by ASG + Fermilab

Mu2e Solenoid Summary (2)

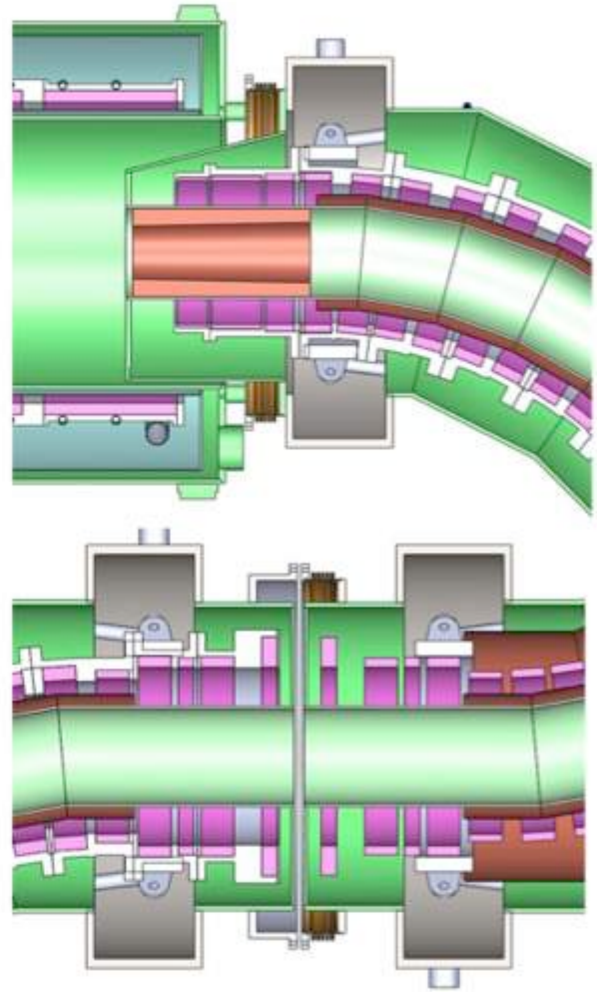


Figure 7.25. TSu Cryostat Interfaces. Top: TSu-PS interface; Bottom; TSu-TSd interface.

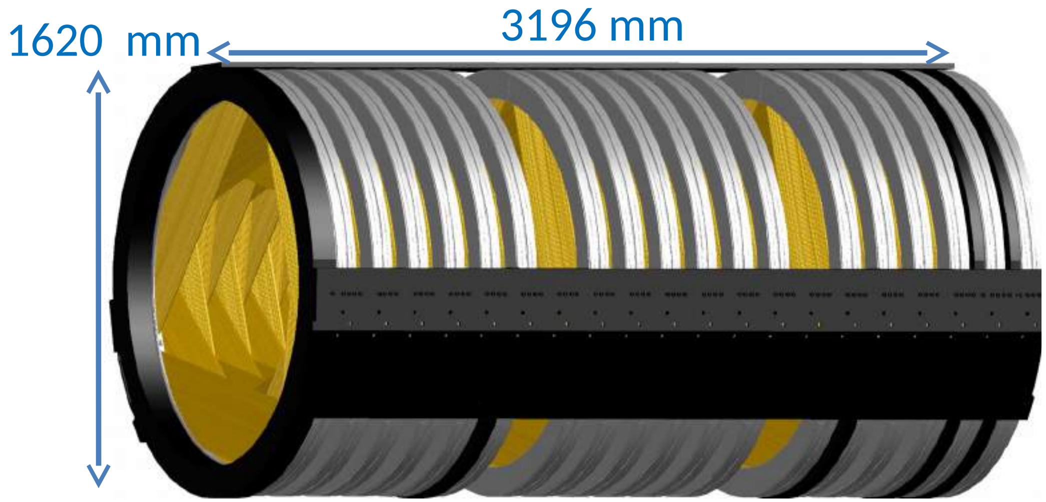
- Designs are finalized.
- TS fabrication has begun.
- PS, DS fabrication ready to start.

The Mu2e Tracker (1)

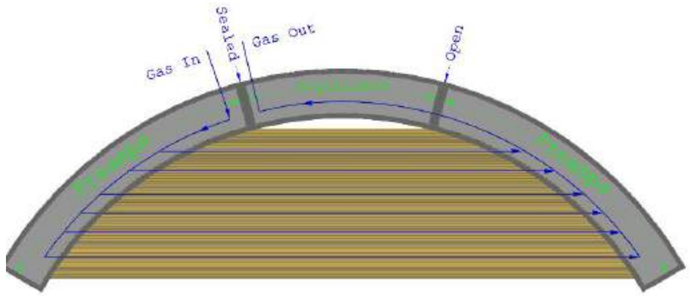
- Tracker is made of arrays of straw drift tubes

- ~ 20000 tubes arranged in planes on stations,
- the tracker has 18 stations.

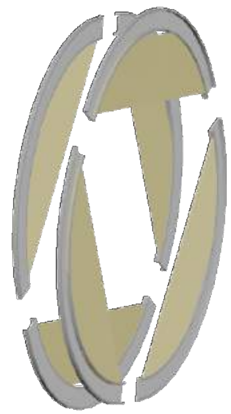
- Tracking at high radius ensures operability (beam flash produces a lot of low momentum particles, large DIO background.)

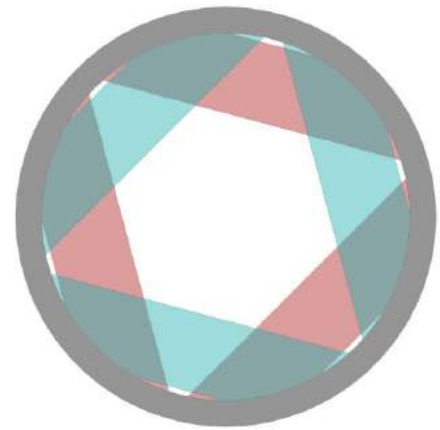


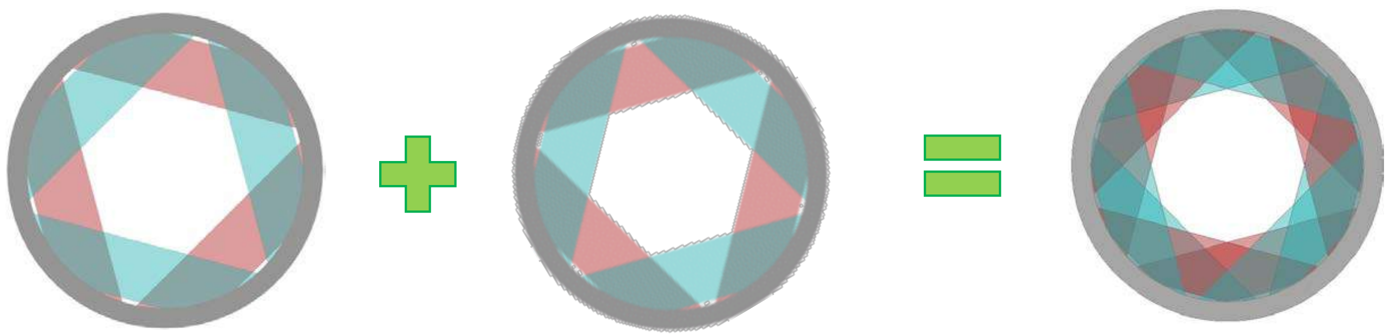
The Mu2e Tracker (2)



Custom ASIC for time division:
σ ≈ 5 mm at straw center



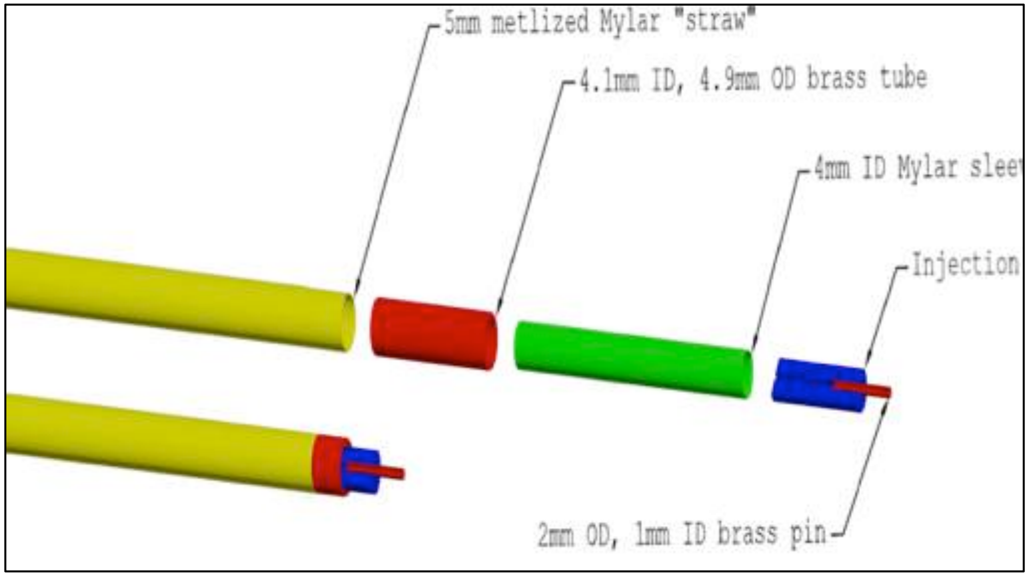




- Self-supporting “panel” consists of 96 straws, 2 layers, 48 straws/layer
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- >20 k straws total

Straw Characteristics

Straw tube



Characteristics:

- 5mm diameter and 334-1174 mm length
- 25 μm W sense wire (gold plated) at the center
- 15 microns Mylar wall
- Must operate in vacuum
- 80/20 Ar/CO_2 with HV < 1500 V

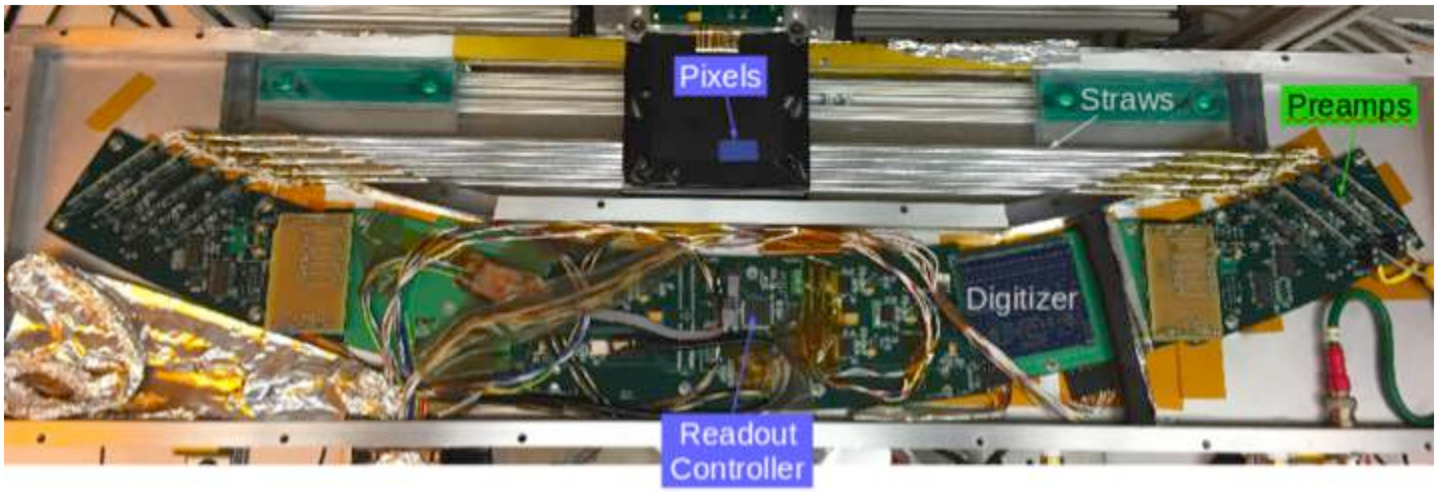
Straw tubes

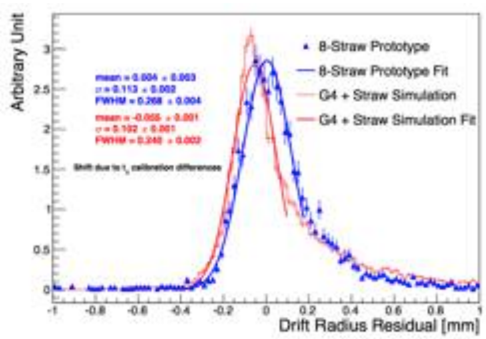
- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm) never done before**

First Prototype Panel

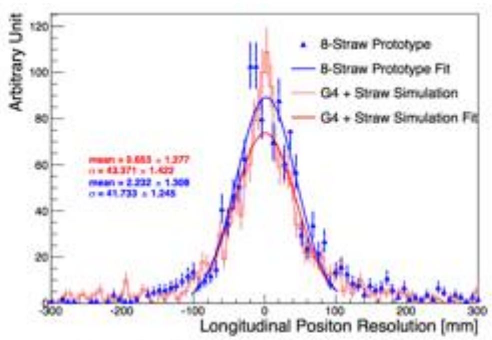
- Starting pre-production prototype now

8 Channel Prototype





Transverse Resolution
(Data vs MC)
$\sigma_{data} = 0.113 \pm 0.002$ mm
$\sigma_{MC} = 0.102 \pm 0.001$ mm



Longitudinal Resolution
(Data vs MC)
$\sigma_{data} = 42 \pm 1$ mm
$\sigma_{MC} = 43 \pm 1$ mm

Parameter	Value	Reference
N electrons per ionization	$< N >= 2$	NIMA 301, 202(1991)
Energy per ionization electron	39 eV	NIST (27-100 eV) and G4
Avg. Straw Gain	70k	Prototype (PAM, ^{55}Fe)
Threshold Value	12 mV	Prototype (DVM, ^{55}Fe)
Threshold Noise	3 mV	Spice Sim. (V. Rusu)
Shaping Time	22 ns	Prototype (^{55}Fe)

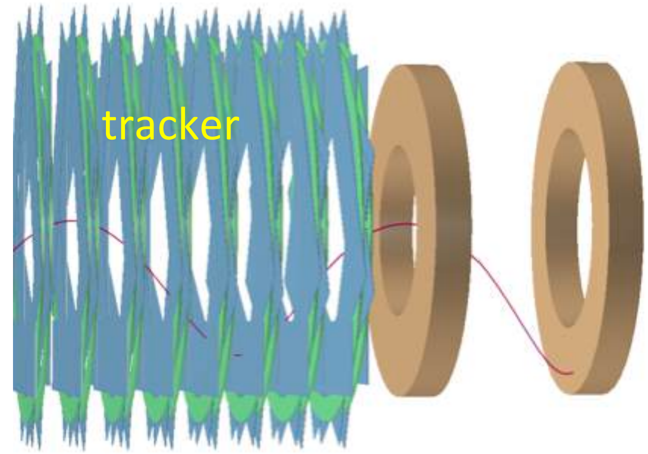
- Measured gain, crosstalk, resolution, …

Calorimeter System

Calorimeter requirements:

→ Particle Identification to distinguish e/mu
→ Seed for track pattern recognition
→ Tracking independent trigger
→ Work in 1 T field and 10^{-4} Torr vacuum
→ **RadHard up to 100 krad, 10^{12} n/cm^2/year (test at EPOS)**

Two disks separated by ½ wavelength (70 cm)

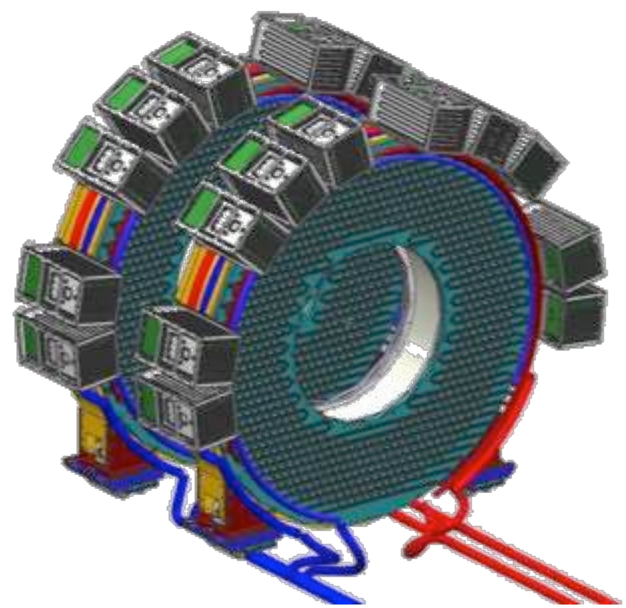


Calorimeter choice:

High granularity crystal based calorimeter with:

→ σ/E of O(5%) and Time resolution < 500 ps
→ Position resolution of O(1 cm)
→ almost full acceptance

for CE signal @ 100 MeV



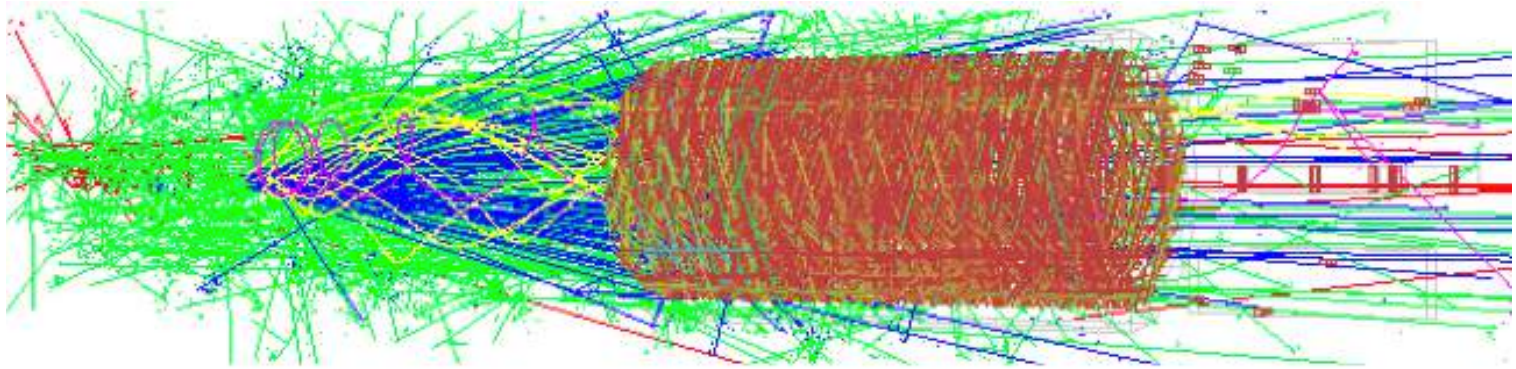
Disk geometry

- Square crystals
- Charge symmetric, can measure

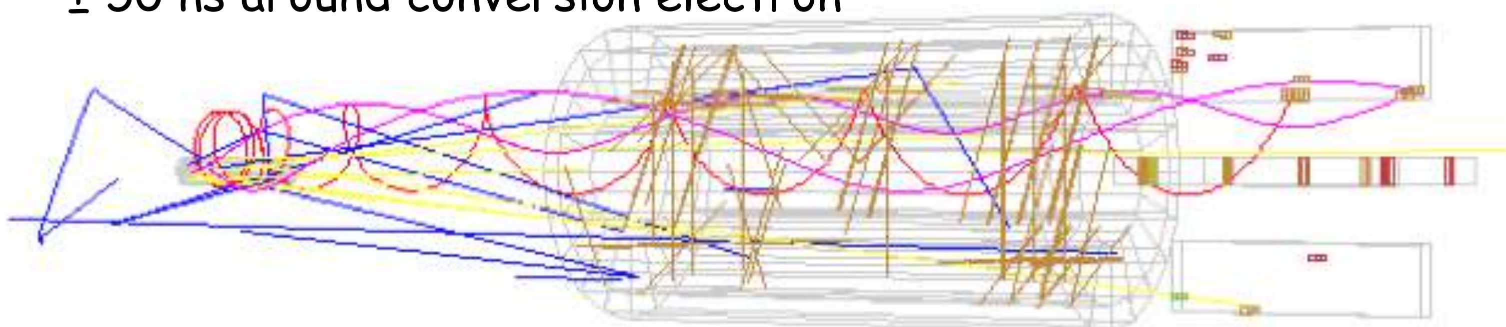
$$\mu^- N \rightarrow e^+ N$$

A typical Mu2e event: Calo track seeding

500 – 1695 ns window



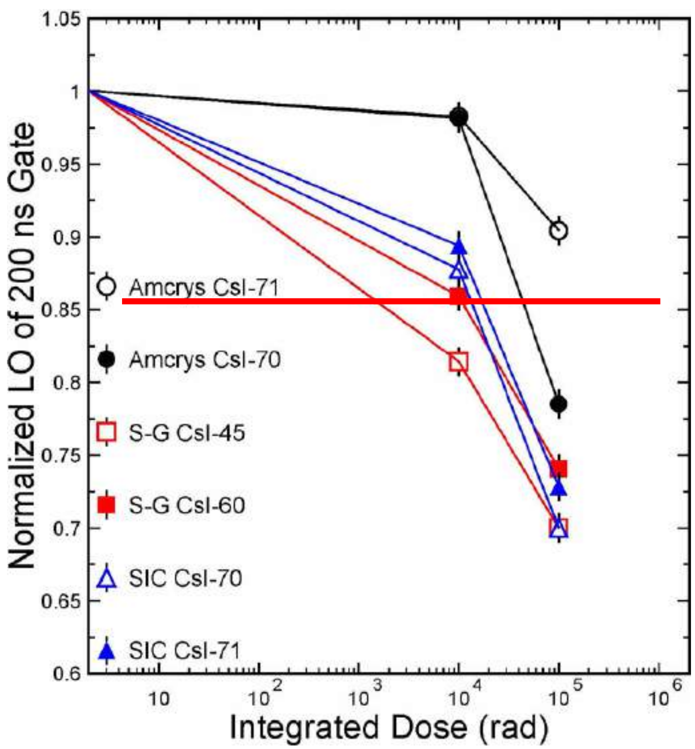
± 50 ns around conversion electron

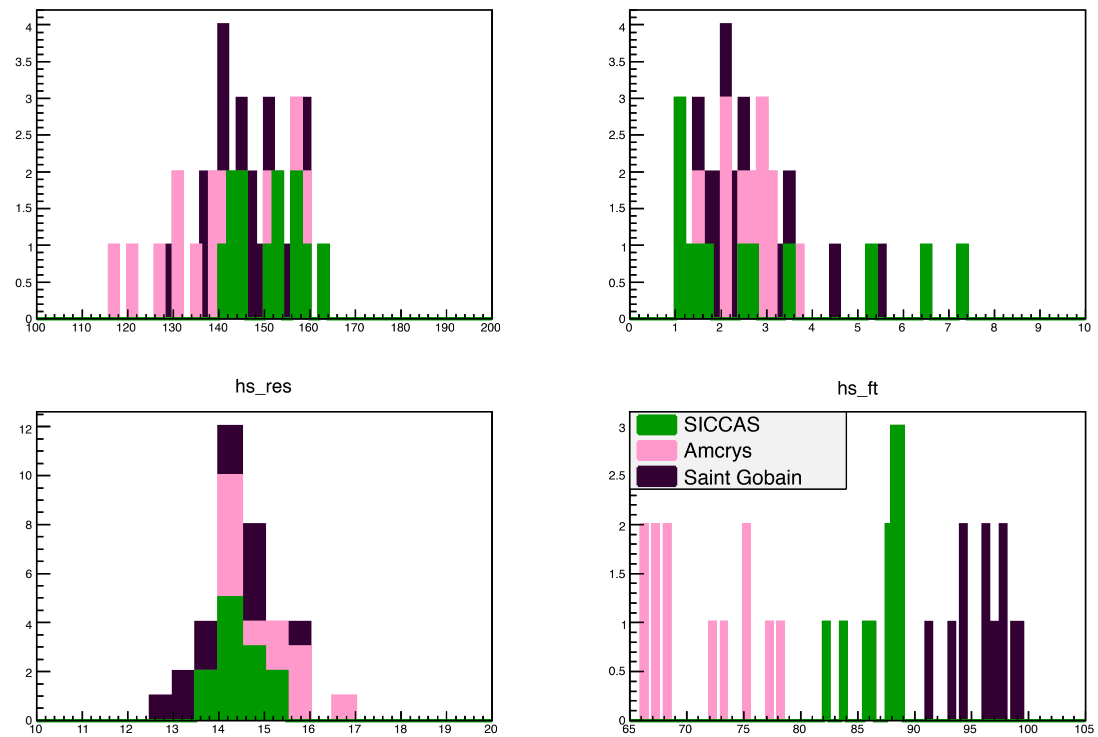


Search for tracking hits with time and azimuthal angle compatible with the calo clusters (|ΔT| < 50 ns) → **simpler pattern recognition + higher efficiency**

Mu2e Crystals: un-doped CsI

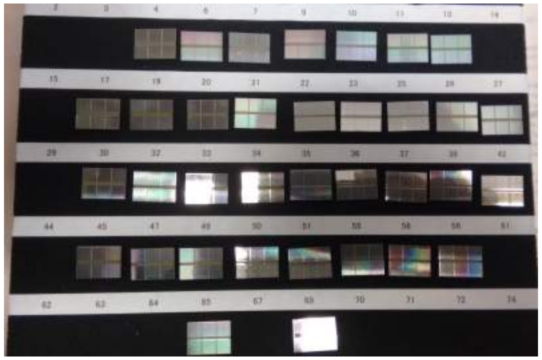
Density (g/cm3)	4.51
Radiation length (cm)	1.86
Moliere Radius (cm)	3.57
Refractive index	1.95
Peak luminescence (nm)	310
Decay time (ns)	26





UV extended Mu2e SiPMs

Hamamatsu

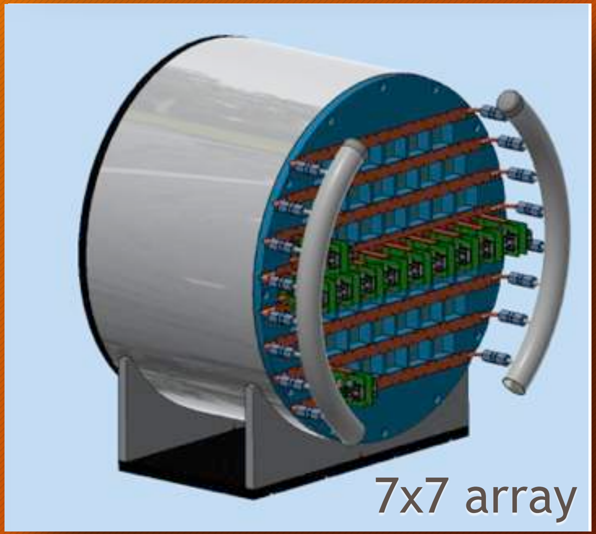


SENSL

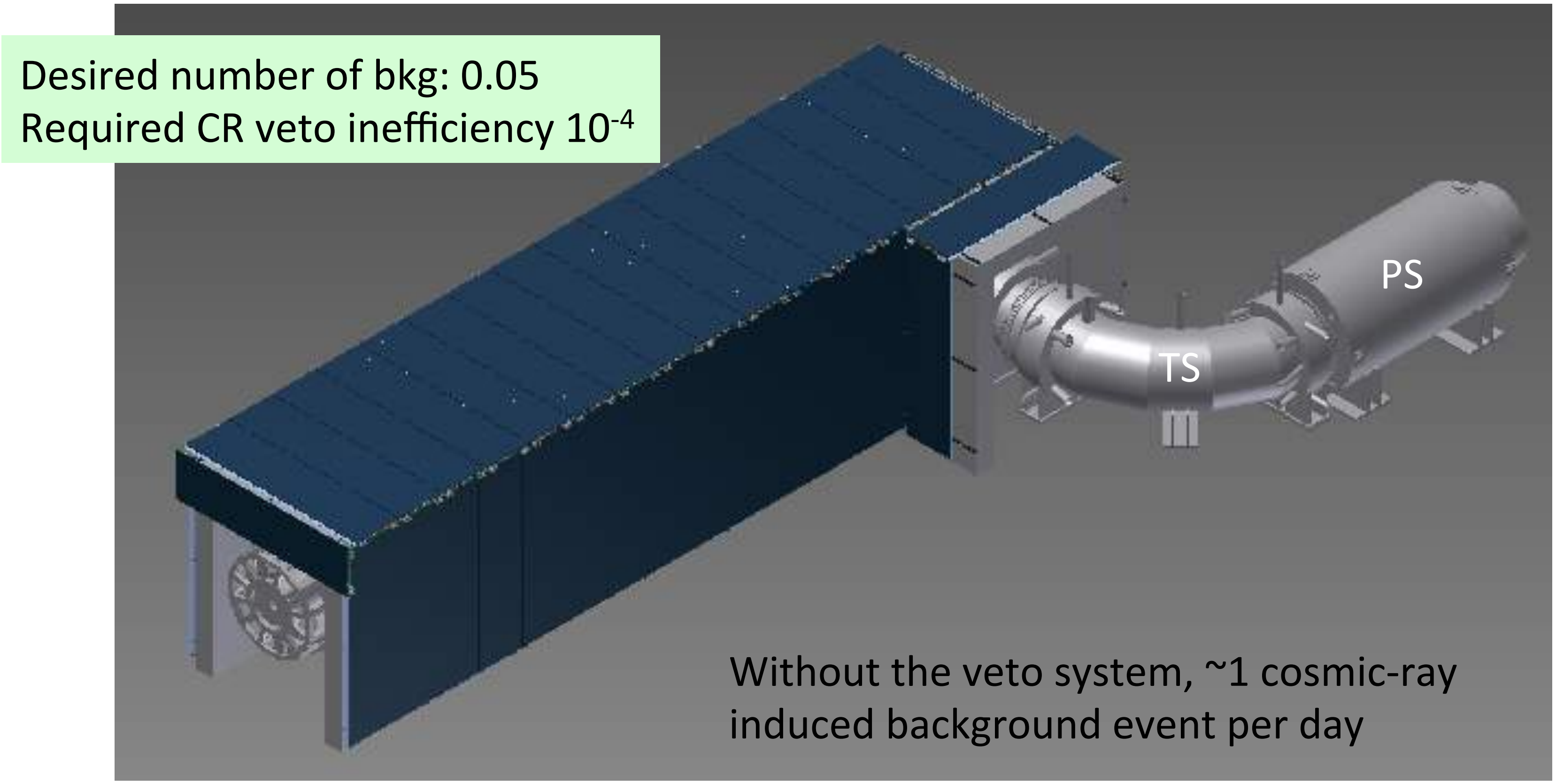
Advansid

- Large area array of 6x6 mm^2 UV extended SiPMs
- Mixed combination of series and parallel arrangement → 2x3
- Gain > 10^6, PDE ~ 25% @ 315 nm, low spread btw cells in the array
- Resilience to neutron flux of up to 1.2 x 10^{12} n_1MeV/cm^2 → Idark increase
- Need to cool them down to 0 °C
- MTTF of O(10^6 hours)
- Pre-production phase underway: 3 producers being selected.

Prototyping and Mockup status

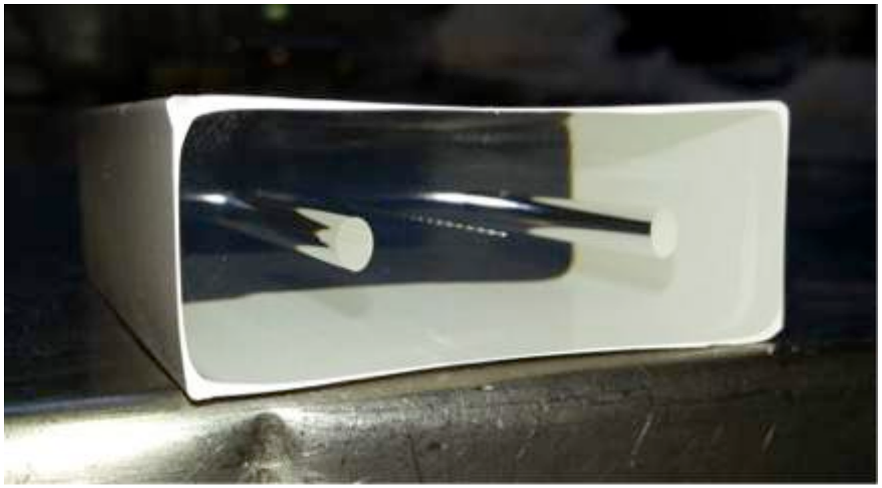


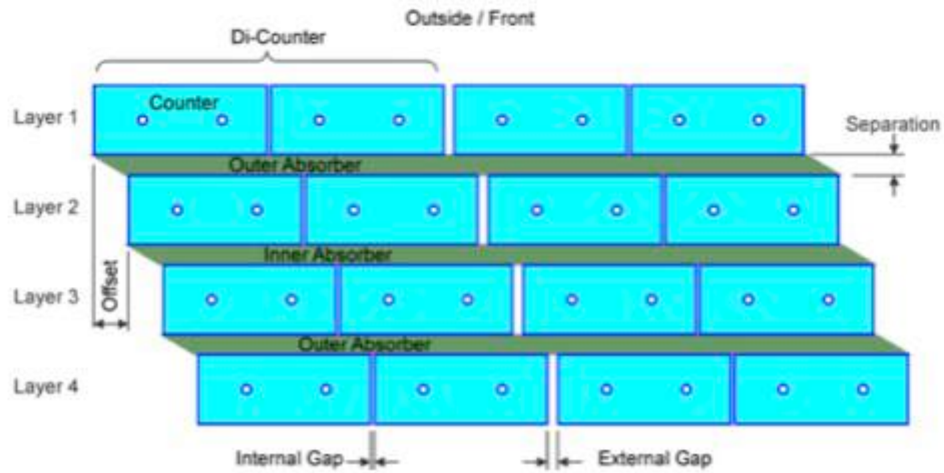
Mu2e Cosmic-Ray Veto



- Veto system covers entire DS and half TS

Mu2e Cosmic-Ray Veto





- 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 Neutron Shielding

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

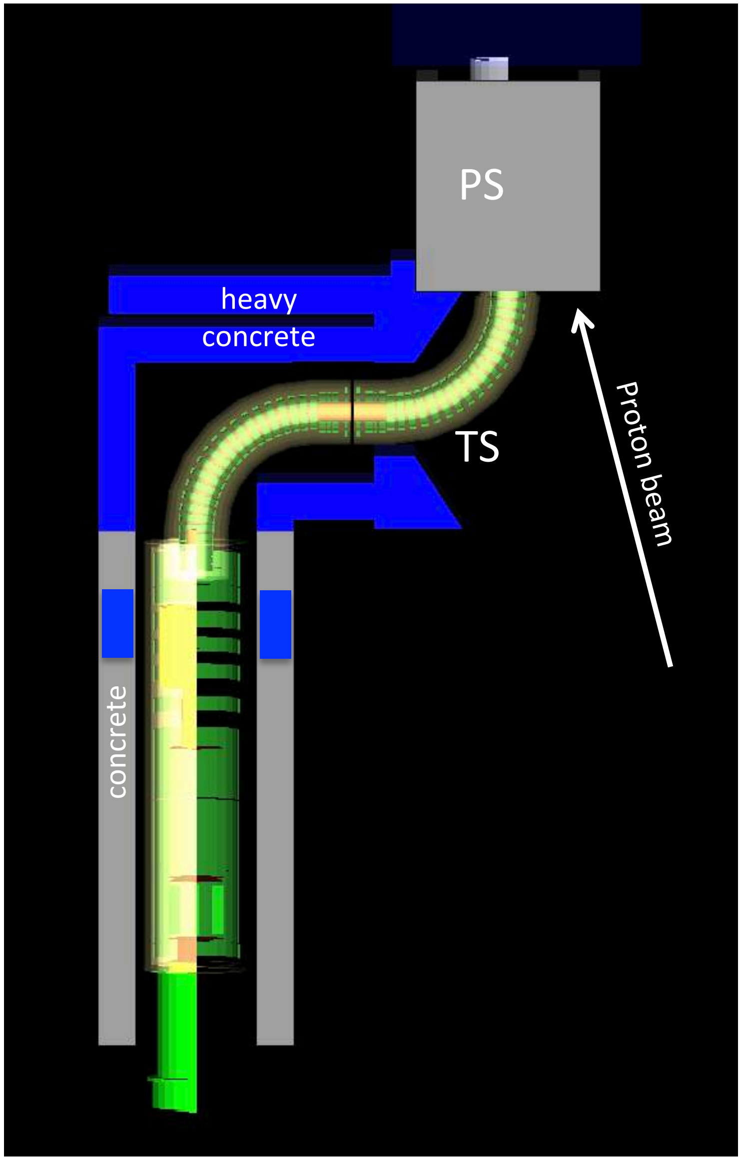
- **Lots of neutrons and subsequent photons (from n- capture and activation processes)**
  - Generate false vetoes in CRV… if rate high enough becomes a source of significant deadtime
  - Cause radiation damage to the read-out electronics (esp. SiPMs)

→ we are using (we intend to use) HZDR P-ELBE for neutron damage characterization of our SiPMs!

→ All of this started in the framework of the European Network Muse, now HZDR is member of Mu2e collaboration!!

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

Mu2e Neutron Shielding

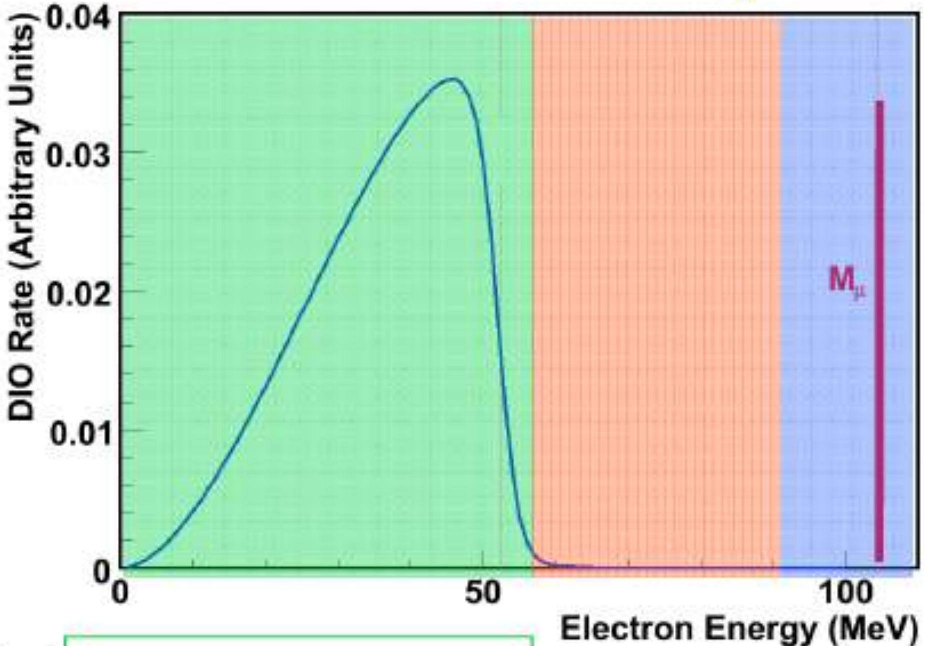


- Have identified a cost effective shielding solution
- Non-trivial optimization required
- Reduces rates of neutrons and photons at CRV to acceptable level

Simulation and comparison between Mars/Geant-4 (and FLUKA?!) is mandatory. Collaboration with HZDR expertise really welcome here

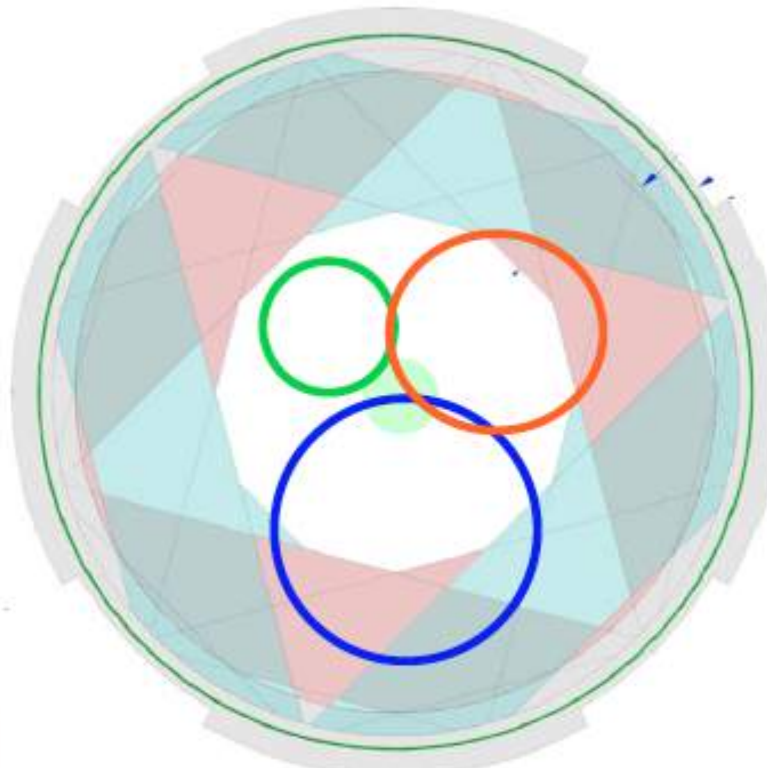
Basic reconstruction scheme

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

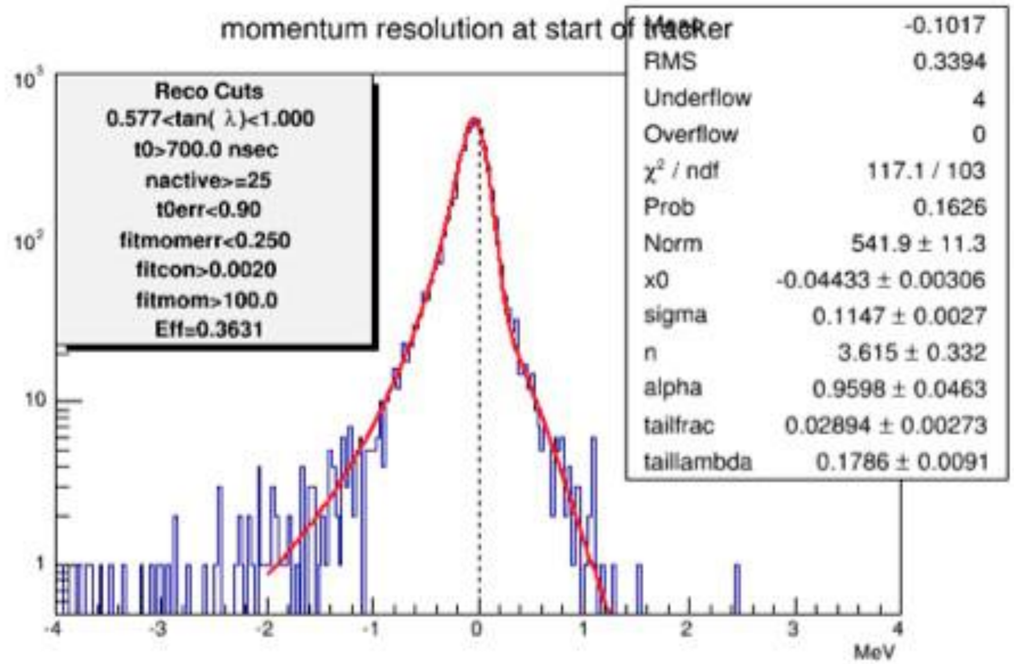
Simulation results on tracker

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

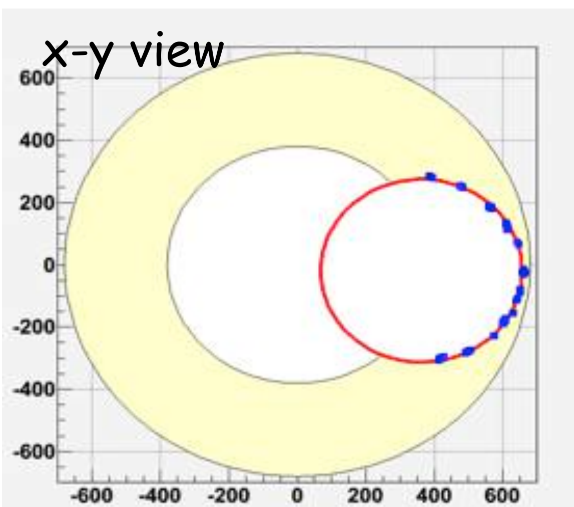
No significant contribution of mis-reconstructed background

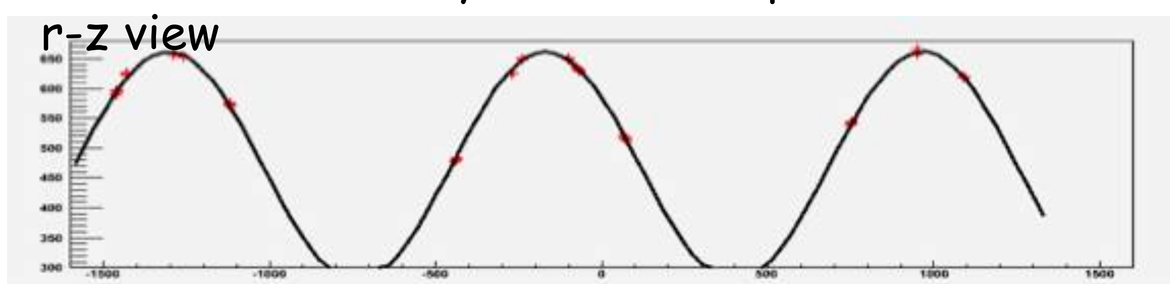
Momentum resolution

core σ~120 keV
tail σ~180 keV (2.5%)

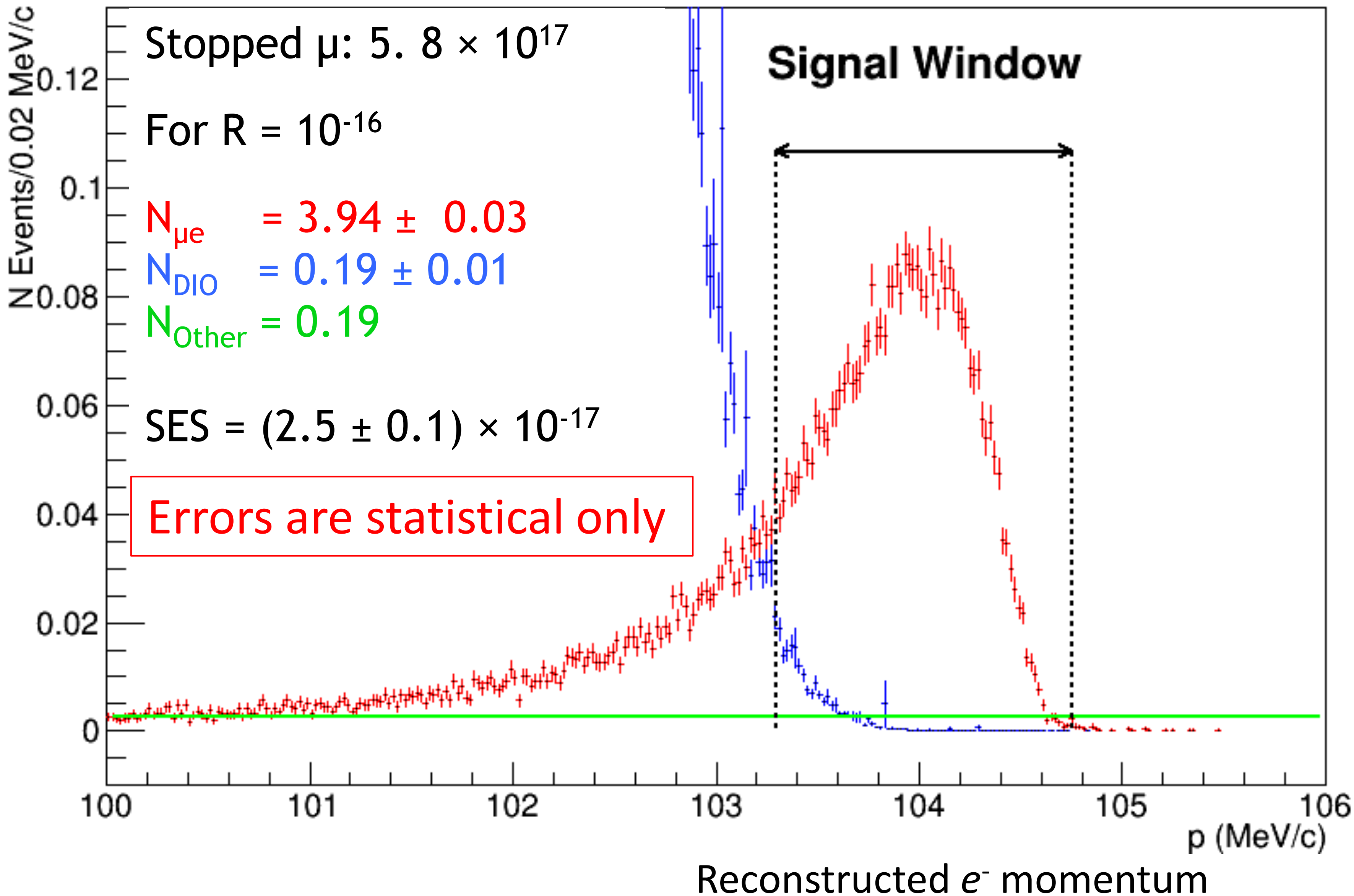


Fit: Crystal Ball + exponential





DIO/CE final count with simulation



Mu2e Expected Background

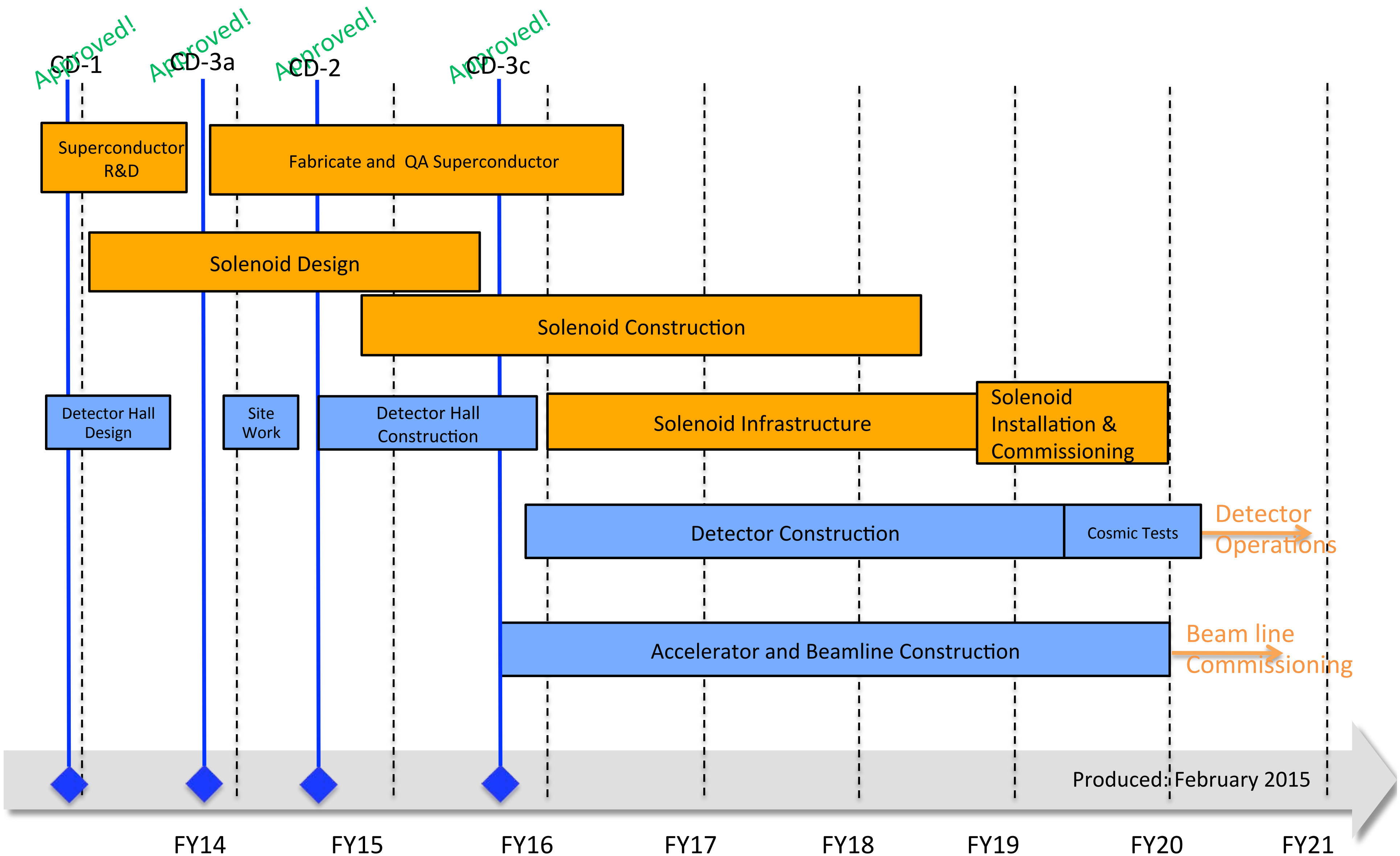
(assuming ~ 10 GHz muon stops, 6×10^{17} stopped muons in 6×10^{7} s of beam time)

Category	Source	Events
	μ Decay in Orbit	0.20
Intrinsic	Radiative μ Capture	<0.01
	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
Late Arriving	π Decay in Flight	<0.01
	Anti-proton induced	0.05
Miscellaneous	Cosmic Ray induced	0.08
Total Background		0.36

Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Upper Limit < 6×10^{-17} @ 90% C.L.

Mu2e Project Schedule



(WhatNext?) 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

→ **x 10 at Mu2e**

Projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232
CLVF-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

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

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

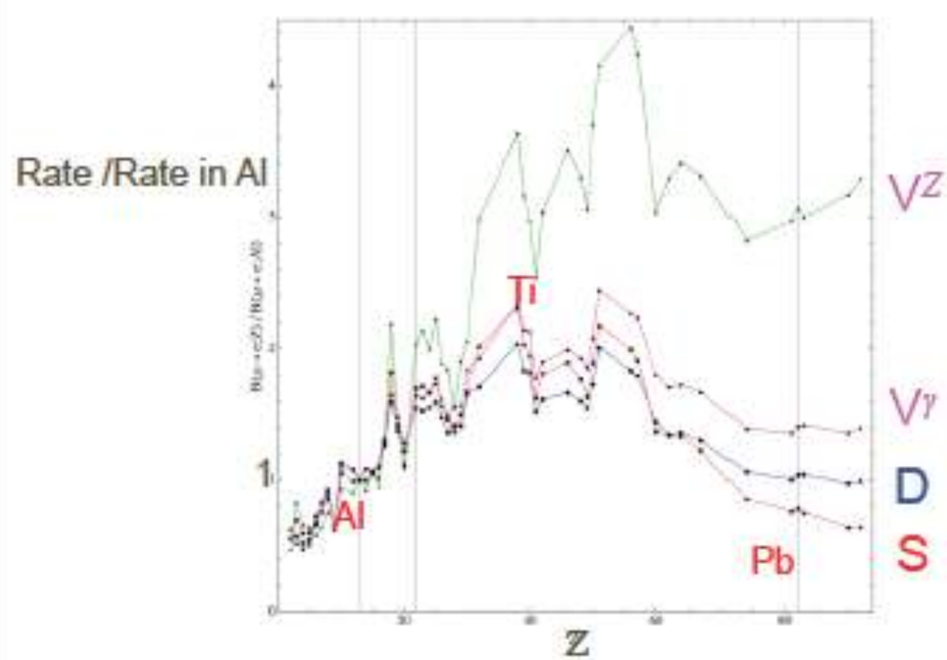


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$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

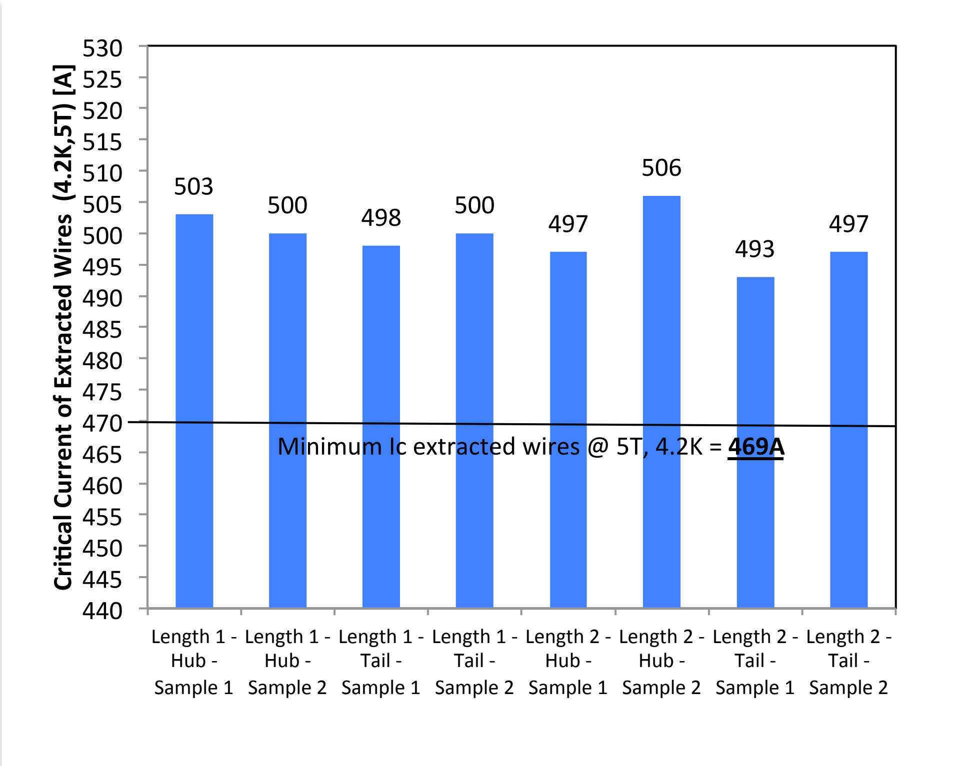
Summary

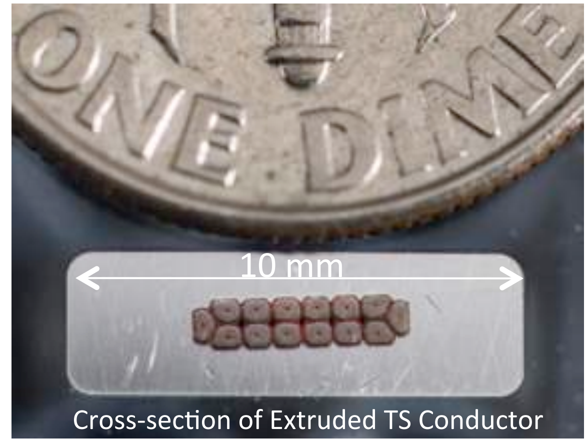
The Mu2e experiment:

- Improves sensitivity 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… will begin commissioning in 2020
- Start discussing about Mu2e-II

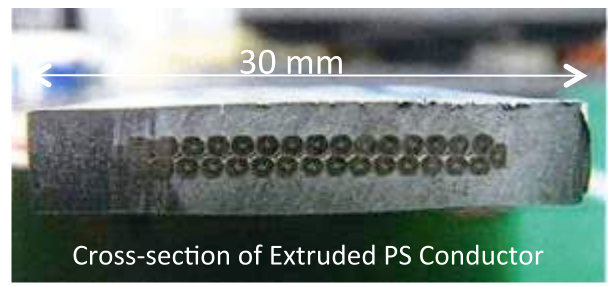
Additional Material

Mu2e Conductor R&D





Cross-section of Extruded TS Conductor



Cross-section of Extruded PS Conductor

SuperConductor production is well along

- **TS and DS conductor done, PS expected end 2016**
- **Need ~75 km total (incl. spares);** about 100% done.

Crystal Choice

	~~LYSO~~	BaF_2	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310

LYSO

CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF_2)

BASELINE-TDR

- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be "solar"-blind
- Medium cost 10$/cc

CsI(pure)

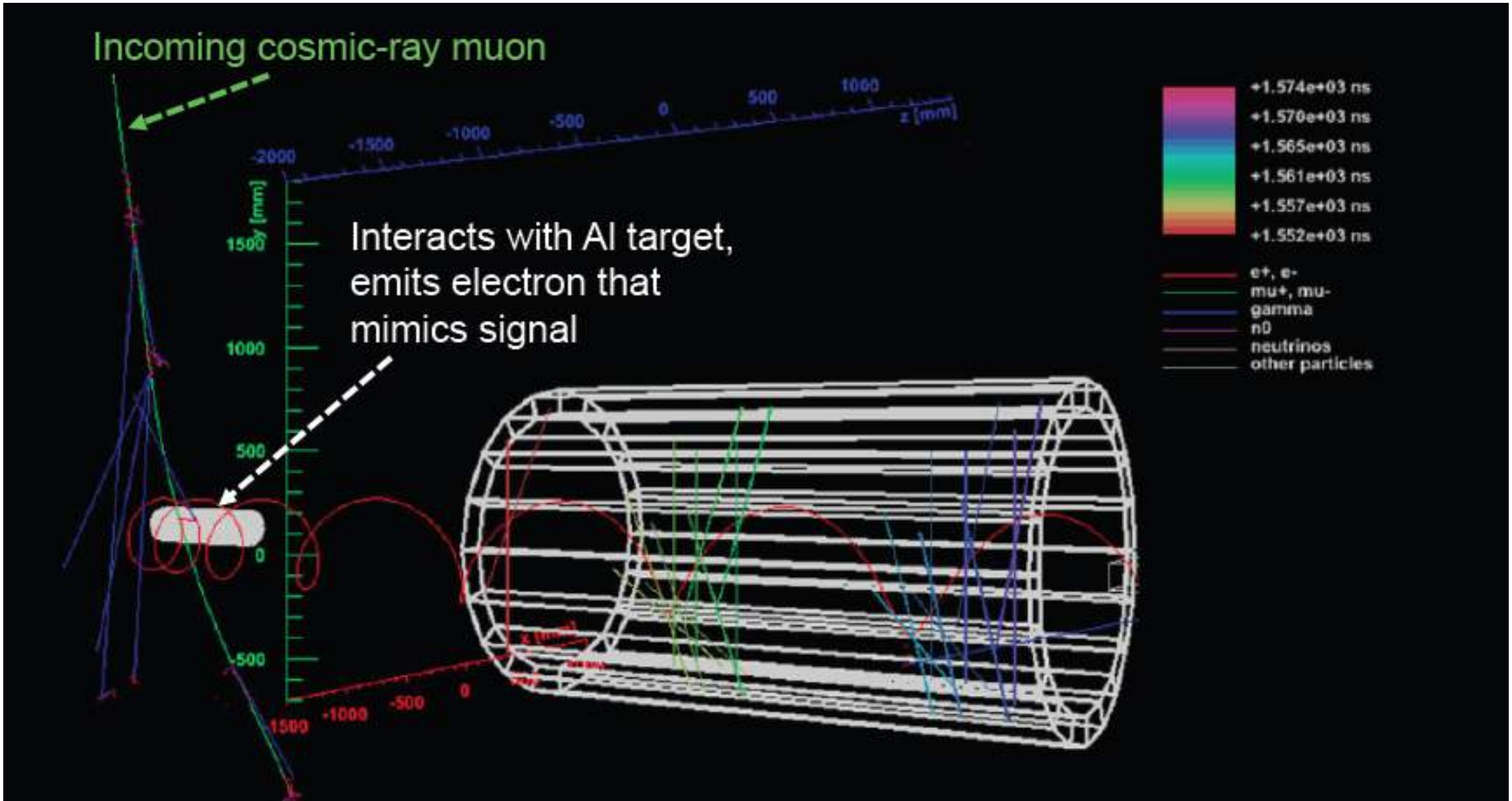
TDR Alternative

- Not too radiation hard
- Slightly hygroscopic
- 20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

Mu2e Track Reconstruction

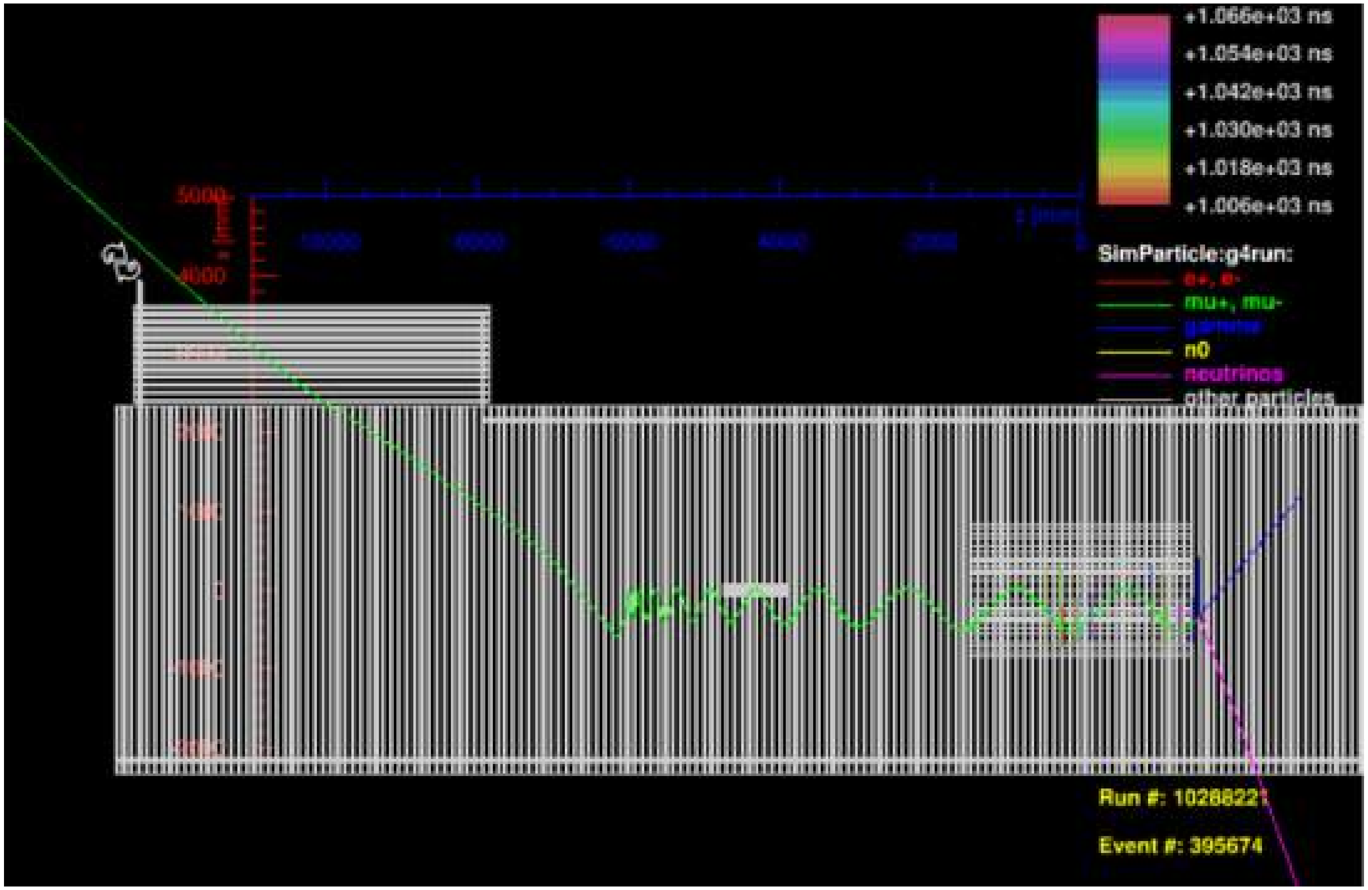
- **Straw-hit rates**
  - From beam flash (0-300 ns): ~1000 kHz/cm^2
    - Need to survive this, but won't collect data
  - Later, near live window (>500 ns)
    - Peak ~ 10 kHz/cm^2 (inner straws)
    - Average ~ 3 kHz/cm^2 (over all straws)

Cosmic Rays are a problem



- This happens once per day!

"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***

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

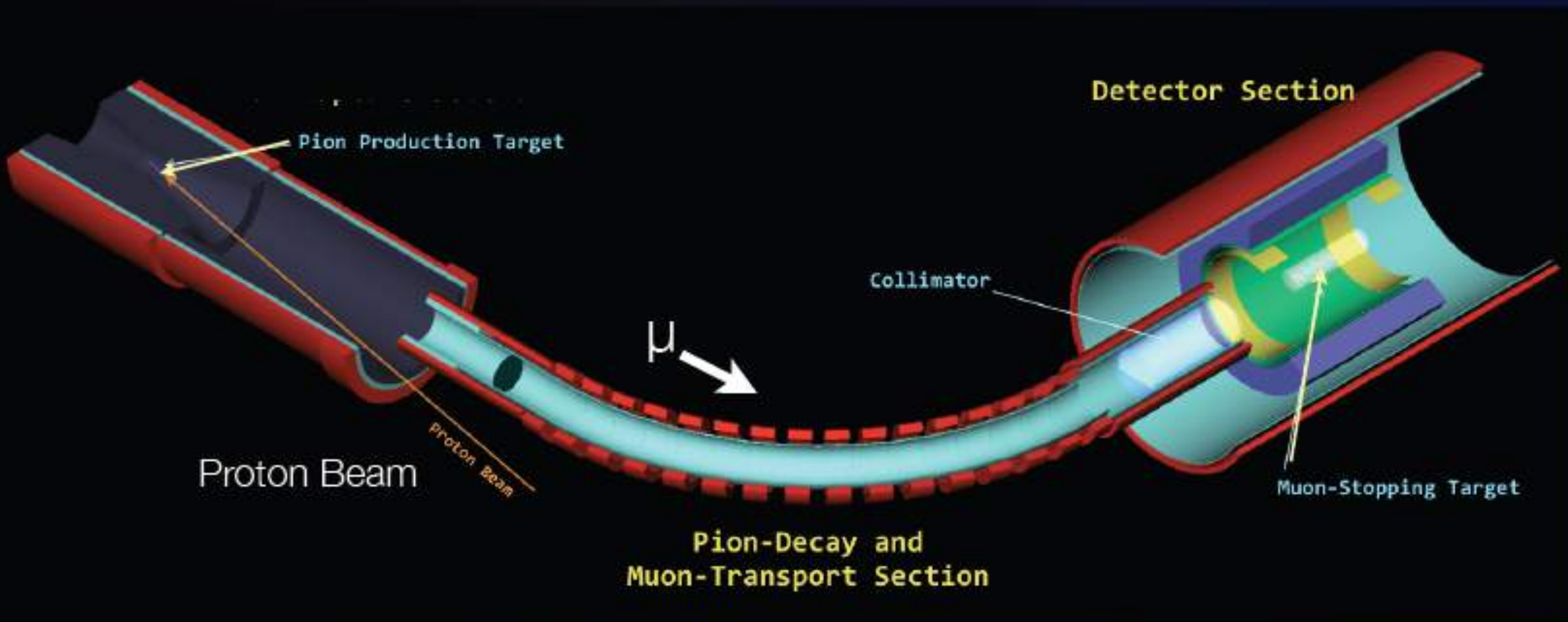
- ❑ Final bend after COMET stopping target efficiently transmits conversion e- and provides rate suppression in detector.

- ❑ **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

Phase-1 could be useful if successful to study background rate
Phase-2 schedule … see Kuno's talk , for Mu2e → looking for Mu2e-II

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

COMET Phase-I Experimental Layout



COMET muon beam-line：

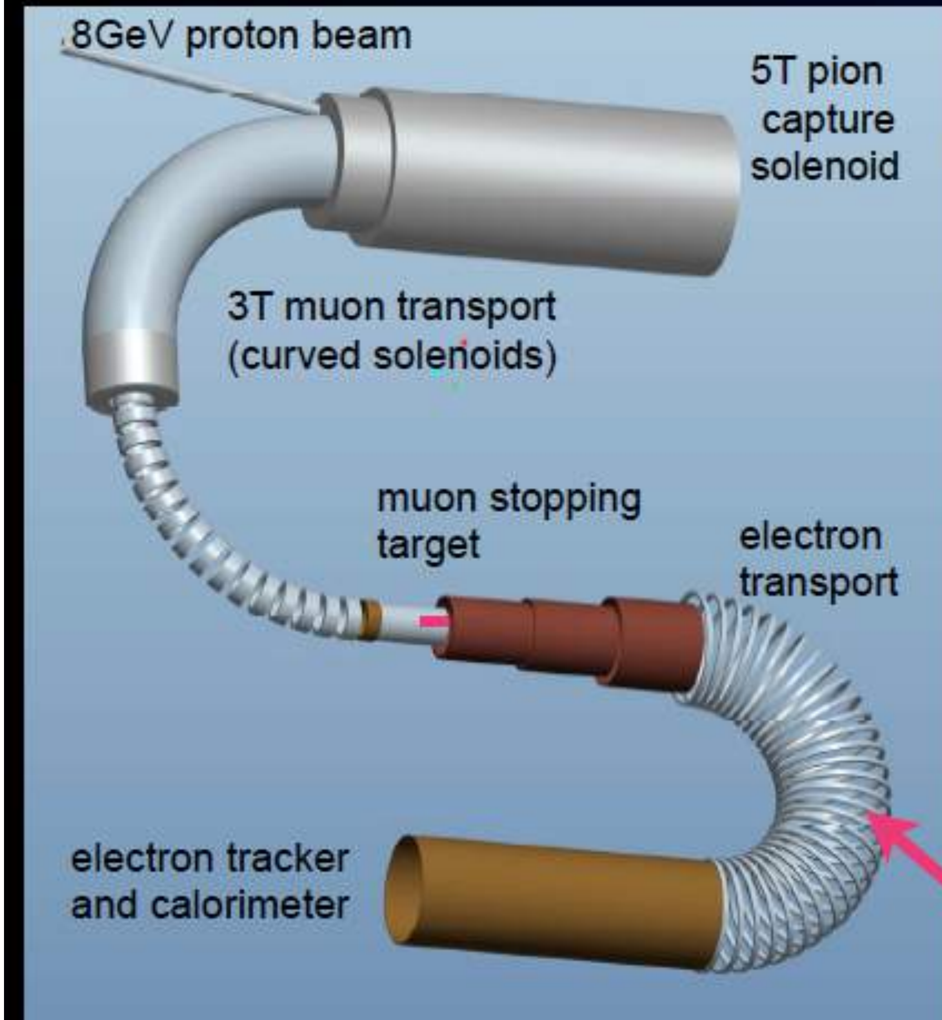
(1~3)x10^9 muon/sec with 3kW beam produced. The world highest intensity.

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.

Other CLFV Predictions

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

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 6\cdot 10^{-3}$	$\sim 6\cdot 10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.02\ldots 0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots 2.0$	~ 5	$0.3\ldots 0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots 1.6$	~ 0.2	$5\ldots 10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$0.08\ldots 0.15$

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 are model dependent**
- **Measure ratios to pin-down theory details**

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.

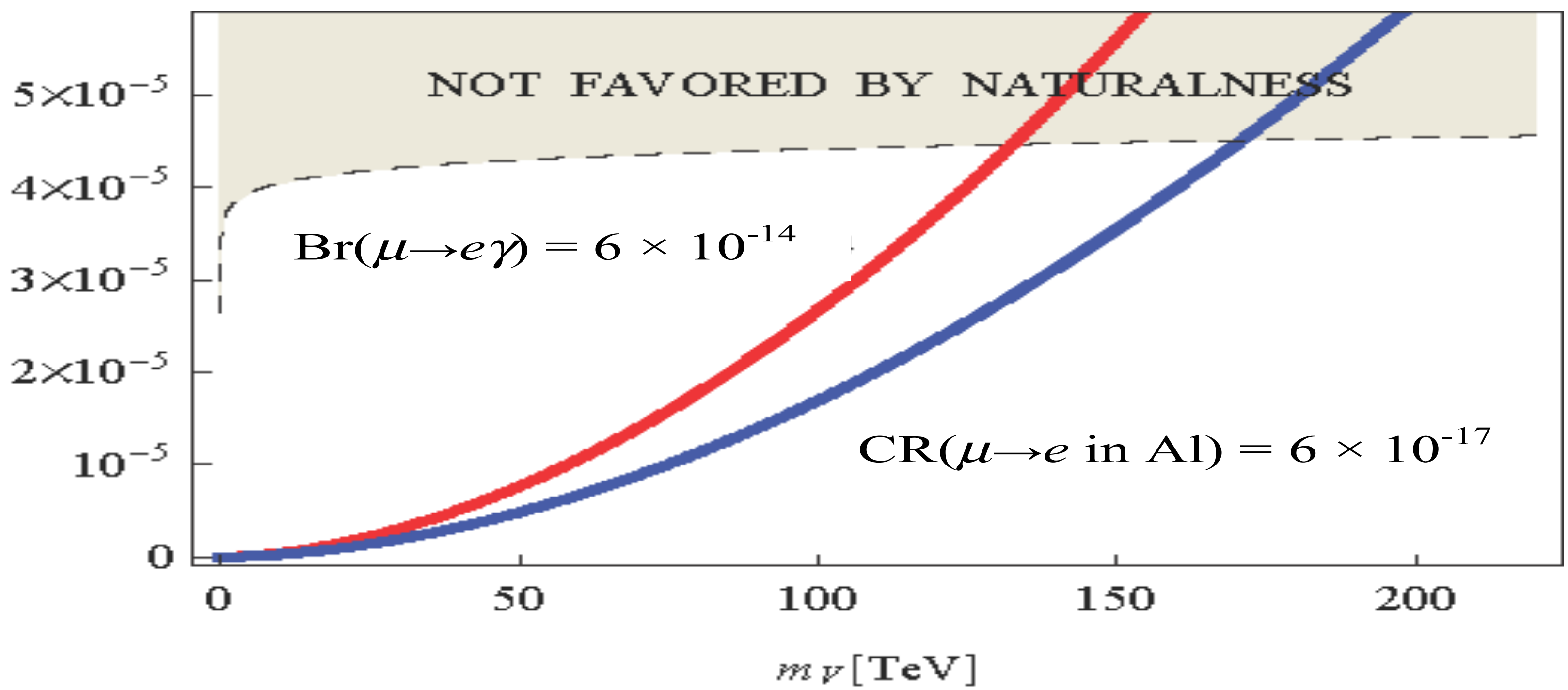
SUSY benchmark points vs LHC

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($\mu \to e$ 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/Belle-2
- All of these will be observable by Mu2e

Specific example: Leptoquarks

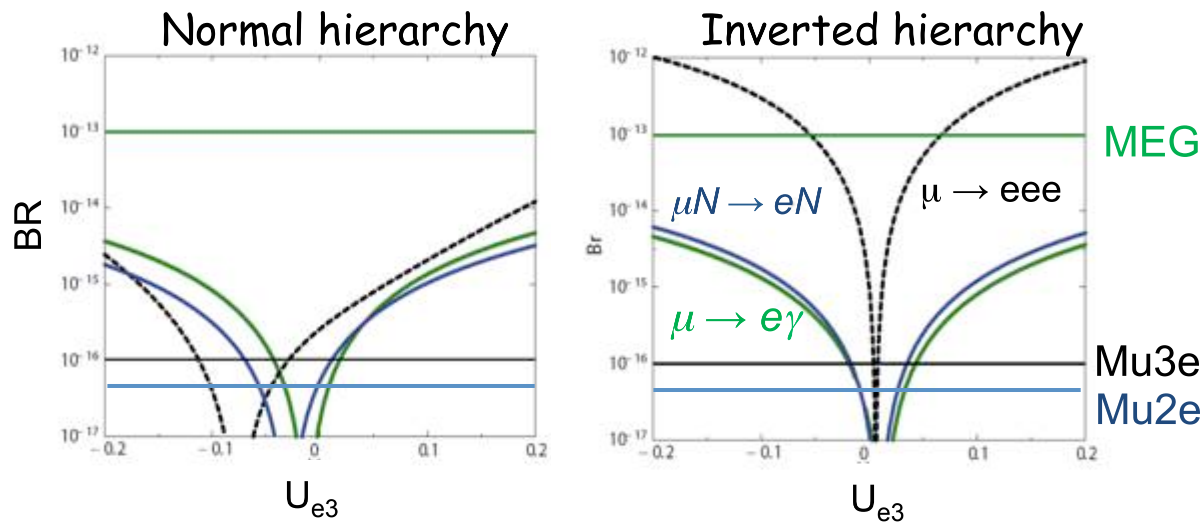


Specific example: Higgs Triplet e LHT

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

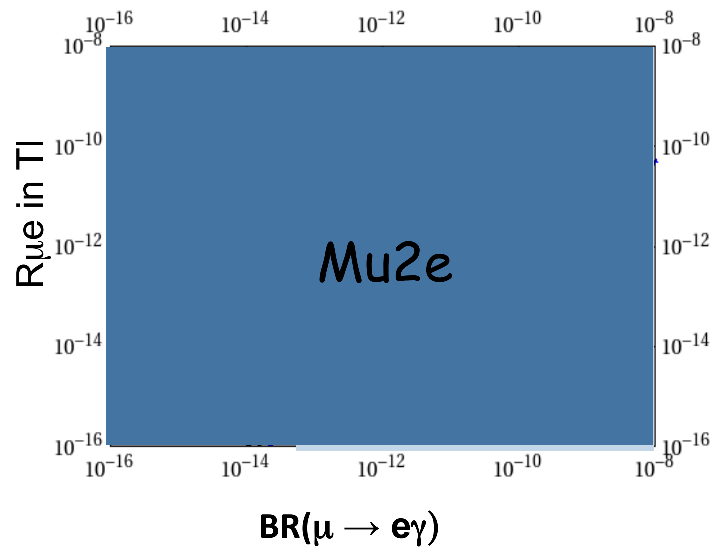
Higgs triplet model

Dependence on neutrino mass hierarchy and θ_{13}



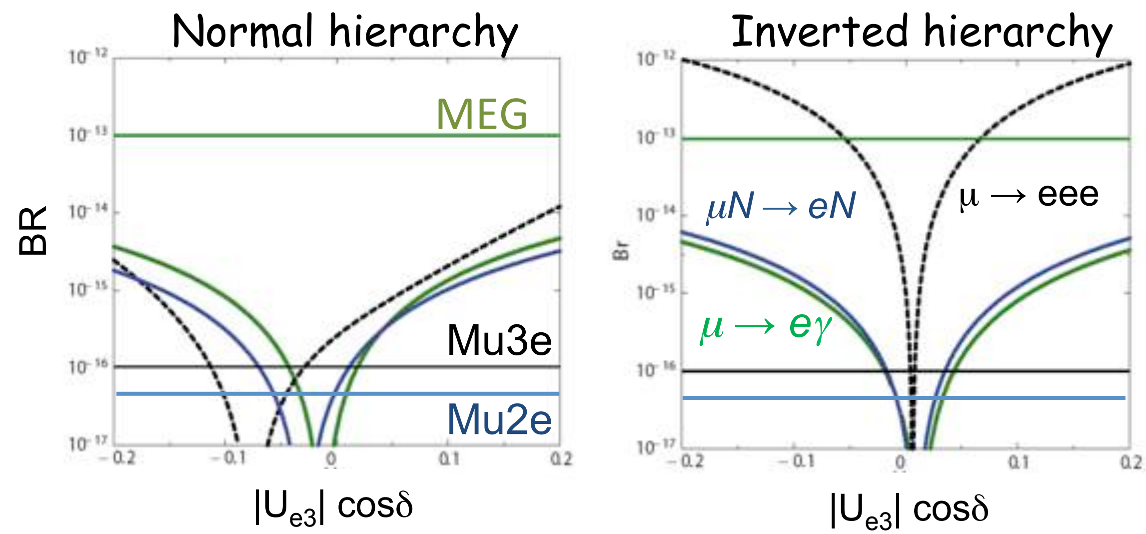
Littlest Higgs with T-parity

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

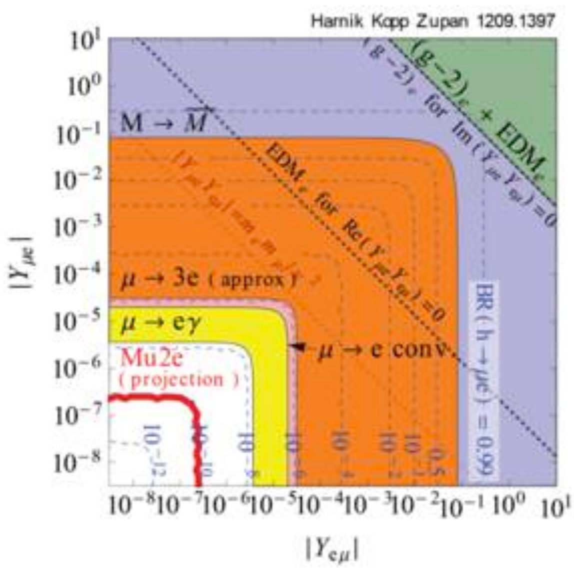


A few more models…

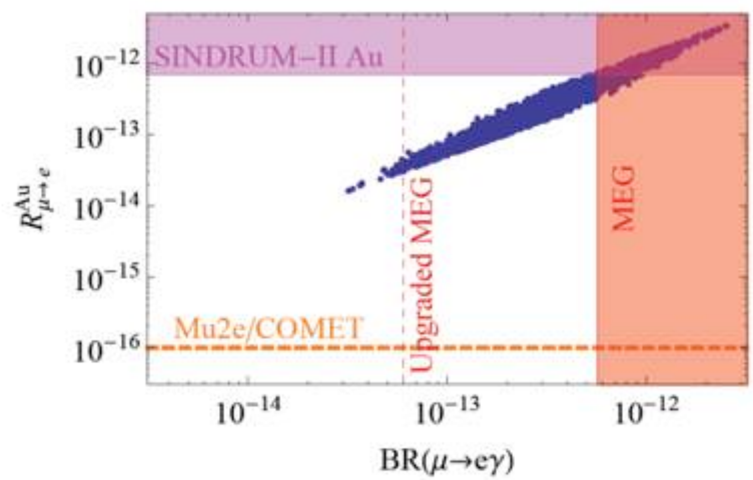
Higgs triplet model



Flavor violating Yukawa couplings



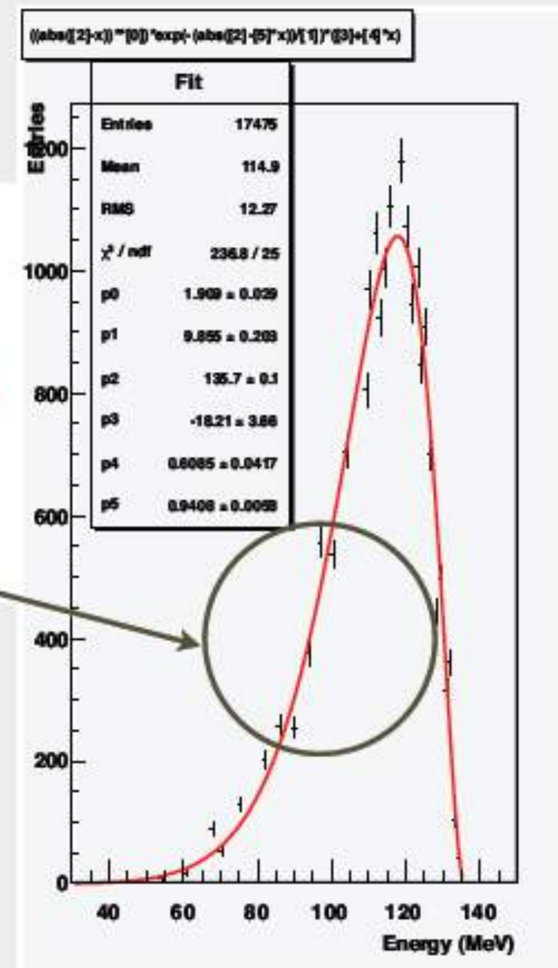
Left-right symmetric models



Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π, neutrons, pbars

- **Radiative pion capture**, $\pi^- + A(N,Z) \rightarrow \gamma + X$.
  - γ up to m_π, peak at 110 MeV; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal: ***limitation in best existing experiment, SINDRUM II?***



energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

also included internal conversion, $\pi^- N \rightarrow e^+ e^- X$

SINDRUM-II Results

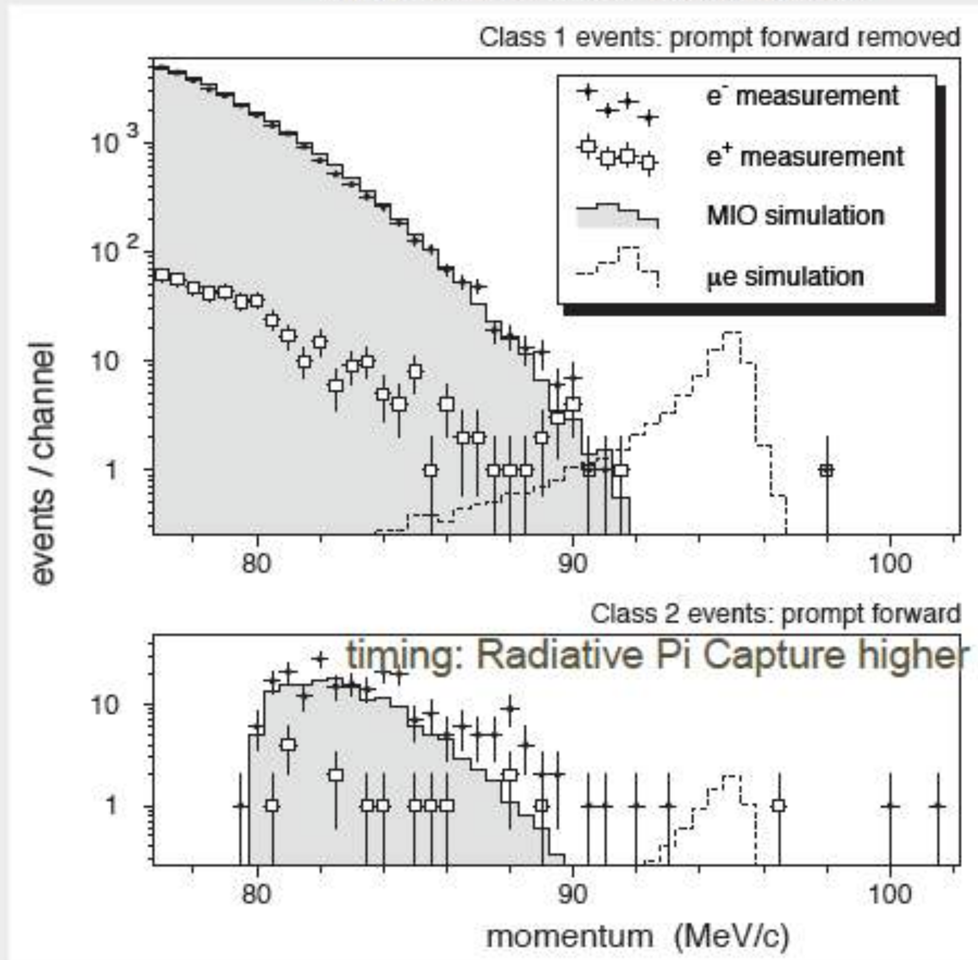
- Final Results on Au:

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

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

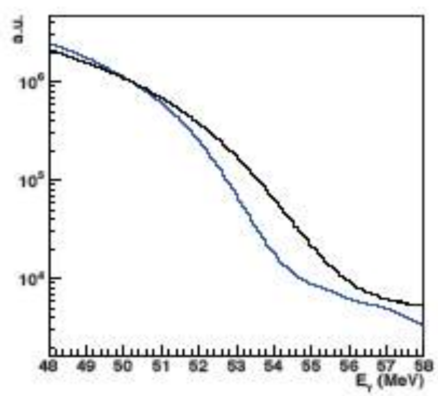
little time separation between signal and prompt background

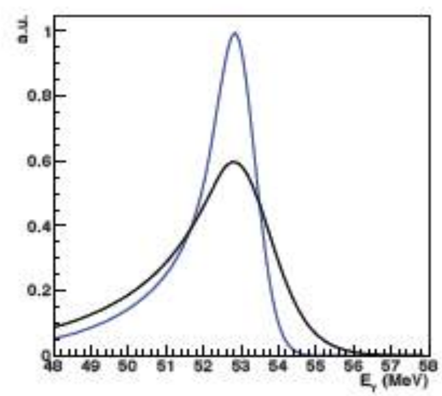
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)



MEG^{UP} sensitivity

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





$$5.7 \times 10^{-13}$$

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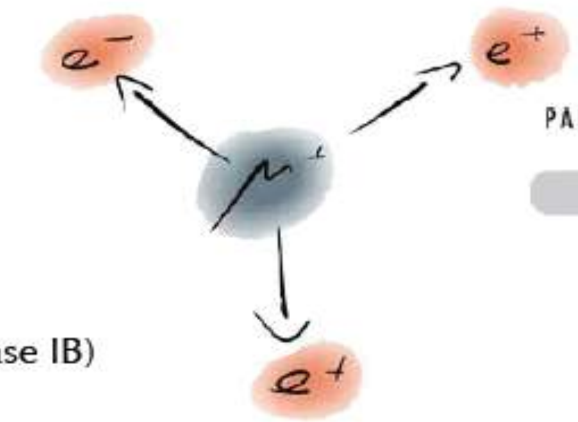
Mu3e at PSI

- Search for $\mu \to e\,e\,e$
  - 10^{-15} sensitivity in phase IA / IB
  - 10^{-16} sensitivity in phase II
- Project approved in January 2013
  - Double cone target
  - HV-MAPS ultra thin silicon detectors
  - Scintillating fibers timing counter (from phase IB)



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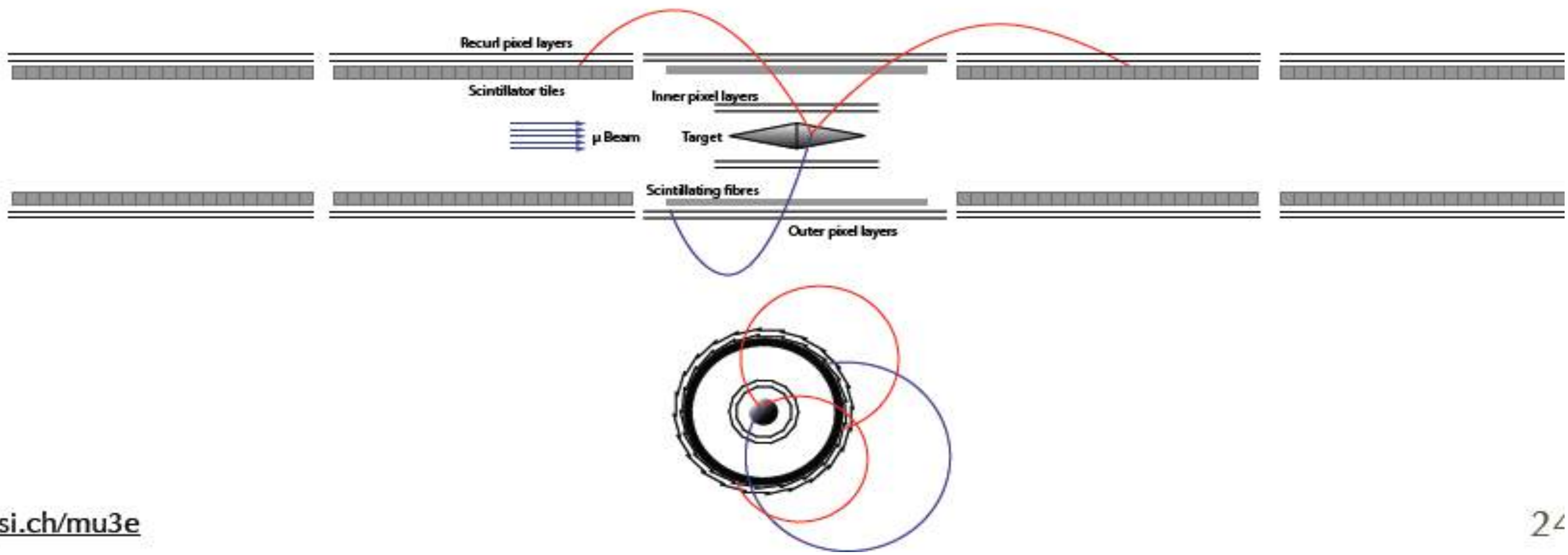

vw.psi.ch/mu3e

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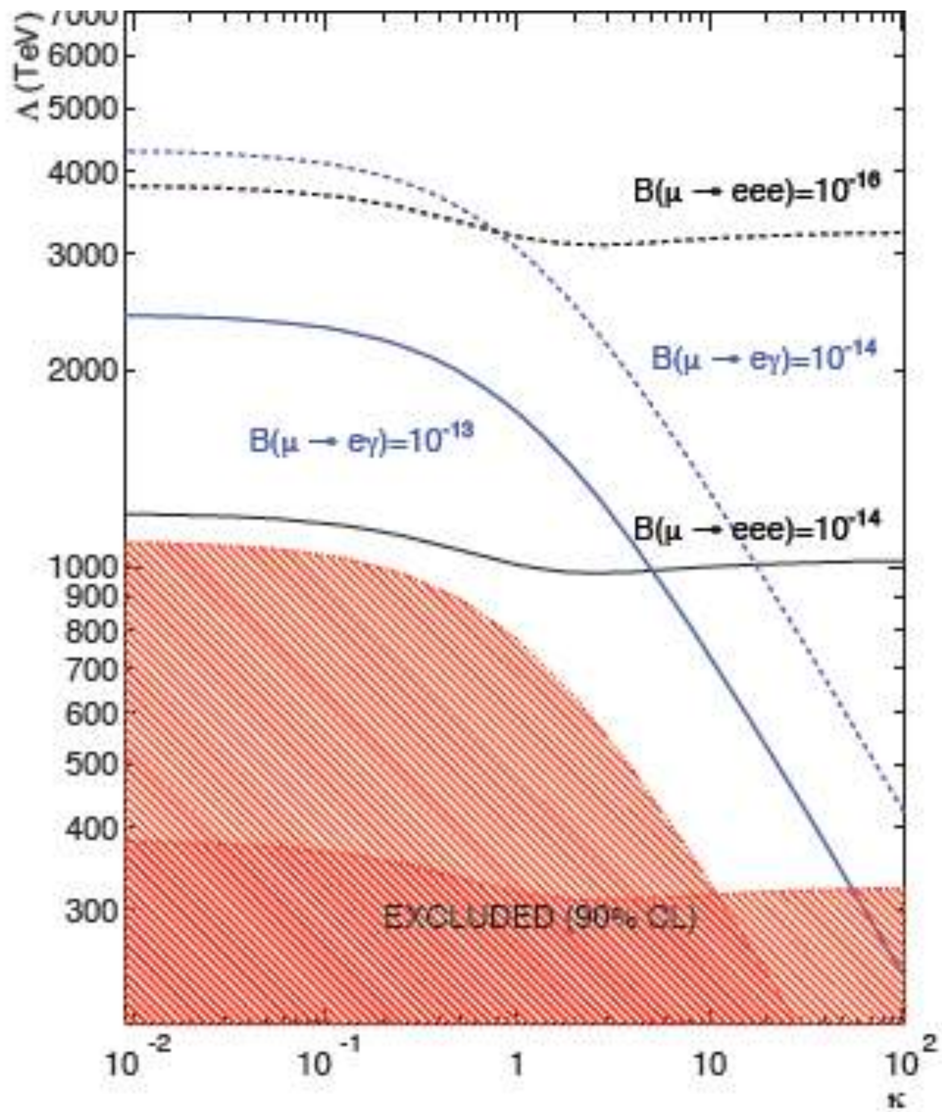
MEG vs Mu3e

- 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)

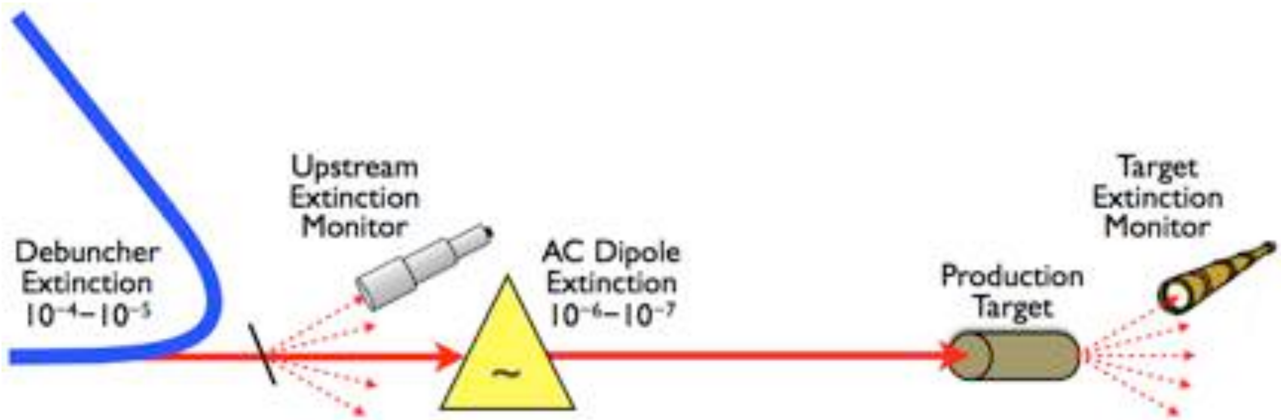
- Next phase aims to 10^{-16} .. Schedule is not yet clear



Mu2e Late Arriving Backgrounds

- Contributions from
  - Radiative π Capture
    - $\pi^- N_Z \text{ --> } N^*_{Z-1} + \gamma$
    - For Al. RπC fraction: 2%
    - E_γ extends out to ~m_π
    - Asymmetric γ ––> e^+e^- pair production can yield background electron
  - Beam electrons
    - Originating from upstream π^- and π^0 decays
    - Electrons scatter in stopping target to get into detector acceptance
  - Muon and pion Decay-in-Flight
- Taken together these backgrounds account for ~10% of the total background and scale *linearly* with the number of out-of-time protons

Extinction Monitor

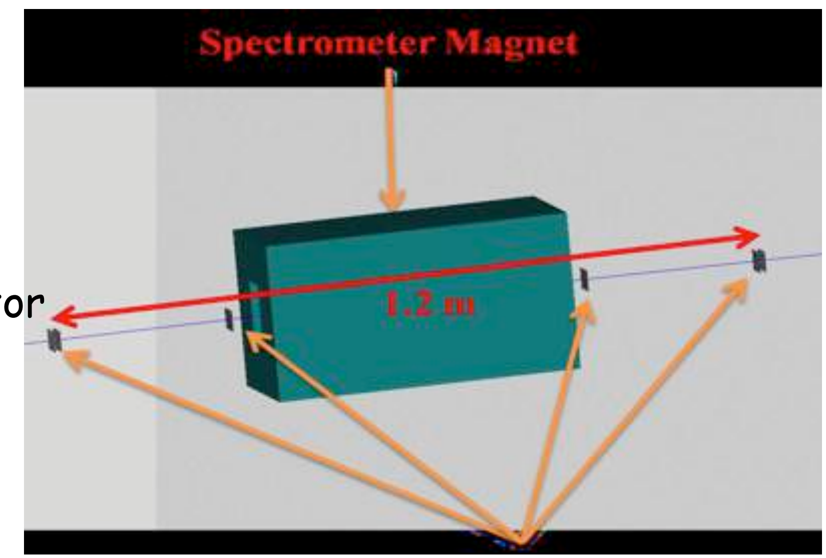


- Thin foils in the debuncher → Mu2e production target transport line (fast feedback)
- Off-axis telescope looking at the production target (slow feedback – timescale of hours)

Spectrometer based on ATLAS pixel detector

Reach a 10^{-10} extinction sensitivity in an hour or so

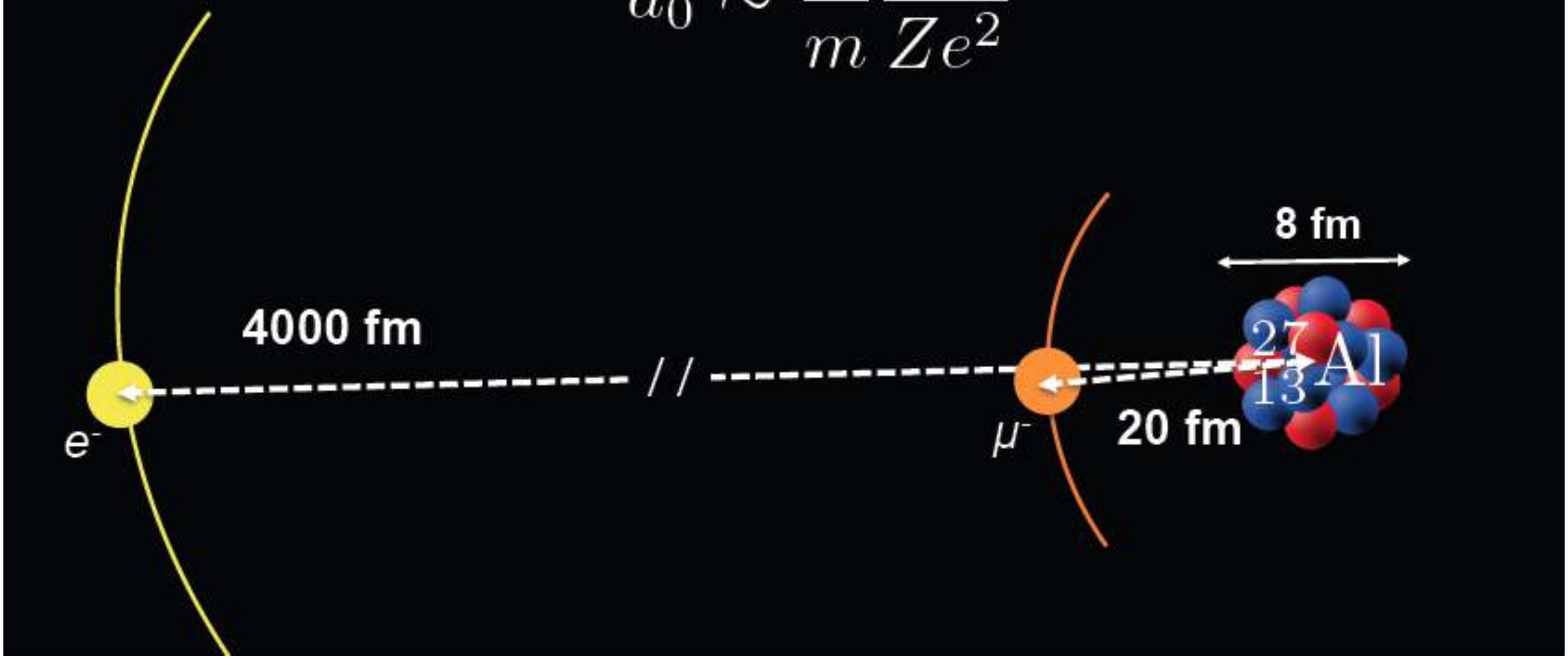
Exit collimator



The Muonic Atom

- Bound muon cascades quickly to 1*s* ground state (emits *X*-rays)
- Bohr radius of ground state:

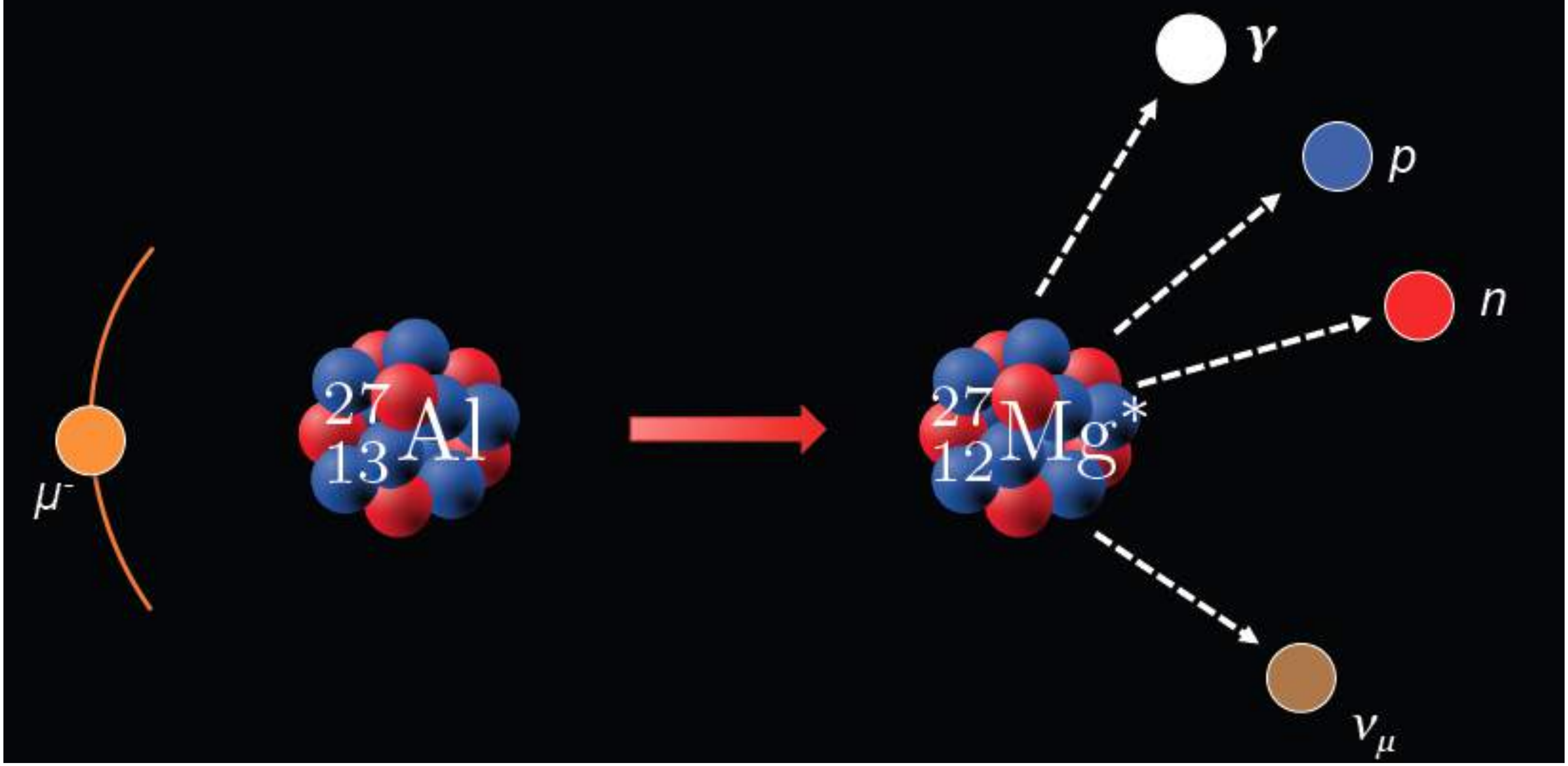
$$a_0 \sim \frac{1}{m}\frac{\hbar^2}{Ze^2}$$



Nuclear Capture processes

- Nuclear capture (61% of bound muons on Al)

$$\mu^- + N \to \nu_\mu + N'$$

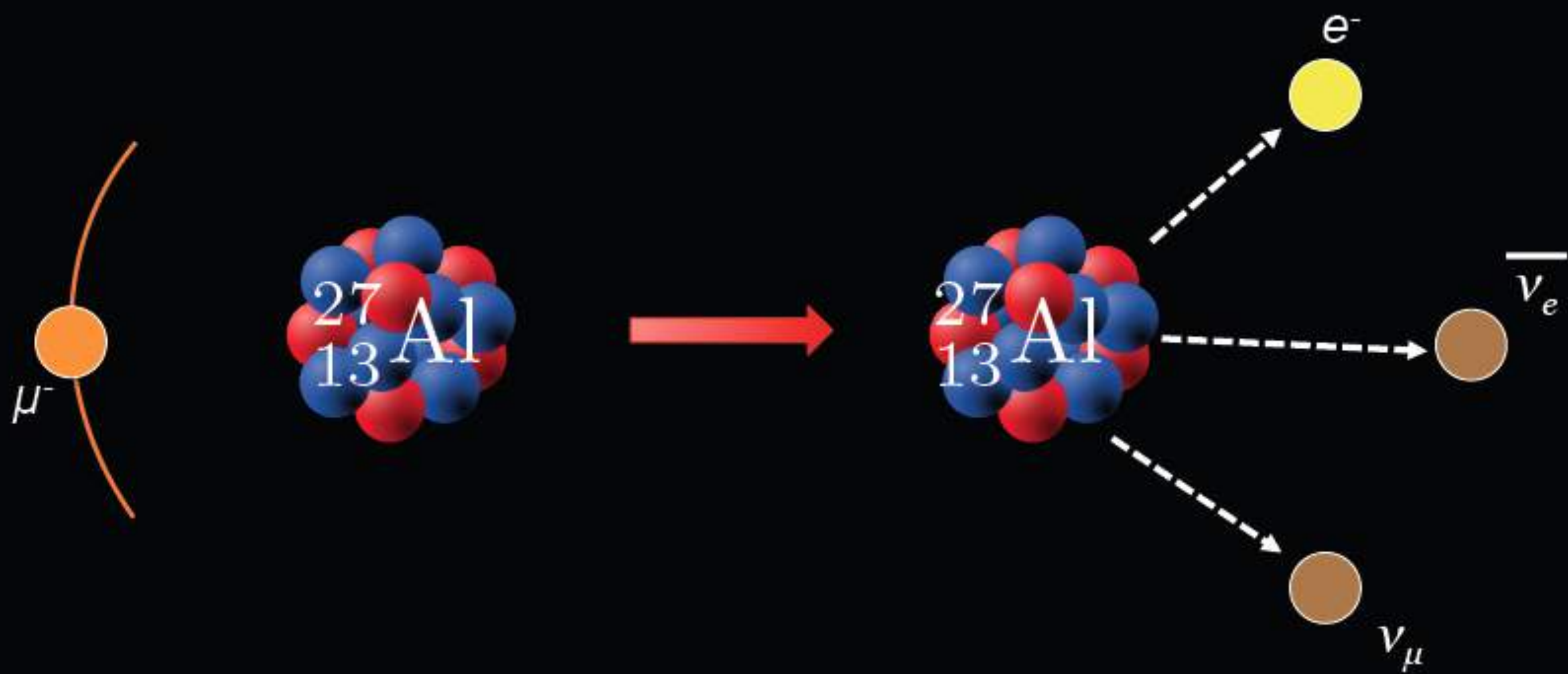


Decay In Orbit

- Decay-in-orbit (39% of bound muons on Al)

  Rest of talk: **DIO**

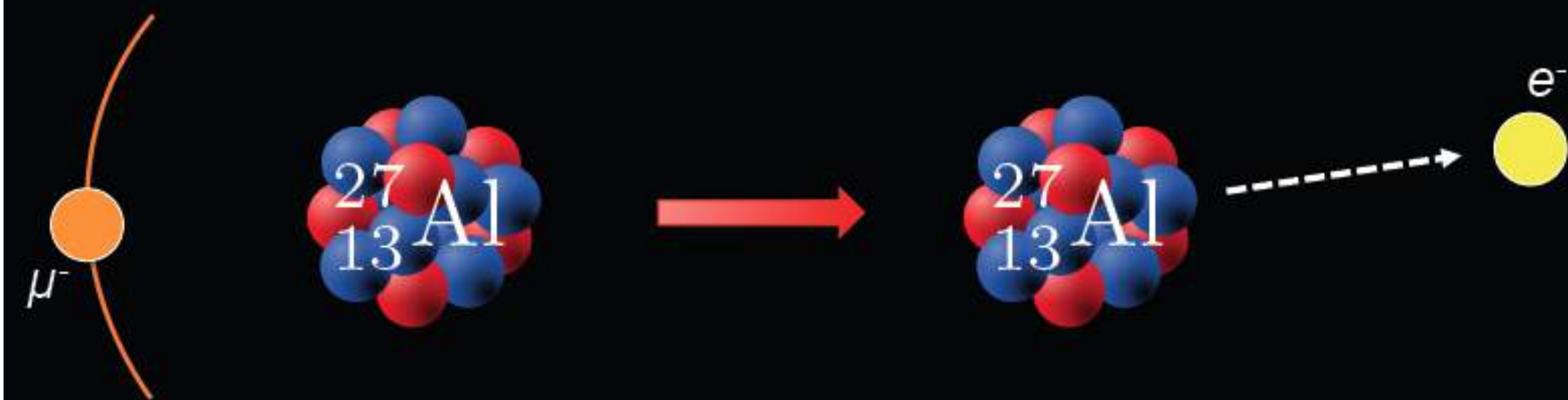
$$\mu^- + N \rightarrow e^- \overline{\nu}_e \nu_\mu + N$$



The signal: Conversion Electron

- Muon to electron conversion

$$\mu^- + N \rightarrow e^- + N$$

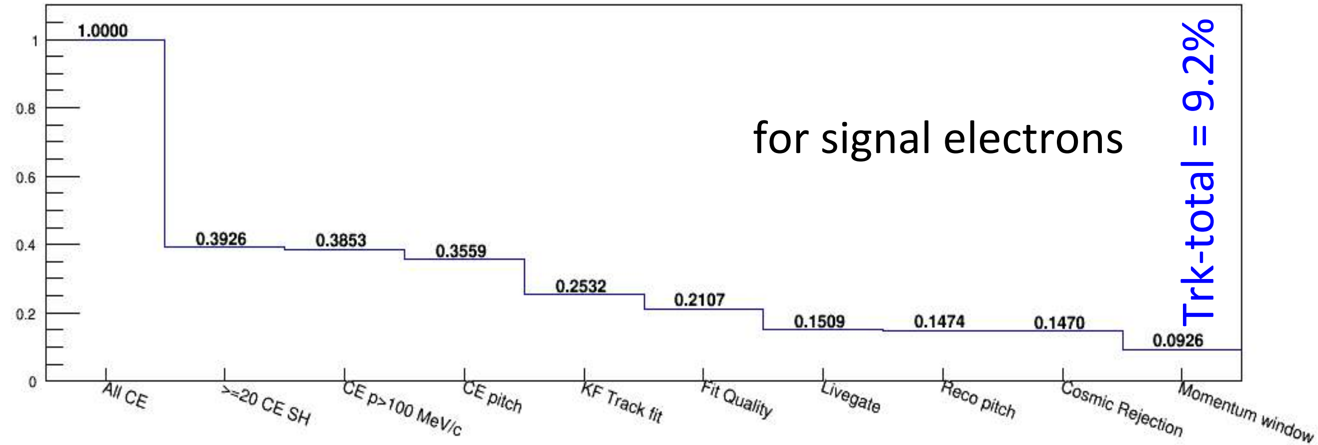


Experimental signature is a mono-energetic electron of energy

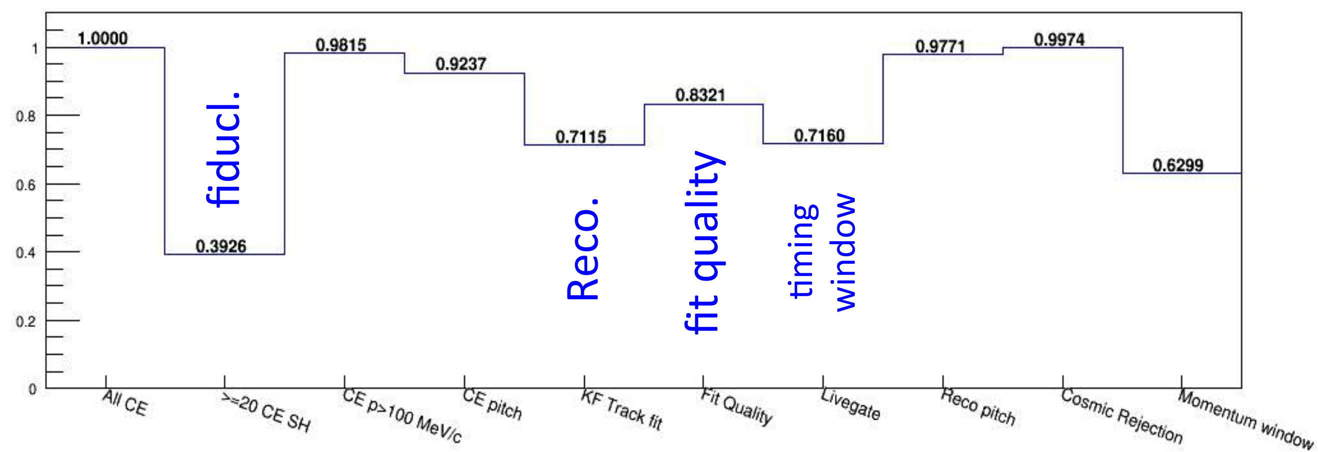
$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\text{recoil}} \\ &= 104.973 \text{ MeV} \quad (\text{for Al}) \end{aligned}$$

We know *exactly* where to look.

Track Reconstruction and Selection

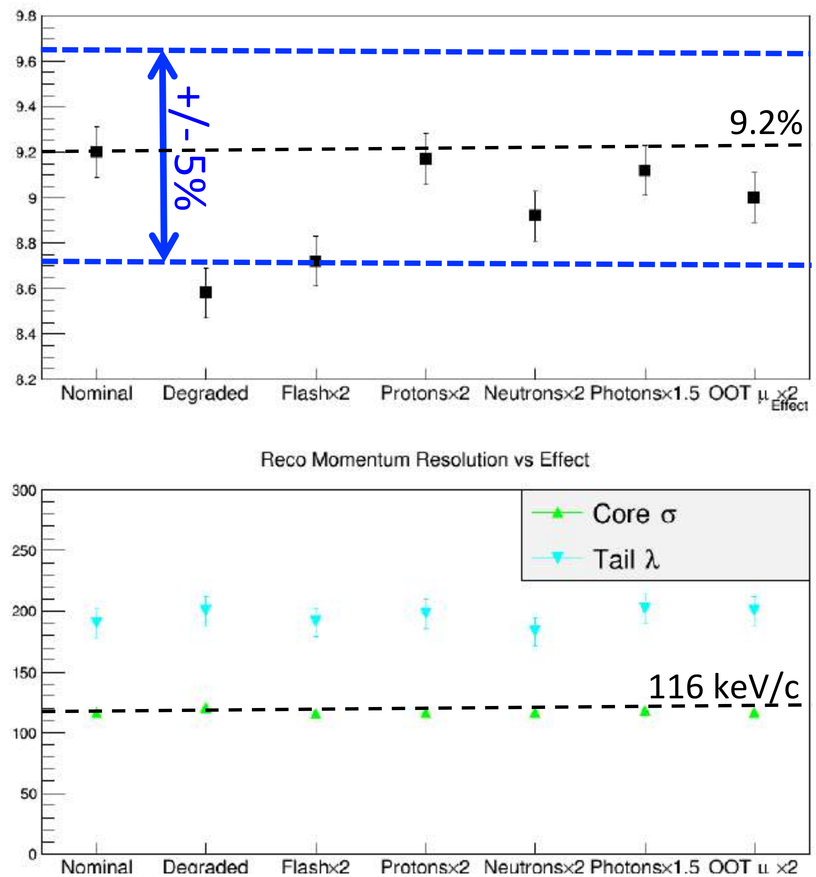


CE iency



Inefficiency dominated by geometric acceptance

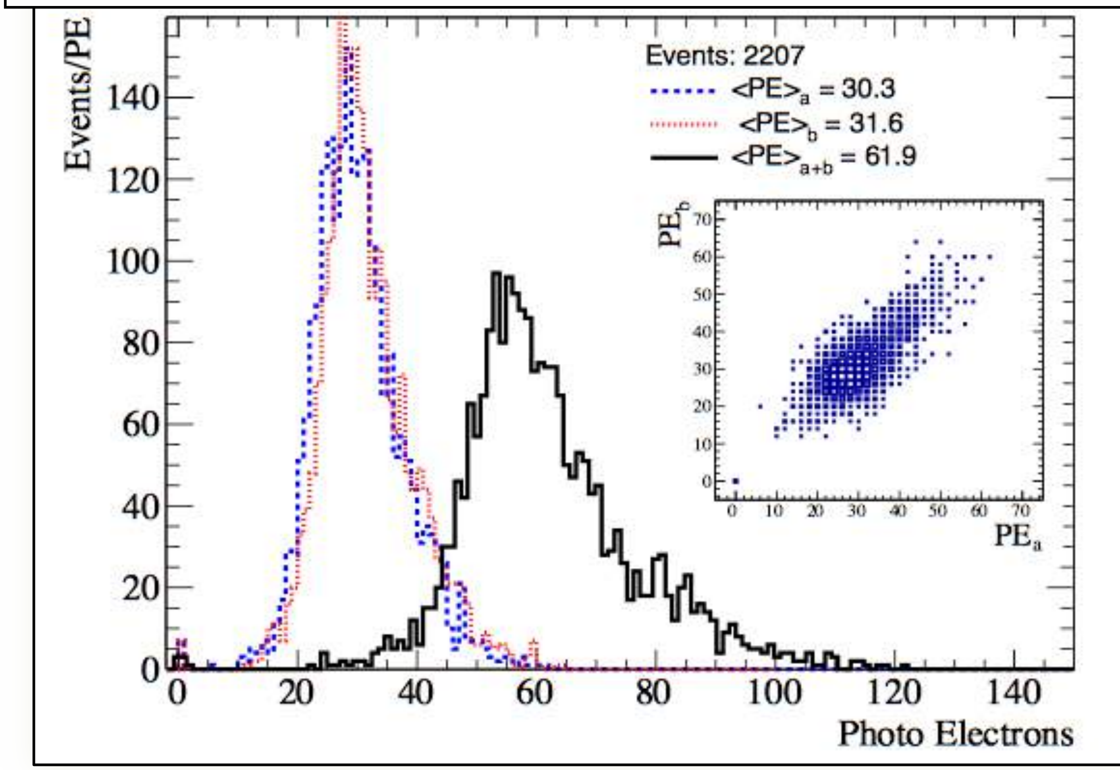
Mu2e Performance



- Robust against increases in rate

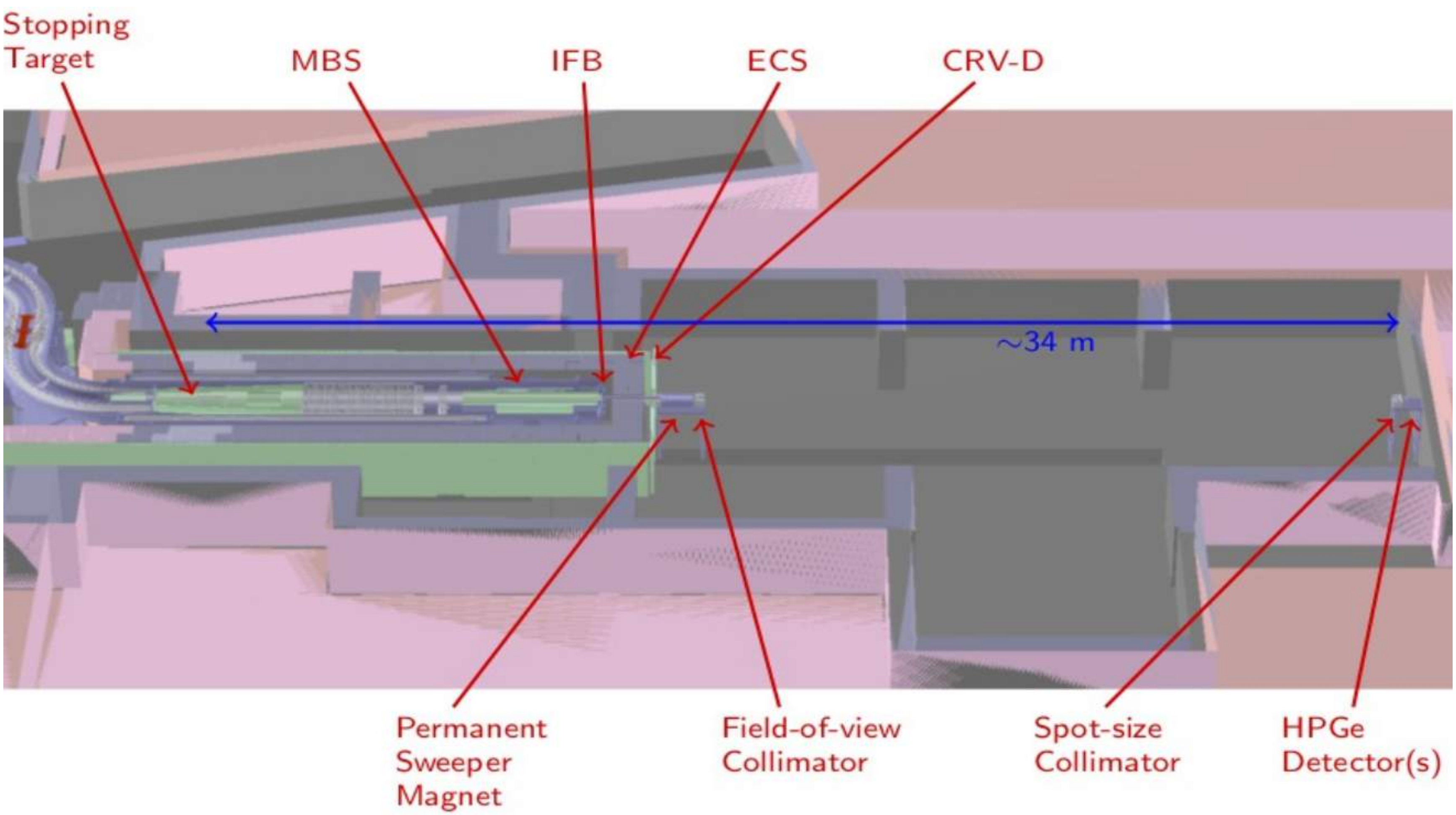
Cosmic Ray Veto

Typical light yield from CRV counter prototype – 20 cm from RO end



- Test beam data to vet design/performance

Stopping Monitor



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

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