Search for new physics with the Mu2e experiment at FERMILAB

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For the Mu2e Collaboration

104° Congresso Nazionale
della Societa' Italiana di Fisica
21/9/2018 COSENZA

The MU2E collaboration

Over 200 Scientists from 38 Institutions (six countries)

Argonne National Laboratory, Boston University, 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**, INFN Genova**, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, **INFN Lecce**, **University Marconi Rome,** Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Michigan, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, **INFN Pisa**, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University/Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University

CLFV processes

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

  similar but complementary to other CLFV processes such as:

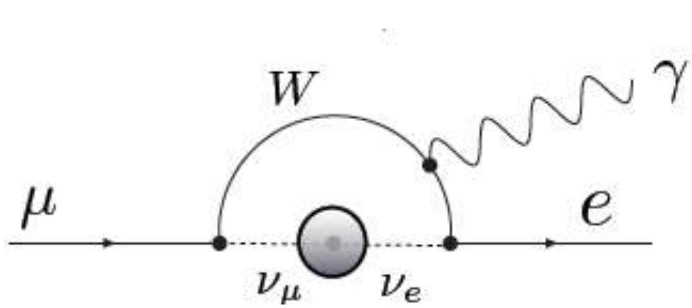
$$\mu^+ \to e^+ + \gamma,\ \mu^+ \to e^+ + e^+ + e^-,\ \tau \to e + \gamma\ ,\ \tau \to \mu + \gamma,\ \tau \to 3e....$$

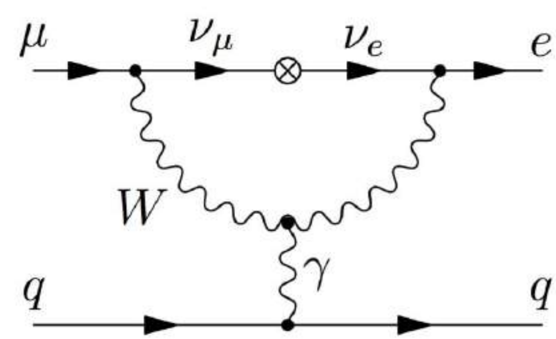
- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \to e^- Al$

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

  → considering neutrino oscillations (LFV) they **are allowed but their BR is negligible 10^{-52}**

  → New Physics could enhance CLFV rates to observable values





Rates and discovery potential

- Most promising CLFV are based on muons:
  - → clean topologies & large rates
  - → the SM contribution is negligible: no SM background
- μ-e conversion covers the BSM on very broad range of models
  - → Three stars signals Discovery potential
  - → Sensitivity across the board

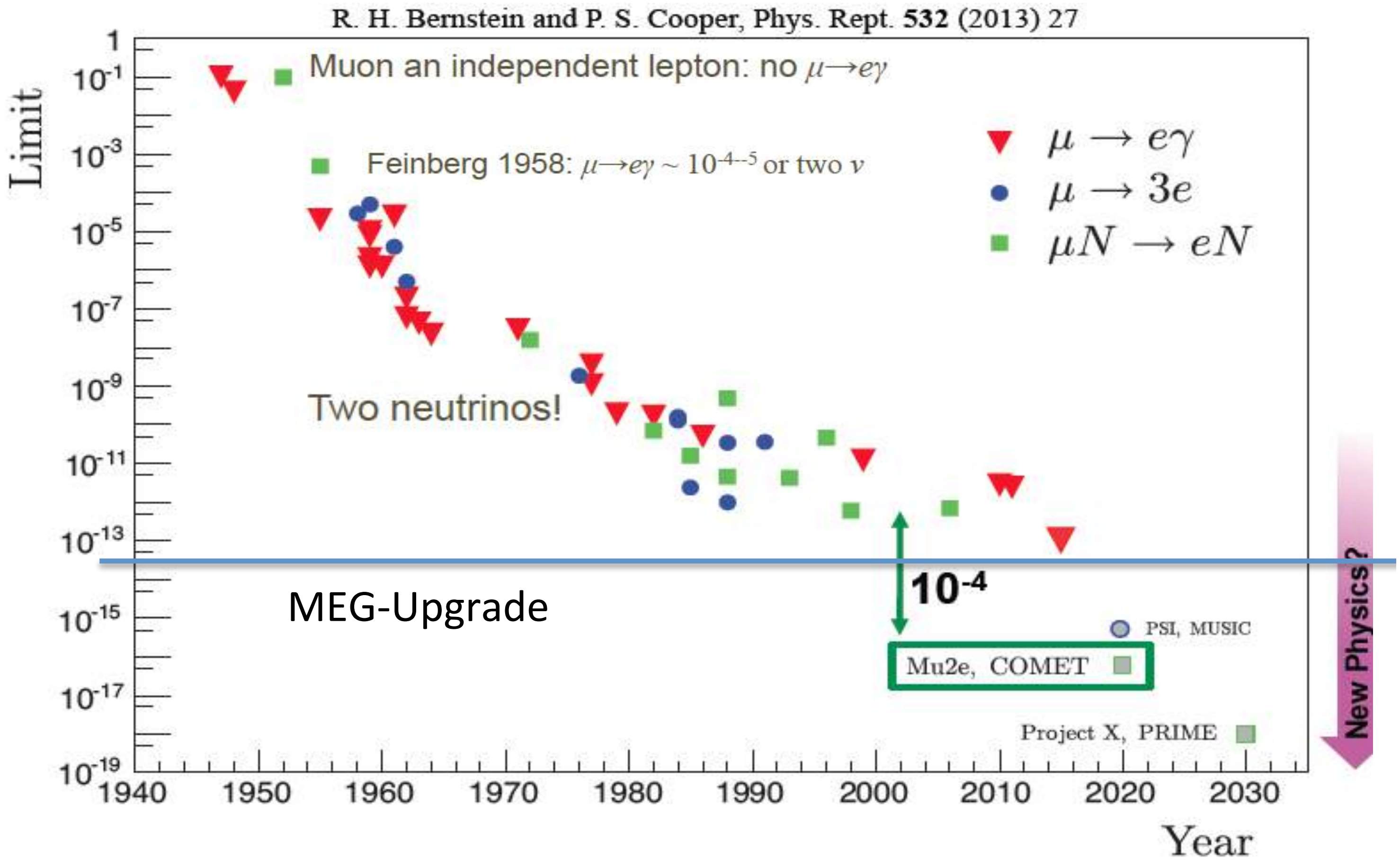
Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	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)

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

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

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.

CLFV history for muons



Current best limits:

MEG-2016
BR(μ→eγ) < 4.2 x 10^{-13}

SINDRUM-1988
BR(μ→3e) < 1 x 10^{-12}

SINDRUM-II 2006
$R_{\mu e}$ < 6.1 x 10^{-13}

MU2E GOAL:
$R_{\mu e}$ = 8 x 10^{-17}

Mu2e (Fermilab) aims to improve by a factor 10^4 the present best limit

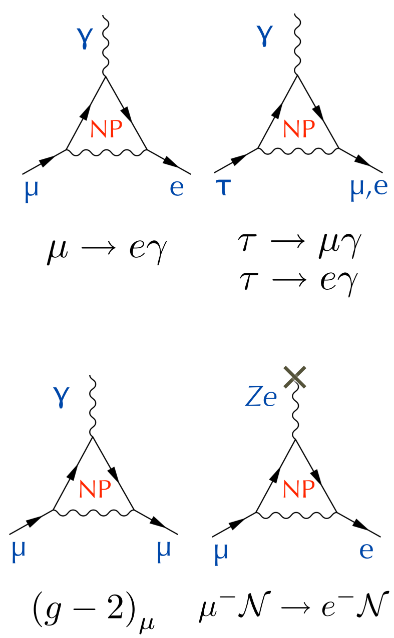
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 8 \times 10^{-17} \text{ (@90\%CL)}$$

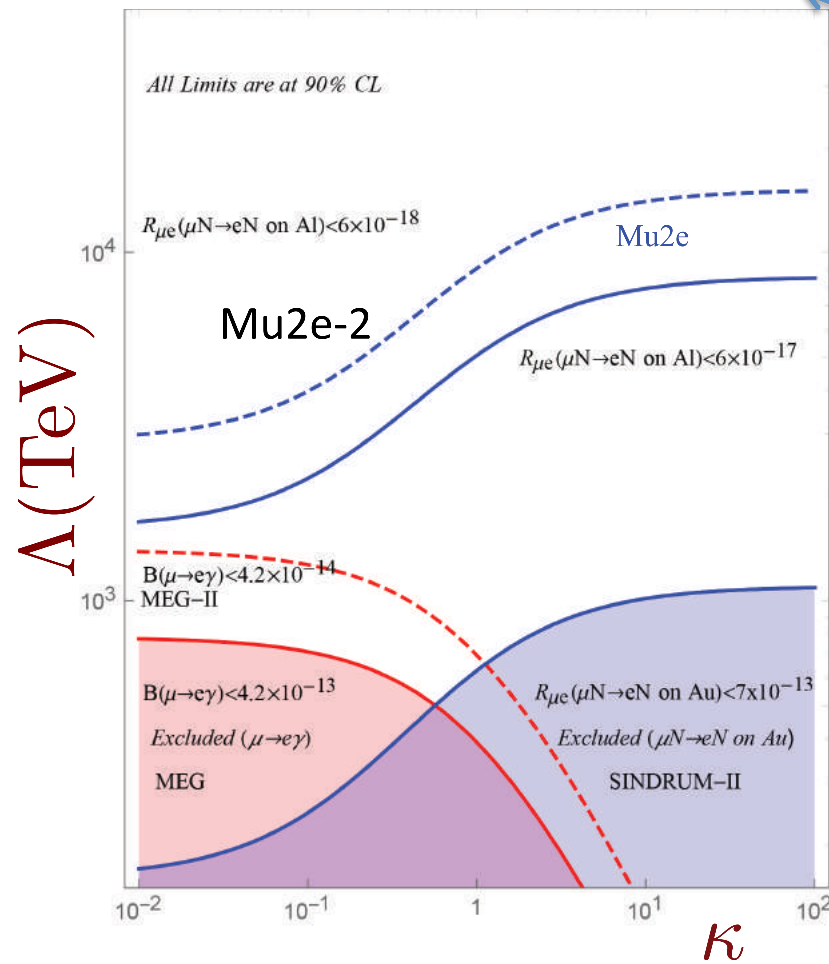
Mu2e vs MEG in the λ/k plane

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

LOOP TERM

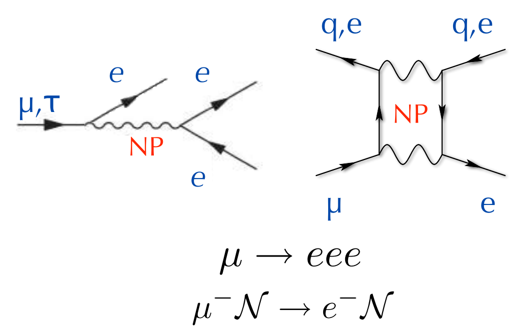
$\kappa \ll 1$





CONTACT TERM

$\kappa \gg 1$

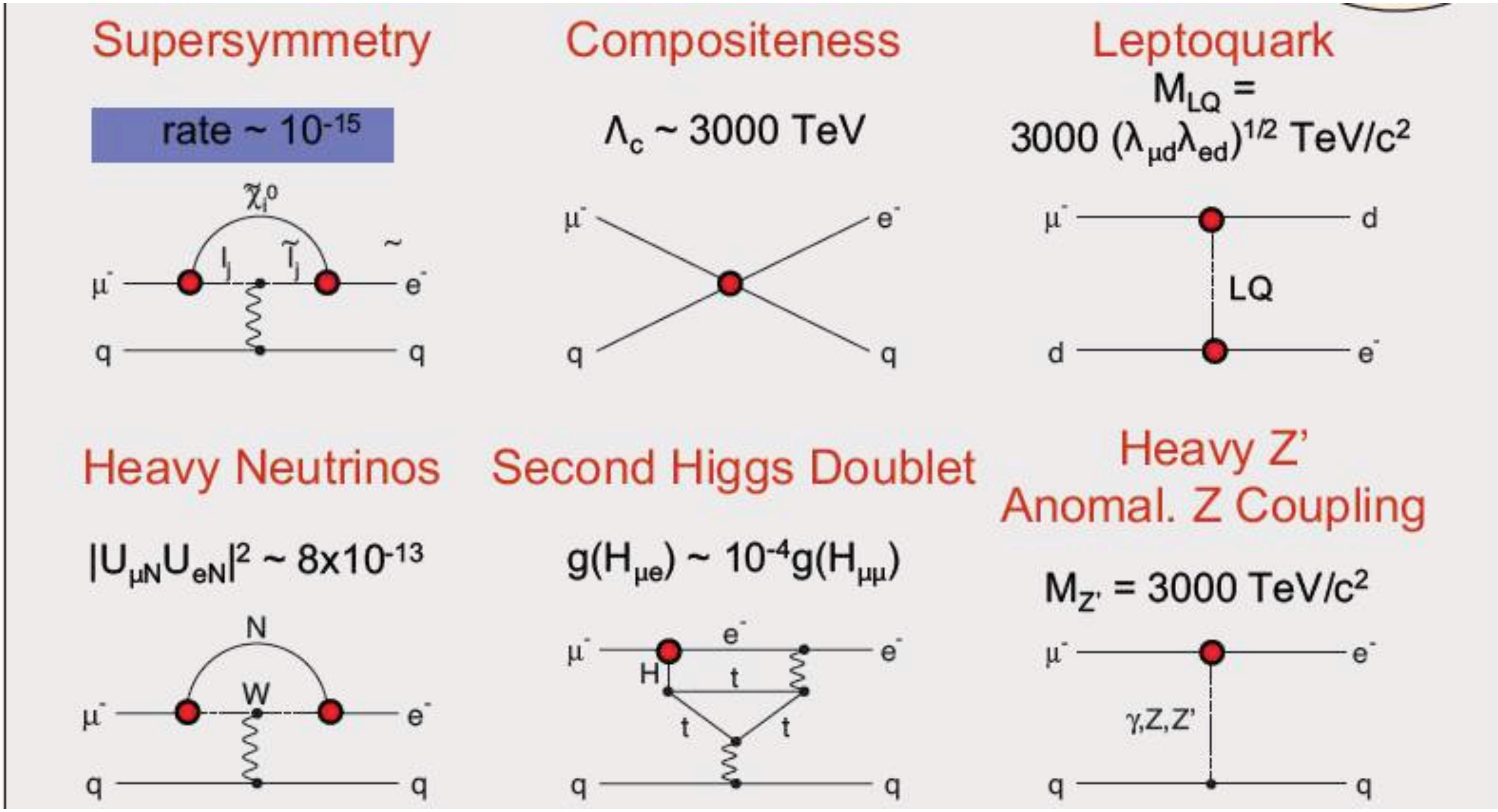


If SUSY seen @ LHC
→ rate ~10^{-15}
Implies O(40) signal events
with negligible background

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

Roughly equal to MEG upgrade in loop-dominated physics

Mu2e physics reach



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

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

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)

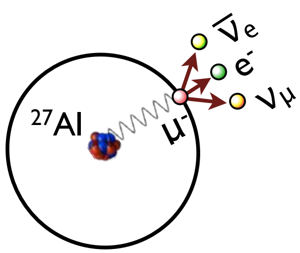
- **Sensitivity to Λ (mass scale) up to thousands of TeV beyond any current existing accelerator**

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:

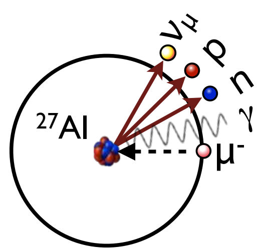
Decay in Orbit (DIO)

(BR=39%)

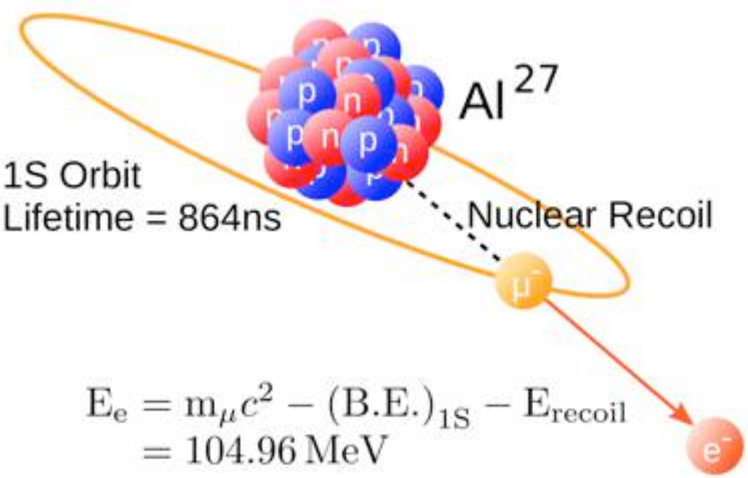


Muon Capture Process

(BR=61%)



Conversion Process



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

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 and rates

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

- **Expected limit: $R_{\mu e}$ < 8 x 10^{-17} @ 90% CL**
  - **Factor 10^4 improvement**

- **Discovery sensitivity: all $R_{\mu e}$ > 2 x 10^{-16}**
  - Covers broad range of new physics theories

- **High rate and large number of stopped muons 10^{18}**
  - Needs intense muon source and efficient transport to target

Need to fight a lot of 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**

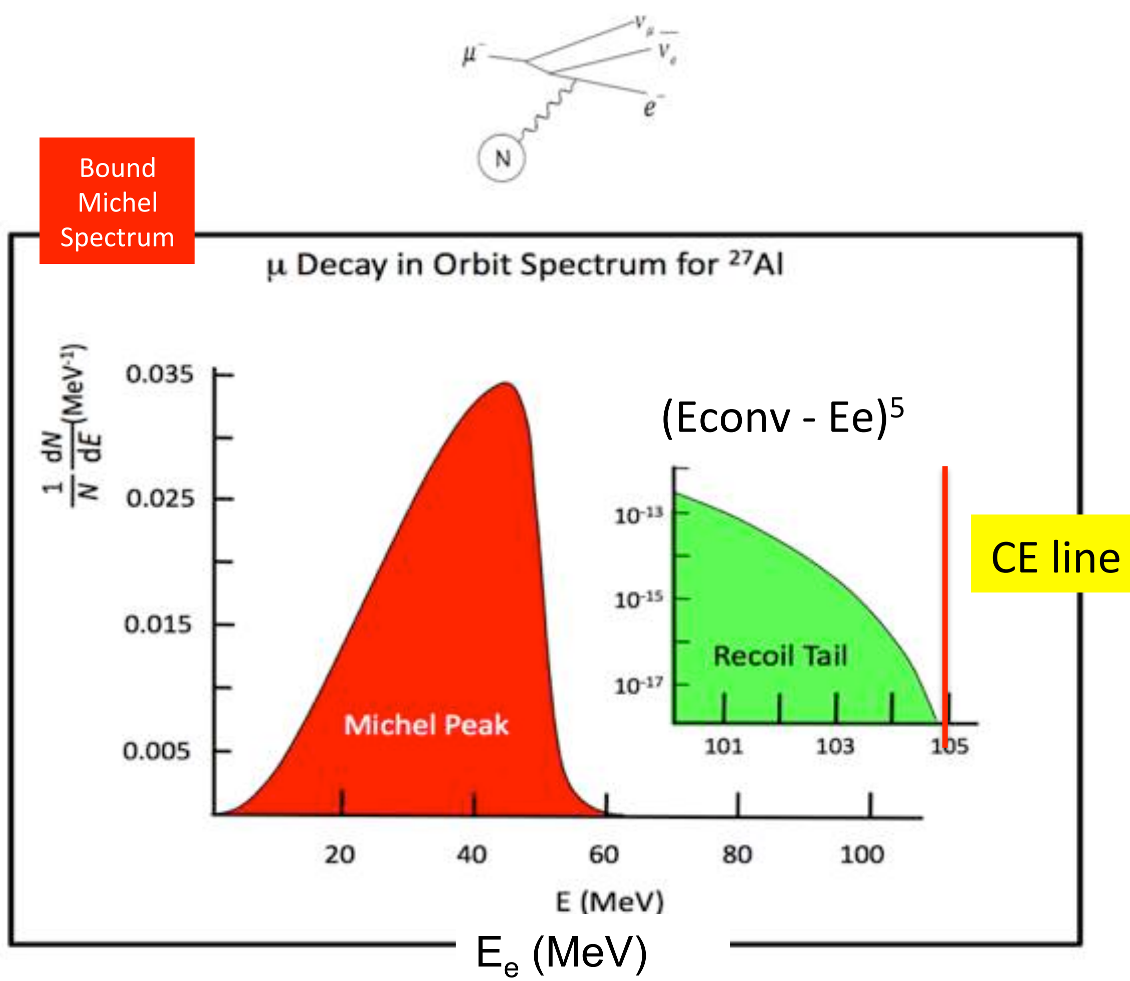
The irreducible DIO background

- ❑ **The decay in orbit (DIO) is the most difficult background**

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

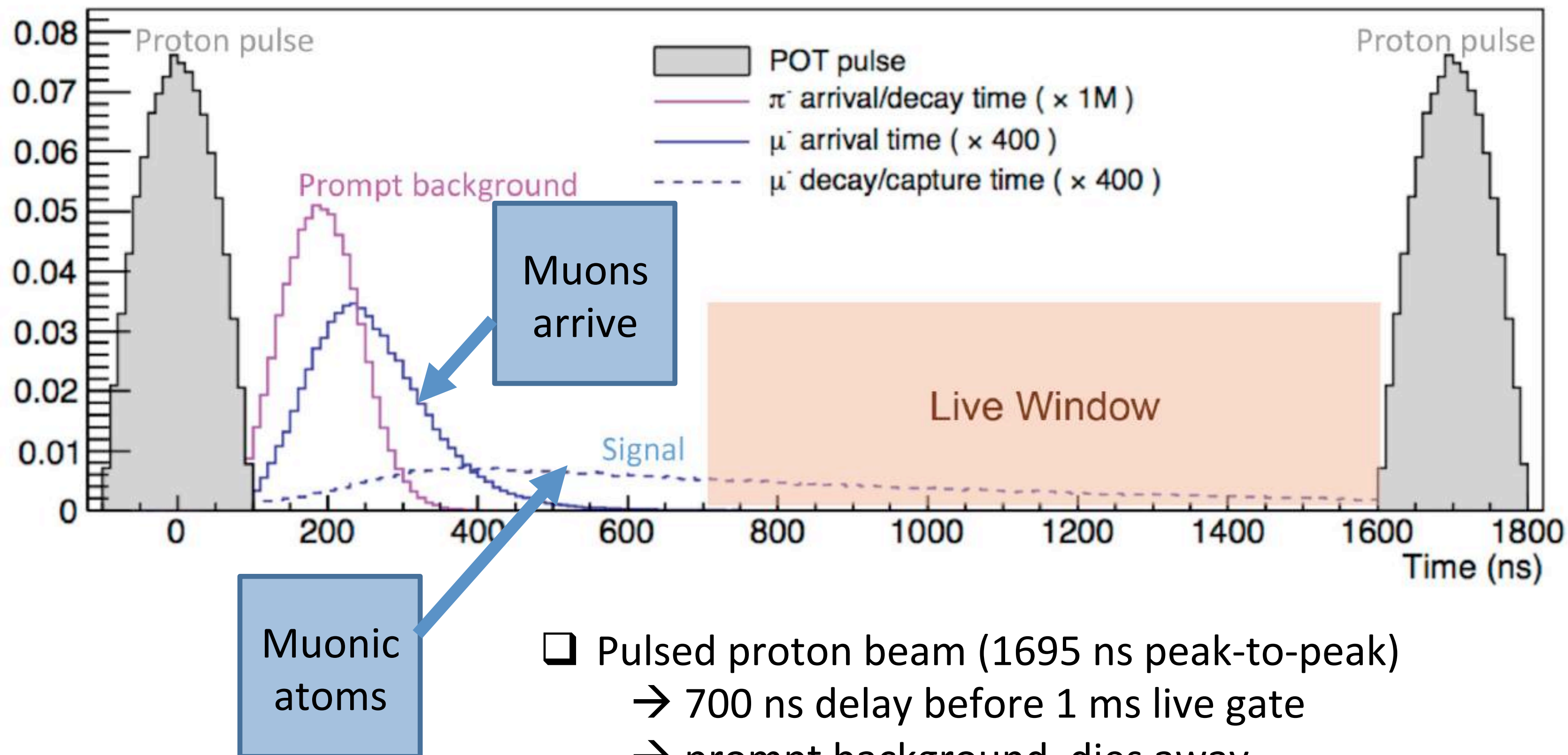
→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

→ To separate DIO endpoint From the CE line we need a high Resolution Spectrometer



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

Beam structure → prompt background



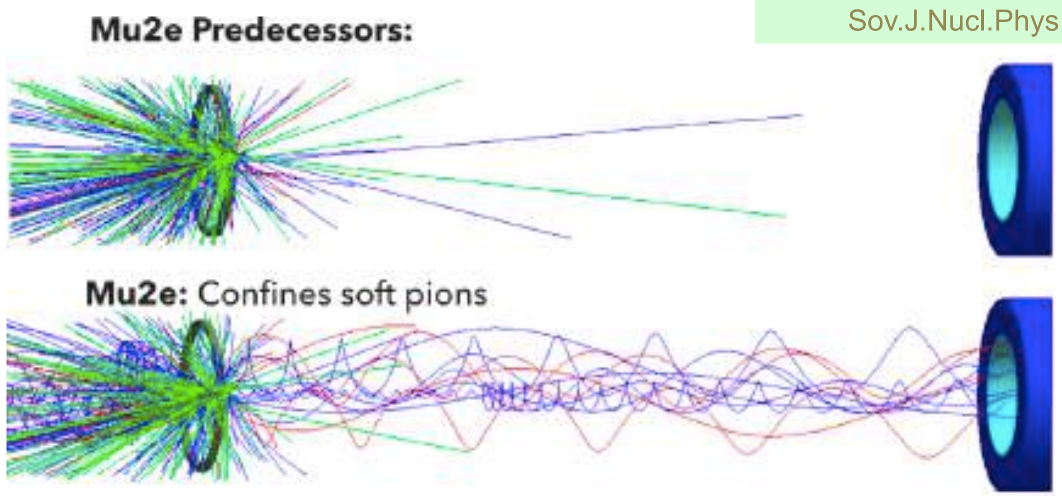
- ❑ Pulsed proton beam (1695 ns peak-to-peak)
  - → 700 ns delay before 1 ms live gate
  - → prompt background dies away
- ❑ Extinction factor (rate of out-of-time protons) below 10^{-10} is required

The trick here is … muonic atomic lifetime
t(mu)Al = 864 ns >> prompt background

Summary: the keys to Mu2e Success

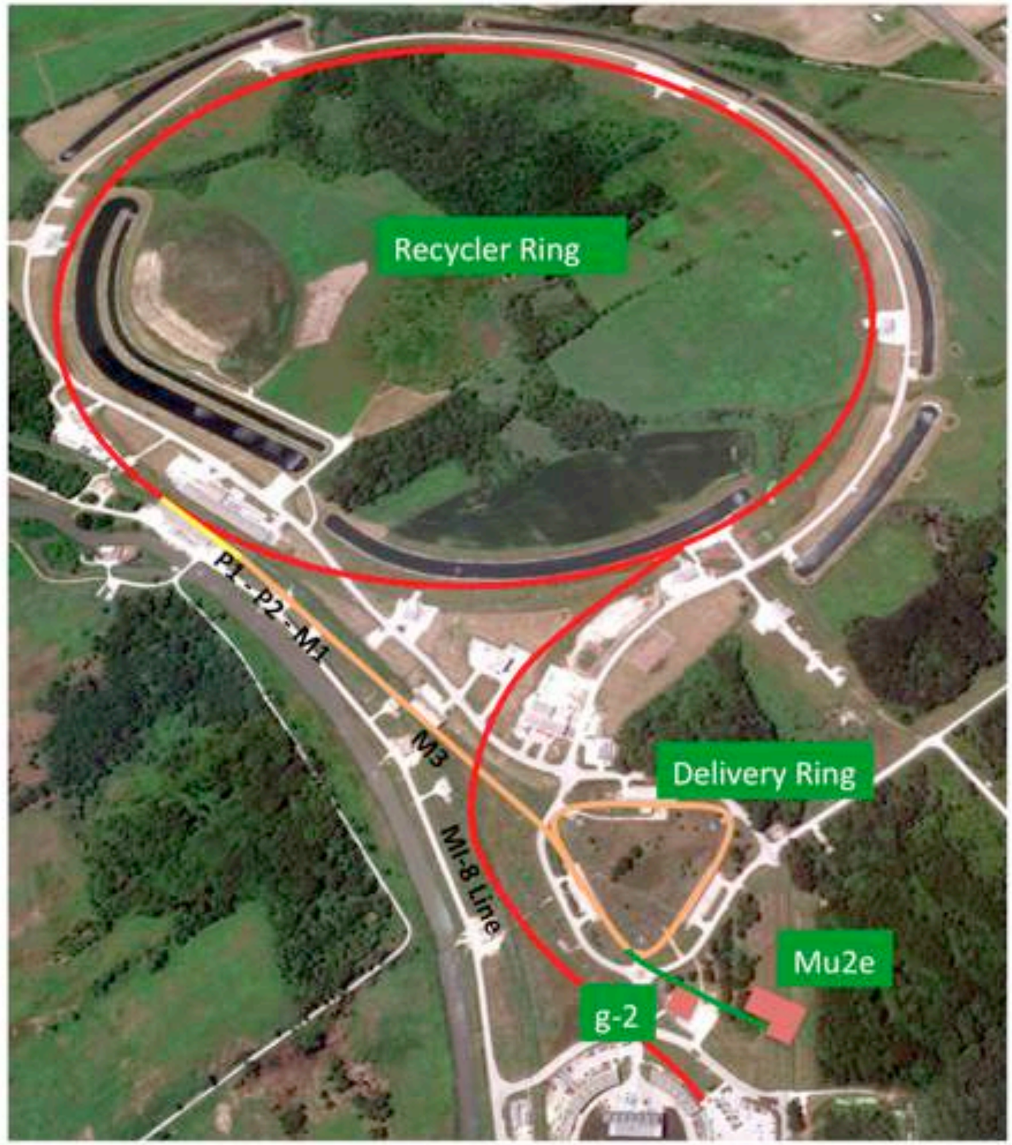
- **High intensity pulsed proton beam**
  - Narrow proton pulses (< ± 125 ns)
  - Very few out-of-time protons (< 10^{-10})
  - $3x10^7$ proton/pulse.
- **High efficiency in transporting muon to Al target**
  - Need of a sophisticated magnet with gradient fields
- **Excellent detector for 100 MeV electrons**
  - → Excellent momentum resolution (< 200 keV core)
  - → Calorimeter for PID, triggering and track seeding
  - → High Cosmic Ray Veto (CRV) efficiency (>99.99%)
  - → Thin anti-proton annihilation window(s)

Concept by Lobashev and Djilkibaev
Sov.J.Nucl.Phys. 49, 384 (1989)



Accelerator Scheme

- Booster: batch of 4×10^{12} protons every $1/15^{th}$ 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 (delivery ring period) and then sent to the Mu2e Detector …**
- It runs together with neutrino beam for NOVA. It cannot run together with g-2)muon.



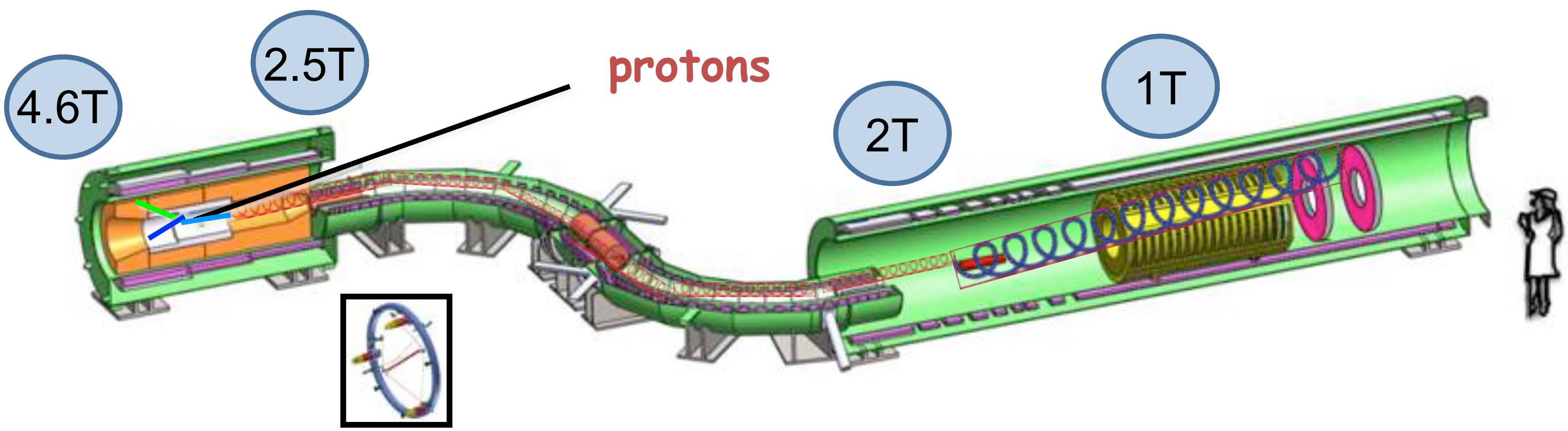
Muon campus & Mu2e Hall status

- Detector Hall Building
  - Broke Ground (April 2015)
  - Building Acceptance (March 2017)
- Infrastructure installation (on going)
  - LCW pipes, Bus bar, Cable Trays
  - Interlocks, Networking, DAQ infrastructure

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 ➔High Muon intensity



→ Heat and radiation shielding
→ Tungsten target.

Transport Solenoid (TS)

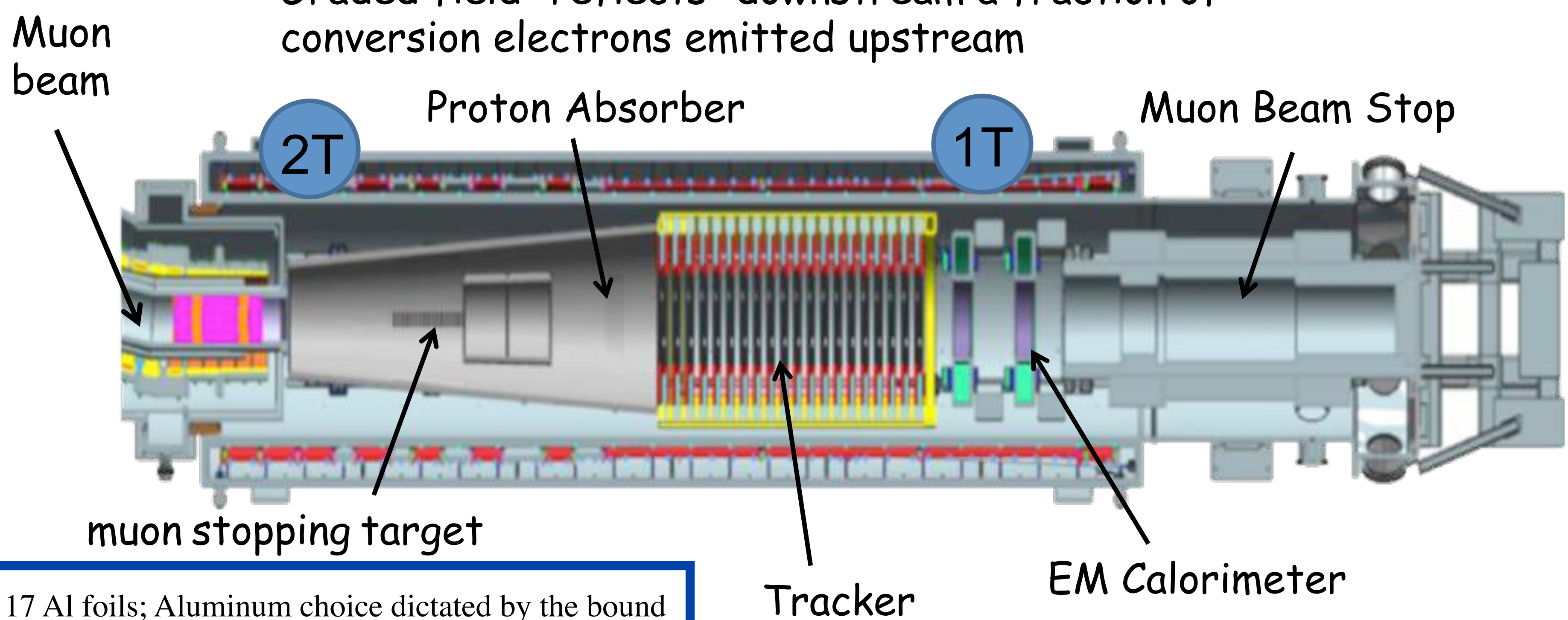
Collimator selects low momentum, negative muons
Antiproton absorber in the mid-section
S-shape eliminates photons andneutrons

Target, Detector and Solenoid (DS)

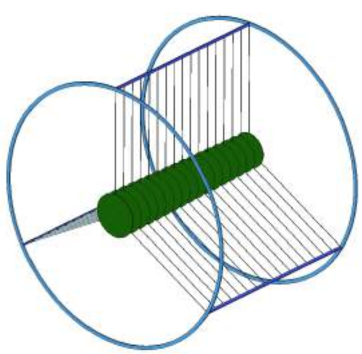
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Detector Solenoid

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



17 Al foils; Aluminum choice dictated by the bound muon lifetime (**864 ns**) that nicely matches the the Mu2e pulsed beam structure for prompts' separation



Sensitivity goal →
~ 6 x 10^{17} stopped muons
3 year runs , 6 x 10^7 sec →
10^{10} stopped muon/sec

Status of PS/DS construction

- Preparing for PS/DS Model Coil Cold Test at General Atomics (Tupelo)
- Coil winding issues with 1st DS unit
  - GA currently modifying winding machine

Cryostated Model Coil at GA Tupelo

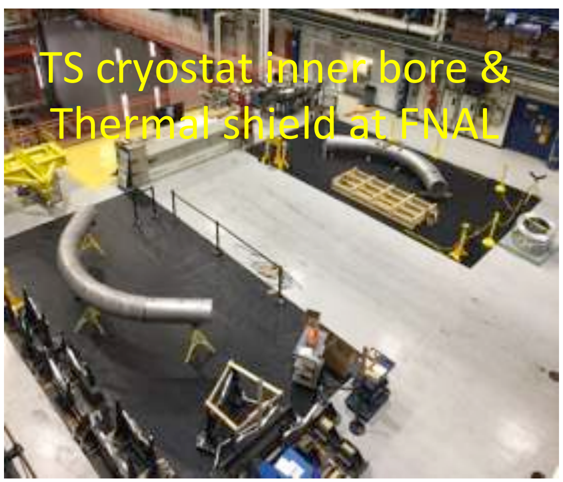
Tooling & DS Warm bore at GA Tupelo

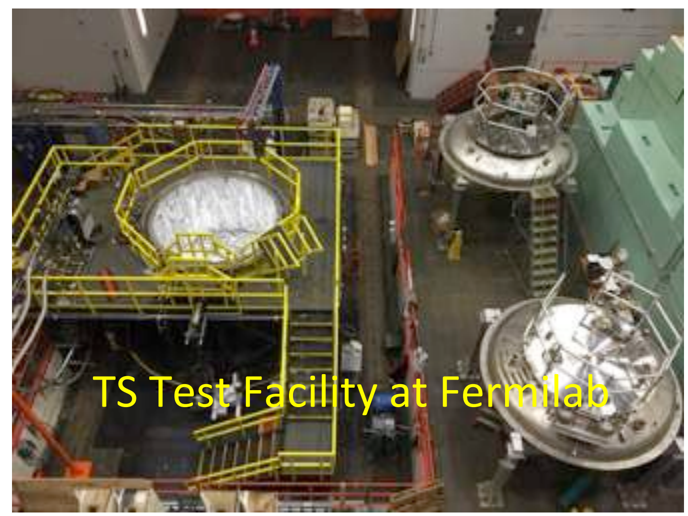
Model Coil at GA Tupelo

Status of TS construction

14 Production TS Units (27 modules) are being fabricated at ASG Superconductors (Genoa)

- 1st TS module completed a successful warm and cold test at Fermilab
- 90% of the all coils (52) have been wound, 75% epoxy impregnated, 38% machined
- Other 3 units expected for the end of this year





The Mu2e Tracker

Detector requirements:

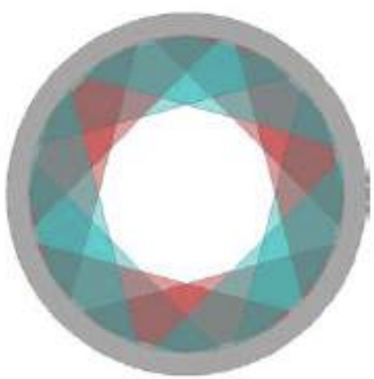
1. Small amount of X_0
2. σ_p < 180 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm² in live window
   - Beam flash of 3 MHz/cm²
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

Low mass straw drift tubes design: **straw**

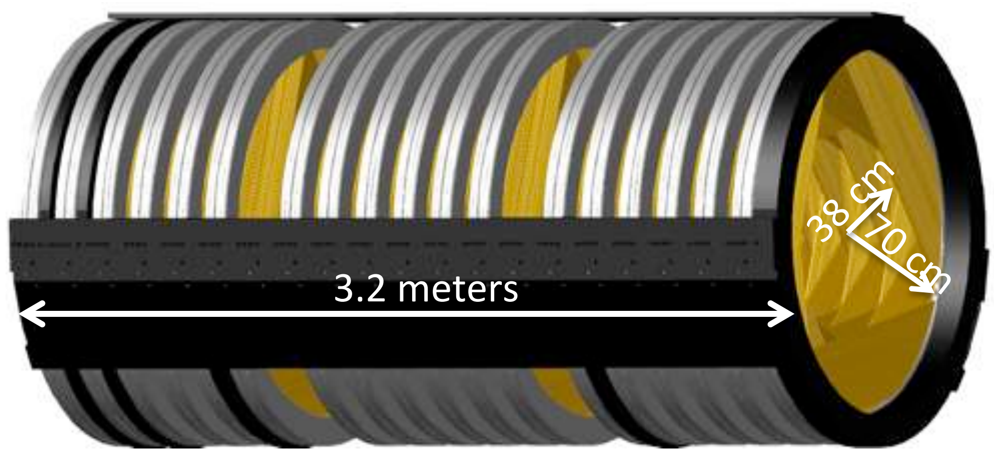
- 5 mm diameter, 33 – 117 cm length
- 15 μm Mylar wall, 25 μm Au-plated W wire
- 80:20 $Ar{:}CO_2$ @ 1 atm
- Dual-ended readout

Tracker Plane

Tracker Station:
2 rotated planes

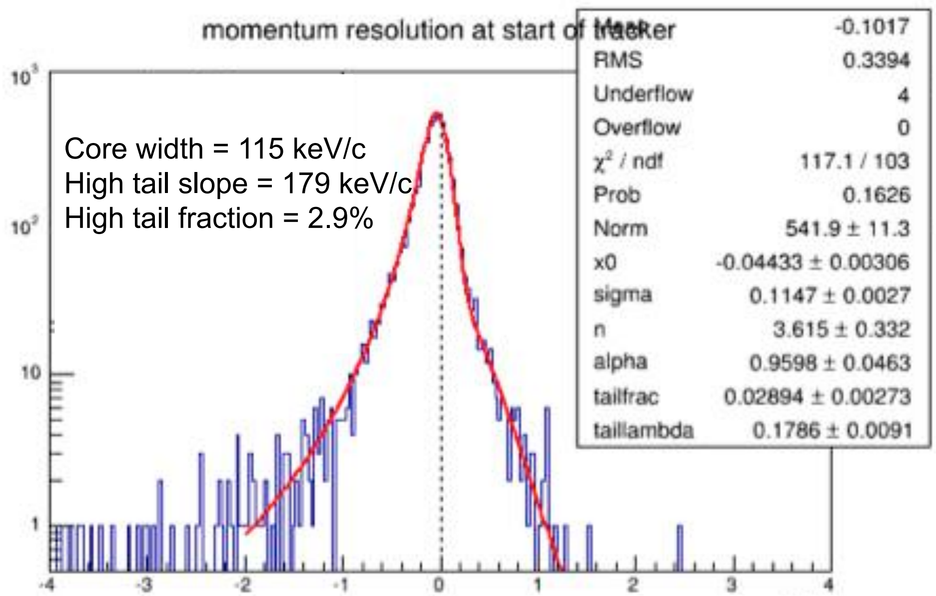


Tracker: 18 stations (>20k tubes)



Mu2e Tracker Performance

Full simulation

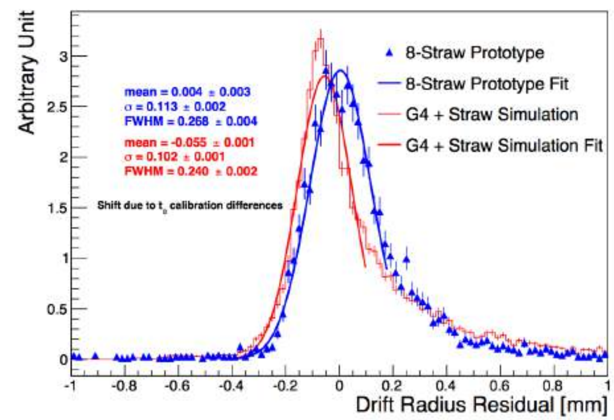


$P_{rec} - P_{tru}$ (MeV/c)

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

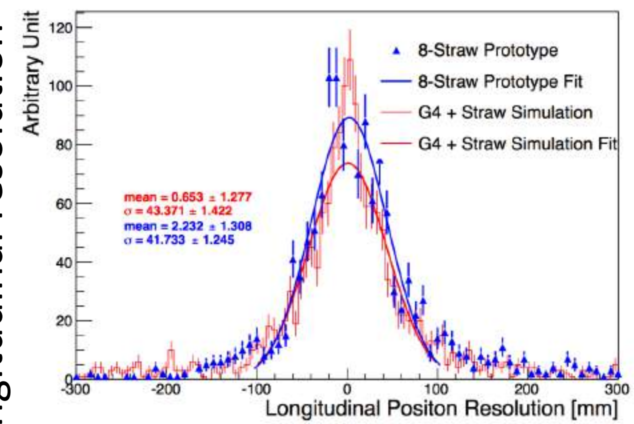
Cosmics, 8 channel prototype

Transverse resolution



σ_{data} = 0.133 ± 0.022 mm
σ_{MC} = 0.102 ± 0.001 mm

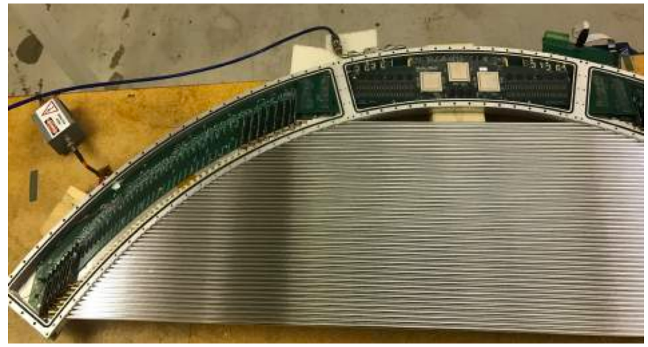
Longitudinal resolution



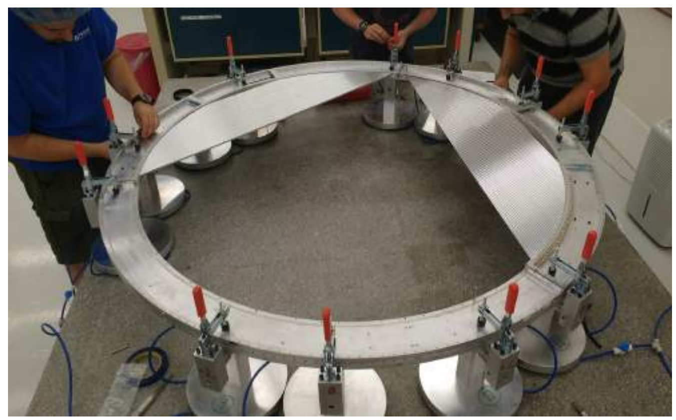
σ_{data} = 42 ± 1 mm
σ_{MC} = 43 ± 1 mm

Mu2e Tracker status

- Straw Procurement Complete (30k straws)
- Panels
  - Design Complete
  - Production assembly fixtures being fabricated
  - UMN Panel Factory & QC Station set up is in progress
- Plane
  - Plane assembly tooling fixture design nearly complete
- Electronics
  - Incorporation of rad hard FPGA in progress



Panel w/Front-End Electronics



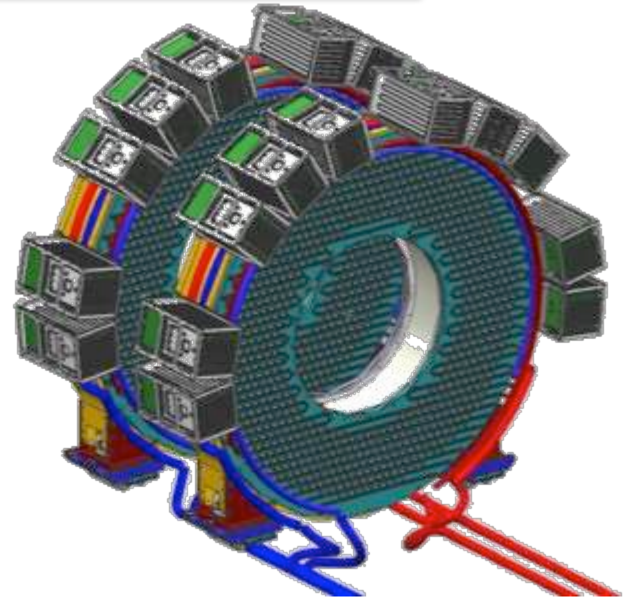
Two panels installed in plane

Panel: Straw Installation

Mu2e 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**



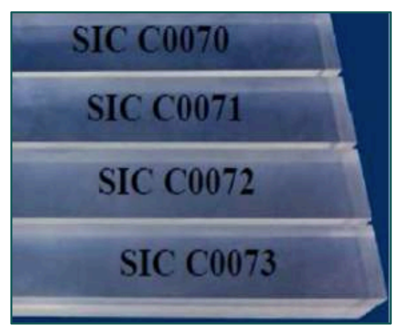
Calorimeter choice:

High granularity crystal based calorimeter with Large area cusotom UV extended SiPMs

→ σ/E of O(10%) and Time resolution < 500 ps
→ Position resolution of O(1 cm)
→ High acceptance **for CE signal @ 100 MeV**
→ FEE on SiPM pins, digital electronics on crates
→ Calibration tools: 6 MeV source and Laser system

Basic Components:

- Undoped CsI crystals
- Mu2e SiPMs + FEE



Annular disk geometry

- Square crystals 34x34x200 mm^3
- Charge symmetric, can measure $\mu^- N \rightarrow e^+ N$

Mu2e Calorimeter performance

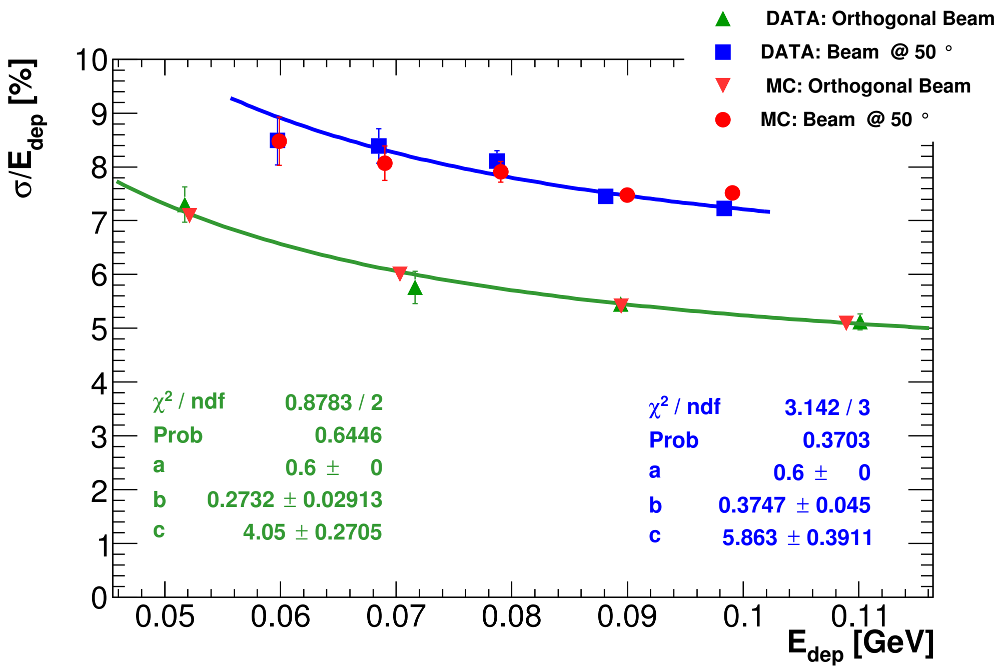
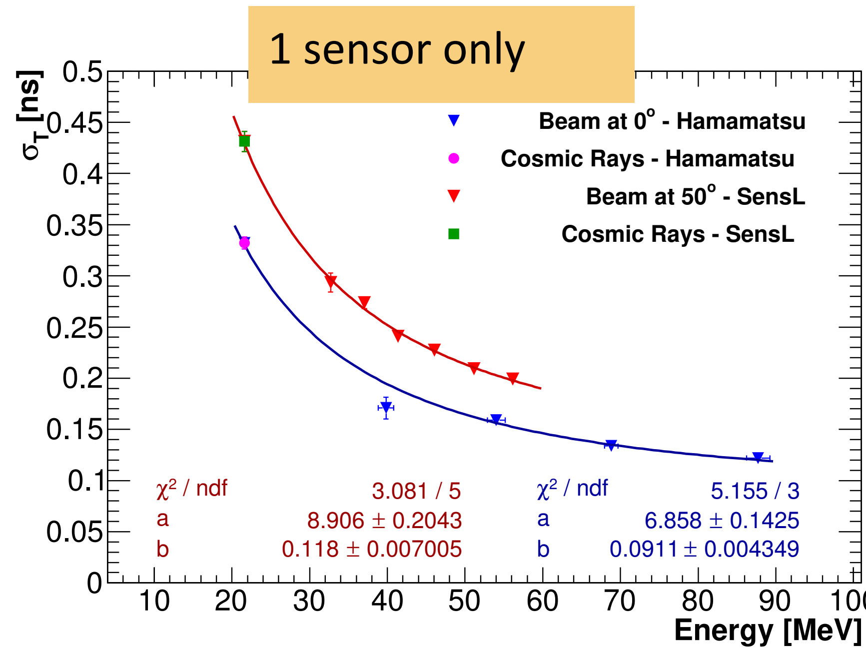


Figure 40: *Energy resolution as a function of the energy deposit in the Module-0 in the orthogonal (blue) and tilted (green) configuration and comparison with the MC expectation.*

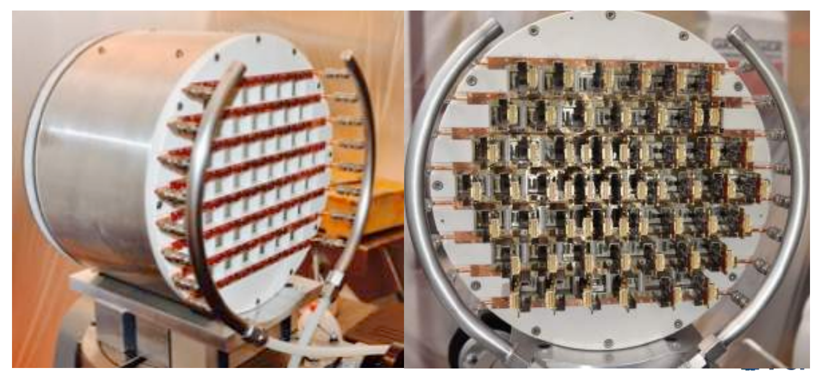


Module-0 51 crystals, 102 SiPM/FEE channels:

➔ 5.4 % (7.3%) energy resolution @ 100 MeV for 0° (50°) impact angles with excellent data-MC agreement

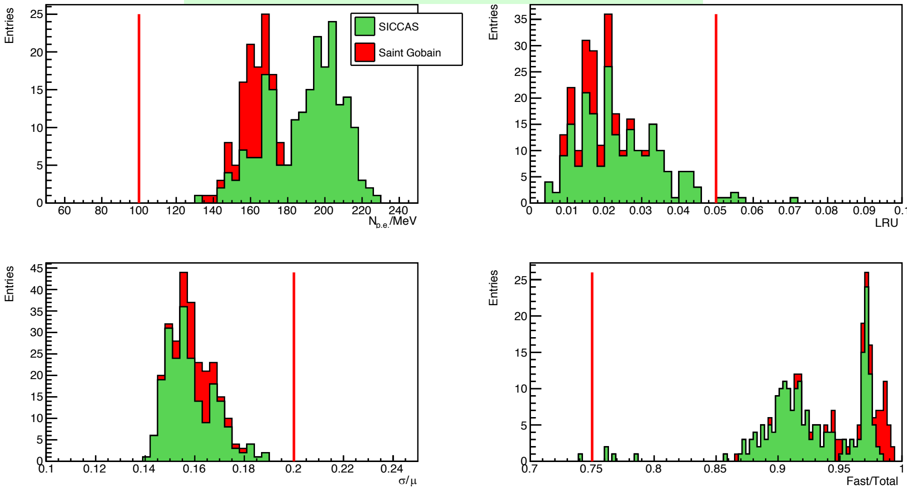
➔ Timing resolution better than 150 ps with one sensor

➔ Mu2e requirements satisfied

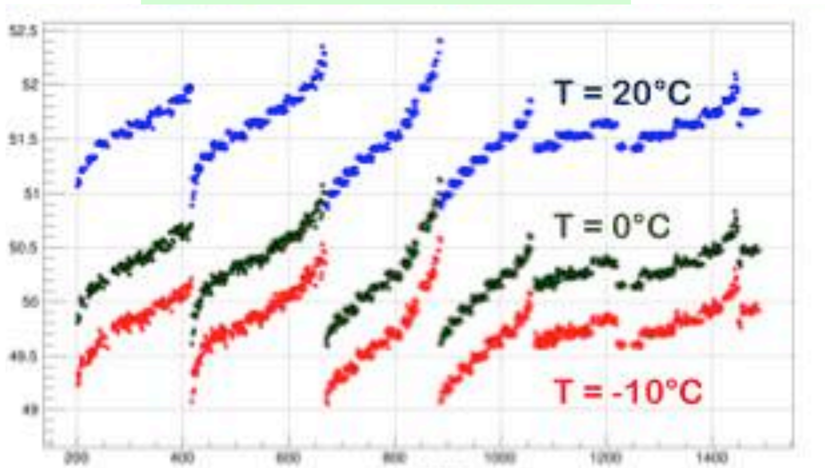


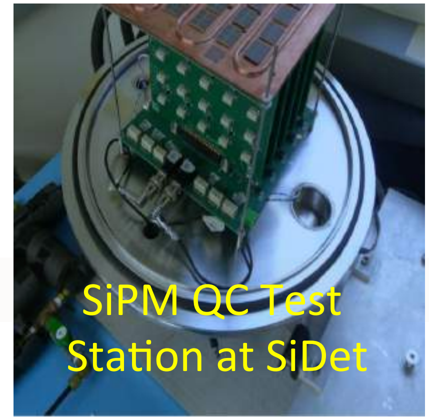
Mu2e Calorimeter status

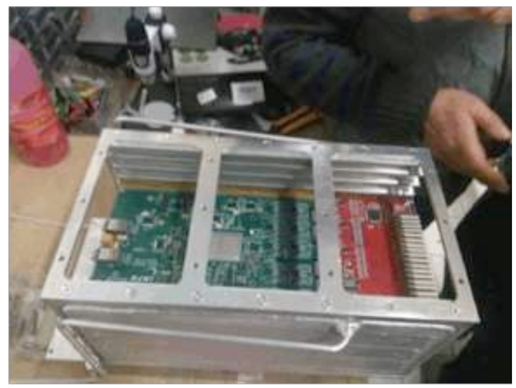
QA of crystal production



QA of SiPM production







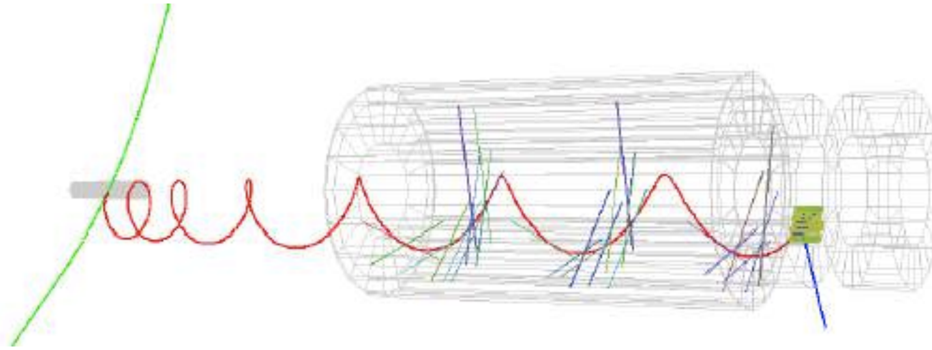
Digital electronics

Mechanical Mock-up

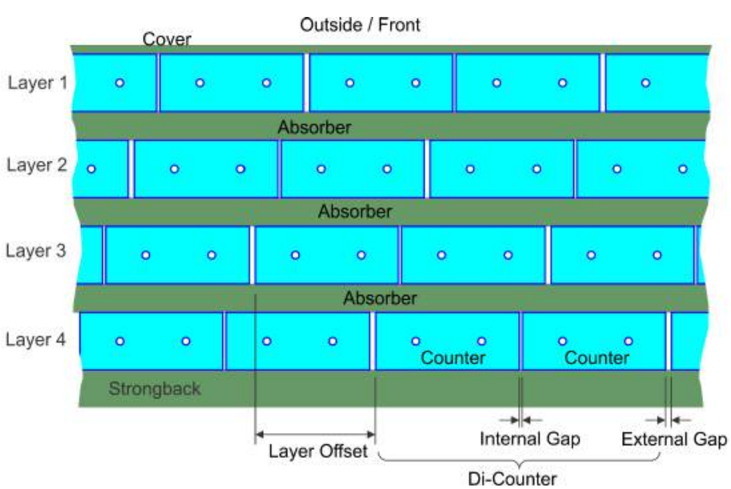
1/3 of 1450 crystals produced and tested
½ of 3250 SiPMs produced and tested

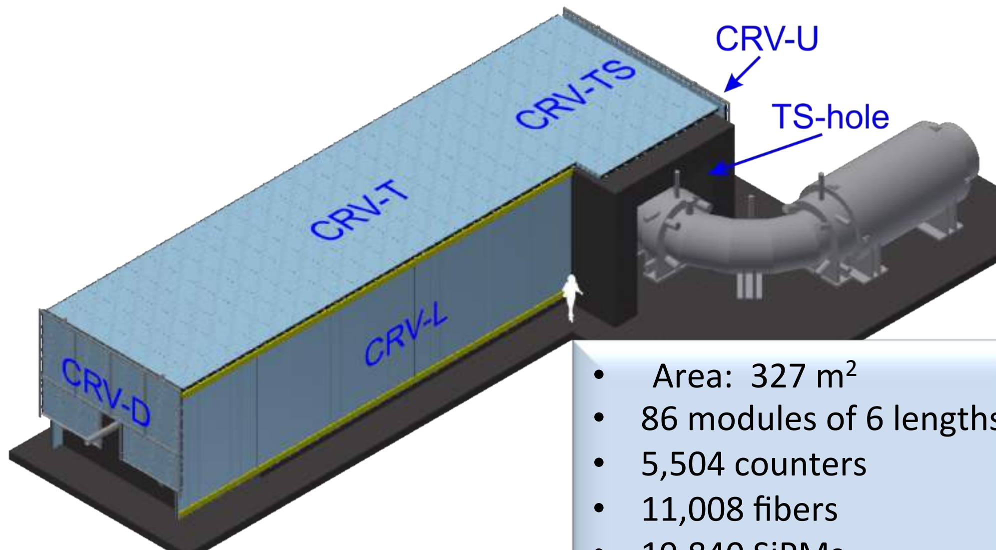
Mu2e Cosmic-Ray Veto

Cosmic ray muons will produce one fake signal event per day without a CRV. The muon itself can fake a 105 MeV e^- or it can knock out an e^-



- **High efficiency (0.9999) veto needed**
- Four layers of extruded plastic scintillator, (5×2) cm^2
- 2 WLS fibers (1.4 mm diameter) + (2×2) mm^2 SiPM readout
- ¾ layers hit: 125 ns veto





- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards

CRV status

- CRV module and electronics designs nearly complete.
- Modules
  - Extrusion fabrication complete
  - Di-counter fabrication started at UVA
- Electronics
  - Pre-production Front-End & Back-End Boards complete
- Installation
  - Installation tests underway at ANL

Scintillator Extrusion

Di-Counter Facility at UVA

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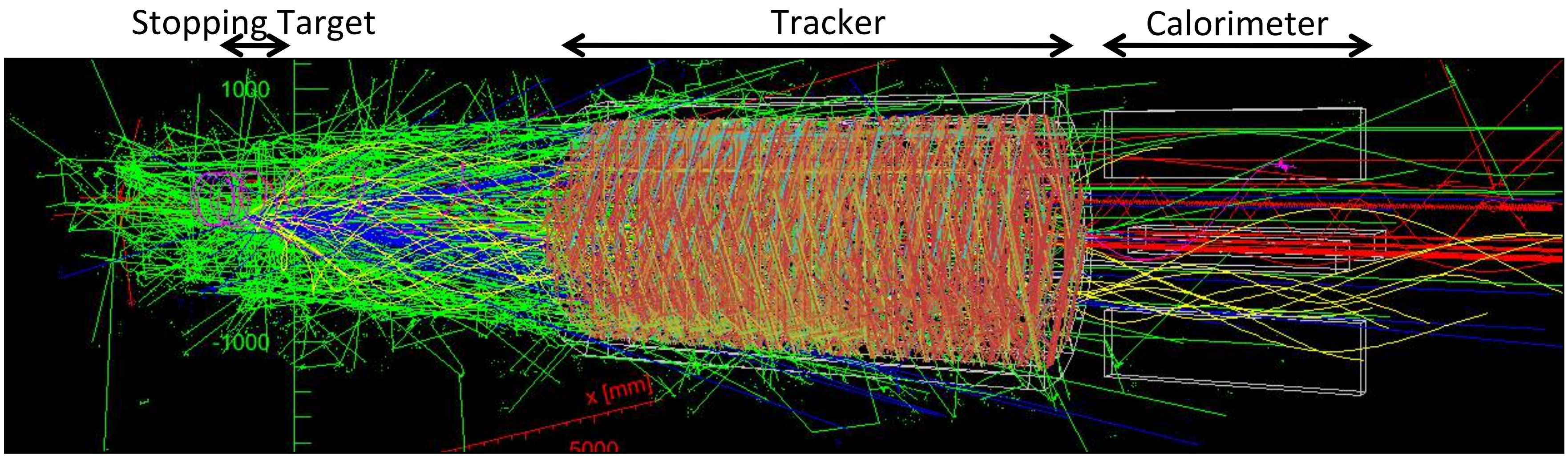
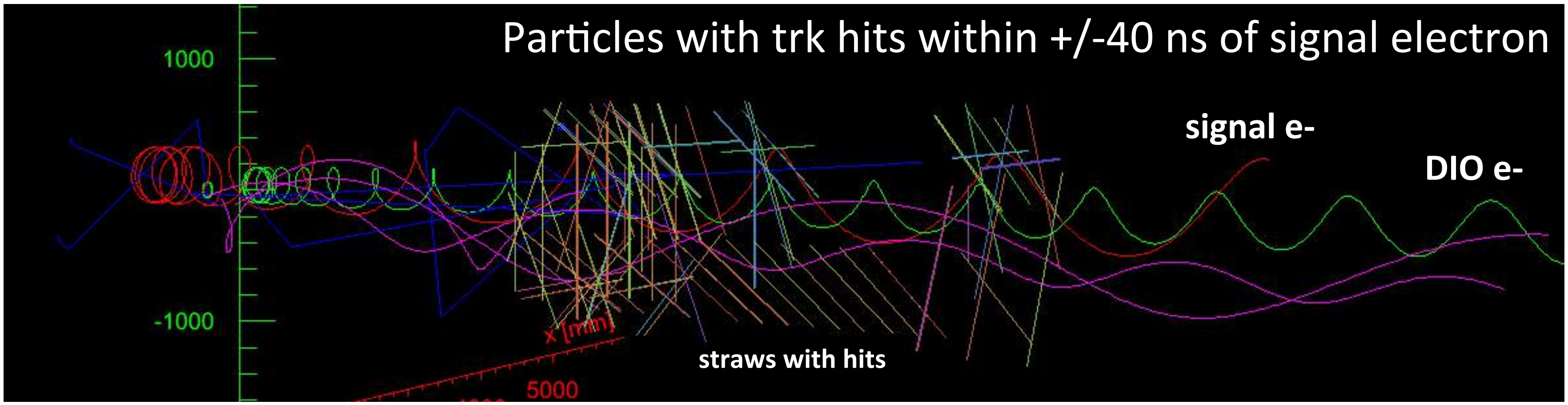
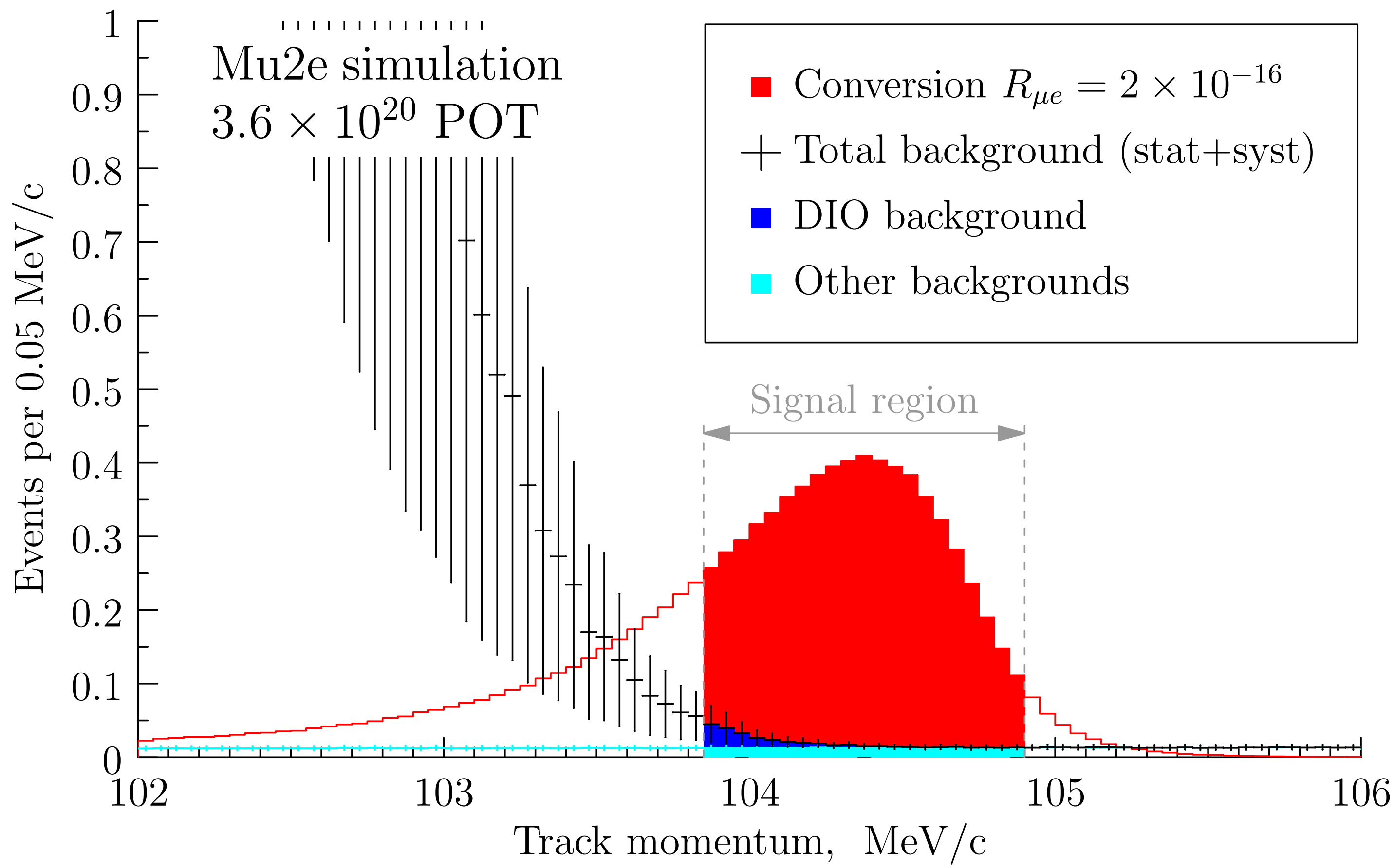
A typical Mu2e signal event

Signal electron, together with all the other hits/tracks occurring simultaneously, integrated over 500-1695 ns window





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)

Mu2e estimateed Background

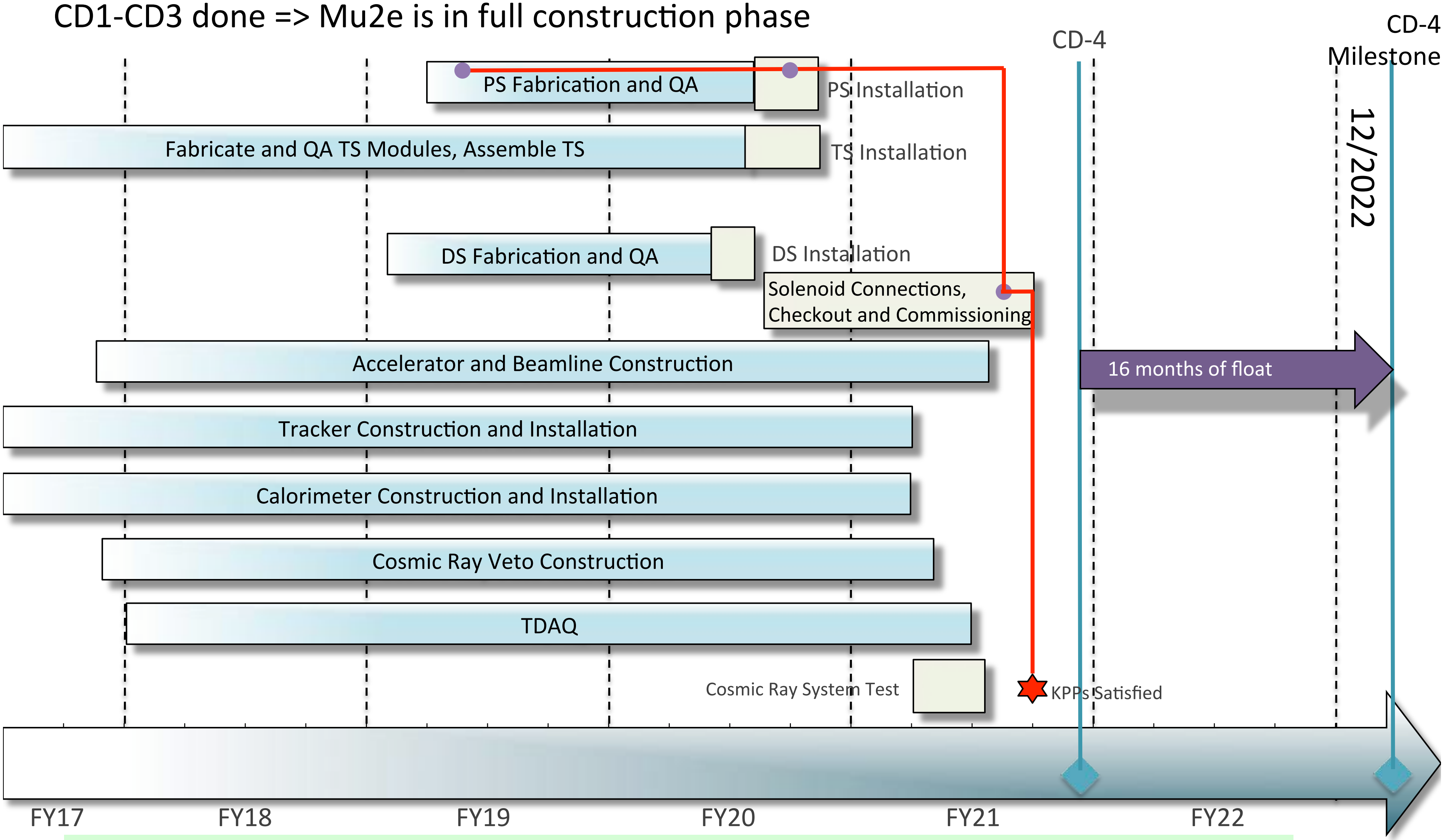
(assuming ~ 10 GHz muon stops, $6x10^{17}$ stopped muons in $6x10^{7}$ s of beam time)

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)**

Upper Limit < 8×10^{-17} @ 90% C.L.

Mu2e Schedule

CD1-CD3 done => Mu2e is in full construction phase



Commissioning middle 2020, first beams end of 2021, stable running 2022-2026

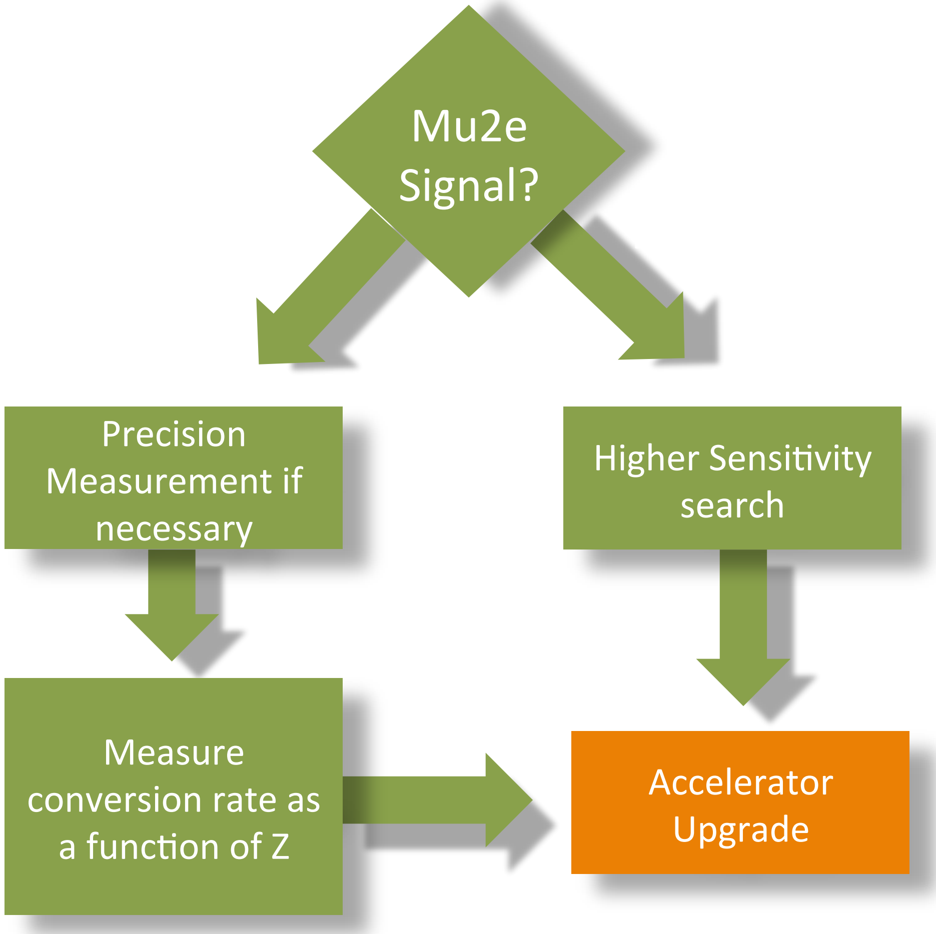
Summary & conclusions

The Mu2e experiment will exploit the highest intensity muon beams of the Fermilab complex to search for CFLV

- Improves sensitivity on conversion exp. 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

Do we need Mu2e-II ??



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

Mu2e-II EOI and problems

Studies for Mu2e-II (x10 reach) continuing

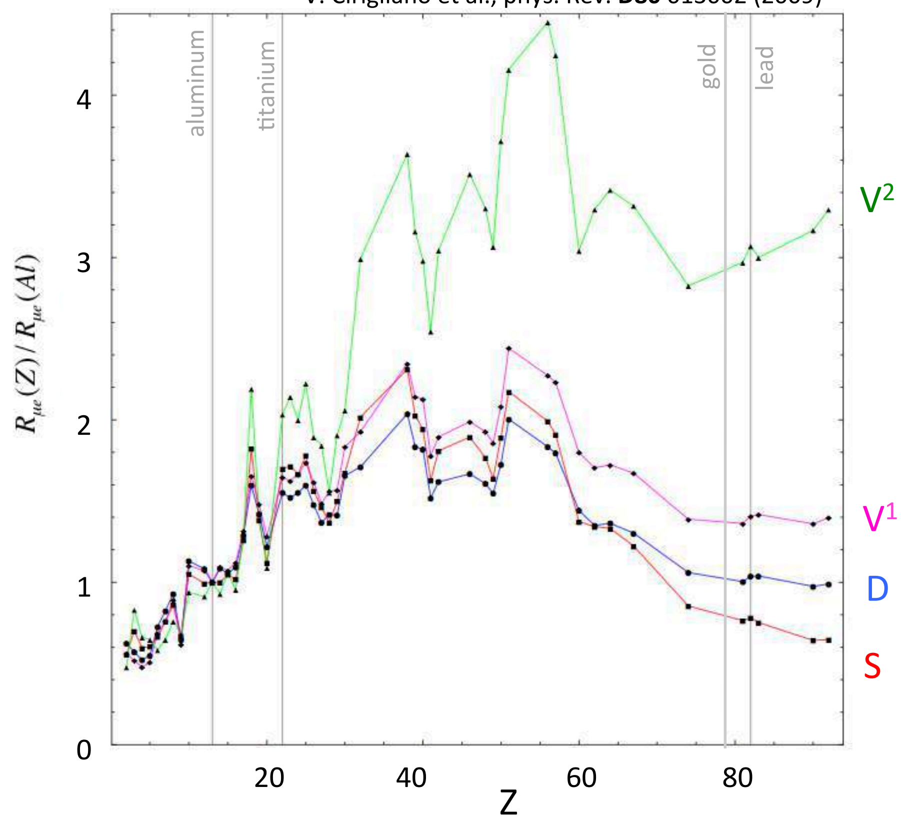
➔EOI written (1307.1168 + 1802.02599)

➔ Need for a large detector, accelerator and solenoid improvement

1) 800 MeV beam from PIP-II Linac
2) it may need a new PS and a radiativelly cooled target to handle higher power and dose
3) radiation safety : needs more shieldings
4) Needs to improve detectors

➔ It CLFV discovered, it could help having runs with different targets to understand the dominant operator contribution

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



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.

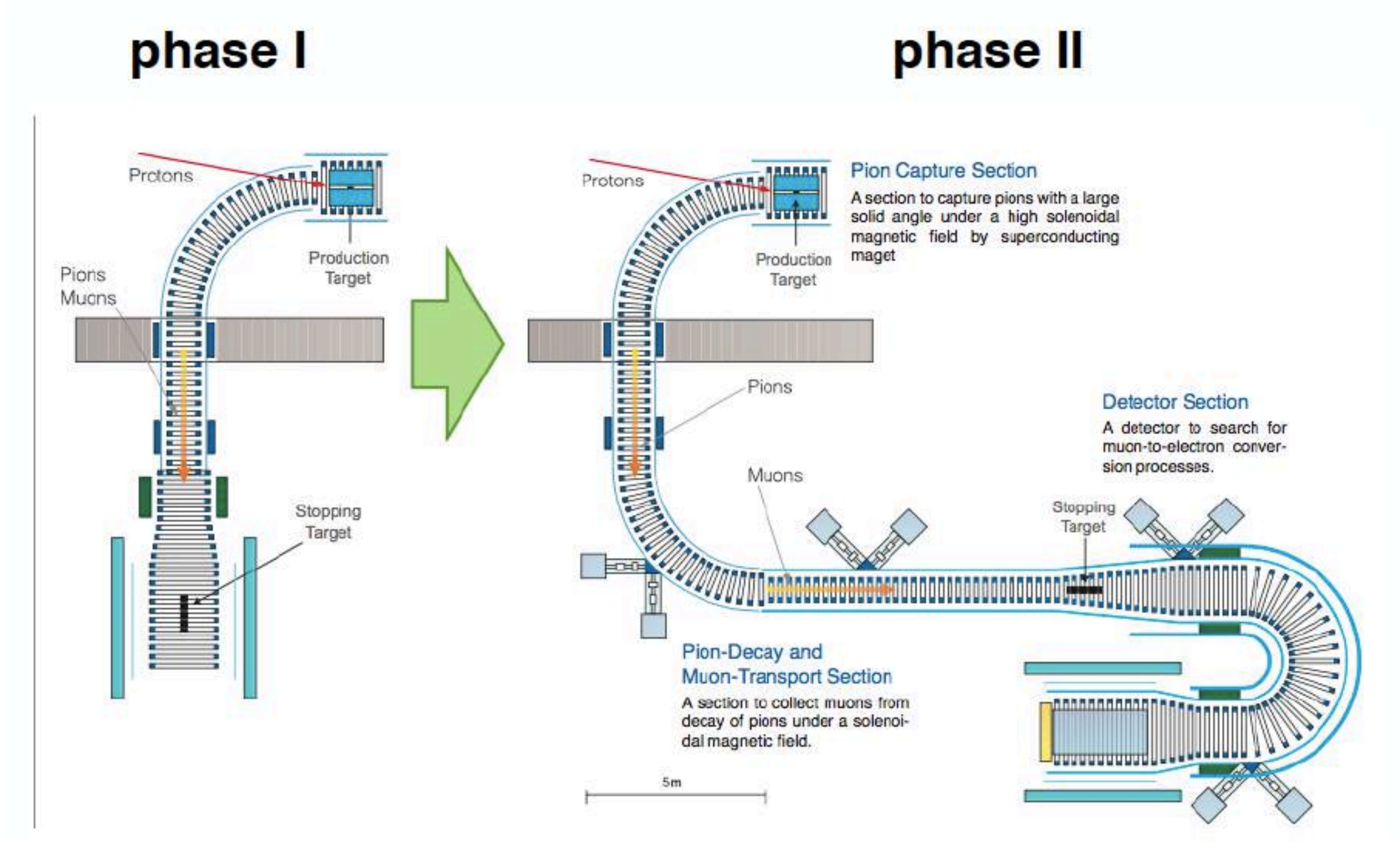
- ❑ **It does not transmit positrons (no $\mu^- N \rightarrow e^+ N$)**

- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam → higher cost (solenoid shielding, neutron shielding)
- Longer solenoids carry "additional-cost" in operation

Phase-1 could be useful → if successful to study background rate
Phase-2 schedule → not yet approved
Mu2e → looking forward to Mu2e-II

- ❑ Great competition/collaboration → ALCAP @ PSI

World program: COMET



Status of Accelerator

- Most beamline elements up to final focus are installed or are being fabricated
- Extinction system prototype AC dipole & collimators fabricated
- Full prototype of Electrostatic Septum by end of CY
- Resonant Extraction Sextupoles are being fabricated in industry
- Production target for beam commissioning being procured.
  - R&D is continuing to develop higher lifetime target design.
- Prototype Remote Target Handling system fabricated and tested

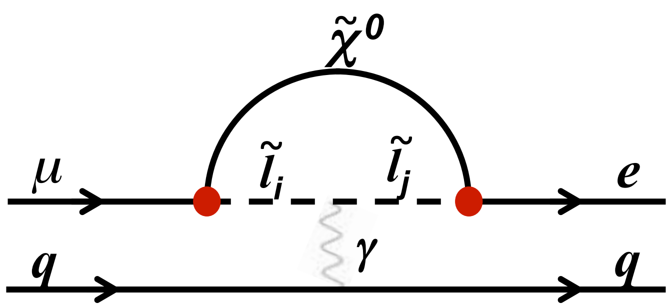
Prototype Remote Target Handler

Res Extraction Sextupole

Extinction Collimator

Specific Example: SUSY

Probe SUSY through loops

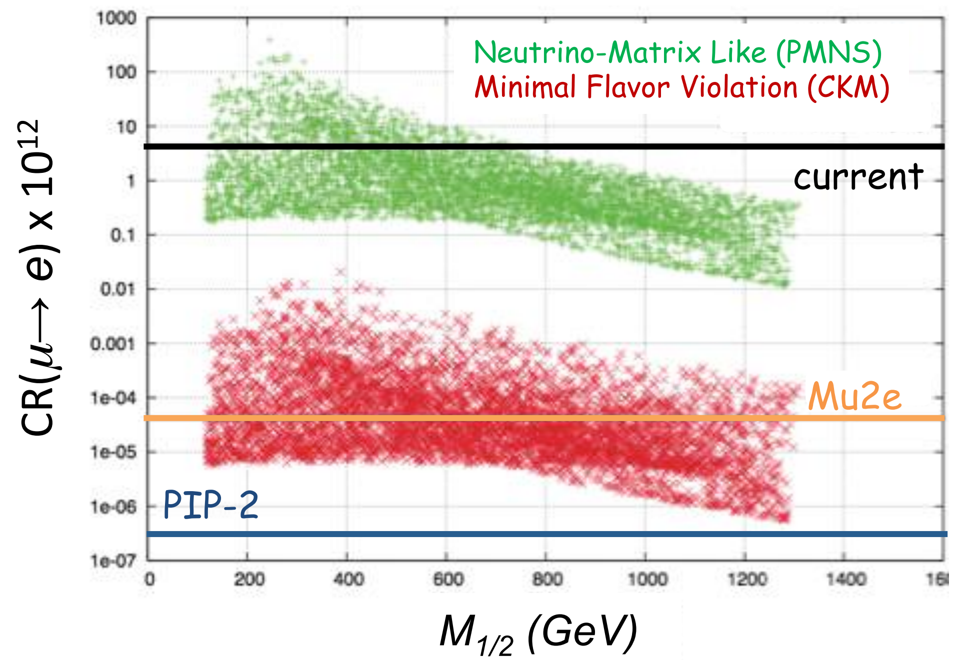


If SUSY seen at LHC → rate ~10^{-15}

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

SUSY GUT in an SO(10) framework

$\mu N \rightarrow eN$ (tanβ = 10)



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

Complementary with the LHC experiments while providing models' discrimination

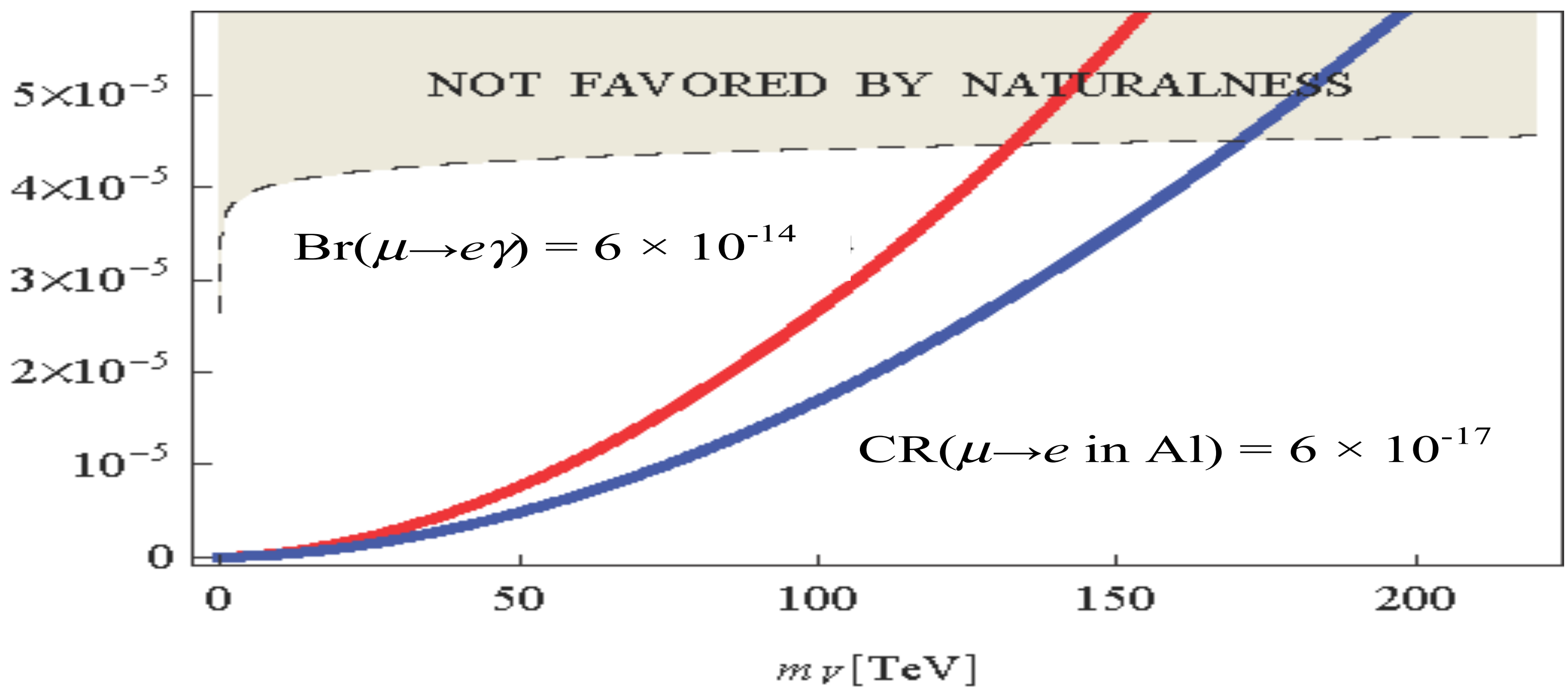
SUSY benchmark points vs LHC

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

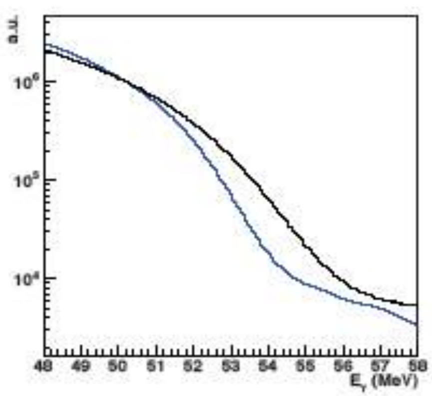
- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

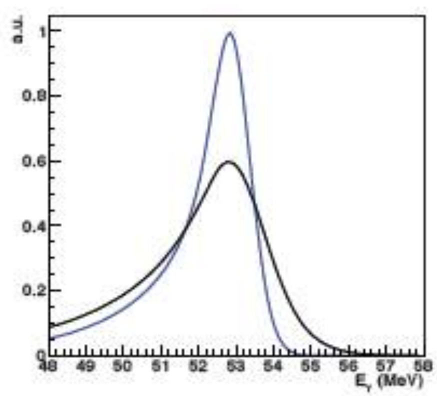
Specific example: Leptoquarks



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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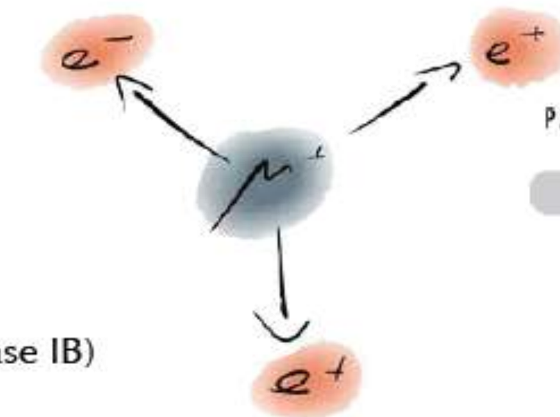
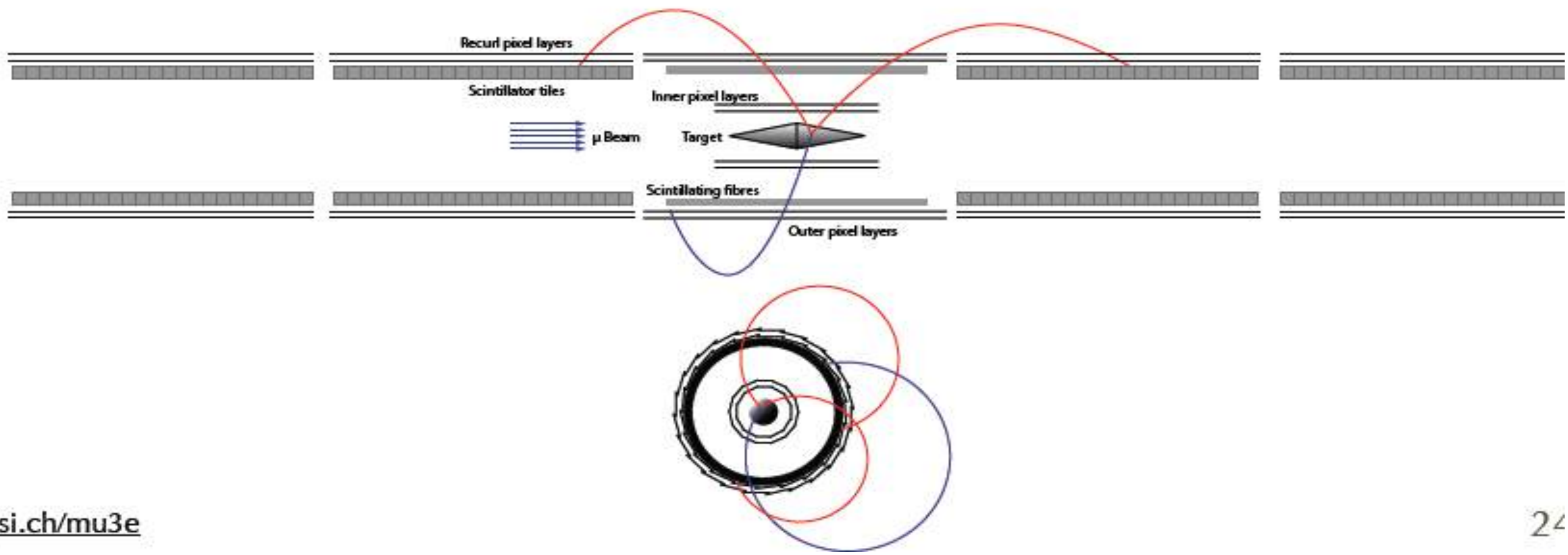
Mu3e at PSI

- Search for μ→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)



PAUL SCHERRER INSTITUT

PSI



vw.psi.ch/mu3e

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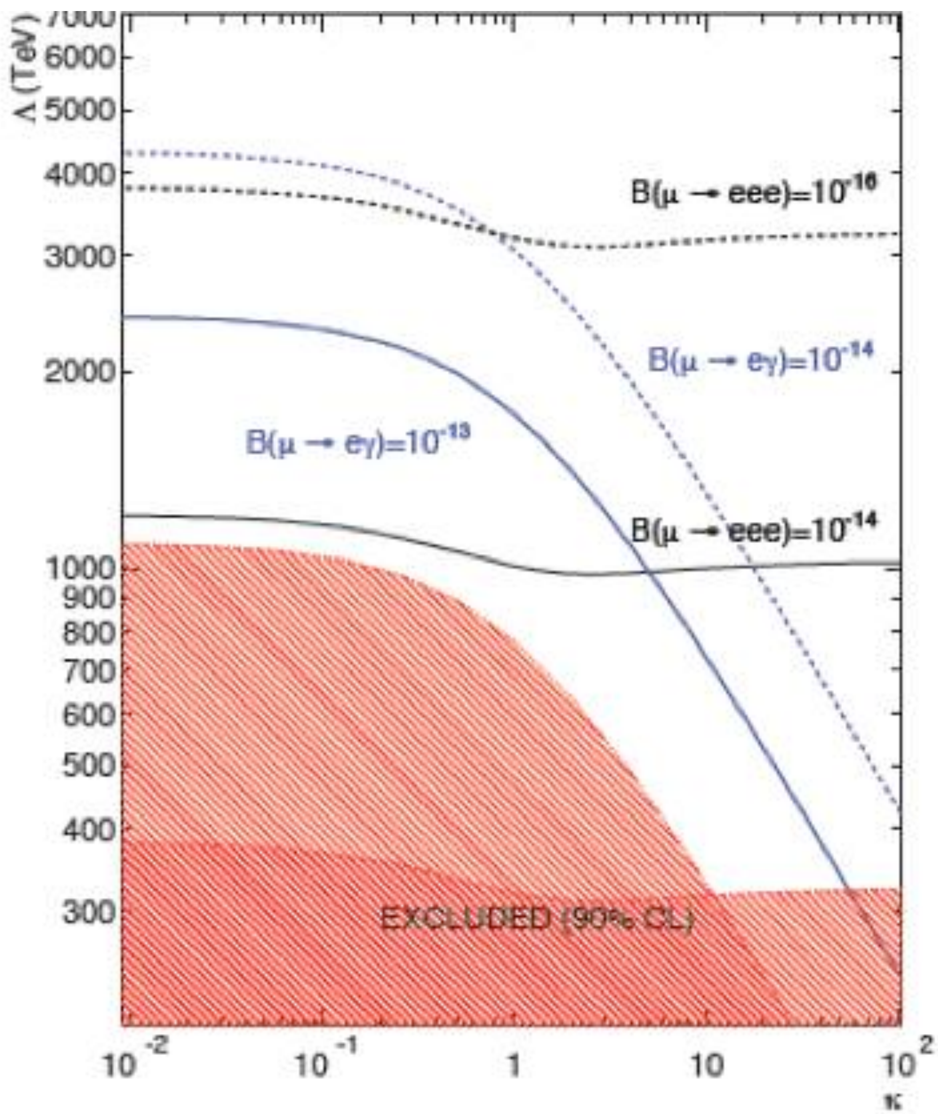
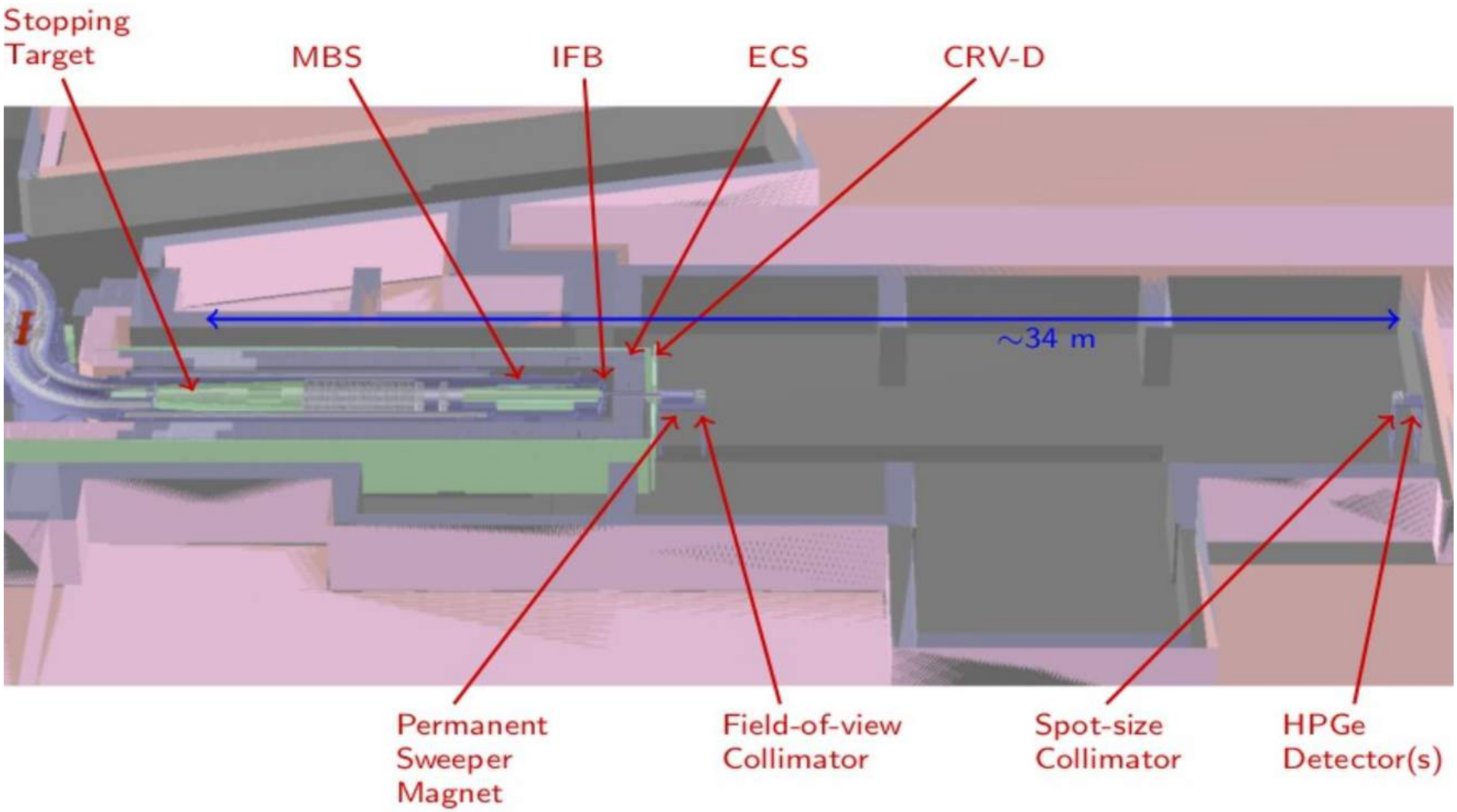
MEG vs Mu3e

- 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



Stopping Monitor



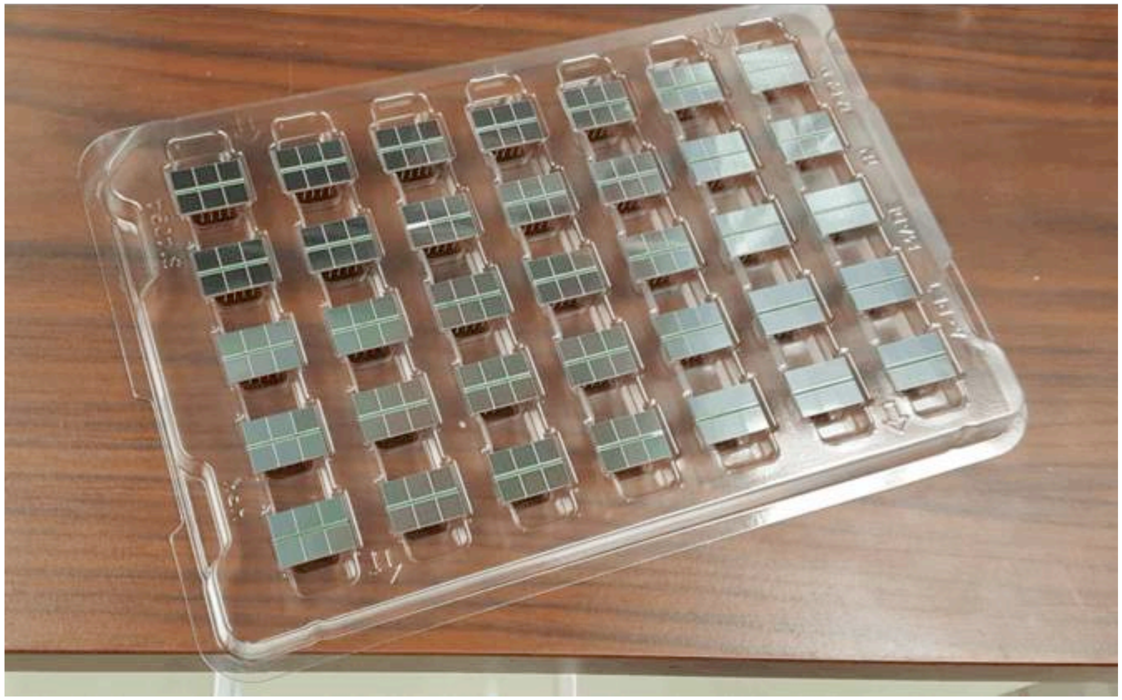
The STM will measure a variety of well understood gamma ray lines … under a high-rate brehmstrahlung background

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 are being built by General Atomics
- TS are being built by ASG superconductors (Ge) + Fermilab

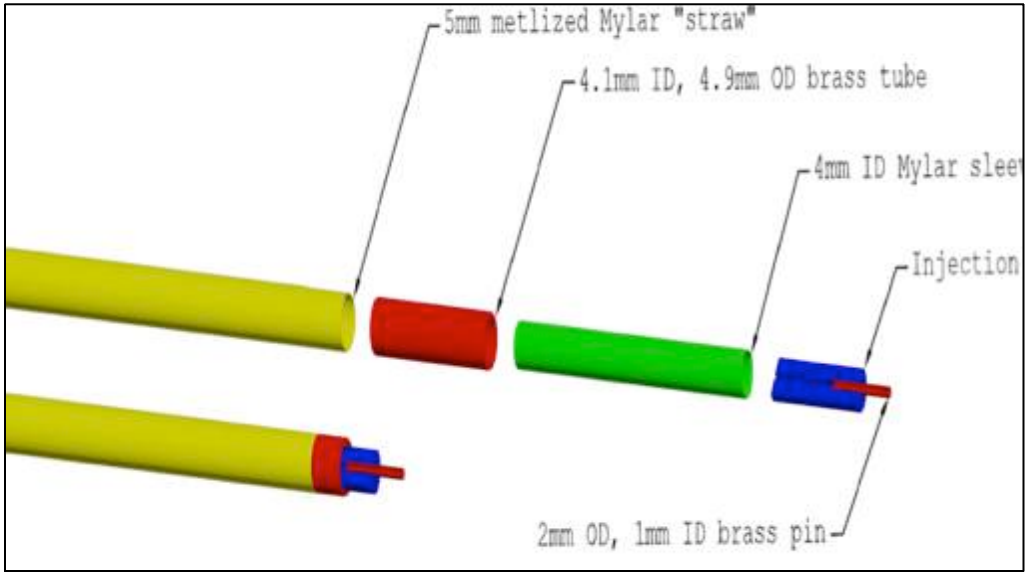
UV extended Mu2e SiPMs



- 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(6x 10^6 hours)**
- Pre-production phase underway: 3 producers being selected.

Straw Characteristics

Straw tube



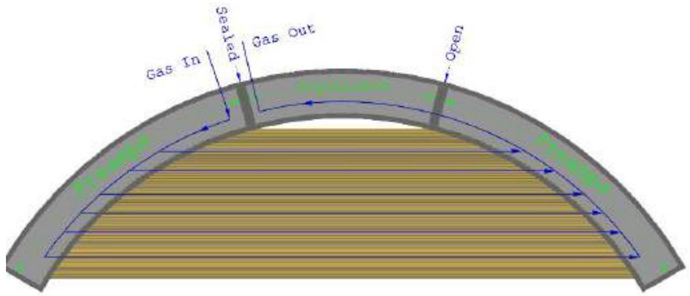
Characteristics:

- 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

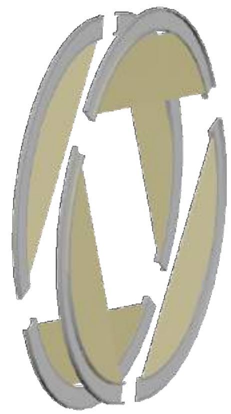
Straw tubes

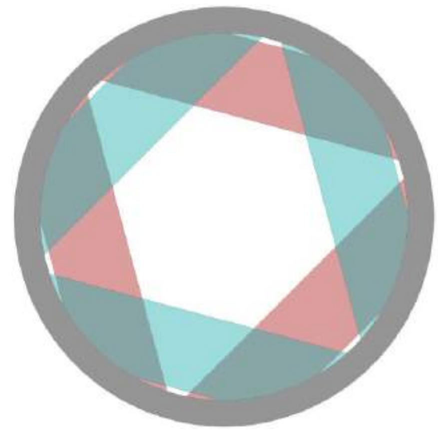
- Proven technology
- Low mass → minimize scattering (track typically sees ~ 0.25 % X_0)
- Modular, connections outside tracking volume
- **Challenge: straw wall thickness (15 μm) never done before**

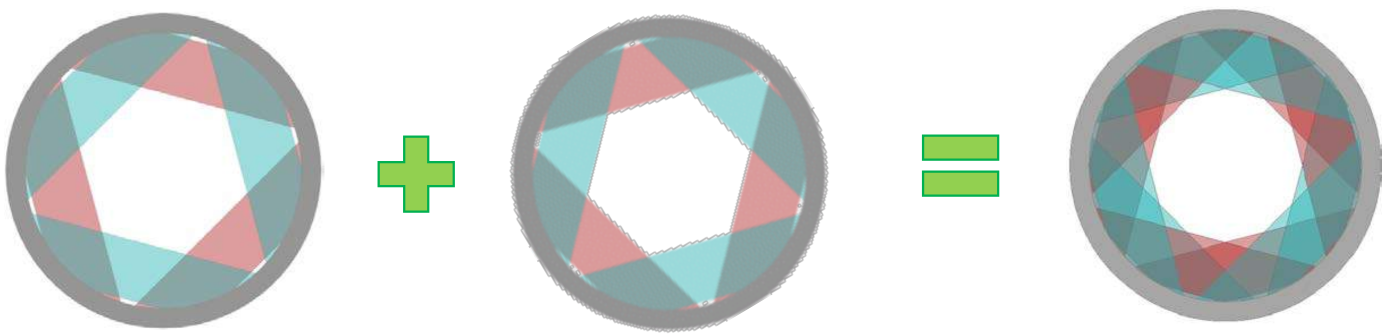
The Mu2e Tracker (2)



Custom ASIC for time division:
$\int \approx$ 5 mm at straw center



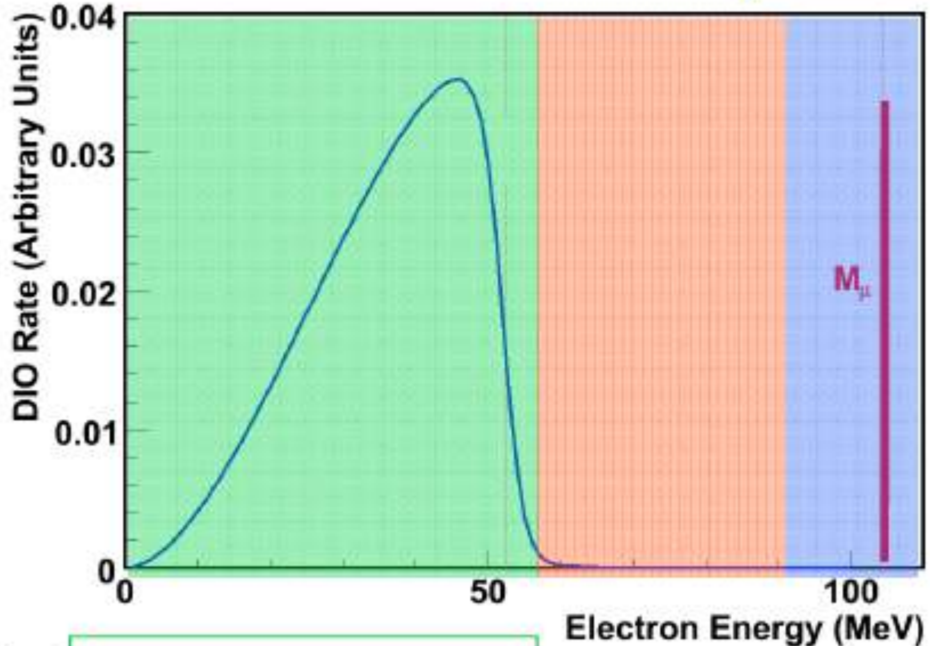




- Self-supporting “panel” consists of 96 straws, 2 layers, 48 straws/layer
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- >20 k straws total

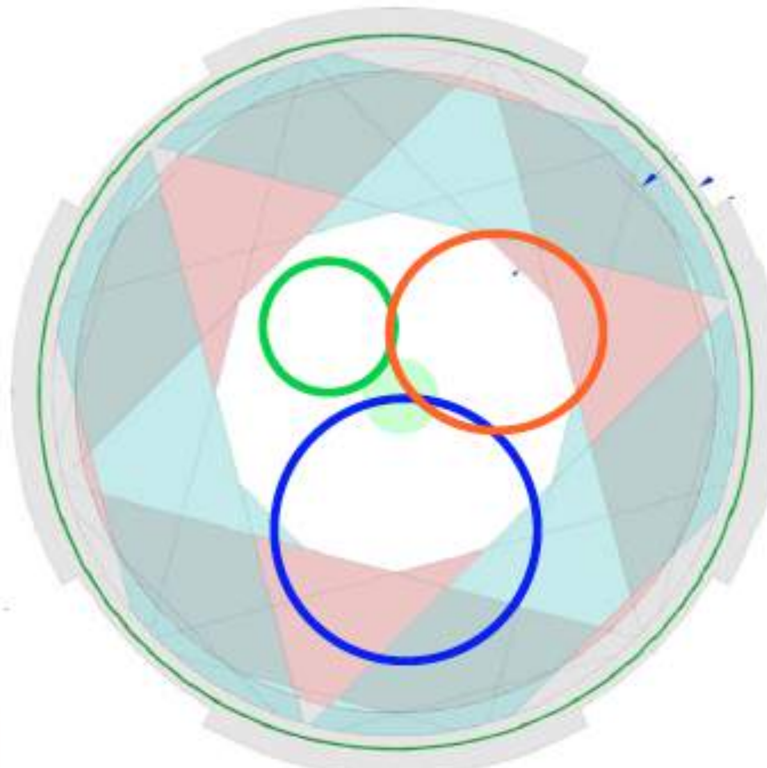
Basic reconstruction scheme

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

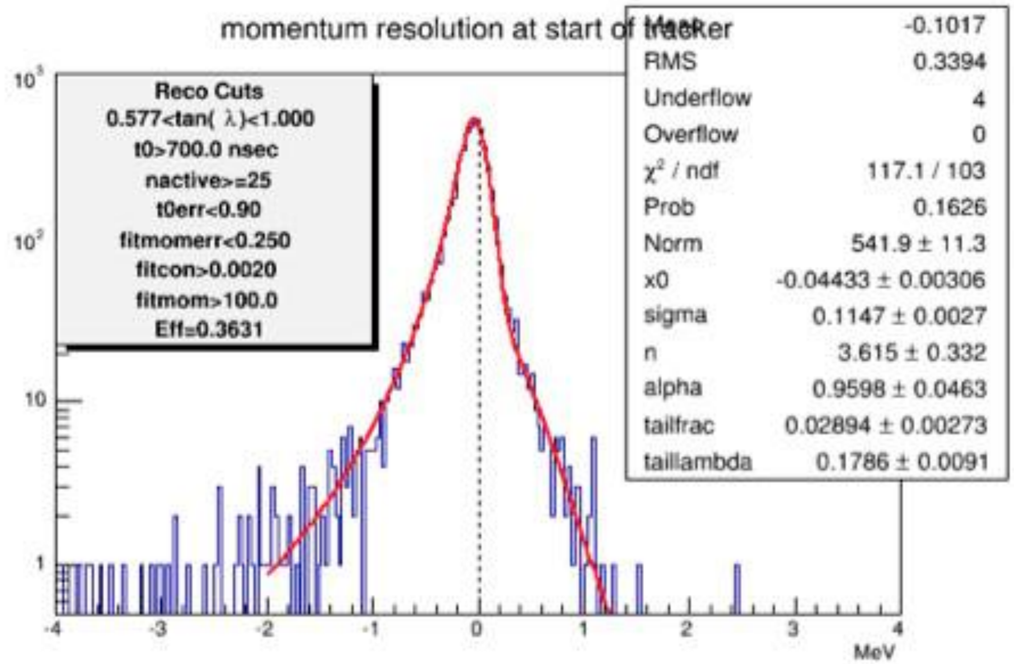
Simulation results on tracker

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

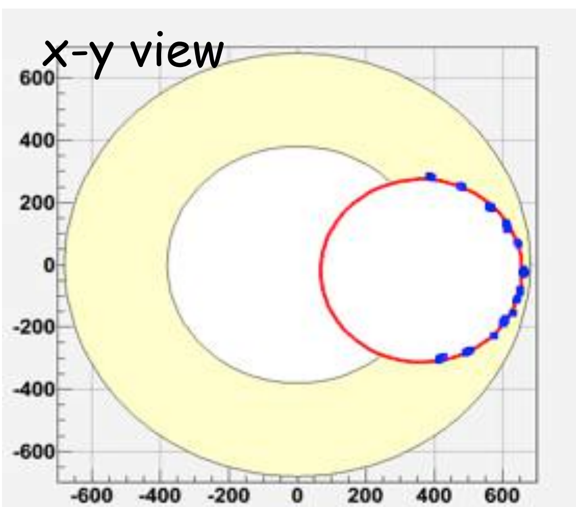
No significant contribution of
mis-reconstructed background

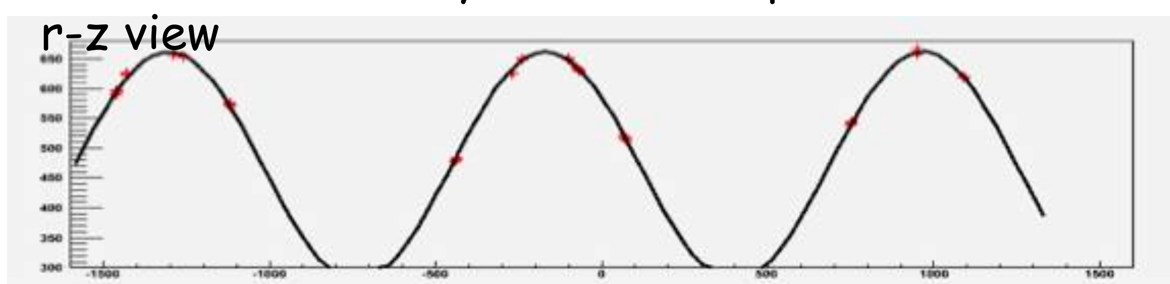
Momentum resolution

core σ~120 keV
tail σ~180 keV (2.5%)

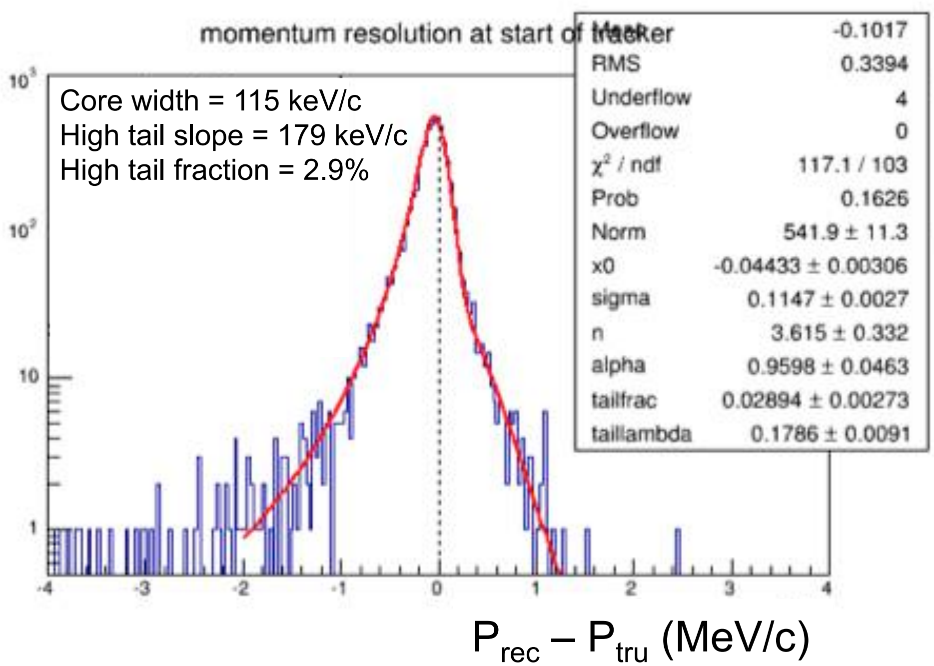


Fit: Crystal Ball + exponential

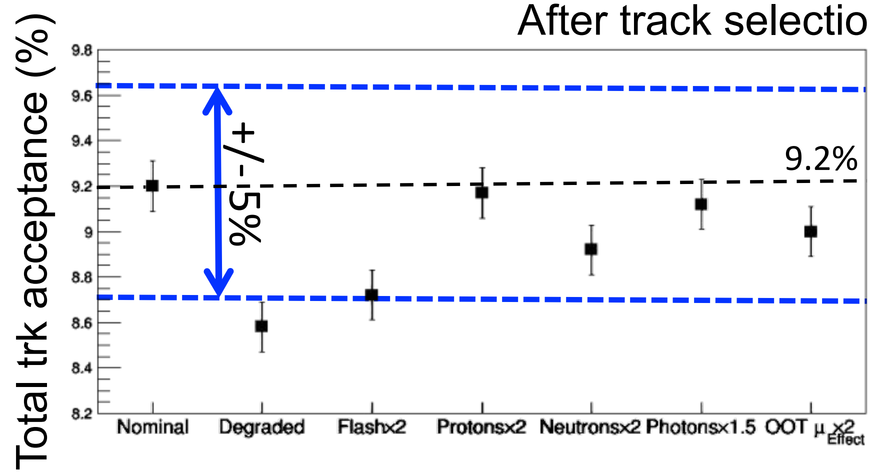


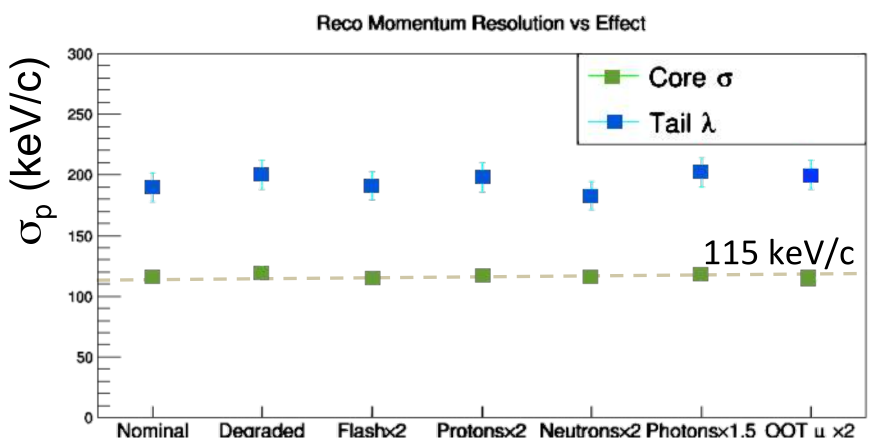


Expected tracker performances from full simulation



After track selection





Variations in accidental hit rate

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

- The full tracker leak rate limit is 6 cm^3/min .
  - many possible sources
  - individual straw leak limit is 9.6 x 10^{-5} cm^3/min
  - 124 straws tested at FNAL last summer;121 passed