Study of the impact of magnetic field uncertainties on physics parameters of the Mu2e experiment

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What is CLFV?

Mu2e is an experiment searching for signature of Charged Lepton Flavor Violation (CLFV)

$D_s^+ \rightarrow \pi^+\pi^0 \quad [c\bar{s} \rightarrow u\bar{d} + (d\bar{d} + u\bar{u})]$

BR $\sim 10^{-4}$

Quark Flavor Mixing
(related Nobel Prize in 2008)

$\nu_\mu \rightarrow \nu_e$

Oscillation phase $\sim 10^{-4}$

Neutrino Flavor Mixing
Nobel Prize in 2015

$\mu \rightarrow e\gamma$

[BR $< 10^{-13}$]

Charged Lepton Flavor Violation (CLFV)

?

Why search for it?

$\mathrm{BR}(\mu \to e\gamma) < 10^{-52}$ in the Standard Model (SM)

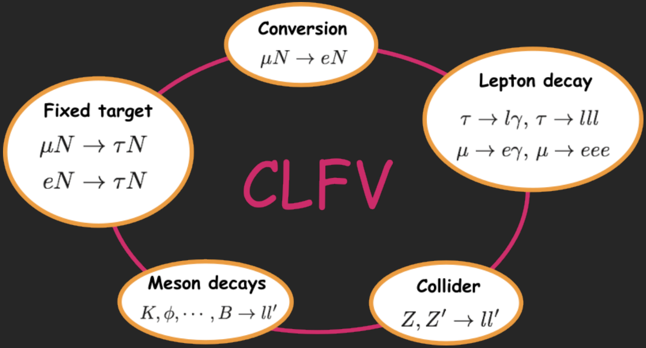
$\Downarrow$

A CLFV observation is an unambiguous signal of New Physics

All New Physics models predict CLFV at variable but substantial rates:
SUSY, extra dimensions, lepto-quarks, W'/Z', extended H sector, heavy ν, ...

Complementary probe to direct New Physics searches at colliders,
with a reach to much higher scales

How to search for it?



Many processes can provide CLFV signal
but sensitivity differs by orders of magnitude

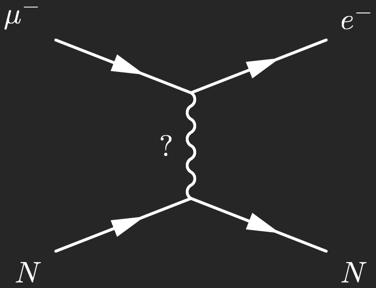
μN $\rightarrow$ eN: best process to look

- Muons are easy to produce and have a long lifetime
- Rare muon processes offer the best combination of New Physics reach and experimental sensitivity

$\mu^+ \rightarrow e^+\gamma$
MEG @PSI

$\mu^+ \rightarrow e^+e^-e^+$
Mu3e @PSI

$\mu^- N \rightarrow e^- N$
Mu2e @Fermilab
COMET @JPARC



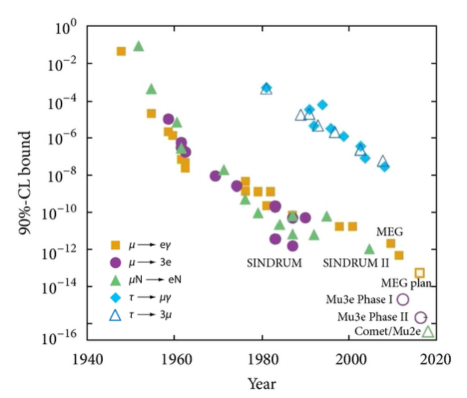
No combinatorial background

Induced in a wide range of New Physics models

$\Downarrow$

Help to discriminate among models

CLFV: Experimental status



MEG 2016

- $Br(\mu \to e\gamma) < 4.2 \times 10^{-13}$

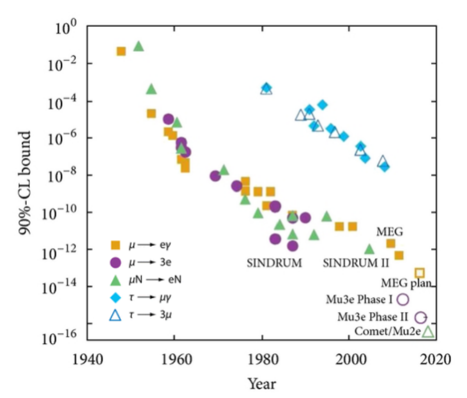
Sindrum-I 1988

- $Br(\mu \to 3e) < 1 \times 10^{-12}$

Sindrum-II 2006

- $R_{\mu e} < 7 \times 10^{-13}$

CLFV: Experimental status



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Sindrum-II 2006

- $R_{\mu e} < 7 \times 10^{-13}$

Mu2e Single Event Sensitivity

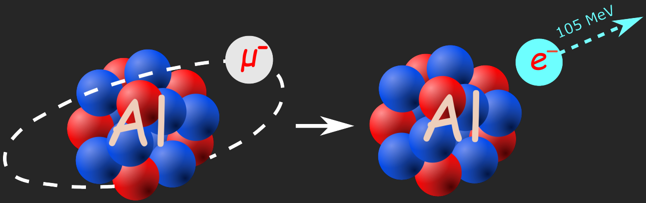
$$R_{\mu e} = \frac{\Gamma(\mu^- + {}^{27}_{13}\mathrm{Al} \to e^- + {}^{27}_{13}\mathrm{Al})}{\Gamma(\mu^- + {}^{27}_{13}\mathrm{Al} \to \nu_\mu + {}^{27}_{12}\mathrm{Mg}^*)} = 2.8 \times 10^{-17}$$

Mu2e in a nutshell

1. Produce 10^{18} muonic ^{27}Al atoms $\Rightarrow$ 1s state
   - Overlap of μ and Al wave function
2. Count "muon conversion electrons" with tracking and calorimetry
   - Mono-energetic electrons emanating from the Al target

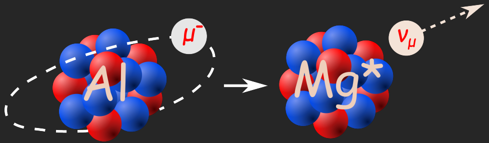
$$E_e = m_\mu c^2 - E_b - E_{recoil} = 104.96 \text{ MeV}$$

3. Suppress background



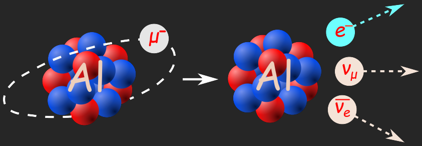
What can happen to the muonic Al?

Nuclear Capture $\sim$ 61%



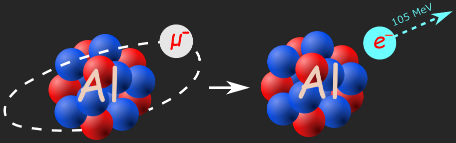
Normalization Factor

Decay in Orbit (DIO) $\sim$ 39%



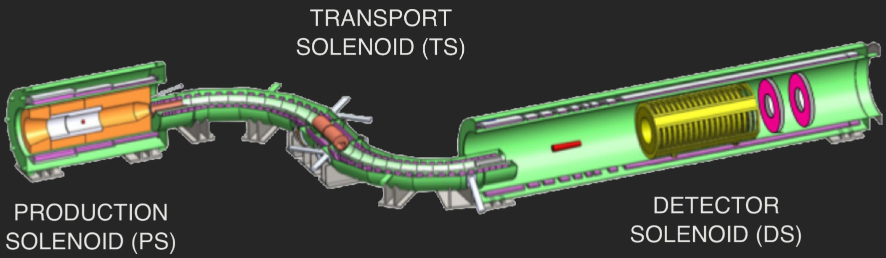
Main Background

Muon Conversion $< 10^{-13}$

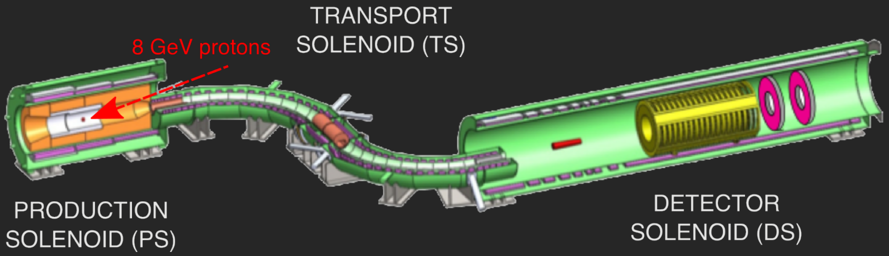


Signal

Mu2e instrumental outlook

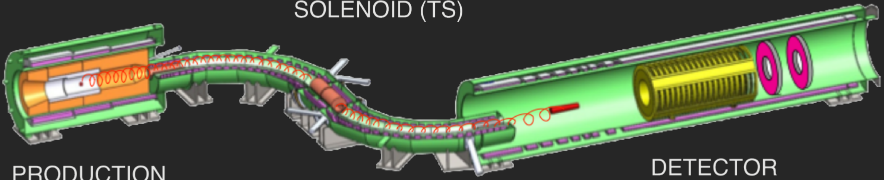


Mu2e instrumental outlook



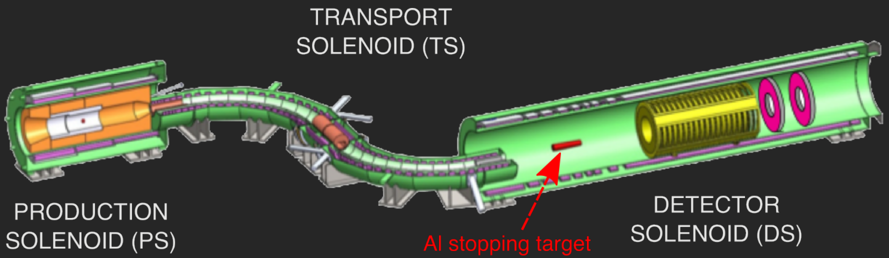
Every second 7×10^{12} protons at 8 GeV interact with a W target

Mu2e instrumental outlook



π are produced and decay into $\mu \Rightarrow$ they spiral into TS

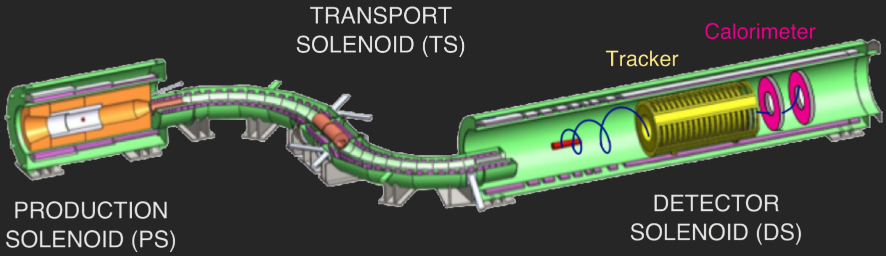
Mu2e instrumental outlook



After 3 years of running, 10^{18} μ^- will be stopped

The hottest muon beamline in the World!

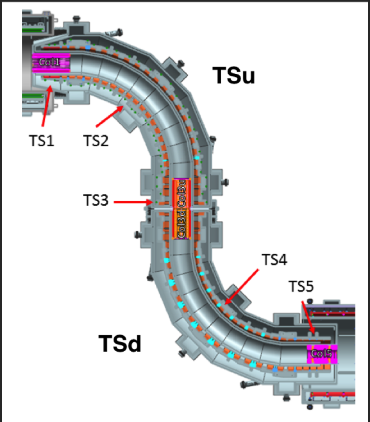
Mu2e instrumental outlook



Muon conversion electrons are detected

TS particularities

This work focuses on the TS solenoid



- The TS has rotated coils to form "S" shape
- The coils experience mechanical and magnetic forces after cooling and powering

$\Downarrow$

TS can be misaligned in going from survey to running conditions

Motivation for this work

Question 1

How are the design functions of TS (μ^+/μ^- splitting, low p selection) affected if TS is misaligned?

Question 2

How do these effects influence the physics of the experiment (expected signal and background rates)?

Question 3

How can we notice if TS is misaligned after cooling and powering?

Which TS misalignments?

Unknown misalignments have a very large number of degrees of freedom

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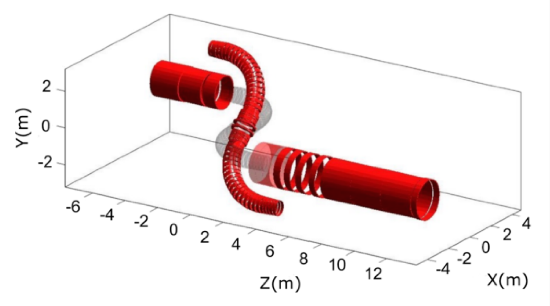
Worst cases are identified as being overall rotations of TSu/TSd as solid objects

Also most likely to happen



Analysed TS misalignments (vertical):

- Small rotations about the X and Z axis ($\sim 0.1^\circ \Rightarrow O$(mm) max coil shift)
- Large rotations about the X and Z axis ($\sim 1^\circ \Rightarrow O$(cm) max coil shift)
- Individual parallel coil displacements ($\sim$ 2 cm) about the Y axis

Topics examined

Muon and Pion Stopping Rates

Sensitive to the overlap of the stopping target with the beam steered by TS onto the target

Background from beam electrons

Sensitive to scattering of the beam off material in the DS region

β Source Test

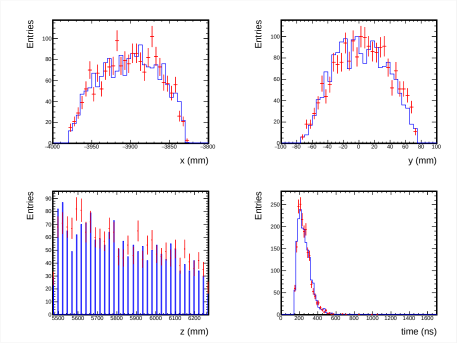
Take advantage of the small Larmor radius of low-momentum e^- to trace approximately the TS field lines and detect misalignments

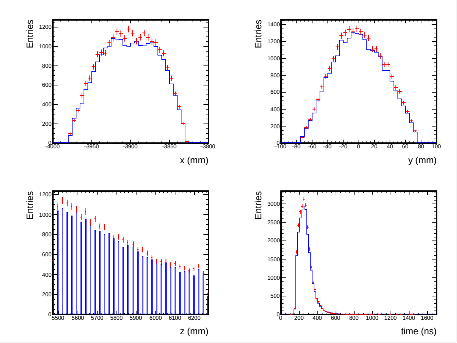
Stopped particles

Distributions of particles stopped at the capture target

Stopped Muon Distributions (10^6 POT)

Stopped Pion Distributions (10^7 POT)





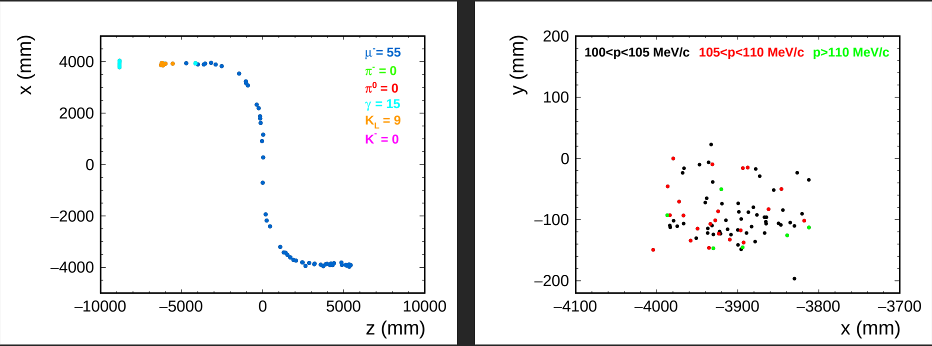
Default field vs
realistic case of 0.1° rotation about $-X$ of both TSu and TSd

For realistic cases, the rates are nearly insensitive to the misalignments

Beam electrons background

Electrons Origin

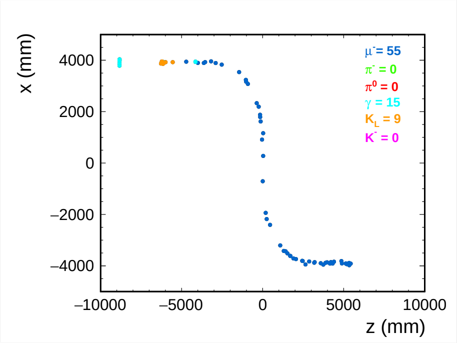
Electrons at the capture target



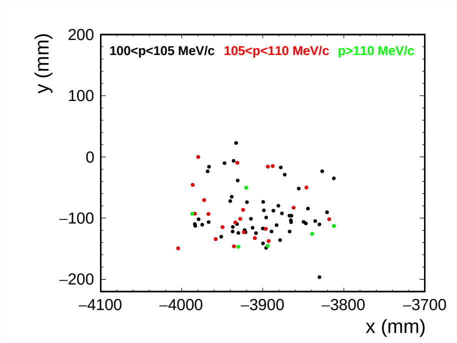
Default field – 2×10^9 POT

Beam electrons background

Electrons Origin



Electrons at the capture target



Default field – 2×10^9 POT

$$N_e \approx (2.5 \pm 1.2) \times 10^{-4}$$

β source test

Why?

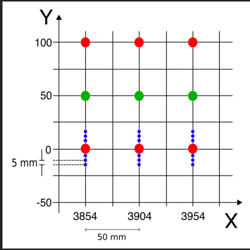
Although signal and background are found barely sensitive to realistic misalignments, a moderately sensitive test of TS misalignments is desired

How?

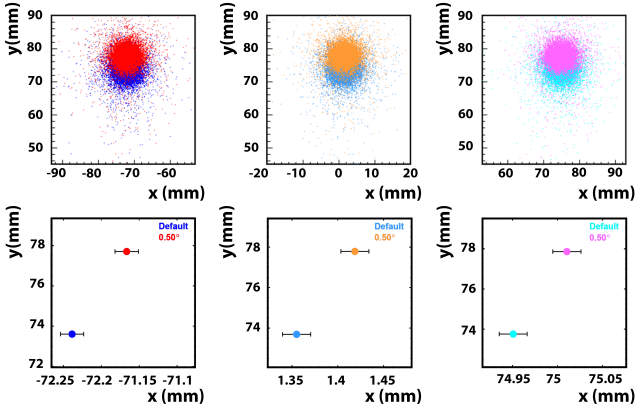
- Low-momentum e^- from a conventional β source: $^{90}Sr/^{90}Y$
  - No background
  - Good momentum range
  - Moderate activity (non hazardous)
  - Assume collimation of 10 msr ($0^\circ \leq \theta \leq 8^\circ$) and point-like source
- Mild vacuum (air at 1 Torr) to let the e^- go though
- Detector with reasonable resolution for low-momentum e^-: FIBER TRACKER (studied by Northern Illinois University)

Results from the β source test

Effect of 0.50° rotation of TS about $-Z$ compared with the default field



Source locations



Conclusions

- Beam electron background estimated to be $(2.5 \pm 1.2) \times 10^{-4}$ or $< 5 \times 10^{-4}$ at 90% C.L., i.e. one of the minor backgrounds of the experiment
- Physics parameters, such as beam electron background and stopping rates affecting signal and background yields, are barely sensitive to realistic TS misalignments of $O(0.1^\circ)$
- β source test sensitive to misalignments of $O(0.1^\circ)$, provided a reasonably good resolution detector ($\sim 300\ \mu$m) and a mild vacuum (~ 1 Torr) are used

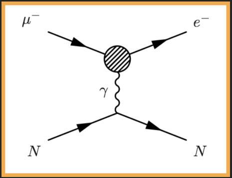
Backup slides

Why $\mu N \to eN$?

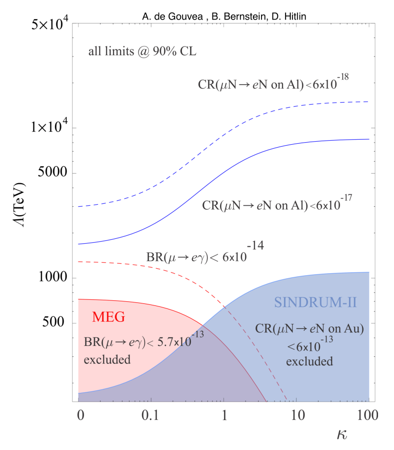
$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

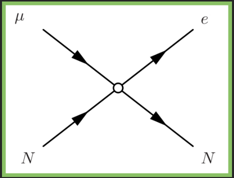
Λ: effective mass scale of New Physics

κ: relative contribution of the contact term



$\kappa \ll 1$





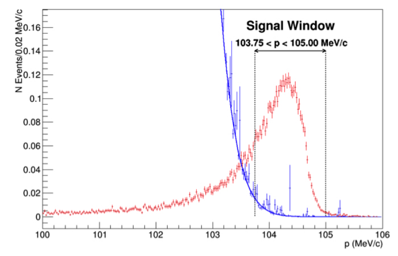
$\kappa \gg 1$

Backgrounds

- μ^- decay in orbit (DIO)
- Radiative μ^- capture

$$\mu^- \mathrm{Al} \to \gamma \nu_\mu \mathrm{Mg}$$

$\longrightarrow$ Momentum resolution



- Radiative π^- capture:

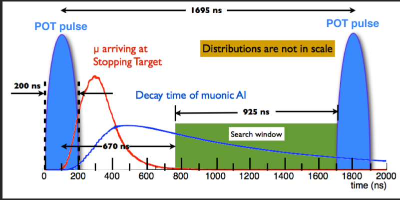
$$\pi^- N \to N^* \gamma, \quad \gamma(Z) \to e^+ e^-$$

- μ^- and π^- decay in flight:

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e, \quad \pi^- \to e^- \bar{\nu}_e$$

- Beam e^-

$\longrightarrow$ Minimize intra-bunch beam and blinding



- $\bar{p}$ $\longrightarrow$ $\bar{p}$ absorber
- Cosmic Rays $\longrightarrow$ Active and passive shielding

Choosing the Stopping Target material

Choose Z based on tradeoff between rate and lifetime

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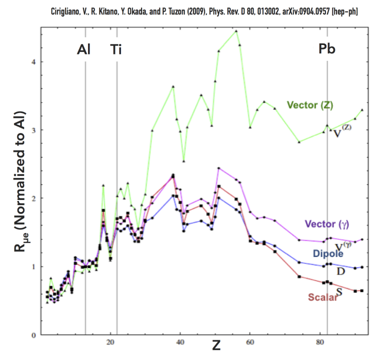
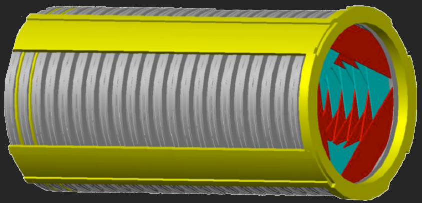
Longer lived reduces prompt backgrounds

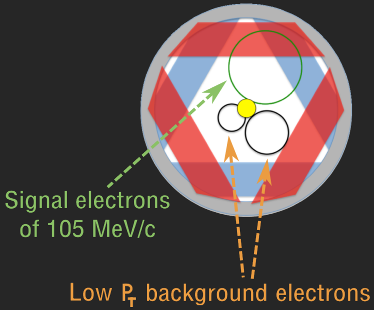


Nucleus	$R_{\mu e}(Z)/R_{\mu e}(Al)$	Bound Lifetime (ns)	Conversion Energy (MeV)
Al(13,27)	1	864	104.96
Ti(22,∼48)	1.7	328	104.18
Au(79,∼197)	$\sim 0.8 - 1.5$	72.6	95.56

The Tracker

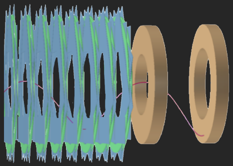
- Principal detector
- $\sim 20,000$ metalized mylar straw drift tubes perpendicular to beam and magnetic field
- Low mass straw tube design
  - → To minimize energy loss and multiple scattering
- Hole in the center of the tracker
  - → Blind to low P_T background
- 180 KeV resolution @105 MeV

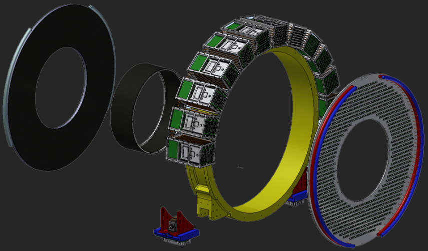




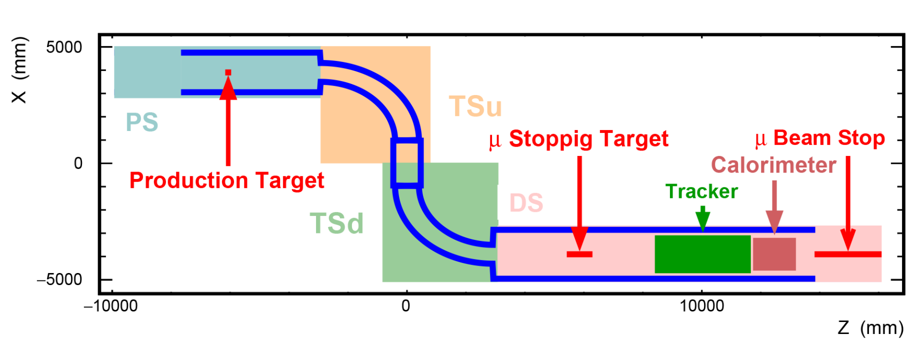
The Calorimeter

- Particle identification to distinguish μ^- / e^- + background rejection by cross-checking the tracker
- $\sim$ 1350 pure Cesium Iodide crystals within two annular disks
  $\rightarrow$ Blind to low P_T background
- Almost full acceptance for conversion electron signal @100 MeV



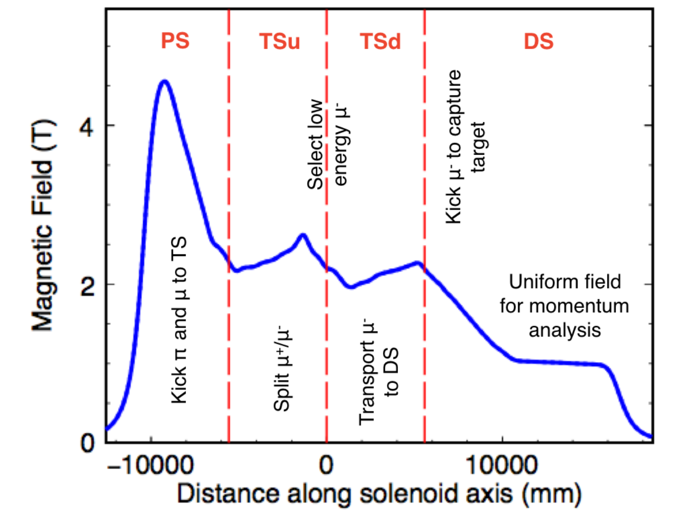


Field Maps and Transport Line



Simulated particles are traced inside the area covered by the field maps

The Mu2e Magnetic Field

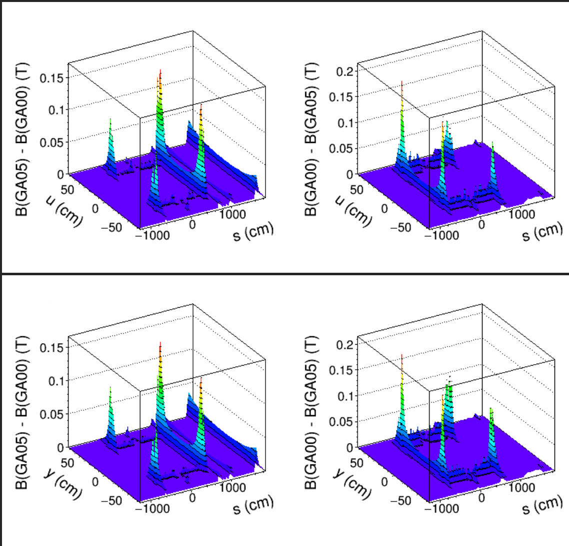


This work focuses on the TS solenoid

Validating different solenoid designs

Field comparison between split coil (GA00) and helical winding (GA05) designs

- Different design only in DS
- Relevant differences observed in DS region
- Local maxima at TS coils are spurious
- Same machinery used to validate misaligned solenoid maps for this thesis work



Methodology and toolkit

- Calculation of field maps with varied geometries using MATLAB
- Validation of varied field maps using ROOT
- Physics simulation using the varied maps with GEANT4 in the framework of the Mu2e Offline software
- Analysis of simulation results using ROOT

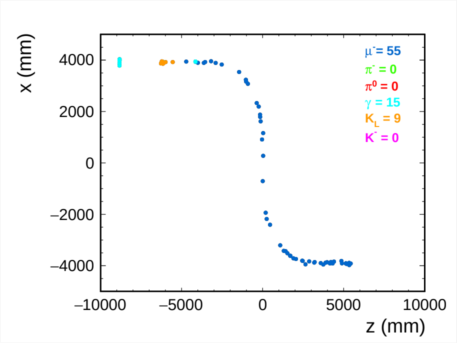
μ^-/π^- Stopping Rates and Fractional Yield Differences

	$R_\mu(\times 10^{-3})$	$R_\pi(\times 10^{-8})$	$\delta N_\mu/N_\mu^{(0)}(\%)$	$\delta N_\pi/N_\pi^{(0)}(\%)$
Default (old design)	1.86 ± 0.04	8.82 ± 0.06		
Default (new design)	1.83 ± 0.04	8.41 ± 0.05		
New Design 0.15° wrt $-Z$ TSu, 0.15° wrt $-Z$ TSd	1.85 ± 0.04	8.80 ± 0.06	-1.04 ± 3.33	-3.42 ± 0.95
New Design 0.50° wrt $-Z$ TSu, 0.50° wrt $-Z$ TSd	1.78 ± 0.04	4.94 ± 0.03	3.16 ± 3.22	13.80 ± 0.83
Old Design 0.1° wrt $+X$ TSu, 0.1° wrt $-X$ TSd	1.87 ± 0.04	8.33 ± 0.05	-0.32 ± 3.29	-0.80 ± 0.90
Old Design 0.1° wrt $-X$ TSu, 0.1° wrt $+X$ TSd	1.81 ± 0.04	9.44 ± 0.06	2.52 ± 3.22	0.55 ± 0.90
Old Design 0.1° wrt $+X$ TSu, 0.1° wrt $+X$ TSd	1.92 ± 0.04	9.07 ± 0.06	-3.17 ± 3.36	-1.63 ± 0.91
Old Design 0.1° wrt $-X$ TSu, 0.1° wrt $-X$ TSd	1.81 ± 0.04	8.26 ± 0.05	2.31 ± 3.22	5.60 ± 0.86
Old Design 1° wrt $+X$ TSu, 1° wrt $-X$ TSd	1.77 ± 0.04	11.33 ± 0.07	4.73 ± 3.16	-5.16 ± 0.93
Old Design 1° wrt $-X$ TSu, 1° wrt $+X$ TSd	1.47 ± 0.04	7.14 ± 0.05	21.21 ± 2.75	25.33 ± 0.73
Old Design 1° wrt $+X$ TSu, 1° wrt $+X$ TSd	1.47 ± 0.04	2.82 ± 0.02	20.94 ± 2.76	32.55 ± 0.68
Old Design 1° wrt $-X$ TSu, 1° wrt $-X$ TSd	1.02 ± 0.03	8.13 ± 0.07	45.22 ± 2.13	44.11 ± 5.93
Old Design 20 mm wrt +Y TSu, 20 mm wrt +Y TSd	1.92 ± 0.04	10.64 ± 0.07	-3.06 ± 3.35	-4.67 ± 0.93
Old Design 20 mm wrt −Y TSu, 20 mm wrt −Y TSd	1.90 ± 0.04	9.24 ± 0.06	-2.20 ± 3.33	-0.79 ± 0.90
Old Design 20 mm wrt +Y TSu, 20 mm wrt −Y TSd	1.94 ± 0.04	8.72 ± 0.06	-4.14 ± 3.37	0.74 ± 0.90
Old Design 20 mm wrt −Y TSu, 20 mm wrt +Y TSd	1.89 ± 0.04	9.10 ± 0.06	-1.61 ± 3.31	-0.41 ± 0.90

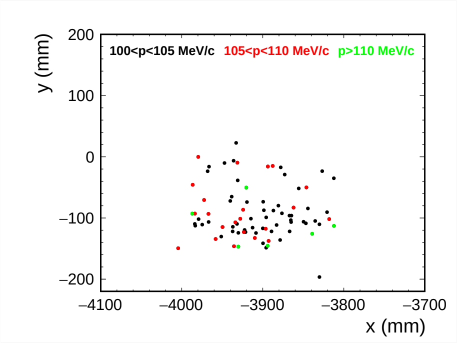
For realistic cases, the rates are nearly insensitive to the misalignments

Beam electrons

Electrons Origin



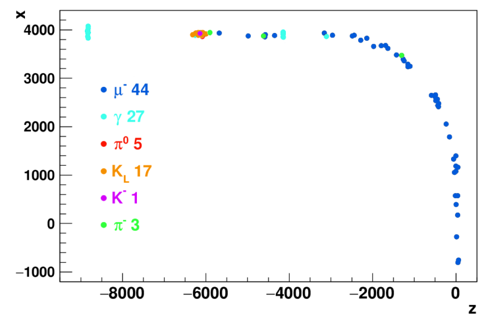
Electrons at the capture target



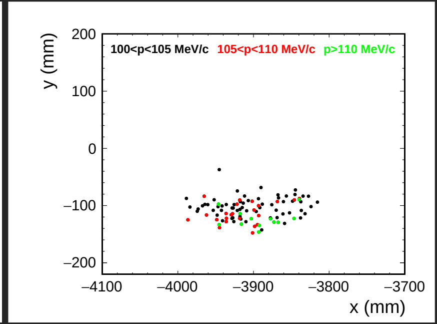
Default field – 2×10^9 POT

Beam electrons in previous study

ELECTRONS ORIGIN



ELECTRONS AT THE CAPTURE TARGET

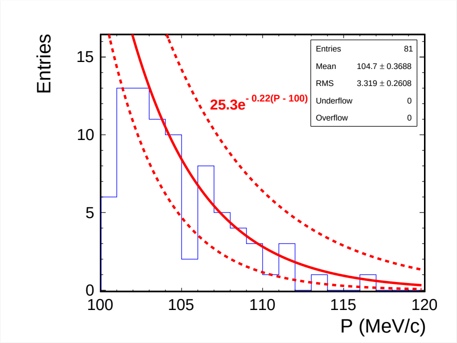


DEFAULT FIELD – 5×10^9 POT

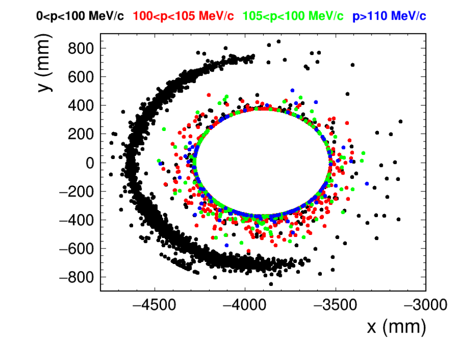
Older analysis considered only electrons created up to TS3

Beam electrons in the tracker

Electrons at the capture target



Electrons in the tracker



Default field – 2×10^9 POT

Electrons are resampled at the capture target by a factor of 10^6

Beam electrons background

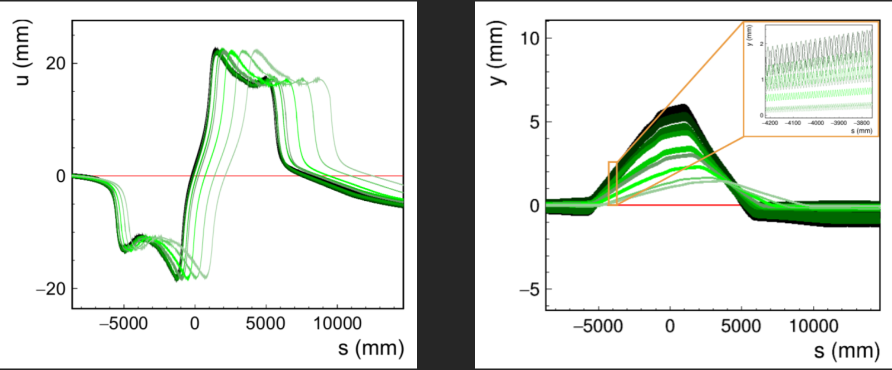
Field Maps	N_{stat} ($\times 10^{15}$)	e^- at capture target BEFORE resampling	e^- in the tracker BEFORE cuts	e^- in the tracker AFTER cuts (N_e)	N_{bkg} ($\times 10^{-5}$)
Previous Estimation (old design)	5.0	97	632	7	2
Default (old design)	2.0	50	4504	17	13
Default (new design)	2.1	81	4106	27	19
New Design 0.15° wrt $-Z$ TSu, 0.15° wrt $-Z$ TSd	2.0	89	3841	18	14
New Design 0.50° wrt $-Z$ TSu, 0.50° wrt $-Z$ TSd	1.9	133	3010	22	17
Old Design 0.1° wrt $-X$ TSu, 0.1° wrt $+X$ TSd	2.0	77	4364	36	27
Old Design 0.1° wrt $+X$ TSu, 0.1° wrt $-X$ TSd	2.0	61	5771	36	27
Old Design 0.1° wrt $+X$ TSu, 0.1° wrt $+X$ TSd	1.8	63	5204	34	28
Old Design 0.1° wrt $-X$ TSu, 0.1° wrt $-X$ TSd	2.0	63	3255	23	17
Old Design 1° wrt $-X$ TSu, 1° wrt $+X$ TSd	2.0	4	N/A	N/A	N/A
Old Design 1° wrt $+X$ TSu, 1° wrt $-X$ TSd	1.8	387	26575	216	180
Old Design 1° wrt $+X$ TSu, 1° wrt $+X$ TSd	1.8	14	1029	3	2
Old Design 1° wrt $-X$ TSu, 1° wrt $-X$ TSd	2.0	191	4926	55	42

$$N_e \approx \frac{N}{N_{stat}} \times 3 \cdot 10^{20} \times 10^{-10} \times 0.5 = (2.5 \pm 1.2) \times 10^{-4}$$

N	=	number of electrons in tracker with $104 < P < 106$ MeV/c and $0.4 < P_z/P < 0.7$
$\mathbf{N_{stat}}$	=	number of simulated POT $\times$ resampling factor (10^6)
$\mathbf{3 \times 10^{20}}$	=	expected number of POT in the experiment
$\mathbf{10^{-10}}$	=	extinction factor
0.5	=	live time window

Why a β source test?

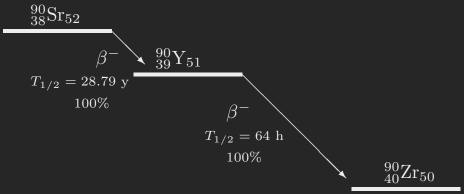
- Although signal and background are found barely sensitive to realistic misalignments, a moderately sensitive test of TS misalignments is desired
- This can be done with low-momentum e^- from a conventional β source
- Assume a mild vacuum (air at 1 Torr) to let the e^- go though

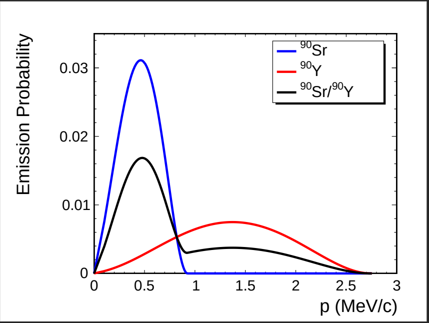


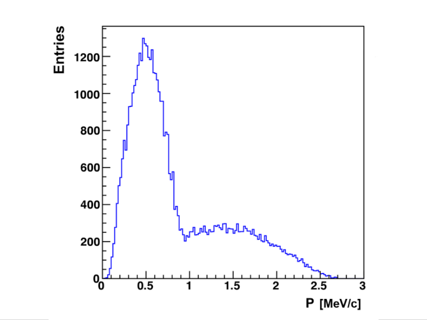
e^- trajectories for $0.4 < p < 2.4$ MeV/c

β source: $^{90}Sr/^{90}Y$

- No background
- Good momentum range
- Moderate activity (non hazardous)
- Assume collimation of 10 msr ($0^\circ \leq \theta \leq 8^\circ$) and point-like source







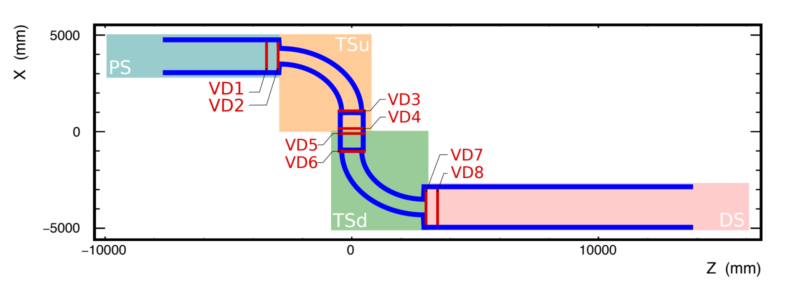
Conditions for the β source test

- Obvious source location in PS (to scan the whole TS)
- Low-momentum e^- path length $\sim$ Larmor radius $\times$ No. of helical rotations $\gg$ TS length $>$ range in STP air
- Mild vacuum needed $\Rightarrow$ also improves resolution by reducing multiple scattering
- Basic simulations performed using 1 Torr
- Dependence of resolution on pressure also studied (0.05 Torr and 50 Torr)

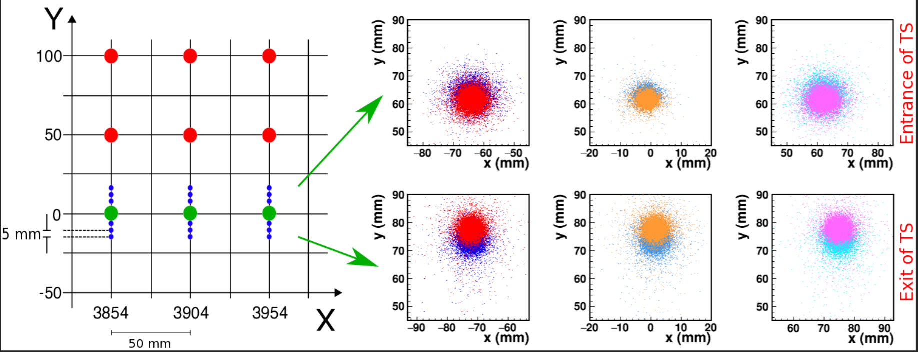
Electron Energy (MeV)	Range (m)
0.1	0.1
0.2	0.4
0.3	0.8
0.5	1.7
0.7	2.6
1	4.1
1.25	5.3
1.5	6.6
1.75	7.8
2	9

Low momentum electron detector

- Detector should have reasonable resolution for low-momentum e^-
- A good option is a fiber tracker, studied by Northern Illinois University
- "Virtual detectors" (ideal planes) used in this thesis, bearing some features of a fiber tracker:
  - (X,Y) resolution: 300 μm
  - Momentum threshold: 200 keV/c



Procedure

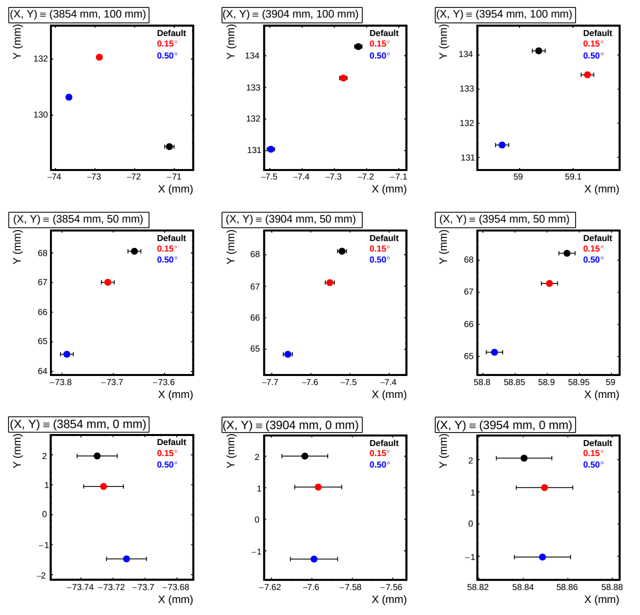


Source locations examined for each misalignment

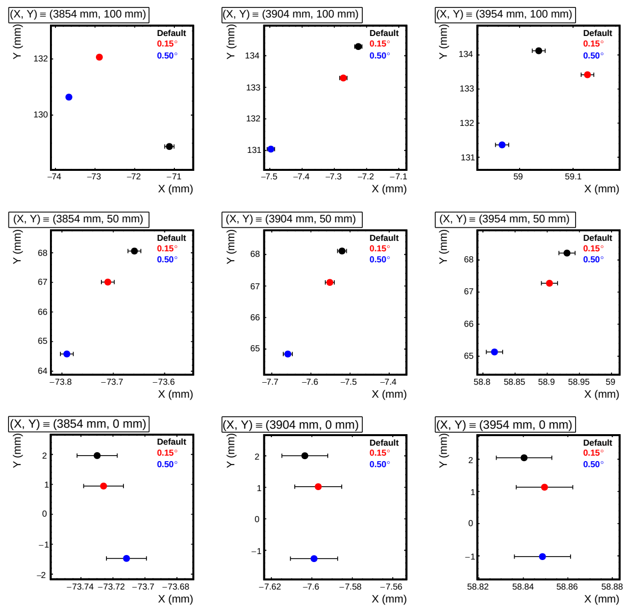
Effect of 0.50° rotation of TS about $-Z$ (top) compared with the default field (bottom)

Primary and secondary e^- (δ rays) are analyzed together, outliers are cut at 4σ

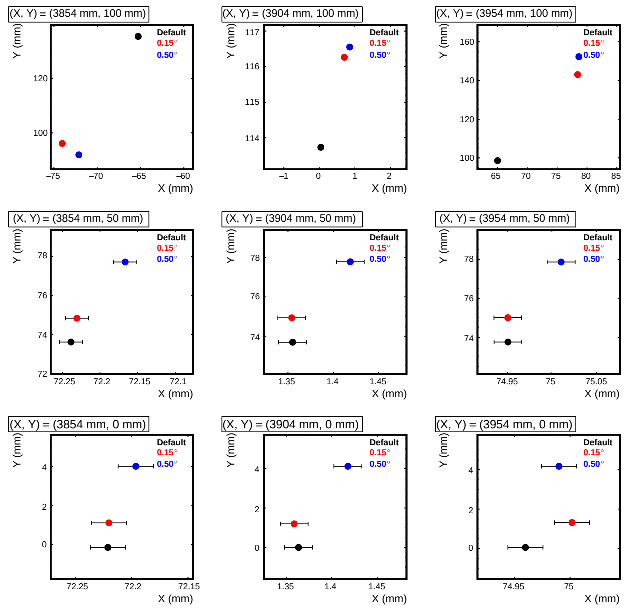
TSu exit, rotation about $-Z$ axis, source above XZ plane



TSu exit, rotation about −Z axis, source above XZ plane



TSd exit, rotation about −Z axis, source above XZ plane



β source test: what's next?

- The thesis provides a proof of principle of the test. The test is important in as much as it demonstrates sensitivity to misalignments down to $O(\text{mm})$.
- The simulation will integrate for the adopted electron detector
- The impact of the material traversed by the source electrons will be studied
- Eventually, an evaluation of the cost and a detailed deployment plan of the measurement will be made