Preliminary Results from the AlCap Experiment
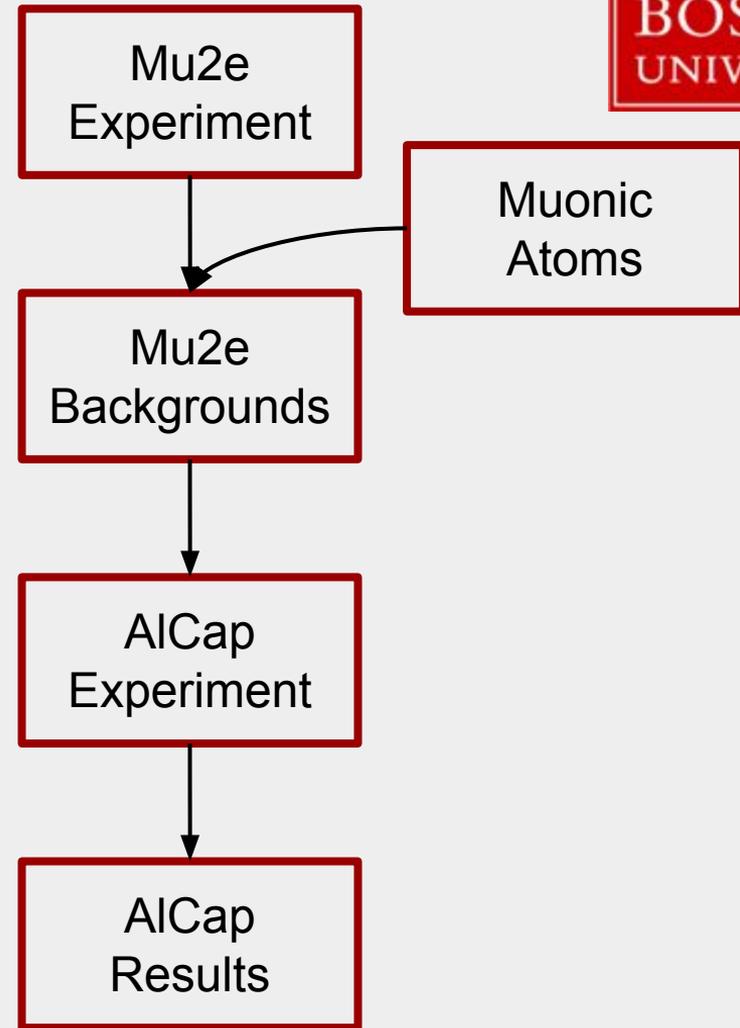
John Quirk
on behalf of AlCap Collaboration
Boston University
PSI 2019

Mu2e Experiment

Muonic Atoms

Mu2e Backgrounds

AlCap Experiment

AlCap Results

Muon to Electron Conversion Experiments

Mu2e and COMET are looking:
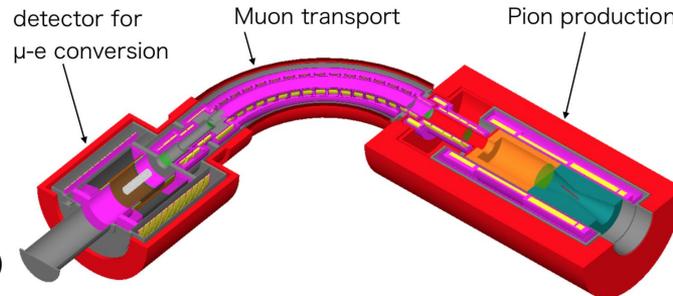
1. For a *rare* μAl interaction ($R_{\mu e}$(Au)<7×10^{-13})[*]

2. Through a *lot* of μAl (>10^{18}) generated noise, background, and damage

Consequently, must understand muon-aluminum interactions

[1] W. H. Bertl *et al.* (SINDRUM II), Eur. Phys. J. **C47**, 337 (2006)

Mu2e @ FNAL
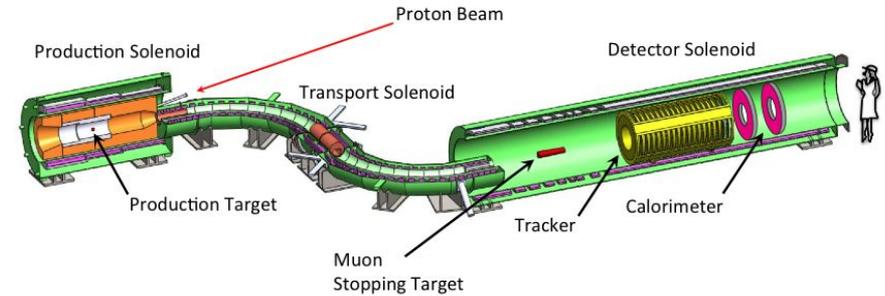
COMET @ JPARC [TDR]

COMET Phase-I Layout

Muonic Atoms

```
Atomic Capture
    |
    v
Atomic Cascade
   /        \
  v          v
Decay In Orbit   Nuclear Capture
```

$$\Delta E^{\mathrm{Al}}_{2p \to 1s} \approx 347 \mathrm{keV}$$

$$Br^{\mathrm{Al}}_{2p \to 1s} \approx 80\%$$

Basic Capture

$$\mu^- \xrightarrow{\hspace{2cm}} \nu_\mu$$

W

$$p \left\{ \begin{array}{l} u \longrightarrow d \\ u \longrightarrow u \\ d \longrightarrow d \end{array} \right\} n$$

Nuclear Capture

105 MeV

Legend

e^-
μ^-
p
n
N

$$\mu^- + {}^{27}_{13}\text{Al} \rightarrow \nu_\mu + {}^{A}_{Z}N + \ldots (n, p, \gamma)$$
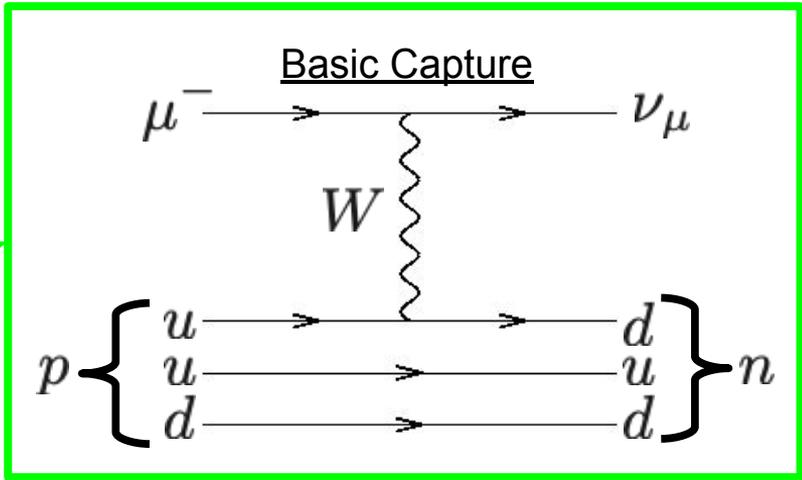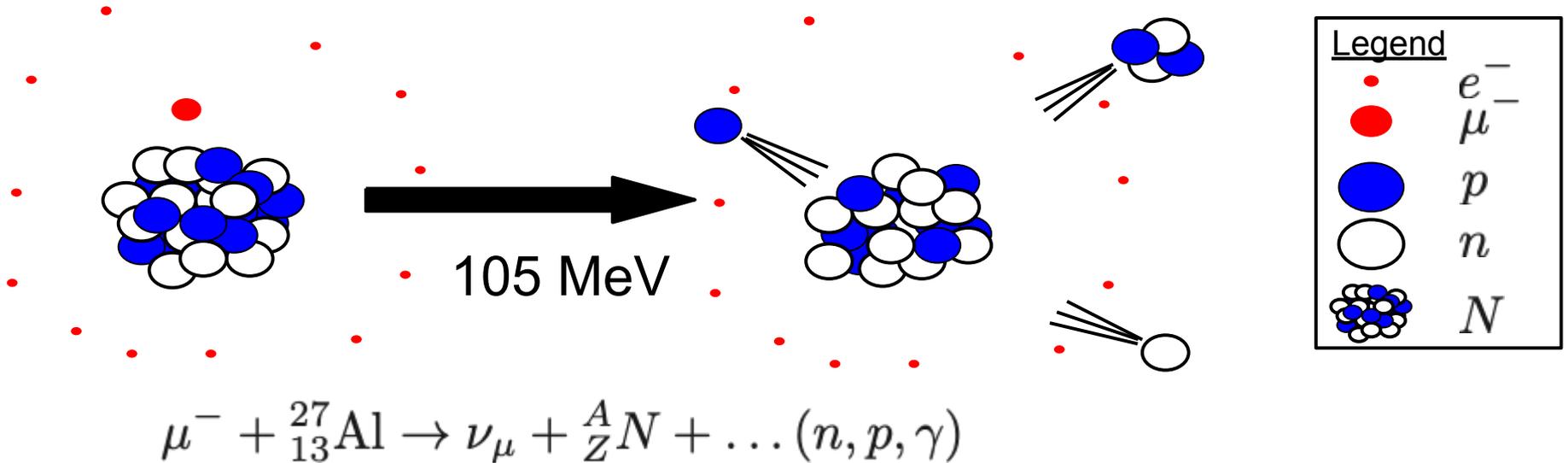
Issues for Mu2e

Heavy Charged Particles:
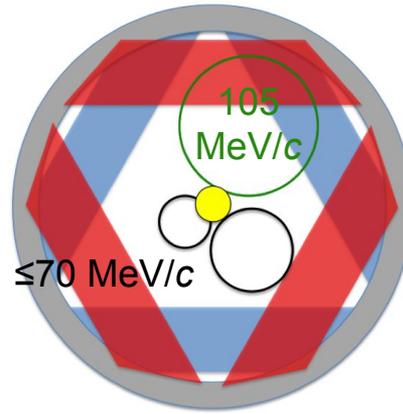
- Protons in momentum acceptance (>70 MeV/c) cause tracker hits
- Proton absorber: reduces hits → reduced $\Delta p_{conv.\ e}$
- Tradeoff: conversion e^- resolution ↔ proton hits

Neutral Particles:

- X-rays used for counting muon stops
- γs pair-produce, create backgrounds
- Neutrons highly penetrating → accidental cosmic ray veto triggers
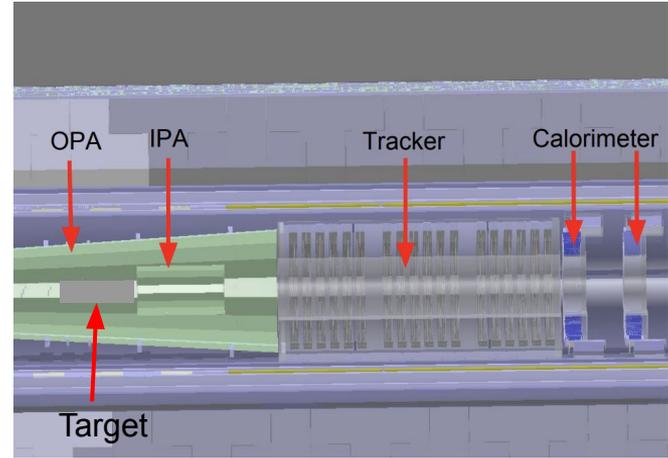
M. MacKenzie Mu2e Internal 2018

Conversion e^-	105	MeV
Detected Proton:	5.8	MeV
Undetected Proton:	≤ 2.6	MeV

Work Packages

WP1: Charged Particles

- Proton emission rate of μAl
  - Assess noise hits
- Previous spectrum >40 MeV
  - No use to Mu2e

Previous measurement:
K. S. Krane et al., Phys. Rev. C **20**, 1873 (1979)

WP2: Photons

- μAl Capture/activation γs
  - Muon counting
- *X*-rays from candidate target and structures
  - Muon counting
  - Noise hits

Previous measurement:
Measday et al., Phys. Rev. C **76**, 035524 (2007)

WP3: Neutrons

- Spectrum from target and structures
  - Noise hits
  - Previous measurement had no neutron energy information

Previous measurement:
Macdonald et al, Phys. Rev. **139**, B1253 (1965)

Work Packages

WP1: Charged Particles	WP2: Photons	WP3: Neutrons
• Proton emission rate of μAl ○ Assess noise hits • Previous spectrum >40 MeV ○ No use to Mu2e	• μAl Capture/activation γs ○ Muon counting • X-rays from candidate target and structures ○ Muon counting ○ Noise hits	• Spectrum from target and structures ○ Noise hits ○ Previous measurement had no neutron energy information

Previous measurement:
K. S. Krane et al., Phys. Rev. C **20**, 1873 (1979)

Previous measurement:
Measday et al., Phys. Rev. C **76**, 035524 (2007)

Previous measurement:
Macdonald et al, Phys. Rev. **139**, B1253 (1965)

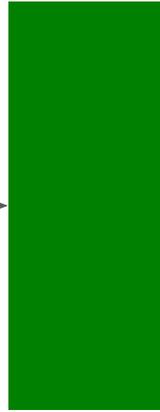# Difficulty in Proton Energy Measurement

Al target

E_0 = 3 MeV

p

d*x* = 25μm
E_{loss} = 900 keV

Requirements:
- Vacuum
- Thin target
- Tight beam

Si Detector

E_{meas} = 2.1 MeV

K. S. Krane et al., Phys. Rev. C **20**, 1873 (1979)

AlCap Setup

μ

Chamber
- Cylindrical
- Stainless steel
- Under vacuum
- 30cm $\varnothing \times$ 60 cm
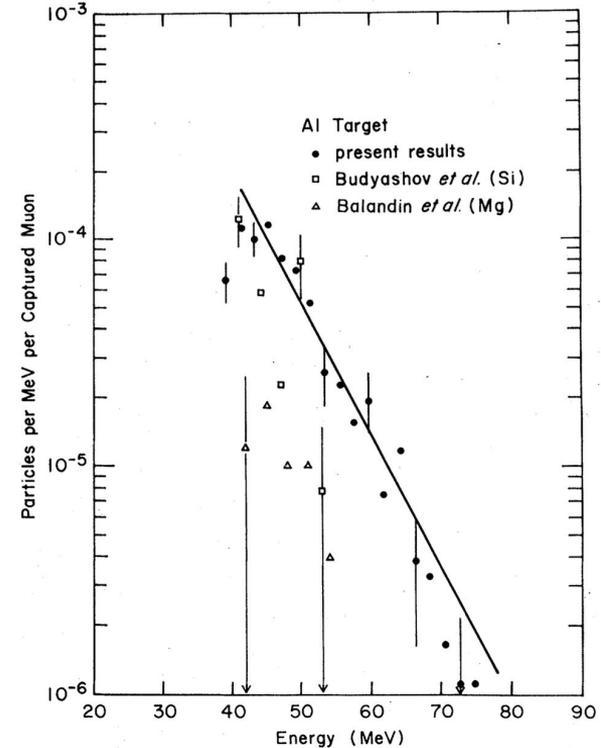
Key
——	Plastic Scintillator
——	Silicon Detector
——	Wire Chamber
——	Liquid Scintillator
——	Germanium Detector
——	Lead Shielding
——	Stainless Steel

Ge

Beam counter

Collimator

PID Package

Target

Punch through veto detector
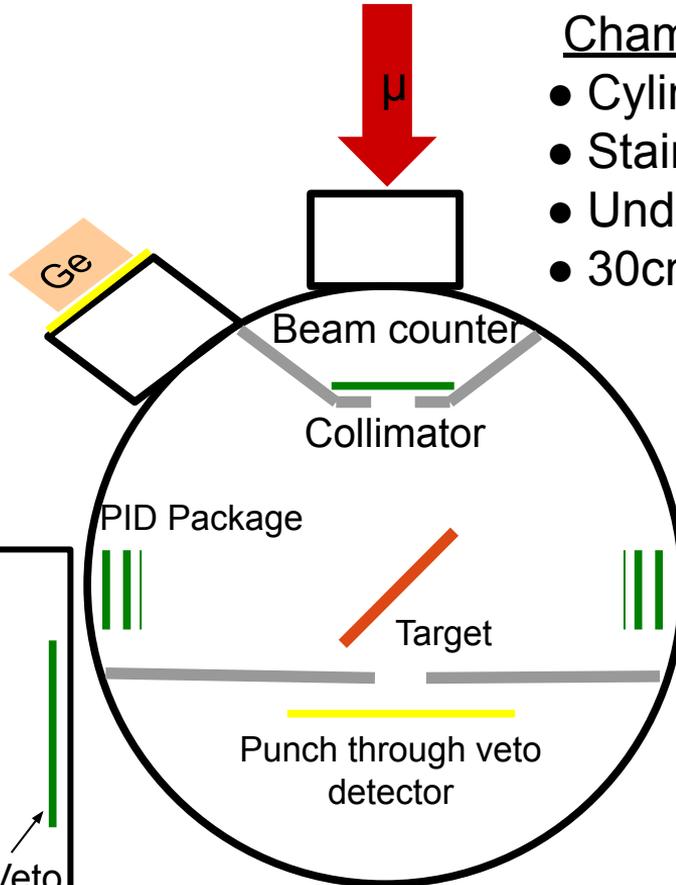
~30cm

~60cm

Particle Identification Package   *E*

Target

dE   Veto

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Lead shielding kills scattered muons: $t_{\mu Pb} < t_{\mu Al}$

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AlCap Setup
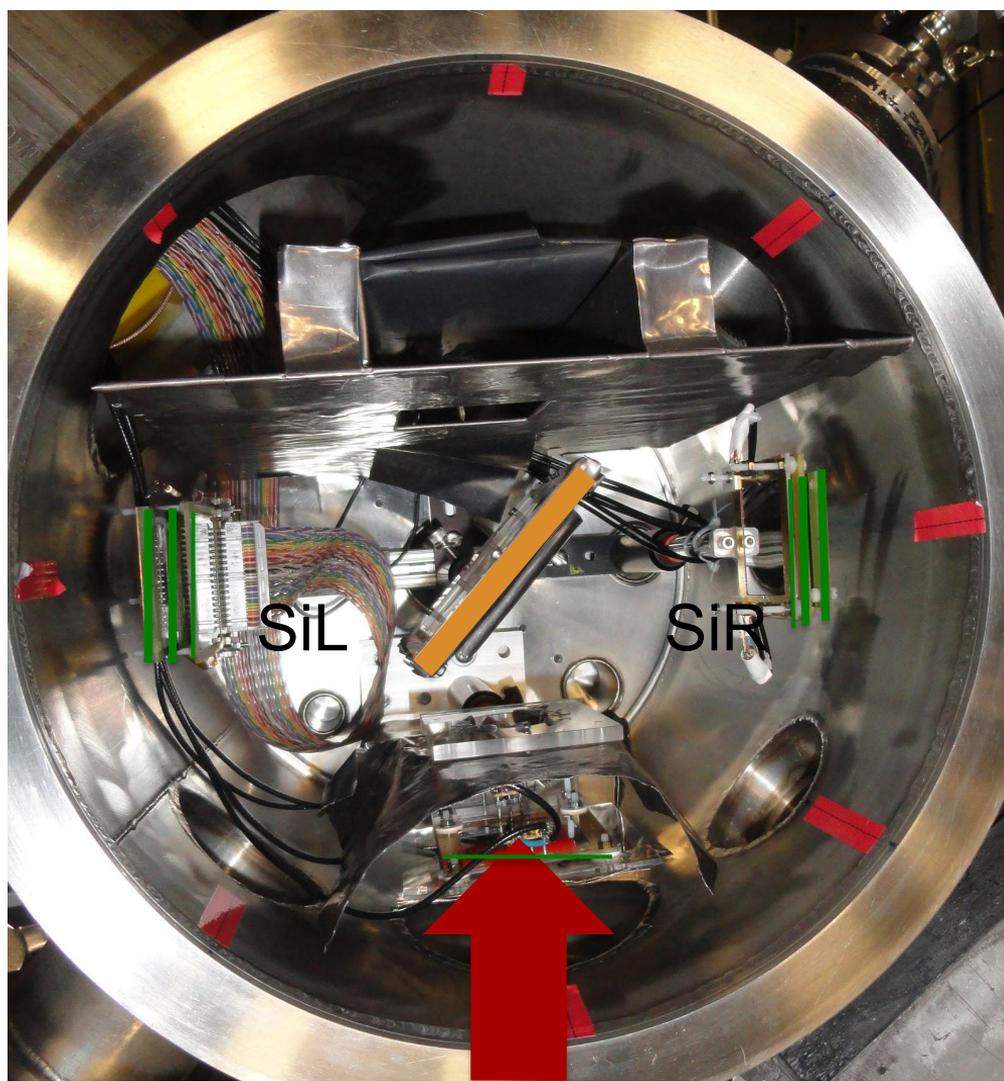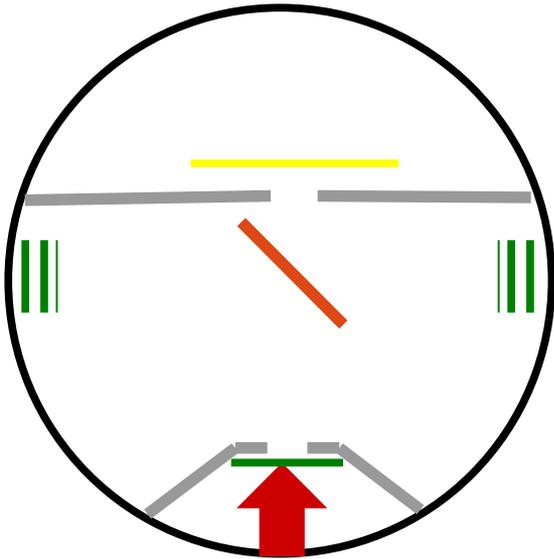
Proton Measurement
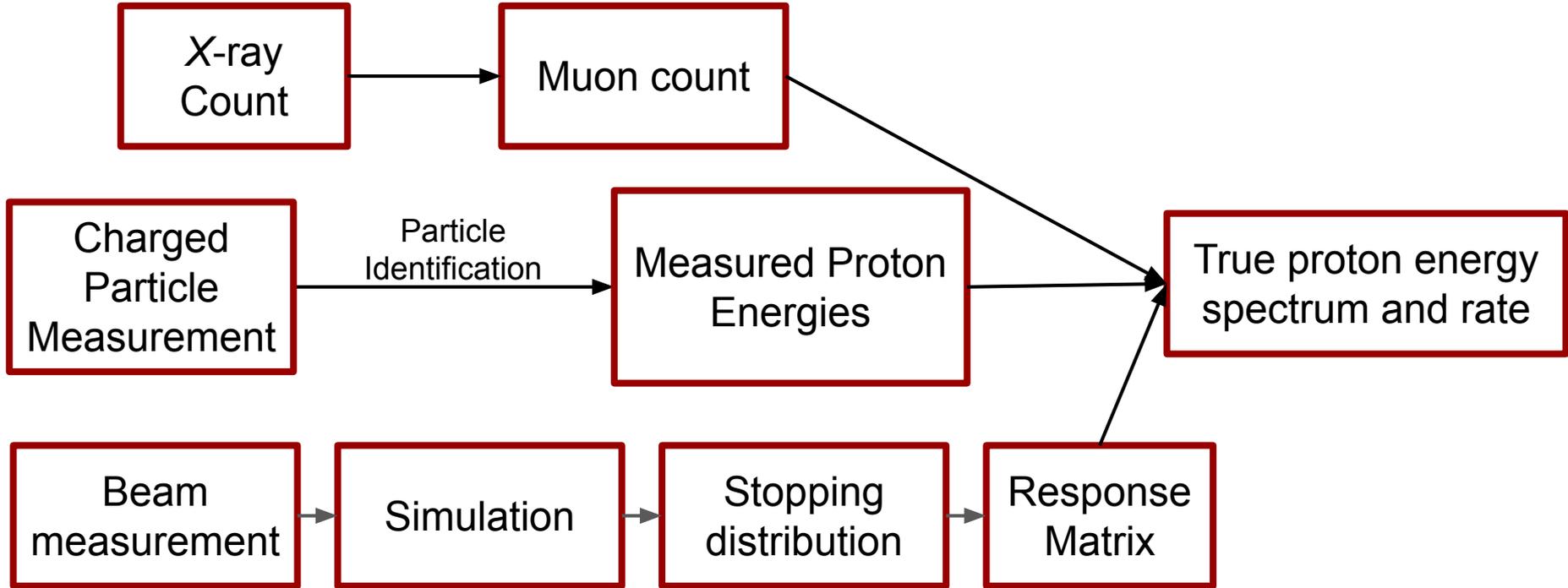
Muon Count from X-rays

$$N_\mu = \frac{N_{2p-1s}}{\epsilon_{2p-1s} \times I_{2p-1s}}$$

2p-1s *X*-rays	84215(510)
Ge Efficiency @ 347 keV	$6.6(2) \times 10^{-4}$
X-ray Intensity (/μ-stop)	79.8(8)%
Stopped Muons	$160(5) \times 10^6$

X-Ray Spectrum (Al50 Target) ±200ns

$1.6e+08 \pm 5.2e+06$ μ

GeFit

χ^2 / ndf	426.2 / 52
Bkg y-int	7943 ± 304.4
Bkg Slope	−19.2 ± 0.9
Al Amp	1.219e+04 ± 5.784e+01
Al Energy	345.4 ± 0.0
Pb Amp	2452 ± 28.4
Pb Energy	349.6 ± 0.0
Sigma	0.9418 ± 0.0035

μ+Pb→^{207}Tl

Al 2p-1s

Raw Count

Energy [keV]
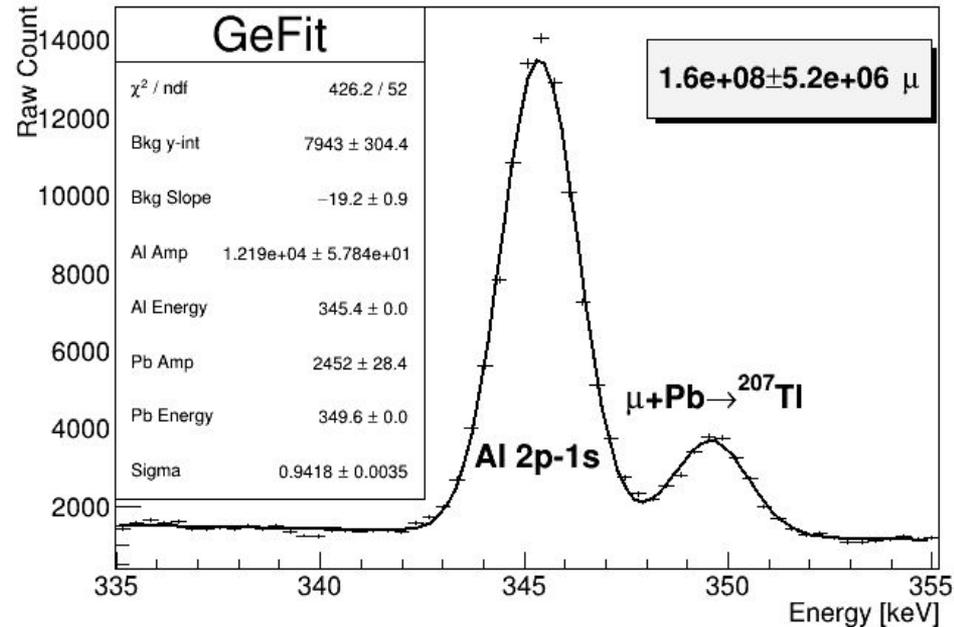
Particle Identification: dE/dx Method

1. Particles lie on distinct dE vs. E bands
2. Fit transformed bands to gaussians
3. Cut on particle species

Particle Identification Package

Target

E

dE Veto

SiR Proton Cut

Rotated Log-Log Slice

t

d

p

Scattered μ
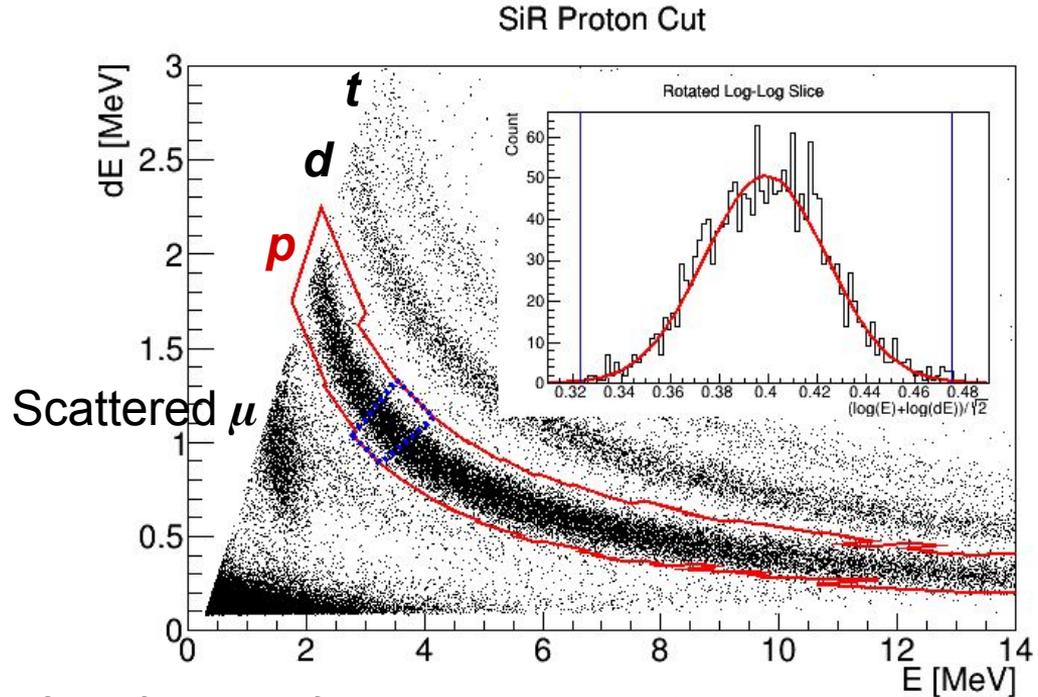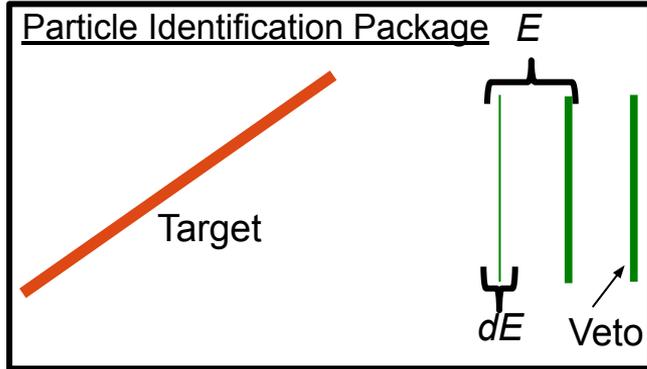
Classify by transformed (Log-Log, rotation) energies:

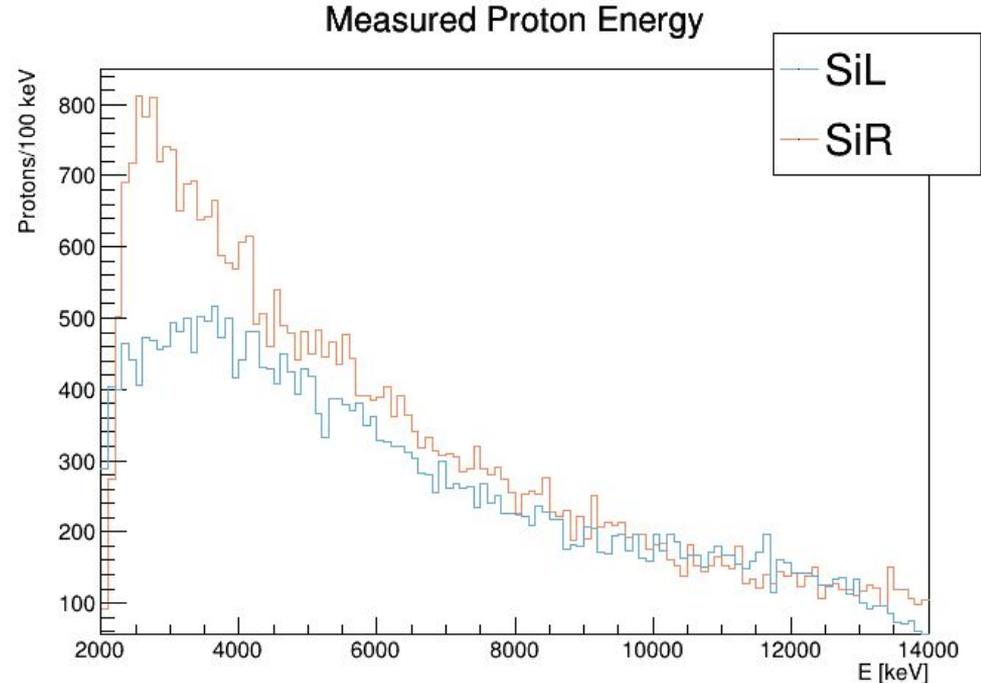$$(E, dE) \rightarrow \left(\frac{\log(E) - \log(dE)}{\sqrt{2}}, \frac{\log(E) + \log(E)}{\sqrt{2}} \right)$$

Measured Proton Energy

Selection:

- $\lambda_{\mu Pb}$ = 80ns $\rightarrow$ 400ns < t_p
- $dt_{Si1-Si2}$ < 200ns
- $T_{neighboring\ \mu}$ > 10µs
- Protons only

Left/Right Differences Understood:
- Target stopping distribution pushes SiR energies lower
- SiR is a larger detector; $\Omega_{SiR} > \Omega_{SiL}$
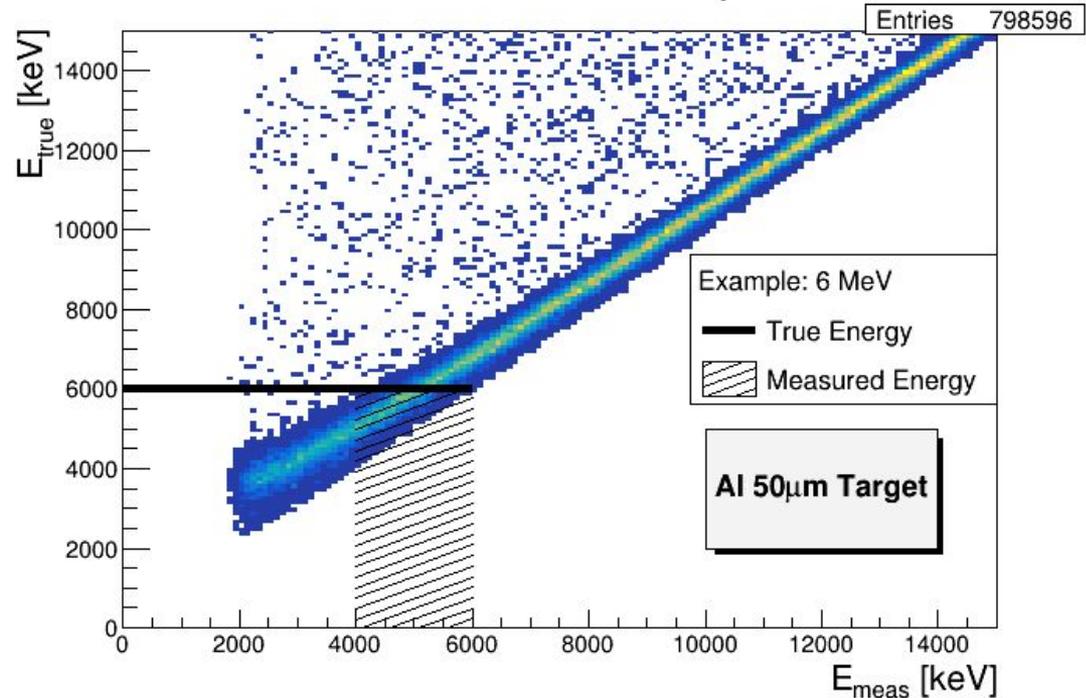- Thin SiL higher threshold $\rightarrow$ high E difference

Measured Proton Energy

Unfolding

$$E_{meas} = M \times E_{true}$$

- Response matrix:
  $M \ni \{\varepsilon_{geom}, \varepsilon_{\mu\text{-stop}}(E_{true})\}$
- Obtained from MC
- BayesUnfold(M, E_{meas}) = E_{true}
- M relatively linear, simplifying unfolding

D'Agostini, 2010, arXiv:1010.0632

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Simulated SiR Proton Response

Example: 6 MeV
True Energy
Measured Energy

Al 50μm Target

Systematics: 3.5-10 MeV

Backgrounds and Efficiencies	PID (Energy Cut) Acceptance	3.3%	Beam & Stopping Distribution	Stopping Depth	2.1%
	Pb Contamination	0.87%	Unfolding	Iterations	0.17%
Calibration	Si ECal	0.4%		Bin width	0.17%
Geometry	Target Position	0.75%		Energy Bound	1.4%
	Detector Position	5.6%			
			Total	**Statistical**	**3.2%**
				Systematic	**7.1%**

Proton Emission in Aluminum

Proton Emission
(3.5-10 MeV)
per μ-capture

0.0207(7)$_{stat}$(15)$_{syst}$

Proton Emission Rate

PRELIMINARY
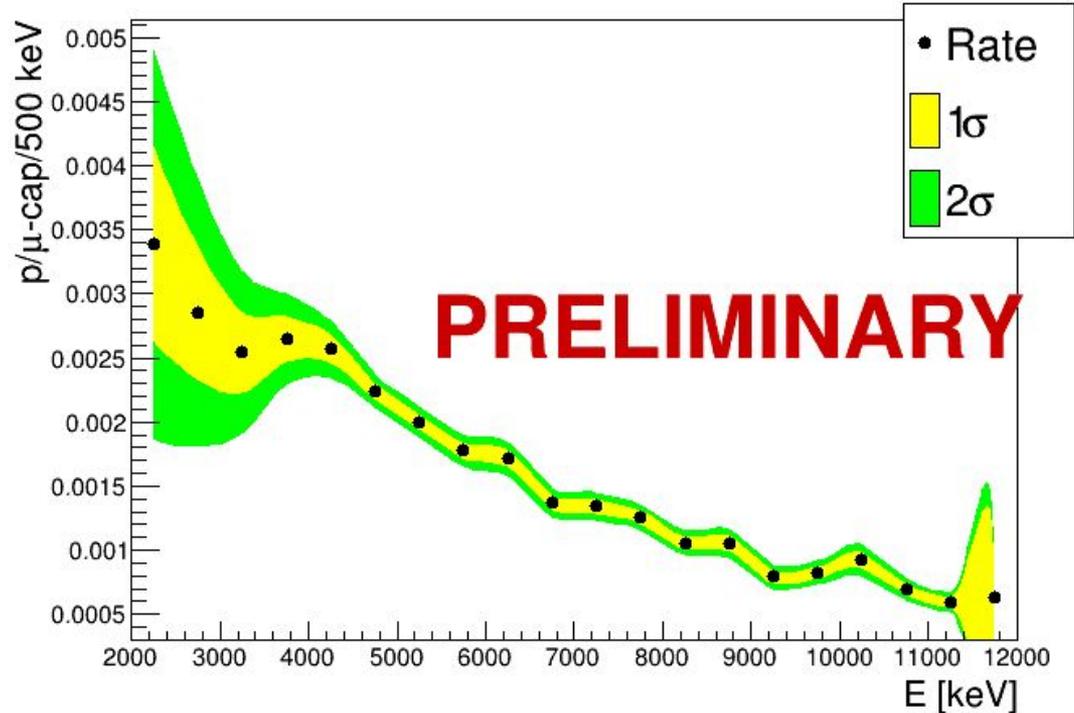
Impact for Mu2e

Inner proton absorber:

- Reduces proton detector hit rate
  - Decrease noise hit rates
- Degrades conversion e^- signal
  - Degrades signal momentum resolution
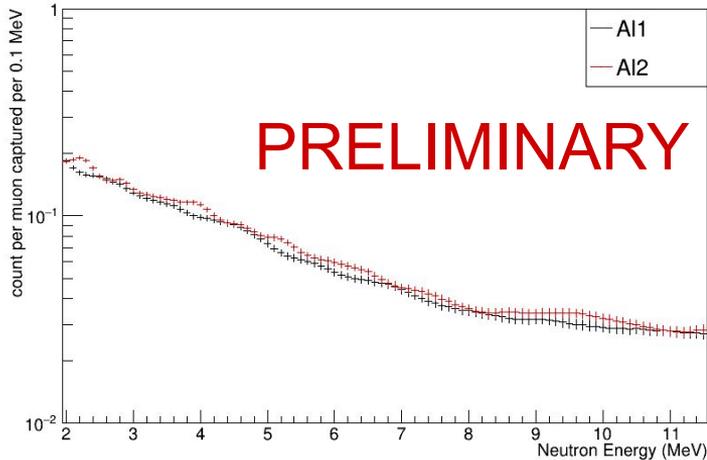 - Reduces signal energy
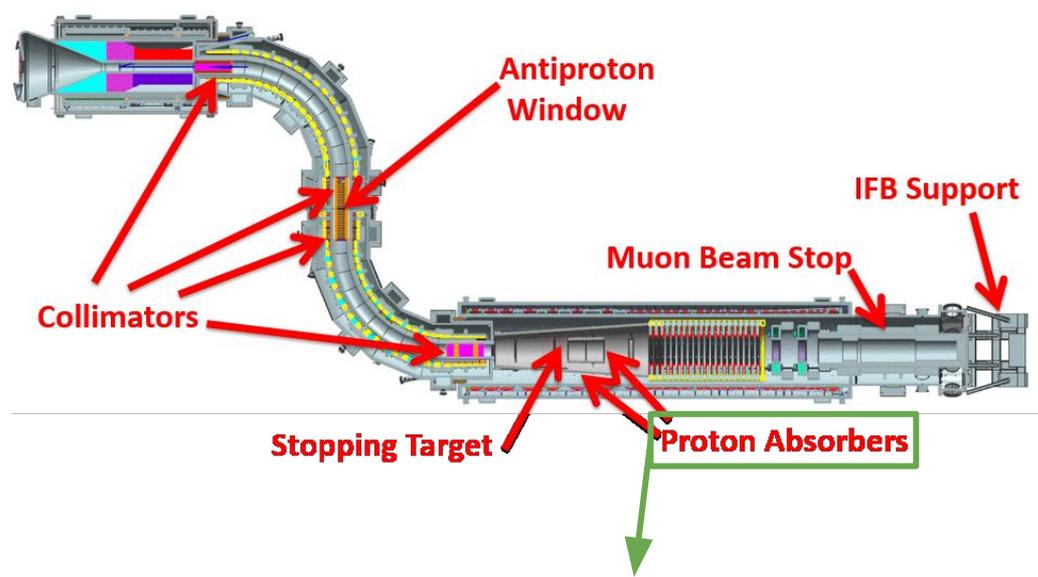
Actual proton rate factor of ~3 lower than expected → Mu2e thinner proton absorber, COMET removed absorber → less degradation of signal energy resolution.

Neutron Status

- Used 2 neutron detectors (BC501a)
- Preliminarily report 0.44(3) n/μ-capture in 2-11.5 MeV

Unfolded Neutron Spectra

PRELIMINARY

**Measured Neutron Spectra**
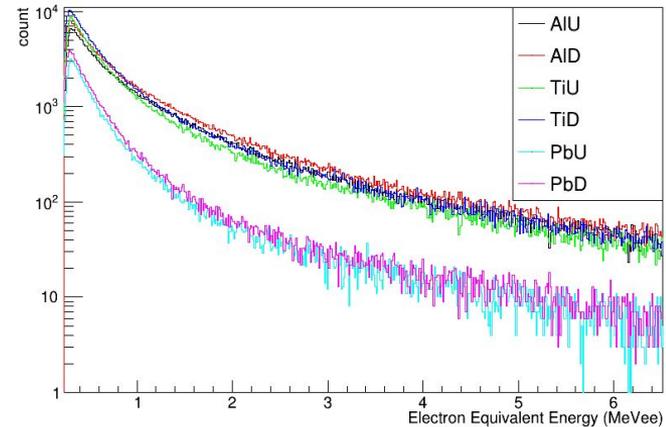
	Detector 1 Raw *n* Count	Detector 2 Raw *n* Count
Al	289026	337627
Ti	295309	349783
Pb	80521	94698

X/ɣ-rays

- Data taken on: Al, Ti, W, Pb
- Analysis in progress
- Al/Ti for normalization
- W/Pb for backgrounds

Photon	Energy [keV]	Emission rate
Al (26Mg*)	1808.7	0.51 ± 0.05
Ti (2p-1s)	931.0	0.90 ± 0.04
W (4f-3d)	761.0 783.6	0.25 ± 0.01 0.19 ± 0.01

Ti 2p-1s

natural W spectrum

geL
Entries 173965
Mean 334.5
Std Dev 241.8
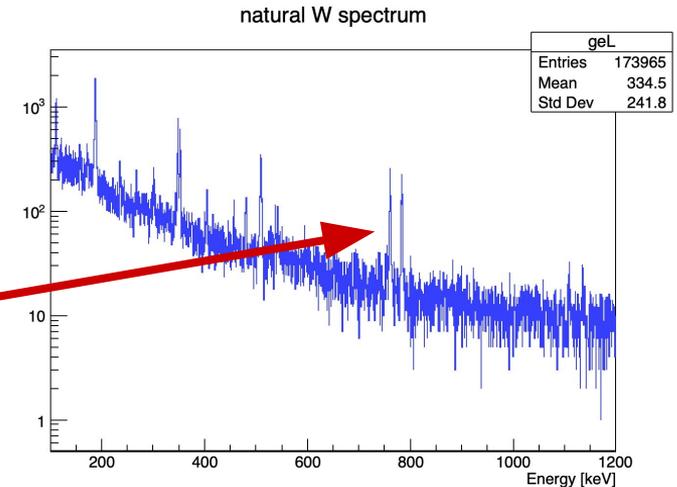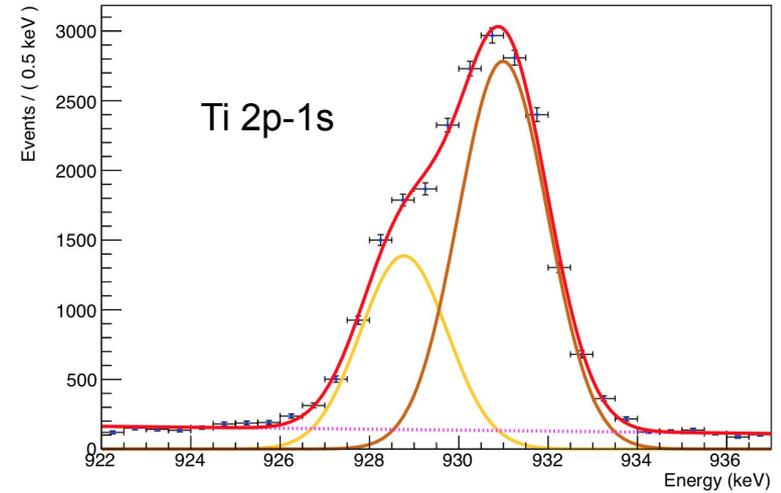
AlCap Status

- AlCap reports preliminary results for proton emission (3.5-10 MeV) per muon capture in aluminum of **$0.0207(7)_{stat}(15)_{syst}$**
  - TWIST recently reported (arXiv:1908.06902) $0.0322(7)_{stat}(22)_{syst}$ over 3.4 MeV
- Additional aluminum datasets still being analyzed
- Further results forthcoming on deuteron and triton, as well as on Si and Ti targets
- Photon and neutron analyses from a number of targets are in progress

THANK YOU!

COMET

Mu2e
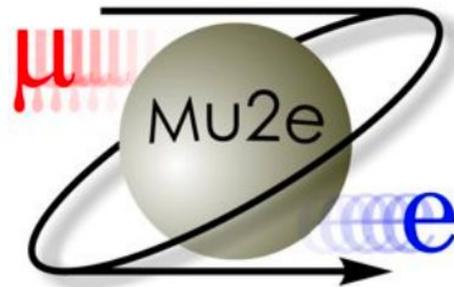
Stopping Depth in Target

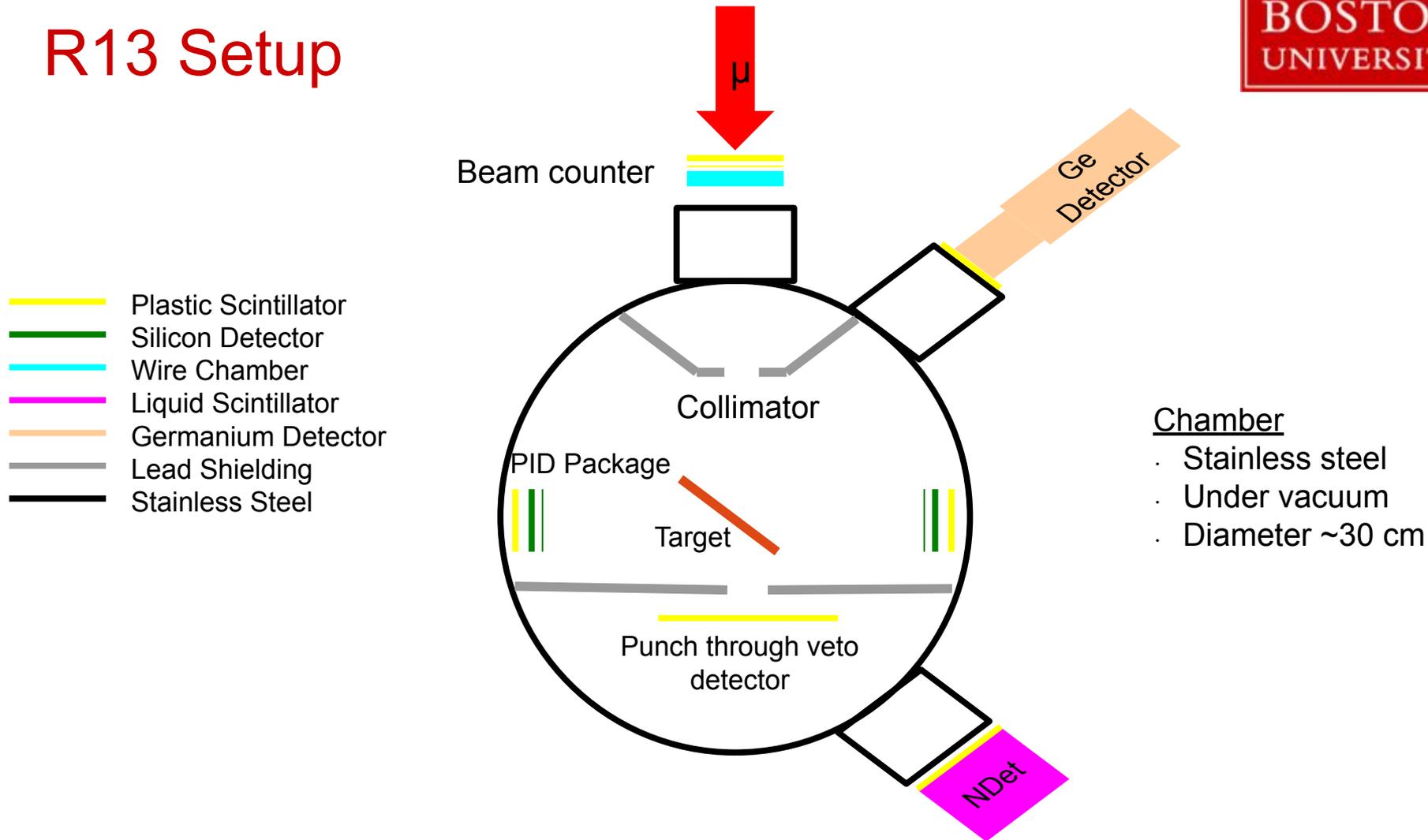3.5-10 MeV rates as function of muon stop position
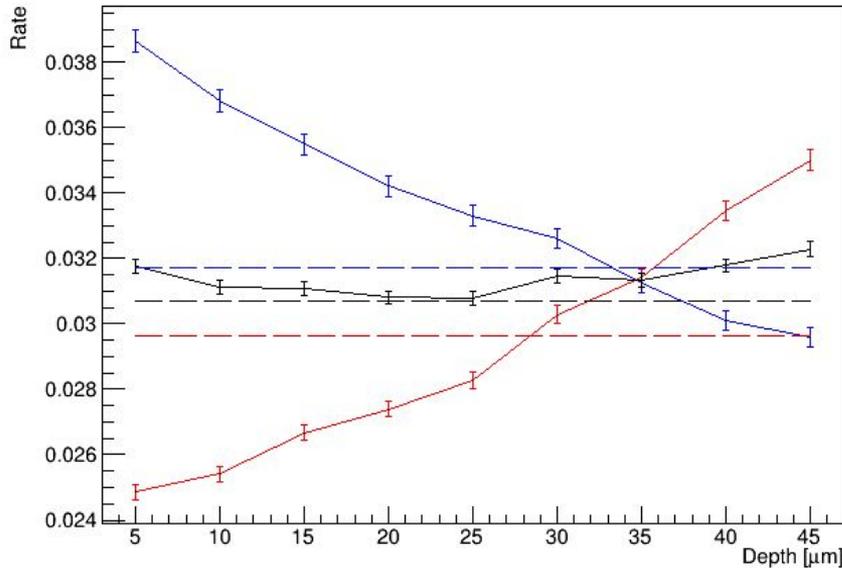
4-8 MeV rates as function of muon stop position
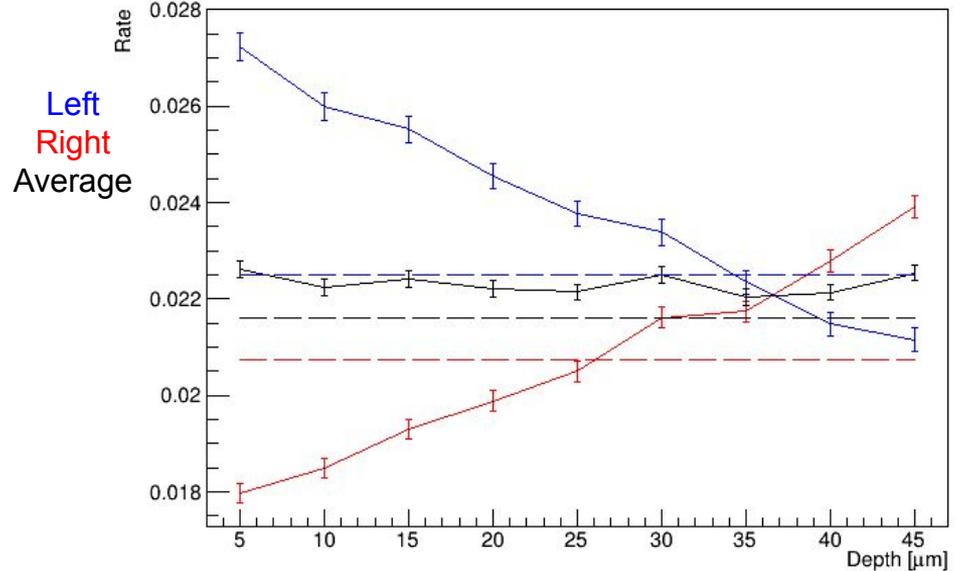
Left
Right
Average

While the effects on the individual detector arms is significant, averaging them cancels this out.
Ideally, the unfolded rates would agree in the left and right arms.
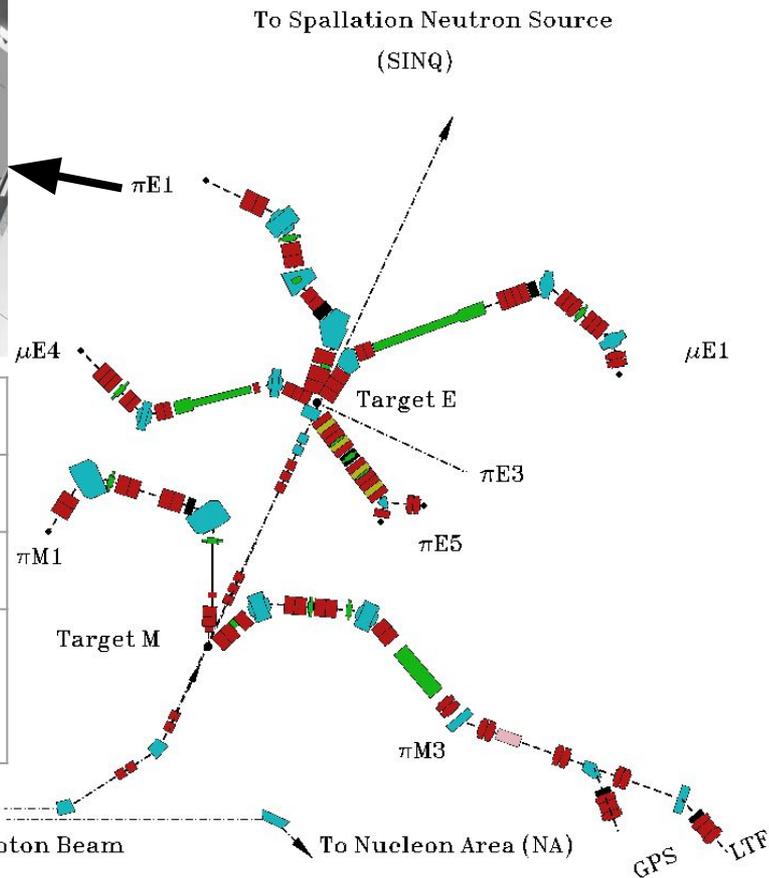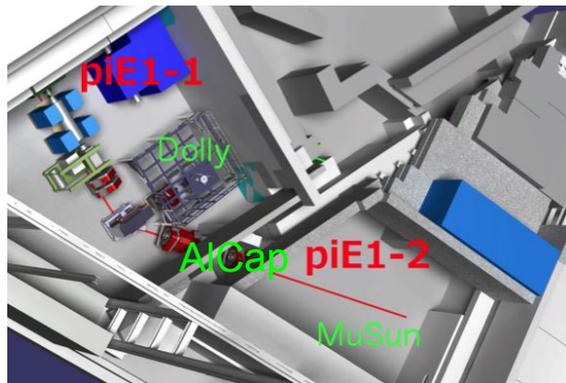
R13 Setup

Campaigns

Campaign	R13	R15a	R15b
Dates	Nov 28-Dec 23 2013	Jun 8-21 2015	Nov 5-22 2015
Work Packages	WP 1, 2, 3	WP 2, 3 (Neutral particles)	WP 1 (Charged particles)
Beamline	πE1	πE5	πE1
Targets	Al, Ti, Si (Passive)	Al, Ti, H2O, Pb, Steel	Al, Ti, Si

Paul Scherrer Institut (PSI)

- Highest current, highest power proton accelerator (2.2mA, 590MeV cyclotron)
- Most intense muon beam
- Number of DC muon beamlines to choose from to balance rate and momentum bite
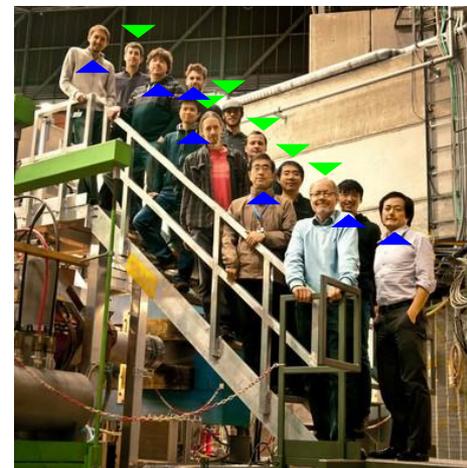
Beamlines at PSI

piE1-1
Dolly
AlCap piE1-2
MuSun

Beamline	πE1	πE5
Campaign	R13, R15b	R15a
Ω (msr)	13	150
Momentum Resolution (FWHM)	0.26%	2%

To Spallation Neutron Source (SINQ)

πE1

μE4

μE1

Target E

πE3

πM1

πE5

Target M

πM3

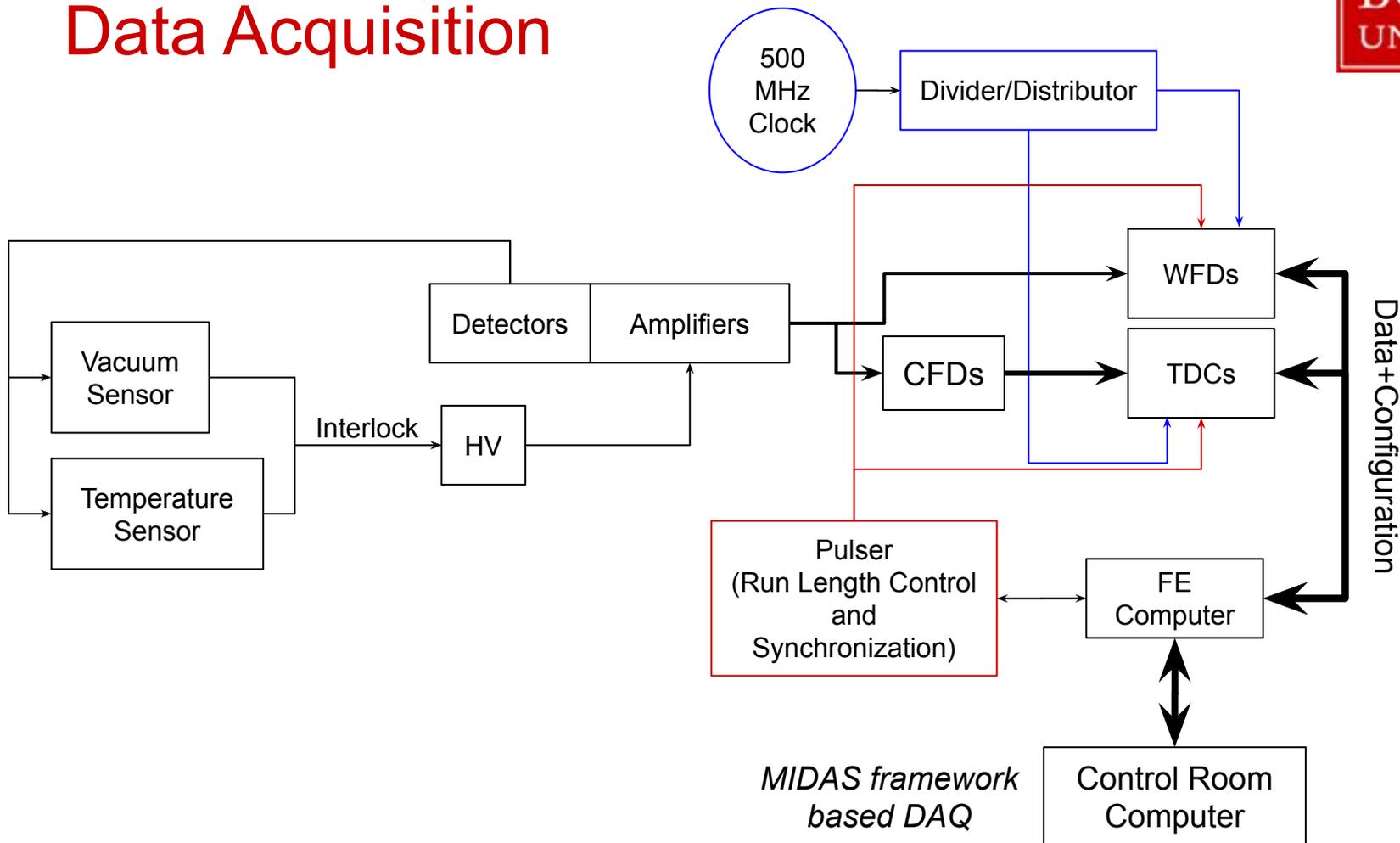Proton Beam   To Nucleon Area (NA)   GPS   LTF

(Some) Collaborators

Experiments
Mu2e
COMET

Data Acquisition

MIDAS framework based DAQ

Sanity Check: Lifetime = 864ns

TME Time SiL Al50

Left	
Entries	33512
Mean	1355
Std Dev	812.9
χ^2 / ndf	453.7 / 447
BG Flat	0.1797 ± 0.1862
Al Amp	304.3 ± 5.8
Al Lifetime	873.9 ± 12.0

TME Time SiR Al50

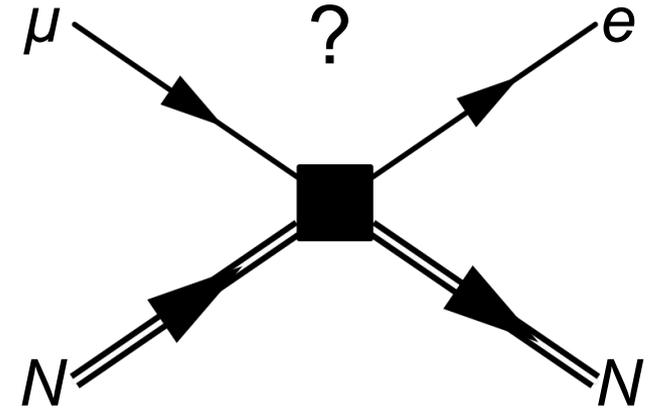| Right	
Entries	37583
Mean	1362
Std Dev	825.4
χ^2 / ndf	476 / 447
BG Flat	0.5397 ± 0.2040
Al Amp	340.4 ± 6.3
Al Lifetime	866.8 ± 11.4
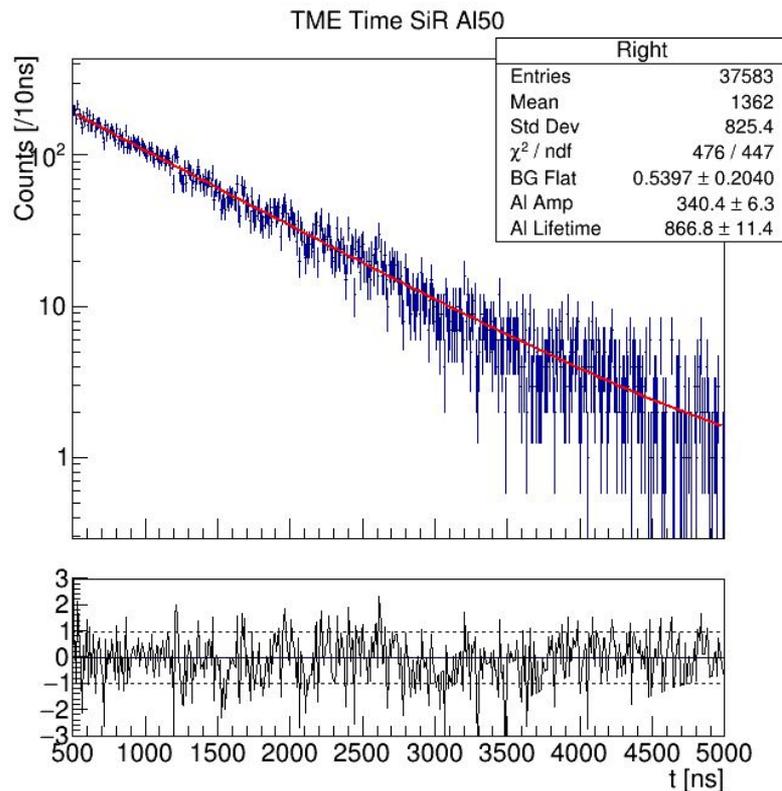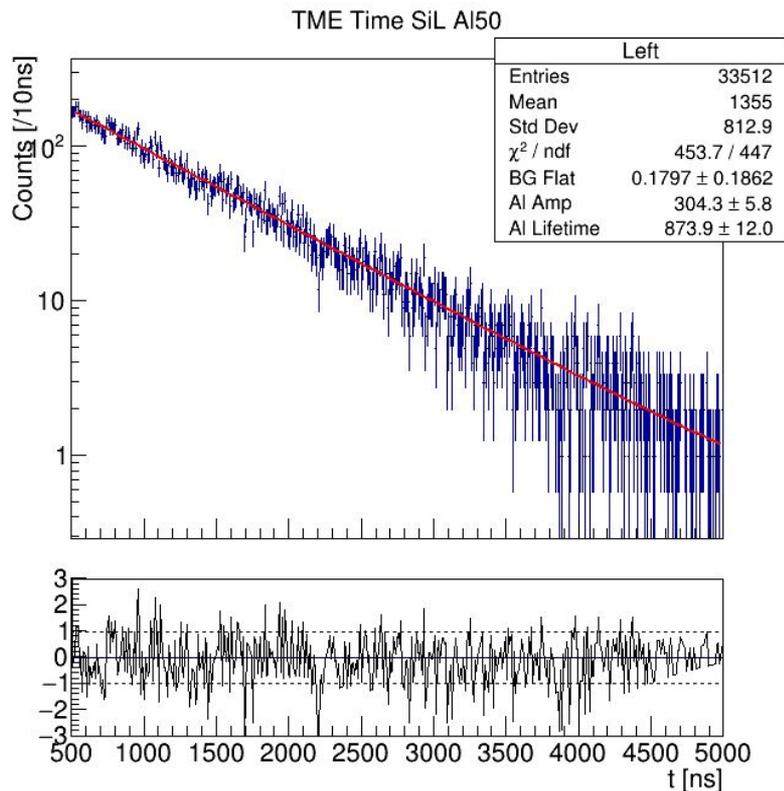
Hit Time and Energy

Silicon Pulse
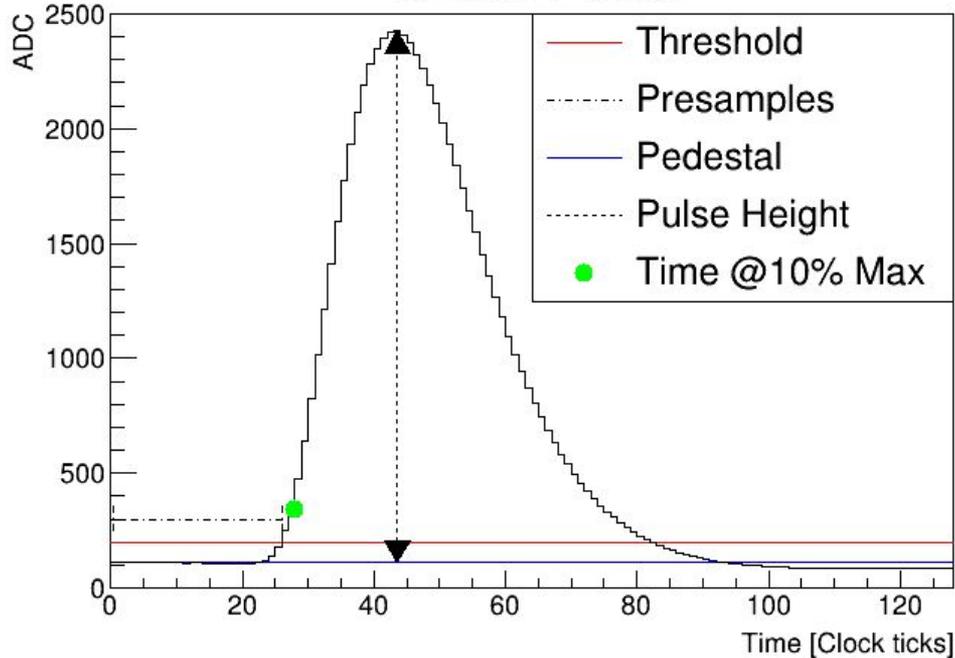
1. Pulse passes preset threshold, triggering data taking in that channel (each channel is self-triggered)
2. Number of presamples before trigger used to calculate pedestal, preset number of samples taken
3. Maximum height from pedestal taken as energy
4. Interpolated clock tick where pulse hits 10% of maximum taken as time

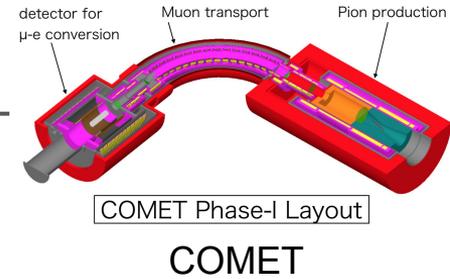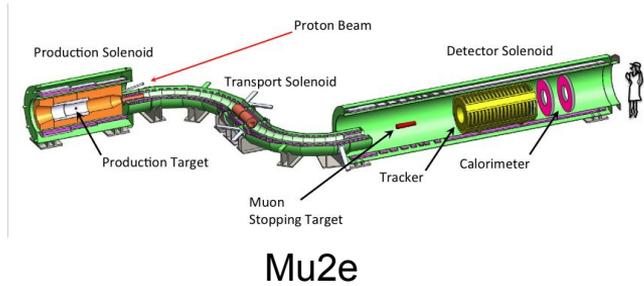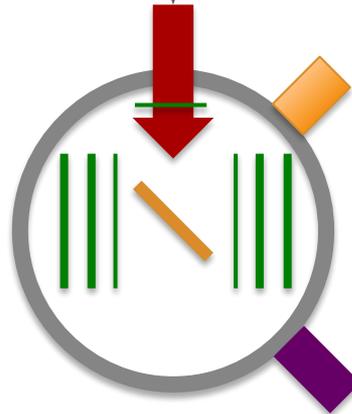# Charged Lepton Flavor Violation: $\mu \rightarrow e$
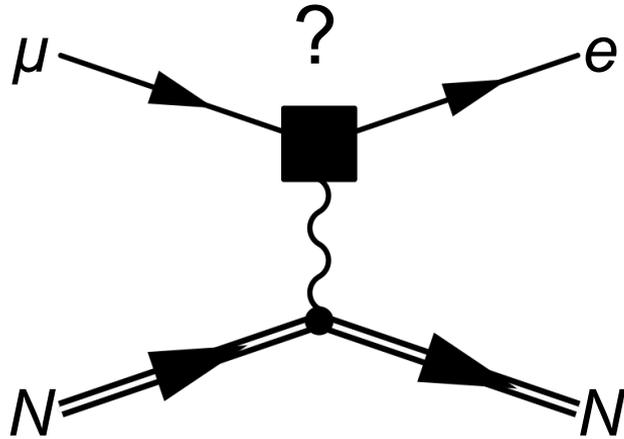
New Physics

$$R_{\mu e}^{\mathrm{Au}} = \frac{\Gamma_{\mathrm{conv}}(\mu \mathrm{Au} \rightarrow e\mathrm{Au})}{\Gamma_{\mathrm{capt}}(\mu \mathrm{Au})} < 7 \times 10^{-13}$$

W. H. Bertl *et al.* (SINDRUM II), Eur. Phys. J. **C47**, 337 (2006)

AlCap: The Aluminum Capture Experiment

Mu2e

COMET Phase-I Layout

COMET
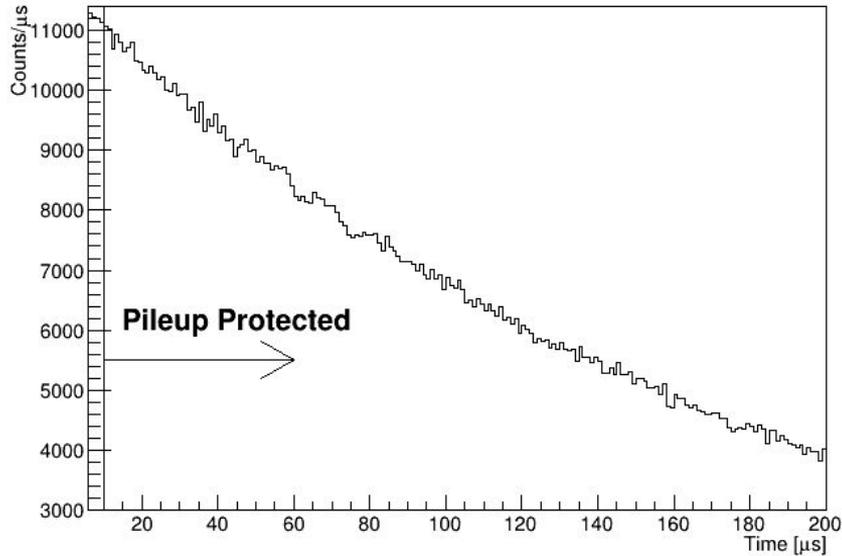
AlCap @ Paul Scherrer Institut (PSI)

Pileup Protection

Time Between Entering Muons

Counts/μs vs Time [μs]

Pileup Protected

Muon Beam Counter
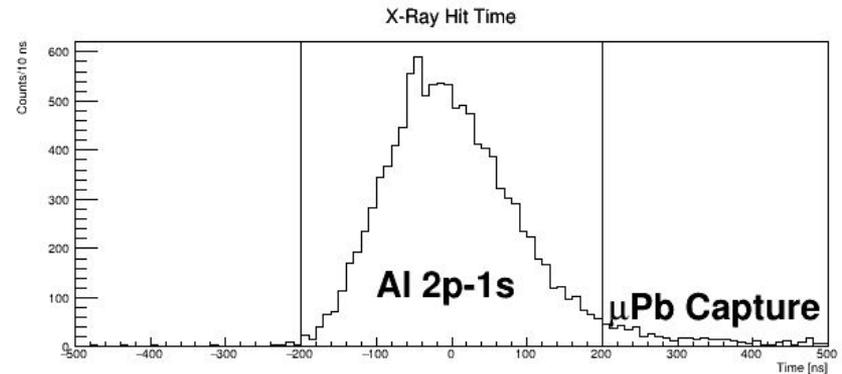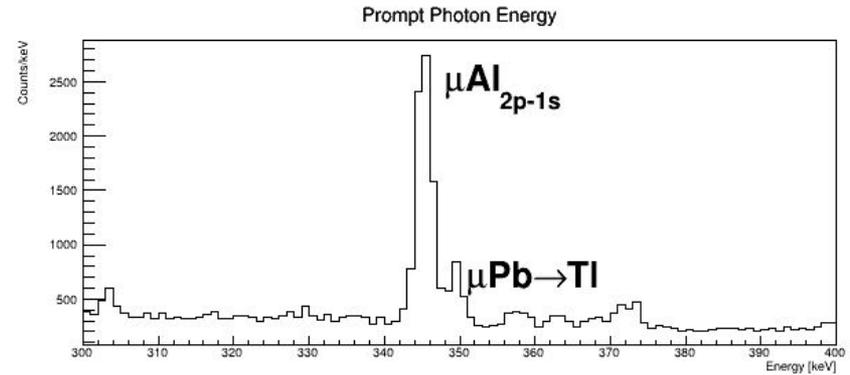
Counts/10 keV vs Energy [keV]

e   μ
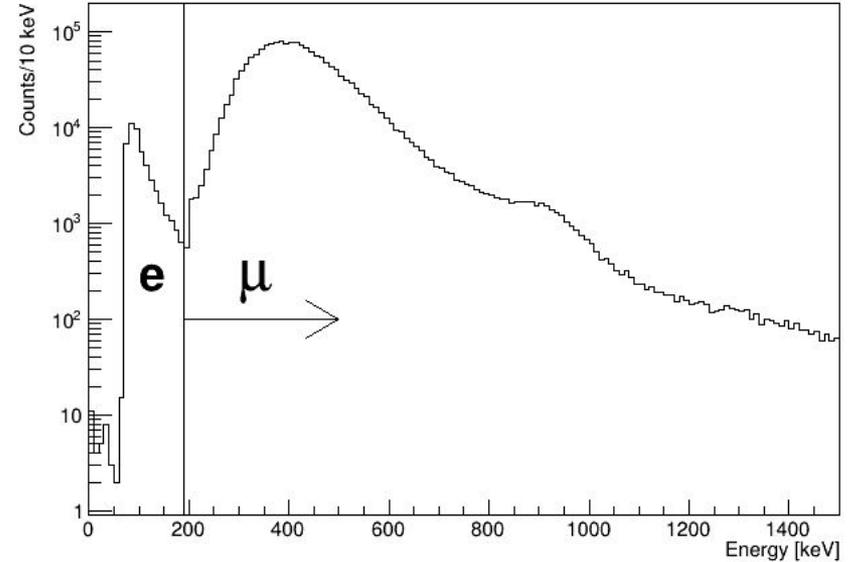
The beam counter (SiT) was placed as close as possible to the target; greatly improved muon stopping fraction.
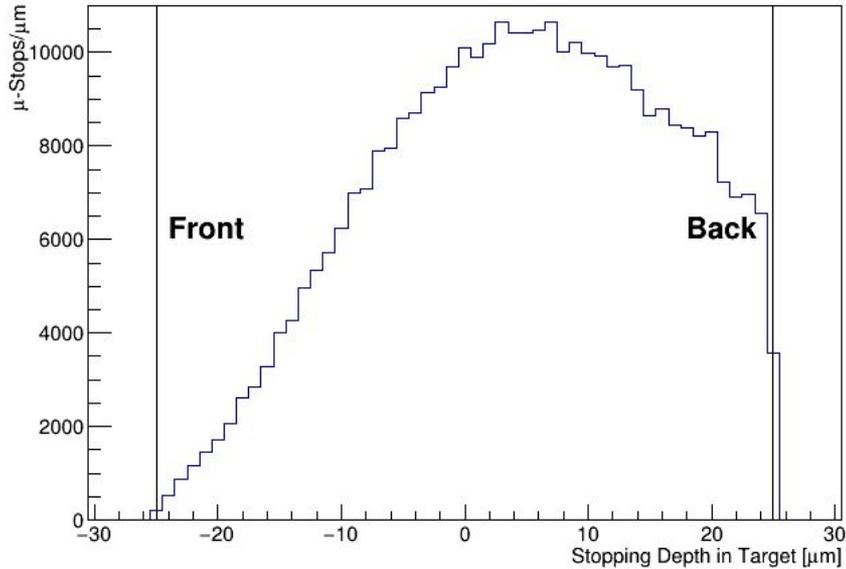Pileup protection rejects 4.9% of muons

Muon Count from X-rays

$$N_\mu = \frac{N_{2p\text{-}1s}}{\epsilon_{2p\text{-}1s} \times I_{2p\text{-}1s}}$$

Prompt Photon Energy

$\mu Al_{2p\text{-}1s}$

$\mu Pb \rightarrow Tl$

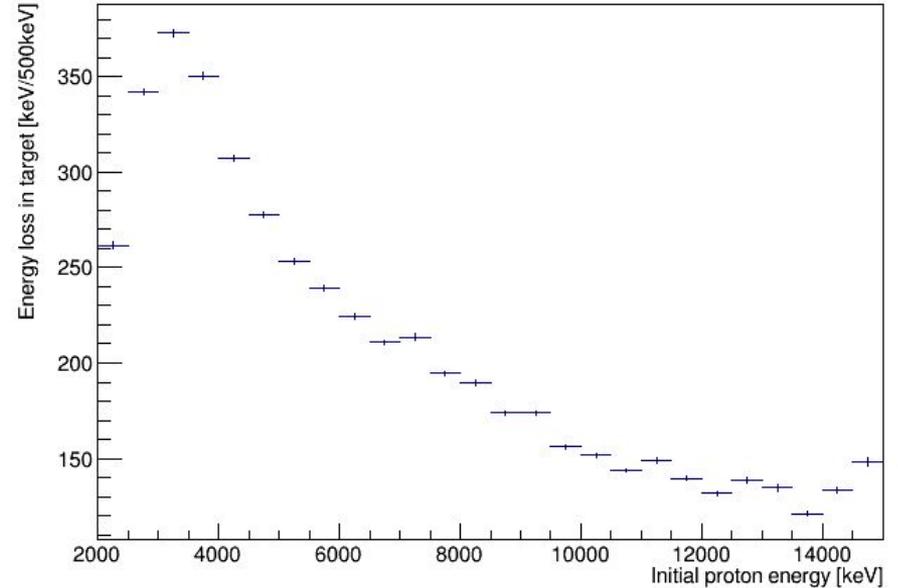X-Ray Hit Time

Al 2p-1s

μPb Capture

Energy Loss in Target

Muon Stopping Dsitribution (Simulation)

Target Self-Absorption (MC)

A proton's energy loss in the target is dependent on stopping location and initial energy

Unfolded Spectrum

- Poorer statistics at lower energies
- Some structure seems to appear, but will disappear after considering systematics

Unfolded Proton Spectrum

Includes only proton statistical error