First Results of the AlCap Experiment

Andrew Edmonds

NuFACT 2022

on behalf of the AlCap collaboration

BOSTON UNIVERSITY

Muon-to-Electron Conversion Searches

COMET and Mu2e will search for **charged lepton flavor violation**

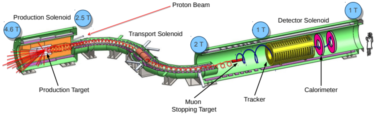
- any observation would be clear evidence of New Physics (SM: $\sim 10^{-52}$)

Specifically, they will search for the $\mu \to e$ **conversion process** in Al

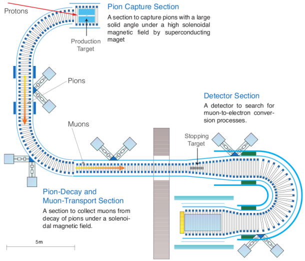
- very simple signal: an **electron with momentum 105 MeV/c**

They will have single event sensitivities of $\sim 10^{-17}$

- current 90% UL $< 7 \times 10^{-13}$ (SINDRUM-II)
- Mu2e and COMET will improve sensitivity by **four orders of magnitude!**
- Mu2e-II / PRISM will aim for a further one to two order of magnitude beyond this



Mu2e @ FNAL



COMET Phase-II @ J-PARC

Nuclear Muon Capture

In order to reach these unprecedented senstivities, COMET and Mu2e will be **stopping $O(10^{18})$ muons**

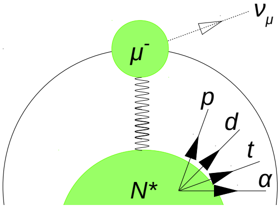
- $\sim$60% of the stopped muons will be captured by the nucleus
- $\mu^- + N(Z, A) \rightarrow \nu_\mu + N^*(Z-1, A)$

Approximately 105 MeV of energy needs to be accounted for:

- the neutrino takes most of it, and
- $\sim$20 MeV (on average) is distributed to the nucleus

This can put the nucleus in an excited state

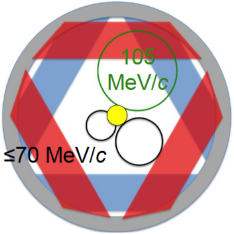
- results in the **emission of p, d, t, α** which will enter the COMET Phase-I/Mu2e detectors



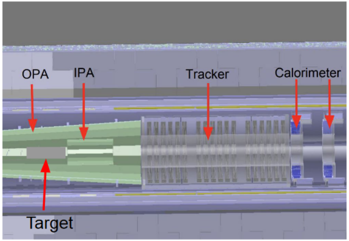
Heavy Charged Particles in COMET and Mu2e

COMET and Mu2e detectors optimized for $p > 70$ MeV/c acceptance

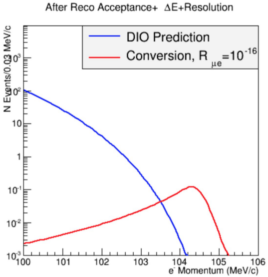
- **low energy** p, d, t, α will enter detector
  - 70 MeV/c proton has $E_k = 2.6$ MeV
- they are **highly ionizing** $\rightarrow$ will generate background hits and damage detector
- depending on rate, COMET Phase-I and Mu2e might need proton absorbers
  - thickness is tradeoff between p hits and momentum resolution



Cartoon of Mu2e Tracker



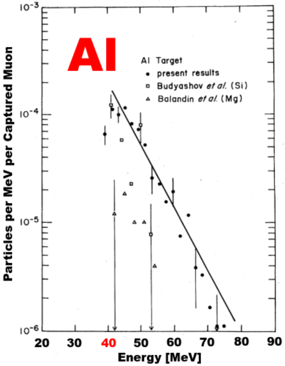
M. MacKenzie Mu2e Internal 2018



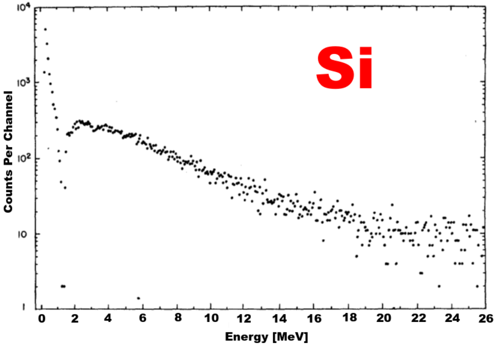
Literature

Large uncertainties in the literature:

- for Al, only know proton yield at high energies ($E > 40$ MeV)
- low energy only known for Si (where target = detector)
- composition ($p : d : t : \alpha$) not measured



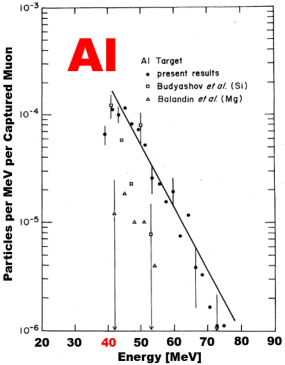
(K. S. Krane et. al. Phys.Rev.C 20 1873 (1979))



(S. E. Sobottka and E. L. Wills Phys.Rev.Lett. 20 (1968) no.12, 596)

It's a tricky measurement!

- doesn't take a lot of material to stop a low energy heavy charged particle
- therefore, need thin targets to get to the lowest energies
- therefore, need muon beam with narrow momentum width



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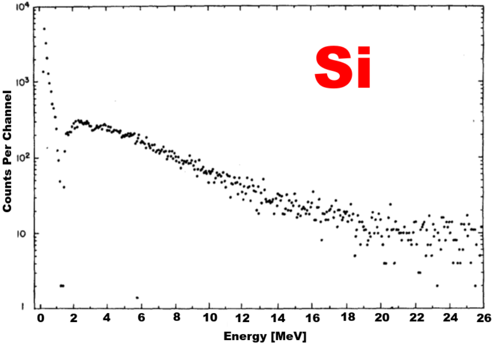


(S. E. Sobottka and E. L. Wills Phys.Rev.Lett. 20 (1968) no.12, 596)

AlCap

The AlCap experiment is a joint venture between members of Mu2e and COMET **to measure the yield and spectrum** of **individual charged particles** after nuclear muon capture.

Ran at PSI and collected charged particle data on Al, Si and Ti

COMET

Mu2e

大阪大学 OSAKA UNIVERSITY

Imperial College London

Institute of High Energy Physics
Chinese Academy of Sciences

BERKELEY LAB

BROOKHAVEN NATIONAL LABORATORY

UCL

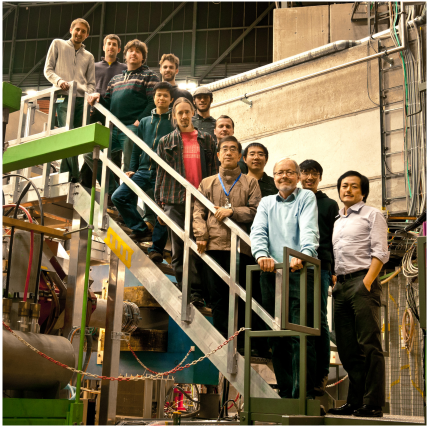
Fermilab

Argonne NATIONAL LABORATORY

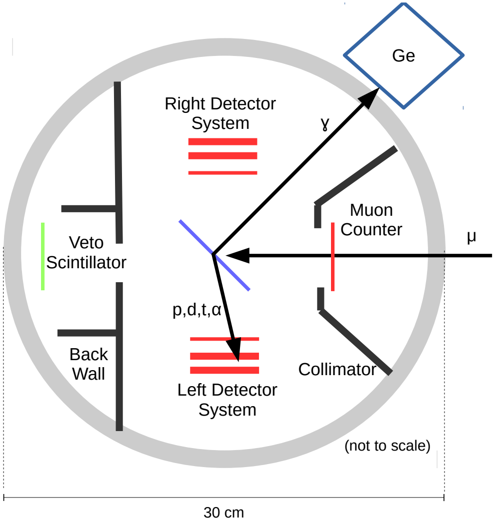
INFN

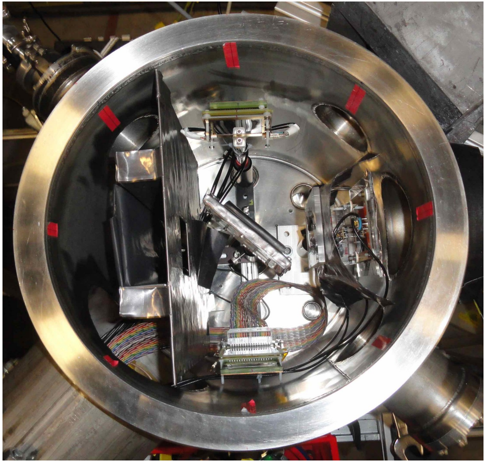
BOSTON UNIVERSITY

And thanks to our respective funding agencies for their support!



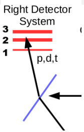
Experimental Setup

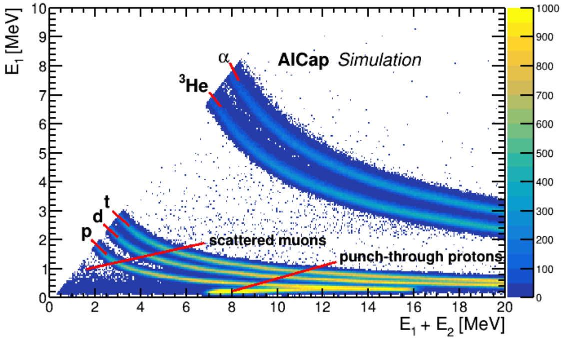




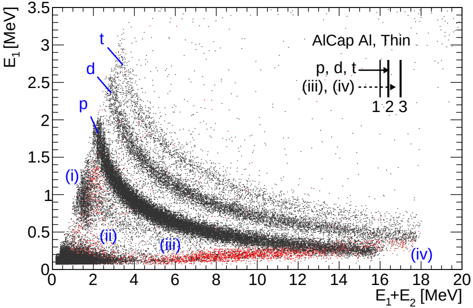
Particle ID

With the layered silicon detectors, we can **identify the different particle types** because dE/dx rises sharply when going to lower energies:



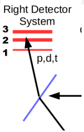


Simulation



Data (Zoom-in on y-axis)

Particle ID



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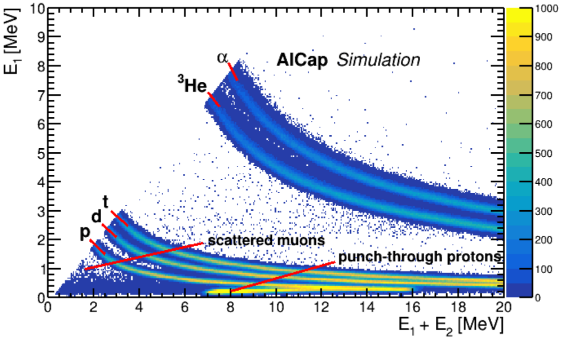
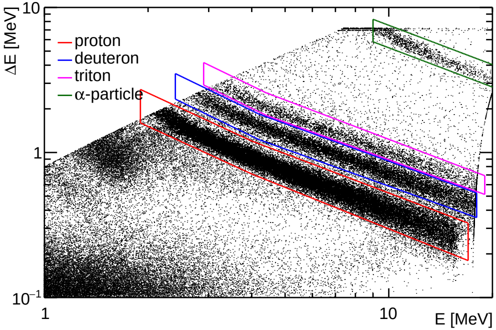


Simulation



Data (Log-Log Scale)

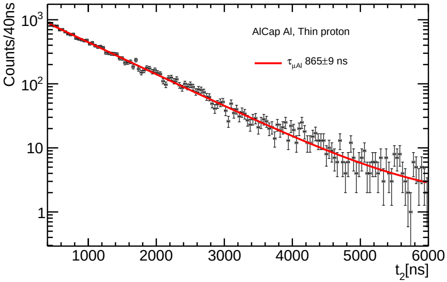
Measured Energy Spectra

Extract particle bands and check lifetime is consistent with muonic atom lifetimes (below)

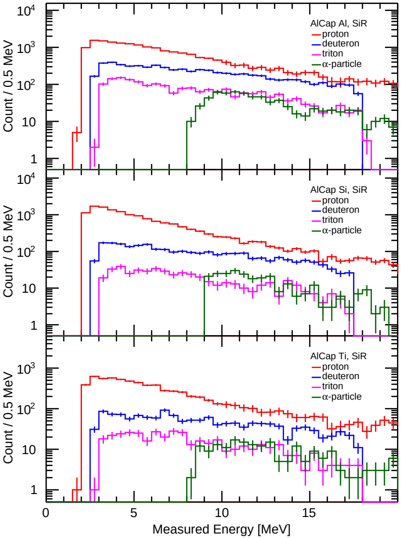
- literature: $\tau_{\mu \text{Al}} = 864(2)$ ns

Energy spectra of extracted particle bands (right)

- need to **correct for energy loss in target**



Arrival time of extracted protons

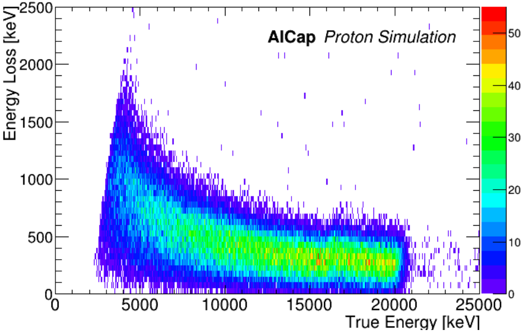


Unfolding Energy Spectrum

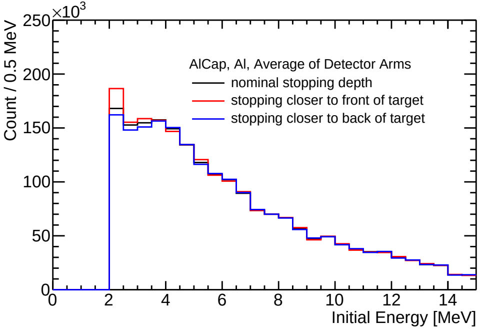
We **correct for energy loss in target** using RooUnfold's **Bayesian unfolding** methods

- need a response matrix from simulation

Energy Loss of Protons in Target (simulation)



When we take the average of the two arms, we are insensitive to the muon stopping depth



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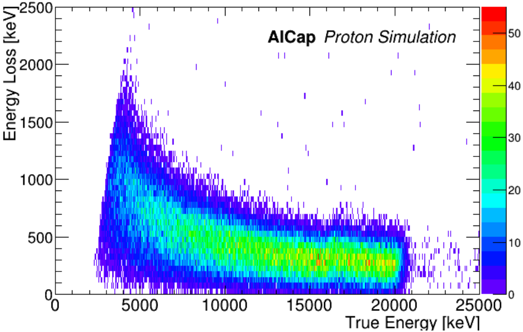
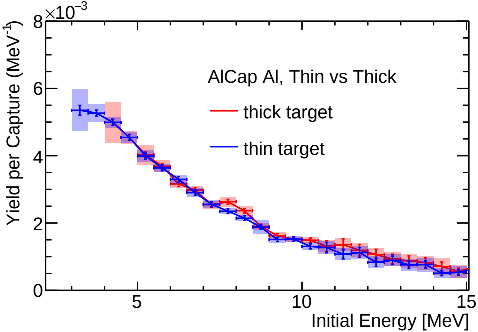
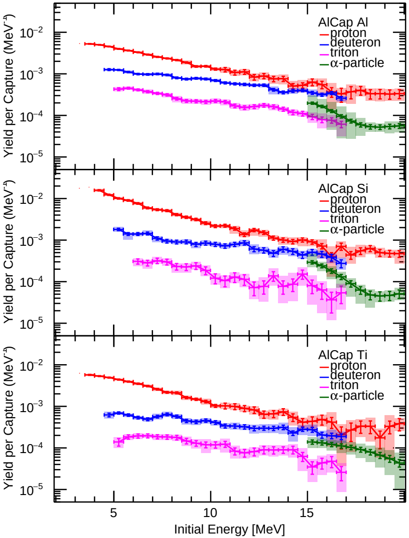


Cross-check with a thicker Al target



Results



Results published in
Phys.Rev.C 105 (2022) 3, 035501

Found that **yields for Al were significantly lower than COMET/Mu2e had assumed**

- COMET Phase-I will forgo a proton absorber
- Mu2e proton absorber will be thinner and shorter than originally planned

Results

We **fill in significant gaps in the literature**

	aluminum			silicon		titanium
Direct measurements:	AlCap	TWIST [20]	Krane et.al. [19]	AlCap	Sobottka-Wills [14]	AlCap
$(\mu^-, \tilde{p})$	[3.5≤E≤20.0] 26.64(28)(77)	[3.4<E] 32.2(2.3)	–	[4.0≤E≤20.0] 52.5(6)(18)	–	[3.5≤E≤20.0] 26.48(35)(80)
$(\mu^-, \tilde{d})$	[4.5≤E≤17.0] 8.46(9)(24)	[4.5<E] 12.2(1.1)	–	[5.0≤E≤17.0] 9.80(22)(41)	–	[4.5≤E≤17.0] 5.02(10)(20)
$(\mu^-, \tilde{t})$	[5.0≤E≤17.0] 2.58(4)(9)	–	–	[6.0≤E≤17.0] 1.70(8)(10)	–	[5.0≤E≤17.0] 1.36(5)(7)
$(\mu^-, \tilde{\alpha})$	[15.0≤E≤20.0] 0.44(1)(9)	–	–	[15.0≤E≤20.0] 0.57(3)(10)	–	[15.0≤E≤20.0] 0.45(2)(5)
$(\mu^-$, all charged)	–	–	[40<E] 1.38(9)	[1.4≤E≤26] 171(30)	[1.4≤E≤26] 150(20)	–
Activation measurements[a]*:*	Wyttenbach et. al. [18]	Heusser-Kirsten [17]				
$^{A}_{Z}X(\mu^-, pn)^{A-2}_{Z-2}X$	28(4)	–				
$^{A}_{Z}X(\mu^-, p2n)^{A-3}_{Z-2}X$	–	35(8)				
$^{A}_{Z}X(\mu^-, \alpha)^{A-4}_{Z-3}X$	7.6(1.1)	–				
Theory:	Lifshitz-Singer [12]			Lifshitz-Singer [12]		
$(\mu^-, \tilde{p})$	40			–		
$(\mu^-, \tilde{d})$	12			21		
$(\mu^-, \tilde{\alpha})$	20			34		
$(\mu^-$, all charged)	–			144		
$^{A}_{Z}X(\mu^-, p)^{A-1}_{Z-2}X$	9.7			32		
$^{A}_{Z}X(\mu^-, d)^{A-2}_{Z-2}X$	6.0			8.2		
$^{A}_{Z}X(\mu^-, \alpha)^{A-4}_{Z-3}X$	7.3			17		

First measurement of triton emission

- useful for direct dark matter searches with silicon detectors

First measurements from muonic titanium

- an alternate material for COMET/Mu2e

Stimulate theoretical interest in muon-nucleus interactions

- see e.g. this paper that investigated nuclear models in the context of soft errors in memory devices

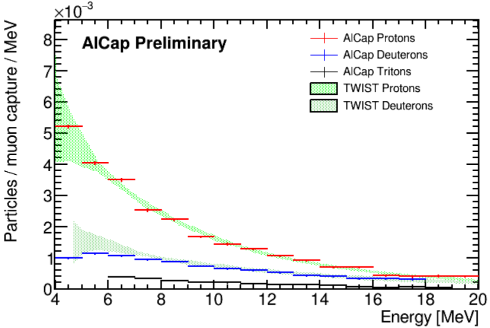
Comparison with Literature (Al)

Most recent comparison in literature is from TWIST

- measured momentum → complementary technique

AlCap and TWIST are consistent with each other

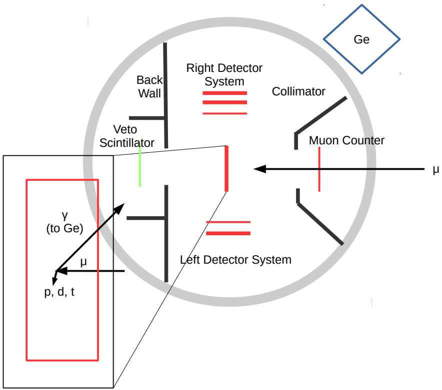
- we achieved higher precision in low-energy region important for COMET/Mu2e

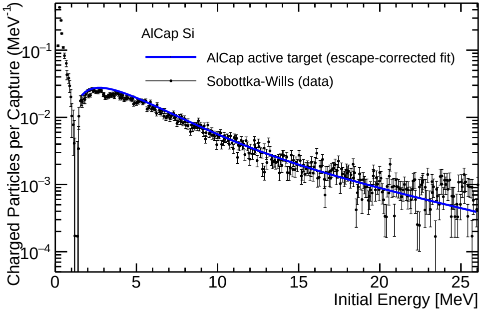


Note: TWIST spectra extend to higher energies than shown in this plot

Comparison with Literature (Si)

Collected data with an active Si target to cross-check with Sobottka-Wills measurement





AlCap and Sobottka-Wills are consistent with each other

What's Next?

Another goal of the AlCap experiment is to **measure the characteristic muonic X-rays and γ-rays** that COMET/Mu2e will use to normalize their measurements

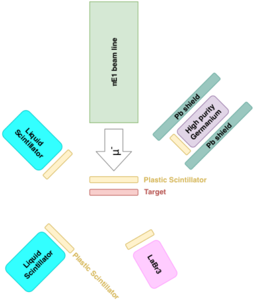
- large uncertainty on intensity of 1809 keV γ-ray ($I = 51(5)\%$)
- muons stopping in other materials could produce background peaks

Different experimental set up

- no vacuum chamber
- very thick targets

Paper in preparation

- will improve precision on the intensity of the 1809 keV γ-ray



Conclusion

AlCap have published the spectra of protons, deuterons, tritons, and α-particles emitted after nuclear muon capture on Al, Si, and Ti.

These results:

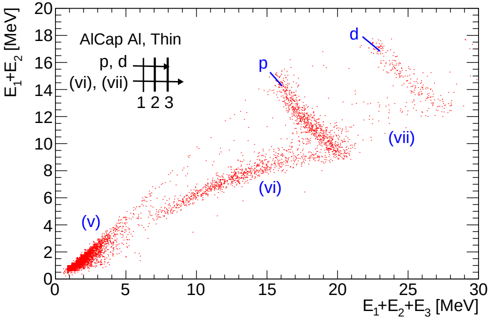
- fill in significant gaps in the literature,
- led to a reevaluation of the proton absorber designs in COMET/Mu2e, and
- we hope will stimulate renewed theoretical interest in muon-nucleus interactions

Thanks for listening! Any questions?

Backup slides

Three-Layer Particle ID

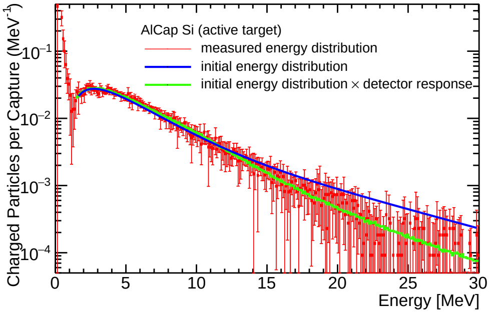
Three-plot allows us to extend energy range of proton measurement to 17 MeV

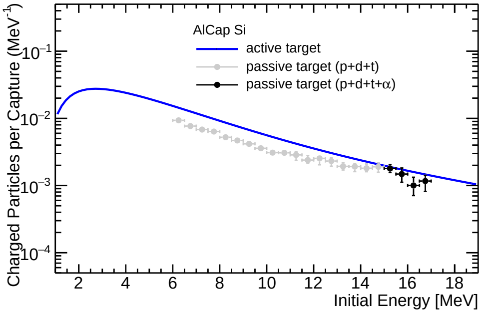


AlCap Active Target Analysis

We assume some initial energy distribution (blue), fold it with the detector response (green), and fit parameters until we match the data (red).

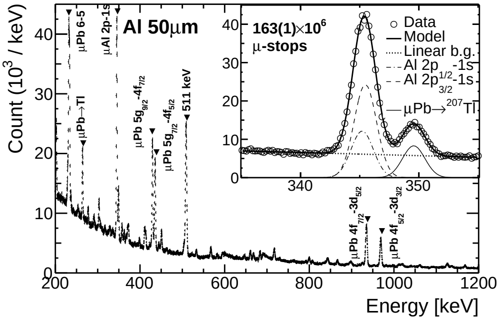
We can compare this to the result from the main ("passive") analysis in the range $15 < E < 17$ MeV where all particle types are observed





Normalization

We count the number of stpoped muons by fitting the $2p - 1s$ X-ray that is emitted when the muon stops and falls down the energy levels



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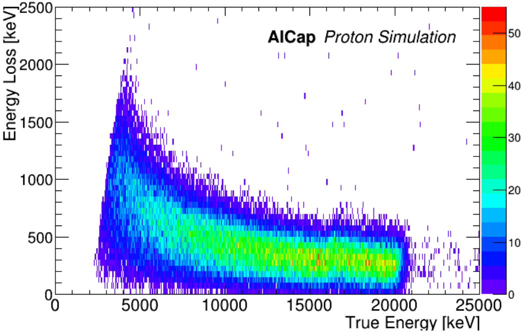
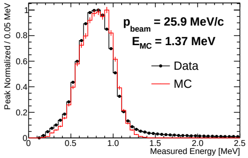
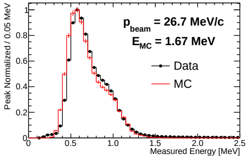
Energy Loss of Protons in Target (simulation)



Muon beam simulation tuned to data to get correct stopping depth:



Lower p



Higher p