AlCap

Aluminium Capture of muons

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11th August 2015

NuFact15

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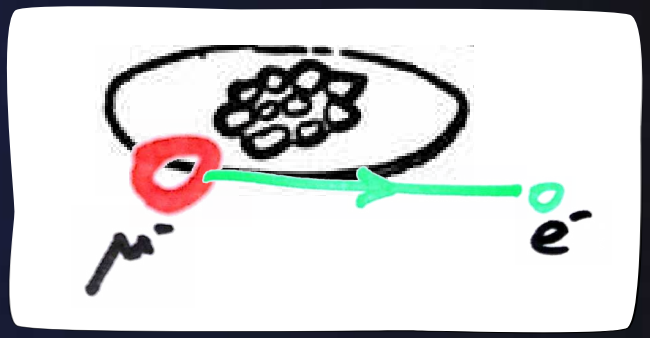
Muon to Electron Conversion

Neutrinoless conversion of a muon to an electron in the presence of a nucleus

$$\mu^- + \mathrm{N(A,Z)} \rightarrow \mathrm{e}^- + \mathrm{N(A,Z)}$$

Conversion signal on Aluminium is a mono-energetic electron:

$$E_e = 104.9 \text{ MeV}$$



Typically define the conversion rate by:

$$\mathcal{R} = \frac{\Gamma(\mu\text{-}e \text{ conversion})}{\Gamma(\mu \text{ capture})}$$

Current limit from SINDRUM-II (90% C.L) on gold:

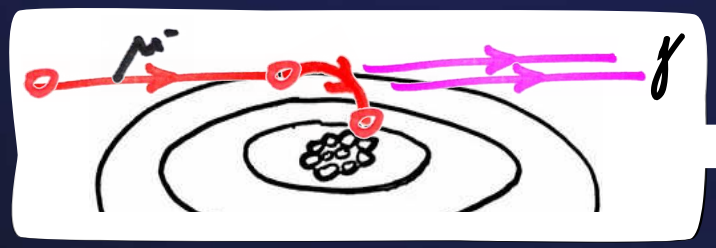
$$\mathcal{R} < 7 \times 10^{-13}$$

Future experiments (COMET, Mu2e) use aluminium, aiming for:

$$\mathcal{R} \sim 10^{-17}$$

Muon to Electron Conversion

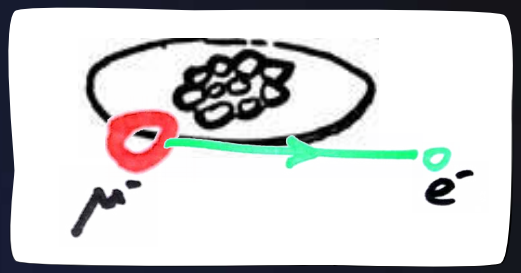
- High sensitivity of modern μ-e conversion searches requires many muons to be stopped
- Negative muons stop in material, forming muonic atoms



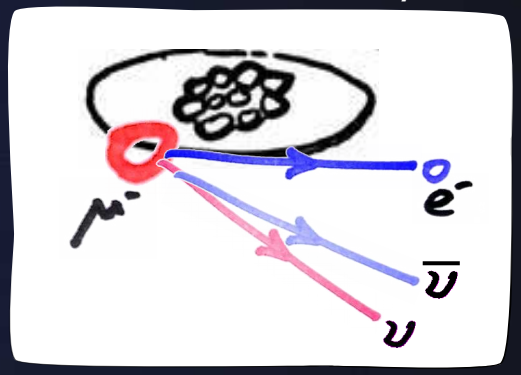
Electromagnetic Cascade to the Ground state

- Target materials:
  - Previously lead, gold, titanium
  - Mu2e and COMET: aluminium

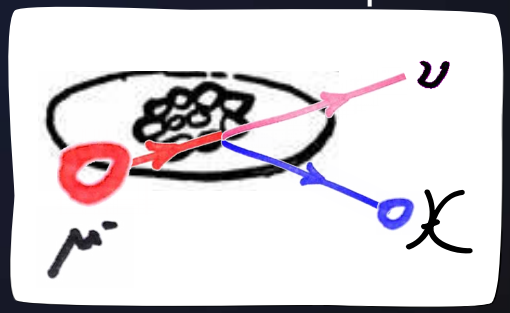
Muon to Electron Conversion



Bound Muon Decay

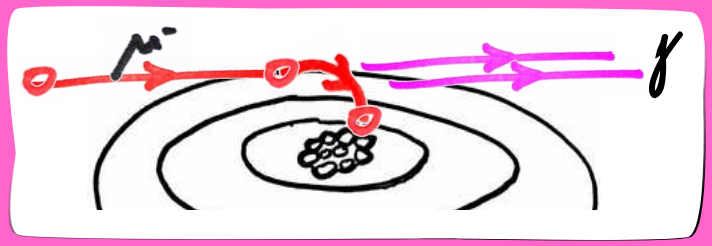


Muon Nuclear Capture



Muon to Electron Conversion

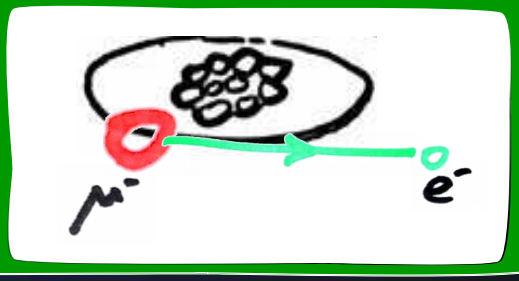
- Number of stopped muons (normalisation)
- Radiation hardness for electronics



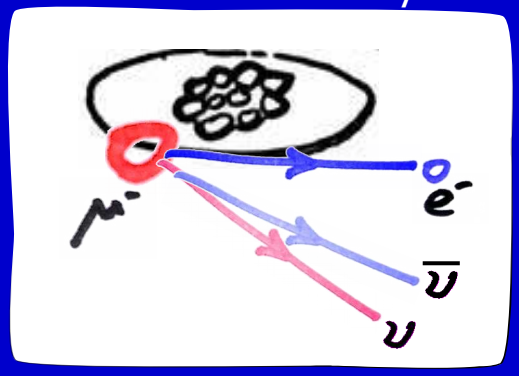
Need to understand all other stopped muon processes to high precision

Muon to Electron Conversion

Signal

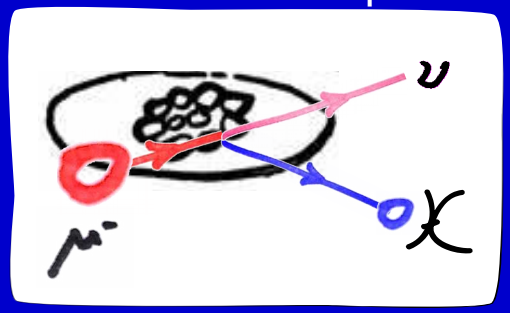


Bound Muon Decay



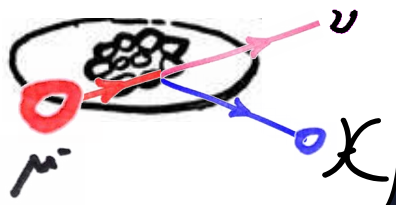
- Backgrounds
- Detector occupancy
- Radiation hardness for electronics

Muon Nuclear Capture

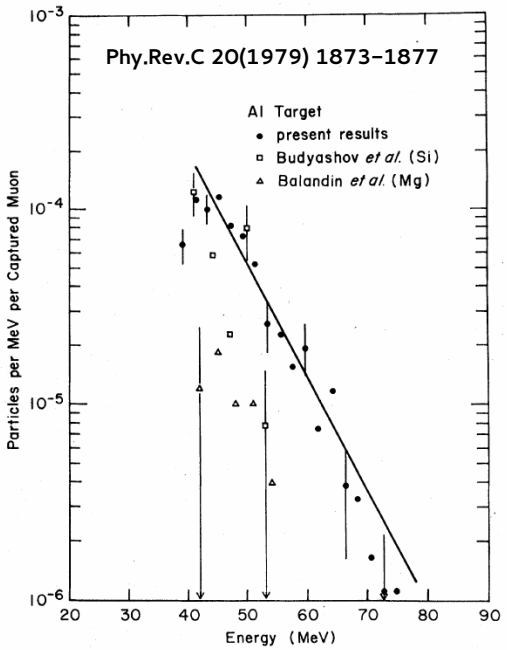


Nuclear Capture of the Muon

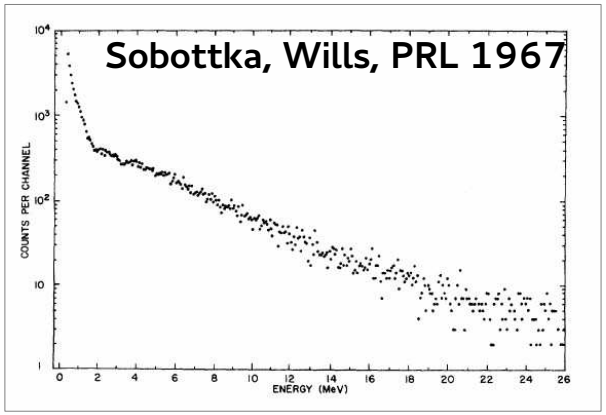
$$\mu^- + {}^{27}\mathrm{Al} \rightarrow \nu + {}^{27}\mathrm{Mg}^*$$
$$B.R. = 60\%$$



- Subsequent nuclear de-excitation results in:
  - Protons, deuterons, alphas
  - Gamma rays
  - Neutrons
- Existing description incomplete
- COMET and Mu2e have conservatively assumed Si emission rate for protons from Al: 15% per muon capture emit a proton



Proton emission spectrum above 40 MeV

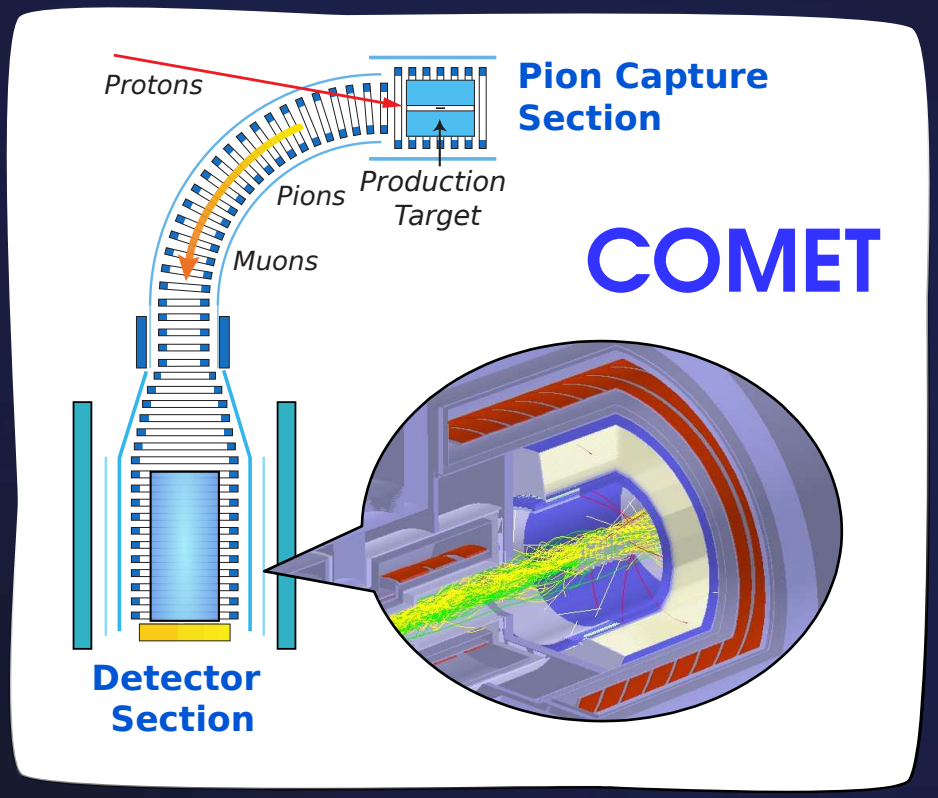


Inclusive Emission of charged particles from capture on silicion

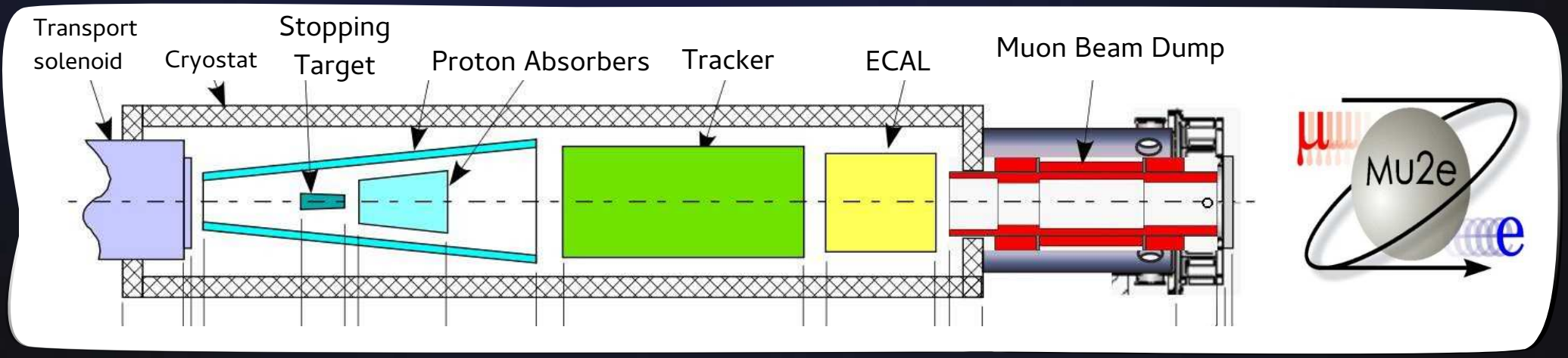
Target A, Z	$A-2, Z-2$ (μ^-, pn) (10^{-3})	$A-4, Z-3$ (μ^-, α) (10^{-3})
${}^{27}_{13}\mathrm{Al}$	28 ± 4	7.6 ± 1.1

Proton and alpha emission per muon capture
Wyttenbach et al. Nuc. Phys. 1978

How does this impact COMET / Mu2e?



- Affects:
  - COMET Phase-I physics measurement with the Cylindrical Detector
  - Mu2e Tracker and Calorimeter
- Problems:
  - Radiation hardness requirements
  - Detector occupancy
  - Neutrons can veto events in active cosmic ray veto
- Solutions:
  - Proton absorbers
  - Radiation hard electronics
  - Lower rates



AlCap Work Packages

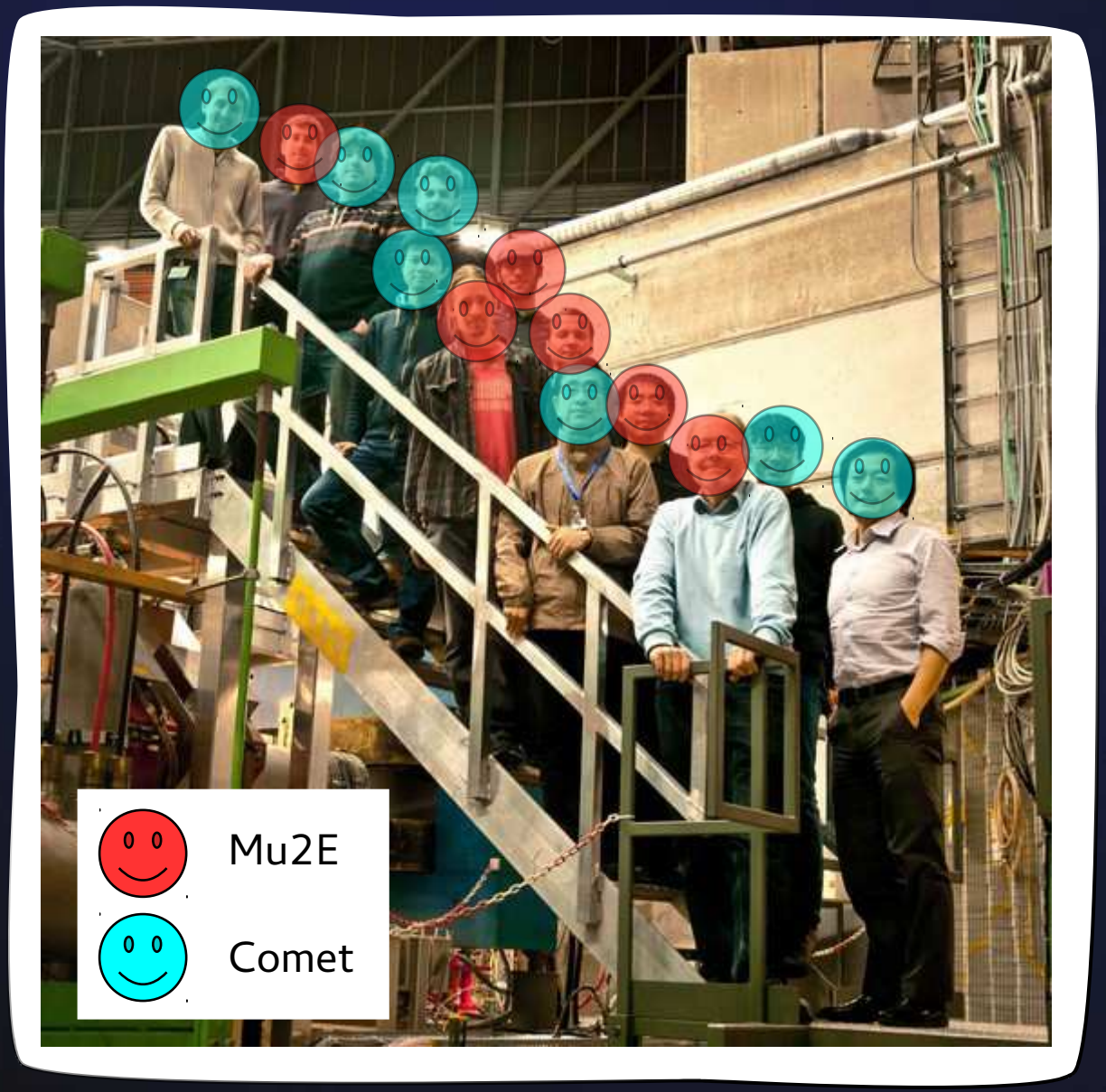
- WP1: Charged Particle emission after Muon Capture
  - Rate and spectrum with precision 5-10% down to 2.5 MeV
  - Dominant rate in tracker for Mu2e and COMET Phase-I
- WP2: X-ray and Gamma Emission after Muon Capture
  - X-ray and gamma ray for normalization (by Ge detector), radiative muon decay (by LYSO detector)
- WP3: Neutron Emission after Muon Capture
  - Rate and spectrum from 1 MeV up to 10 MeV
  - BG for calorimeters and cosmic-ray veto, damage to electronics

Run 1 (2013)	**Run 2 (2015)**	**Run 3 (2015)**
WP1 and WP2	WP2 and WP3	WP1 and WP2

The AlCap Collaboration

- COMET:
  - Osaka University
  - IHEP China
  - Imperial College London
  - University College London
- Mu2e
  - Argonne NL
  - Boston University
  - BNL
  - INFN
  - Fermilab
  - Univ. of Houston
  - Univ. of Washington

The AlCap Collaboration



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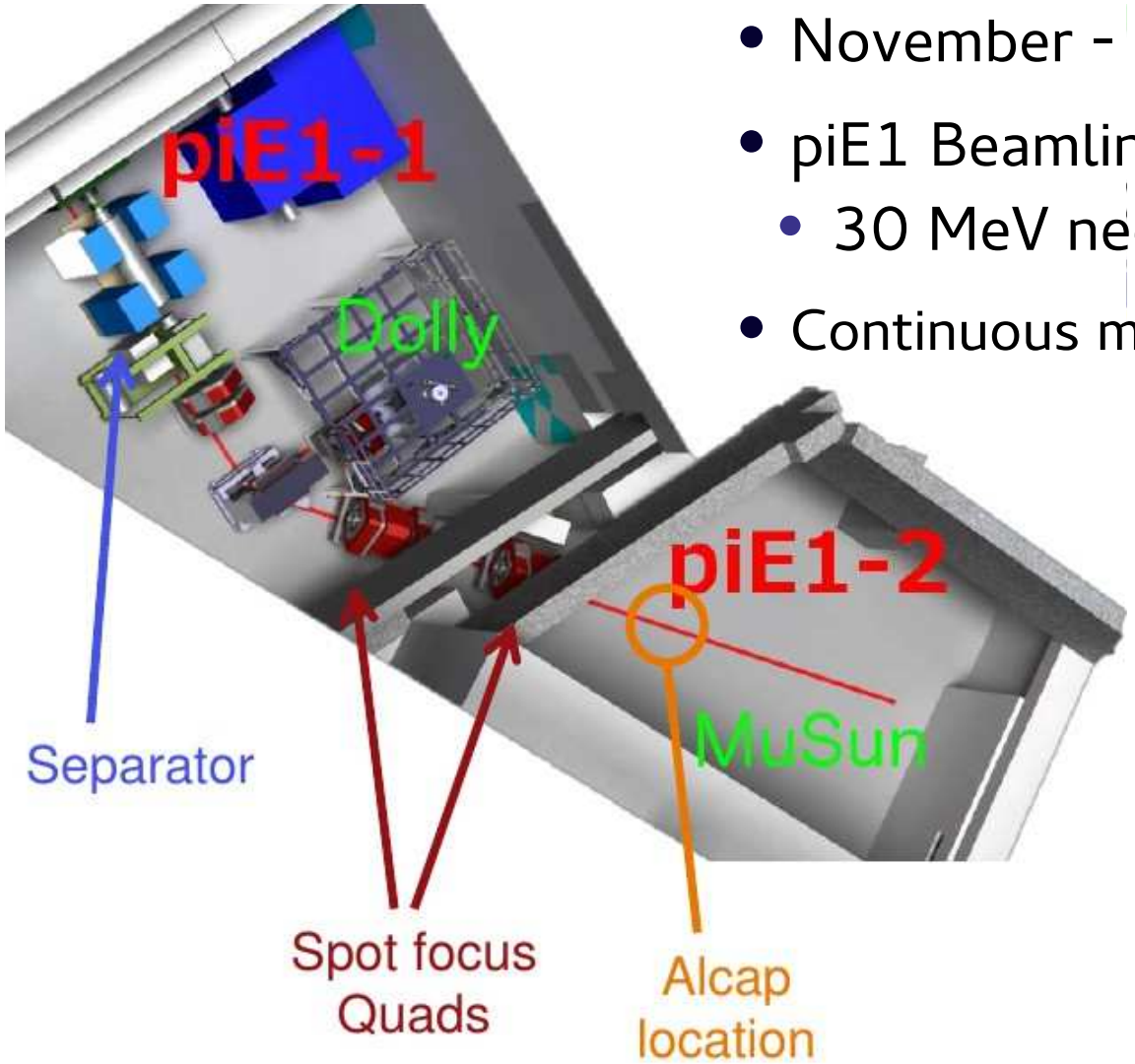
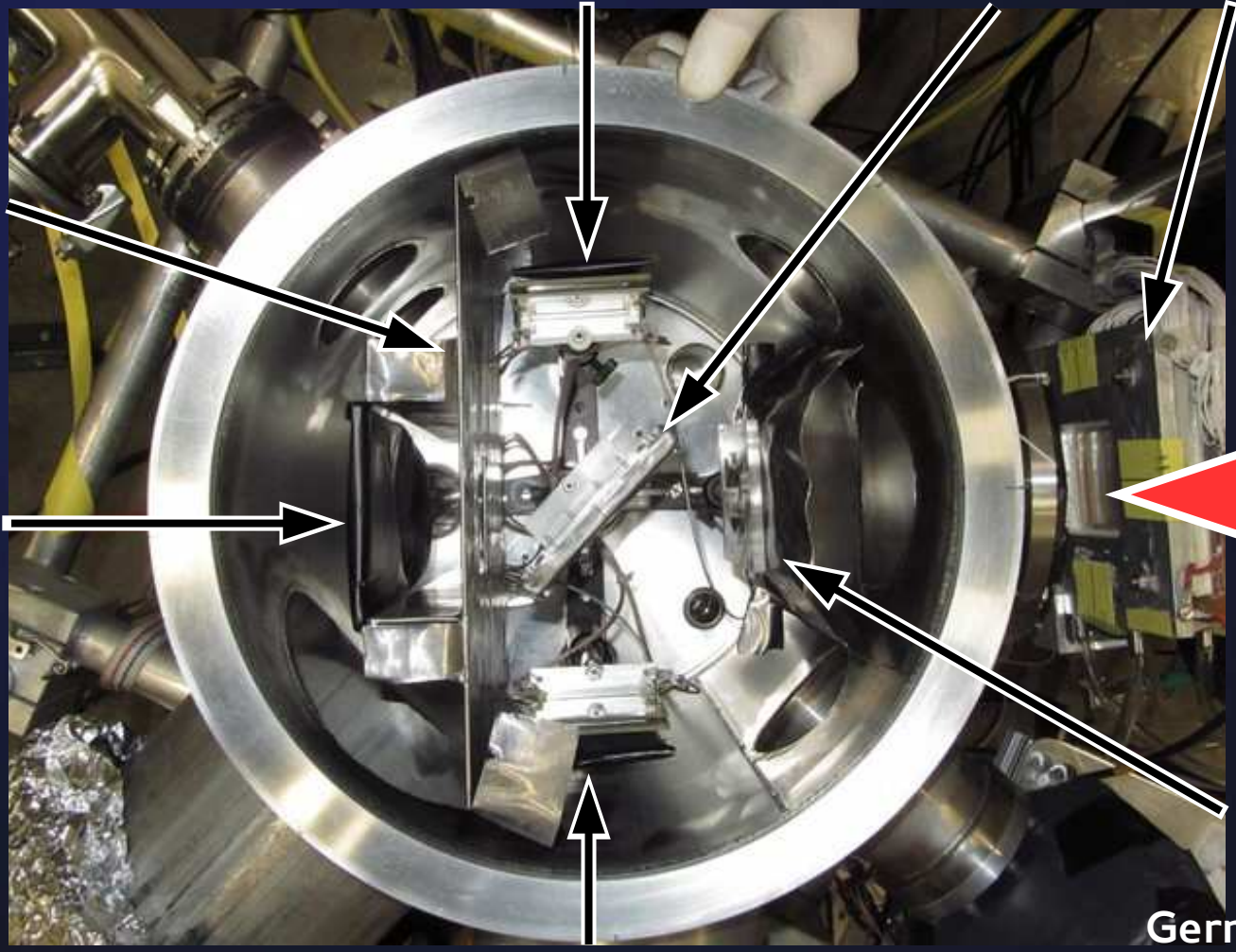
  - Fermilab
  - Univ. of Houston
  - Univ. of Washington

Run 1: Charged Particles, Gammas

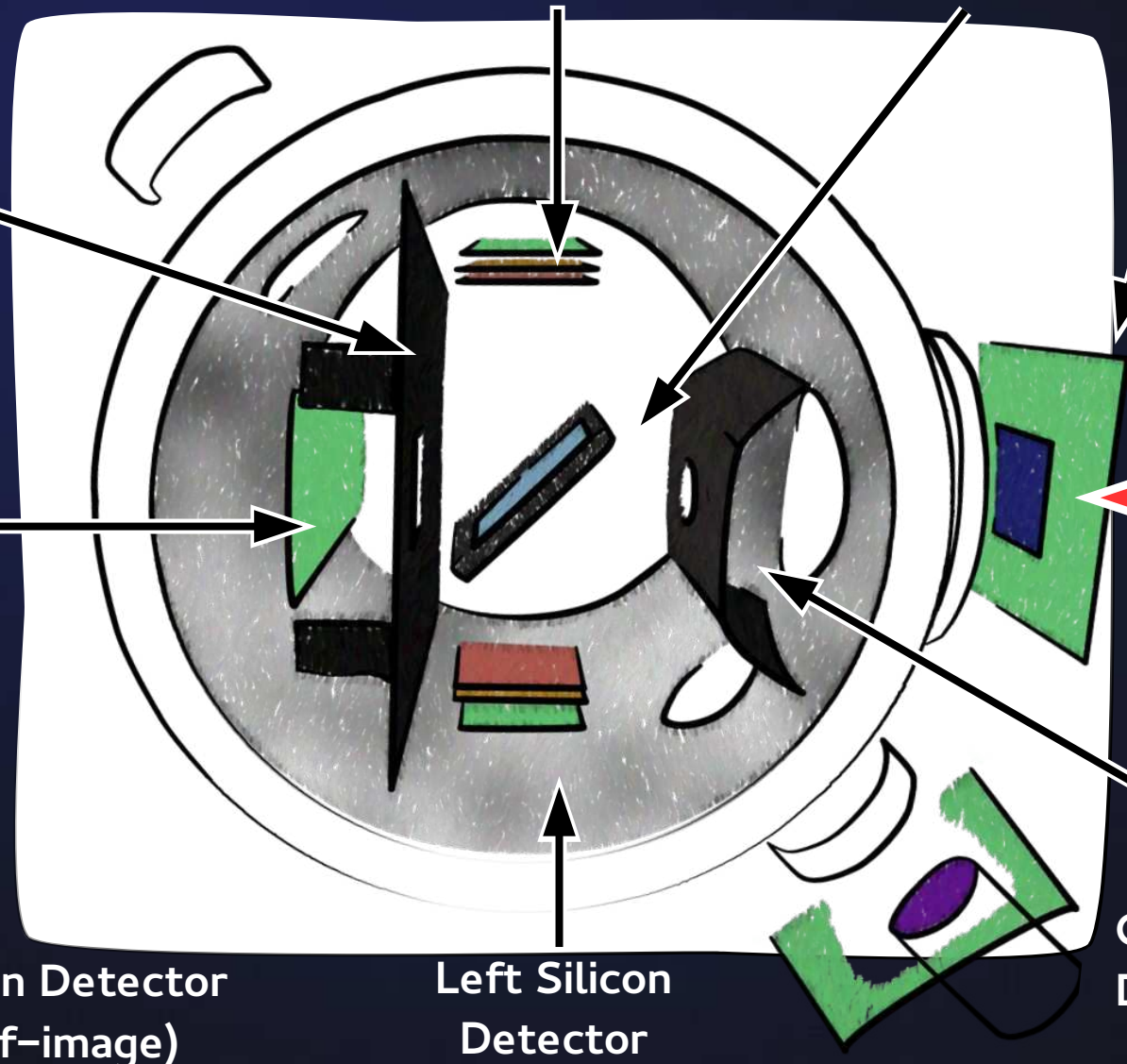


- Paul Scherrer Institute (PSI)
- November - December 2013
- piE1 Beamline
  - 30 MeV negative surface muons
- Continuous mode at about 3-6 kHz

Run-1: Setup


Right Silicon Detector
Target
Muon Taggers: MuSc, MuPC
Vacuum Pump
Lead Shielding
Muon Veto Scintillator
μ^-
30 MeV/c, 3-6 KHz
Collimator
Germanium Detector
Neutron Detector (Out-of-image)
Left Silicon Detector

Run-1: Setup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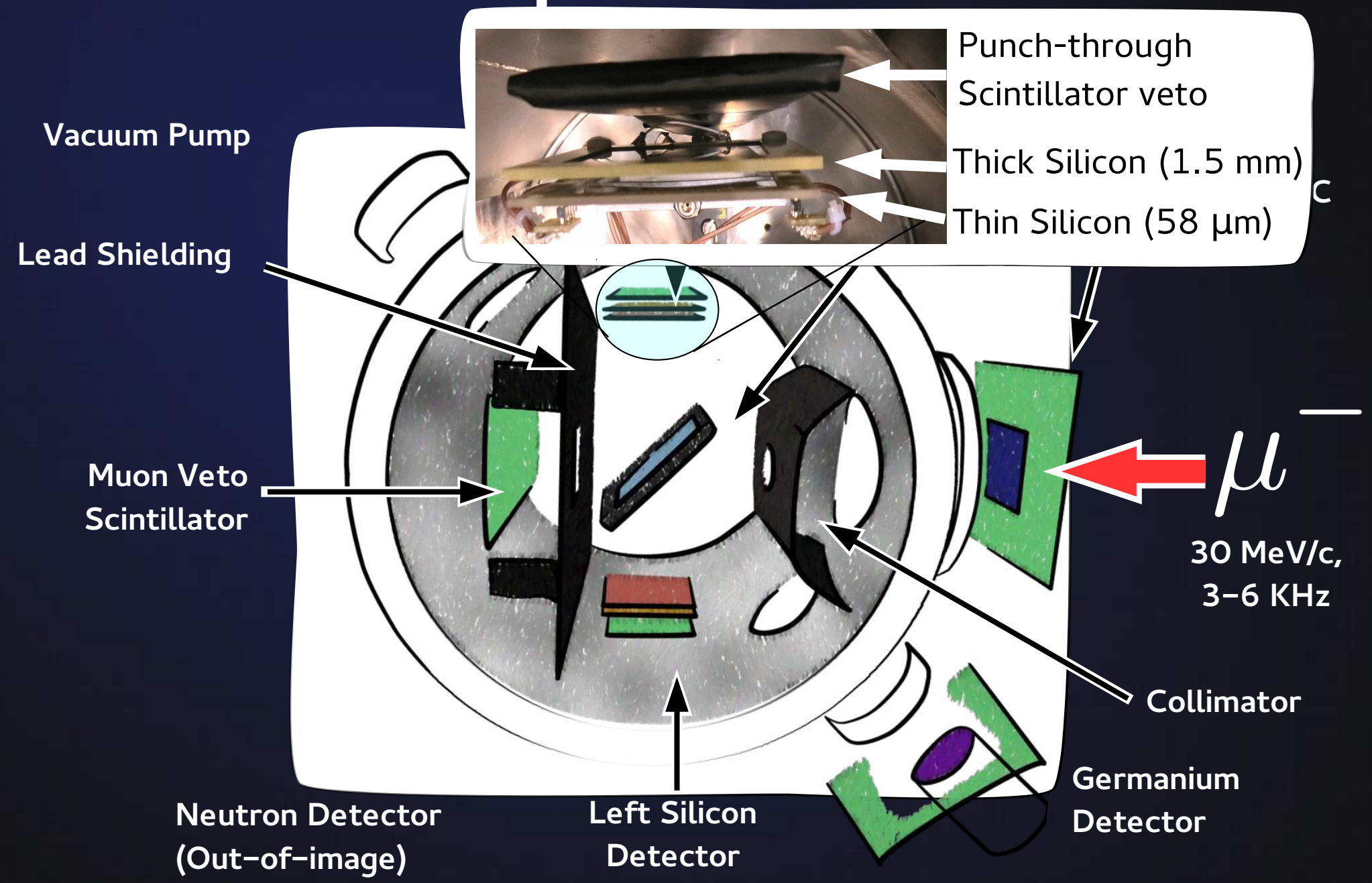
Run-1: Setup

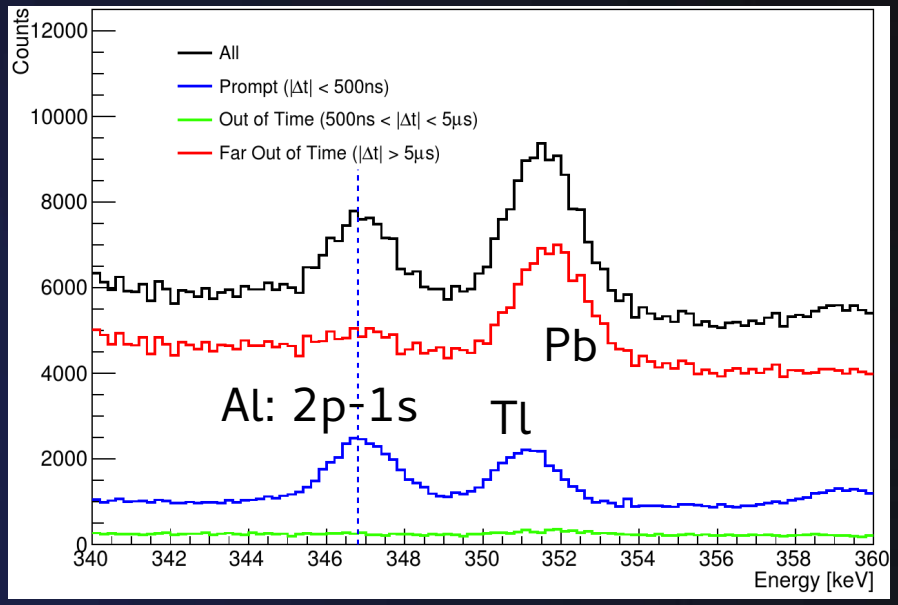

Punch-through
Scintillator veto
Thick Silicon (1.5 mm)
Thin Silicon (58 μm)
Vacuum Pump
Lead Shielding
Muon Veto
Scintillator
μ^-
30 MeV/c,
3-6 KHz
Collimator
Germanium
Detector
Neutron Detector
(Out-of-image)
Left Silicon
Detector

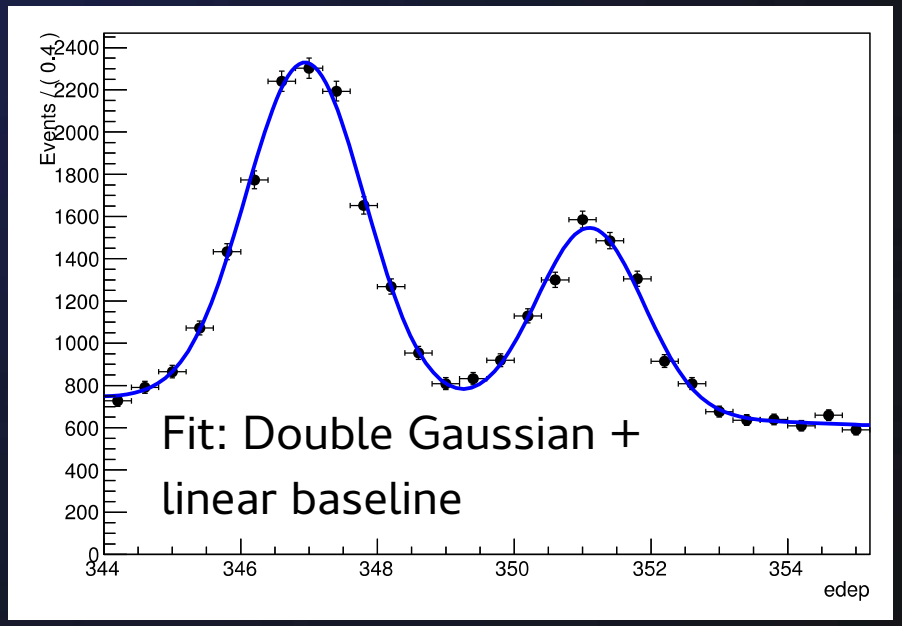
Run-1: Datasets

Target	Beam Momentum (x28 MeV/c)	Number of Muons ($x10^7$)	Comments
Si (1500 μm)	1.32	2.78	Active Target
	1.30	28.9	Cross check with existing Si data
	1.10	13.7	
Si (62 μm)	1.06	1.72	Passive Target
Al (100 μm)	1.09	29.4	
	1.07	4.99	
Al (50 μm)	1.07	88.1	

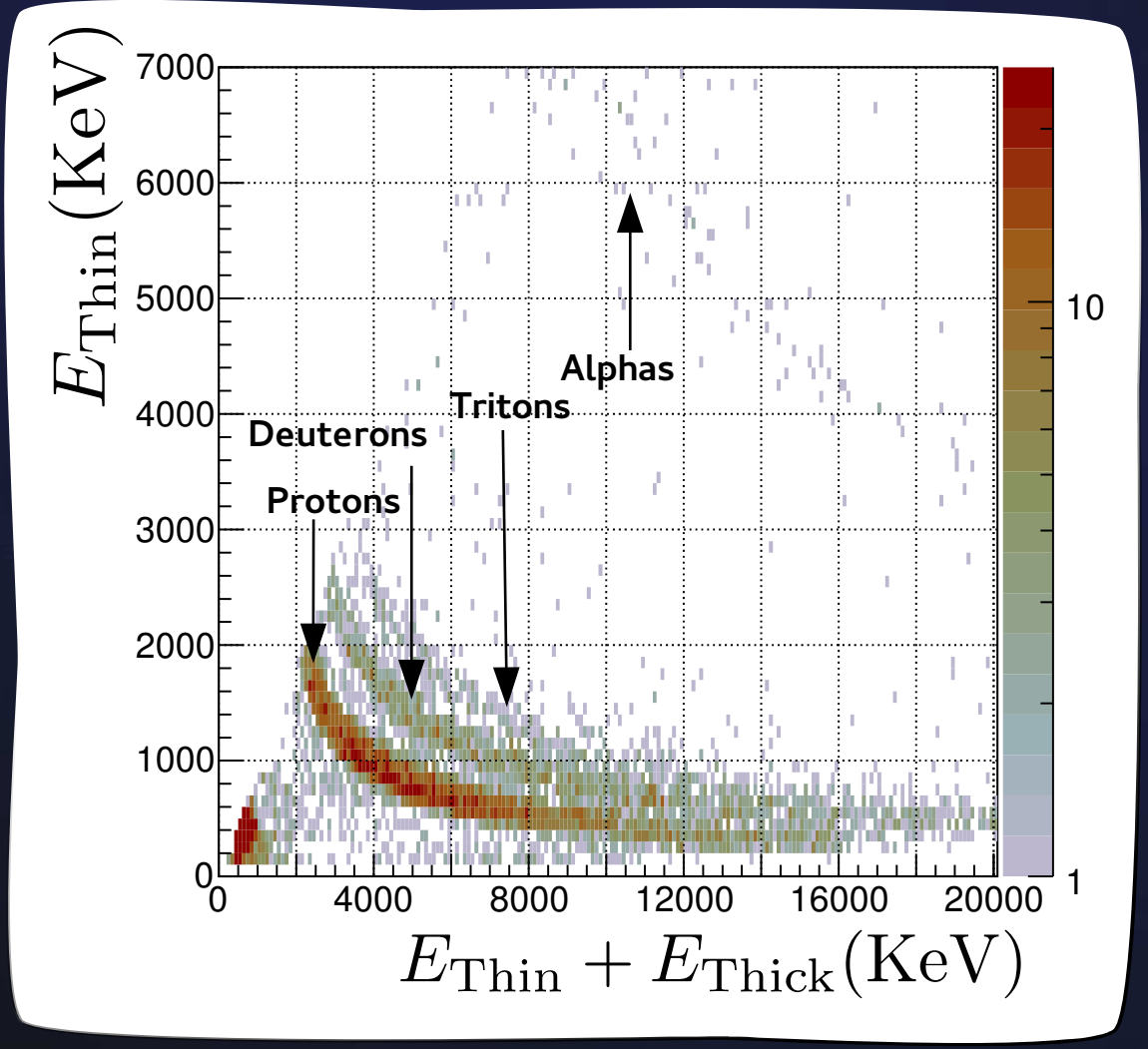
Number of Stopped Muons

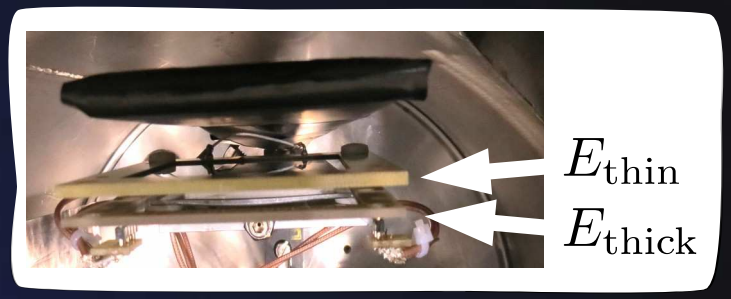
- Germanium detector
  - X-rays from muon electromagnetic cascade to 1s orbital
- Muon selection criteria
  - Incoming muon cuts
    - Muon scintillator energy
  - Muon pile-up protection
  - Prompt X-rays (<500ns)
- Fit 2p-1s peak at 347 KeV
  - Gaussian
  - Background:
    - Linear baseline
    - Second Gaussian for nearby Pb/Tl capture peak





Charged Particle Measurement





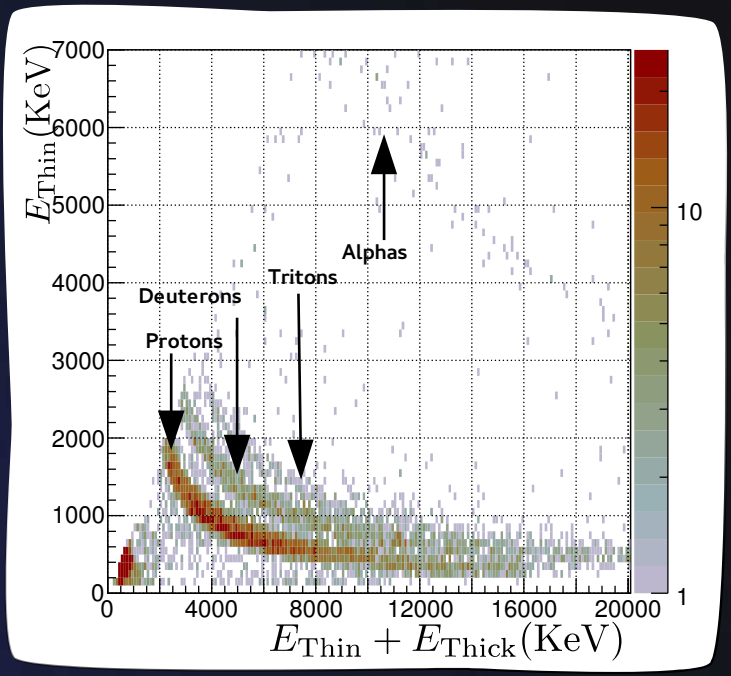
Identification of Stopped Particle Species using Thin and Thick energy deposits:

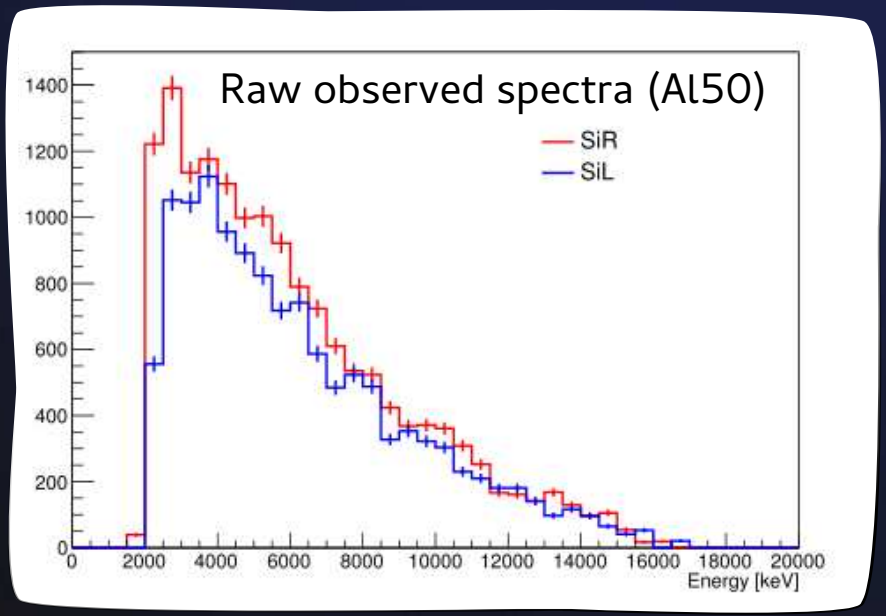
$$E_{\mathrm{Thin}} = \frac{dE}{dx}\Delta x$$

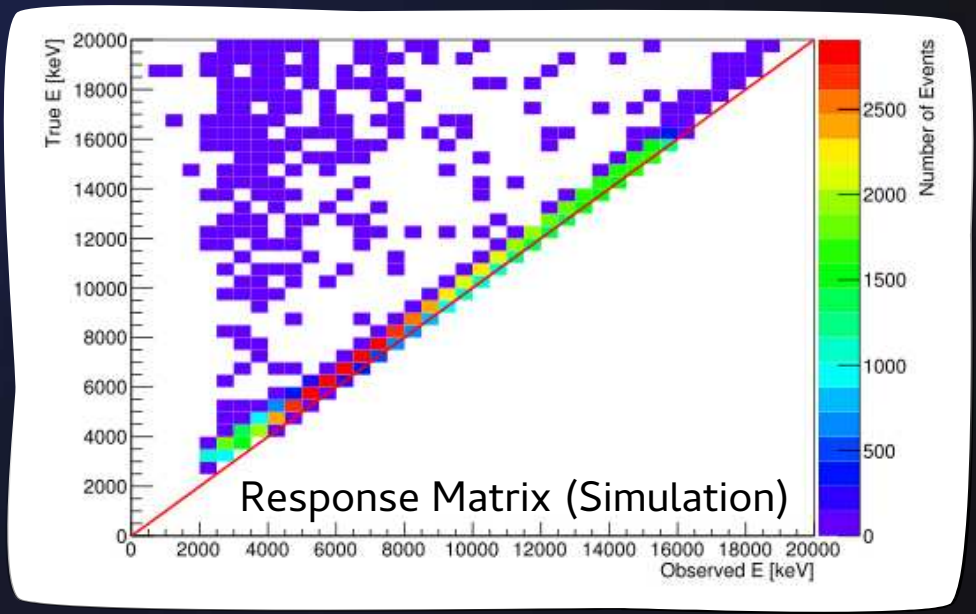
$$E_{\mathrm{Thin}} + E_{\mathrm{Thick}} = E_{\mathrm{Total}}$$

Charged Particle Measurement

- Hit selection criteria:
  - Time of hit > 100 ns since muon (removes scattered muons, lead capture products)
  - PID cut
    - Geometric
    - Probability based on Monte Carlo



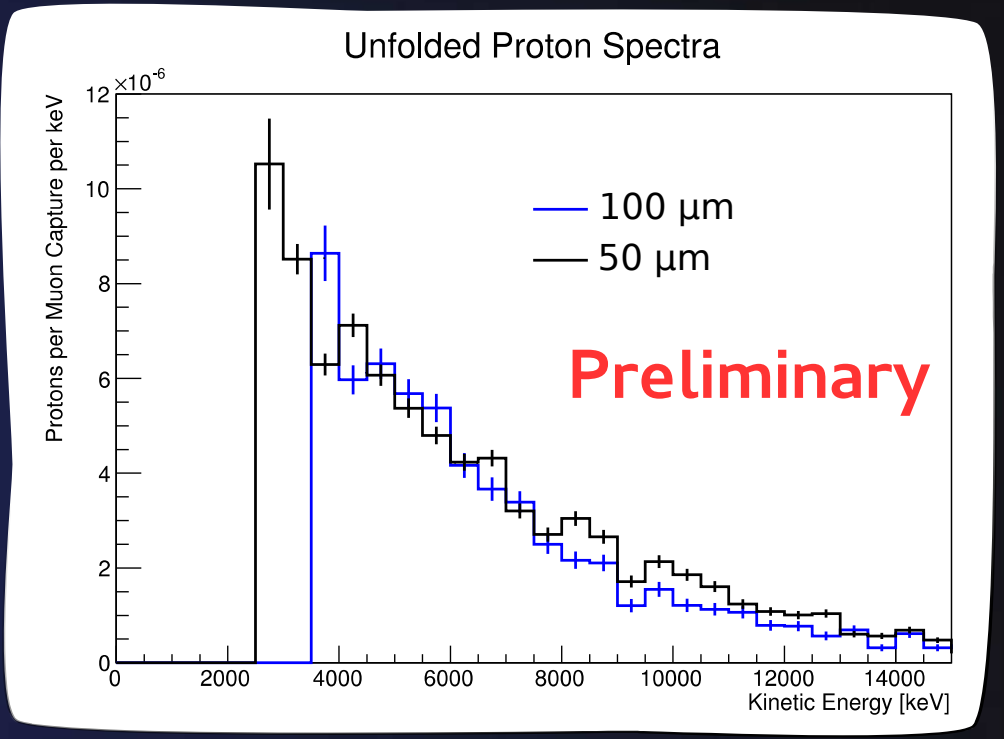




Run-1: Results (on-going)

So far:

- Proton Emission Spectrum from 3.5 to 10 MeV
- Proton emission per muon capture:
  - 0.020 (from 4 to 8 MeV)
  - 0.035 (integrated extrapolation)
  - Uncertainty about 9%



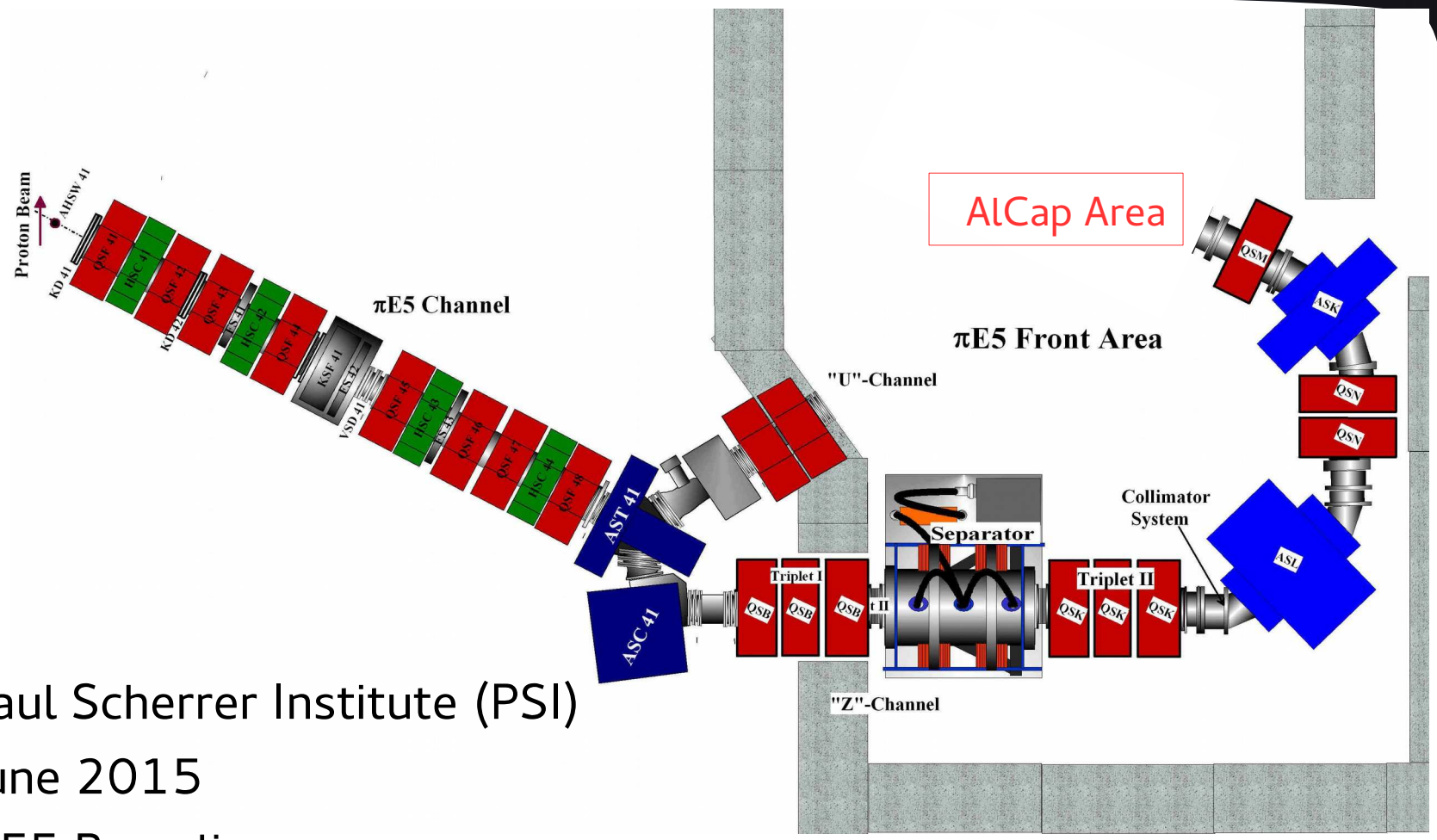
On-going:

- Deuteron, triton and alpha bands
- Final, combined proton emission rate

Impacts:

- COMET: Proton absorber removed
- Mu2e: Proton absorber re-optimised
- Changes to simulation code:
  - Vanilla Geant4 predicts about 30% of muon captures produce a proton
  - Fluka similar

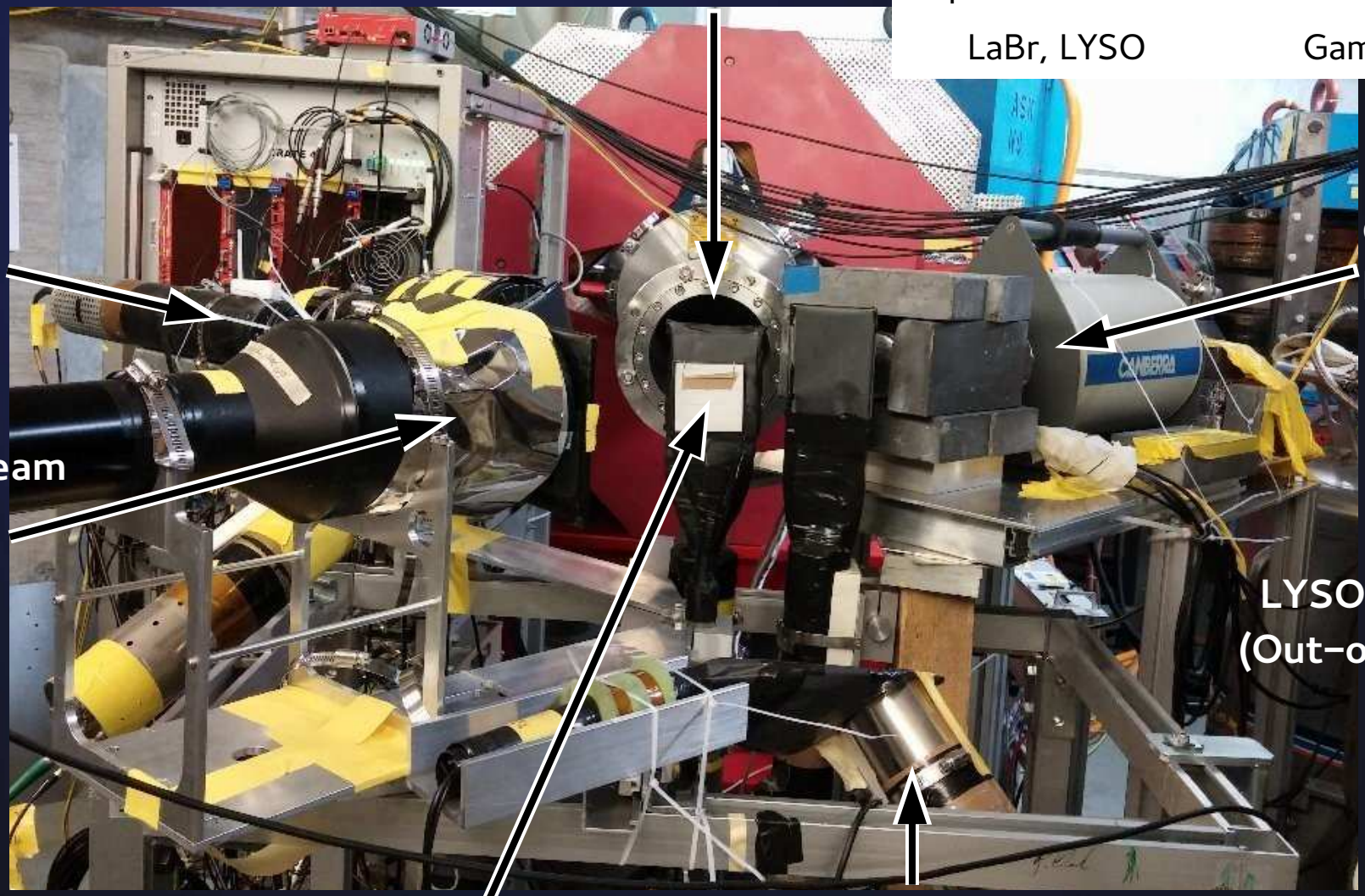
Run 2: Neutral Particles



- Paul Scherrer Institute (PSI)
- June 2015
- piE5 Beamline
  - 36 MeV/c negative muons
- Continuous mode at about 10 KHz

Run-2: Setup

Detectors	Purpose
Ge-1	Gamma / X-rays
Ge-2	Activation study
Liquid Scintillators	Neutrons
LaBr, LYSO	Gammas



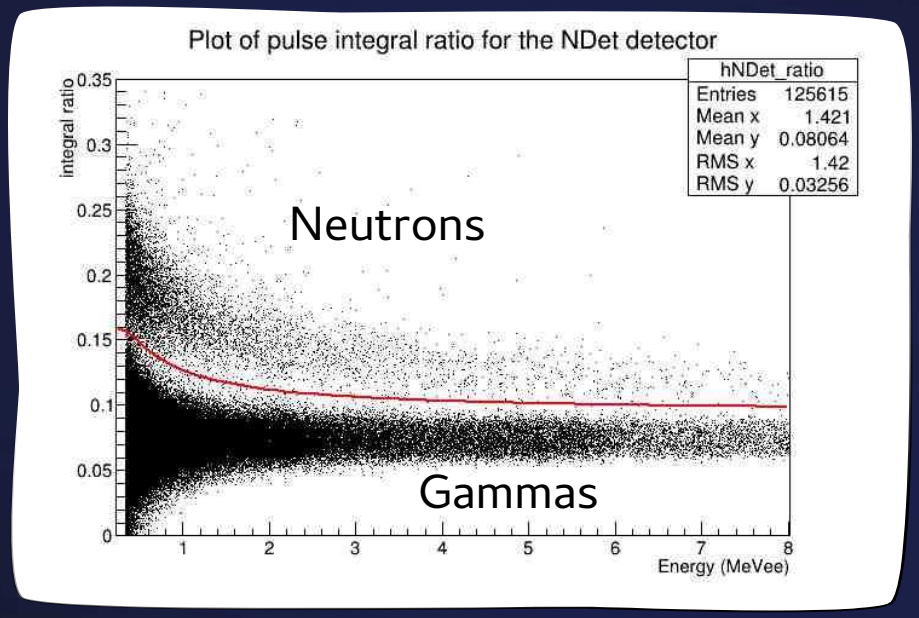
Run-2: Datasets

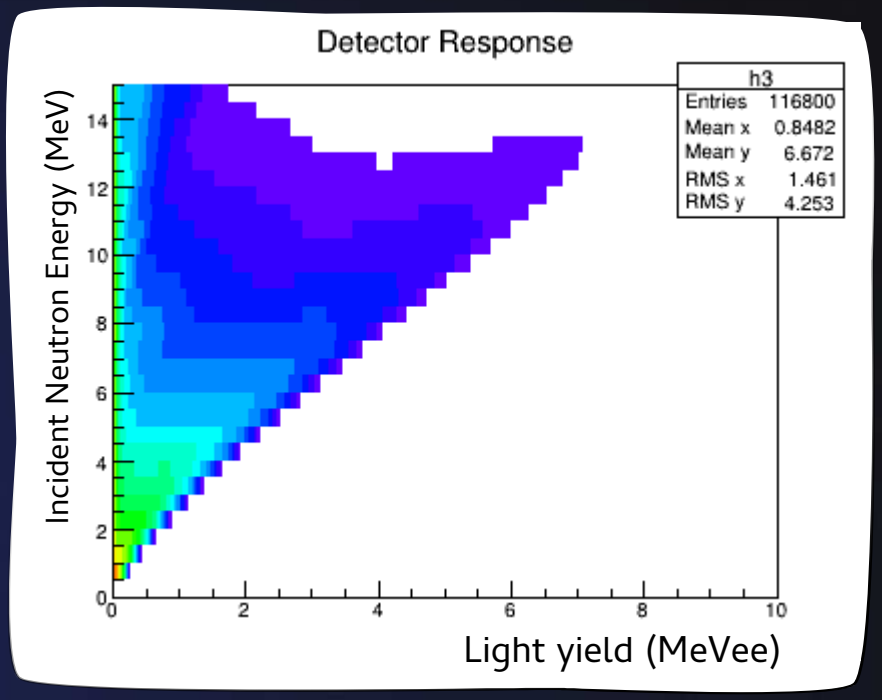
- Want to consider other materials from COMET / Mu2e beamline

Target	Target Thickness (mm)	Approximate Exposures (hours)
Al	2	42
Ti	1.1	24
Pb	1.5	9
Water	~6 (not uniform)	4.5
Empty	~	3

- Changes since Run-1:
  - Improved ADCs
  - Time calibration using on-going test pulse signal
  - High energy gammas with LYSO
  - Neutron detectors already calibrated
  - No vaccuum chamber
- Additional activation study:
  - Very delayed x-rays from muon radioactive magnesium produced by capture
  - 844 KeV line with ~9.5 minute lifetime
  - Possible counting method for number of stopped muons

Run-2: Analysis





- Data quality checks underway
- Liquid Scintillator neutron detectors
  - Pulse Shape Discrimination
  - Careful detector calibration to obtain detector response
    - Measured with at TUNL before Run-2
  - Spectrum unfolding
- Other detectors:
  - LYSO / LaBr being worked on separately

Future Prospects

- Run-1 analysis
  - Remaining charged particles (deuteron, triton, alpha)
  - Final proton emission rate
- Run-2 analysis
- Run-3
  - November 2015
  - Repeat charged particle set-up
  - Improvements:
    - Digitiser
    - Extend upper energy limit
    - More calibration runs
    - Larger statistics
    - More target materials
    - Pre-amplifiers in chamber for less noise
- Publications
  - Theses: Nam Tran (submitted), Andrew Edmonds (submitted), John Quirk, Ben Krikler, Damien Alexander
  - Final results paper

Summary

Future μ-e conversion searches require improved knowledge of the muon capture process

- Emission spectra
- Branching ratios

Run-1 has successfully observed proton spectrum from 3.5 to 10 MeV

- Analysis being finalised
- Much lower proton rate than has previously been used for COMET / Mu2e studies (3% measured c.f. 15% used)

Run-2 measured neutrons and gammas

- Analysis on-going

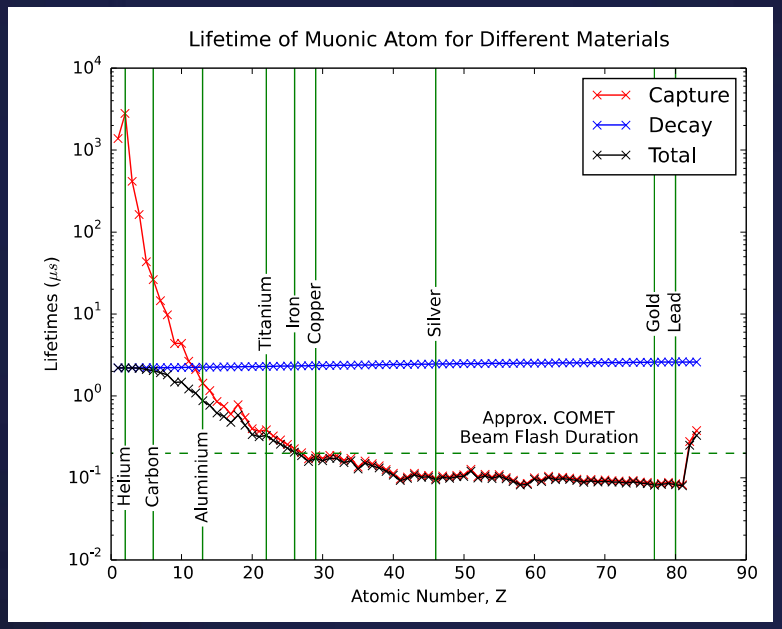
Run-3 will take place in November

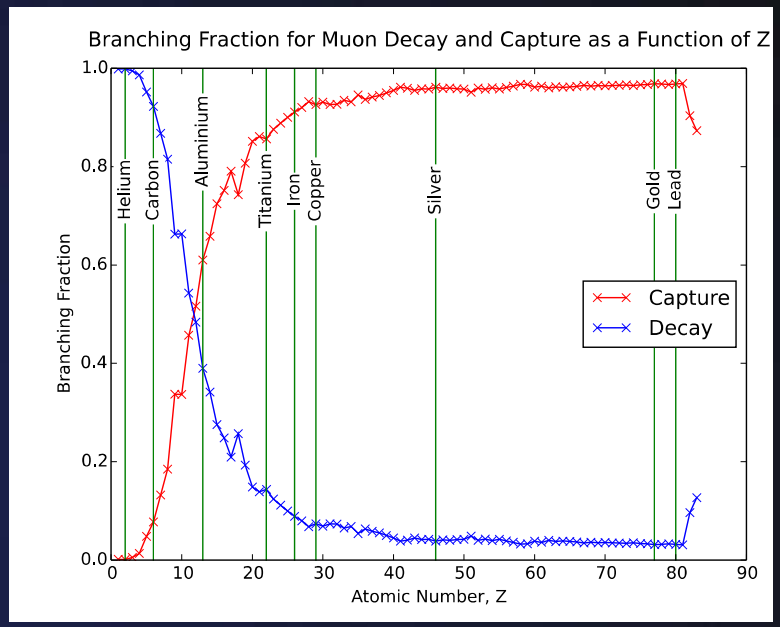
- Improve Run-1 uncertainty
- Increase energy range of recovered spectrum
- Widen selection of target materials

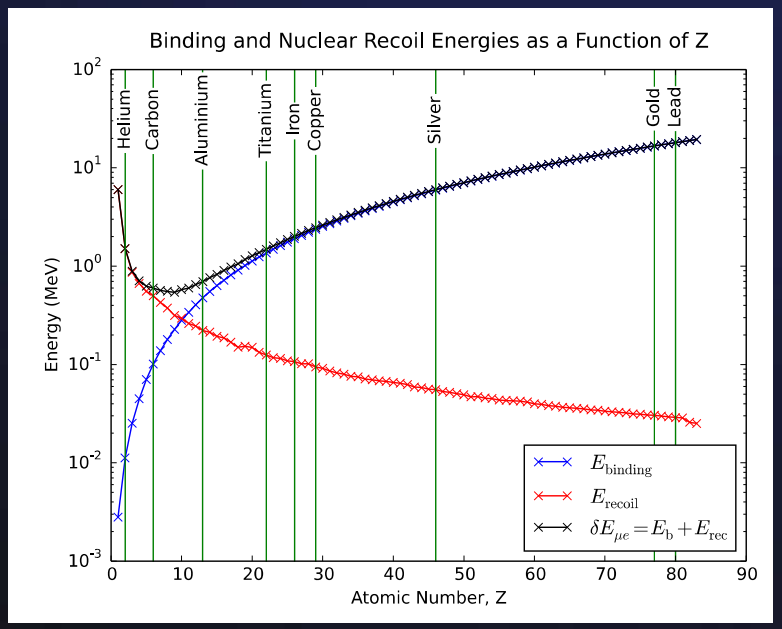
Muito Obrigado!

Why an Aluminium Target?

Extracted from Geant4 v10 Stopped Muon Physics Models

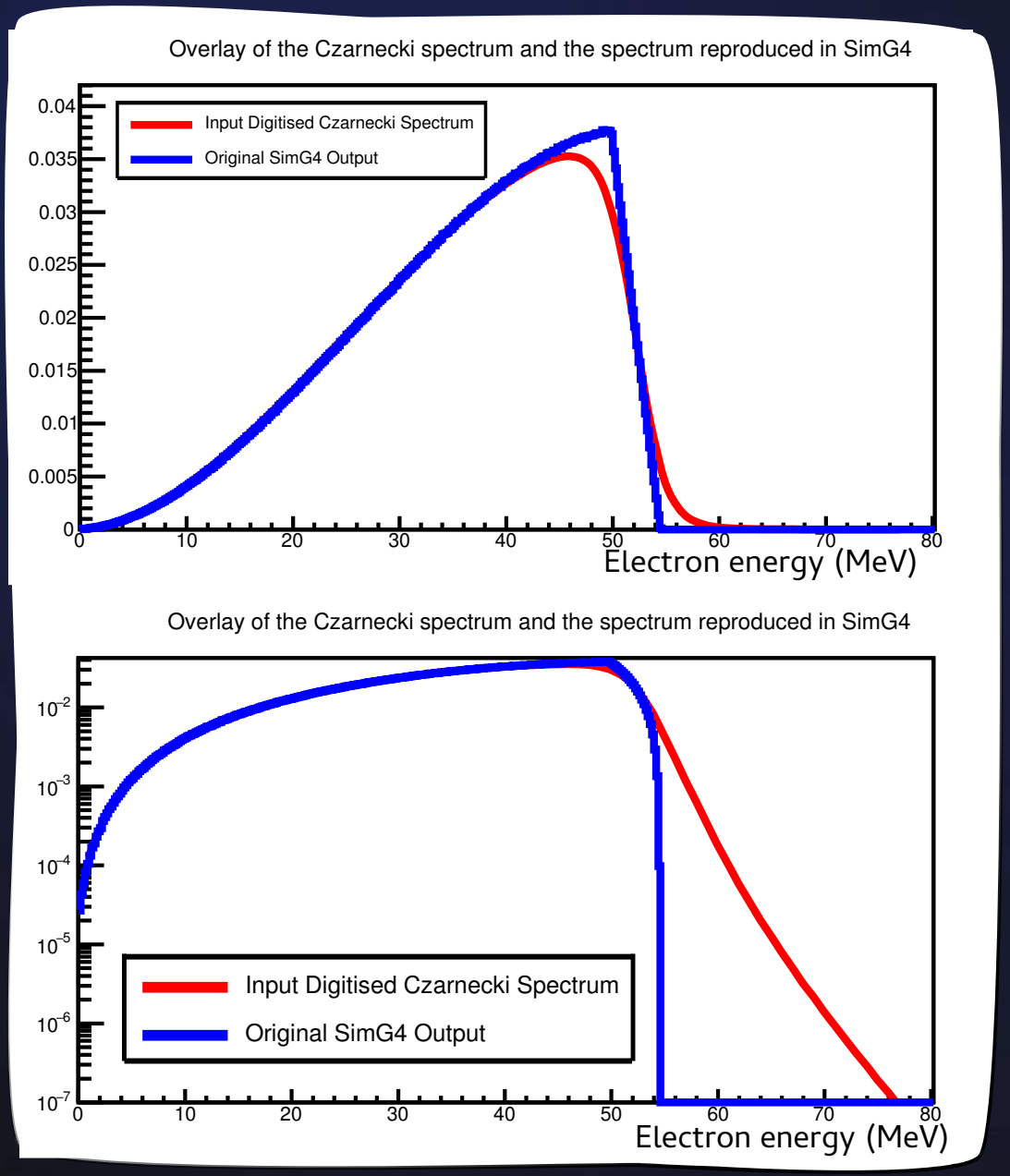






- Maximise atomic lifetime compared to beam flash duration
- Minimise binding and nuclear recoil energies
- (Phase-I: Minimise emissions following muon nuclear capture)
- Additionally, aluminium is:
  - Isotopically pure
  - Mechanically stable

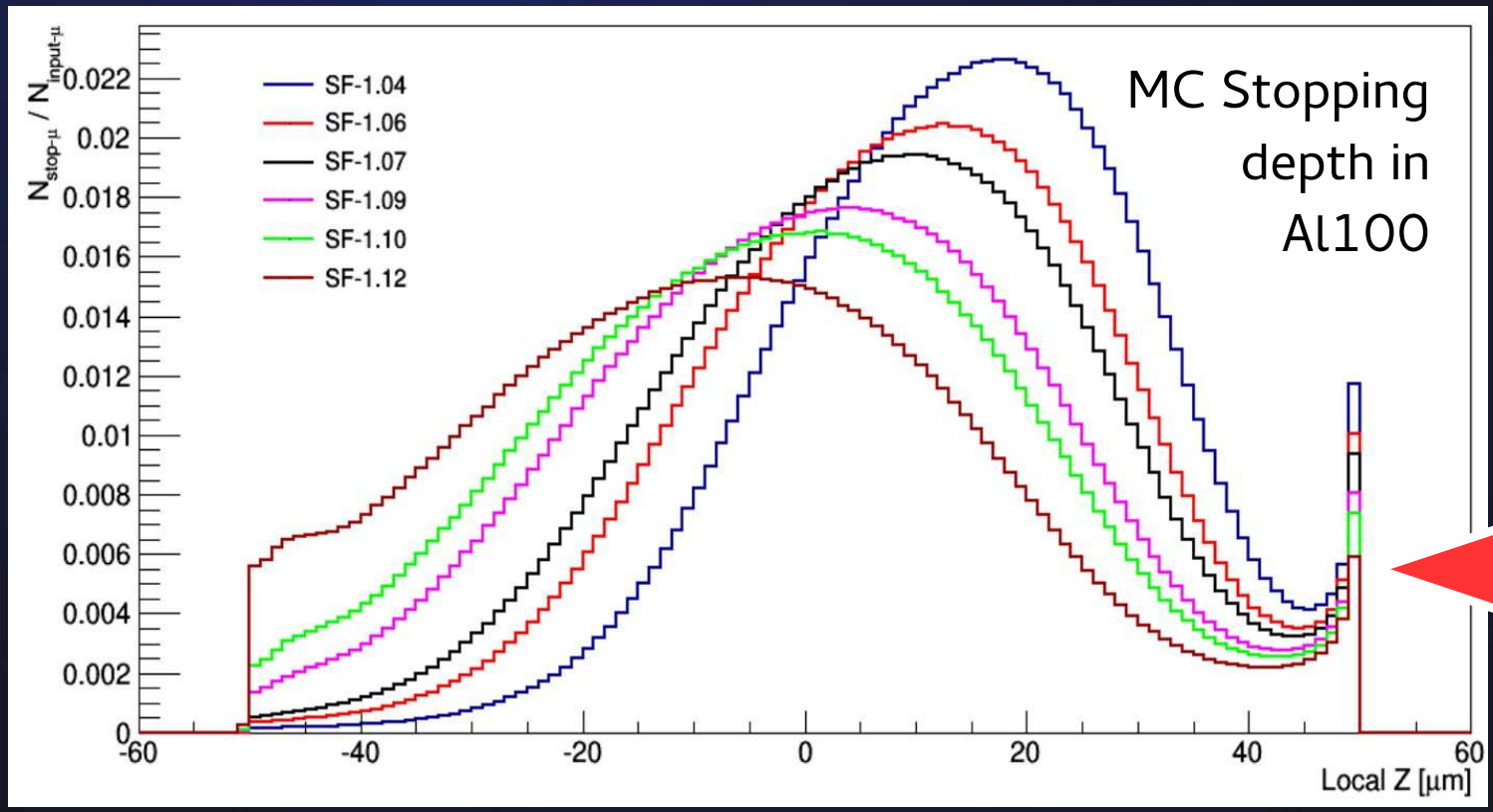
Bound Muon Decay



- Bound Muon Decay aquires high energy tail w.r.t free muon decay
  - Due to involvement of nucleus
  - Neutrinos can be arranged to carry away no kinetic energy
  - Kinematics become the same as μ-e conversion
- Spectrum is well modelled
  - Not included in Geant4 by default

Run-1: Beam Tuning

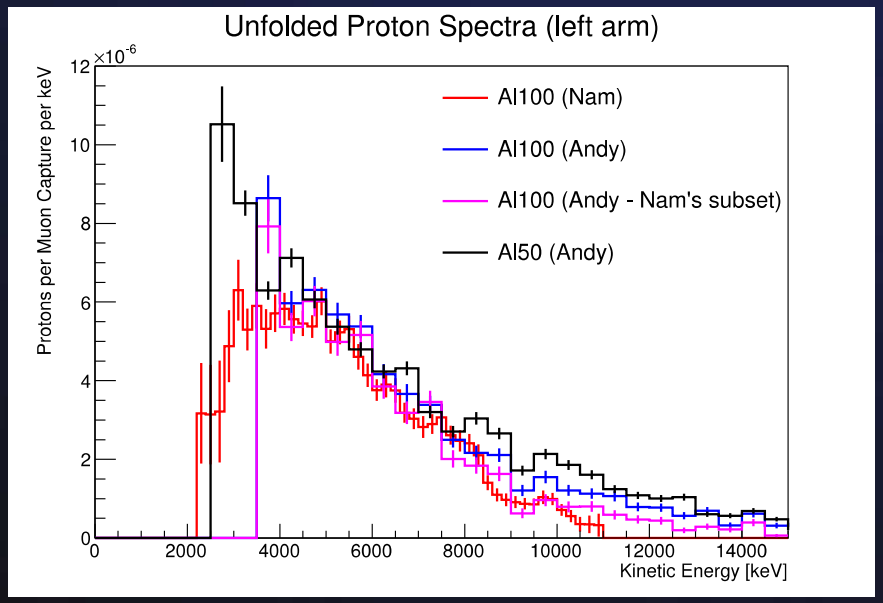
- Important for asymmetry in target and detector arms

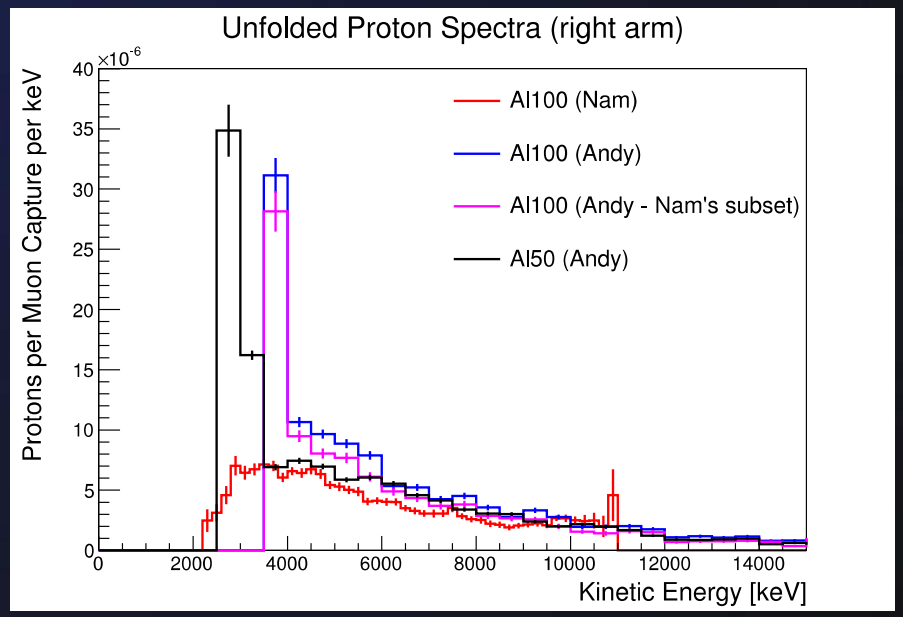


μ^-

Run–1: Analysis Systematics

- Dominated by unfolding (5%) and nuclear capture normalisation
- Timing (cuts and resolution): 4%
- PID and / or energy cuts:
  - About 3 or 4%
- Analysis is being finalised and cross checked
  - Some remaining discrepancies:

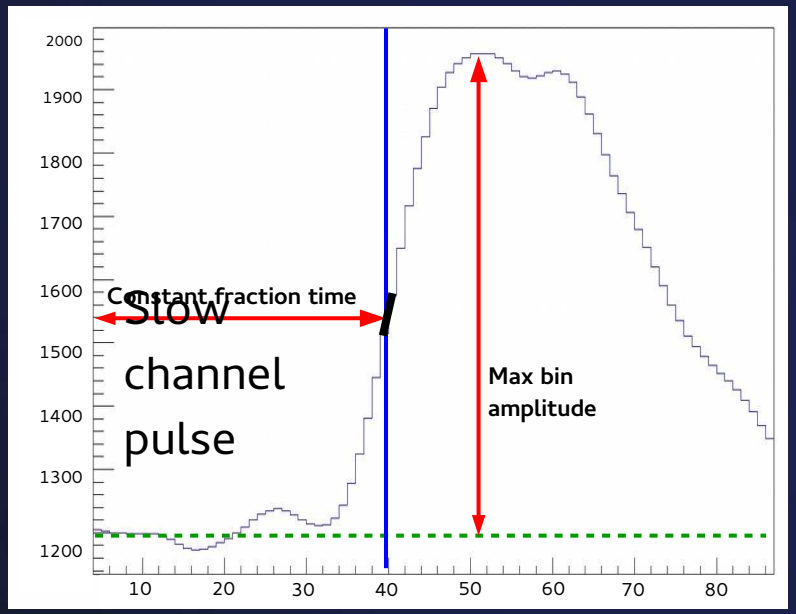


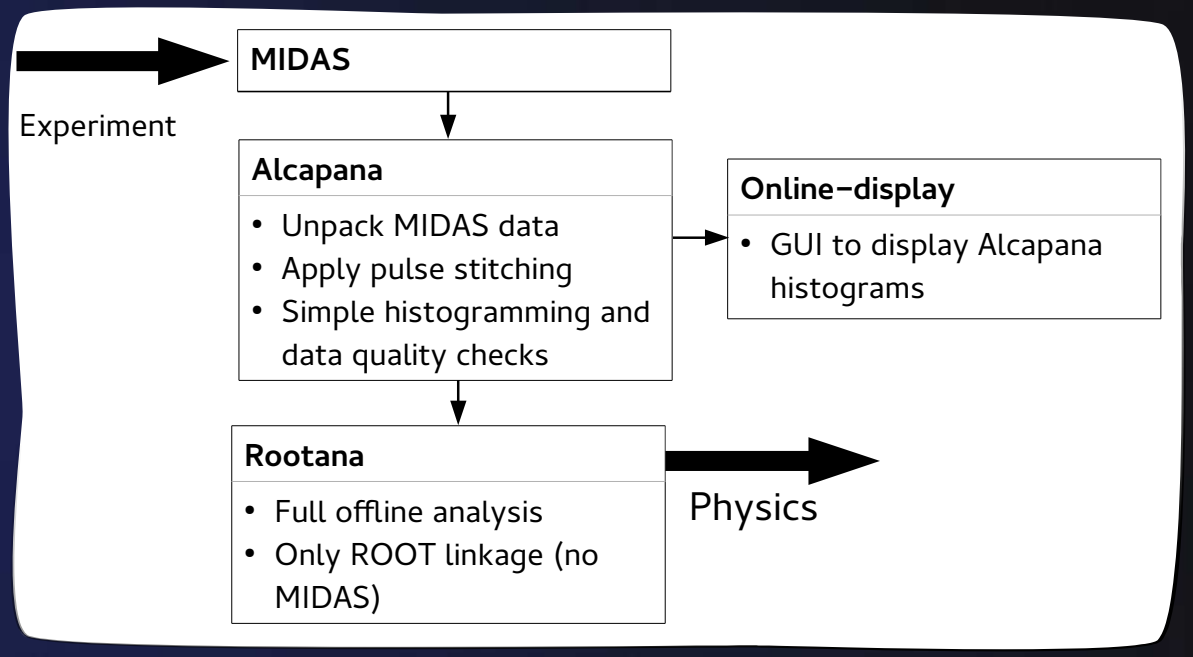


Run–1: DAQ Configuration

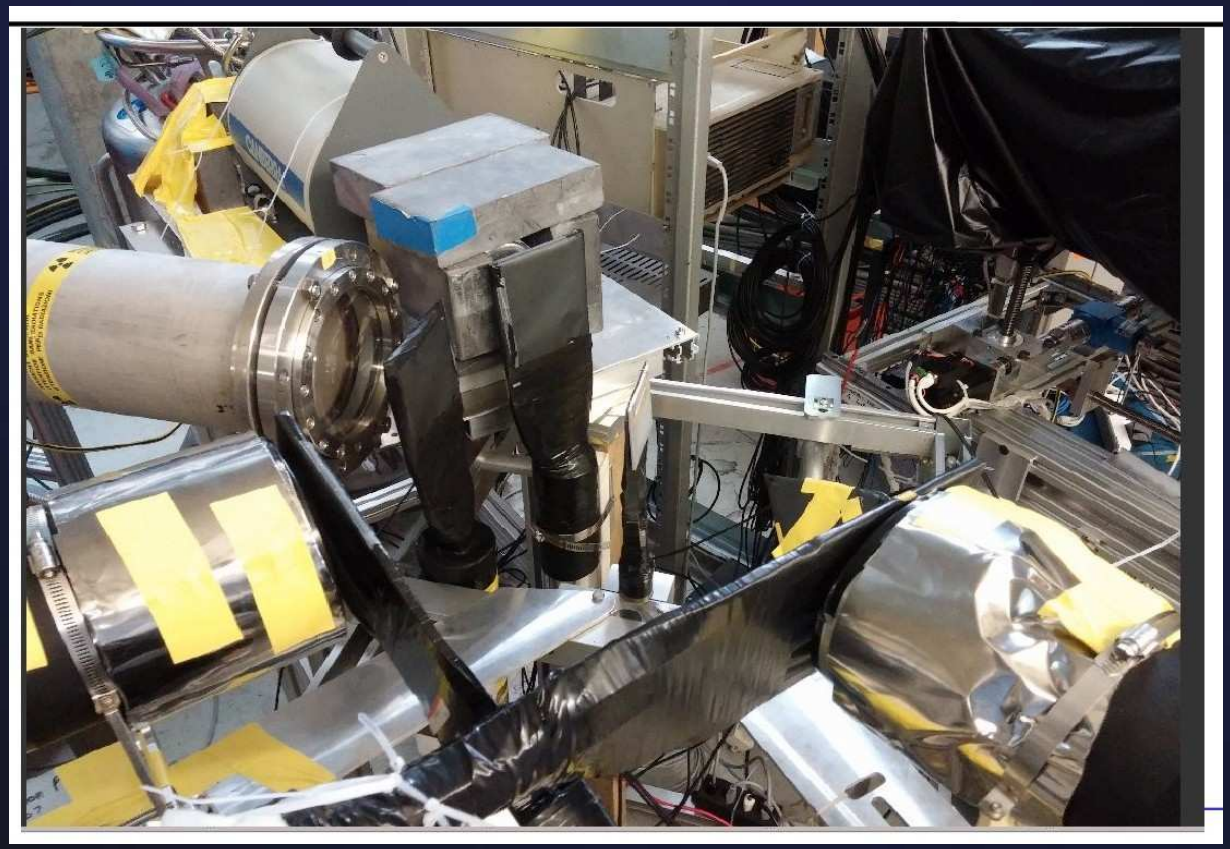
- General
  - MIDAS based
  - Self-triggering on each channel
  - 28 channels
- Silicon:
  - Fast read-out channel (rise: 100 ns, 400 ns width)
  - Slow channel: 2 μs width
  - Custom FADC digitisers: Fast (170 MHz), Slow: (17 MHz)
- Other channels:
  - CAEN digitisers (issues with common trigger)
  - 250 MHz
  - Used for Germanium, Scintillators

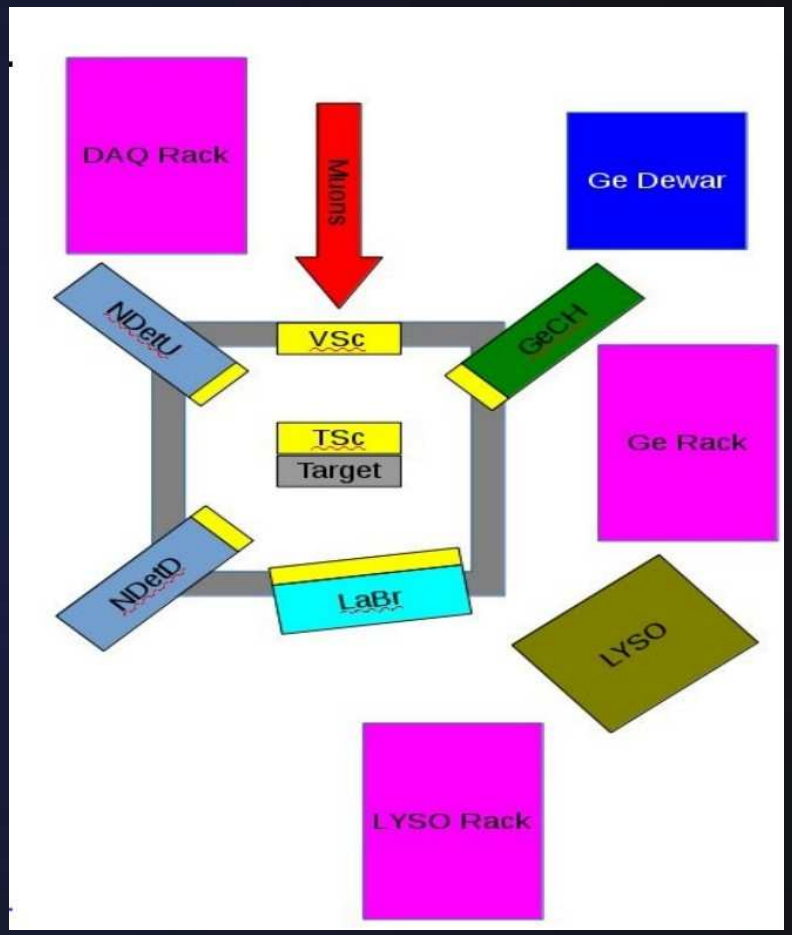
Run-1: Analysis





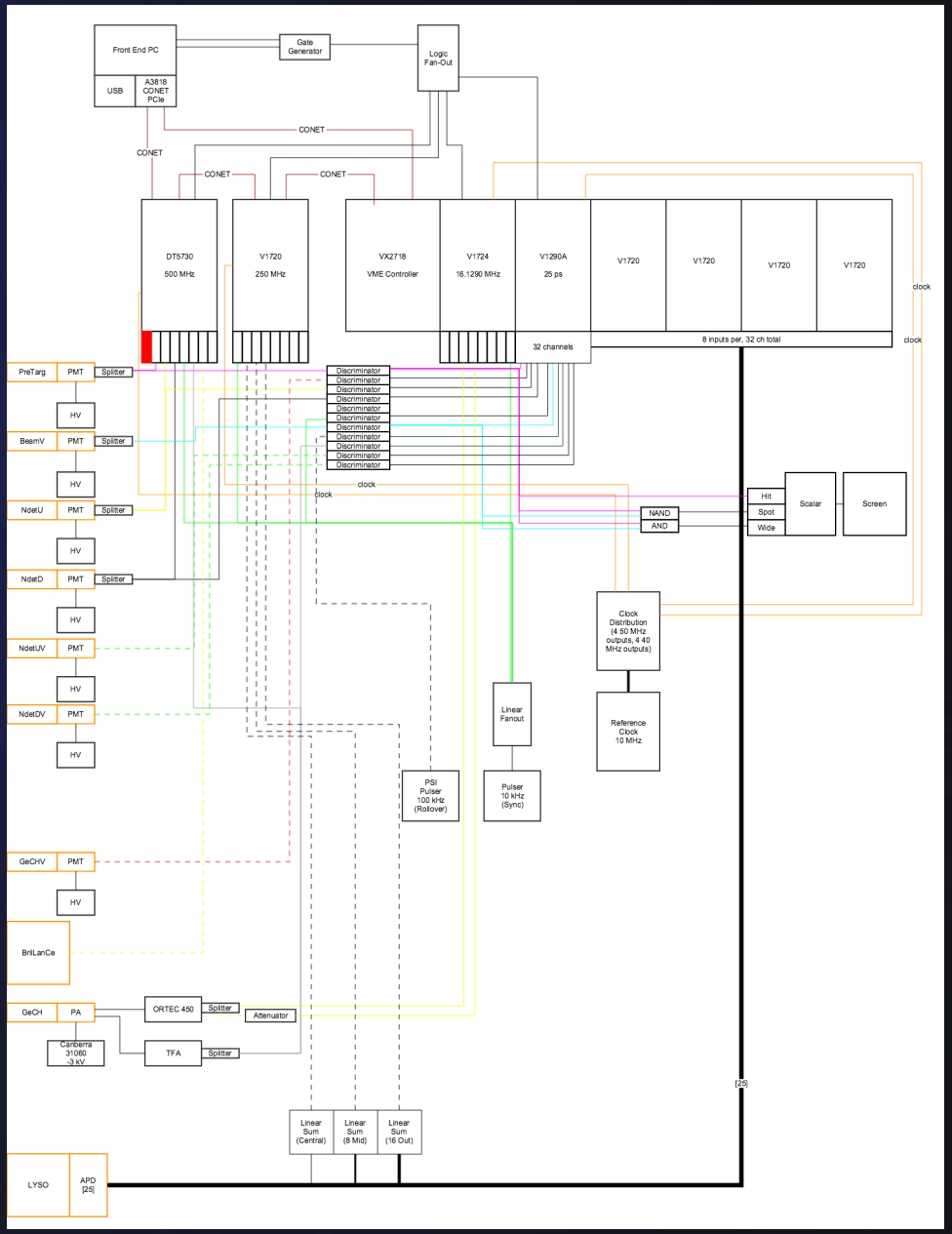
Run-2: Set-up



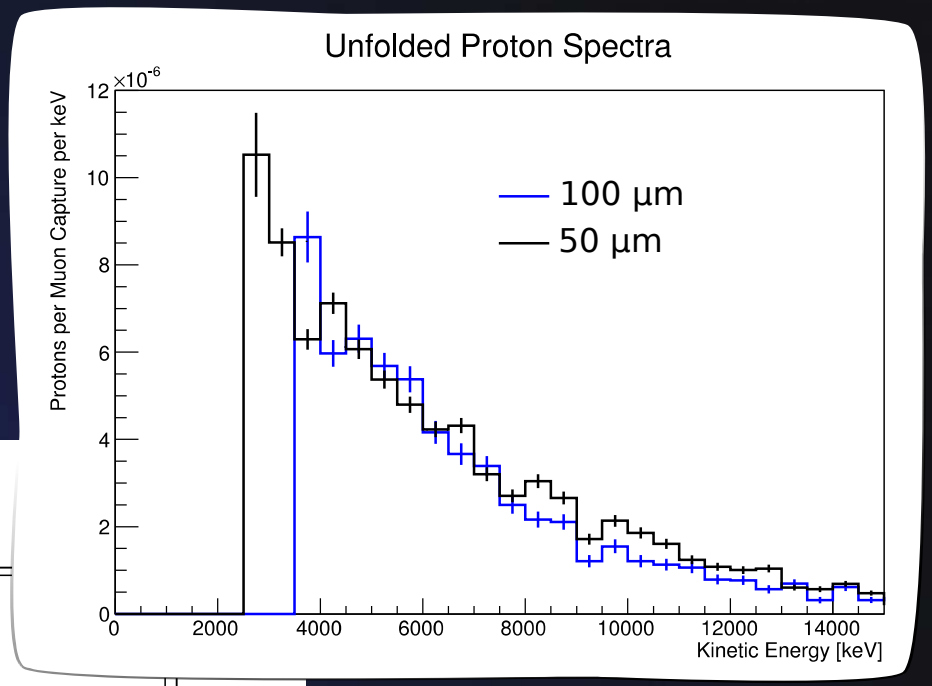

DAQ Rack
Muons
Ge Dewar
NDetU
VSc
GeCH
TSc
Target
Ge Rack
NDetD
LaBr
LYSO
LYSO Rack

Run-2: DAQ Systems

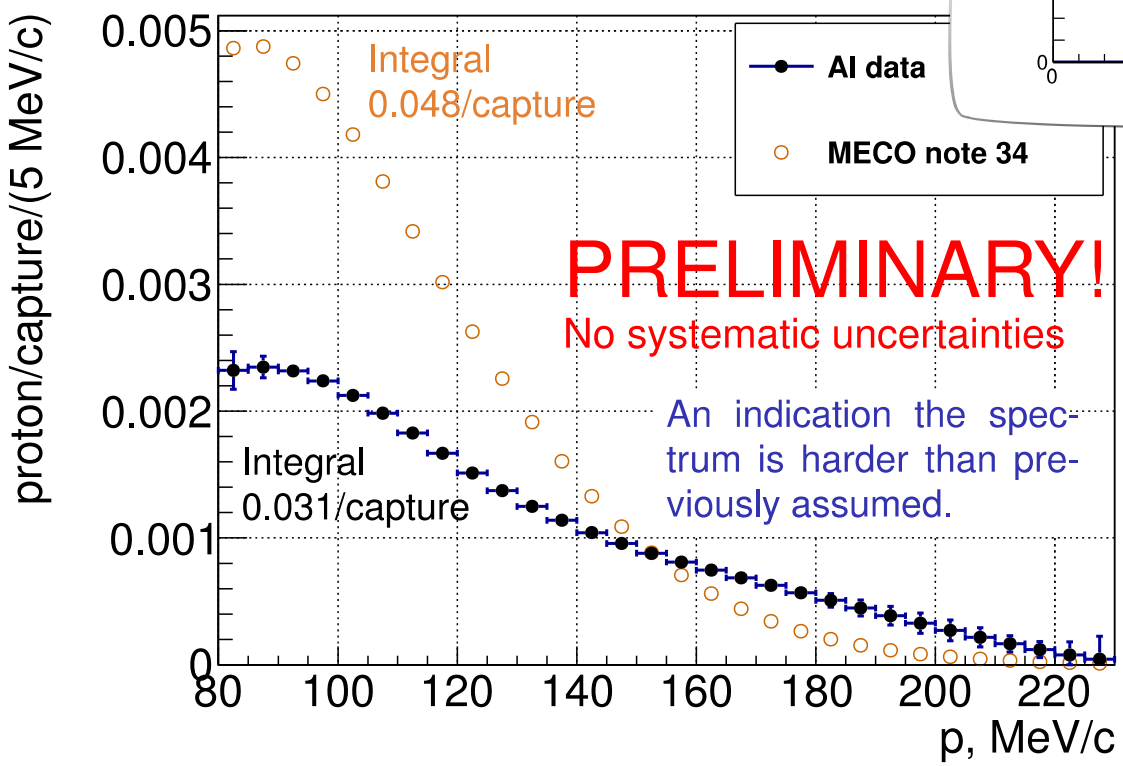
- CAEN digitizers (DT5730, V1720)
- Separate DAQs for:
  - Aggregate
    - MIDAS based
    - ~ 25 Channels
  - LYSO
  - Activation study
- Most digitizers 500 or 250 MHz



TWIST data



Unfolded protons



MECO n 3.4 Ed Hungerford is a 10.4 s" ba 17.1 measur 25.4 Kinetic Energy (MeV)

Andrei Gaponenko 39 2015-02-06