The AlCap Experiment

Andrew Edmonds
LBNL Seminar, 6th May 2015

Outline

- Overview
- Experimental Layout
- Summary of First Run
- Preliminary Result of First Run
- Conclusion

Overview

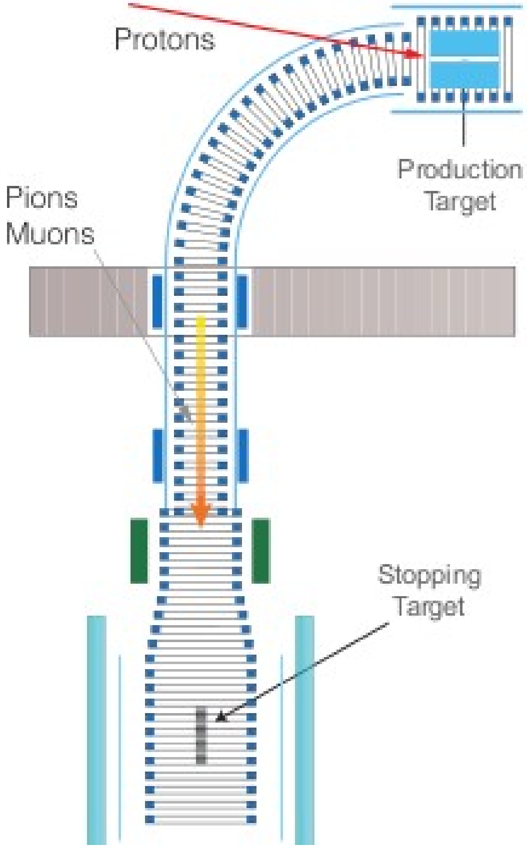
- AlCap will measure the particles that are emitted after a muon is captured by a nucleus

$$\mu^- + p \rightarrow \nu_\mu + n$$

- This can leave the nucleus in an unstable state and produce various secondaries

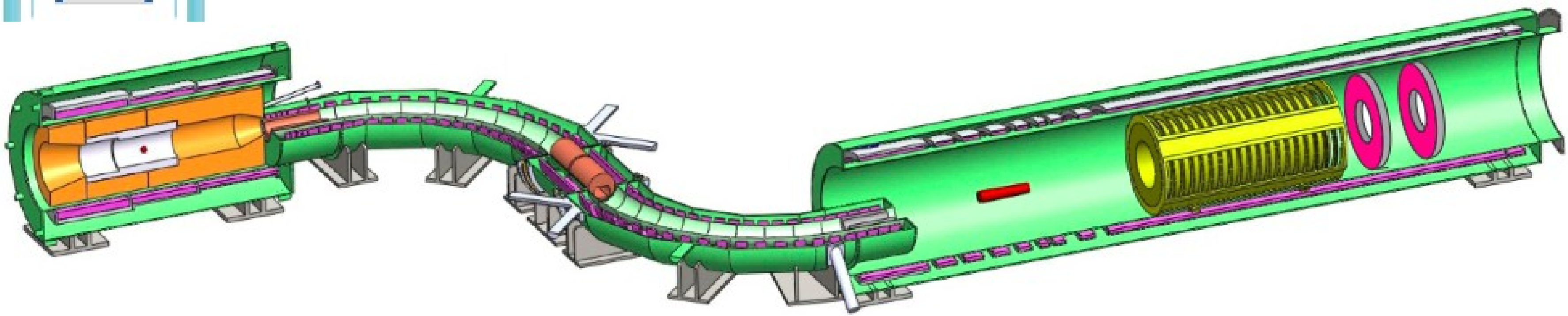
Why Do We Care?

COMET Phase-I



- This is a background process for the next generation of muon-to-electron conversion searches (COMET/Mu2e)
- These experiments will fire a large number of muons into an aluminium stopping target
  - ~60% of these will be captured by the nucleus

Mu2e

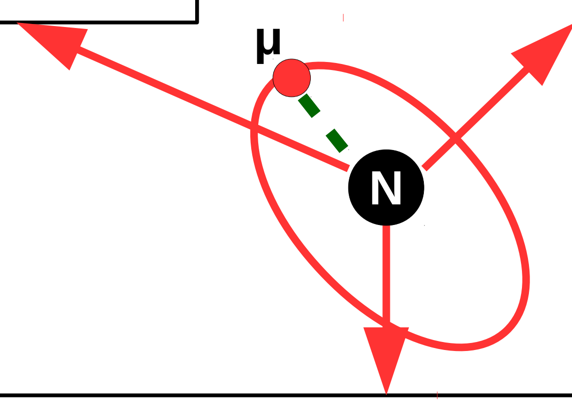


Why Do We Care?

- These experiments need to know what other particles will be emitted from the stopping target

Protons
- Can give hits in a tracker that fool track-finding algorithms
- Will increase detector rates possibly leading to significant dead time

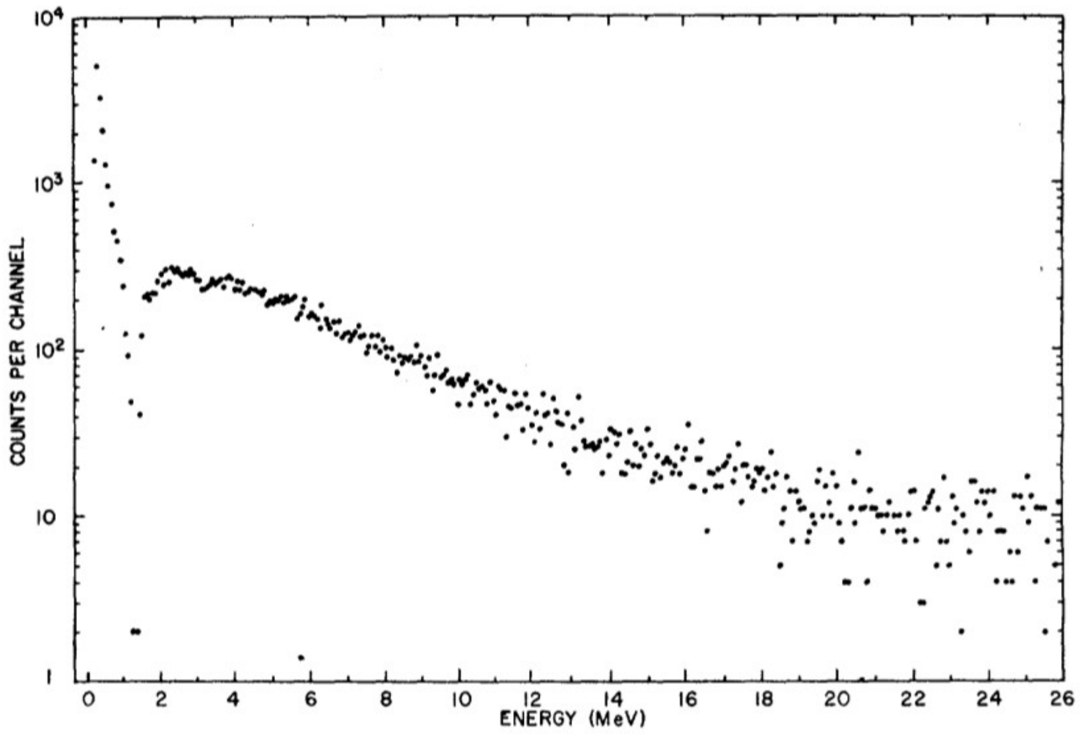
Neutrons
- Can leave experiment and trigger cosmic-ray veto
- Can interact with material and produce high energy photons that can pair produce electrons



Photons
- Can be used to count the number of stopped muons

Current Data

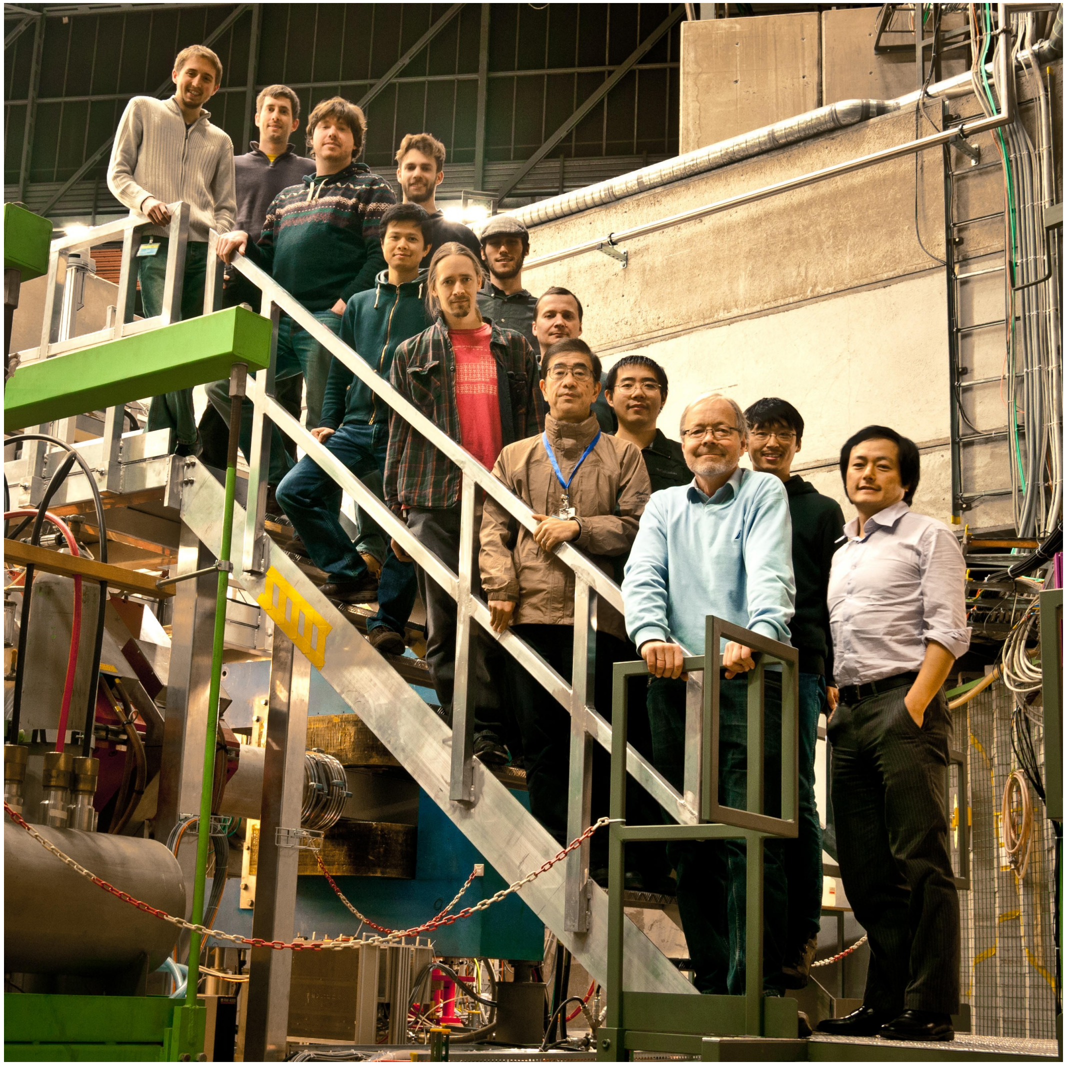
- Current data is not ideal for COMET or Mu2e
  - Does not distinguish between particles
  - Data from aluminium is at high energies (more than 40 MeV)
  - Data in the relevant energy range (O(1) MeV) is from silicon
- Currently, COMET uses a paramaterisation of the silicon data which assumes 0.15 protons emitted per nuclear muon capture



Current Data from Muon Capture on Silicon

The AlCap Collaboration

- Joint collaboration between COMET and Mu2e
- First run was Nov/Dec 2013 at PSI using the πE1 beamline



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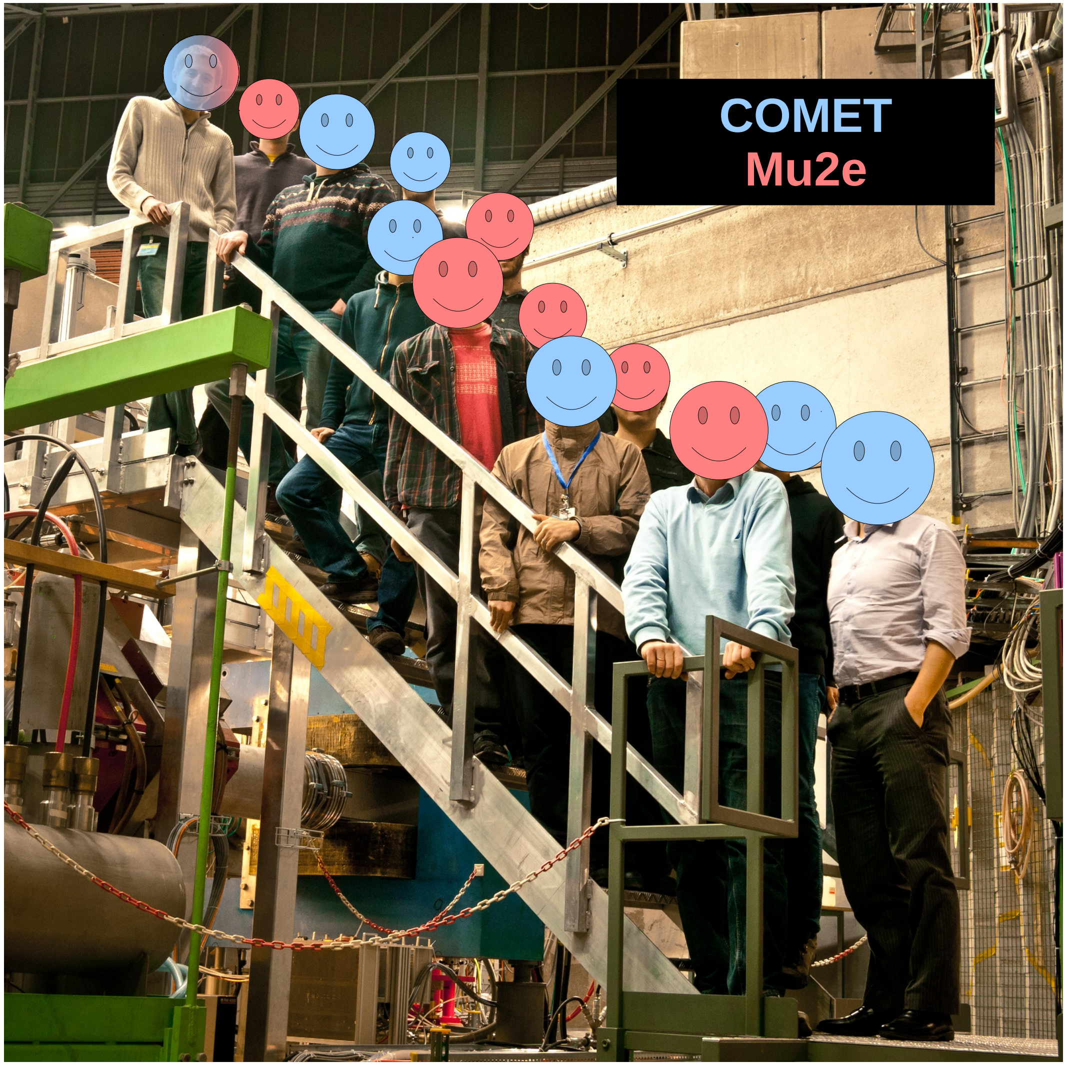
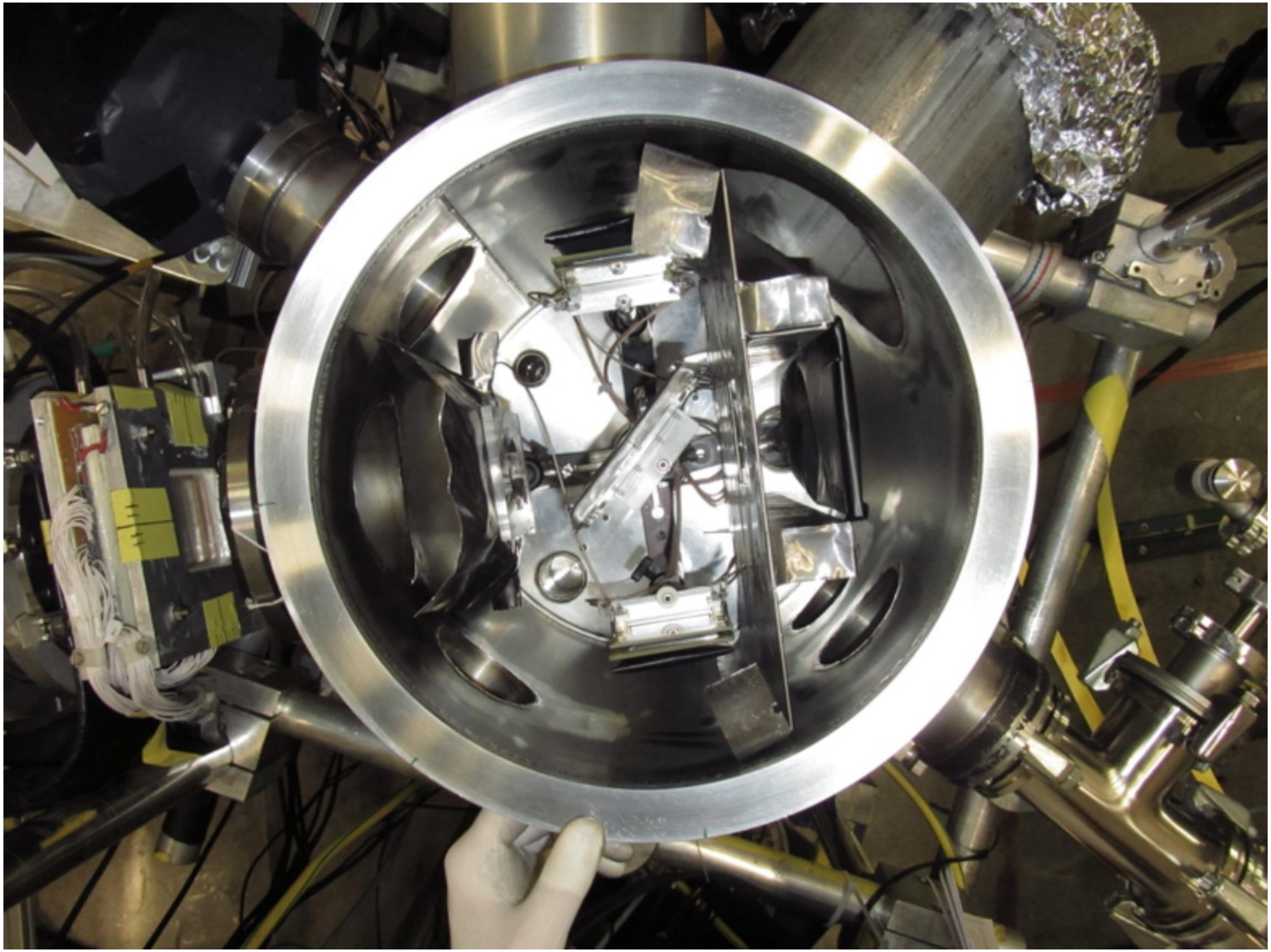
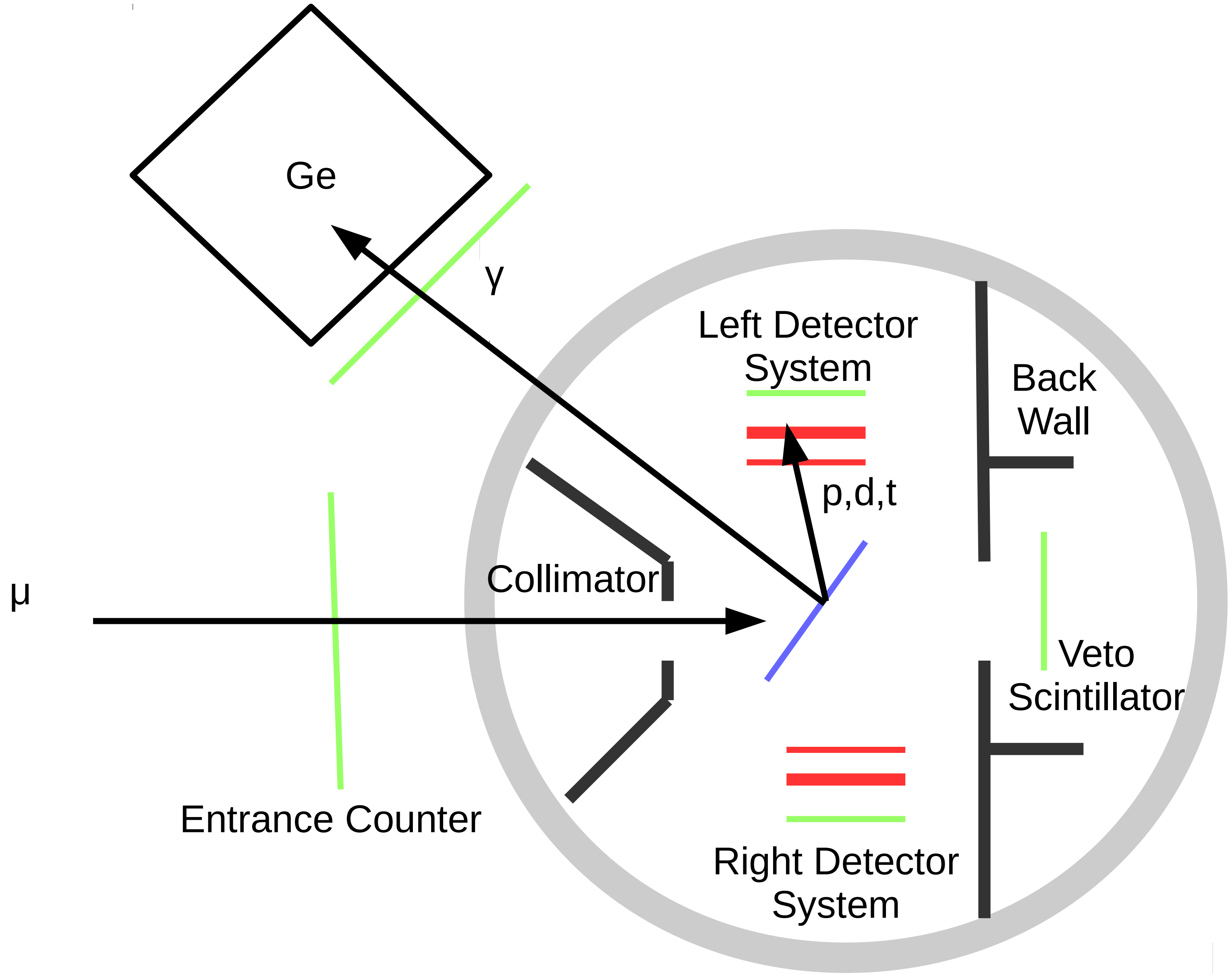


AlCap Aims

- Protons
  - Establish the rate and spectrum of proton emission with a precision of 5% down to 2.5 MeV
- Photons
  - Investigate some possible normalisation techniques for COMET and Mu2e
- Neutrons
  - Establish the rate and spectrum of neutron emission from 1 MeV up to 10 MeV

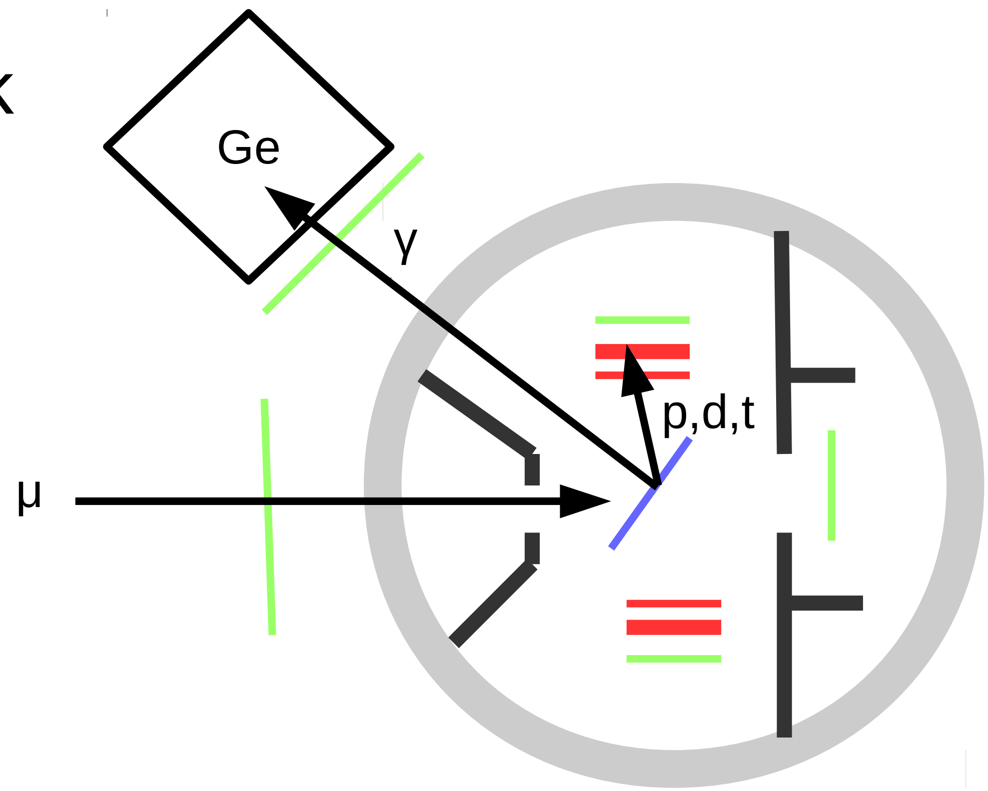
Experimental Layout




Ge
γ
Left Detector System
Back Wall
p,d,t
μ
Collimator
Veto Scintillator
Entrance Counter
Right Detector System

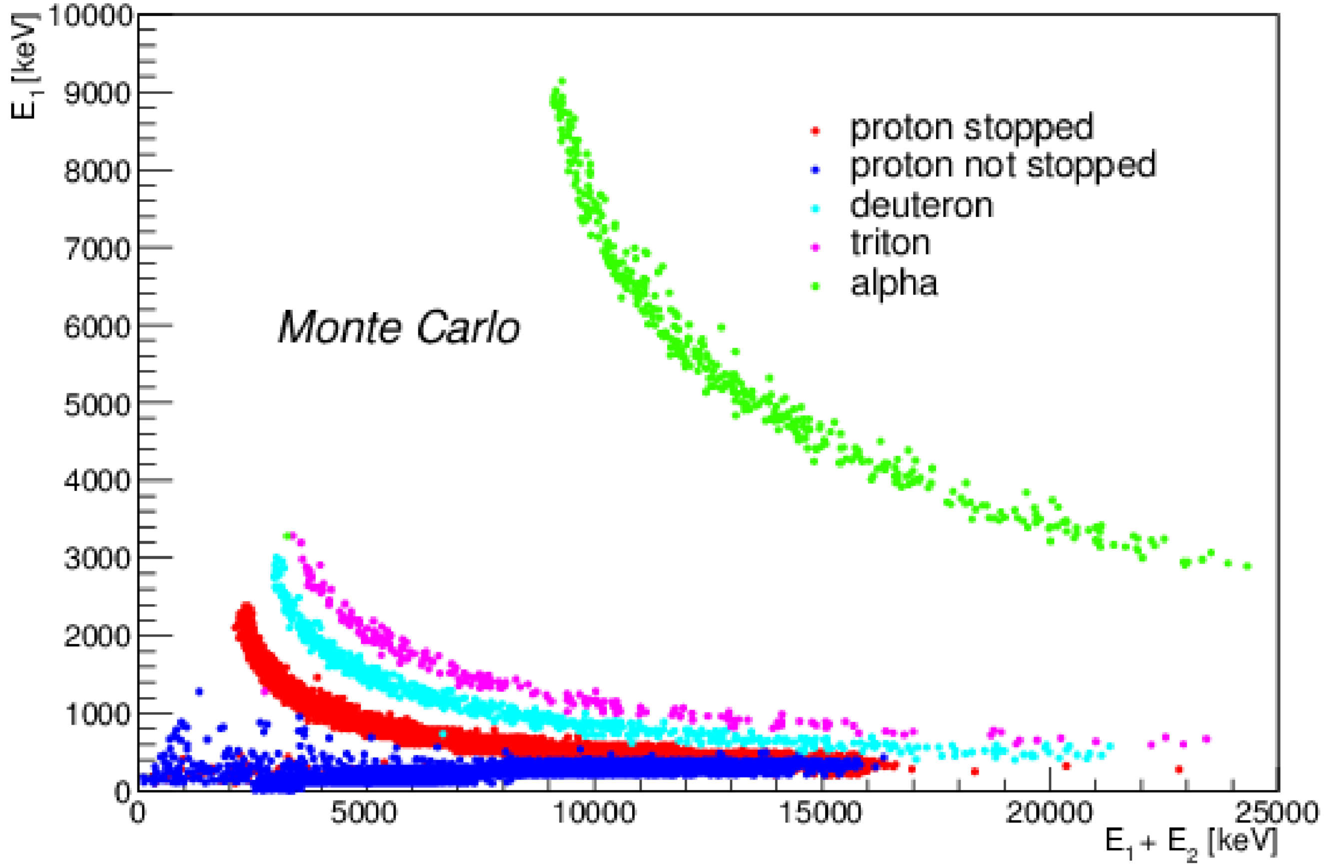
Targets

- Want to collect data on:
  - Silicon: as a cross-check on previous data
  - Aluminium: the material that COMET and Mu2e will be using for their searches
  - Titanium: a possible alternative material that both COMET and Mu2e may use



Silicon Detectors

- Each silicon package contains a thick (1500 μm) and thin (65 μm) silicon layer
- Particle ID can be performed by dE/dx



Germanium Detector

- As soon as a muon is stopped, it descends into the 1s state and emits muonic X-rays
- These are characteristic of the material the muon has stopped in
- For AlCap, the important X-rays are:

Material	Transition	Energy [keV]	Intensity [%]
Al	2p-1s	346.828 ± 0.002	79.8 ± 0.8
Si	2p-1s	400.177 ± 0.005	80.3 ± 0.8

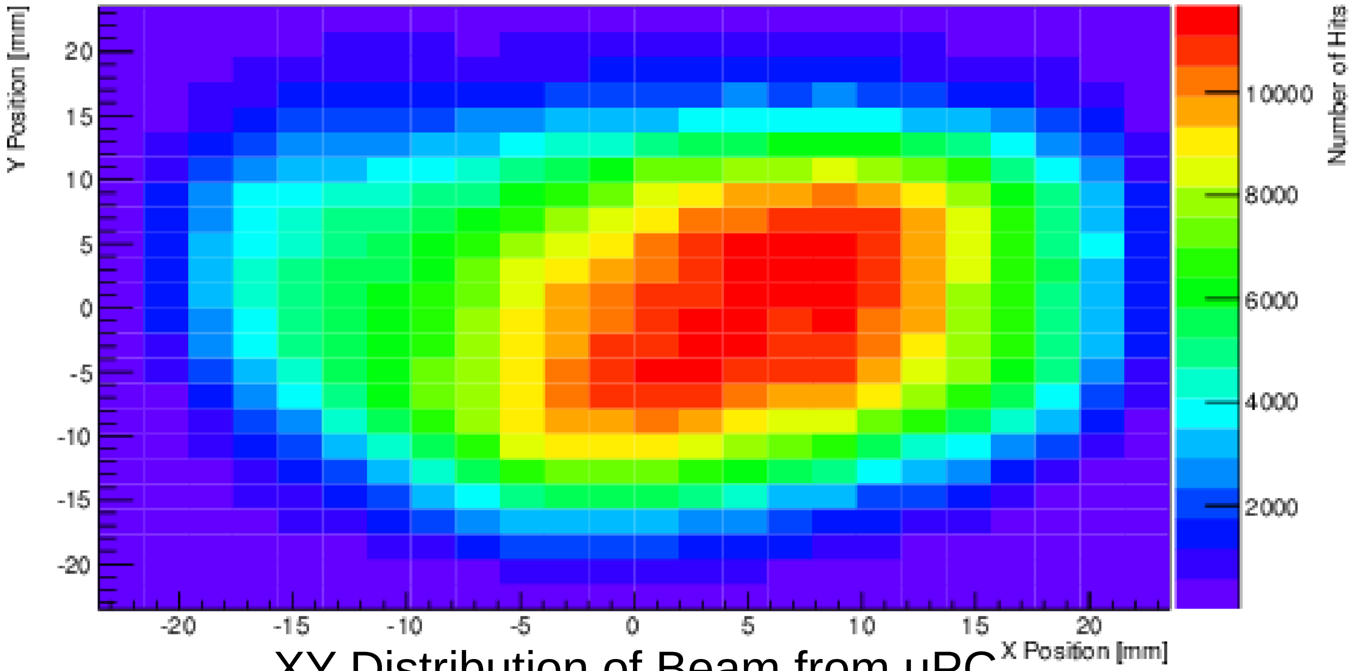
- Can determine the number of muons stopped for normalisation

Lead Shielding

- Lead is used to shield parts of the experiment other than the target because of its much shorter muonic atom lifetime
  - τ_{Pb} = 80 ns
  - τ_{Al} = 864 ns
  - τ_{Si} = 767 ns
- So, to ensure we are only looking at particles emitted from the target, we apply a timing cut

Entrance Counter

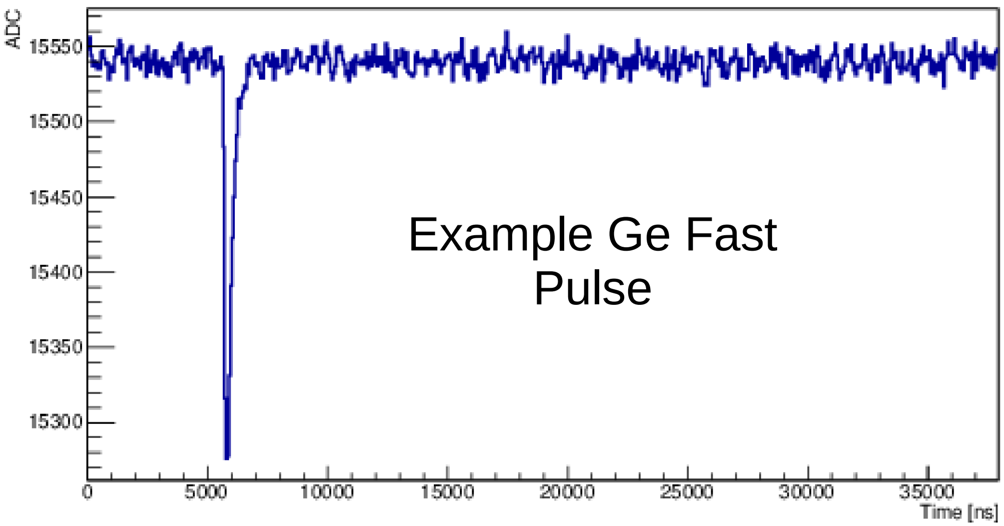
- Consists of:
  - μSc – thin scintillator
  - μScA – thick scintillator with a hole
  - μPC – a wire chamber that gives an XY distribution of the beam

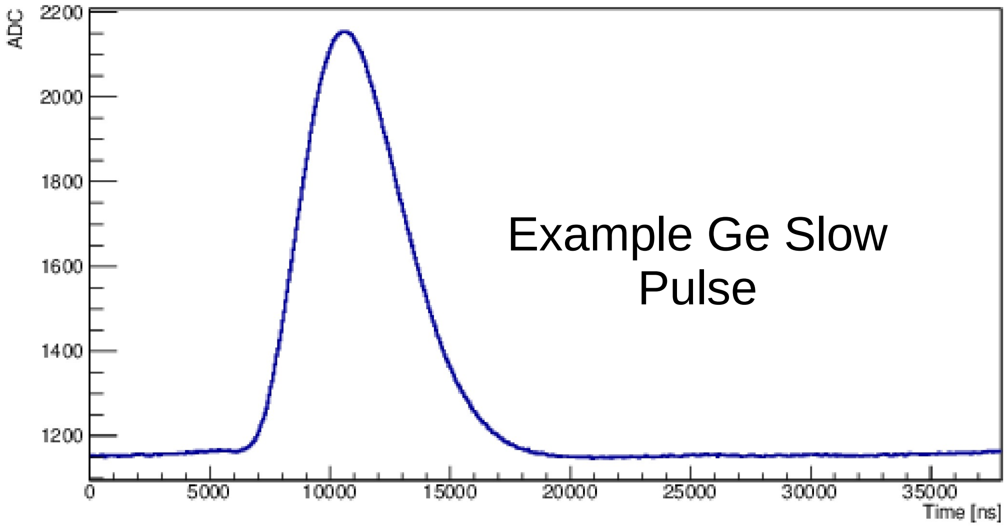


XY Distribution of Beam from μPC

Frontend Electronics

- Signals from the germanium and the silicon detectors are split and pass through a “fast” and “slow” amplifier

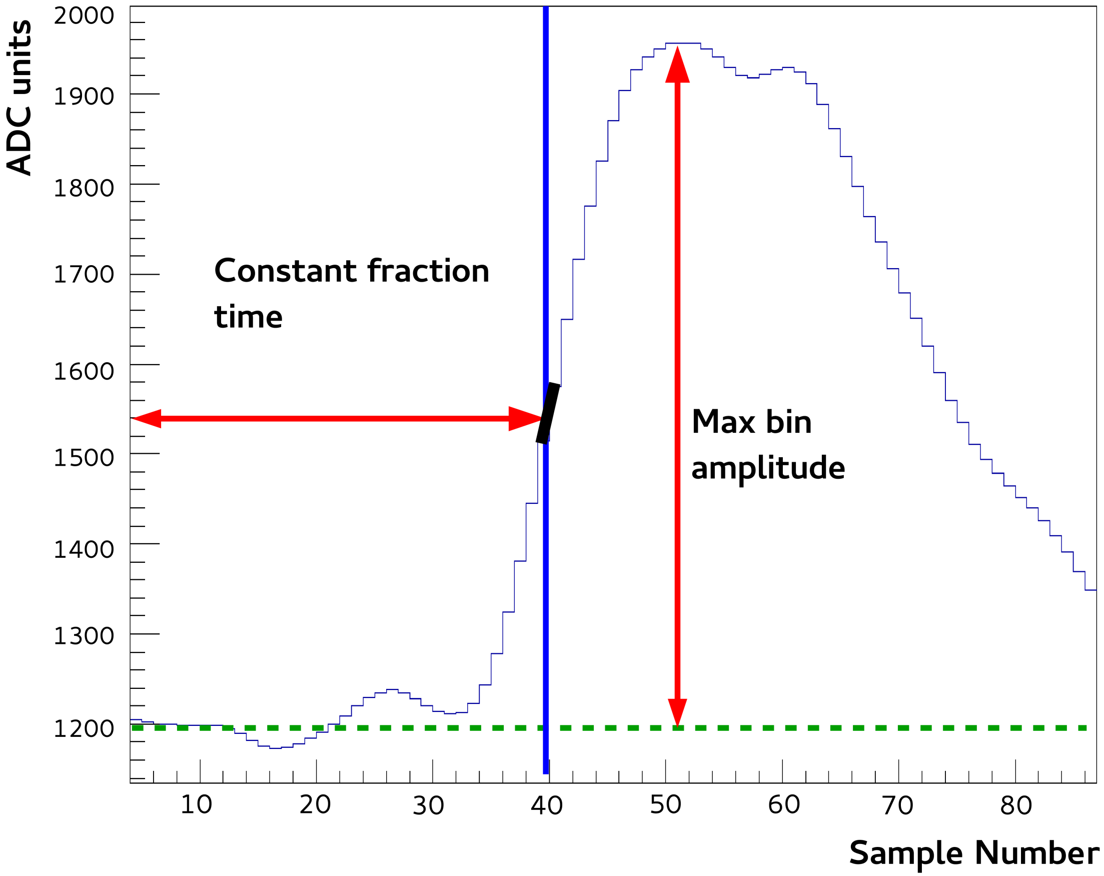




- Idea is that we get a more precise measurement of the time from the fast pulse and of the energy from the slow pulse

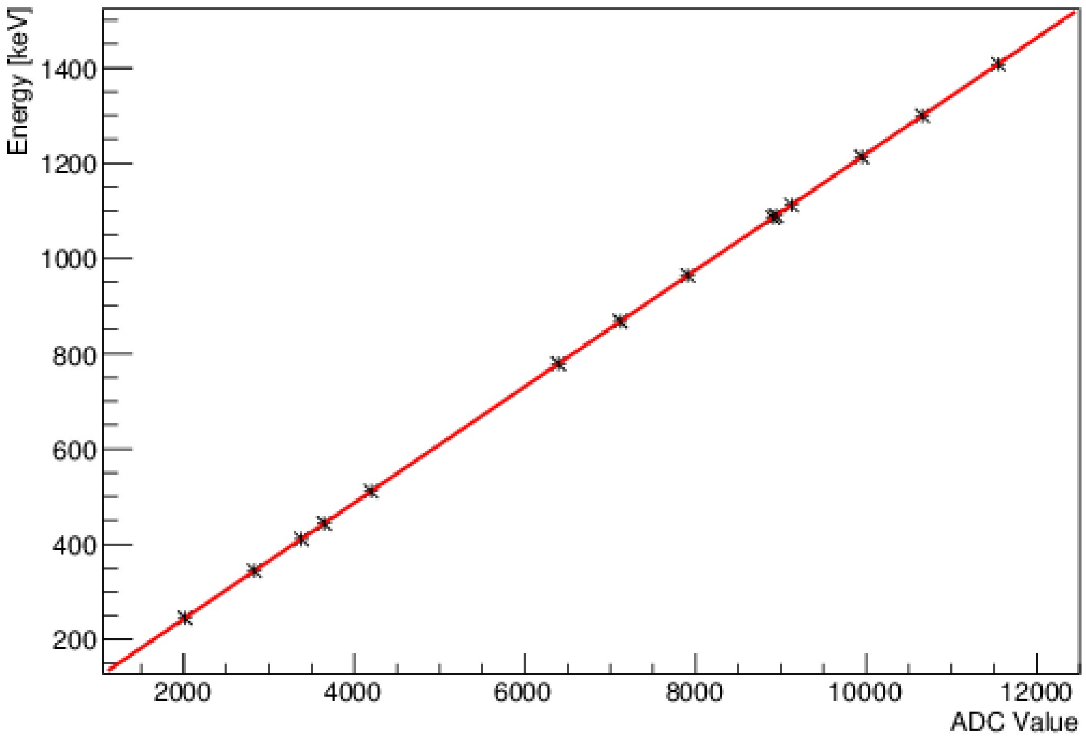
Waveform Analysis

- Get the time using a constant fraction method
- Get the energy from the amplitude of the slow pulse



Calibration

- Thick Silicon:
  - 5422 keV alpha peak from Am-241 source
  - MIP peak from beam electrons (466 keV)
- Thin Silicon
  - 5484 keV alpha peak from Am-241 source
  - Pulse signal calibrated on the thick silicon to 1 MeV
- Germanium
  - Many gamma ray lines from Eu-152 source



Ge Calibration Curve

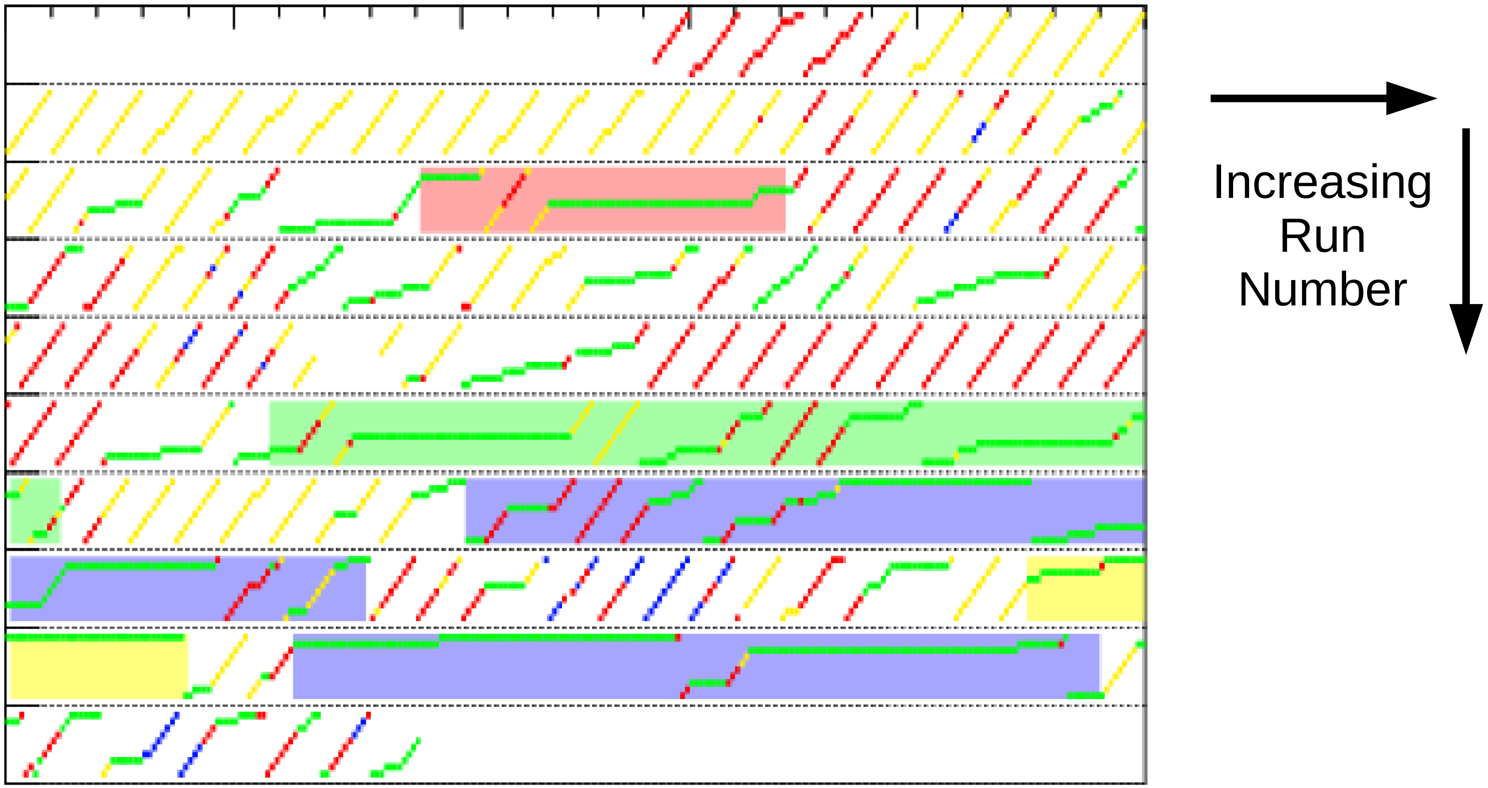
First AlCap Run

- Run performed at PSI in Nov/Dec 2013 with a focus on measuring the proton spectrum
- Summary of the data collected:

Target	Beam Momentum [x 28 MeV/c]	Integrate Run Time [h]	Number of Muons
Si (1500 µm) (Active Target)	1.30	10.3	2.89×10^8
Si (62 µm) (Passive Target)	1.06	10.5	1.72×10^8
Al (100 µm)	1.09	13.8	2.94×10^8
Al (50 µm)	1.07	43.0	8.81×10^8

Run Summary

- Plot of the data quality



- NB Had a problem with the veto scintillators

Rate of Proton Emission in Al50

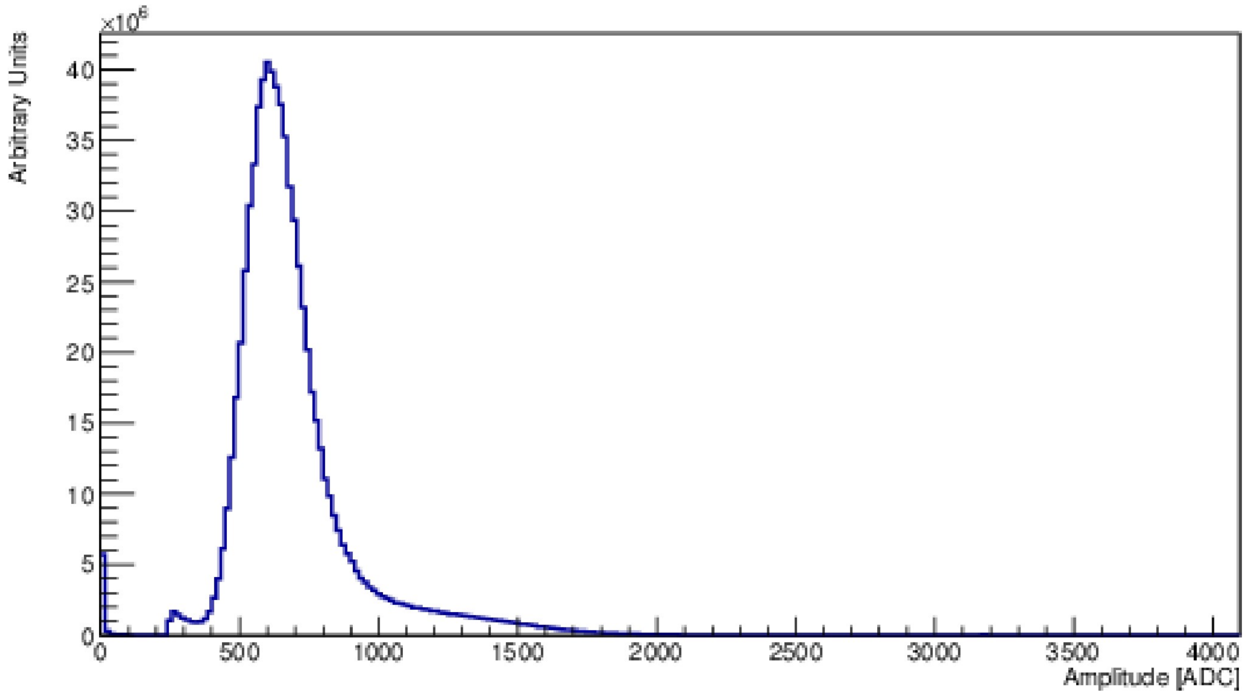
- A preliminary analysis of proton emission in the Al50 dataset has been performed
- Rate is normalised to the number of muons captured

$$R = \frac{N_p}{N(\mu p \rightarrow \nu_\mu n)} = \frac{N_p}{0.609\, N_{\mu - stop}}$$

Fraction of stopped muons that are captured

Entering Muon Definition

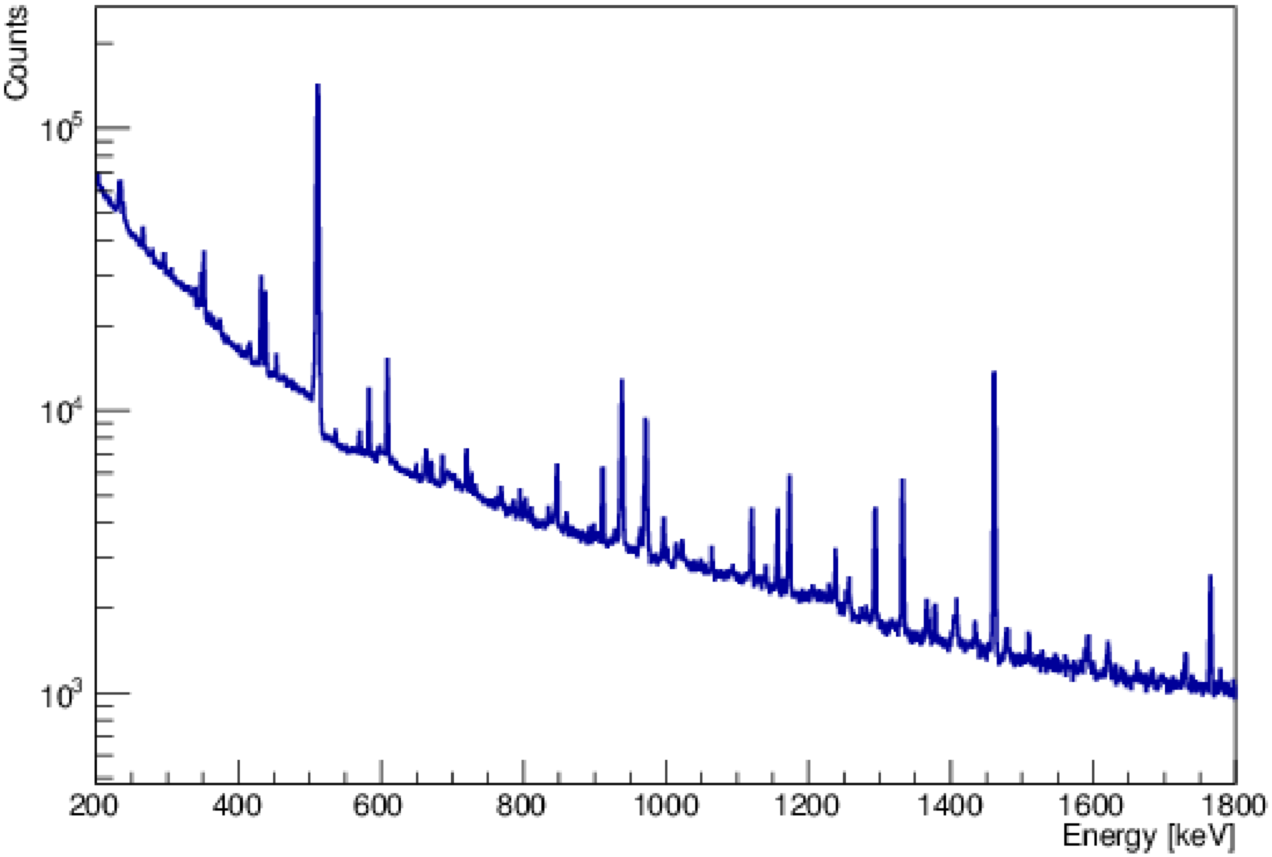
- Define an entering muon as one with
  - an amplitude in the μSc more than 230 ADC
  - no other entering muons within 15 μs
- In the Al50 dataset, there are 603M entering muons



Pulse Amplitude Spectrum in the μSc

Number of Stopped Muons

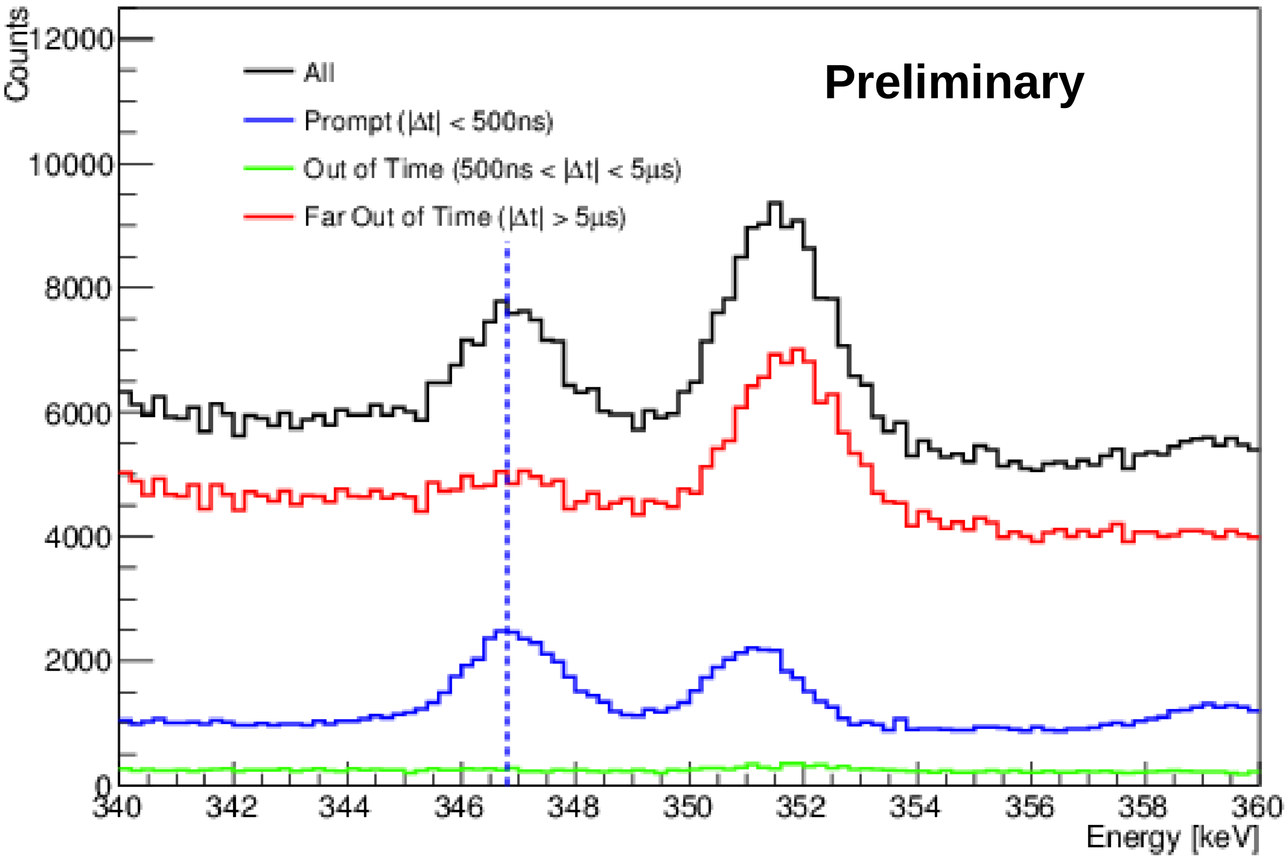
- Full X-Ray Spectrum



Number of Stopped Muons

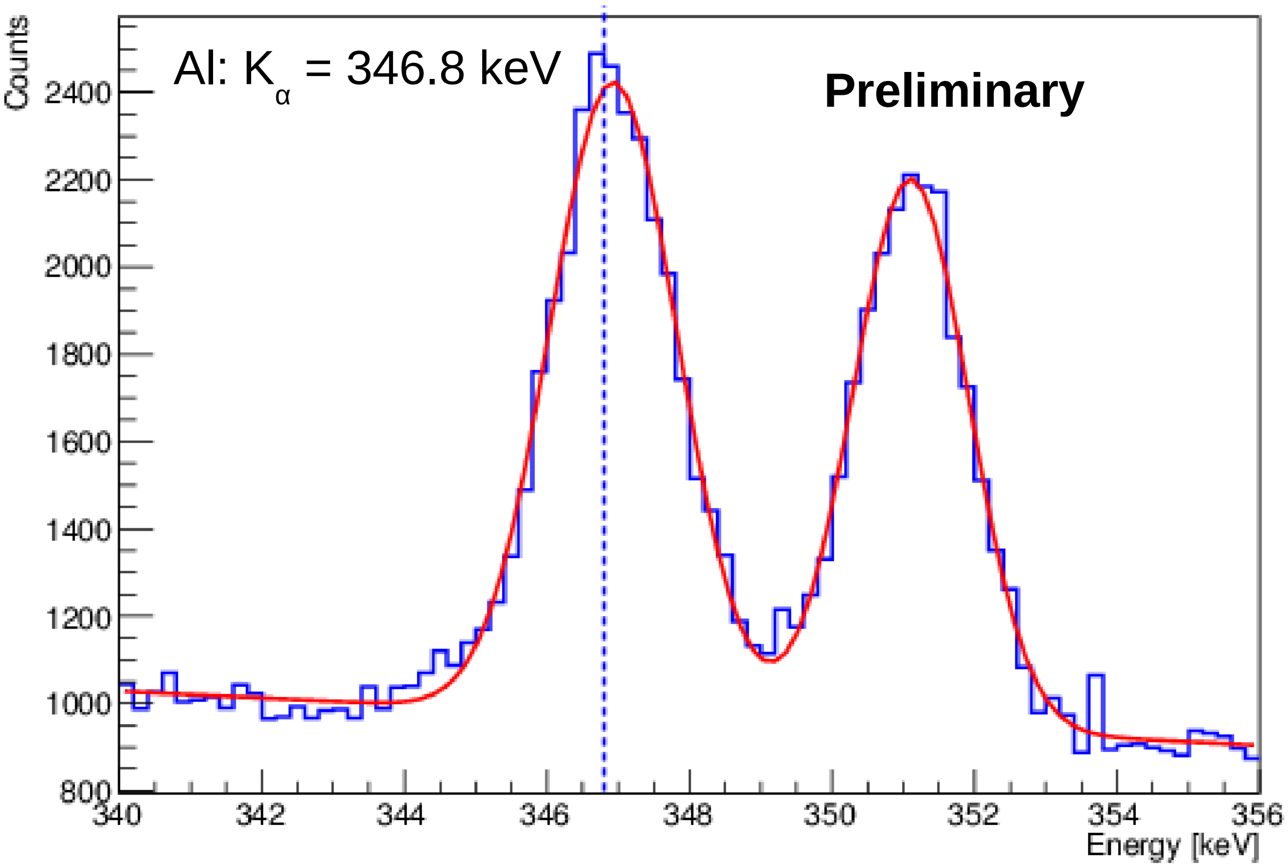
- Zooming into the region of the Al X-ray, can clean it up by setting a ±500 ns cut

Al: K_α = 346.8 keV



Number of Stopped Muons

- Fitting to a double Gaussian with a linear background, it is found that there are 41M stopped muons => 24.6M captured muons



Rate of Proton Emission in Al50

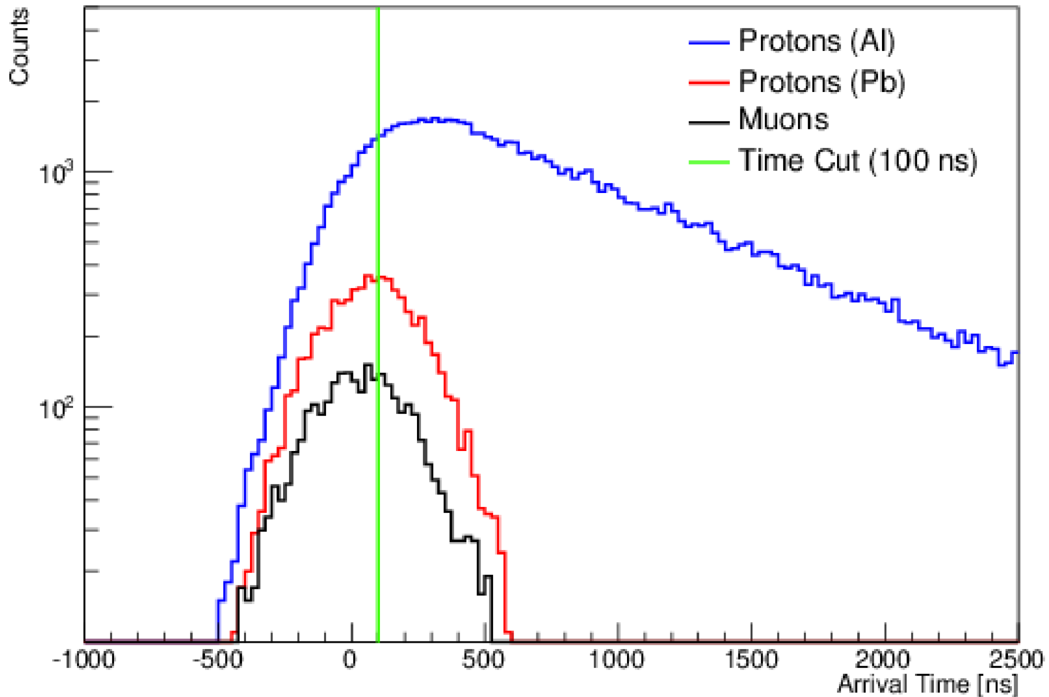
$$R = \frac{N_p}{N(\mu p \rightarrow \nu_\mu n)} = \frac{N_p}{0.609\, N_{\mu-stop}}$$

Rate of Proton Emission in Al50

$$R = \frac{N_p}{N(\mu p \rightarrow \nu_\mu n)} = \frac{N_p}{24.6 \times 10^6}$$

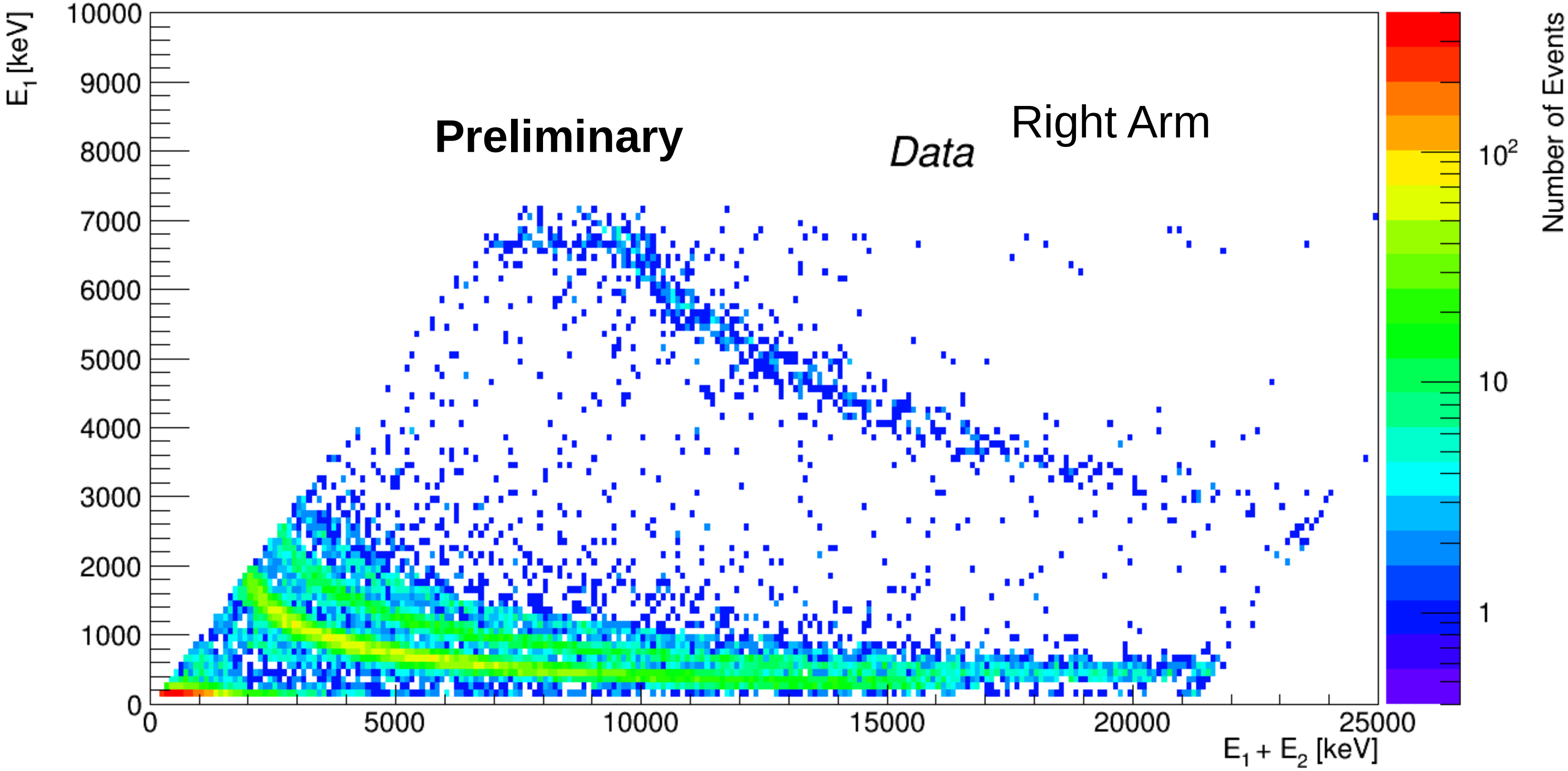
Number of Protons

- Create “muon events”, where hits in Si detectors are assigned to a central muon
- Add a timing cut (100 ns) to remove scattered muons and lead captures
- Efficiency and purity estimated from MC



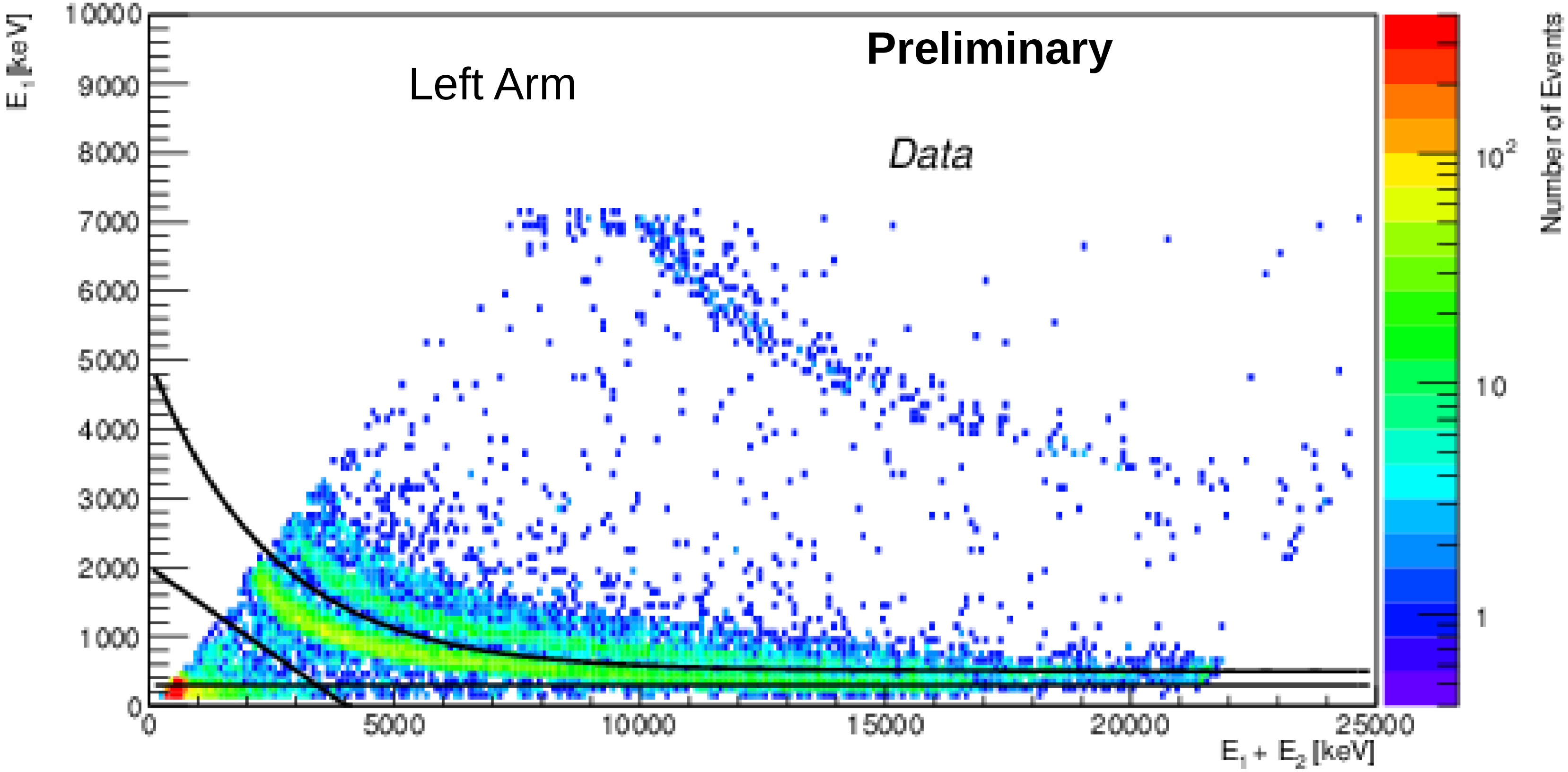
Particle ID Plots

- Plot hits in the silicon detector if:
  - energy in thick layer > 100 keV
  - energy in thin layer > 100 keV
  - time difference between thin and thick hit < 500 ns

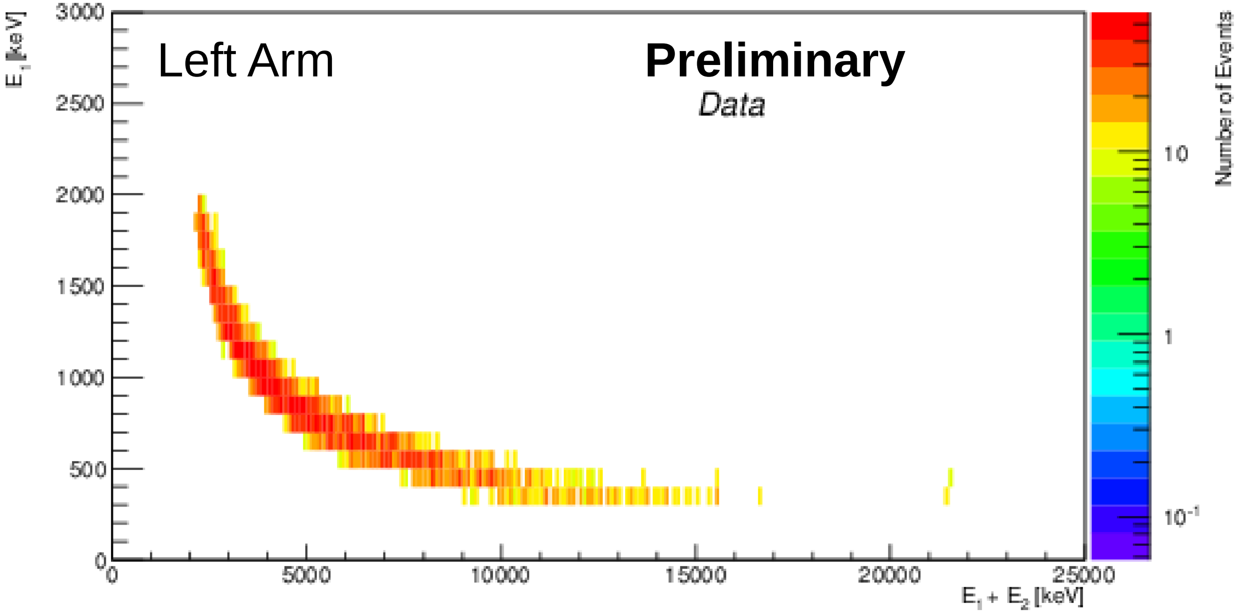


Number of Protons

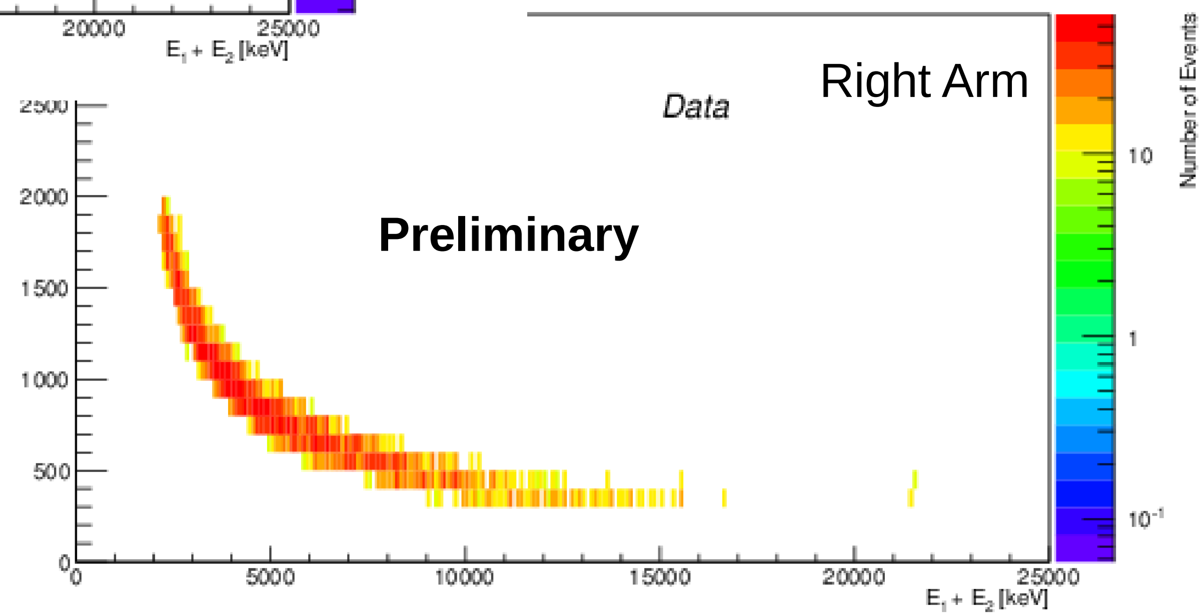
- Can see the proton band clearly
- So some simple cuts can be made to extract it



Extracted Proton Bands

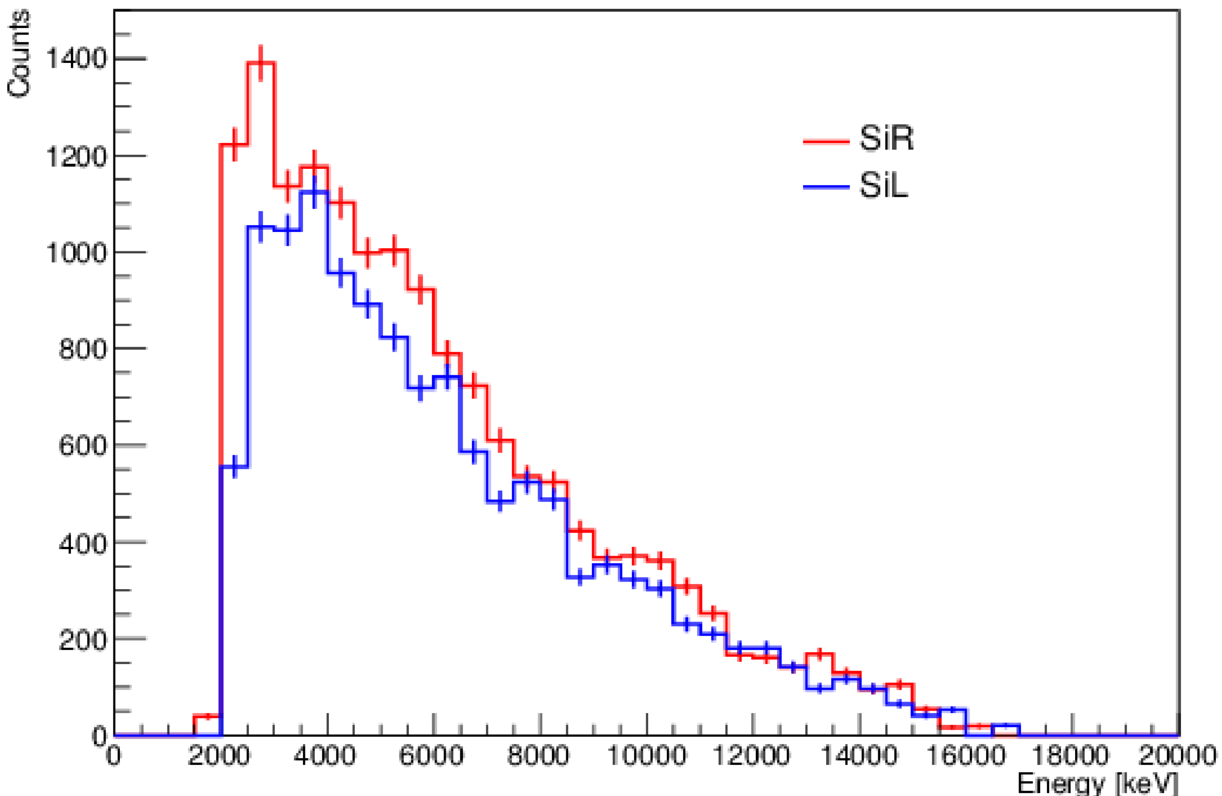


Can then project onto the x-axis to get the measured energy spectrum...



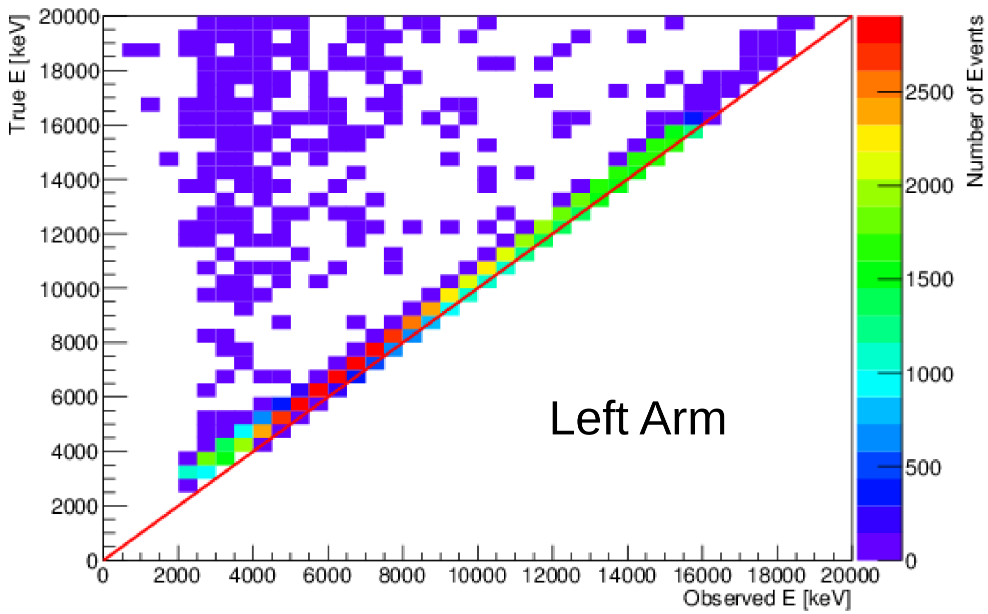
Number of Protons

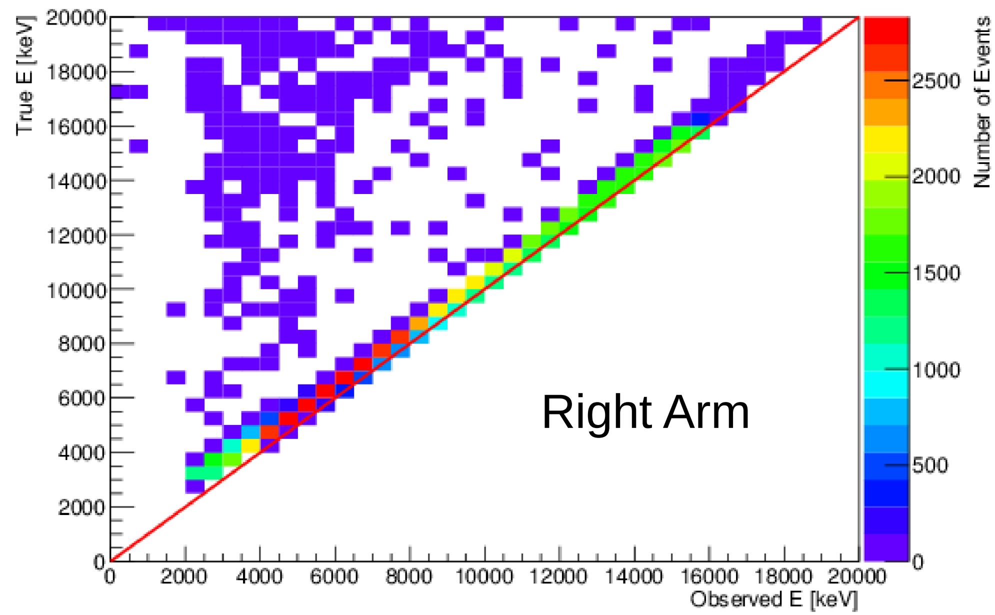
- After taking into account the efficiency and purity of the selection (obtained from MC), it was found that, between 2.5 and 10 MeV there are:
  - Left: $(10.7 \pm 0.1) \times 10^3$
  - Right: $(12.4 \pm 0.1) \times 10^3$



Unfolding the Proton Spectra

- This does not include the geometrical acceptance or the energy lost as the proton leaves the target
- We create a response matrix for each arm from the MC

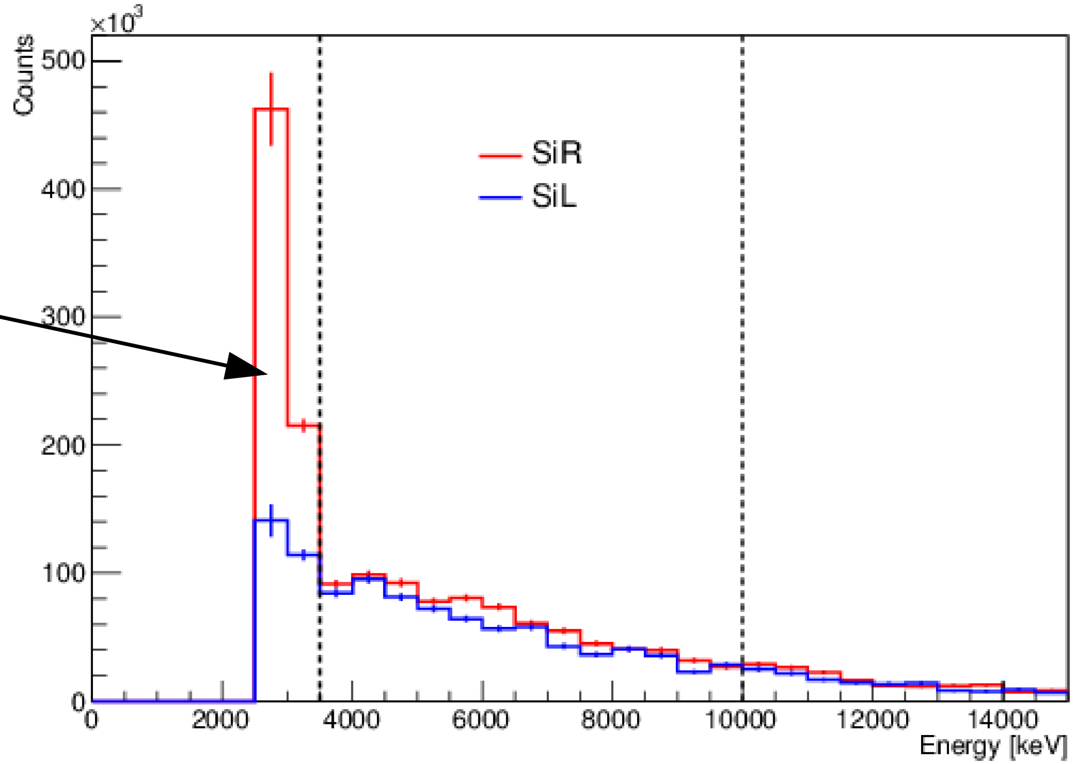




Number of Protons

- The final, unfolded spectra are:

Odd behaviour due to the unfolding

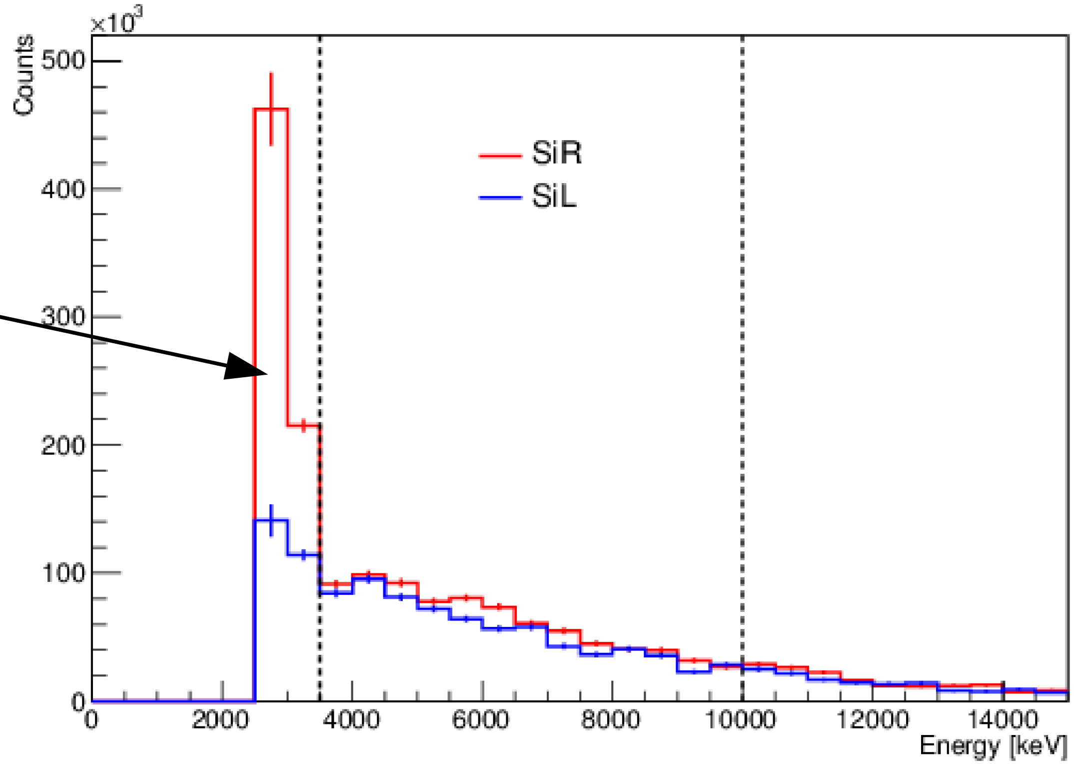


- Between 3.5 and 10 MeV there are:
  - Left: (0.744 ± 0.009 (stat.) ± 0.08 (syst.)) x 10^6
  - Right: (0.843 ± 0.010 (stat.) ± 0.09 (syst.)) x 10^6

Number of Protons

- The final, unfolded spectra are:

Odd behaviour due to the unfolding



- The unfolding of both arms should give the same distribution and so:
  - $N_p = (0.79 \pm 0.09) \times 10^6$ between 3.5 and 10 MeV

Rate of Proton Emission in Al50

$$R = \frac{N_p}{N(\mu p \rightarrow \nu_\mu n)} = \frac{N_p}{24.6 \times 10^6}$$

Rate of Proton Emission in Al50

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Rate of Proton Emission in Al50

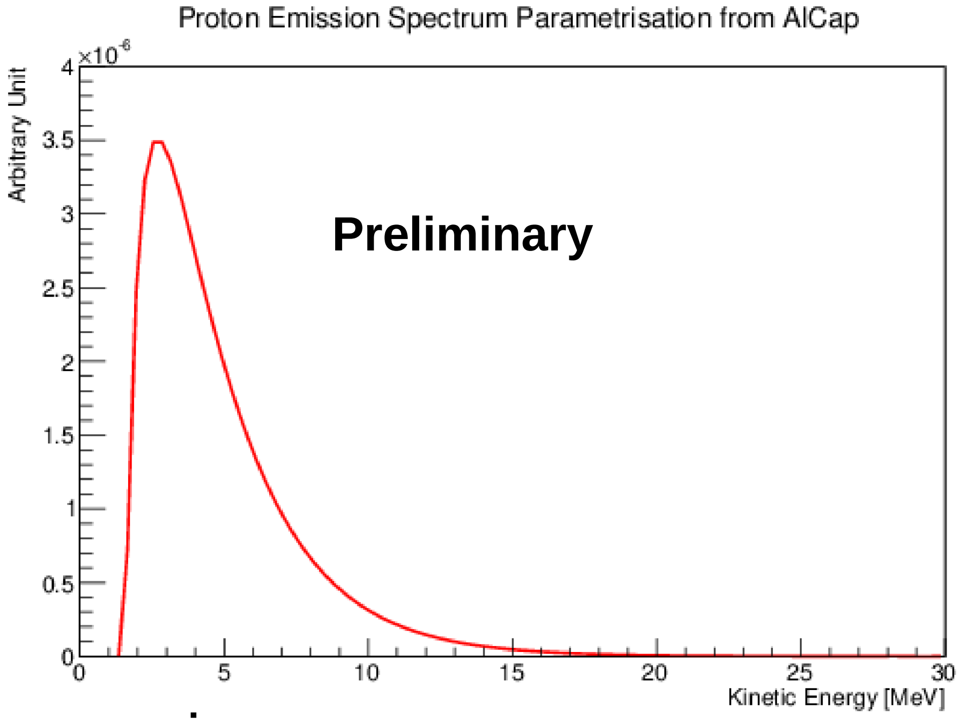
- The preliminary result is then, between 3.5 and 10 MeV:

$$R = 0.032 \pm 0.004 \text{ protons per muon capture}$$

- In this region, the COMET parameterisation (from Si) gives 0.09 protons per muon capture
  - The rate in Al is significantly lower

Other Analyses

- In the Al100 dataset, the rate of proton emission was found to be 0.035 ± 0.02 protons per muon capture
  - Agrees within error of the Al50 analysis
- Also in the Al100 dataset a parameterisation of the spectrum was found:



- Silicon analyses are in progress

AlCap Future

- Continue analysis of 2013 data
- Collect new data in two new runs this year
  - June 2015: measurement of neutrons and photons
  - November 2015: another measurement of protons with more targets

Conclusion

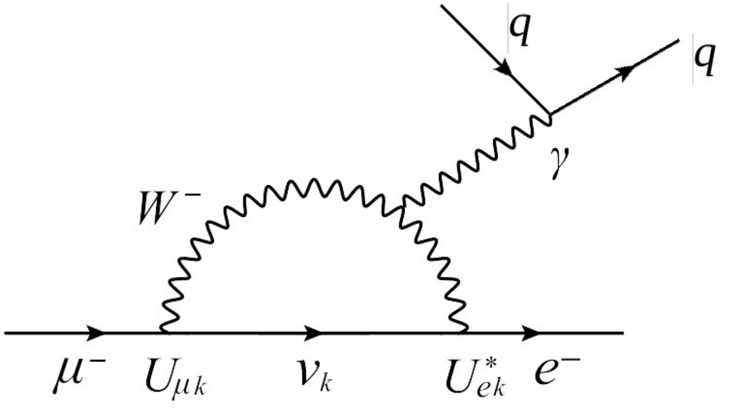
- AlCap is aiming to measure the rate and spectrum of particles emitted after nuclear muon capture
- A preliminary analysis of protons has been performed
- Have two more runs to collect data on neutrons, photons and more data on protons

Thanks for Listening
Any Questions?

BACK UP

Charged Lepton Flavour Violation

- Know that lepton flavour isn't conserved in neutrino oscillations
- CLFV has not been observed
- SM prediction of CLFV is $O(10^{-54})$
  - Therefore, if observed at any higher rate, it will be clear evidence of physics BSM



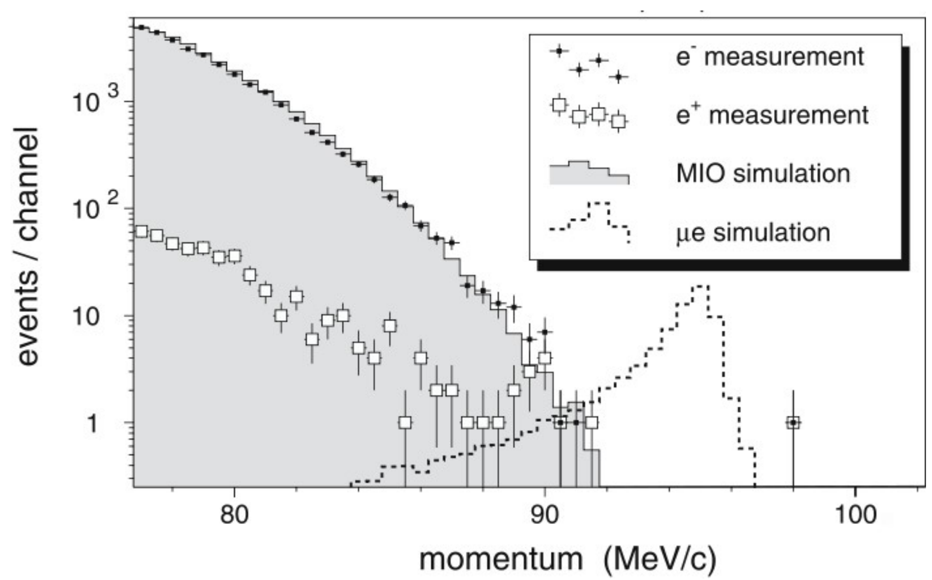
Standard Model Feynman diagram of the process μN→eN

μ-e Conversion

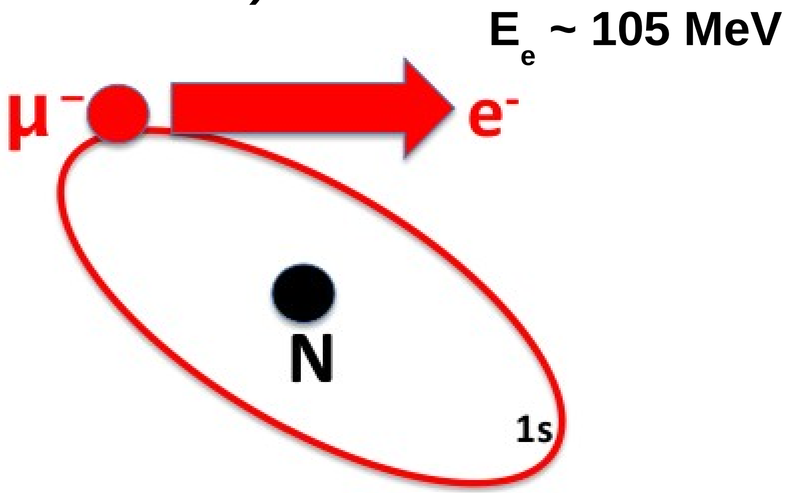
- COMET will be searching for the charged lepton flavour violating process

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

in Al with a branching ratio sensitivity of $O(10^{-17})$
(Current limit: $BR(\mu^- Au \rightarrow e^- Au) < 7 \times 10^{-13}$)



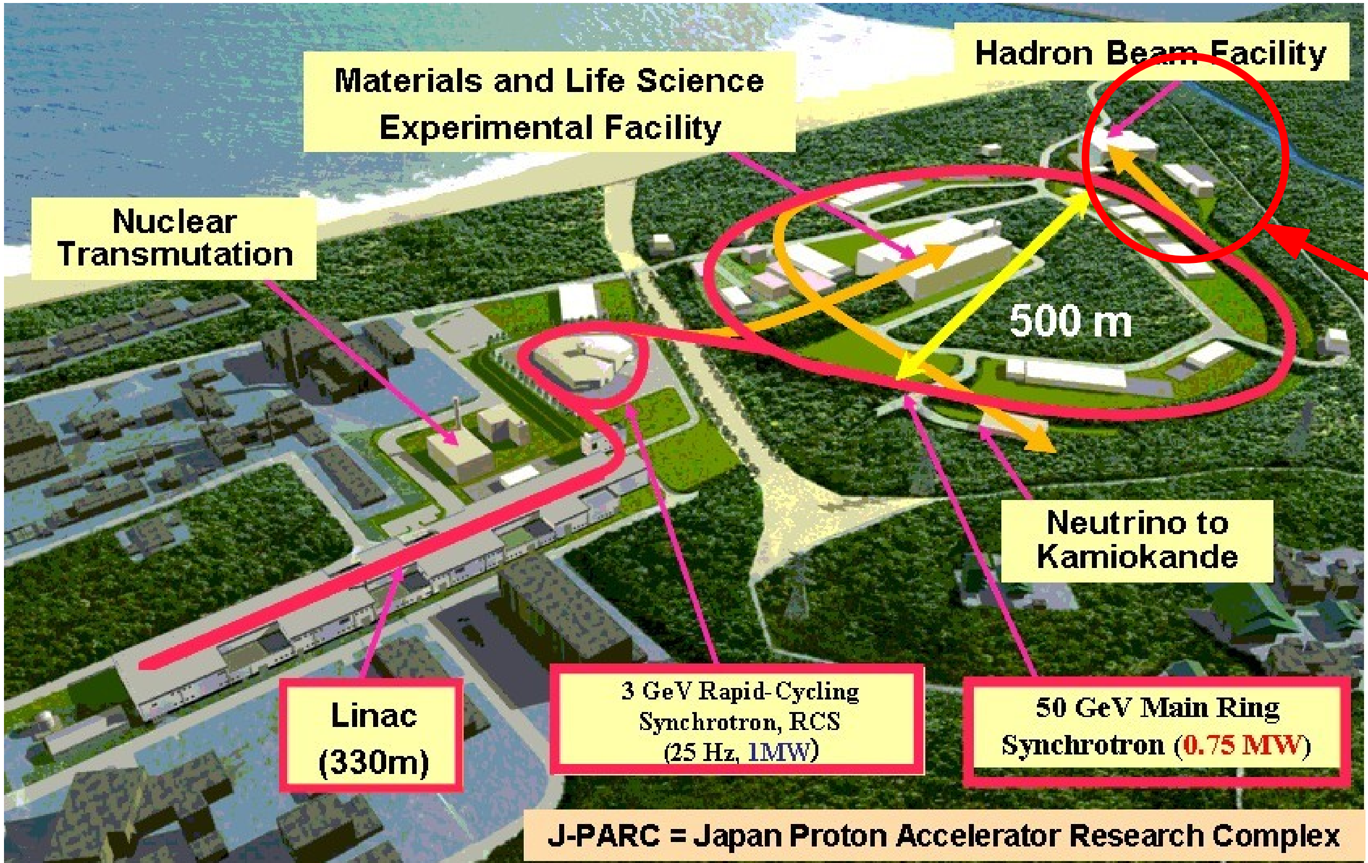
SINDRUM results of search for μ-e conversion in gold



Cartoon of μ-e conversion

COMET

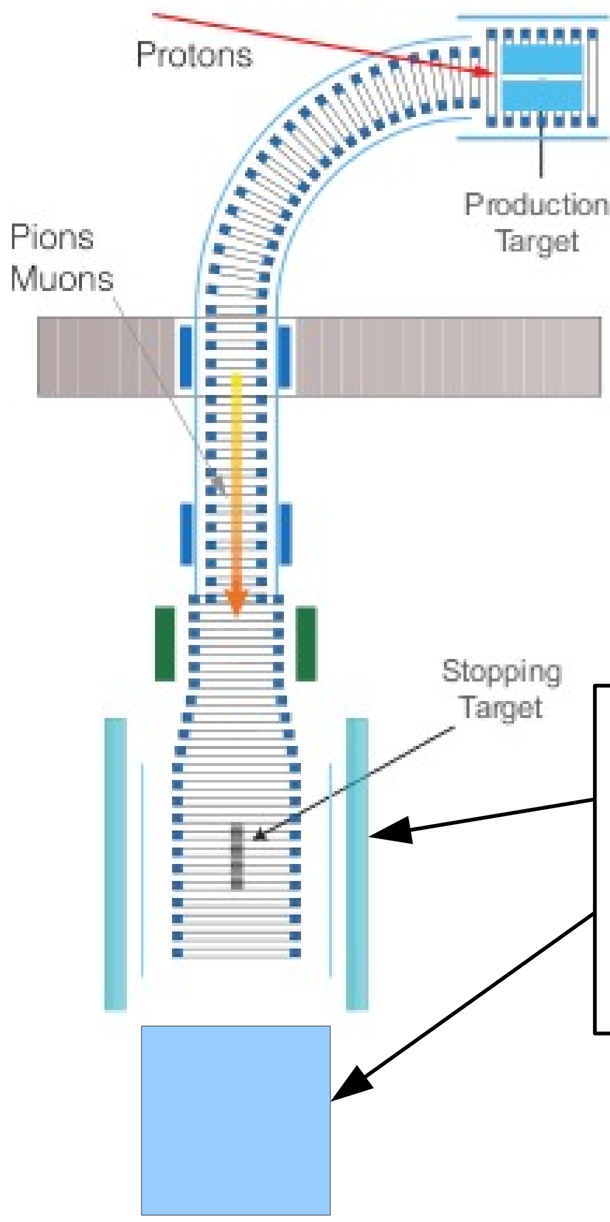
- Will be built at J-PARC in two phases
  - Phase-I (2016): S.E.S = 3×10^{-15}
  - Phase-II (2019): S.E.S = 3×10^{-17}



COMET will be built here

Starting in 2016
~3 months running
S.E.S = 3×10^{-15}

COMET (Phase-I)

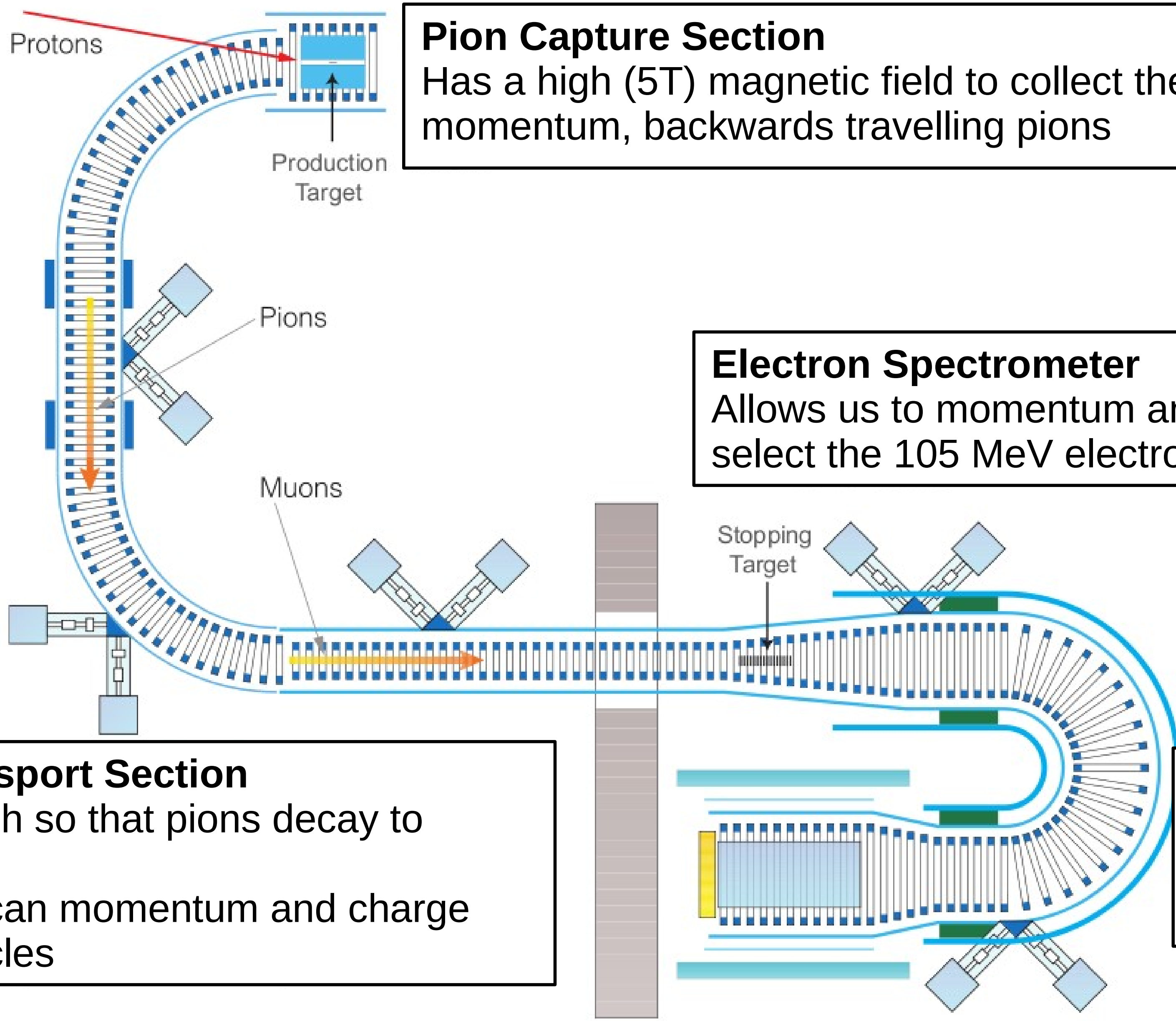


Phase-I Aims
Search for μ-e conversion process with a S.E.S of 3×10^{-15}
Study the backgrounds for Phase-II

Phase-I Detector
A cylindrical detector (CyDet) for the μ-e conversion search
A prototype ECAL and straw tube tracker (StrECAL) for the background studies

COMET (Phase-II)

Starting in 2019
~1 year running
S.E.S = 3 x 10^{-17}



Pion Capture Section
Has a high (5T) magnetic field to collect the low momentum, backwards travelling pions

Electron Spectrometer
Allows us to momentum and charge select the 105 MeV electrons

Muon Transport Section
Long enough so that pions decay to muons
Curved so can momentum and charge select particles

Detector
Straw tube tracker and ECAL

Backgrounds

- Once the muon is stopped it can decay normally
  - Decay in orbit (DIO)

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$

Can produce electrons with energies close to the signal region => use **high resolution detectors**

SINDRUM results of search for μ-e conversion in gold