Status of the AlCap experiment

NUFACT2019, Daegu, S. Korea

Mark Wong on behalf of the AlCap collaboration

2019/08/30

UNIVERSITÉ Clermont Auvergne
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Previous talks:
NUFACT2014 arXiv:1501.04880
CIPANP2018 arXiv:1809.10122

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Funding provided in part by DOE

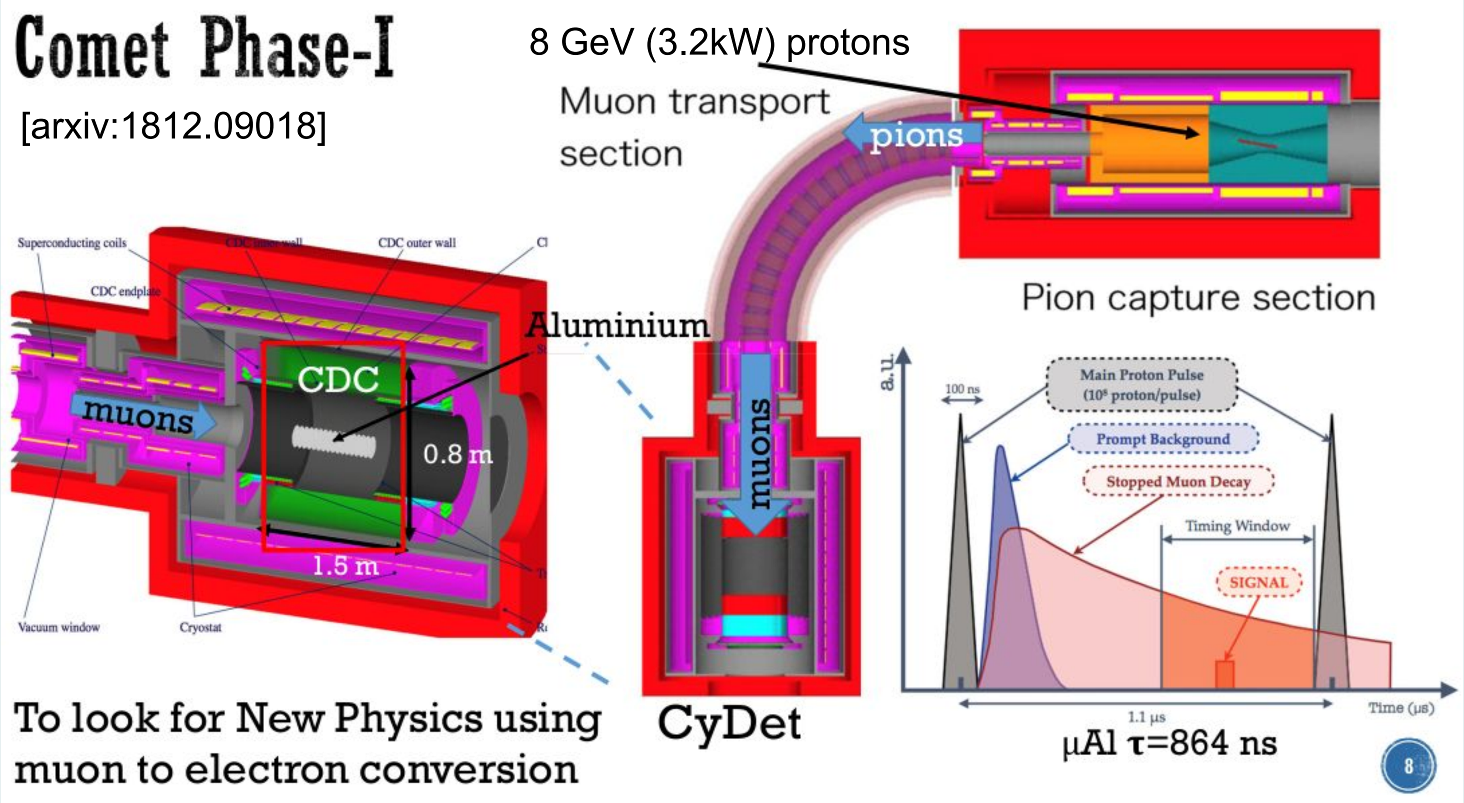
Motivation

- Nuclear muon capture on aluminium

$$\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + X + \{n, p, d, t, \alpha\}$$

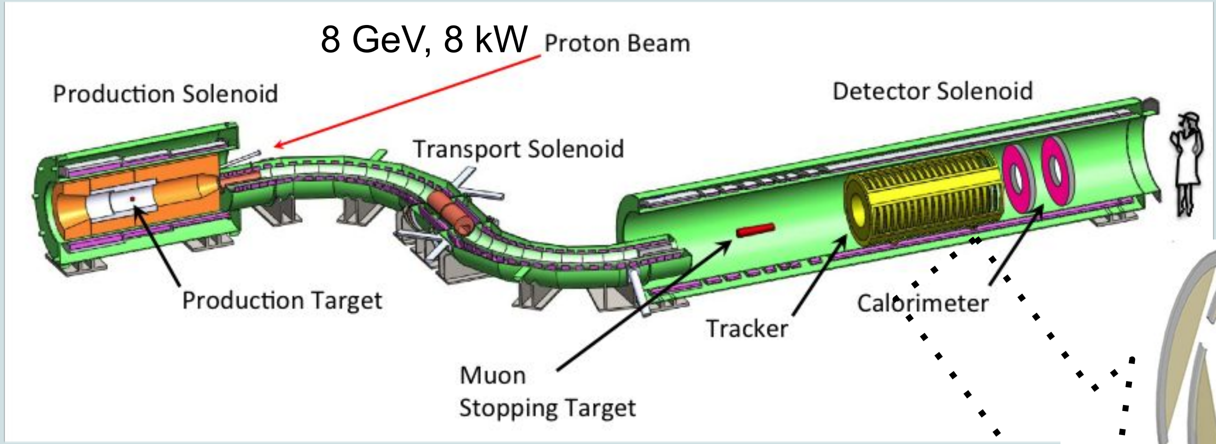
  is a dangerous background process for μ^- - e^- conversion experiments COMET Phase-I (talk by T. Y. Xing) and Mu2e (talk by R. Bonventre)
- Depending on their rate and spectra of the emitted protons, the tracking detectors have to be shielded which deteriorates their resolution, while neutrons can induce noise and electronic damage
- Relevant proton energy range 3.5 - 8 MeV; existing data only above 40 MeV.
- AlCap experiment at PSI to obtain this information.

COMET

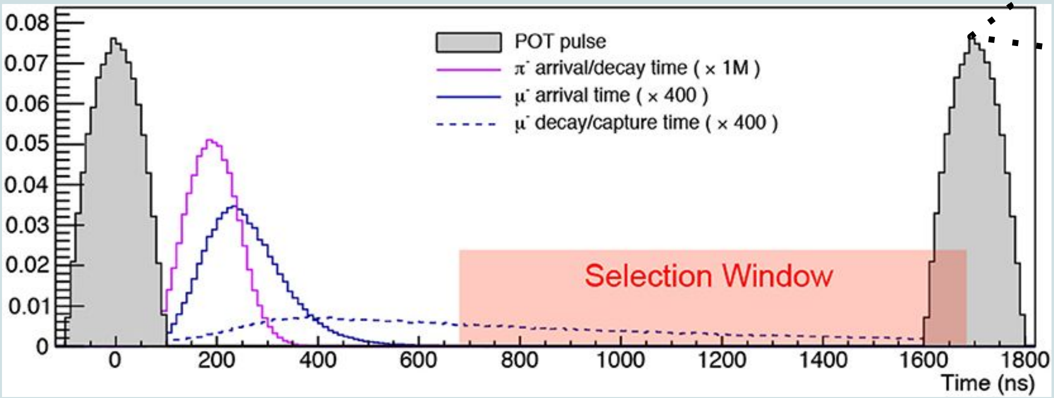


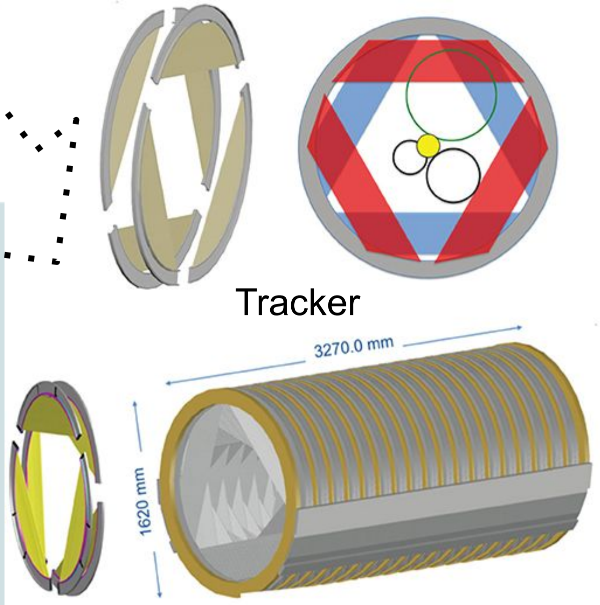
Comet Phase-I
[arxiv:1812.09018]
8 GeV (3.2kW) protons
Muon transport
section
pions
Pion capture section
Superconducting coils
CDC outer wall
CDC endplate
Aluminium
CDC
muons
0.8 m
1.5 m
Vacuum window
Cryostat
muons
CyDet
a.u.
100 ns
Main Proton Pulse
Prompt Background
Stopped Muon Decay
Timing Window
SIGNAL
1.1 μs
Time (μs)
μAl τ=864 ns
To look for New Physics using
muon to electron conversion

Mu2e

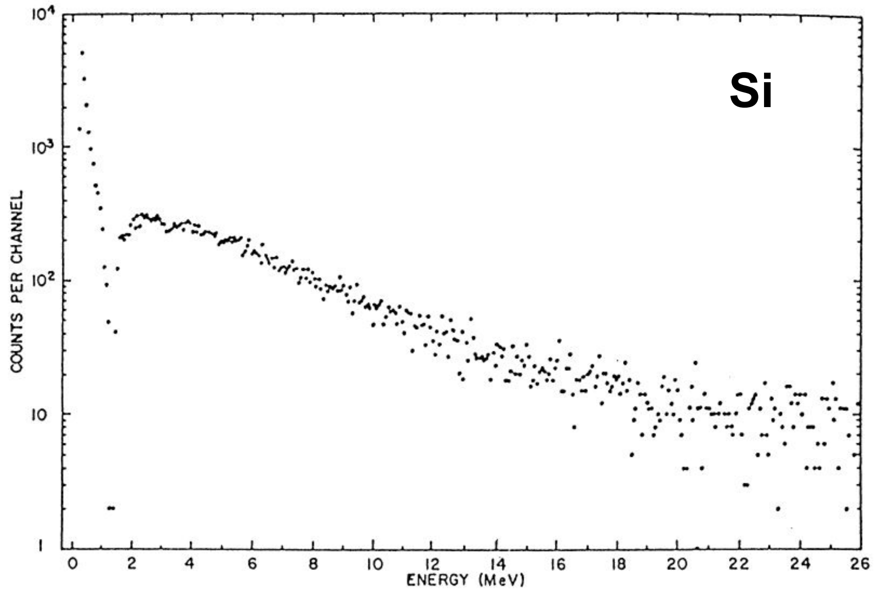


[arxiv:1501.05241]

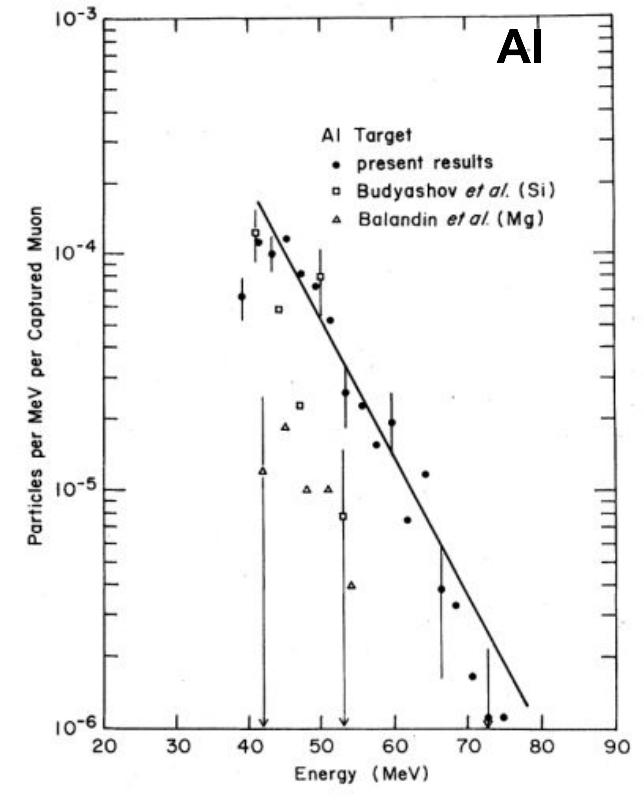




Some history of μ-capture Al

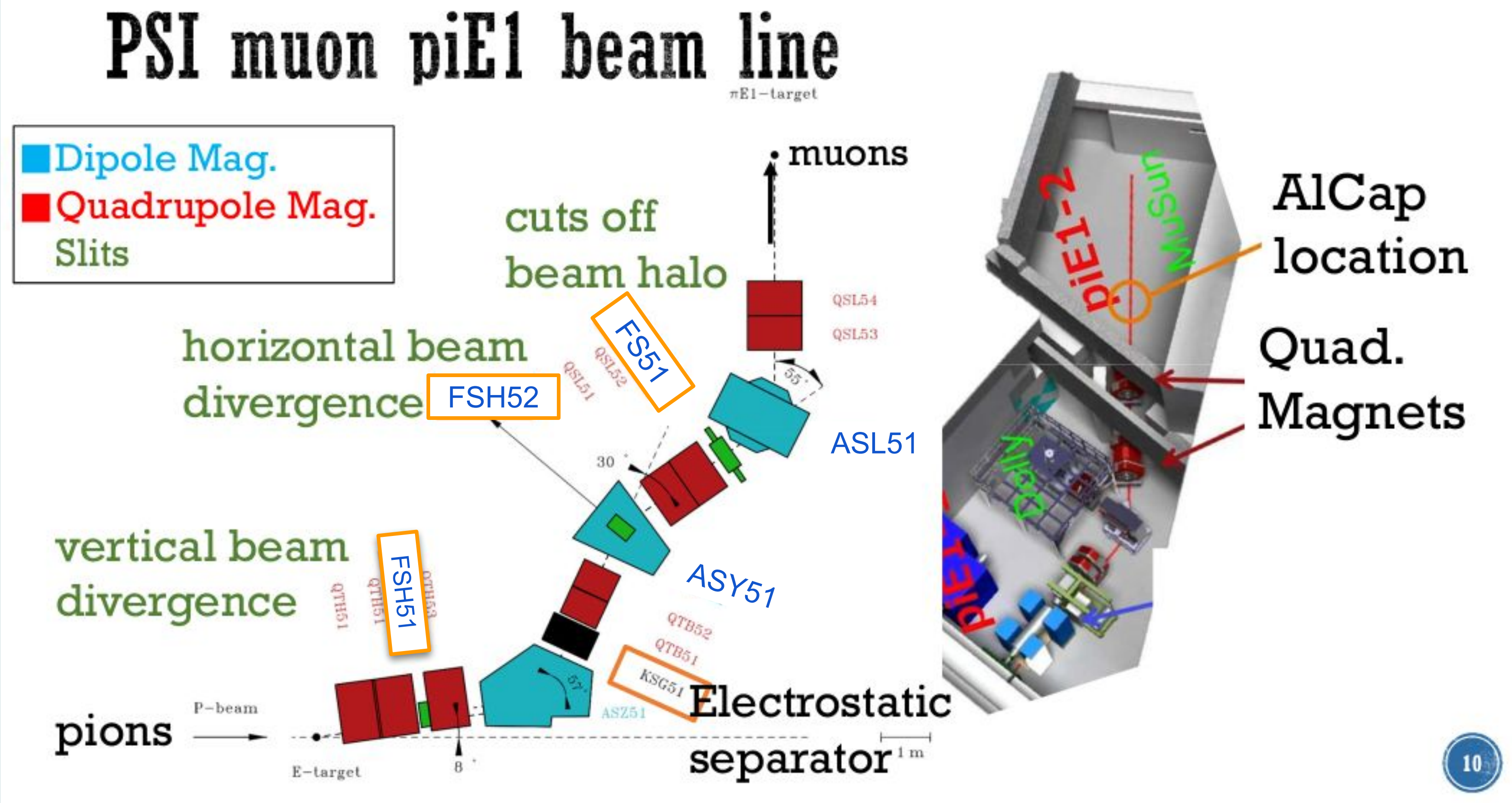


Phys. Rev. Lett. 20, 596 (**1968**)
Rate = 15%(p, d, t, α)
Protons = 5.3%
(Sov. J. Nucl. Phys. 13 (1971) 310)



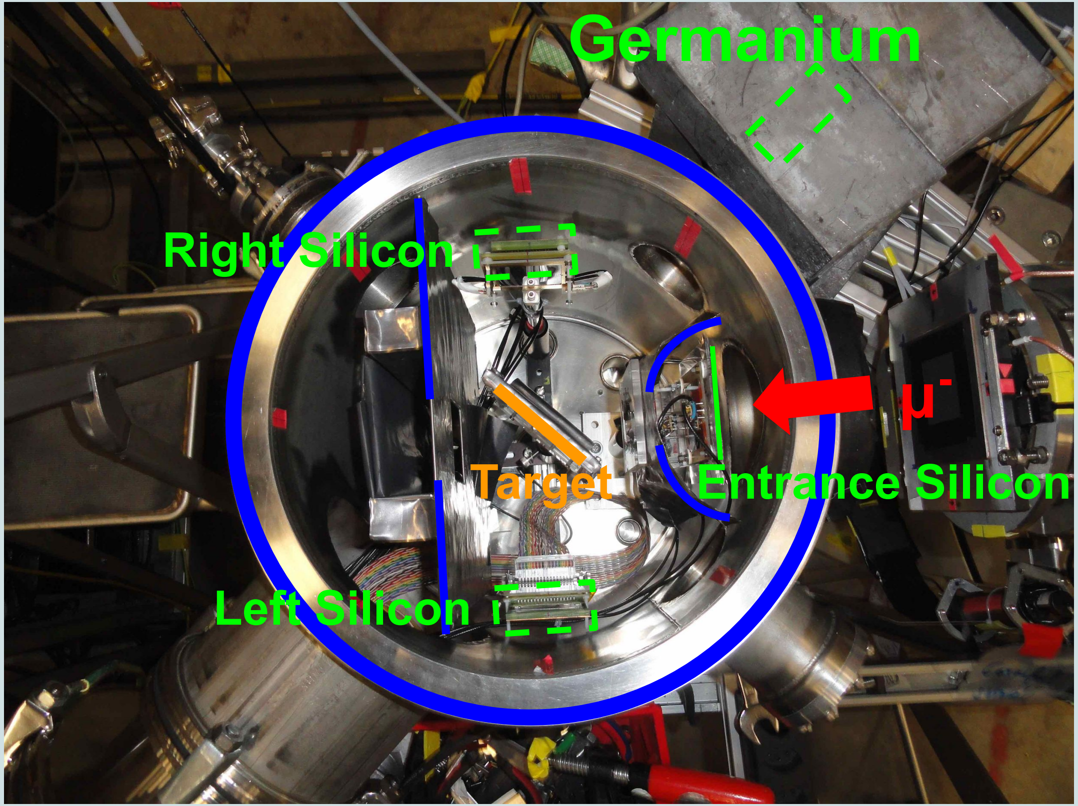
Phys. Rev. C 20 (**1979**) 1873
1.27mm Al target, threshold for protons was 30 MeV.

Muon source



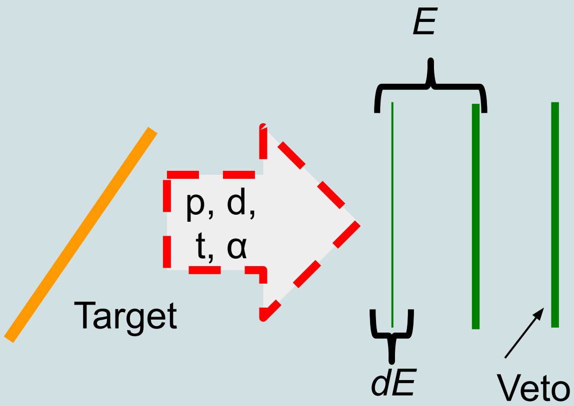
PSI muon piE1 beam line
πE1−target
muons
Dipole Mag.
Quadrupole Mag.
Slits
cuts off
beam halo
QSL54
QSL53
horizontal beam
divergence
FSH52
FS51
QSL52
QSL51
ASL51
30
55
vertical beam
divergence
FSH51
QTH51
QTH52
QTH53
ASY51
QTB52
QTB51
KSG51
Electrostatic
separator
57
ASZ51
pions
P−beam
E−target
8
1 m
piE1-2
MuSun
AlCap
location
Quad.
Magnets
Dolly
piE1
10

Experimental setup



For this talk
Target: Al 50 μm
Momentum: 25.9 MeV/c, 26.2 MeV/c
Run time 25.2hrs
Muon beam rate: 6-8kHz
Other targets:

Al 100 μm	25.6 hrs
Si 50 μm	8.4 hrs
Ti 50 μm	10.4 hrs



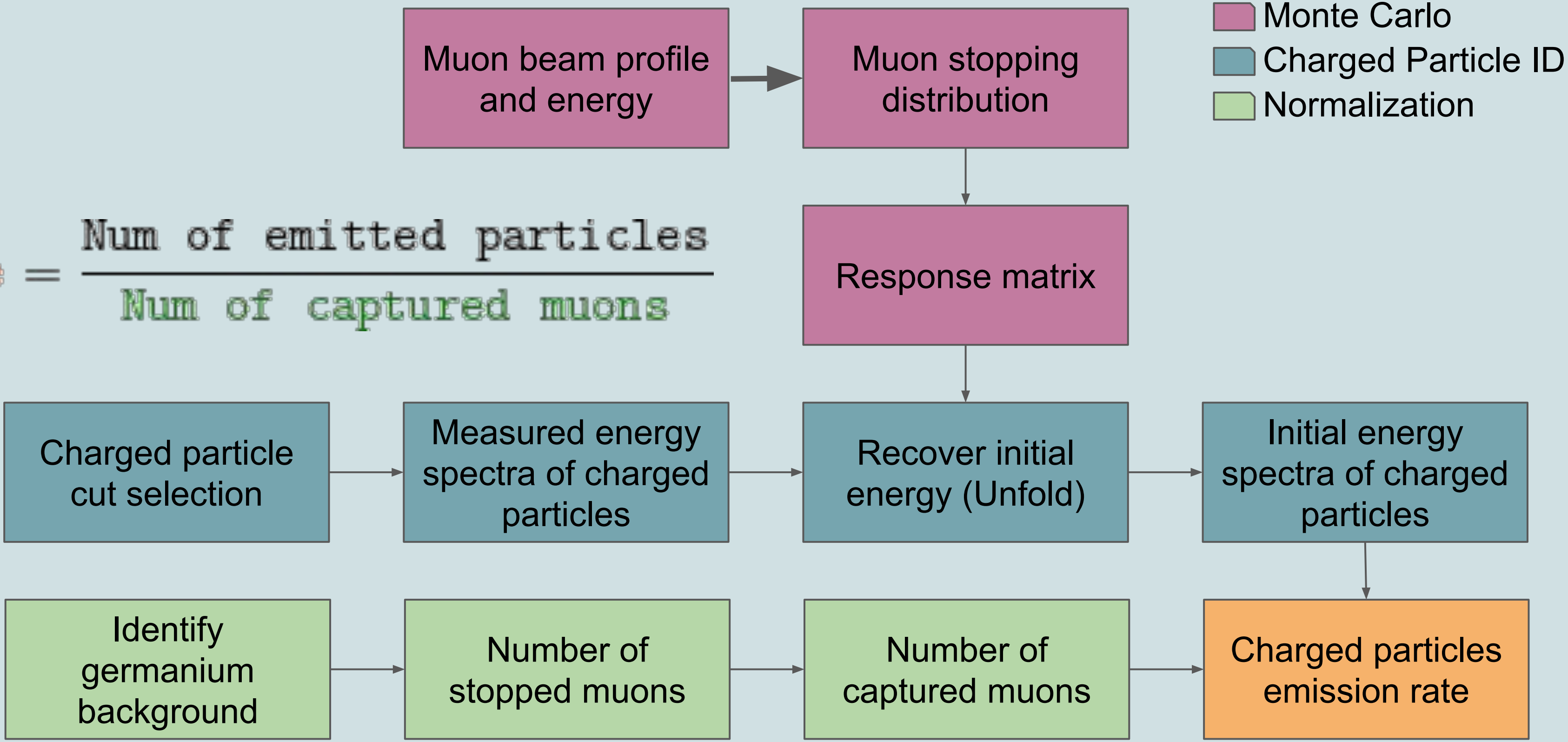
Work packages

Today

WP1: Protons	WP2: Photons	WP3: Neutrons
Determine proton emission rate following muon nuclear capture to assess tracker occupancy and damage	• Gammas from nuclear capture and activation • *X*-rays and gammas from other targets • Noise hits • Normalization	• Determine neutron spectra from materials used for shielding in Mu2e/COMET • Cause noise hits, corrupt electronics' memory

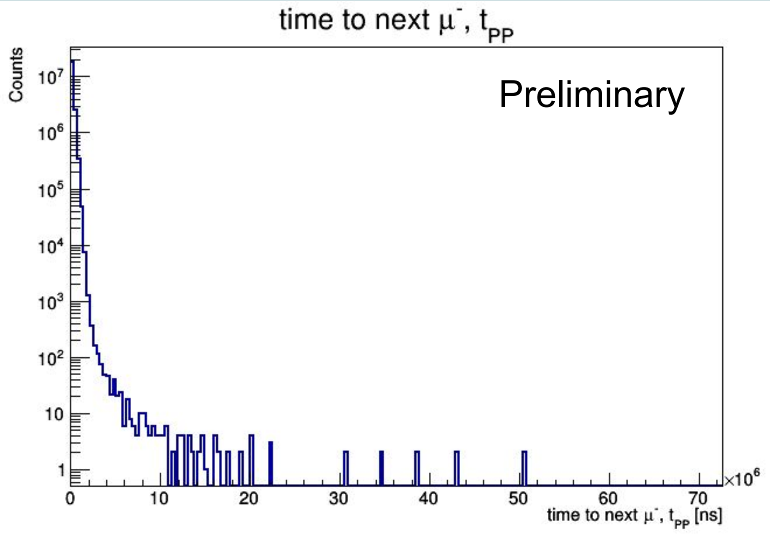
Analysis overview

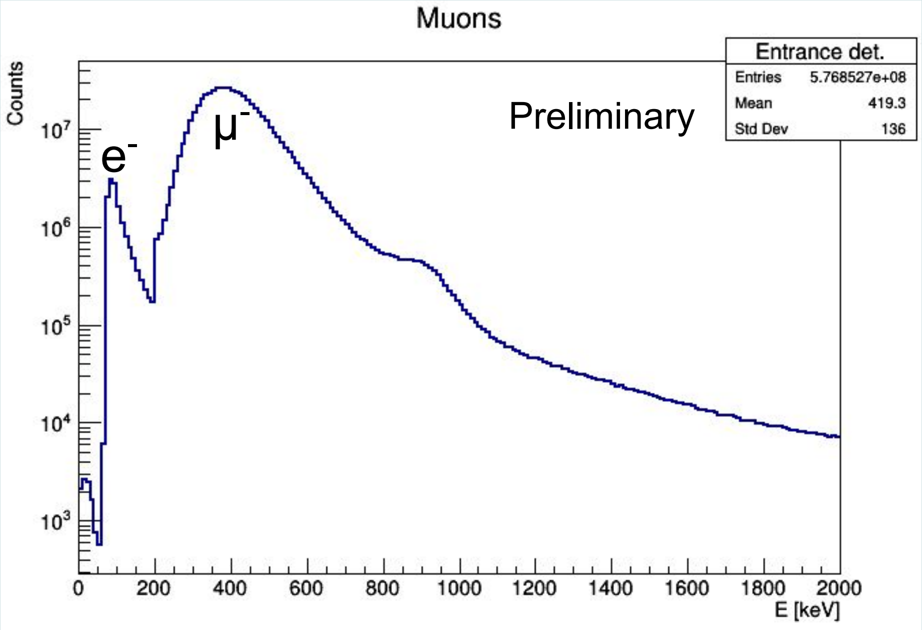
$$\text{Rate} = \frac{\text{Num of emitted particles}}{\text{Num of captured muons}}$$



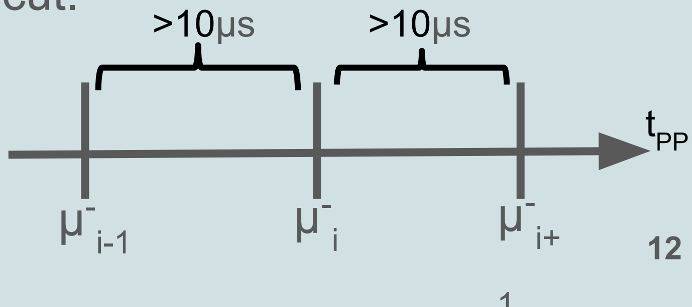
Normalization & Charged particle ID

Pileup protection





- Muons are selected with a 200 keV E threshold cut.
- Choose to reject muon events that occur within ±10μs to prevent double counting.
- Particles/x-ray from assoc. muons are used for further analysis.



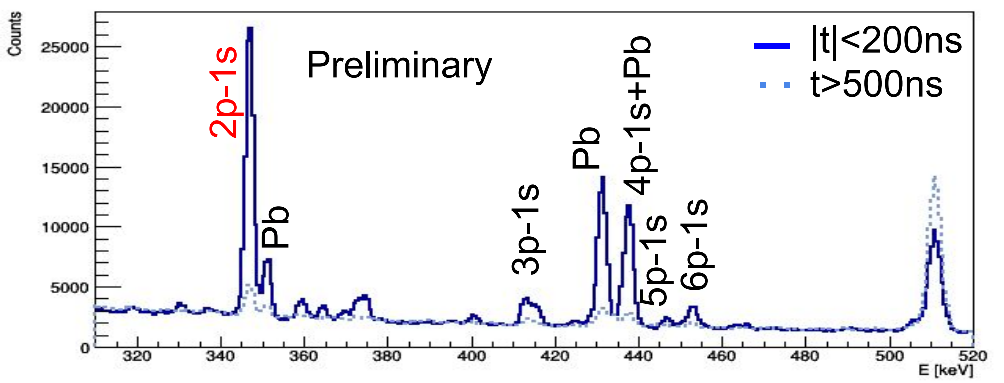
Normalization

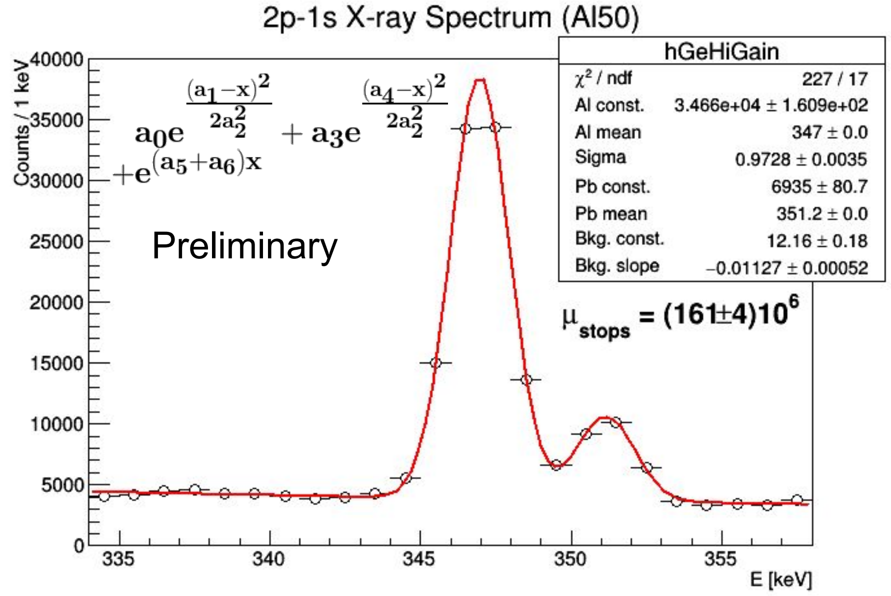
With **μAl 2p-1s** x-rays.
Main ^{214}Pb background at ~351 keV.
Time cut, |t|<200 ns.
Includes pileup protection.

$$\mathrm{Total} = \frac{\mathrm{Counts}}{\mathrm{Acceptance} \times \mathrm{Emission\ probability}}$$

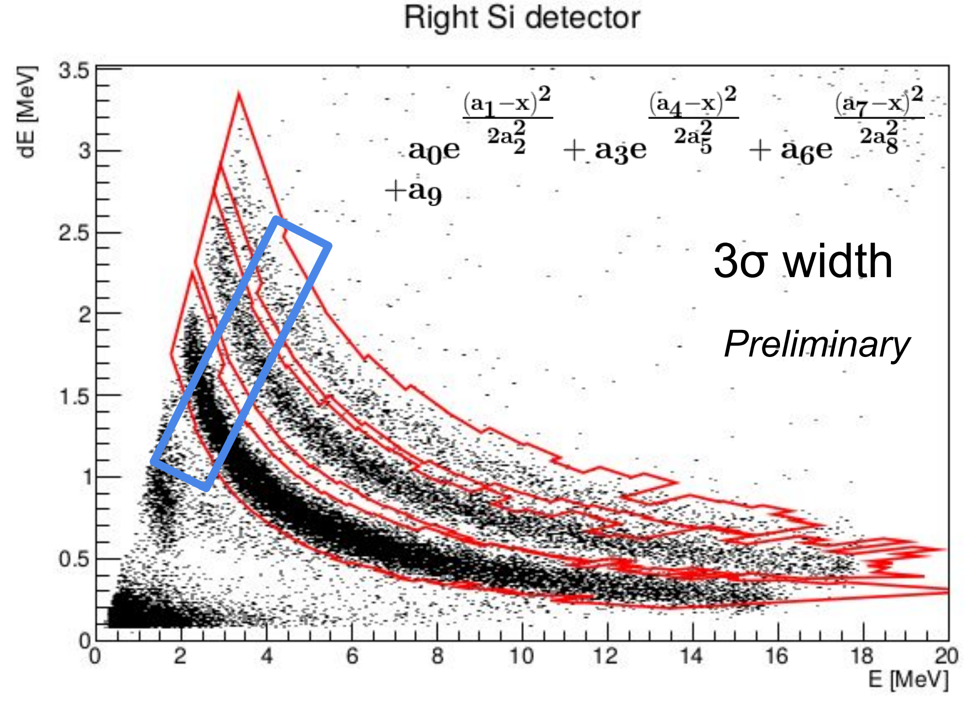
2p-1s muonic *X*-rays	85337±1766
Acceptance @ 347 keV	$(6.63\pm0.10) \times 10^{-4}$
Emission prob. (/μ-stop)	79.8(8)% *
Stopped Muons	$(161\pm4) \times 10^{6}$

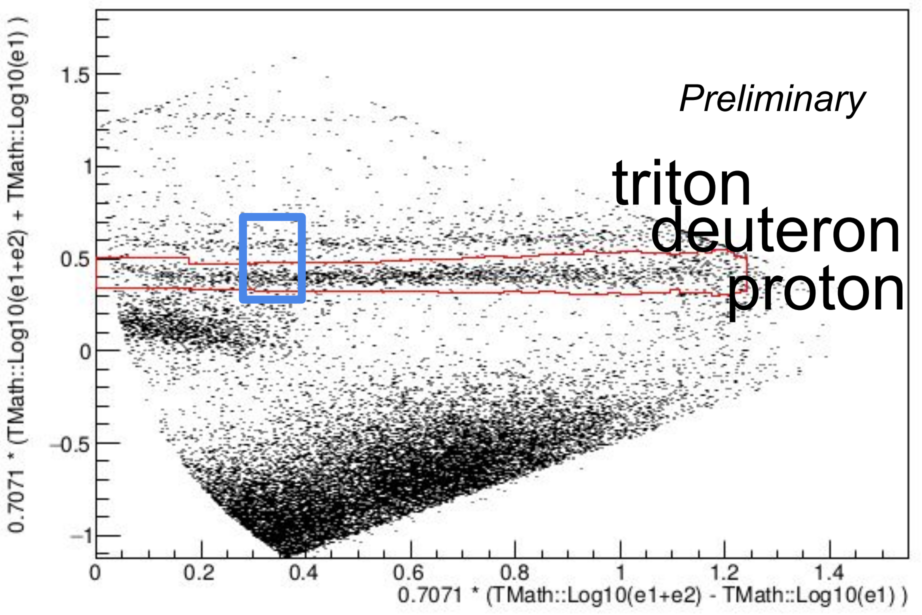
* Phys Rev C 76, 035504 (2007)





Charged particle ID

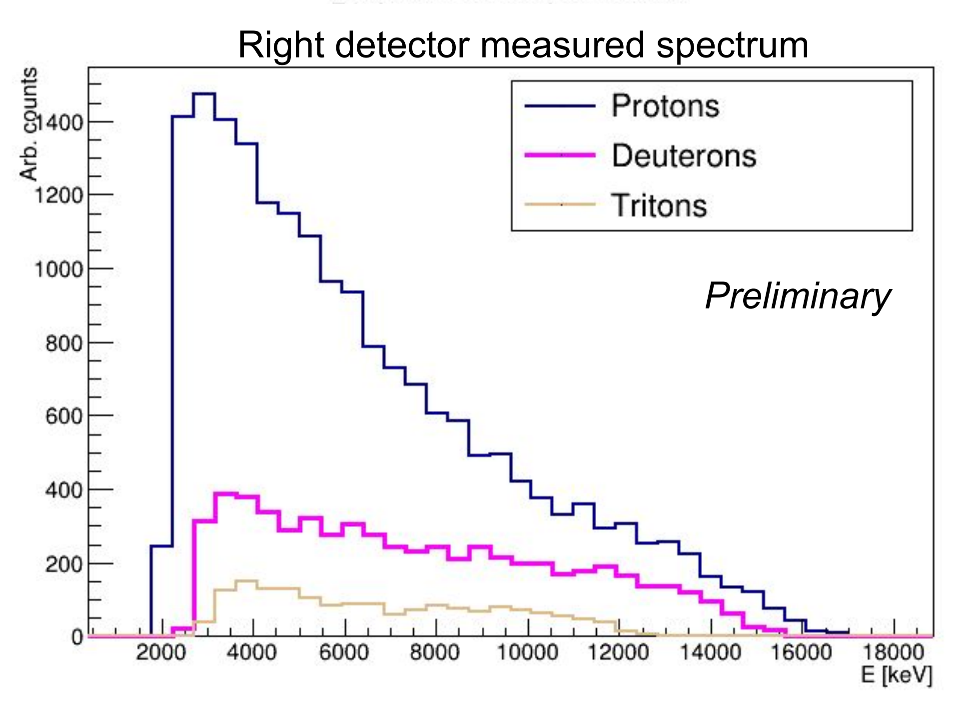




1. Take Log of x-, y-axis and rotate -45º.
2. Fit three gaussians (+ const. bkg.) for particles in ~1 MeV energy bins.
3. Possible to vary tightness of selection cut (1 - 4 σ).

Raw folded energy spectrum

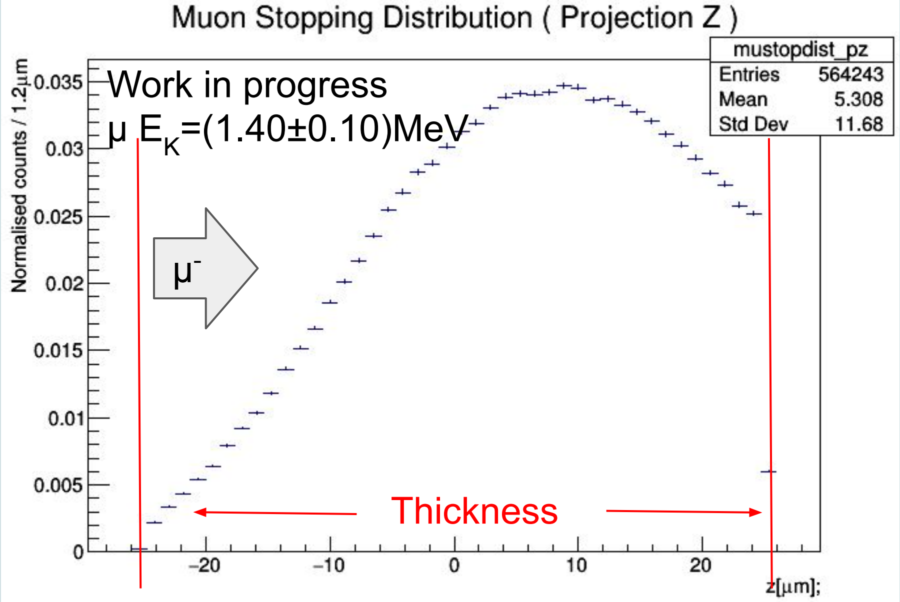
- Reject events if origin muon is within ±10 μs from next and previous muon.
- Coincidence time within 200 ns of the mean.
- Reject time < 500 ns to significantly reduce μPb contamination.
- Particle ID within 3σ.

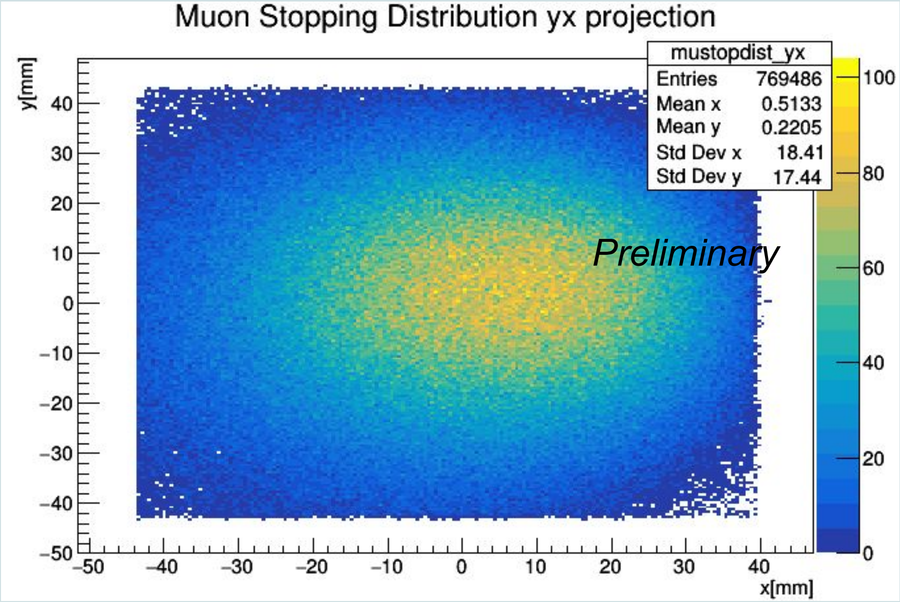


Monte Carlo studies

Muon beam simulation

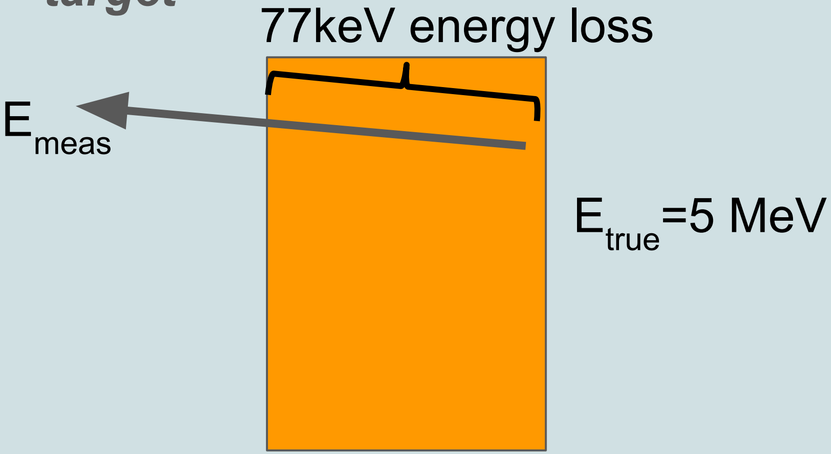
- Monte Carlo samples are generated with muons of different kinetic energies to obtain stopping distributions for the various targets under study.
- These energies are being validated by runs with active Si target.





Recover initial particle energy

Proton energy loss plot in Al 50 μm target



$$E_{loss} \approx \rho L \frac{dE}{dx}$$

Iterative Bayesian unfolding

[arxiv:1010.0632, arxiv:1105.1160]

Generate a transfer matrix, *M*

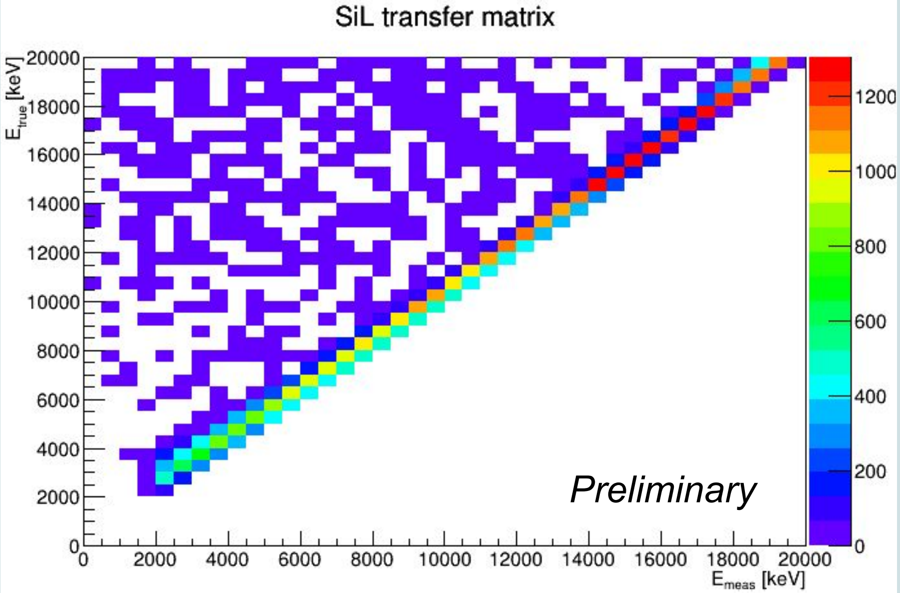
M contains geometrical and detector efficiencies as well as particle energy loss information

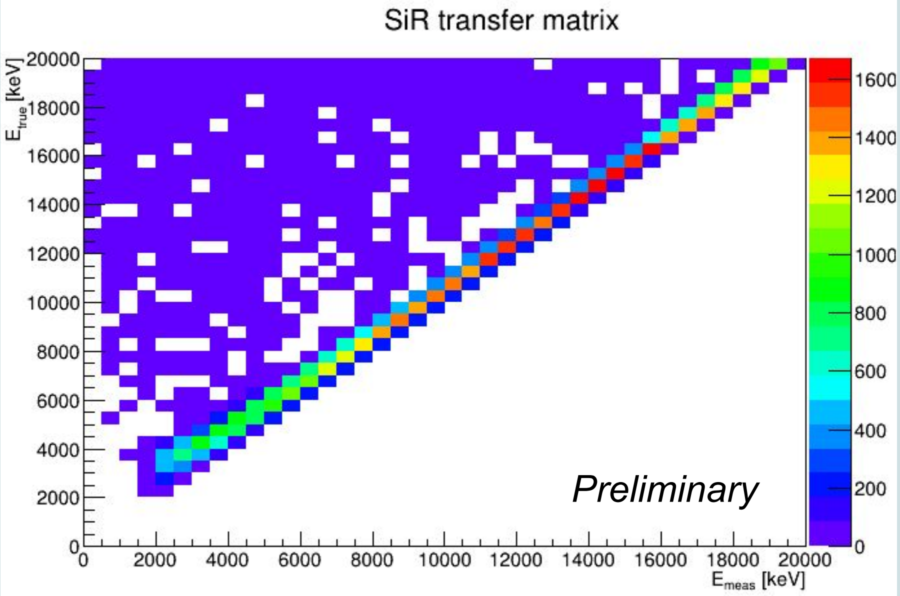
Probability of obtaining E_{meas} from E_{true}.

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

Then we can apply unfolding/deconvolution to obtain E_{true}

Transfer matrix





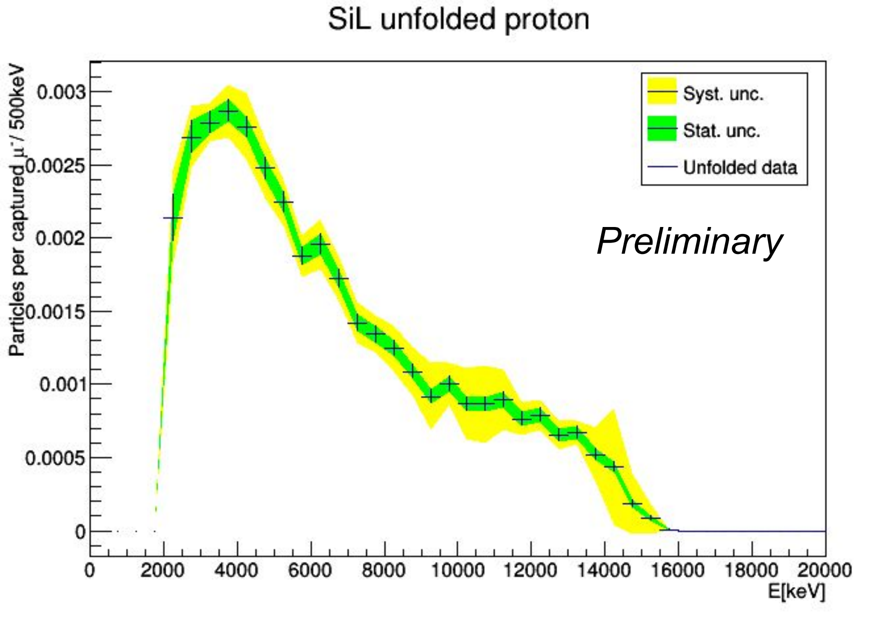
- Initial starting position of particles determined from muon stopping distribution.
- Energy of particles uniformly distributed from 0 to 20MeV.

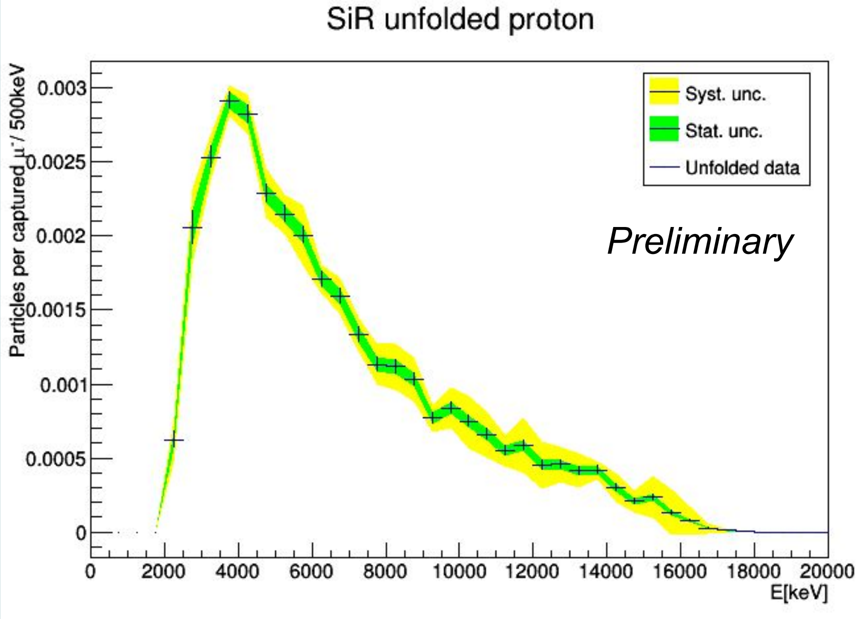
Energy unfolding

Preliminary results

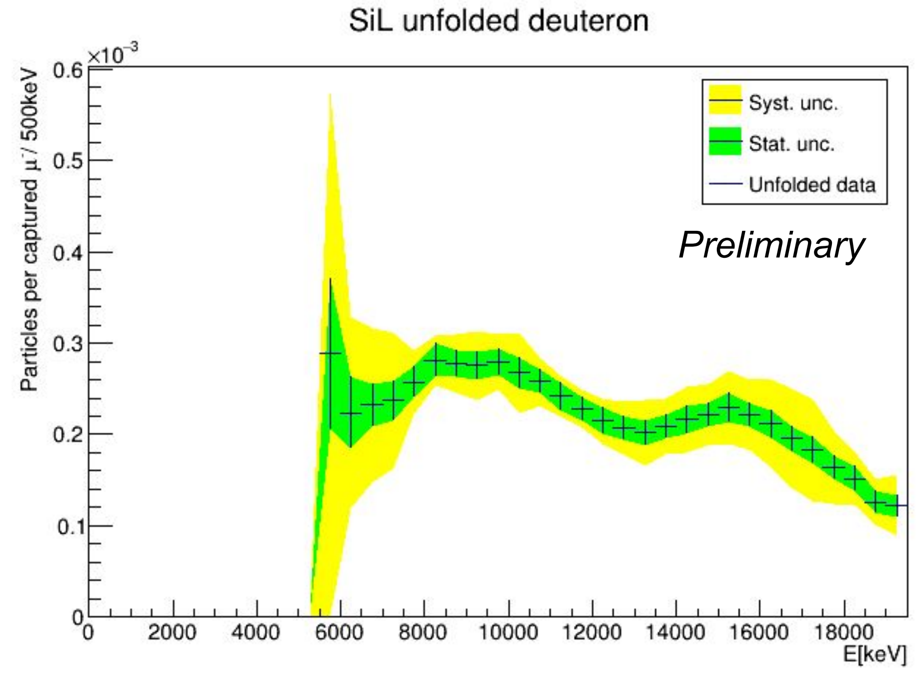
$$\text{Rate} = \frac{\texttt{Number of emitted charged particles}}{0.56 \times 0.609 \times \texttt{Number of stopped muons}}$$

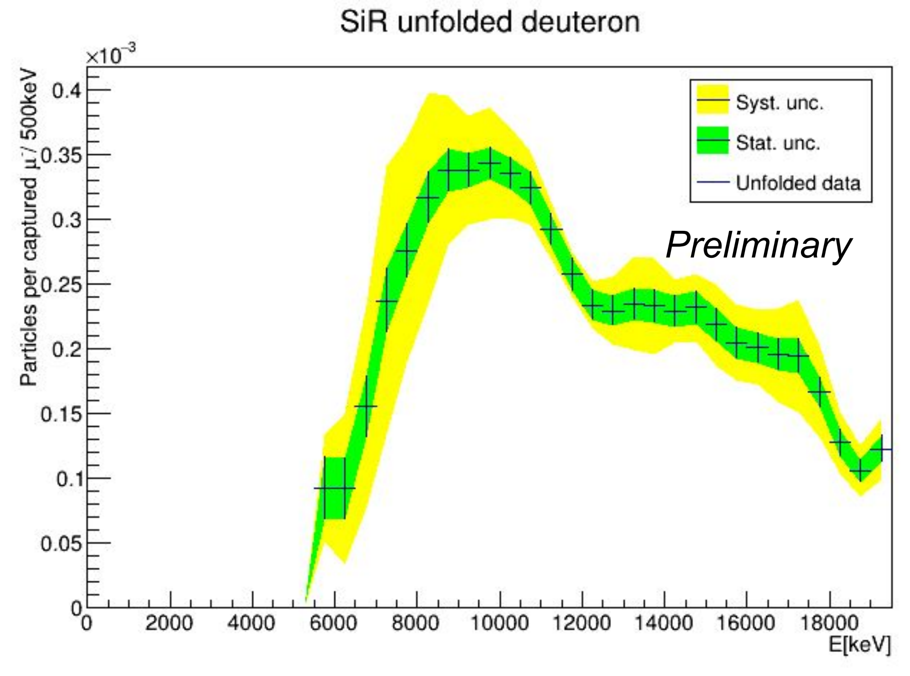
μAl lifetime 500ns cut corr., 0.56. Al μ capture rate, 0.609 [Phys. Rev. C, 35, 1986].





Preliminary results



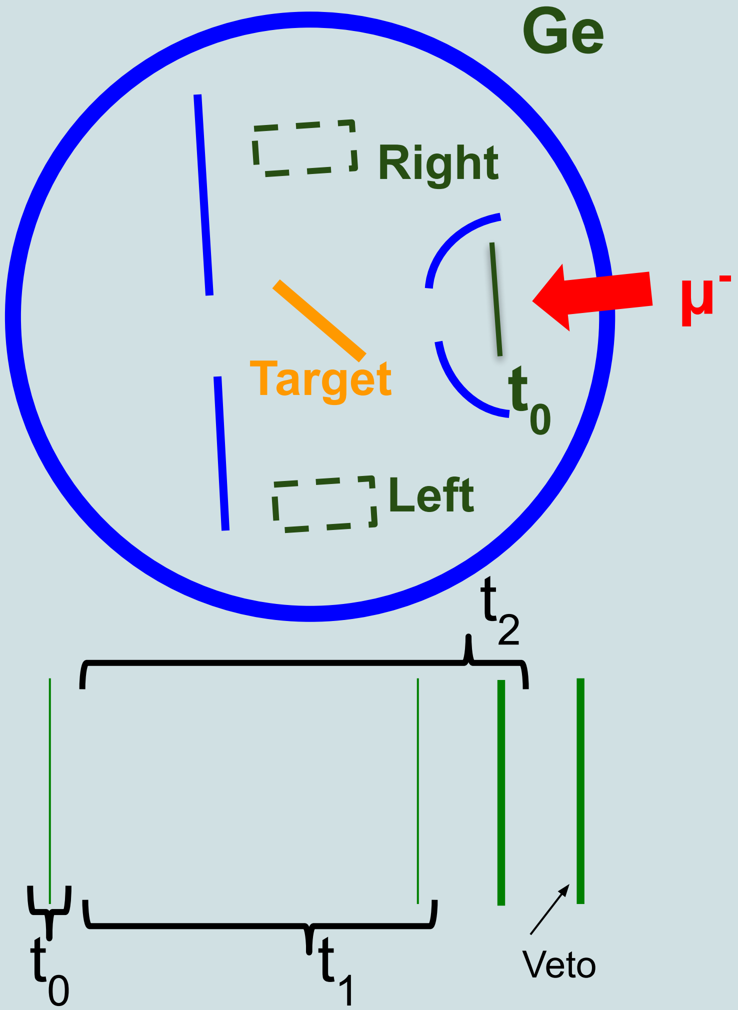


Systematics

Systematics

- μAl lifetime, t_2
- Coincidence time, $dt = t_2 - t_1$
- Effect of pileup protection
- PID efficiency and contamination
- Veto efficiency (in-progress)
- Muon beam simulation and unfolding (in-progress)

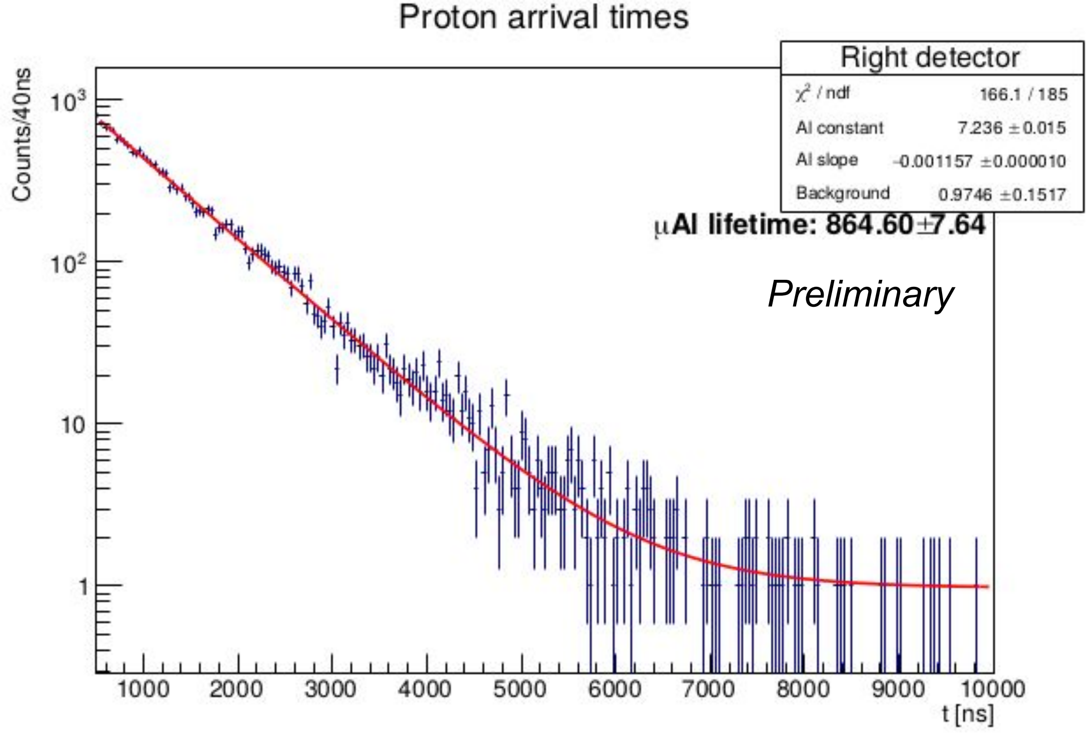
The effects of different cut widths are evaluated in 500 keV bins up to 20 MeV.



* Unfortunately, the left detector did not have a working veto

µAl lifetime

Cut [ns]	Correction factor
300	**0.71**
400	0.63
500	**0.56**
600	0.50



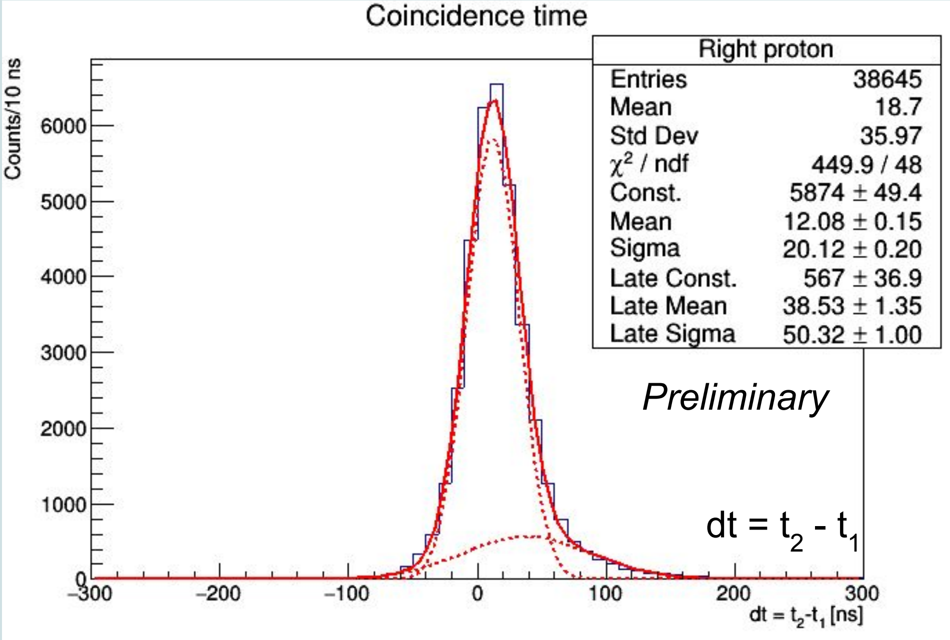
- We expected negligible contamination from µPb *(τ=75ns) protons after 500ns.
- Error is from comparison between 300ns and 500ns cut after correction.
- Lifetime reproduced and agrees with previous literature of *864(2) ns.

* T. Suzuki et al., Phys. Rev. C 35 (1987) 2212.

Si-detector coincidence time

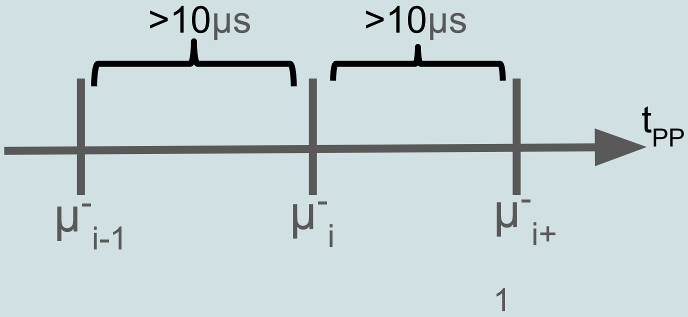
- The late time tail is due to protons with different E arriving with different ***dt*** spread.
- Separately fit the ***dt***s constructed from 1 MeV bins with a Gaussian.

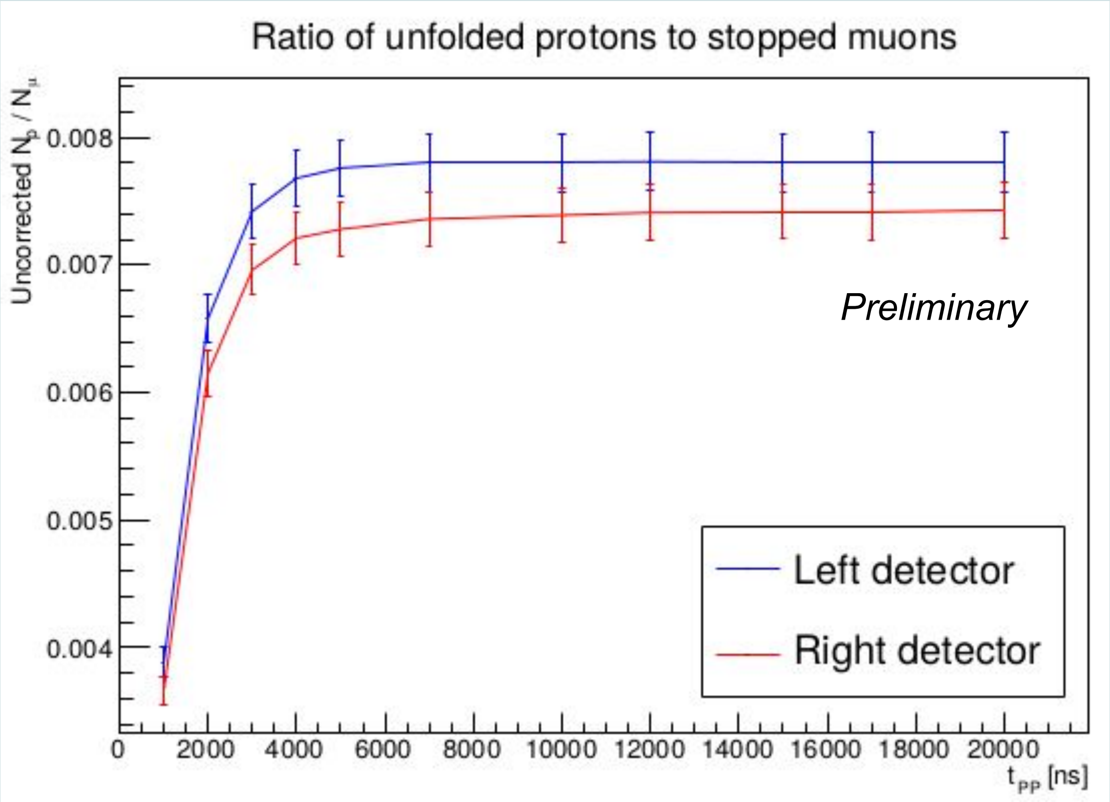
Cut	**Correction factor**
1σ	**0.682**
2σ	0.954
3σ	**0.996**
4σ	0.999



Effect of pile-up protection

Larger t_{PP} reduces statistics but keeps ratio stable.





What’s next?

No longer taking any data.

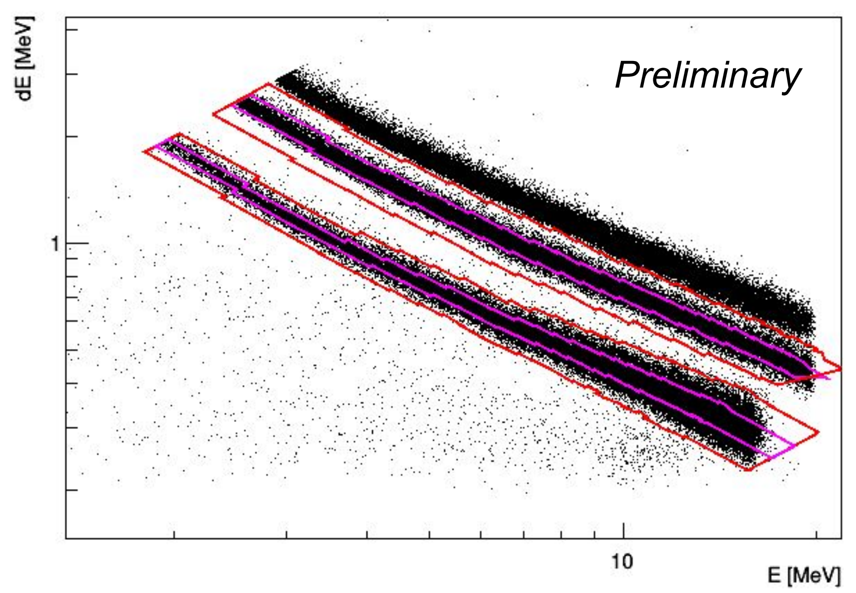
Finalize absolute rates and their uncertainities. Maybe @ PSI2019 this Oct.

- Al 50 μm Monte Carlo simulation
- Al 100 μm for consistency
- Ti 50 μm as an alternative muon target (Future experiments)
- Neutrons and gammas

Backup

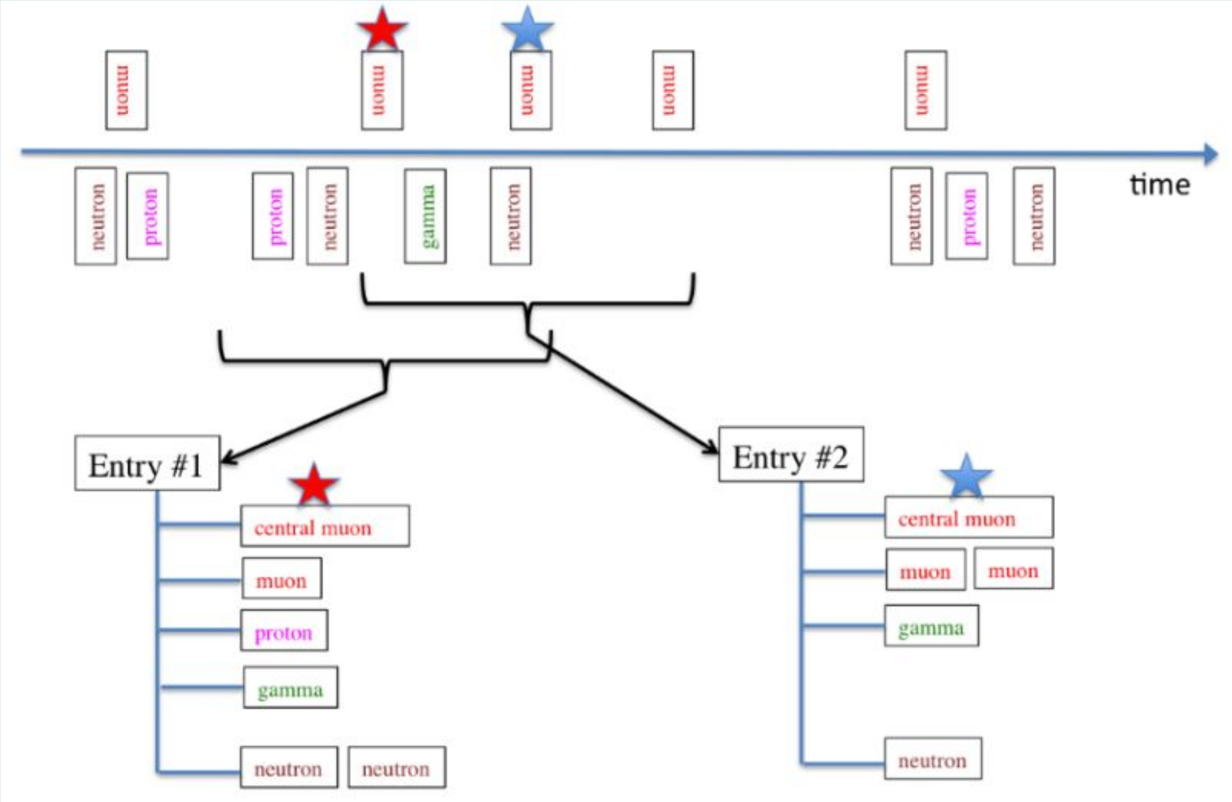
PID efficiency and contamination

- Estimated by applying the same PID algorithm on MC generated charged particles.
- Simple gaussian smearing with detector resolution spread are also added.
- From the efficiency matrix, PID for charged particles are ~99%.

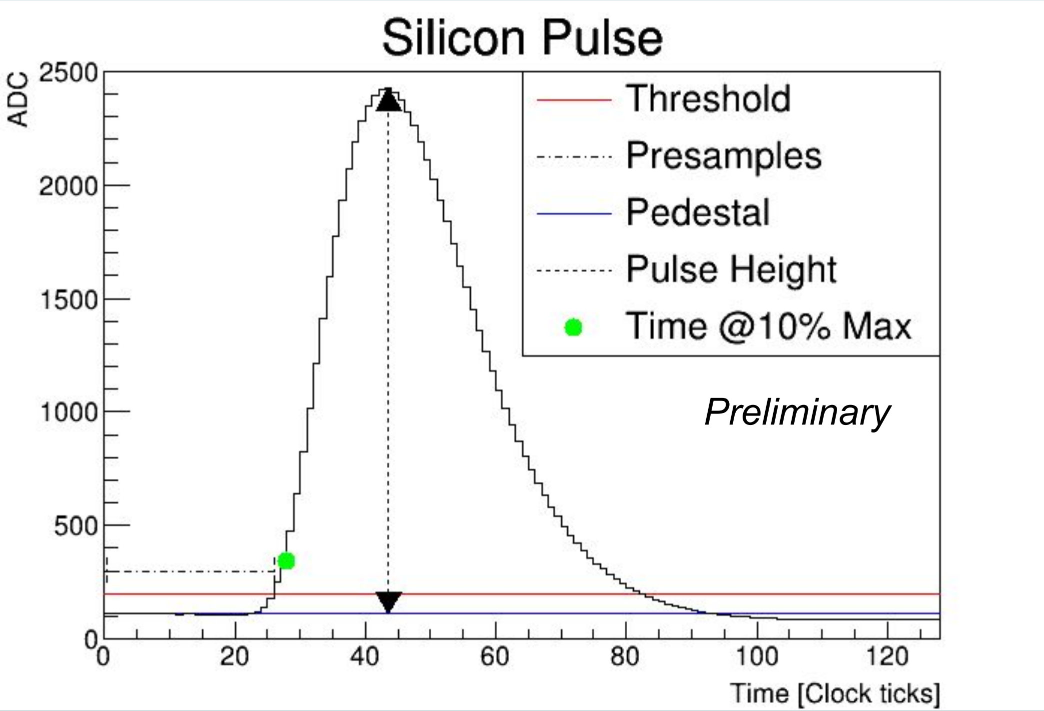


$$\begin{bmatrix} p_{\mathrm{meas}} \\ d_{\mathrm{meas}} \\ t_{\mathrm{meas}} \end{bmatrix} = \begin{bmatrix} \epsilon_{pp} & \epsilon_{pd} & \epsilon_{pt} \\ \epsilon_{dp} & \epsilon_{dd} & \epsilon_{dt} \\ \epsilon_{tp} & \epsilon_{td} & \epsilon_{tt} \end{bmatrix} \begin{bmatrix} p_{\mathrm{true}} \\ d_{\mathrm{true}} \\ t_{\mathrm{true}} \end{bmatrix} \qquad \epsilon_{3\sigma} = \begin{bmatrix} 0.9876 & 0.0001565 & 0.0002317 \\ 0.001582 & 0.9926 & 0.01685 \\ 0.0009489 & 0.04443 & 0.9834 \end{bmatrix}$$

Muon centred tree structure



Typical pulse structure



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

μAl lifetime (from Deuterons)

Still agrees with the published lifetime data although not as well as protons.