Update on The HERA System for Radiation Monitoring on Orion Exploration Missions and the International Space Station

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On behalf of the HERA team at NASA/UH/Wyle

HERA EM-2 Team

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UH/SRAG - T. Campbell-Ricketts, D. Turacek, L. Pinsky

Also a very large number of people who contributed to the EM1 work (notably A. Bahadori, now at KSU and A. Empl)

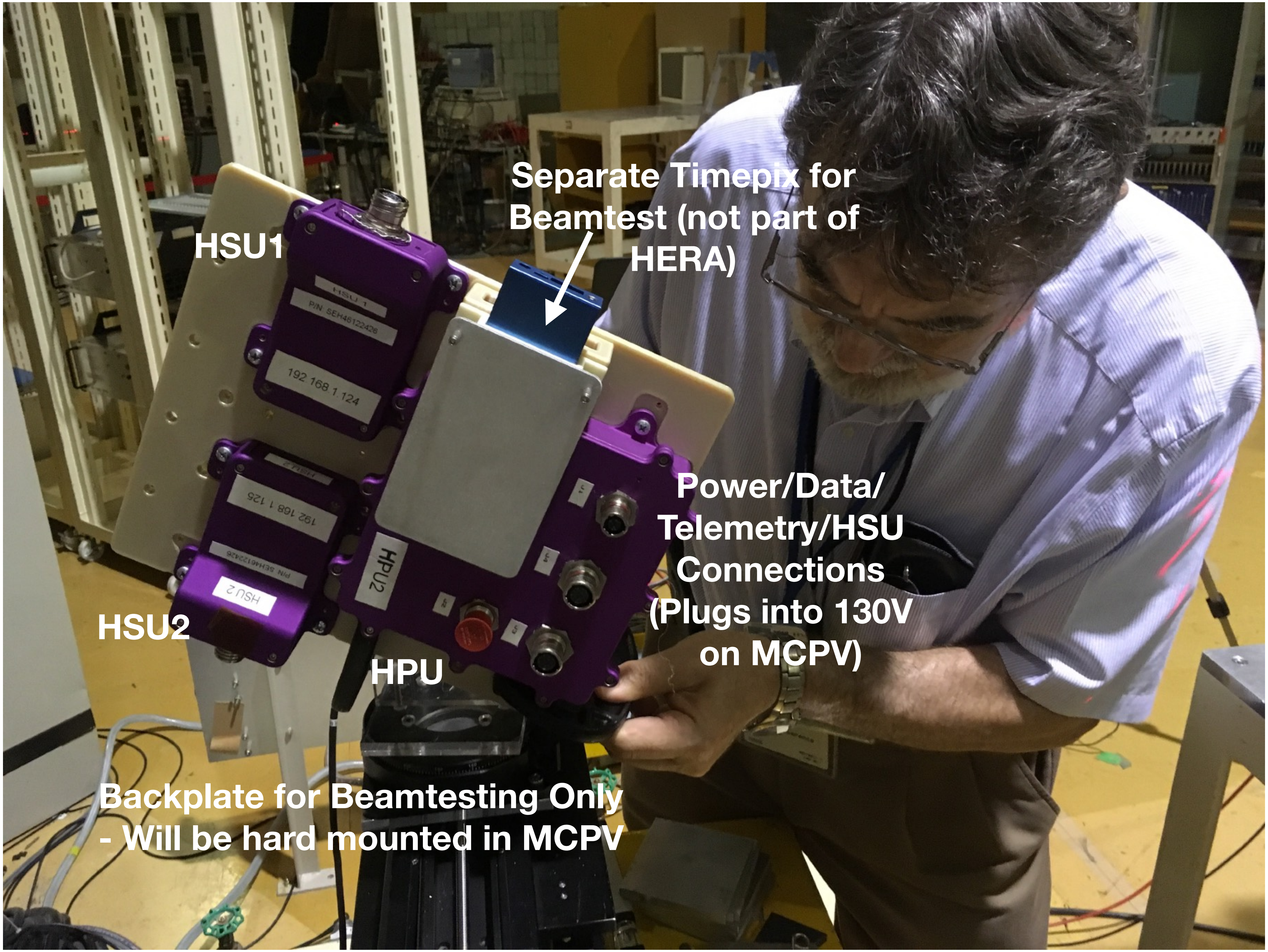
And of course thanks are due to the support of staff at Advacam, NSRL, BNL Tandem, Chicago Proton Center and HIMAC

(Apologies to anyone I left off here!)

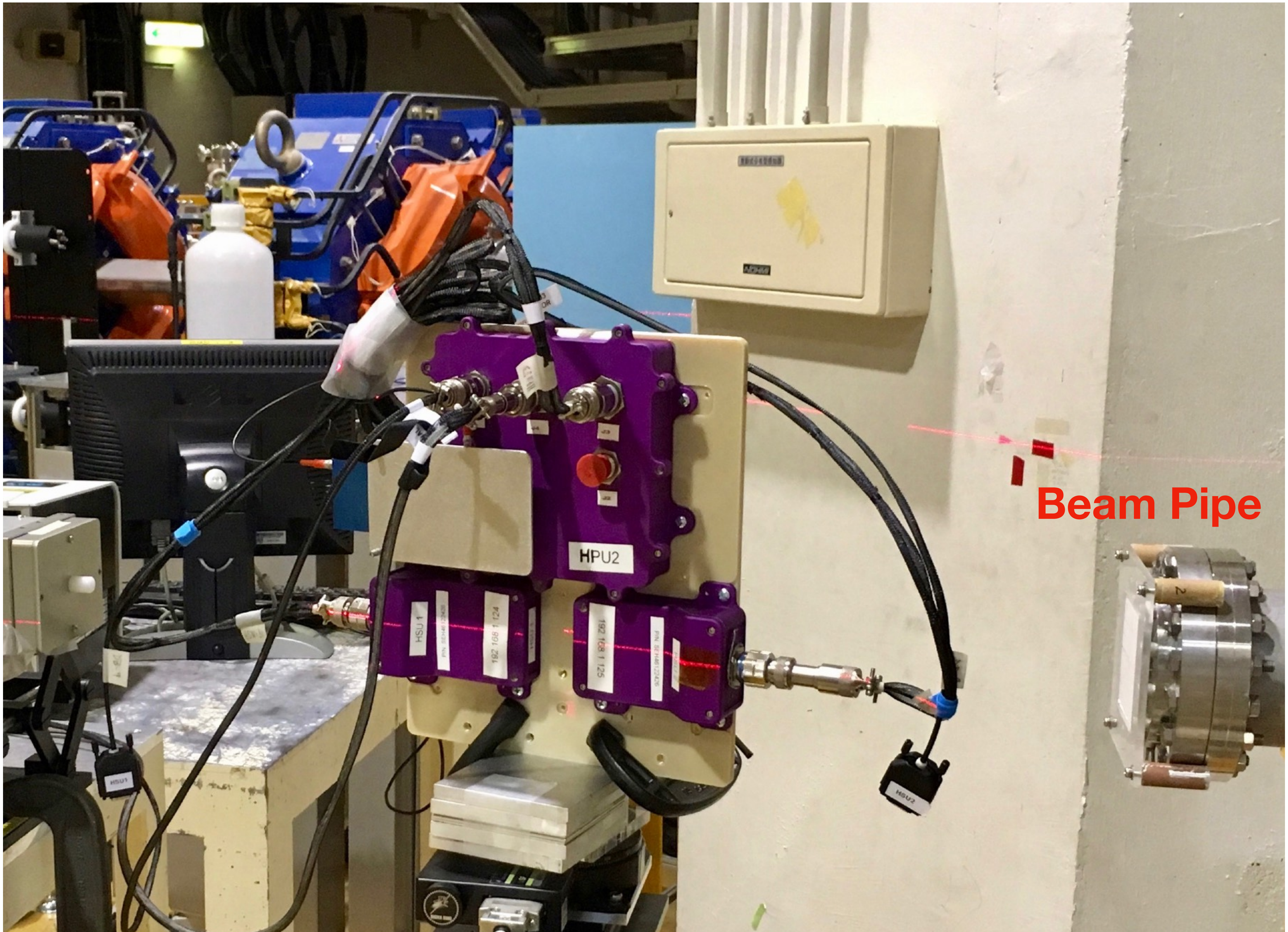
HERA Overview

- HERA (Hybrid Electronic Radiation Assessor) is a radiation detection system for the Orion MCPV
- Primary duties are monitoring crew vehicle radiation levels and caution and warning
- HERA consists of a central Hera Processing Unit (HPU) attached to 2 separate Hera Sensor Units (HSU)
- Both HSU’s + the HPU contain a Timepix hybrid pixel detector
- All data processing done on board, no raw data sent to ground

HERA at HIMAC



HERA at HIMAC

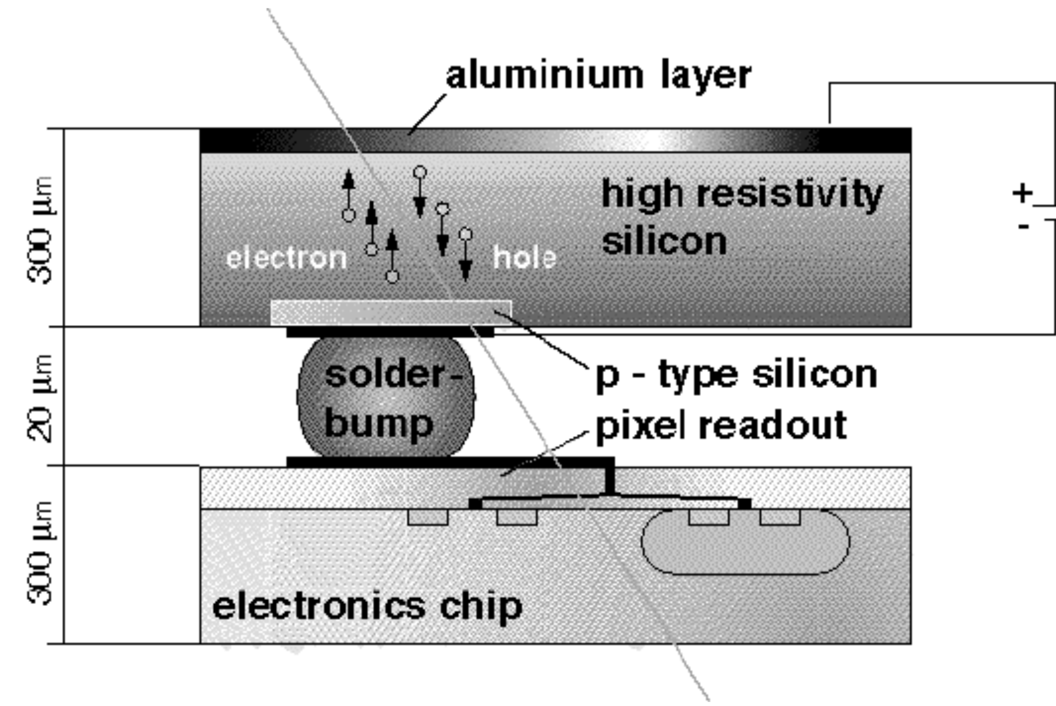


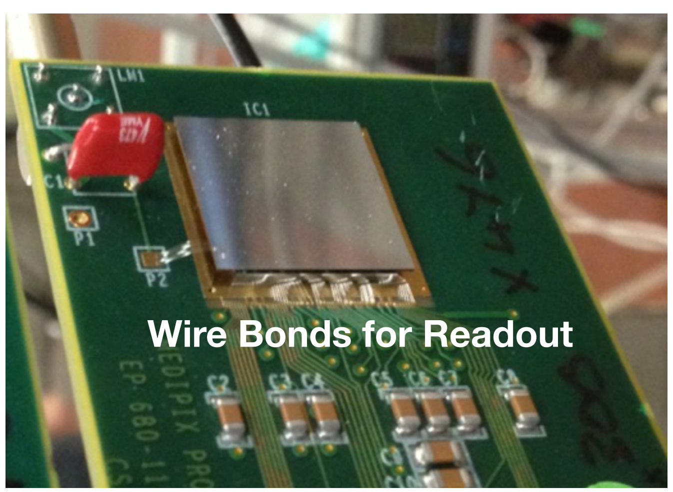
HERA Systems

- HERA Orion EM-1, installed in MCPV Capsule
- HERA ISS, EM-1 spare unit, flying on ISS late 2018
- HERA EM-2 (+), engineering units delivered, software + hardware V&V in progress, qual unit coming later this year, 6 flight systems in 2019
- Deep Space Gateway - currently in design phase
- This talk largely focuses on the software upgrades to HERA from EM-1 to EM-2, hardware largely unchanged

Hybrid Pixel Detectors and Cluster Analysis

- Key feature of Hybrid Pixel Detector for our application -> continuous Silicon Volume (1.4 x 1.4 cm) 500um thick
- Volume segmented into 256 x 256 energy measuring pixels
- (We currently use Timepix developed by Medipix2 collaboration at CERN)
- Enables **imaging of track structure**
- **Techniques shown in this talk applicable to any energy measuring hybrid pixel detector**

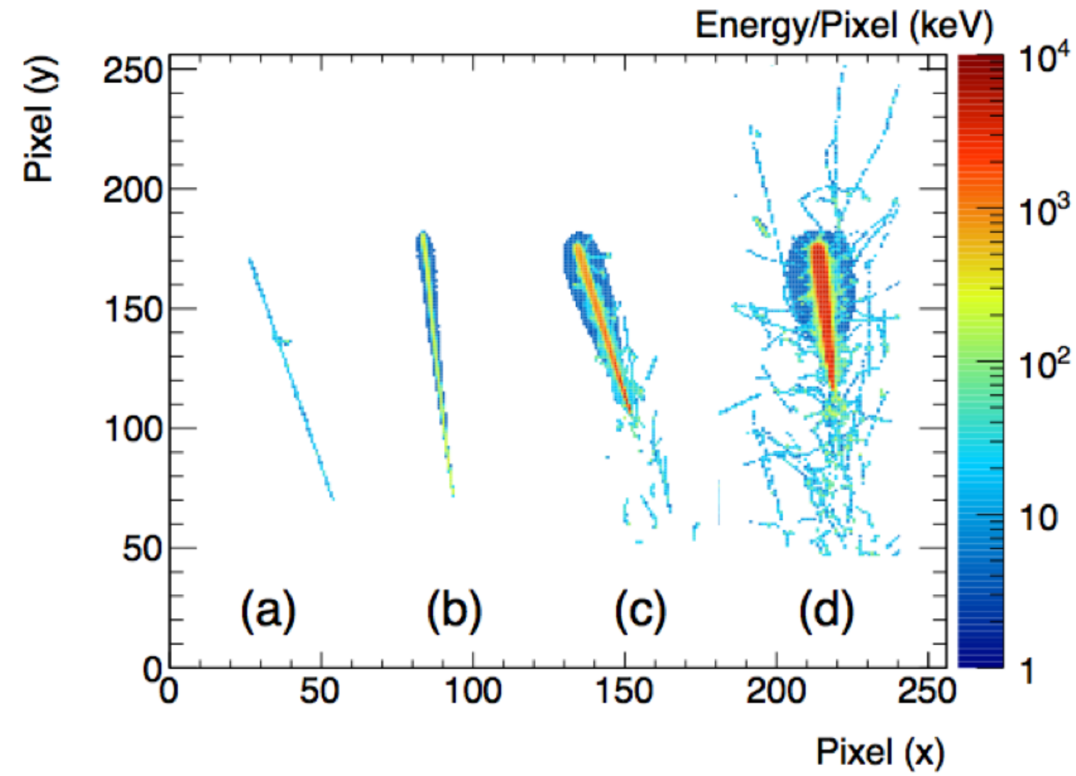




Timepix on Probe Board

Stopping power and Geometry

- Stopping power = dE/dX.
- Lots of work done dE -> advanced calibration, saturation (volcano) correction, < 2 MeV/px good, ~8 MeV/okay
- dX - good as well, need to account for cluster shape + sensor thickness assumption



(a)	$\text{LET}_{\text{Si}} = 0.52\,\text{keV}\,\mu\text{m}^{-1}$	Alt. $= 71.0°$	Az. $= 84.6°$
(b)	$\text{LET}_{\text{Si}} = 5.45\,\text{keV}\,\mu\text{m}^{-1}$	Alt. $= 82.0°$	Az. $= 84.0°$
(c)	$\text{LET}_{\text{Si}} = 54.8\,\text{keV}\,\mu\text{m}^{-1}$	Alt. $= 66.7°$	Az. $= 81.4°$
(d)	$\text{LET}_{\text{Si}} = 233\,\text{keV}\,\mu\text{m}^{-1}$	Alt. $= 84.2°$	Az. $= 81.1°$

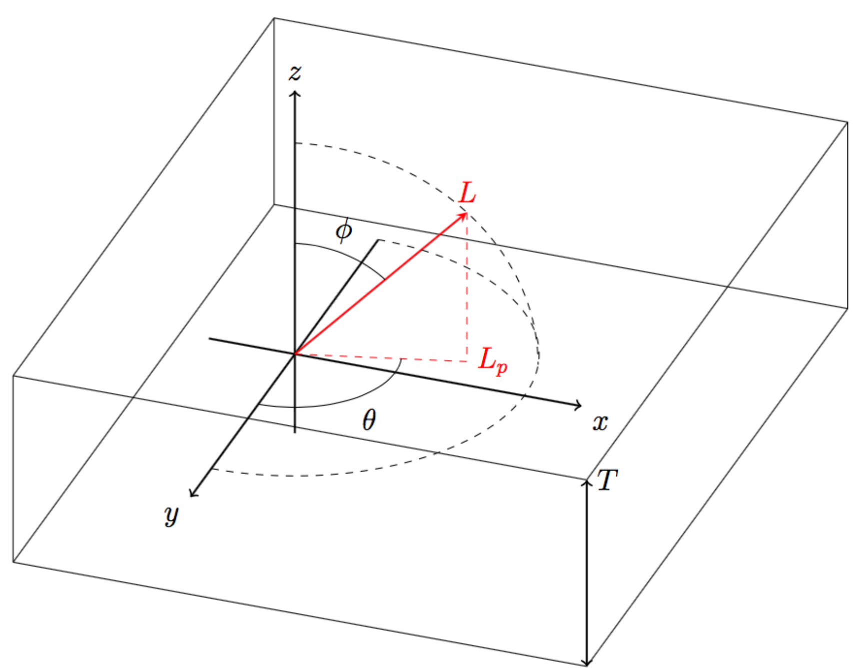
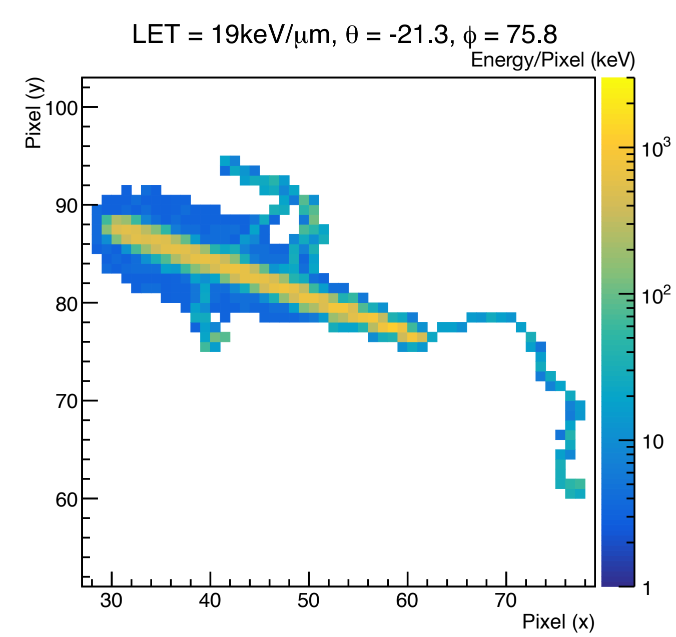
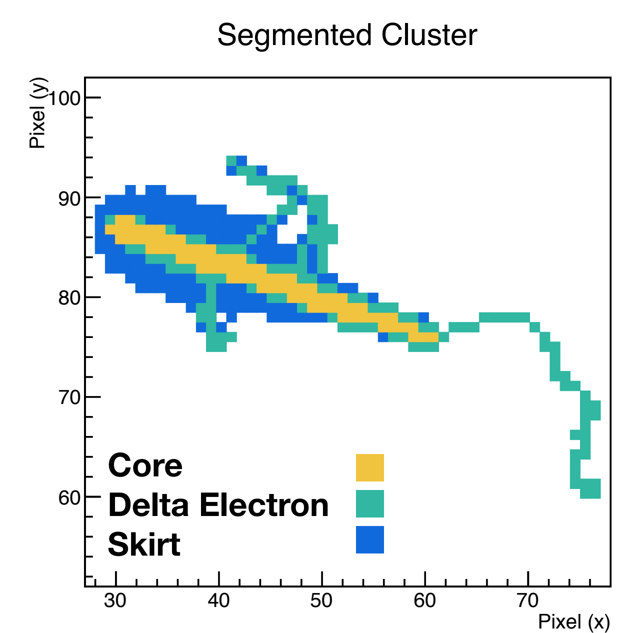
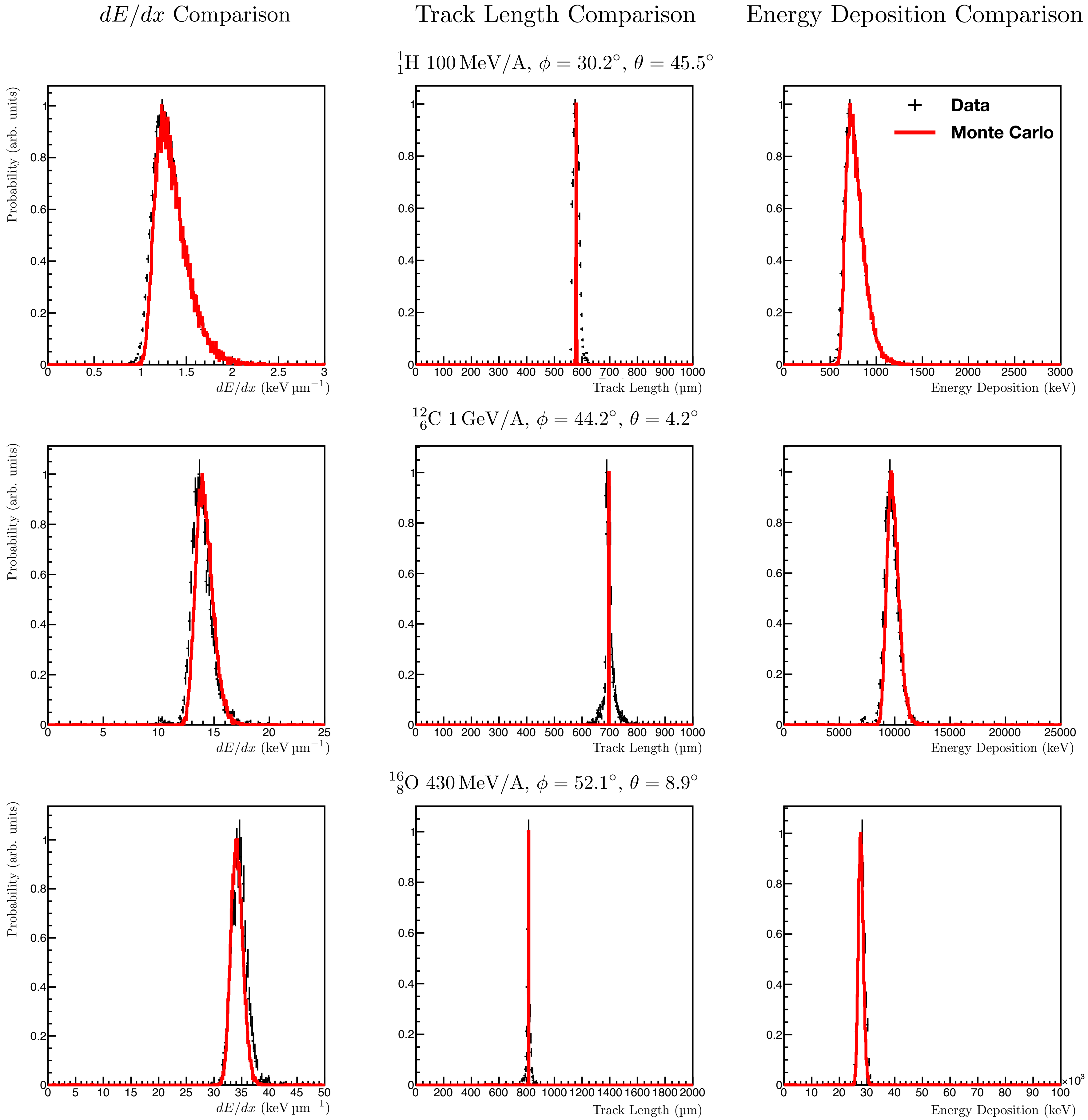


Figure 3.6: Measurement of the azimuth angle θ and altitude ϕ relative to the sensor axes from a penetrating track of length L over a sensor of thickness T.

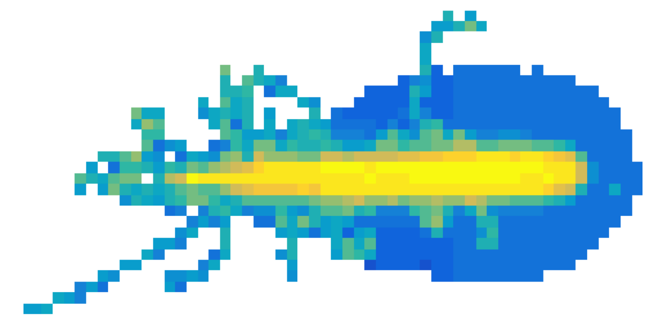






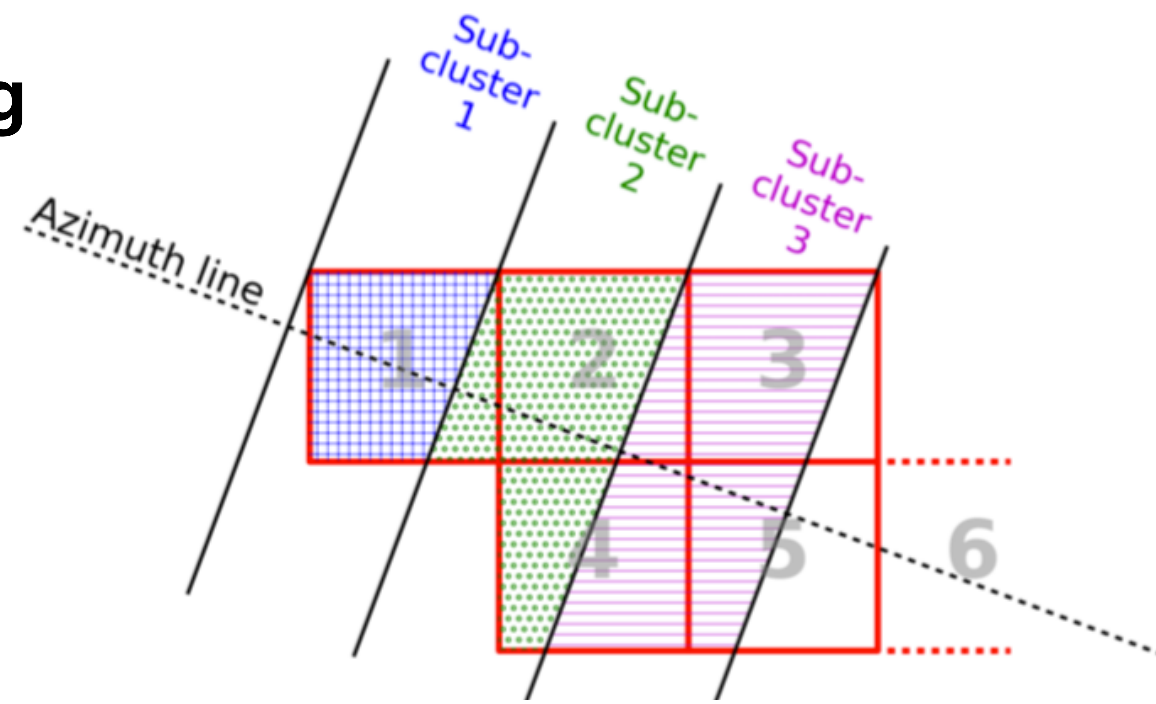
Stopping power measurement performance compared to an 'ideal' Monte Carlo simulation of stopping power in a Timepix sensor like Si block

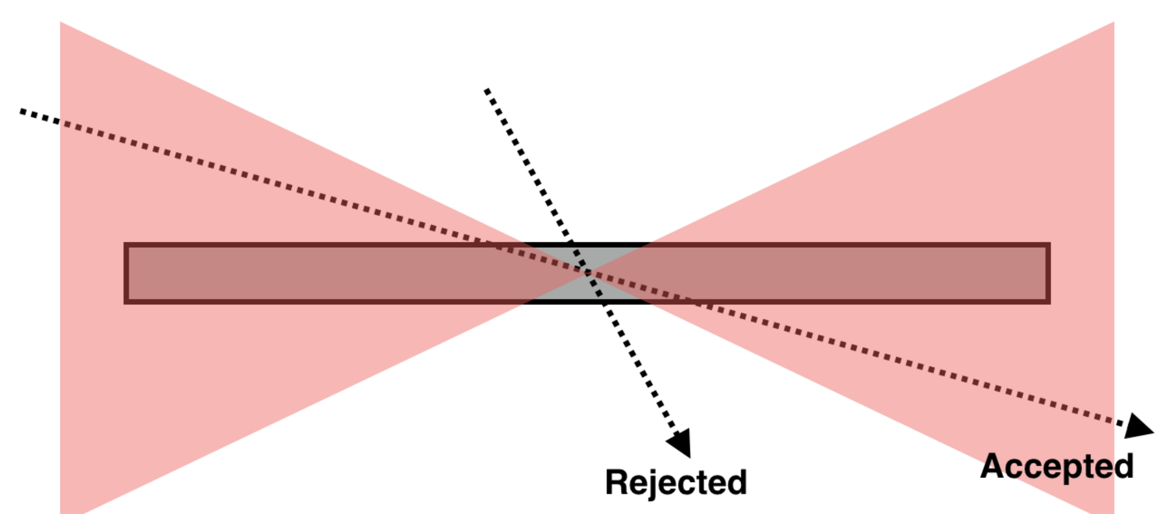
Single Layer Telescope Concept



Argon, 650 MeV/A @ 75 degrees

- Space radiation is mostly isotropic and long tracks are **much more interesting**
- Every time a track passes through an additional pixel we are measuring the particle properties again - just like a particle telescope.
- A 75 degree track passes through 2mm of silicon in a 500 um sensor - 34 subclusters
- Acceptance region is the inverse of a conventional telescope





Maximum Likelihood Energy Reconstruction

- Treat each sub cluster as an independent measurement of cluster stopping power.

- Select as truth the hypothesis that most agrees with the ensemble of measurements

$$P(E_j \mid \Delta E_1, \ldots, \Delta E_n, \Delta x) \propto \prod_{i=2}^{n-1} P(E_j) \times P(\Delta E_i \mid E_j, \Delta x)$$

- i.e. for each tested energy hypothesis, get the probability of each subcluster, the total probability of the measurement is found by multiplying the individual probabilities

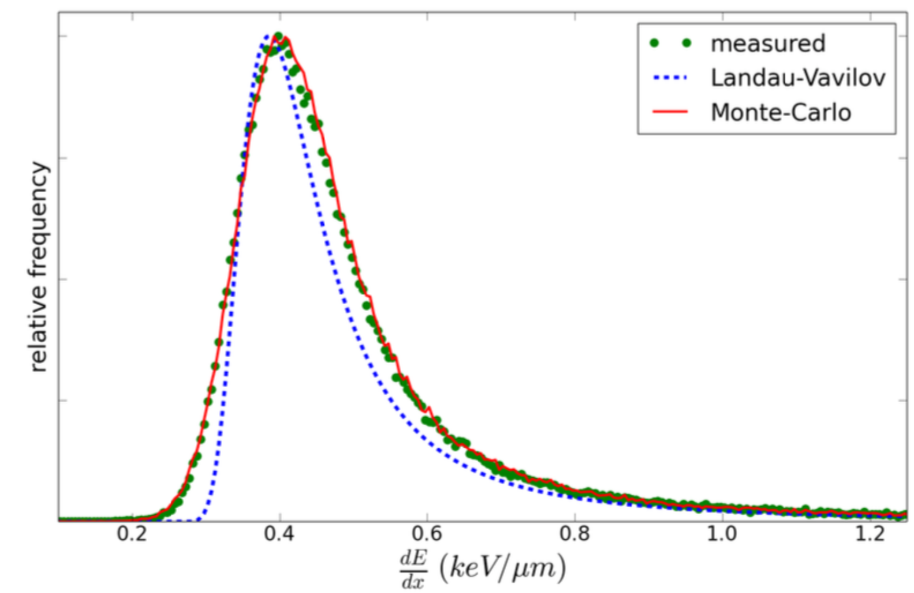
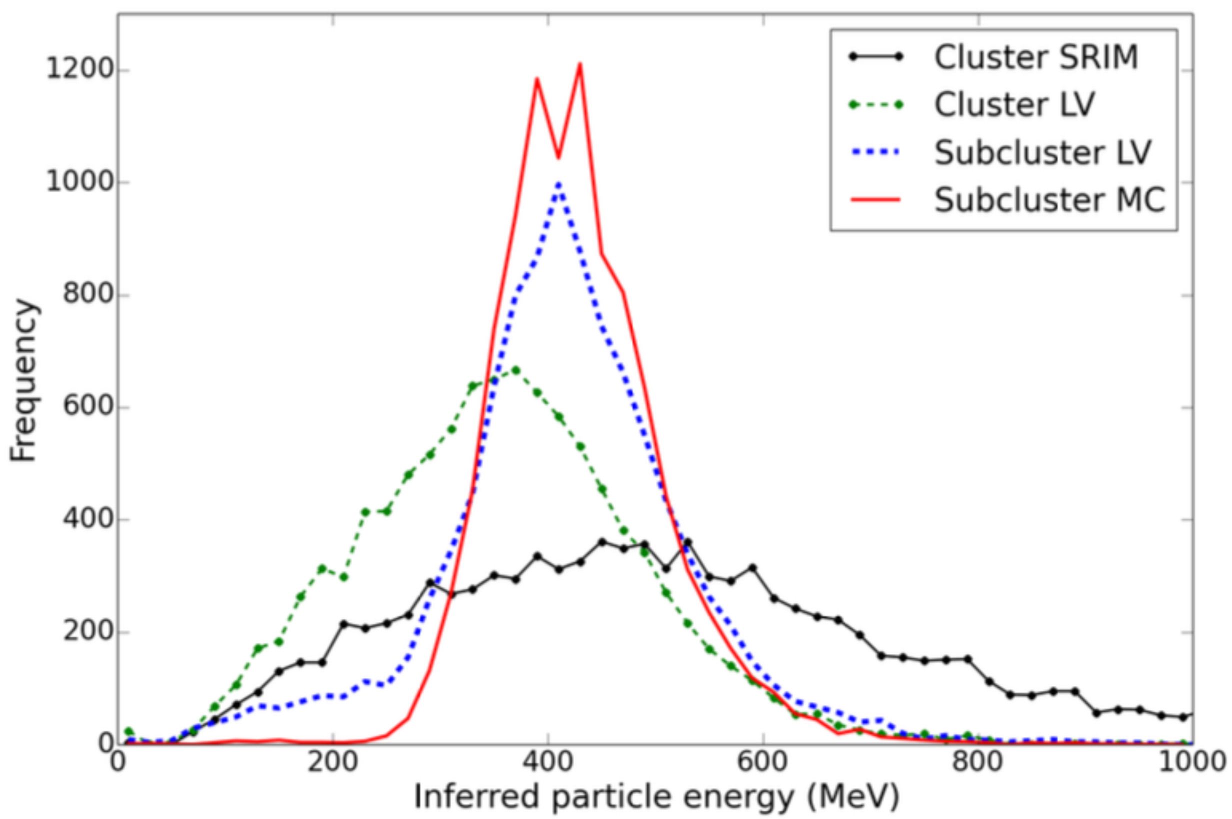


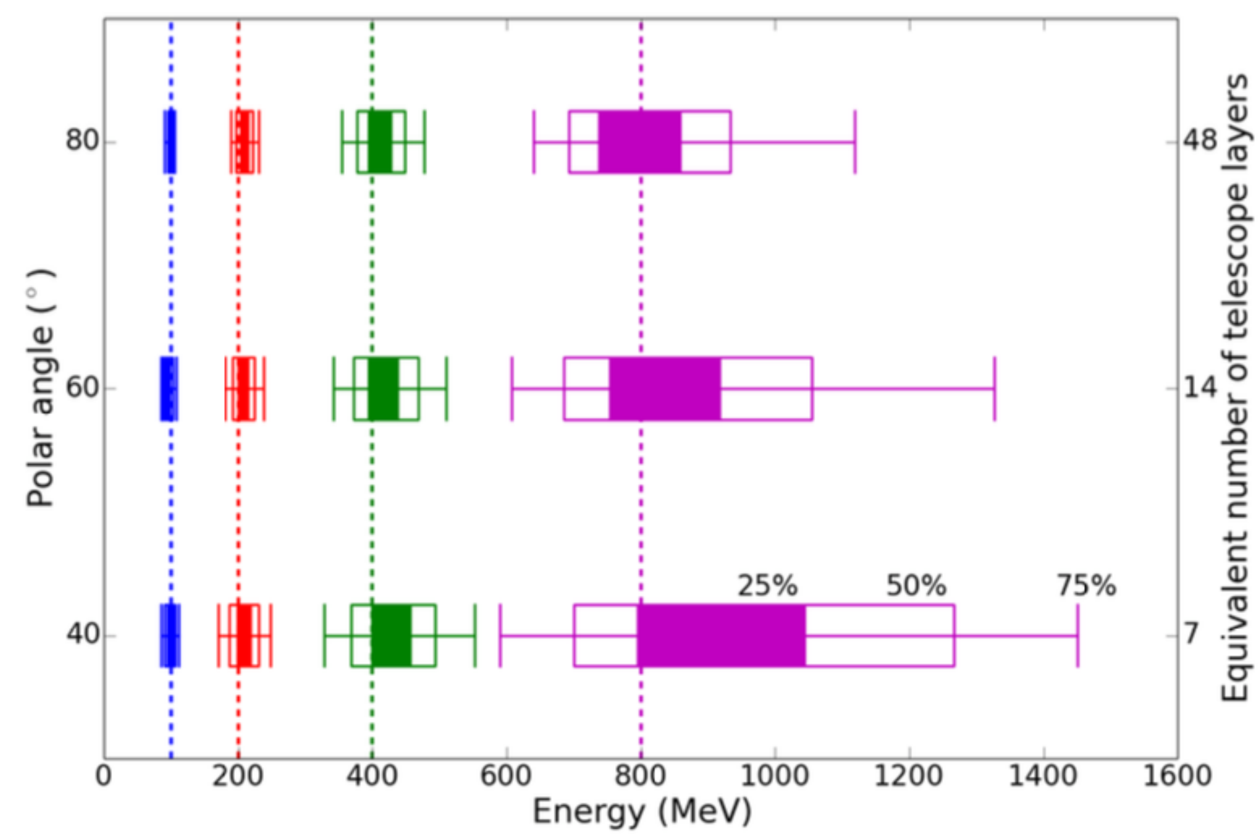
FIG. 2: Measured and modeled dE/dx spectrum of 400 MeV protons.

M. Kroupa et al, Featured Article, App. Phys. Lett, 112, 134103 (2018)

Maximum Likelihood Energy Reconstruction



Comparison of Different Methods of Energy Reconstruction



Confidence intervals reconstructed energy distributions as a function of polar angle for 100, 200, 400 and 800 MeV protons

Shape Testing of Z,E Hypotheses

- For any given LET/polar angle combination there are multiple Z,E candidates (including multiple for same Z, stopping, not stopping etc)
- Stopping power proportional to Z^2 - lower Z candidates have less E for the same stopping power
- Lower Z candidates **can slow down more**
- **Construct theoretical profiles and compare to subcluster measurements, use to eliminate possible candidates**

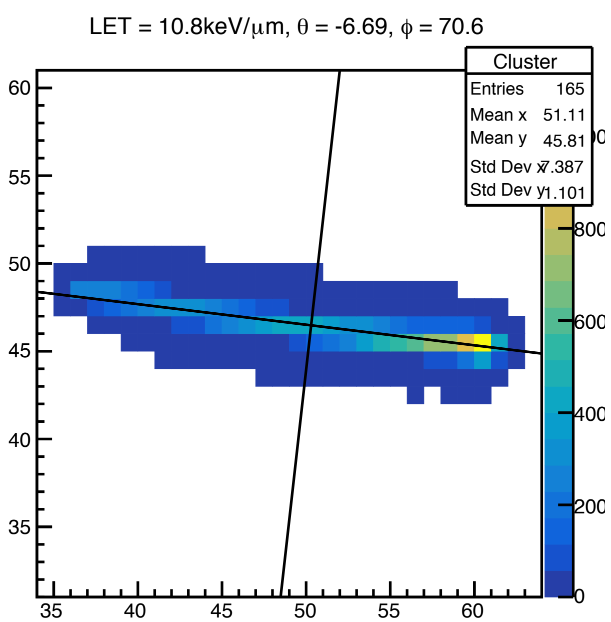
Example Z/E Candidates for 12.5 keV/um @ 75.9º

- Proton, 12.4 MeV
- Stopping proton, 9.4 MeV
- Alpha, 36.4 MeV/A
- Carbon ~ min ionising

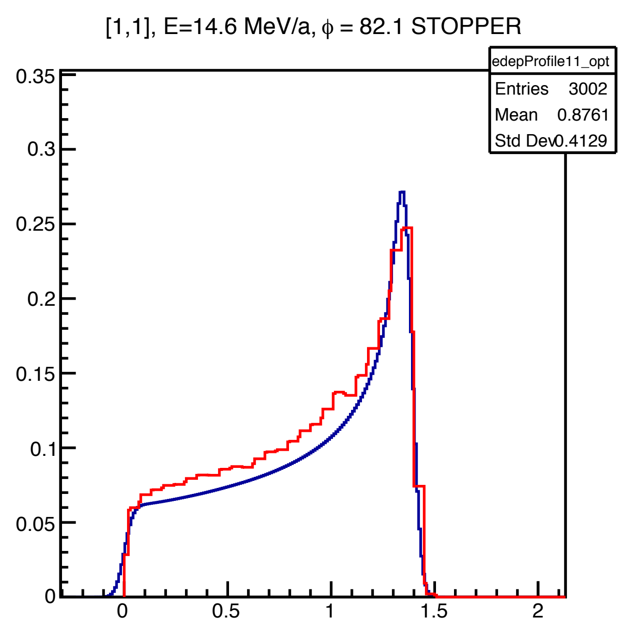
Implementation

- Candidates looked up from precomputed tables of most probable energy given measurement
- Theoretical profiles constructed using Monte Carlo simulation database + cuts to account for particular cluster geometry
- Fast, ~ total database size 500kB per tested species

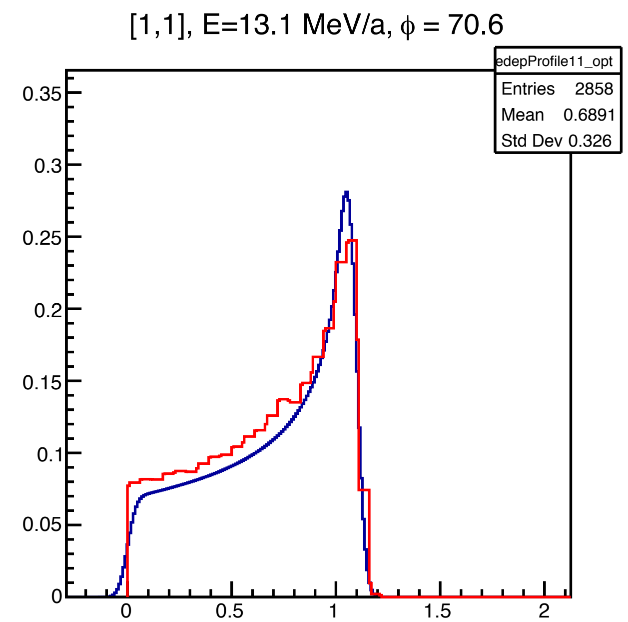
Bragg peak is Unambiguous



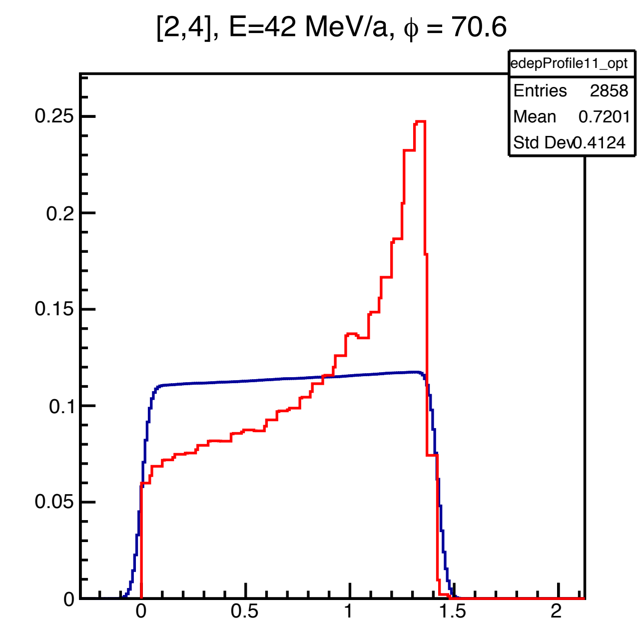
Cluster



Proton (1)



Proton (2)



Alpha

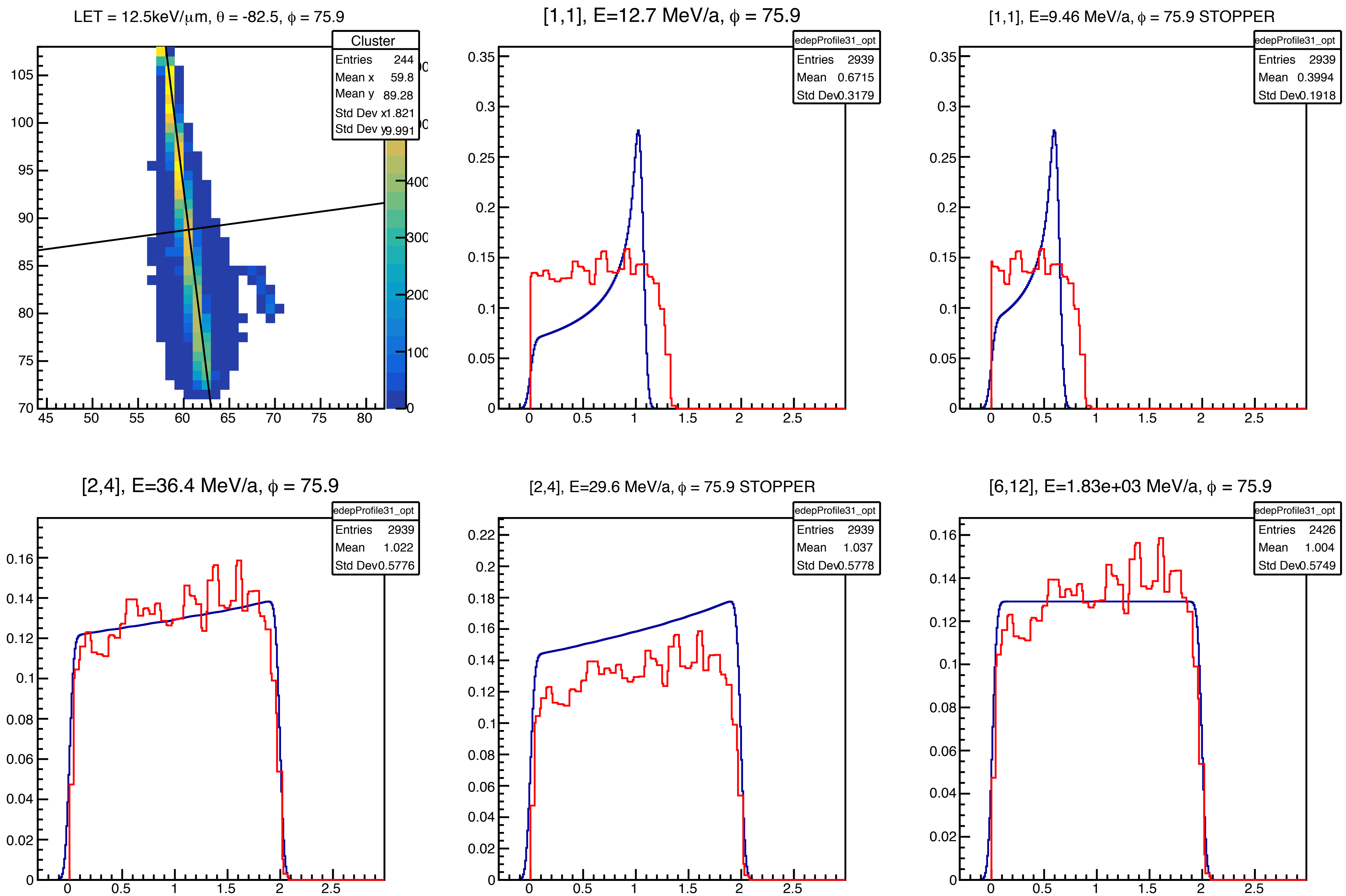
Candidate z = 1, a = 1, energy = 14.6168 MeV/A, angle = 82.1485 deg fit with confidence --> 0.872026, Fit KS = 1.65857

Candidate z = 1, a = 1, energy = 13.0921 MeV/A, angle = 70.568 deg fit with confidence --> 0.774096, Fit KS = 3.19688

Candidate z = 2, a = 4, energy = 42.0369 MeV/A, angle = 70.568 deg fit with confidence --> 0.69175, Fit KS = 2.23267

- Histogram fit can be used to accept/reject low energy hypotheses with high confidence

What about this?



Candidate z = 1, a = 1, energy = 12.7415 MeV/A, angle = 75.8843 deg fit with confidence --> 0.390663, Fit KS = 12.9771
Candidate z = 1, a = 1, energy = 9.45946 MeV/A, angle = 75.8843 deg fit with confidence --> 0.263922, Fit KS = 16.2384
Candidate z = 2, a = 4, energy = 36.4225 MeV/A, angle = 75.8843 deg fit with confidence --> 0.919645, Fit KS = 0.571681
Candidate z = 2, a = 4, energy = 29.5515 MeV/A, angle = 75.8843 deg fit with confidence --> 0.762476, Fit KS = 6.11248
Candidate z = 6, a = 12, energy = 1829.37 MeV/A, angle = 75.8843 deg fit with confidence --> 0.911157, Fit KS = 0.752165

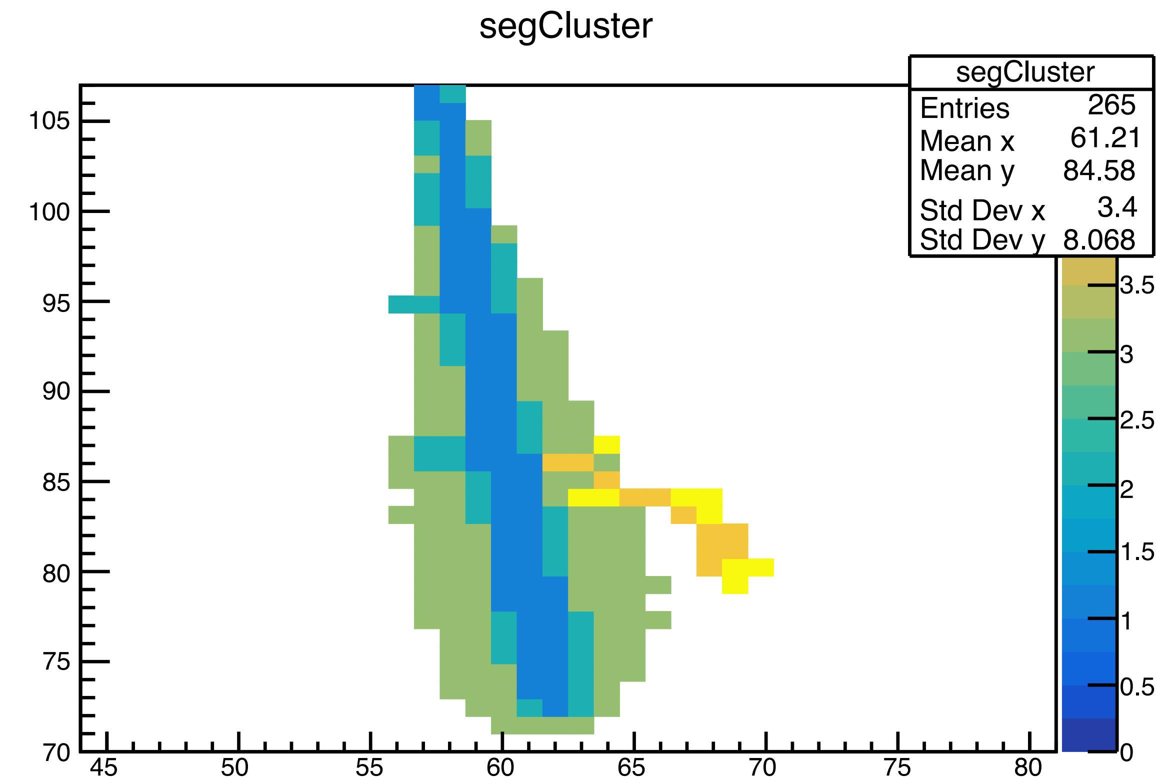
Delta Electron Kinematic Veto

- The longest identified delta electron can be used as a Kinematic veto - exclude hypothesis - previous case is not proton or alpha.

- Cutoff here is 56 MeV/A - eliminates alpha candidate from previous slide.

- Lots of different methods for identifying deltas - we select seed pixels on the cluster periphery and 'grow' the electrons towards the core.

- Far more sensitive is P(delta) given Z,E - direction of future work…



$$\beta > \sqrt{\frac{T}{2m_e + T}}$$

$$E > Am_p(\gamma - 1)$$

$$\frac{E}{A} > m_p\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

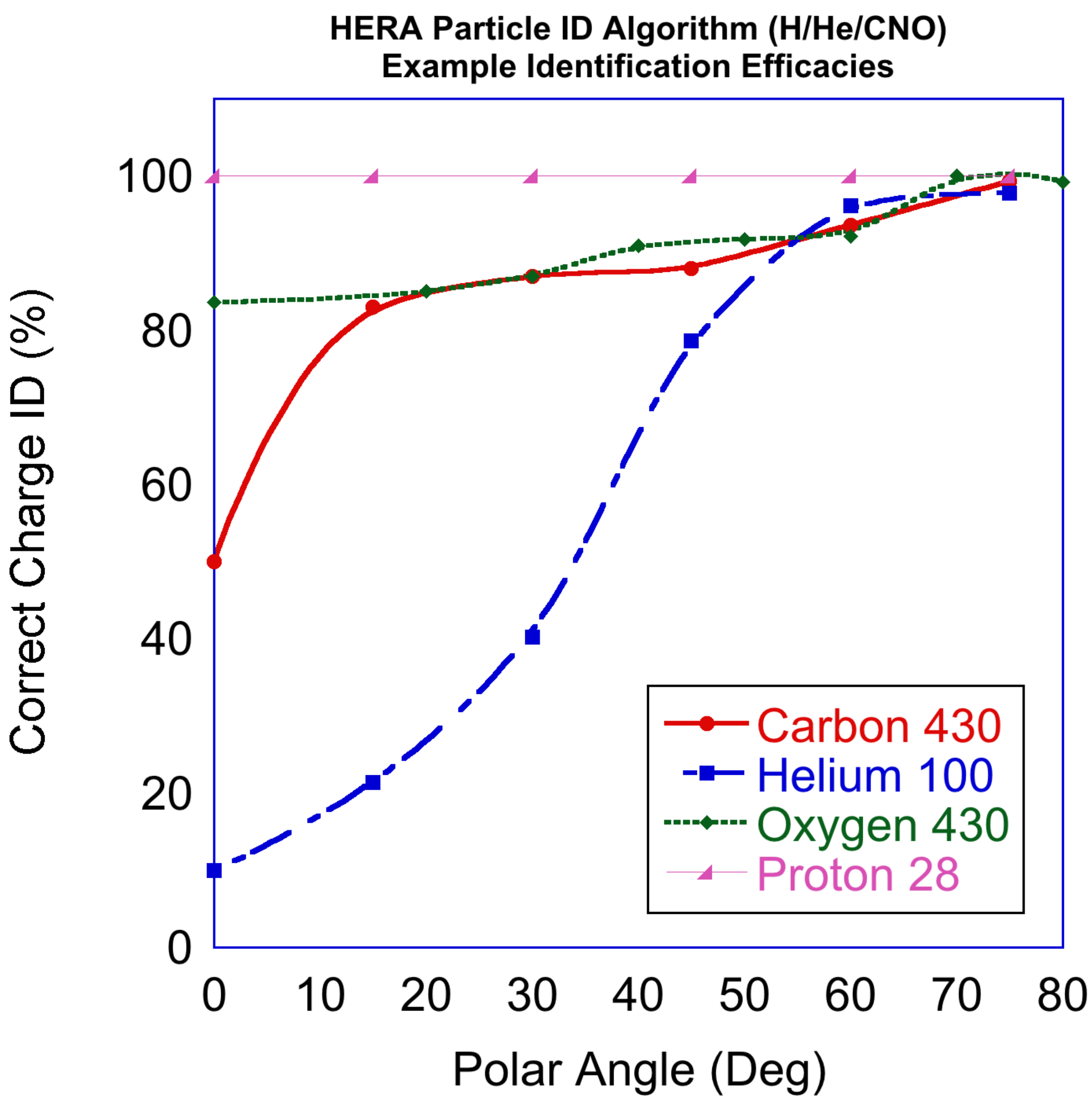
HERA Binning Scheme

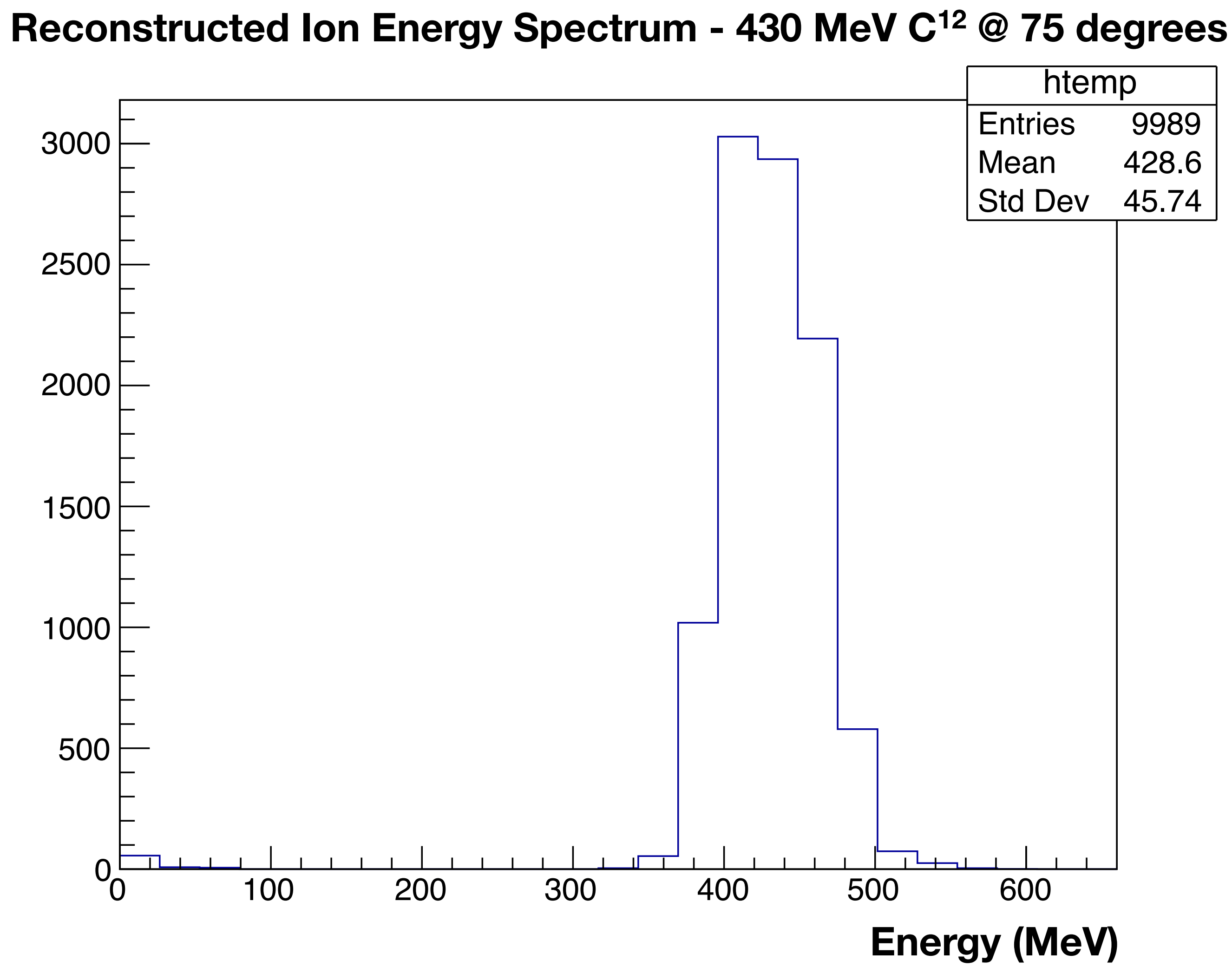
- HERA calculates dose and LET for all incoming particles
- For tracks > 45 degrees (configurable in flight) it also performs a more sophisticated analysis based on the algorithms described above
- 1 set of 21 bins is transmitted back to ground each minute
- Schedule rotates every 5 minutes
- Bin definitions + schedule configurable

Bin	nBins	Energy Range	
Proton	21	5 MeV, 1 GeV+	~Log
Alpha	6	0 - 100 MeV+	Lin
CNO	19	100 MeV/A - 1.5 GeV/A	Log
Neon+	1	Inclusive	
Interaction	1	Inclusive	
Photon	13	5 keV - 50 keV	~Lin
Electron	1	Inclusive	

Binset	Description
1	All Proton Bins
2	Alphas/Photons/Electron/Unbin
3	CNO/Ne+/Interaction
4	LET (Log, 0.1-10 keV/um)
5	LET (Log, 10 - 1000 keV/um)

Example Performance - HERA Implementation





Future Work

- HERA for MCPV will be complete or close to it by the next WRMISS
- HERA for Deep Space Gateway still in development
- Possible directions include neutron sensitivity, integration with other (non Timepix) detectors, multilayer devices, further algorithm improvements, Timepix 2….
- Stay tuned for WRMISS 2019!

Any Questions?

"Radiation, unlike smoking, drinking, and overeating, gives no pleasure, so the possible victims object"

–Issac Asimov

Backup Slide - Complete HERA Algorithm