Prospects for the measurement of TeV cosmic ray Iron nuclei using Large-Sized Telescope of CTAO

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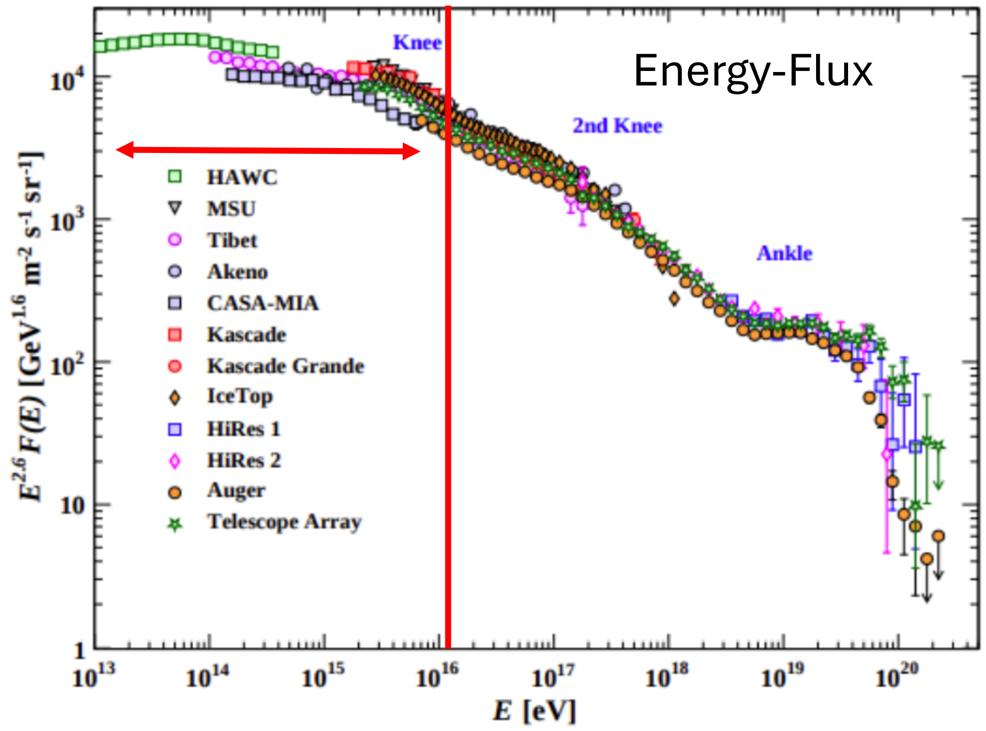
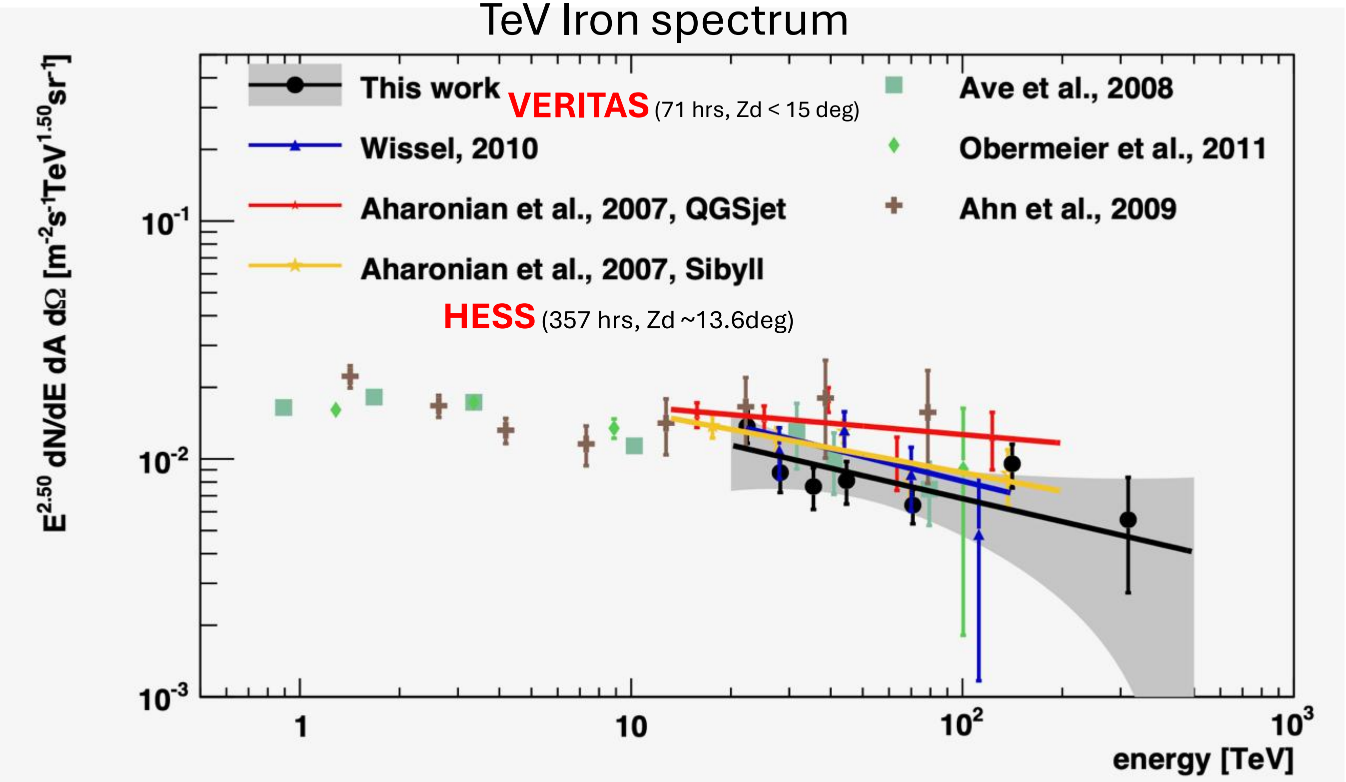
TeVPA2026 (Tendo) Sep 2, 2026

Origin of galactic Cosmic ray



Credit: R.L. Workman et al.(2022)



Credit: Archer, A et al.(2018)

The origin below Knee is considered to be supernova remnant within the galaxy.

Proton, helium, and iron are the most abundant in that order in the TeV energy band.

Currently, protons and helium are measured with high precision through balloon experiments, but this is not the case for iron.

➡High precision measurements with the array of CTAO-LST

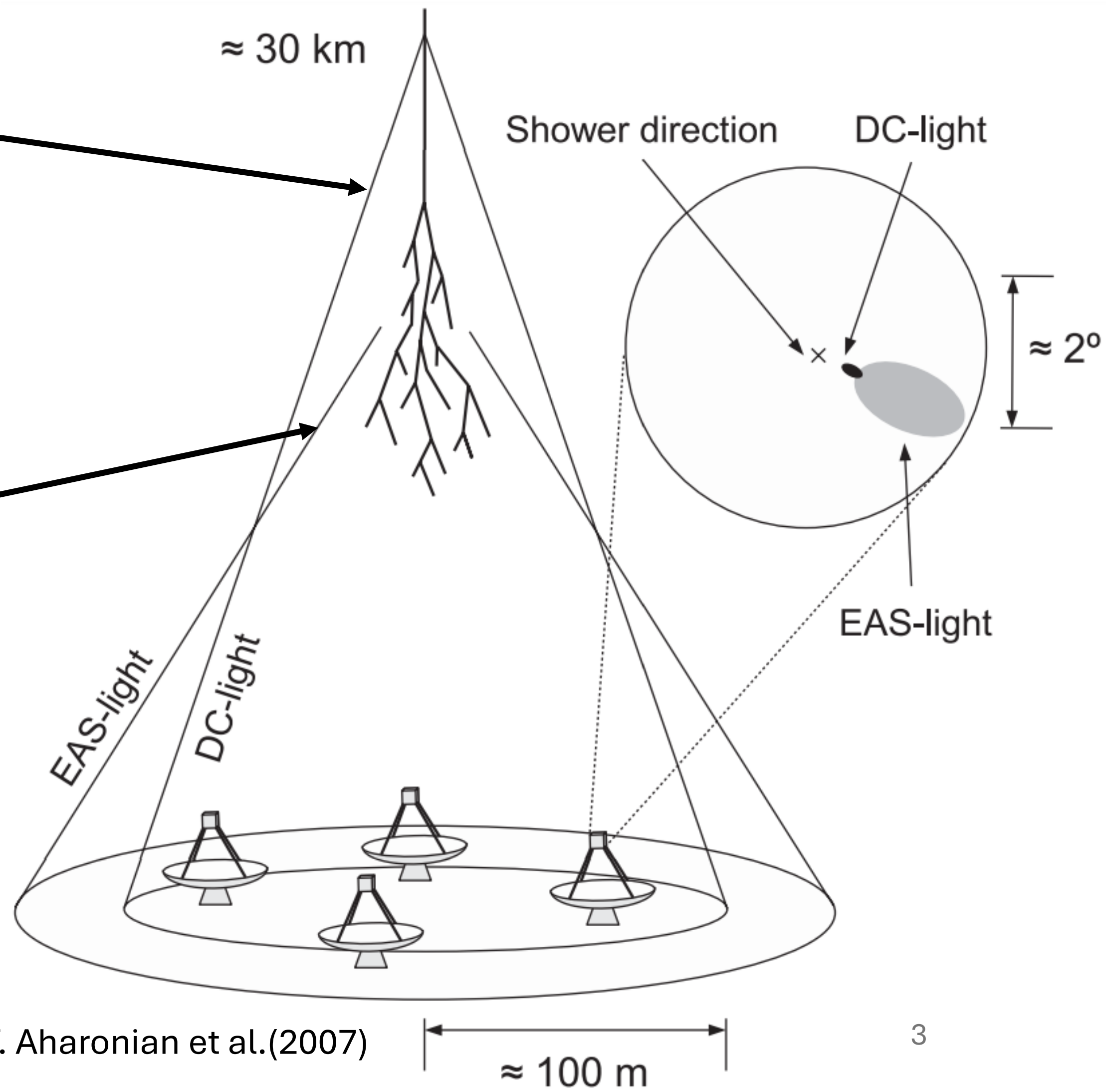
Direct Cherenkov light

primary particle・・Direct Cherenkov light
（charge $\propto Z^2$）

DC light is more prominent
for iron than for protons, etc.

Secondary particle・・Extensive Air Shower（EAS）

Credit: S. Nozaki



Credit: F. Aharonian et al.(2007)

Objective

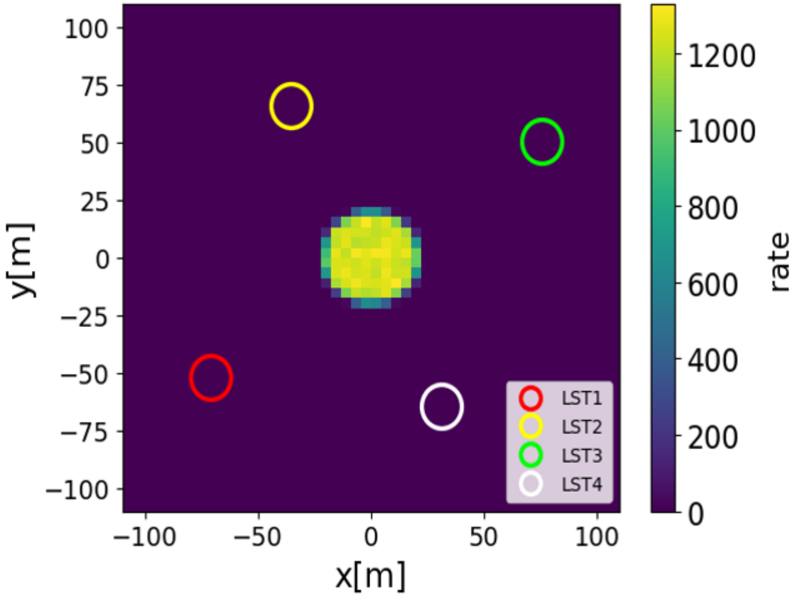
Obtain a high-precision energy spectrum of iron with LSTs (4 LSTs of CTAO-North)
in order to investigate the origin of galactic cosmic rays.

- Conduct iron reconstruction
  using cosmic rays simulation (Fe, Proton, N, Si) with array of LSTs.
- Check if LSTs can observe them at a higher zenith angle (20deg).
- Search for direct Cherenkov event candidates
  from LST-1 real data to check analysis method.

Simulation Conditions (4 LSTs)

- energy range　10 ～ 100 TeV
- telescope angle　zenith 20° (south pointing)
- nuclides:　Proton, Nitrogen, Silicon, Iron
- Core distance：　0-20m (CSCAT)
- Power law index：　-2
- The number of events is 90,000 each.

Core distribution



For the power law weighting,

Yue+2018 was referenced. (Flux equation)

$$\Phi_i(E) = \Phi_{0,i}\left(\frac{E}{\mathrm{TeV}}\right)^{-\gamma_i} \times \exp\left(-\frac{E}{E_{c,i}}\right)$$

Credit: Yue et al.(2018)

Species	$\Phi_{0,i}$ $(\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{sr}^{-1}\cdot\mathrm{TeV}^{-1})$	γ_i	ϵ_b (TeV)	ϵ_c (TeV)
p	8.79×10^{-2}	2.57	15	120
He	6.20×10^{-2}	2.51	15	120
C	1.05×10^{-2}	2.56	15	120
O	1.35×10^{-2}	2.56	15	120
Ne	4.73×10^{-3}	2.56	15	120
Mg	7.43×10^{-3}	2.56	15	120
Si	8.78×10^{-3}	2.56	15	120
Fe	1.50×10^{-2}	2.56	15	120

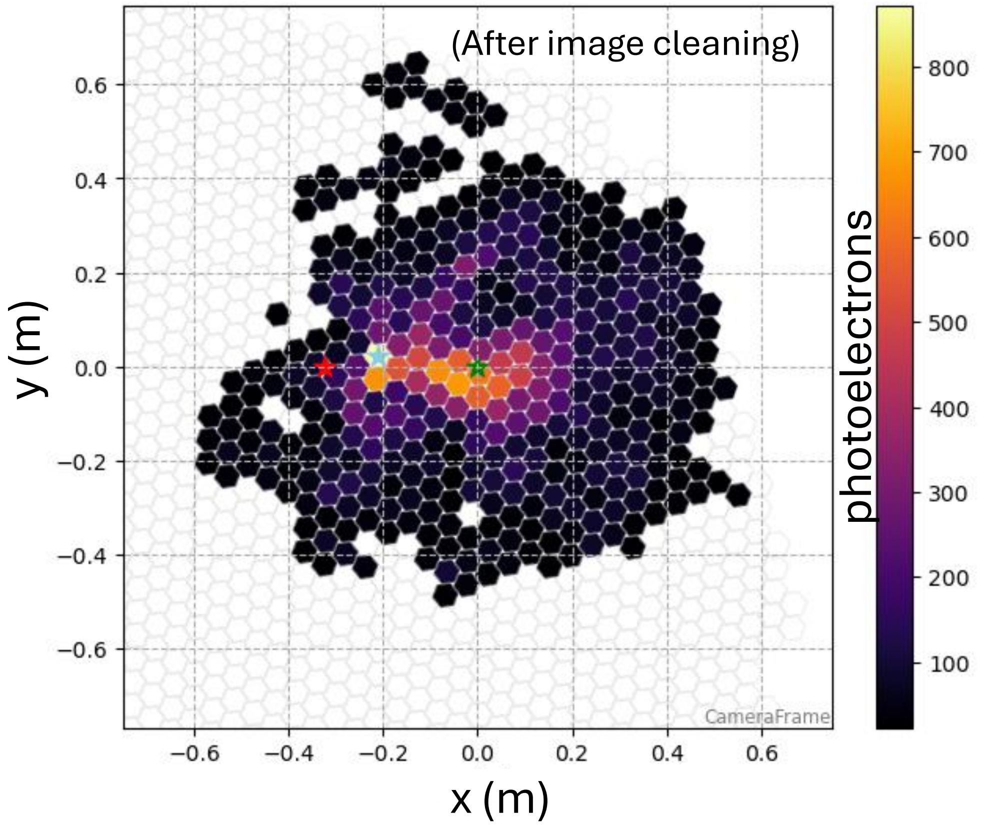
Credit: Yue et al.(2018)

Event selection and Z-reconstruction (only LST1 was analyzed)

$$Q = \frac{I_{dc\_pix}}{I_{neighbor\_pix}}$$

The pixel with the largest Q value is the DC pixel.

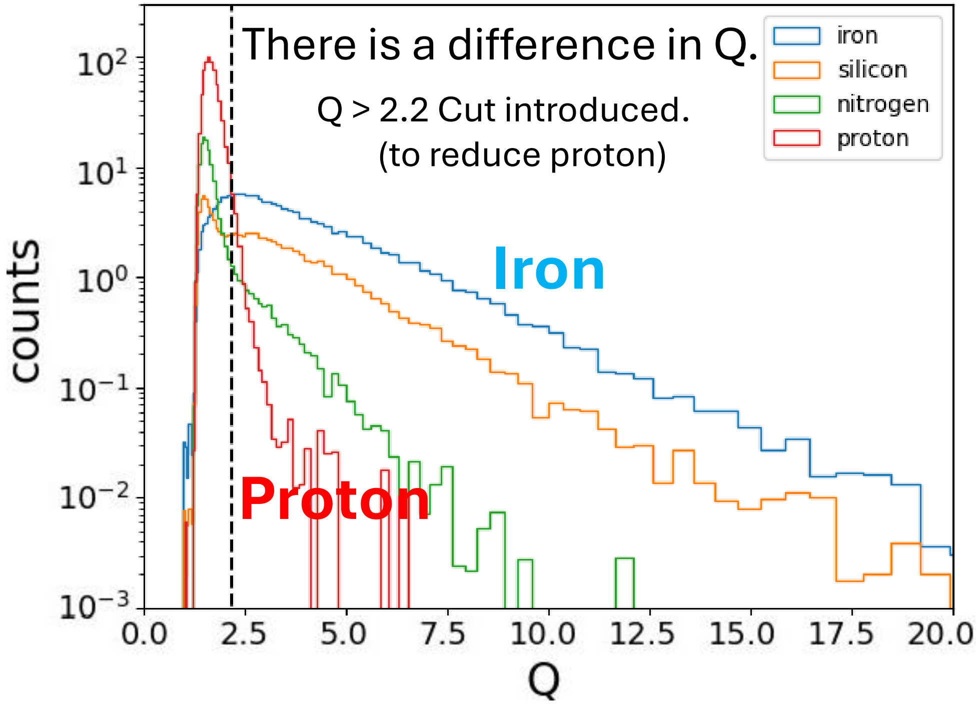
Iron MC image



★ ・・・ True arrival direction

★ ・・・ DC pixel

★ ・・・ Shower center of gravity



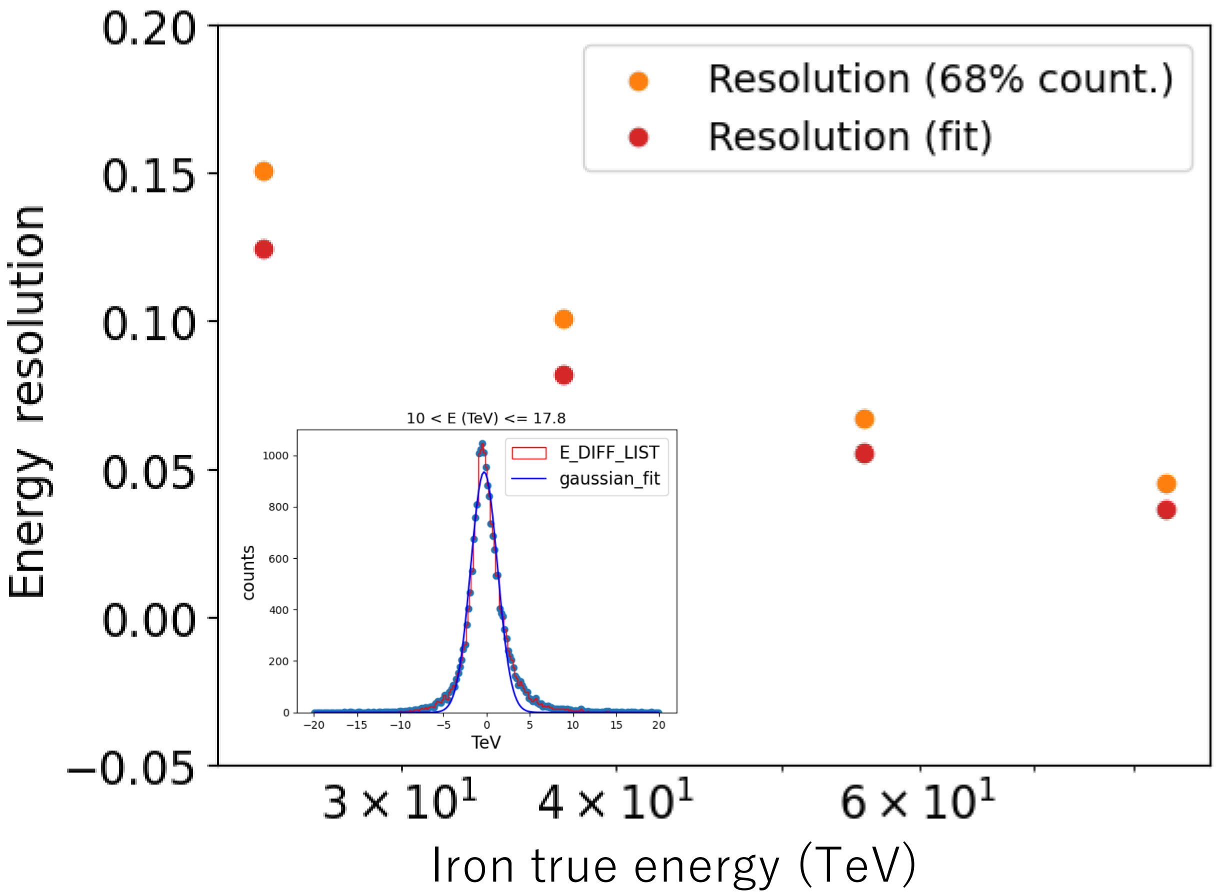
$$Z = d(E)\sqrt{I_{DC}(E)}$$

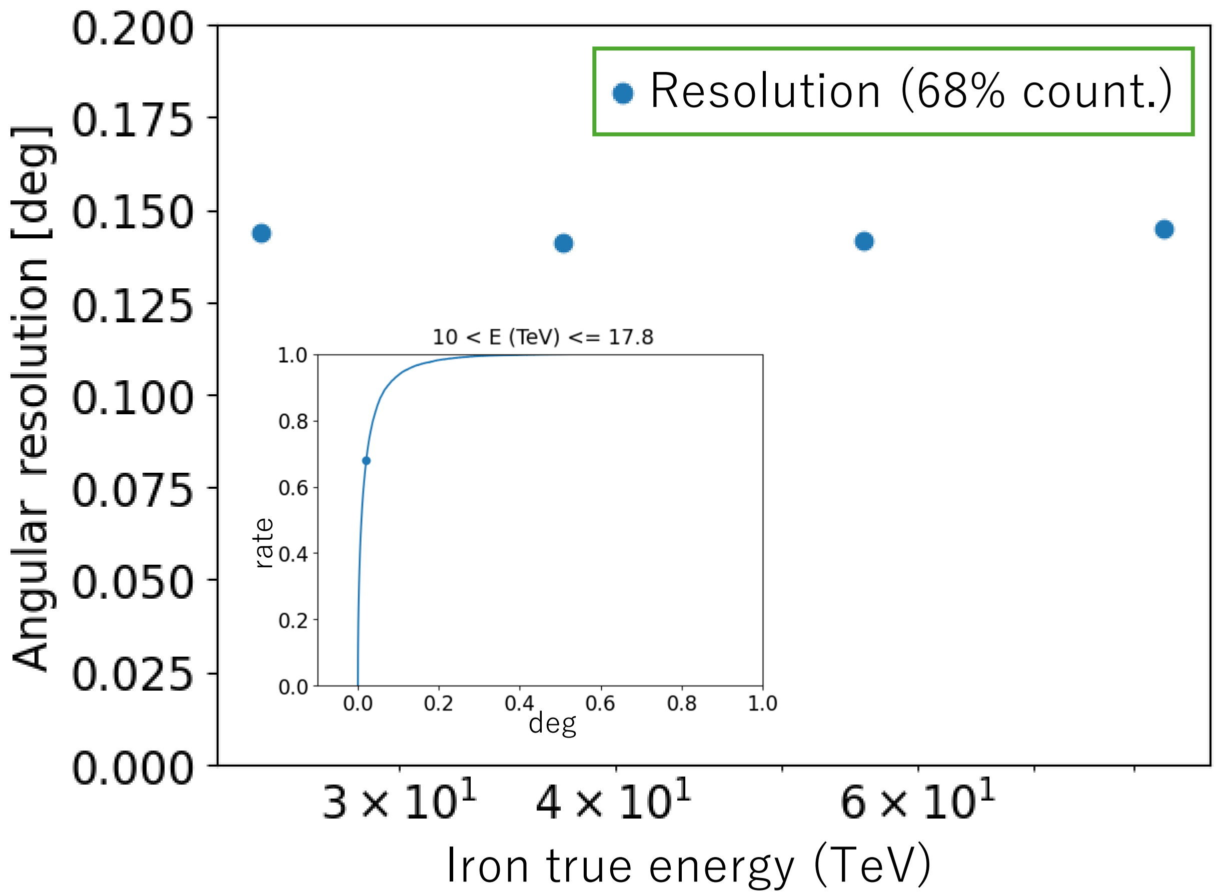
($I_{dc} = I_{dc\_pix} - I_{neighbor\_pix}$)

Conduct charge reconstruction with this equation

(Here, we used event cut using relative positions between three points (★★★).)

Energy, Arrival direction reconstruction with LST array





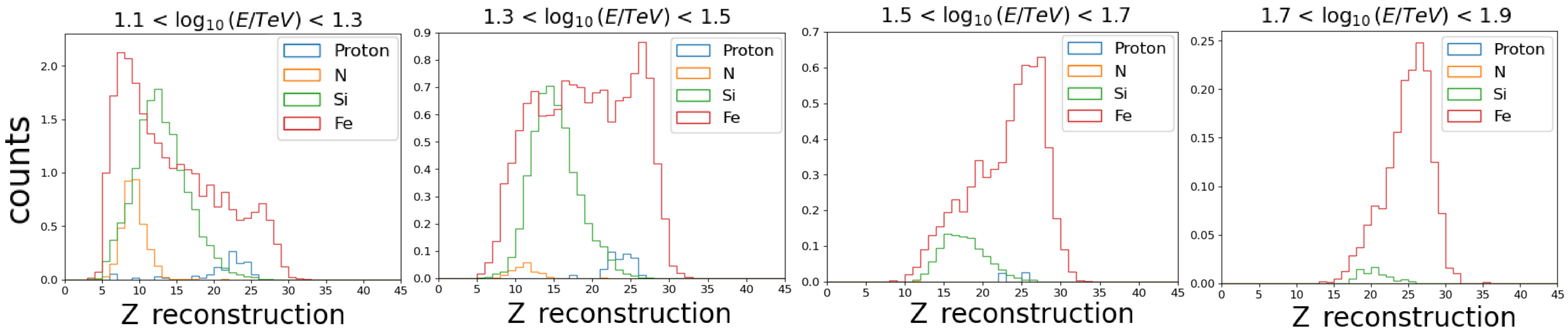
Energy resolution ~10%
Considered to have good resolution because core<20m

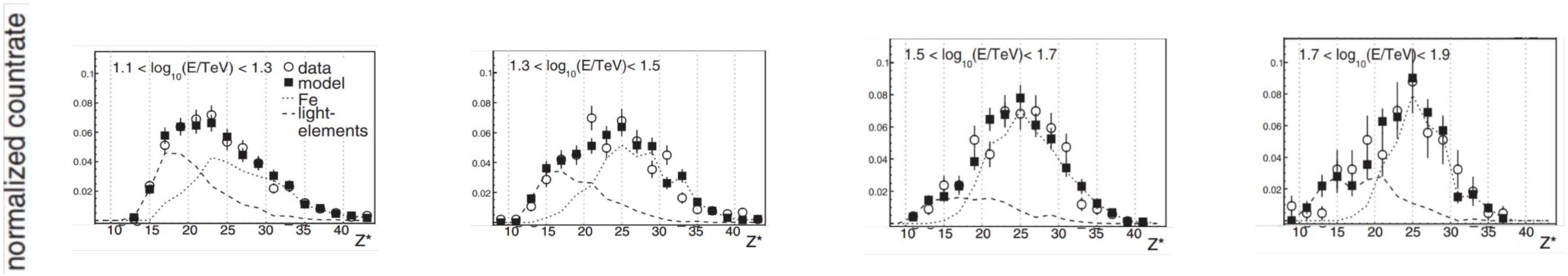
Angular resolution ~0.14deg.
This is 1~2 pixels in size.

Z-reconstruction results in each energy range

Comparison with HESS paper (HESS is below)

The red histogram (Fe) corresponds to the dashed Fe line in HESS.

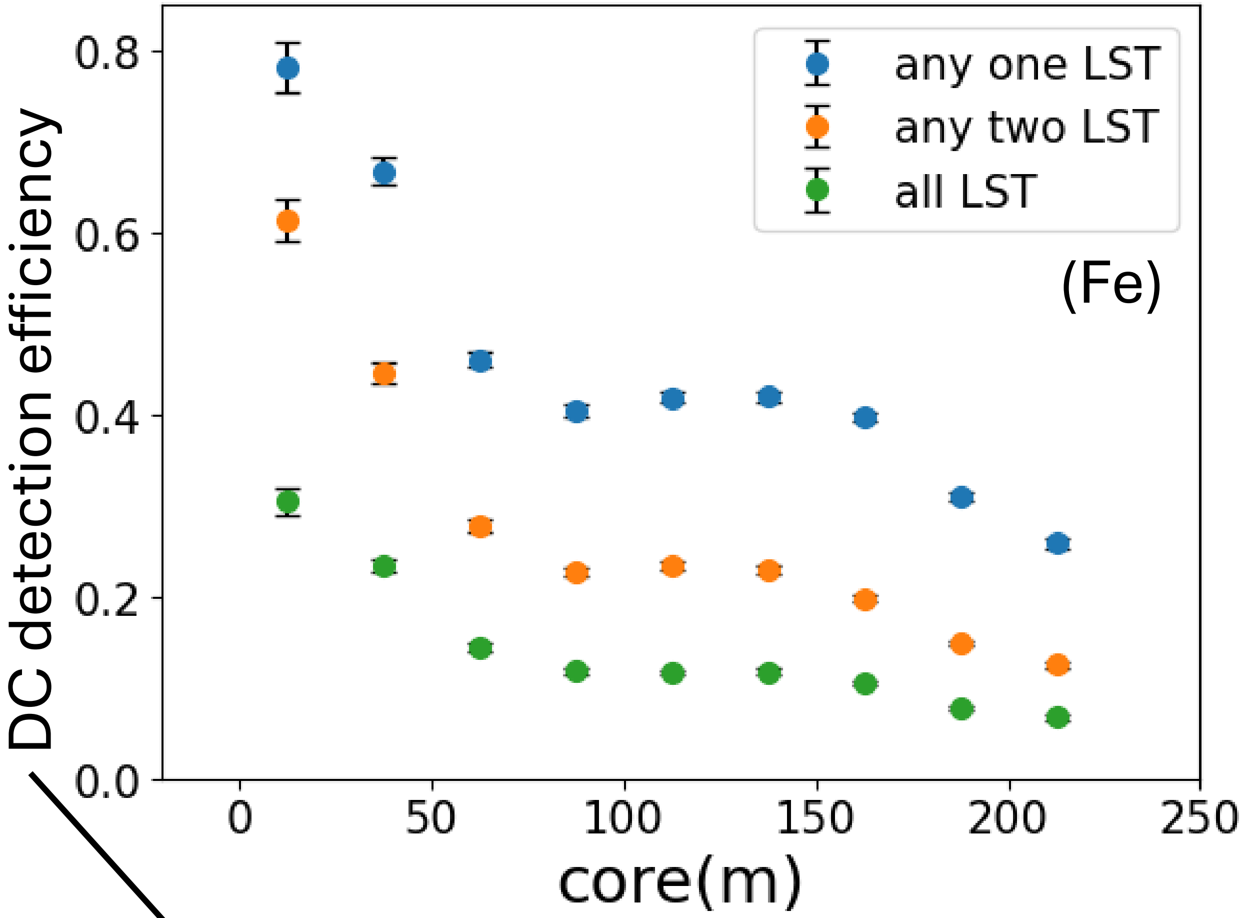




Credit: F. Aharonian et al.(2007)

The purity of iron increases as energy increases.
This is consistent with the HESS results.

DC detection efficiency vs Core



$$\frac{\text{Number of events that meet the DC event criteria}}{\text{Number of Triggered Events}}$$

In the next step, we will analyze simulations data (core < 200m)

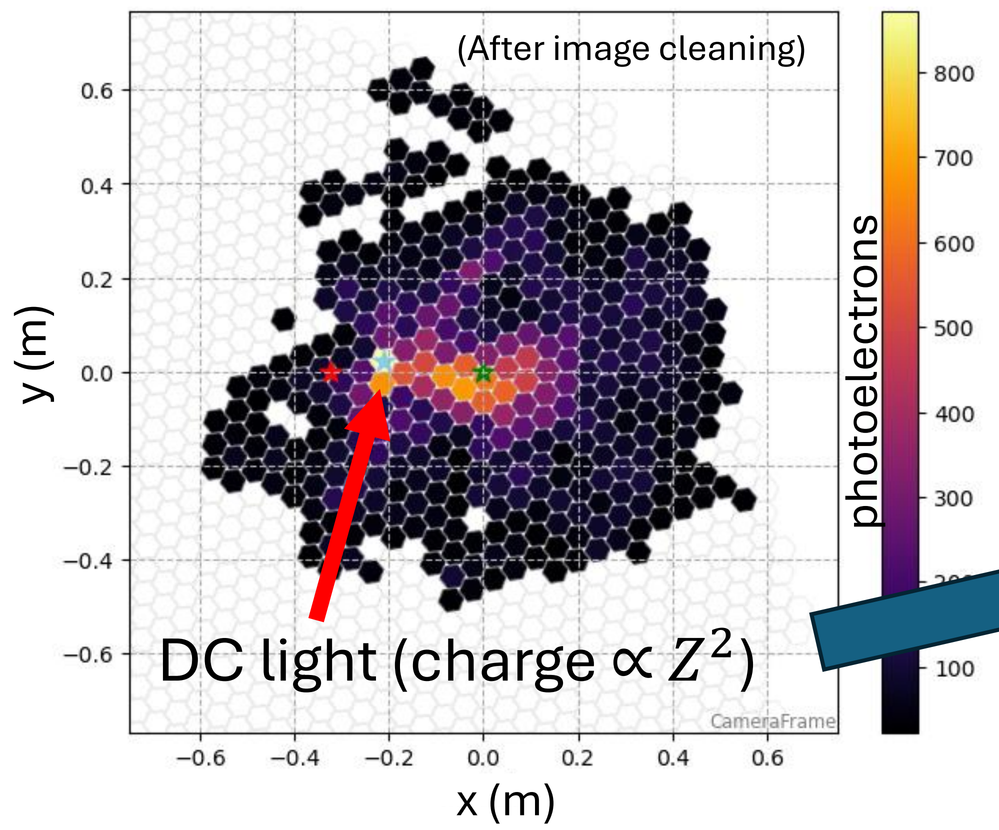
Simultaneous observations
・・・better BG rejection capability
(HESS uses any two)

Observations with 1~2LST
・・・ better detection efficiency

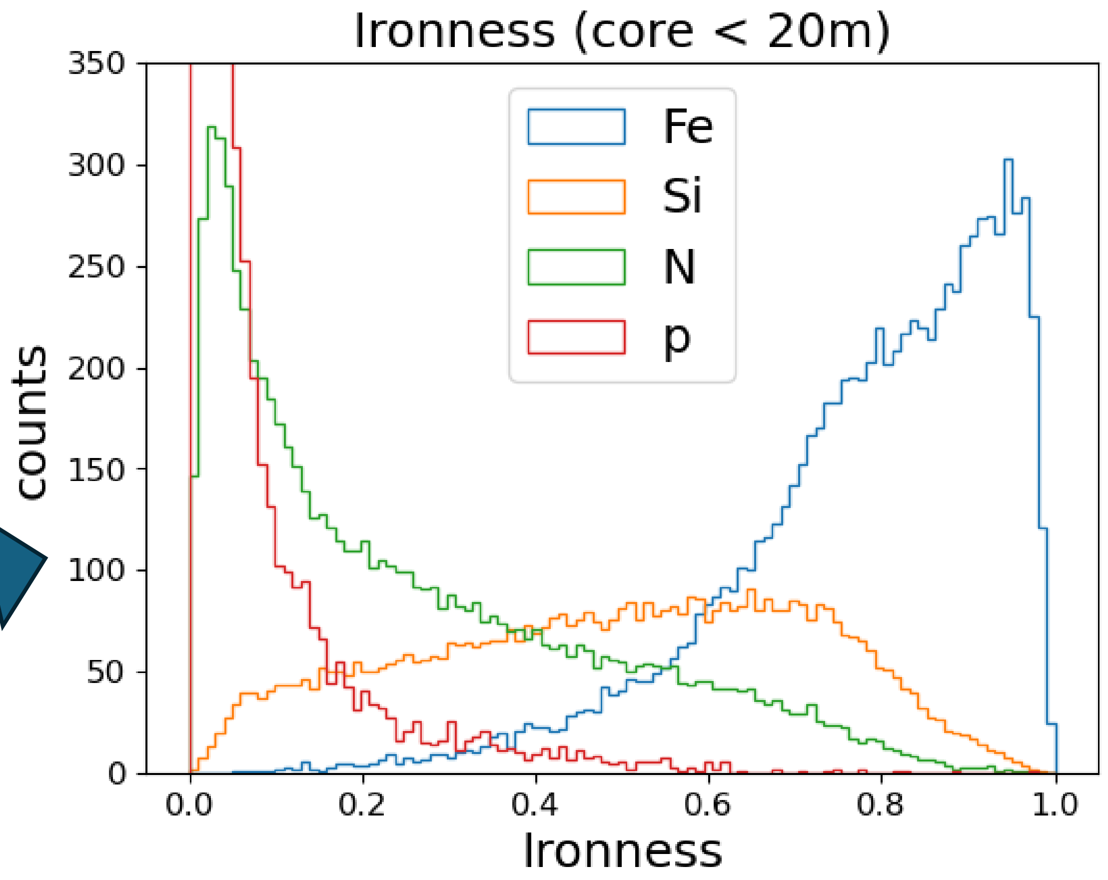
Explore the best observation conditions by considering both BG removal capability and detection efficiency.

Ironness reconstruction using RF

Iron MC image



Q value,
Intensity,
Charge max

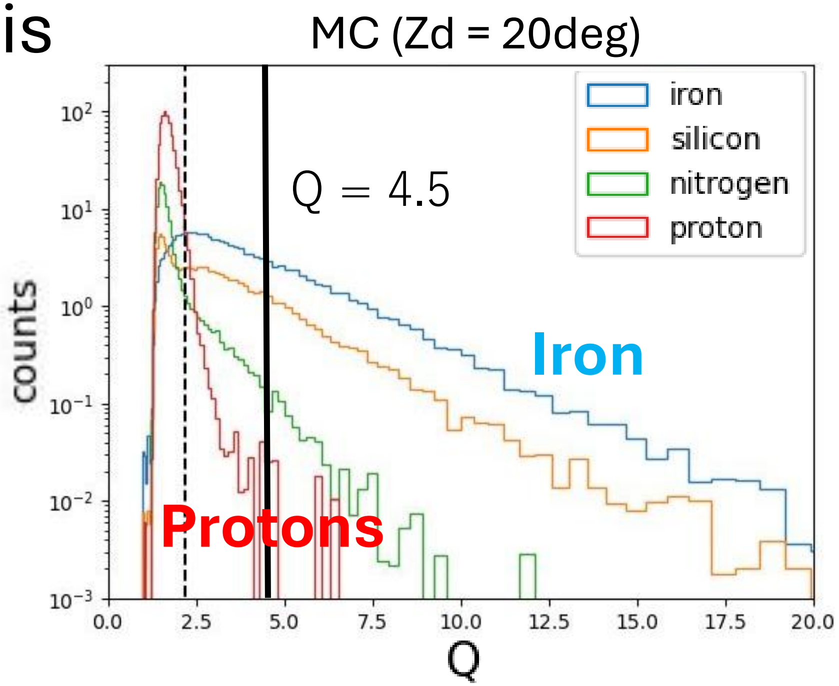


Using Random Forest Classifier method and the feature (DC light charge ∝ Z^2), we can estimate **Ironness** (indicates how “iron-like”).
Going forward, we will use this parameter to calculate the effective area and sensitivity.

LST-1 real data analysis

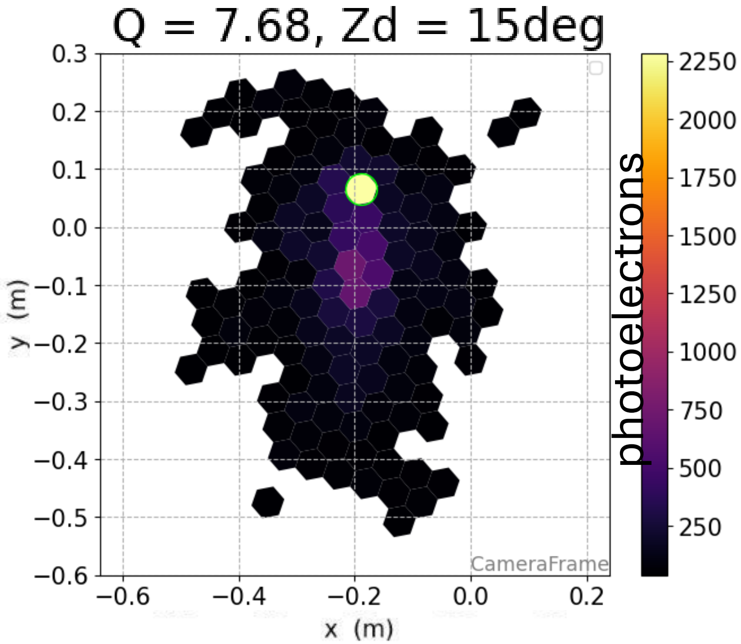
Q distribution
 obtained from simulation →

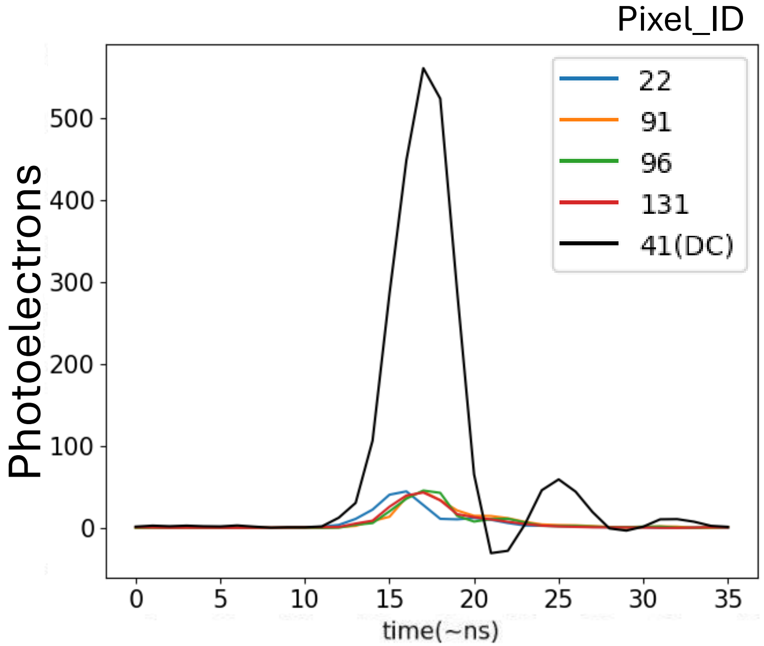
Q > 4.5 (excluding protons)



Data used: 20250824/Cyg-X3
Time: 30minutes Zenith : 17deg (ave.)

	Number of events
All events	13,285,259
Events (Q > 4.5, intensity > 10,000)	87
DC-like events (by eyes)	42 (/87)
proton-like events (by eyes)	0 (/87)
noise or unknown (by eyes)	45 (/87)





Waveforms of large peak pixels and DC pixel are shown.
DC pixels are low gain.

Direct Cherenkov pixel has large signals because it has high light intensity.
This matches the characteristics of DC light.

It can be the first DC event!

Summary and Future Prospects

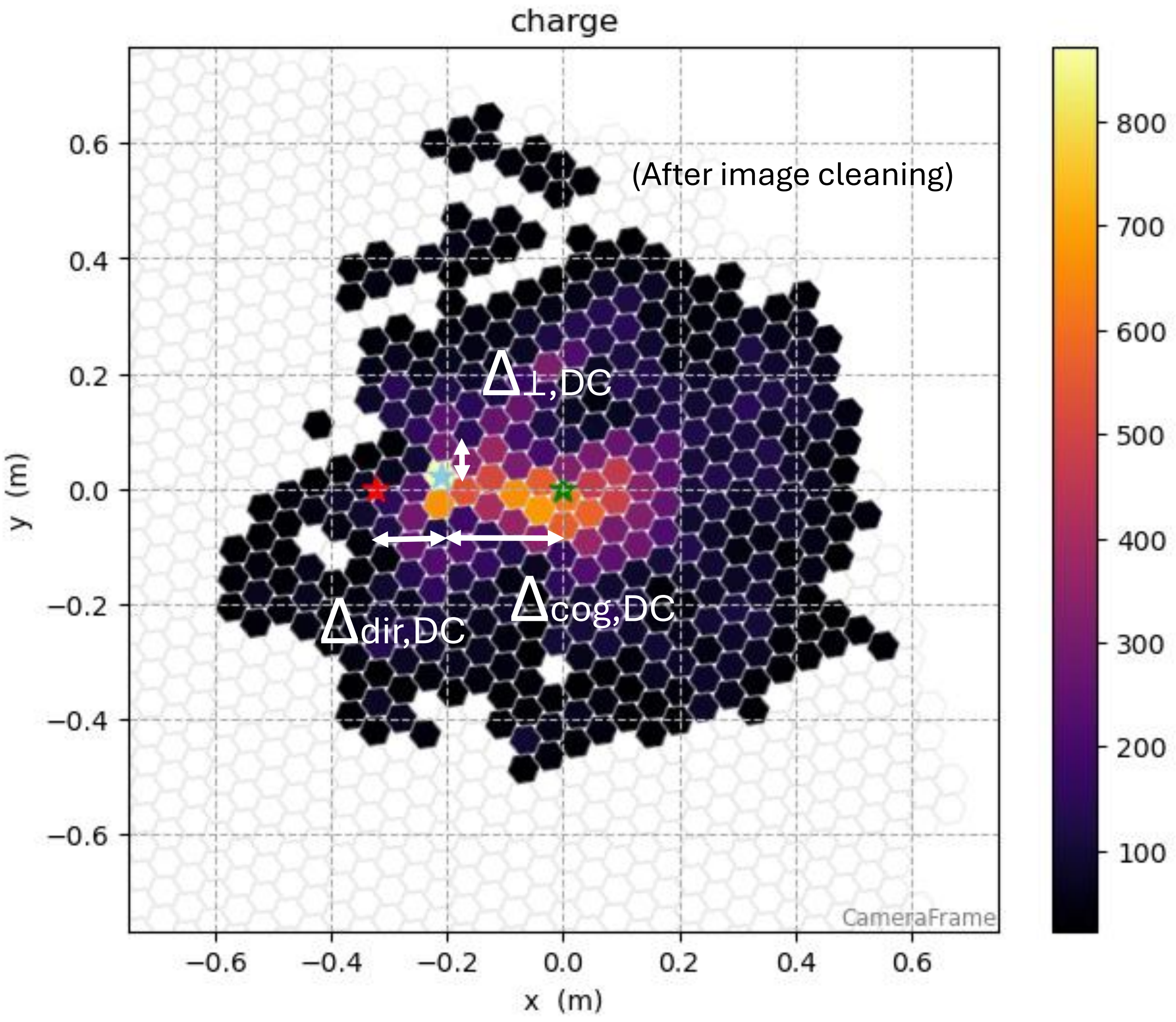
The objective is to obtain a high-precision energy spectrum of iron with LST array in order to investigate the origin of galactic cosmic rays.

- Performed reconstruction of energy and arrival direction using Random Forest method.
- Performed Z-reconstruction using simulation data.
- CTAO LSTs may be possible to observe iron at a higher zenith angle (20 deg) than in previous studies (~15deg).
- Found Direct Cherenkov event candidates from LST-1 real data (Zd = ~17deg)

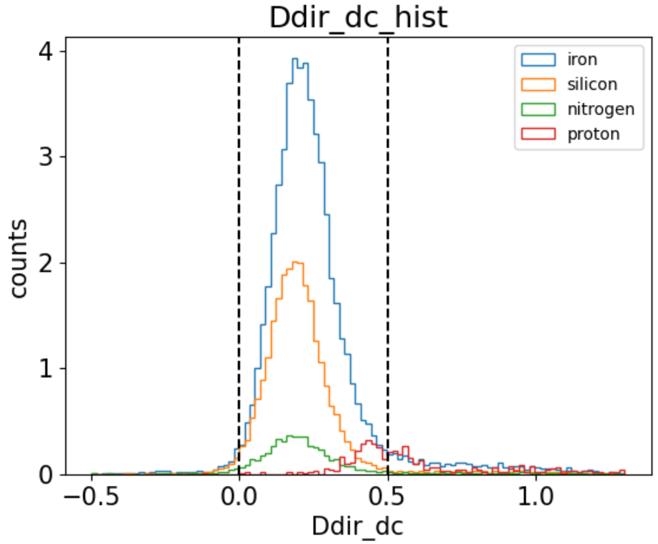
Future prospects:

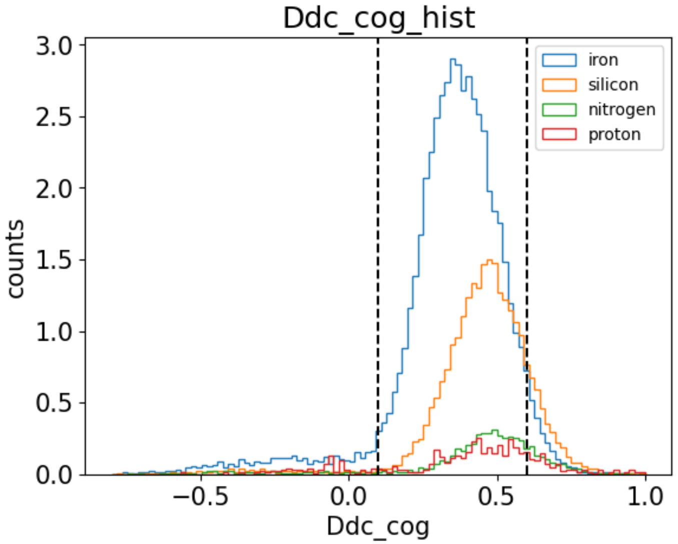
- Ironness-reconstruction with 4 LSTs and calculate sensitivity for iron.
- Obtain iron spectrum from LST-1 real data.

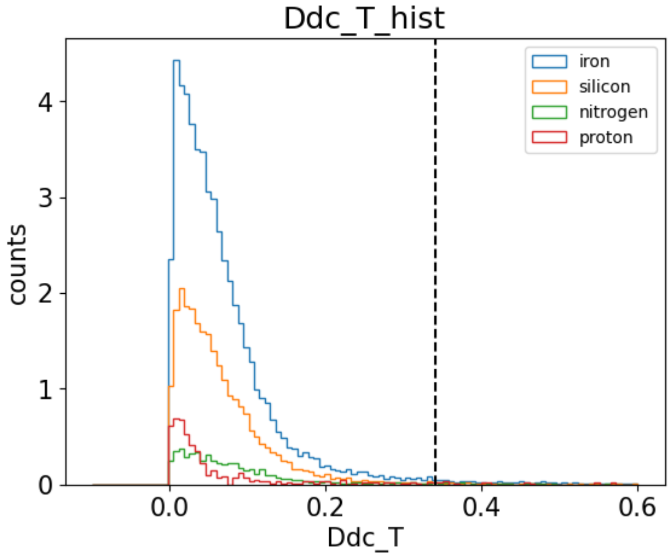
Event Cut Parameters



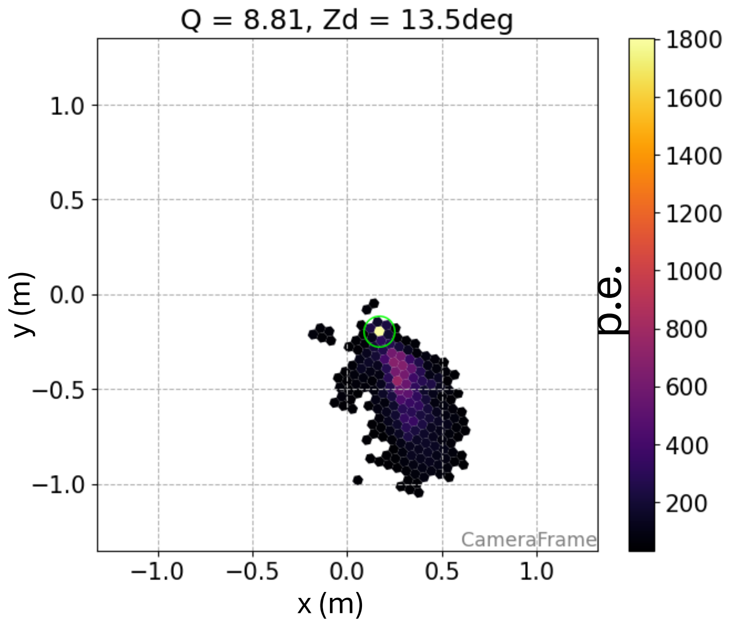
Δ distribution

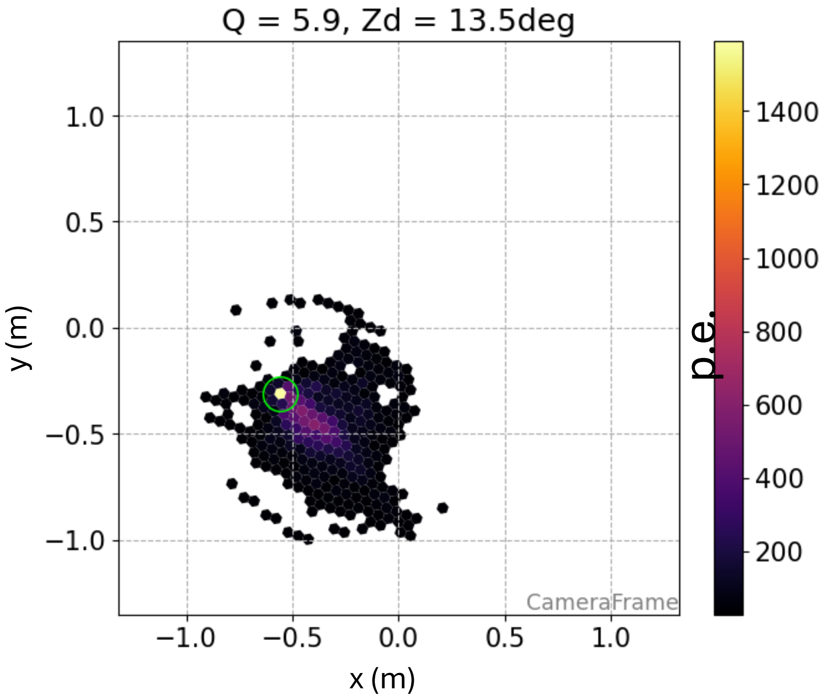


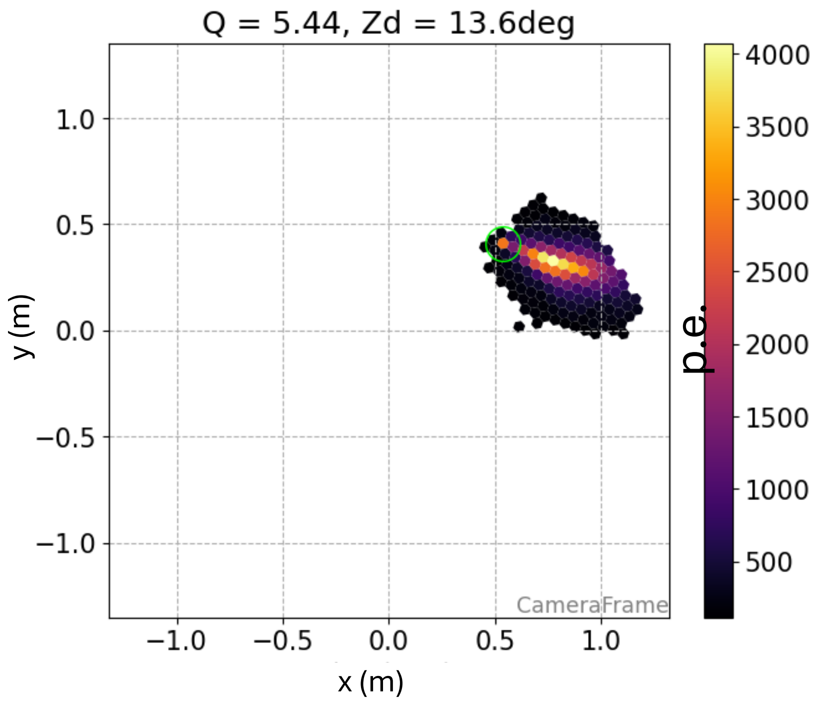


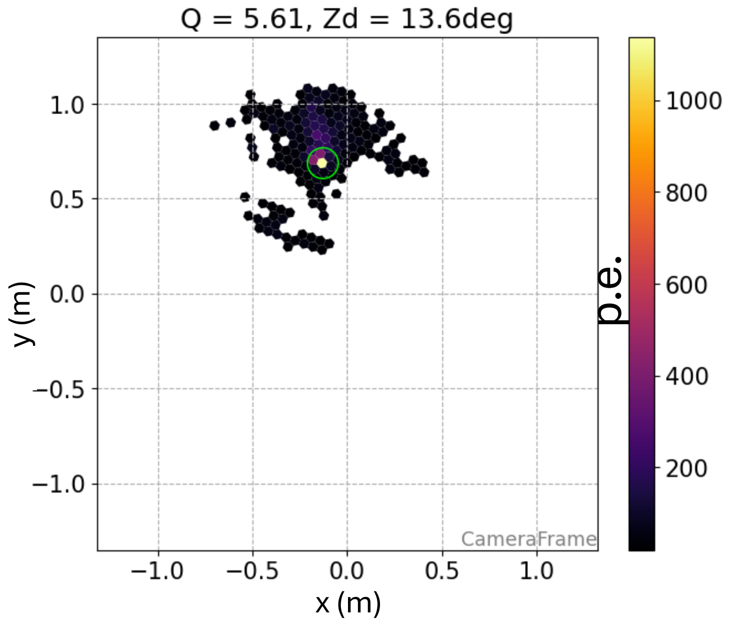


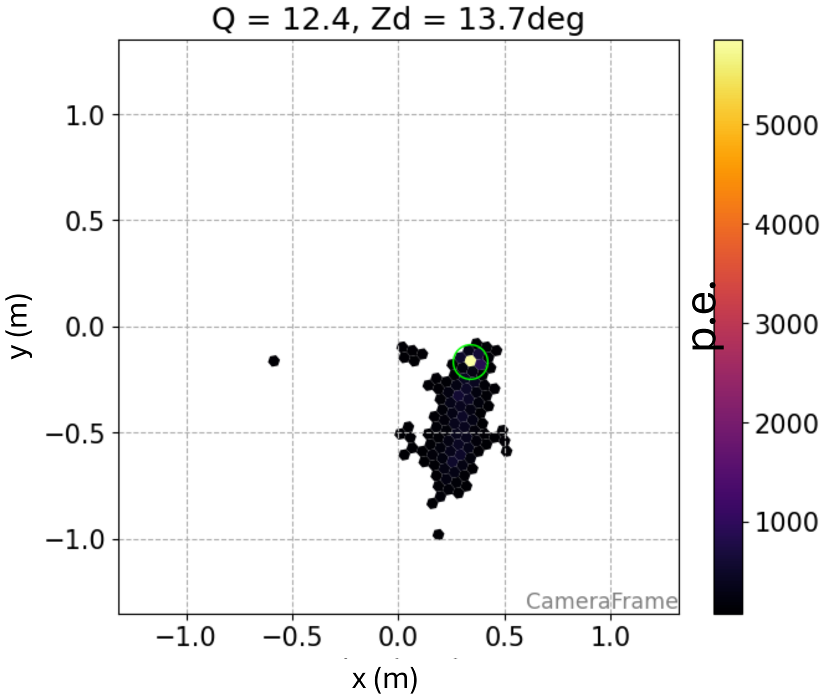
DC candidates

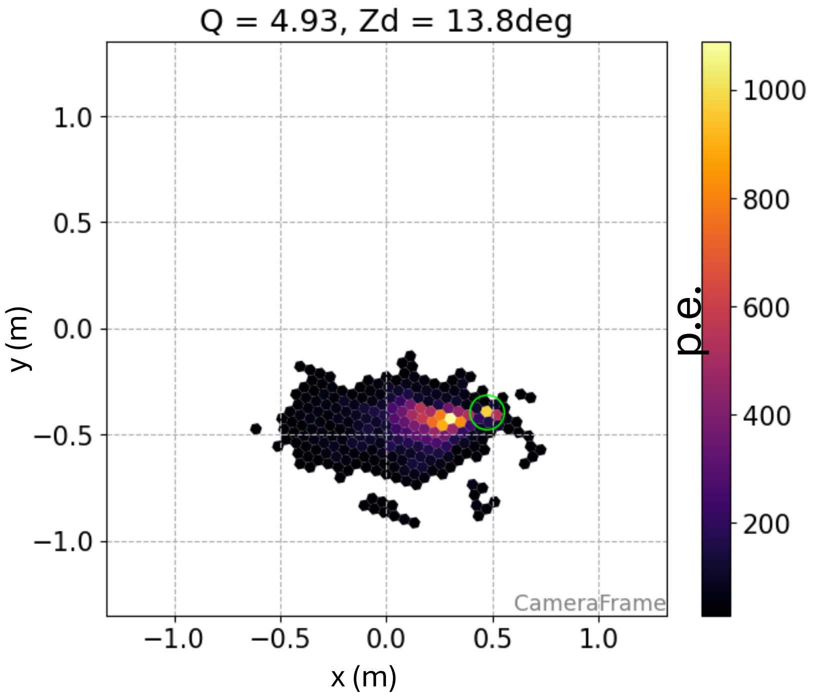




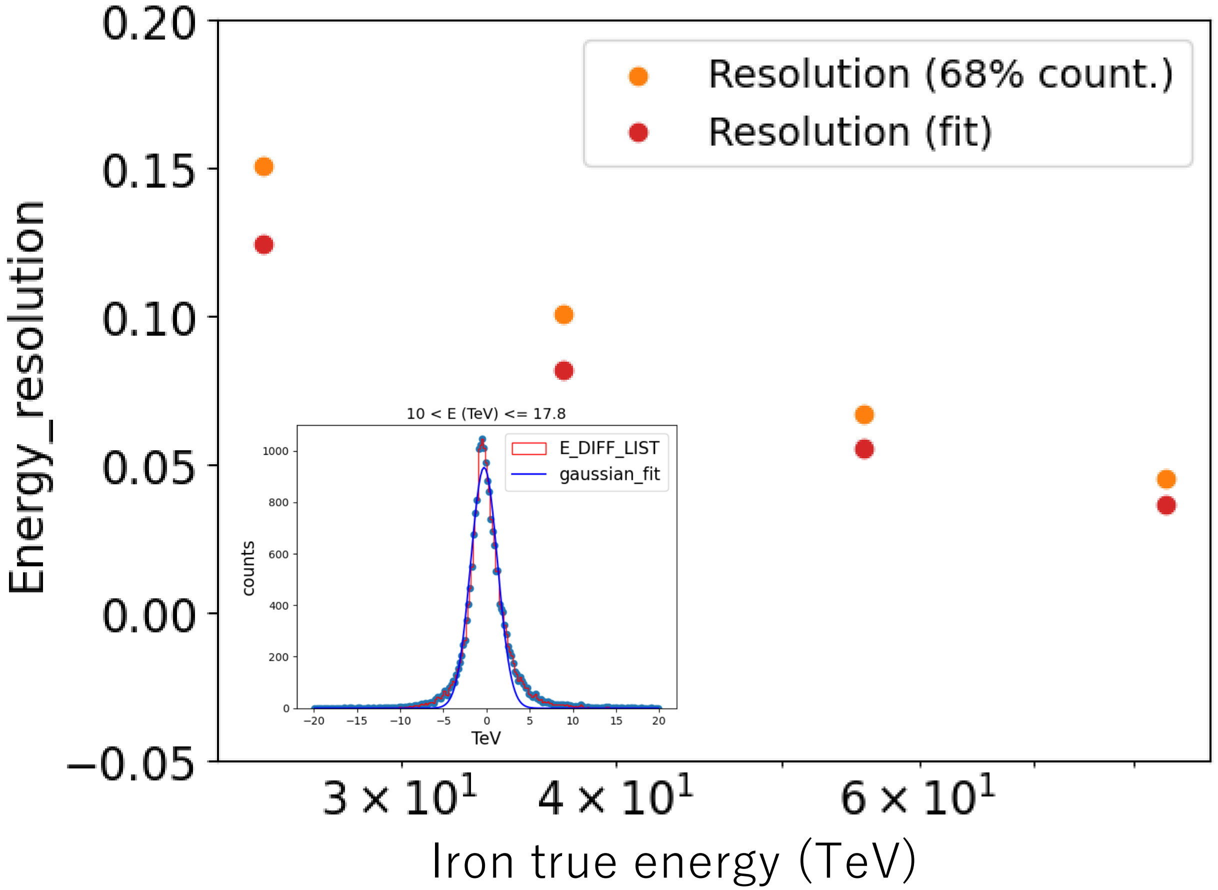




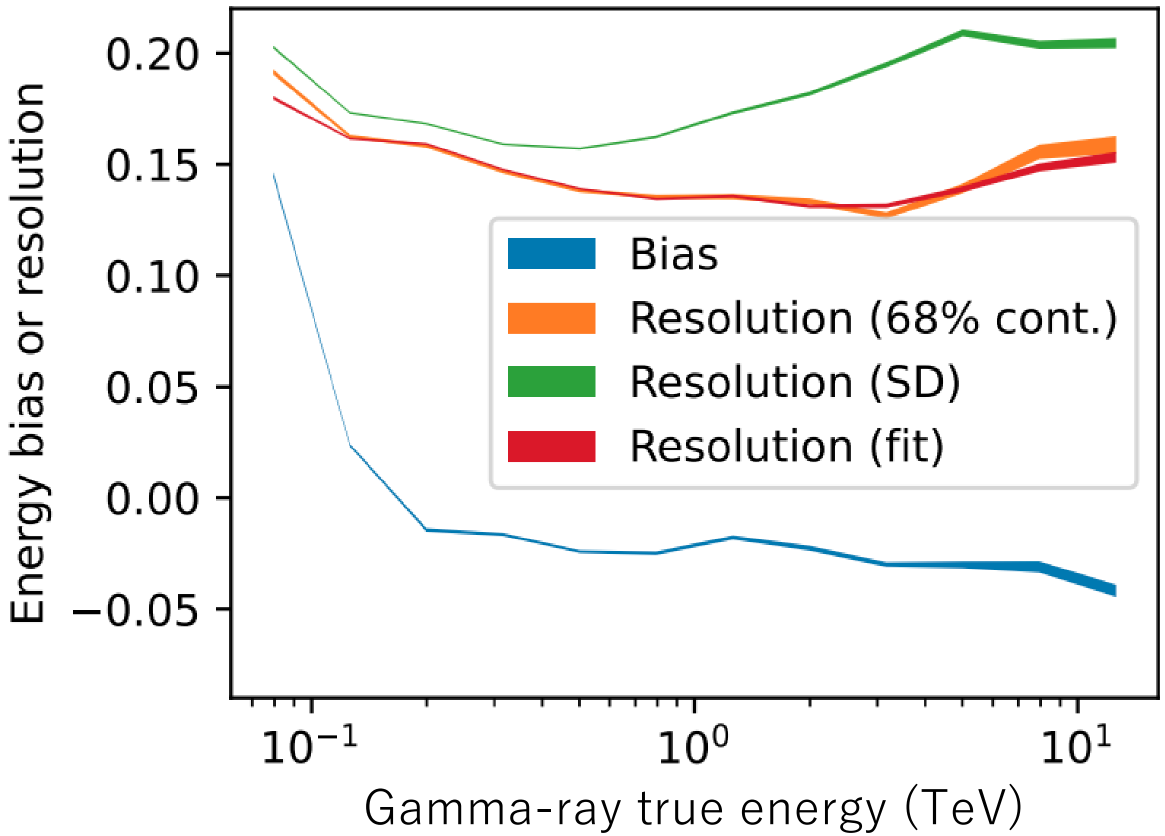




Energy reconstruction with LST array



magic+lst1 gamma-ray performance



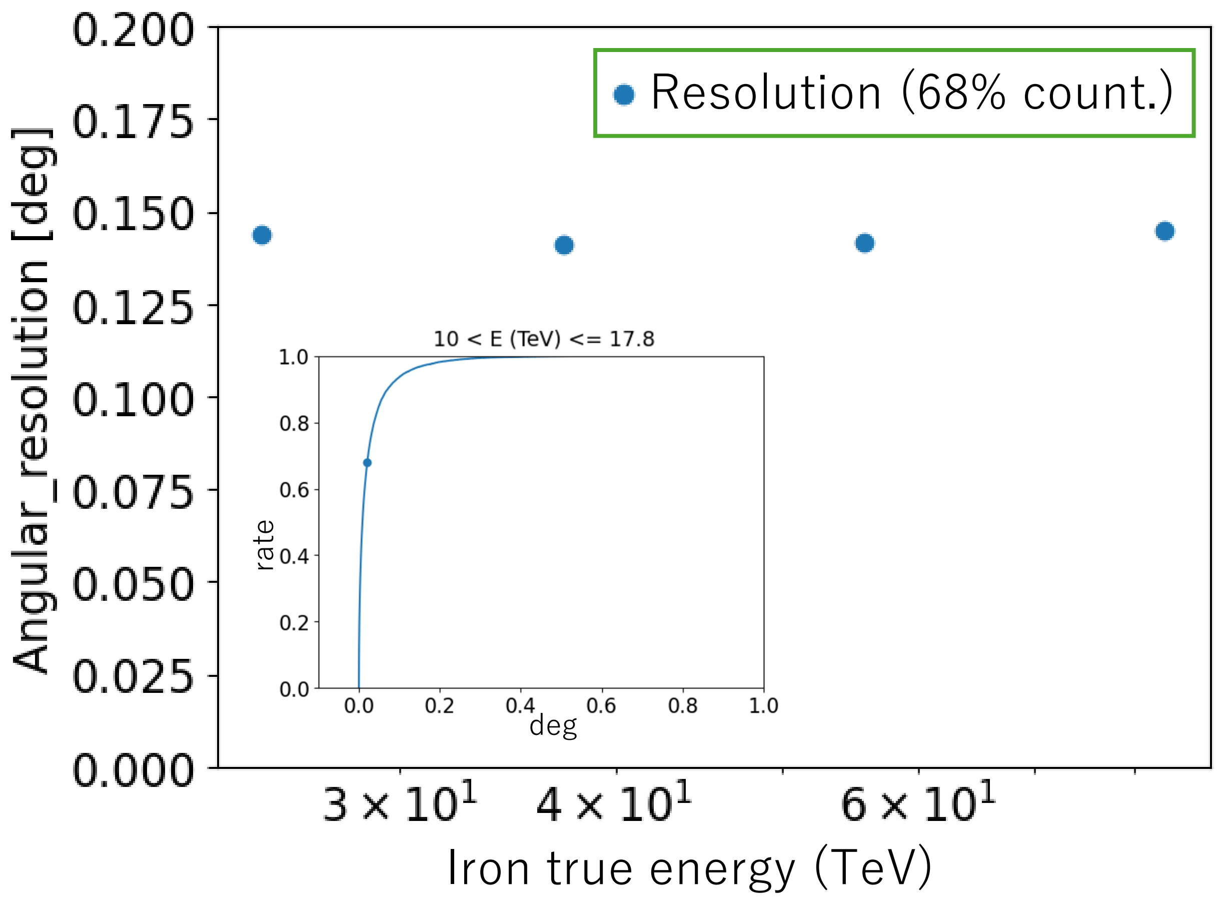
https://www.aanda.org/articles/aa/pdf/2023/12/aa46927-23.pdf

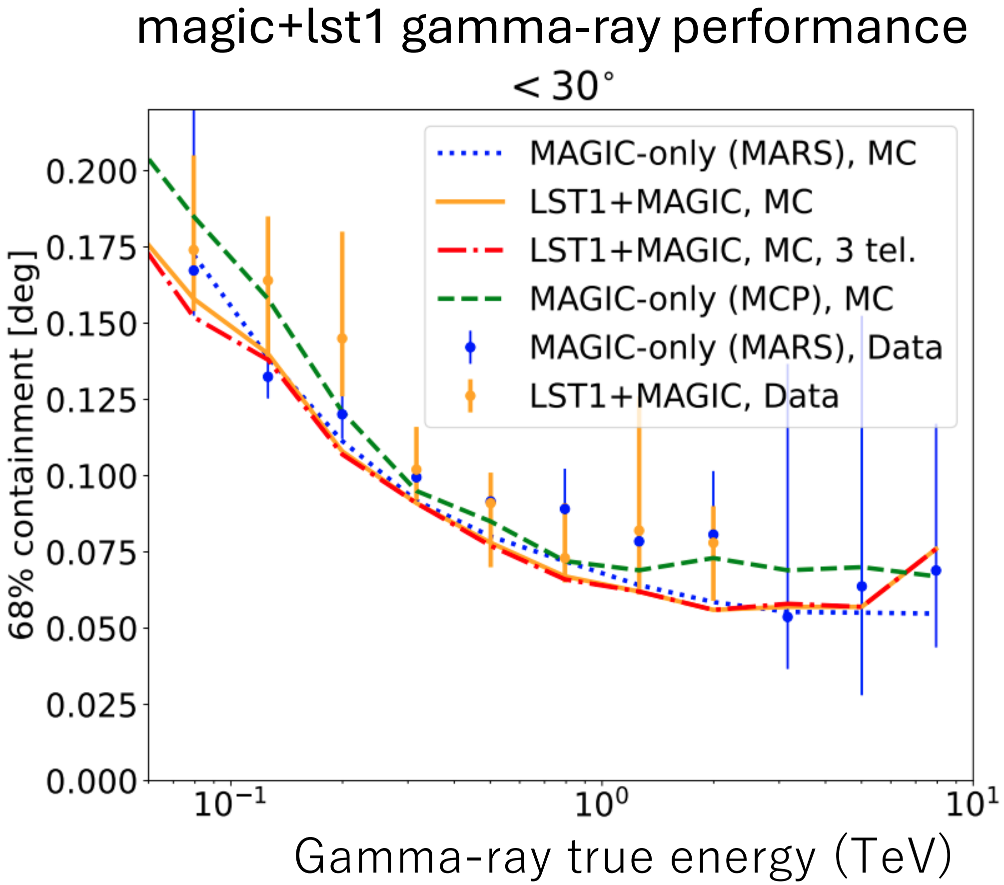
Energy resolution ~10%

Considered to have good resolution because core<20m

We can estimate energy.

Arrival direction reconstruction with LST array



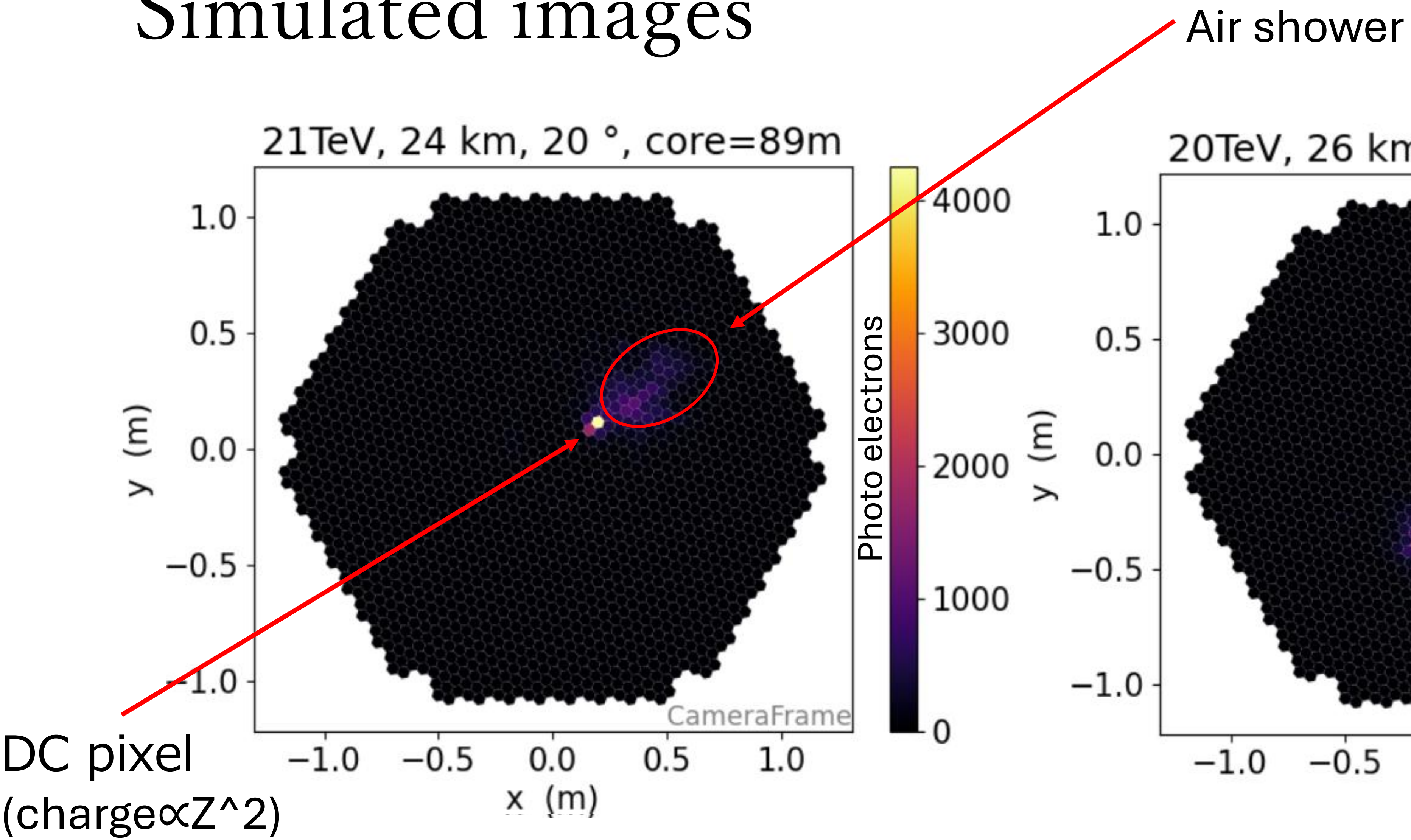


https://www.aanda.org/articles/aa/pdf/2023/12/aa46927-23.pdf

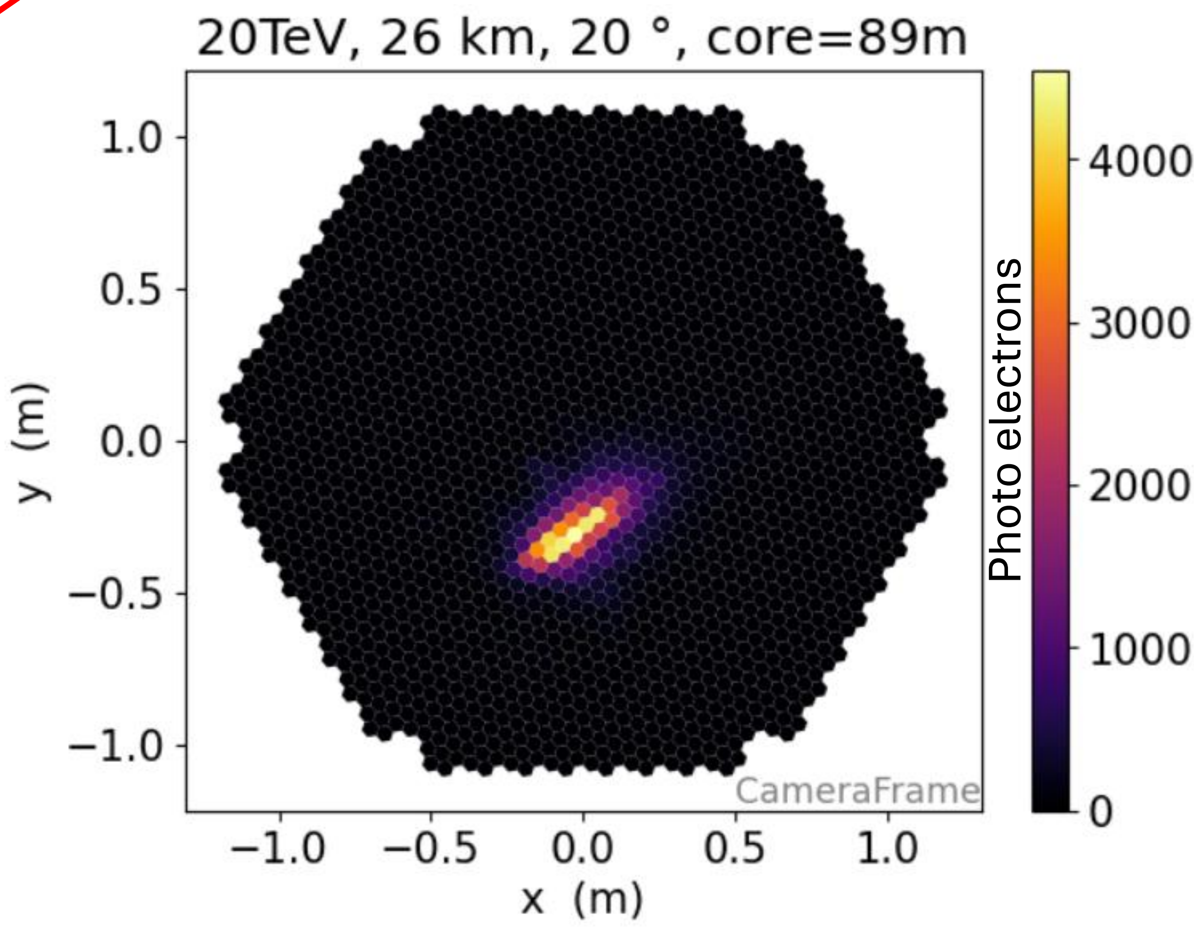
Angular resolution ~0.14deg. This is 1~2 pixels in size.

We can roughly estimate arrival direction. → Perform Z-reconstruction with these values.

Simulated images



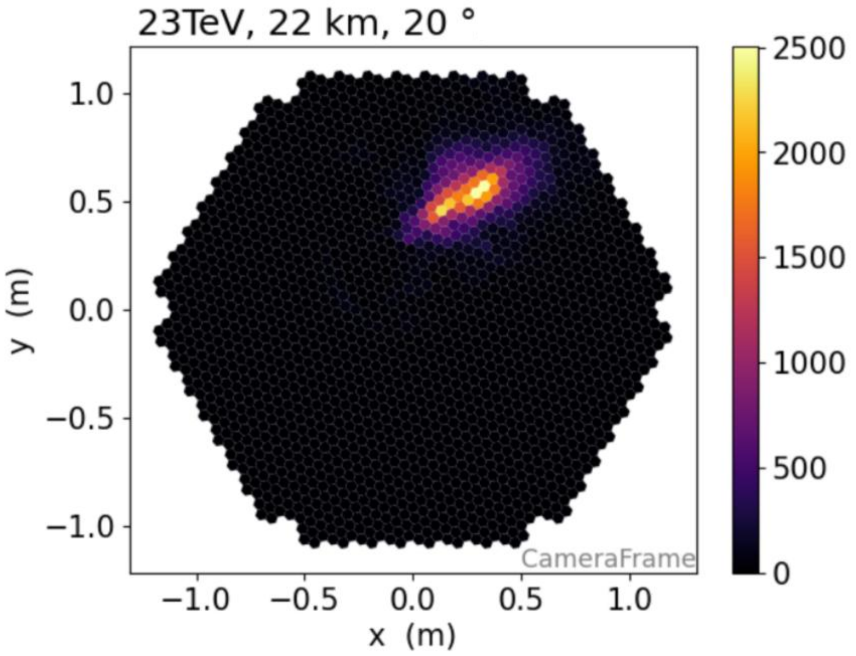
iron



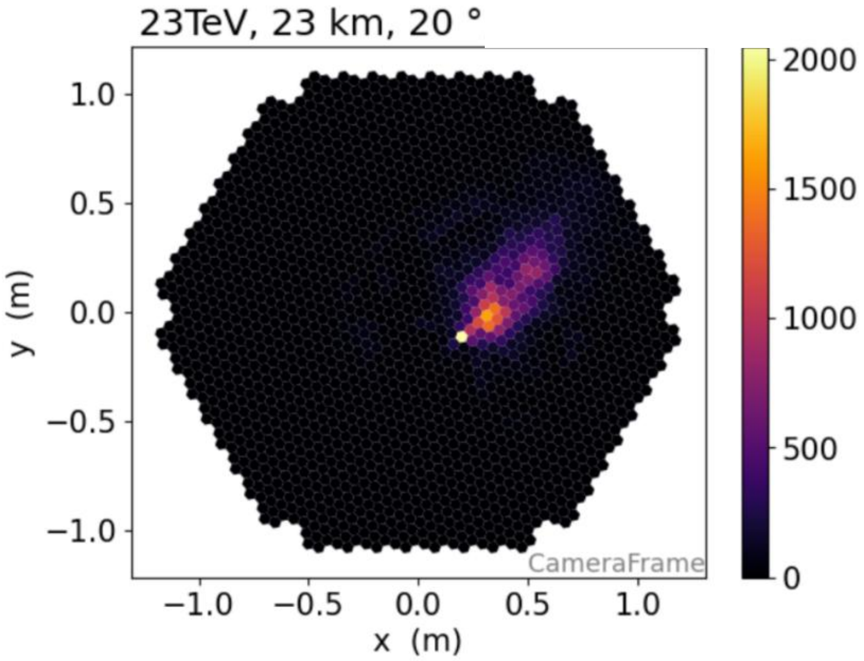
proton

Typical images

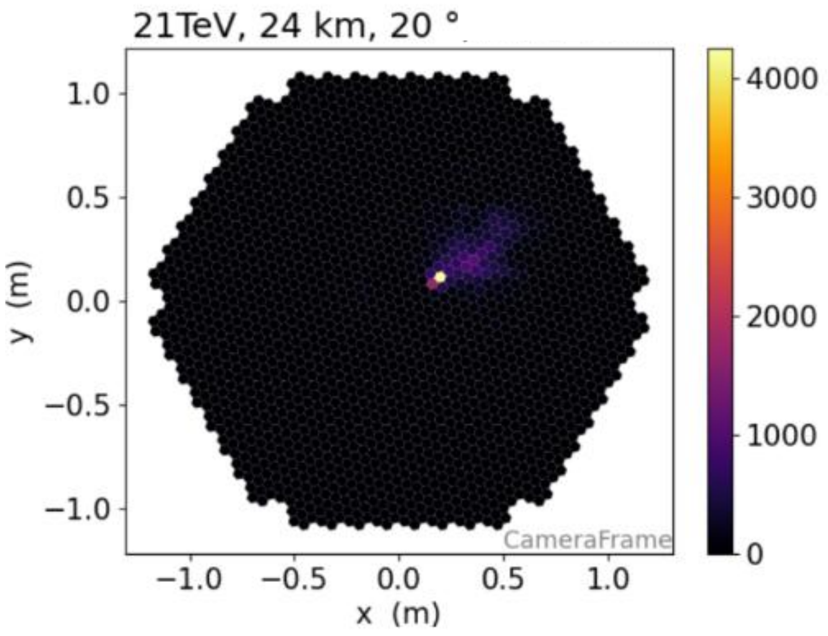
Nitrogen



Silicon



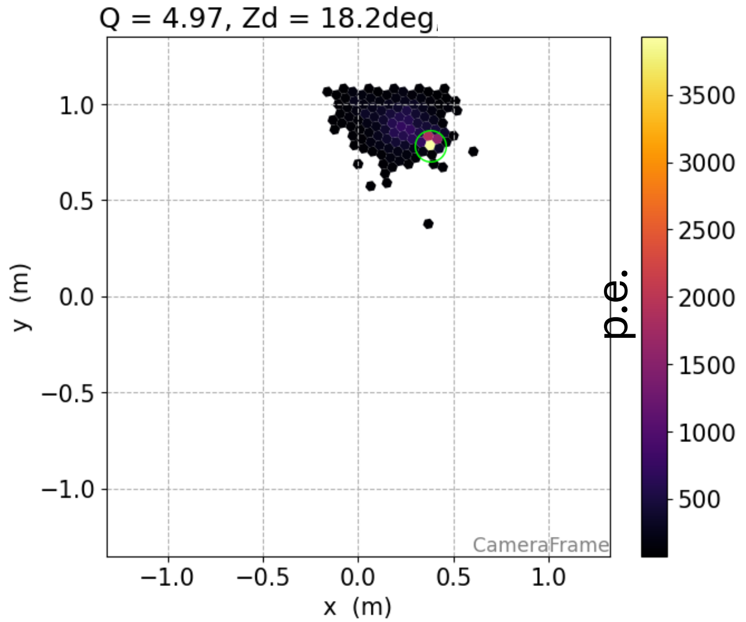
Iron

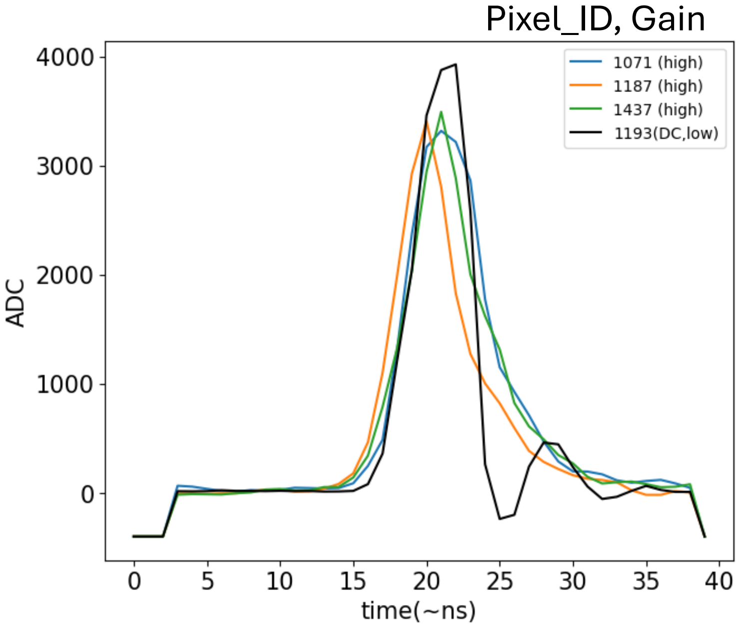


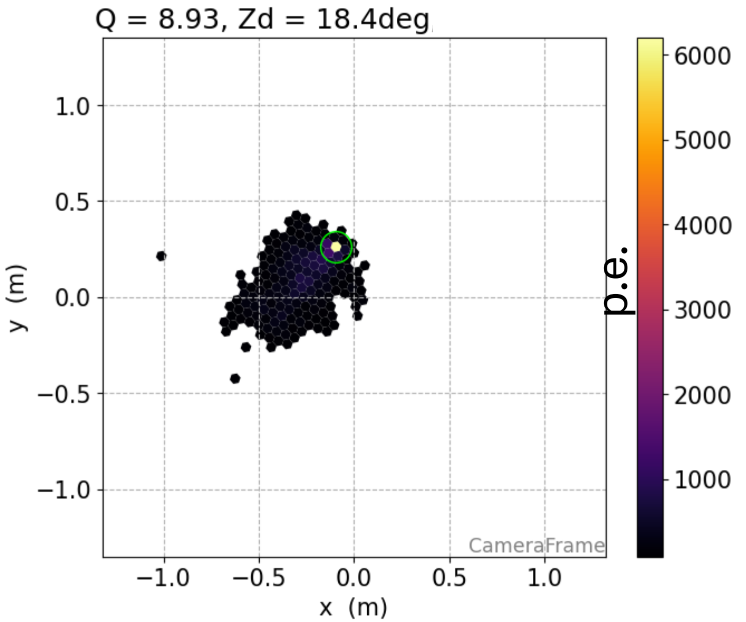
Though DCpixel is visible in silicon and iron, Iron's pixel is stronger because intensity is proportional to the square of Charge(Z).

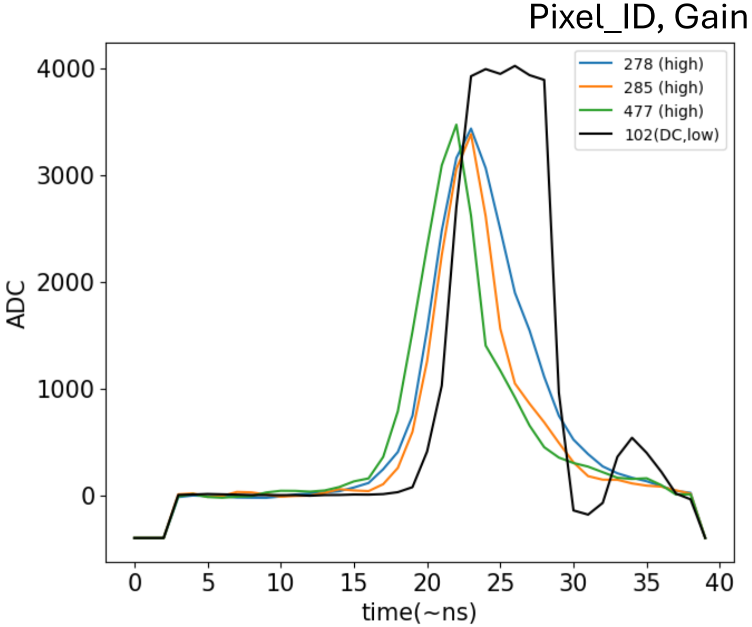
DC candidate
(saturated events ~7/42events)

Waveforms of large peak pixels and DC pixel are shown.
DC pixels are low gain.





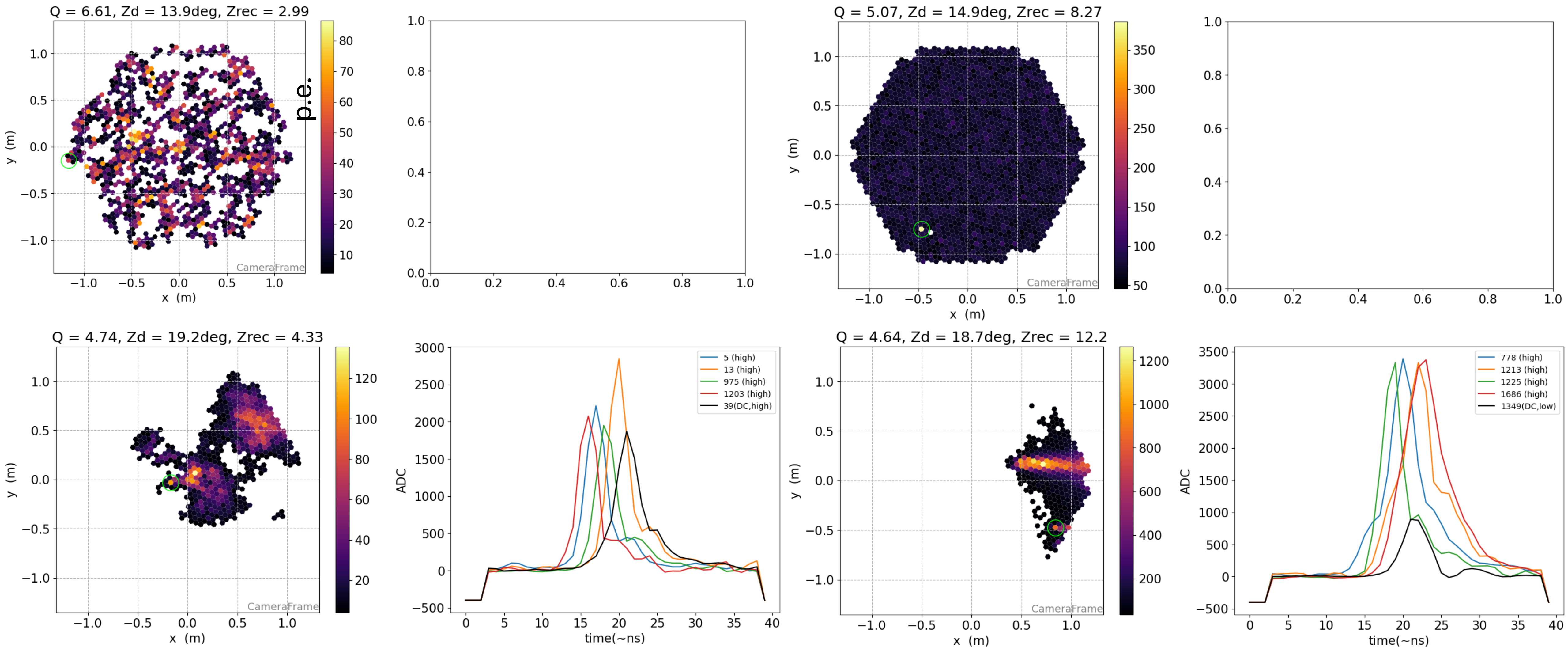




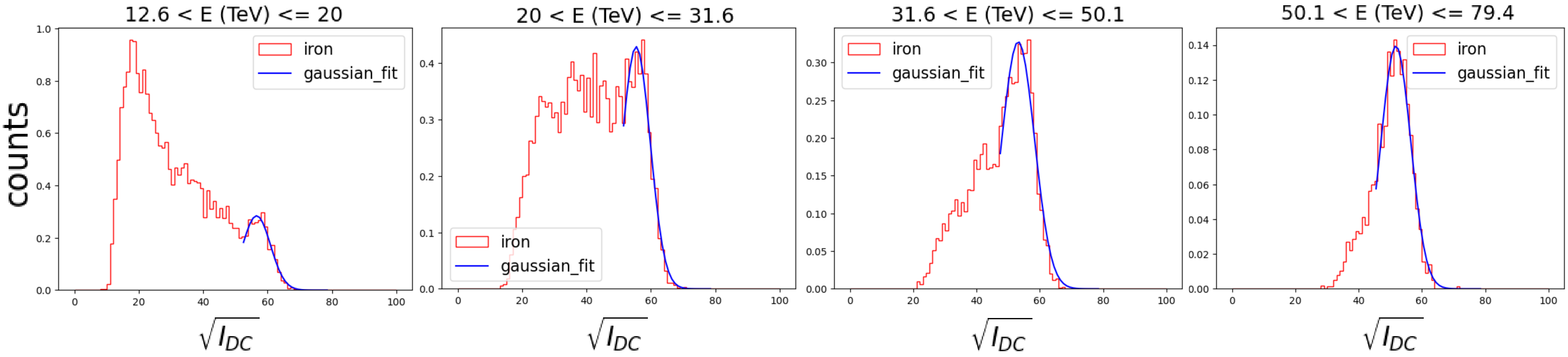
The PMT saturation study currently underway will be important going forward.

Other DC-like events are listed in the backup slides.

DC candidate (strange)



D(E)



$$Z = d(E)\sqrt{I_{DC}(E)}$$