Cerenkov Events Seen by the TALE Air Fluorescence Detector

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Outline

- **TA L**ow **E**nergy extension (TALE) Fluorescence Detector.
- Cerenkov Events
- Reconstruction Method / Performance
- Data Set
- A First Spectrum
- Summary and Outlook

Telescope Array Collaboration

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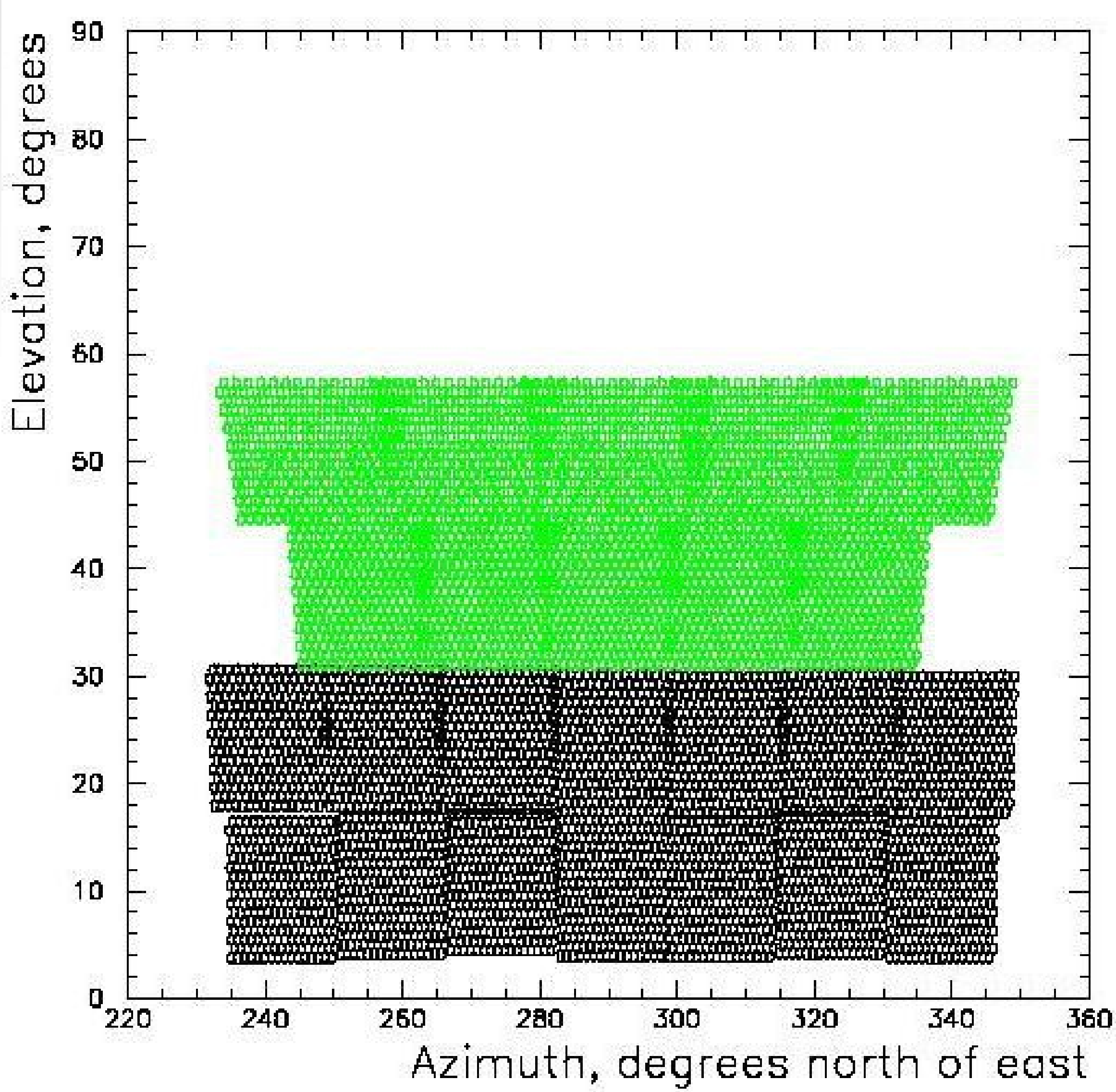
Middle Drum TALE Observatory Site (14+10 Telescopes)

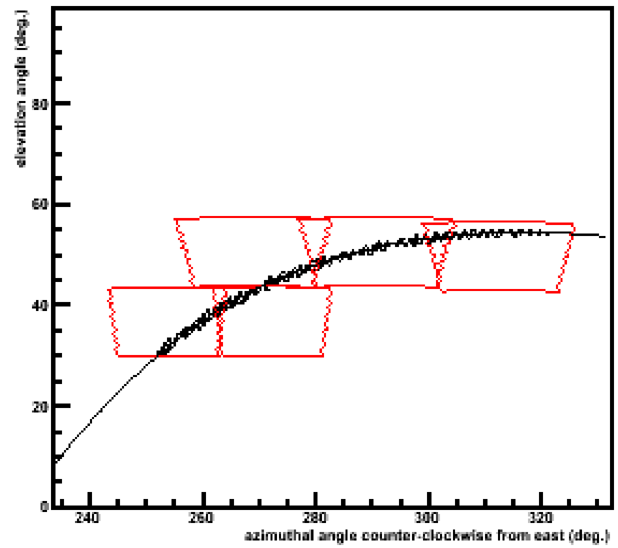
Middle Drum TA/TALE Viewing Range

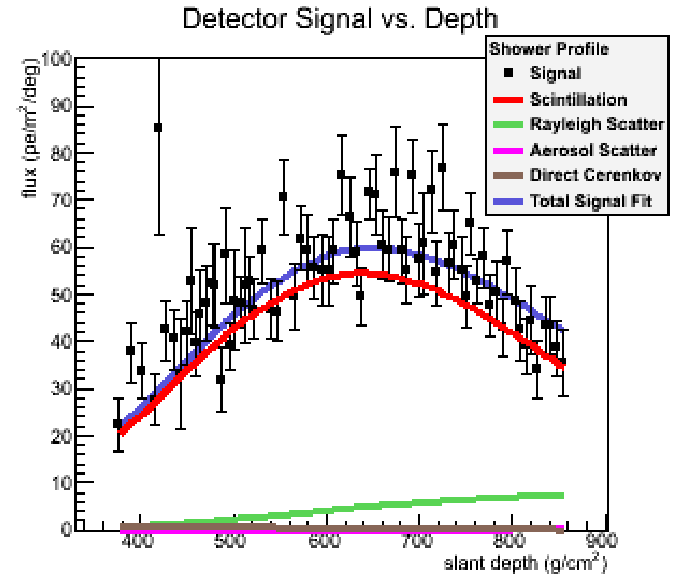
- TAMD + TALE
- 14 lower telescopes make up TA (Middle Drum) Detector.
- 10 higher telescope (new addition) make up the TA-Low Energy extension Detector.
- TALE telescopes equipped with (HiRes2) FADC electronics.

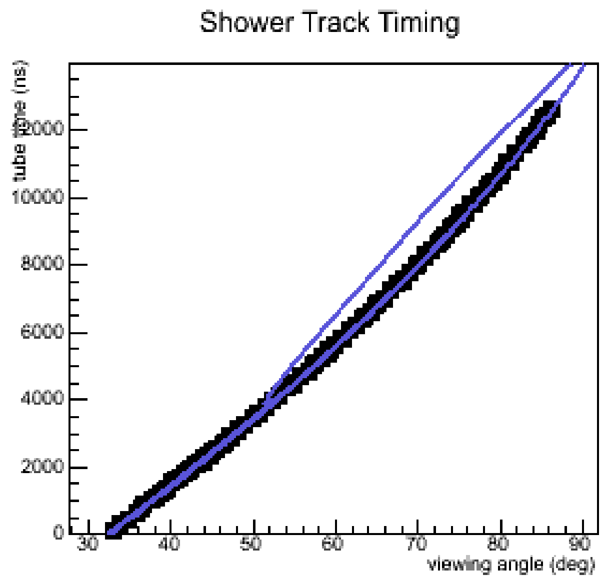


Example Fluorescence event seen by TALE FD

- Five telescope (eight with ring 1-2 mirrors) event.
- Event duration ~ few micro-seconds
- Long angular extent
- Likely to trigger ground array
- Threshold ~3e16 eV







TALE event data

Event Starting: 7: 0:0.695370

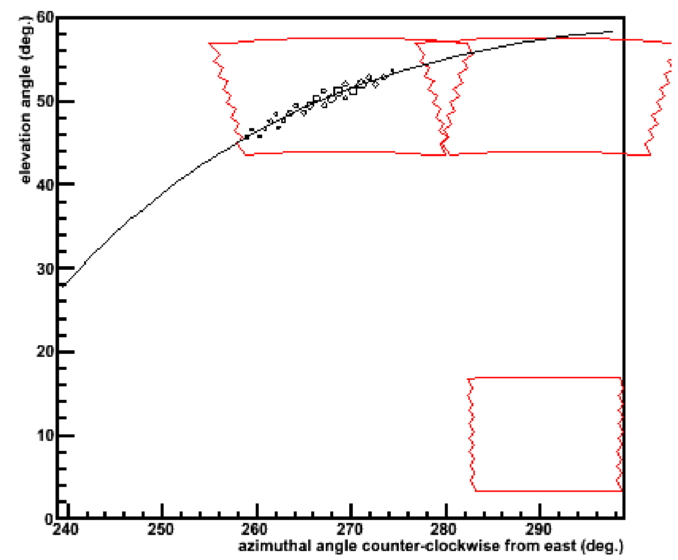
Energy: 0.530 EeV
Shower max size: 3.565e+08 particles
Shower max depth: 631.247 g/cm^2
Profile Fit χ^2/ndf: 1.2395

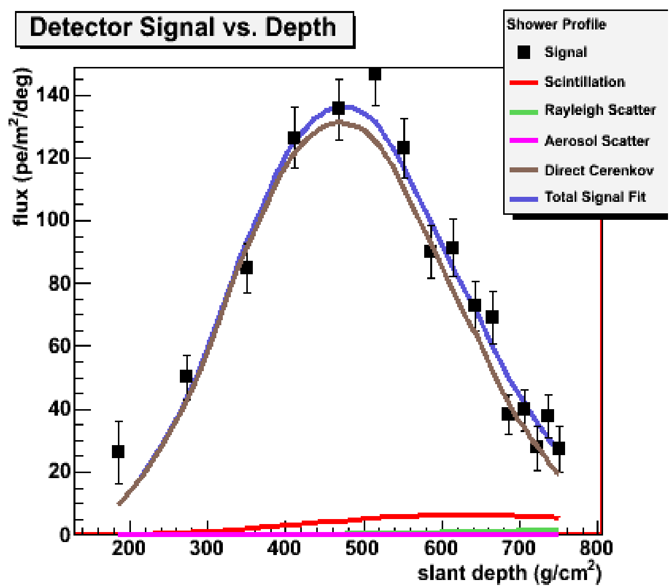
Rp Magnitude: 5.839 km
ψ angle: 55.1 degrees

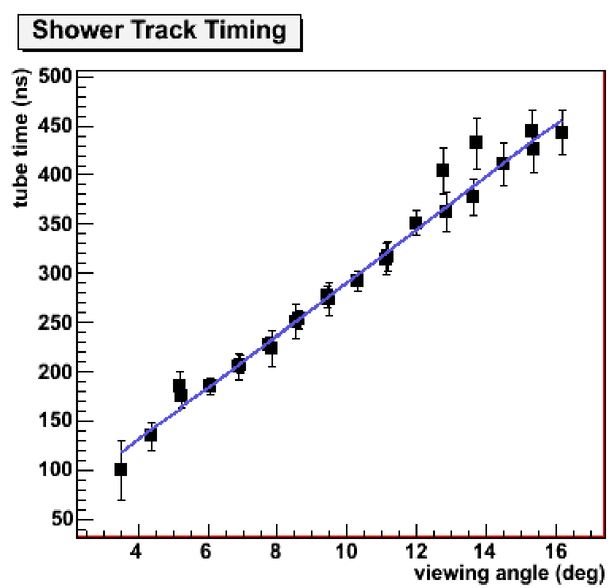
Shower azimuthal angle: 8.2 degrees
Shower zenith angle: 48.0 degrees
Angle to Magnetic field: 60.5 degrees

Example Cerenkov event seen by TALE FD

- Most C'kov events are single telescope
- Event duration ~100ns - ~600 ns
- Short angular extent
- Unlikely to trigger surface detector
- Threshold ~3e15 eV







TALE event data

Event Starting: 0: 0:0.139663747441801

Energy: 9.241 PeV
Shower max size: 6.143e+06 particles
Shower max depth: 605.810 g/cm^2
Profile Fit χ^2/ndf: 0.7362

Rp Magnitude: 0.912 km
ψ angle: 106.9 degrees

Shower azimuthal angle: -80.1 degrees
Shower zenith angle: 35.0 degrees

TALE Event Reconstruction

- Event reconstruction entails reconstructing:
- Shower geometry:
  - Required for profile/energy reconstruction
  - Arrival direction of primary particle (anisotropy)
- Shower profile/energy:
  - Primary particle energy (spectrum)
  - Profile xmax indicates particle type (composition)

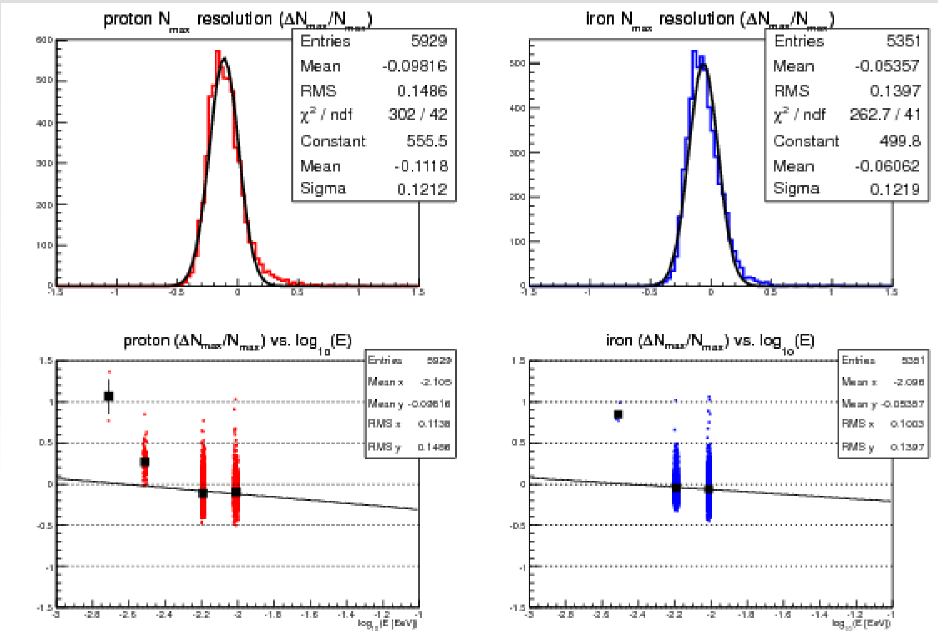
TALE Event Reconstruction

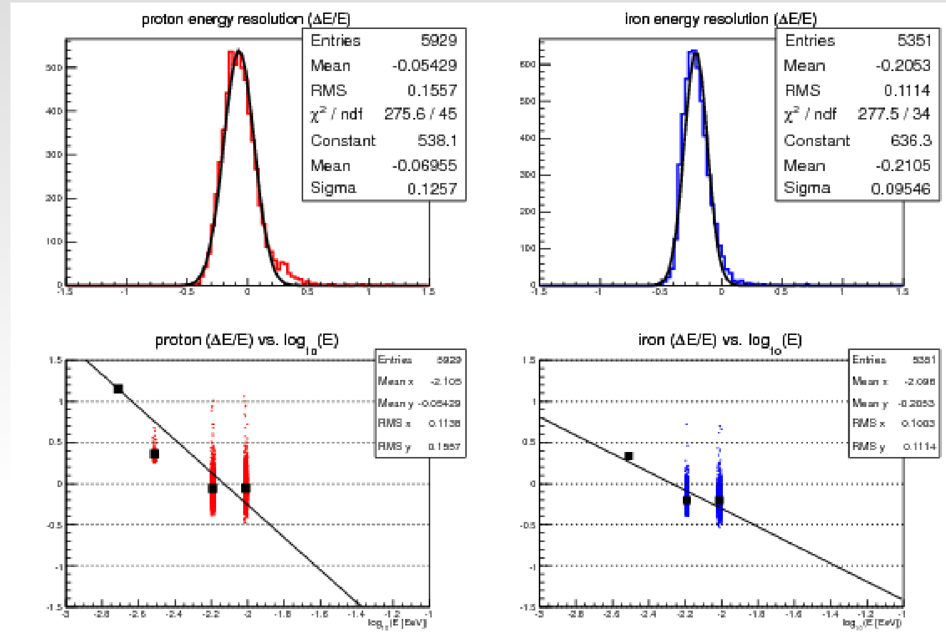
- Event reconstruction method:
- TALE Cerenkov events are reconstructed as *monocular* events:
  - Surface array data not available for vast majority of events (energy too low, and/or core location outside of array)
- Profile constrained Geometry Fit (PCGF) method (developed and used for HiRes-I analysis) is adapted for TALE.
  - Event angular extent (track-length) too short.

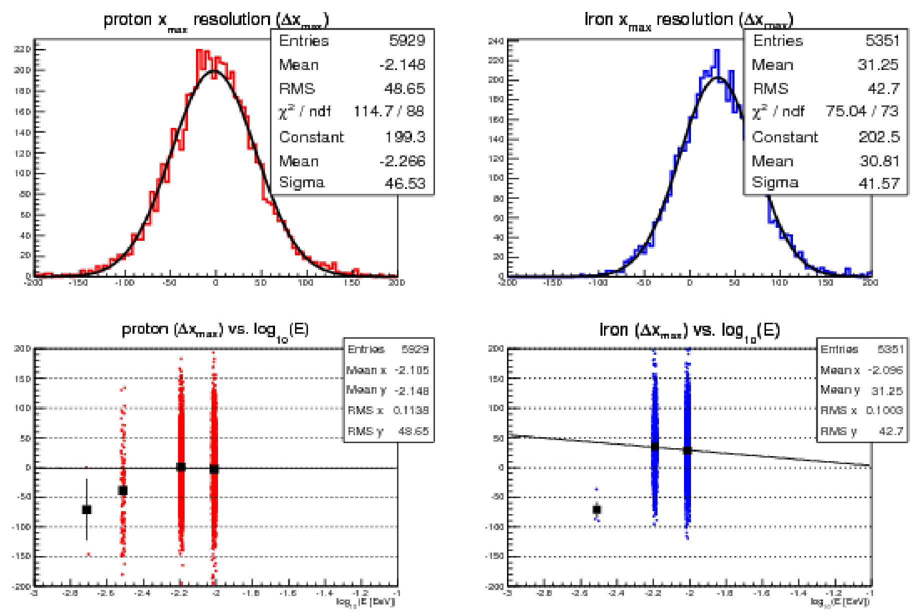
TALE Corsika-IACT MC

- Corsika / IACT (arXiv:0808.2253 [astro-ph])
  - Full 3D MC shower development
  - Cerenkov photons production
  - Cerenkov photons detection (sphere surrounding telescope mirror)
- We can test our reconstruction code (and parameterizations) ***against an external, "true MC" simulation***.

Events with reconstructed E > 4 PeV

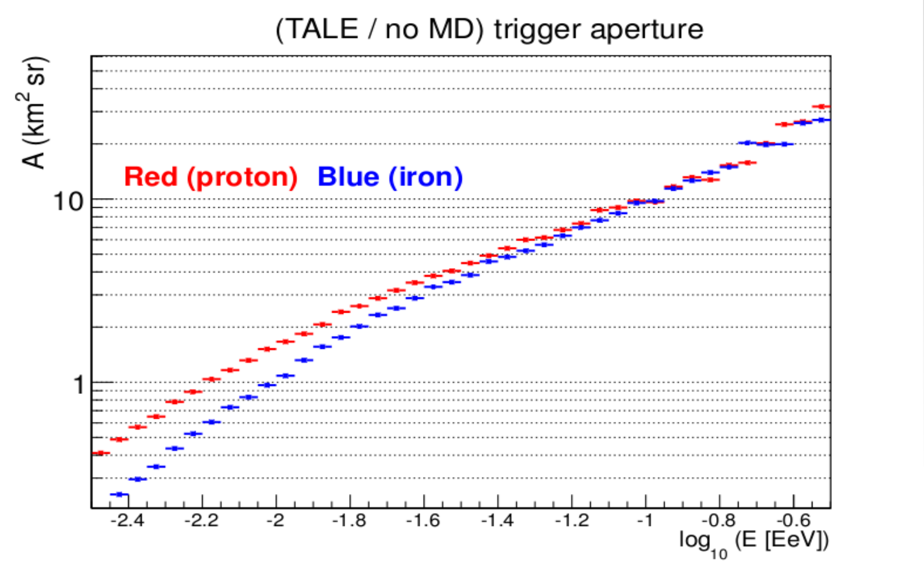


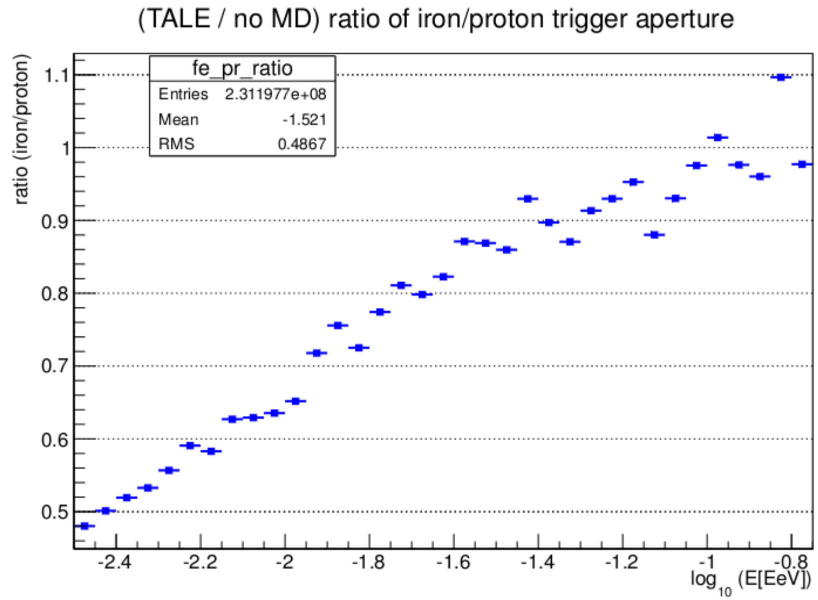




TALE Trigger Aperture

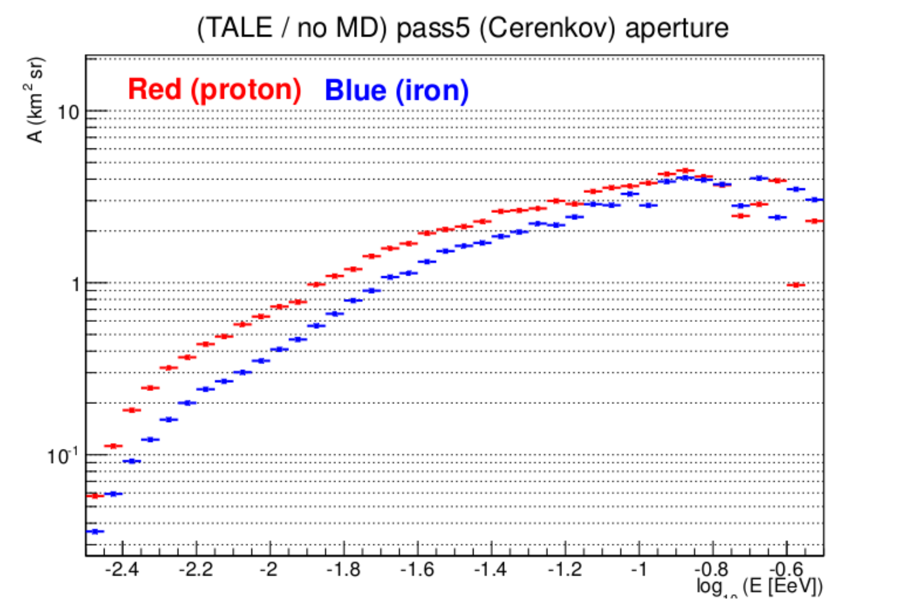
- Protons penetrate deeper and are more likely to trigger.
- At higher energies, composition dependence becomes less pronounced.

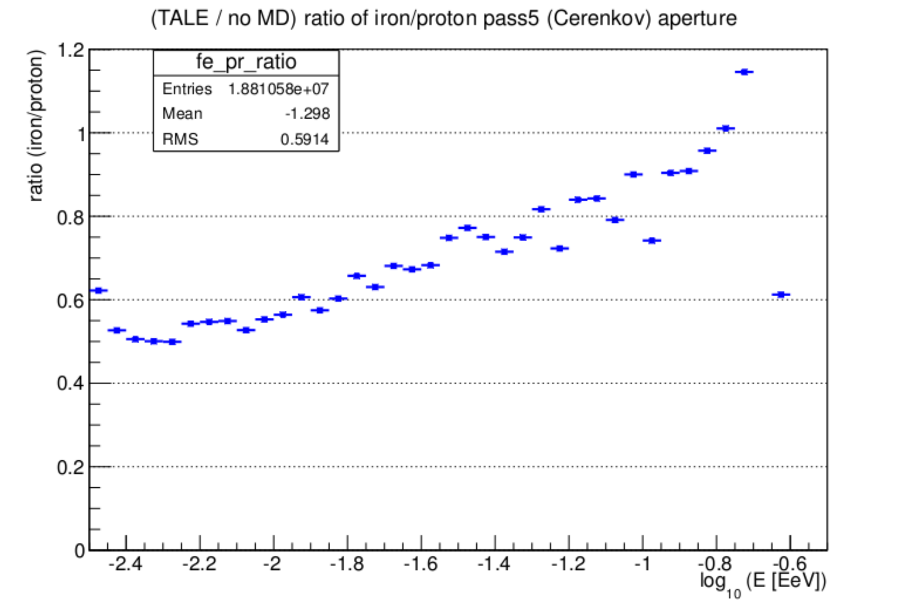




TALE Cerenkov Reconstructible Aperture

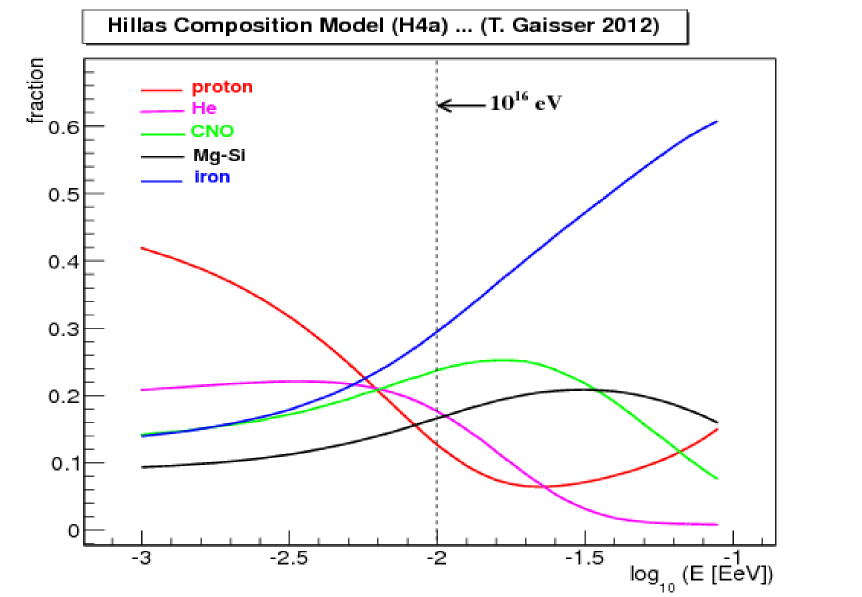
- Cut on Cerenkov fraction limits growth of aperture at high energies.
- Iron/Proton reconstruction efficiency slightly different.
- Note: Above 10^{17} eV fluorescence overtakes Cerenkov. (not shown)

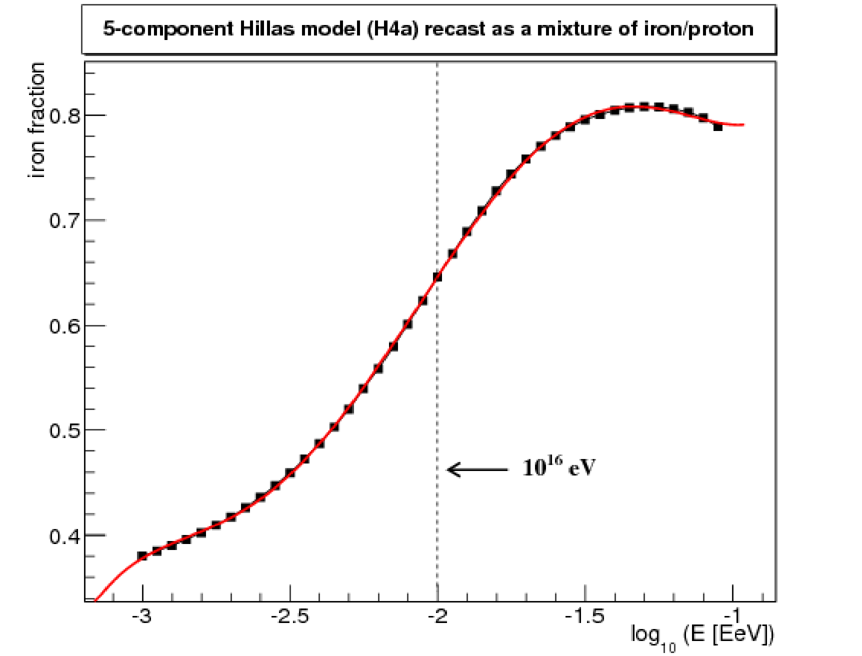




Composition Assumption

- T. Gaisser in a 2012 paper proposed a composition model based on ideas of Hillas (2005) and based on available CR data (CREAM experiment and others)
- In the second plot I assign the intermediate nuclei to either proton or iron components based on their atomic mass. … This is a temporary solution due to lack of simulations with these primaries.





TALE Data 09/06/13-12/06/13

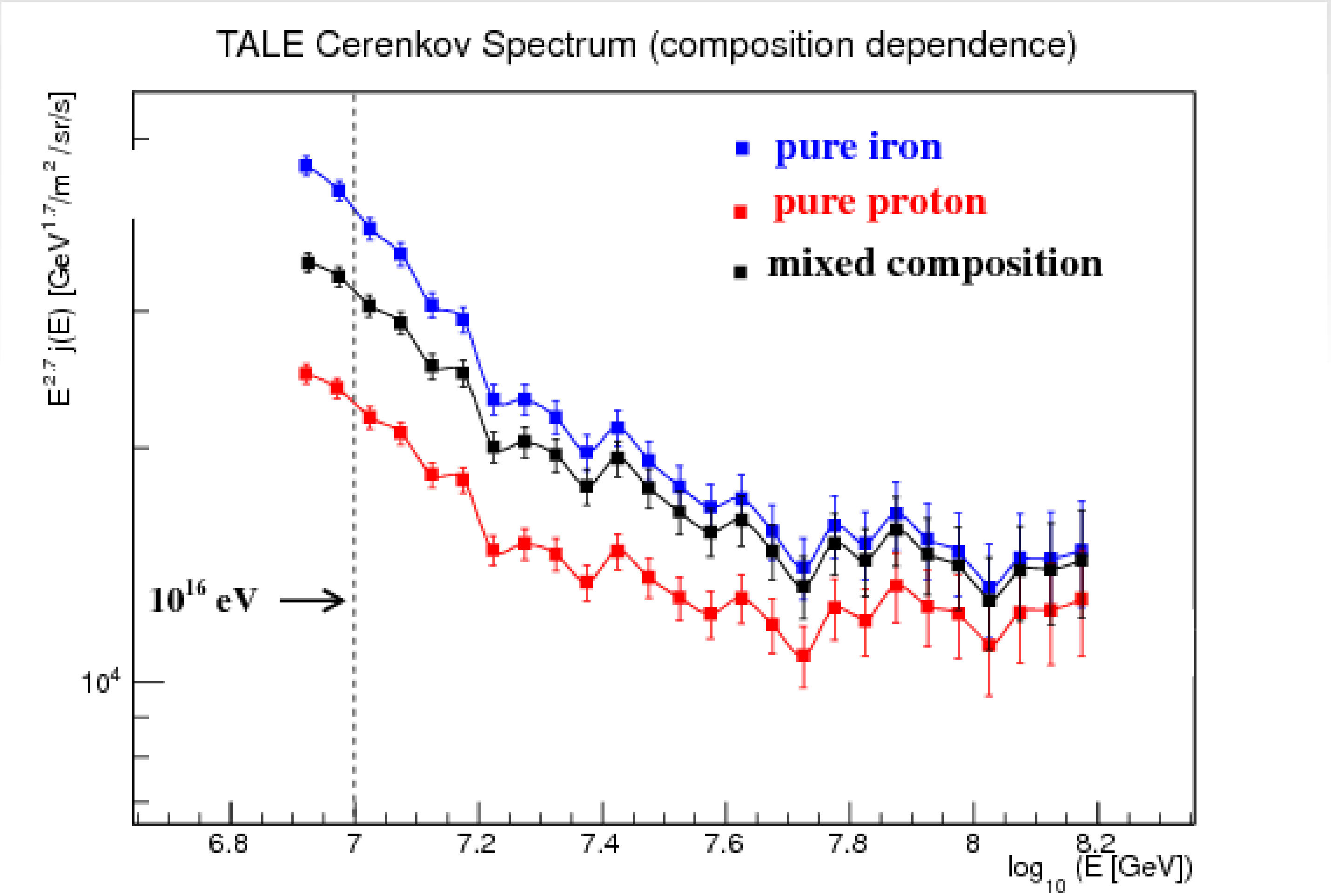
- Most of run nights included.
- Good weather selection: "clear overhead".
- Some nights, only 8 or 9 live mirrors. Average given is per 10 mirrors.
- ***130 hours*** total

```
ontime summary:
mirid 15 ontime        158.6642 hours
mirid 16 ontime        167.8622 hours
mirid 17 ontime        130.3042 hours
mirid 18 ontime        125.0672 hours
mirid 19 ontime        169.2778 hours
mirid 20 ontime        173.4100 hours
mirid 21 ontime        159.7686 hours
mirid 22 ontime        176.2797 hours
mirid 23 ontime        155.4814 hours
mirid 24 ontime        171.9464 hours
  all mir average    158.8062 hours   ( 9528.37 minutes)
ring3 mir average    155.4914 hours   ( 9329.49 minutes)
ring4 mir average    162.1209 hours   ( 9727.25 minutes)
```

```
ontime summary:
mirid 15 ontime        130.2761 hours
mirid 16 ontime        139.2289 hours
mirid 17 ontime        106.0219 hours
mirid 18 ontime        102.7808 hours
mirid 19 ontime        138.9392 hours
mirid 20 ontime        141.1650 hours
mirid 21 ontime        130.4131 hours
mirid 22 ontime        143.1025 hours
mirid 23 ontime        126.3481 hours
mirid 24 ontime        138.6161 hours
  all mir average    129.6892 hours   ( 7781.35 minutes)
ring3 mir average    127.5420 hours   ( 7652.52 minutes)
ring4 mir average    131.8363 hours   ( 7910.18 minutes)
```

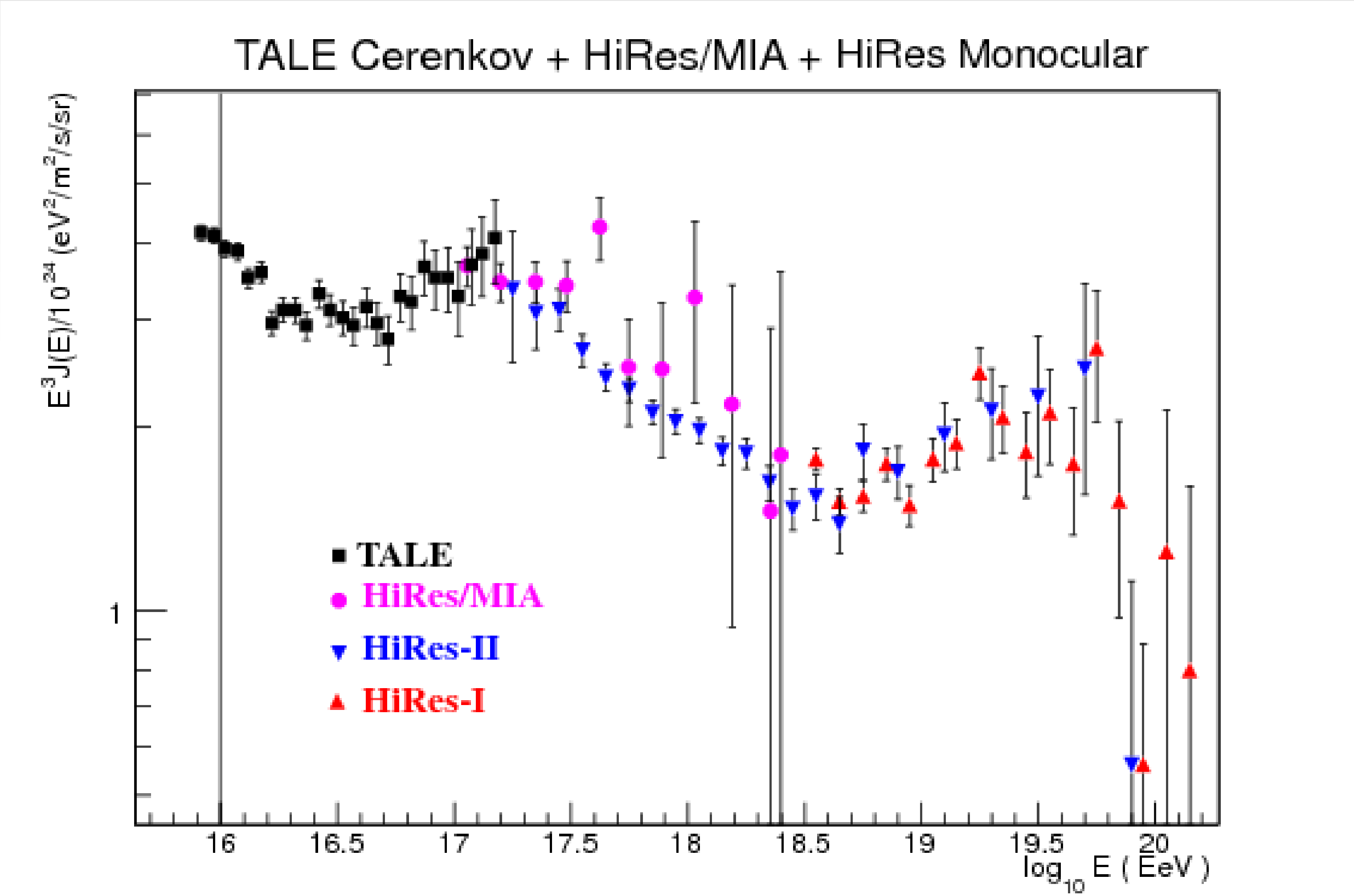
Spectrum (1)

- Spectrum using H4a composition compared to spectra with a pure proton/iron composition



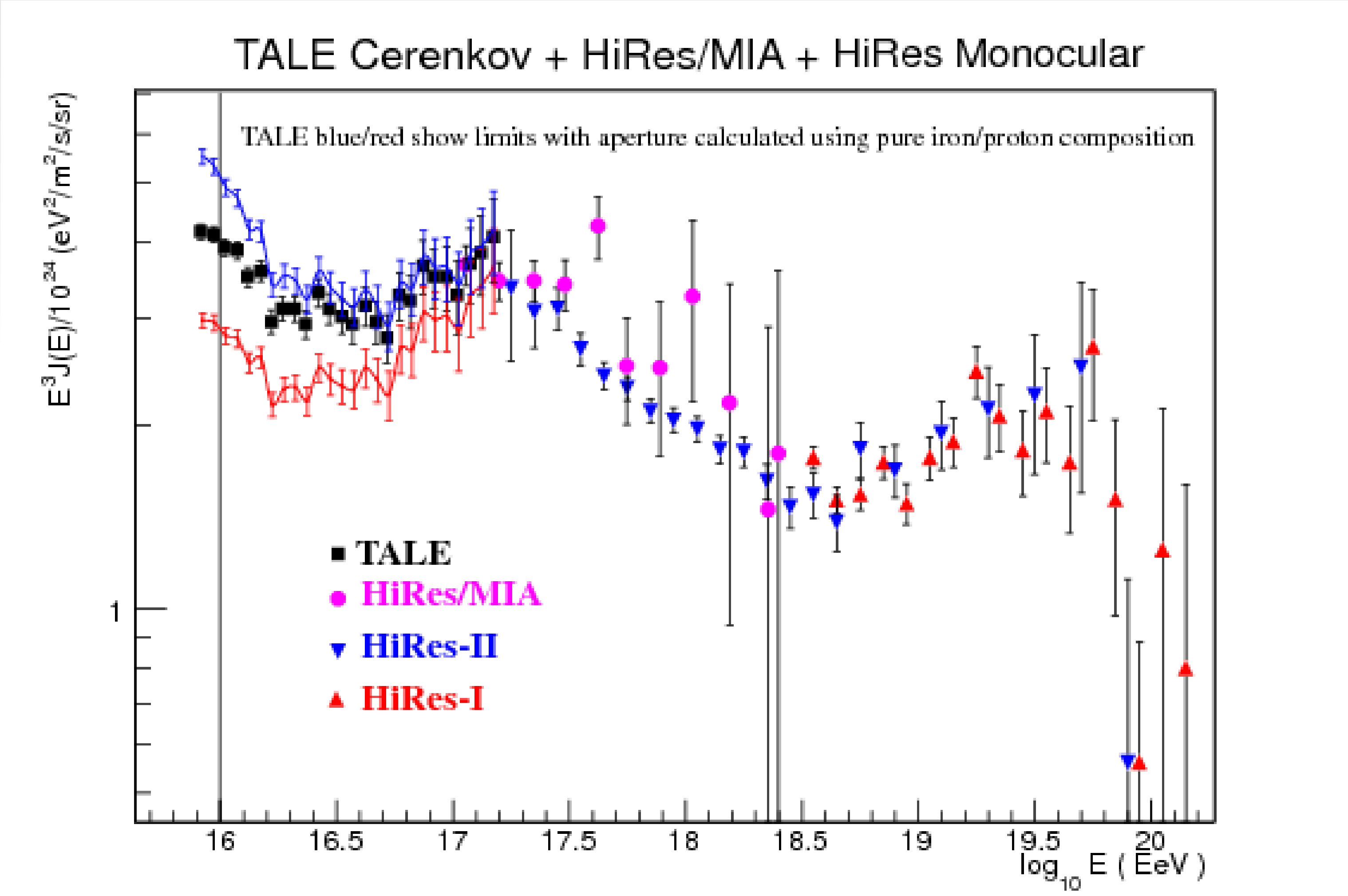
Spectrum (2)

- TALE along with HiRes monocular spectrum and the HiRes/MIA spectrum



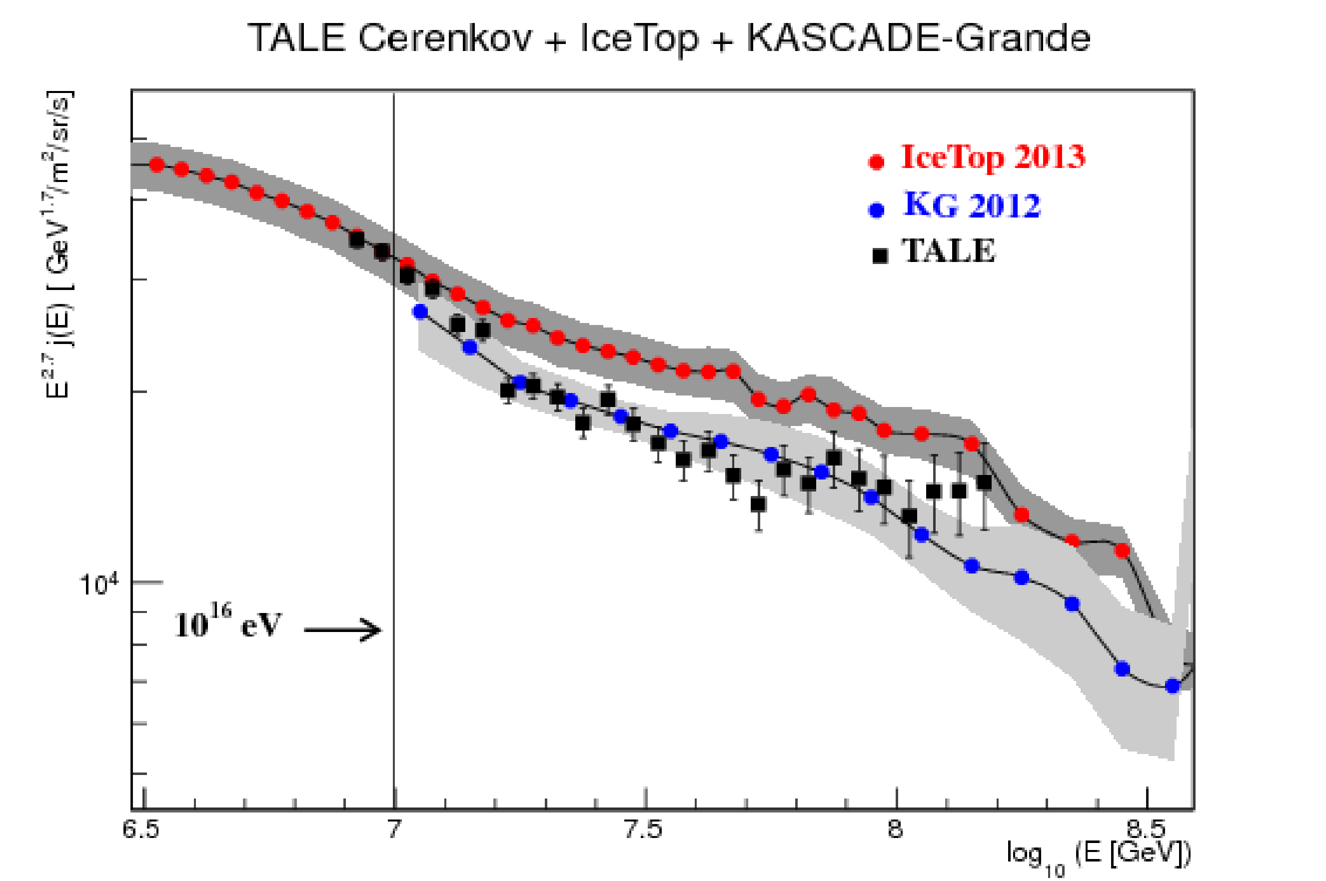
Spectrum (3)

- TALE spectra calculated using a pure iron/proton composition.



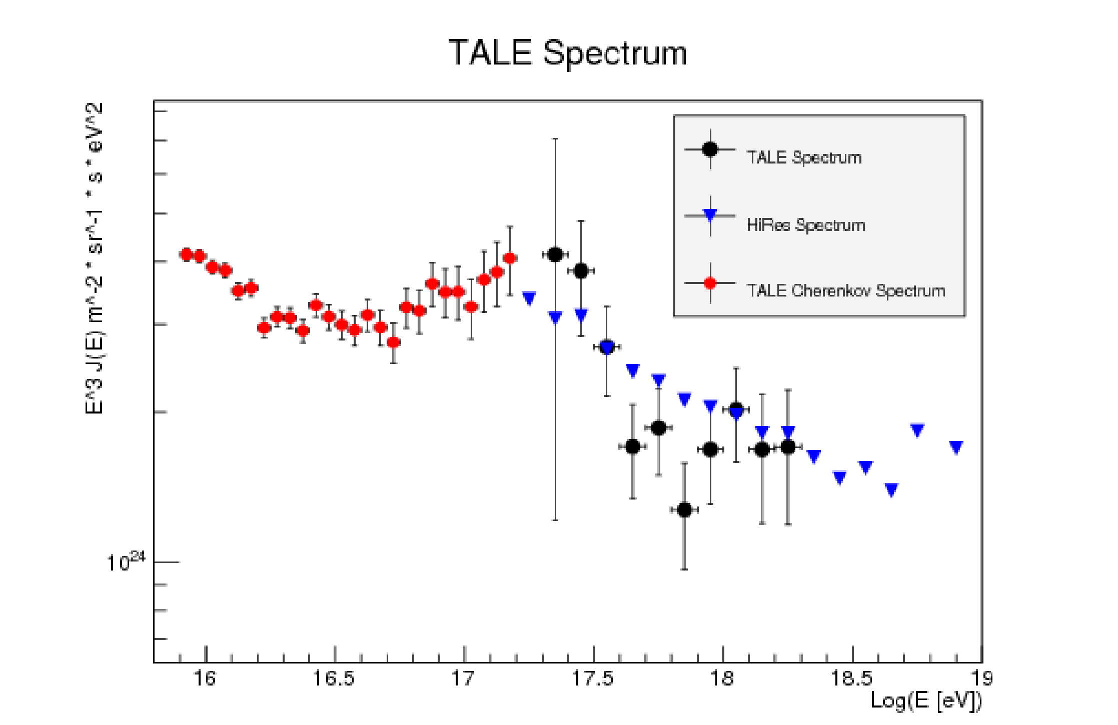
Spectrum (4)

- TALE spectrum compared to measurements from other experiments.



Spectrum (5)

- Lastly, TALE Cerenkov along with TALE Fluorescence Spectrum.
- Fluorescence spectrum presented this morning (session J8) by Z. Zundel: “Fluoresence Detection of Cosmic Ray Air Showers Between $10^{16.5}$ eV and 10^{19} eV with the Telescope Array Low Energy Extension (TALE)”



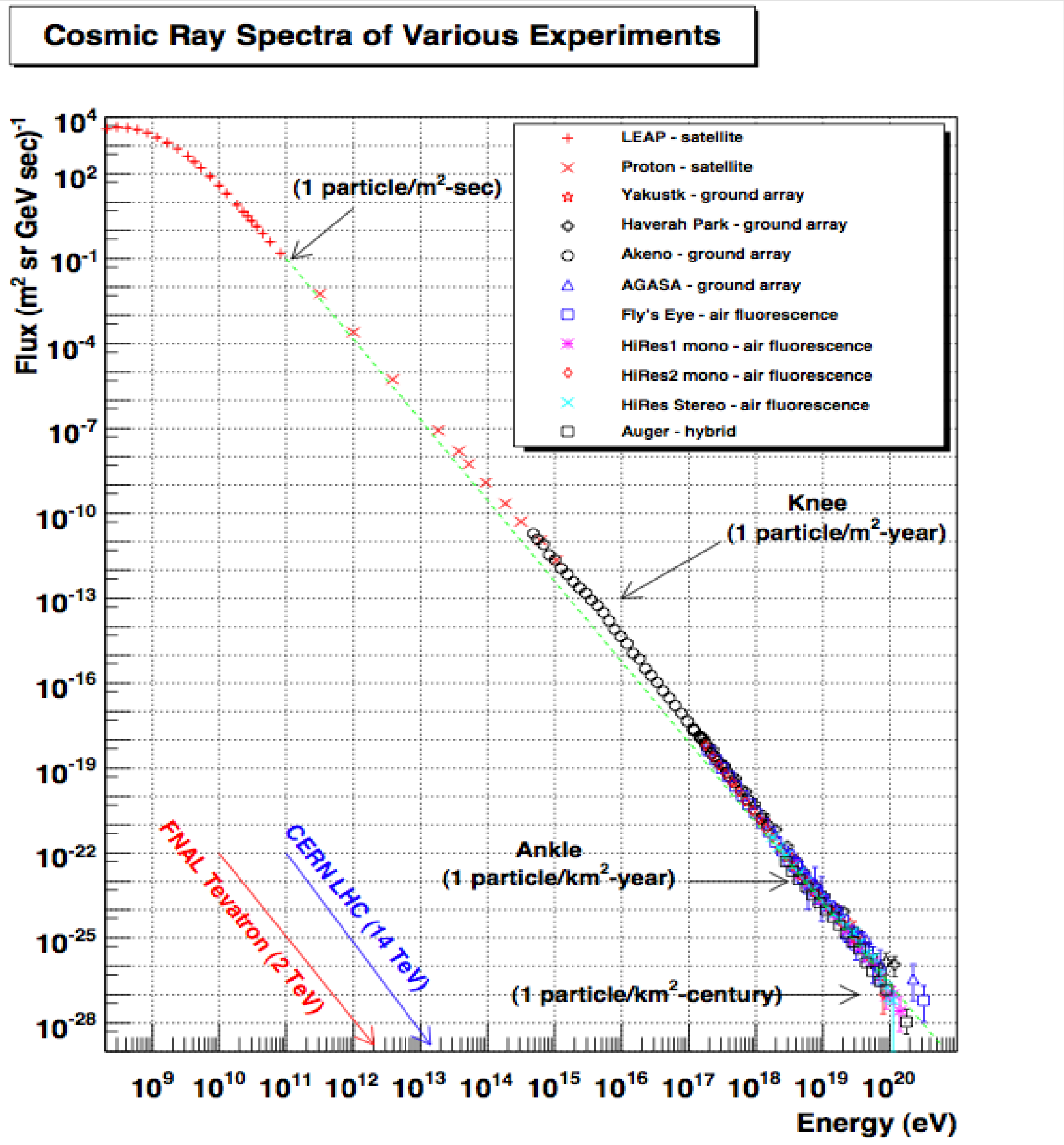
Summary and Outlook

- We developed a new event reconstruction technique which allows us to use TALE as an Imaging Air Cerenkov Telescope.
- TALE as a Cerenkov detector can reach energies lower than 10^{16} eV with very high statistics.
- We performed a first calculation of the cosmic rays energy spectrum using TALE data from the first three months of operation.
- We are just starting, a lot is still left to learn and do.

Backup Slides

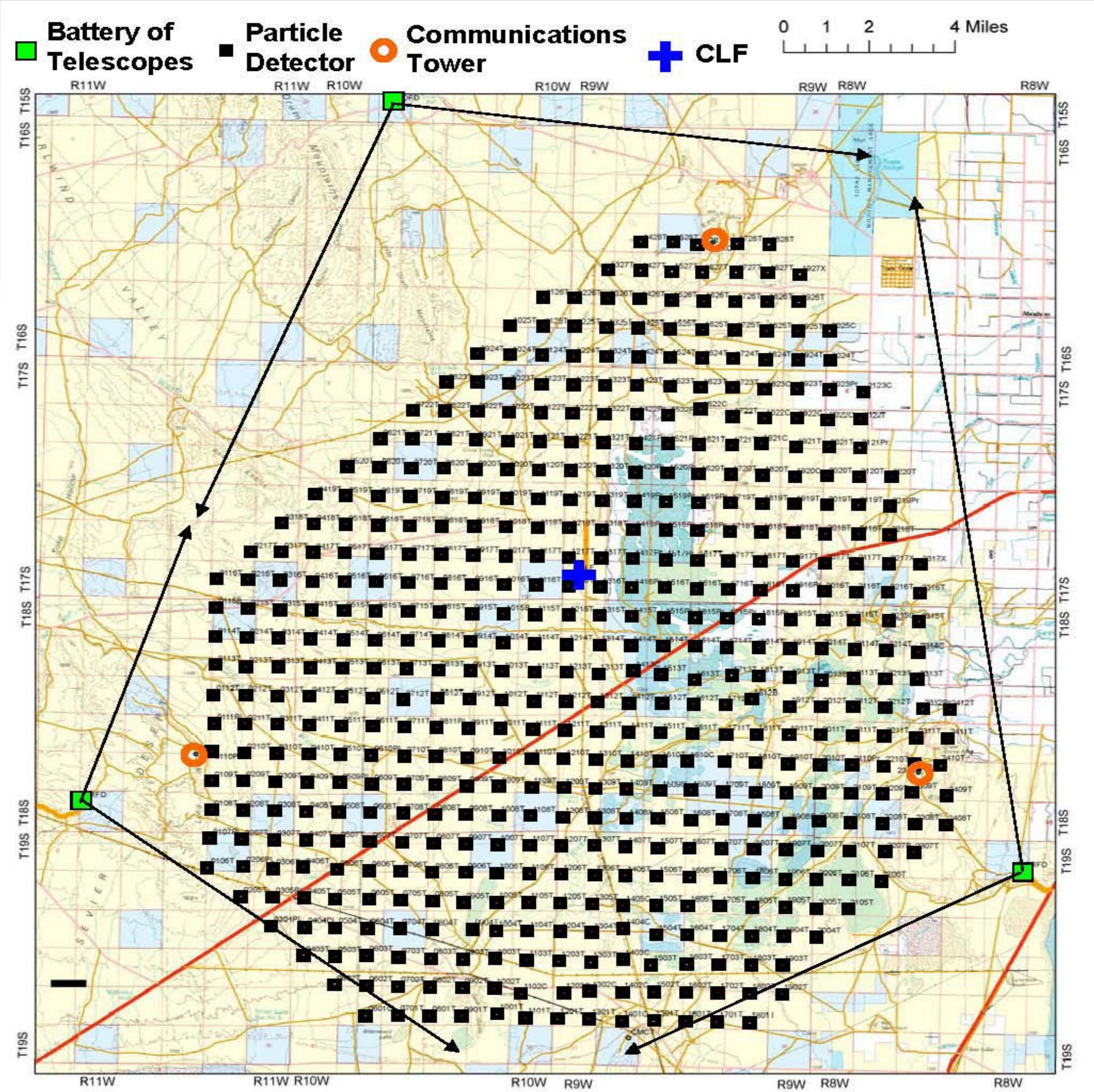
Telescope Array Experiment

- The Telescope Array (TA) experiment was originally designed for the study of ultra high energy (above ~1×10^{18} eV) cosmic rays.
- TA is a follow up experiment to AGASA/HiRes experiments with the goal of improving on both.
- TA Low Energy extension (TALE) aims to lower the energy threshold of the experiment to well below 10^{17} eV.



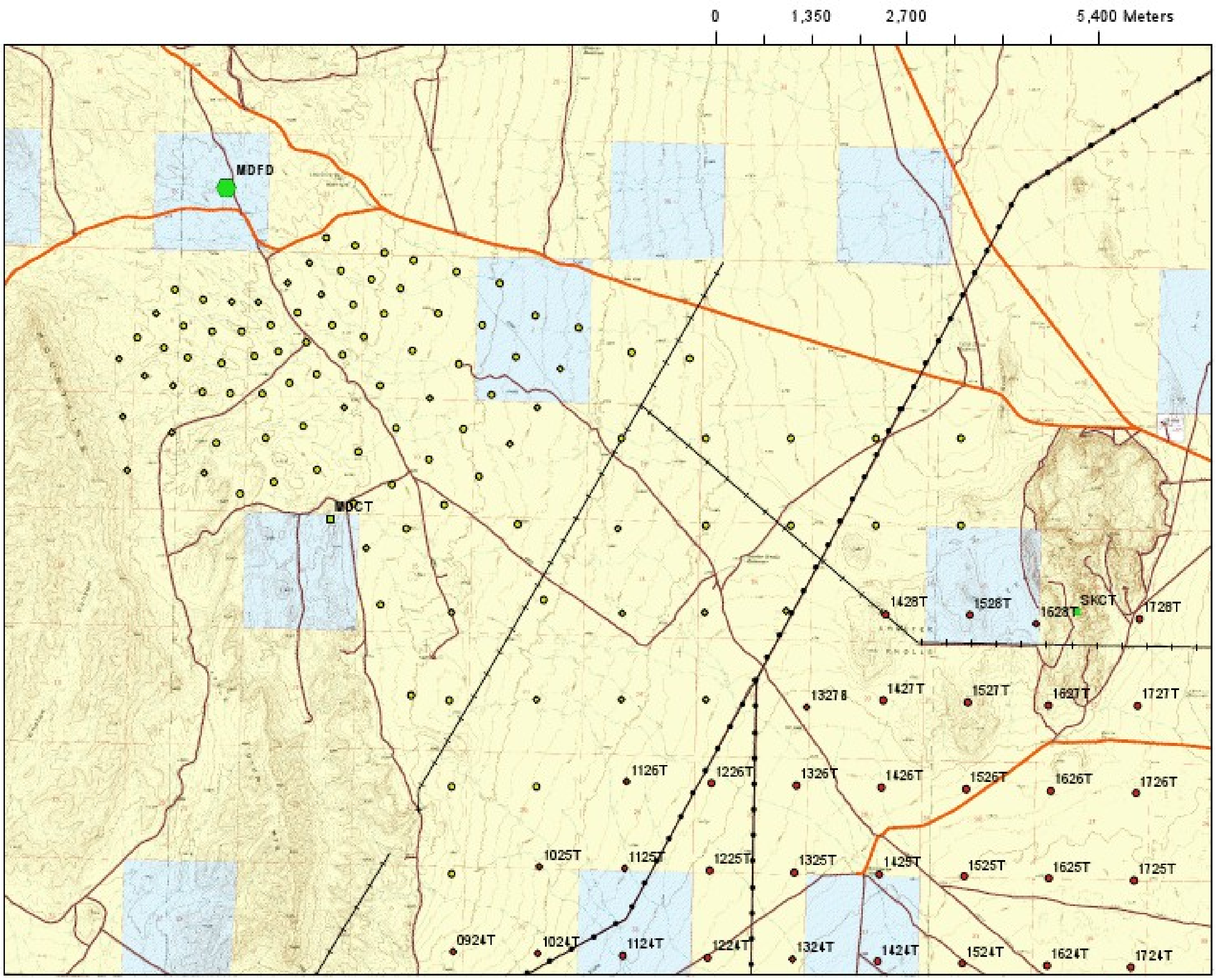
Telescope Array Experiment

- TA is located in Millard County, Utah, ~200 km southwest of Salt Lake City.
- Surface Detector: 507 scintillation counters 1.2 km spacing. (***run 24/7***)
- Three Fluorescence



TALE Surface Detector Infill Array

- Infill Array operates 24/7.
- However, when FD is on, we get the opportunity for hybrid observation.



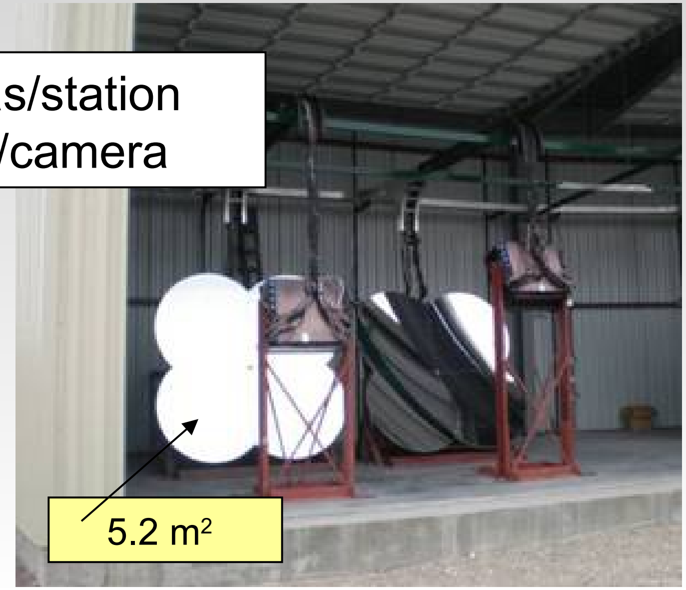
TA Fluorescence Detectors

Refurbished from HiRes

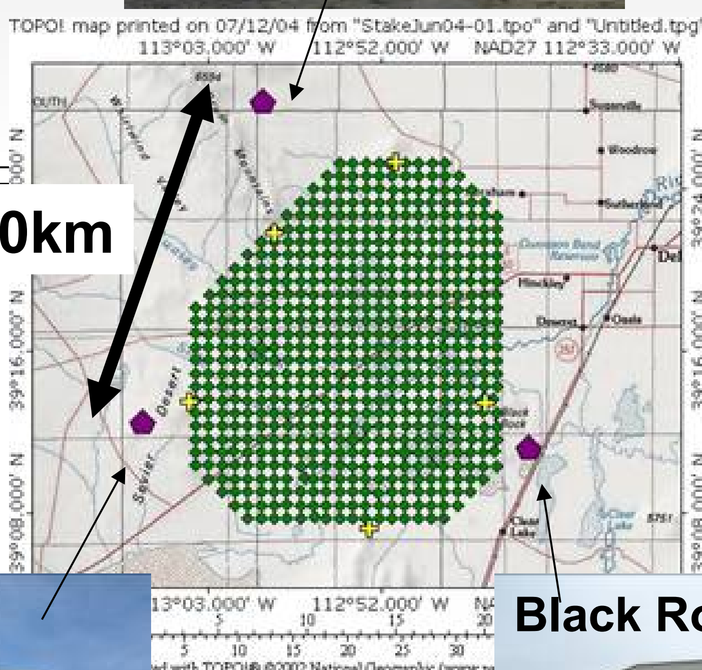
Observation started Dec. 2007

Middle Drum

14 cameras/station
256 PMTs/camera



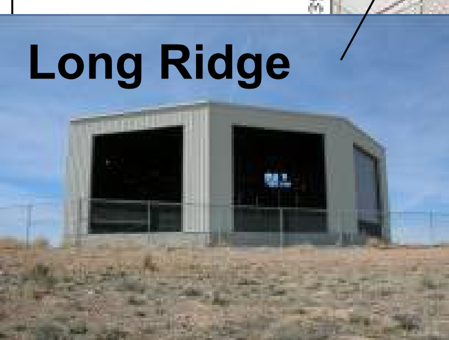
5.2 m²



~30km

Observation started Nov. 2007

Long Ridge



Observation started Jun. 2007

Black Rock Mesa

New FDs

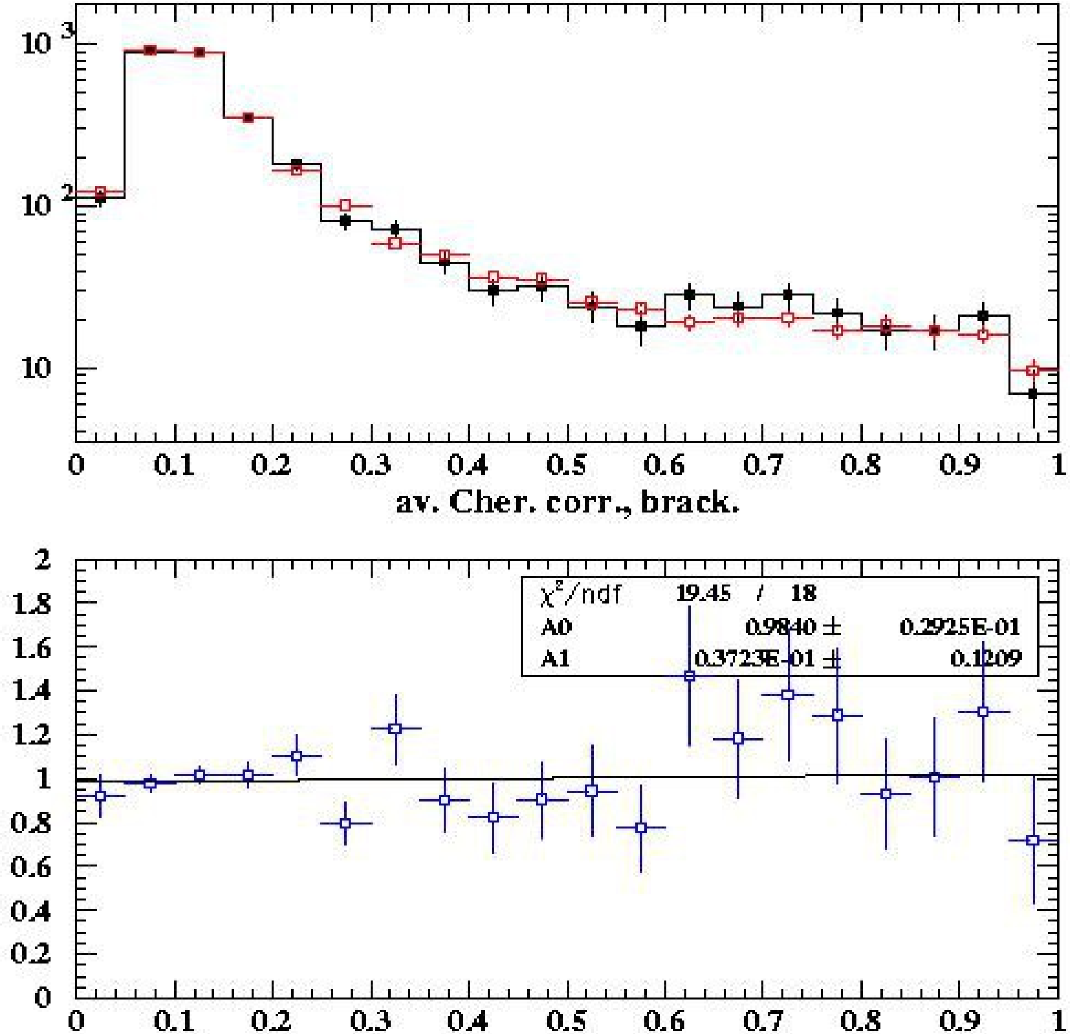
256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

~1 m²

6.8 m²

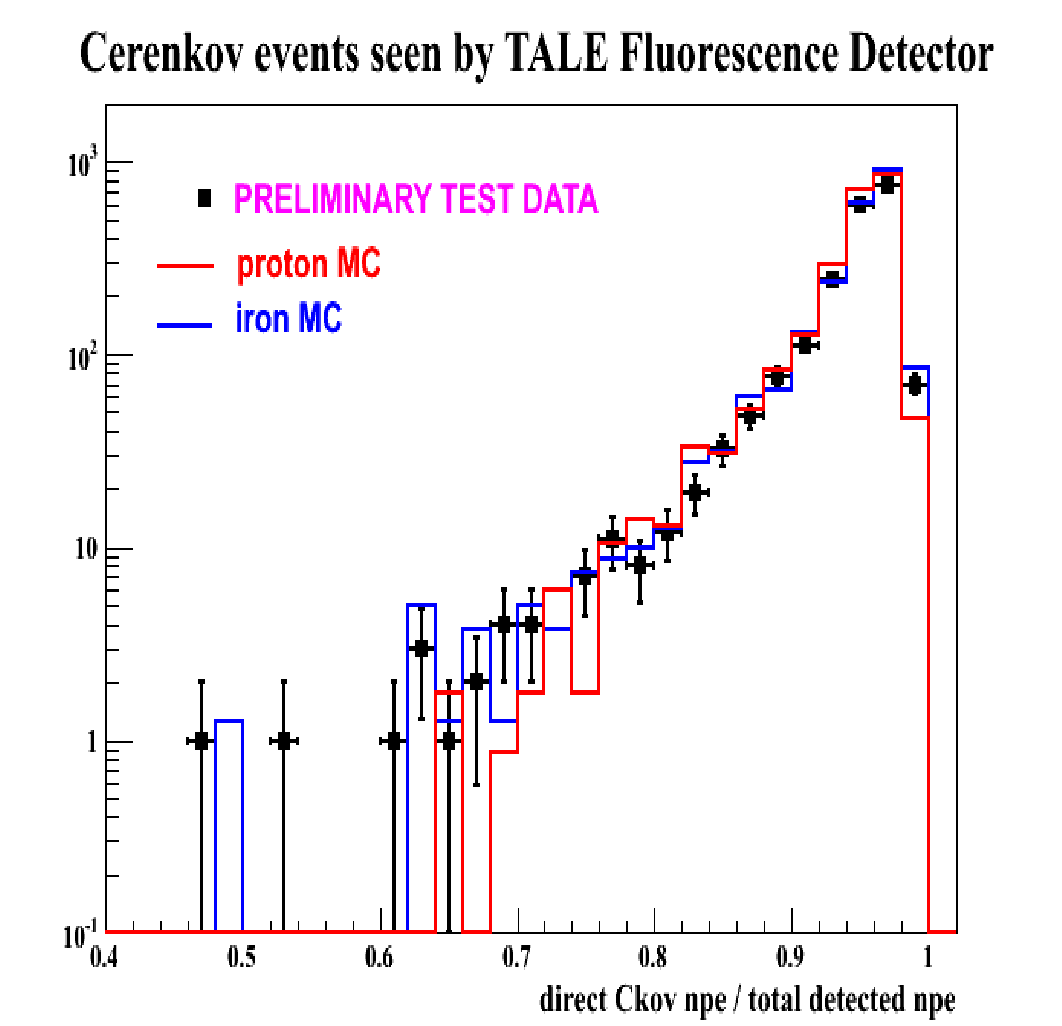
Cerenkov Contribution to Detected Signal

- HiRes-II event set.
- Most events have less than 20% contribution from direct ***and*** scattered Cerenkov light.



Cerenkov Contribution to Detected Signal

- TALE Cerenkov event set.
- Most events have more than 90% contribution from ***direct*** Cerenkov light.



TALE Corsika-IACT MC

- Corsika / IACT (arXiv:0808.2253 [astro-ph])
  - Full 3D MC shower development
  - Cerenkov photons production
  - Cerenkov photons detection (sphere surrounding telescope mirror)
- We can test our reconstruction code (and parameterizations) ***against an external, "true MC" simulation***.

TALE Corsika-IACT MC

- Simulation specific to TALE telescopes.
- MD coordinates origin, magnetic filed.
- TA “typical” atmosphere

```
OBSLEV  1.586655e5                              observation level (in cm) (MD - 2Radius)
MAGNET  21.95 46.40                             magnetic field (TA .. Middle Drum)

ATMOSPHERE 11  F                                !TAZ external atmos model (TA Typical)

CERSIZ  5.0                                     !TAZ bunch size Cherenkov photons
CWAVLG  300. 420.                               !TAZ Cherenkov wavelength band

CSCAT   100 2.5e5 0.                            !TAZ scatter Cherenkov events

ARRANG  0.0                                     !TAZ rotation of array to north
TELESCOPE    1848.30    -1635.03     251.03     129.54  !TAZ CT 1 =TALE mir 15
TELESCOPE    2137.39    -1629.84     251.84     129.54  !TAZ CT 2
TELESCOPE    2576.55    -1959.19     252.47     129.54  !TAZ CT 3
TELESCOPE    2849.93    -2053.28     253.05     129.54  !TAZ CT 4
TELESCOPE    3226.95    -2463.69     253.37     129.54  !TAZ CT 5
TELESCOPE    3297.67    -2744.10     253.07     129.54  !TAZ CT 6
TELESCOPE    3588.58    -3209.51     253.05     129.54  !TAZ CT 7
TELESCOPE    3559.09    -3497.11     252.46     129.54  !TAZ CT 8
TELESCOPE    3673.34    -4033.99     251.83     129.54  !TAZ CT 9
TELESCOPE    3547.29    -4294.15     251.02     129.54  !TAZ CT10
```

TALE Corsika-IACT MC

- Simulation fully determines:
  - number of photons
  - location of photon hits (before mirror Reflection)
  - arrival times at the detector

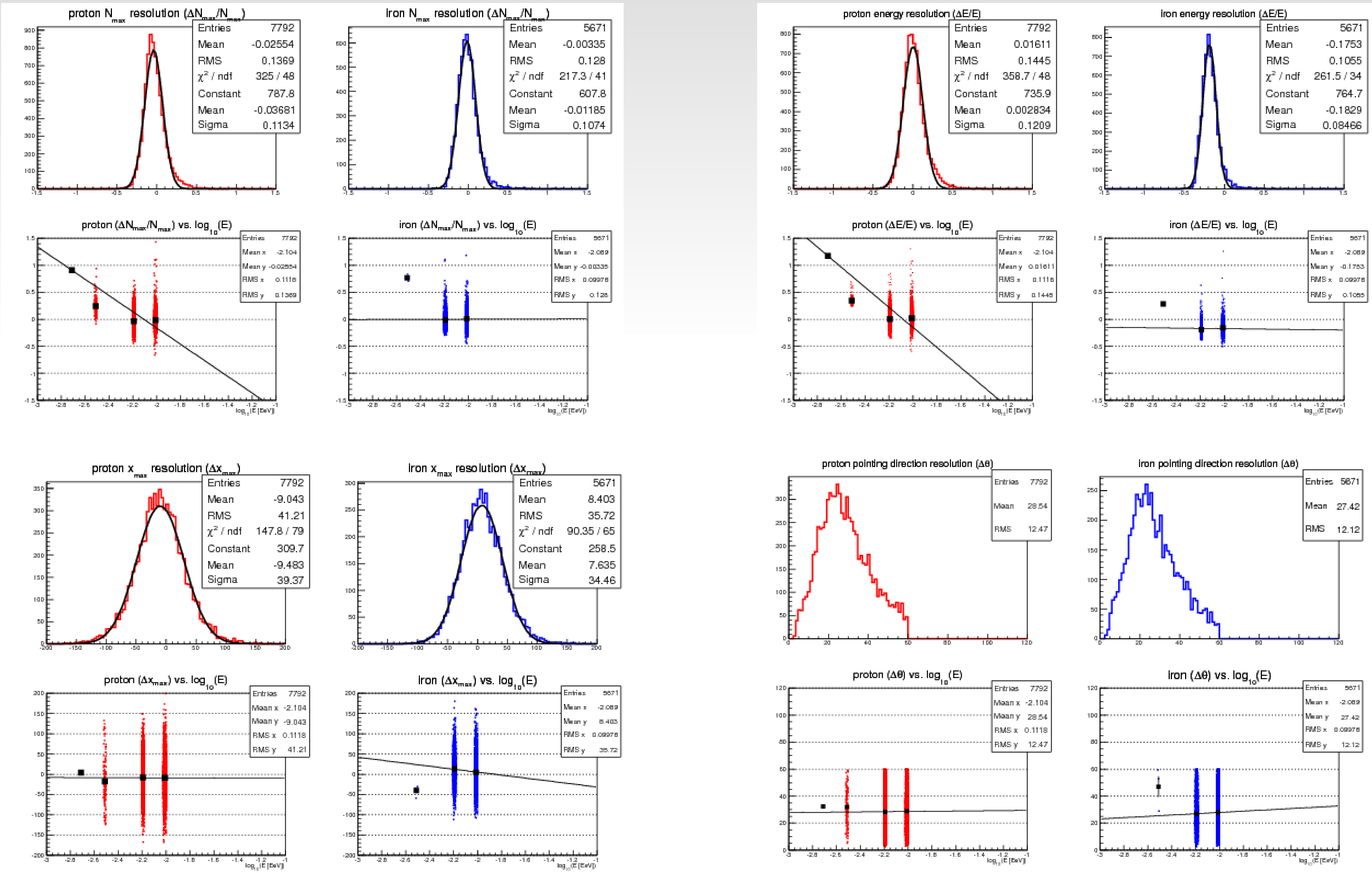
```
/**
 * Photons collected in bunches of identical direction, position, time,
 * and wavelength. The wavelength will normally be unspecified as
 * produced by CORSIKA (lambda=0).
*/

struct bunch
{
   float photons; /**< Number of photons in bunch */
   float x, y;    /**< Arrival position relative to telescope (cm) */
   float cx, cy;  /**< Direction cosines of photon direction */
   float ctime;   /**< Arrival time (ns) */
   float zem;     /**< Height of emission point above sea level (cm) */
   float lambda;  /**< Wavelength in nanometers or 0 */
};
```

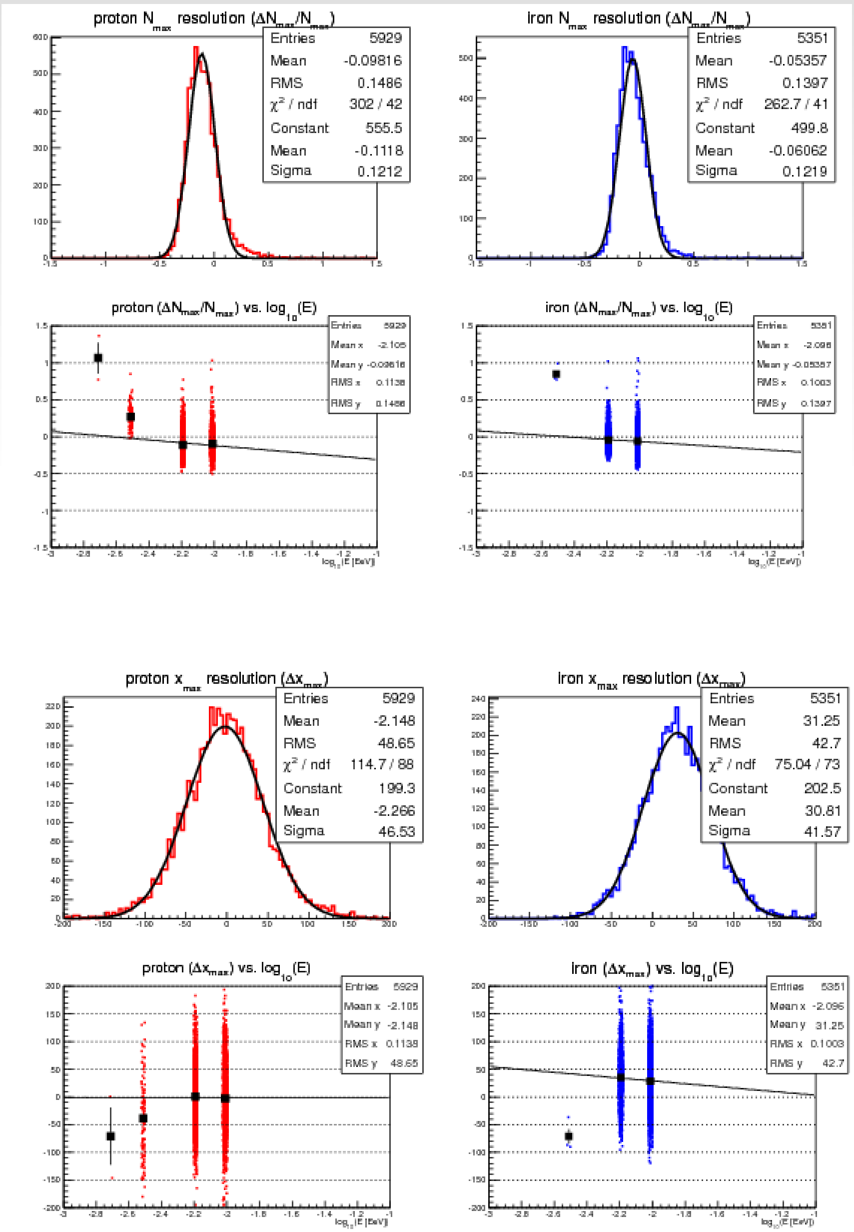
Corsika-IACT simulation results

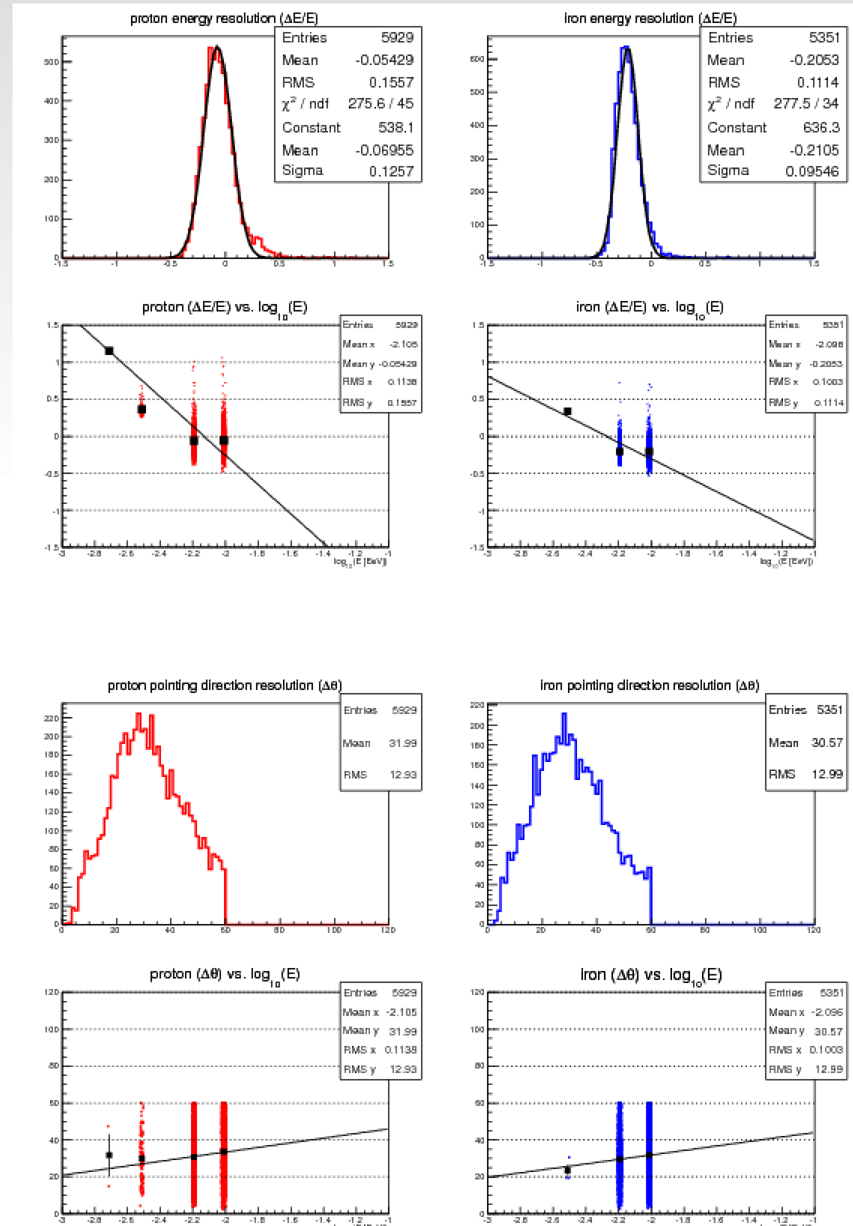
- Look at bias and resolution of reconstruction of MC generated with both options.
- Simulation energies: 2, 3, 5, and 10 PeV
- Shown distributions are for events with reconstructed energy ***greater than*** 4 PeV

With “mine” option



With “theirs” option





Comparison (Bias)

	Mine (proton / iron) Reconstruction Bias	Theirs (proton / iron) Reconstruction Bias	Diff (proton / iron)
Nmax	-4. / -1. %	-11. / -6. %	7. / 5. %
Energy	-0. / -18. %	-7. / -21. %	7. / 3. %
Xmax	-9.5 / 7.6 (g/cm^2)	-2.2 / 30. (g/cm^2)	-7.3 / -22.4 (g/cm^2)

Comparison (Resolution)

	Mine (proton / iron) Reconstruction: Gaussian fit sigma	Theirs (proton / iron) Reconstruction: Gaussian fit sigma	Diff (proton / iron)
Nmax	11. / 10. %	12. / 12. %	1. / 2. %
Energy	13. / 8. %	13. / 10. %	0. / 2. %
Xmax	39. / 34. (g/cm^2)	46. / 42. (g/cm^2)	7. / 8. (g/cm^2)

Corsika-IACT conclusion

- There are still some small differences between simulations done within the detector MC framework and what Corsika predicts:
- Proton energy/Nmax differ by ~7%
- Proton xmax off by ~7 gm
- Iron energy/Nmax differ by ~5%/3%
- Iron xmax by ~22gm
- Widths of all distributions are slightly larger with Corsika simulations.

Known Issues

- No nightly detector or atmospheric calibration. We are working on implementing such a procedure.
- Only proton and iron showers have been considered so far in the MC and analysis. We need to include at least one more intermediate primary.
  - Shower missing energy correction, aperture calculation, etc.
- Reconstruction and quality cuts are still work in progress.