The Cosmic Ray Energy Spectrum above 2 PeV measured by the TALE Fluorescence Telescopes

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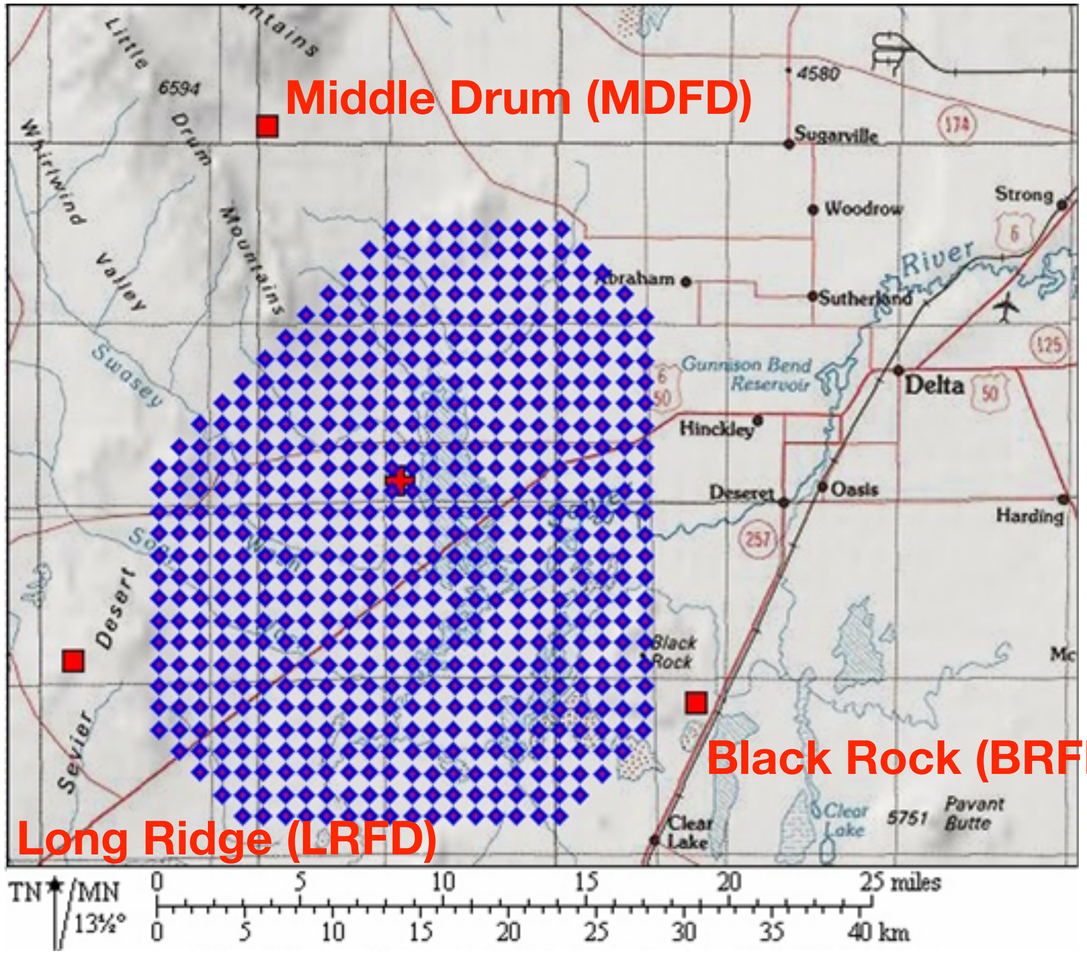
Outline

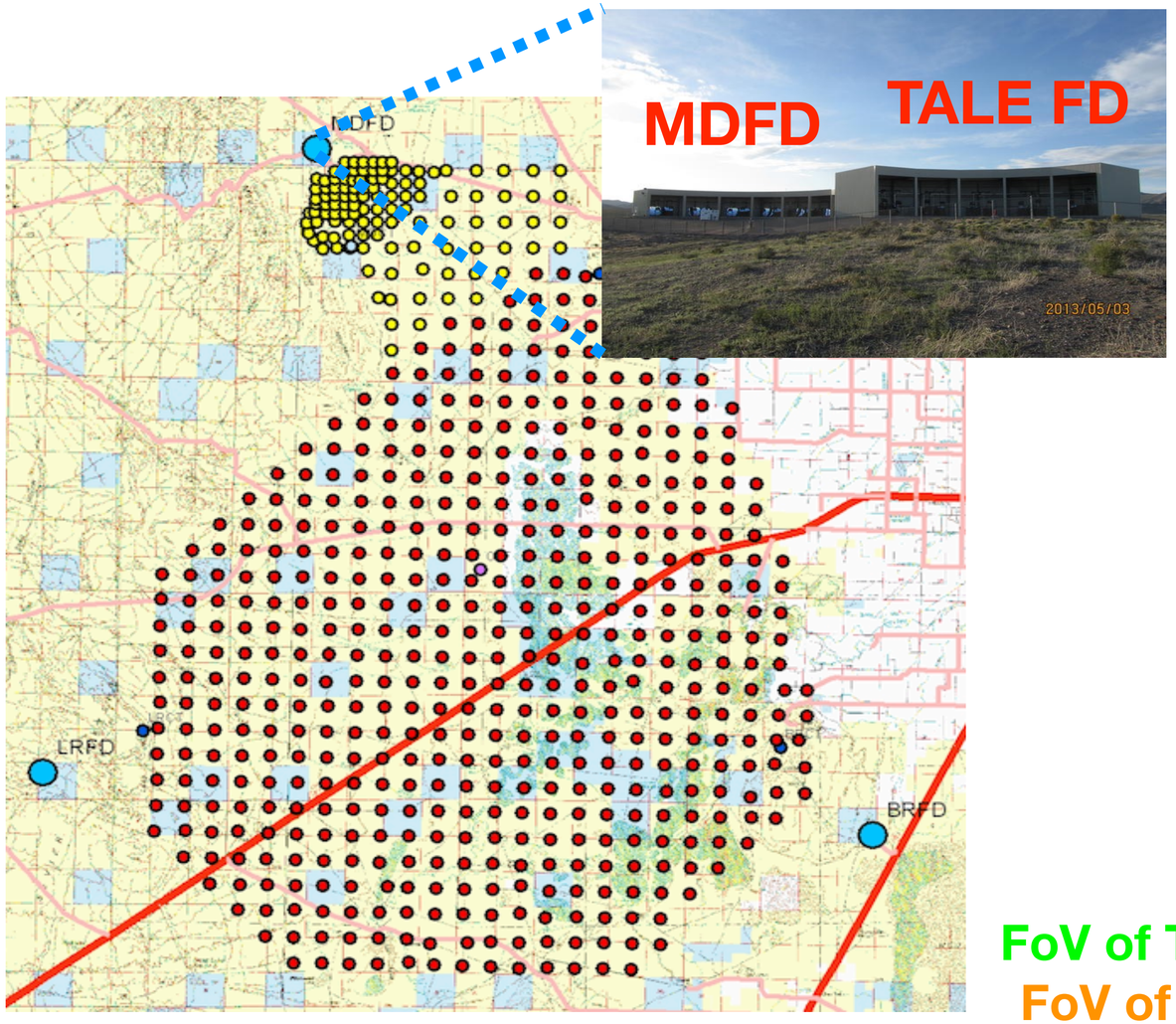
- Telescope Array Low Energy Extension (TALE) Fluorescence Detector
- Spectrum Data/MC Set (a progress report on an incomplete study)
    - MC simulations prioritized for composition study (T. AbuZayyad)
    - New preliminary Spectrum based on EPOS-LHC Conex
        - Affect missing energy correction and aperture calculation - changes energy scale slightly
        - New QGSJETII-03 MC set corresponding to the full 2400 hr data (work in progress)
- Energy Spectra
    - ApJ published TALE energy spectrum (QGSJETII-03) with ~2 years of data
    - Updated TALE energy spectrum (EPOS-LHC) with ~ 4 years of data
- Summary

The Telescope Array Experiment (TA)



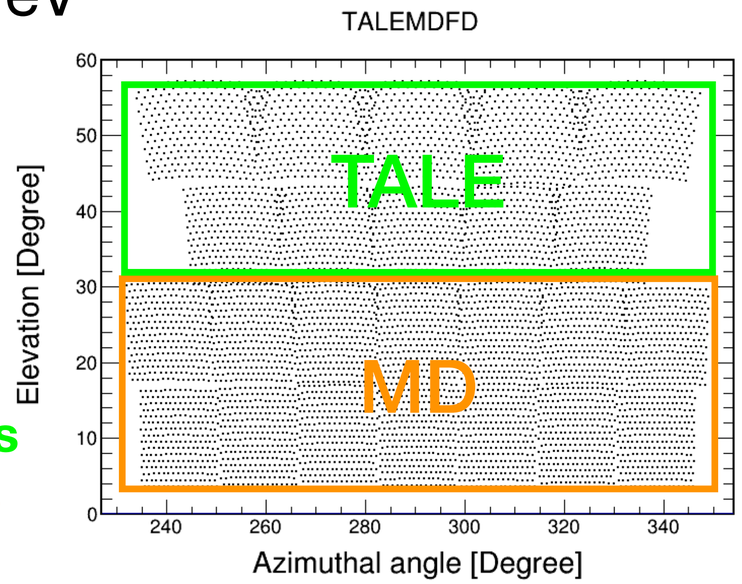
- Largest cosmic ray observatory in the northern hemisphere.
- Observes cosmic rays with energies greater than 10^{18} eV
- 3 telescope stations (■) overlooking an array of 507 scintillator surface detectors (◆)
  - Black Rock fluorescence detector
  - Long Ridge fluorescence detector
  - Middle Drum fluorescence detector
- Central Laser Facility (+)

TA Low Energy Extension (TALE)



- 10 new telescopes looking higher in the sky (31-59° in elevation) at MDFD site
- 80 infill array surface detectors (●)
- Extends the sensitivity of TA down to $10^{15.3}$ eV

FoV of TALE telescopes
FoV of MD telescopes



Spectrum Data/MC set

ApJ published TALE energy spectrum 2018

- **Data : June 2014 - March 2016**
- On-time : ~ 1000 hours
- Good weather data :
  clear over head and no haze
- Fluorescence dominate events included
- **MC : QGSJET II-03 with CONEX**
- Four primaries : p, He, CNO, Fe
- Fit X_{max} distribution to four independent composition to determine primary fraction

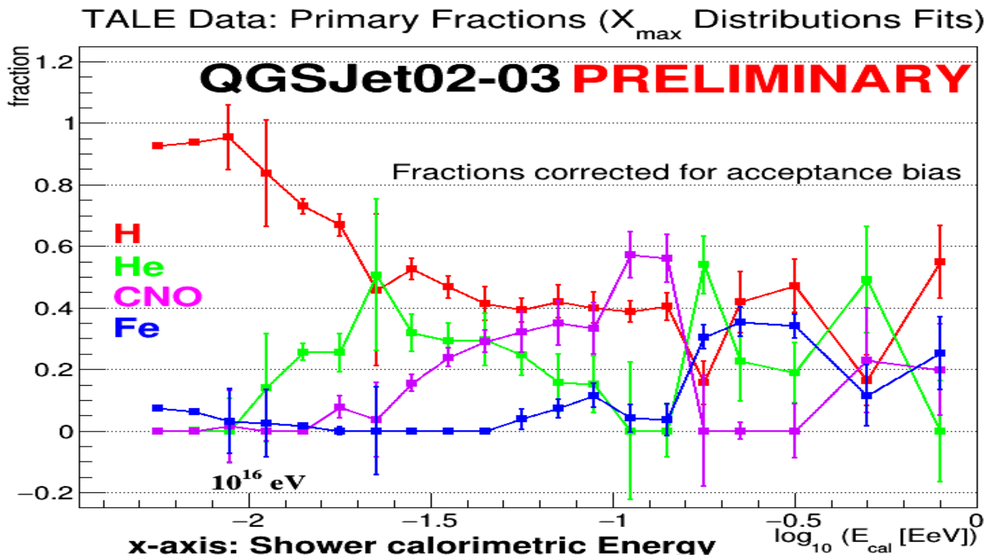
Updated TALE energy spectrum

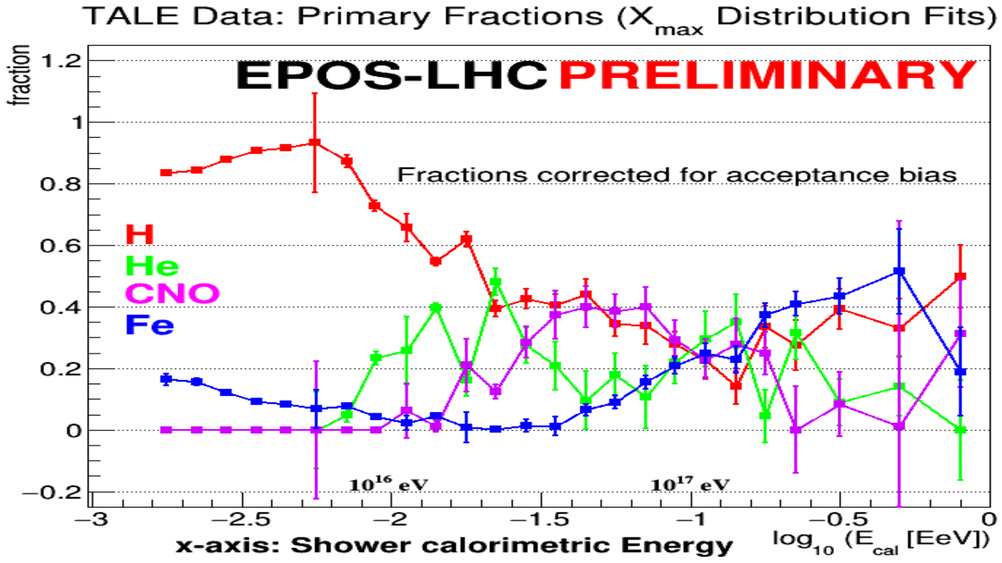
- **Data : June 2014 - November 2018**
- On-time : ~ 2633 hours
- Good weather data :
  clear overhead and no haze
- Cherenkov light dominated events
- **MC : EPOS-LHC with CONEX**
- Four primaries : p, He, CNO, Fe
- Fit X_{max} distribution to four independent composition to determine primary fraction

Spectrum/Aperture Calculation (1/2)

Primary Mixture from X_{max} fit

- For each energy bin:
  - Fit X_{max} distribution to four independent elements : p, He, CNO, Fe
- Obtain primary fractions (composition assumption) for each hadronic interaction model.
- Result in difference in the overall normalization in the spectrum :
  - Aperture estimation
  - Missing energy correction

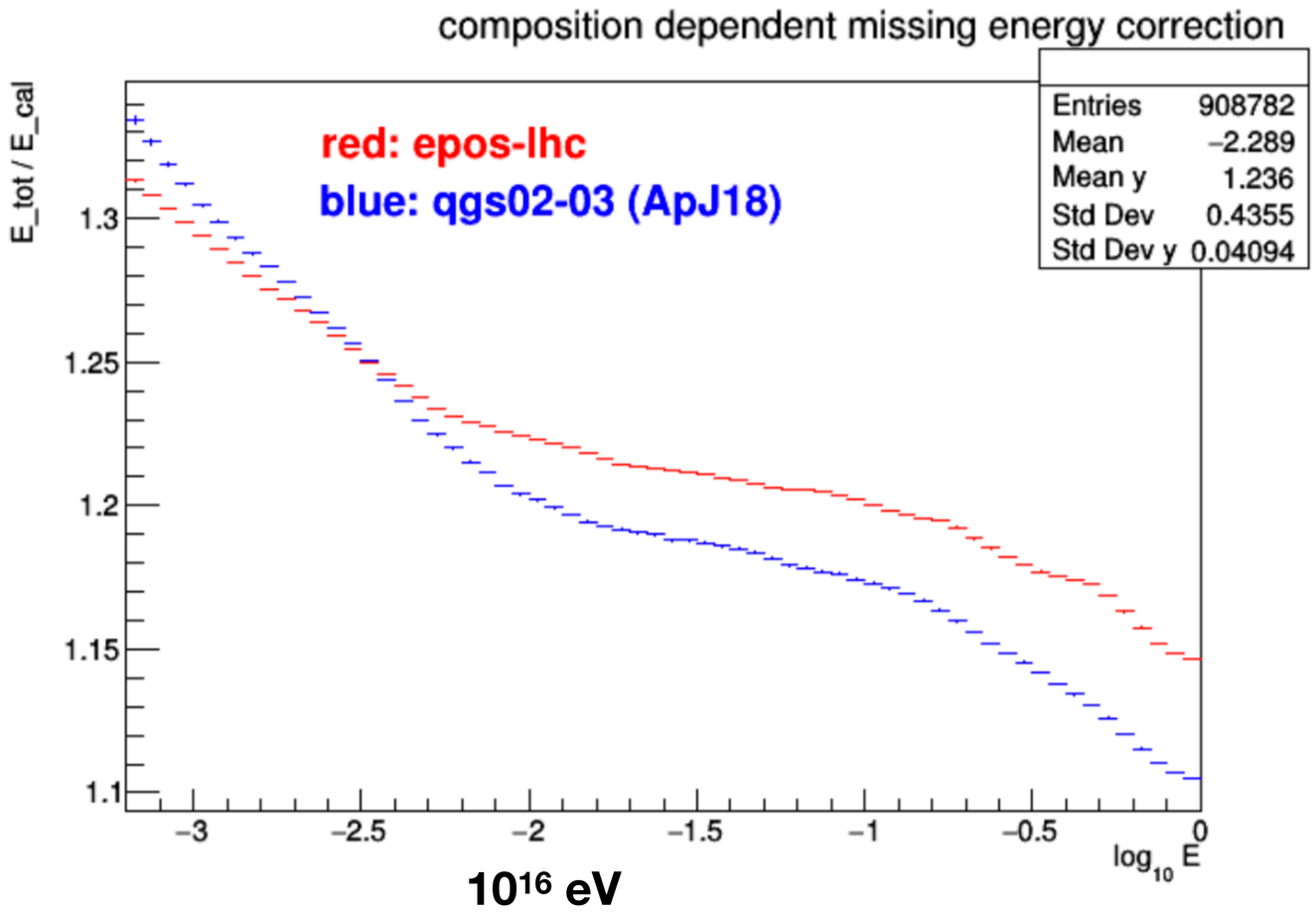




Spectrum/Aperture Calculation (2/2)

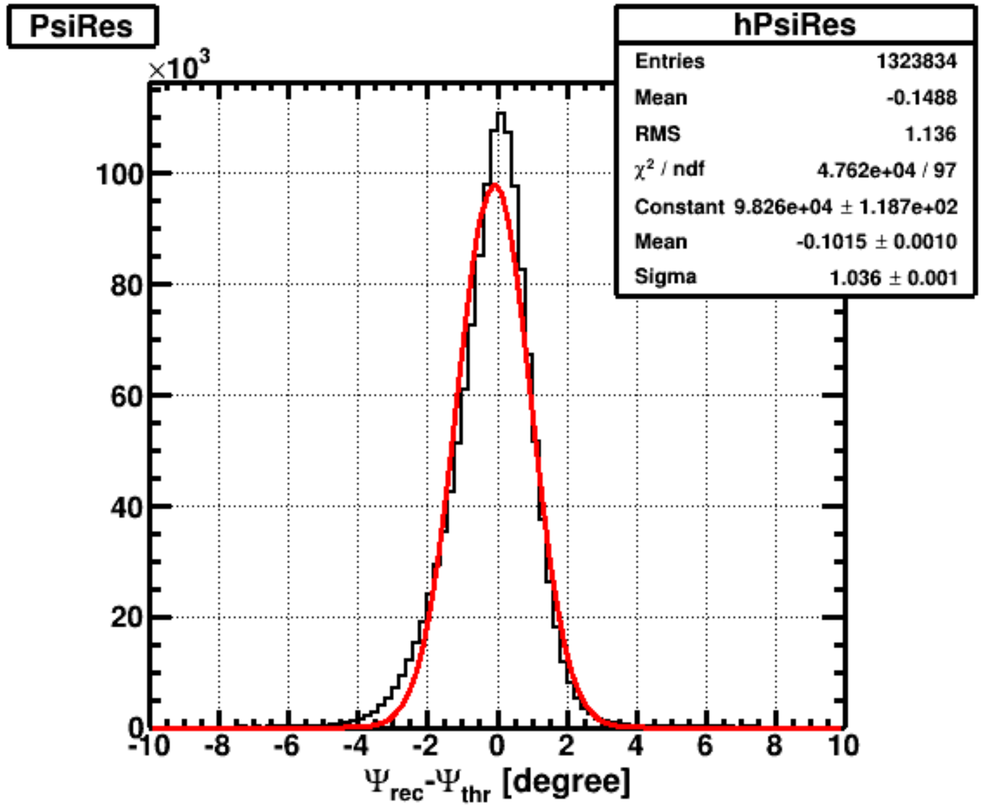
Missing Energy Correction

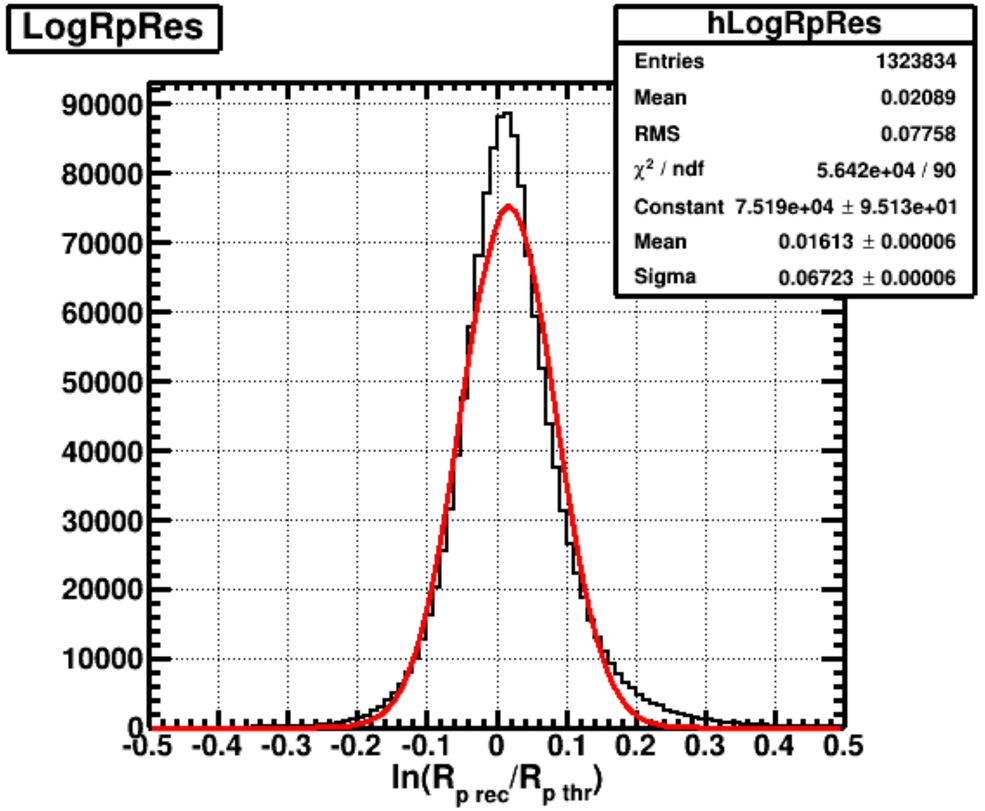
- Different missing energy corrections between QGSJET II-03 and EPOS-LHC hadronic models at the same energy
  - Each hadronic model has its own composition dependent missing energy correction
- Result in difference in the spectra
- Note that TA missing energy correction measurement agrees with QGSJETII-03 hadronic model.



Resolutions

- Compare reconstructed values to thrown values.

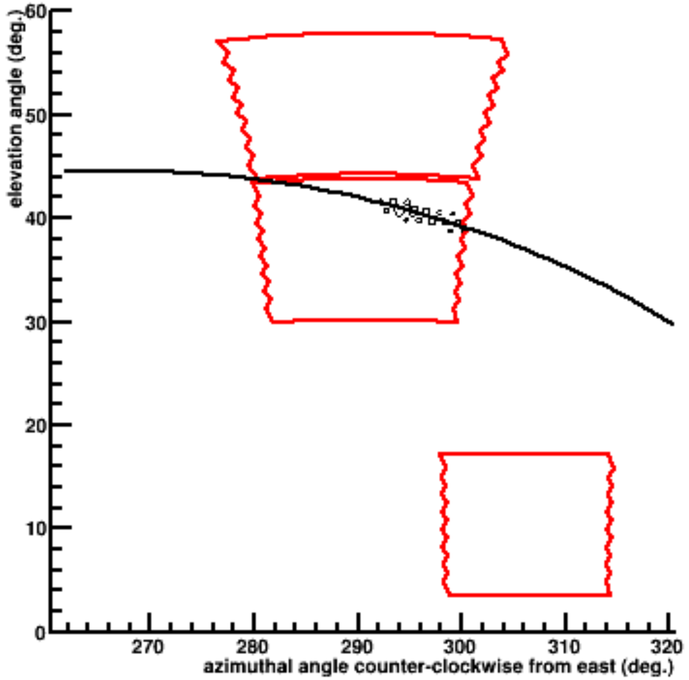




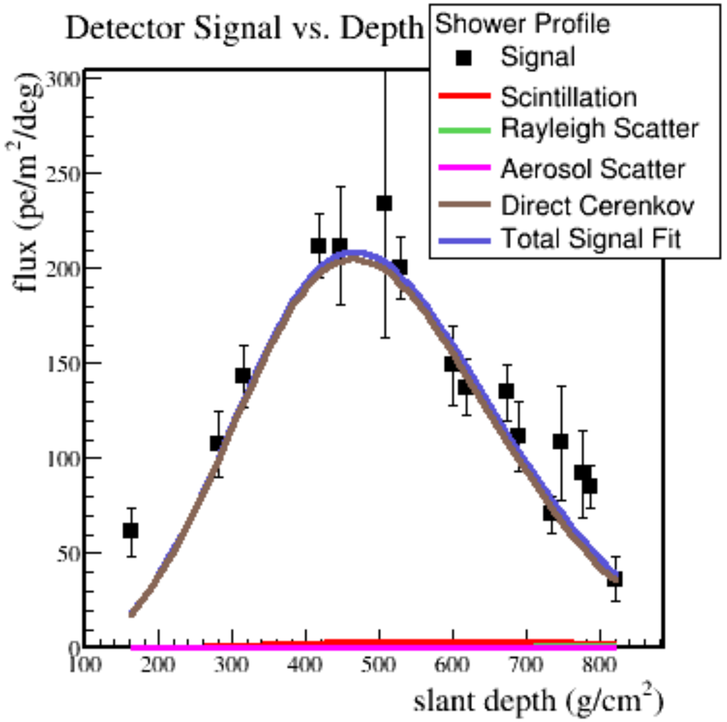
Data Event Example

- Cherenkov dominant event - one TALE telescope event

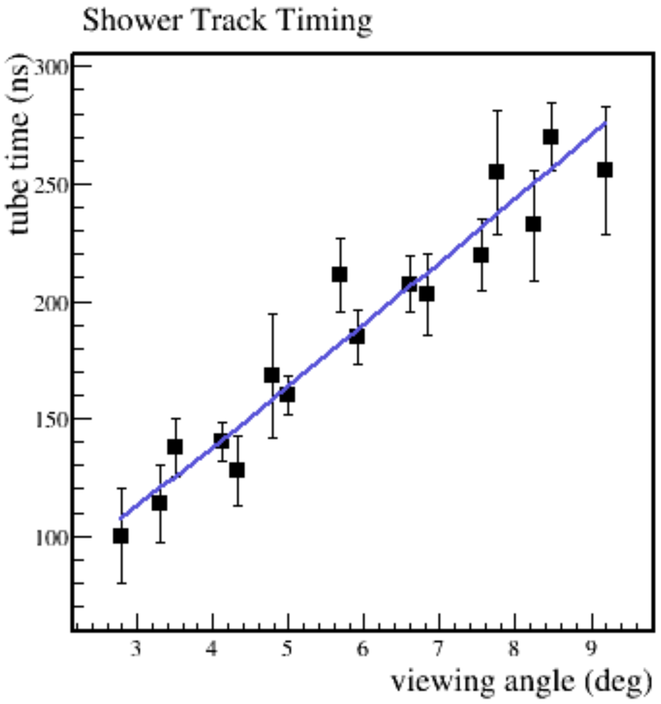
Event Display



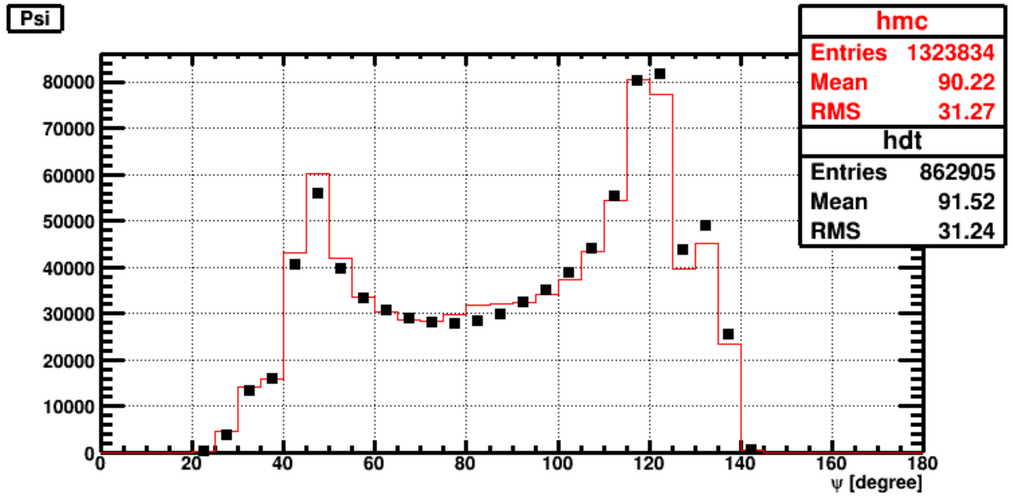
Profile fit

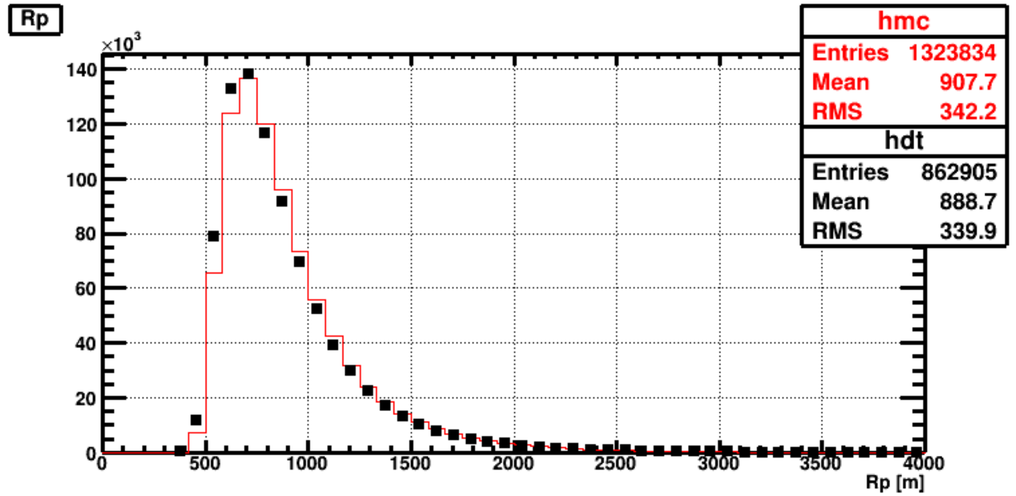


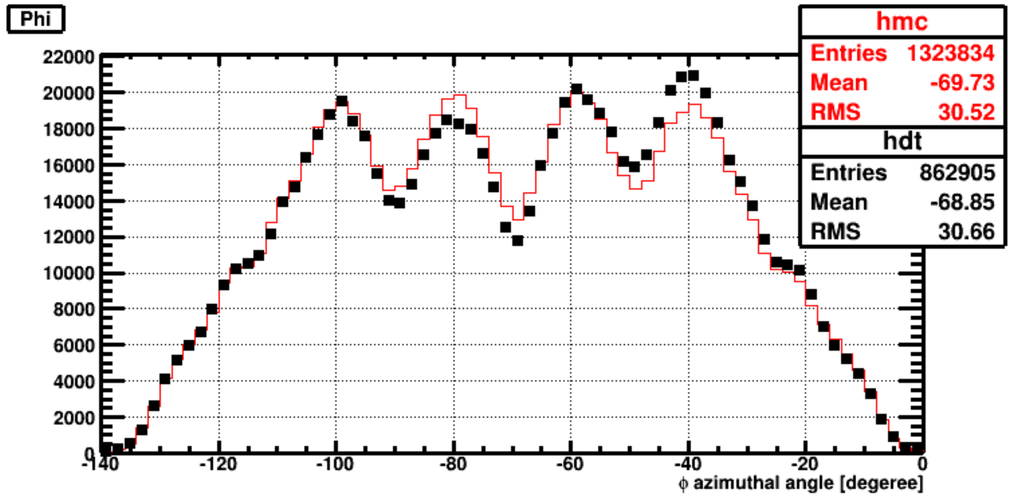
Time vs Angle fit

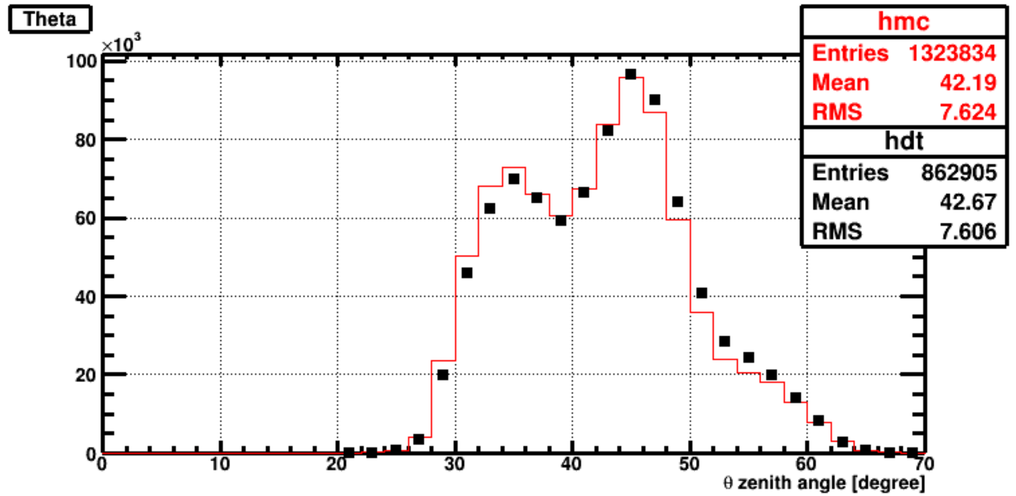


Data/MC Comparisons





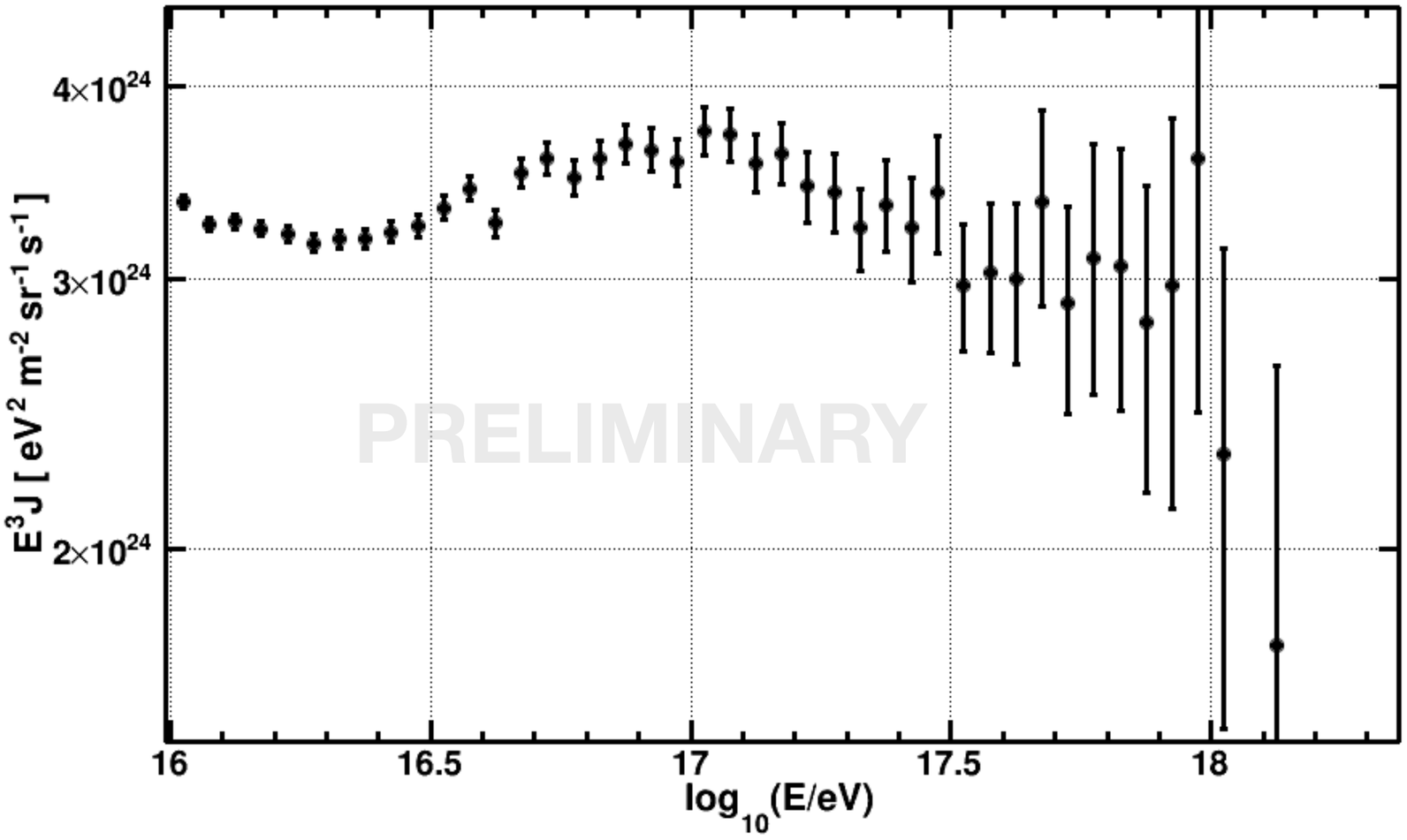




TALE Energy Spectrum (1/4)

June 2014 - November 2018

Using EPOS-LHC,
- primary fraction derived
- aperture calculated
- missing energy correction applied

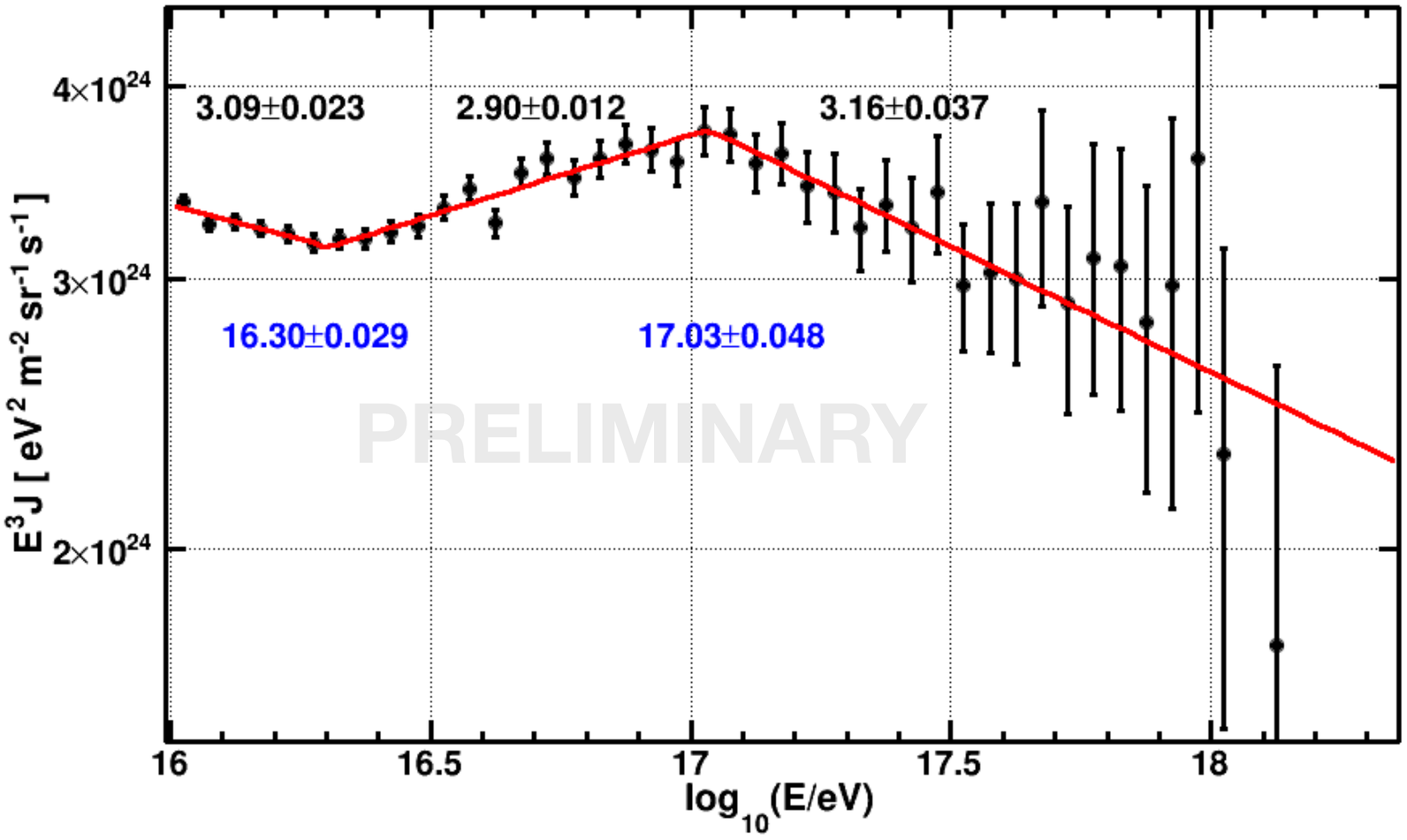


TALE Energy Spectrum (2/4)

June 2014 - November 2018

Using EPOS-LHC,
- primary fraction derived
- aperture calculated
- missing energy correction applied

Broken power law fit
- 2nd knee at $10^{17.03}$ eV
- ankle-like feature at $10^{16.30}$ eV

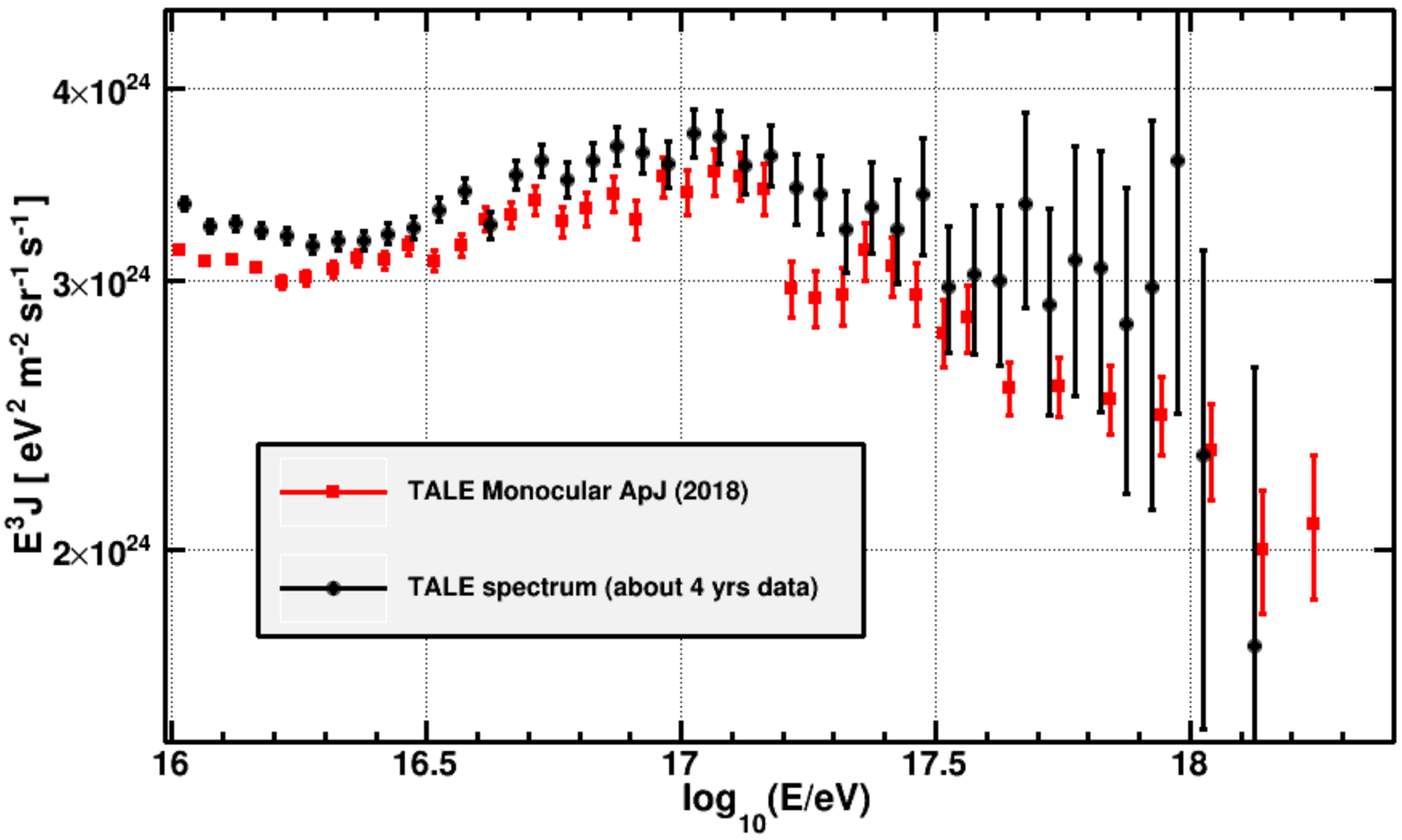


TALE Energy Spectrum (3/4)

June 2014 - November 2018

Using EPOS-LHC,
- primary fraction derived
- aperture calculated
- missing energy correction applied

June 2014 - March 2016
ApJ published 2018
Using QGSJET II-03,
- primary fraction derived
- aperture calculated
- missing energy correction applied



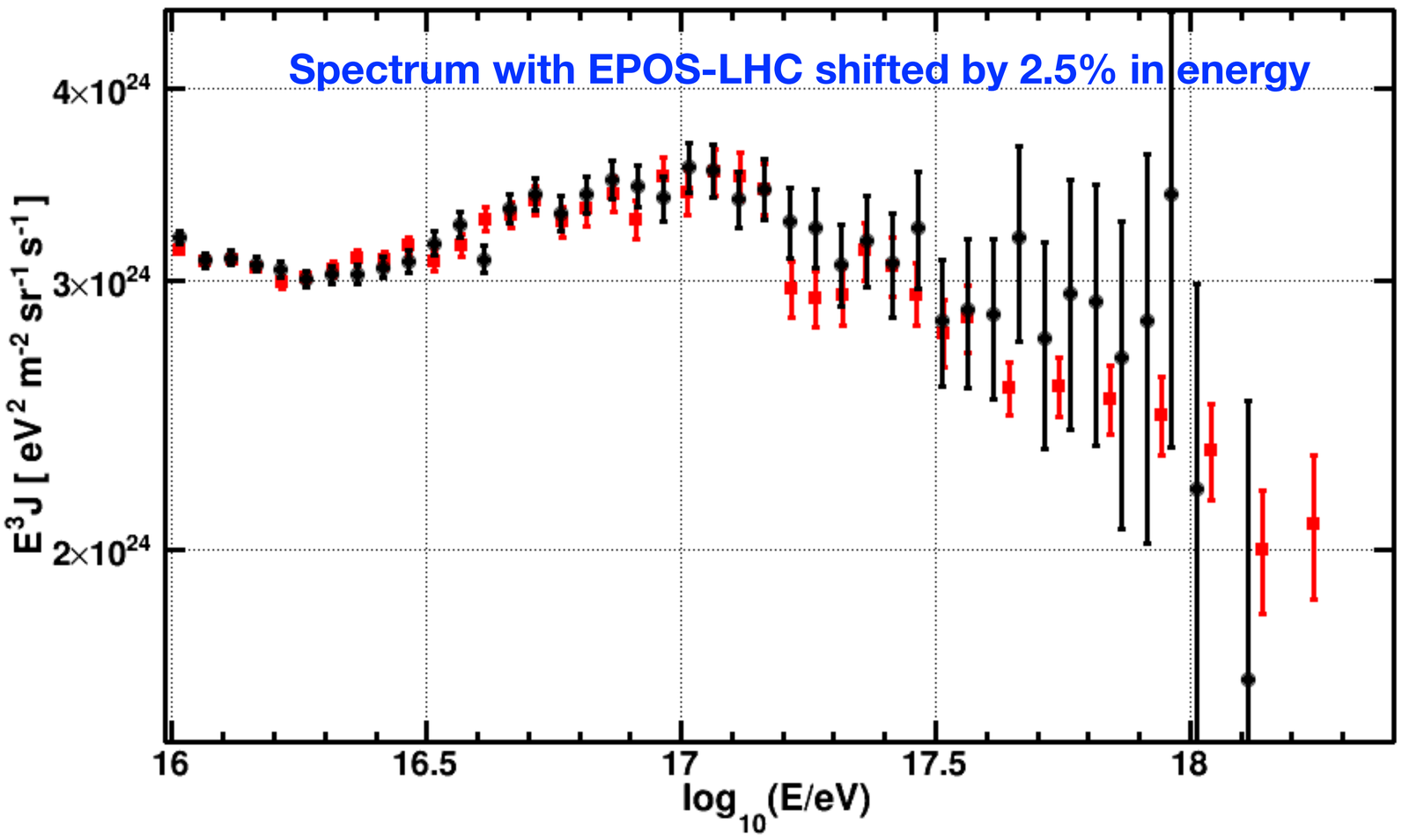
TALE Energy Spectrum (4/4)

June 2014 - November 2018

Using EPOS-LHC,
- primary fraction derived
- aperture calculated
- missing energy correction applied

June 2014 - March 2016
ApJ published 2018

Using QGSJET II-03,
- primary fraction derived
- aperture calculated
- missing energy correction applied



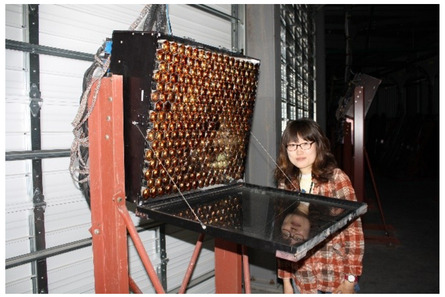
Summary

- We presented a new preliminary measurement of the energy spectrum based on EPOS-LHC simulation
    - Resources (MC simulation) prioritized for composition study
    - Published spectrum (ApJ 2018) was based on QGSJETII-03
    - Affect the missing energy correction - changes energy scale slightly 2.5%
    - Also affect the aperture calculation
    - Energy range in the measured spectrum: 10^{16} - $10^{18.4}$ eV — two features are observed
        - “ankle-like feature” a hardening of the spectrum at $10^{16.30}$ eV
        - “the second knee” a steepening of the spectrum at $10^{17.03}$ eV
- Work in progress : QGS simulations being calculated and fluorescence dominated events being added

Back Up Slide

The Telescope Array Experiment (TA)

14 telescopes @ station
Reutilized from HiRes II



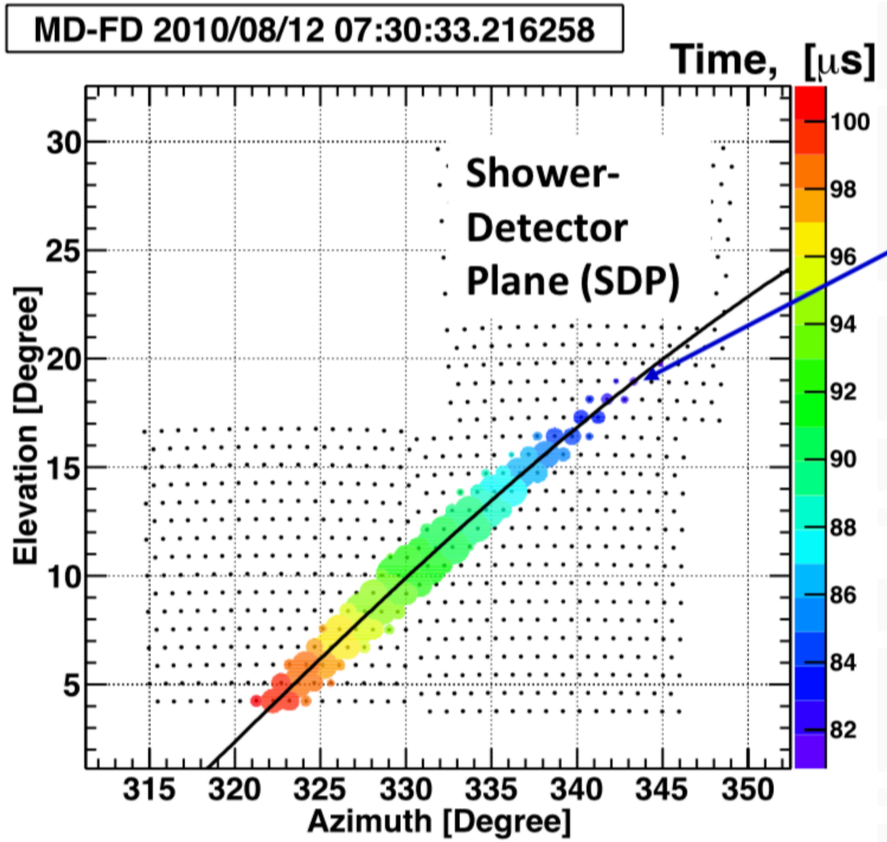
Long Ridge (LRFD)

Middle Drum (MDFD)

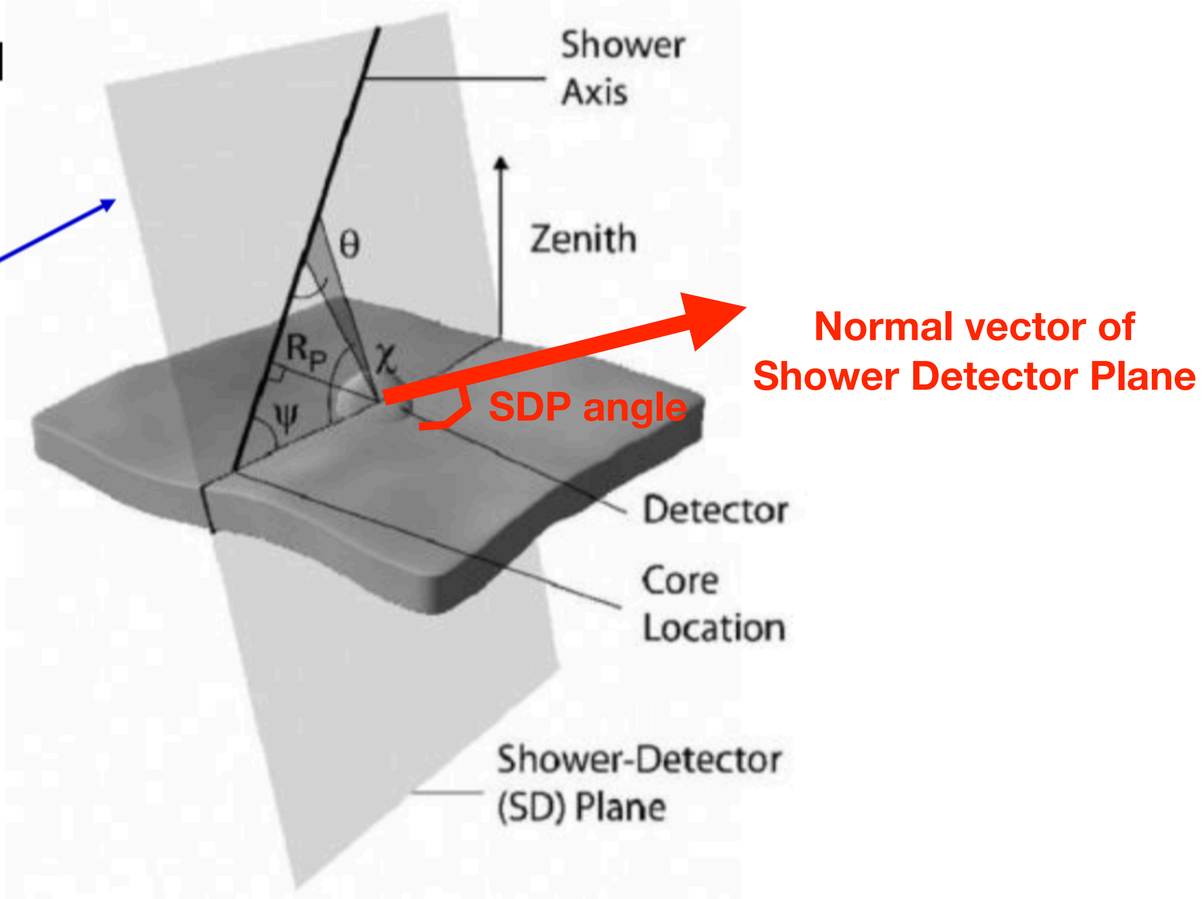
Black Rock Mesa (BRFD)

12 telescopes @ station
new telescopes

“Reconstruction” of an air shower

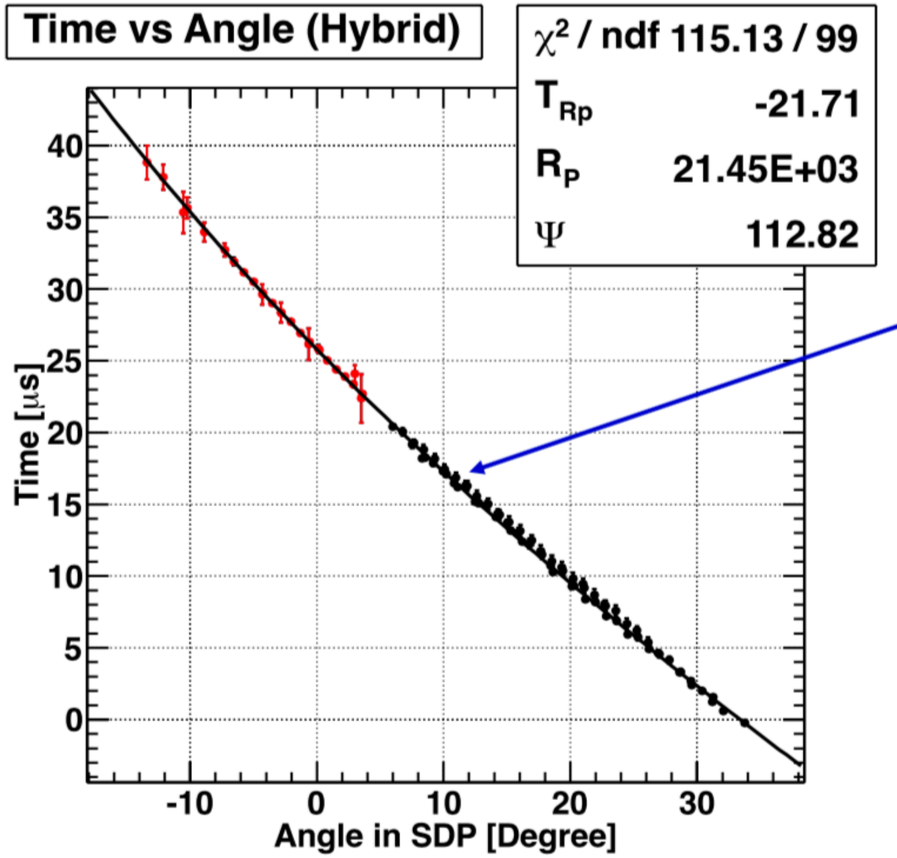


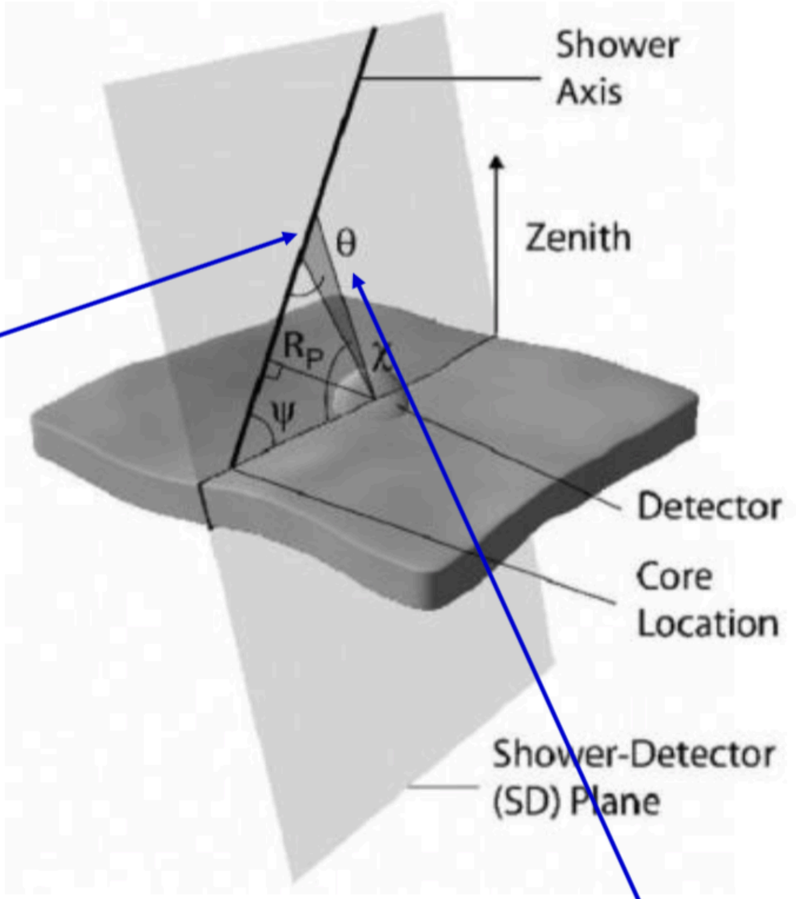
Event Display showing pattern of hit pixels



Direction of hit pixels fitted to a shower-detector plane (SDP)

Timing Fit

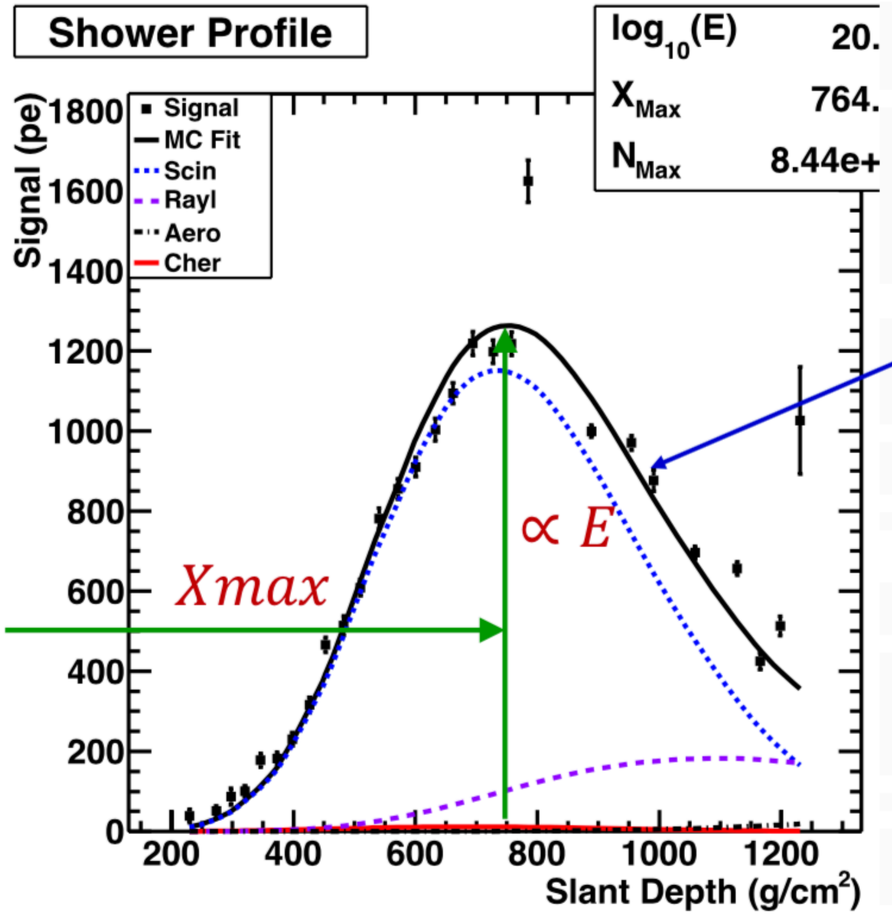


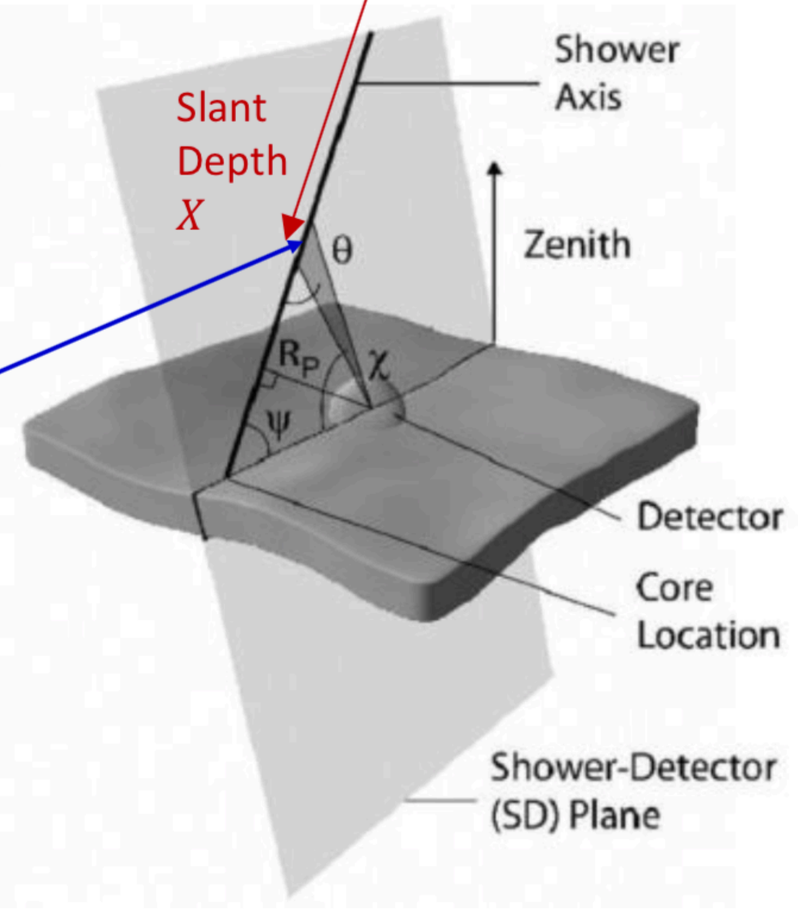


Arrival times of signal light in each pixel is fitted as a function of the SDP θ angles: **Gives direction of primary cosmic ray**

$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$

Shower Profile Fit





SDP θ angles converted to slant depth.
Light signal fitted to depth to give energy E and $Xmax$ (depth of maximum)

Spectrum/Aperture Calculation

Missing Energy Correction