TALE FD Cosmic Ray Composition and Spectrum Update

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Outline

- Introduction
- TALE Detector
- Data and Analysis
- Results
- Summary

Introduction

- I review results on the measurement of the cosmic-ray energy spectrum and composition using the Telescope Array Low Energy Extension (TALE) Fluorescence Detector (FD).
- Mass composition is inferred through measuring the shower development X_{max}.
- The measurement covers the cosmic rays energy range $10^{15.3}$ – 10^{18} eV

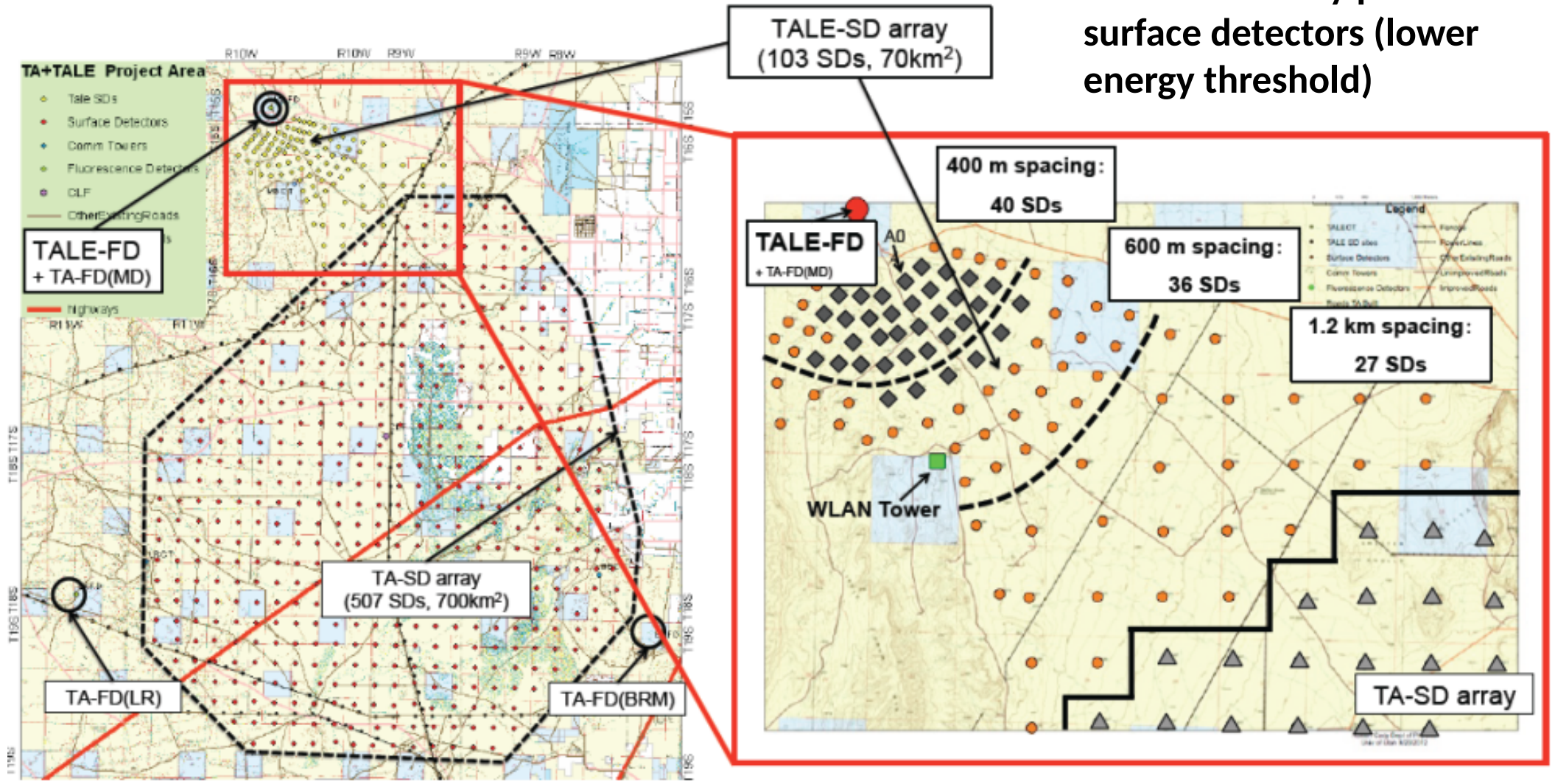
Introduction

- TALE FD energy spectrum measurement using two years of data was published in ApJ in 2018: DOI: 10.3847/1538-4357/aada05
- TALE FD mass composition results based on four years of data were published in ApJ in 2021: DOI: 10.3847/1538-4357/abdd30
- The analysis was updated to use seven years of data for the ICRC 2021 meeting:
  - https://pos.sissa.it/395/346/pdf
  - https://pos.sissa.it/395/347/pdf
- Here we review results presented at the ICRC and show updated results using nine years of data.
  - Work in progress (**Not ready for publication yet**)

Telescope Array (TA) Low Energy Extension (TALE)

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

TALE surface detector array of more densely packed surface detectors (lower energy threshold)



All 10 Telescopes installed and in operation **since fall 2013**

80 scintillation surface detectors deployed:

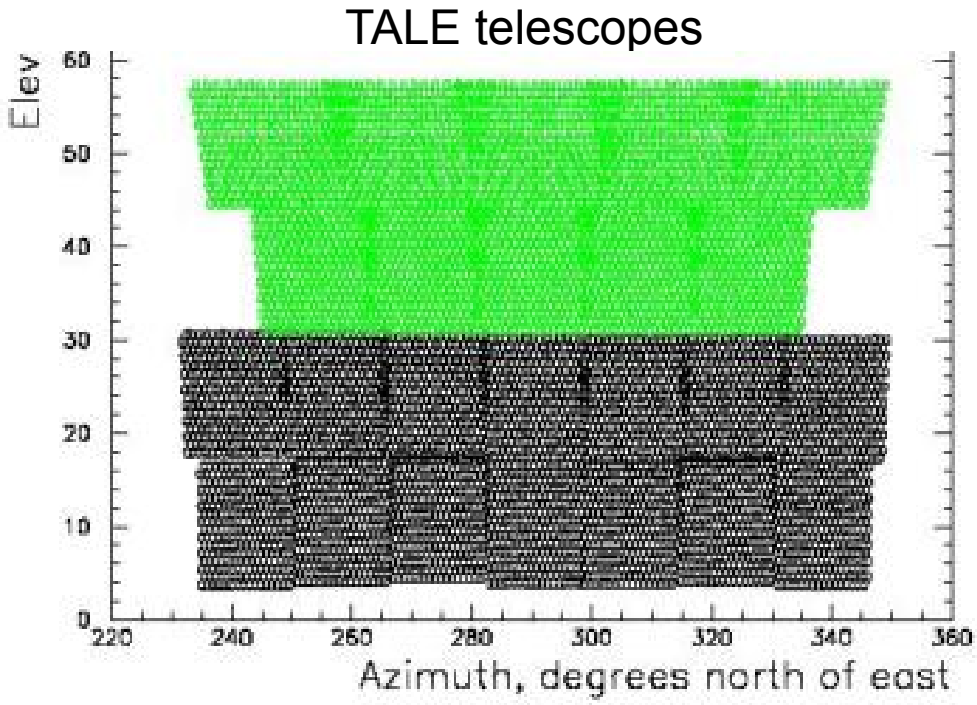
40 SDs with 400m spacing

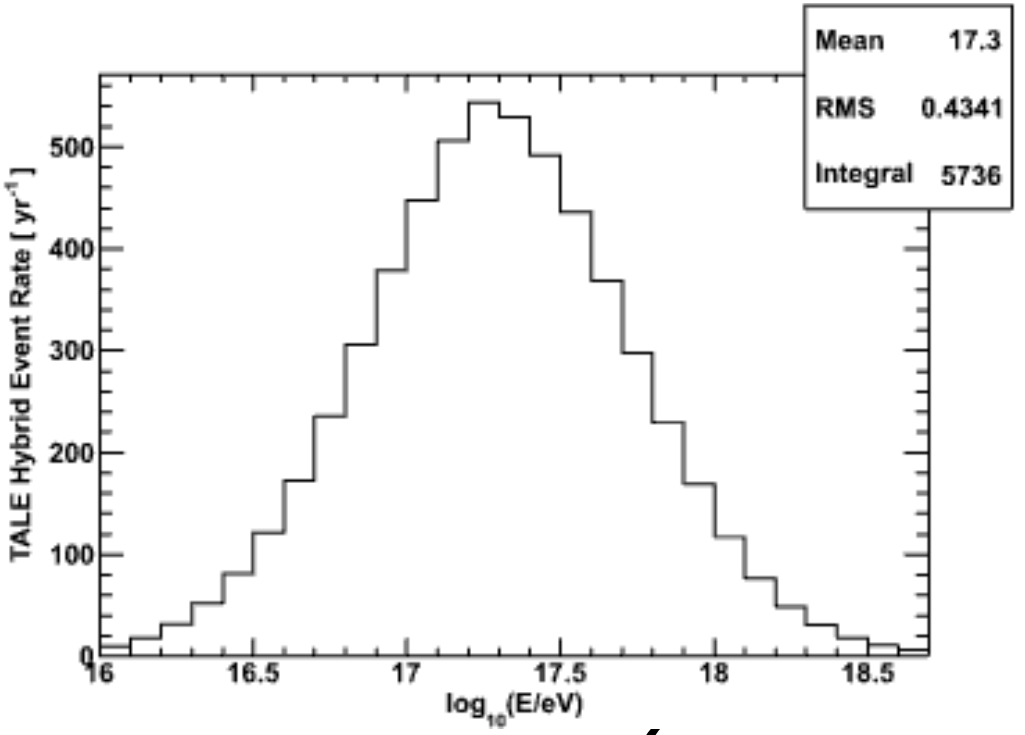
40 SDs with 600m spacing

Majority started operations in **summer of 2017**.

TALE Fluorescence Detector

- 10 high-elevation telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Operate in conjunction with the TA Middle Drum FD.



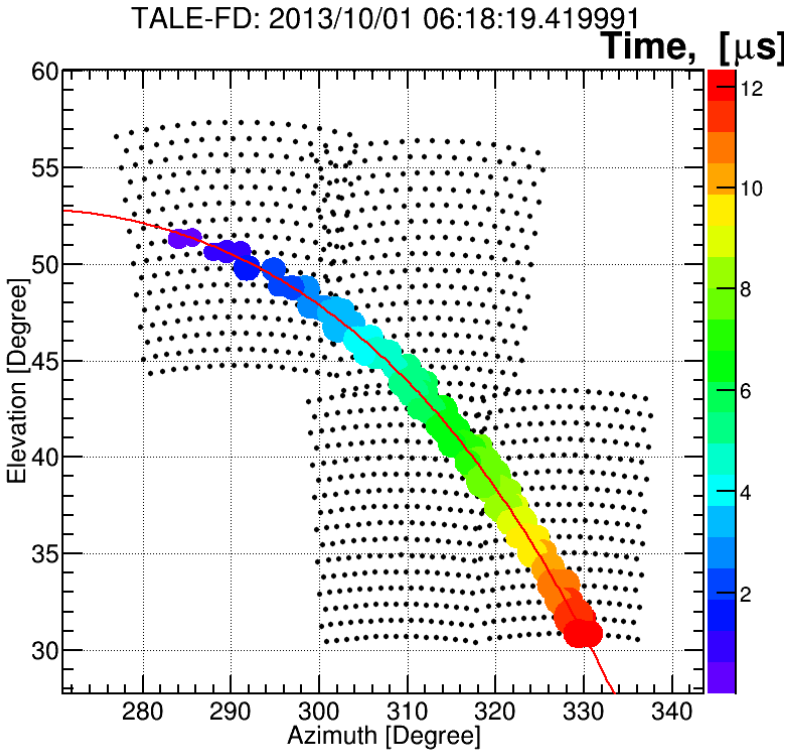


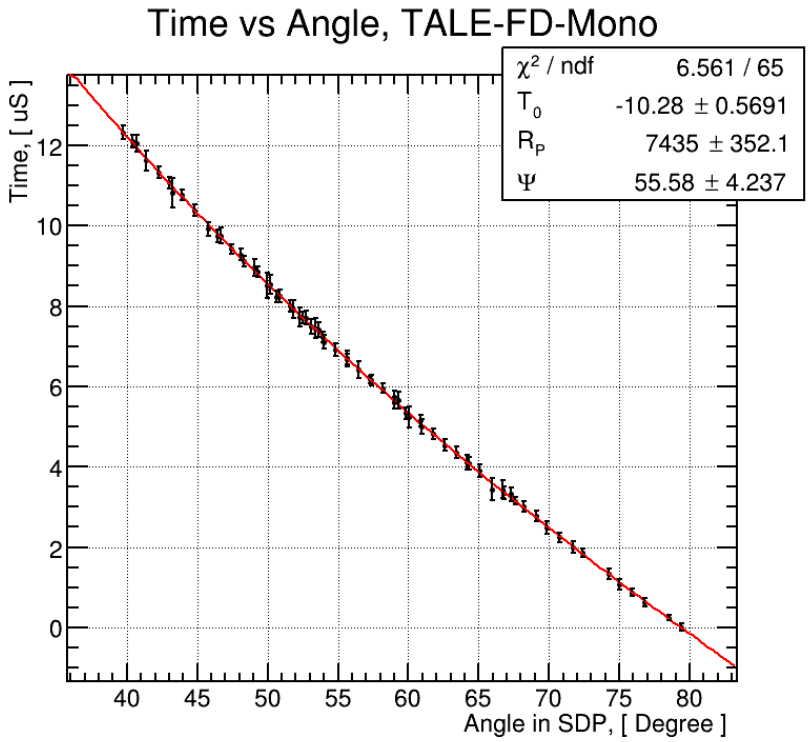
Expected TALE hybrid events per year

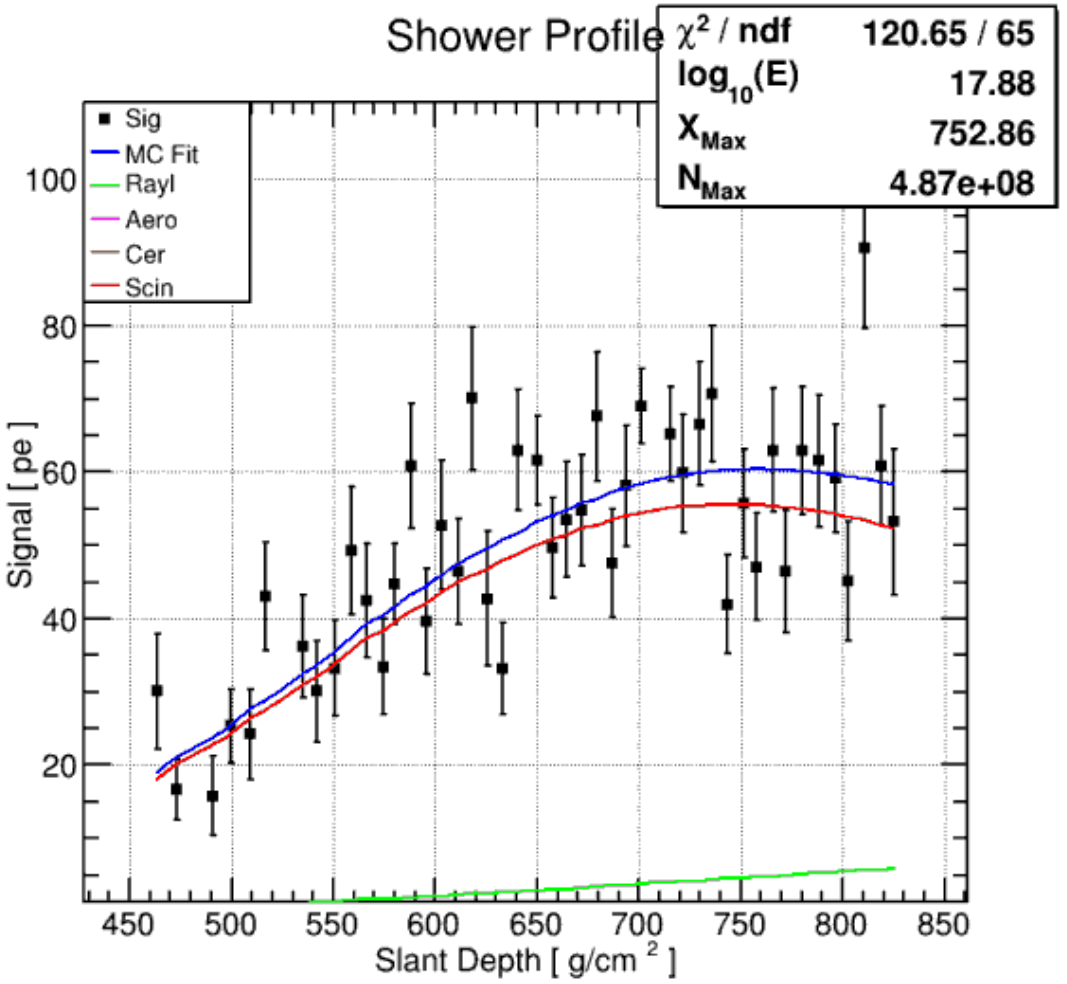
TALE FD Event

For TALE FD reconstruction: we combined the time and profile fit: simultaneous Profile Constrained Geometry Fit (PCFG)

originally developed for HiRes monocular analysis

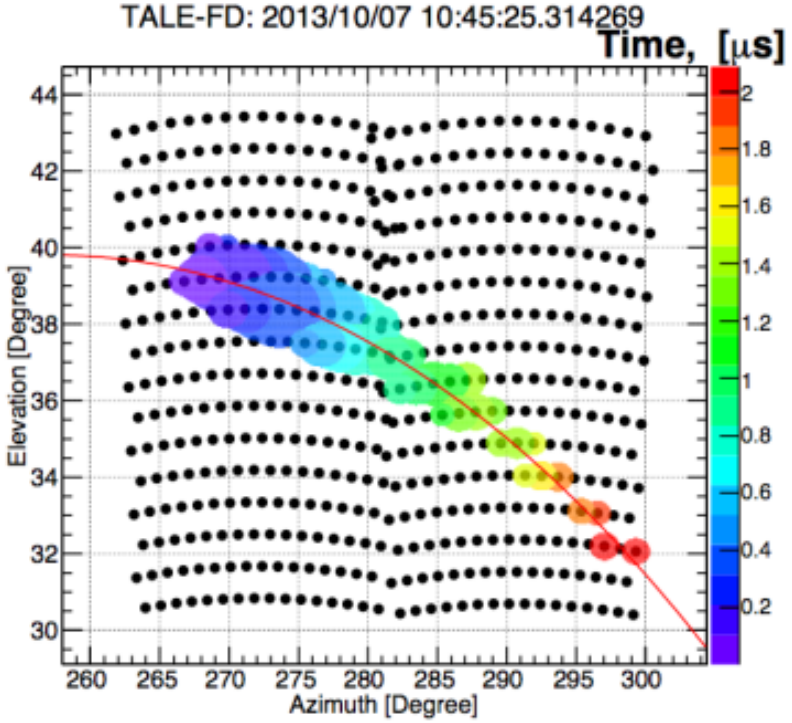


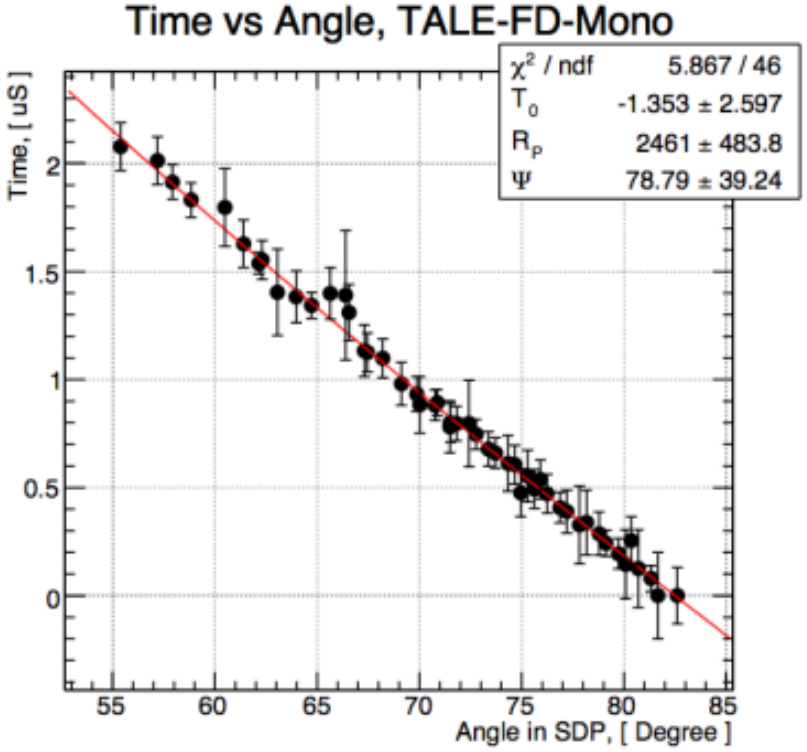


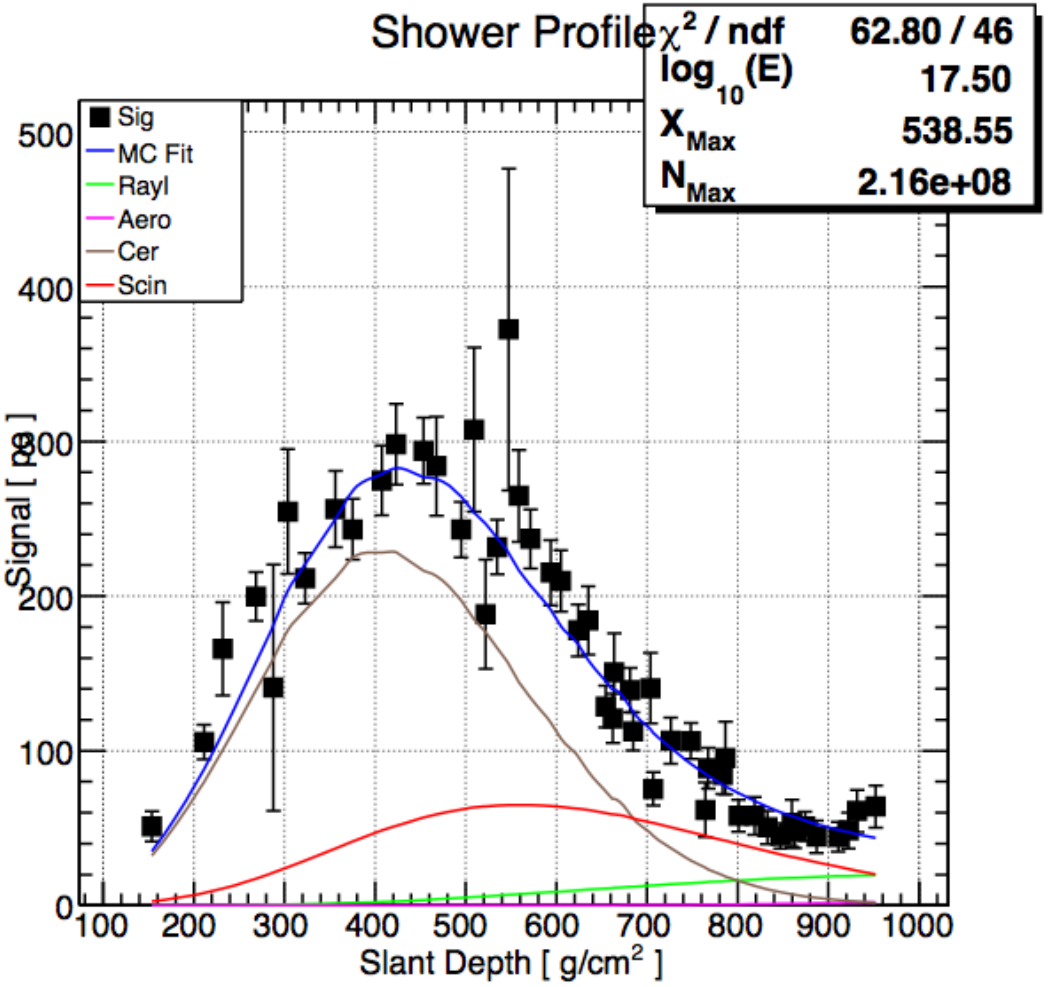


TALE Cherenkov Event

PCGF turns out to work very well on
Cherenkov light dominated events







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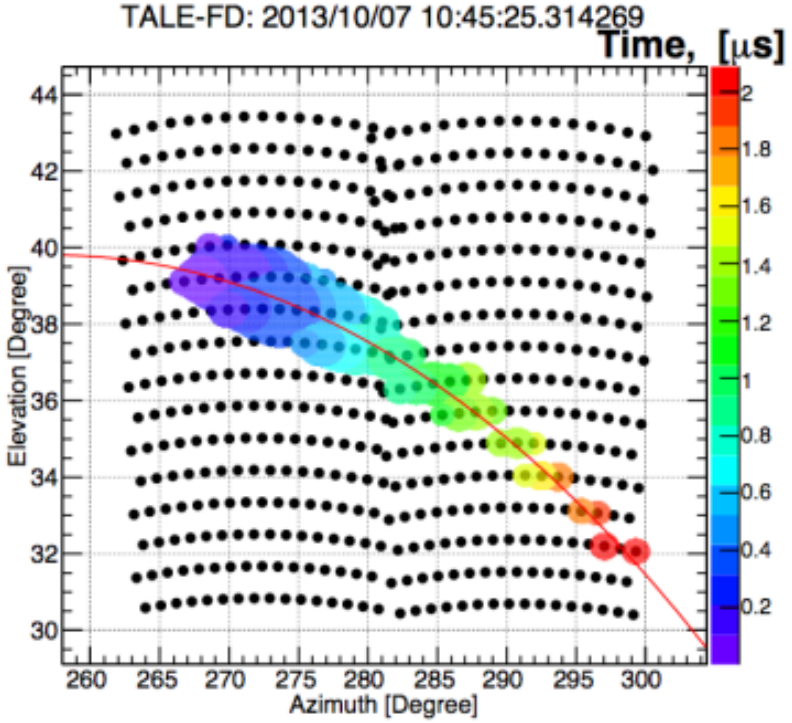
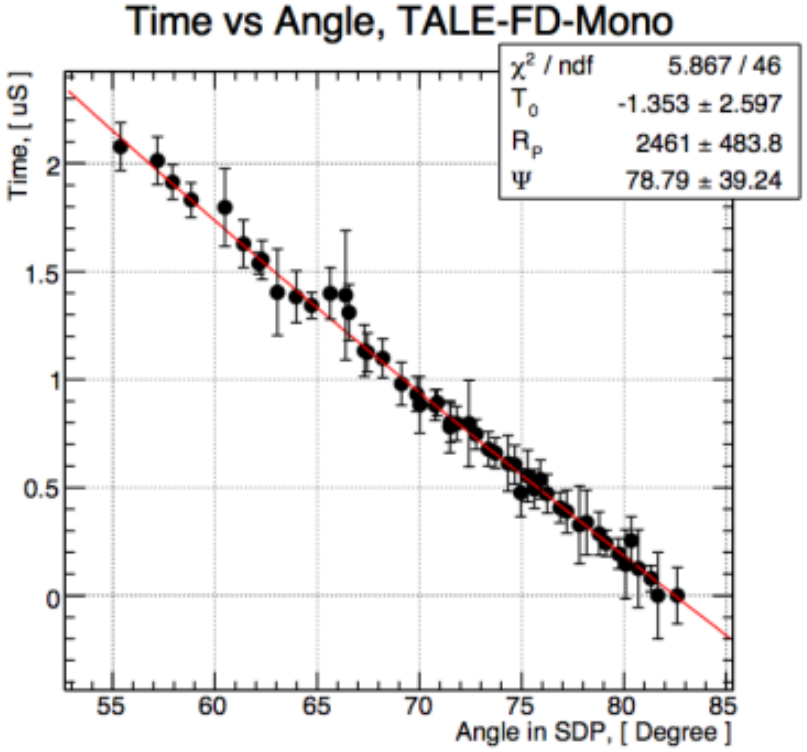
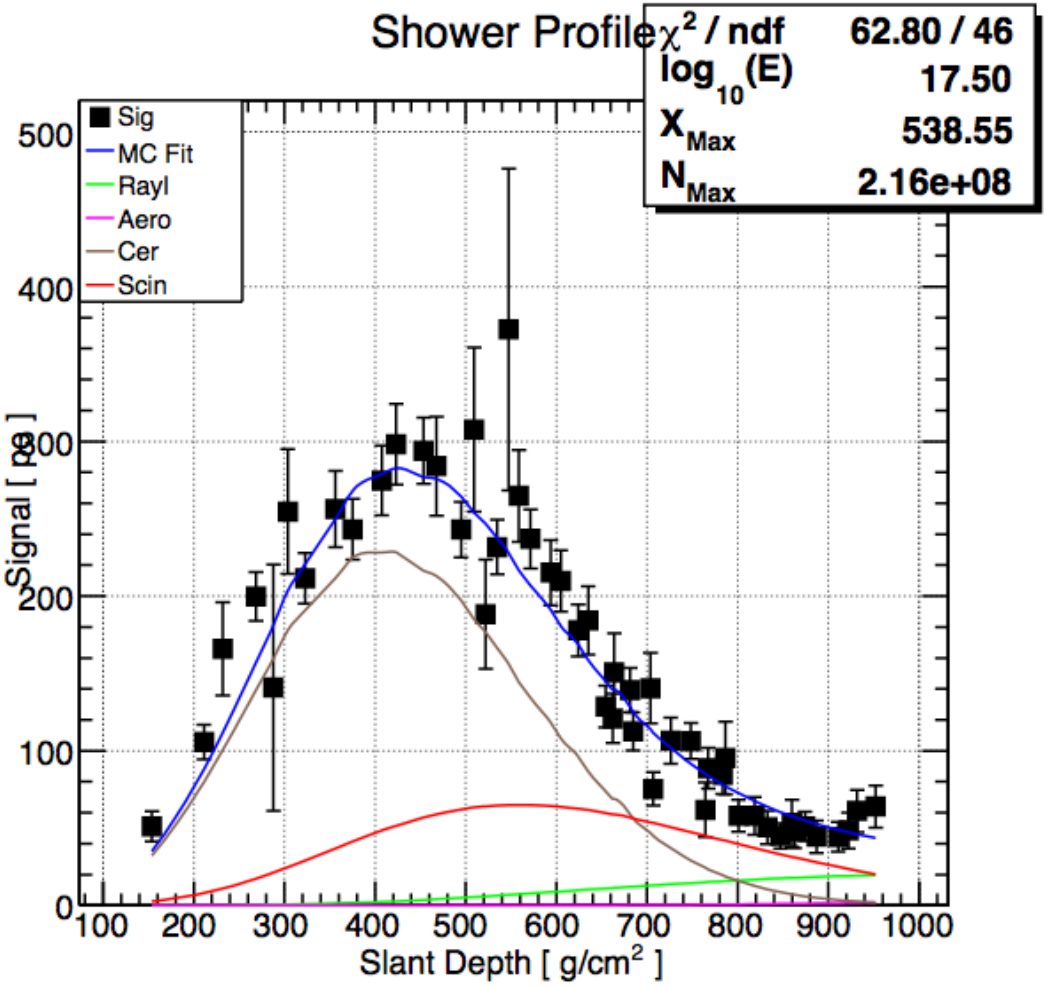
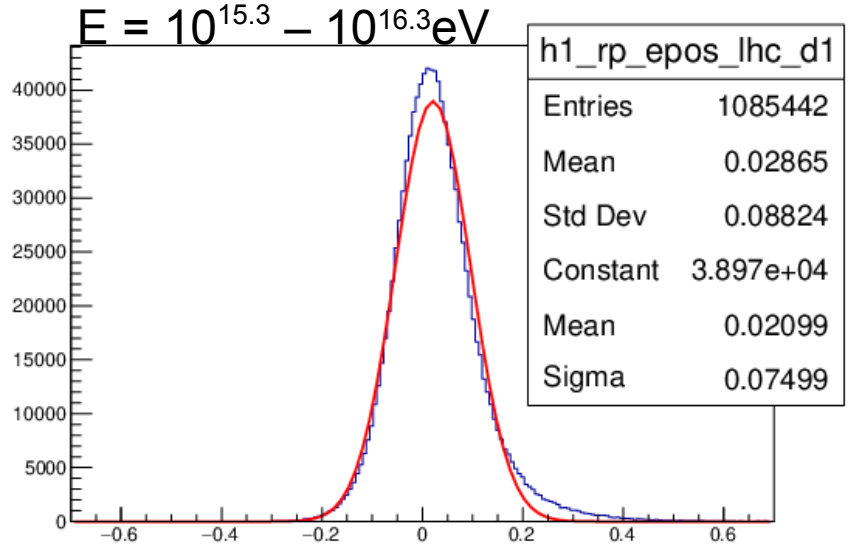


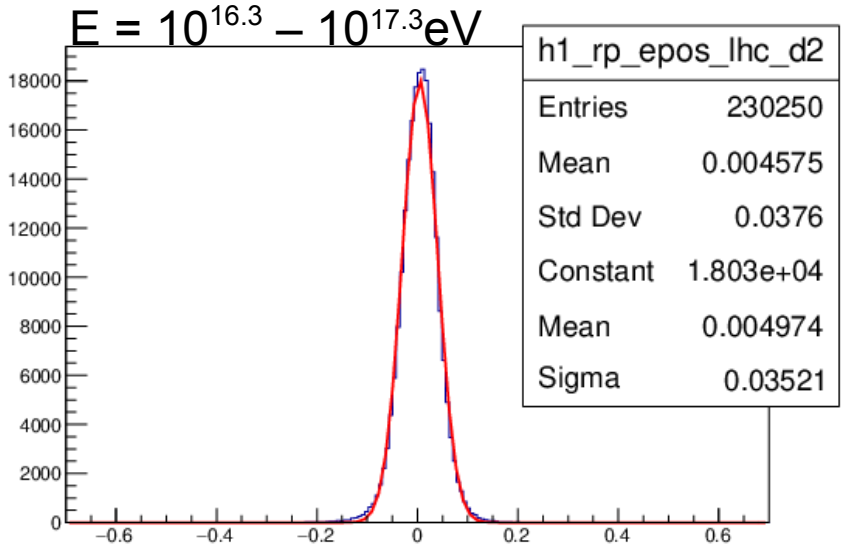


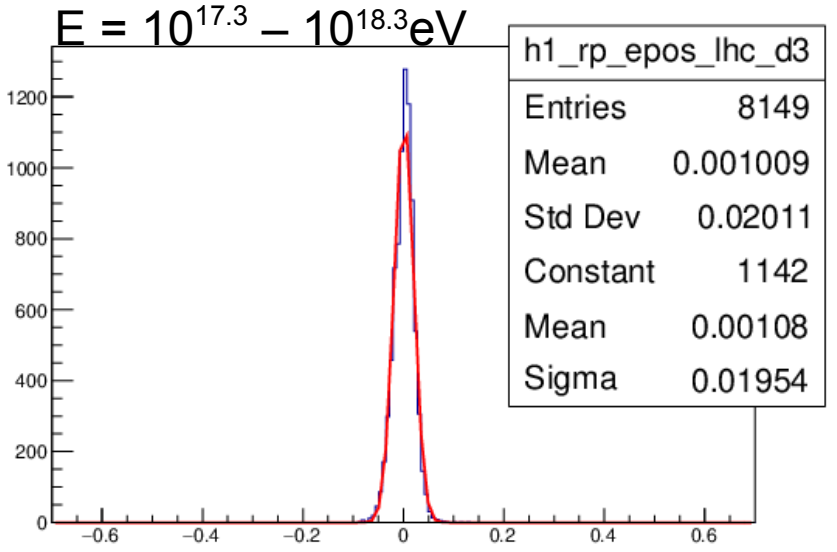


Reconstruction Resolution (Geometry) (1)

- One histogram per decade in energy starting at E = $10^{15.3}$ eV
- Shower Track R_p [m]
- Histogram: ΔR_p / R_p



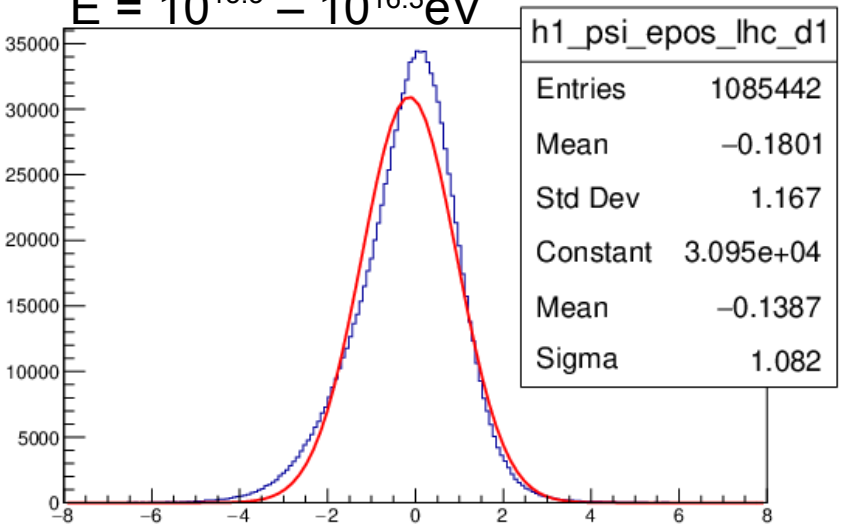




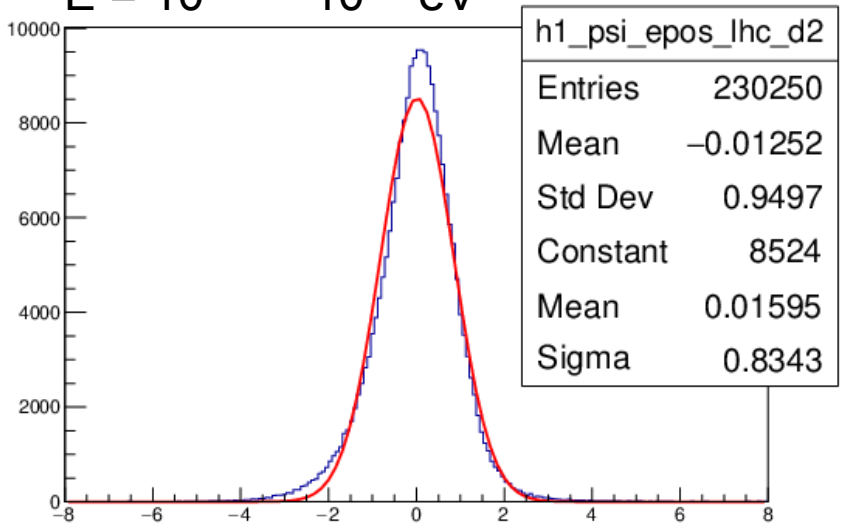
Reconstruction Resolution (Geometry) (2)

- One histogram per decade in energy starting at E = $10^{15.3}$ eV
- Shower Track ψ angle (degree)
- Histogram: $\Delta\psi$ (degree)

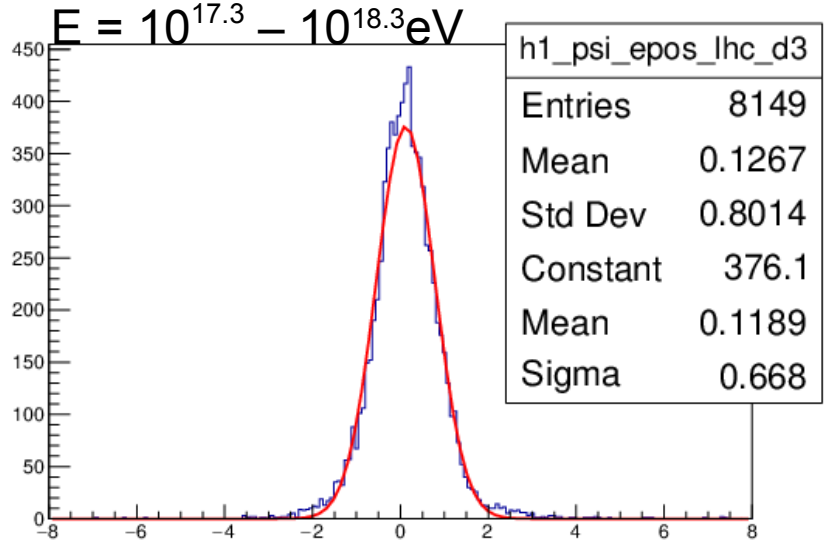
E = $10^{15.3}$ – $10^{16.3}$eV



E = $10^{16.3}$ – $10^{17.3}$eV

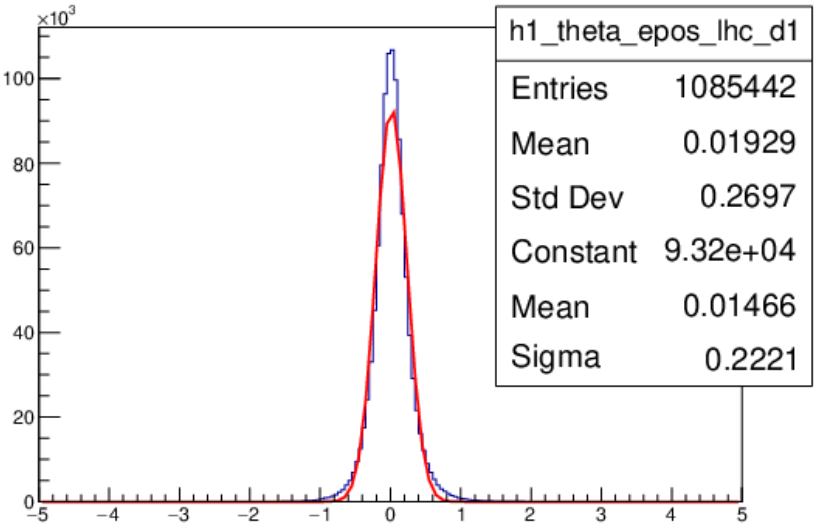


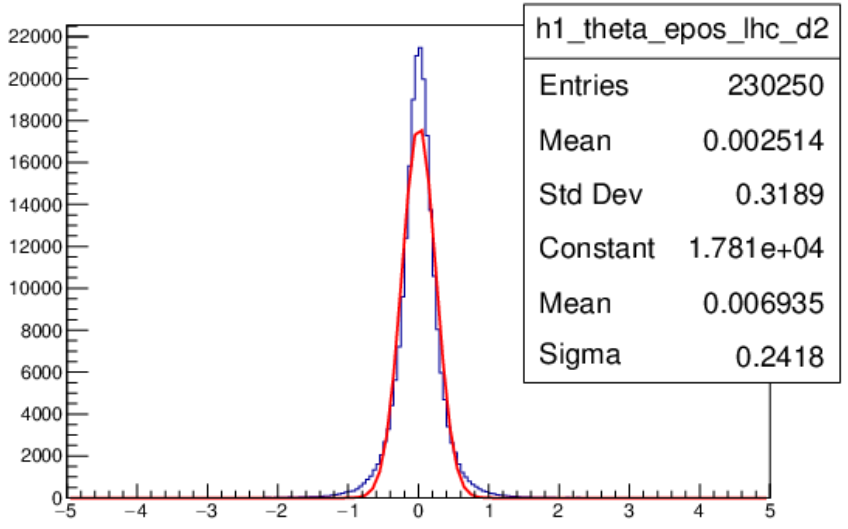
E = $10^{17.3}$ – $10^{18.3}$eV

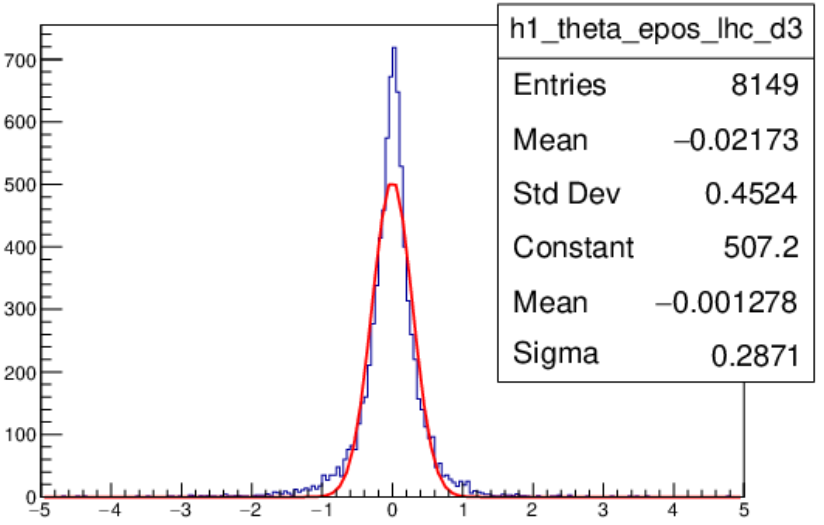


Reconstruction Resolution (Geometry) (3)

- One histogram per decade in energy starting at E = $10^{15.3}$ eV
- Shower Track zenith angle (degree)
- Histogram: $\Delta\theta$ (degree)

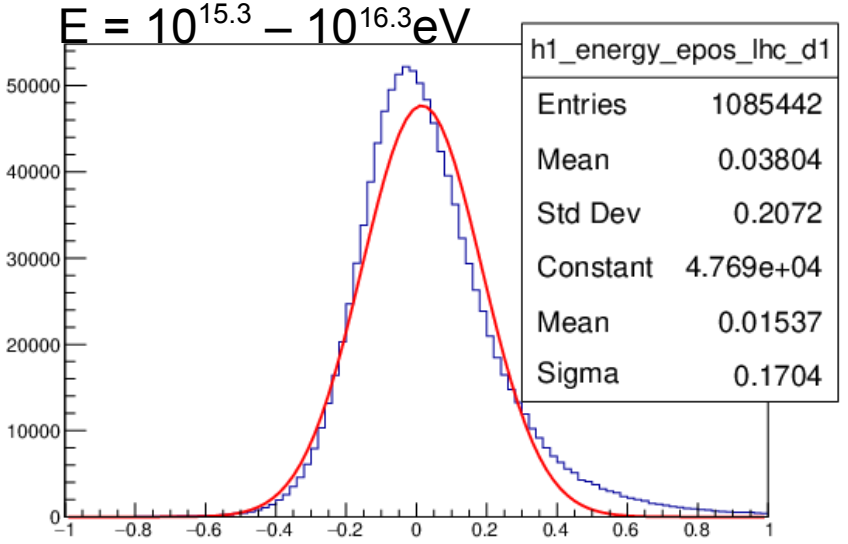


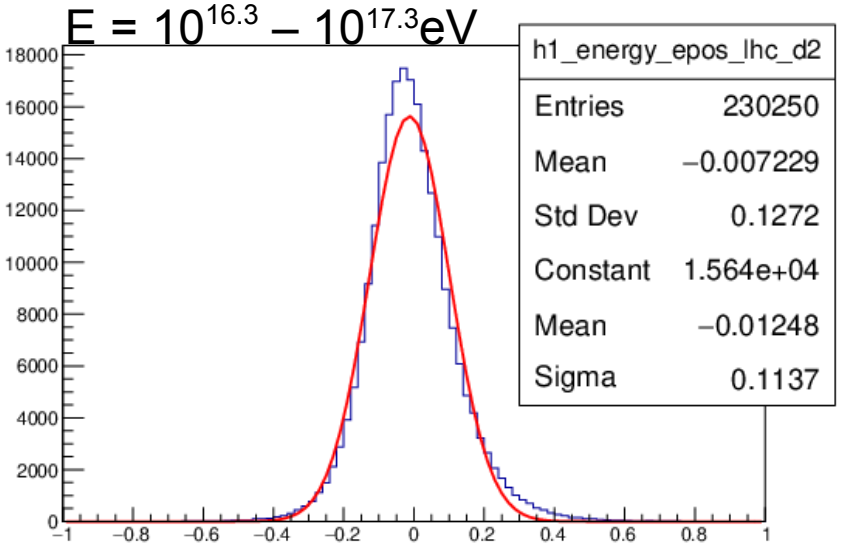


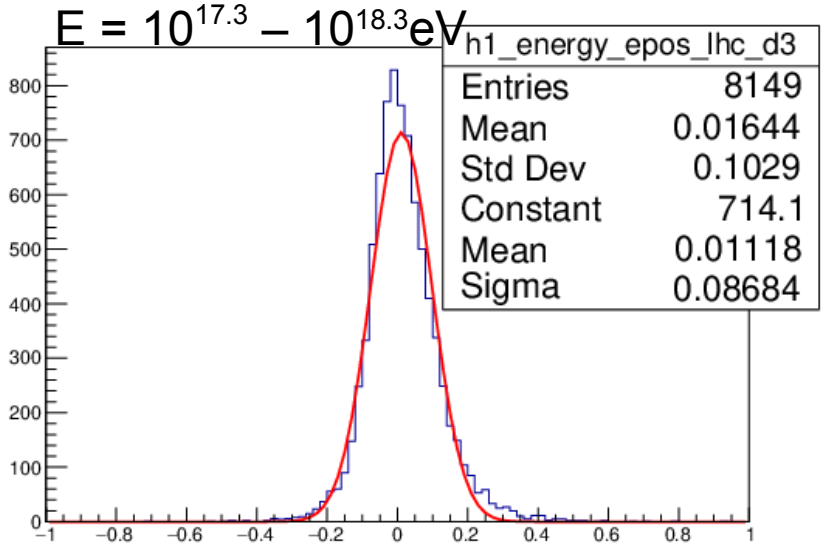


Reconstruction Resolution (Energy)

- One histogram per decade in energy starting at E = $10^{15.3}$ eV
- Shower Energy [eV]
- Histogram: ΔE / E



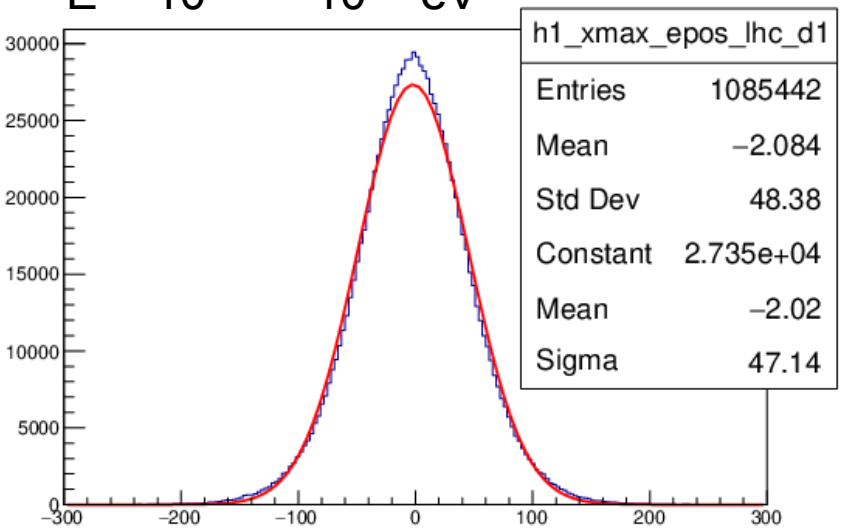




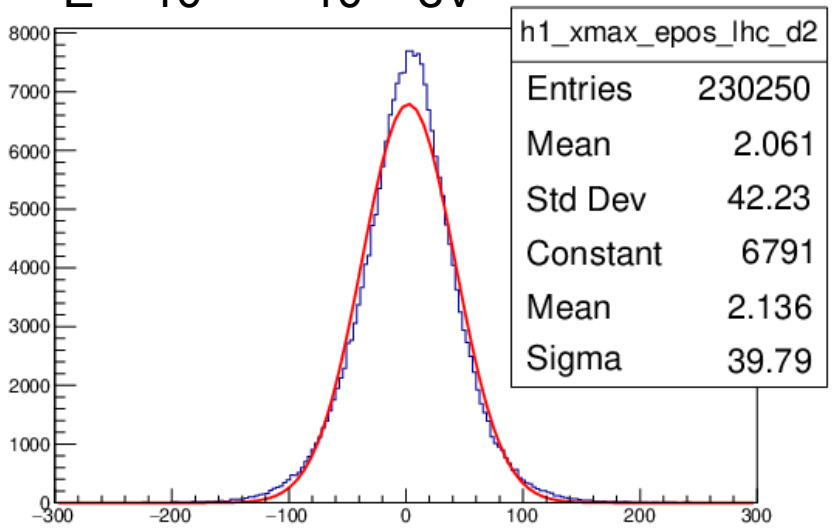
Reconstruction Resolution (Xmax)

- One histogram per decade in energy starting at E = $10^{15.3}$ eV
- Shower X_{max} [g / cm^2]
- Histogram: ΔX_{max} [g / cm^2]

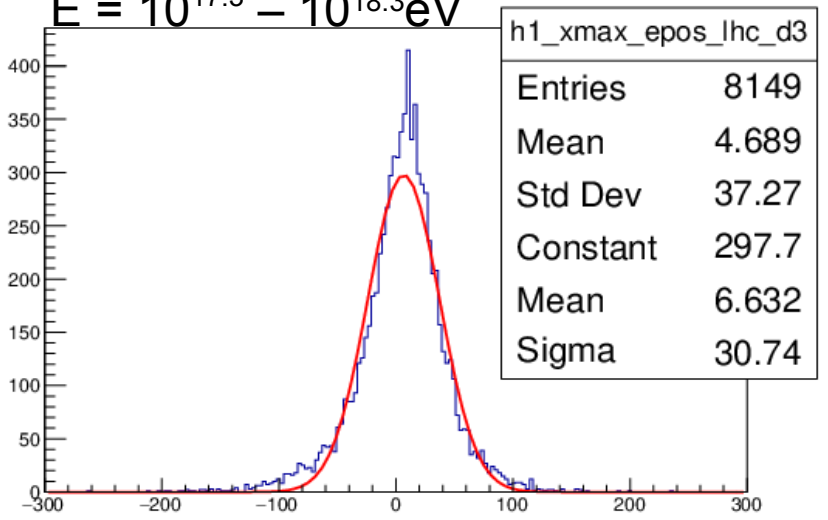
E = $10^{15.3}$ – $10^{16.3}$eV



E = $10^{16.3}$ – $10^{17.3}$eV



E = $10^{17.3}$ – $10^{18.3}$eV



Data Sets

- TALE FD monocular data (Cherenkov light dominated).
- Data collection period: 06/2014 – 11/2018 (*published ApJ 2021*)
- 2633 hours of observation
- ICRC 2021 updated data:
  - 12/2018 – 04/2021: 822 hours of observation
- Latest update:
  - 05/2021 – 09/04/2022: 675 hours of observation
- Data collection period: 06/2014 – 04/2021 (*ICRC 2021*)
- 3456 hours of observation
- Update through 09/04/2022 (This meeting)
  - 4131 hours

Data Set Update

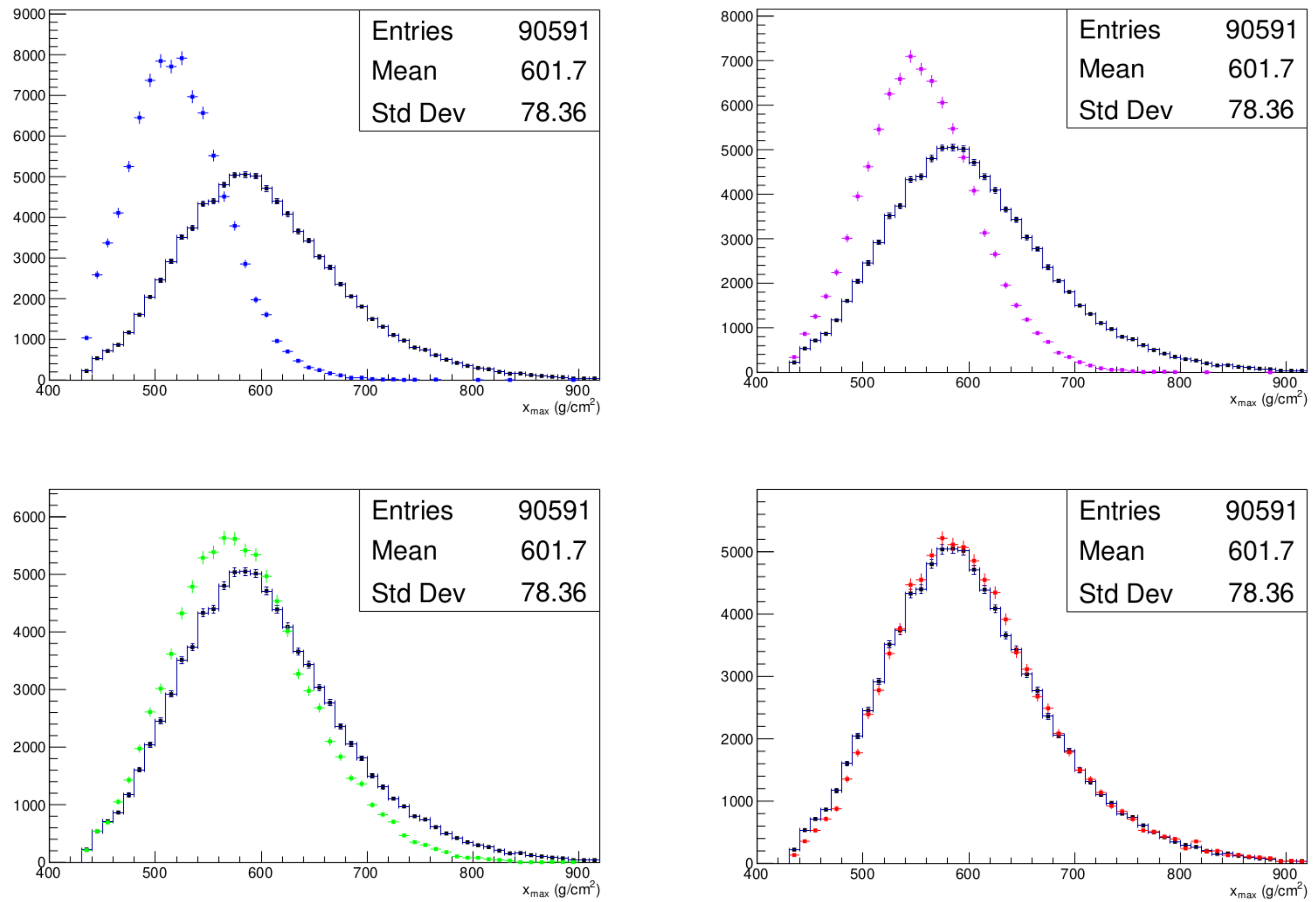
- Detector data was calibrated and reconstructed for the period 05/2021 – 09/04/2022
- Good weather selection was made
- Event reconstruction and Event selection same as the published composition measurement.
- MC simulations for this period have not been performed and I am relying on the existing four year simulation set to be representative of the new data.

Composition Analysis: Primary Fractions (Xmax Fits)

- Event reconstruction: Shower calorimetric energy (E_{cal}), shower Xmax for each event.
- Events (Data & MC) binned in energy; bins [0.1 in log(E)]
- At each energy bin:
  - Fit Data Xmax distribution histogram as a sum of four (MC) primary Xmax distributions:
    - Primaries: proton, helium, nitrogen (CNO), iron.
    - MC / Data reconstructed, filtered identically.
- Energy range: $15.2 < \log10(E_{cal}\ [eV]) < 18.0$
  - Run out of statistics above 10^{18} eV.
- Use ROOT's TFractionFitter to do actual fit.

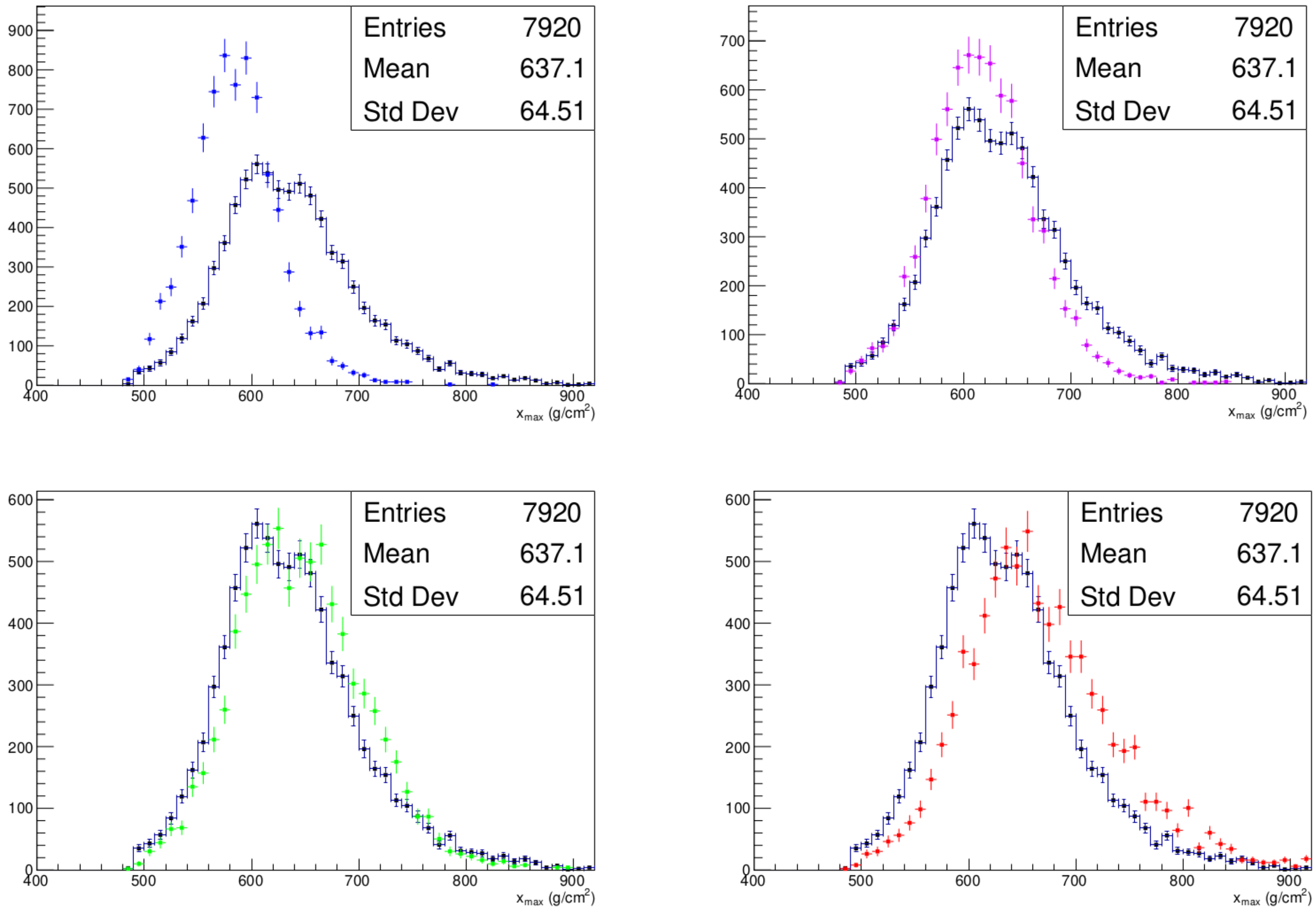
Example X_{max} distributions (1)

- Data and MC events reconstructed with energies in the range of:
- $15.7 < \log_{10}(E_{cal}) < 15.8$
- All Plots: (Black) **Data**
- Top left: **Iron**
- Top right: **CNO**
- Bottom left: **Helium**
- Bottom right: **Proton**



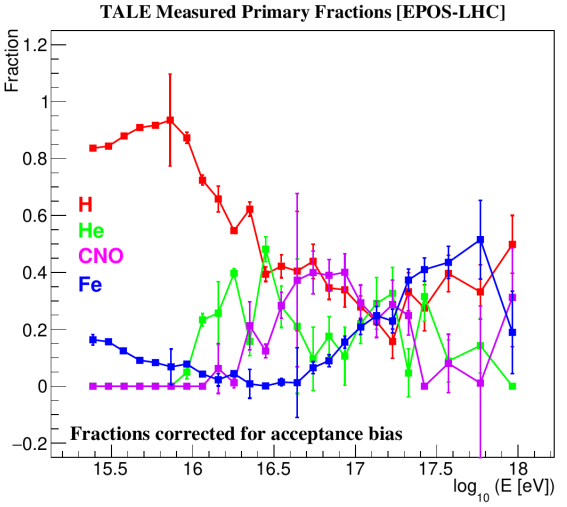
Example X_{max} distributions (2)

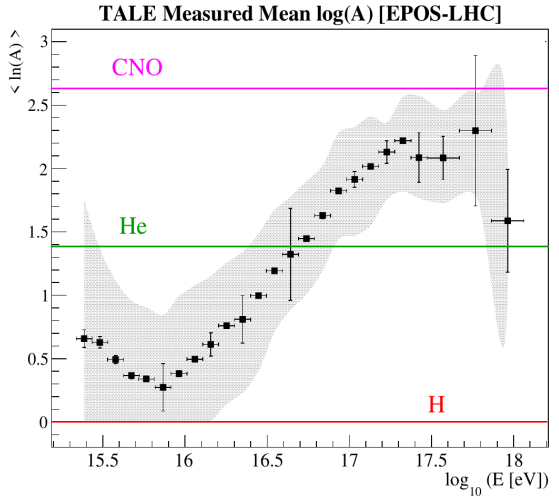
- Data and MC events reconstructed with energies in the range of:
- $16.7 < \log_{10}(E_{cal}) < 16.8$
- All Plots: (Black) **Data**
- Top left: **Iron**
- Top right: **CNO**
- Bottom left: **Helium**
- Bottom right: **Proton**



Fit results (EPOS-LHC)

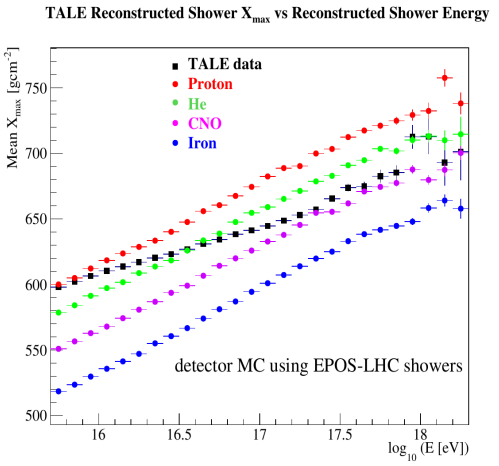
- Published results based on four years of data.
- Lowest Energy bin starts at: $\log_{10}(E_{cal}) = 15.2$
- Mean log(A) calculated as a weighted sum of log(A) for each of 4 fit primaries.
- TALE data <ln (A)> from fractions in top figure.

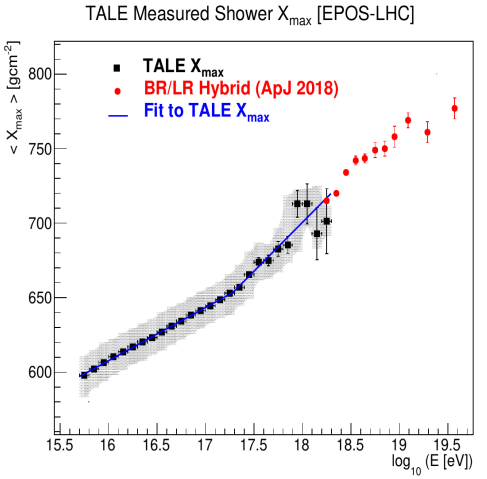




Mean Reconstructed X_{max} vs. Shower Energy

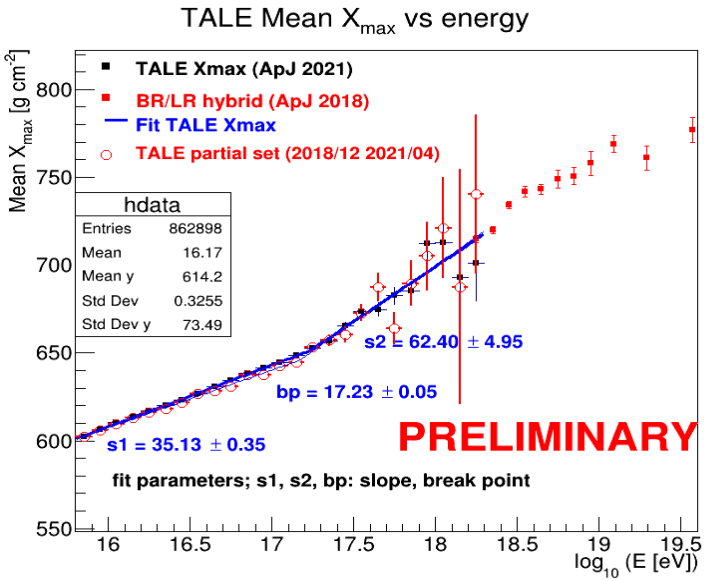
- (Top Figure): Reconstructed Data $<X_{max}>$ vs. Shower total Energy starting at log(E [eV]) = 15.3
  - Also shown, results for 4 MC primaries.
- (Bottom Figure): A broken line fit to TALE data $<X_{max}>$
  - Break point: 17.23 +/- 0.05
  - Slope before: 35.13 +/- 0.35
  - Slope after: 62.40 +/- 4.95
- (Bottom Figure): Also shown (red squares) are $<X_{max}>$ reported by TA using hybrid events from Black Rock / Long Ridge FD's and the main SD array.

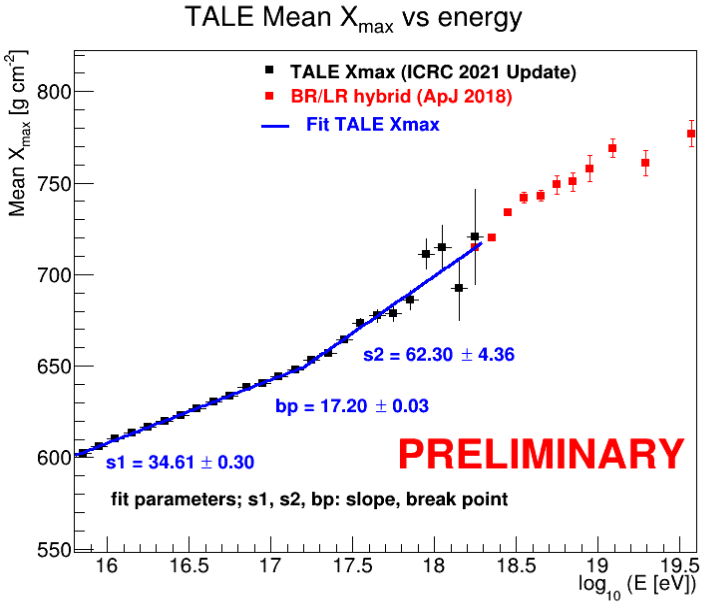




Mean Reconstructed X_{max} vs. Shower Energy

- Including data collected between 2018/12 through 2021/04
- (Top Figure): New Data <X_{max}> compared to published data (2014/06-2018/11)
- (Bottom Figure): All data along with updated broken line fit to data <X_{max}>
- (Both Figures): Also shown (red squares) are <X_{max}> reported by TA using hybrid events from Black Rock / Long Ridge FD's and the main SD array.





Nine year update

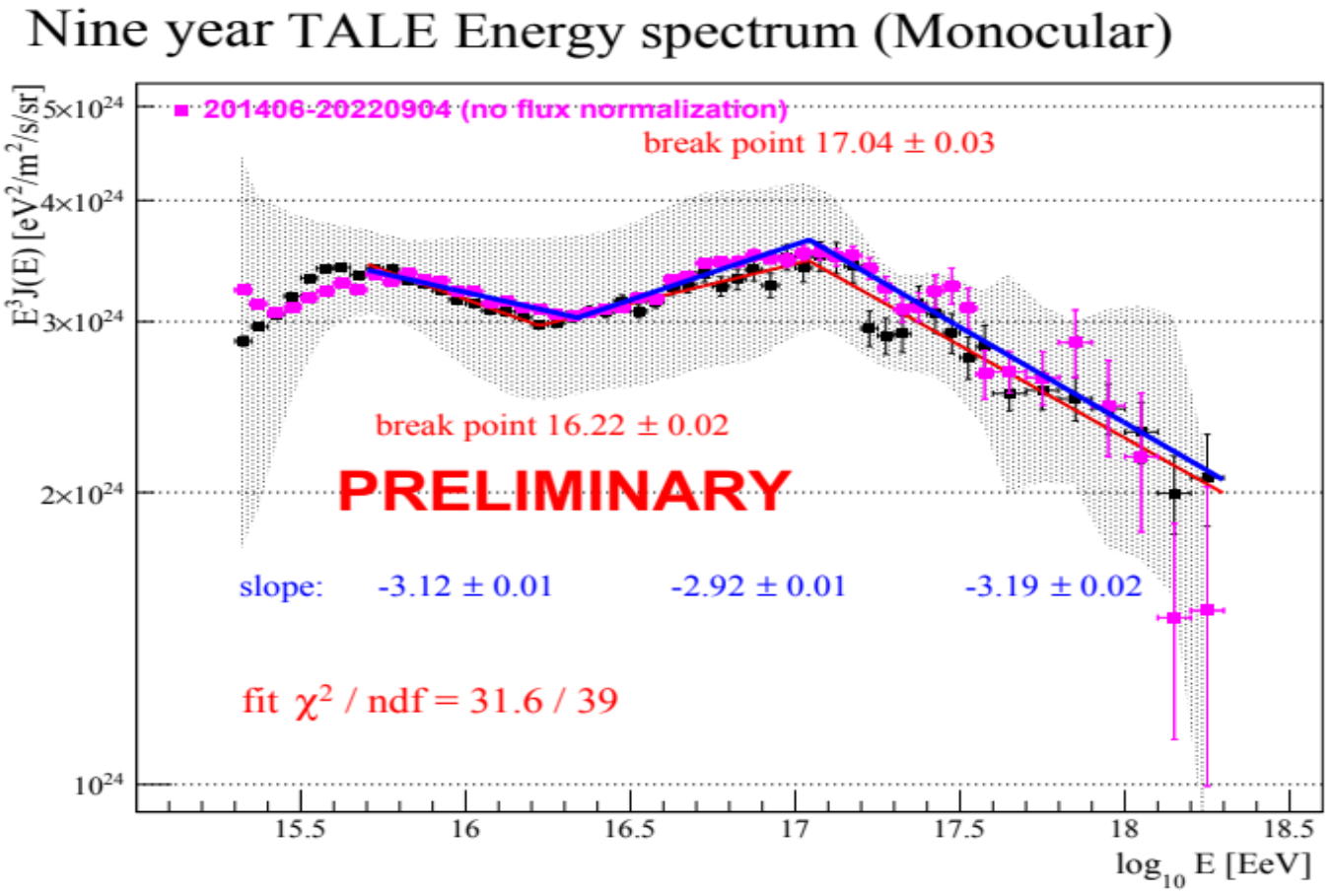
New Data on-time
(Applies to both updates)

- Accurate detector exposure calculation requires MC simulation with information about status of each telescope (on or off) for a particular time period.
- Period starting in December 2018 does not have corresponding MC simulation.
- To estimate the exposure for the period starting December 2018, *I **required** that the CR flux from this period have the same normalization as the flux measured using the four year data set*, i.e. the set with the accurate exposure calculation.
- Effective on-time was found to be 770 hours; slightly above the average value of 751 hours.
  - This is most likely due to the fact that most of the data was collected in winter months with better visibility than yearly average.

Energy Spectrum (1)

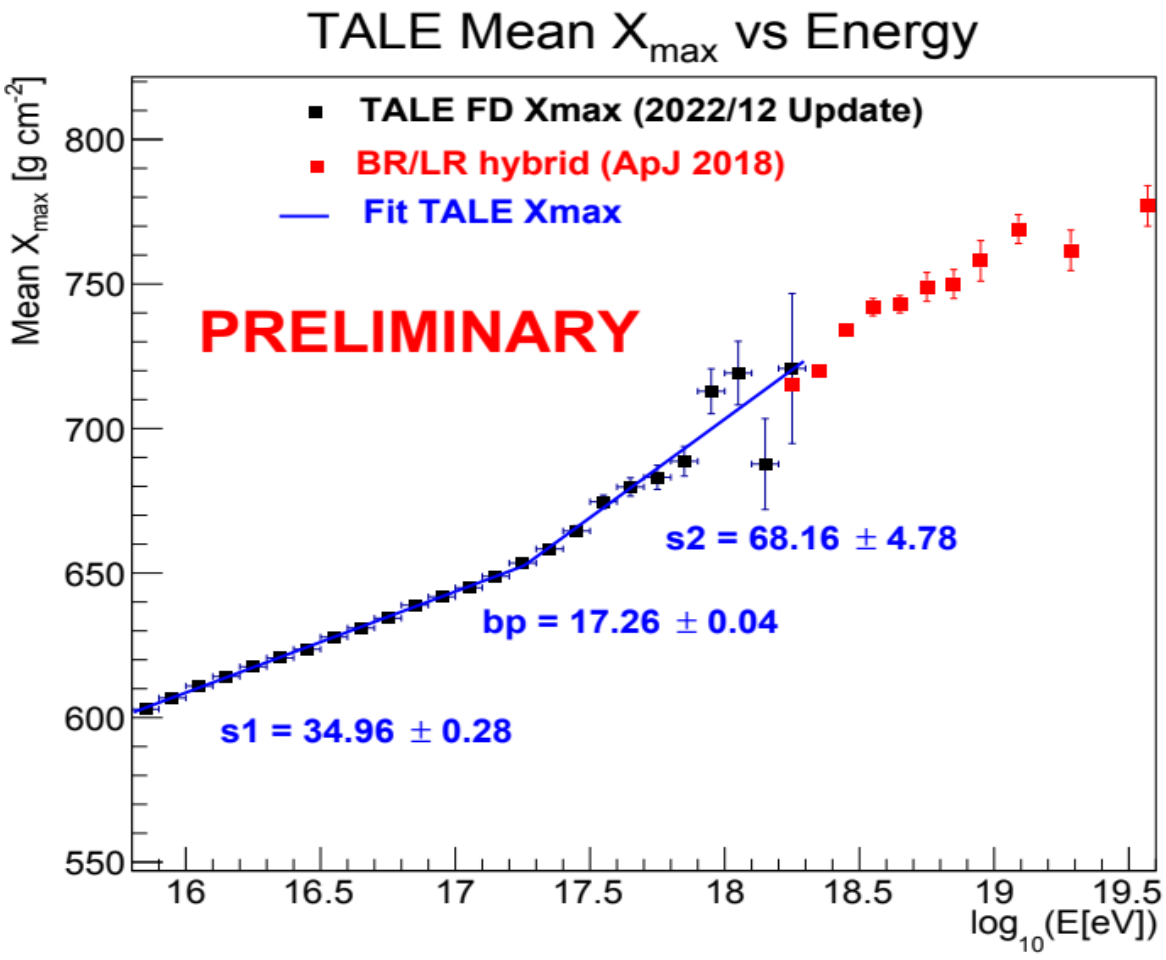
- Updated spectrum compared to ApJ 2018.
  - QGSJetII-03 → EPOS-HHC [Missing Energy]
  - All Events → Composition event selection

Energy Spectrum (2)



Mean Reconstructed X_{max}

- Including data collected between 06/2014 through 09/04/2022



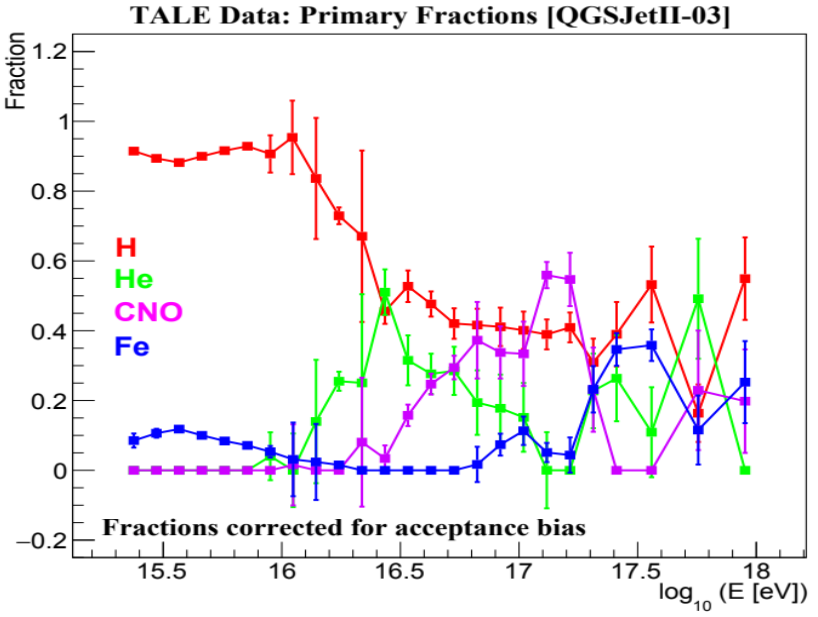
Summary

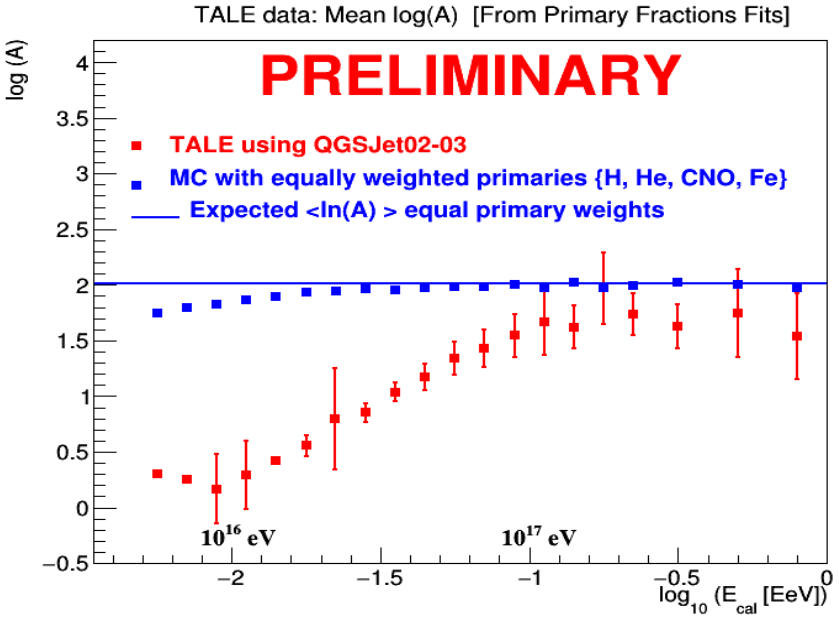
- Presented a TALE measurement of cosmic rays composition;
  - Updated through August 2022
- Data X_{max} distributions were fit to a mix of four primaries (p, He, CNO, Fe)
- Results: Fit primary fractions; mean log (A) calculated from fit primary fractions
- Mean X_{max} variation with shower energy shows a break in the elongation rate at $E = 10^{17.2}$ eV.

BACKUP SLIDES

Fit results (QGSJetII-03)

- Lowest Energy bin starts at: $\log_{10}(E_{cal}) = 15.7$
- Mean log(A) calculated as a weighted sum of log(A) for each of 4 fit primaries.
- MC thrown with equal number of primaries: <ln (A)> = 2.01
- Reconstructed MC <ln (A)> blue squares.
- TALE data (corrected fractions) shown in red.





Reconstructed MC Primary Fractions (Equal fractions thrown)