Cosmic ray mass composition measurement with the TALE hybrid detector

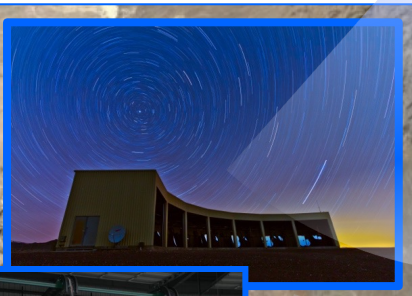
- Introduction
  - TA and TALE Detectors
- Hybrid Reconstruction and Performance
- Data analysis
  - Data/MC comparison
  - Mass Composition Analysis
- Conclusions

Keitaro Fujita
ICRR, University of Tokyo
for the Telescope Array Collaboration

6th International Symposium on Ultra High Energy Cosmic Rays
- UHECR2022 -

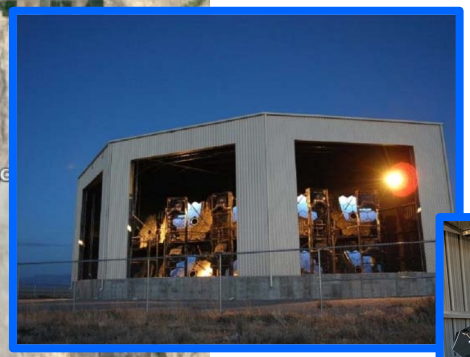
Telescope Array Detectors

Fluorescence Detectors(FDs)
Middle Drum(MD) station
14 telescopes
+ TA Low energy Extension (TALE) 10 telescopes



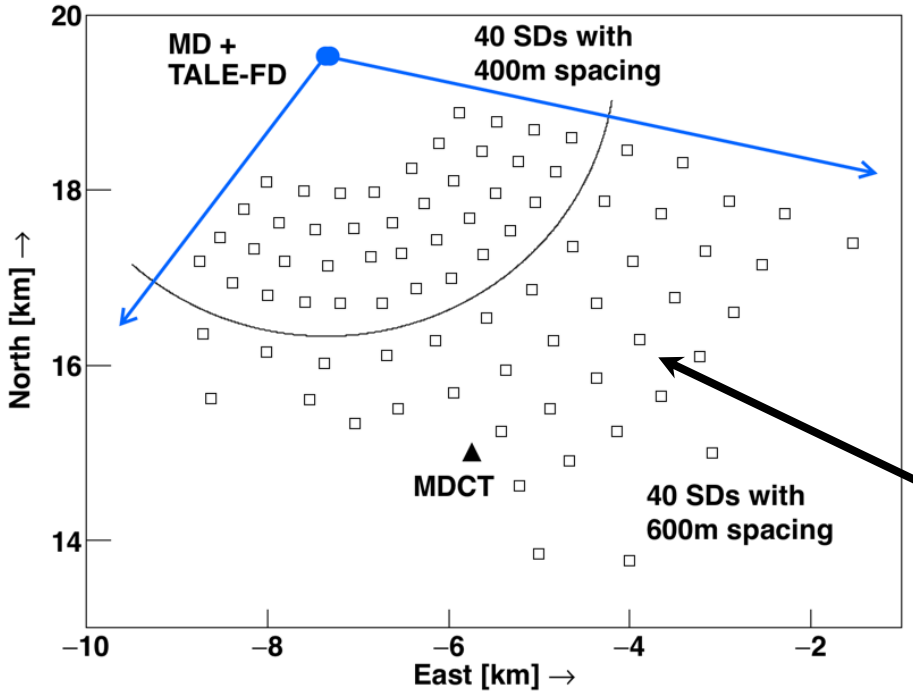
Surface Detector(SD) array
507 scintillation detectors, each 3m^2
1.2 km spacing
total coverage ~ 700km^2

FDs
Black Rock Mesa(BRM) station
12 telescopes



FDs
Long Ridge(LR) station
12 telescopes

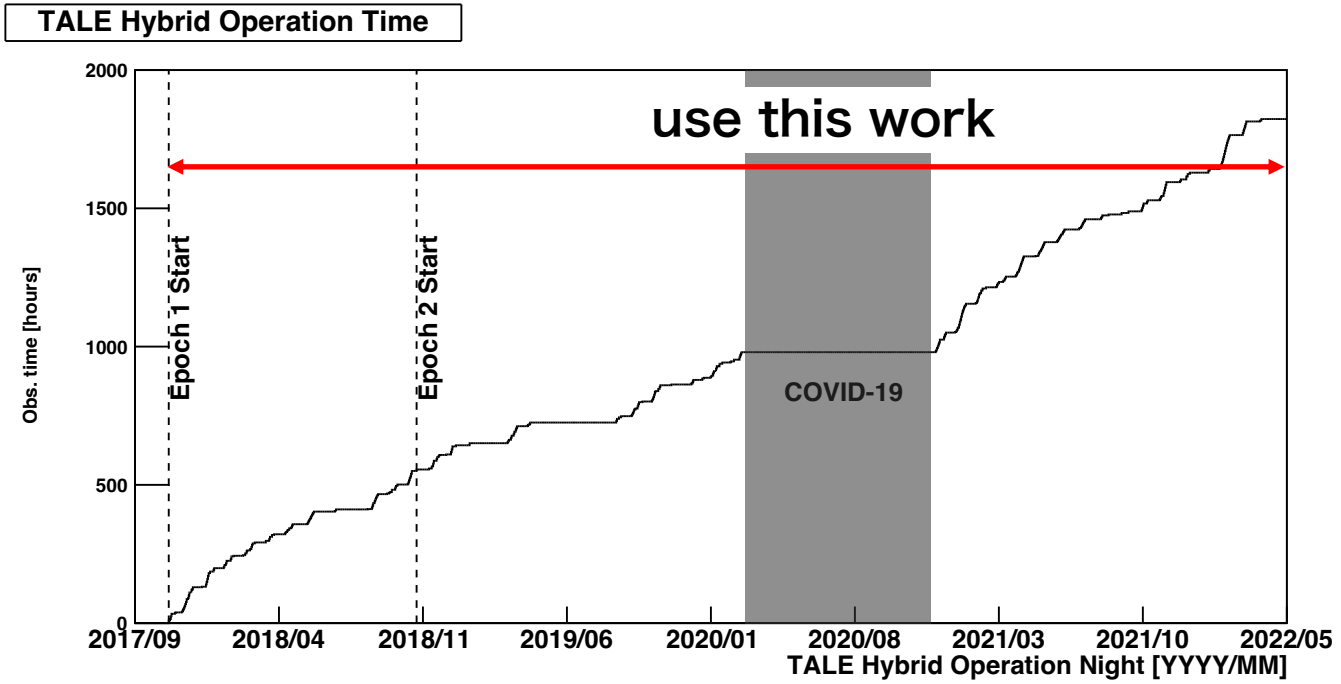
TA Low energy Extension(TALE)



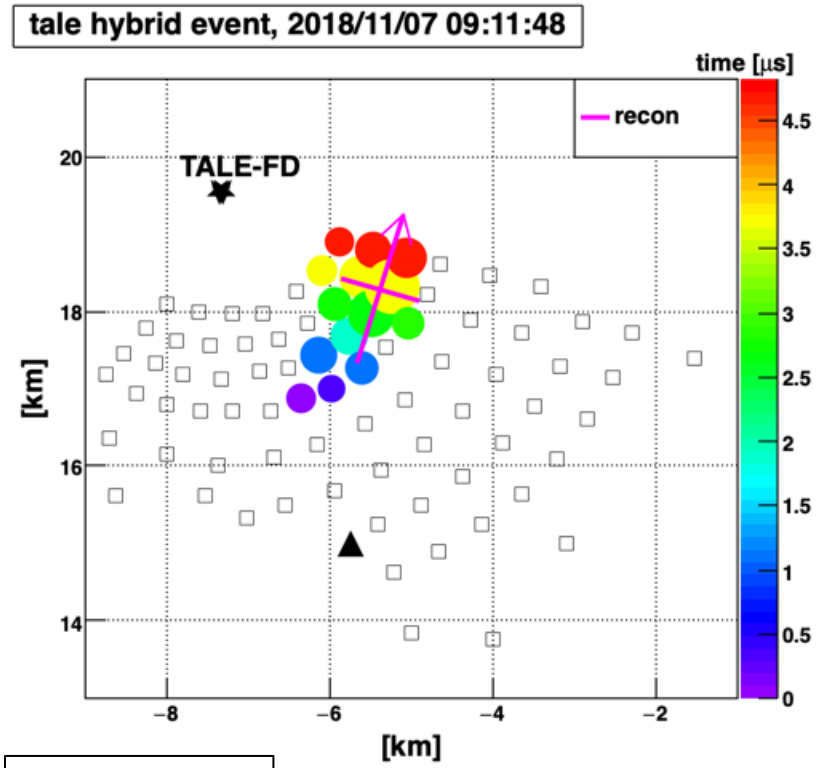
- Low energy CRs-induced shower
  - Not so bright, higher $X_{\max}$
    → high elevation telescope
  - compact shower size
    → dense SD array
- Low energy target: E > 10^{16} eV
- Constructed in north part of TA site
- Same concept as TA detector
  - 10 Fluorescence Telescopes
  - 80 Surface Detectors, 20 km^2
- Operation: FD since Sep. 2013
  SD since Nov. 2017

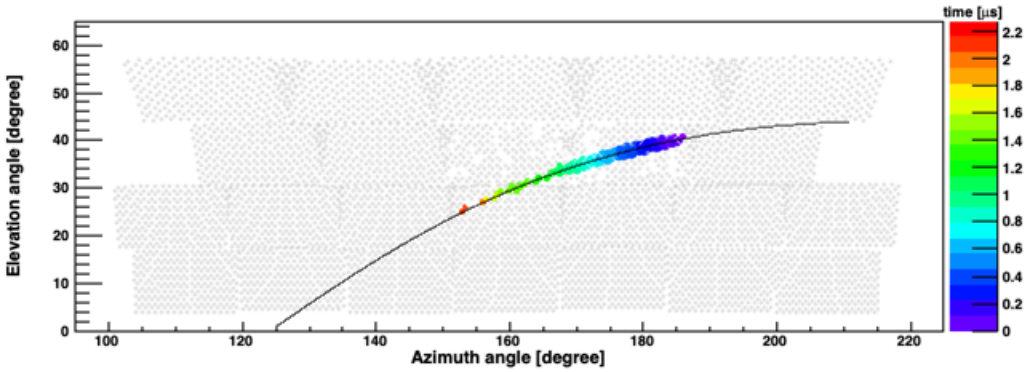
TALE-Hybrid Operation Status

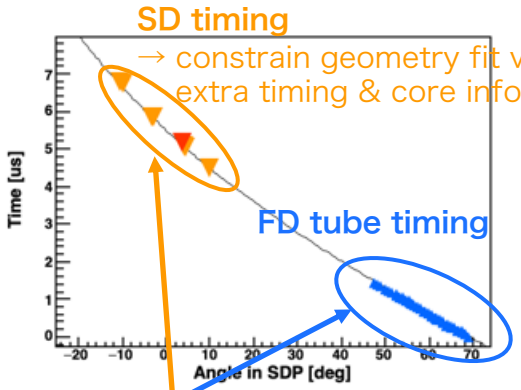
- 2017/11/19 - 2018/11/13, 550hours, Epoch1
  - Both detector running independently
- 2018/11/14 - 2020/02/29, 430hours, Epoch2
  - hybrid trigger system working
- 2020/03 - 2020/11: suspended due to COVID19
- 2020/12 – 2022/05, 980hours, Epoch3

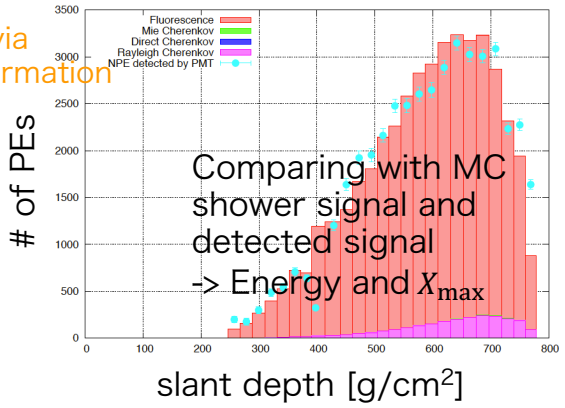


Event Reconstruction

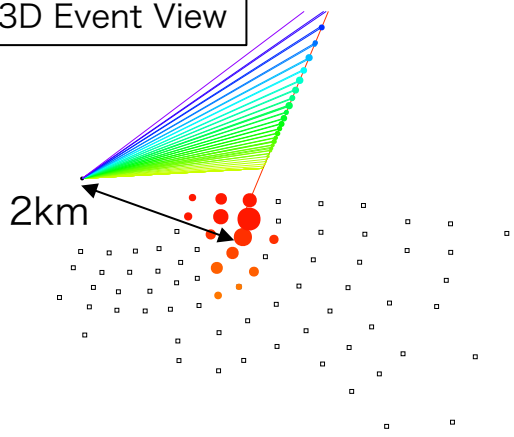


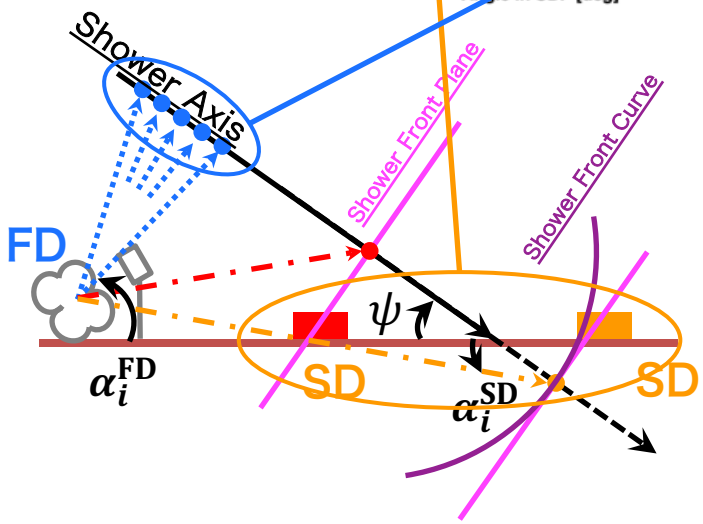






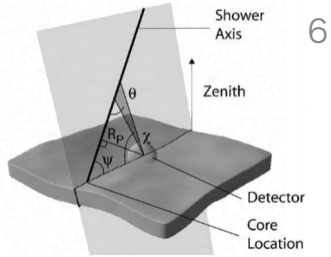
3D Event View



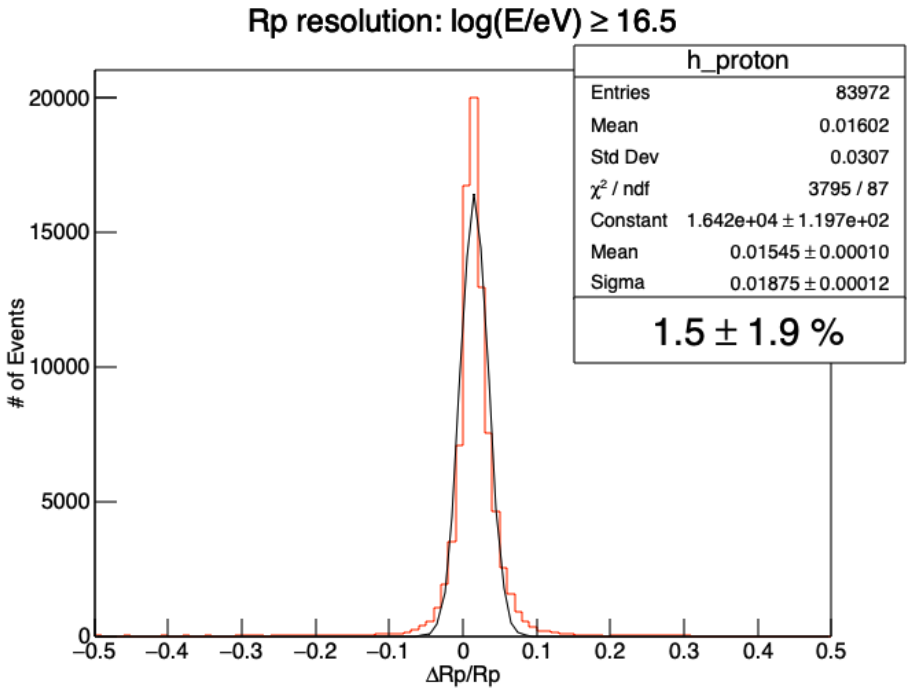


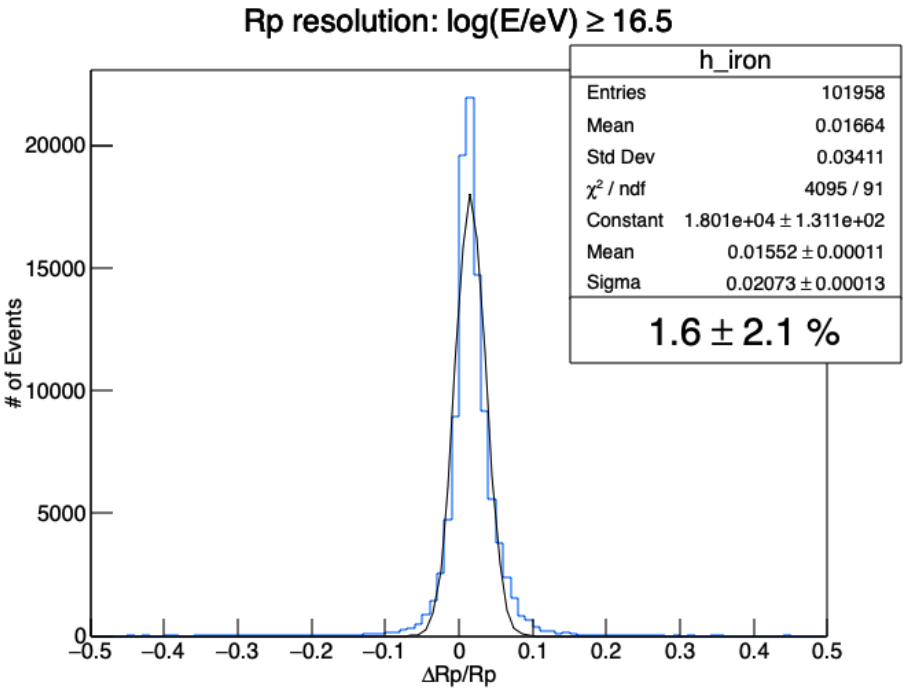
Hybrid analysis provides most precise and statistical for composition studies using shower maximum X_{max}

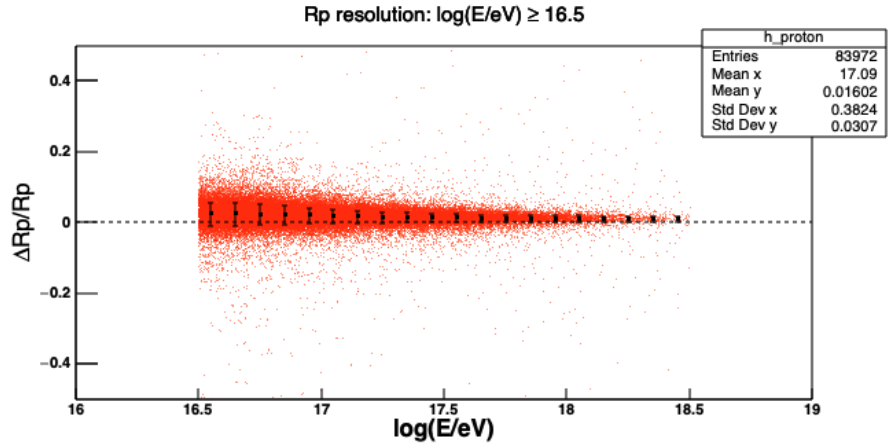
Reconstruction Resolution

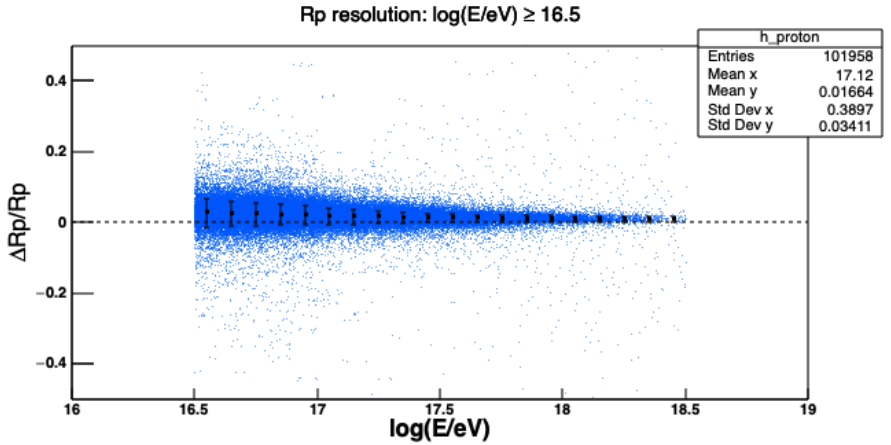


- Rp resolution for proton and iron

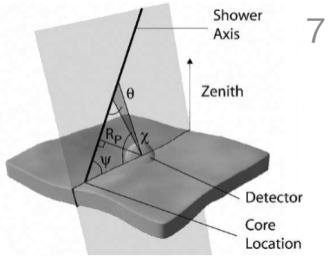




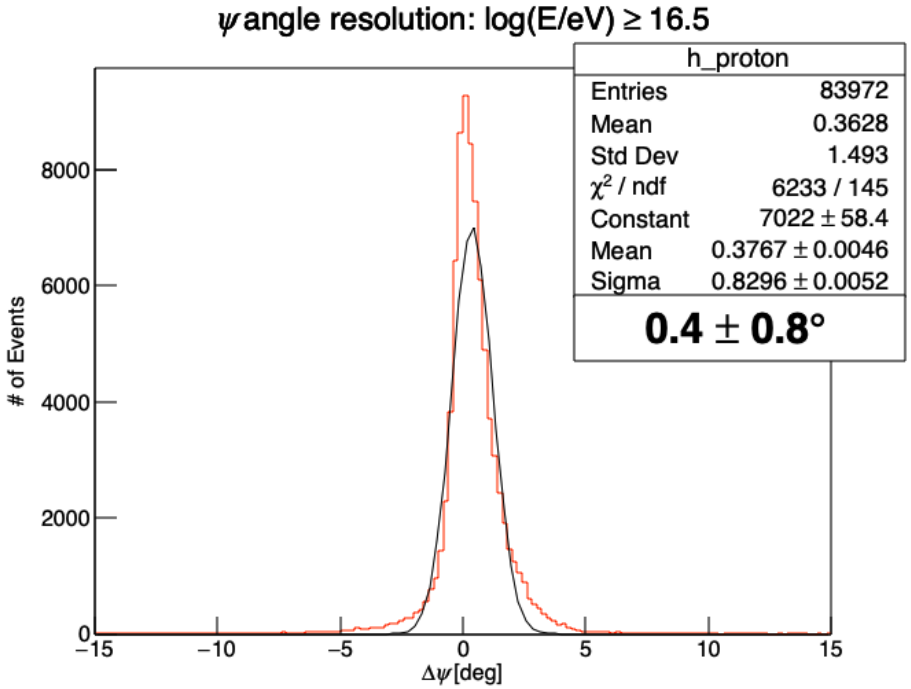


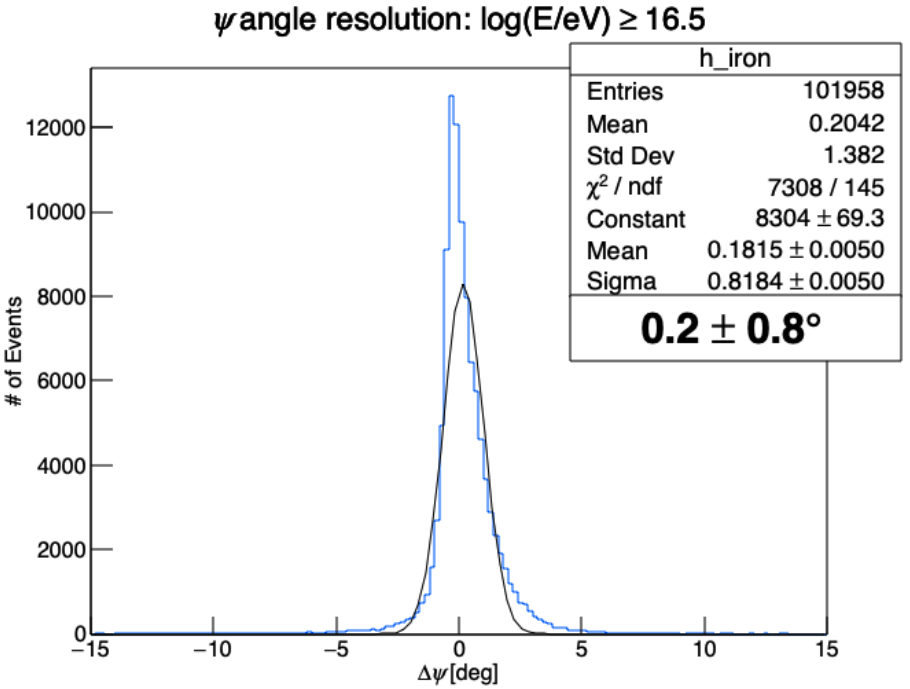


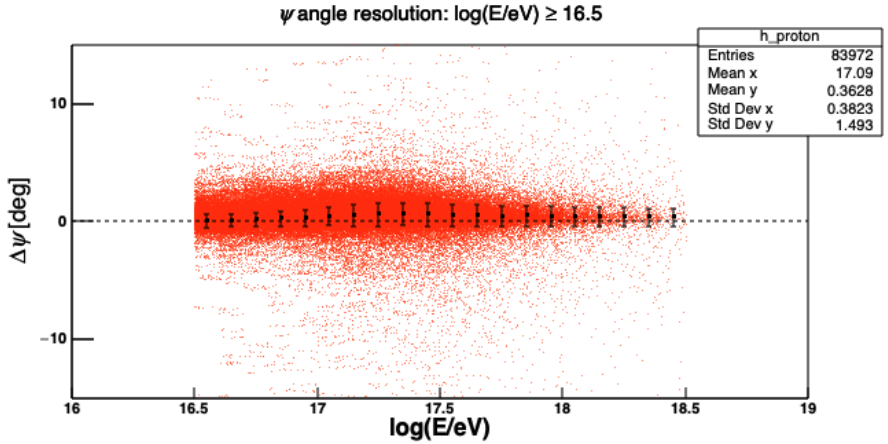
Reconstruction Resolution

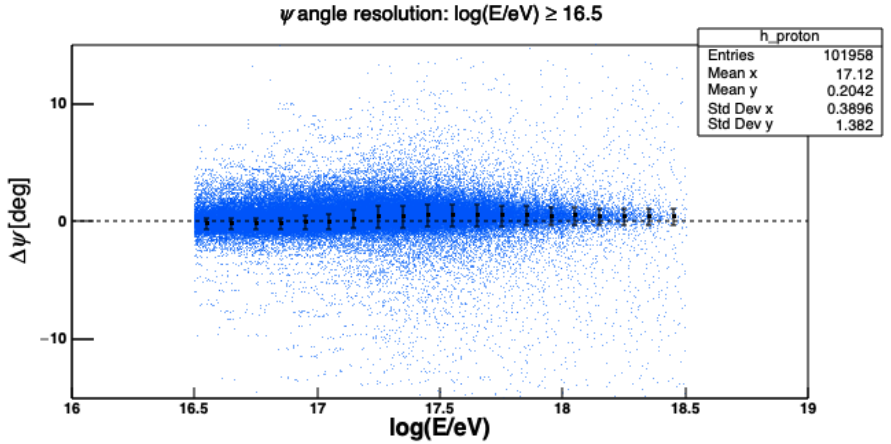


- Psi angle ψ resolution for proton and iron



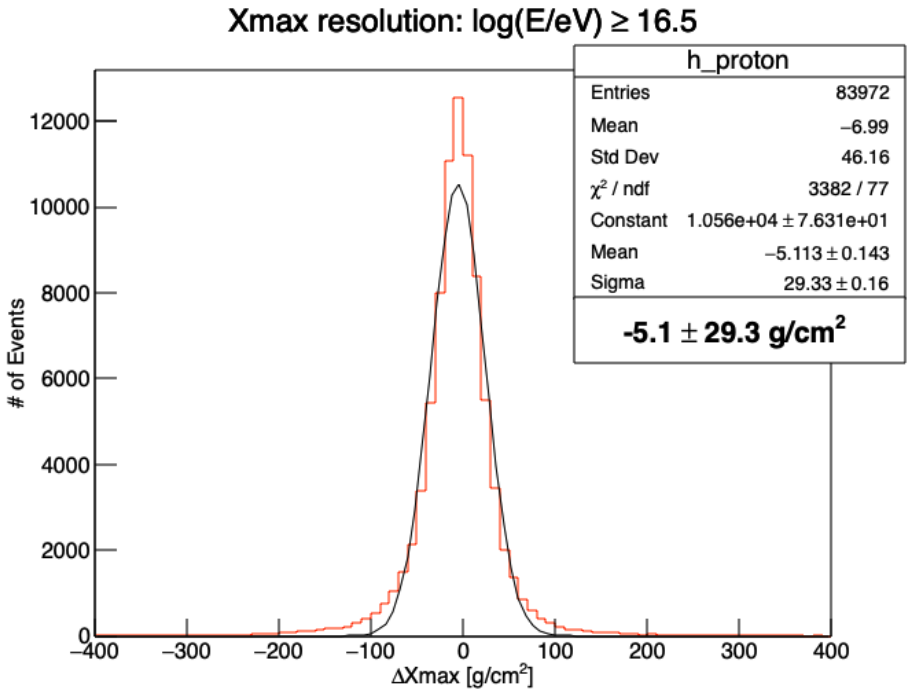


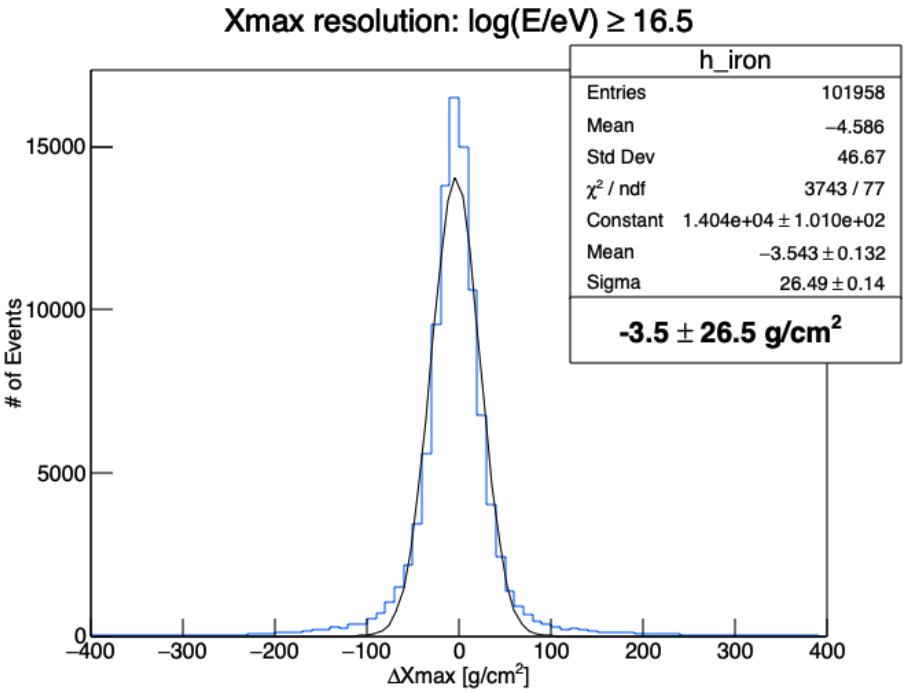


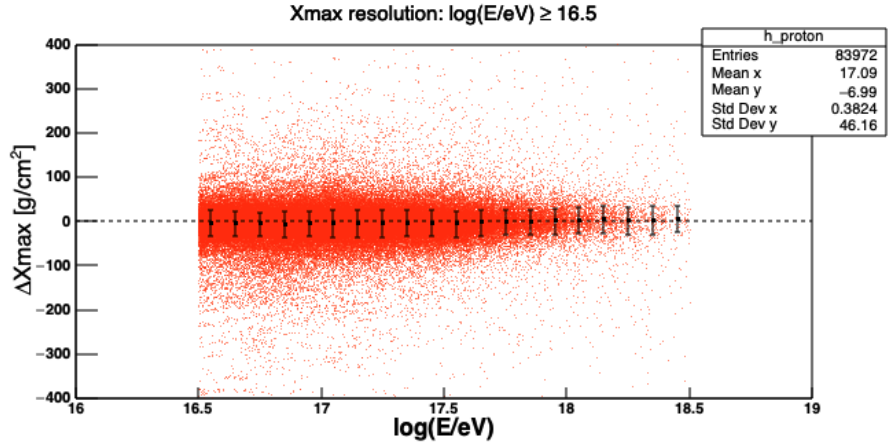


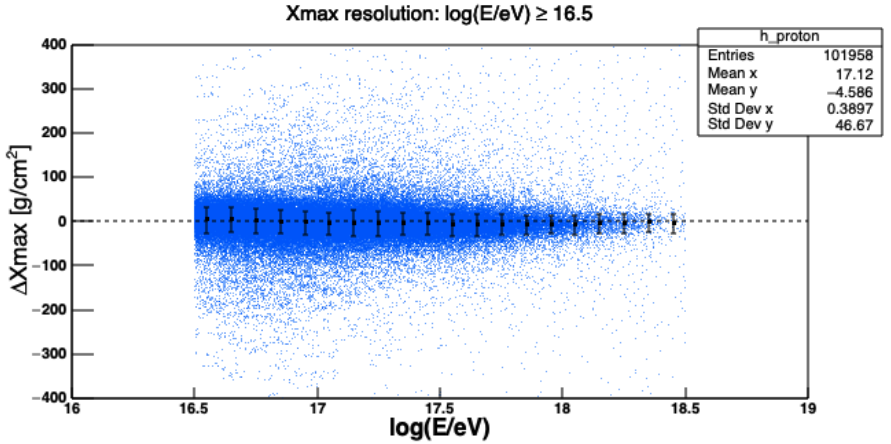
Reconstruction Resolution

- $X_{\max}$ resolution for proton and iron



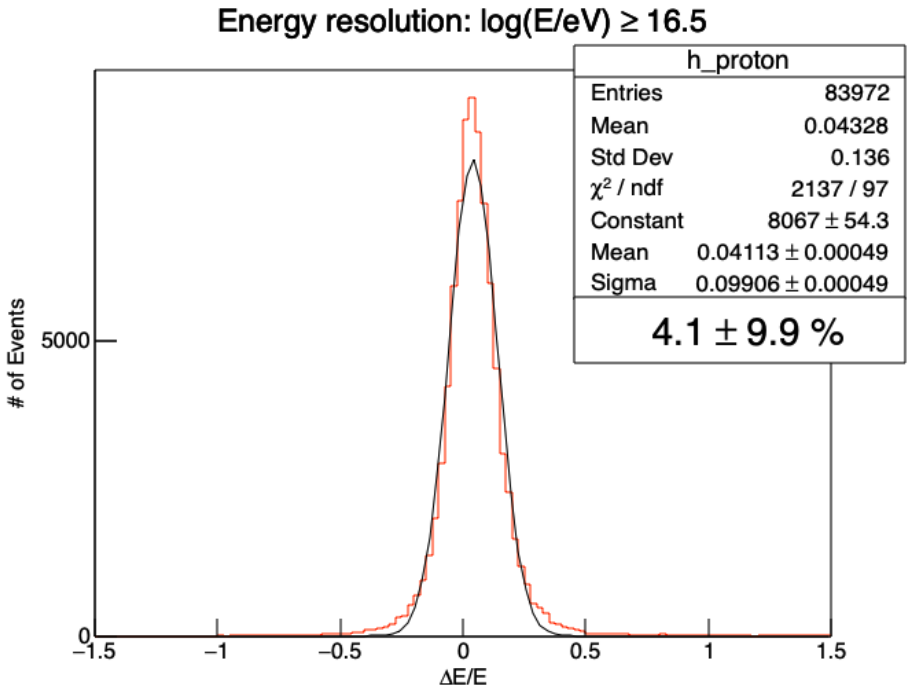


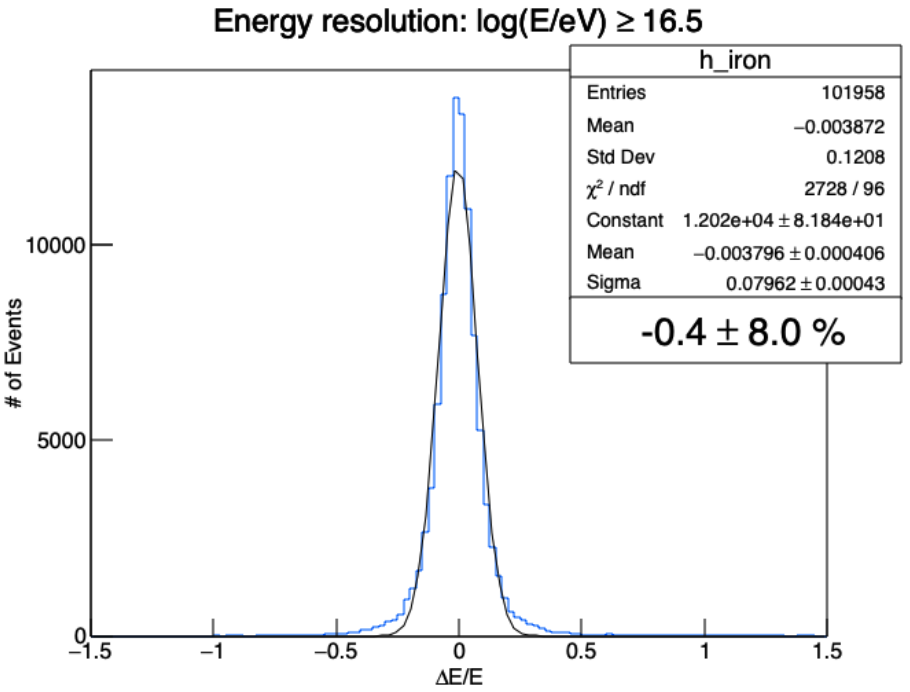


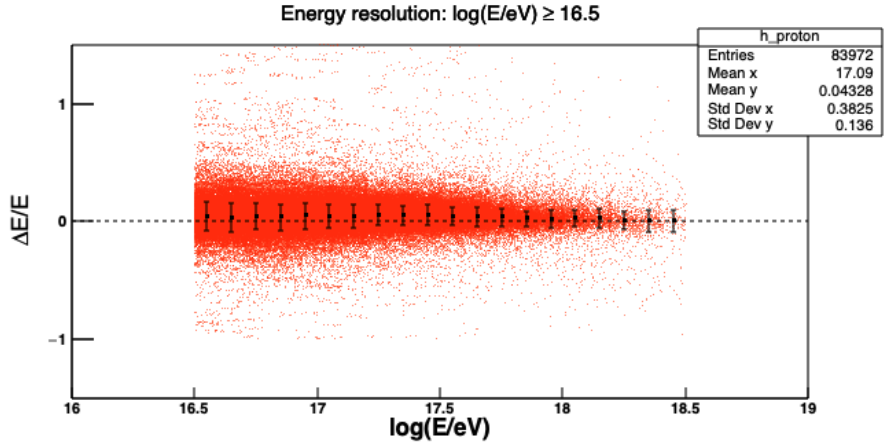


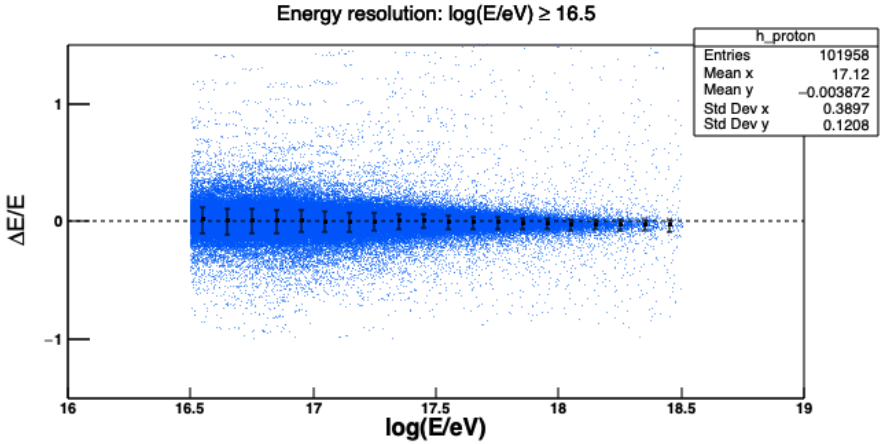
Reconstruction Resolution

- Energy resolution for proton and iron









Data/MC Comparison

- **Hybrid Dataset**
  - 2017/11/19 - 2018/11/13
    550hours, self trigger mode
  - 2018/11/14 - 2020/02/29
    430hours, hybrid trigger mode
  - 2020/12 – 2022/05
    980hours, hybrid trigger mode

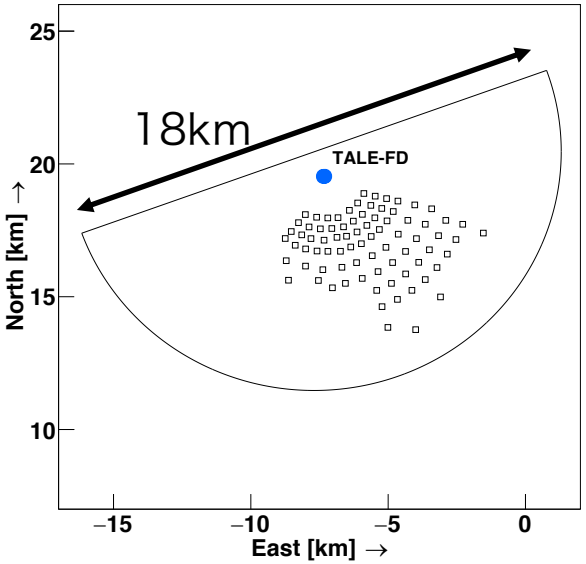
- **MC Dataset**
  - CORSIKA QGSJETII-04 proton, iron
  - Energy : log(E/eV) = 16.45 -18.55
    slope: -2.9, log(E/eV) < 17.1
    -3.2, log(E/eV) > 17.1
  - Zen. angle: 0 ~ 60°
  - Azi. angle: 0 ~ 360°
  - Area: Semi-Circle in bottom Fig.

- **Quality Cuts in this study**
  - FL is defined as fluorescence light > 75 %
  - CL is as fluorescence light < 75 %

Variable	CL	FL
No saturated PMTs in FD	applied	
SD detected ≥ 1 MIPs	applied	
X_{max} bracketing cut	applied	
Angular track-length [deg]	track > 6.5°	
Event duration [ns]	> 100 ns	
# of PMTs	> 10	
# of Photo-electrons / # of PMTs	> 50	
# of Photo-electrons		> 2000

Table 1: Quality Cuts Applied in this study

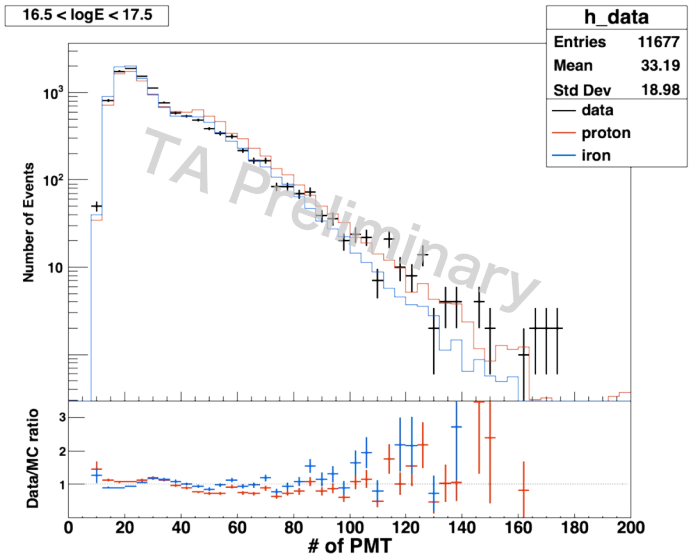
Generation Area

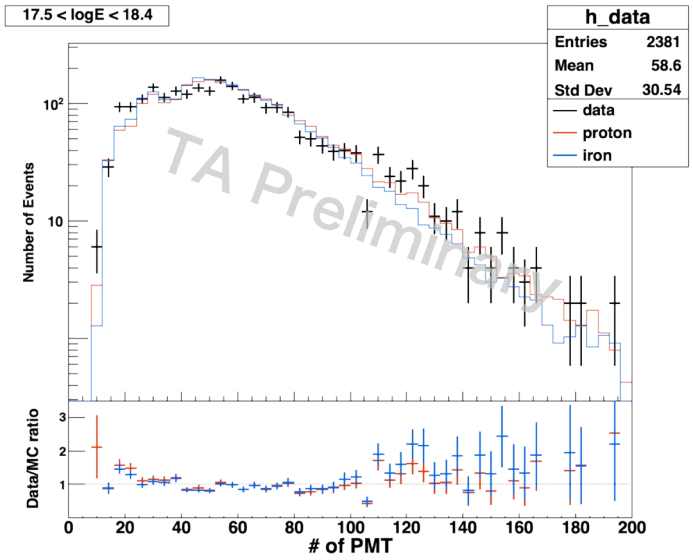


Data/MC Comparison(1/3)

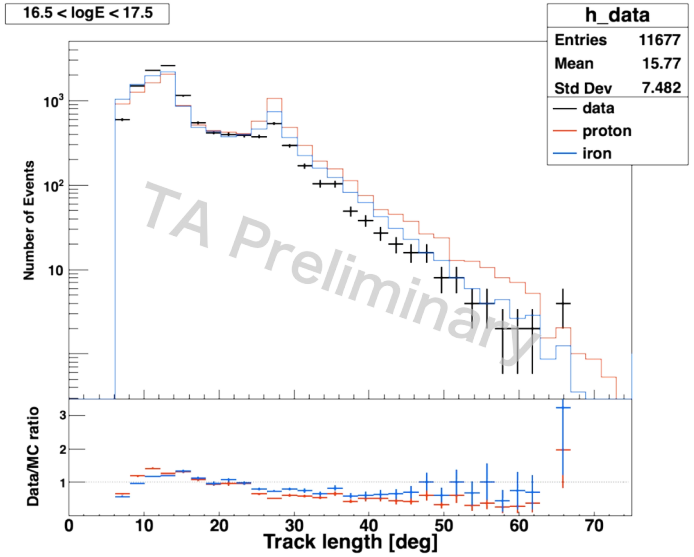
- Left: $16.5 < \log_{10}(E/eV) < 17.5$, Right: $17.5 < \log_{10}(E/eV) < 18.4$

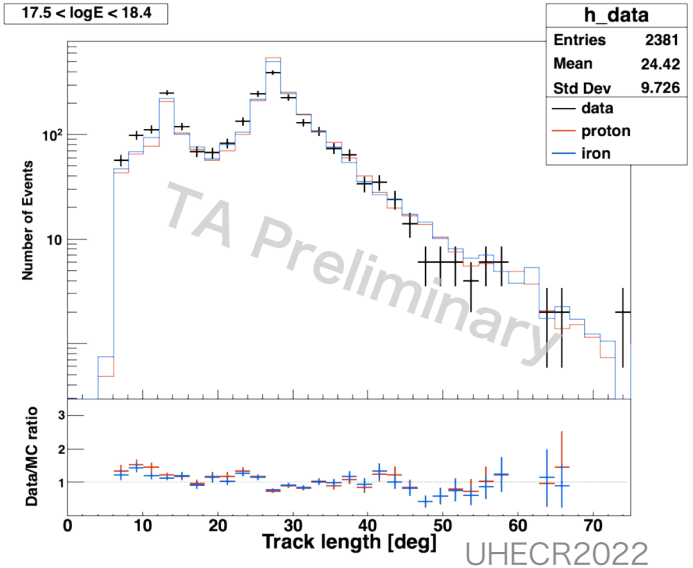
# of PMT





Track Length

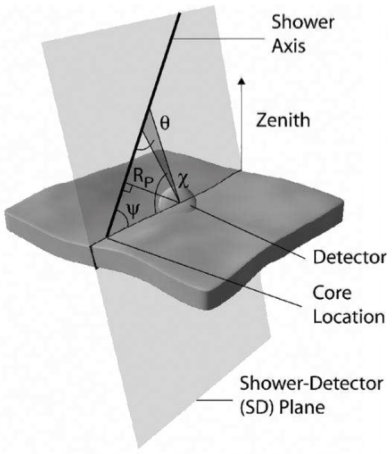




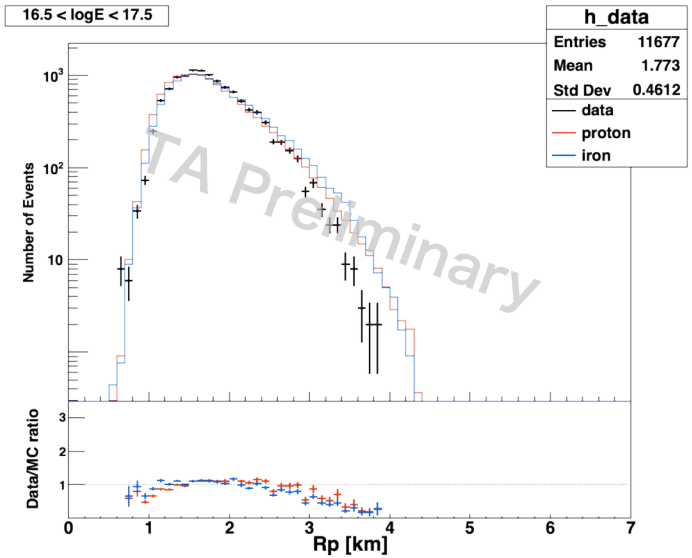
Data/MC Comparison(2/3)

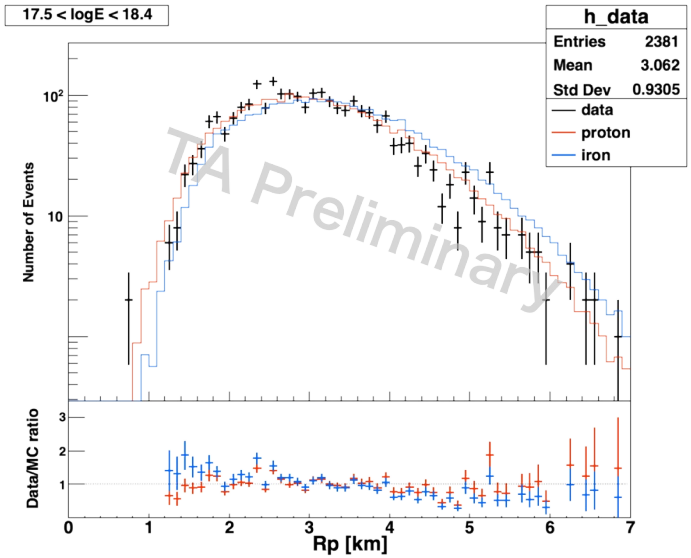
- Left: $16.5 < \log_{10}(E/eV) < 17.5$, Right: $17.5 < \log_{10}(E/eV) < 18.4$

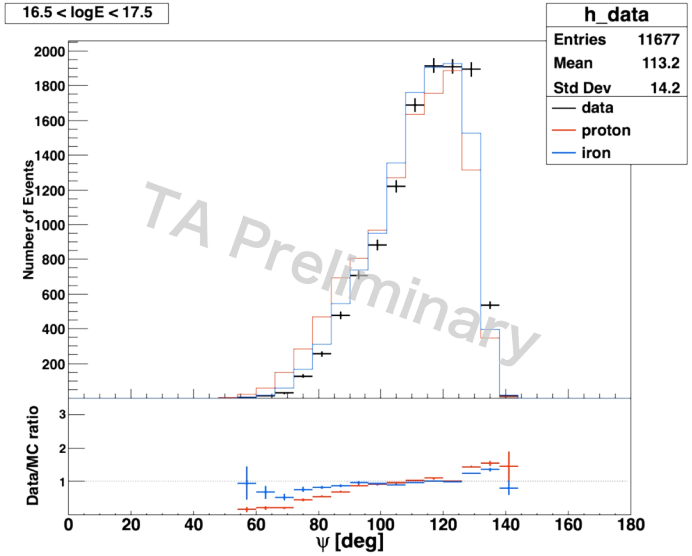
Rp
(impact parameter)

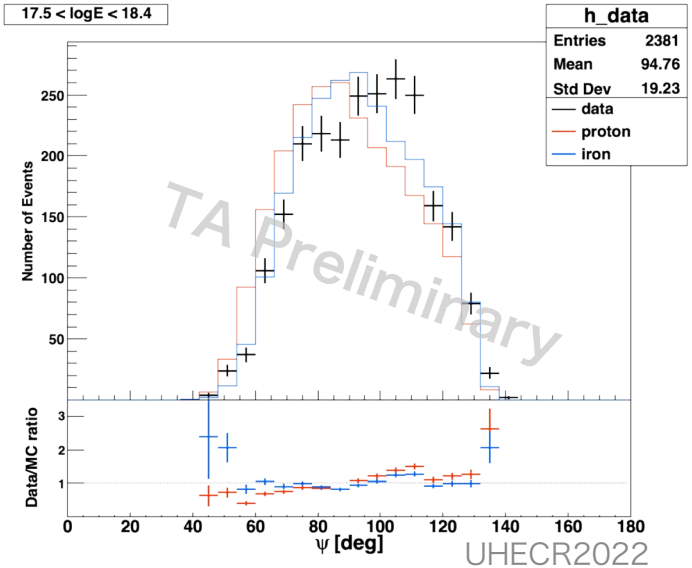


ψ angle





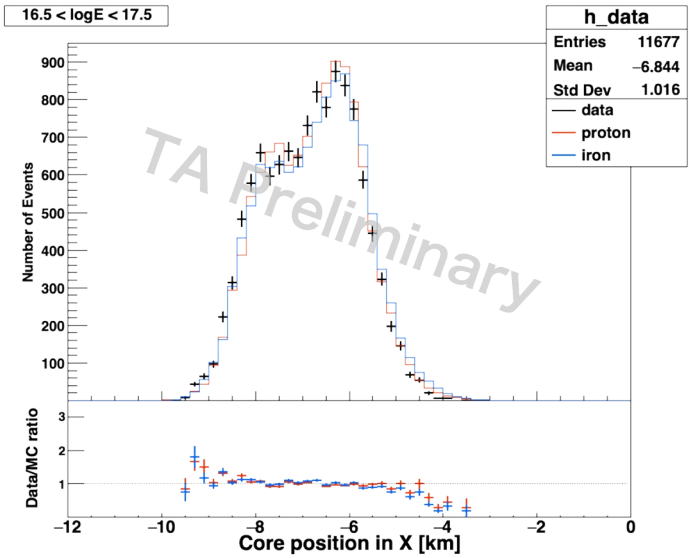


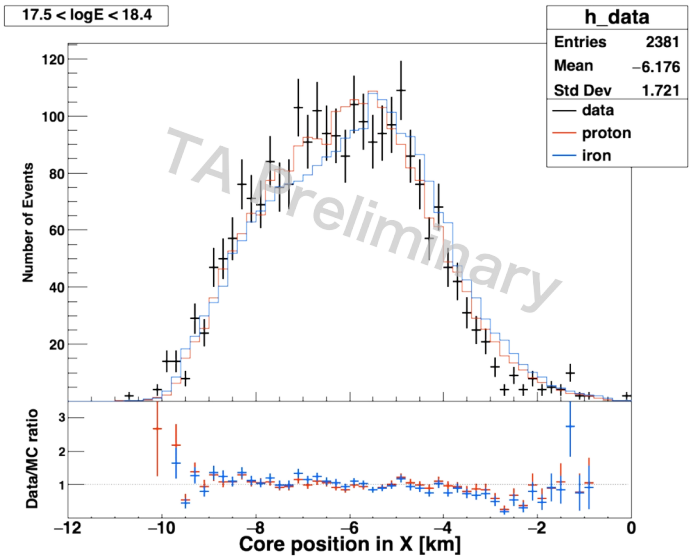


Data/MC Comparison(3/3)

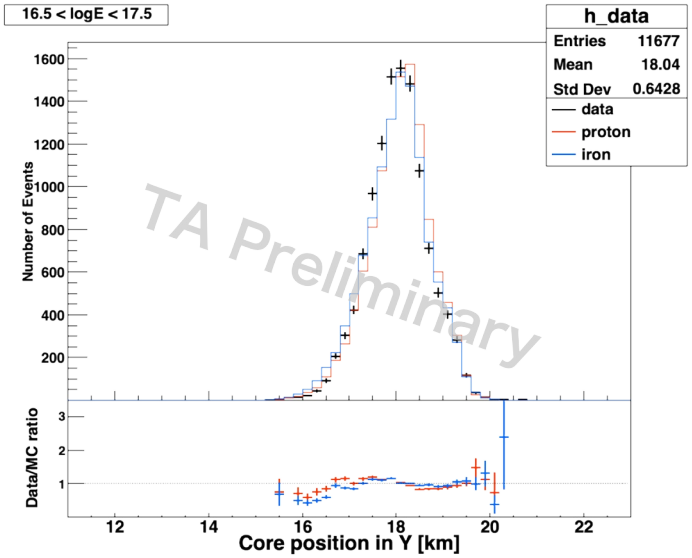
- Left: $16.5 < \log_{10}(E/eV) < 17.5$, Right: $17.5 < \log_{10}(E/eV) < 18.4$

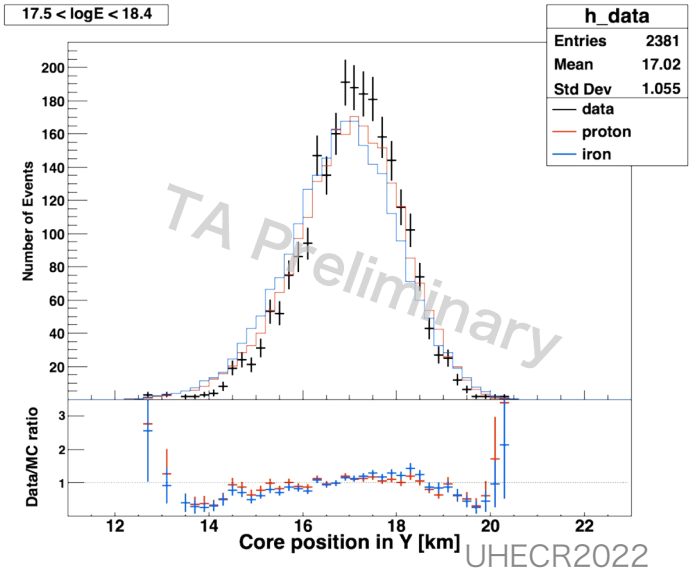
Core X
(West-East)





Core Y
(South-North)

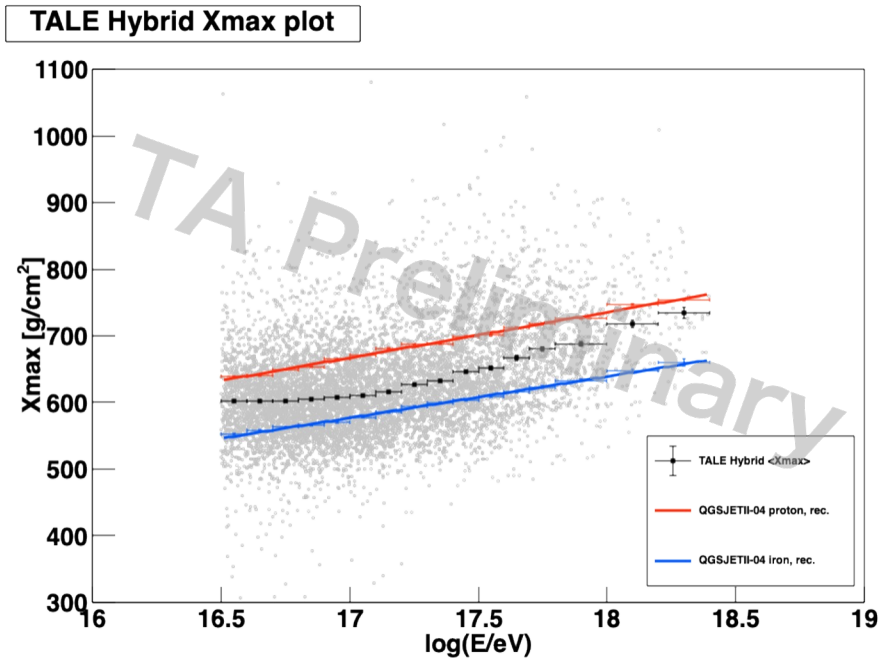


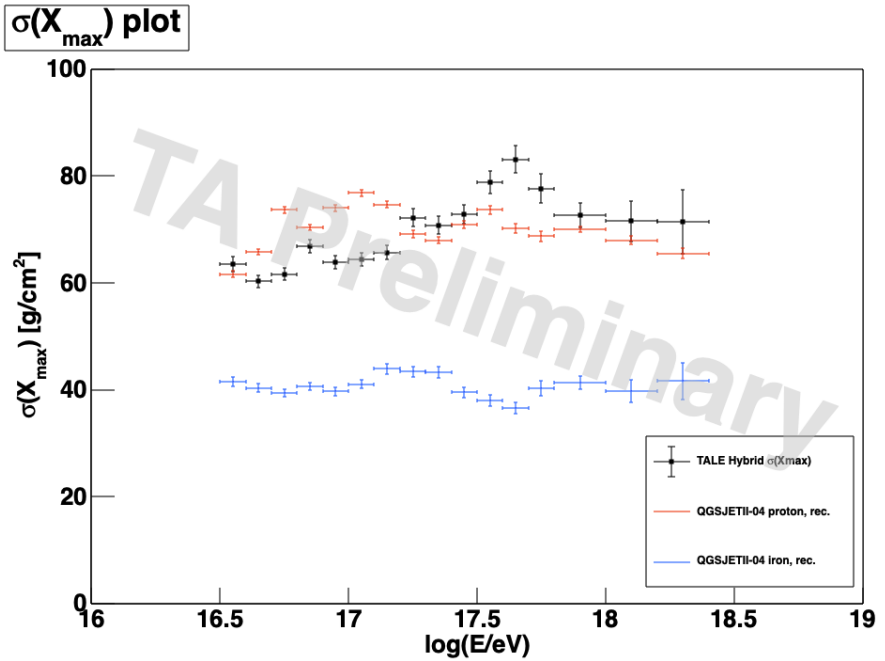


Mass Composition

TALE Hybrid Composition

- Measured reconstructed $\langle X_{\max} \rangle / \sigma(X_{\max})$ vs. shower energy
  - Nov. 2017 - May. 2022 (4 yrs, 1880 hours)



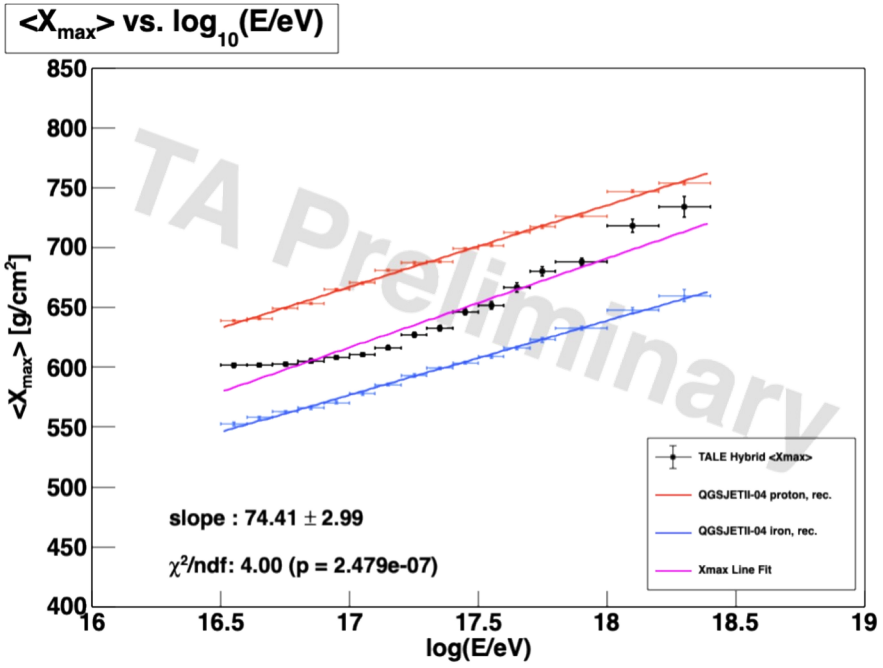


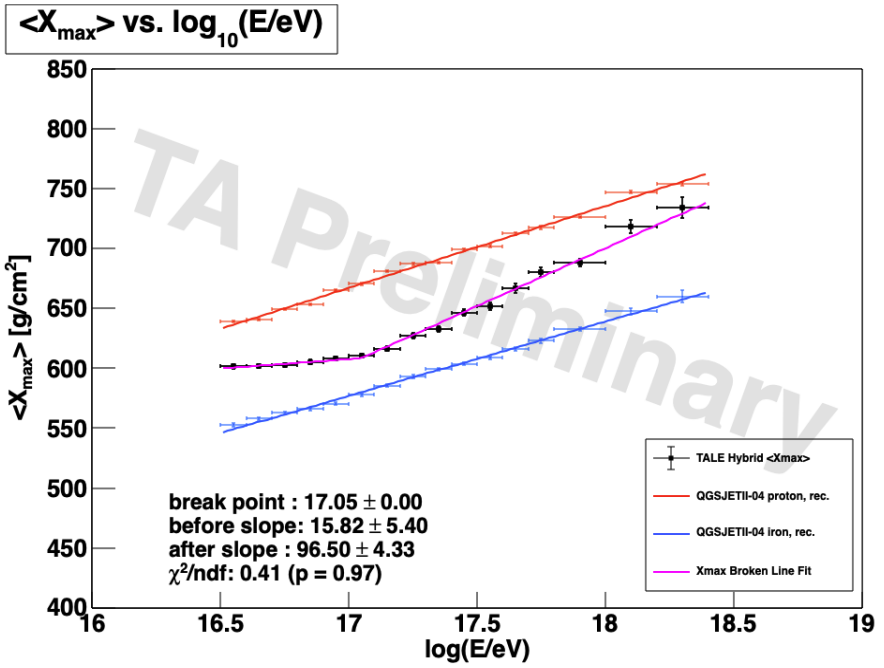
$\langle X_{\max} \rangle / \sigma(X_{\max})$ along with predictions of QGSJETII-04 proton, iron

4 yrs TALE Hybrid data E > $10^{16.5}$ eV
14058 events after quality cuts

TALE Hybrid Composition

- Measured reconstructed $\langle X_{max} \rangle$ vs. shower energy
  - Nov. 2017 - May. 2022 (4 yrs, 1880 hours)
- Fitted by single/broken line functions





$D_{10} = 74 \pm 3$ g/cm²/decade

$D_{10}^{before} = 16 \pm 5$ g/cm²/decade

$D_{10}^{after} = 97 \pm 4$ g/cm²/decade

$\log_{10}(E_{break}/\mathrm{eV}) = 17.1$

MC elongation rate [g/cm²/decade]

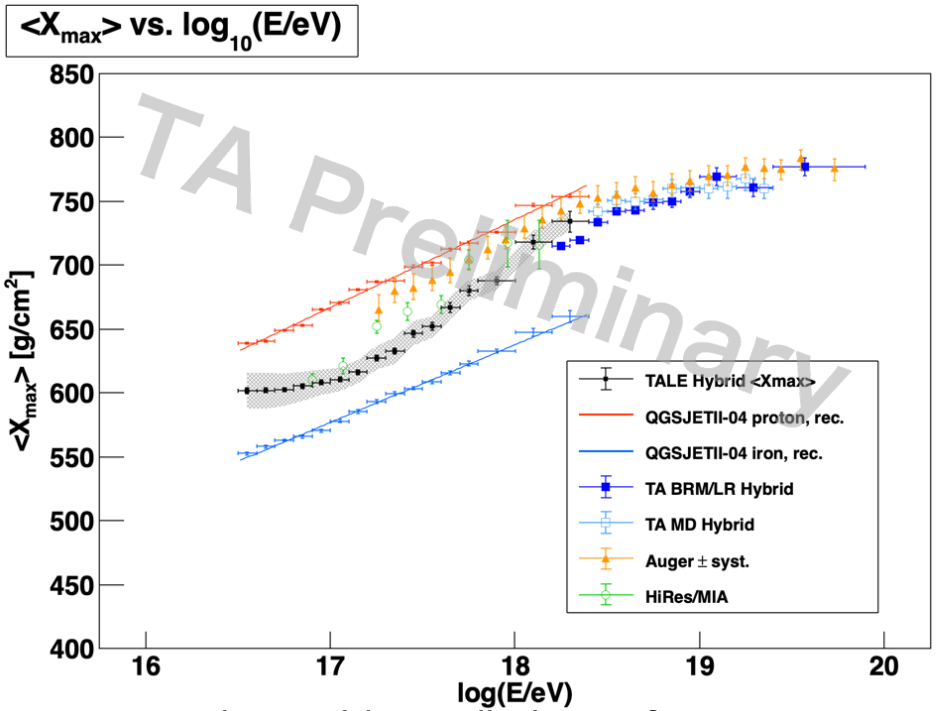
	proton	iron
D_{10}^{MC}	68 ± 2	62 ± 2

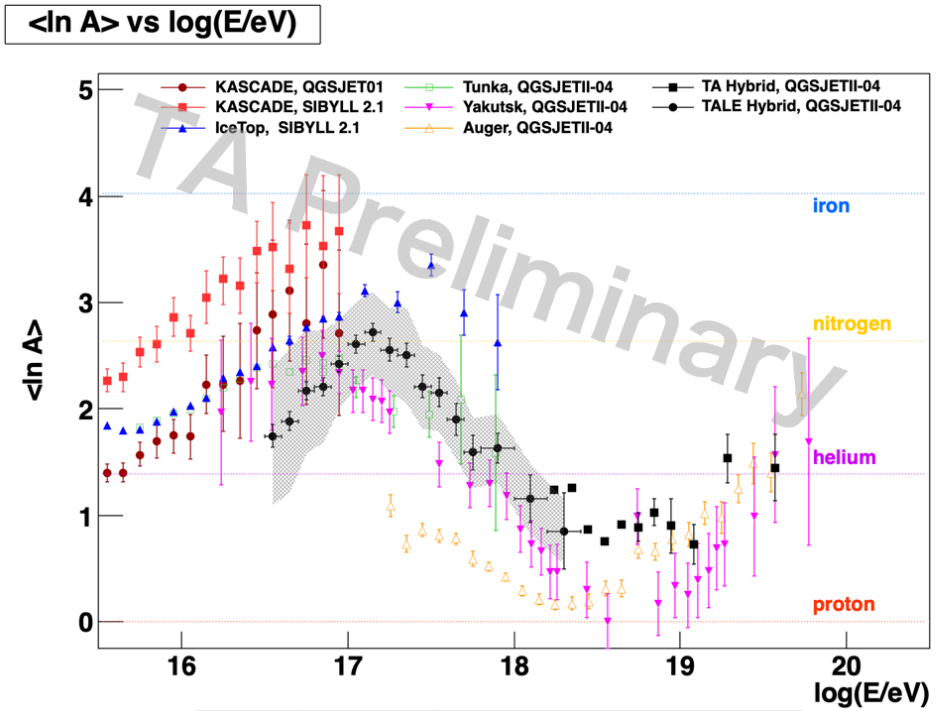
Suggest heavy to light above 10^{17} eV

TALE Hybrid Composition

- **TALE Hybrid** $\langle X_{\max} \rangle, \langle \ln A \rangle$ vs. $\log_{10}(E/\mathrm{eV})$

$$\langle \ln A \rangle = \frac{X_{\max}^{\mathrm{data}} - X_{\max}^{\mathrm{proton}}}{X_{\max}^{\mathrm{iron}} - X_{\max}^{\mathrm{proton}}} \cdot \ln A_{\mathrm{iron}}$$





$\langle X_{\max} \rangle$ along with predictions of QGSJETII-04 proton, iron

4 yrs TALE Hybrid data E > $10^{16.5}$ eV
14058 events after quality cuts

Systematic uncertainty on $\langle X_{\max} \rangle$ is less than 14 g/cm^2

Sources	$X_{\max}$
Photonic Scale	5 g/cm^2
Relative Time of FD and SD	3.5 g/cm^2
Fluorescence yield	5 to 1 g/cm^2
Cherenkov model	11 to 3 g/cm^2
Atmosphere	1.4 g/cm^2
Missing energy	3 g/cm^2
Total	13.8 to 7.1 g/cm^2

Conclusions

- Focused on studying the cosmic ray mass composition in the energy range of $10^{16.5}$ - $10^{18.4}$ eV using 4yrs the TALE Hybrid data

- Data/MC is agreement

- Mass composition
  - Elongation rate:
    Clearly shown a broken structure
    - D_{10}^{before} = 16 ± 5 g/cm²/decade
    - D_{10}^{after} = 97 ± 4 g/cm²/decade
    - $\log_{10}(E_{\mathrm{break}}/\mathrm{eV})$ = 17.1
    - Suggest light to heavy below 10^{17} eV, then getting lighter above
  - Smoothly connected to TA hybrid measurement