The Cosmic ray energy spectrum in the 2nd knee region measured by the TALE-SD array

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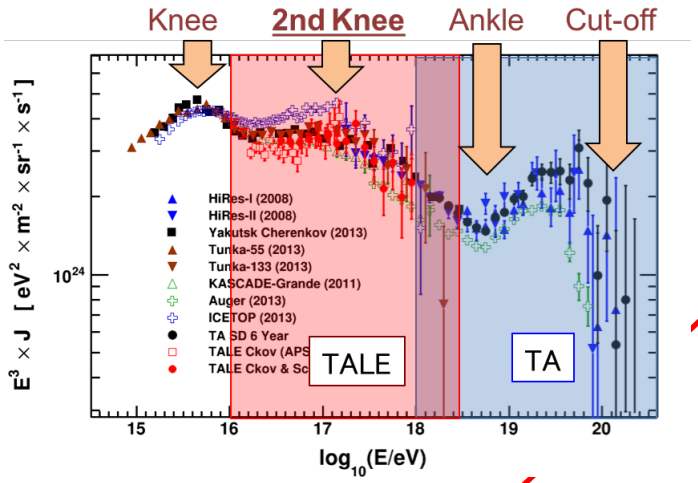
for the Telescope Array Collaboration

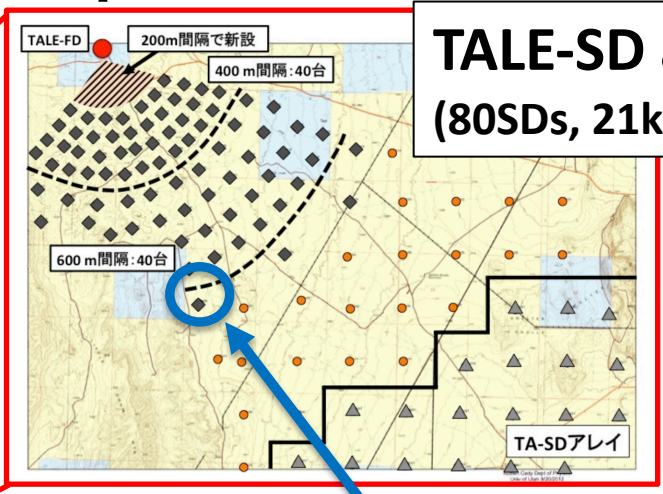
37th International Cosmic Ray Conference – ICRC2021

Outline

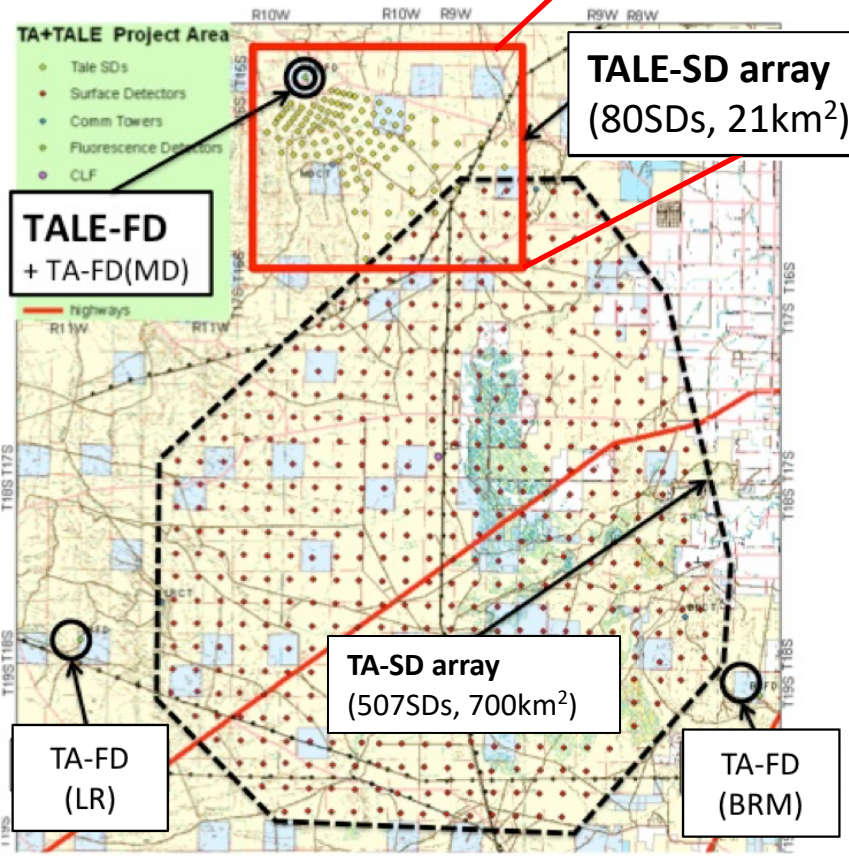
- Telescope Array Low Energy Extension (TALE) experiment
  - TALE-SD array Operation
- Event reconstruction
- TALE-SD array performance
- DATA/MC comparison
- TALE-SD array aperture
- Summary

TALE (TA Low energy Extension) experiment





TALE-SD array
(80SDs, 21km^2)



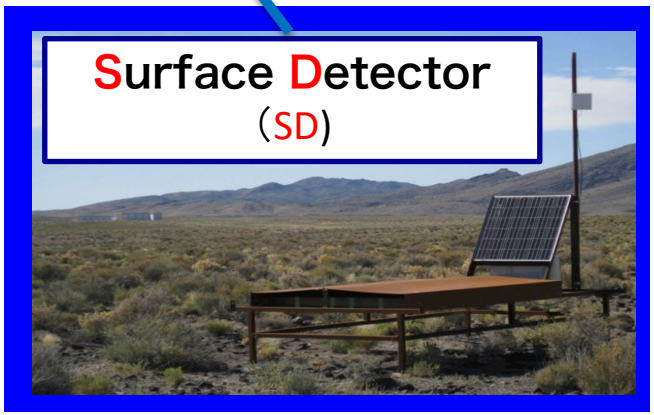
TALE-SD array
(80SDs, 21km^2)

TALE-FD
+ TA-FD(MD)

TA-SD array
(507SDs, 700km^2)

TA-FD
(LR)

TA-FD
(BRM)



TALE-SD	80 SDs : 400m and 600m spacing Operation since Feb. 2018 SD is the same as TA
TALE-FD	10 FDs in the TALE station Elevation: 30° - 57° Azimuthal: 114°

TALE-SD array Operation (Sep. 2019～June 2021)

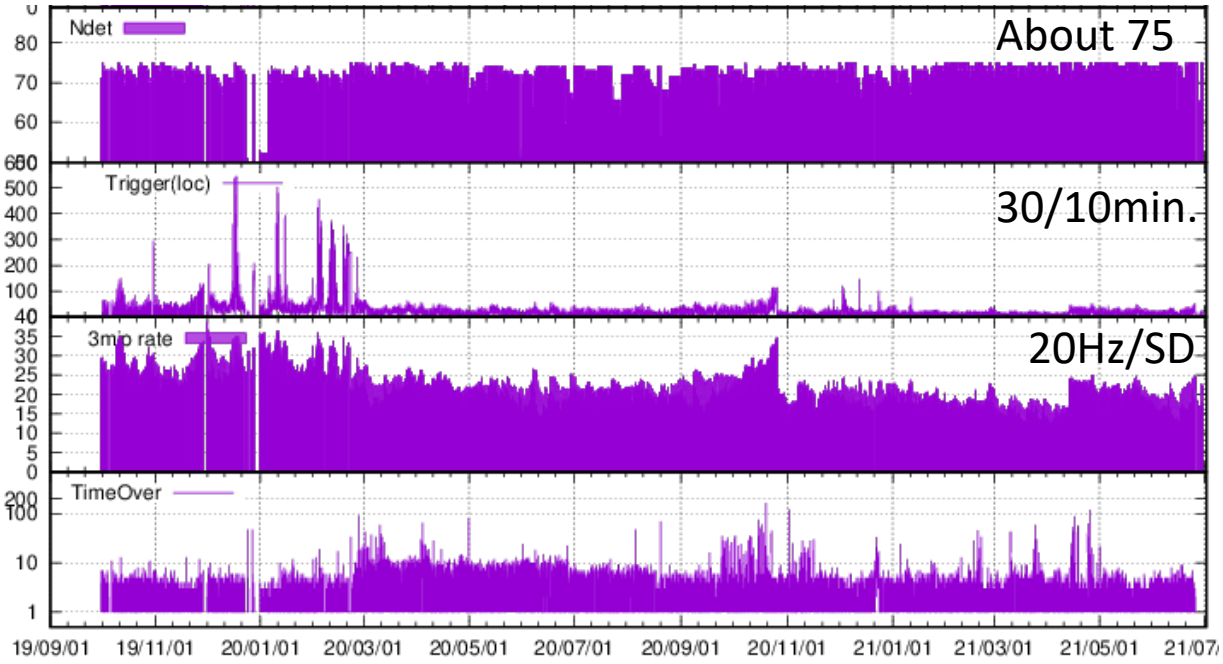
Trigger condition (Average rate)
Trigger 0 (keep waveform) : 0.3 particle equivalent or better signal (700~800Hz/SD)
Trigger 1 (detector hit) : 3 particle equivalent or better signal (20Hz/SD)
Trigger 2 (event) : More than 4 detector hit triggers (Trigger 1) within 8μs (30/10min.)

Number of SDs in DAQ

Number of event triggers per 10 minutes (trigger 2)

Average number of detector hit triggers (trigger 1)

Number of trigger data collection timeout occurrences from all SDs



Event reconstruction

Air shower geometry fit -> arrival direction(θ, ϕ)

Geometry function

$$t^{fit} = T_0 + \frac{l}{c} + \tau$$

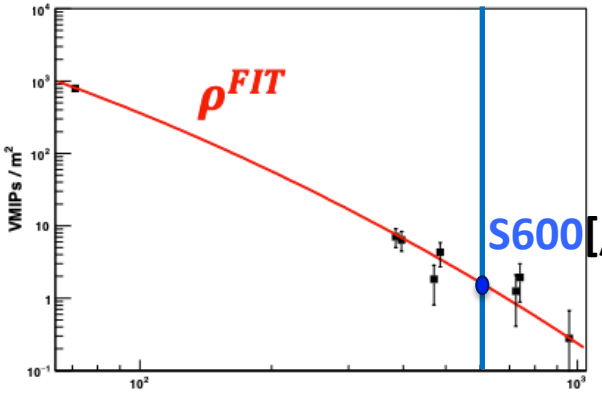
$$\tau = (8\times10^{-10})a(\theta)(1.0+\frac{s}{30[m]})^{1.5}\rho^{-0.5}[s]$$

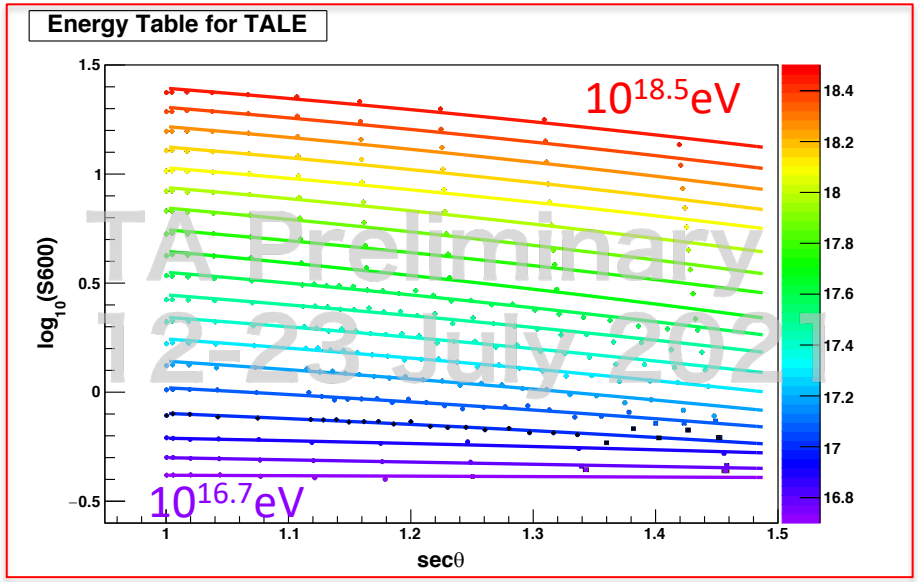
Lateral distribution fit -> core position (X, Y), particle density

Lateral distribution function

$$\rho^{FIT}(s) = A\left(\frac{s}{91.6[m]}\right)^{-1.2}\left(1+\frac{s}{91.6[m]}\right)^{-(\eta(\theta)-1.2)}\left(1+\left(\frac{s}{1000[m]}\right)^2\right)^{-0.6}\ [/m^2]$$

$$\eta(\theta) = 3.97 - 1.79(\sec\theta - 1)$$



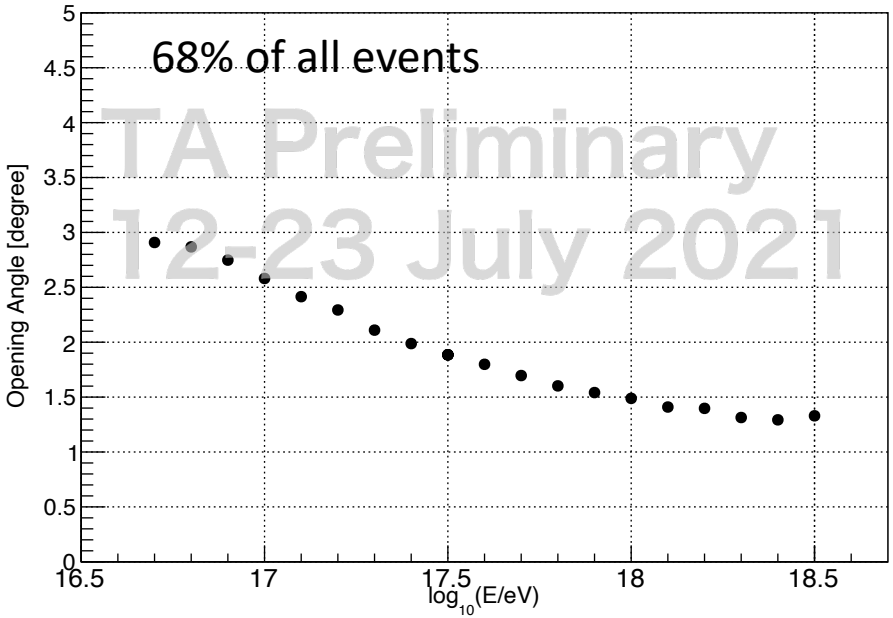


θ + **S600** with "Energy Estimation Table" -> **primary energy**

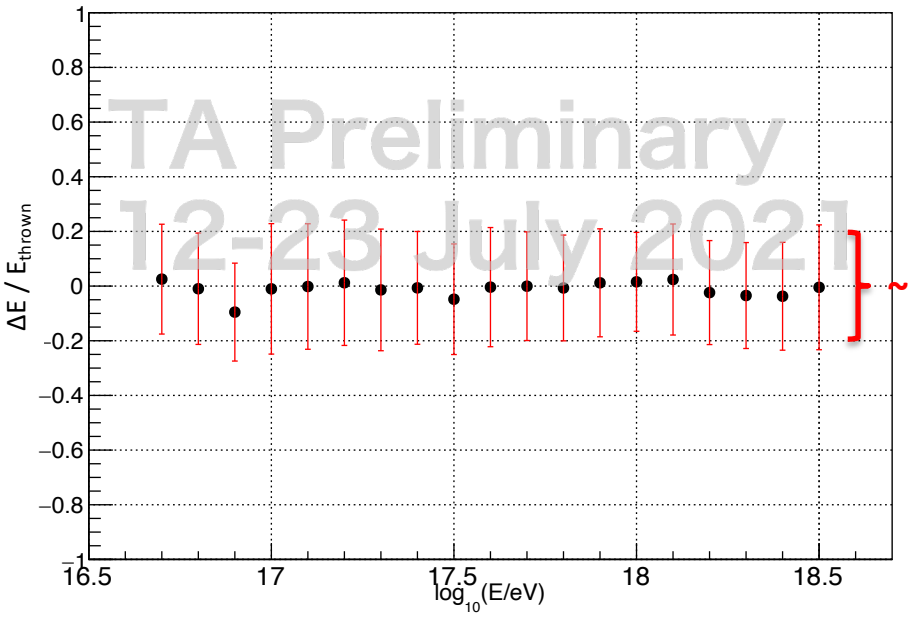
TALE-SD array performance (MC simulation)

Proton, $10^{16.7}$ - $10^{18.5}$ eV (dlogE = 0.1)

Arrival direction resolution



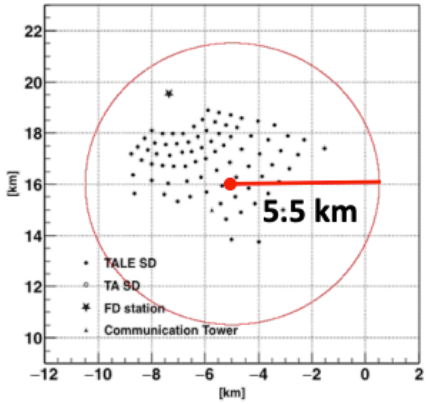
Energy resolution



Log(E/eV)	16.8	17.0	17.2	17.4	17.6	17.8	18.0	18.2	18.4
Opening angle[°]	2.87	2.58	2.29	1.99	1.80	1.60	1.49	1.40	1.29
$\Delta E/E_{thrown}$ Mean ± σ	-0.0097 ±0.2037	-0.0102 ±0.2386	0.0121 ±0.2293	-0.0066 ±0.2063	-0.0038 ±0.218	-0.0068 ±0.1935	0.0156 ±0.1809	-0.0238 ±0.1902	-0.0372 ±0.1974

DATA/MC comparison

MC Simulation Date Set



Array time state : 2019/10/02 ~ 2020/01/29

primary : proton, QGSJET Ⅱ-04

Energy : $10^{16.95}$ eV - $10^{18.55}$ eV

Zenith angle θ : 0° - 65° , Azimuth angle ψ : 0° - 360° (Uniform random)

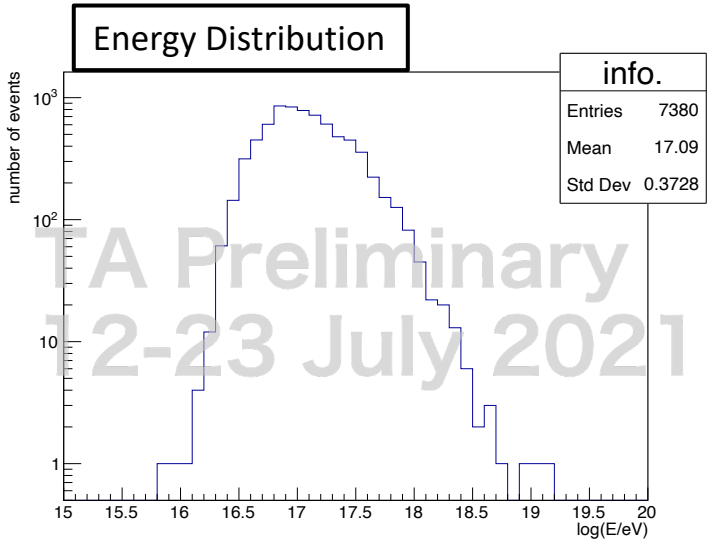
Core position : random (Right Figure)

TALE-SD array : 80 (any4)

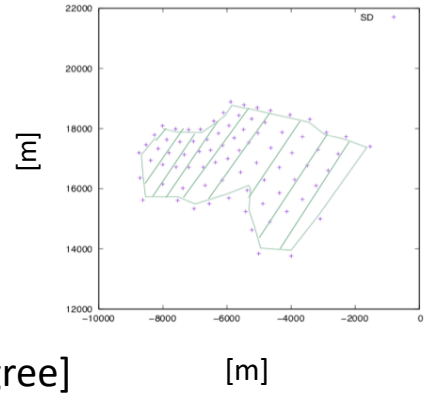
any4 : More than 4 detector hit triggers (3 particle equivalent or larger signal) within 8μs

REAL Date Set

Time period : 2019/10/02 ~ 2020/01/29



Event selection



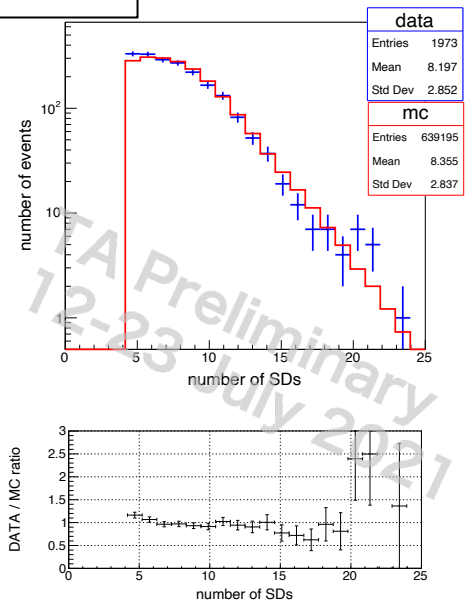
- # of SDs >=5
- χ_G^2/d.o.f. <= 4 , χ_L^2/d.o.f. <= 2
- recon. Zenith angle <= 45 [degree]
- $(\sigma_\theta^2 + \sin^2\theta\sigma_\phi^2)^{1/2}$ <= 2.5 [degree]
- S600Err / S600 <= 0.25
- Reconstructed core position approximately 100m inward from the edge of the array

1ry: pure proton

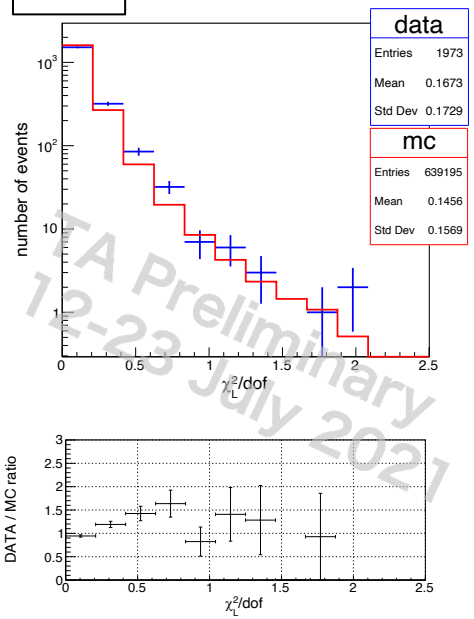
DATA/MC comparison @ 17.3 < log(E/eV) < 18.5

- MC
- TALE DATA

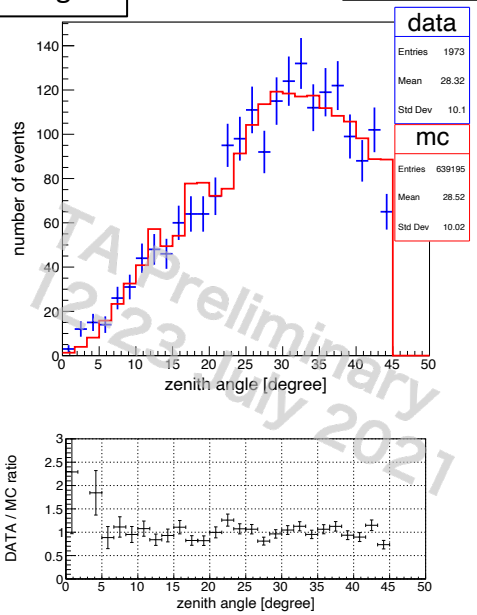
of SDs



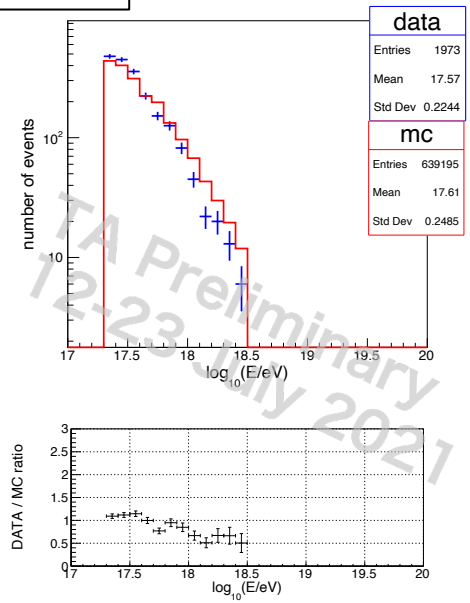
ChiL



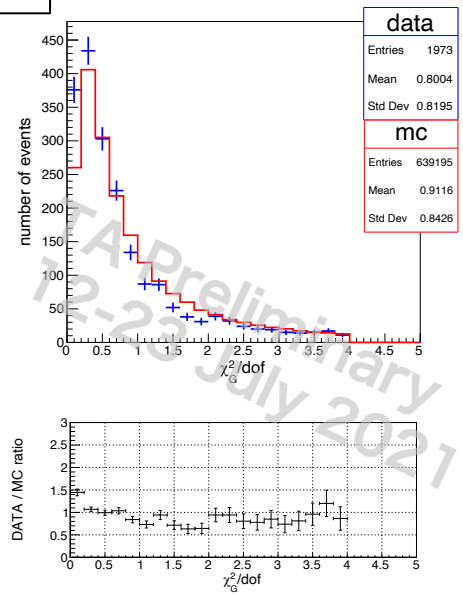
Zenith angle



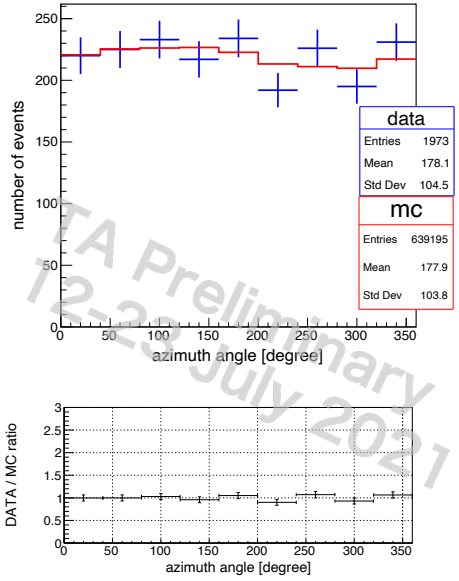
Energy



ChiG



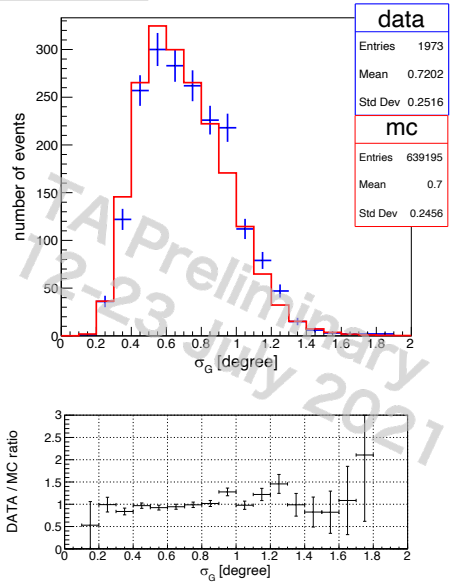
Azimuth angle



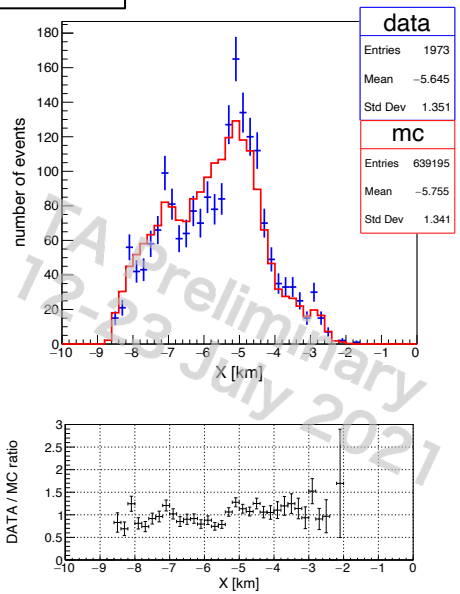
1ry: pure proton

DATA/MC comparison @ 17.3 < log(E/eV) < 18.5

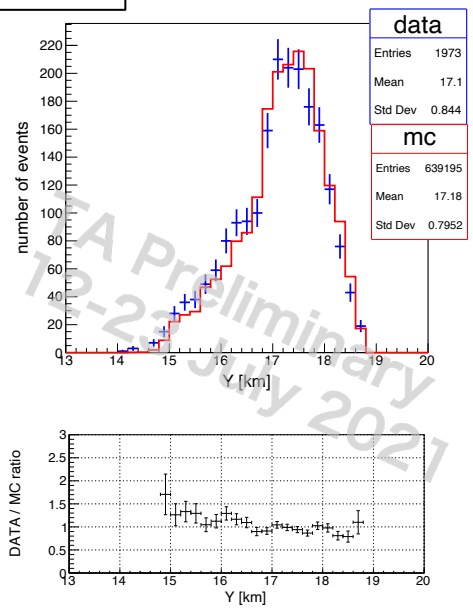
$(\sigma_\theta^2 + \sin^2\theta\sigma_\phi^2)^{1/2}$



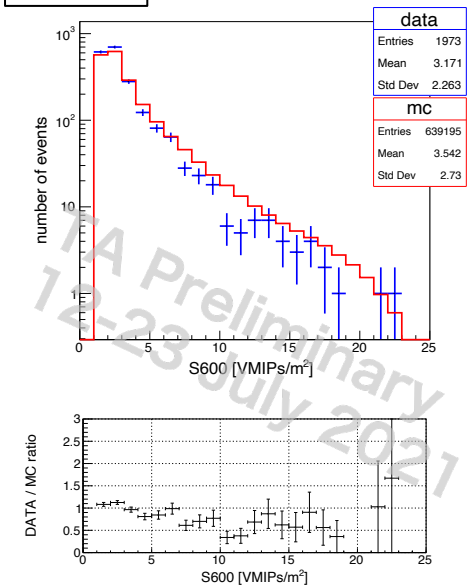
CoreX



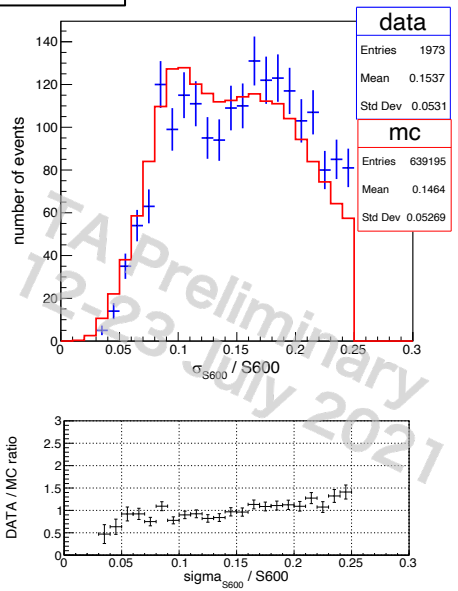
CoreY



S600



S600Err/S600

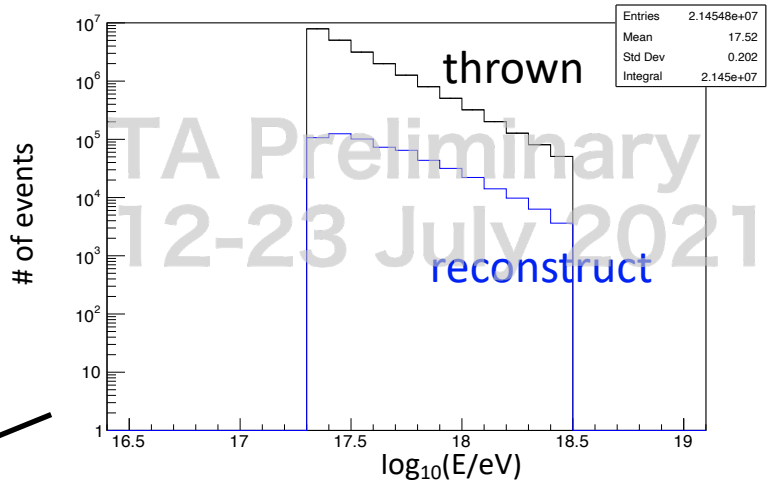


- MC
- TALE DATA

TALE-SD array Aperture (pure proton)

Obs. Time : 2019/10/02 ~ 2020/01/29

Energy range : 17.3 < log(E/eV) < 18.5



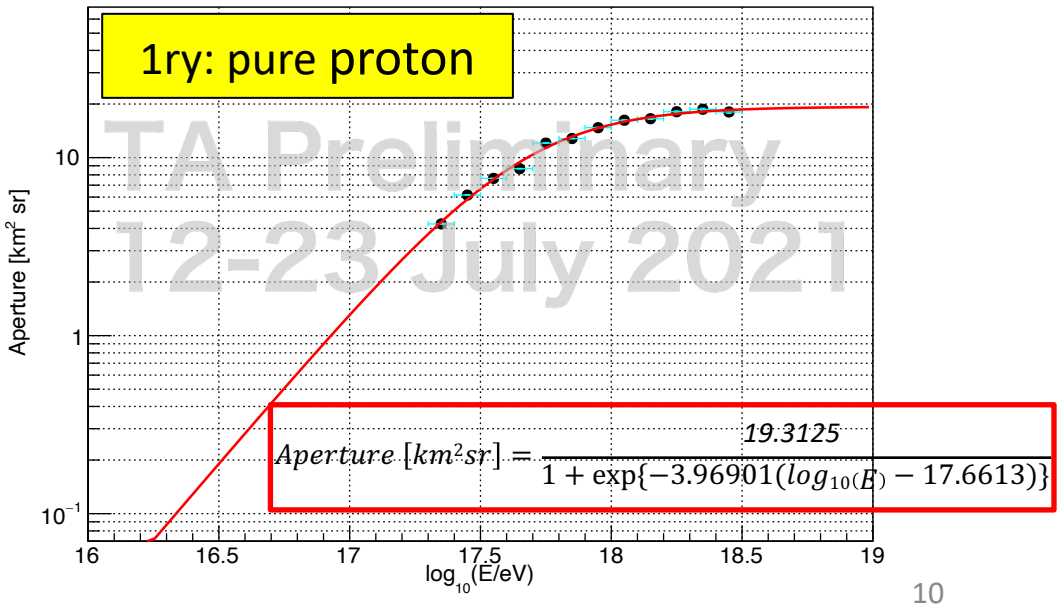
Aperture = $\varepsilon \cdot A_{\text{thrown}} \Omega_{\text{thrown}} [km^2 sr]$

$$\varepsilon = N_{\text{REC}}^{\text{AllCut}} / N_{\text{THROWN}}$$

$$A_{thrown} = \pi \times 5.5^2 [km^2]$$

$$\Omega_{\text{thrown}} = \int_0^{2\pi} d\varphi \int_0^{65^\circ} d\theta \sin\theta \cos\theta$$

Aperture



Summary

- Compare TALE SD DATA and MC @ $17.3 < \log(E/eV) < 18.5$
  → There were no big differences.

- Report the preliminary aperture of the TALE-SD array,
  assuming a pure proton in MC simulation

Plan

- Obtain the energy estimation table, the aperture
  by considering the composition of cosmic rays

  →Firstly, We will do the same analysis assuming pure iron in MC simulation.