Recent results from the Telescope Array

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for the Telescope Array Collaboration

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Outline

- Introduction
  - TA detector and operation
- TA results
  - Spectrum
    - Hybrid spectrum / FD mono spectrum / SD spectrum
  - Particle composition
    - Xmax (FD stereo)
  - Anisotropy (SD)
    - AGN correlations / auto-correlations / LSS correlations
- Summary

The Telescope Array Collaboration

International collaboration that consists of about 120 researchers from Japan/US/Korea/Russia

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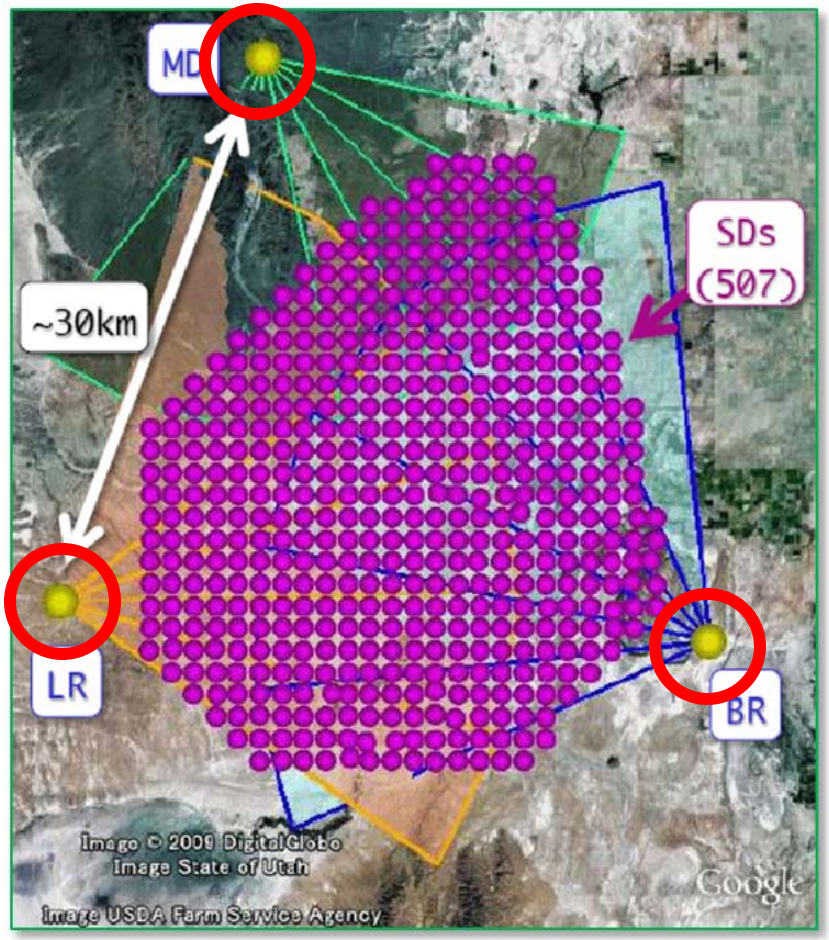
TA detector

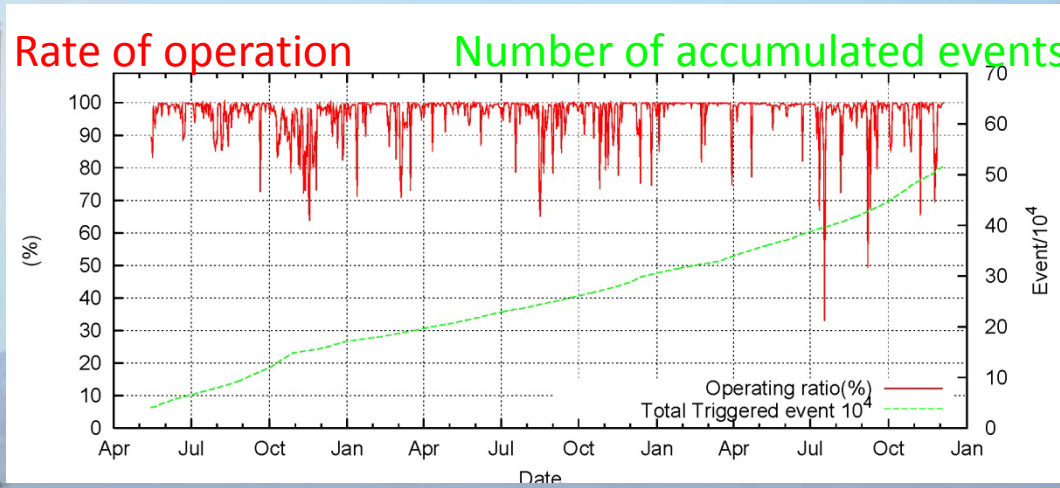
- **Surface detector (SD)**
  - Plastic scintillator (a la AGASA)
  - 507 SDs
  - 1.2km spacing, 680km^2
- **Fluorescence detector (FD)**
  - 3 stations（BR, LR, MD）
    - 38 telescopes（12＋12＋14）(a la HiRes)
- Location
  - Utah, USA
    - About 200km south to Salt Lake City
    - 39.3^{o}N, 112.9^{o}W
    - Altitude ~1400m

transfer HiRes telescopes



The largest detector in northern hemisphere

Surface Detector



Radio communication

Powered by solar cells

1.2 km spacing

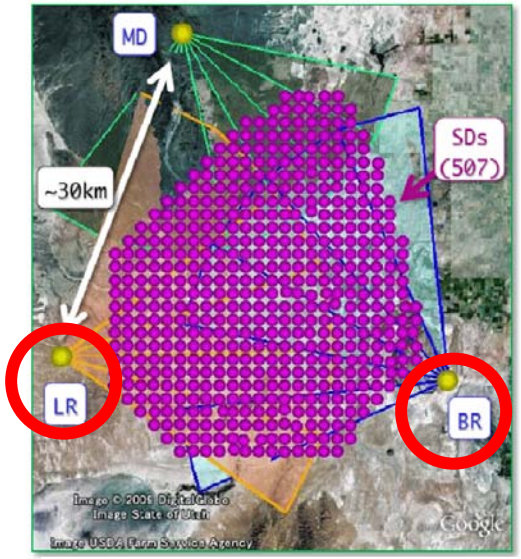
Plastic scintillator

- 3m^2, 1.2cm thickness
- 2 layers overlaid
- WLSF readout
- 50 MHz 12-bit FADC

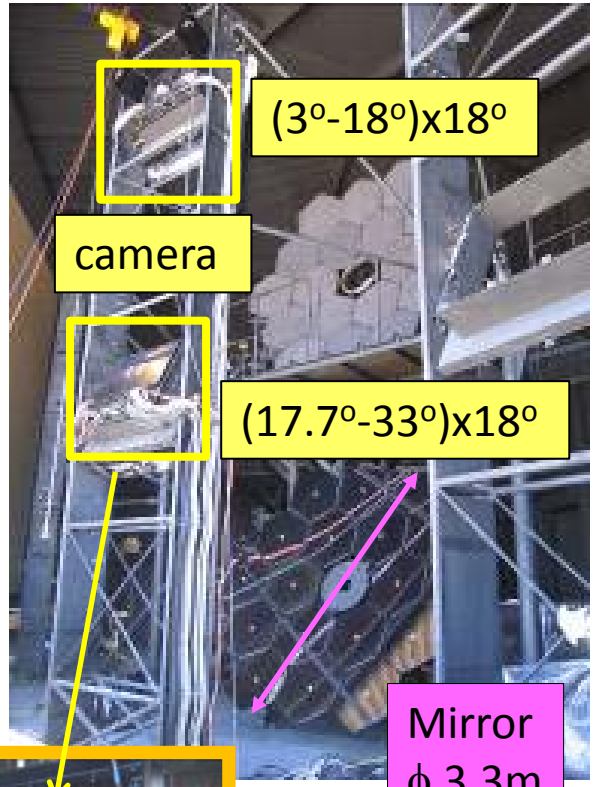
In operation as SD array since March, 2008

Fluorescence detector

- BR/LR site : new telescopes

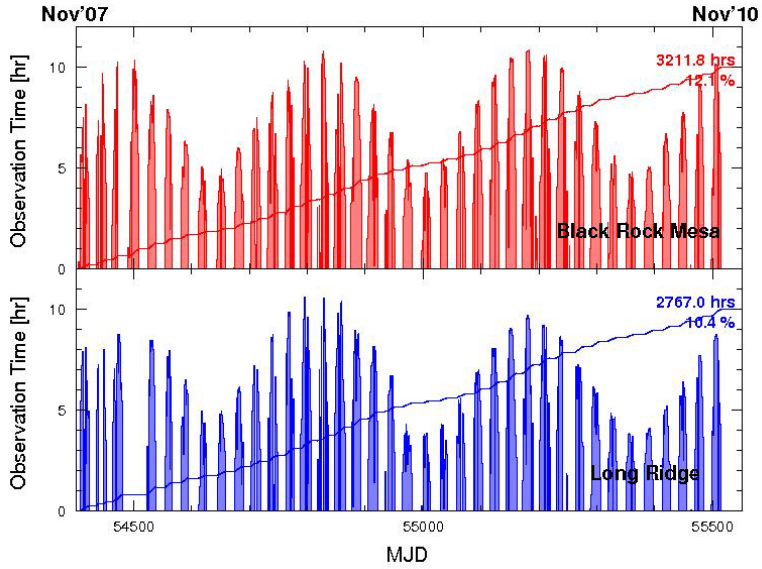


FOV: 3-33° in elevation
108° in azimuth

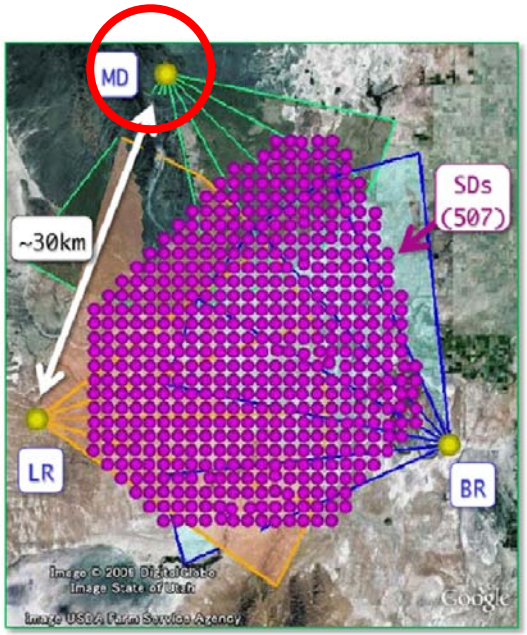


~1m

Camera
16x16=256 PMTs
Hamamatsu R9508

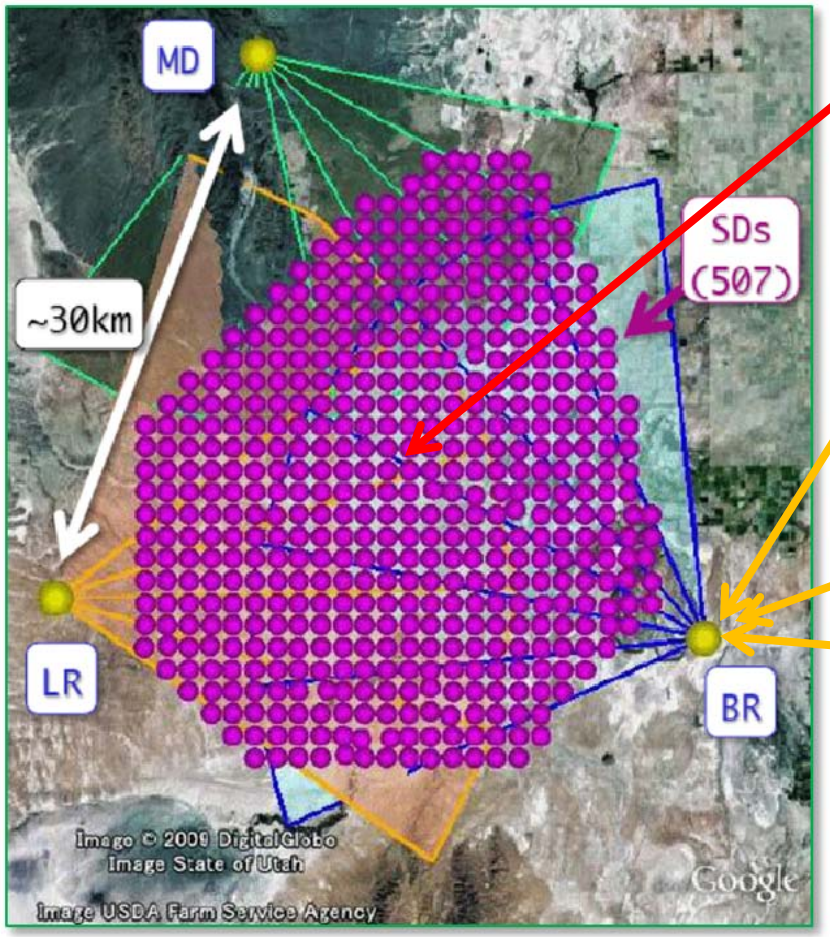


FD station at MD site



One FD station in the north
Transferred from HiRes
- 5.2m^2 mirror
- 3^o-34^o evelvation with 1^o pixel
- S/H electronics

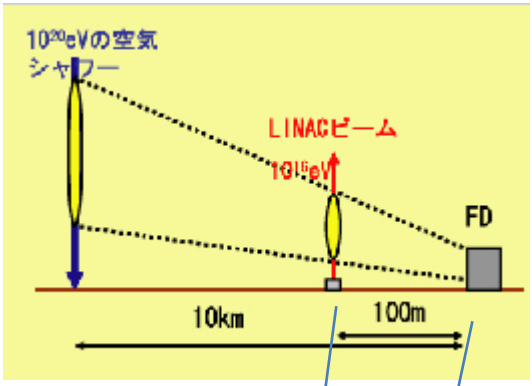
Atmospheric monitor・calibration
(for fluorescence detectors)

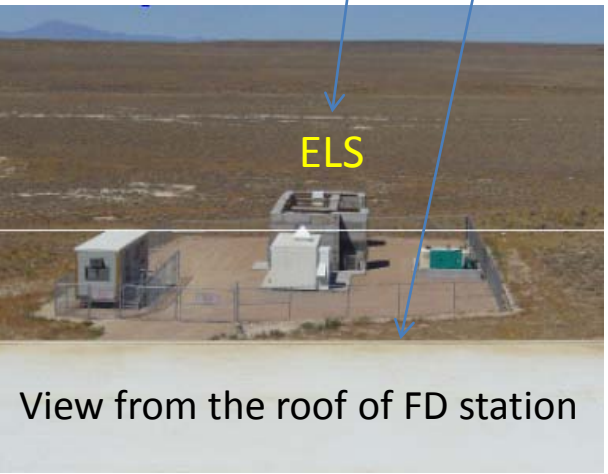


(poster by Y.Takahashi)

- Central Laser Facility
  - Observe sidescattering of laser from each FD station as a standard candle
- LIDAR : (poster by T.Tomida)
  - Observe backscattering of laser→measure transparency of atmosphere
- IR camera : cloud monitor (poster by F.Shibata)
- Compact Electron Linac
  - Absolute energy calibration of fluorescence detectors (talk by T.Shibata)

First light from ELS

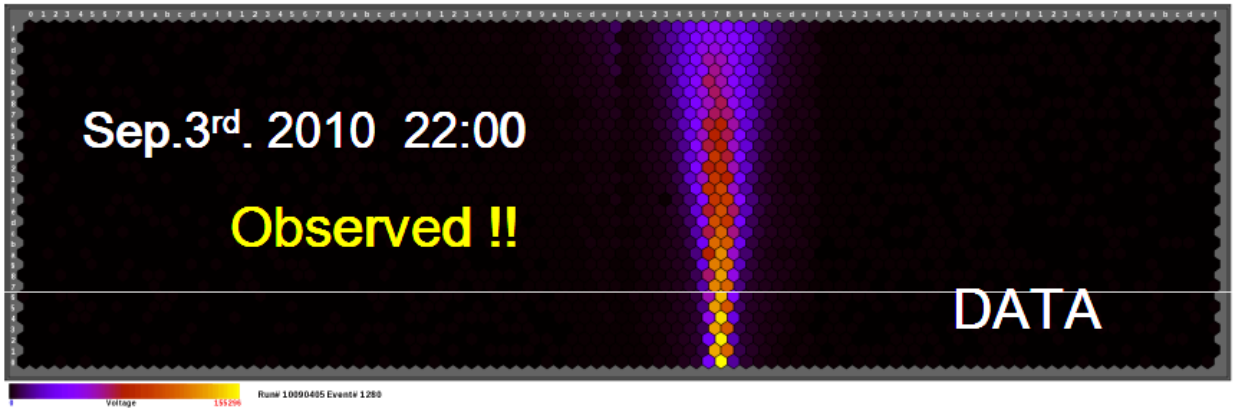


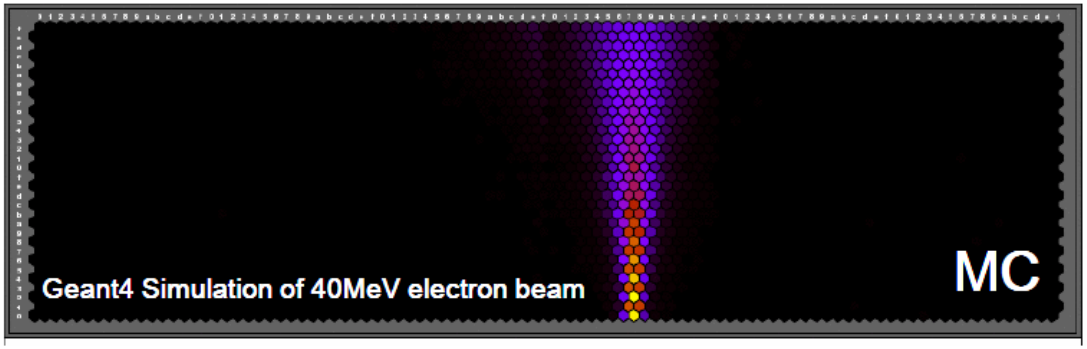


View from the roof of FD station

FD Observation

Sep.3rd.2010 Beam Shot into the Sky, and Observed by FD





Hybrid trigger

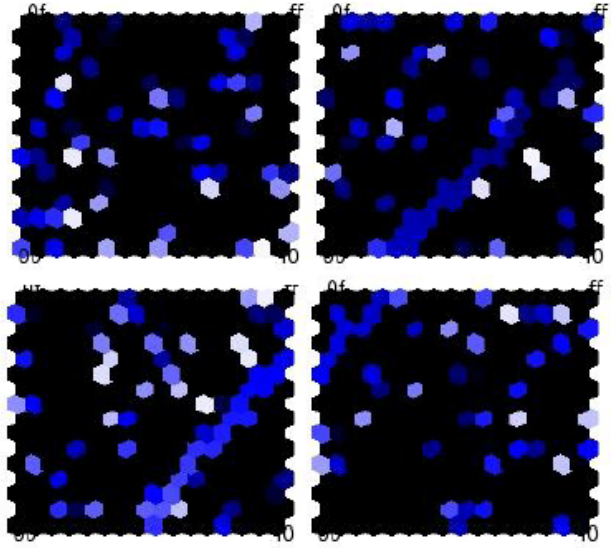
(poster by R.Ishimori)

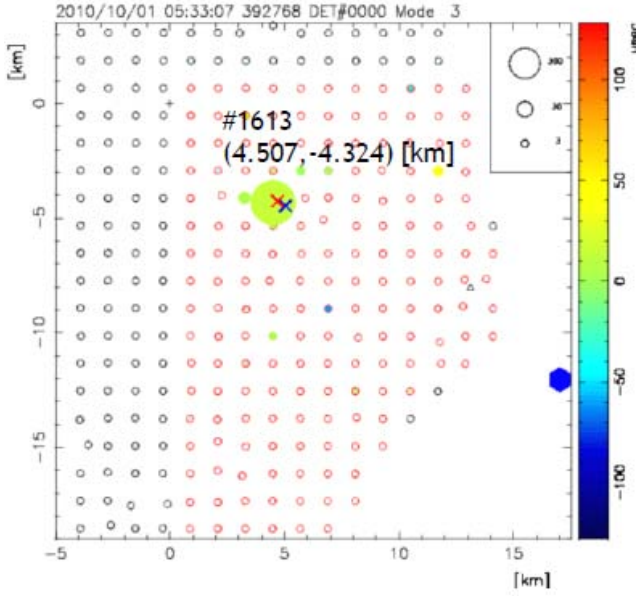
SD shower trigger
three adjacent SDs
3 MIPs

Hybrid trigger
When FD is triggered, FD requests the collection of SD waveform.

Installed this fall

The first hybrid trigger event





Spectrum

- Hybrid spectrum
  - BRM/LR FD (new telescopes) + SD
- MD FD mono spectrum
  - HiRes refurbished telescope
  - Direct comparison of energy scales and energy spectra between HiRes and TA
- SD spectrum
  - Plastic scintillator surface detectors (a la AGASA)

Hybrid Spectrum

(talk&poster by D.Ikeda)

- FD mono analysis + SD information→improve reconstruction
- Aperture is flat for >10^{19}eV by SD

Hybrid analysis: Data and MC

- **Geometry: Hybrid**
- **Energy: FD**

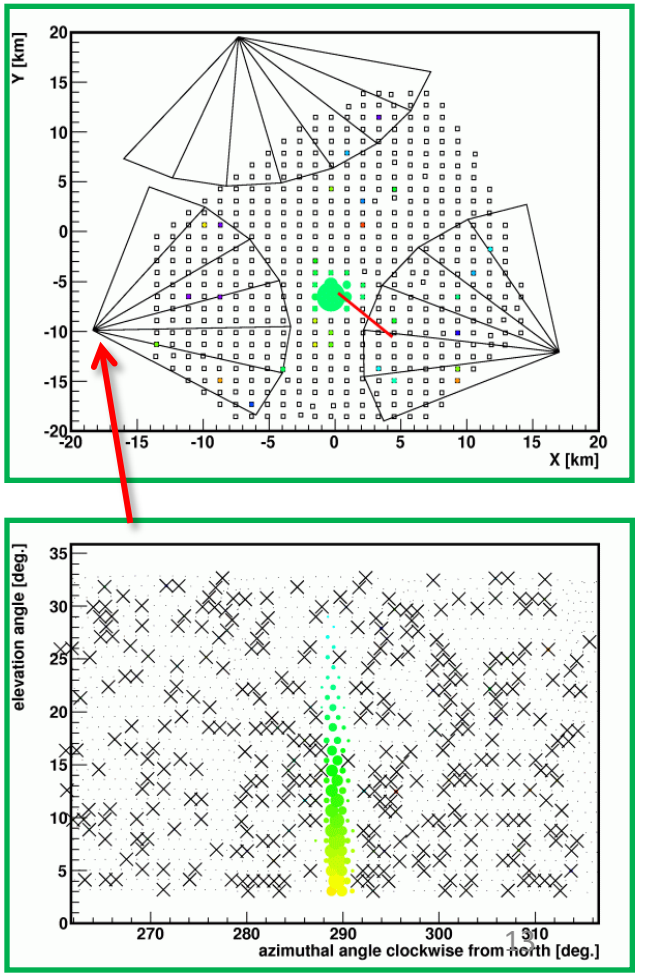
Data:

- date: May/27/2008 – Sep/28/2009 (~1.5years)
  - **BR + LR** (new telescopes) with SDs
  - Good weather days
  - 1978 events (FD-SD timing coincidence <200us)
- Cut condition
  - Xmax has to be observed.
  - Zenith angle < 45degrees

MC:

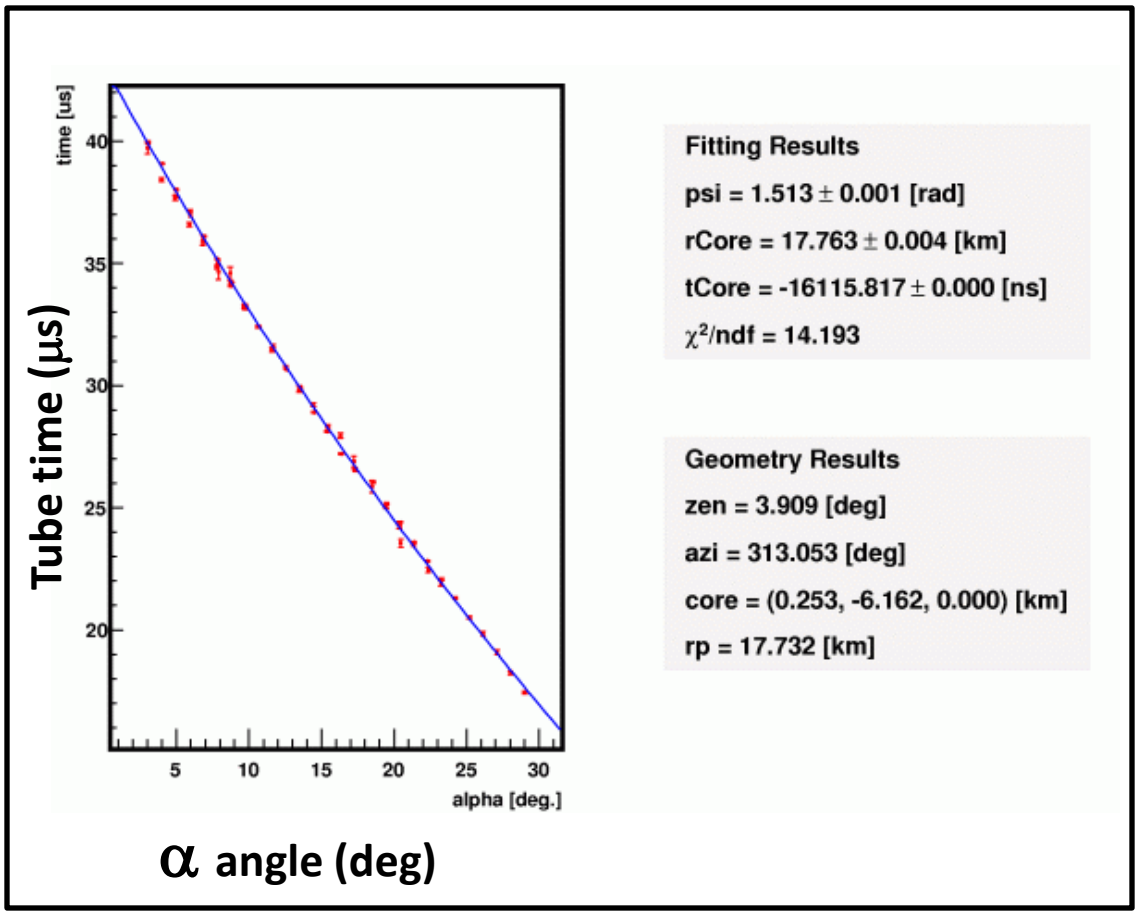
- Air shower:
  - COSMOS, proton, QGSJET-II
  - Slope: -3.1
  - Isotropic distribution
- Detector :
  - All of calibration constant with time dependence
  - Simulate trigger, front-end electronics, and DAQ
- Aperture / Exposure

The example of the Hybrid event 2008/12/30



Geometrical reconstruction

FD mono analysis + timing of one SD



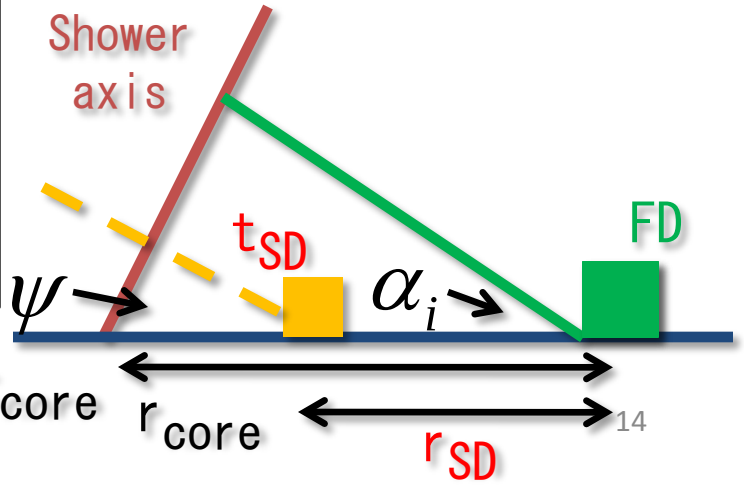
Mono reconstruction

$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

Hybrid reconstruction

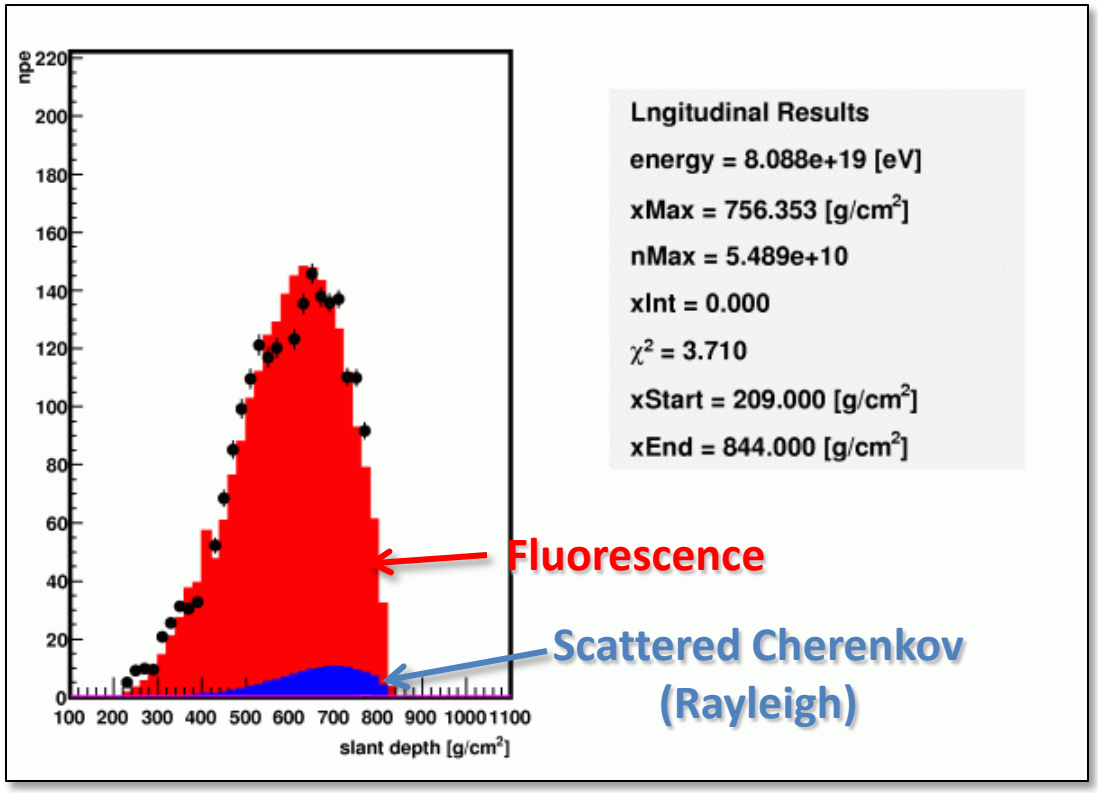
$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

$$t_{core} = t_{SD} + \frac{1}{c}(r_{core} - r_{SD})\cos\psi$$

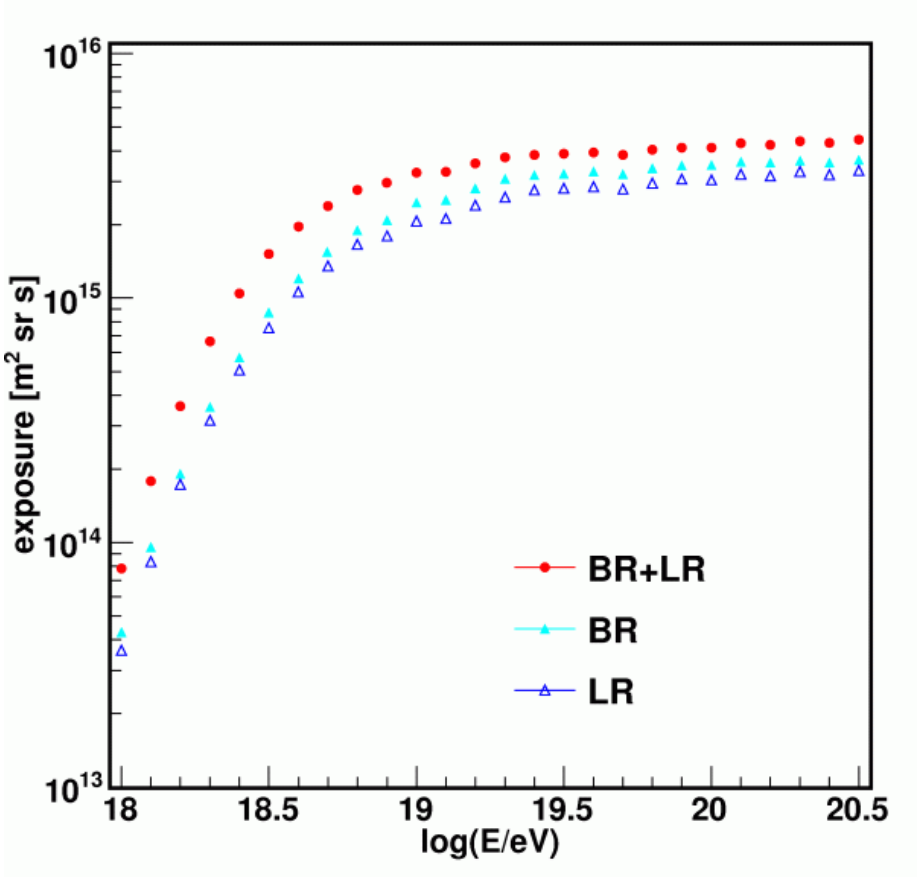


Shower profile reconstruction

- Xmax has to be observed
- Energy > $10^{18.65}$eV
- Zenith angle < 45 degree



Exposure



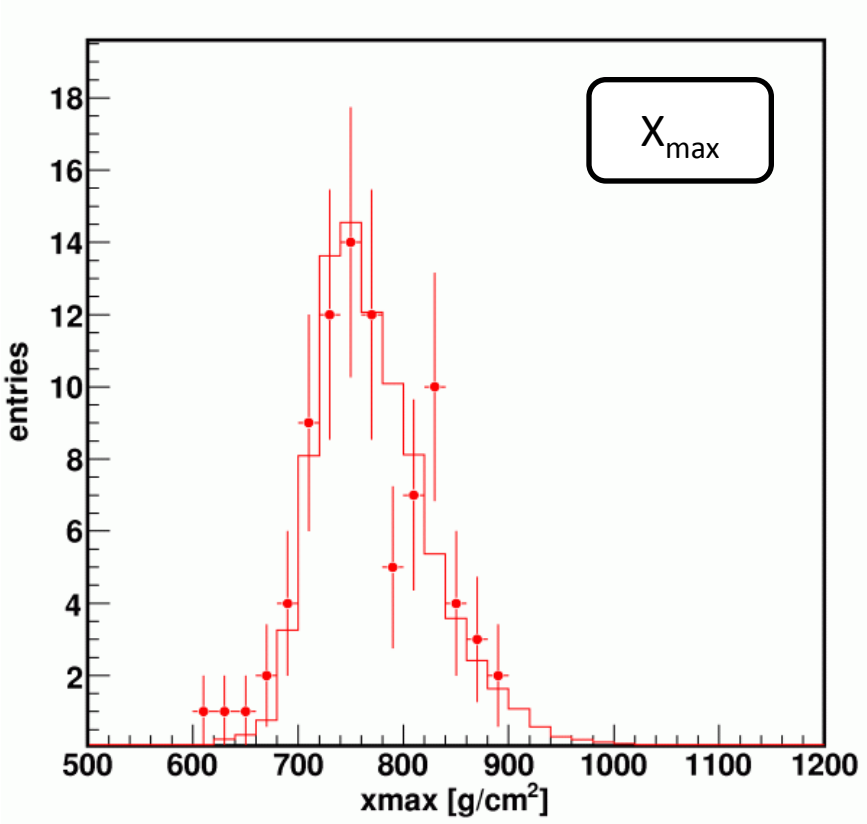
The aperture is calculated from MC simulation.

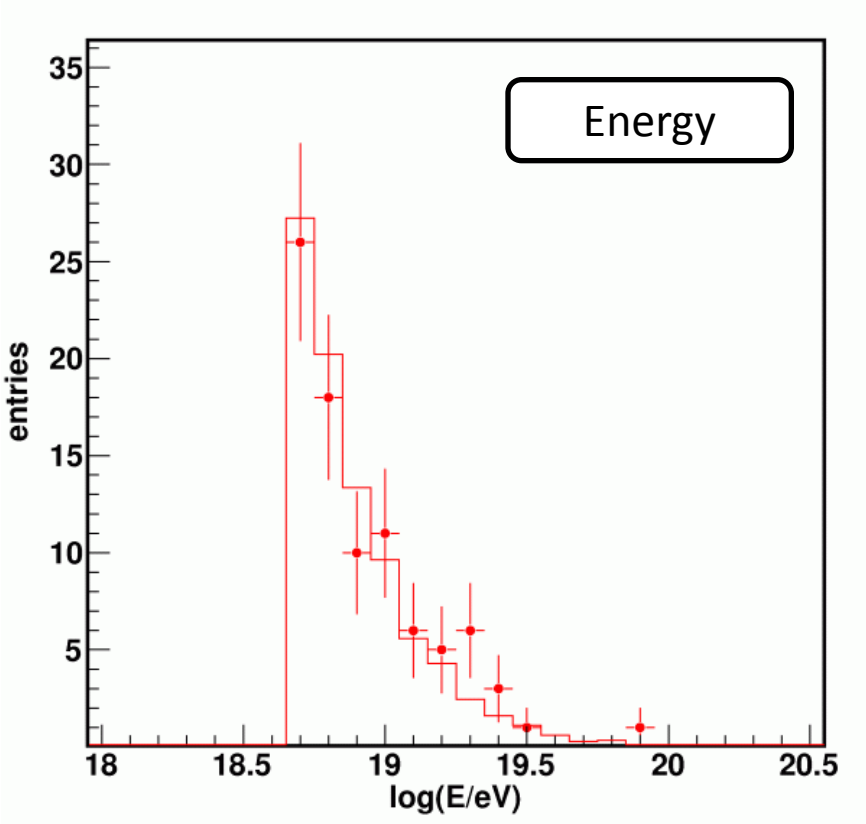
Exposure: ~3*10^{15} m^2 sr s (>~10^{19}eV)

(MC: Cosmos QGSJET II)

Data/MC comparison

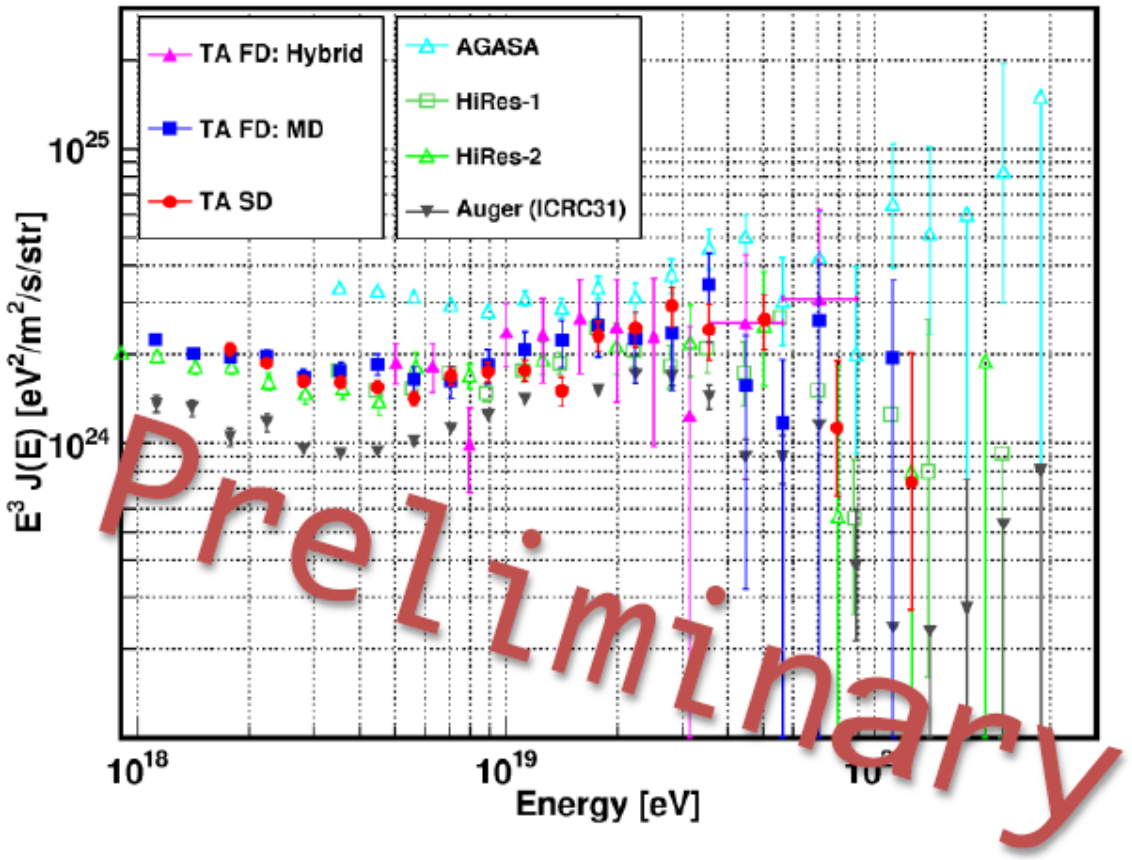
- BR station
- Filled circles : data
- Histograms : MC





Energy spectrum

TA 1.5 years of hybrid events on BR and LR station



Systematic errors

Item	Systematic error
Fluorescence yield	12%
Detector	10%
Atmosphere	11%
Primary particle mass	5%
MC correction	3%
Total	19%

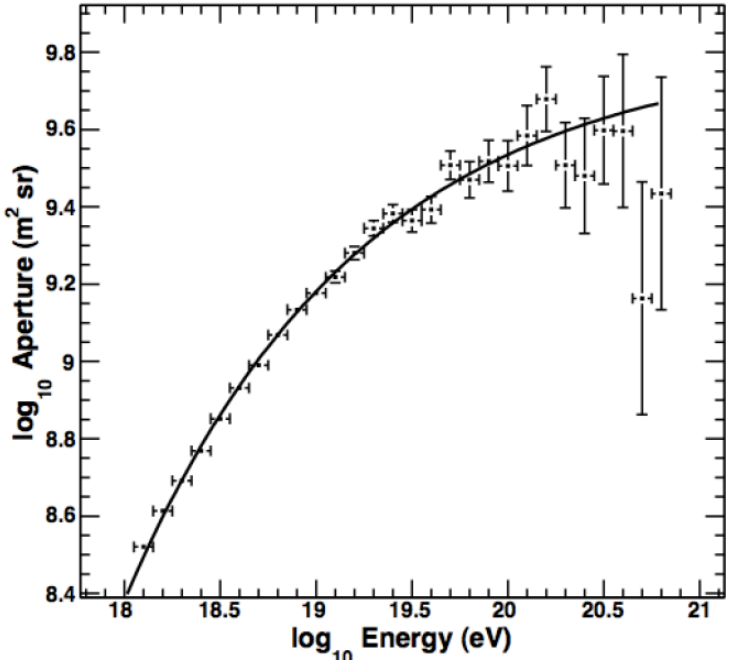
Middle Drum (MD) FD Analysis

- 14 refurbish HiRes-1 telescopes
- TAMD mono processing is identical to HiRes-1 monocular one.
  - Same program set, event selection, cuts
  - Using the same “average” atmospheric model
- The differences
  - the telescope location and pointing directions
  - Thresholds (~20% lower than HiRes-1)

MD mono energy spectrum

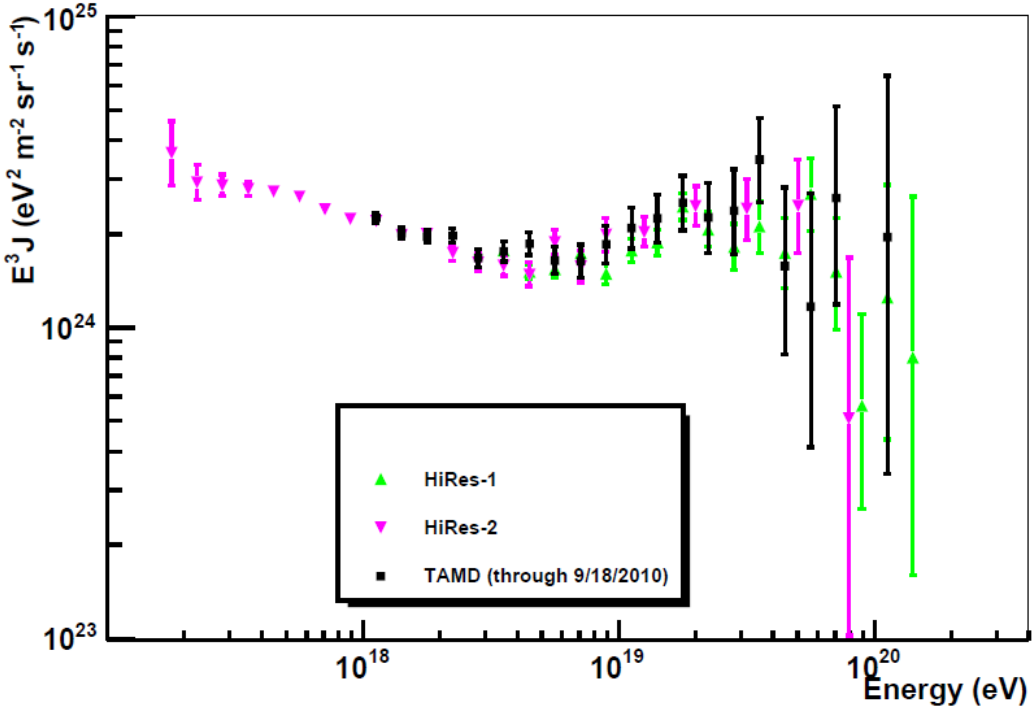
- Data: 2007/Dec~2008/Sep
- MC: CORSIKA/QGSJET events

Aperture



~1/2 HiRes ($E>10^{19}$eV)
~1/4 the exposure of HiRes-1

Spectra



Preliminary MD spectrum in good agreement with HiRes

SD spectrum

- SD reconstruction
  - LDF, timing fit
- MC
  - First energy estimation
- Data/MC comparisons
  - SD energy vs. FD energy
- SD spectrum

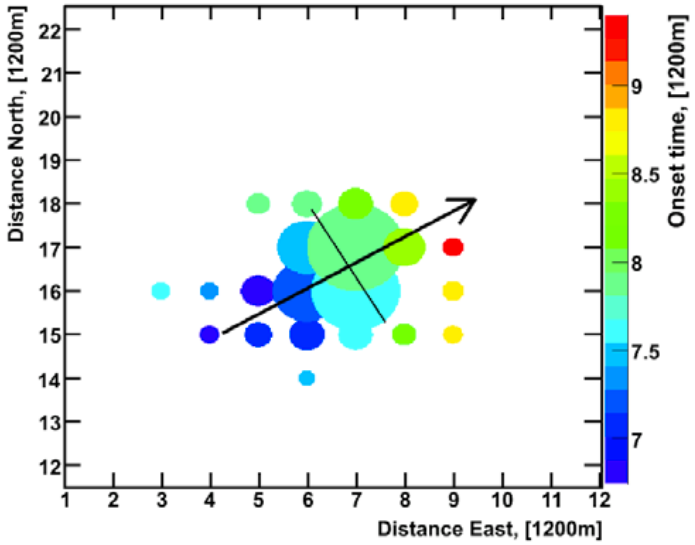
Data set

- May/2008 – Feb/2010 (1.75 years)
- Exposure ~1500km^2 sr yr (~AGASA 13 years)
- Cuts:
  - LDF χ^2/ndf < 4.0
  - Border Cut > 1.2km
  - Zenith Angle < 45 degrees
  - Pointing direction uncertainty < 5 degrees
  - Fractional S800 uncertainty < 0.25

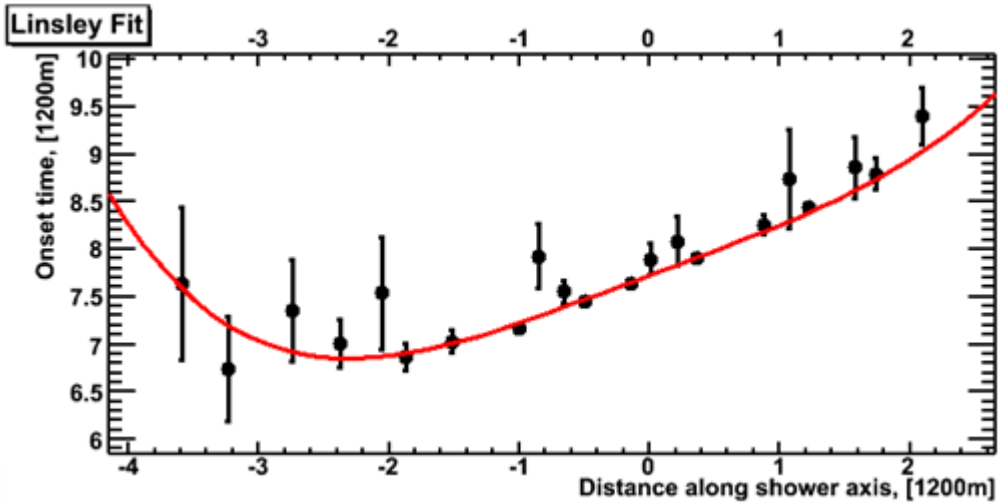
→ 6264 events

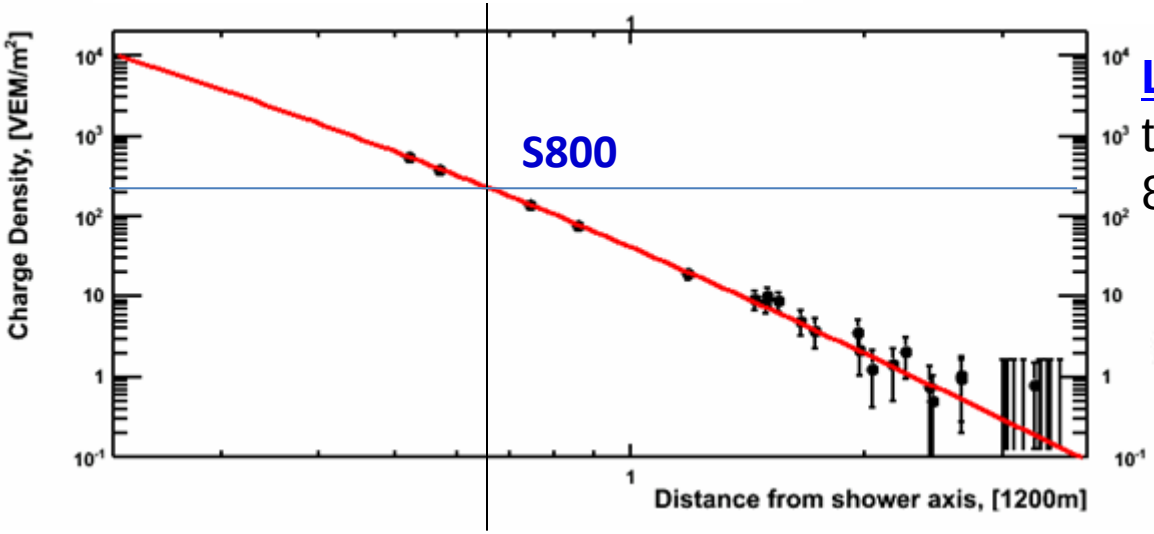
SD event reconstruction

2008/Jun/25 - 19:45:52.588670 UTC



Time fit to determine **geometry**
(modified Linsley)





r = 800m

Lateral Density Distribution Fit
to determine **S800** (charge density 800m from the shower axis)

Fit with AGASA LDF

$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2} \left(1+\frac{r}{R_M}\right)^{-(\eta-1.2)} \left\{1+\left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

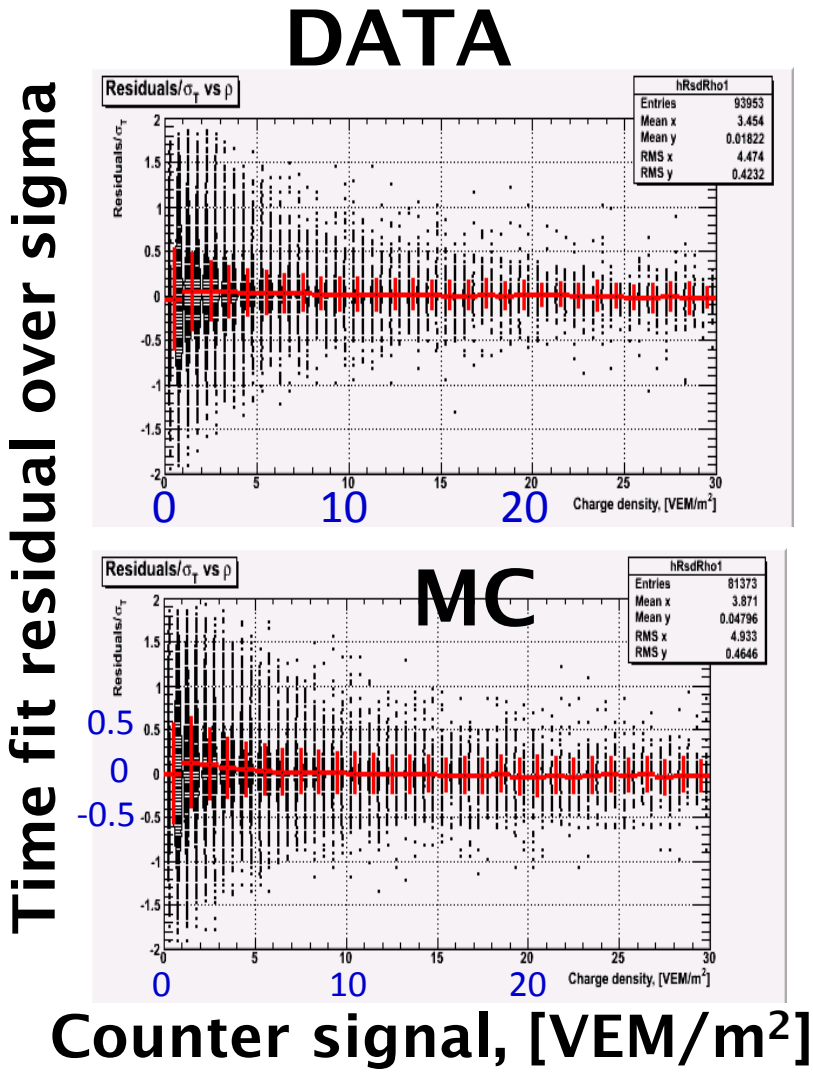
$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62)\,(\sec\theta - 1)$$

- S(800)→Primary Energy

SD Monte Carlo

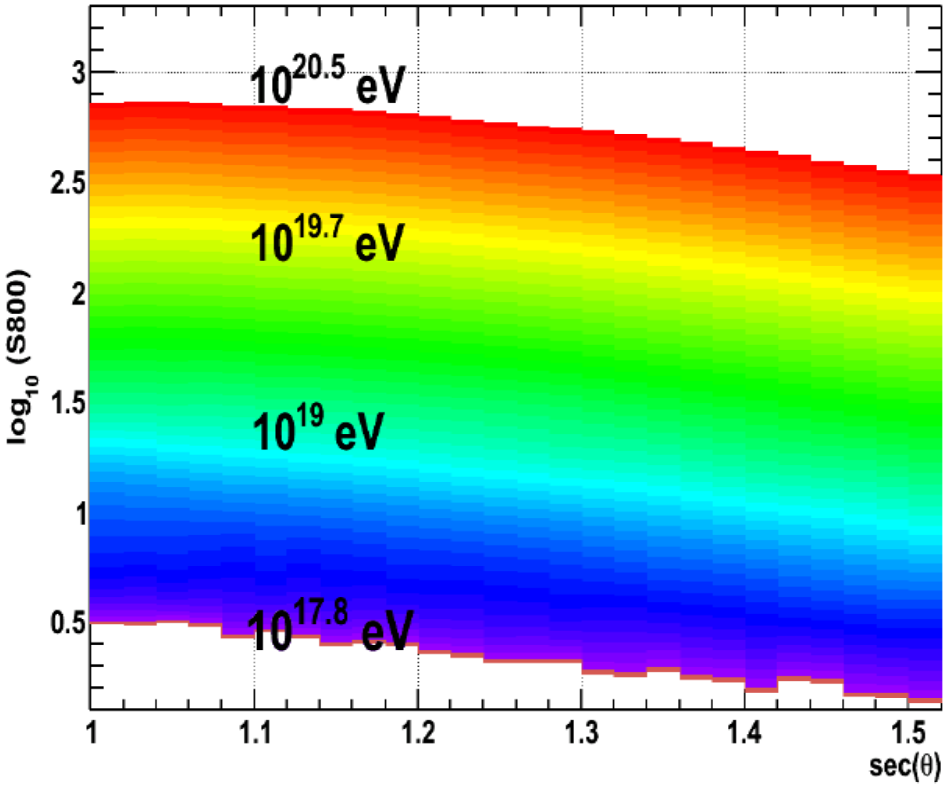
- Simulate the data exactly as it exists.
  - Start with previously measured spectrum and composition.
  - **Use Corsika/QGSJet-II air shower events.**
  - Throw with isotropic distribution.
  - Simulate detector response (GEANT4), trigger, front-end electronics, DAQ.
  - Write out the MC events in same format as data.
  - Analyze the MC with the same programs used for data.
- Test with data/MC comparison plots.

Fitting results



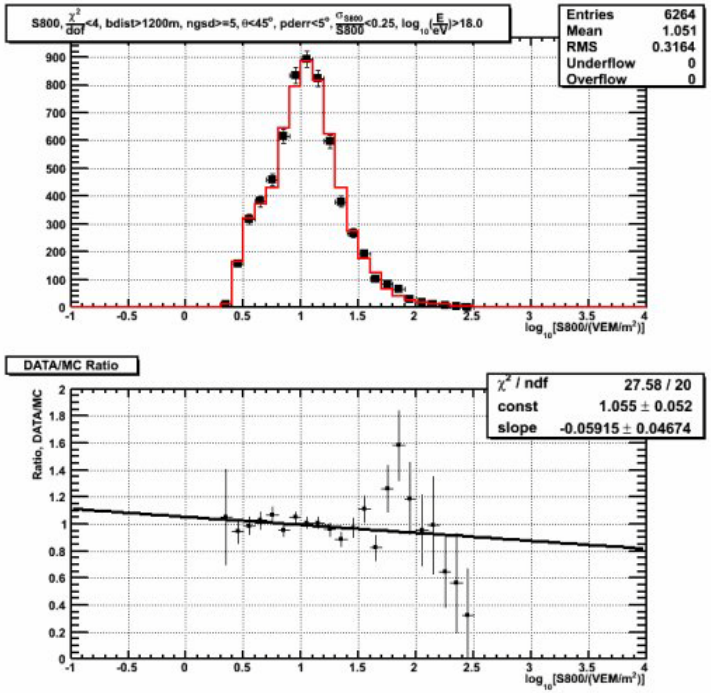
- Fitting procedures are derived solely from the data
- Same analysis is applied to MC
- Fit results are compared between data and MC
- MC fits the same way as the data.
- Consistency for both time fits and LDF fits.
- Corsika/QGSJet-II and data have same lateral distributions!

First Estimate of Energy

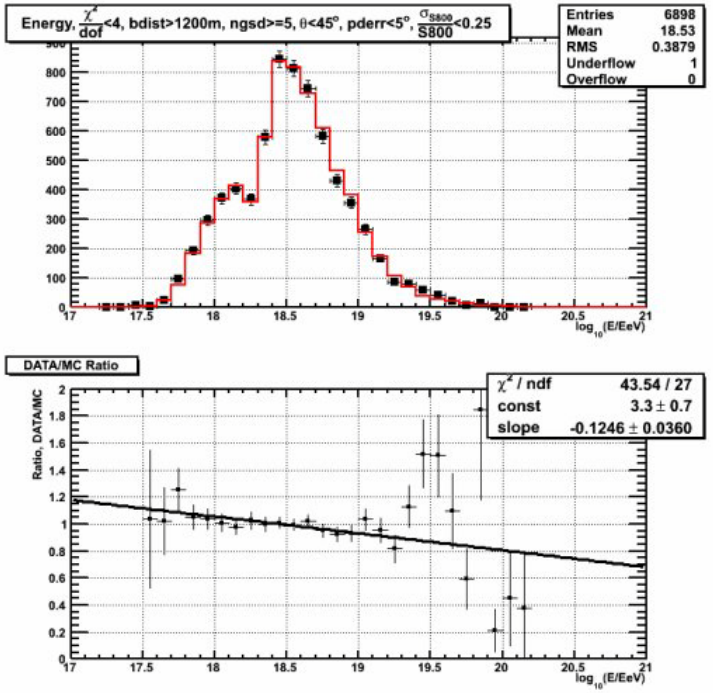


- Energy table is constructed from the MC
- First estimation of the event energy is done by interpolating between S800 vs sec(θ) lines

DATA/MC: S800, Energy

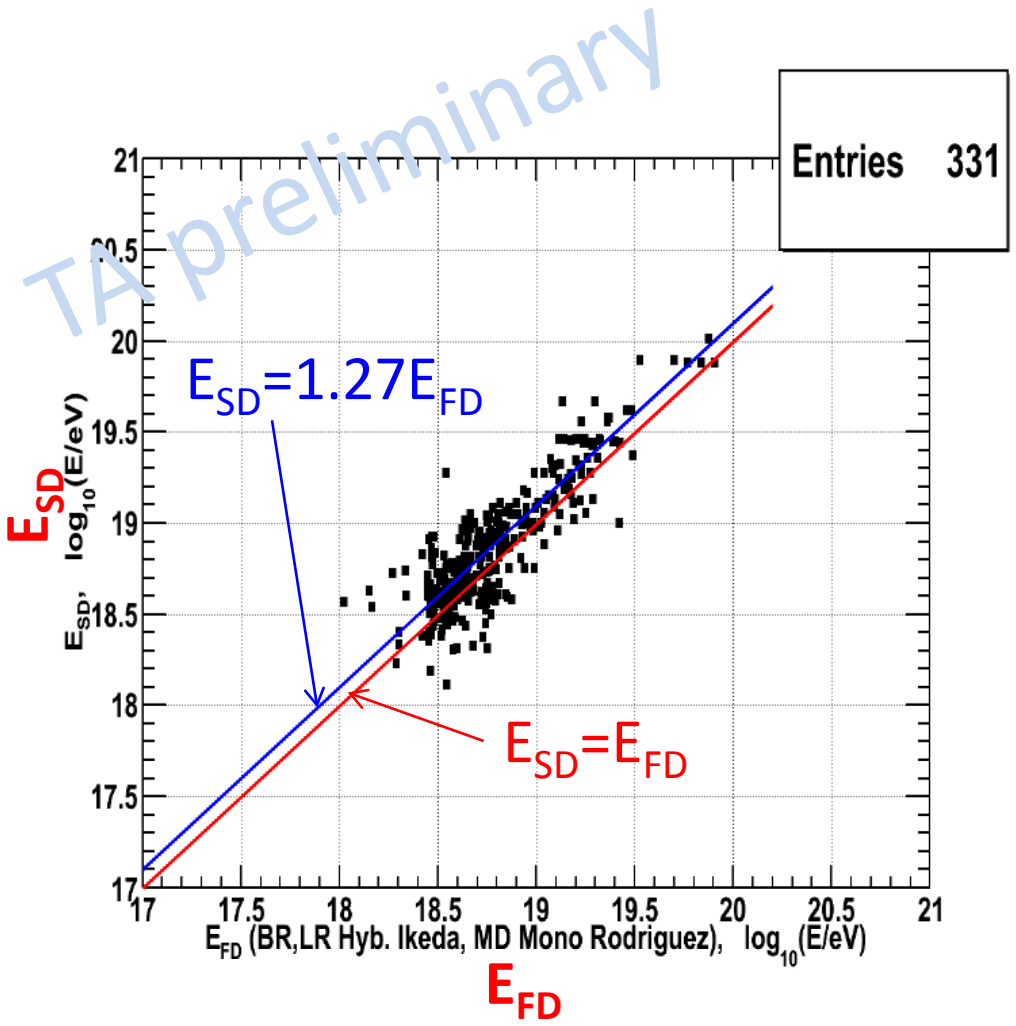


S800



Energy

Comparison of E_{SD} and E_{FD}

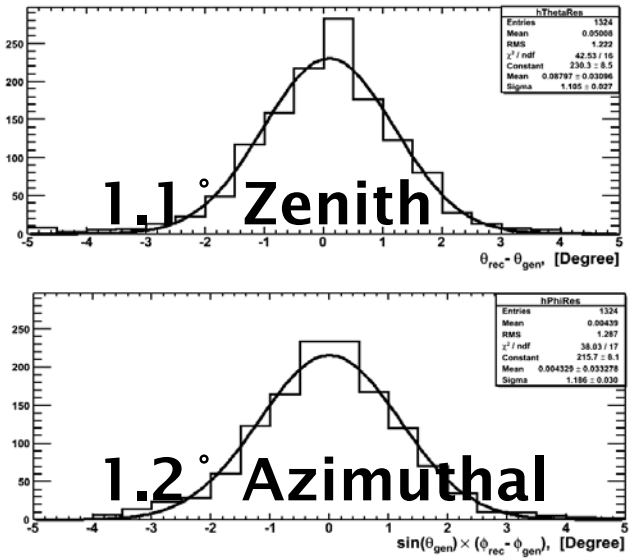


- Energy scale is determined experimentally by FD without referring to MC.
- Set SD energy scale to FD energy scale using well-reconstructed events detected by both detectors.
- 27% renormalization.
  - Systematic error 19%

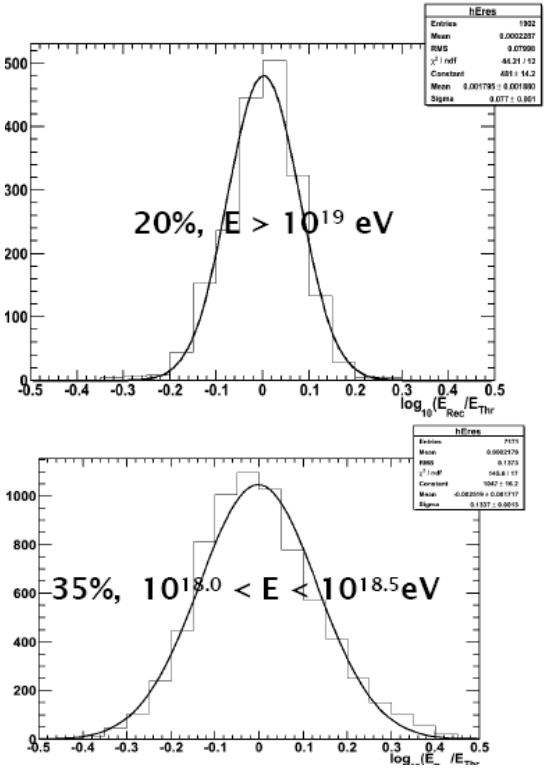
    (from systematic error of energy by hybrid analysis)

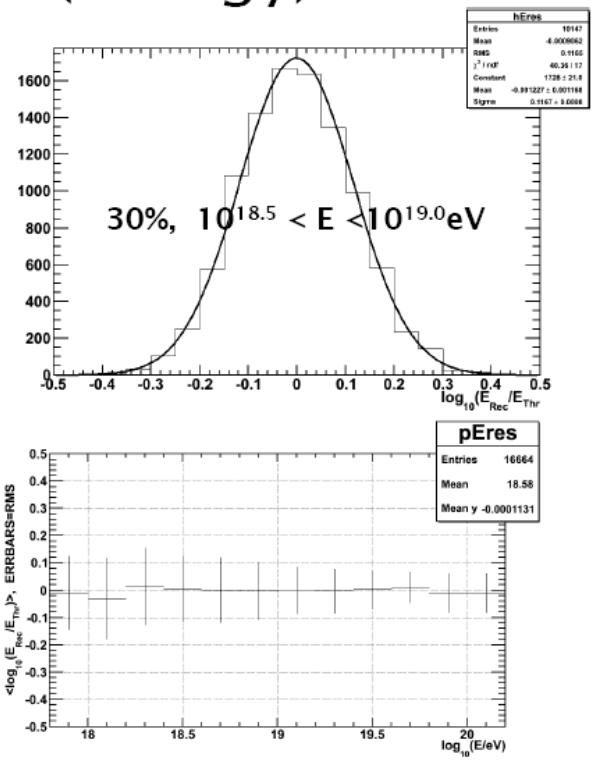
TA SD Resolution

Resolution (Arrival direction)



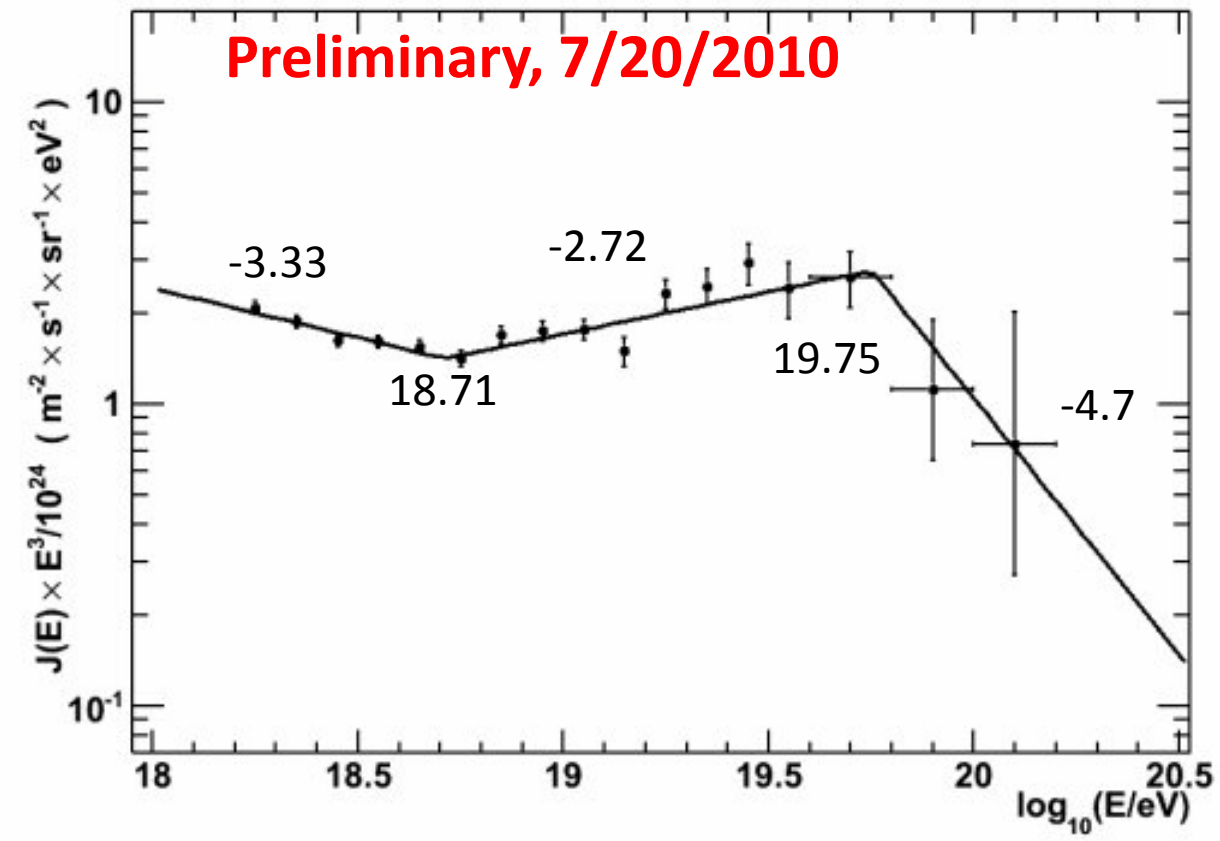
Resolution (Energy)



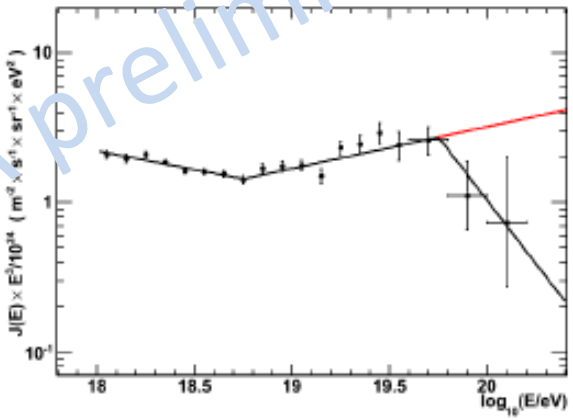


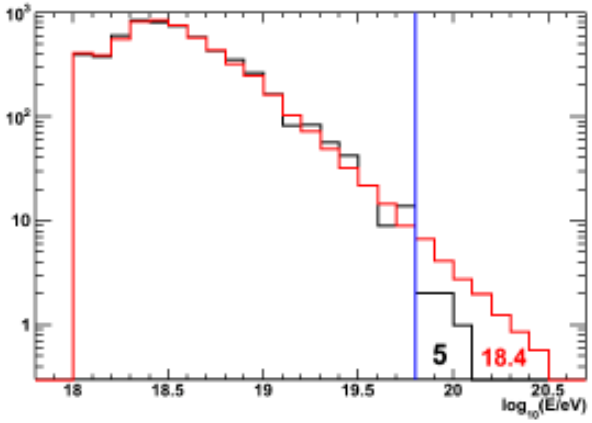
TA SD Spectrum

TA SD energy is rescaled to FD energy.



Significance of the Suppression





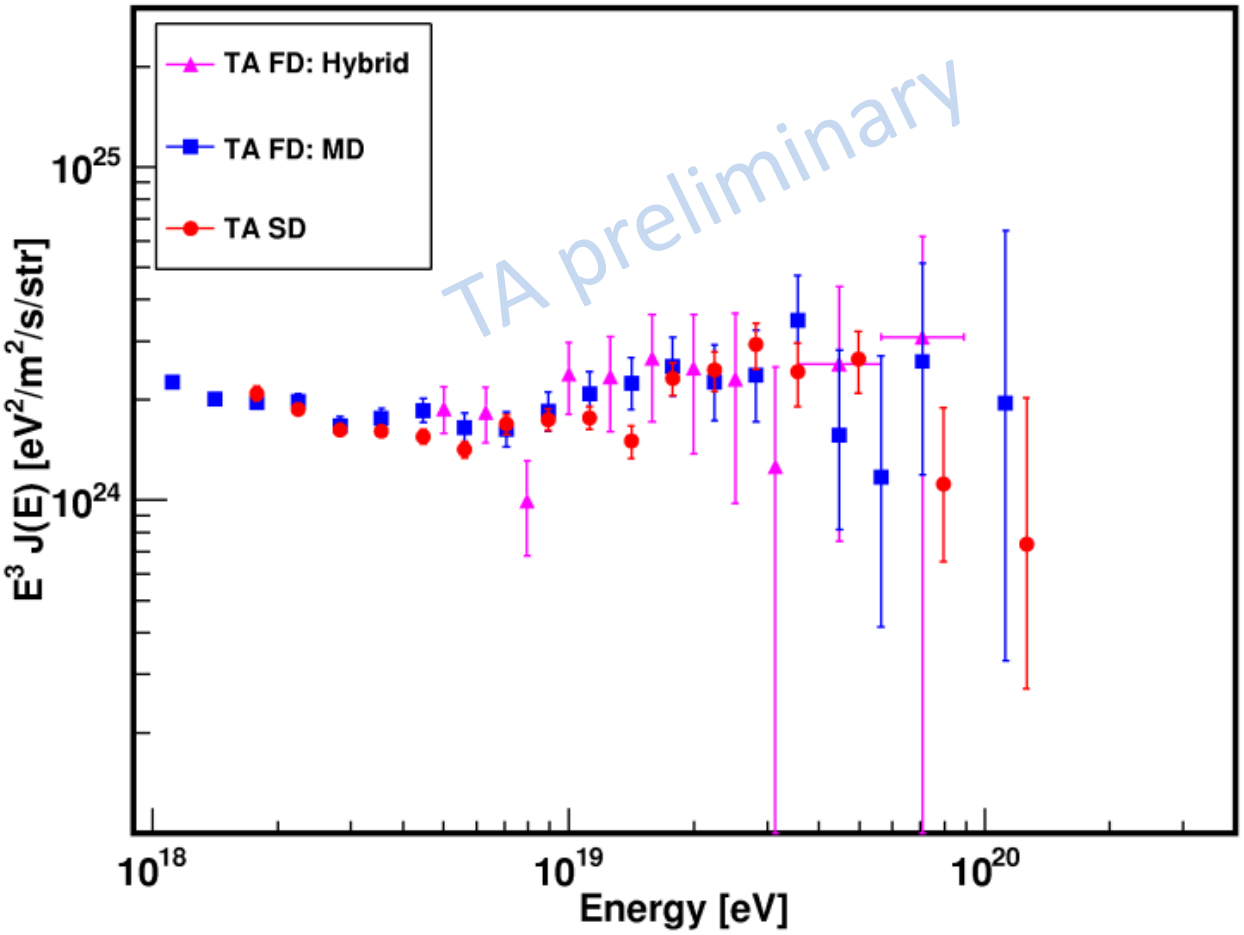
- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TASD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}$E bins after $10^{19.8}$eV bin:
  - $N_{EXPECT} = 18.4$
  - $N_{OBSERVE} = 5$

$$\text{PROB} = \sum_{i=0}^{5} Poisson(\mu = 18.4; i) = 2.41 \times 10^{-4}$$

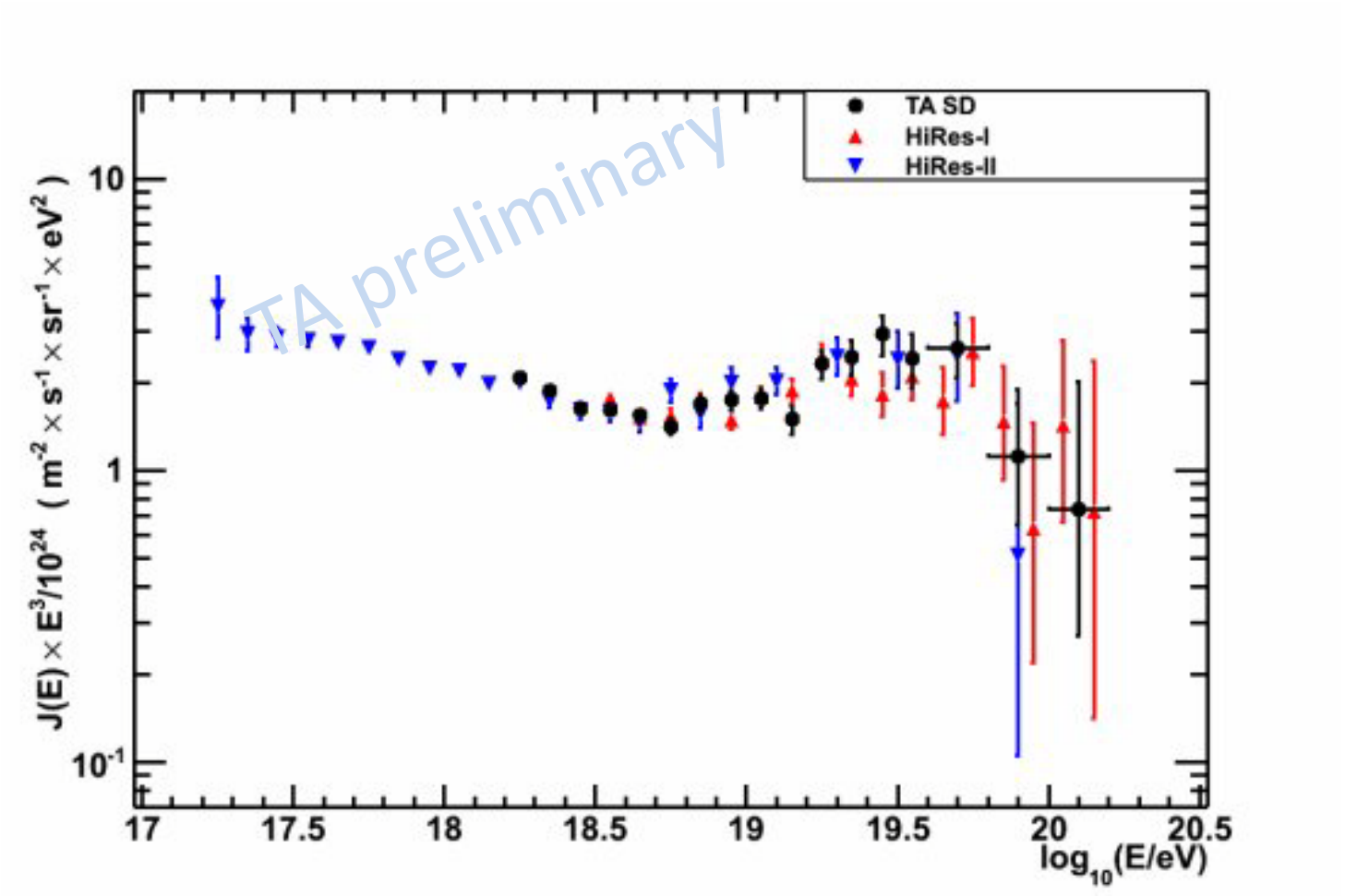
(3.5σ)

TA SD energy is rescaled to FD energy.

TA SD, Middle Drum FD Monocular, and TA Hybrid Spectra

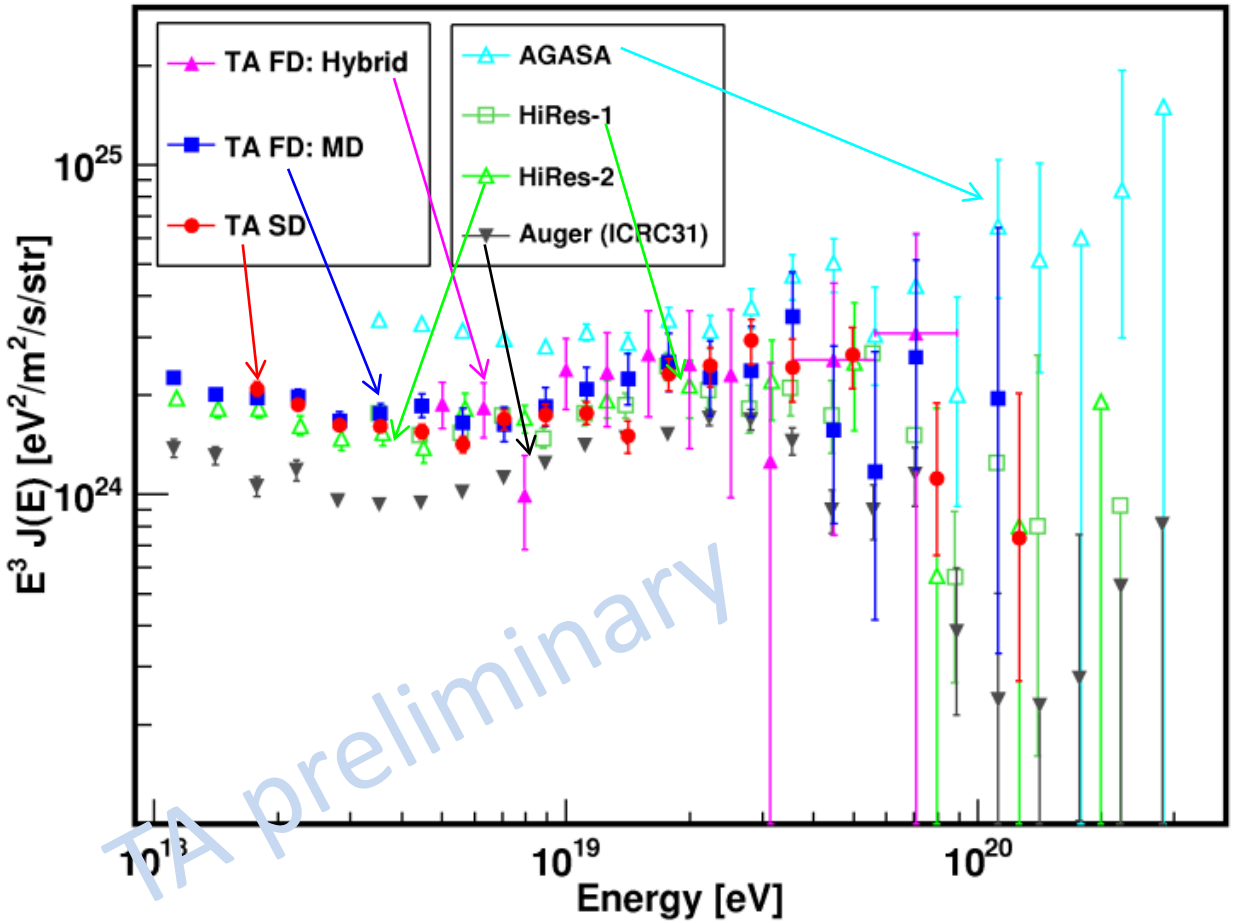


TA SD and HiRes Spectra



AGASA, Auger, HiRes, TA Spectra

TA SD energy is scaled to FD energy.

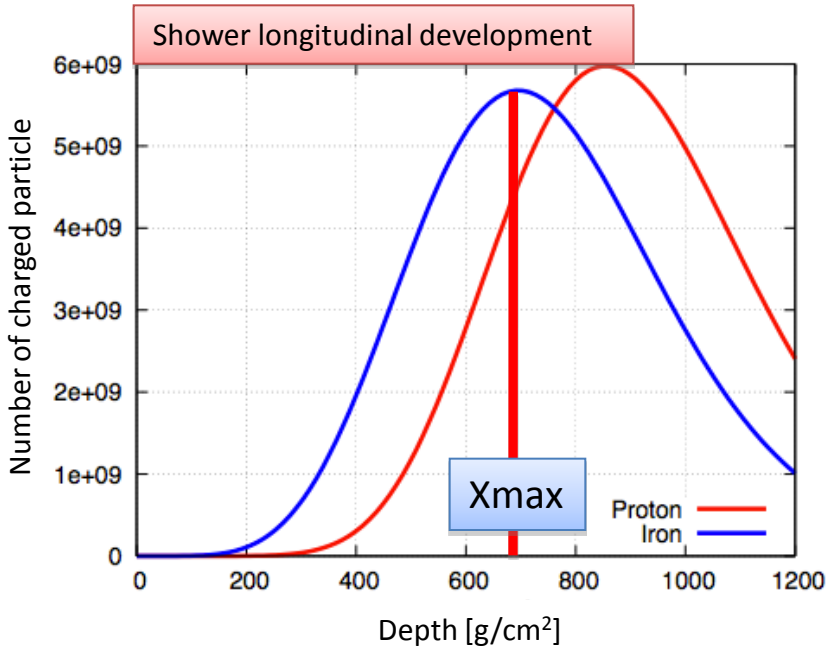


TA SD spectrum is consistent with TA MD mono and hybrid spectra, and consistent with HiRes-I and HiRes-II spectra.

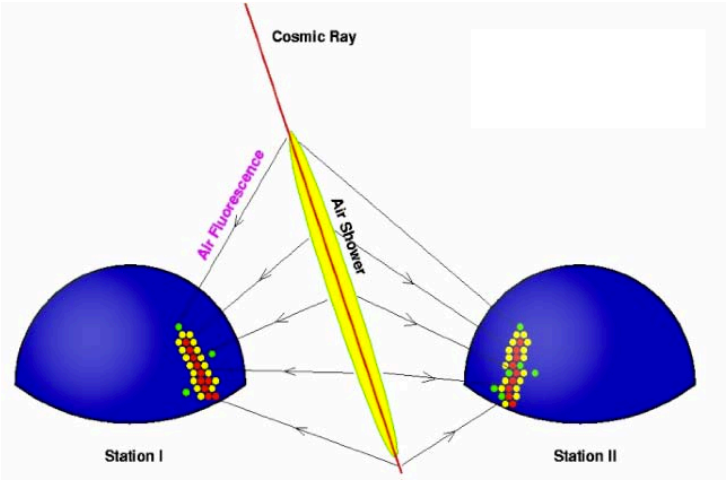
Mass composition
(Xmax technique)

(talk&poster by Y.Tameda)

- Shower longitudinal development strongly depends on their primary particle type.
- FD observes shower development directly.
- Xmas is one of the efficient parameter for determining primary particle type.

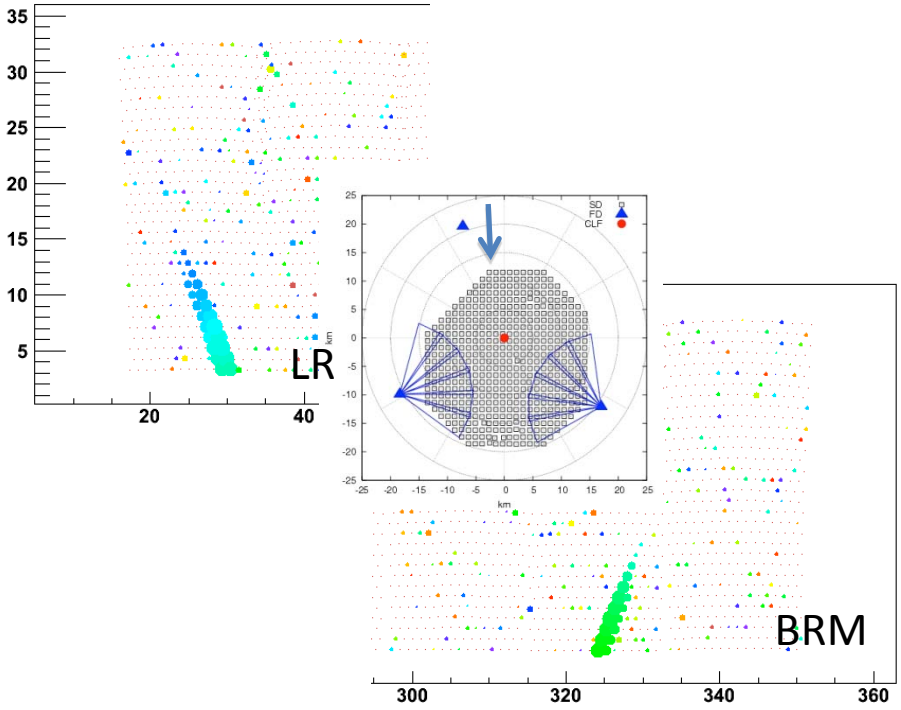


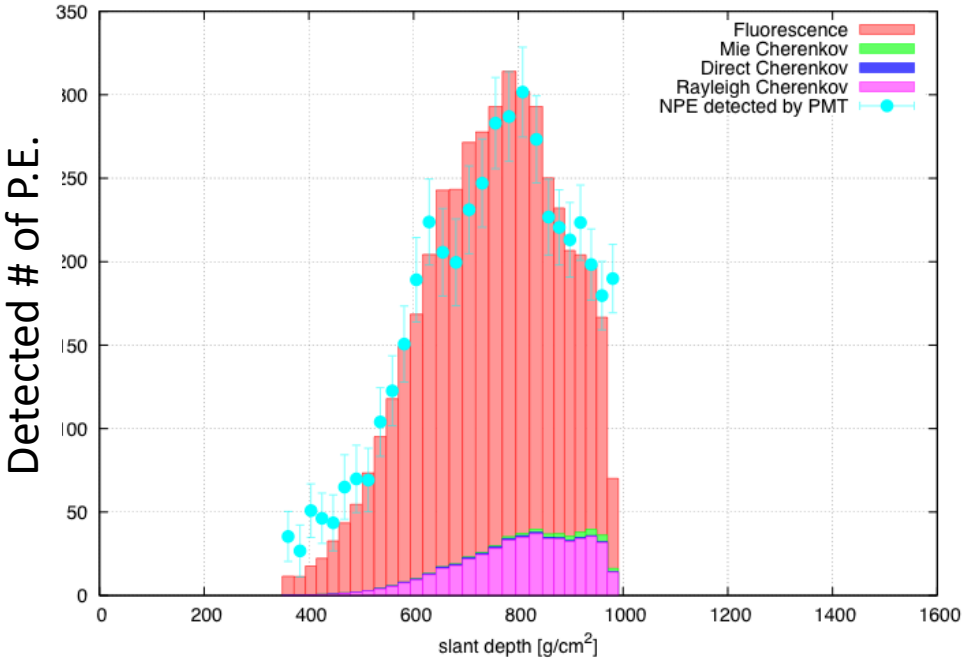
FD stereo analysis



Shower axis is determined better by FD stereo reconstruction than by FD mono reconstruction.

FD Stereo Event



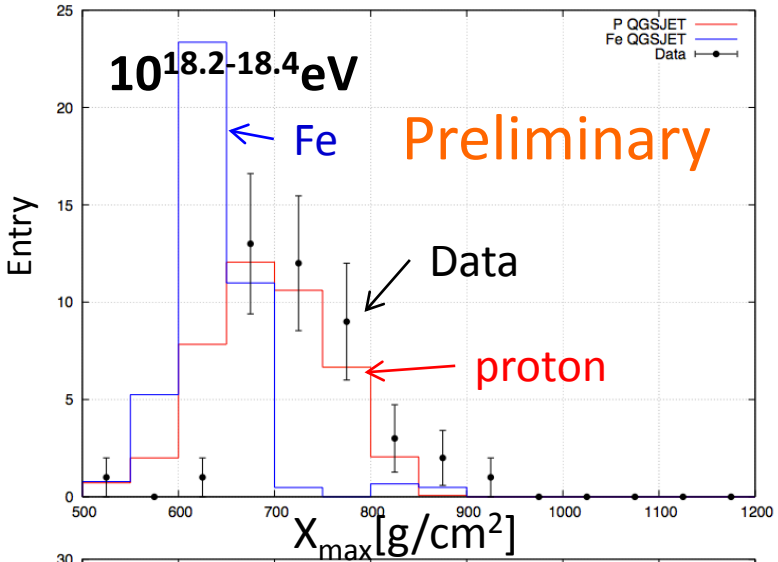


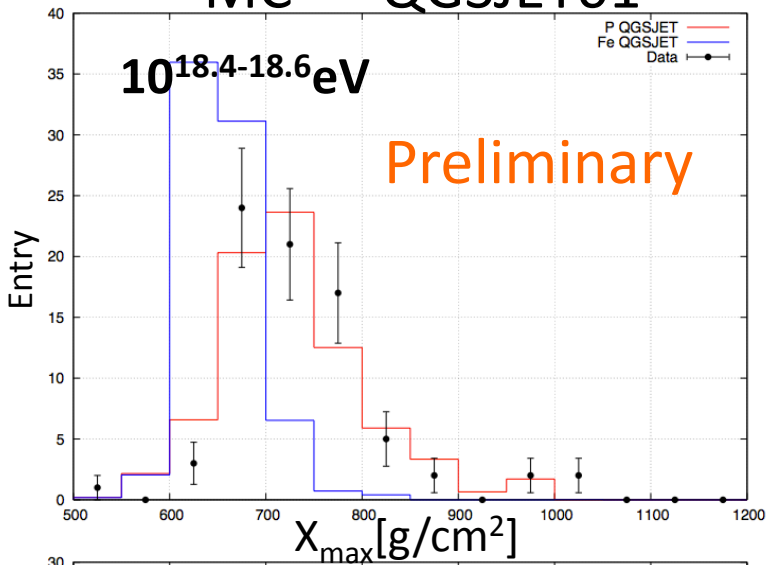
Date	log(E/eV)	Xmax	zenith	azimuth	Xcore	Ycore
2008/09/04	19.71	890 g/cm^2	44.3^o	-3.0^o	-3.1	14.2

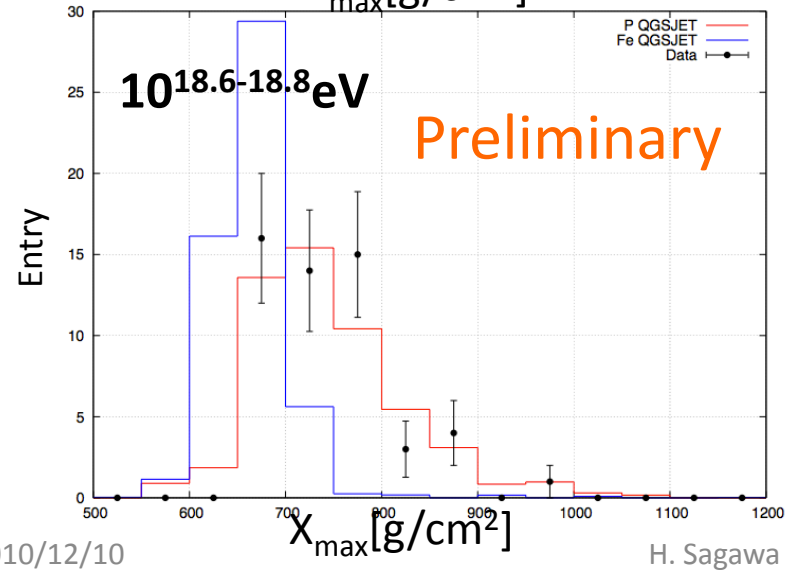
X_{max} Data/MC comparison

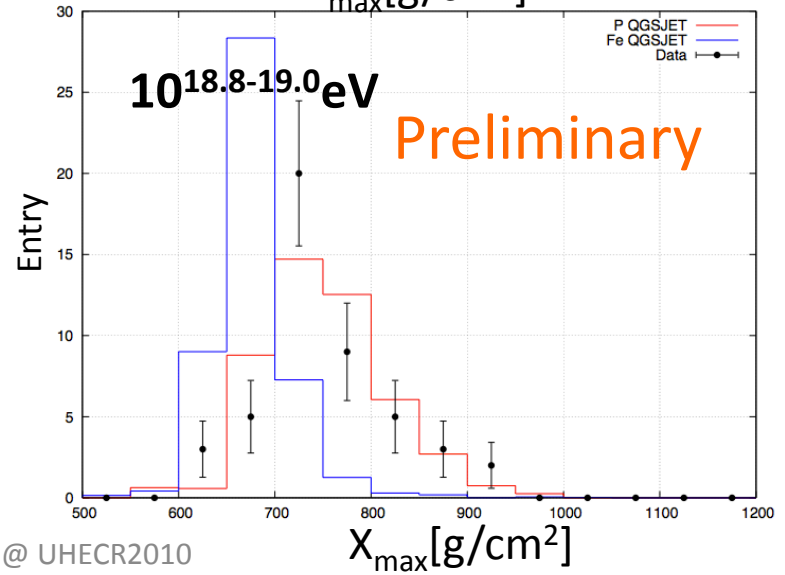
Dataset: 2007/Nov ~ 2010/Sep (~3yrs)

X_{max} = reconstructed X_{max}
MC = QGSJET01



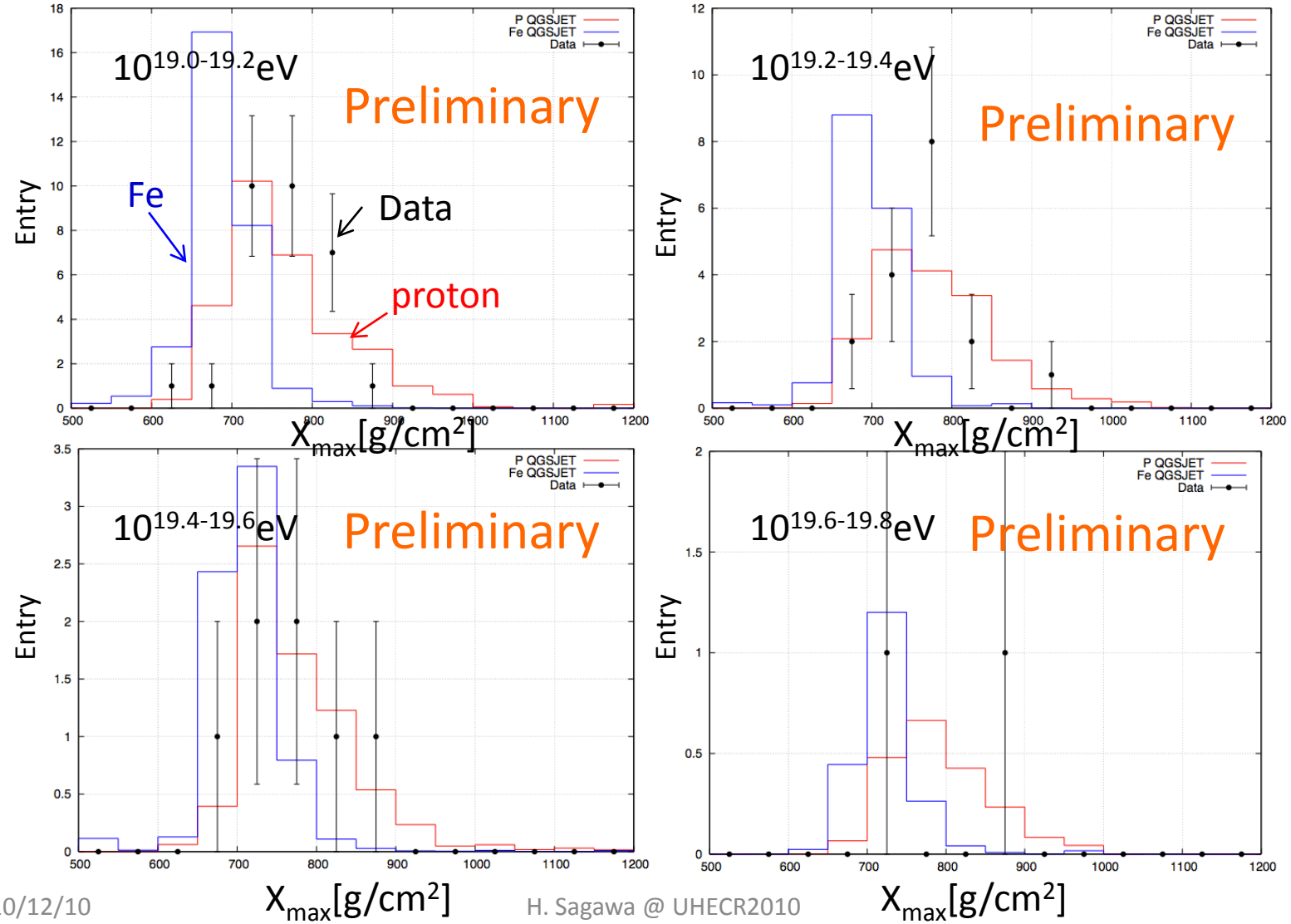






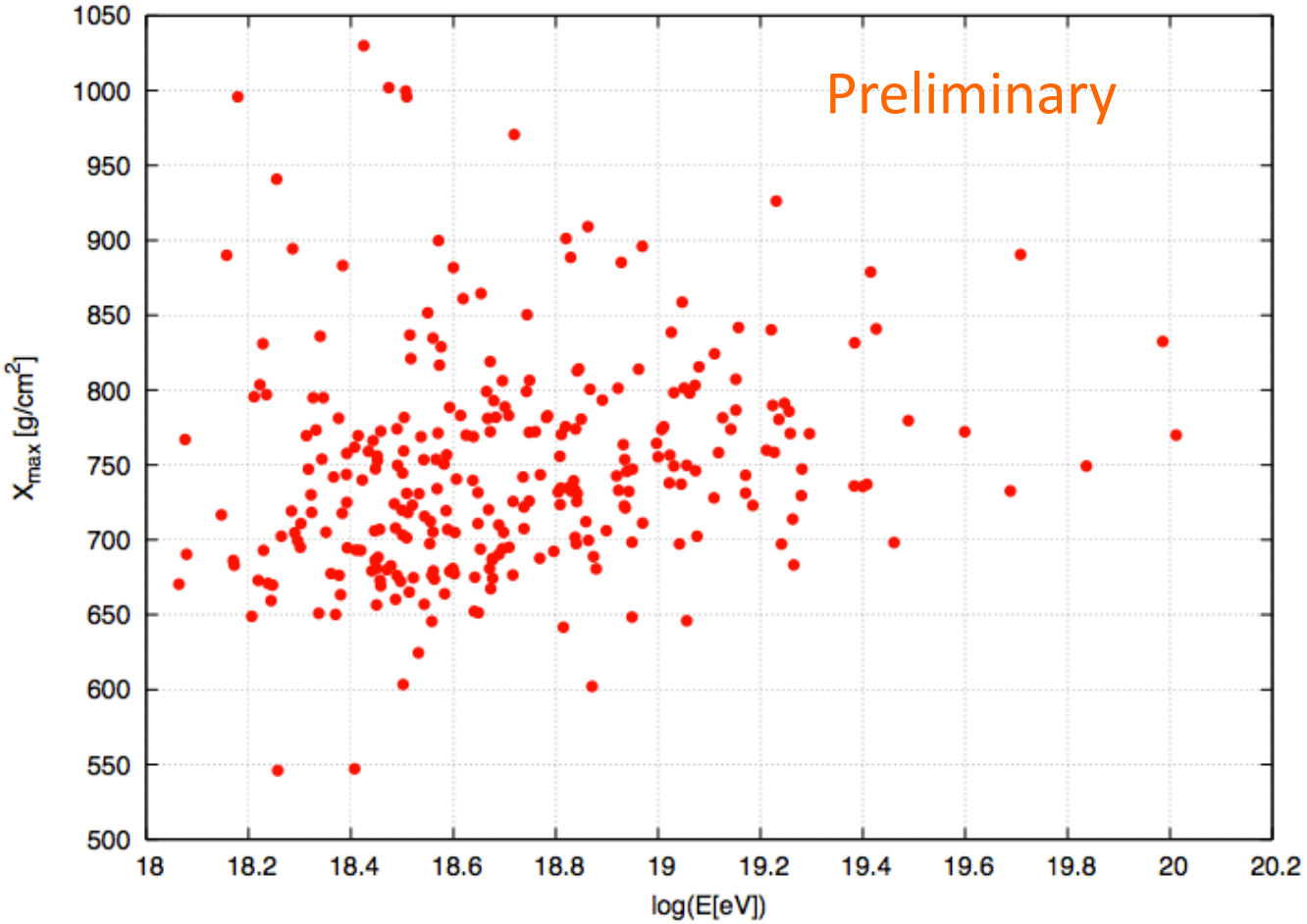
X_{max} Data/MC comparison

X_{max} = reconstructed X_{max}
MC = QGSJET01



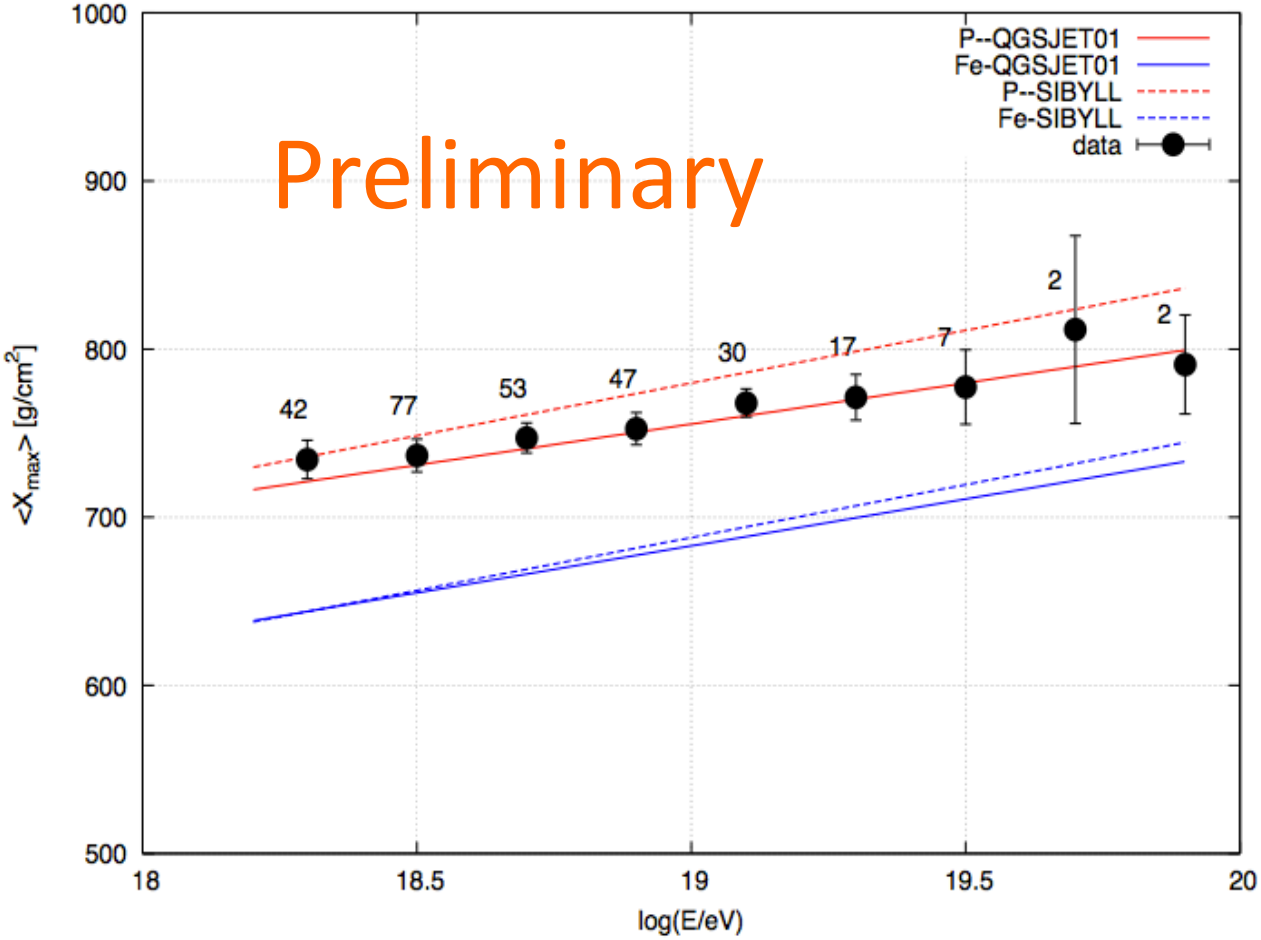
X_{max} vs. Energy

X_{max}= reconstructed X_{max}
Energy=reconstructed energy



$<X_{max}>$ vs. Energy

X_{max}= reconstructed X_{max}
Energy=reconstructed energy



Mass composition of the data is consistent with proton.

Anisotropy

(talk by P.Tinyakov)

- LSS correlation (under study)
- AGN correlation
- autocorrelation

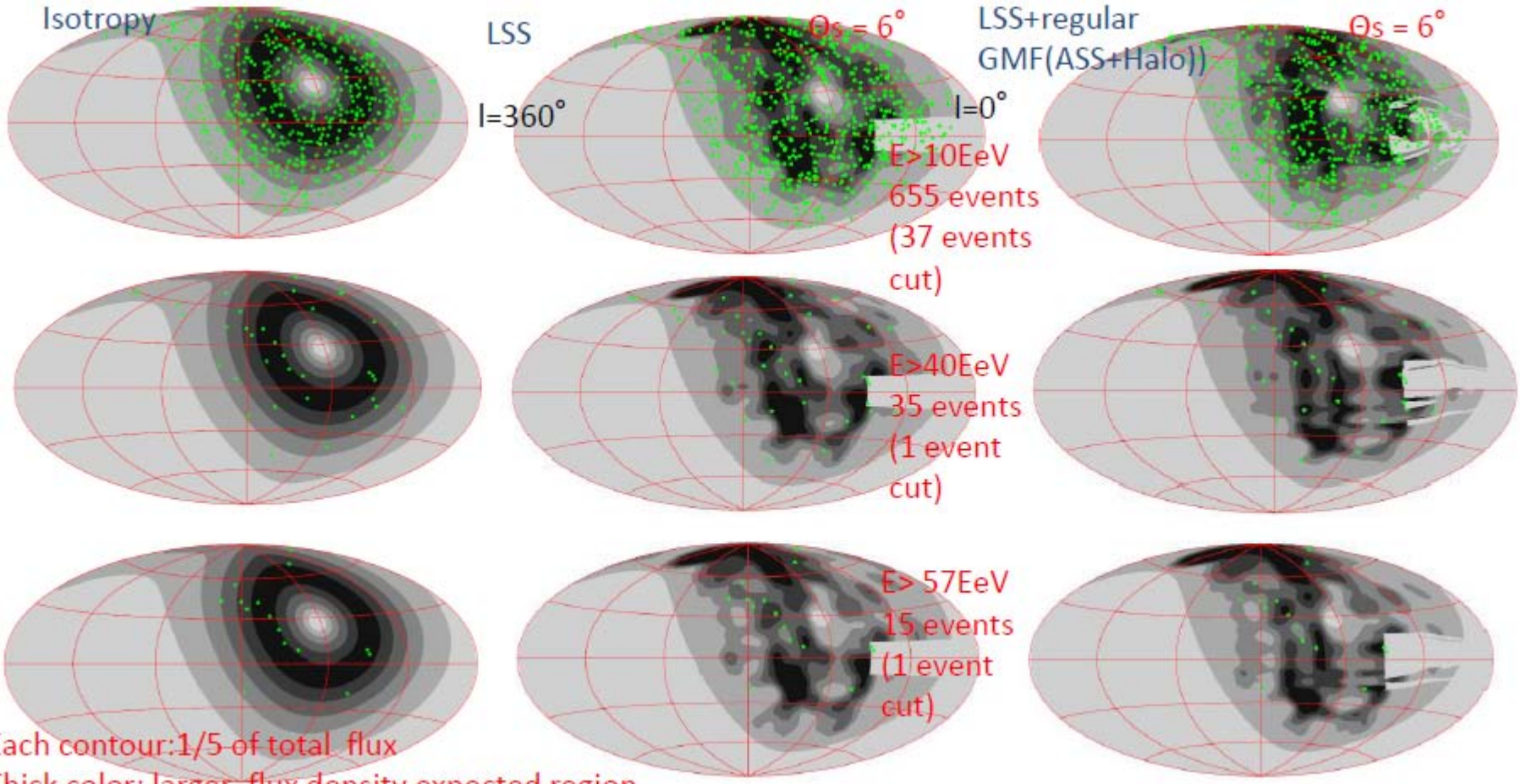
LSS correlation

(poster by E.Kido)

- 2Mass Extended Source (XSCz)
  - m<12.5
  - 5Mpc<D<250Mpc
- Injection spectrum index = -2.4, proton
- Propagation (int. with CMB photon & D^{-2} loss)
- Smearing angle (free parameter)
- Galactic Magnetic Field (GMF)

Flux maps overlaid with data

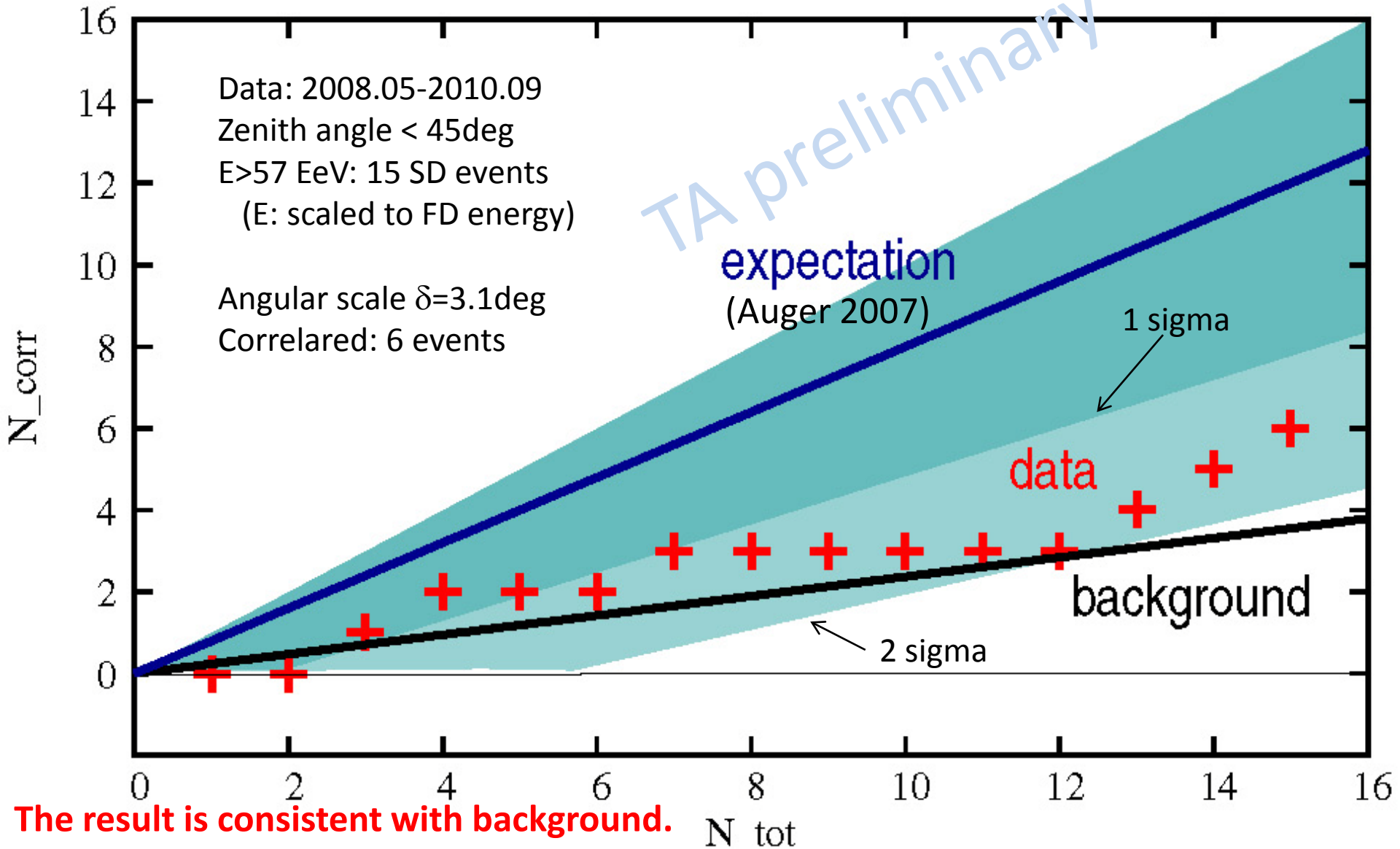
Data set: SD events from 2008/May to 2010/Sep



LSS correlation is under study

Correlation with AGN

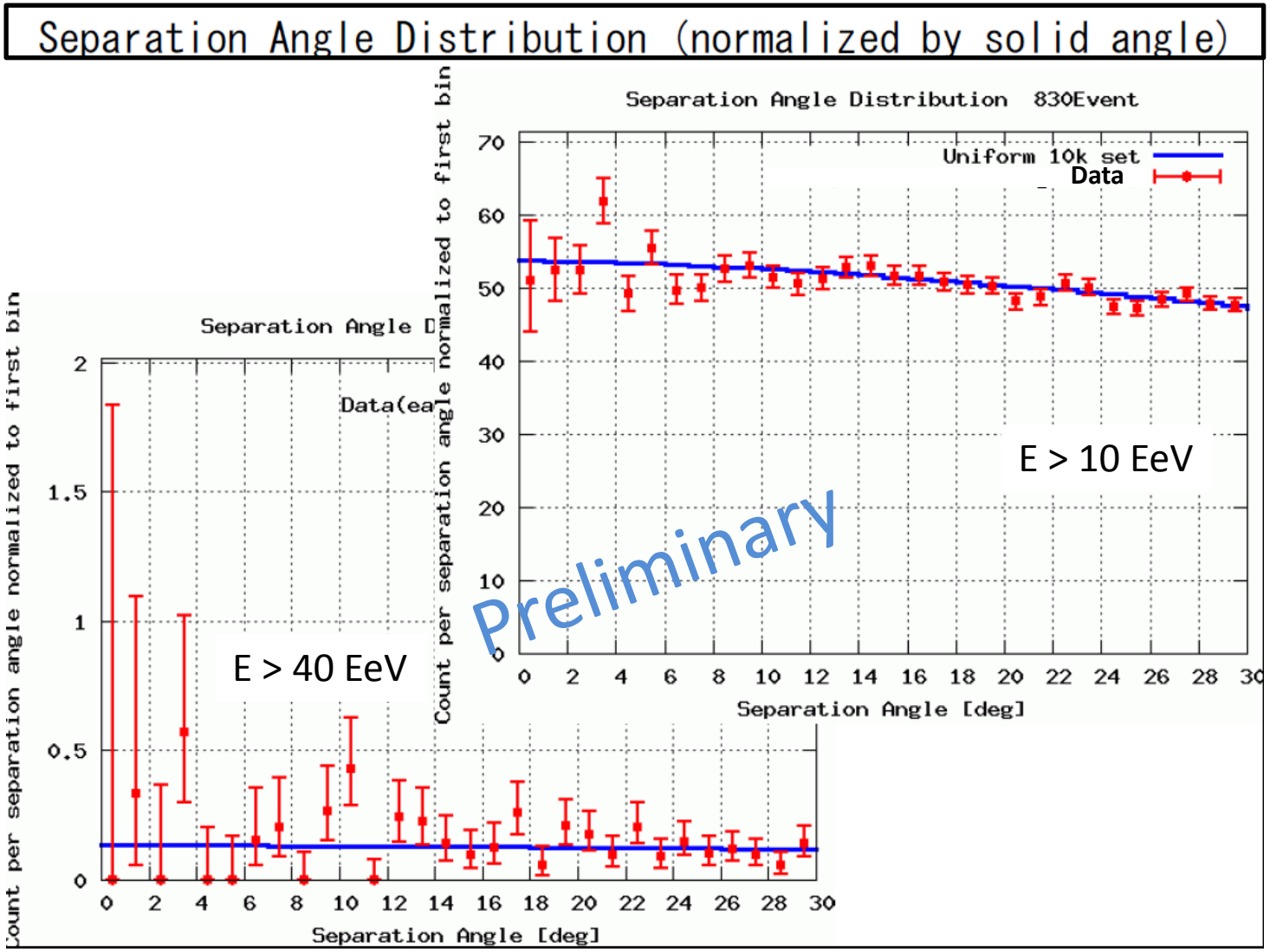
(talk by P.Tinyakov)



The result is consistent with background.

Autocorrelation

(poster by T.Okuda)



Consistent with background

Summary

- The TA is the largest detector in the northern hemisphere.
- SD, FD mono, and hybrid spectrum:
  - Consistent with each other and HiRes-1,2
  - Evidence for suppression (from SD) [3.5σ]
- Xmax analysis: FD stereo
  - consistent with proton
- Anisotropy:
  - AGN: Ncorr=6 (consistent to Nbkg~4) for E>57 EeV
  - N(separation angle<2.5deg)= 1 (consistent with N_{bkg}=0.8) for E>40 EeV