Results from the Telescope Array Experiment

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@ AlbaNova University Center on 2011.08.1

Outline

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  - Spectrum (FD mono / SD / Hybrid)
  - Composition (FD stereo)
  - Arrival direction (SD)
    - LSS correlations / AGN correlations / auto-correlations
III. Conclusions

The Telescope Array Collaboration

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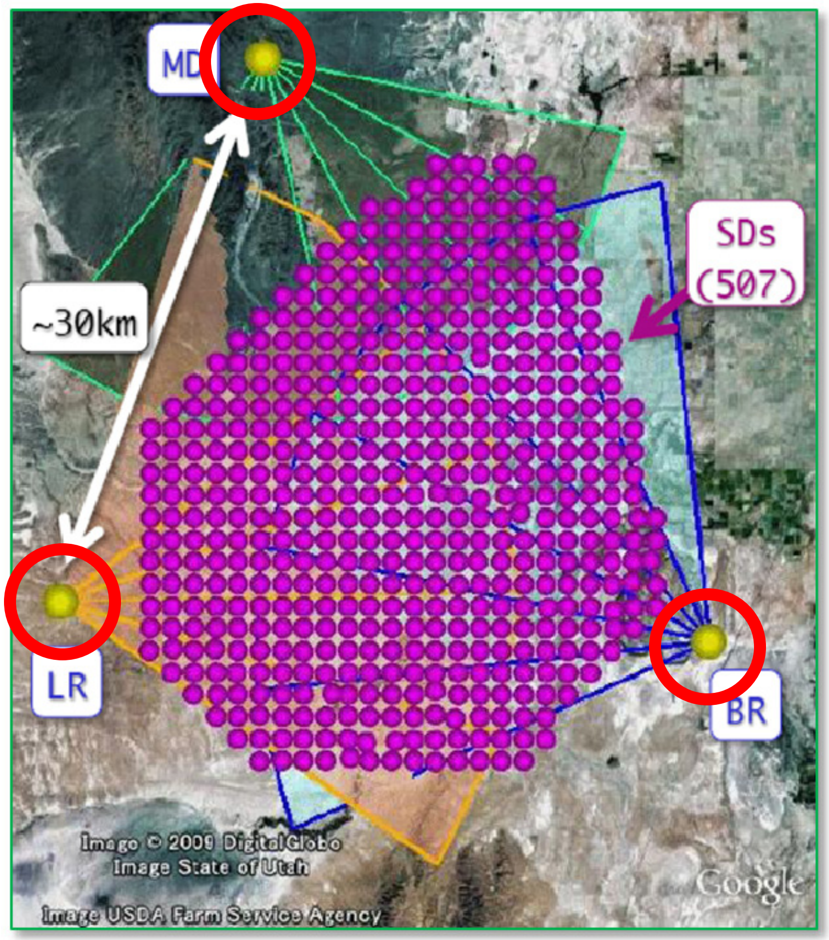
~120 researchers from Japan/US/Korea/Russia

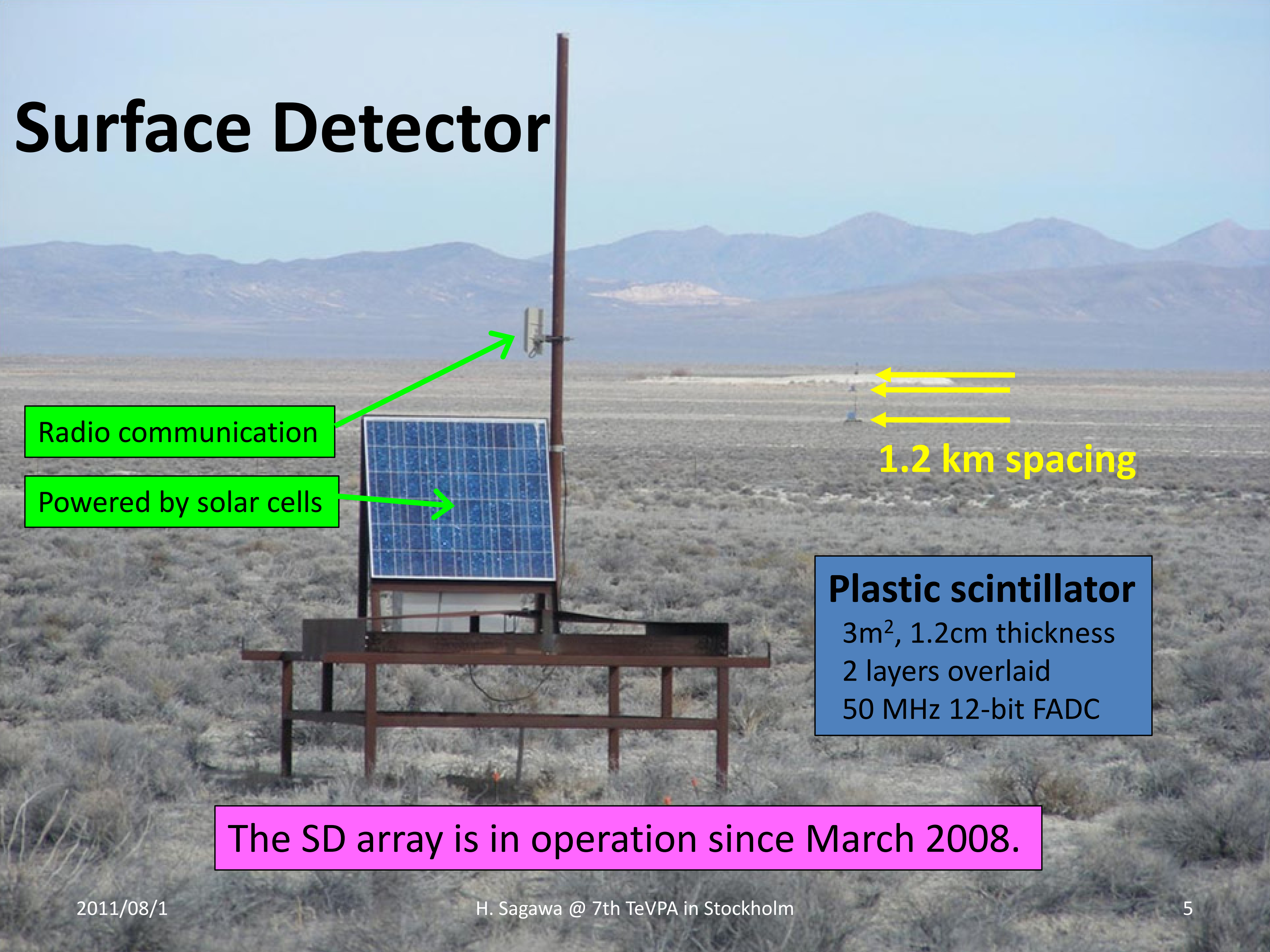
TA detector

- **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
    - ~200km south to Salt Lake City (39.3^{o}N, 112.9^{o}W)
- ~1400m a.s.l.



The largest detector in northern hemisphere

Surface Detector



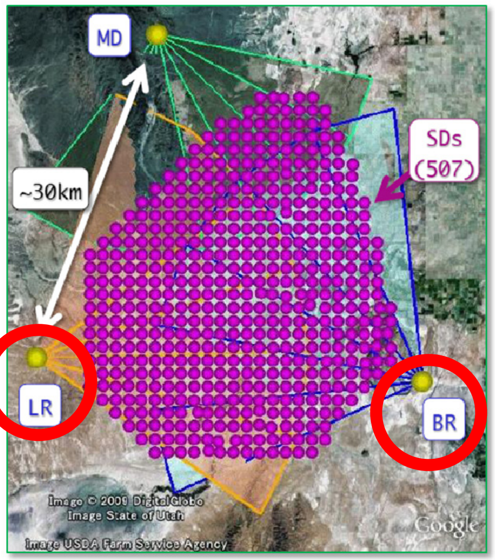
Plastic scintillator

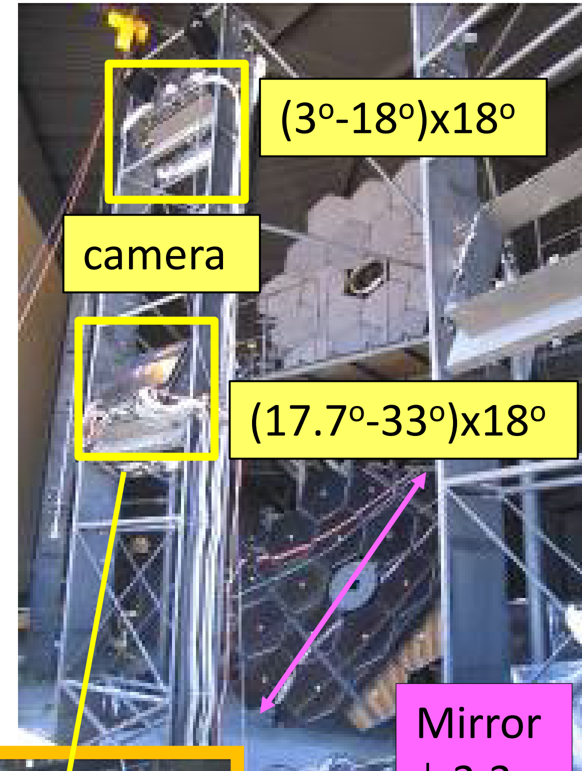
- $3m^2$, 1.2cm thickness
- 2 layers overlaid
- 50 MHz 12-bit FADC

The SD array is in operation since March 2008.

Fluorescence Detector (FD)

- BR/LR site : new FDs





Mirror
ϕ 3.3m

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

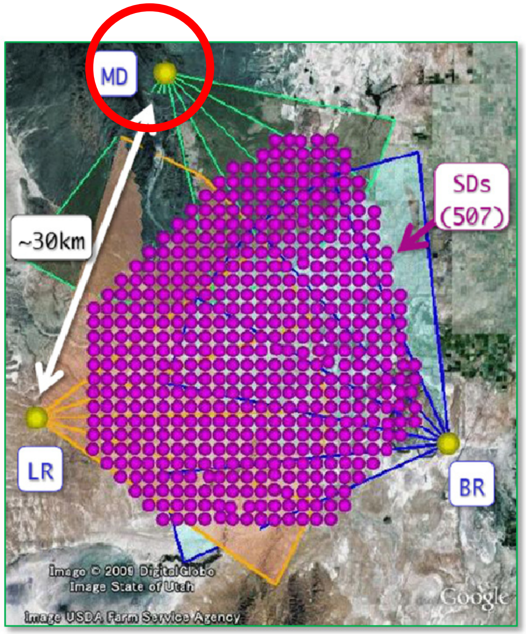
12 cameras/station

FADC readout
(40 MHz sampling)

~1m

Camera
16x16=256 PMTs
Hamamatsu R9508

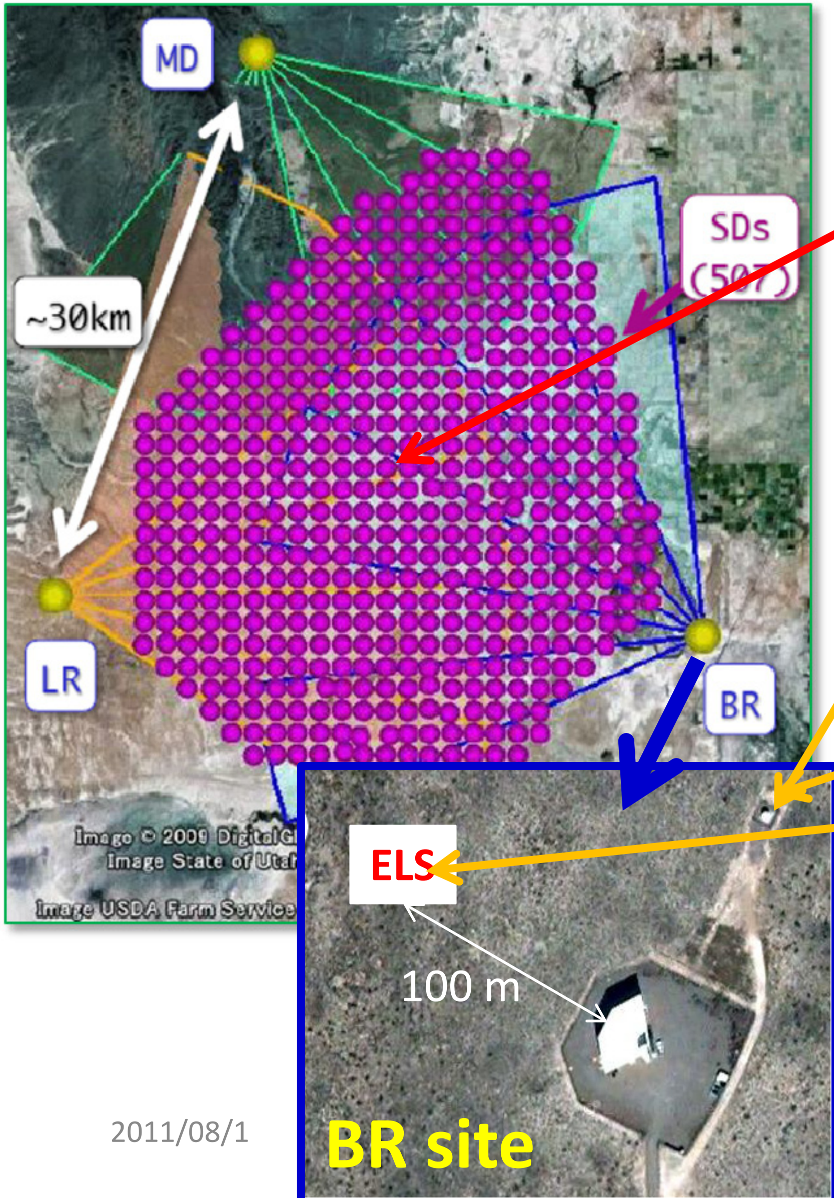
FD station at MD site



Transferred from HiRes

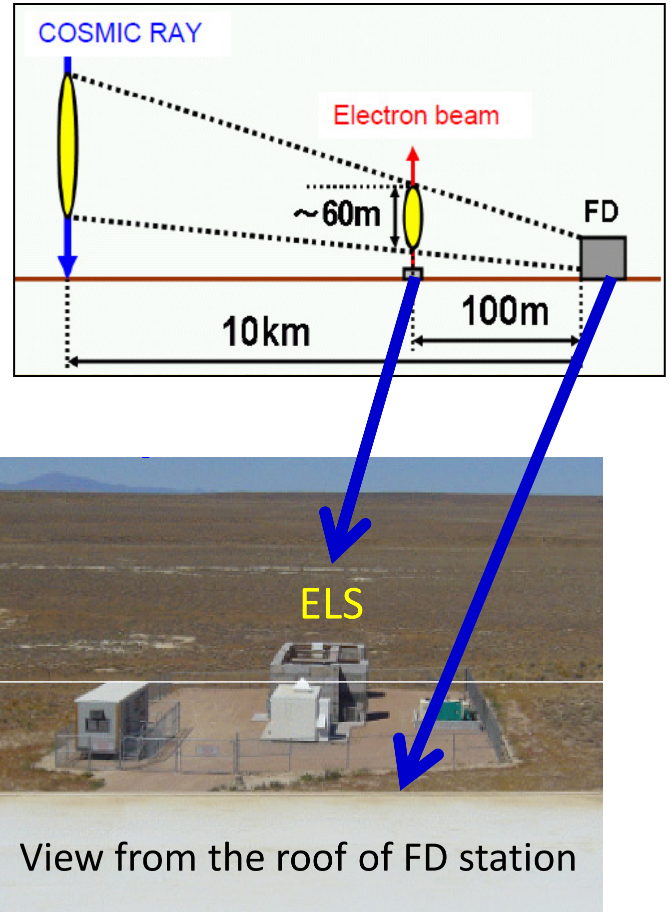
- 14 cameras/station
- 256 PMTs/camera
- 3^o-31^o elevation with 1^o pixel
- 114^o in azimuth
- $5.2m^2$ mirror
- S/H electronics

Atmospheric monitor・calibration
(for fluorescence detectors)



- Central Laser Facility
  - Observe sidescattering of laser from each FD station as a standard candle
- LIDAR :
  - Observe backscattering of laser→measure transparency of atmosphere
- IR camera : cloud monitor
- Electron Light Source (ELS)
  - End-to-end absolute energy calibration of fluorescence detectors

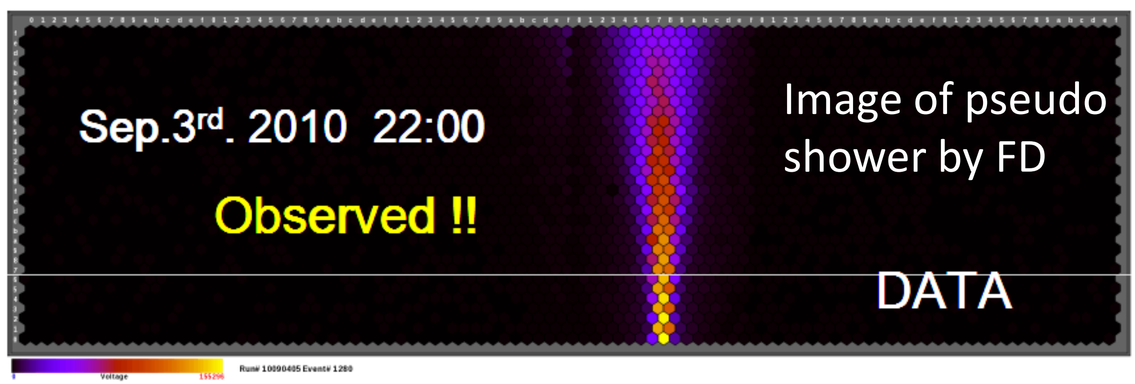
ELS (Electron Light Source)
[compact electron linear accelerator]



Specification
. electron energy: 40 MeV (max)
. current: 10^9 electrons/pulse
. pulse width: 1 μsec

By an electron beam with known total energy, we will perform end-to-end absolute energy calibration of FD.

First light



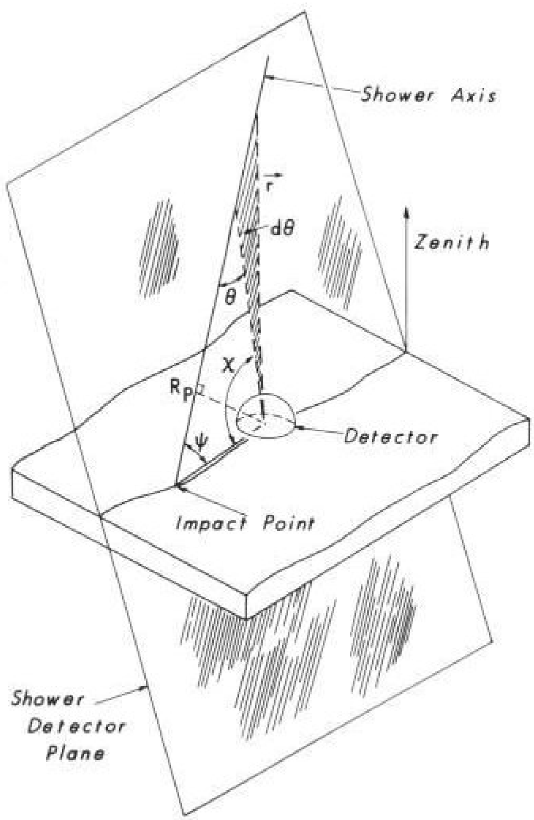
Spectrum

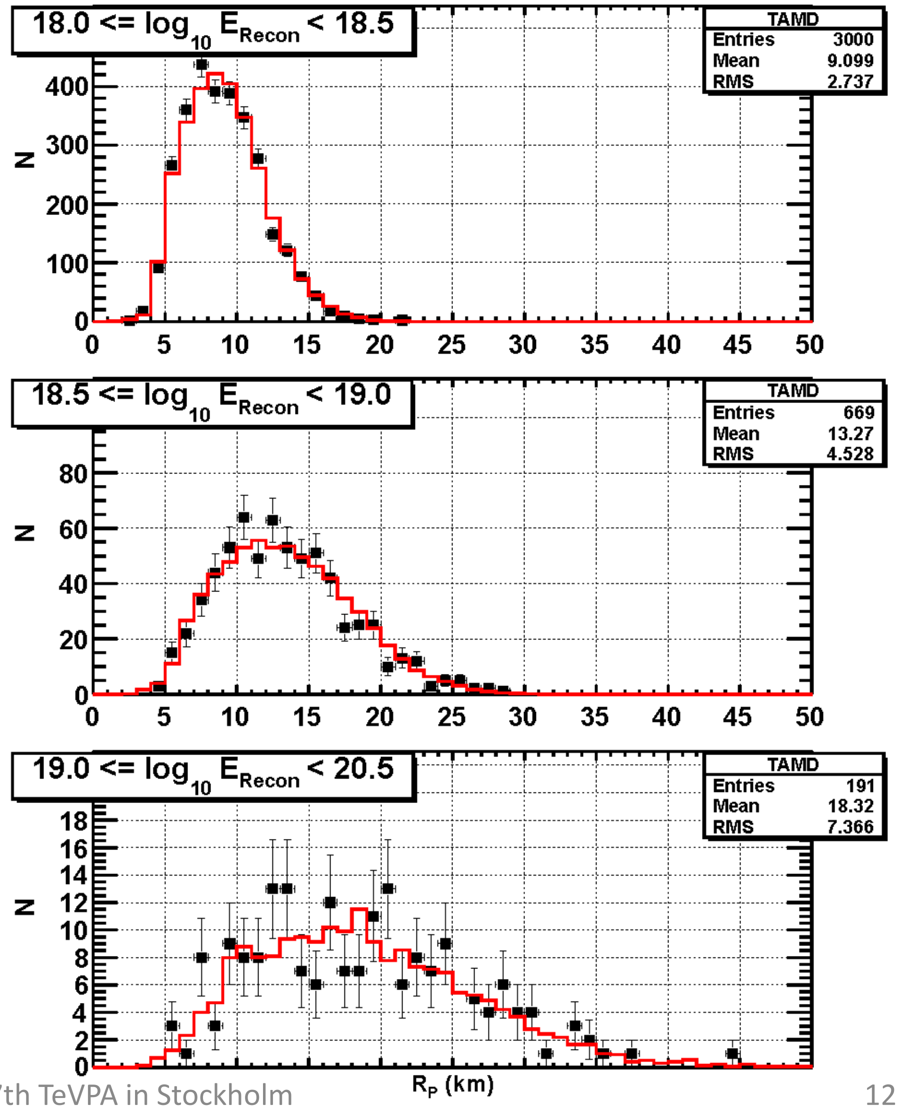
- MD FD mono spectrum
  - HiRes refurbished telescope
  - Direct link of energy scales and energy spectra between HiRes and TA
- SD spectrum
  - Plastic scintillator surface detectors (a la AGASA)
- Hybrid spectrum
  - BRM/LR FD (new telescopes) + SD

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)

Impact parameter R_p

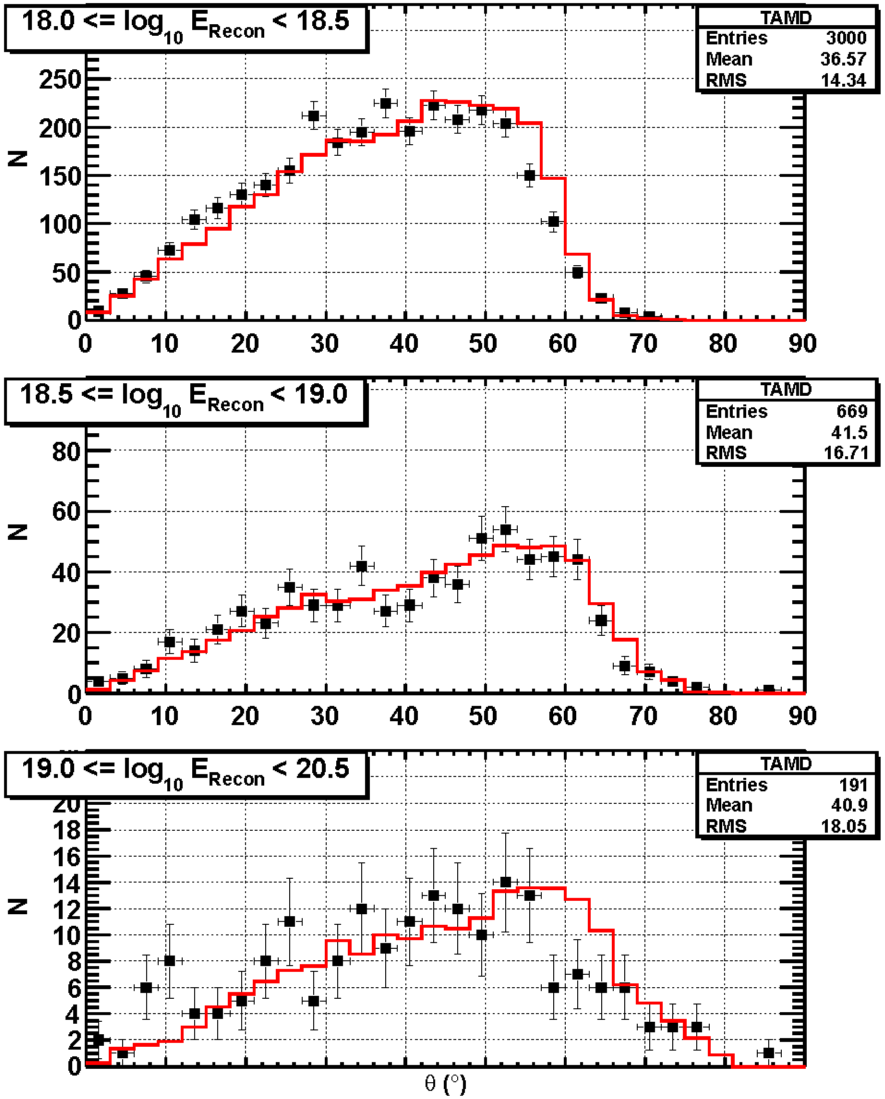




Black: TA MD data

Red: MC

Zenith angle θ

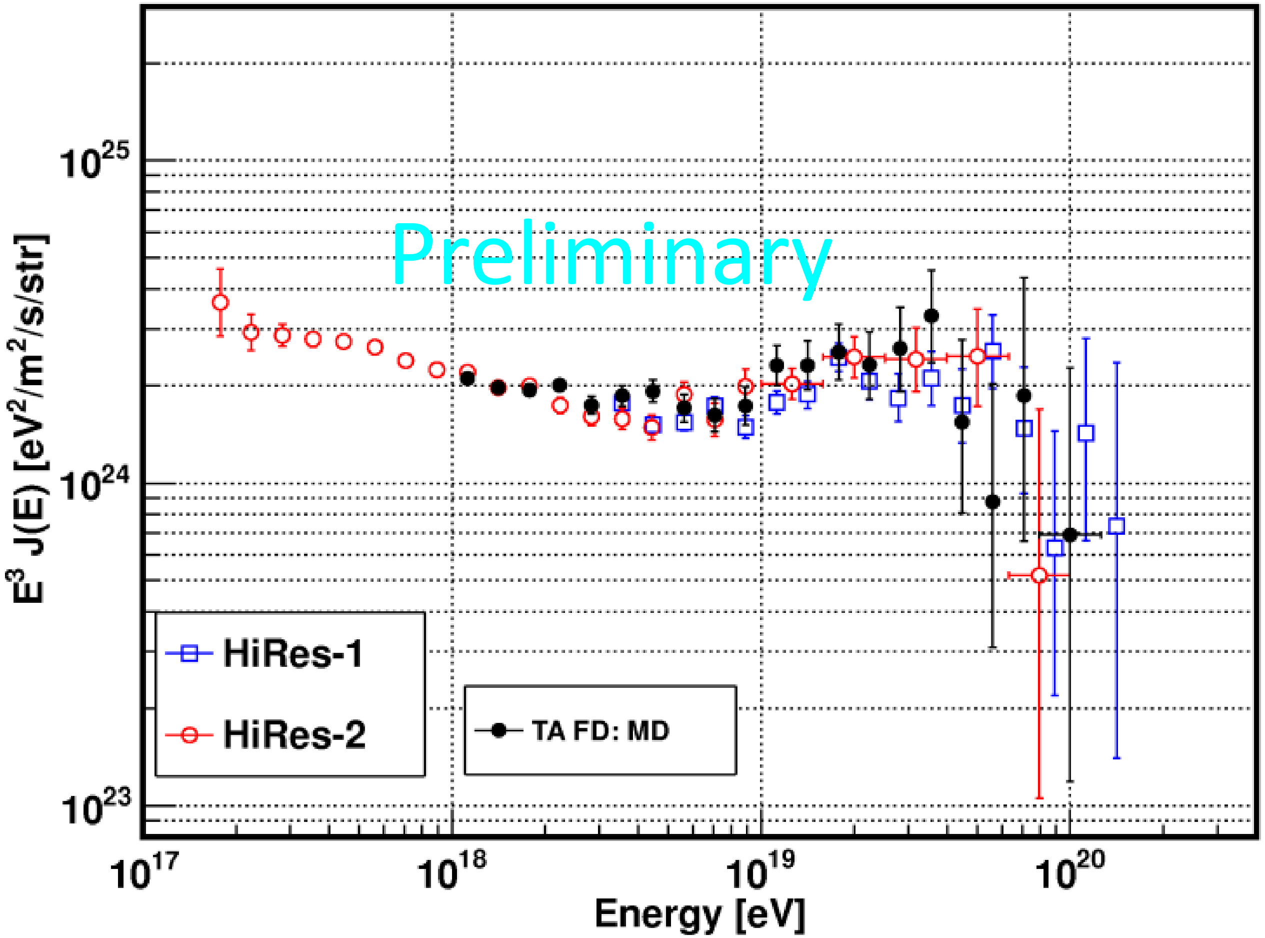


Black: TA MD data

Red: MC

MD mono energy spectrum

- Data: 2007/Dec~2010/Dec



in good agreement with HiRes

SD spectrum

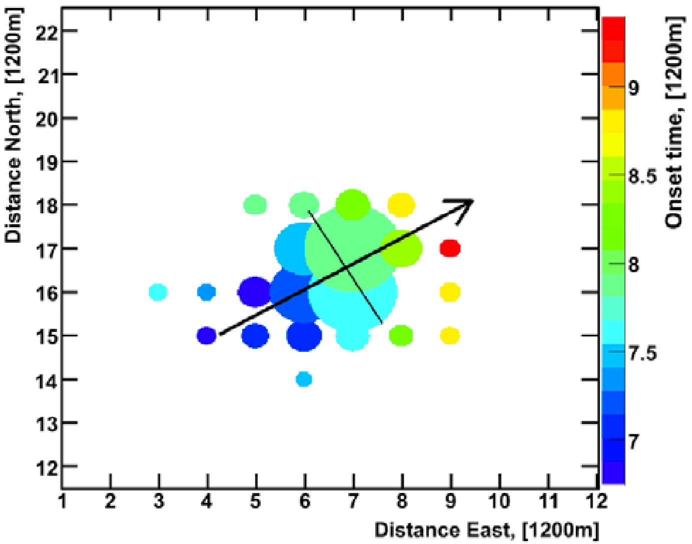
- SD reconstruction
  - LDF, timing fit
- MC
  - First energy estimation
- Data/MC comparisons
  - SD energy vs. FD energy
- SD spectrum

SD data set

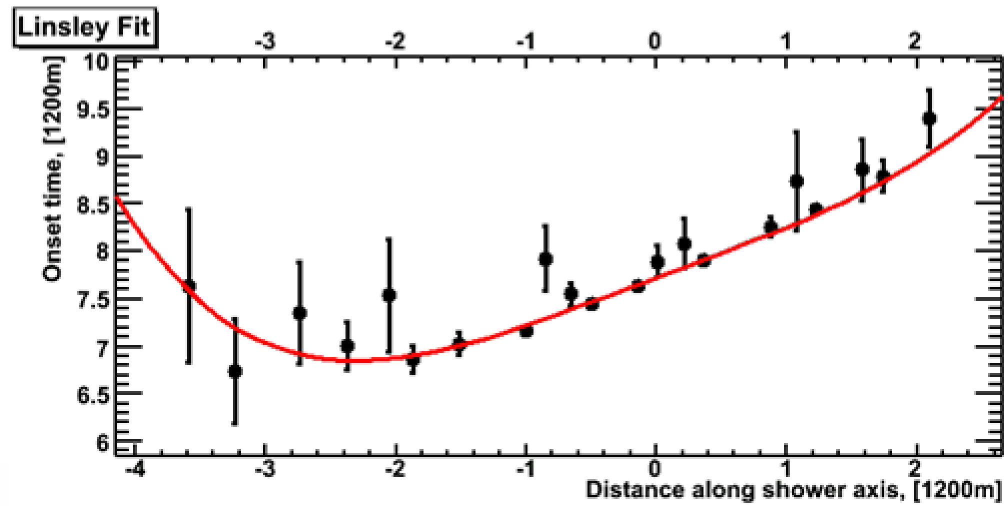
- May/11/2008 – Apr/25/2011 (~3 years)
- Exposure ~2700km^2 sr yr
- Cuts:
  - LDF χ^2/ndf < 4.0
  - Border Cut > 1.2km
  - Zenith Angle < 45 degrees
  - Pointing direction uncertainty < 5 degrees
  - Fractional S800 uncertainty < 0.25

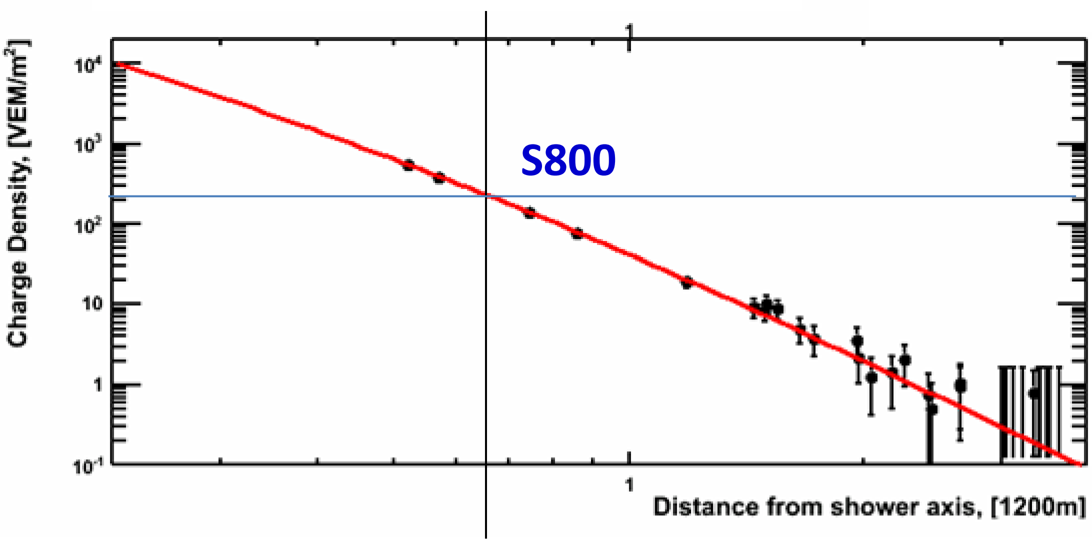
SD event reconstruction

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

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

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

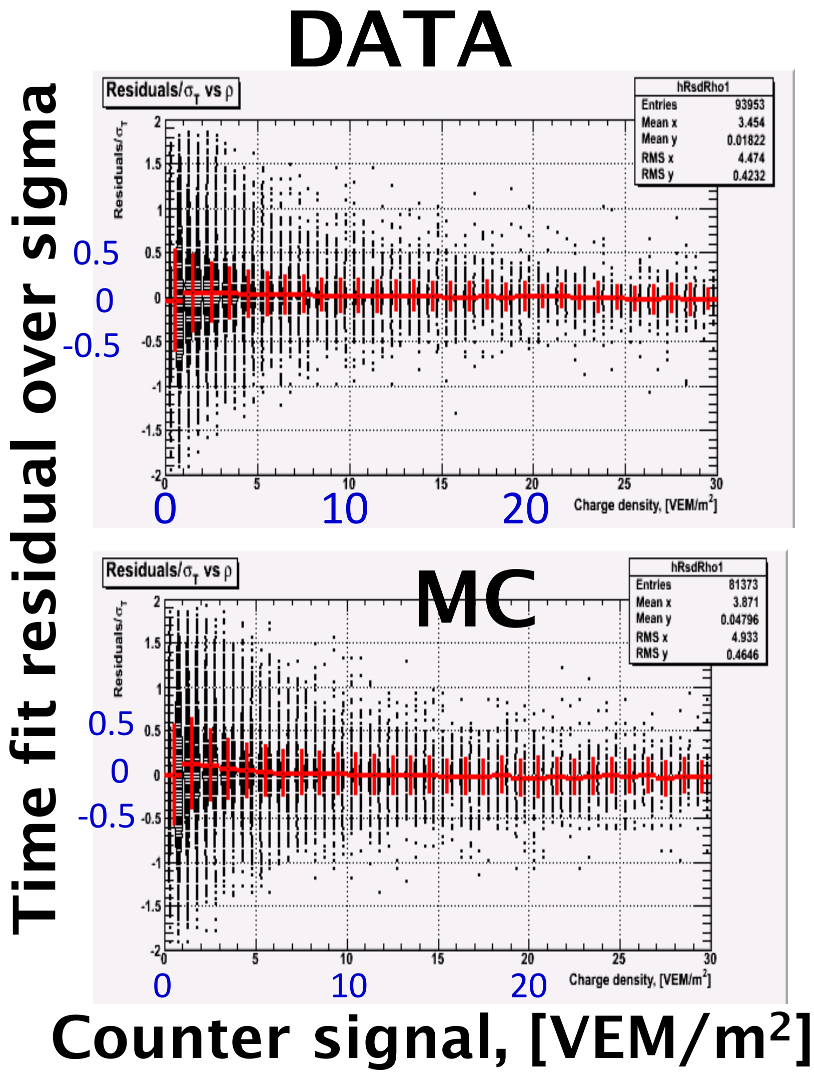
- S(800)→Primary Energy

SD Monte Carlo

- Simulate the data exactly as it exists.
  - Start with previously measured spectrum and composition.
  - **Use <u>Corsika/QGSJet-II</u> air shower events.**
    - 10^{-6} thinned and de-thinned
  - 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.

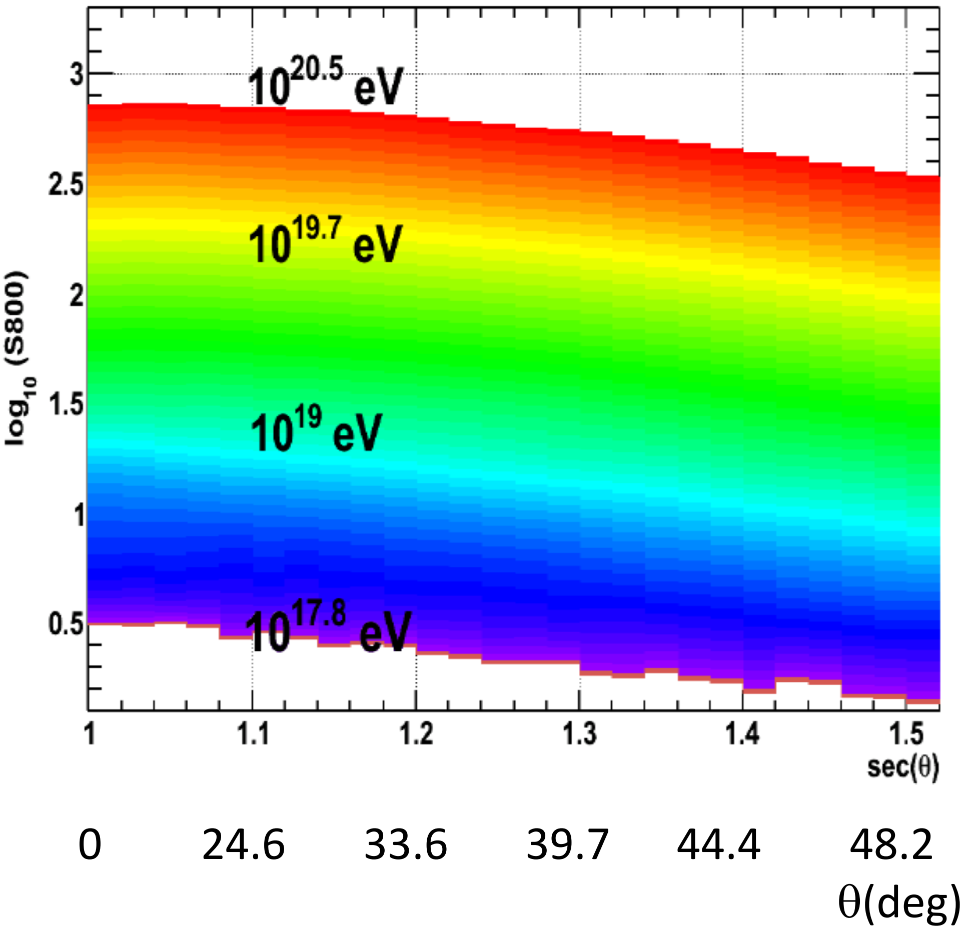
B.T.Stokes et al. , arXiv:1103.4643, arXiv:1104.3182 [astro-ph]

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

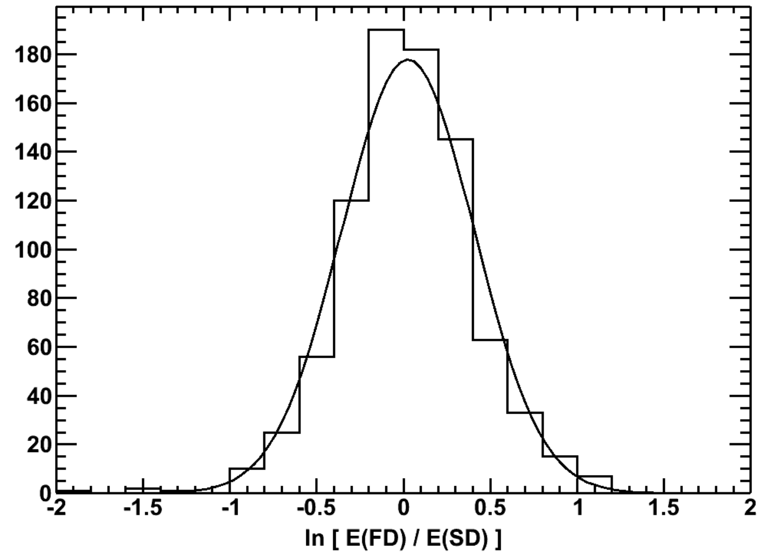


- Energy table is constructed from the MC
- First estimation of the event energy is done by interpolating between S800 vs sec(θ) lines

Energy Scale

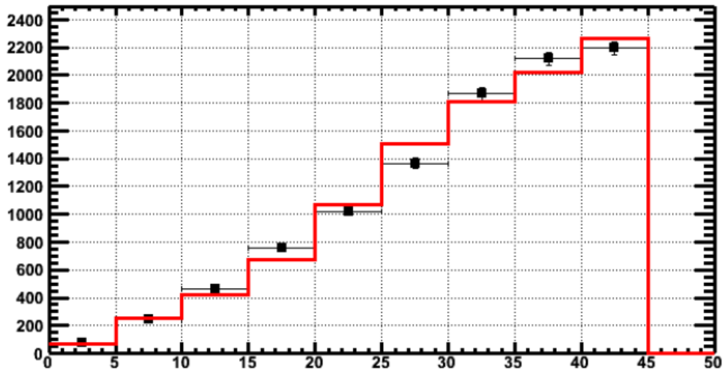
- Energy scale is determined more accurately by FD than by CORSIKA QGSJET-II
- Set SD energy scale to FD energy scale using well-reconstructed events seen by both detectors.
- 27% renormalization

$$E_{SD}=E'_{SD}/1.27$$

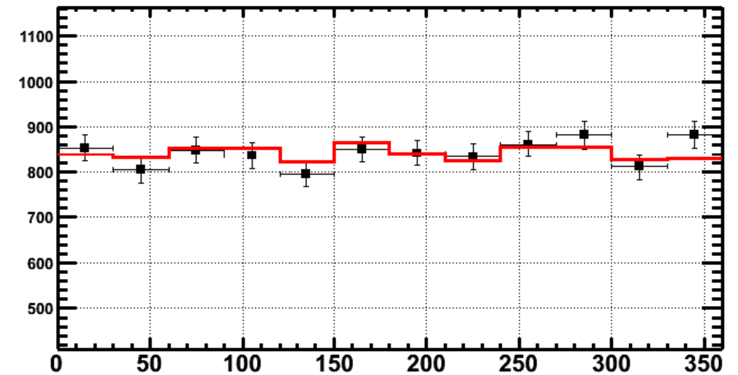


- Ratio of FD to SD after SD renormalization – FD data from all three stations included.

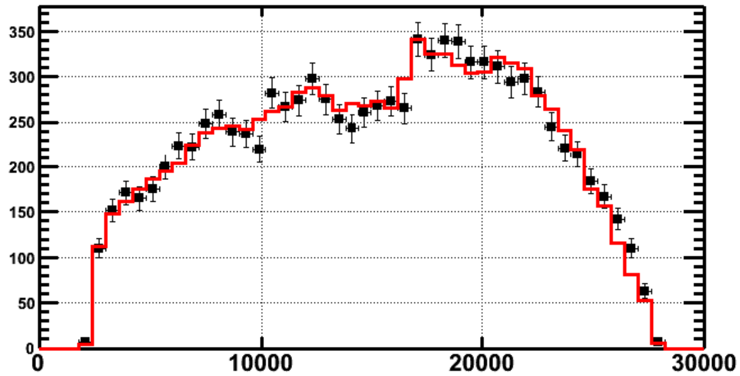
Data/MC comparison



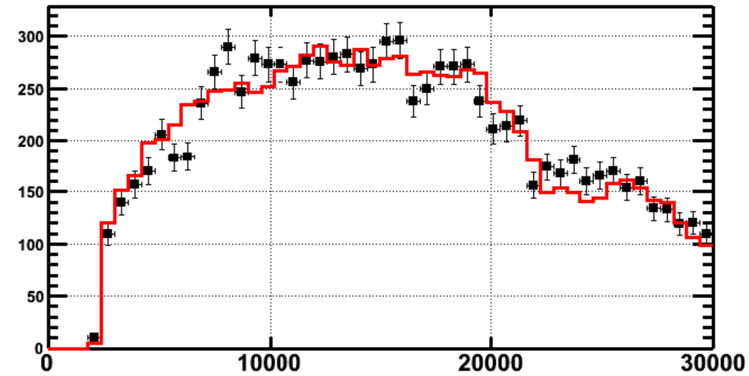
Zenith angle (deg)



azimuthal angle (deg)



XCORE (m)

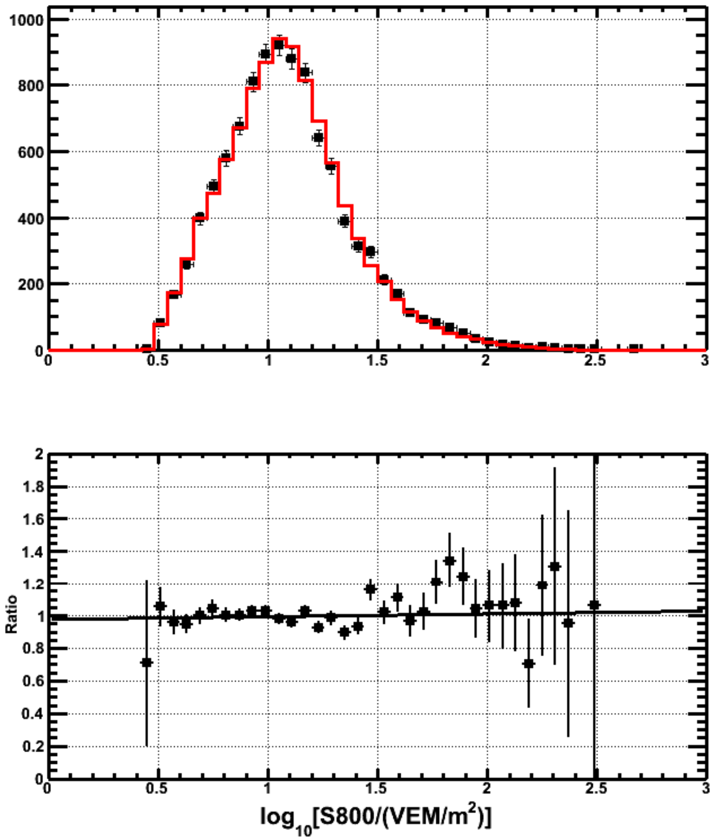


YCORE (m)

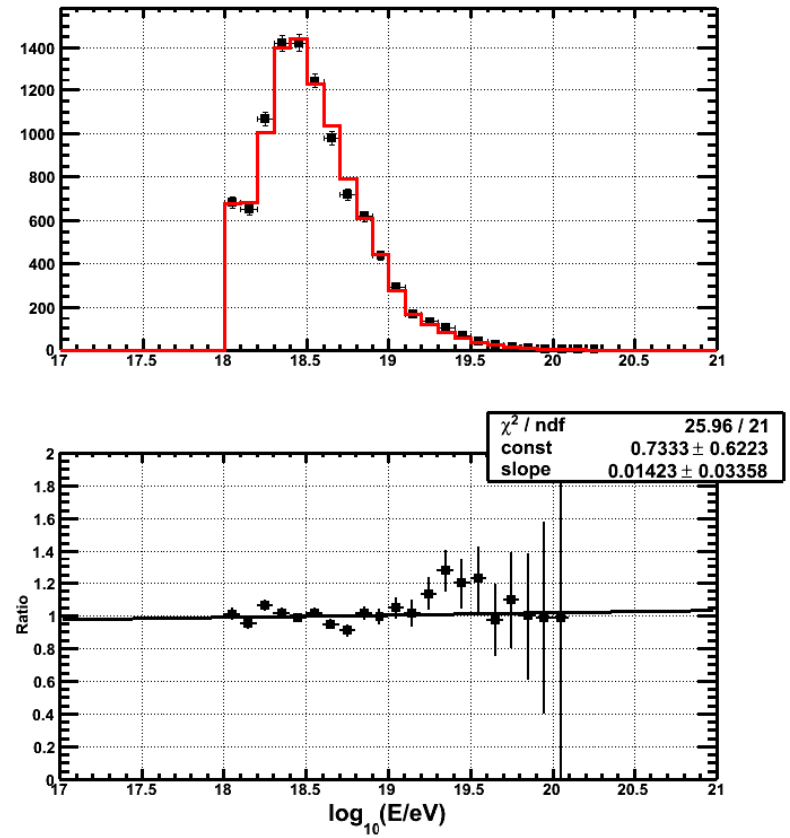
Black: TA SD data

Red: MC

DATA/MC: S800, Energy



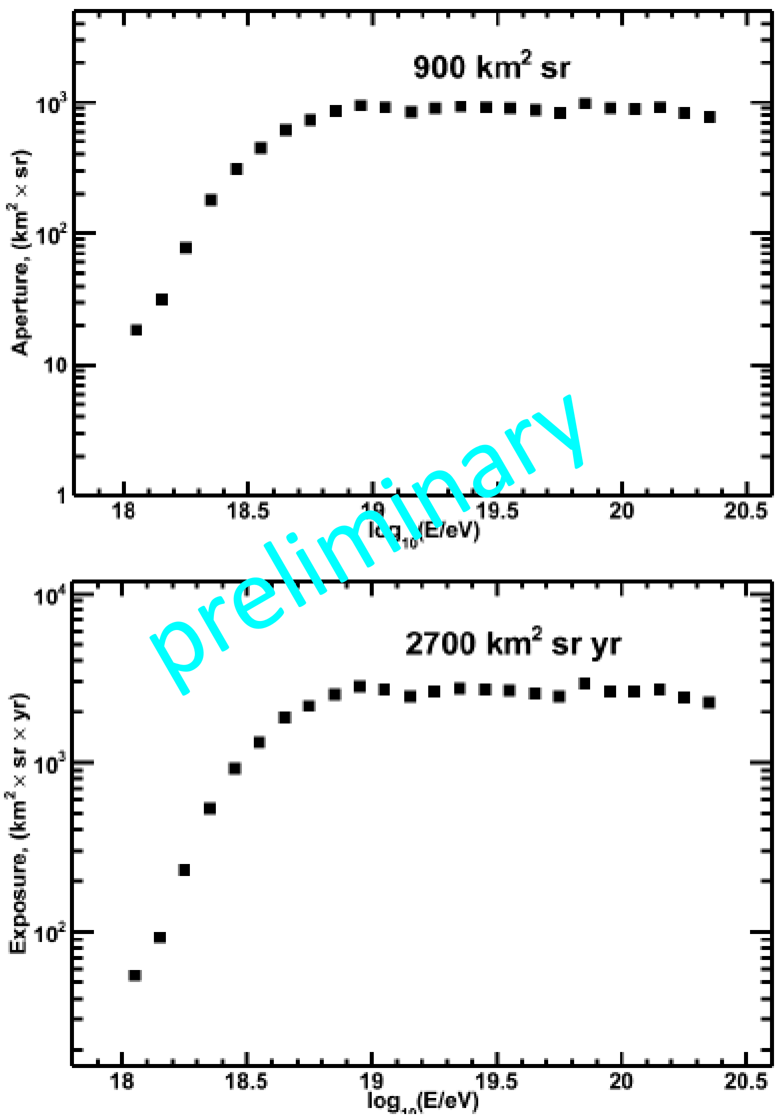
S800



Energy

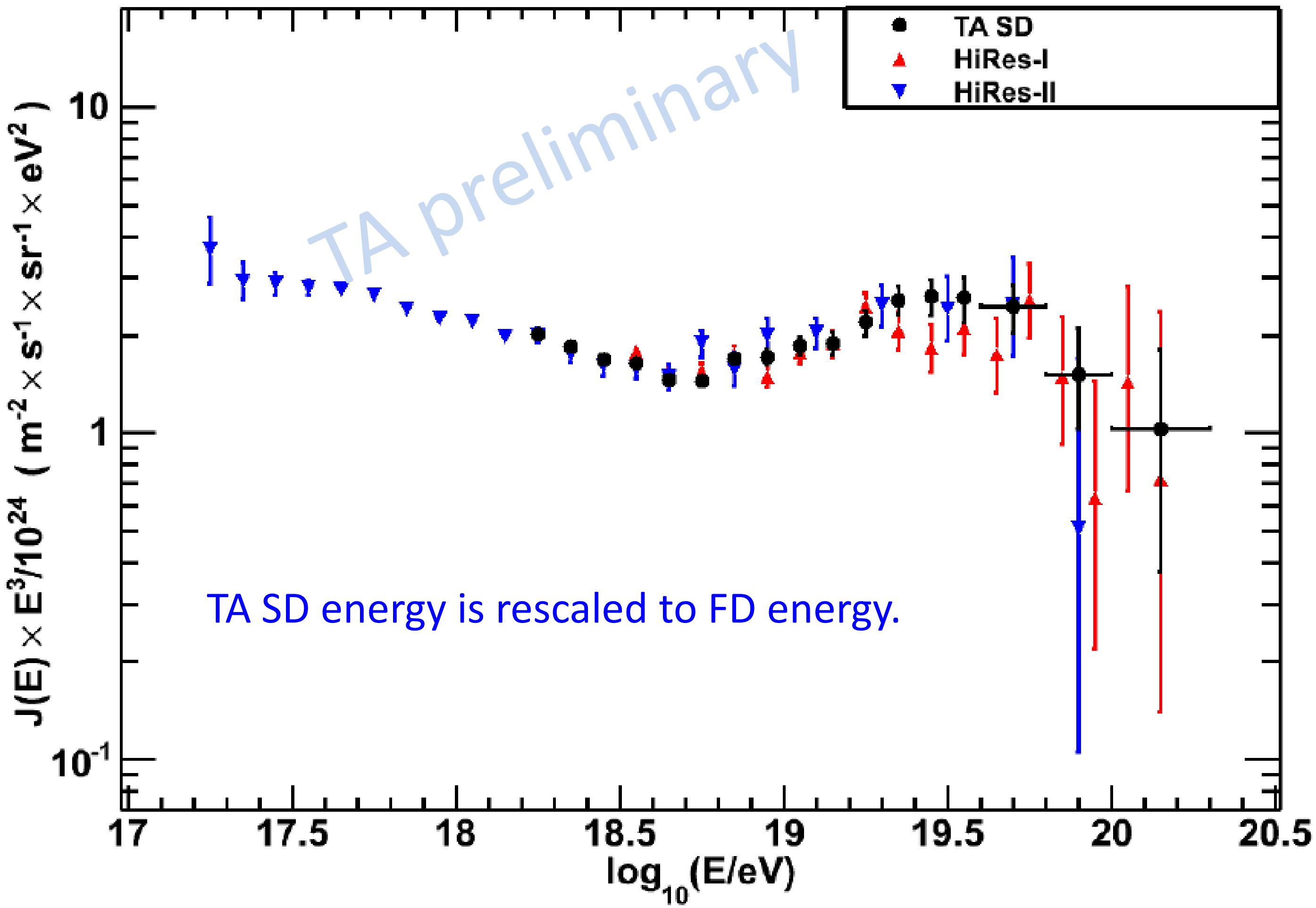
Black: TA SD data
Red: MC

Aperture and Exposure



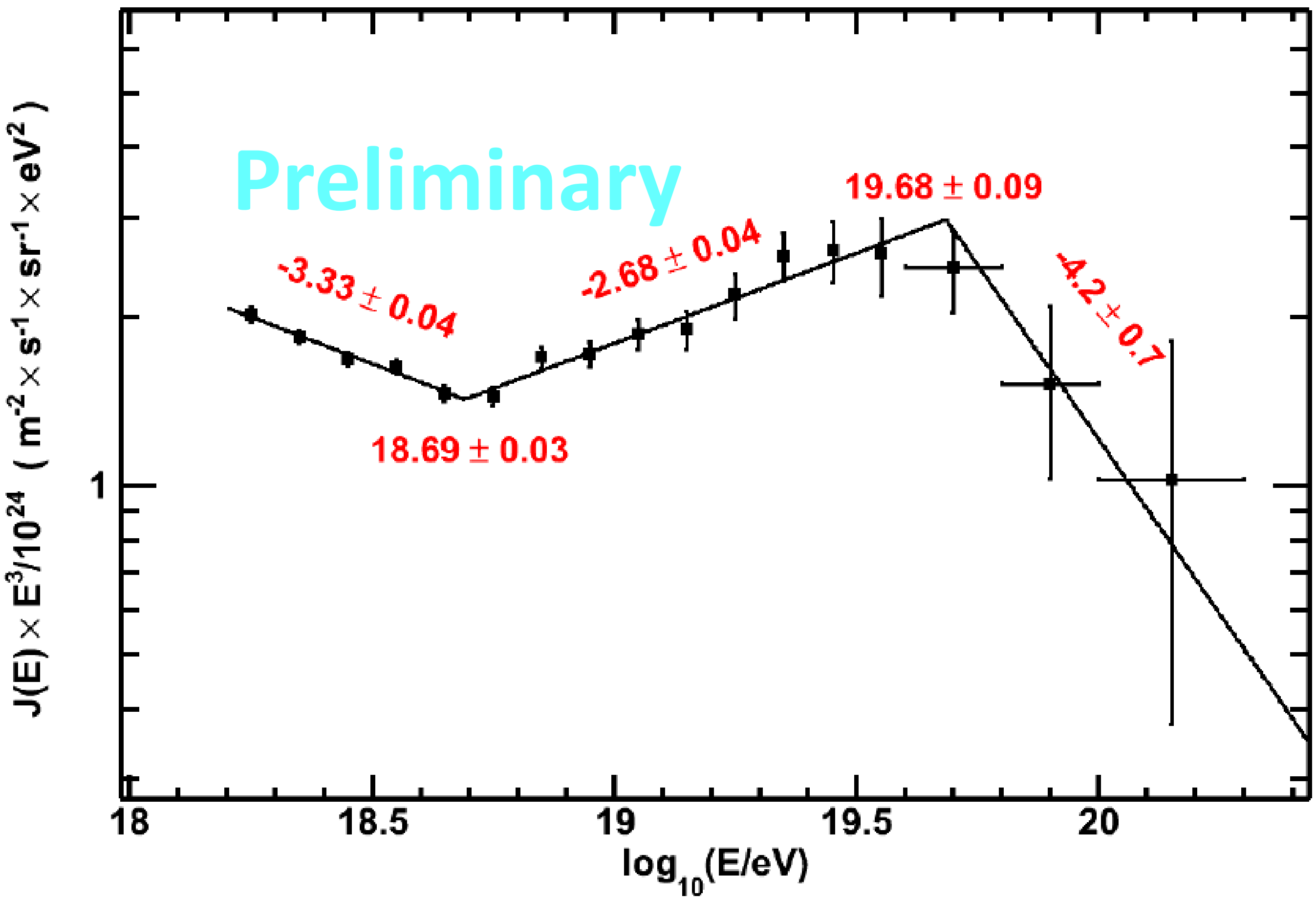
- E > 10^{19} eV
  - Aperture = 900 km^2 sr
  - Exposure = 2700 km^2 sr yr
- Data set
  - 2008/05/11 – 2011/04/25
  - 1080 days ~ 3 years
- GZK effect folded into the MC

TA SD and HiRes Spectra



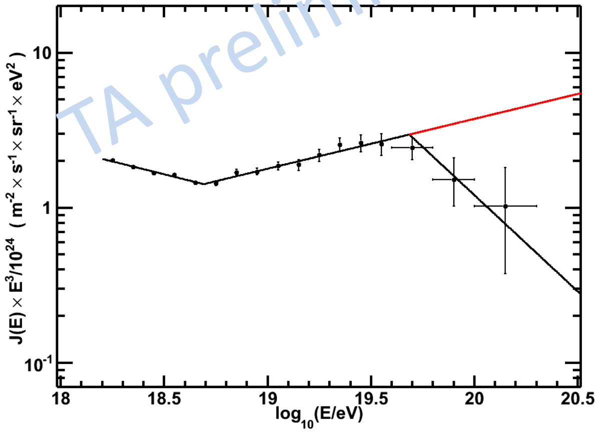
in agreement with HiRes spectra

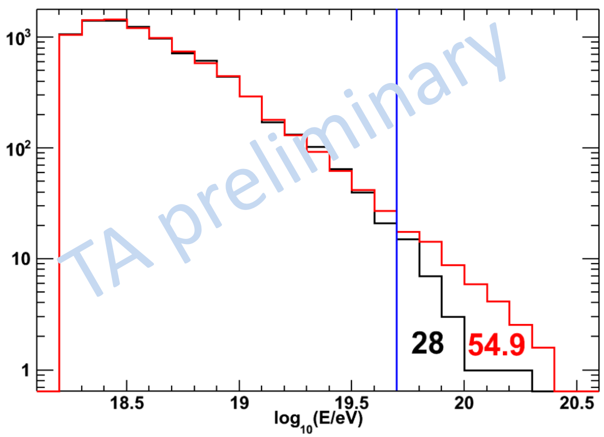
TA SD Spectrum



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 TA SD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}E$ bins after $10^{19.7}$eV bin:
  - N_{EXPECT} = 54.9
  - $N_{OBSERVE}$ = 28

$$\mathrm{PROB} = \sum_{i=0}^{28} \mathrm{Poisson}(\mu = 54.9; i) = 4.75 \times 10^{-5}$$

(3.9σ)

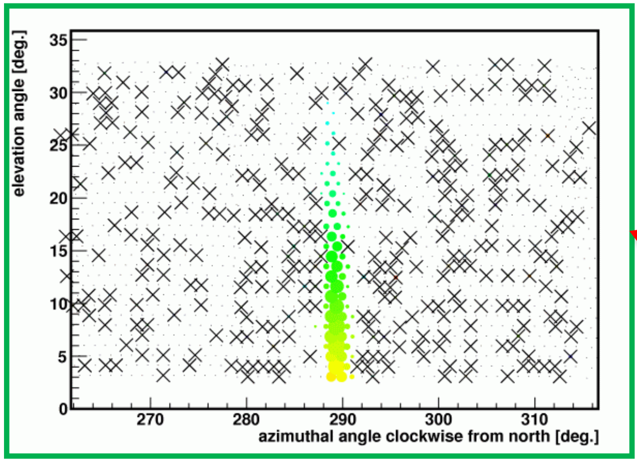
TA SD energy is rescaled to FD energy.

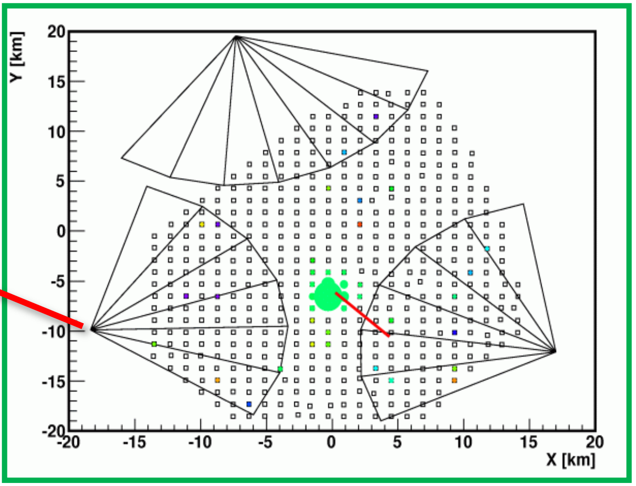
Hybrid Spectrum

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

The example of the Hybrid event
2008/12/30

LR FD station





Hybrid analysis: Data and MC

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

Data:

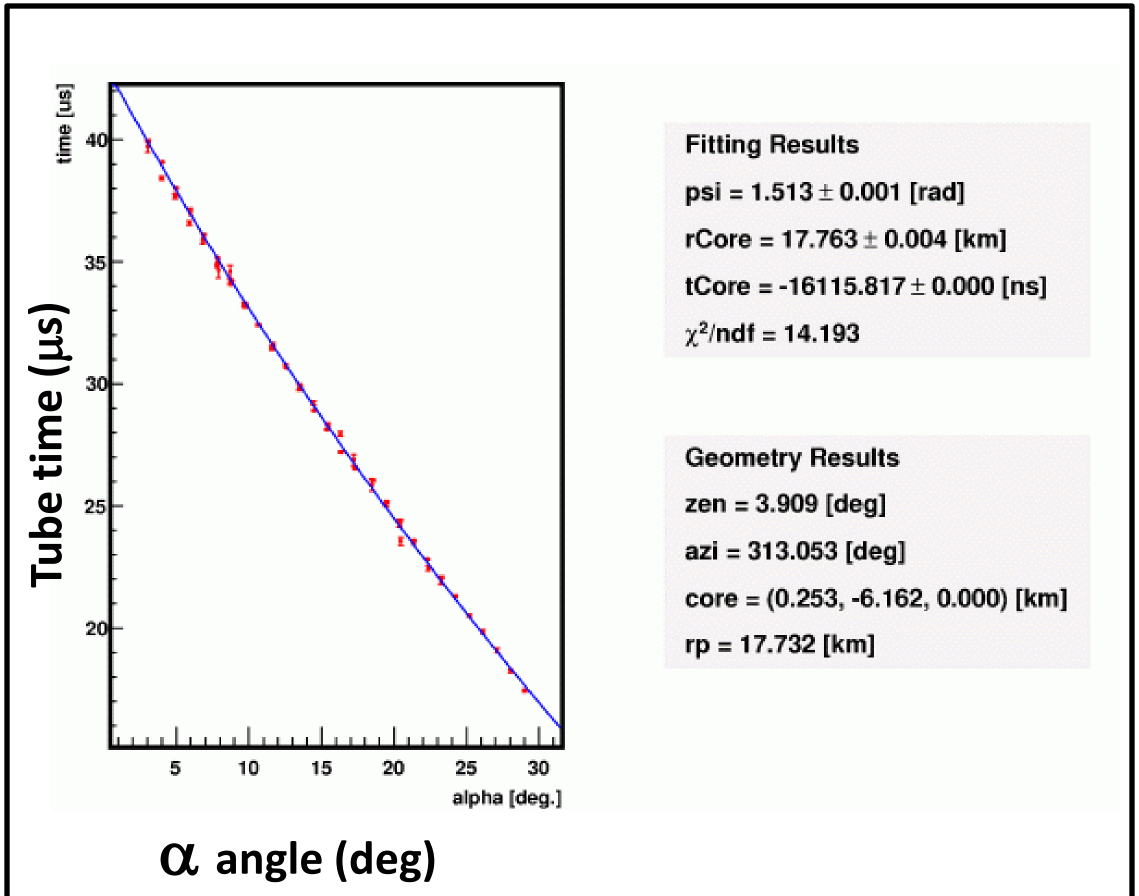
- date: May/27/2008 – Sep/7/2010 (~2.25years)
  - **BR + LR** (new telescopes) with SDs
- Cut condition
  - Xmax has to be observed.
  - Zenith angle < 55degrees

MC:

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

Geometrical reconstruction

FD mono analysis + timing of one SD



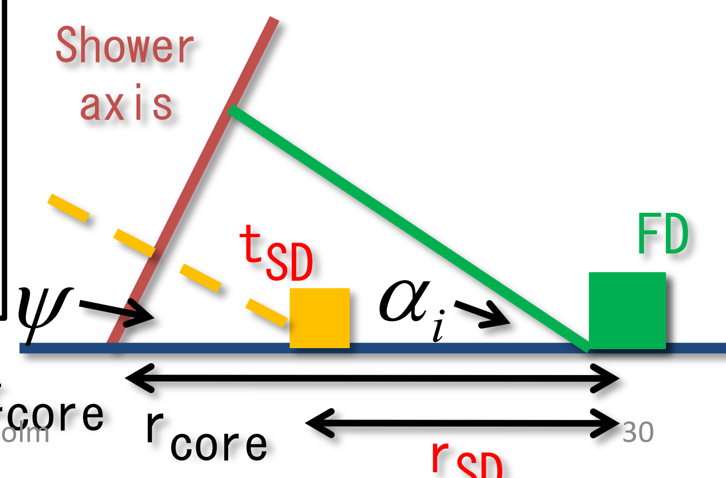
Mono reconstruction

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

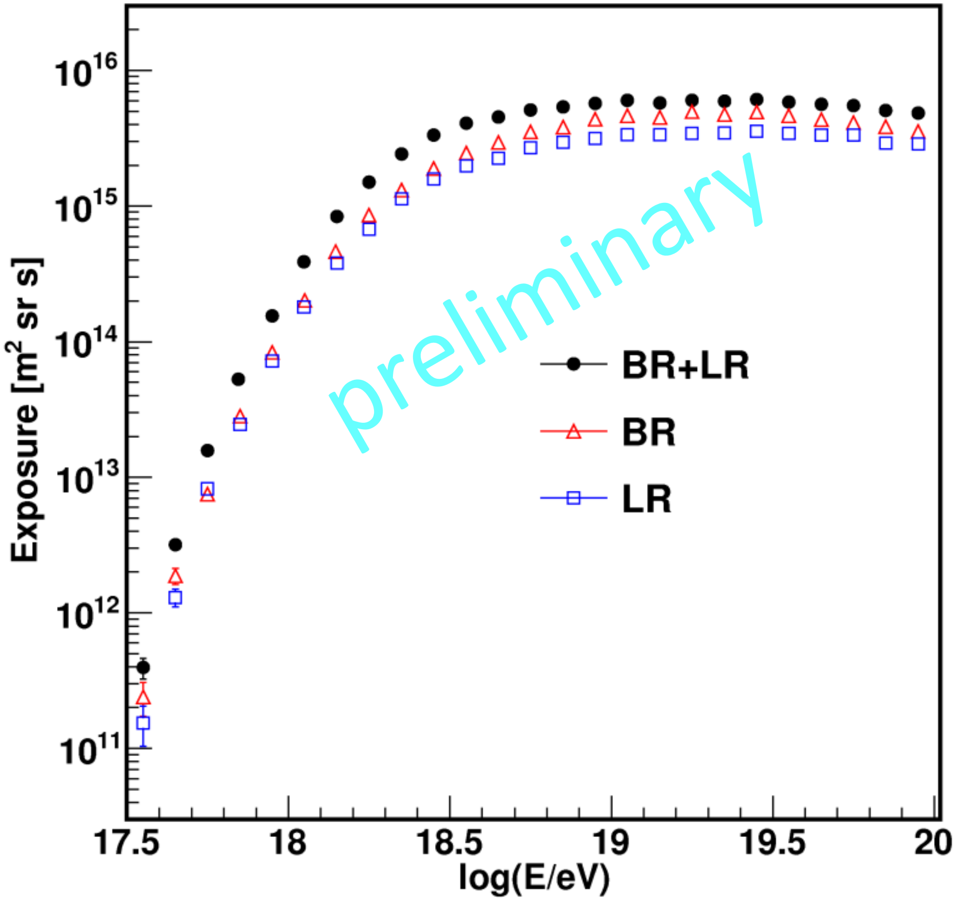
Hybrid reconstruction

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

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



Exposure

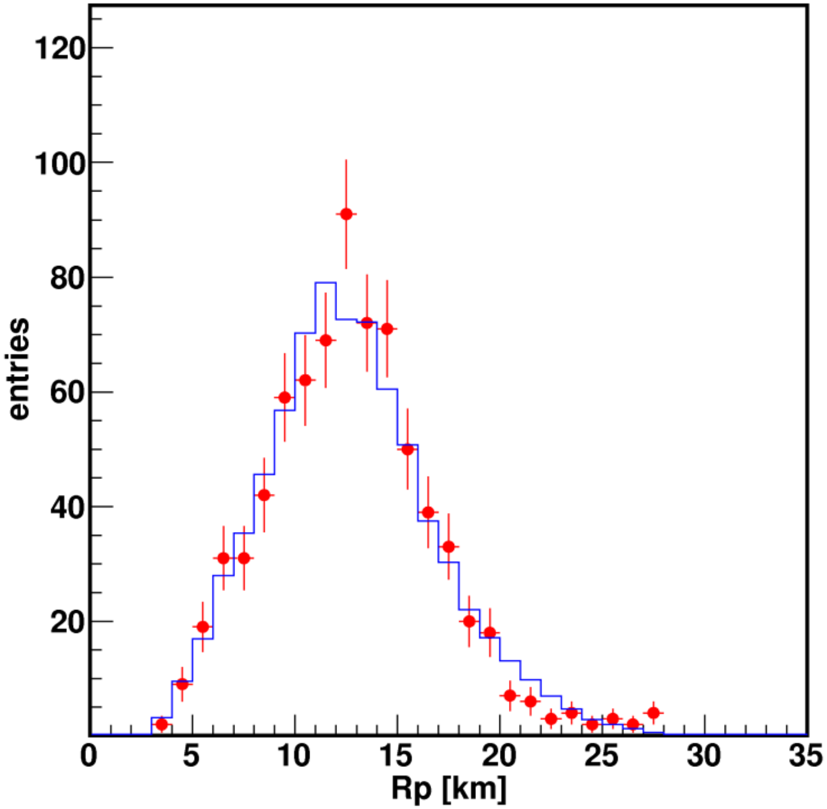


The aperture is calculated from MC simulation.

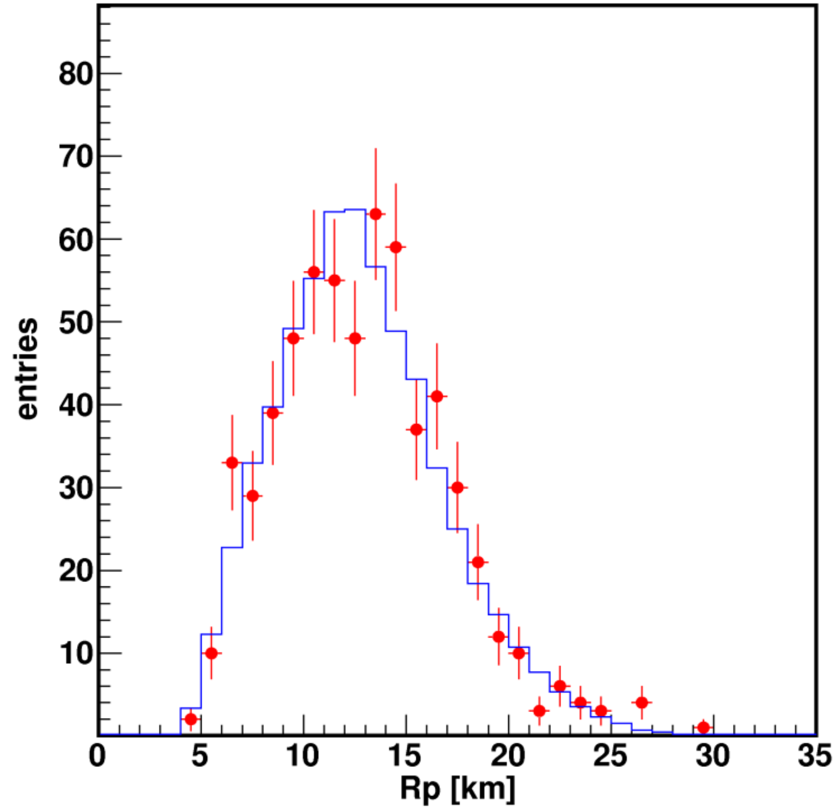
Exposure: ~$6*10^{15}$ m^2 sr s @10^{19}eV

Data/MC comparison impact parameter R_p

BR station



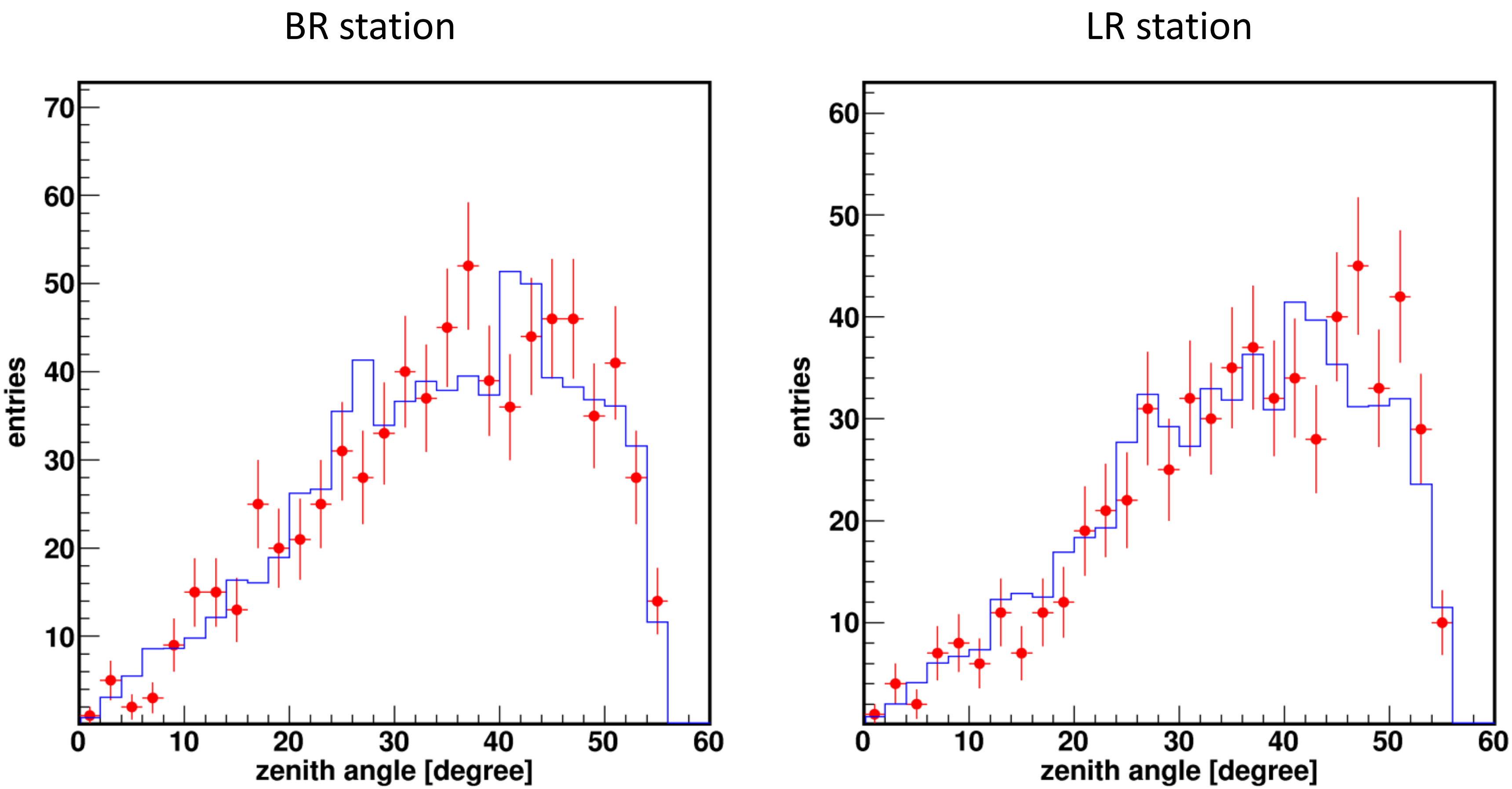
LR station



Red: TA data

Blue: MC

Data/MC comparison
zenith angle θ

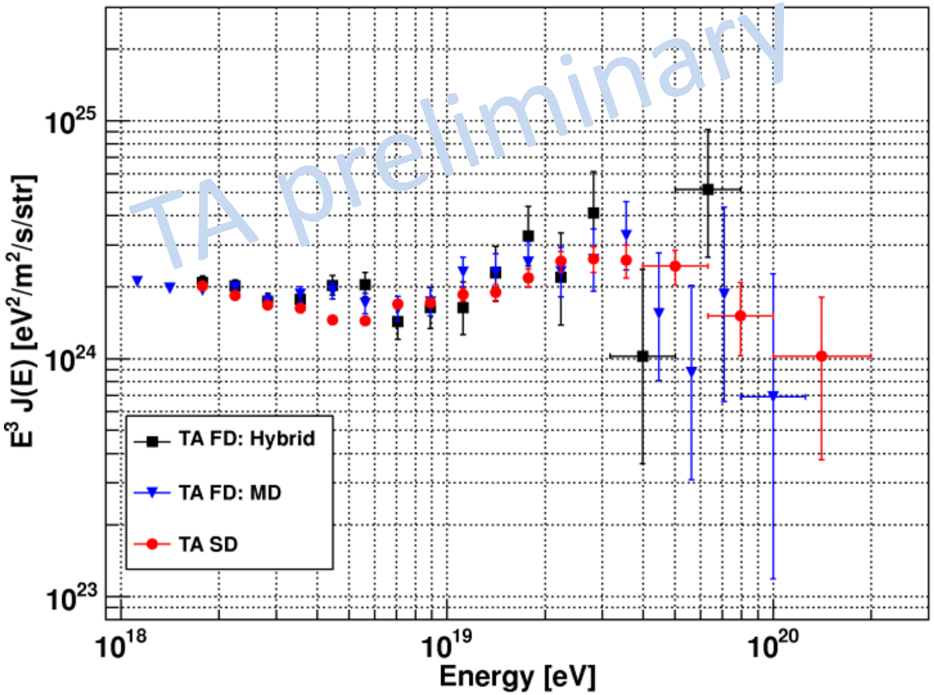


Red: TA data

Blue: MC

Energy spectrum

- Hybrid events at the BR and LR station for TA 2.25 years



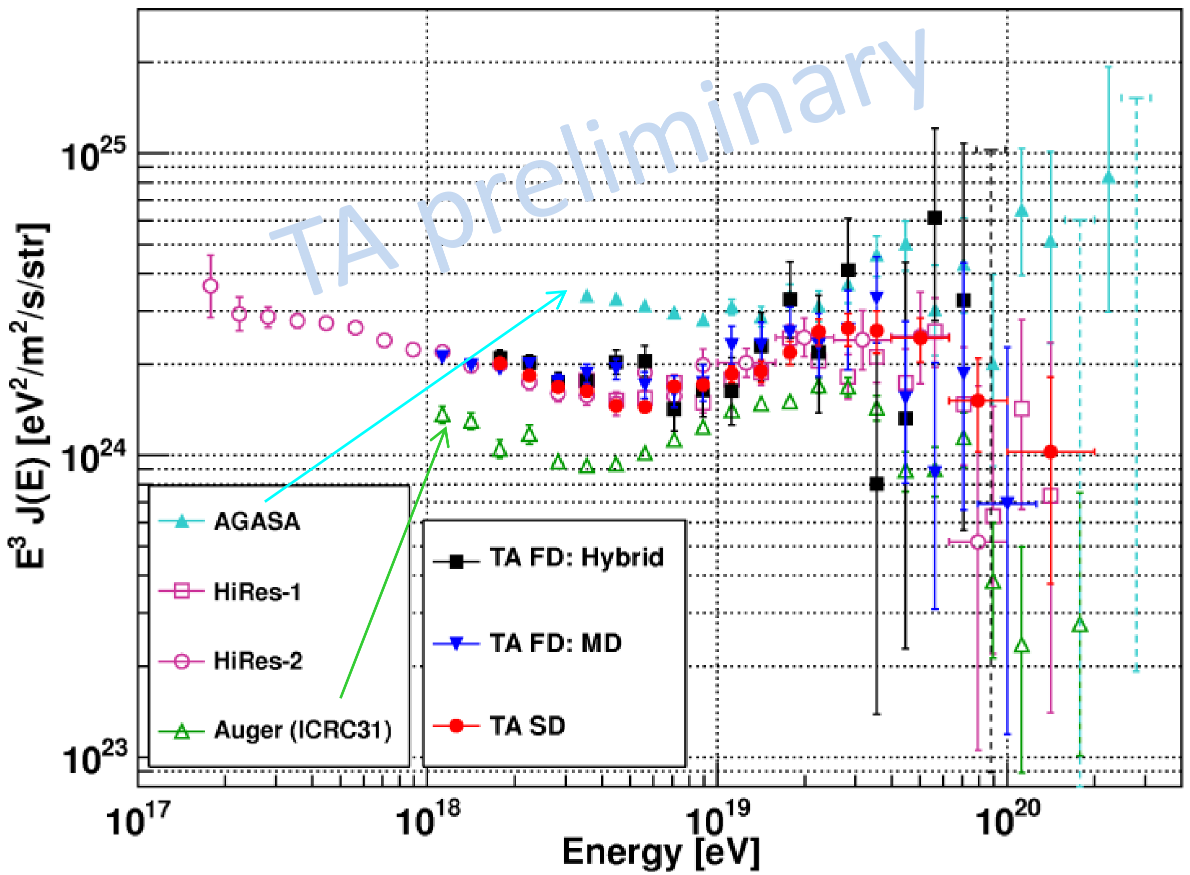
Systematic errors in energy measurement

item	Systematic error
Fluorescence yield	11%
Atmosphere	11%
Calibration	11%
Reconstruction	<12%
Total	23%

TA hybrid spectrum is in agreement with MD mono and SD spectra.

TA, AGASA, Auger, HiRes, AGASA spectra

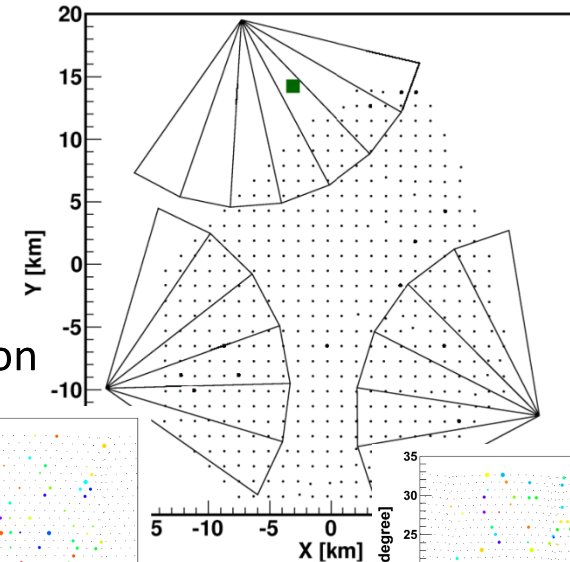
TA SD energy is scaled to FD energy.



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

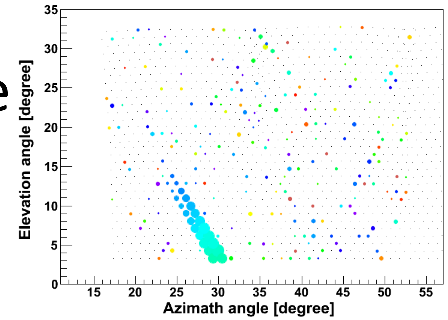
FD stereo composition

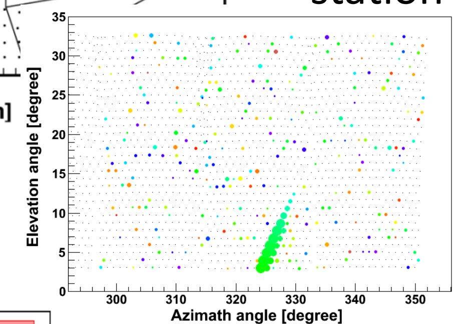
- Measure Xmax for BR/LR FD stereo events
- Create simulated event set
  - Apply the procedure exactly same as with the data



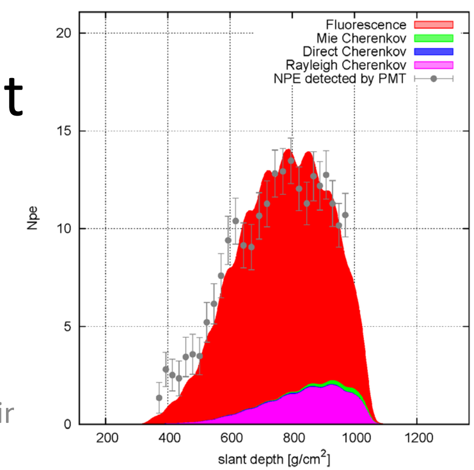
LR FD station

BR FD station

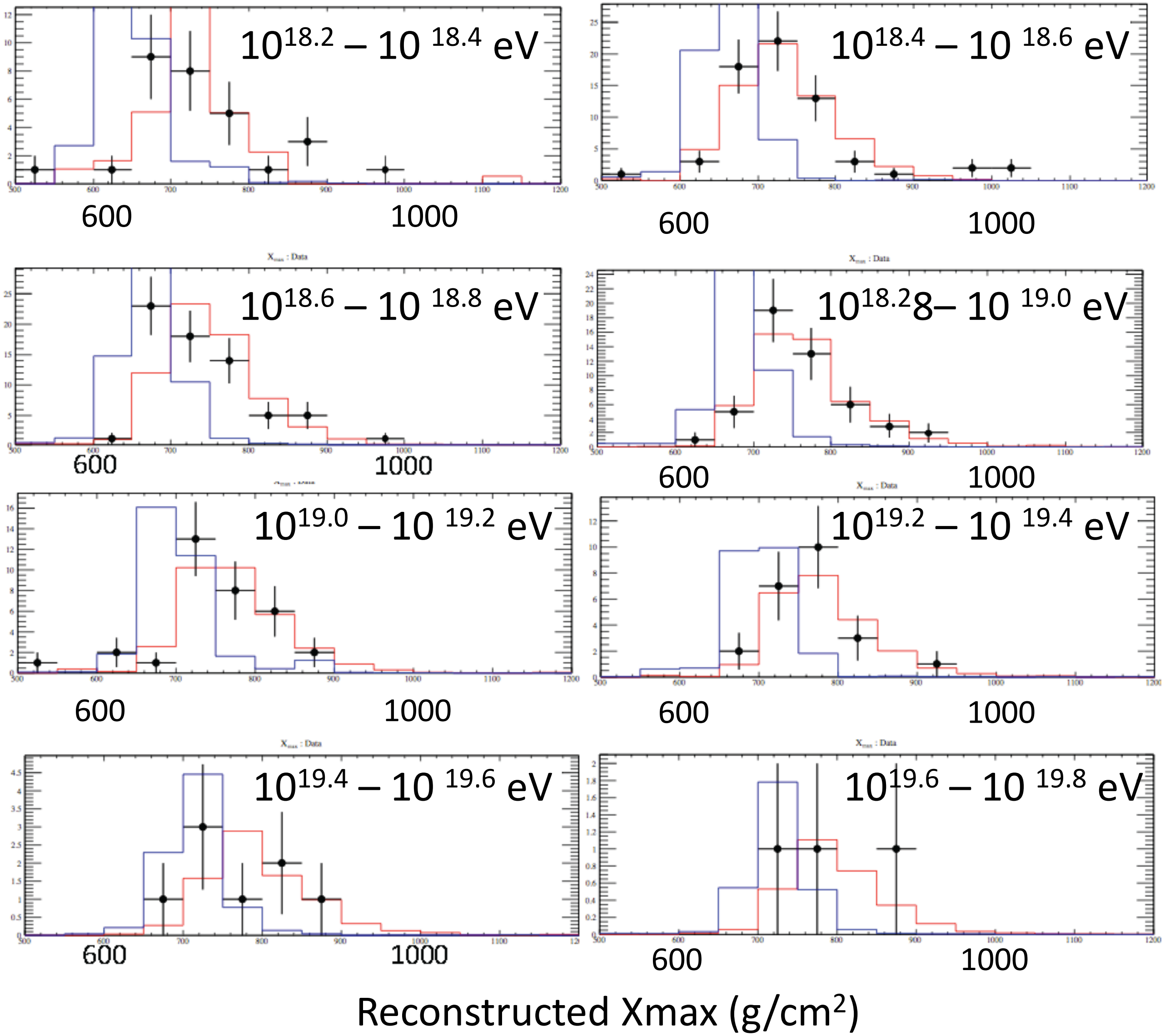




Example of stereo event
2008/09/04
10:51:16



Data/MC comparison of Xmax



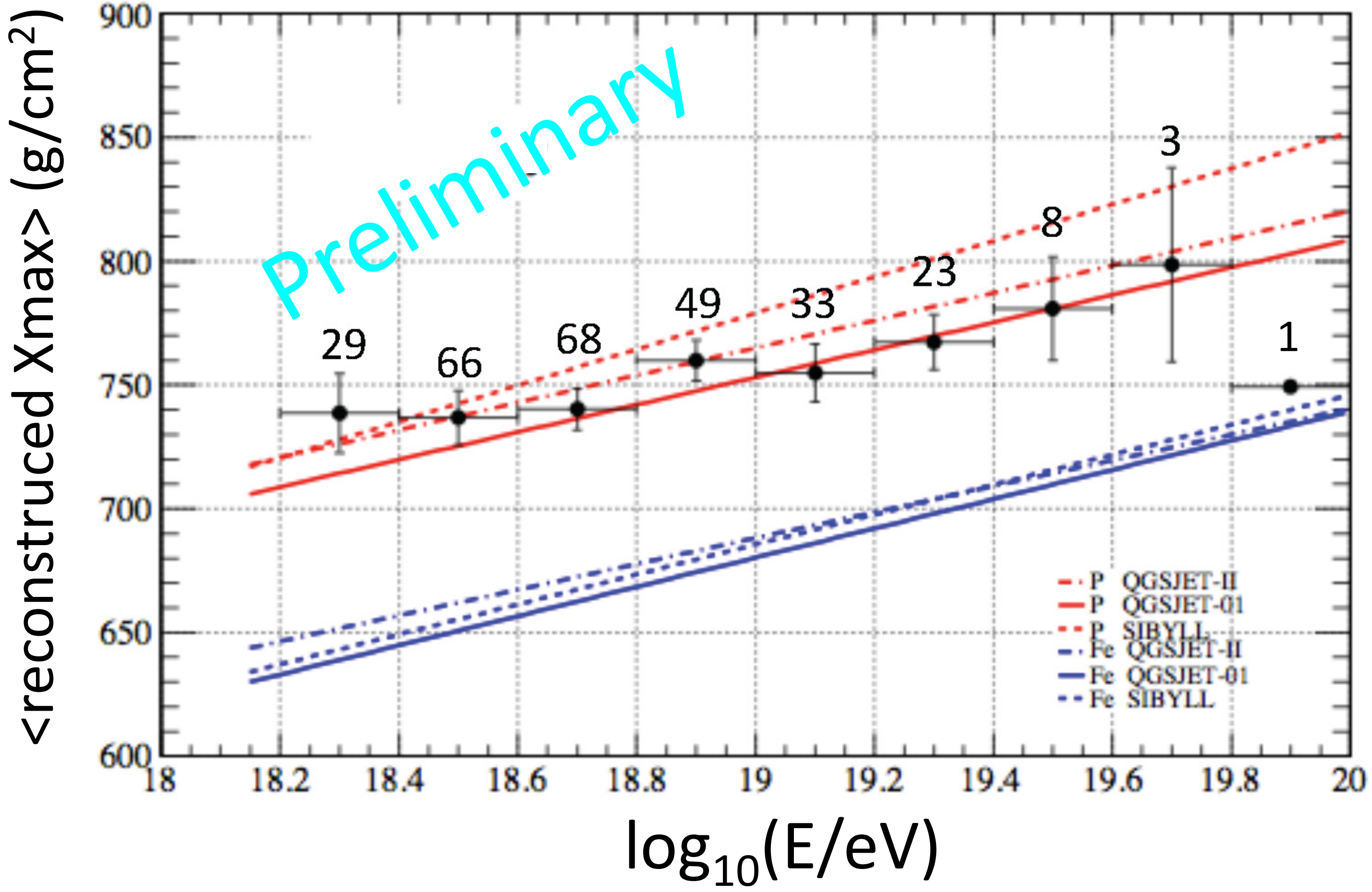
Data points
TA data

Red histogram
QGSJET-II proton

Blue histogram
QGSJET-II Fe

preliminary

<Xmax> vs. logE



Preliminary
<reconstruced Xmax> (g/cm²)
log10(E/eV)
900
850
800
750
700
650
600
18
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20
29
66
68
49
33
23
8
3
1
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL

Arrival direction of UHECRs

- LSS correlation
- AGN correlation
- autocorrelation

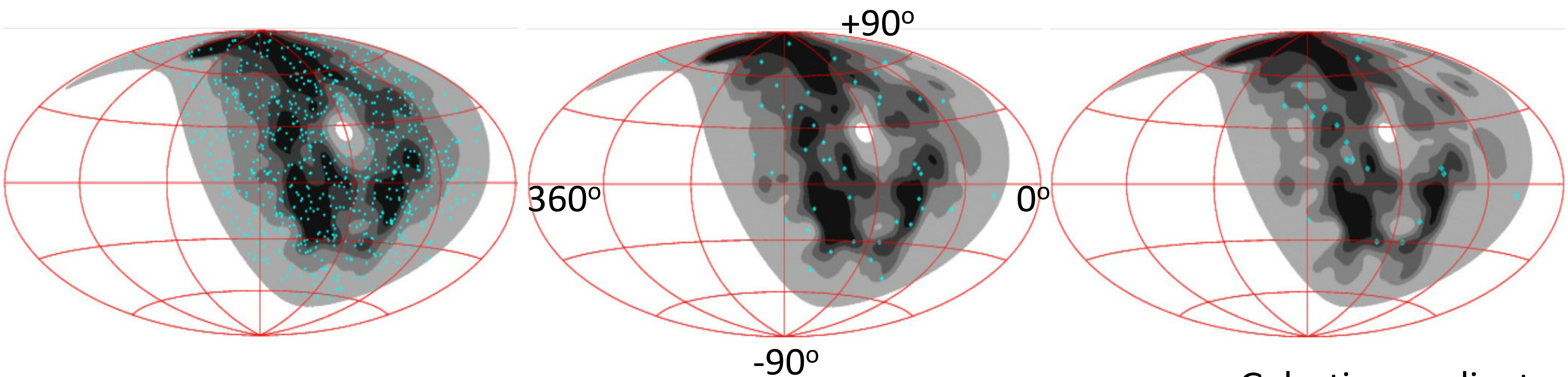
Correlations with LSS

LSS model:

. Galaxies (**2MASS XSCz** catalog, **from 5 Mpc to 250 Mpc**)
. The flux beyond 250 Mpc: uniform
. **Proton** primaries assumed
. All interactions and redshift losses are accounted for

TA SD data (May 2008 to May 2011): light blue points (zenith angle < 45°)

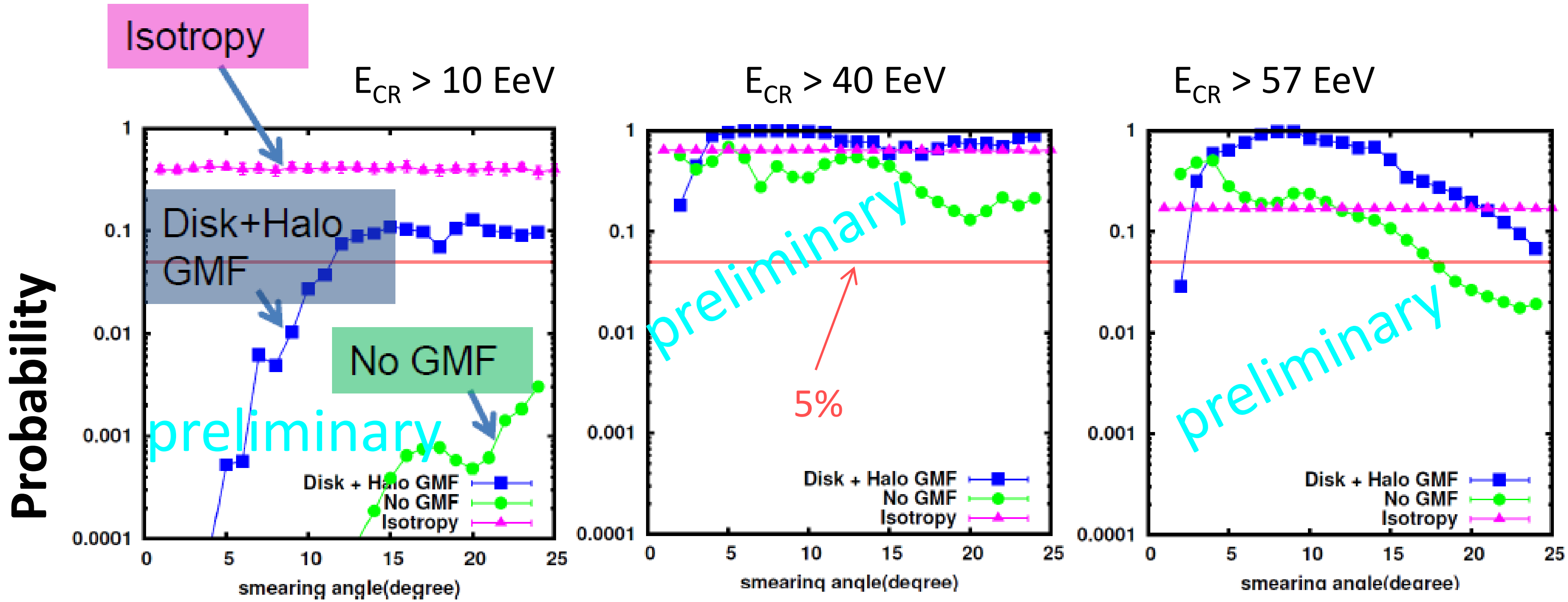
E_{CR}>10 EeV, N_{CR}=854 E_{CR}>40 EeV, N_{CR}=49 E_{CR}>57 EeV, N_{CR}=20



Galactic coordinates

Darker gray region indicates larger flux .
Each region among five regions contains 1/5 of the total flux.

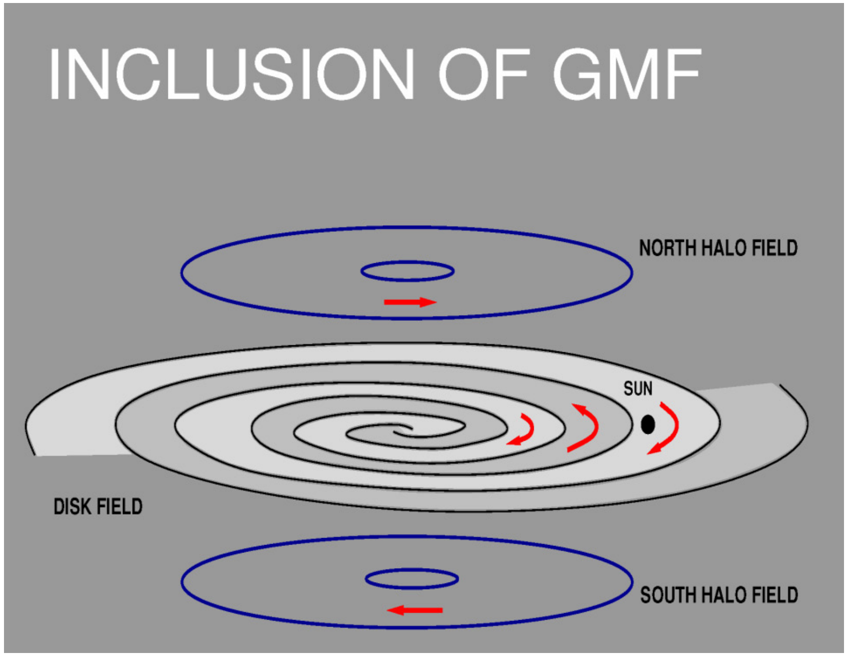
Correlations with LSS



- Data are compatible with LSS model at E_{CR} > 40 EeV and 57 EeV
- With correction for GMF of strong halo component,
  data are compatible with LSS model at E_{CR}>10 EeV.
  the disk component only does not improve.
- Data are compatible with isotropy.

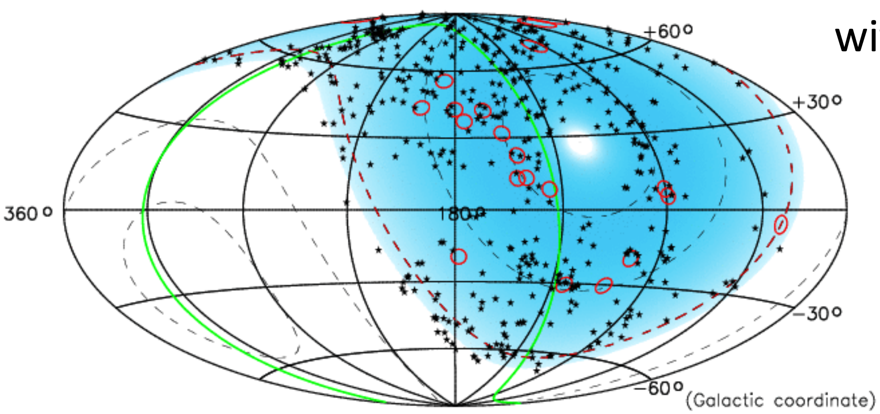
Correlations with LSS
Inclusion of Galactic Magnetic Field (GMF)

- Two-component structure:
  - Antisymmetric halo + symmetric disk field
    - Fits NVSS Rotation Measure (RM) data [Pshirkov et al., to appear in ApJ]

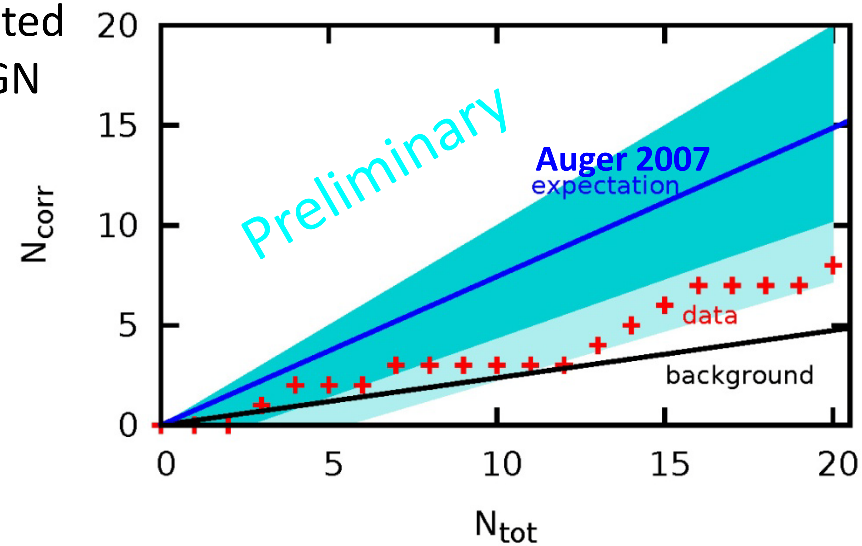


Correlations with AGN

- TA SD data beyond 57 EeV
- Veron catalog 12th edition AGN
  - z<0.018
- Correlations of data with AGN within 3.1°



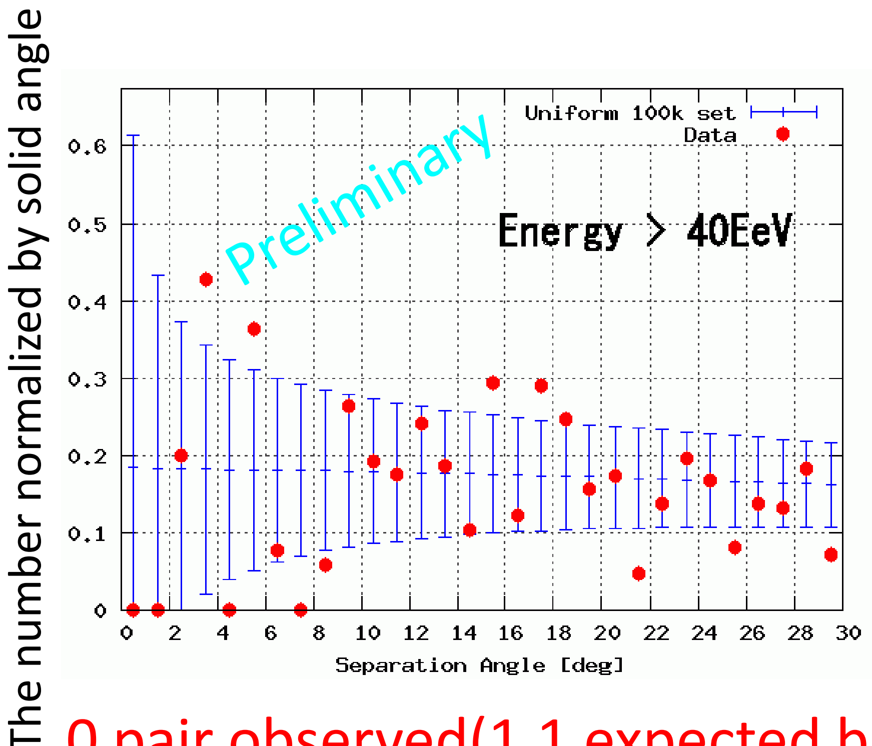
Number of TA data correlated with AGN



Number of TA data

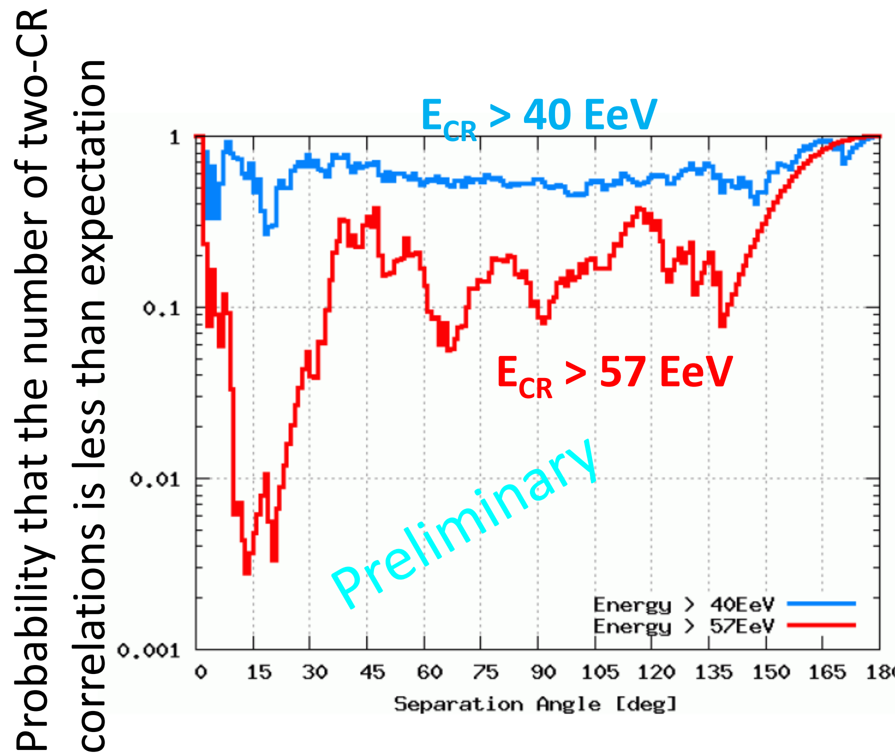
Autocorrelation

- Separation angle θ of two UHECRs above 40 EeV



0 pair observed(1.1 expected bkg) for $\theta < 2.5^{o}$

- Cumulative autocorrealtion



The result is consistent with isotropy.

Summary

- The Telescope Array (TA) is the largest UHECR detector in the northern hemisphere.
  - Hybrid and stereo observation by SD (a la AGASA: plastic scintillator) and FD (a la HiRes: new FDs and refurbished HiRes-I to TA)
  - The SD array and FDs are operating with excellent reliability.
  - End-to-end absolute energy calibration FD with ELS in the near future.
- The SD, FD mono, stereo, and hybrid analyses are being performed.
- The results of spectrum, composition, and arrival directions from TA are presented.
  - More will come at the ICRC in Beijing.