

Results from the Telescope Array Experiment

Contents

- FD mono spectrum
- Hybrid spectrum
- SD spectrum
- Mass composition
- AGN correlation
- Photon search

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for the Telescope Array Collaboration

The Telescope Array Collaboration

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

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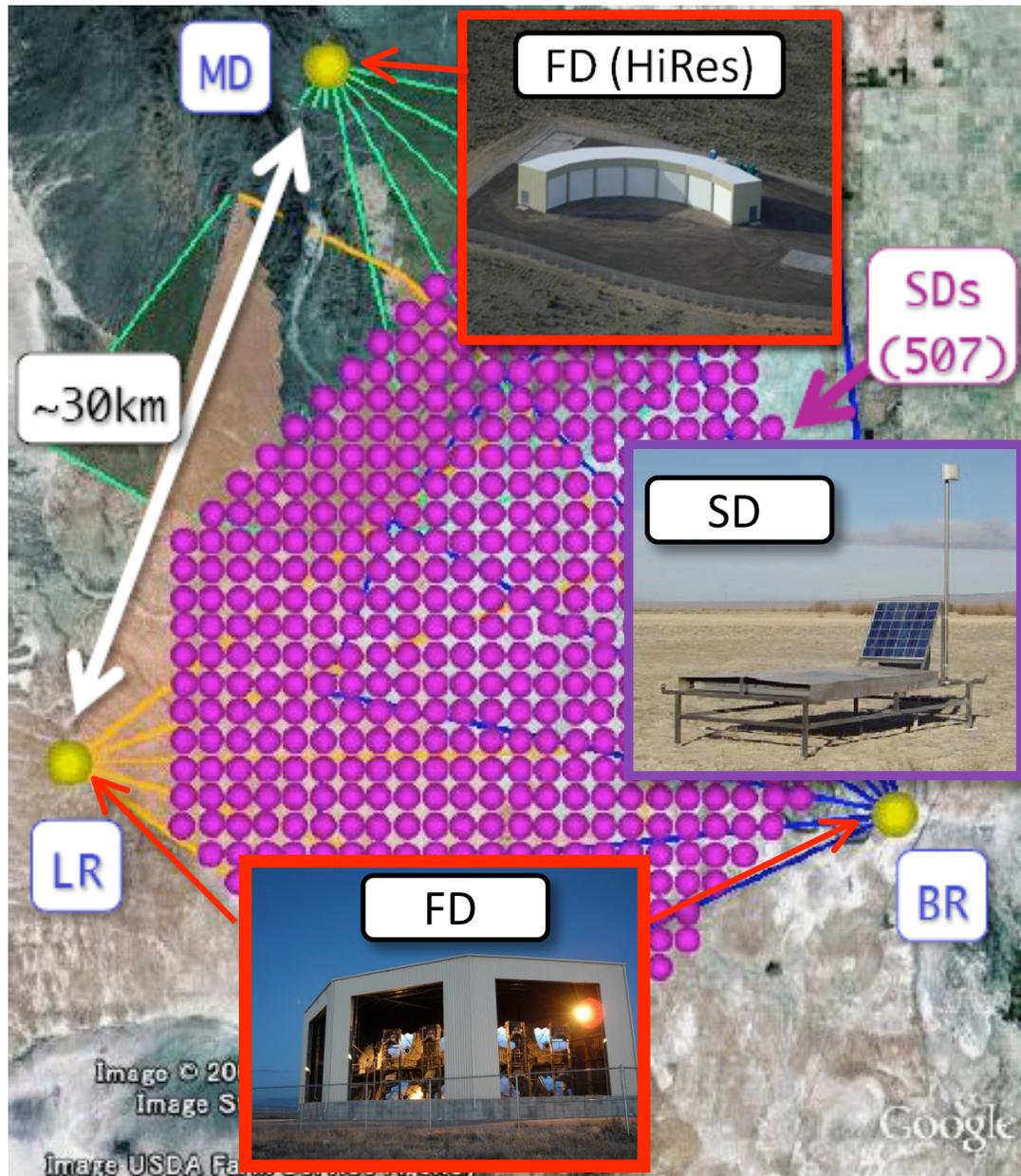
²³Kochi University, Kochi, Kochi, Japan

²⁴Hiroshima City University, Hiroshima, Hiroshima, Japan

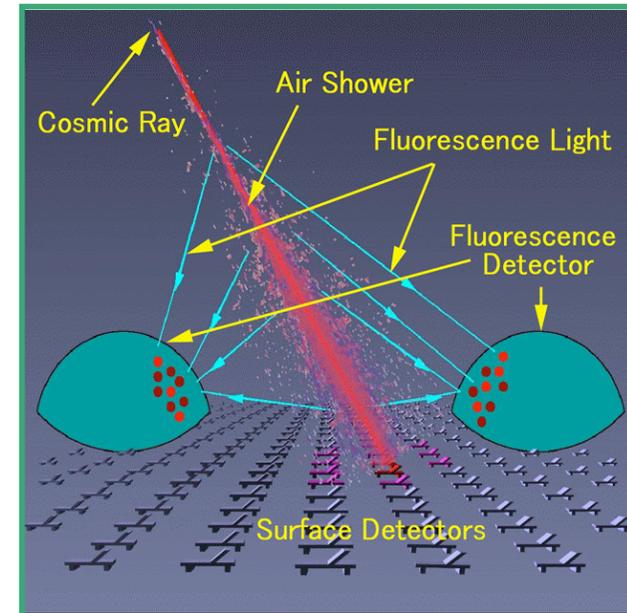
²⁵National Institute of Radiological Science, Chiba, Chiba, Japan

²⁶Ehime University, Matsuyama, Ehime, Japan

Telescope Array Experiment



- Desert in Utah, US (1400m a.s.l.)
 - 507 Surface Detectors (SDs)
 - 1.2km spacing
 - Two layer of plastic scintillator, 3m², 1.2cm thickness
 - 3 Fluorescence Detectors (FDs)
 - Middle Drume (MD) station is transferred from HiRes.
- FD observation : from Nov/2007
- SD observation : from Mar/2008

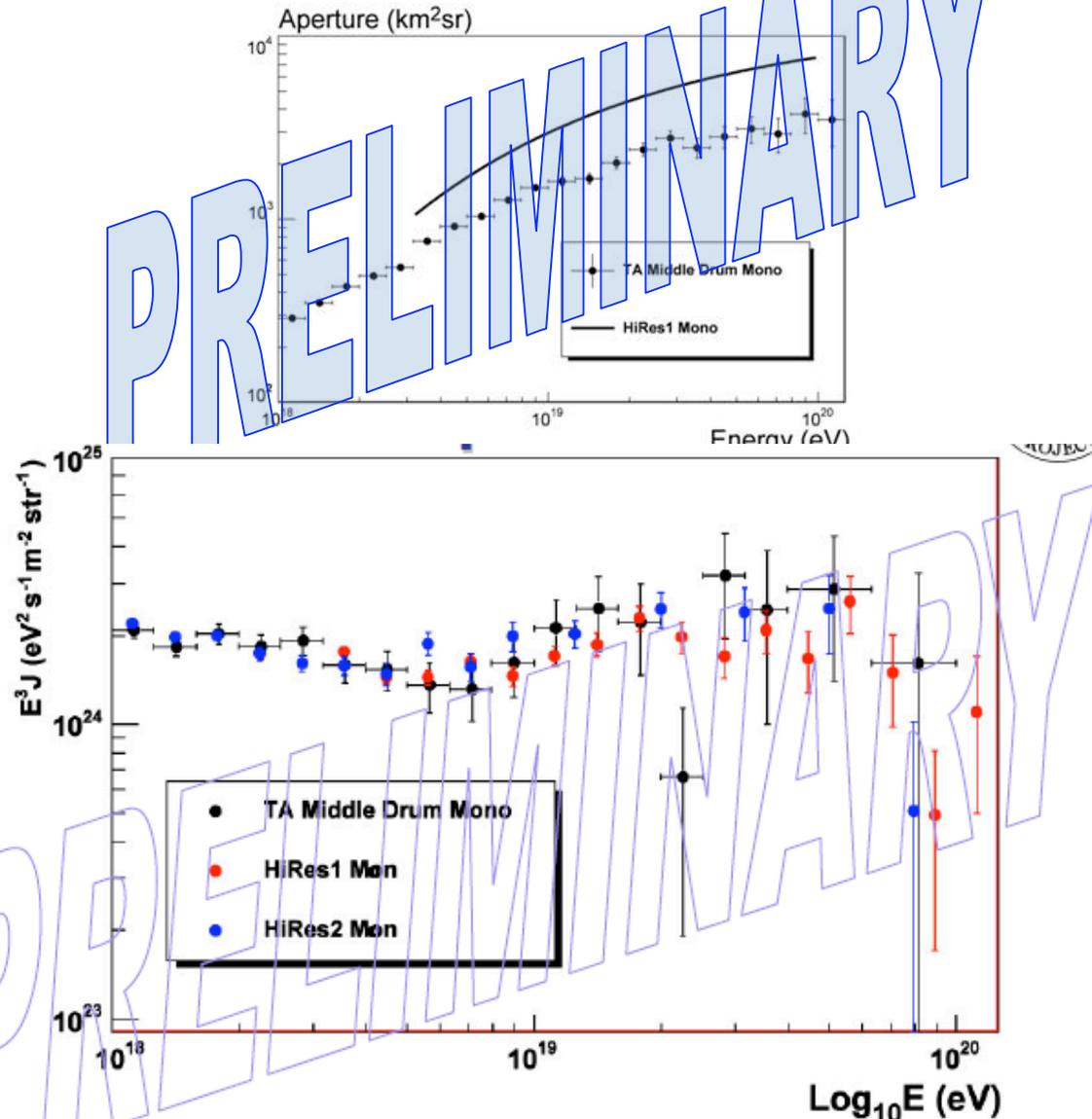


Energy Spectra

Energy Spectra (FD monocular on MD station)

Monocular Energy Spectrum from Middle Drum (MD) Detector

- 14 refurbish HiRes-1 telescopes
- TAMD mono processing is identical to HiRes-1 monocular data analysis
 - Same program set, event selection, cuts
 - Using the same “average” atmospheric model (aerosol VAOD=0.04)
- Differences
 - telescope location and pointing directions
 - Thresholds (~20% lower than HiRes-1)
- **Preliminary MD spectrum in good agreement with HiRes.**



Spectrum from Hybrid analysis: Overview

- Geometry: Hybrid
- Energy: FD

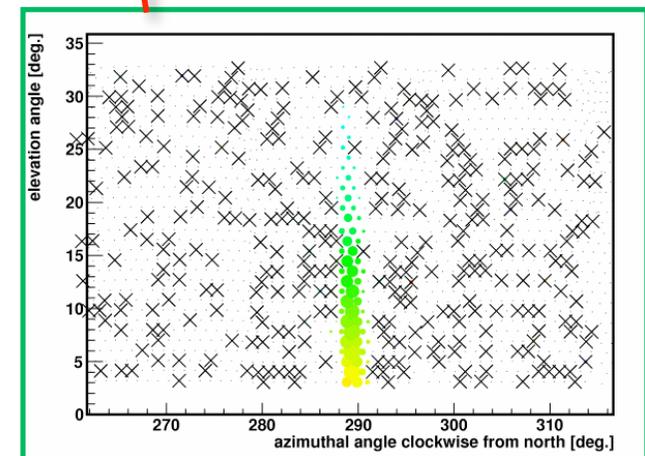
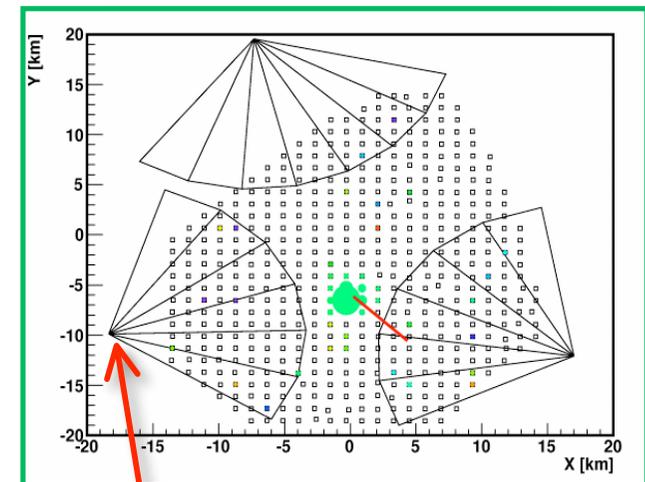
Data:

- date: May/27/2008 - Sep/28/2009 (~1.5years)
 - BR + LR (new telescopes) with SDs
 - Good weather days
 - 1978 events (FD-SD timing coincidence $< 200\mu\text{s}$)
- Cut condition
 - Xmax has to be observed.
 - Zenith angle is less than 45degrees

MC:

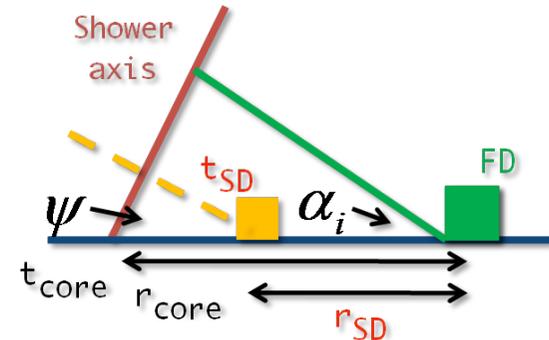
- Air shower:
 - COSMOS, proton, QGSJET-II
 - Slope: -3.1
 - Isotropic distribution
- Detector :
 - All of calibration constant with time dependence
 - Simulate trigger, front-end electronics, and DAQ
- Aperture / Exposure

The example of the Hybrid event
2008/12/30



Reconstruction for Hybrid events Geometry

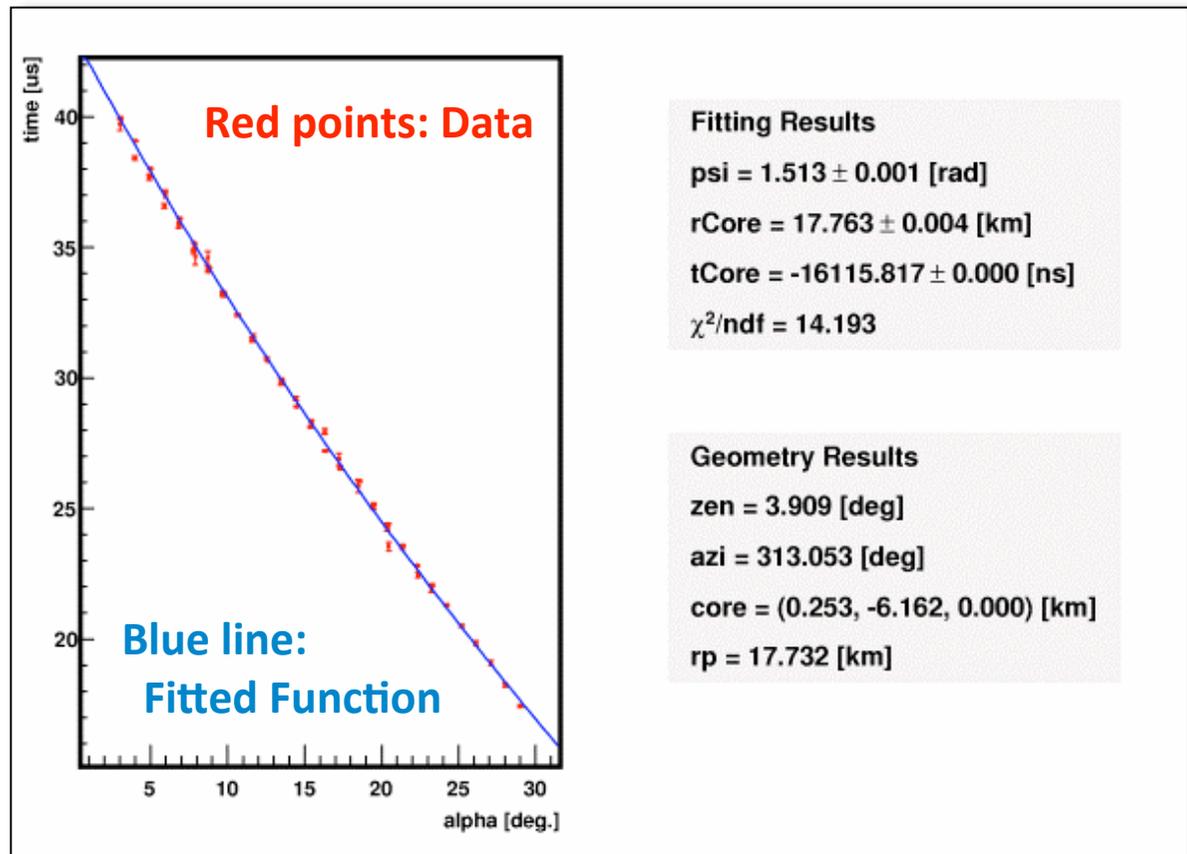
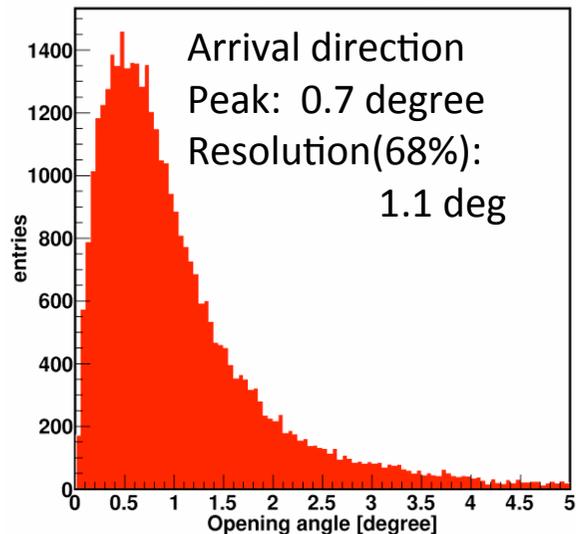
- Geometry is determined by **Hybrid analysis**
 - Traditional analysis of the mono-reconstruction with timing of one SD



Hybrid reconstruction

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

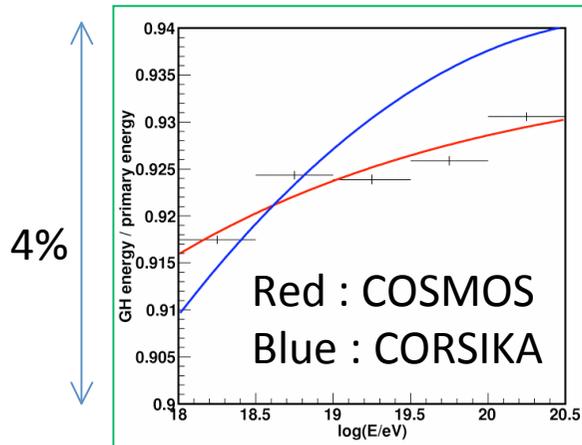
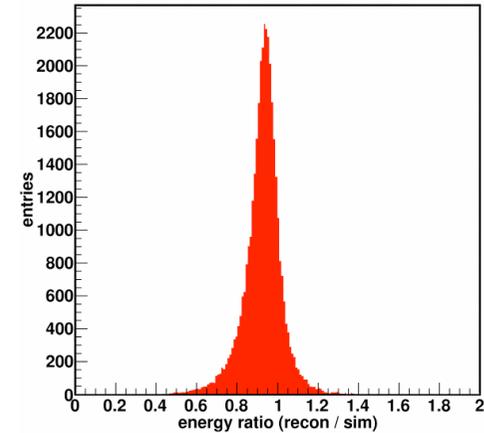
$$t_{core} = t_{SD} + \frac{1}{c} (r_{core} - r_{SD}) \cos \psi$$



Reconstruction for Hybrid events: Primary Energy

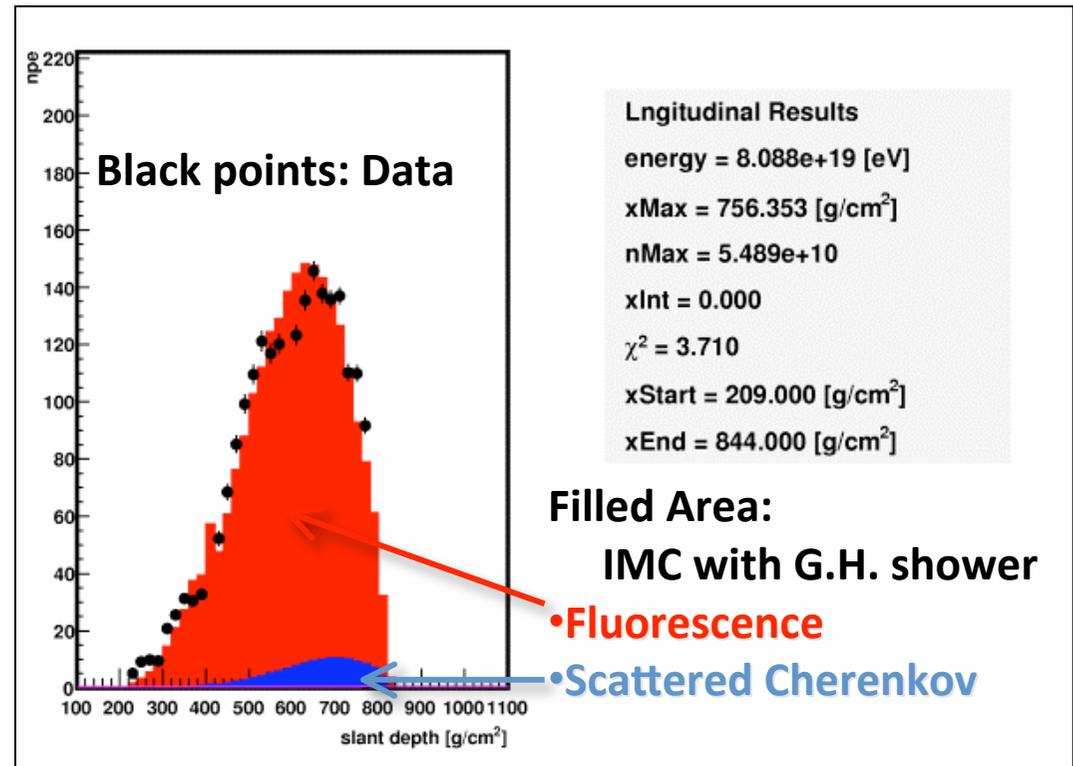
Energy Resolution: 8%

- Primary energy is determined by **FD**
 - **Inverse Monte Carlo Method** (IMC) with **G.H. shower**
 - Fluorescence yield:
 - Absolute: Kakimoto, Spectrum: FLASH
 - Cherenkov lights: **Nerling**
 - Measured atmosphere by LIDAR / Radiosonde
 - Integration of fitted G.H. function as a calorimetric energy
 - Correction of Missing energy from MC



Missing energy: ~8%

- Difference b/w primary energy and Integration of fitted G.H. function.
- Considered with the difference of shower shape b/w G.H. and COSMOS.



Longitudinal Results

energy = 8.088×10^{19} [eV]

xMax = 756.353 [g/cm²]

nMax = 5.489×10^{10}

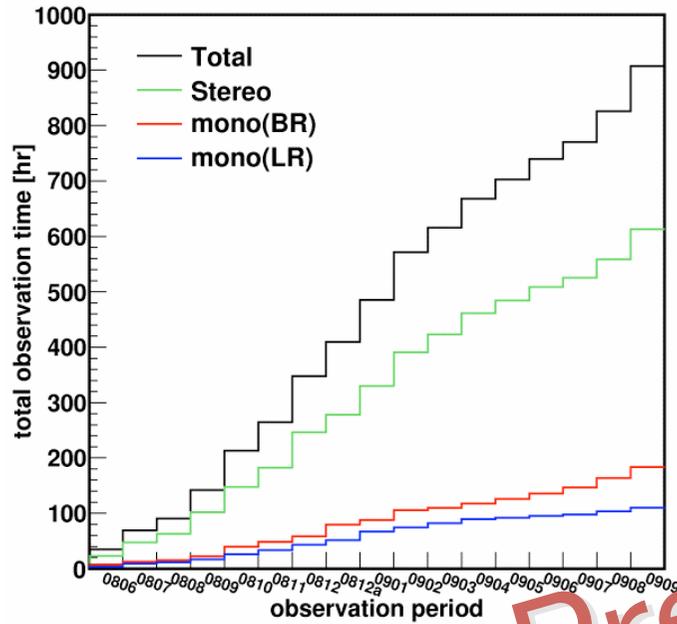
xInt = 0.000

$\chi^2 = 3.710$

xStart = 209.000 [g/cm²]

xEnd = 844.000 [g/cm²]

Exposure, # of events

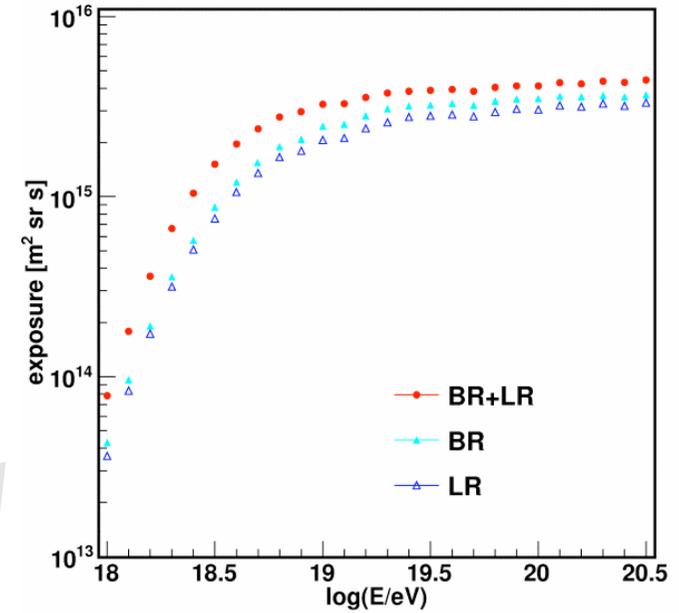


Observation time:

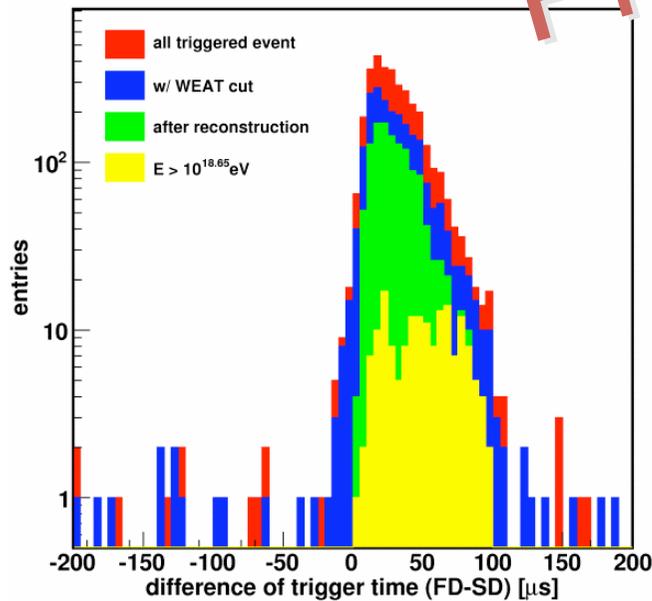
906.8hr

Exposure:

$\sim 3 \cdot 10^{15} \text{ m}^2 \text{ sr s}$



Preliminary

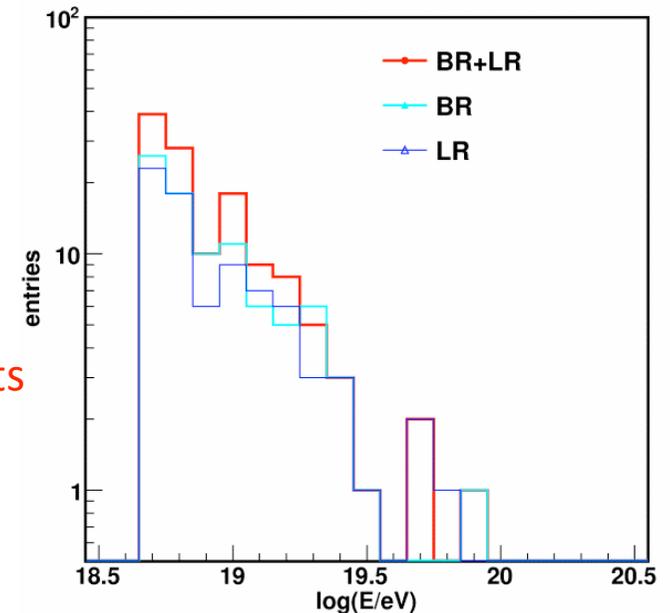


Hybrid event search:

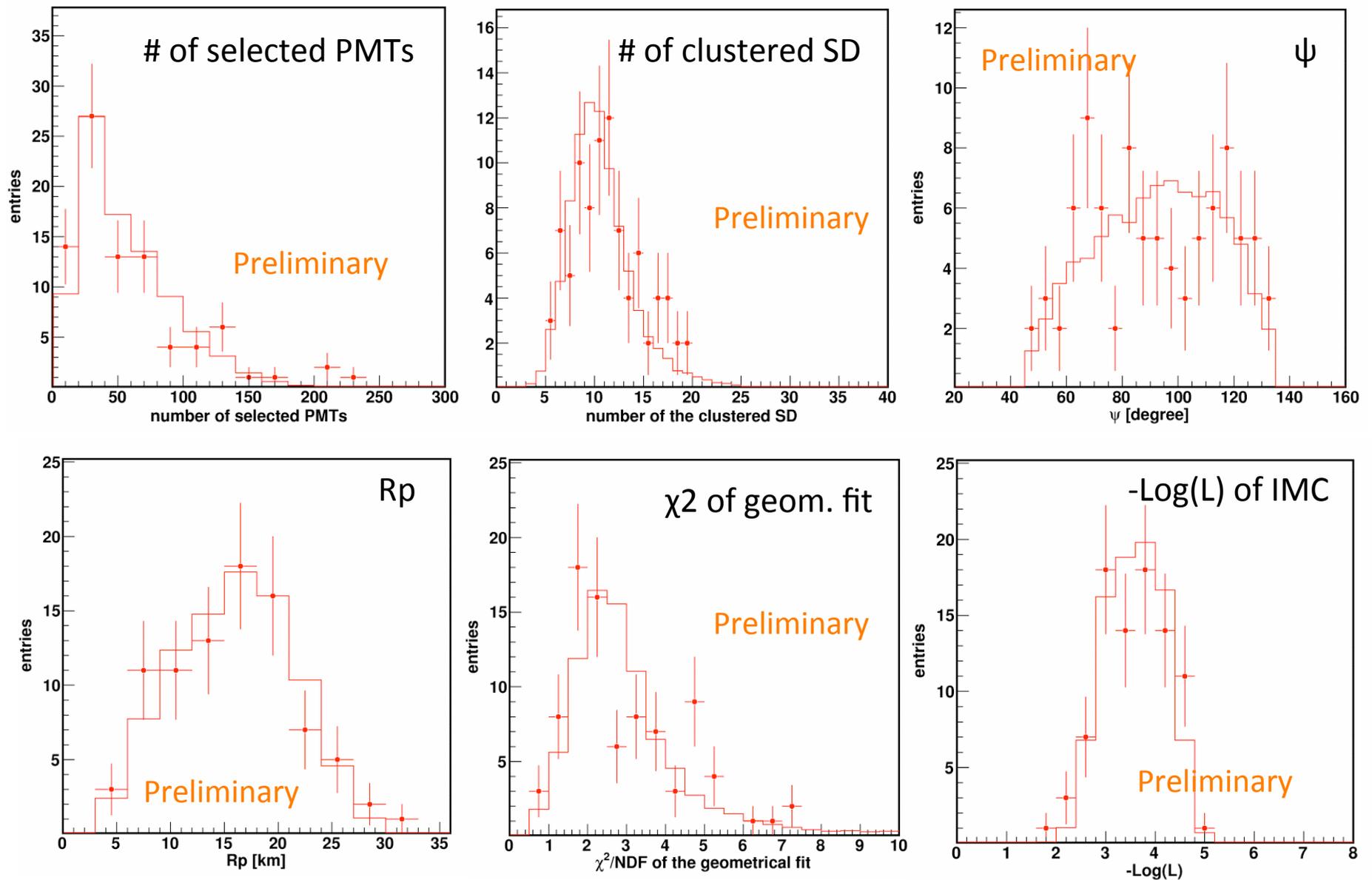
- Coincidence of trigger times (<200µs)
- 1978 events

After cut: 124 events

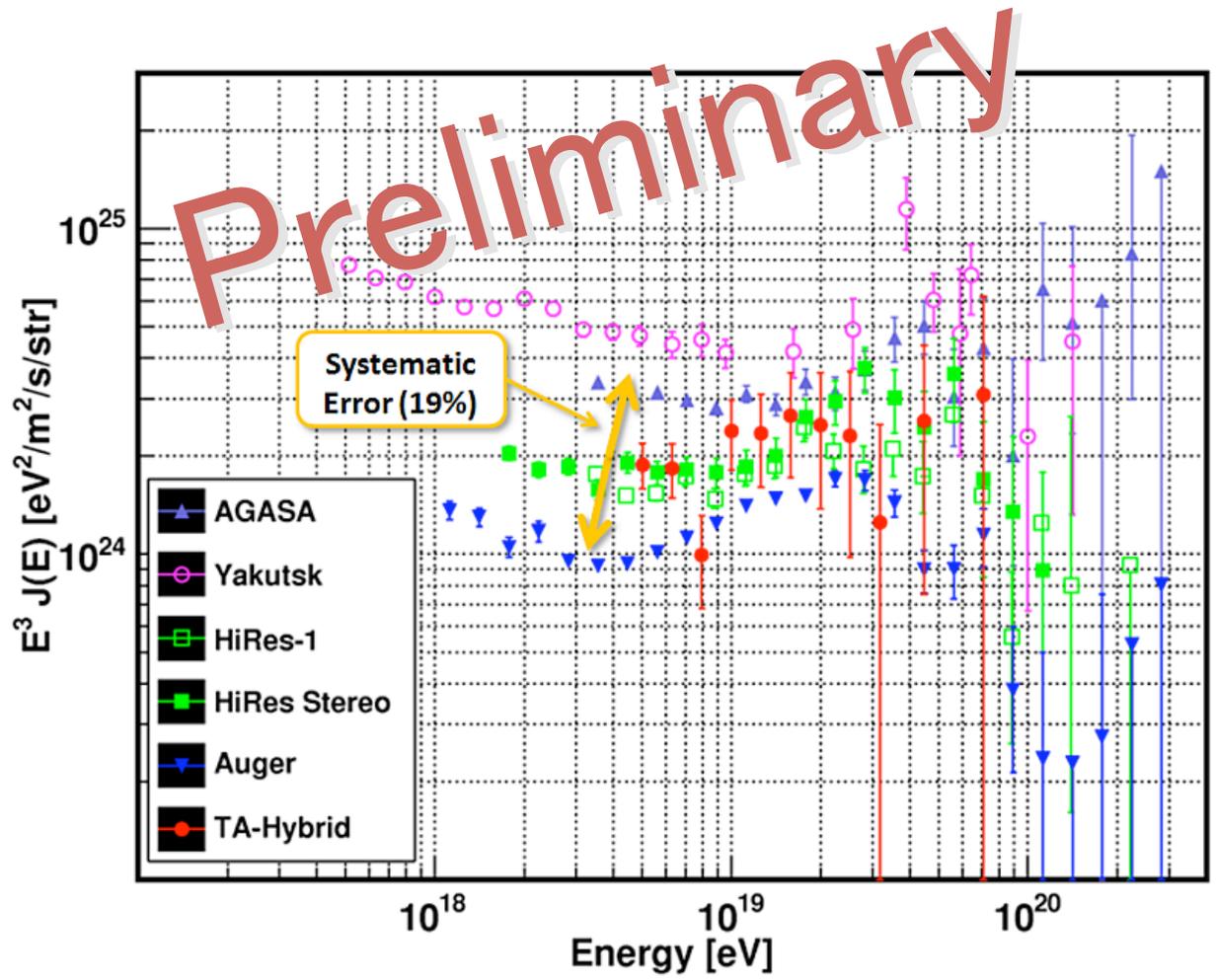
- BR: 87
- LR: 79
- Stereo: 42



Data/MC comparison



Hybrid Spectrum



Systematic errors

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

SD Spectrum Analysis: Overview

Data

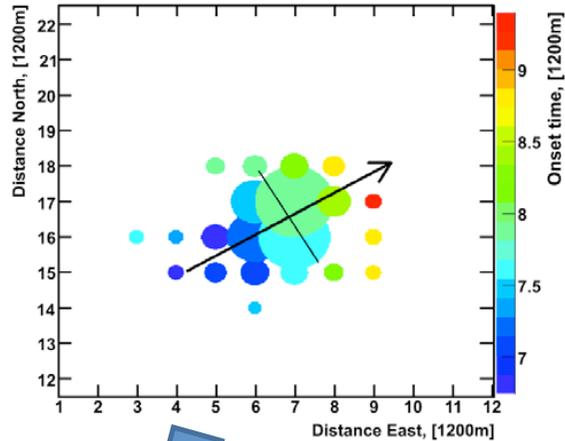
- May/2008 – Feb/2010
 - 1.75 years
 - $\sim 1500 \text{ km}^2 \text{ sr yr}$
($\sim \text{AGASA 13 years}$)
- Cut:
 - χ^2/ndf cut: 4.0
 - Border Cut $> 1.2 \text{ km}$
 - Zenith Angle Cut, 45 degrees
 - Pointing direction uncertainty: 5 degrees
 - Fractional S800 uncertainty: 0.25
- 6264 events

MC

- Simulate the data exactly as it exists.
 - Start with previously measured spectrum and composition.
 - **Use Corsika/QGSJet-II events.**
 - Throw with isotropic distribution.
 - Simulate **trigger**, front-end electronics, DAQ with Geant4.
- Analyze the MC with the same programs used for data.
- Aperture / Exposure obtained by MC
- Test with **data/MC comparison**

SD event reconstruction

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

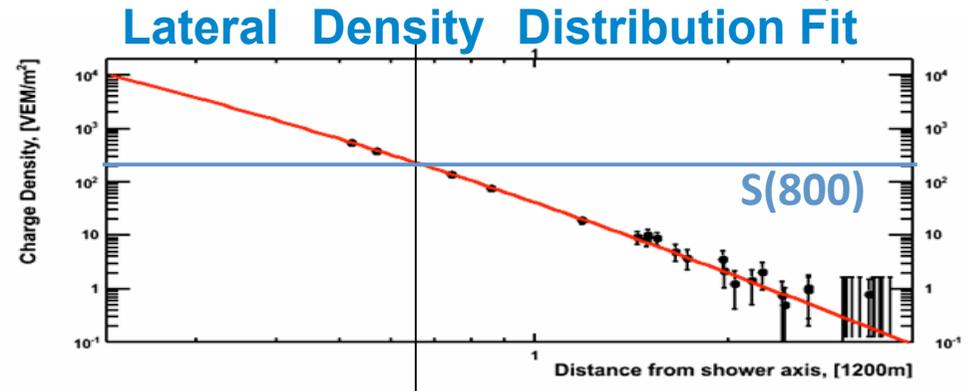
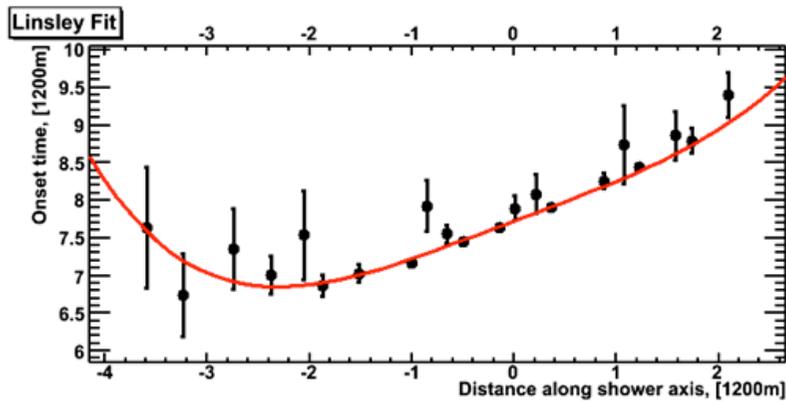


Two fits:

- Time fit to determine event geometry
- Lateral distribution fit (LDF) to determine signal size 800m from the shower axis, $S(800)$

Fitting procedure and formulas are adjusted using only the data.

Geometry Fit (modified Linsley)



$r = 800m$

Fit with AGASA LDF

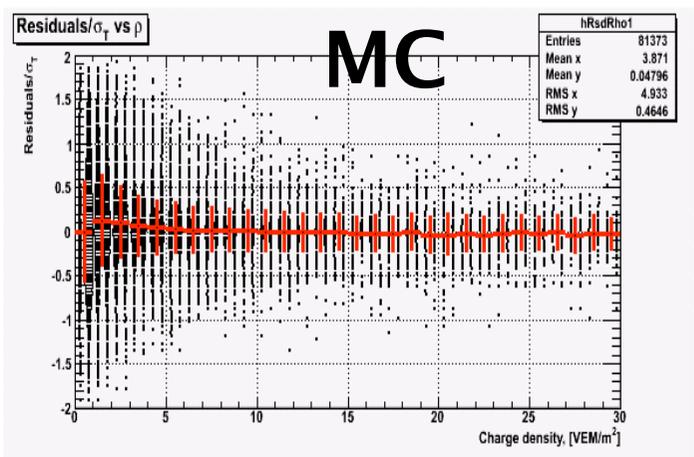
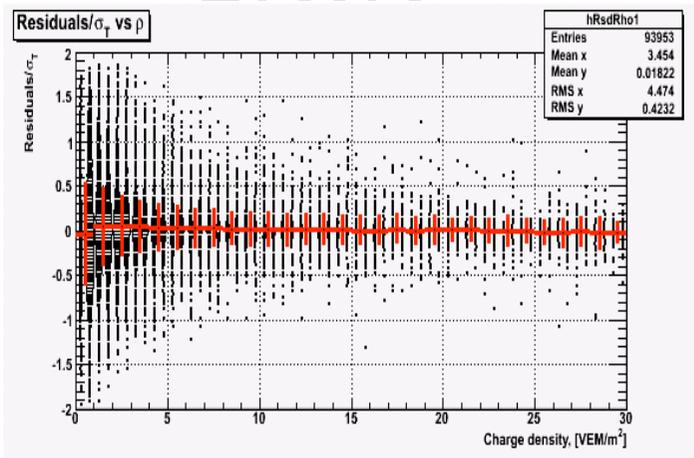
$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2} \left(1 + \frac{r}{R_M}\right)^{-(\eta-1.2)} \left\{1 + \left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

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

Fitting results

DATA

Time fit residual over sigma

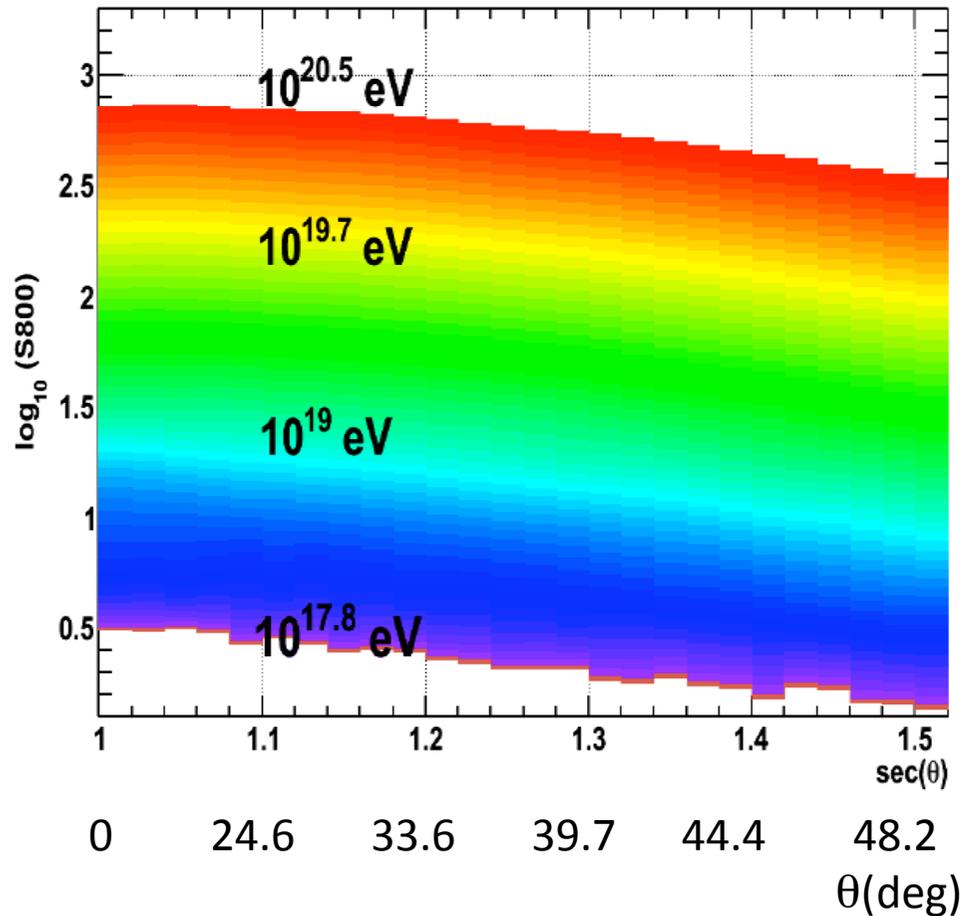


Counter signal, [VEM/m²]

Vertical Equivalent Muon (VEM)

- 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!

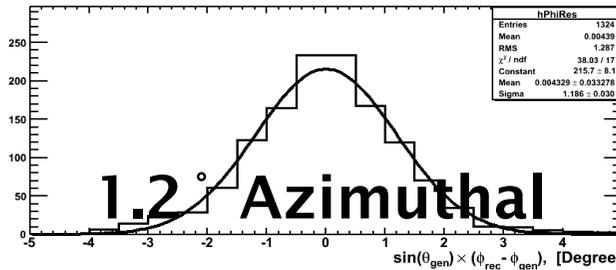
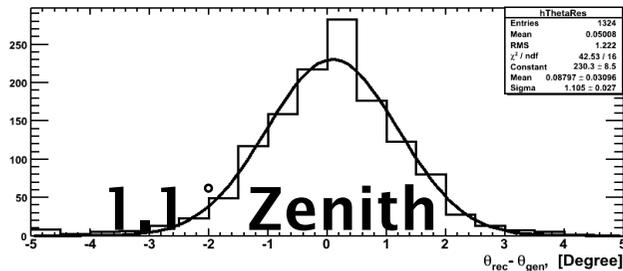
First Estimate of Energy



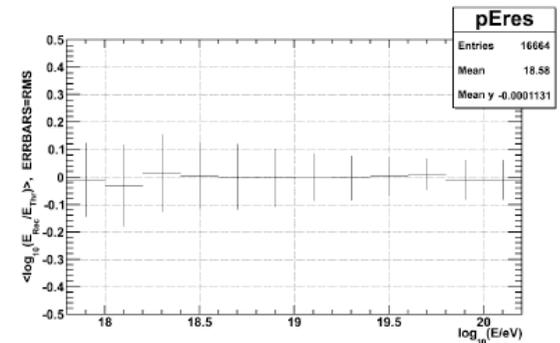
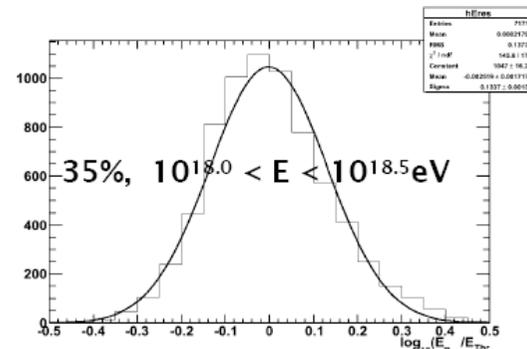
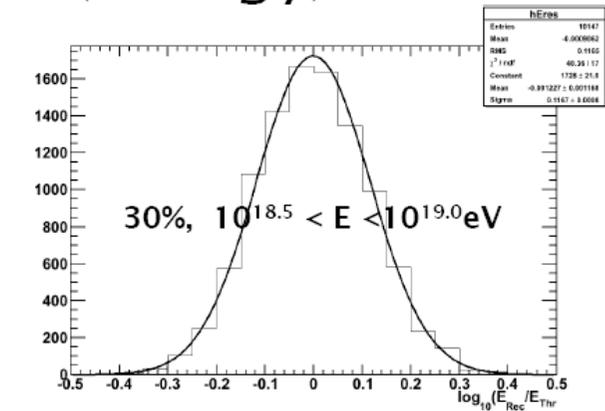
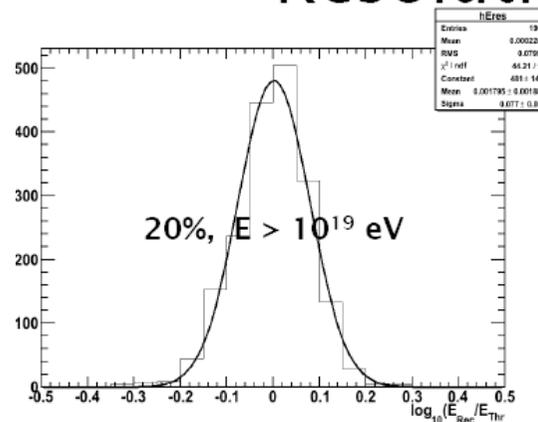
- Energy table is constructed from the MC
- First estimation of the event energy is done by interpolating between S800 vs $\sec(\theta)$ lines

TA SD Resolution

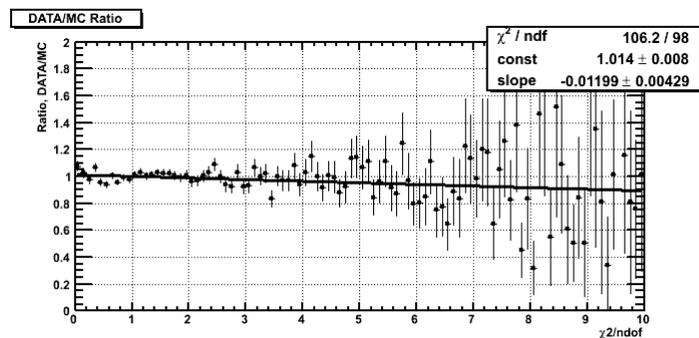
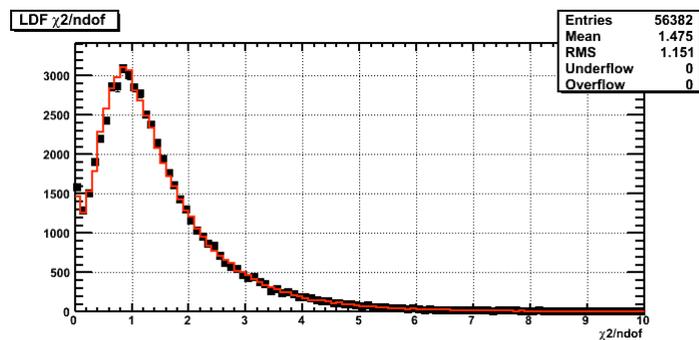
Resolution (Arrival direction)



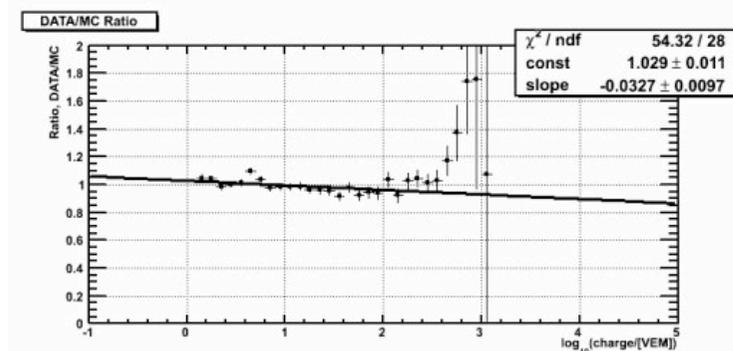
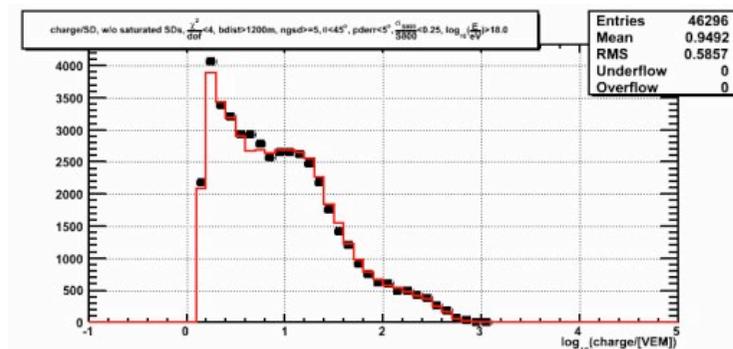
Resolution (Energy)



Data/MC Comparisons

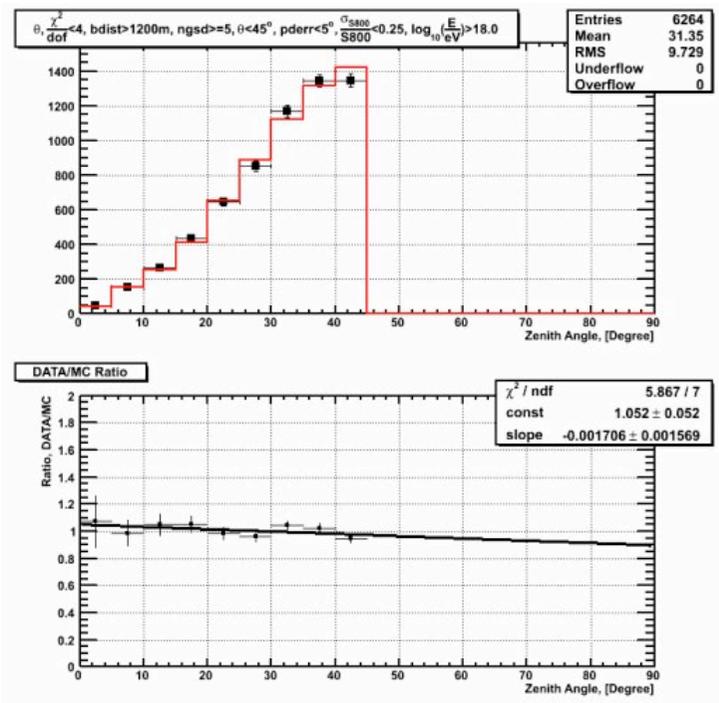


LDF fit χ^2/dof

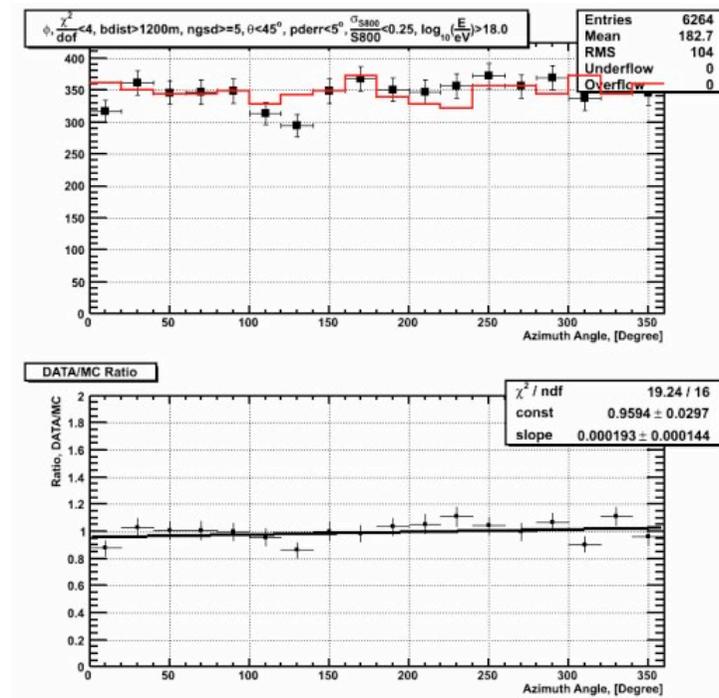


VEM / SD

DATA/MC Event Direction

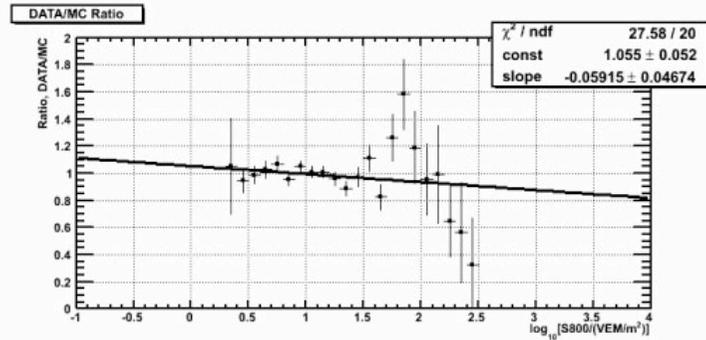
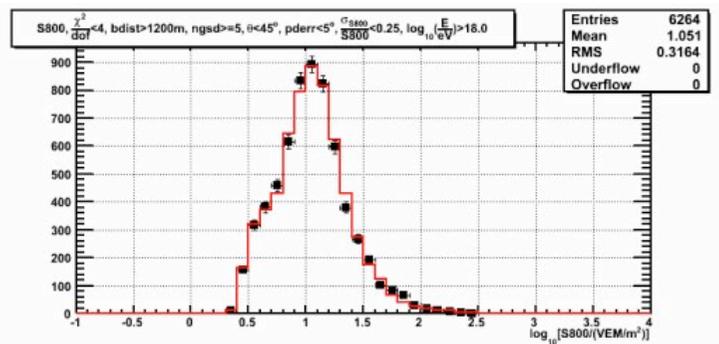


Zenith angle

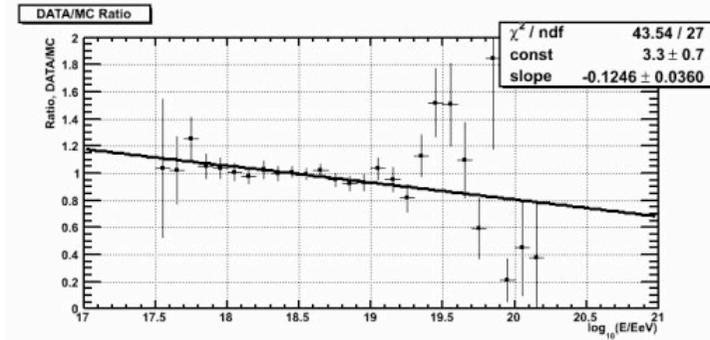
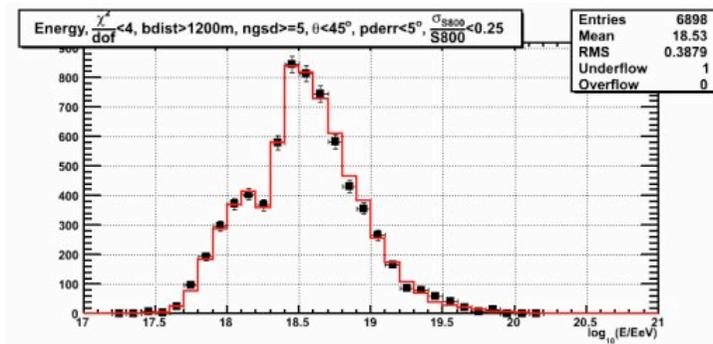


Azimuthal angle

DATA/MC: S800, Energy

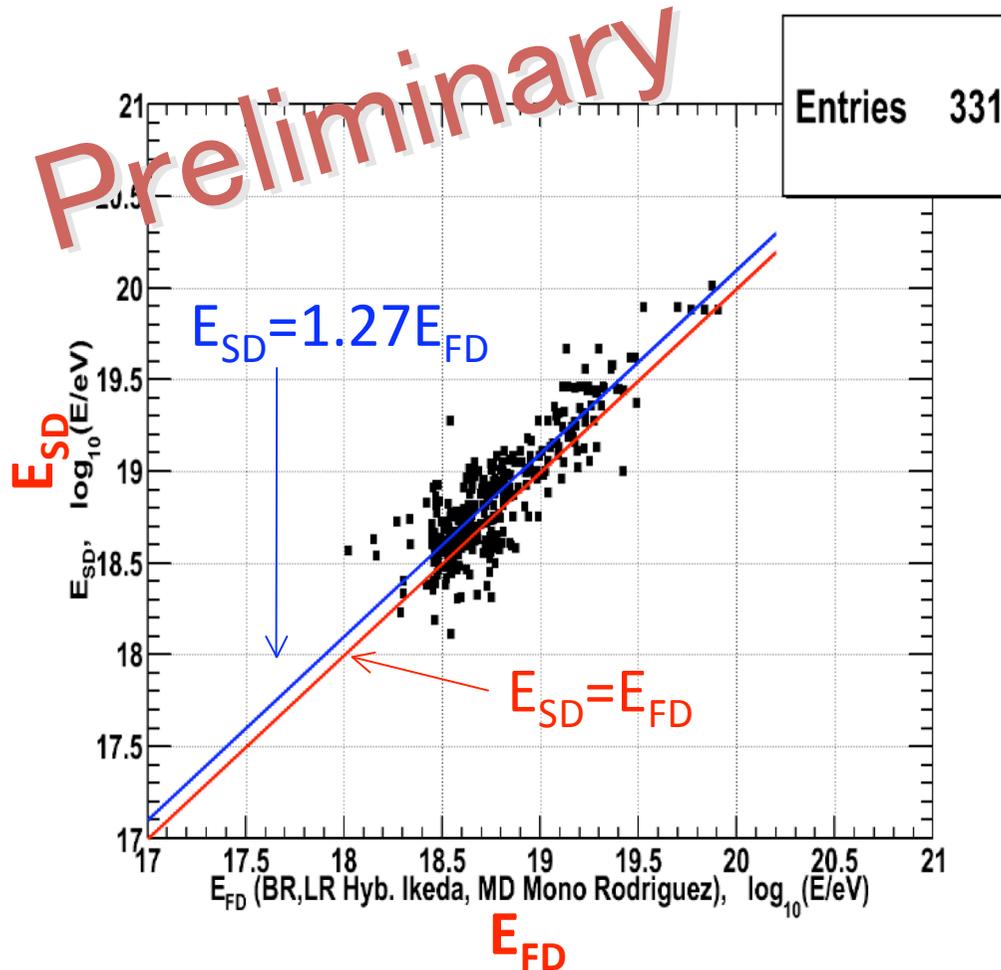


S800



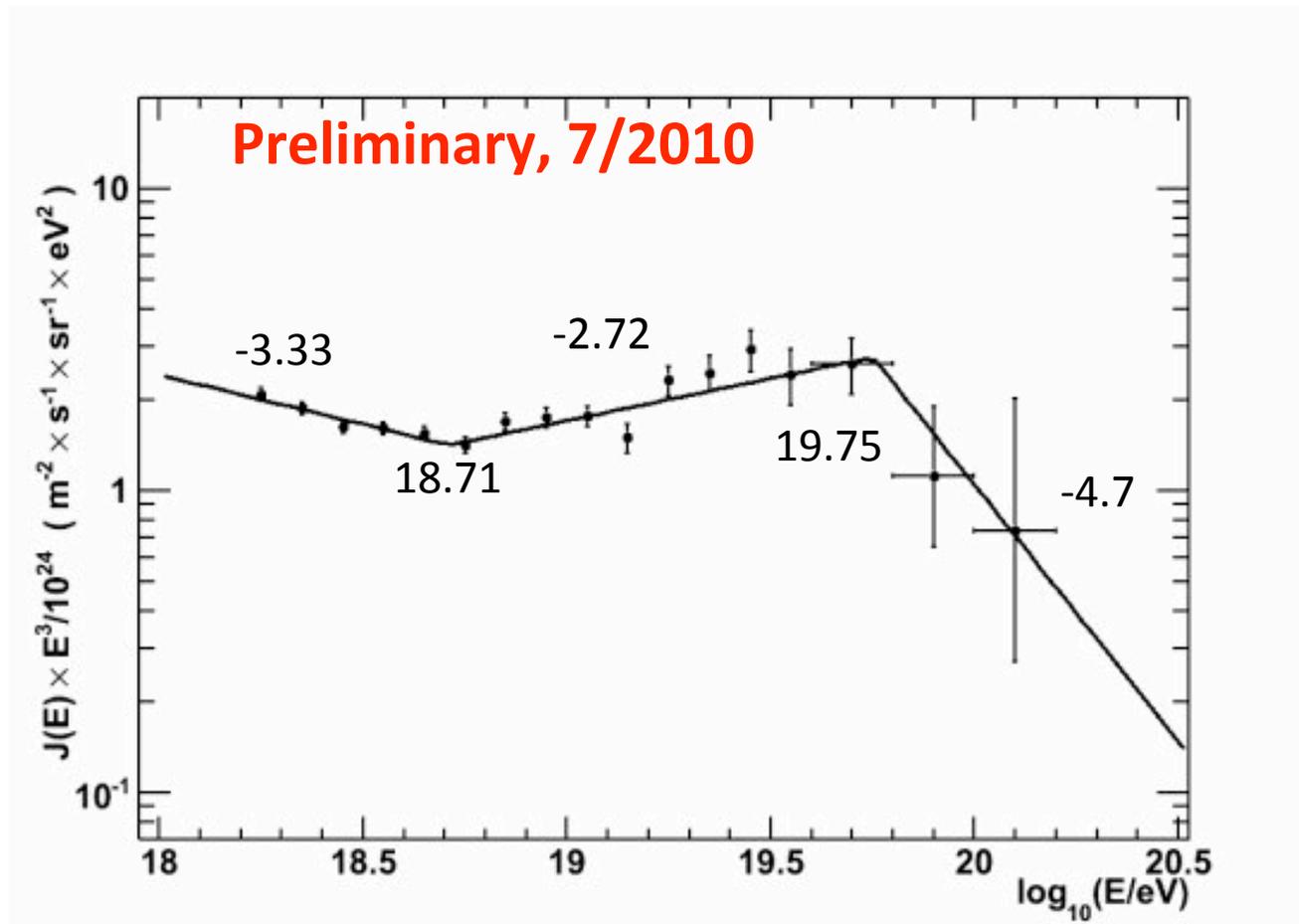
Energy

E_{SD} v.s. E_{FD} Comparison

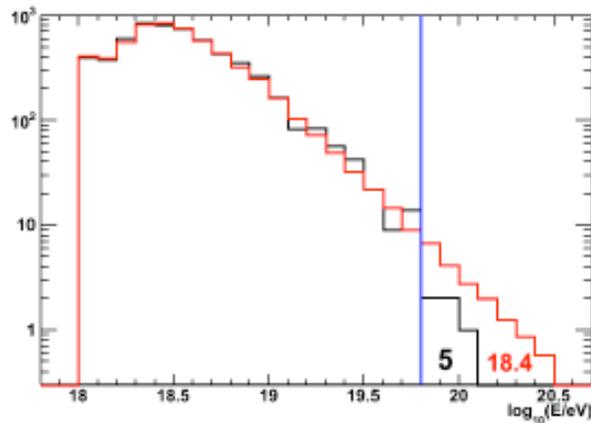
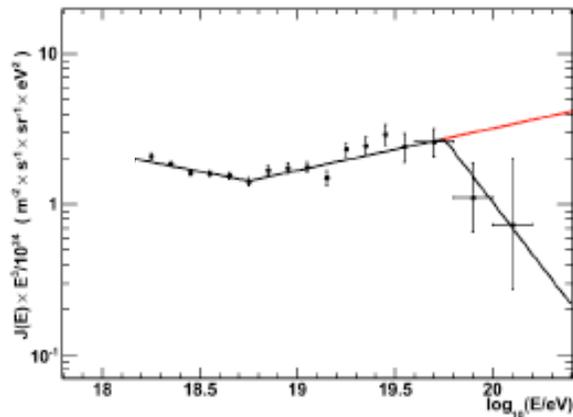


- Energy scale is determined experimentally by FD without referring to MC
- Set SD energy scale to FD energy scale using well-reconstructed events seen by both detectors:
- **27% renormalization.**
 - Systematic error 19% (from systematic error of energy by hybrid analysis)

TA SD Spectrum



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 T ASD 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:

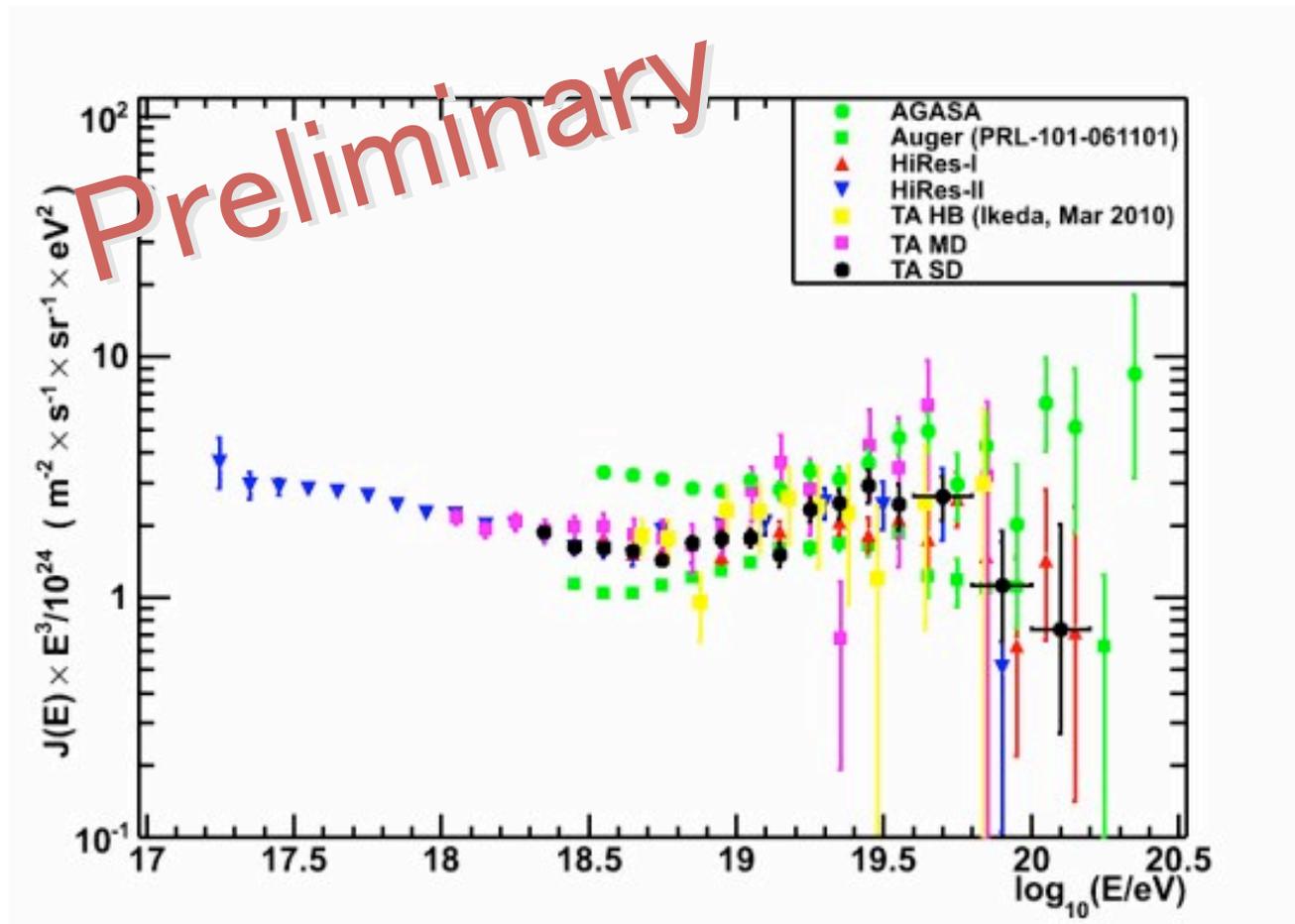
$$- N_{\text{EXPECT}} = 18.4$$

$$- N_{\text{OBSERVE}} = 5$$

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

(3.5 σ)

AGASA, Auger, HiRes, TA Spectra



Mass Composition

Mass Composition

FD stereo analysis: Data MC Comparison

CORSIKA: QGSjet-II, QGSjet-01, SIBYLL

Proton, Iron

thinning factor : 10^{-4}

Data set: FD stereo Nov/2007 – Oct/2009 (~2years)

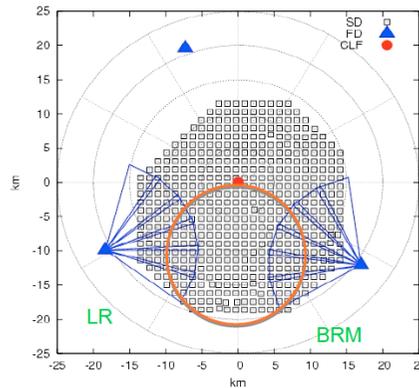
Selection

Energy above $10^{18.6}$ eV

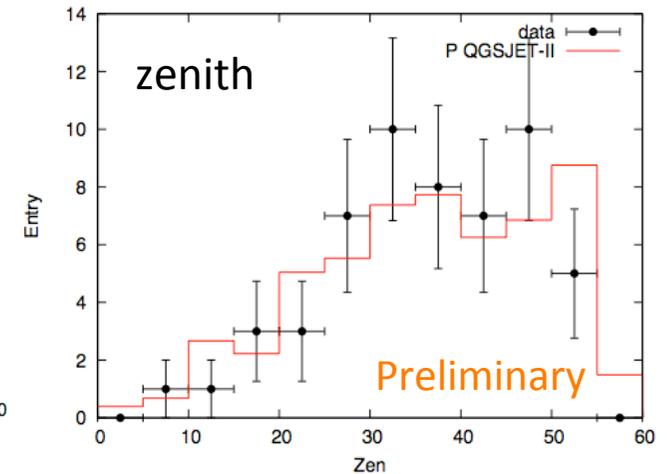
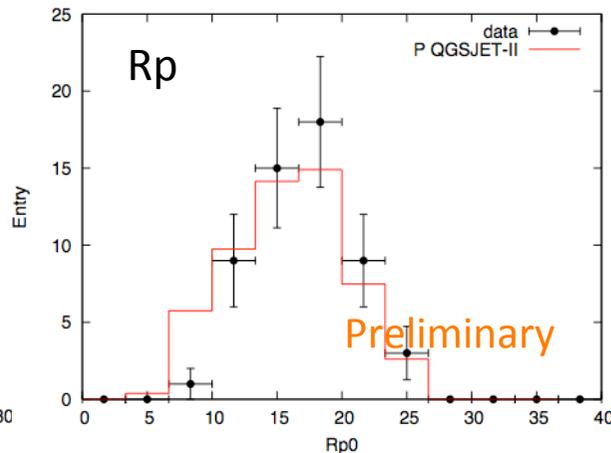
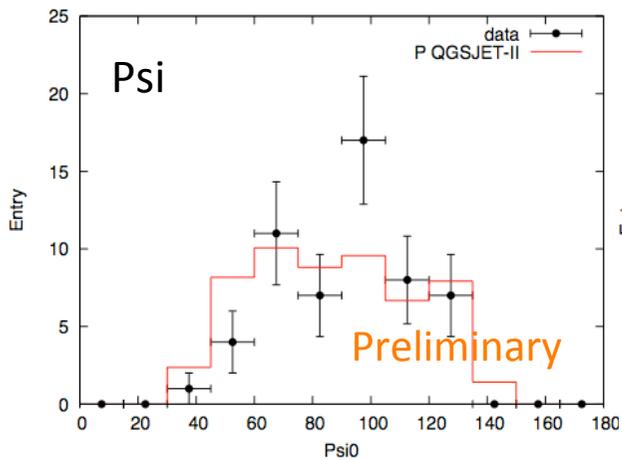
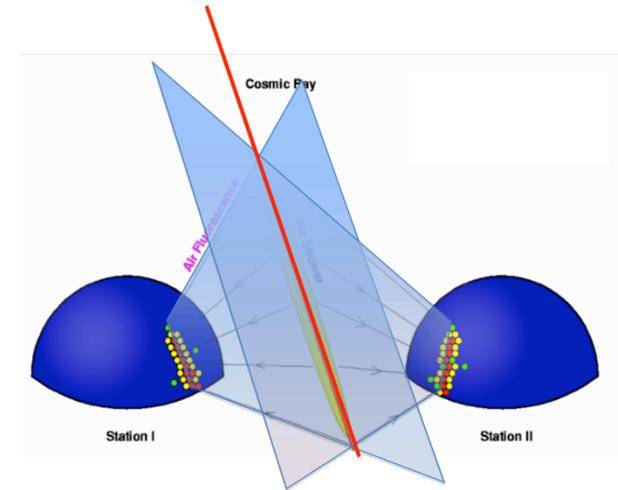
zenith angle < 56deg

core location : within 9.6km

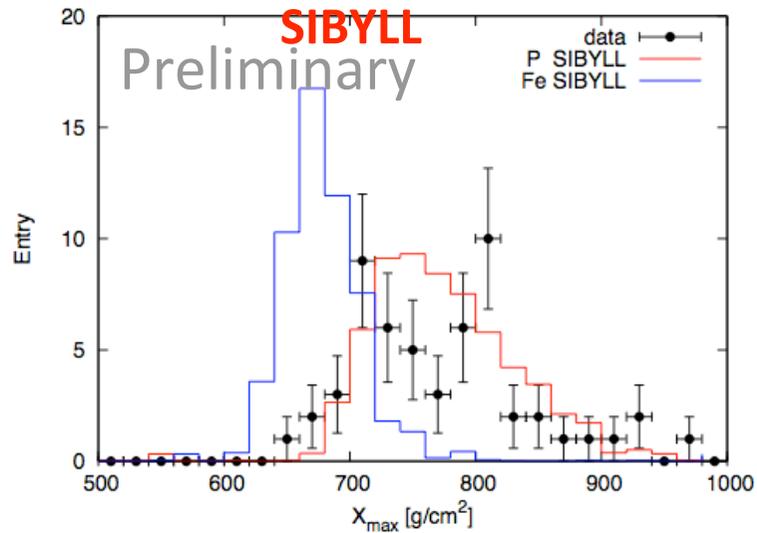
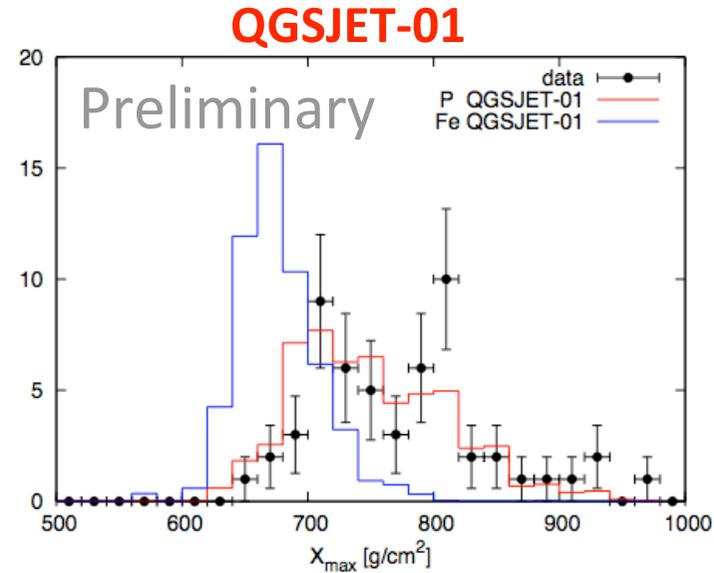
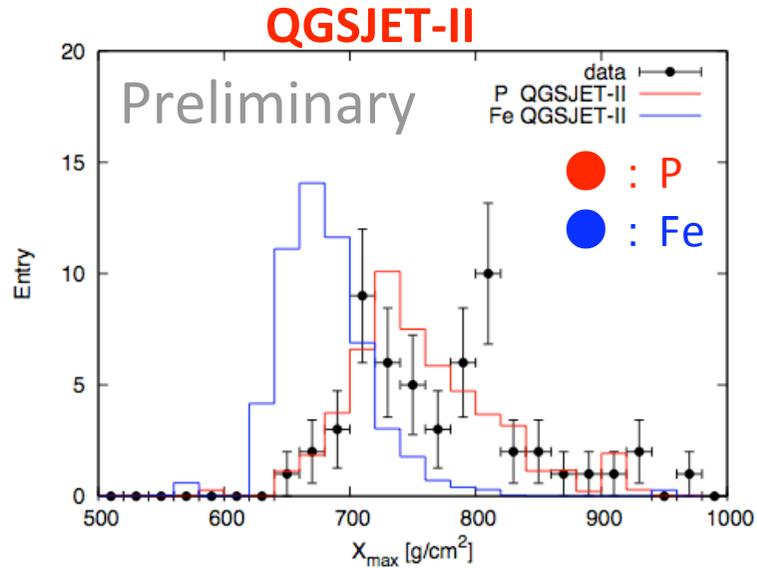
Xmax within the FOV



Stereo reconstruction



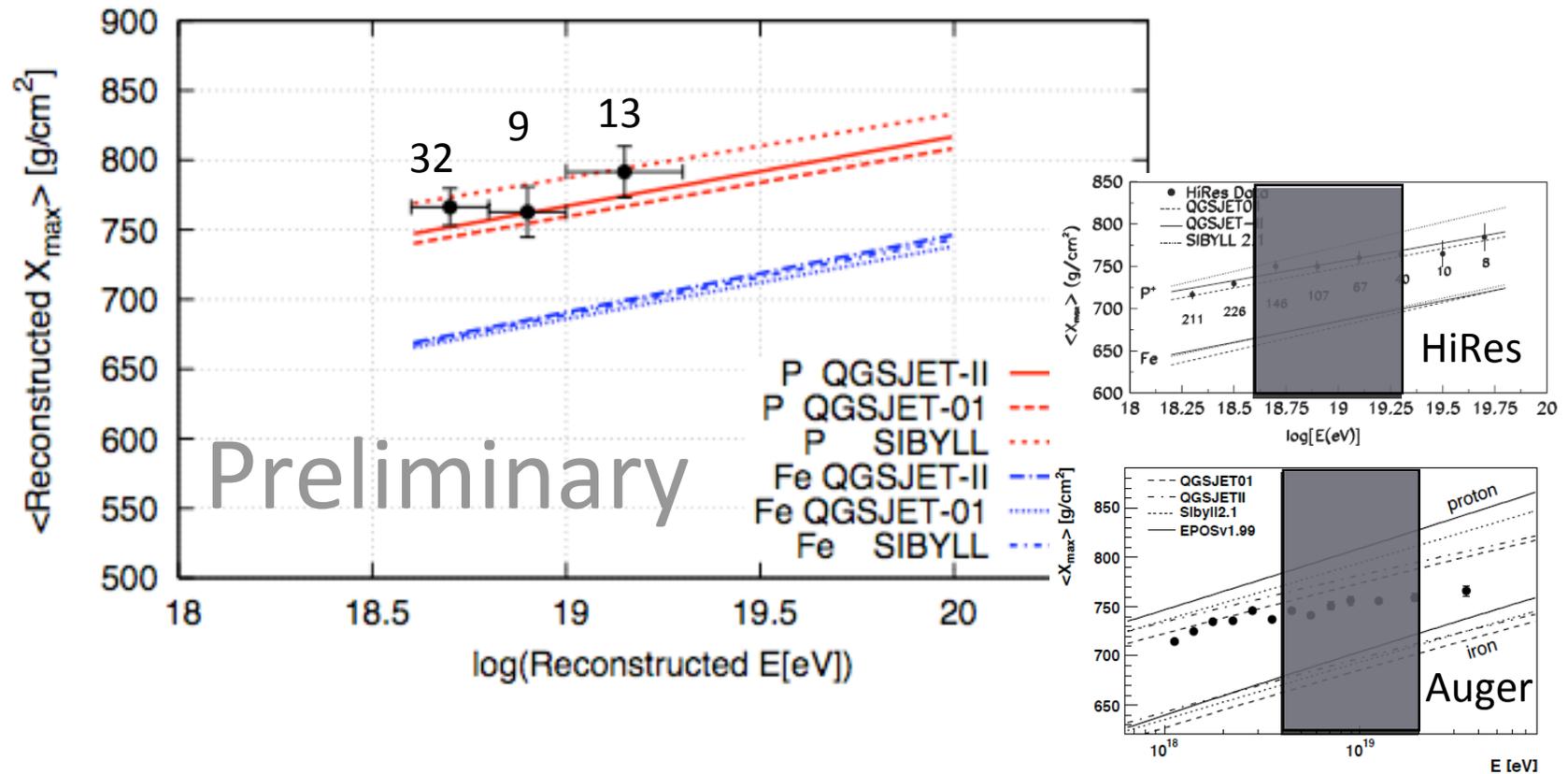
Mass Composition Reconstructed X_{\max} distribution



Chi² / dof

	QGSJET-II	QGSJET-01	SIBYLL
P	1.44	1.046	1.63
Fe	55.54	56.67	85.71

Mass Composition Energy v.s. Reconstructed X_{\max}

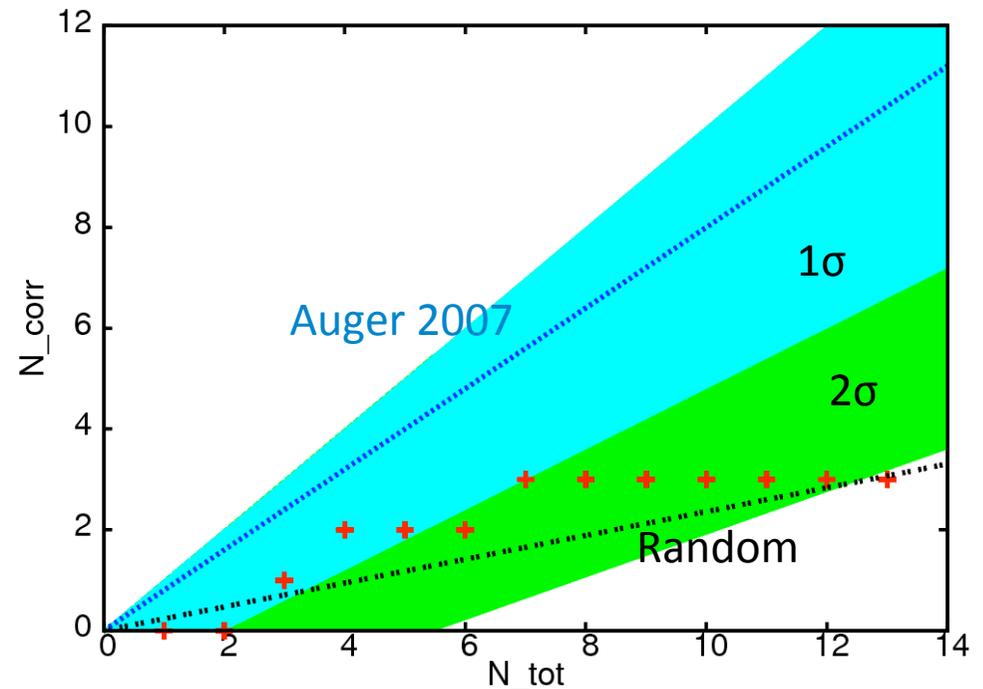


AGN correlation

Search for AGN Correlations

- Auger found correlations with AGN's with (57 EeV, 3.1°, 0.018). 14 events scanned + 13 event test sample appeared in Science article; 2.9σ .
- HiRes data show no significant correlations.
- TA data (13 events) has 3 correlated events, 3.0 expected by chance.

→ No Effect.



Photon Search

Photon Search by SD

Event by event method

Using **shower front curvature** which is observable

Monte Carlo

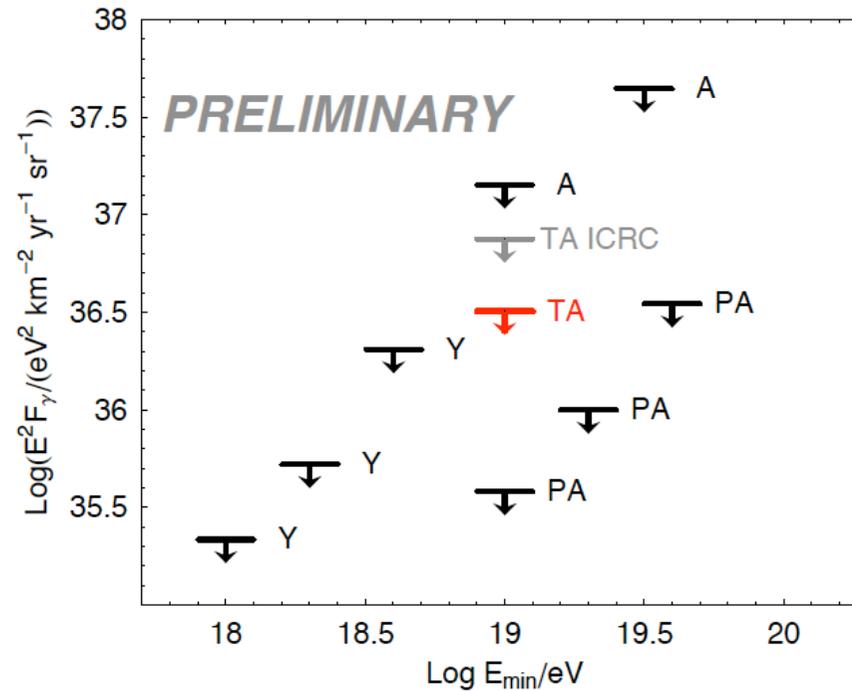
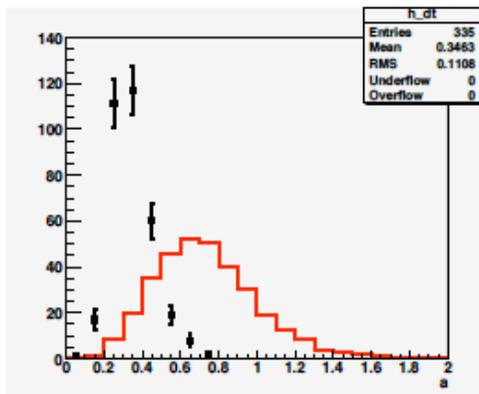
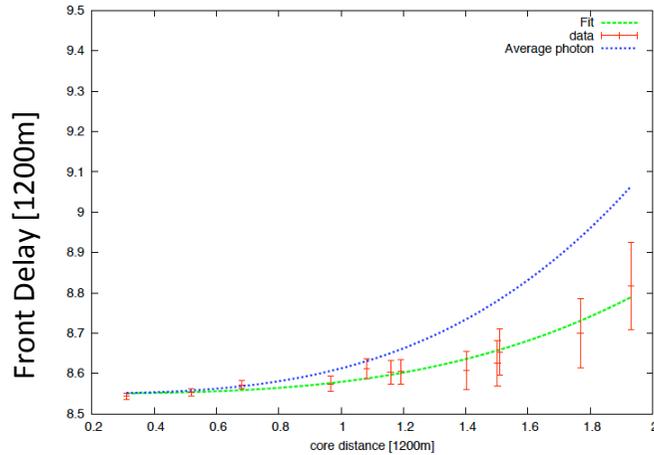
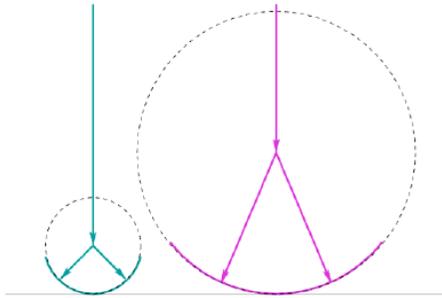
CORSIKA with QGSJET-II, FLUKA and EGS4
 PRESHOWER for geomagnetic field cascade

Detector response : GEANT 4

$E \in [10^{18.4}, 10^{20.5}]$ eV, $\theta \in [0, 60]$

Data set: 2008-05-11 to 2009-10-08

$F < 3.3 \cdot 10^{-2} \text{ km}^{-2}\text{sr}^{-1}\text{yr}^{-1}$ (95% CL) /PRELIMINARY/



Conclusions

- The Telescope Array (TA) Experiment is the largest hybrid UHECR detector in the northern hemisphere.
- The TA is operating very efficiently and collecting data.
- **SD spectrum: consistent with HiRes spectrum ($10^{18.3}\text{eV}\sim 10^{20.2}\text{eV}$)**
 - Suppression at highest energy: 3.5σ away from continued spectrum
- HiRes-refurbished MD spectrum: consistent with HiRes spectrum
- Hybrid spectrum: consistent with HiRes spectrum ($10^{18.7}\text{eV}\sim 10^{19.8}\text{eV}$)
- Composition: consistent with proton ($10^{18.6}\text{eV}\sim 10^{19.3}\text{eV}$)
- AGN correlation: No significance
- Photon search: Upper limit
- SD mono, FD mono, stereo, hybrid, hybrid-stereo analyses are all on-going.

A message from TA ;

We plan to hold a symposium to review

Present Status

Future Prospects

of the study of UHECRs

on Dec.6th-8th (tentative) in Japan.

Please join and discuss !

