



Results from the Telescope Array experiment

H. Tokuno

Tokyo Tech

The Telescope Array Collaboration

The Telescope Array Collaboration

T. Abu-Zayyad,¹ R. Aida,² M. Allen,¹ R. Anderson,¹ R. Azuma,³ E. Barcikowski,¹ J.W. Belz,¹ D.R. Bergman,¹ S.A. Blake,¹ R. Cady,¹ B.G. Cheon,⁴ J. Chiba,⁵ M. Chikawa,⁶ E.J. Cho,⁴ W.R. Cho,⁷ H. Fujii,⁸ T. Fujii,⁹ T. Fukuda,³ M. Fukushima,^{10,11} W. Hanlon,¹ K. Hayashi,³ Y. Hayashi,⁹ N. Hayashida,¹⁰ K. Hibino,¹² K. Hiyama,¹⁰ K. Honda,² T. Iguchi,³ D. Ikeda,¹⁰ K. Ikuta,² N. Inoue,¹³ T. Ishii,² R. Ishimori,³ D. Ivanov,^{1,14} S. Iwamoto,² C.C.H. Jui,¹ K. Kadota,¹⁵ F. Kakimoto,³ O. Kalashev,¹⁶ T. Kanbe,² K. Kasahara,¹⁷ H. Kawai,¹⁸ S. Kawakami,⁹ S. Kawana,¹³ E. Kido,¹⁰ H.B. Kim,⁴ H.K. Kim,⁷ J.H. Kim,⁴ J.H. Kim,¹⁹ K. Kitamoto,⁶ S. Kitamura,³ Y. Kitamura,³ K. Kobayashi,⁵ Y. Kobayashi,³ Y. Kondo,¹⁰ K. Kuramoto,⁹ V. Kuzmin,¹⁶ Y.J. Kwon,⁷ S.I. Lim,²⁰ S. Machida,³ K. Martens,¹¹ J. Martineau,¹ T. Matsuda,⁹ T. Matsuura,³ T. Matsuyama,⁹ J.N. Matthews,¹ M. Minamino,⁹ K. Miyata,⁵ Y. Murano,³ I. Myers,¹ K. Nagasawa,¹³ S. Nagataki,²¹ T. Nakamura,²² S.W. Nam,²⁰ T. Nonaka,¹⁰ S. Ogio,⁹ M. Ohnishi,¹⁰ H. Ohoka,¹⁰ K. Oki,¹⁰ D. Oku,² T. Okuda,²³ A. Oshima,⁹ S. Ozawa,¹⁷ I.H. Park,²⁰ M.S. Pshirkov,²⁴ D.C. Rodriguez,¹ S.Y. Roh,¹⁹ G. Rubtsov,¹⁶ D. Ryu,¹⁹ H. Sagawa,¹⁰ N. Sakurai,⁹ A.L. Sampson,¹ L.M. Scott,¹⁴ P.D. Shah,¹ F. Shibata,² T. Shibata,¹⁰ H. Shimodaira,¹⁰ B.K. Shin,⁴ J.I. Shin,⁷ T. Shirahama,¹³ J.D. Smith,¹ P. Sokolsky,¹ T.J. Sonley,¹ R.W. Springer,¹ B.T. Stokes,¹ S.R. Stratton,^{1,14} T. Stroman,¹ S. Suzuki,⁹ Y. Takahashi,¹⁰ M. Takeda,¹⁰ A. Taketa,²⁵ M. Takita,¹⁰ Y. Tameda,¹⁰ H. Tanaka,⁹ K. Tanaka,²⁶ M. Tanaka,⁹ S.B. Thomas,¹ G.B. Thomson,¹ P. Tinyakov,^{16,24} I. Tkachev,¹⁶ H. Tokuno,³ T. Tomida,²⁷ S. Troitsky,¹⁶ Y. Tsunesada,³ K. Tsutsumi,³ Y. Tsuyuguchi,² Y. Uchihori,²⁸ S. Udo,¹² H. Ukai,² G. Vasiloff,¹ Y. Wada,¹³ T. Wong,¹ M. Wood,¹ Y. Yamakawa,¹⁰ R. Yamane,⁹ H. Yamaoka,⁸ K. Yamazaki,⁹ J. Yang,²⁰ Y. Yoneda,⁹ S. Yoshida,¹⁸ H. Yoshii,²⁹ X. Zhou,⁶ R.R. Zollinger,¹ and Z. Zundel¹

~140 Collaborators

26 Institutions

5 countries



Extensive Air Shower Detectors

Ultra High Energy
Cosmic Ray

Air Shower

Air Fluorescence detectors (FDs)
EAS longitudinal development
Calorimetric Energy determination
~10% duty cycle (moonless clear night)

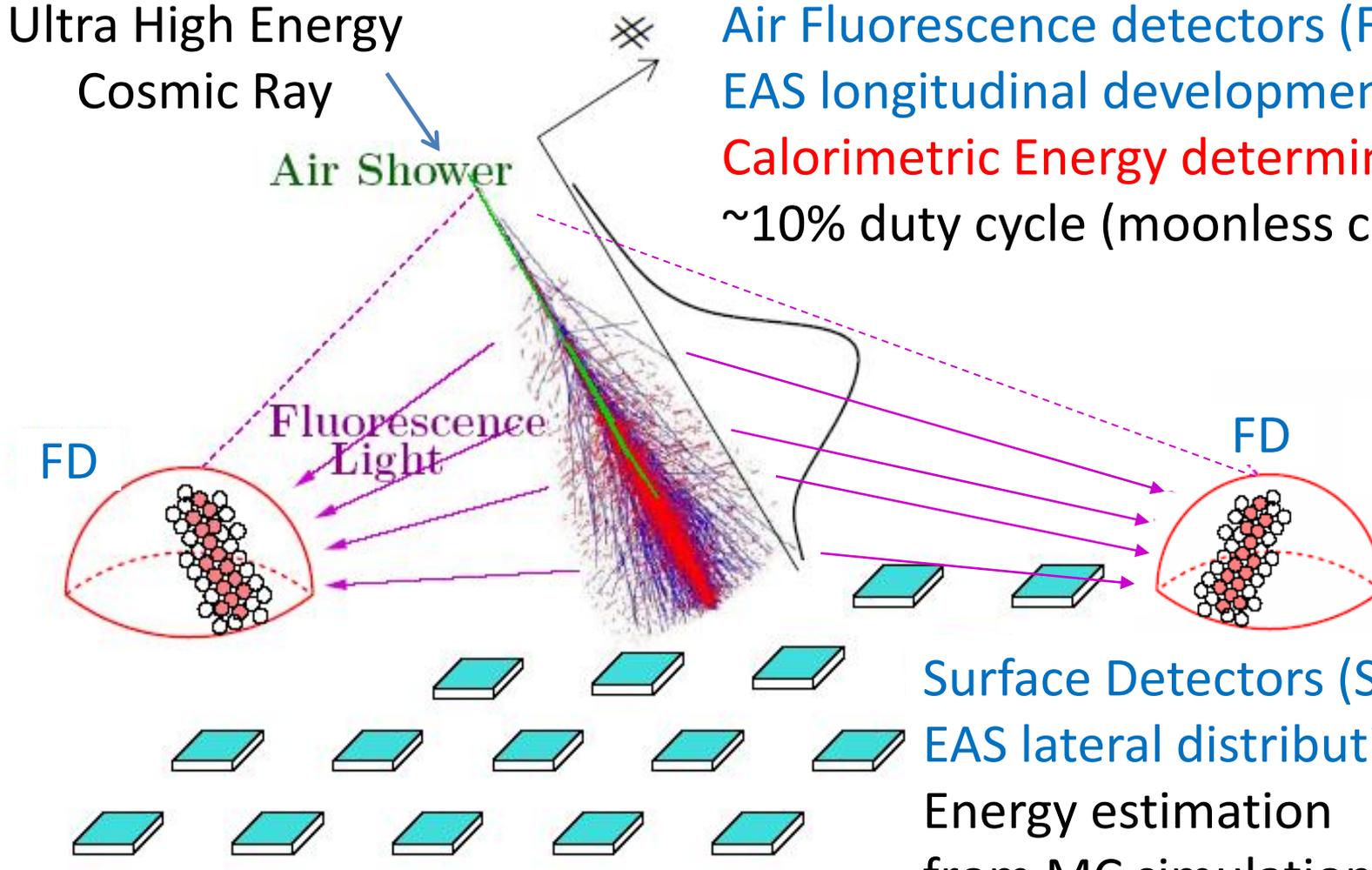
FD

Fluorescence
Light

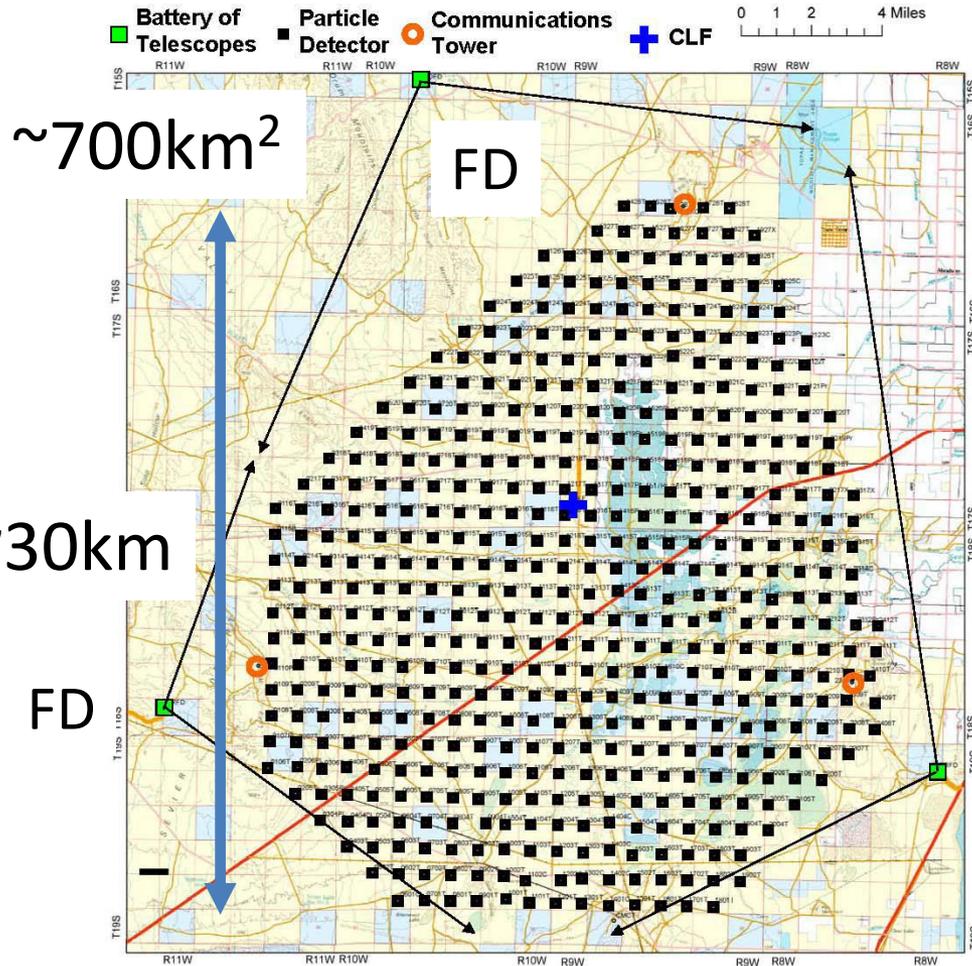
FD

Surface Detectors (SDs)
EAS lateral distribution
Energy estimation
from MC simulation
~100% duty cycle

The two different detectors have different advantages



TA Detectors Utah, USA



507 x Surface Detector



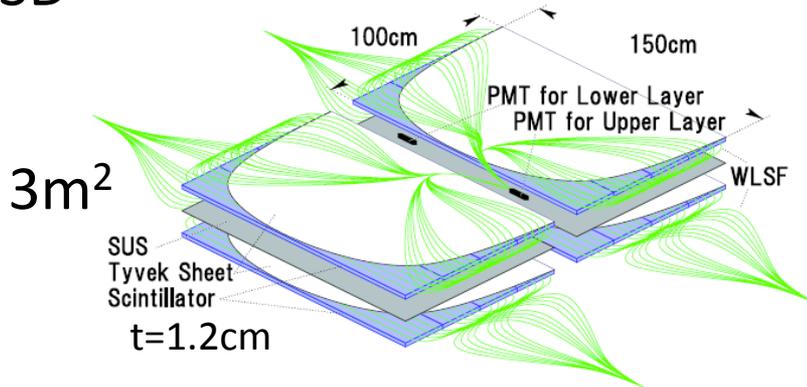
3 x FD stations



FD

Surface Detectors (SDs)

SD



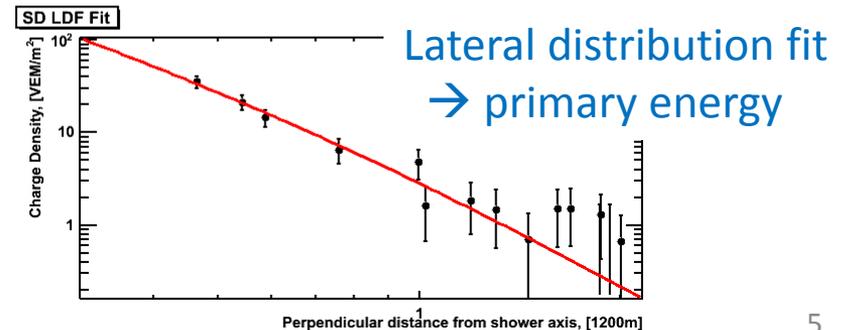
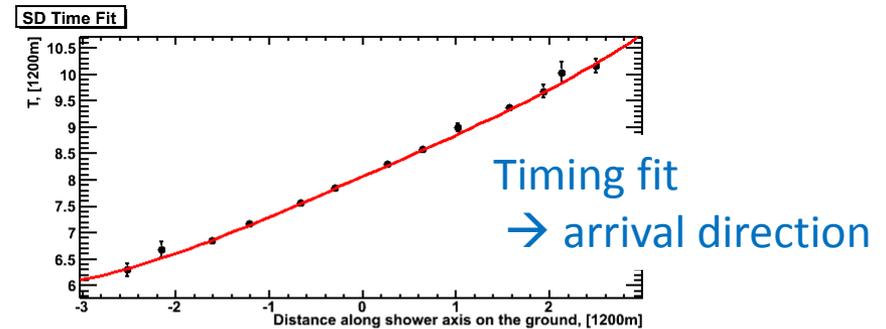
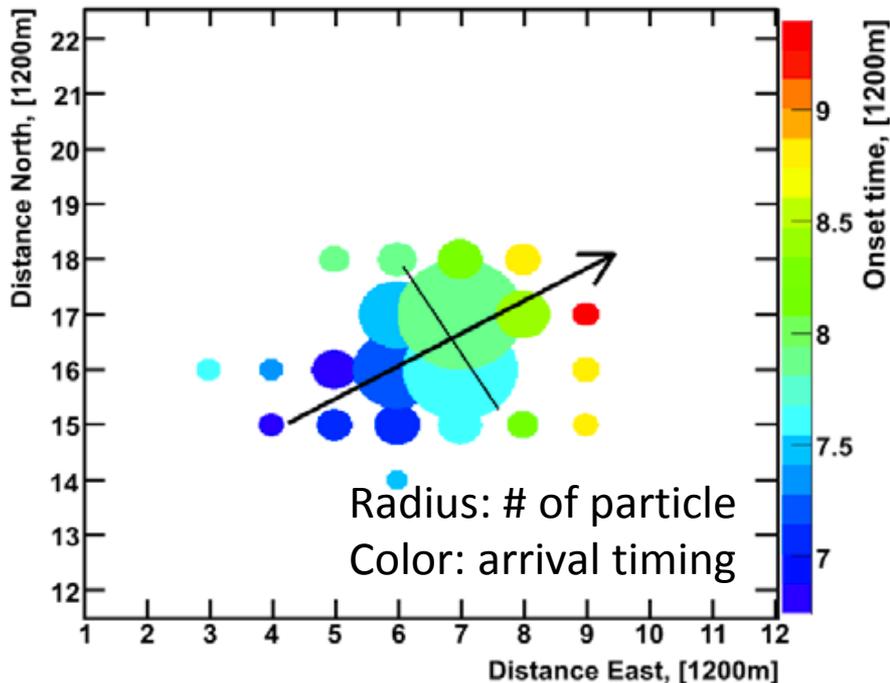
2 layered plastic scintillators

Timing differences

- Arrival direction

Lateral distribution of EAS

- Primary Energy



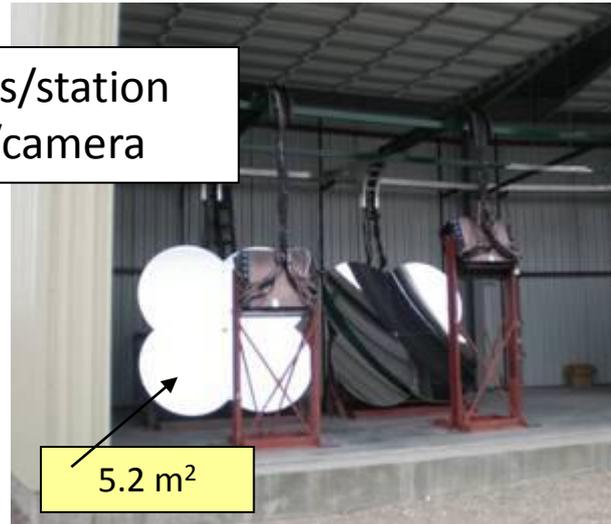
Air Fluorescence Detectors (FDs)

Moved
from HiRes

Middle Drum

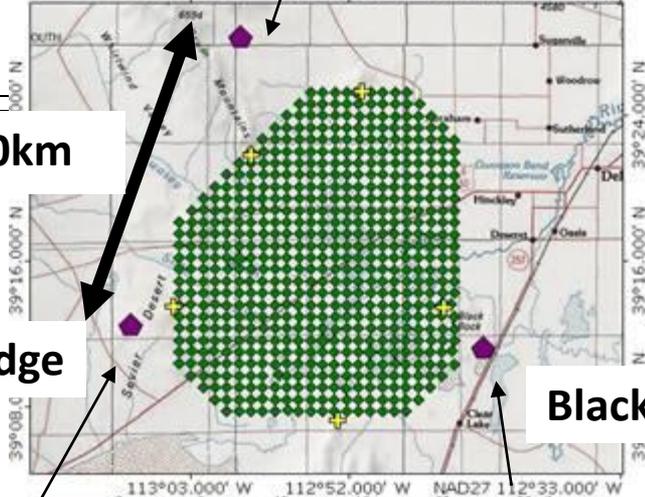


14 cameras/station
256 PMTs/camera



5.2 m²

TOPOI map printed on 07/12/04 from "StakeJun04-01.tpo" and "Untitled.tpg"



~30km

Long Ridge

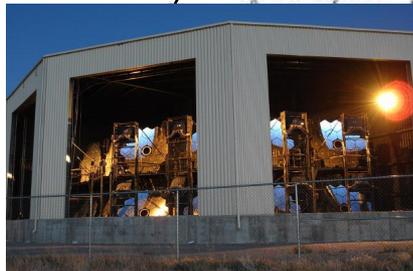
Black Rock Mesa

New FDs

12 cameras/station
256 PMTs/camera

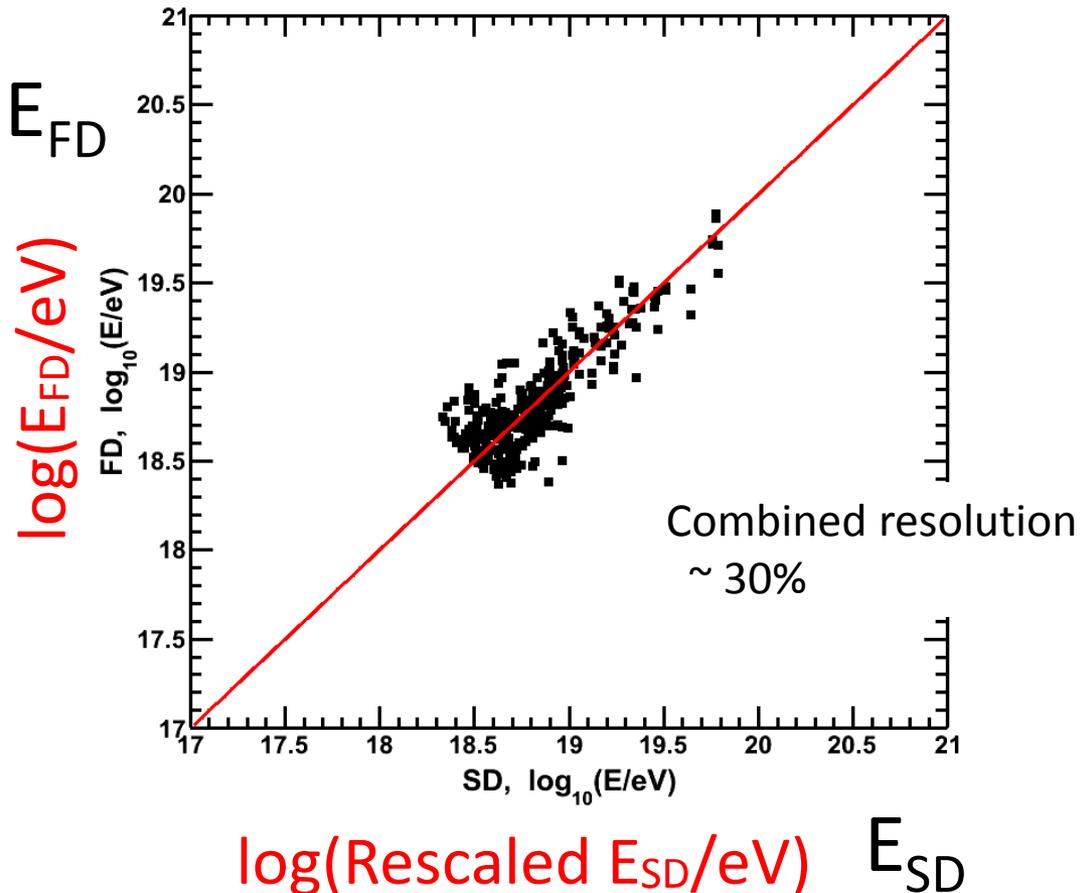


6.8 m²



~1 m²

Energy Scale difference



E_{SD} : Rescaled by E_{FD}

$$E_{SD} = E_{SD(\text{MC-base})} / 1.27$$

FD Energy uncertainties

| Source | Uncertainty(%) |
|--------------------|----------------|
| Fluorescence yield | 11% |
| Detector Gain | 11% |
| Atmosphere | 11% |
| Reconstruction | 10% |
| Total | 22% |

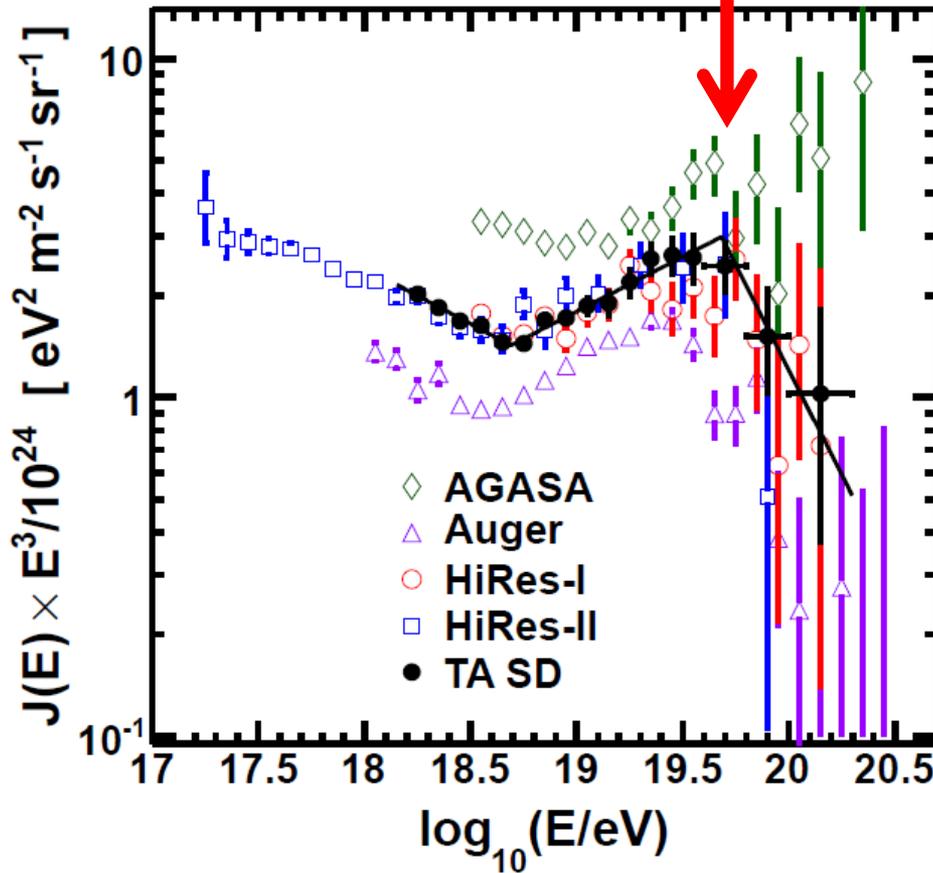
Submitted to PRL
 arXiv:1205.5067

Energy Spectrum from SD data

Energy Spectrum from SD

Cut off structure @ $10^{19.68} \text{eV}$ (48 EeV)

$10^{18} \text{eV} = 1 \text{EeV}$



3 years Observed data
10997 events

$> 10^{19.68} \text{eV}$

Number of expected events
from a linear extrapolation : 54.9

Number of observed events: 28

Poisson probability = 4.75×10^{-5}

3.9 sigma significance
from a linear extrapolation

May 11, 2008 -- April 25, 2011.

Energy $> 10^{18.2} \text{eV}$

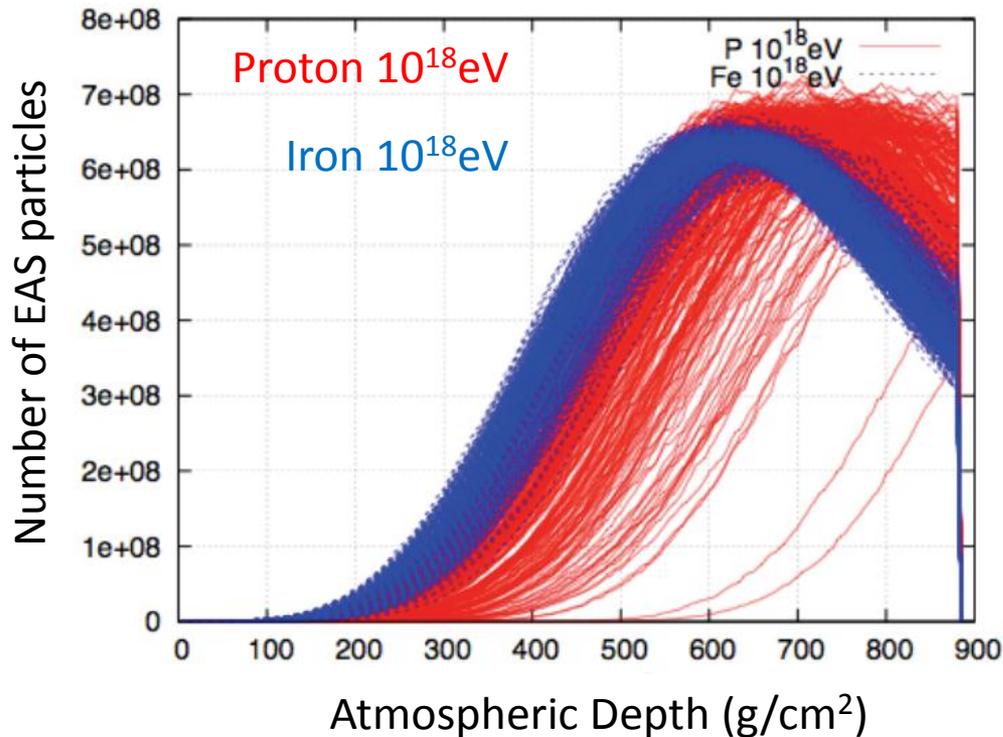
arXiv:1205.5067

Primary Particle type Information from FD data

Longitudinal development of EAS

Longitudinal development

FDs



Maximum development point (X_{max})

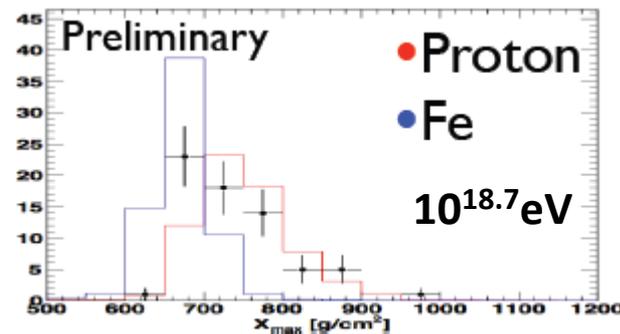
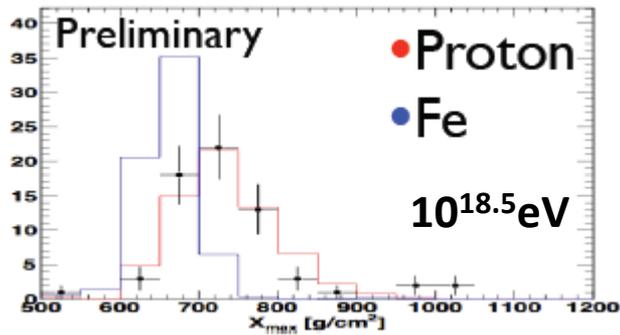
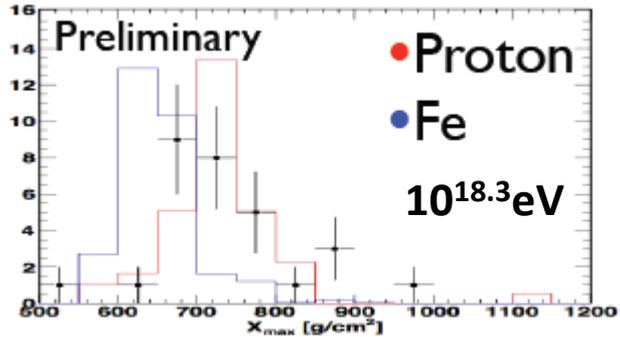
depends on particle type

X_{max} of Proton EASs

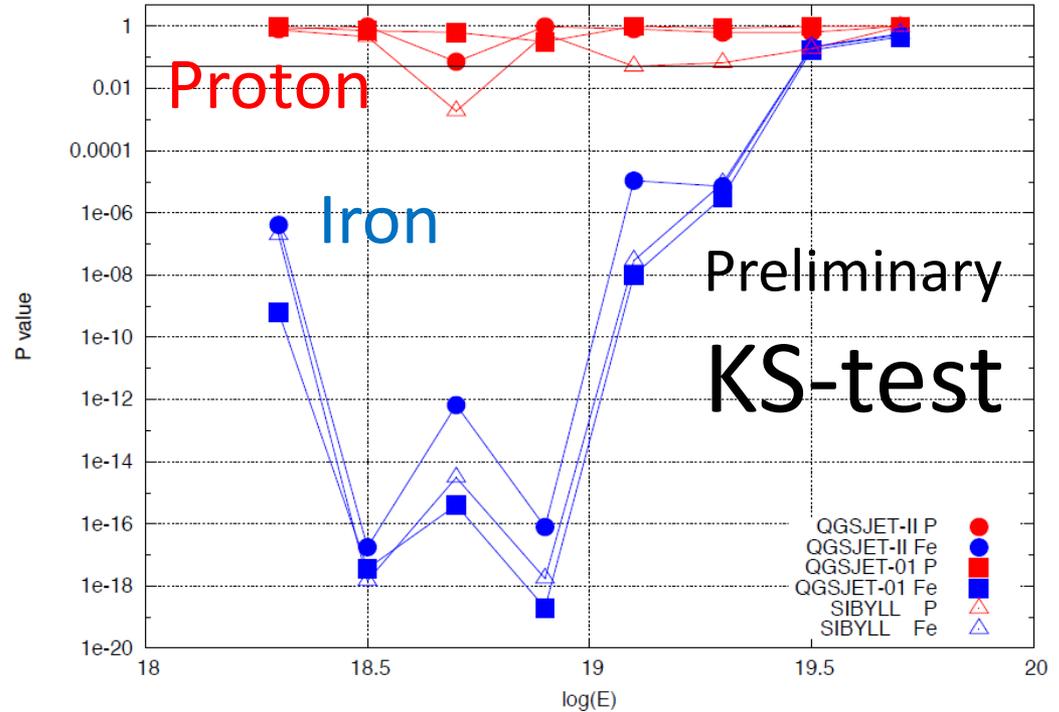
-- Deeper

-- larger fluctuations

Xmax distributions



of events: 30 65 68 49 33 23 8 3



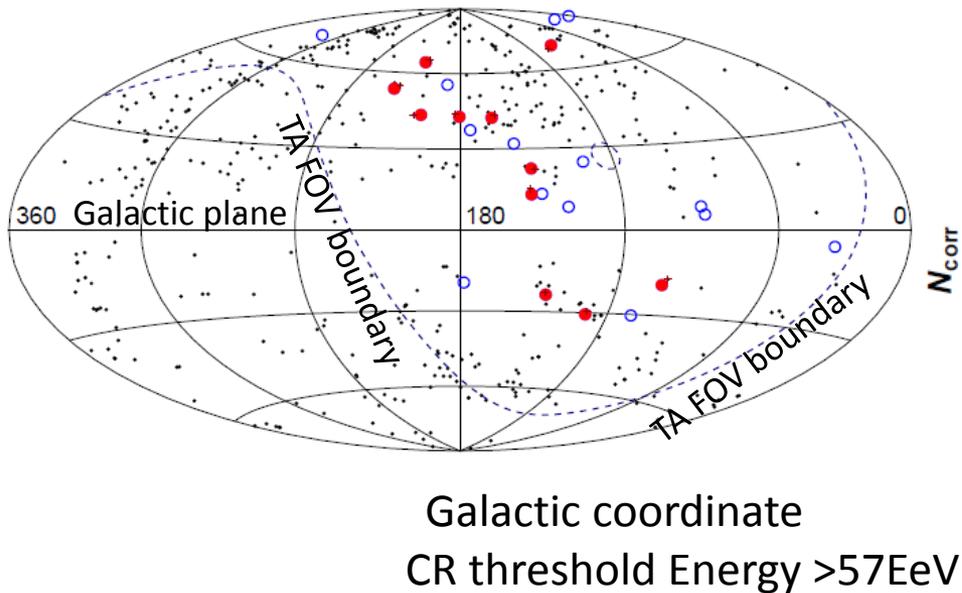
Consistent with Proton MC
 $10^{18.2} - 10^{19.4} \text{eV}$

need more statistics
in other energy ranges

MC: QGSJET-II, FD: Stereo

Arrival directions from SD data

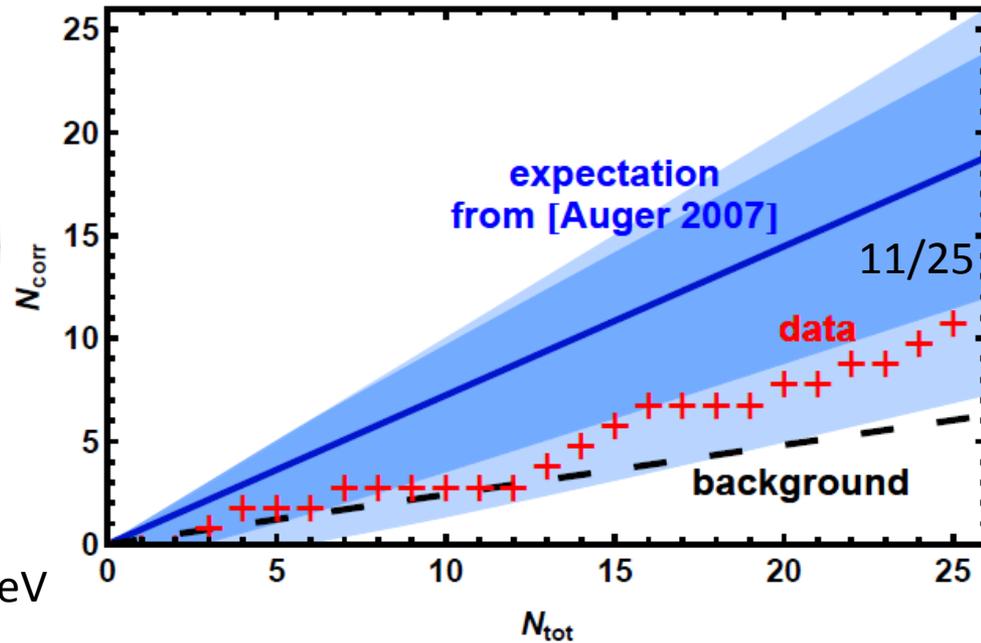
AGN correlation



- Observed CR (AGN found $< 3.1^\circ$)
- Observed CR (AGN not found $< 3.1^\circ$)
- AGN (VCV catalog, distance $< 75\text{Mpc}$)

The 2nd highest event ($10^{20.14}\text{eV}$) falls near an Auger event ($10^{20.09}\text{eV}$) within 1.5°

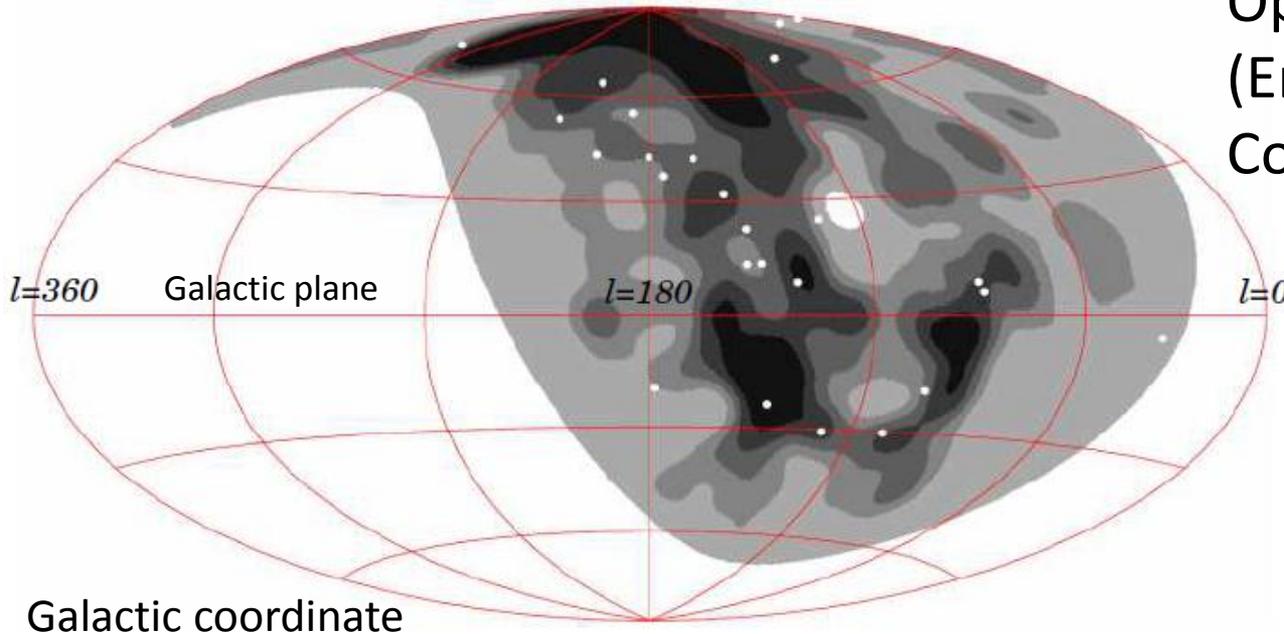
2008Mar11—2011Sep15 (40 Months)



No significant correlation
Consistent with isotropic
(Auto correlation also)

arXiv:1205.5984

Large scale correlation



Open circle: Observed CR
(Energy > 57EeV)

Contours:

Expected flux from
Large scale structure
includes SD exposure

Flux calculation:

Particle type: proton

Matter distribution

Distance <250Mpc:

2MASS extended

D >250Mpc: isotropic

Smearing angle 6°

SD exposure

Larger scale structure correlation and
isotropic hypothesis
both are consistent with our observed data

arXiv:1205.5984

2008Mar11—2011Sep15 (40 Months)

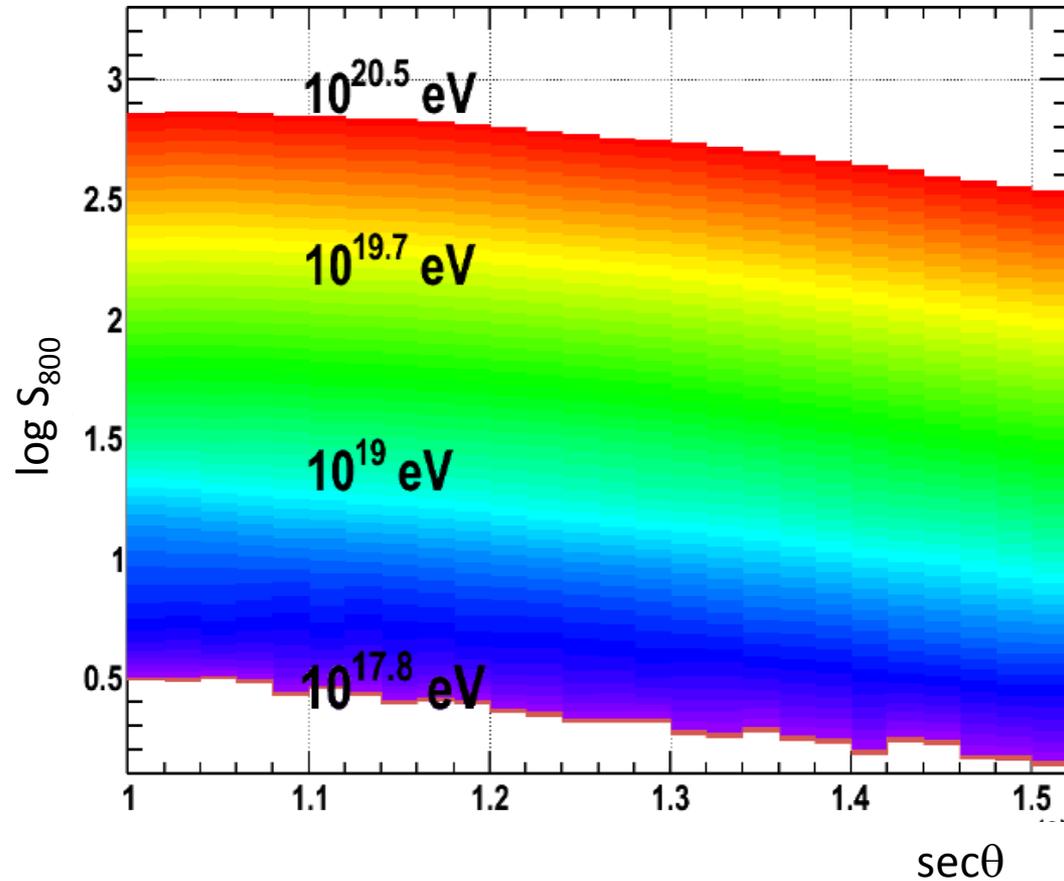
Summary

- FD/SD Observation is running ~4 years (from 2008)
- Energy scale difference between FD and SD: 1.27
 - SD energy is rescaled
 - FD End to End calibration with an electron light source
 - 40MeV, 10^9 electron, 100m far from FD
- **Energy Spectrum** (arXiv:1205.5067)
 - **Cutoff structure @ $10^{19.68}$ eV**
 - 3.9 sigma difference from non-cutoff hypothesis
- **Composition** (preliminary results)
 - **Proton dominant @ $10^{18.2}$ — $10^{19.4}$ eV**
 - need more statistics in other energy ranges
 - systematic uncertainties are studying now.
- **Arrival directions** (arXiv:1205.5984)
 - **Consistent with an isotropic model**
 - No significant correlation (AGNs, Auto-correlation, Large scale structure)

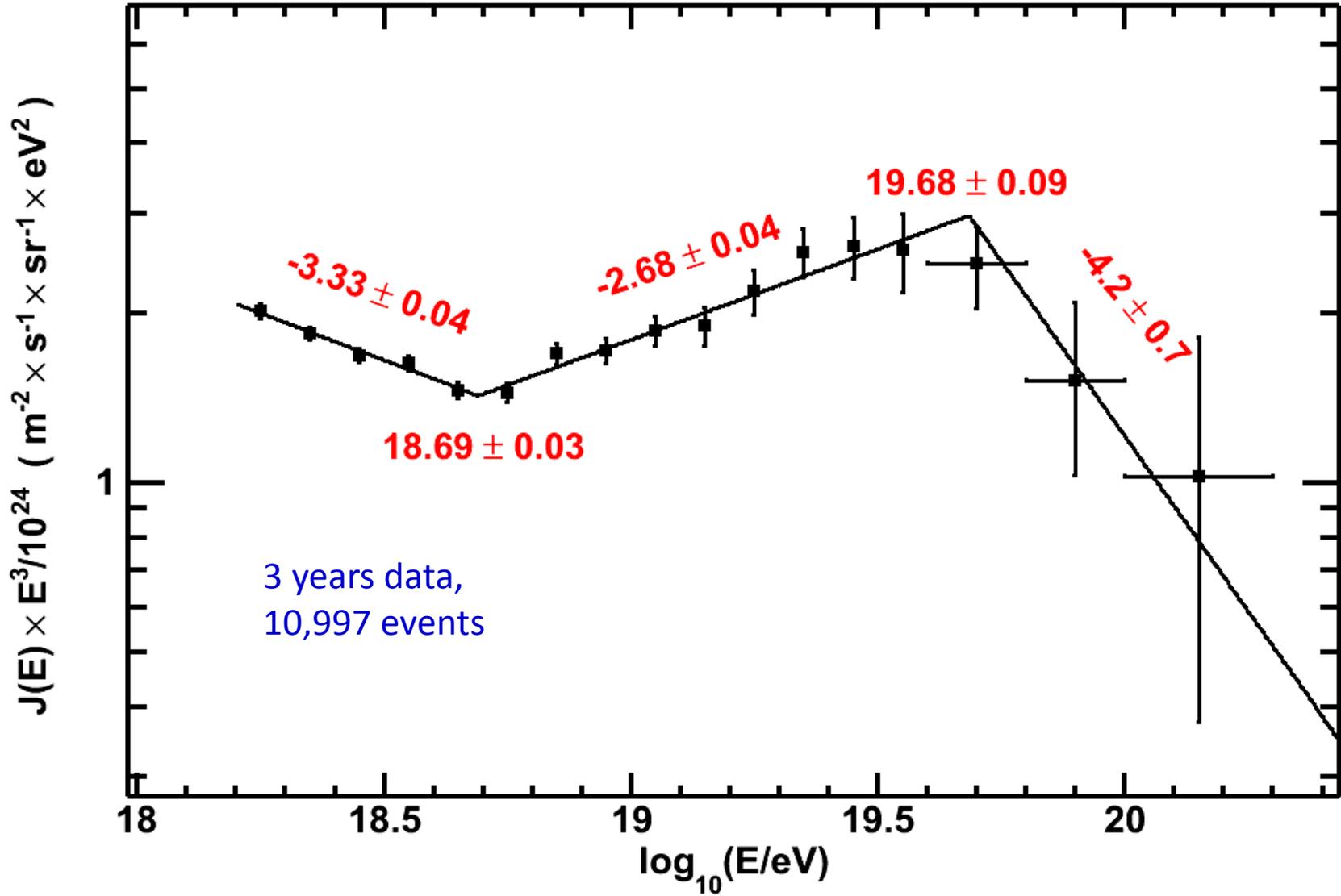
Backup

SD Analysis: Energy Determination

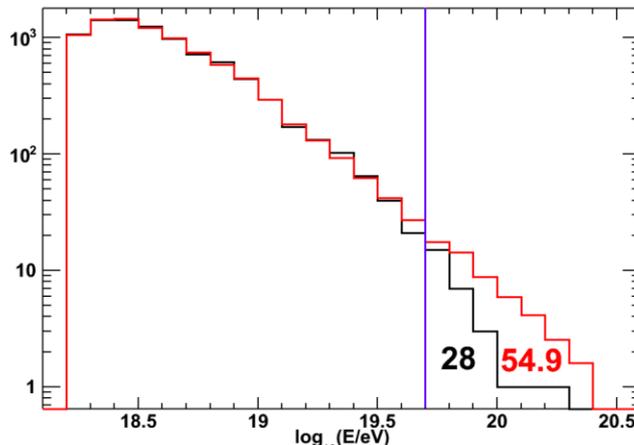
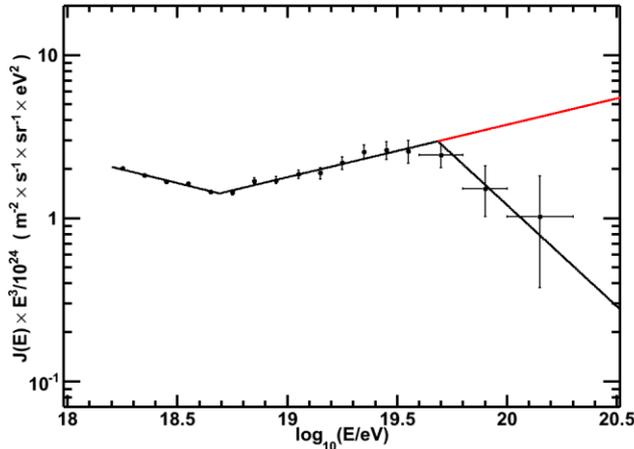
- Energy determination table is constructed from the fitting results of the Monte Carlo.
- First estimation of the event energy is done by interpolating between S_{800} vs. $\sec\theta$ isoclines.



SD Energy Spectrum: Broken Power Law Fit



SD Energy Spectrum: GZK Feature



- 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 $10^{19.7} \text{ eV}$ bin:

$$- N_{\text{EXPECT}} = 54.9$$

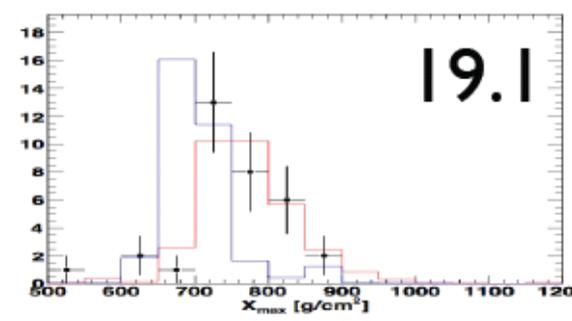
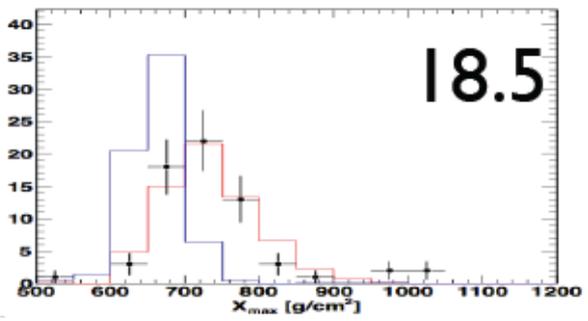
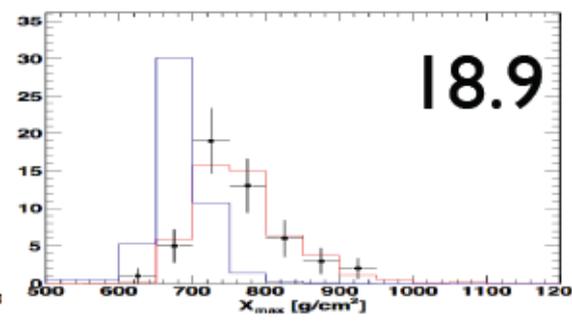
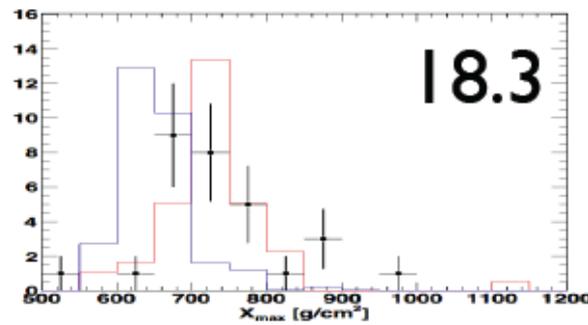
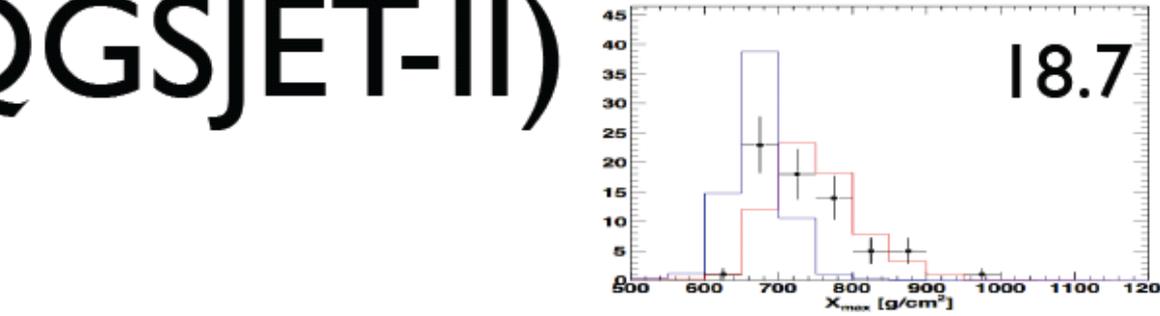
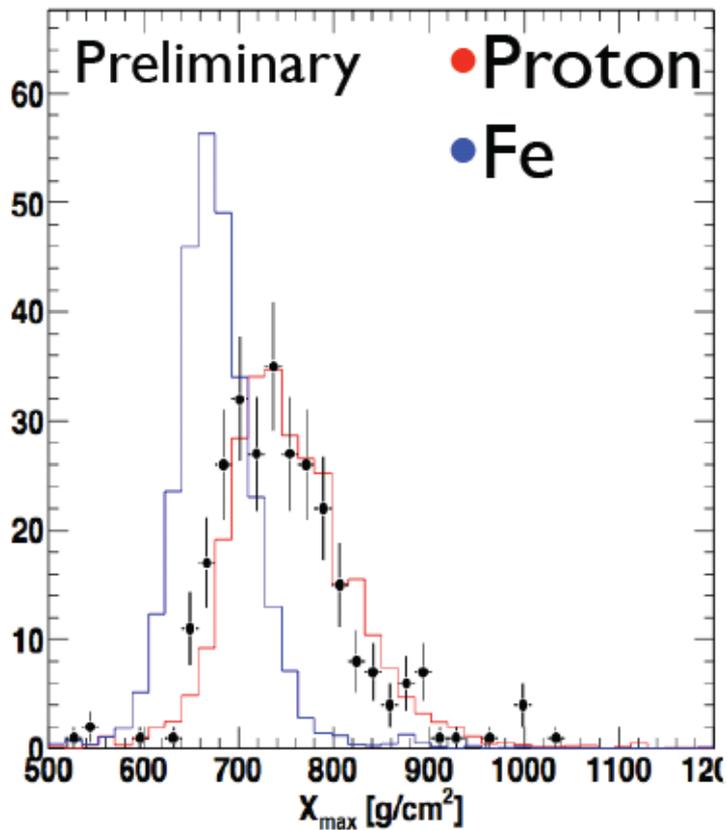
$$- N_{\text{OBSERVE}} = 28$$

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

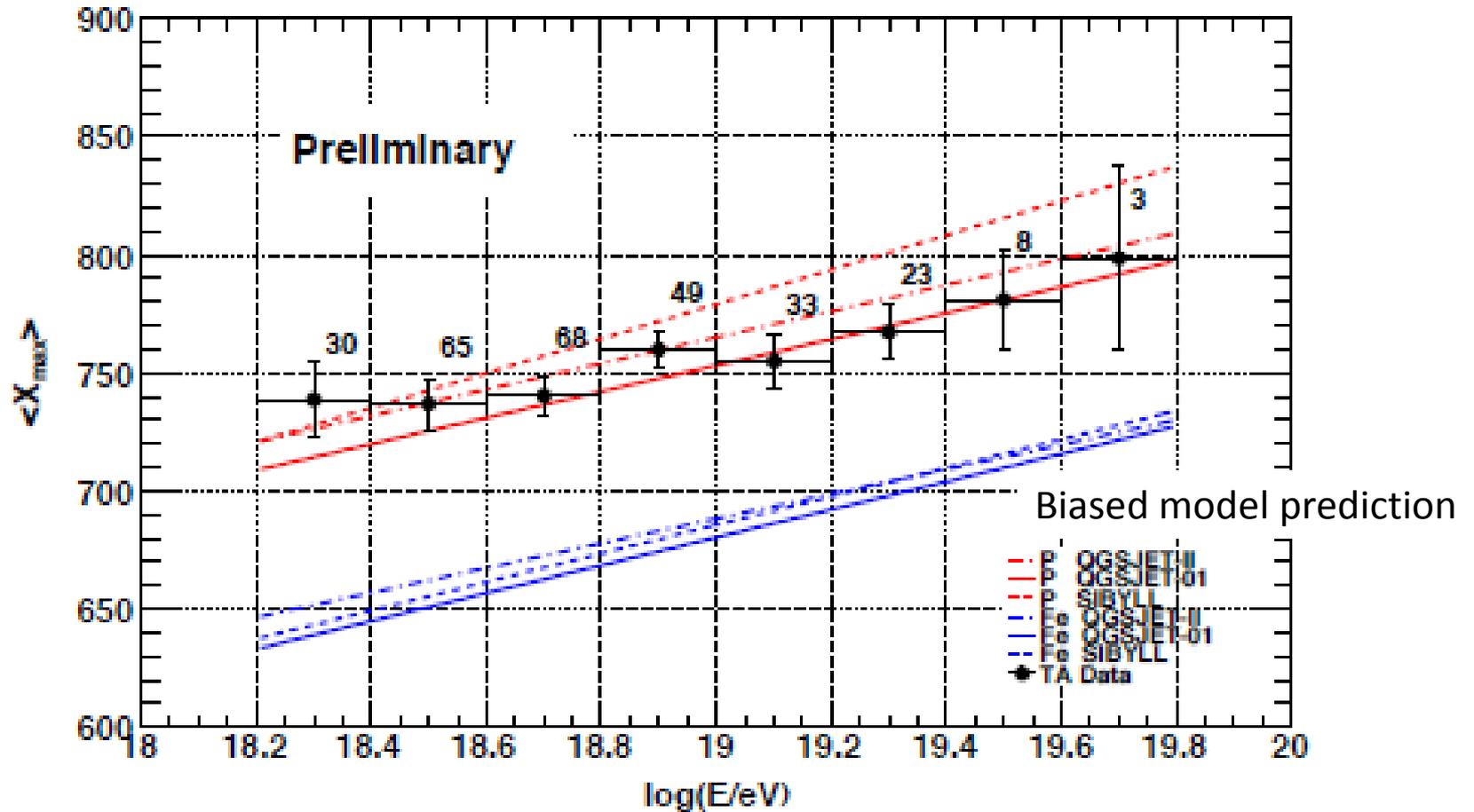
(3.9 σ)

Xmax Distribution MC/Data (QGSJET-II)

TA



Xmax

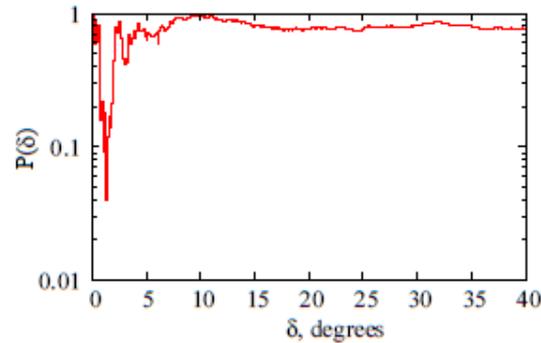
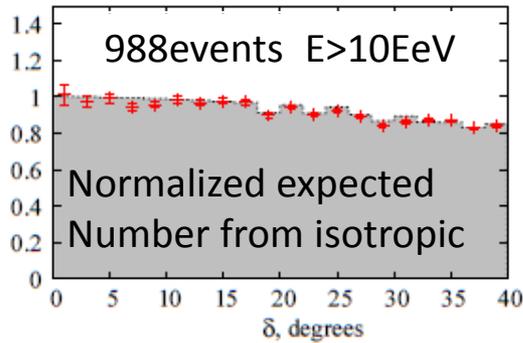


Biased model prediction: includes detection biases

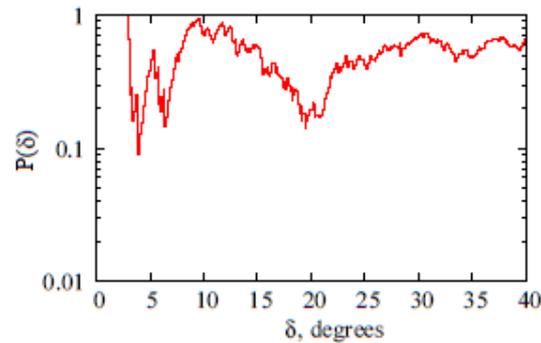
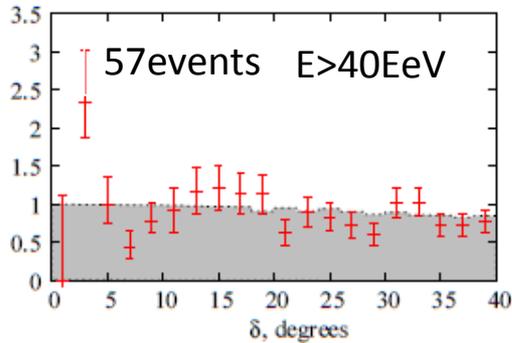
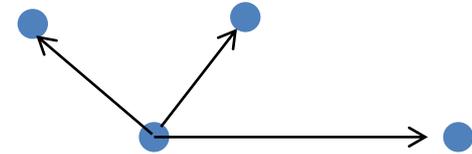
Event cut criteria: relaxed cut

Small scale correlation

of Observed /# of Expected



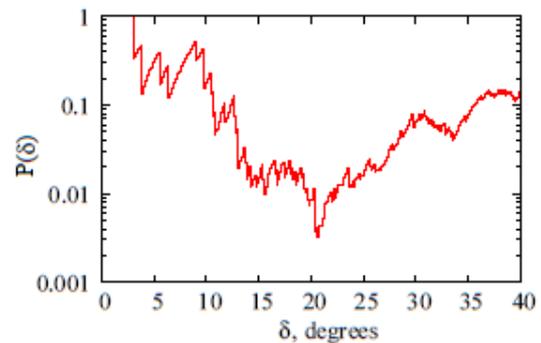
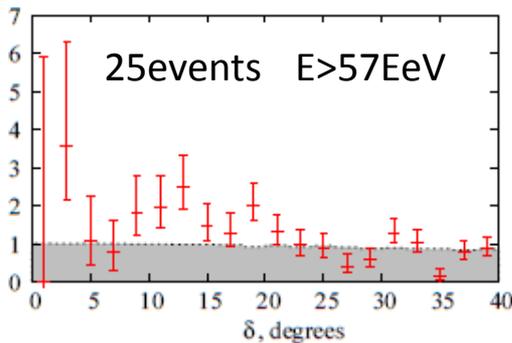
Auto correlation of arrival directions
of observed CR



Opening Angles

Observed CR
Energy > threshold

2008Mar11—2011Sep15

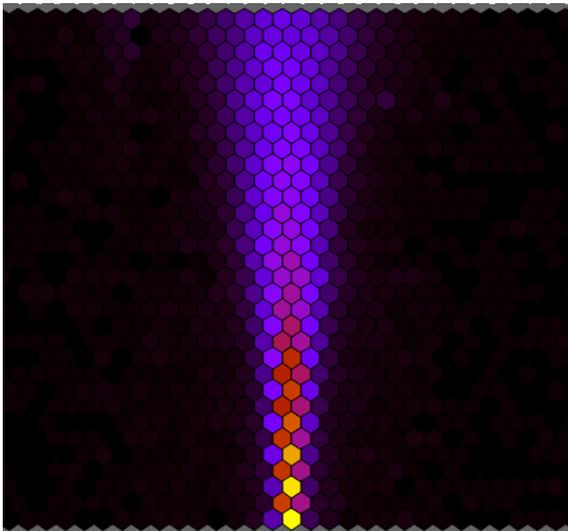


No significant correlation
Consistent with isotropic

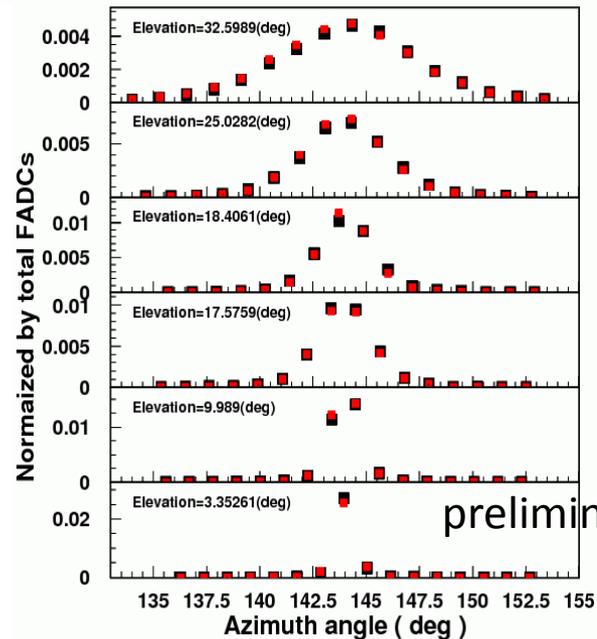
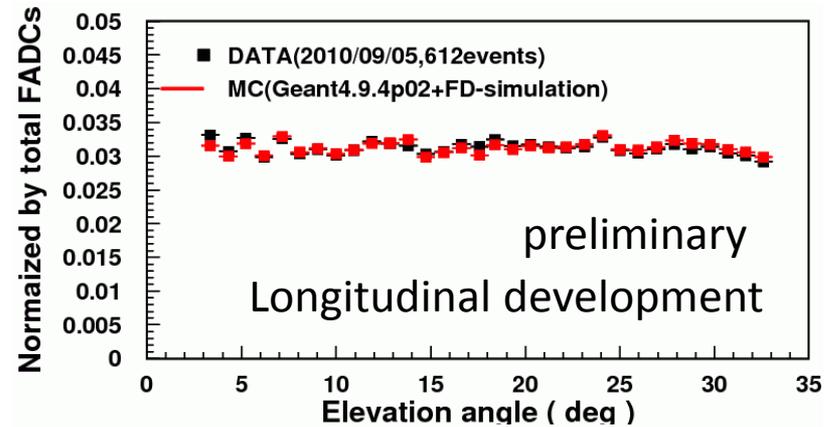
Submitted to ApJ
arXiv:1205.5984

Electron Light Source

40MeV, 10^9 electrons, 1Hz, 100 m from FD **FD End to End Calibration**



Observed Event



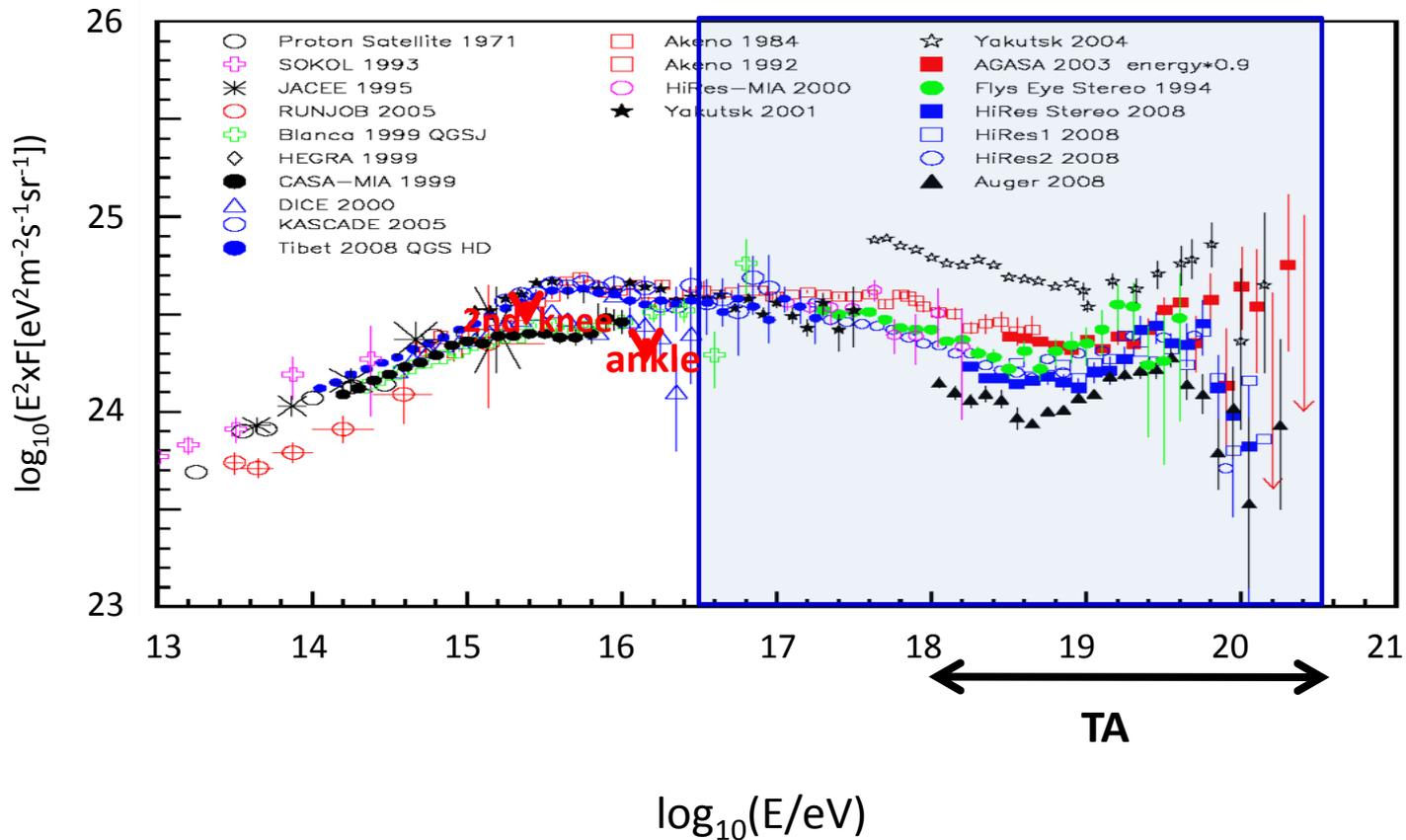
Lateral distribution

● Observed Data
● Simulation

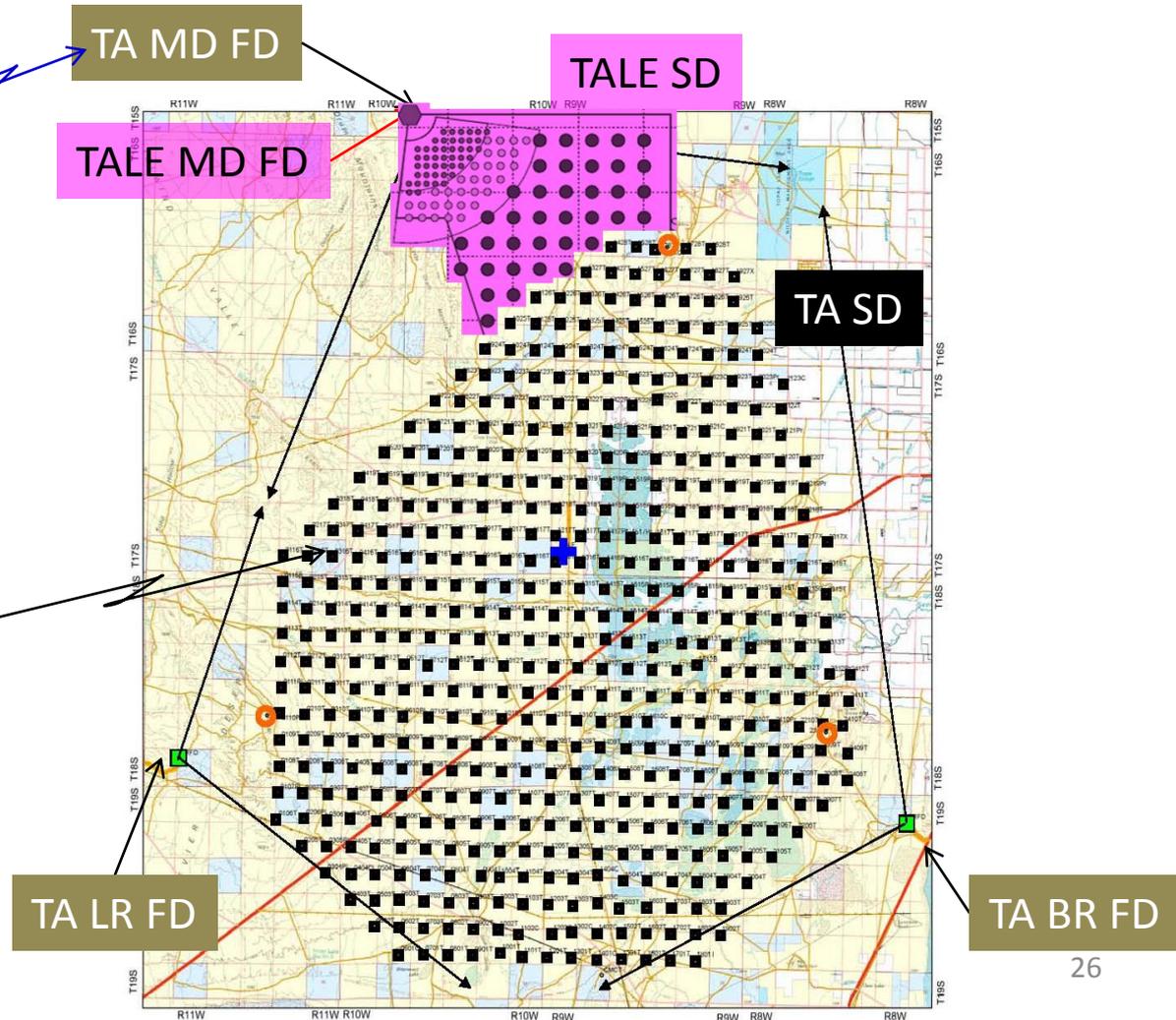
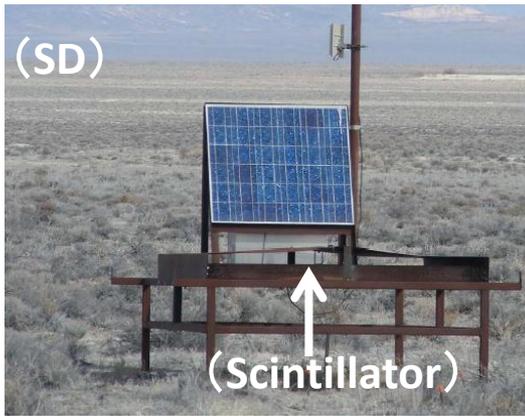
TA Low energy Extension (TALE)

Target Energy range: 16.5 to 19 (TALE)

Transition galactic and Extra-galactic CR



TA+TALE (under construction)



Energy Calibration
FD calibrated by ELS @TA
TA vs. TALE
FD vs. SD