Result from the Telescope Array Experiment

ICRR, The University of Tokyo
Yuichiro TAMEDA
for the Telescope Array collaboration

The TA Collaboration

T Abu-Zayyad[1], R Aida[2], M Allen[1], R Azuma[3], E Barcikowski[1], JW Belz[1], T Benno[4], DR Bergman[1], SA Blake[1], O Brusova[1], R Cady[1], BG Cheon[6], J Chiba[7], M Chikawa[4], EJ Cho[6], LS Cho[8], WR Cho[8], F Cohen[9], K Doura[4], C Ebeling[1], H Fujii[10], T Fujii[11], T Fukuda[3], M Fukushima[9,22], D Gorbunov[12], W Hanlon[1], K Hayashi[3], Y Hayashi[11], N Hayashida[9], K Hibino[13], K Hiyama[9], K Honda[2], G Hughes[5], T Iguchi[3], D Ikeda[9], K Ikuta[2], SJJ Innemee[5], N Inoue[14], T Ishii[2], R Ishimori[3], D Ivanov[5], S Iwamoto[2], CCH Jui[1], K Kadota[15], F Kakimoto[3], O Kalashev[12], T Kanbe[2], H Kang[16], K Kasahara[17], H Kawai[18], S Kawakami[11], S Kawana[14], E Kido[9], BG Kim[19], HB Kim[6], JH Kim[6], JH Kim[20], A Kitsugi[9], K Kobayashi[7], H Koers[21], Y Kondo[9], V Kuzmin[12], YJ Kwon[8], JH Lim[16], SI Lim[19], S Machida[3], K Martens[22], J Martineau[1], T Matsuda[10], T Matsuyama[11], JN Matthews[1], M Minamino[11], K Miyata[7], H Miyauchi[11], Y Murano[3], T Nakamura[23], SW Nam[19], T Nonaka[9], S Ogio[11], M Ohnishi[9], H Ohoka[9], T Okuda[11], A Oshima[11], S Ozawa[17], IH Park[19], D Rodriguez[1], SY Roh[20], G Rubtsov[12], D Ryu[20], H Sagawa[9], N Sakurai[9], LM Scott[5], PD Shah[1], T Shibata[9], H Shimodaira[9], BK Shin[6], JD Smith[1], P Sokolsky[1], TJ Sonley[1], RW Springer[1], BT Stokes[5], SR Stratton[5], S Suzuki[10], Y Takahashi[9], M Takeda[9], A Taketa[9], M Takita[9], Y Tameda[3], H Tanaka[11], K Tanaka[24], M Tanaka[10], JR Thomas[1], SB Thomas[1], GB Thomson[1], P Tinyakov[12,21], I Tkachev[12], H Tokuno[9], T Tomida[2], R Torii[9], S Troitsky[12], Y Tsunesada[3], Y Tsuyuguchi[2], Y Uchihori[25], S Udo[13], H Ukai[2], B Van Klaveren[1], Y Wada[14], M Wood[1], T Yamakawa[9], Y Yamakawa[9], H Yamaoka[10], J Yang[19], S Yoshida[18], H Yoshii[26], Z Zundel[1]

[1]University of Utah, [2]University of Yamanashi, [3]Tokyo Institute of Technology, [4]Kinki University, [5]Rutgers University, [6]Hanyang University, [7]Tokyo University of Science, [8]Yonsei University, [9]Institute for Cosmic Ray Research, University of Tokyo, [10]Institute of Particle and Nuclear Studies, KEK, [11]Osaka City University, [12]Institute for Nuclear Research of the Russian Academy of Sciences, [13]Kanagawa University, [14]Saitama University, [15]Tokyo City University, [16]Pusan National University, [17]Waseda University, [18]Chiba University [19]Ewha Womans University, [20]Chungnam National University, [21]University Libre de Bruxelles, [22]University of Tokyo, [23]Kochi University, [24]Hiroshima City University, [25]National Institute of Radiological Science, Japan, [26]Ehime University

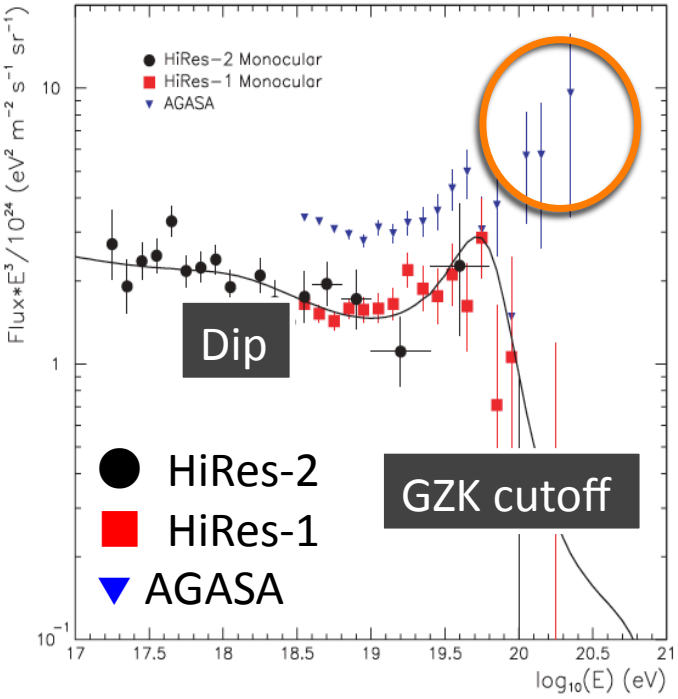
Outline

- Ultra High Energy Cosmic rays
- Telescope Array Experiment
  - Surface detector
  - Fluorescence detector
- Results
  - Energy spectrum
  - Photon Limit
  - Mass Composition
- Summary

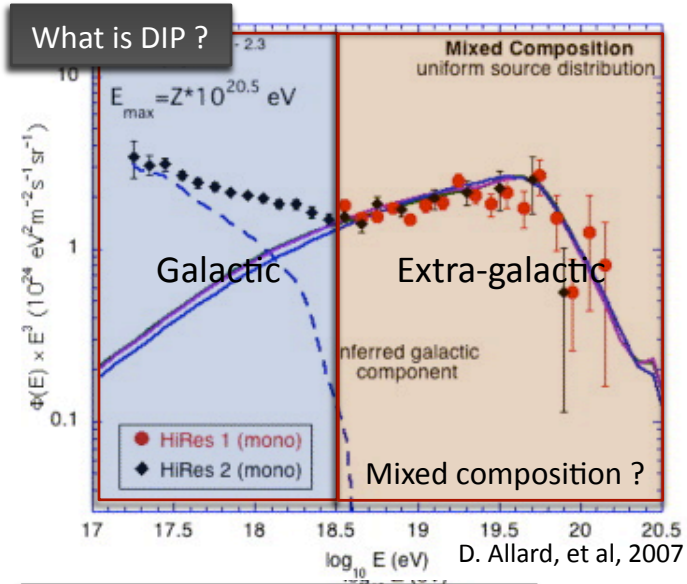
Ultra High Energy Cosmic Rays

Ultra High Energy Cosmic Ray

1. Energy Spectrum
2. Mass composition
3. Arrival direction

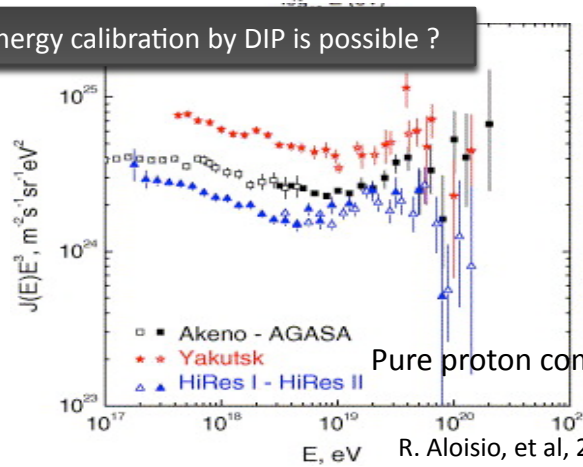


What is DIP ?



D. Allard, et al, 2007

Energy calibration by DIP is possible ?

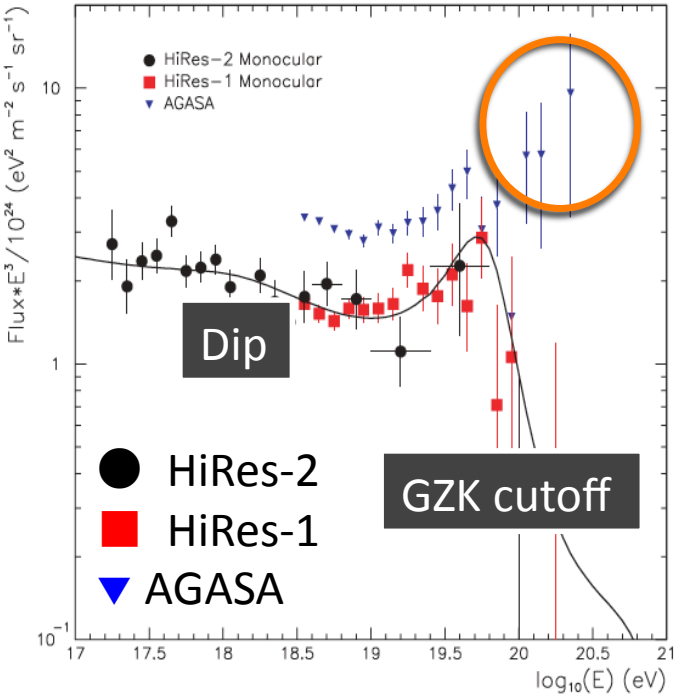


Pure proton composition ?

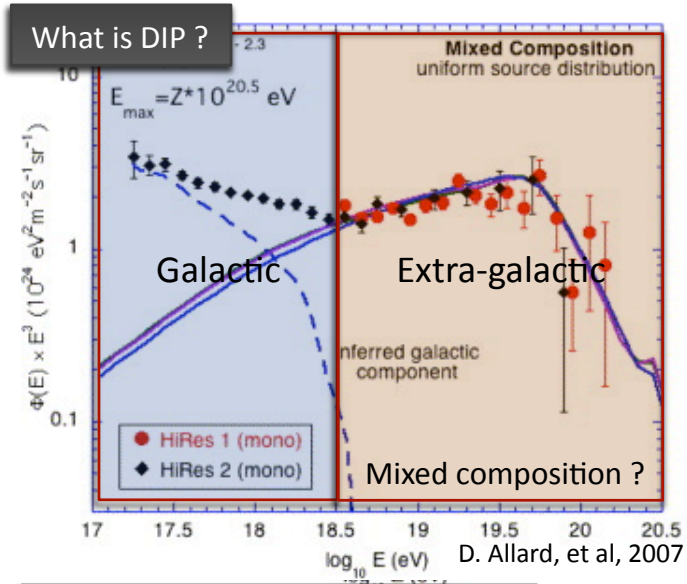
R. Aloisio, et al, 2007

Ultra High Energy Cosmic Ray

1. Energy Spectrum
2. Mass composition
3. Arrival direction

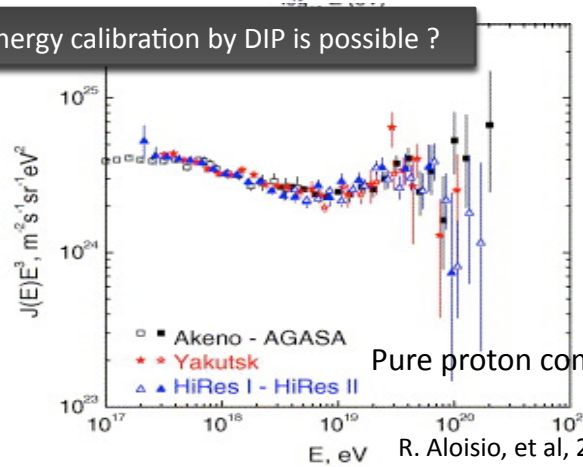


What is DIP ?



D. Allard, et al, 2007

Energy calibration by DIP is possible ?



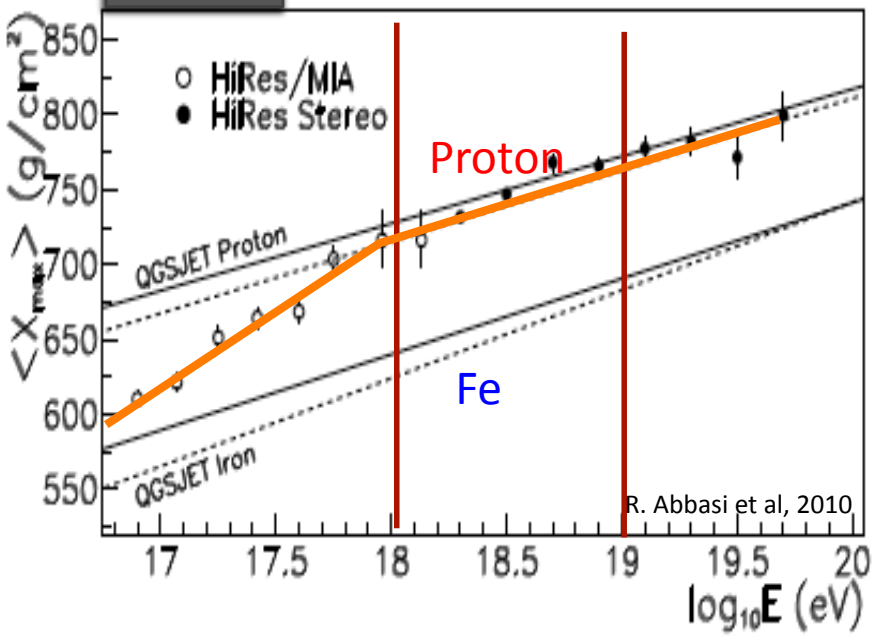
Pure proton composition ?

R. Aloisio, et al, 2007

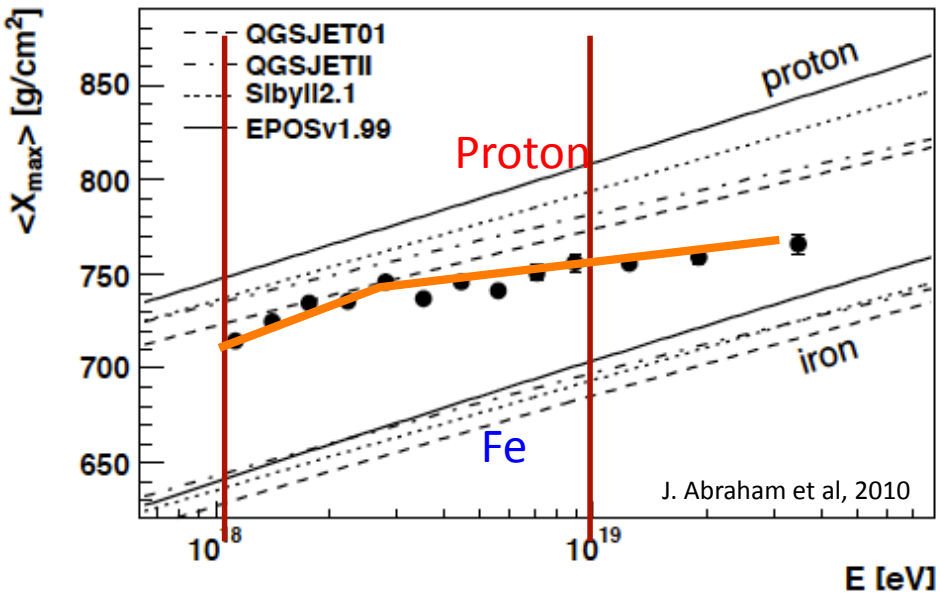
Ultra High Energy Cosmic Ray

1. Energy Spectrum
2. Mass composition
3. Arrival direction

HiRes



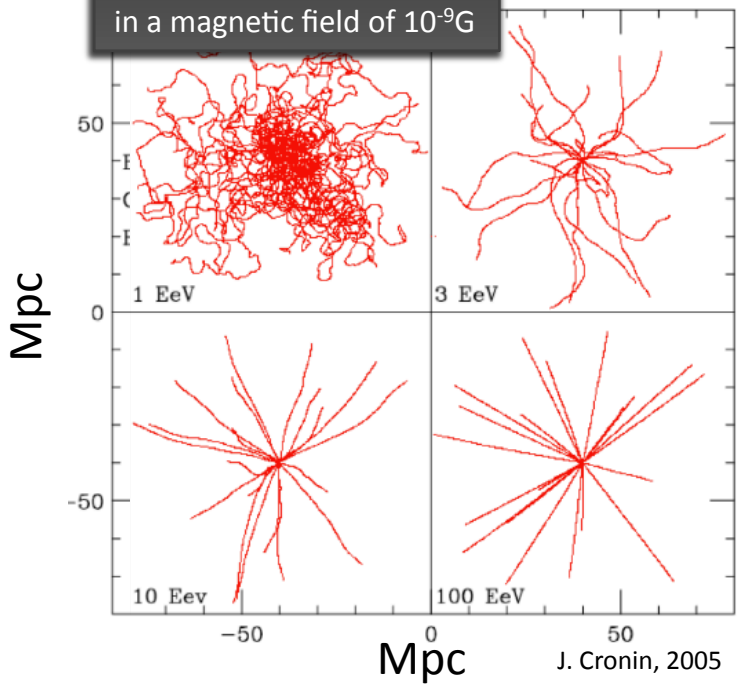
Pierre Auger Observatory (PAO)



Ultra High Energy Cosmic Ray

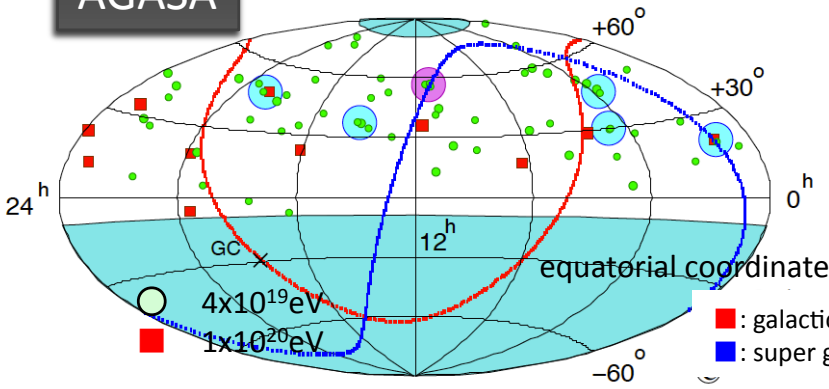
1. Energy Spectrum
2. Mass composition
3. Arrival direction

Proton propagation
in a magnetic field of 10^{-9}G



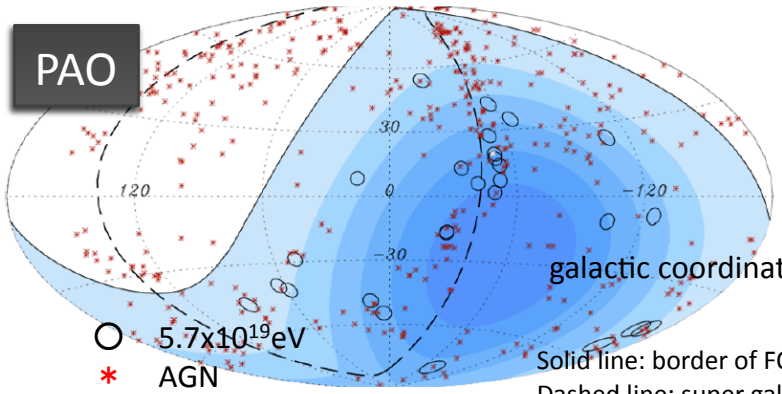
J. Cronin, 2005

AGASA



M.Takeda, et al. 1999

PAO

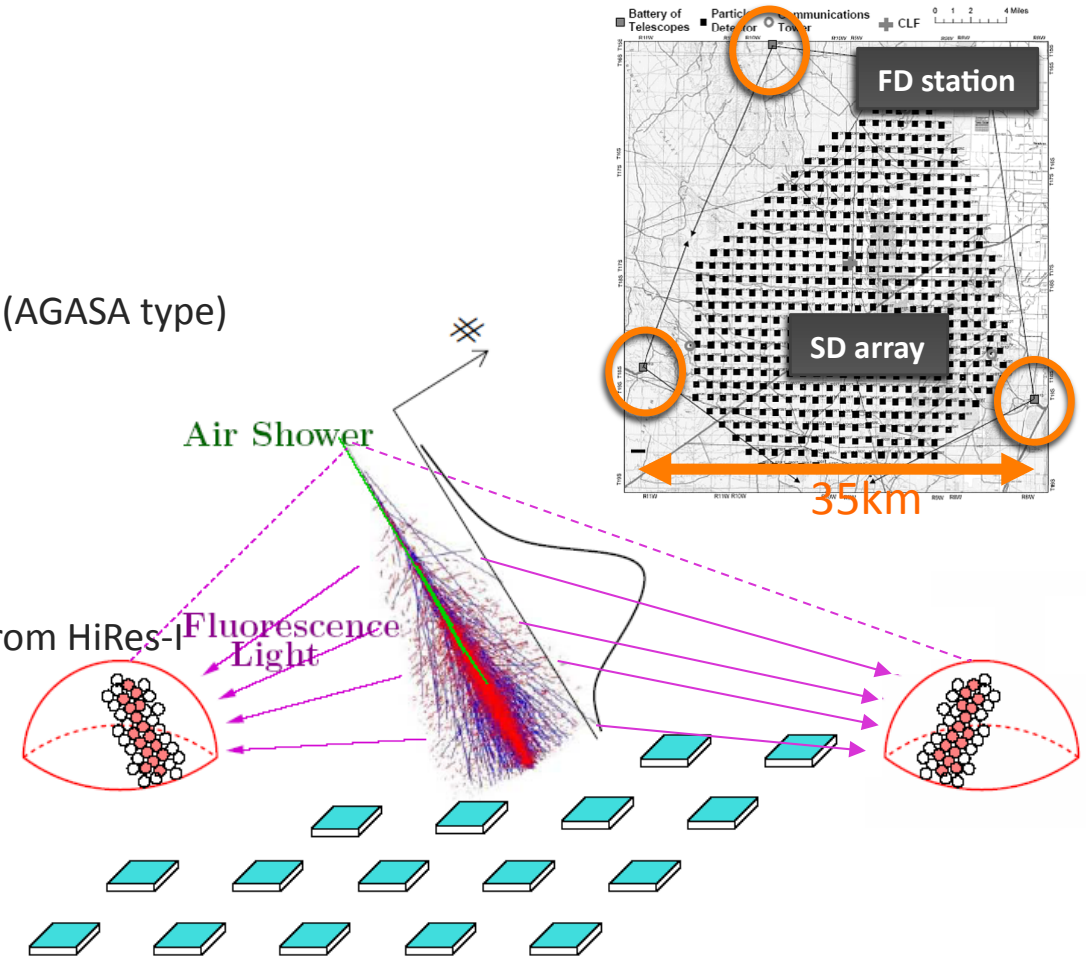


Solid line: border of FOV
Dashed line: super galactic plane
J.Abraham, et al. 2008

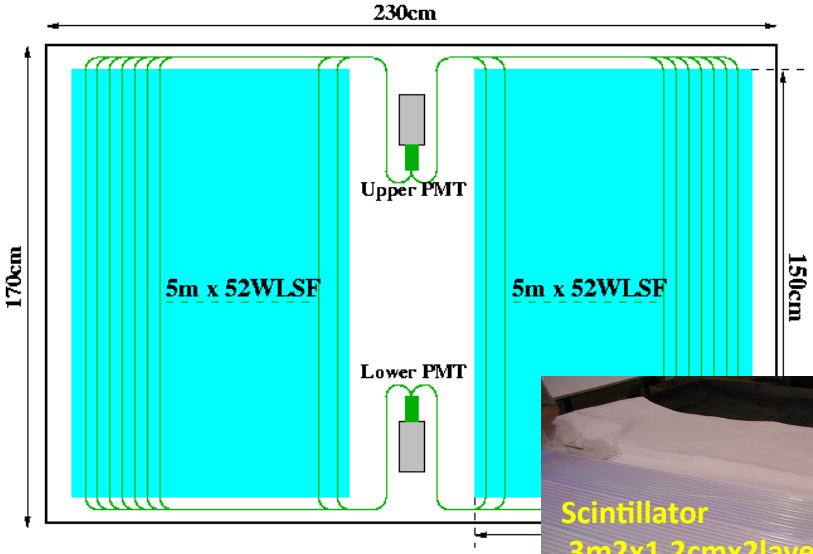
Telescope Array Experiment

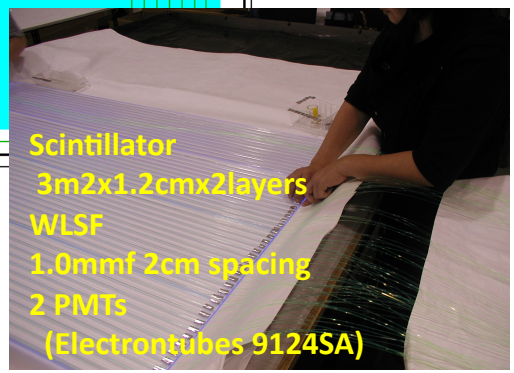
Telescope Array

- Hybrid detector for UHECRs
  - Western desert in Utah, USA
- Surface detector
  - 507 plastic scintillation counter (AGASA type)
  - 1.2 km spacing, 678 km^2
  - Particle density
- Fluorescence detector
  - Three FD stations
  - Northern site was transferred from HiRes-I
  - Longitudinal development
- FD obs. started : Oct, 2007
- SD obs. started : May, 2008

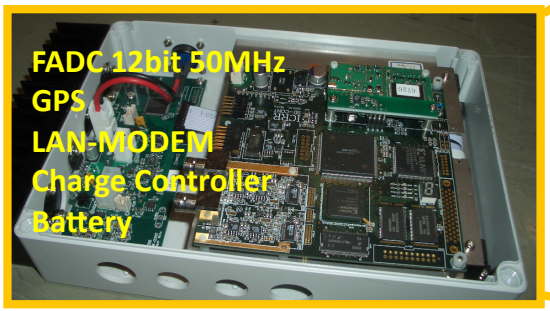


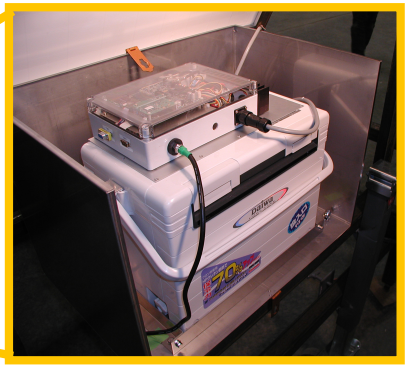
Surface Detector

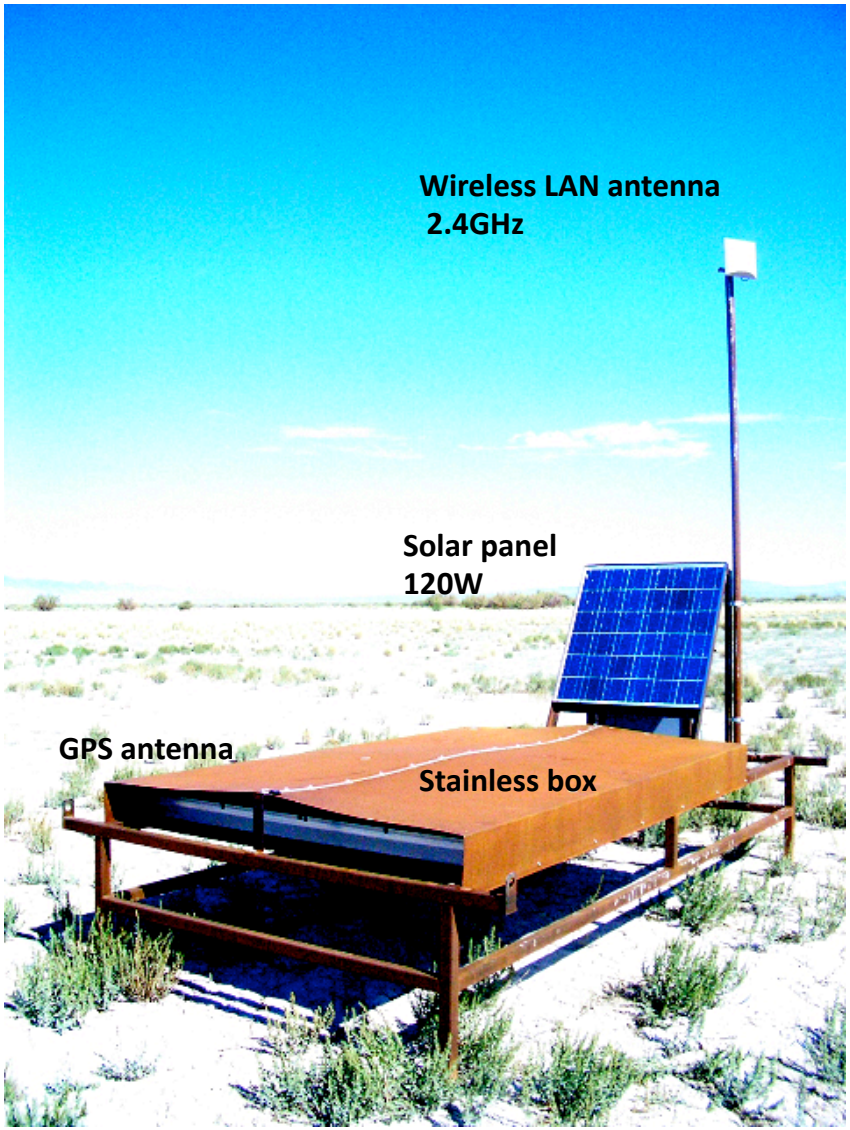




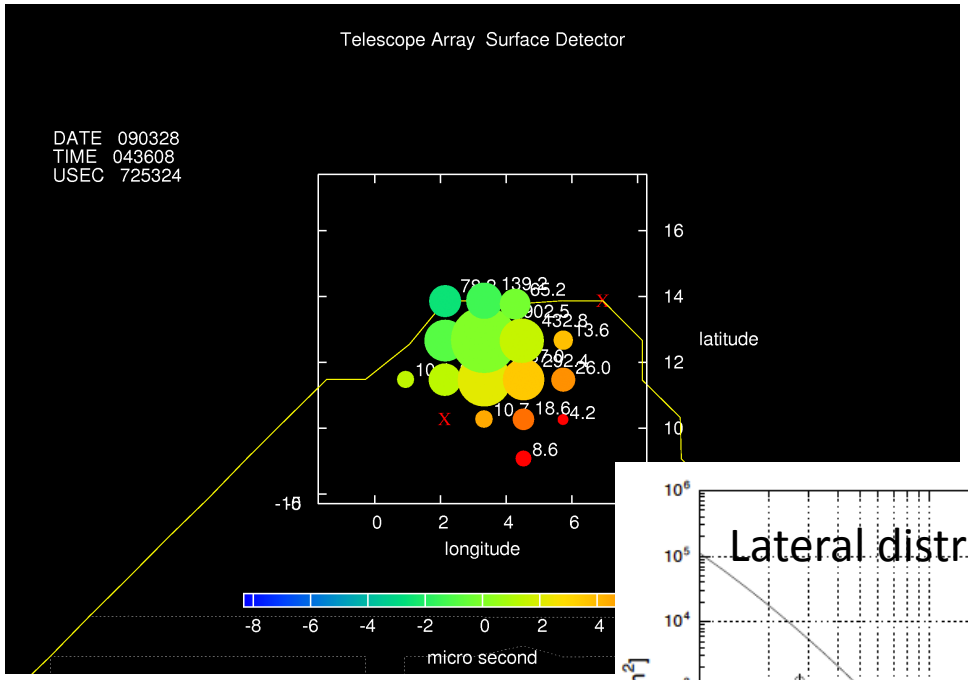
Upper & Lower layer are divided in optics



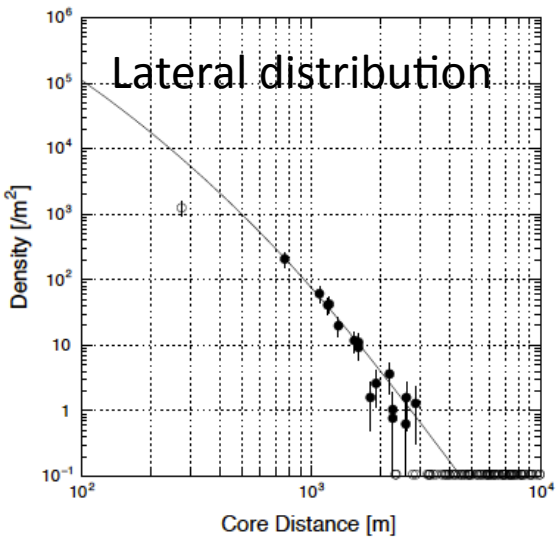


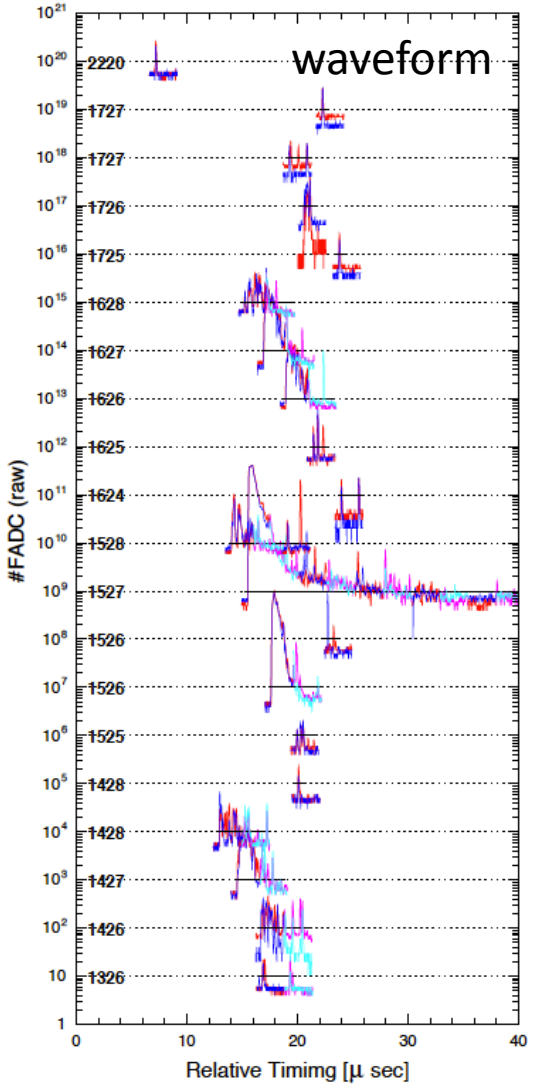


SD Event

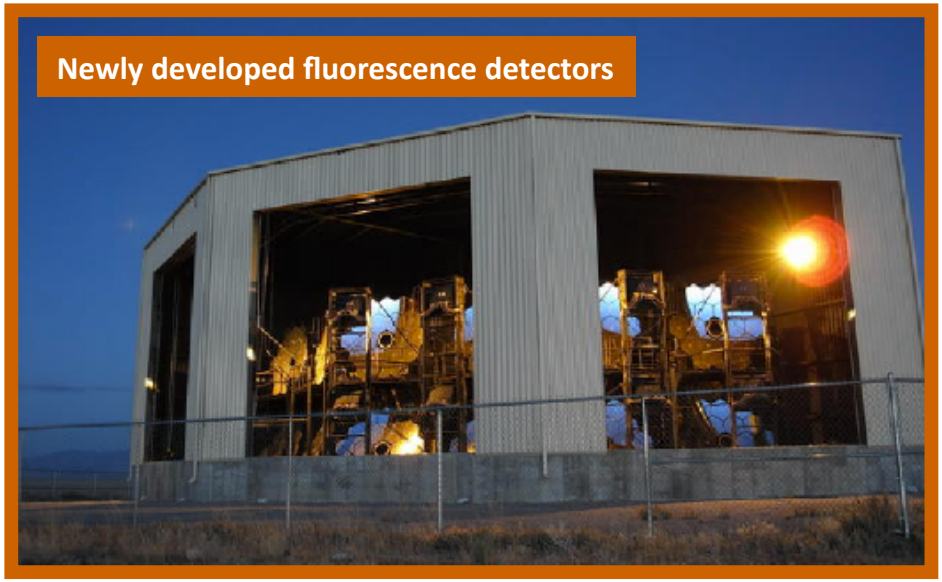


Mar. 28, 2009 04:36:08

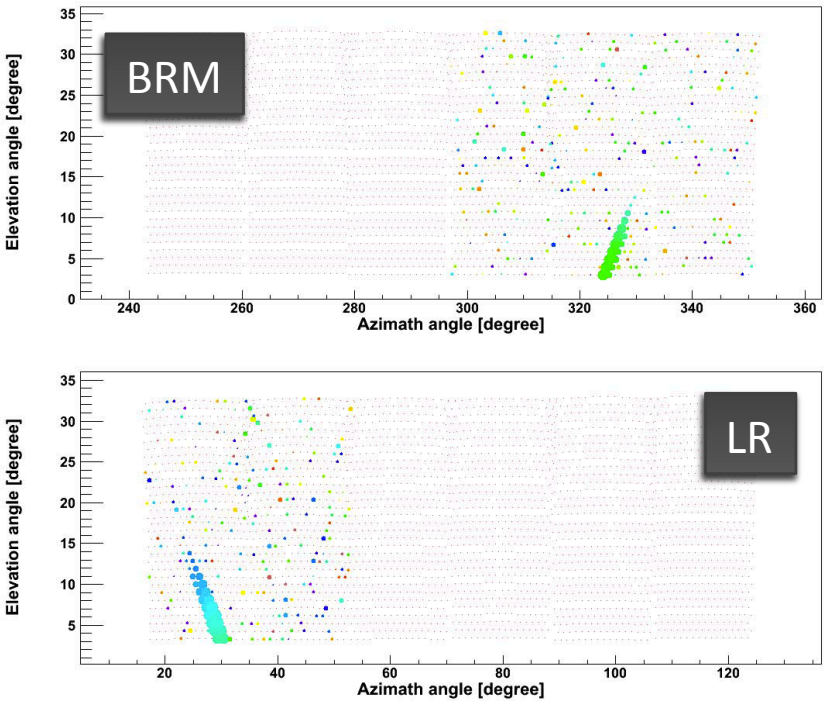


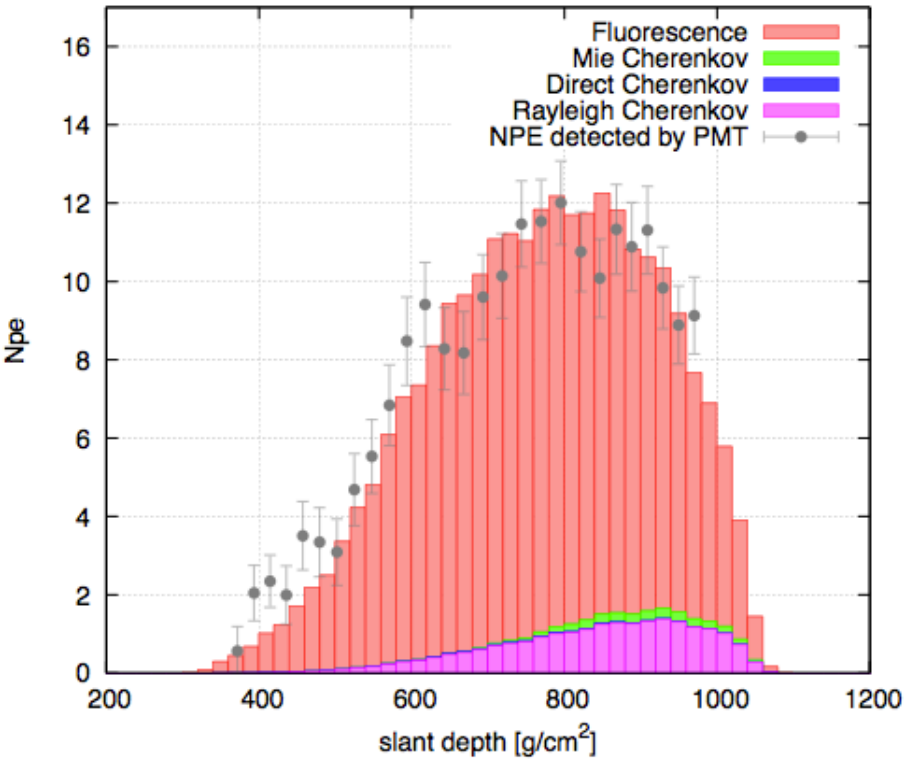


Fluorescence detector



FD Event





zenith	azimuth	core (km)	energy	Xmax
44.35°	-3.05°	-3.05, 14.24	5.11 x 10^{19}eV	894.3 g/cm^2

TA results (Preliminary)

- Energy Spectrum
  - MD
  - FD-SD Hybrid
- Photon Limit
- Mass Composition

TA-MD for energy spectrum

High energy aperture (>10^{19}eV) ≈1/2 HiRes-1

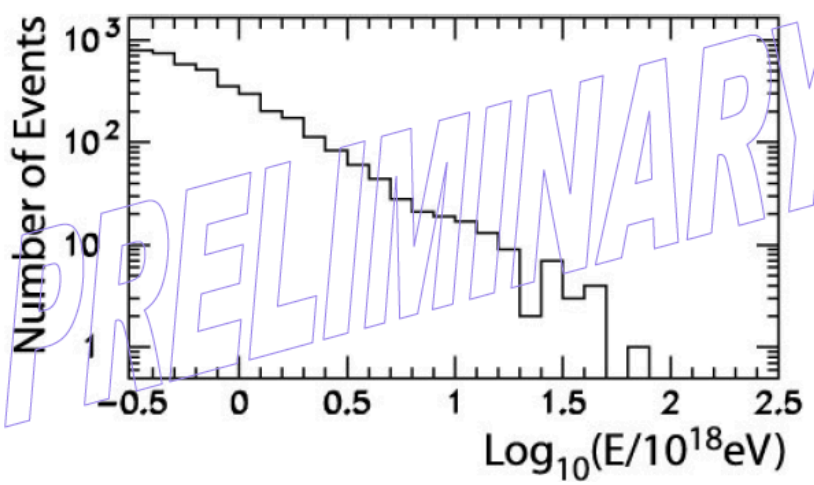
- Two ring configuration gives larger aperture than 1/3 HiRes-1
- One year of running: ≈1/10 of HiRes-1exposure @ 10^{19}eV
- HiRes-1 exposure ≈5 AGASA

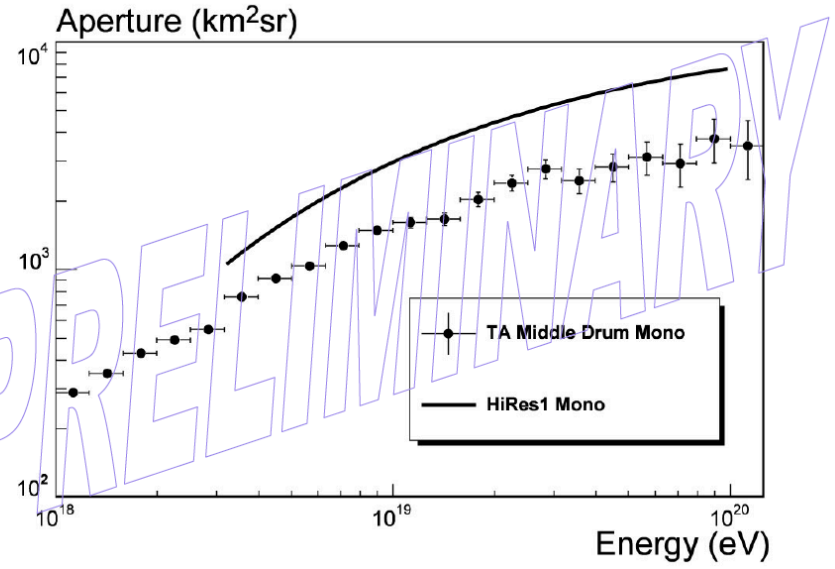
One year of TA-MD ≈1/2 AGASA

This data set is not quite big enough for GZK test!

12/16/2007 -12/07/2008: ~ 13500(=964 hrs = 11%)

good weather: ~ 11000(=786 hrs = 9%)

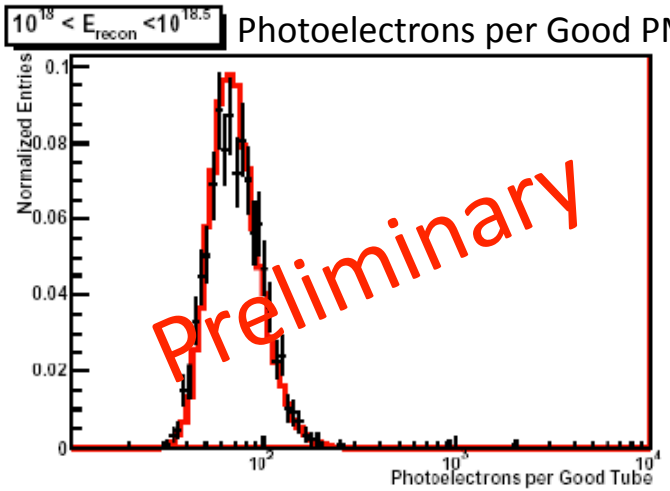


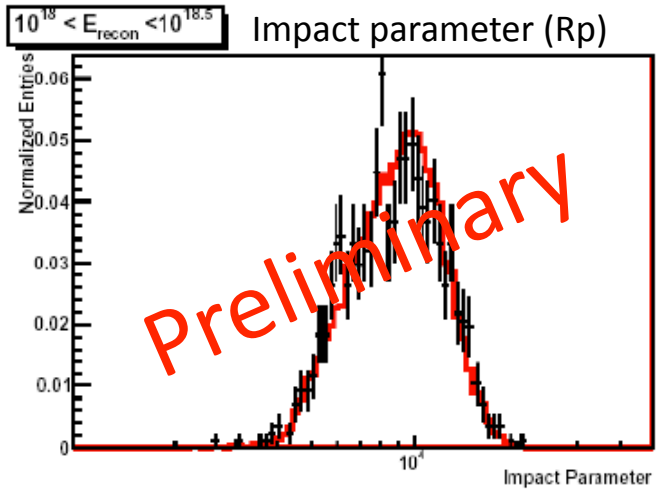


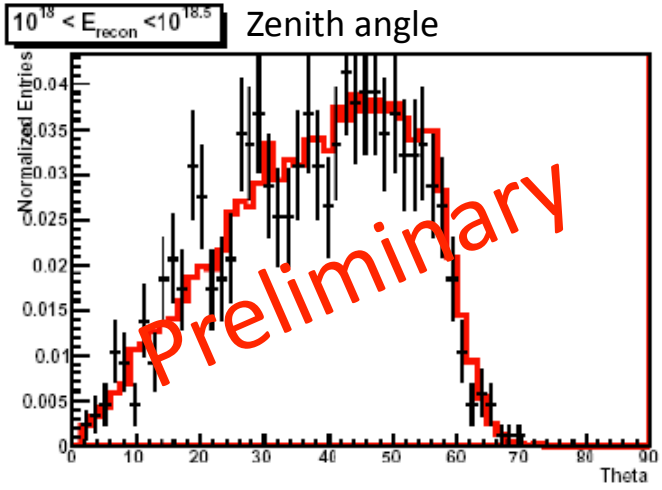
(ICRC2009)

TA-MD: Data MC comparison

Example of Data MC comparison
@ $10^{18\text{-}18.5}$eV

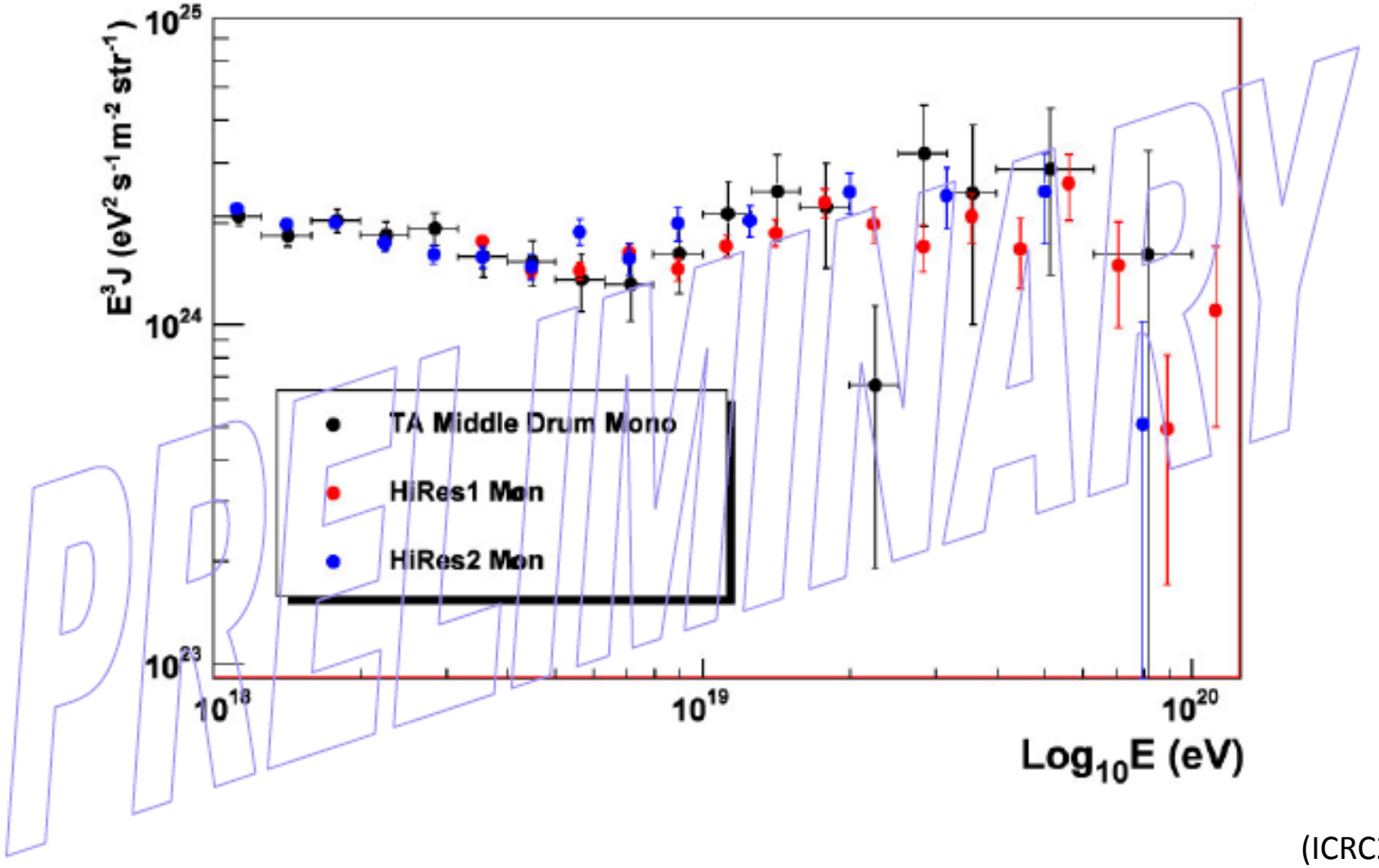






(ICRC2009)

TA-MD : Energy Spectrum



(ICRC2009)

TA-FD & SD Hybrid

TA Hybrid analysis

- Using signal arrival timing of FD and SD
- Angular resolution ~ 1.1deg (mono : ~4.7deg)

Using SD aperture

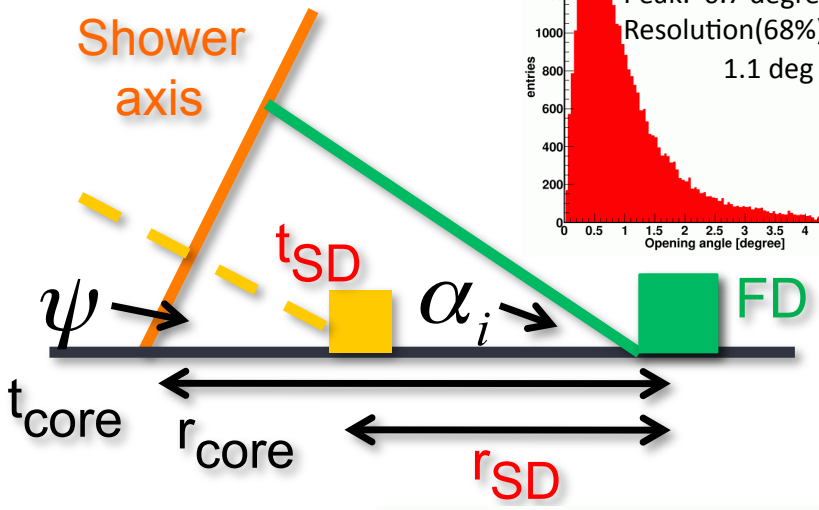
Constant above 10^{19}eV

Data set: BR + LR

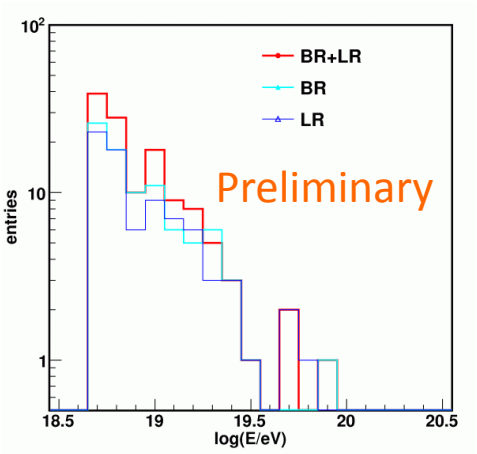
May/27/2008 – Sep/28/2009 (~1.5 years)

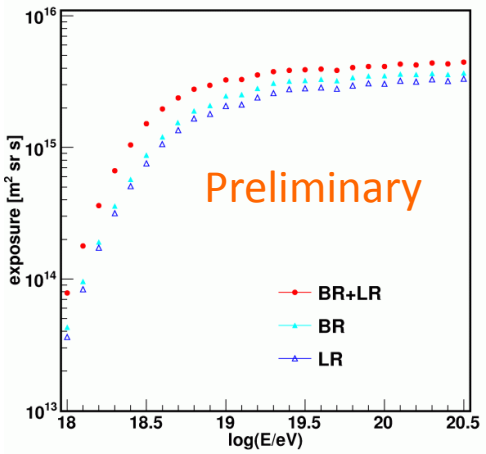
MC: Shower simulation : COSMOS

SD detector response : GEANT4

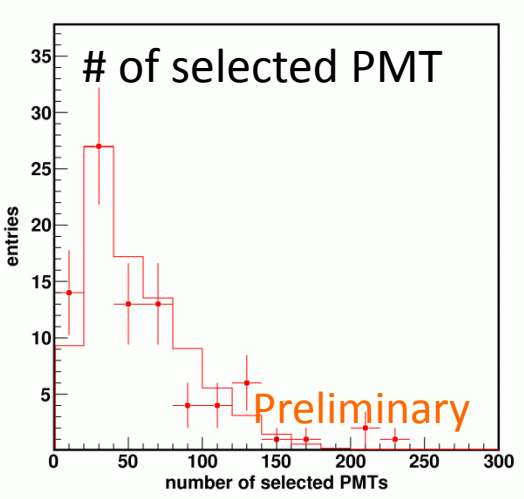


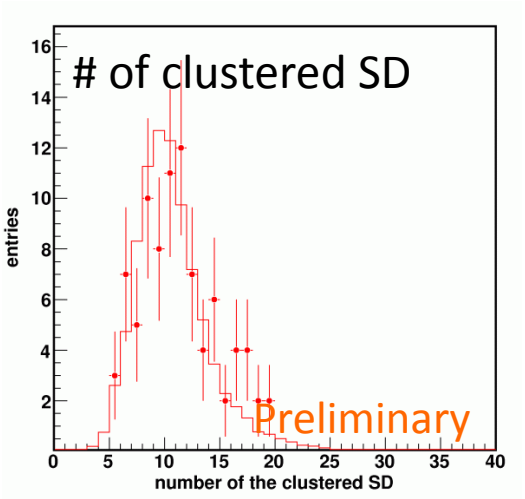
Primary energy	10^{18}eV ~ $10^{20.5}$eV with $E^{-3.1}$
Zenith angle	cosθ=0.65 (≒50degree) ~ 1
Primary particle	Proton
Thinning ratio	10^{-4} (≤10^{20}eV), 10^{-5}(> 10^{20}eV)
Interaction model	QGSJET II (> 80GeV) DPMJET III (<80GeV)
Cut threshold	100keV

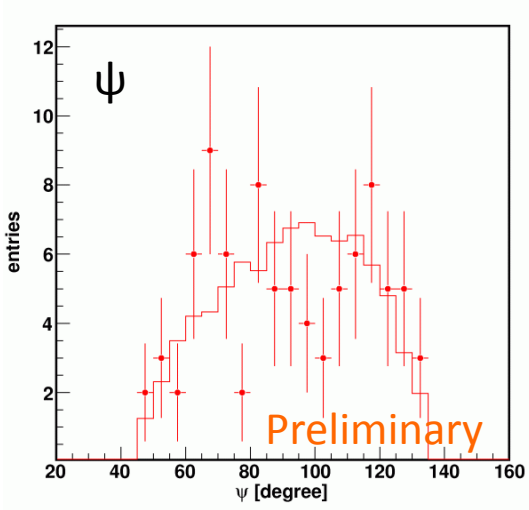


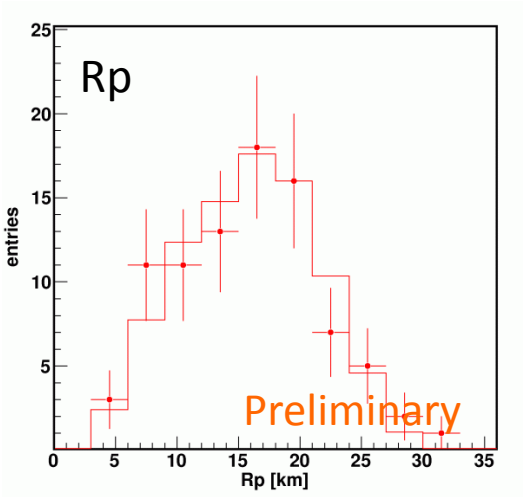


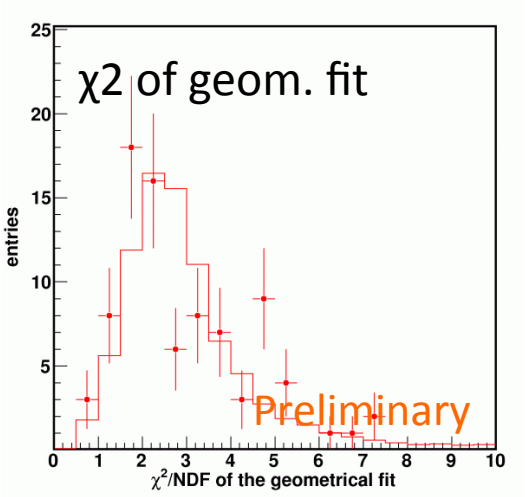
TA-Hybrid: Data MC Comparison

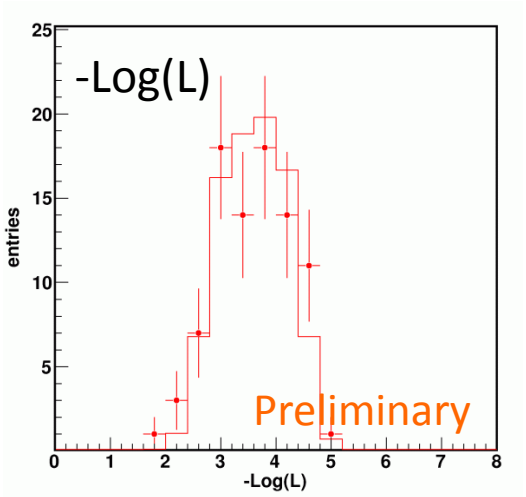




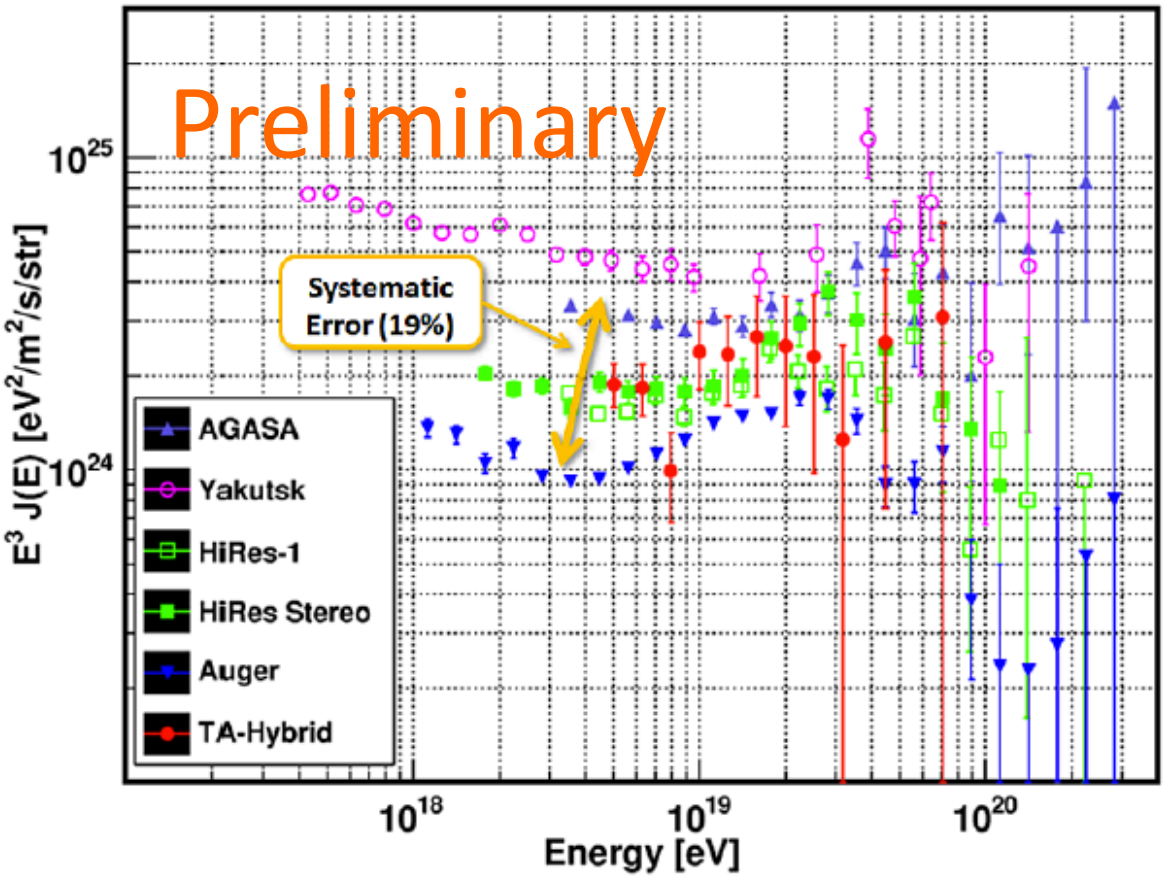








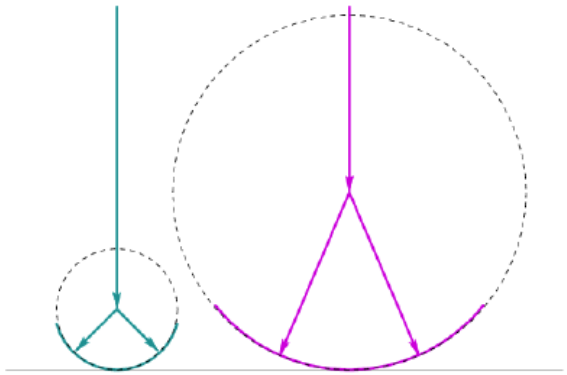
TA-Hybrid : Energy Spectrum

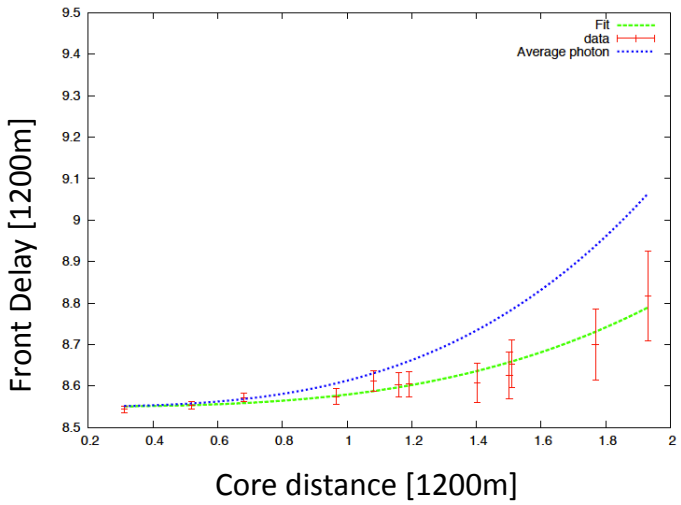


Systematic errors

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

TA-SD : Photon Search



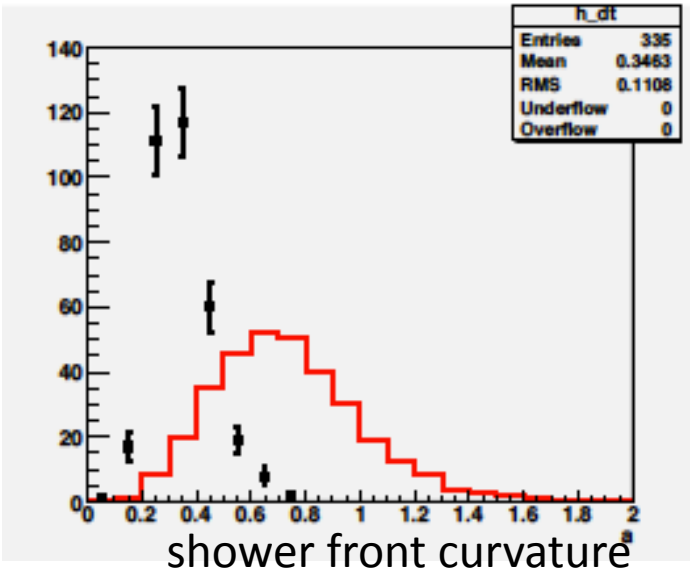


Event by event method

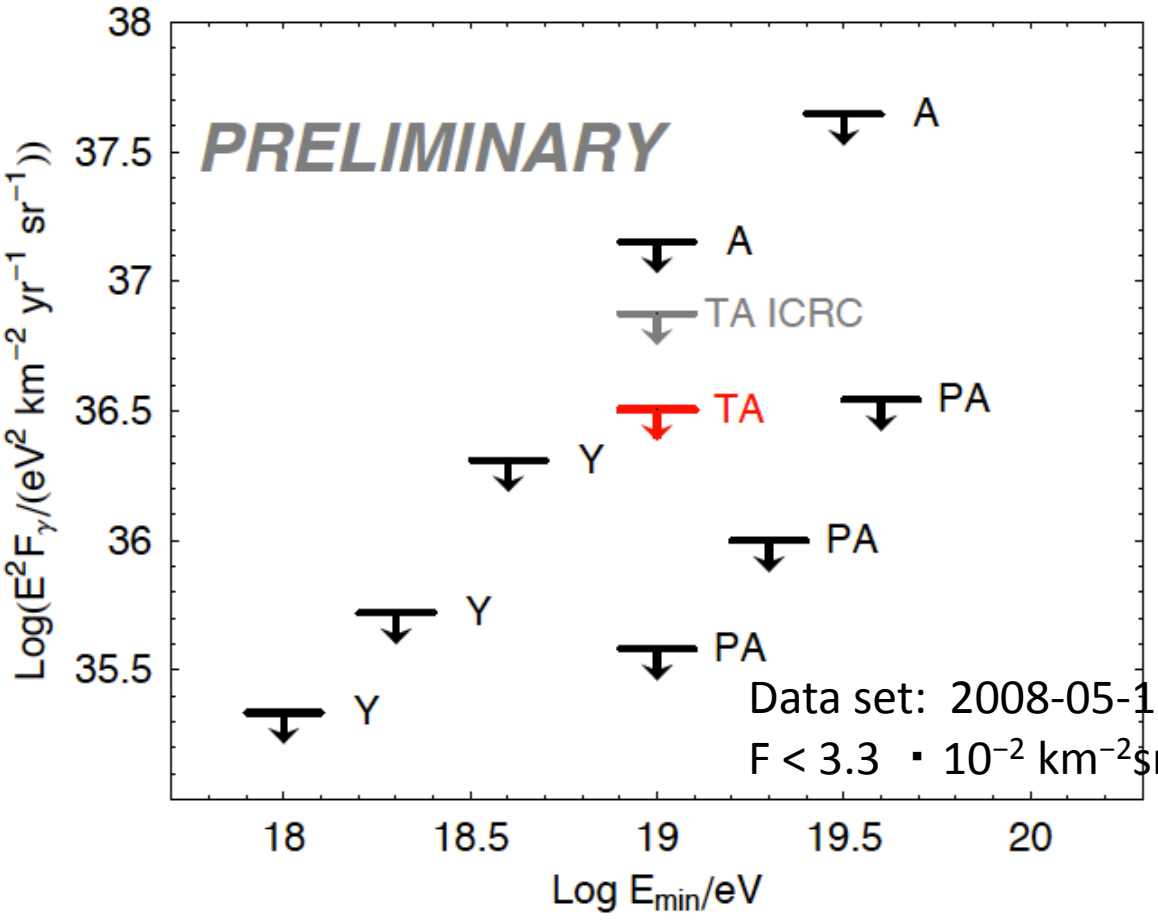
Using shower front curvature which is observable

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, $\theta \in [0, 60]$



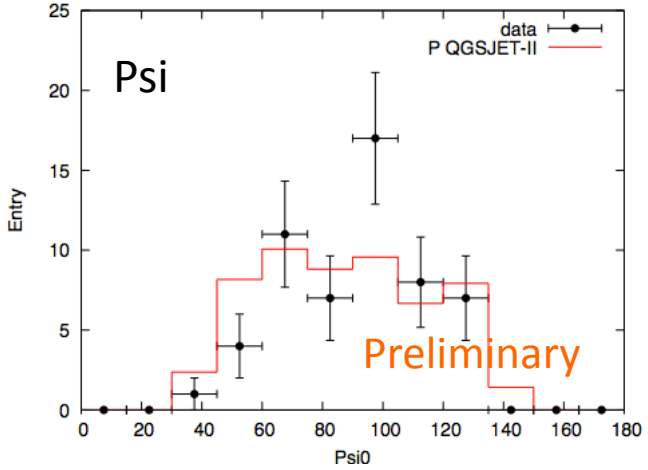
TA-SD Photon Limit

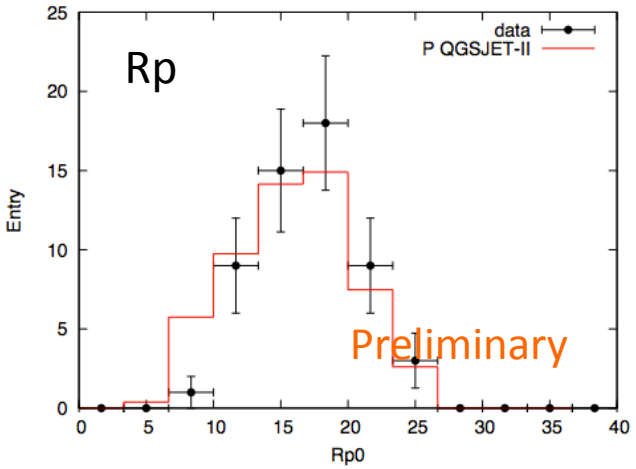


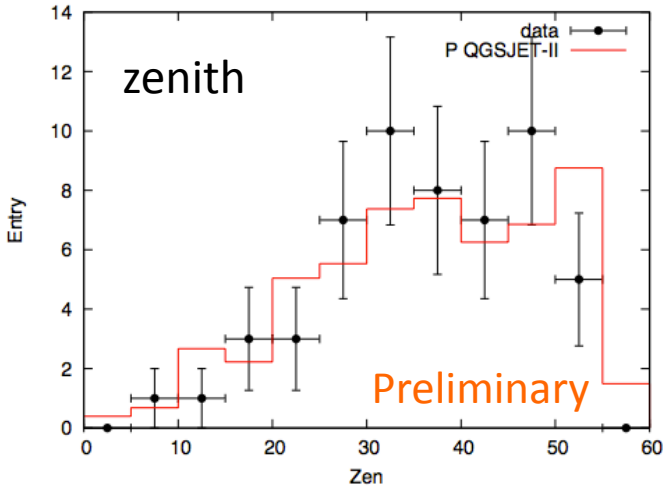
Data set: 2008-05-11 to 2009-10-08

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

TA-FD stereo : Data MC Comparison



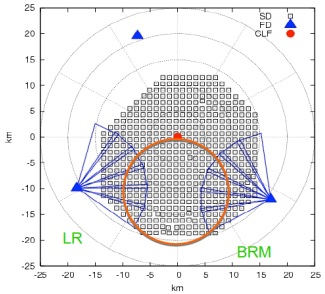




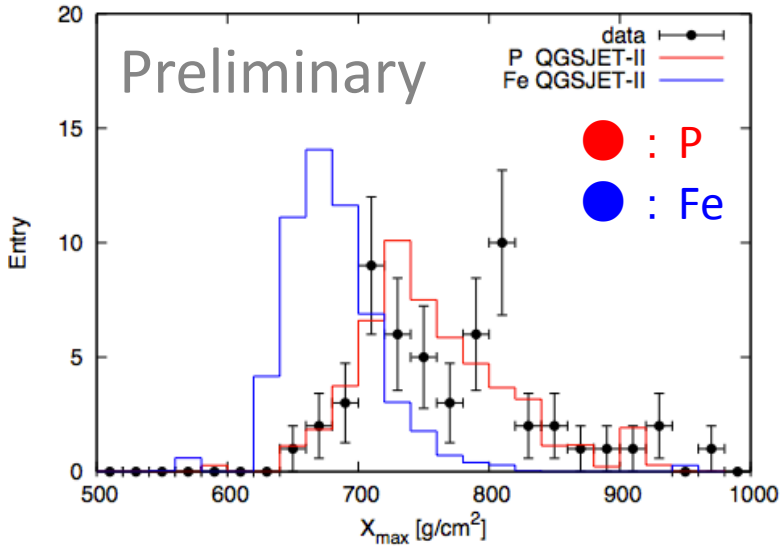
CORSIKA: QGSjet-II, QGSjet-01, SIBYLL
Proton, Iron
thinning factor : 10^{-4}

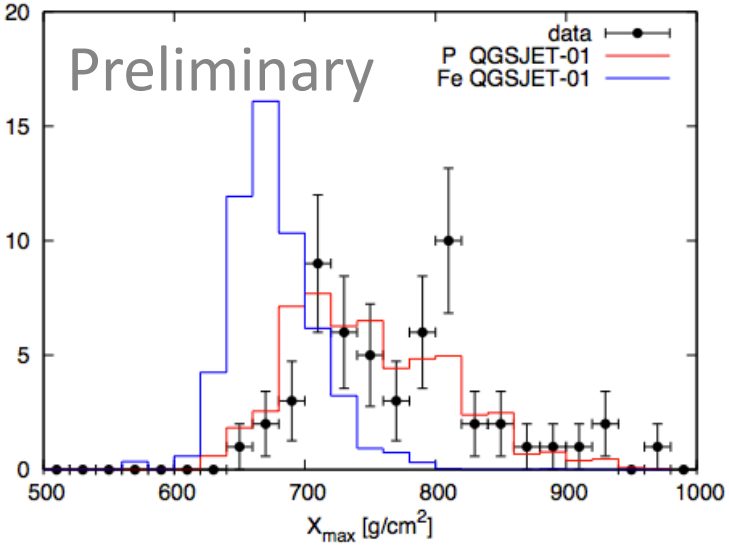
Data set: FD stereo Nov/2007 – Oct/2008

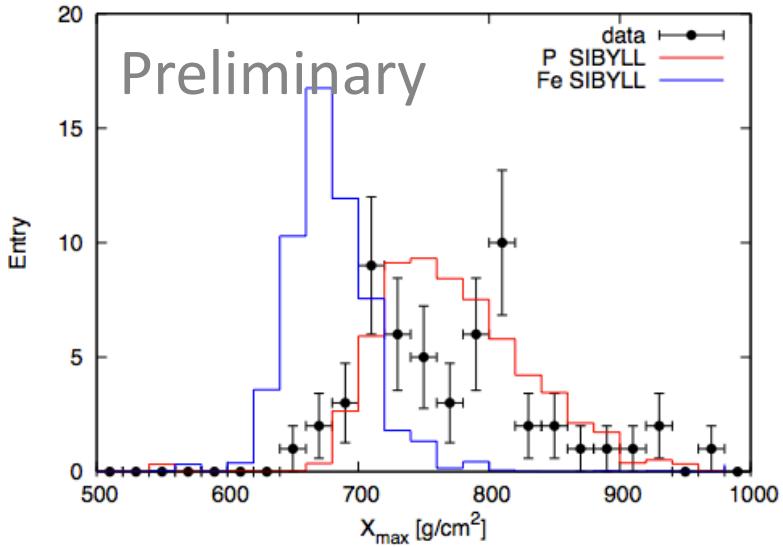
Selection
- Energy above $10^{18.6}$ eV
- zenith angle < 56deg
- core location : within 9.6km
- Xmax within the FOV



TA-FD stereo : Reconstructed Xmax distribution



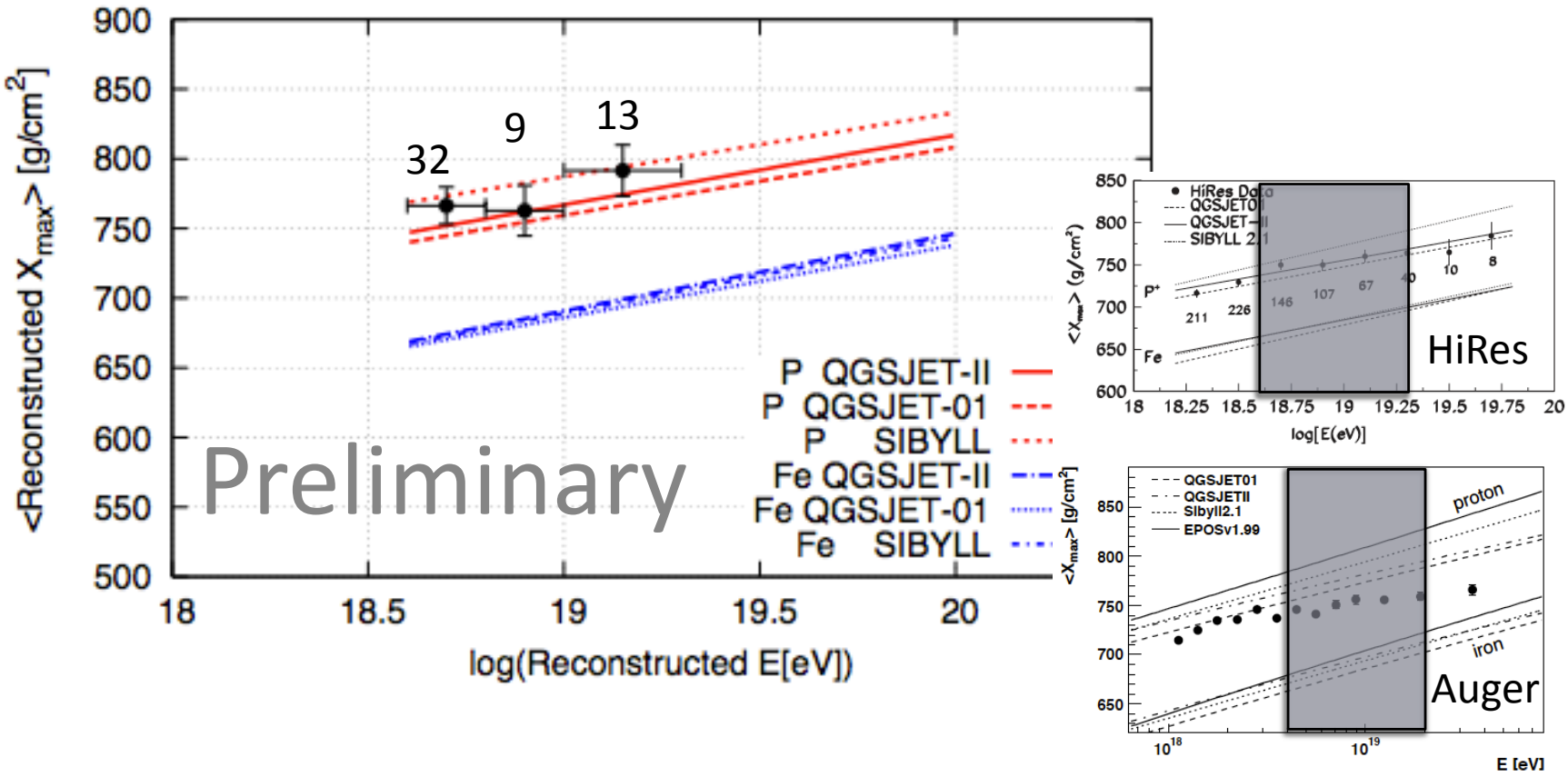




Chi^2 / dof

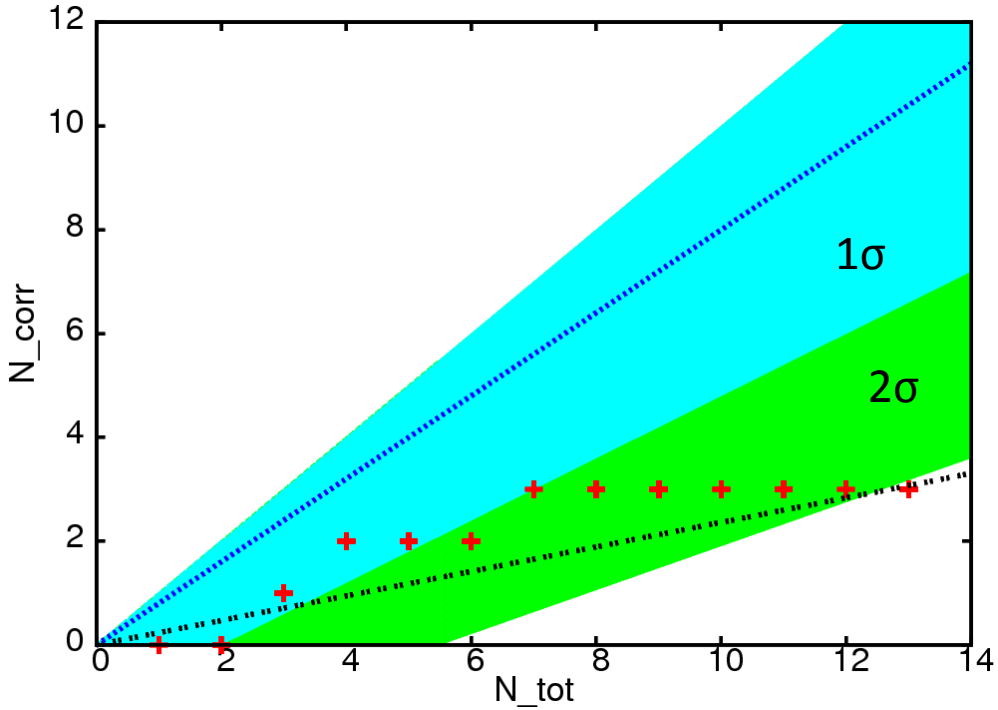
	QGSJET-II	QGSJET-01	SIBYLL
P	1.44	1.046	1.63
Fe	55.54	56.67	85.71

TA-FD stereo : Mass Composition



Search for AGN Correlation

- Auger found correlations with AGN's with (57 EeV, 3.1°,0.018). 14 events scanned + 13 event test sample appeared in Science article.
- Later Auger data (42 events) show no significant correlations.
- HiRes data (13 events) show no significant correlations.
- TA data (13 events) has 3 correlated events, 3.0 expected by chance.
- → **No Effect.**

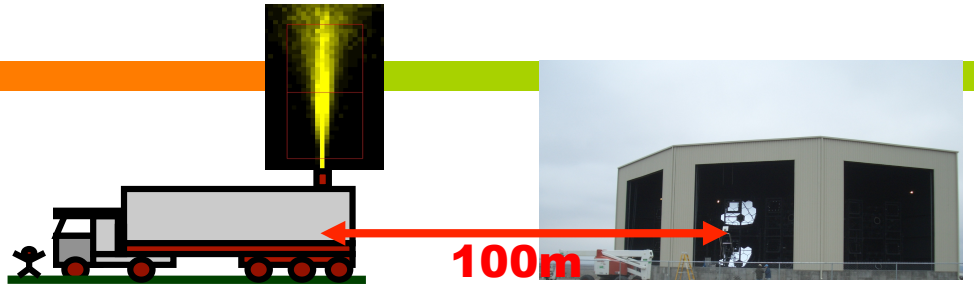


Summary

- Telescope Array:
  - Nov 2007 FD stereo observation started
  - May 2008 SD observation started
  - Detector performance are well understood by MC
- Results (preliminary)
  - MD, Hybrid Energy spectrum
    MD: Dec/16/2007 -Dec/07/2008
    Hybrid: May/27/2008 - Sep/28/2009
  - SD photon limit
    $F < 3.3 \cdot 10^{-2}\ km^{-2}sr^{-1}yr^{-1}$ (95% CL) /PRELIMINARY/
  - FD-stereo Mass composition
    consistent with Proton model @$10^{18.6\text{-}19.3}$eV
  - AGN Correlation
    No

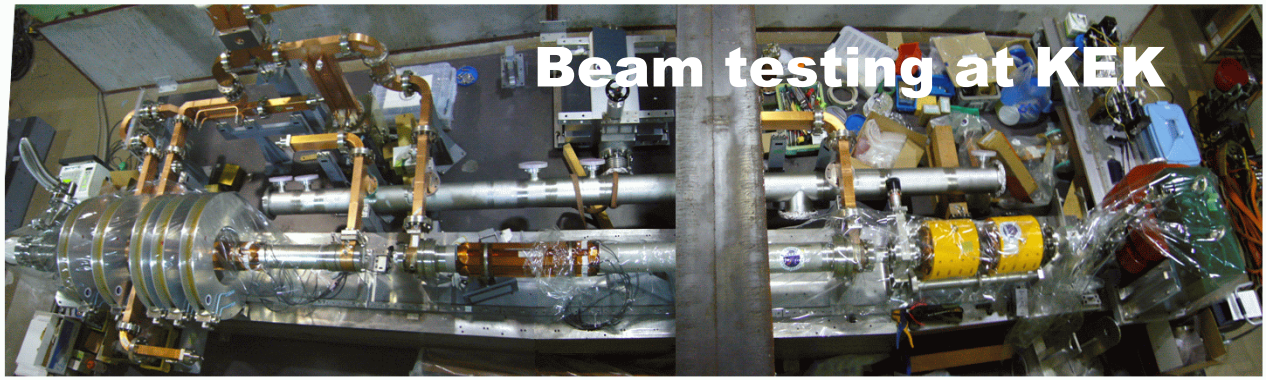
Merci.

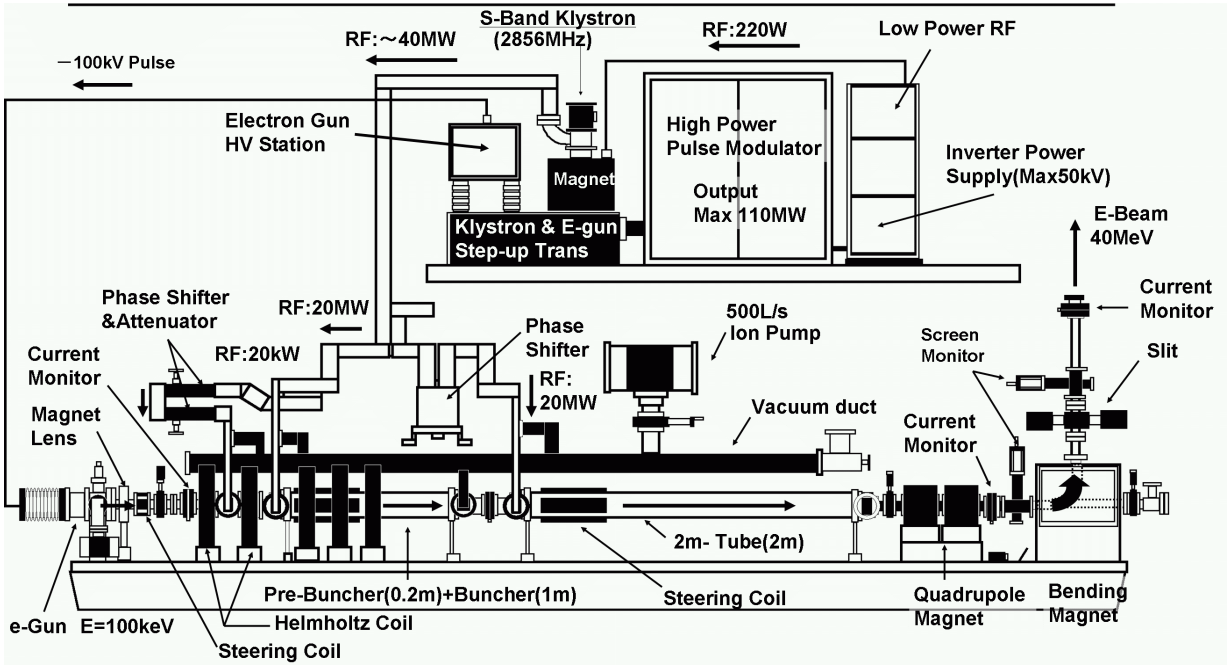
LINAC



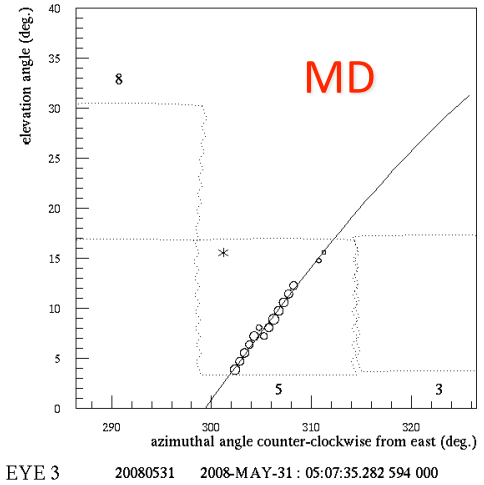
Electron beam
Energy: 40± 1 % MeV
Intensity: 10^9 e- (0.16nC)
Pulse width: 1 μ sec (300m)
Frequency: 1 Hz = 1pps

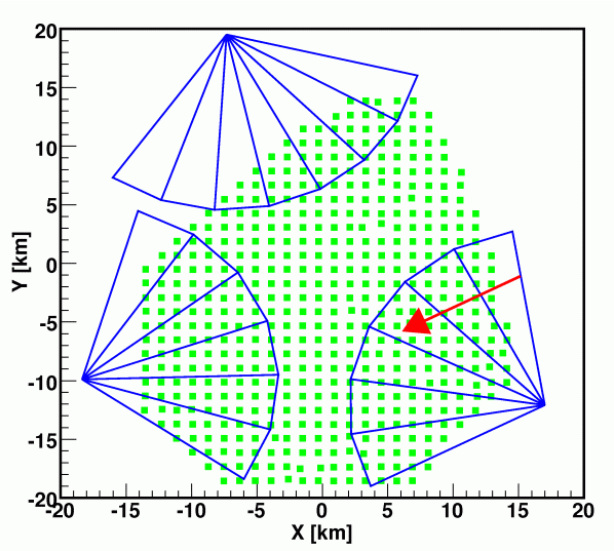
100m away:
40MeVx10^9~10^{16}eV
10km away:
~10^{20}eV



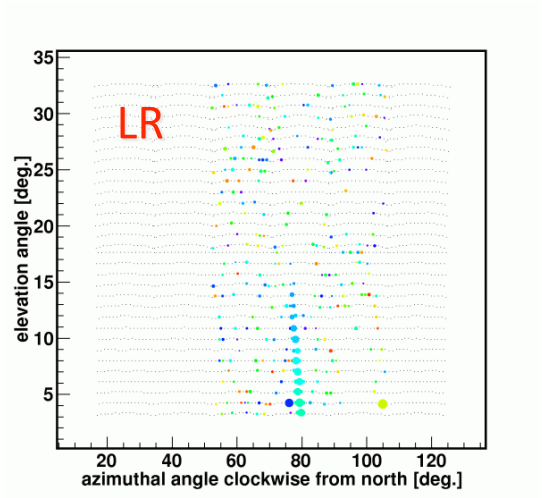


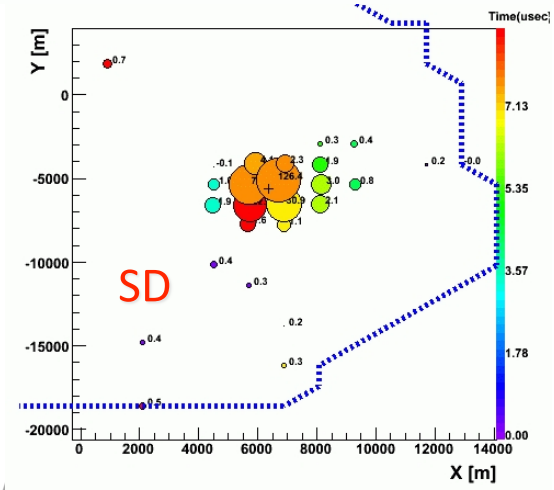
Event sample (May 31, 2008)

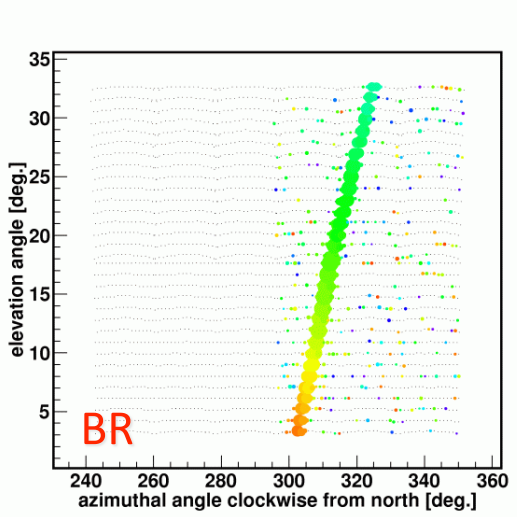




Event example:
Triple FD-SD hybrid
(2008-05-31)







Event reconstruction

- Joint fit of LDF and shower front profile
- 7-parameters:
  - x_{core}, y_{core} – shower core location at the ground level
  - θ, ϕ – zenith and azimuthal angles of primary arrival direction
  - S_{800} – normalization factor for LDF (corresponds to scintillation signal density at 800 meters)
  - t_0 – arrival time for the shower core
  - a – dimensionless Linsley's curvature parameter

$$t(r) = t_0 + t_{plane}(r) + a\, t_L(r)$$
$$t_L(r) = (r/39m)^{1.5}\, LDF(r,\theta)^{-0.5}$$
$$S(r) = S_{800}\, LDF(r,\theta), \quad LDF(800\text{m},\theta) = 1$$

$LDF(r)$ – modified AGASA function
r – core distance in shower plane

Dataset

Dataset:

- Data collected by SD from 2008-05-11 to 2009-10-08
- Geometrical exposure for $\theta \in [\theta_1, \theta_2]$:

$$A_{geom} = 2346 \times (\sin^2\theta_2 - \sin^2\theta_1)\ \mathrm{km}^2\ \mathrm{sr\ yr}$$

Cuts for photon search:

- Number of detectors triggered is 7 or more
- Shower core distance to array boundary is larger than 1 separation unit (1200 m)
- $\chi^2/\mathrm{d.o.f.} < 5$

Calculations

Search region:

▶ $E_{gamma} > 10^{19}$ eV	1395 events
▶ $45^\circ < \theta < 60^\circ$	335 events
▶ $\mathcal{C} > 0.5$	**1 event**
▶ Poisson 95% upper limit:	$\leq$ **5.14 events**

- Total exposure: $A_{total} = 158$ km^2 sr yr
- $F_\gamma < 3.3 \cdot 10^{-2}$ km^{-2}sr^{-1}yr^{-1} (95% CL) */PRELIMINARY/*

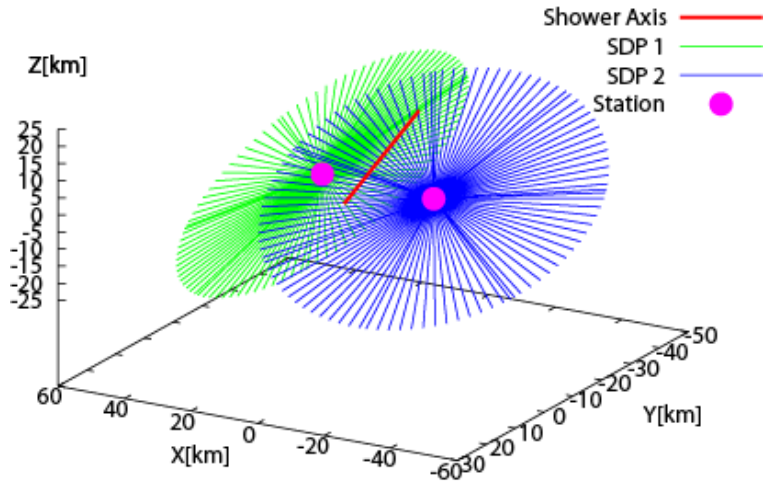
Exposure calculation with photon MC

- We take MC photon set with $E_{mc} > 10^{19}$ eV conservatively assuming E^{-3} spectrum.
- We calculate the fraction of photons entering the search region.

- Geomertical exposure $45^\circ < \theta < 60^\circ$: $A_{geom} = 587$ km^2 sr yr — **100%**
- $n_{det} \geq 7$ — **71%**
- χ^2/d.o.f < 5 — **69%**
- S_{800} cut — **54%**
- $\mathcal{C} > 0.5$ — **27%**

$$A_{total} = 0.27 \times A_{geom} = 158 \text{ km}^2 \text{ sr yr}$$

Geometrical reconstruction

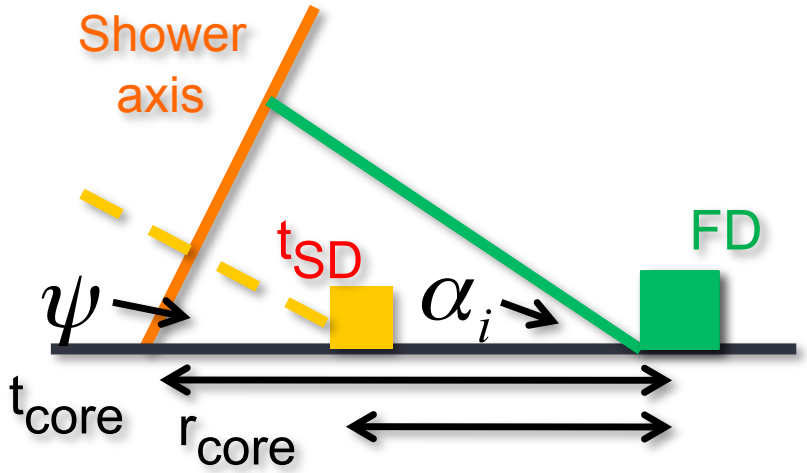


Stereo reconstruction (2FD)

$$\mathbf{s} = \mathbf{n}_{\mathrm{sdp1}} \times \mathbf{n}_{\mathrm{sdp2}}$$

Mono reconstruction (FD)

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



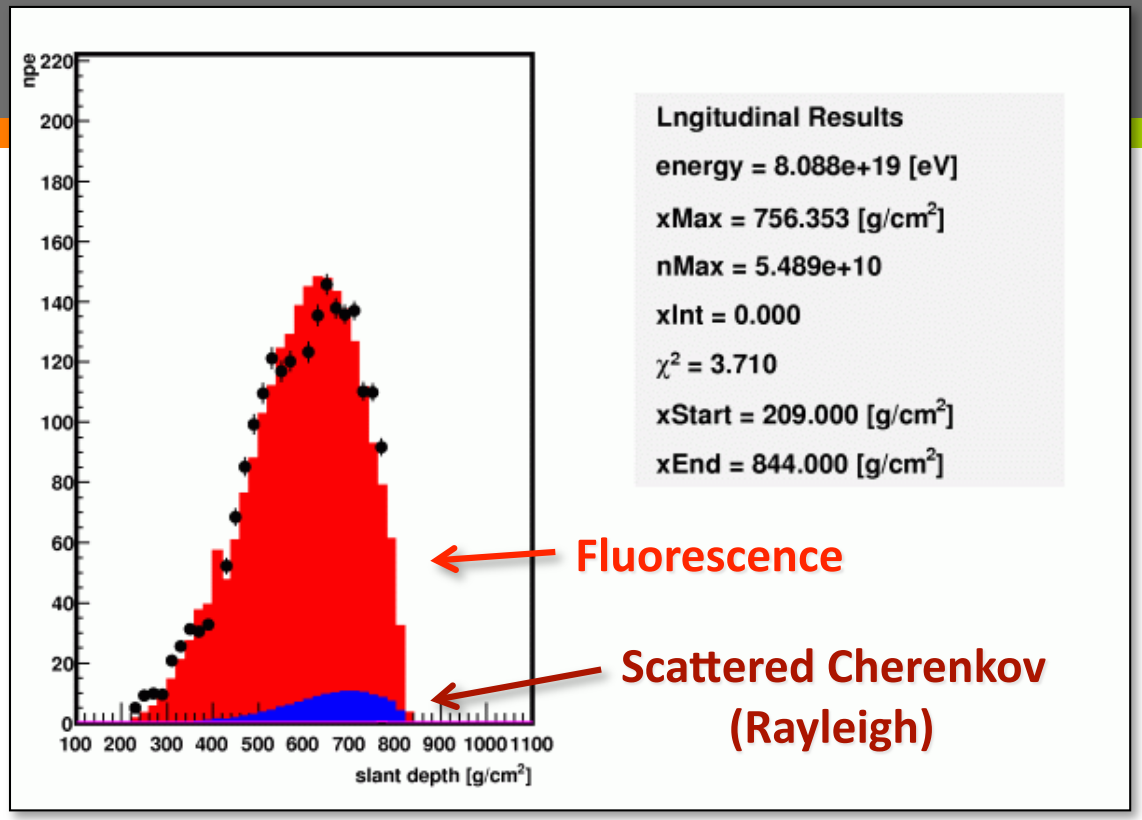
Hybrid reconstruction (FD+SD)

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

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

10.7.20

Shower profile reconstruction



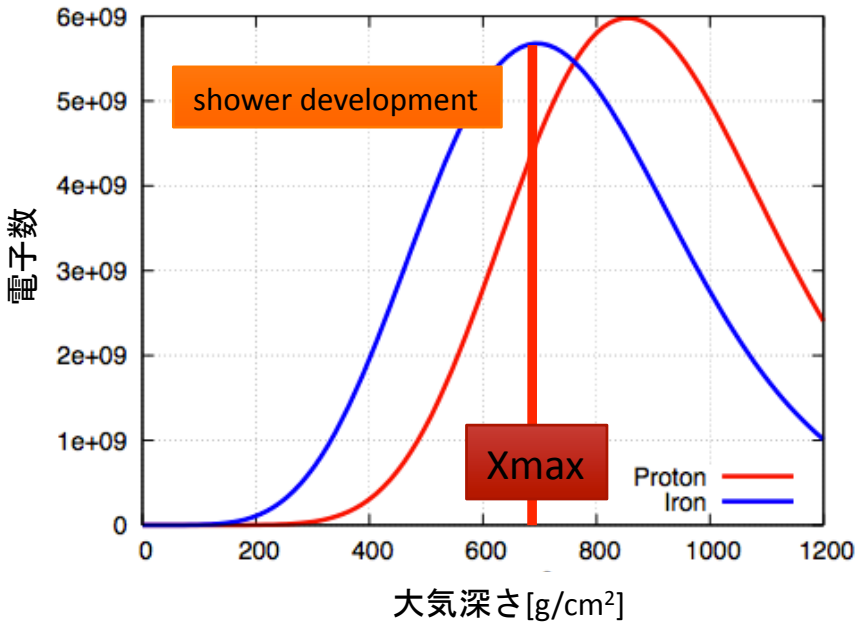
Gaisser-Hillas formula

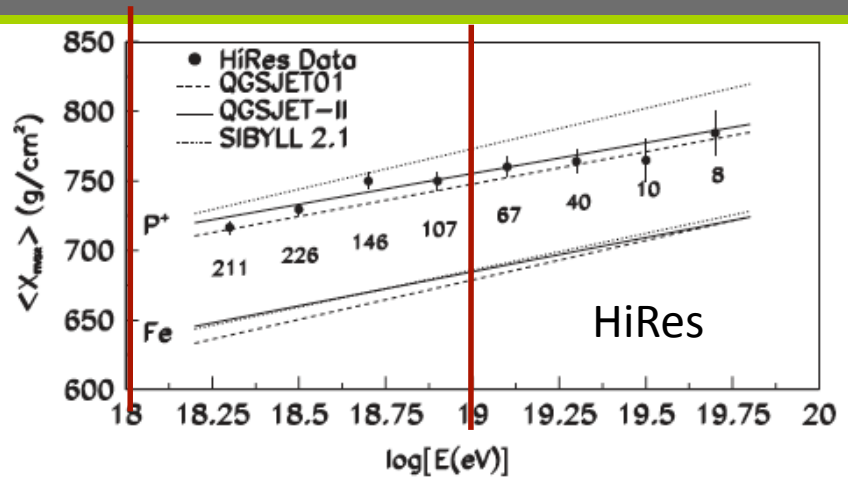
$$N_e = N_{\max}\left(\frac{X - X_0}{X_{\max} - \lambda}\right)^p \exp\left(-\frac{X - X_0}{\lambda}\right)$$

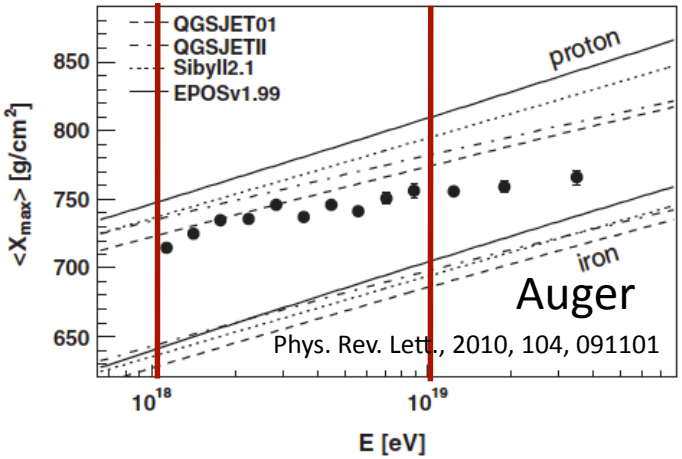
$$p + 1 = \frac{X_{\max}}{\lambda}$$

- Atmosphere: Radiosonde
- Mie scattering: LIDAR typical
  - Attenuation length: 29.4km
  - Scale height: 1km
- Fluorescence model: Kakimoto + FLASH

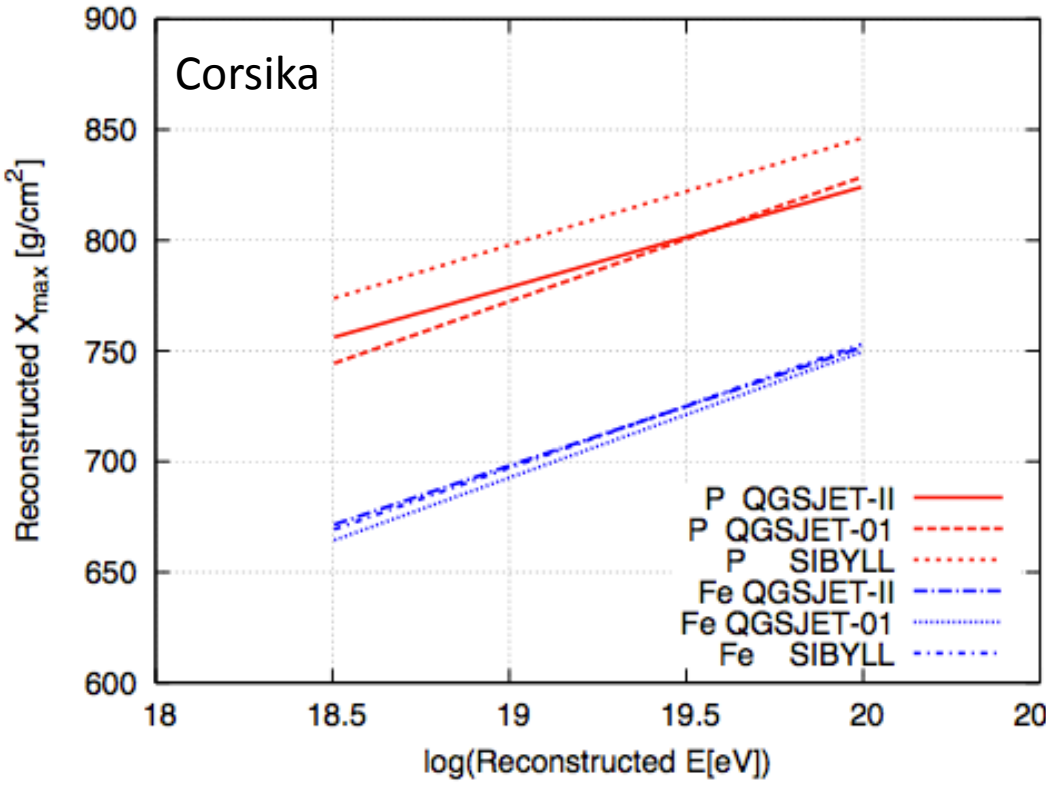
Xmax analysis for Mass composition

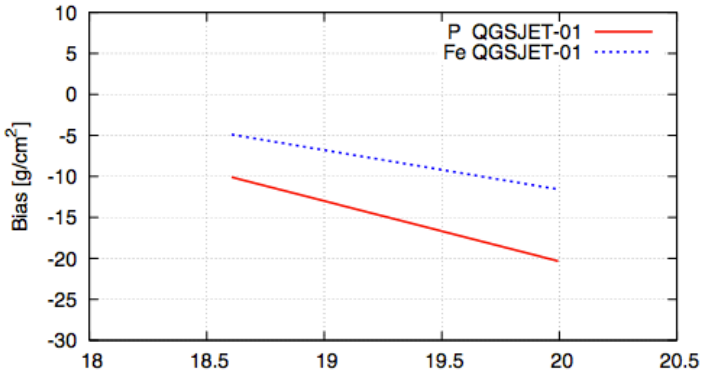


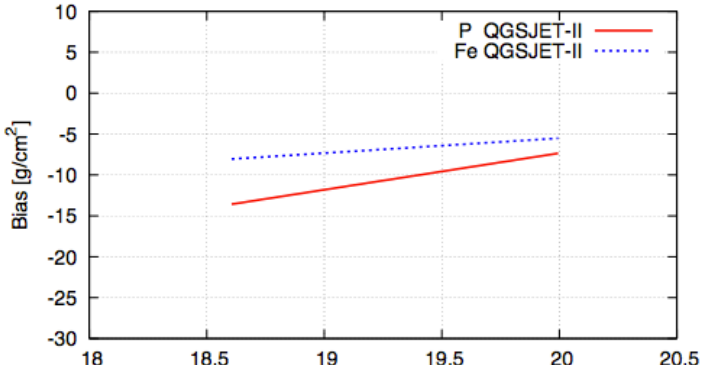


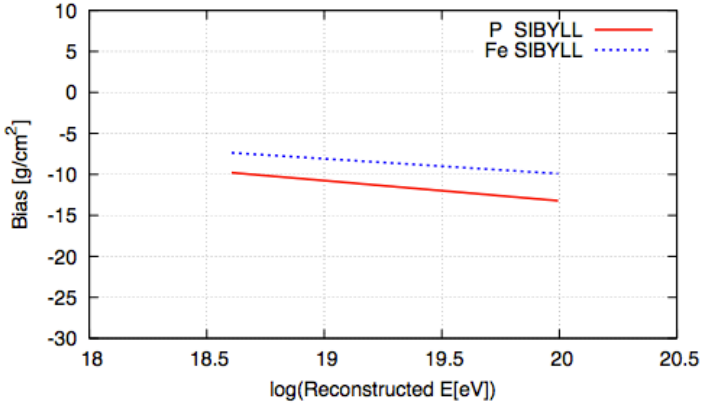


Bias of Rec. Xmax









Bias of rec. Xmax