G.T. Zatsepin memorial readings,
Moscow, June 10, 2011

Status and results of the Telescope Array experiment

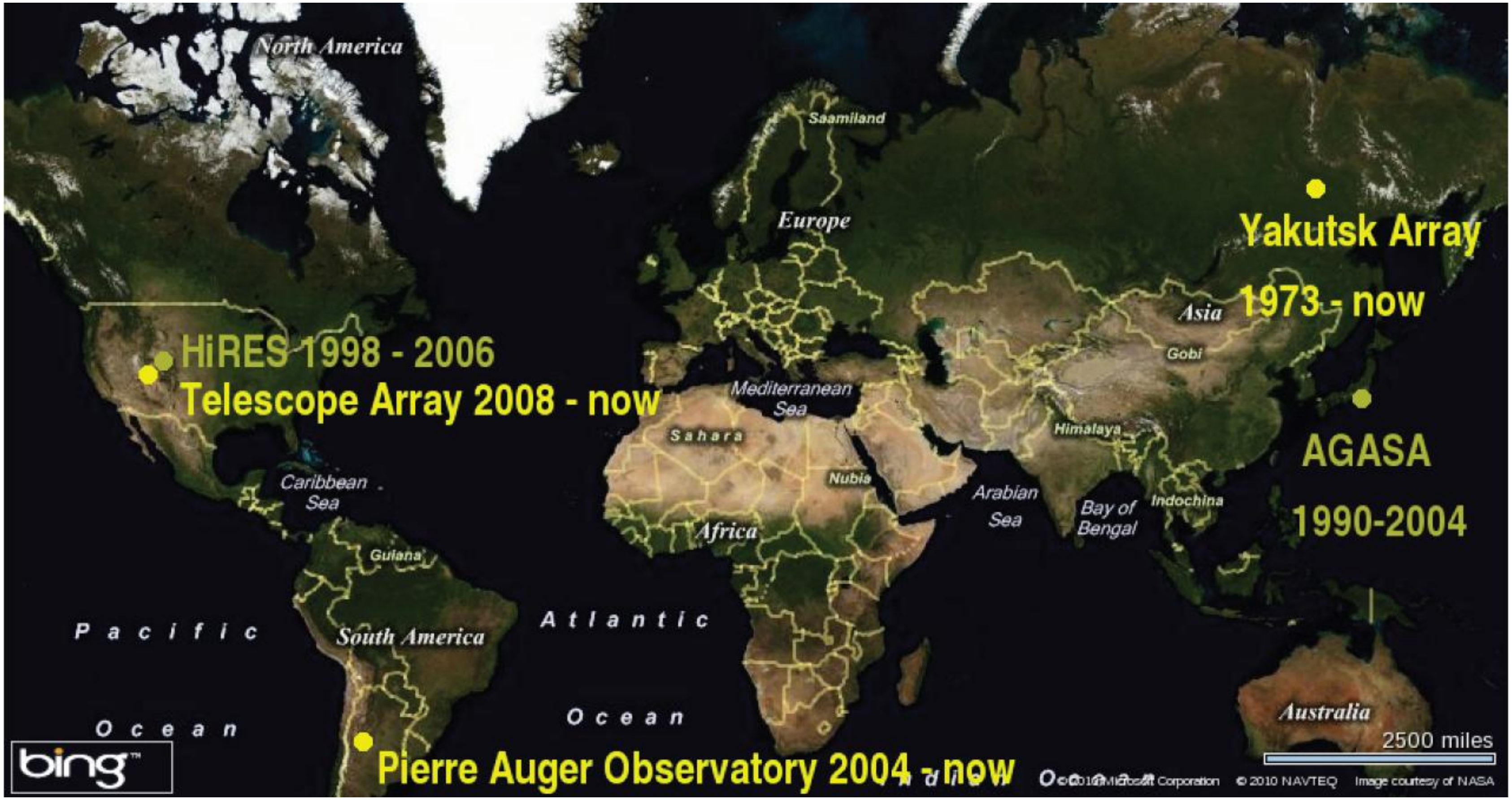
Sergey Troitsky

INR, Moscow
the Telescope Array collaboration

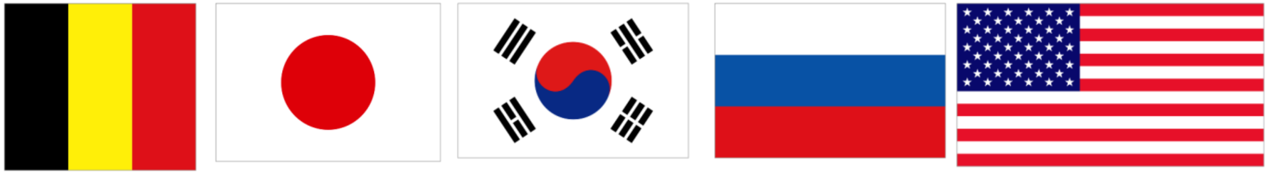
Plan

1. The Telescope Array detection methods
2. Primary energy estimation and cosmic-ray spectrum
3. Primary composition: protons or heavy nuclei?
4. Arrival directions: search for anisotropies
5. Search for primary photons

Ultra-high-energy cosmic rays:
experiments



Telescope Array Collaboration



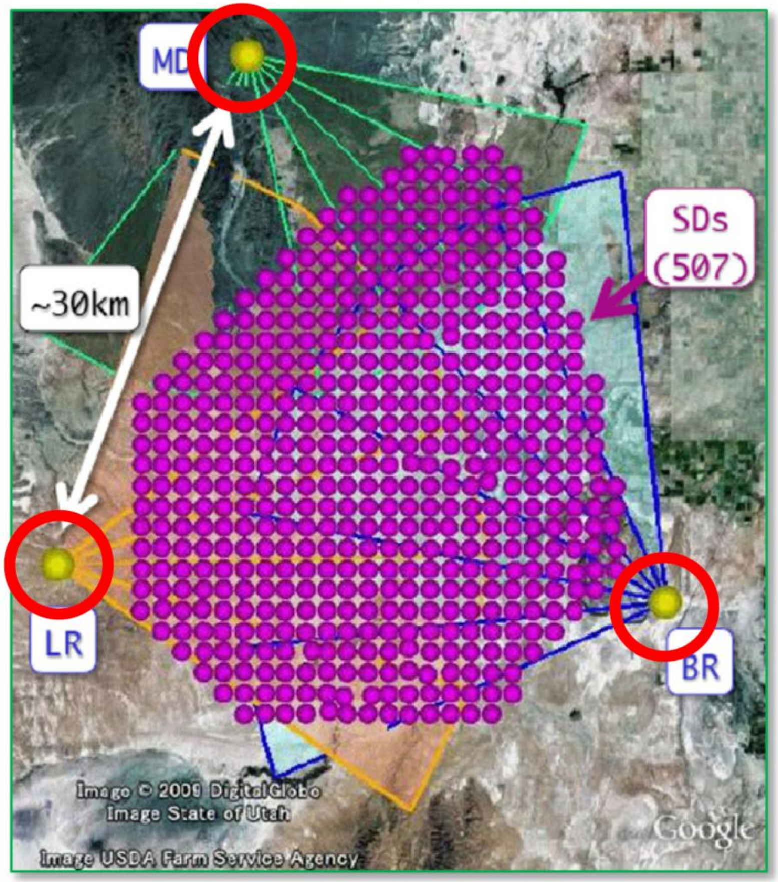
T Abu-Zayyad[1], R Aida[2], M Allen[1], R Azuma[3], E Barcikowski[1], JW Belz[1], T Benno[4], DR Bergman[1], SA Blake[1], O Brusova[1], R Cady[1], BG Cheon[6], J Chiba[7], M Chikawa[4], EJ Cho[6], LS Cho[8], WR Cho[8], F Cohen[9], K Doura[4], C Ebeling[1], H Fujii[10], T Fujii[11], T Fukuda[3], M Fukushima[9,22], 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[1], TA Stroman[1], 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

the Telescope Array is not an array of telescopes…

- **Surface detector (SD)**
  - Plastic scintillator (a la AGASA)
  - 507 SDs S=3 m2
  - 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°N, 112.9°W
    - Altitude ~1400m

transfer HiRes telescopes

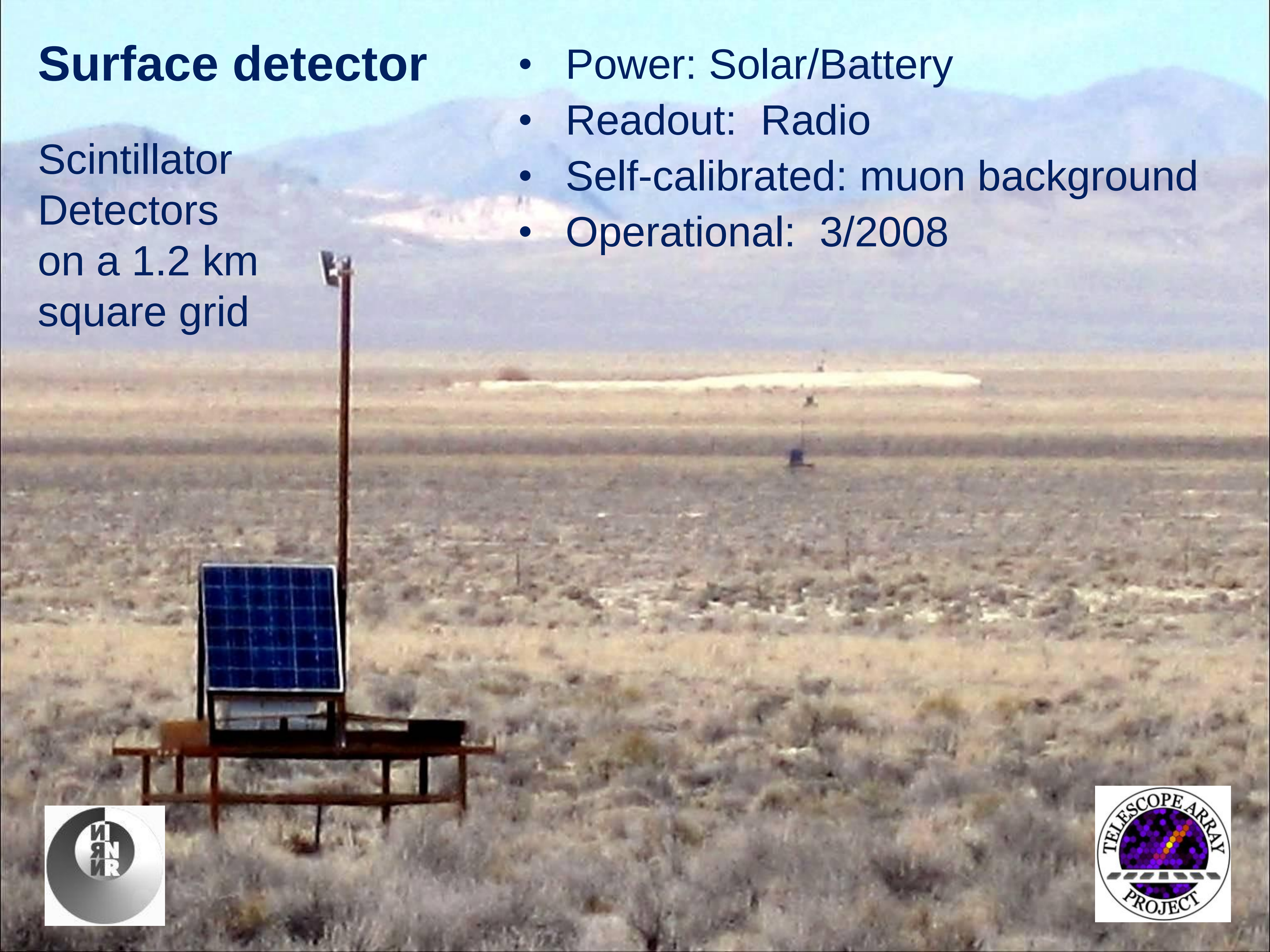


The largest detector in northern hemisphere

Surface detector

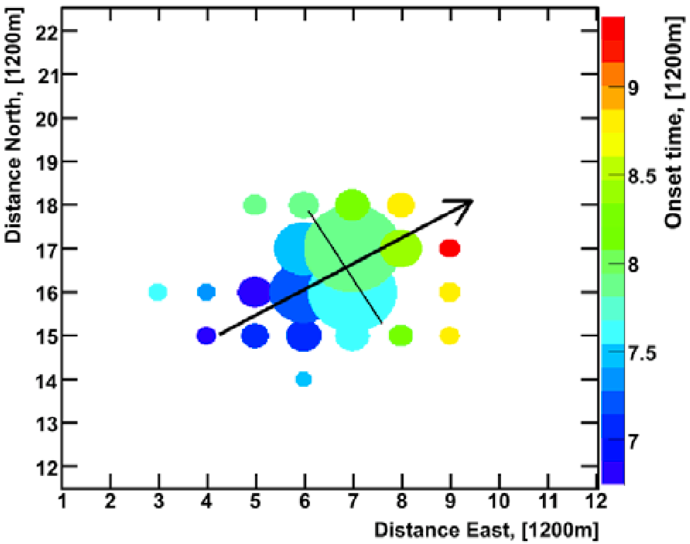
Scintillator Detectors on a 1.2 km square grid

- Power: Solar/Battery
- Readout: Radio
- Self-calibrated: muon background
- Operational: 3/2008

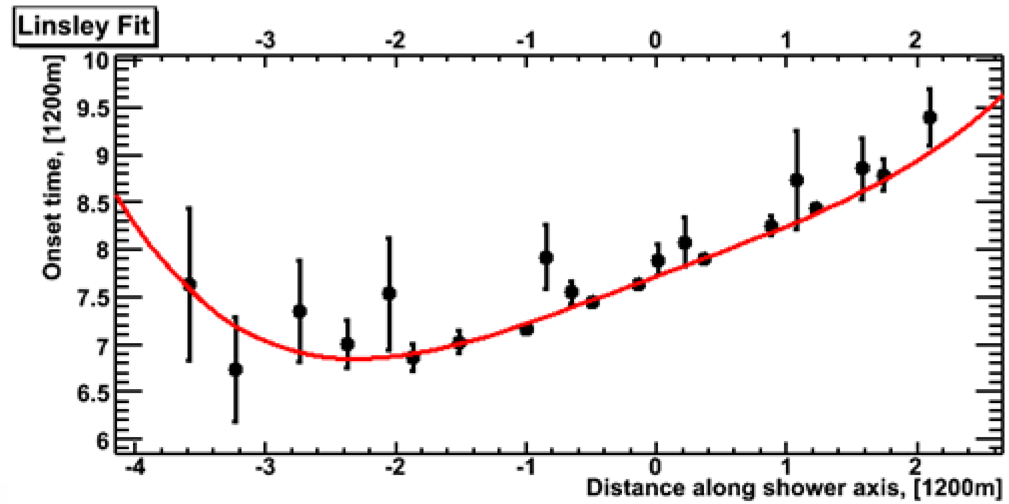


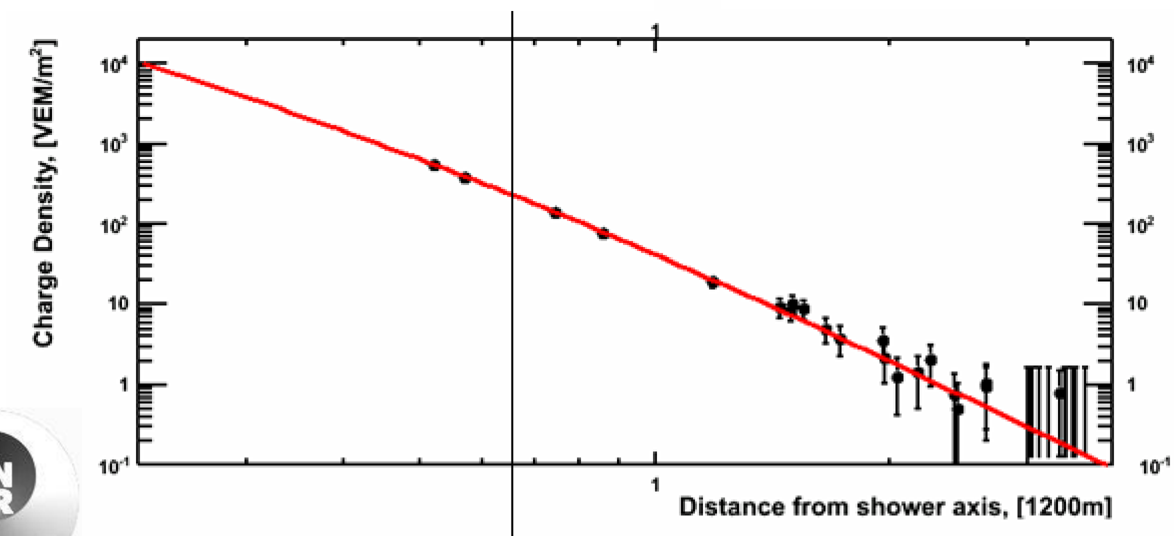
A typical Surface-Detector event

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



Geometry Fit (modified Linsley)



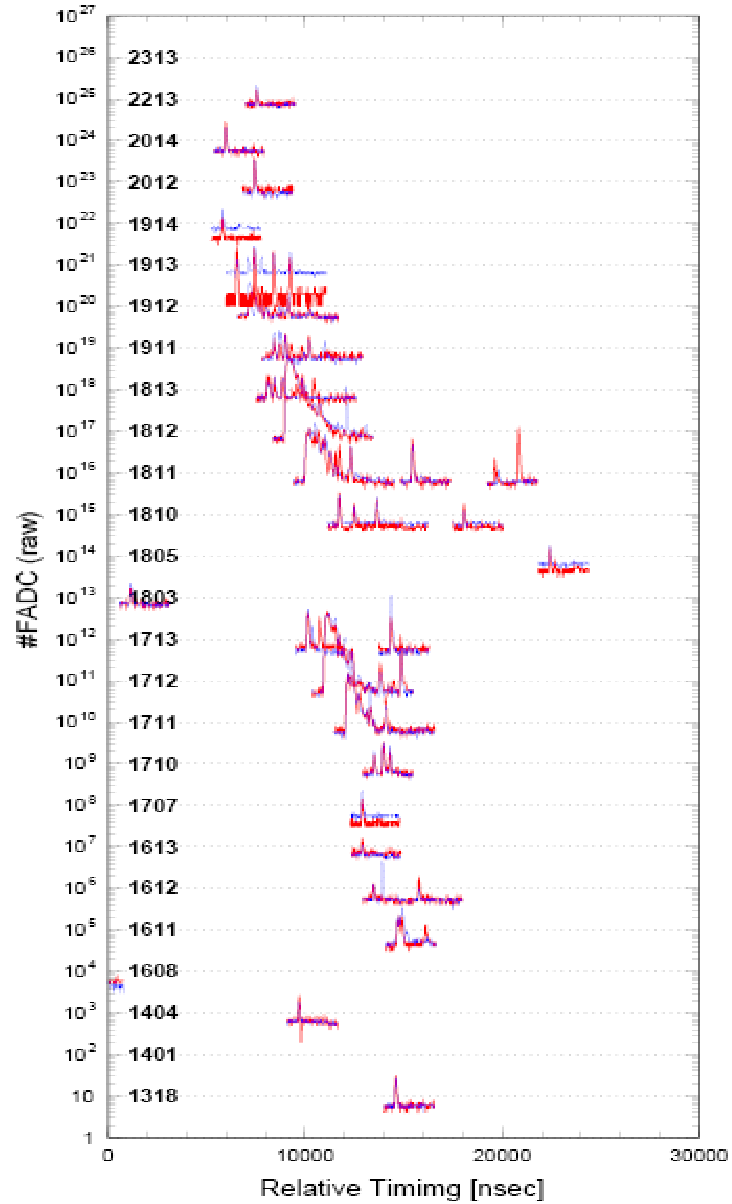


r = 800m

Lateral Density Distribution Fit (AGASA LDF)

A typical Surface-Detector event

timing recorded at each station

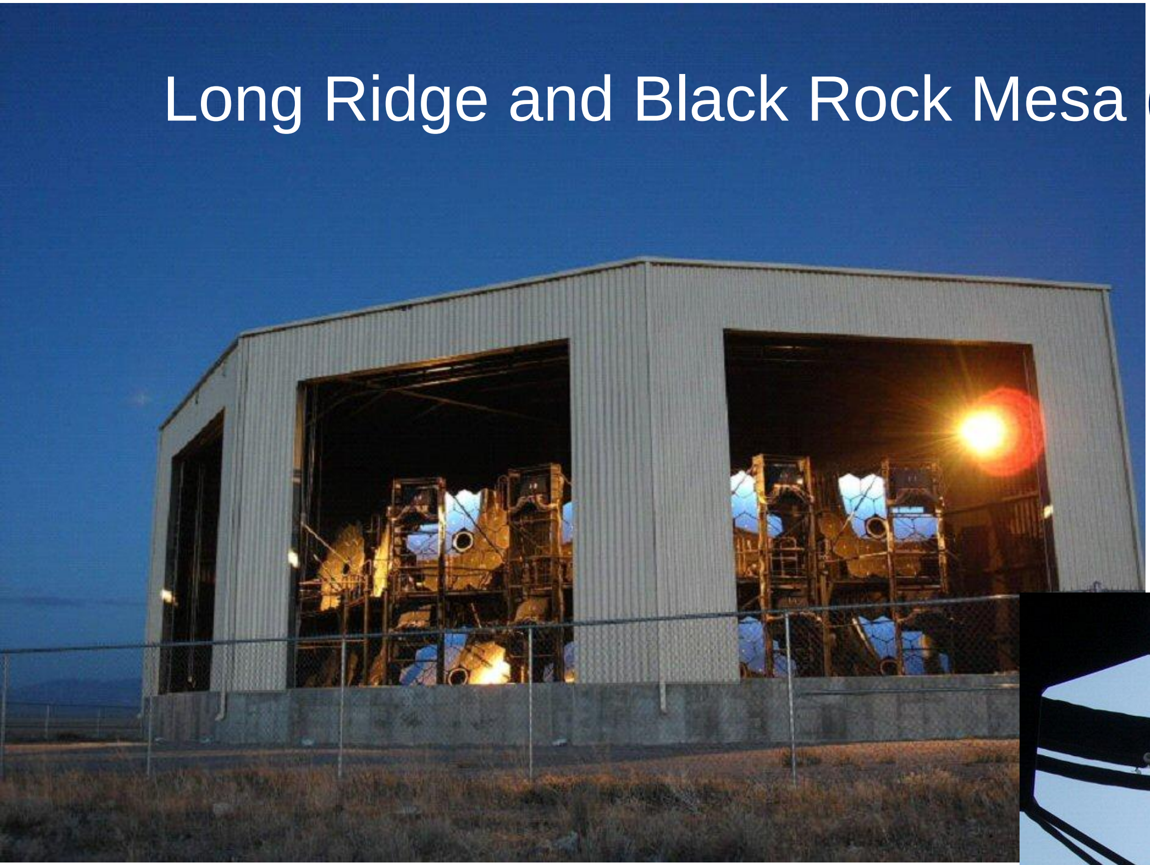


TA fluorescent detector 1:

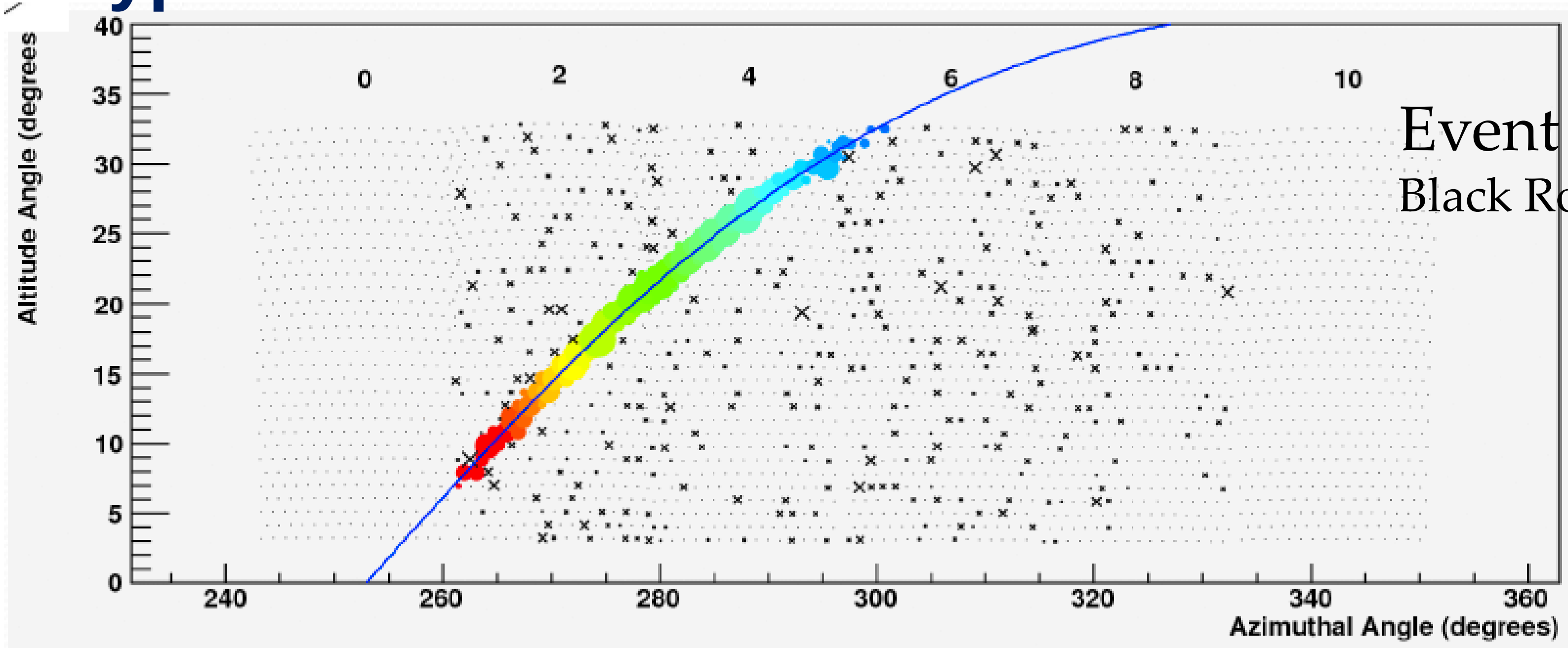
Middle Drum (refurbished HiRes I)

TA fluorescent detectors 2 and 3:

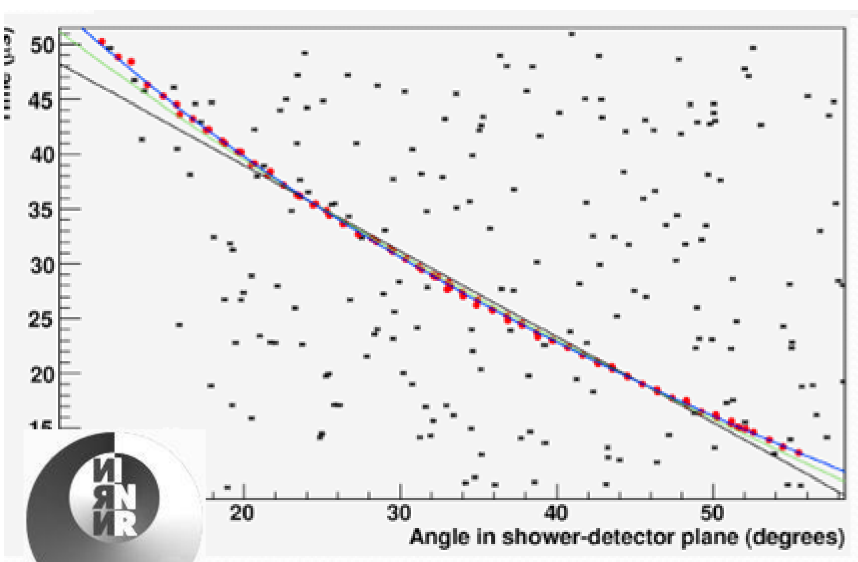
Long Ridge and Black Rock Mesa (brand new)



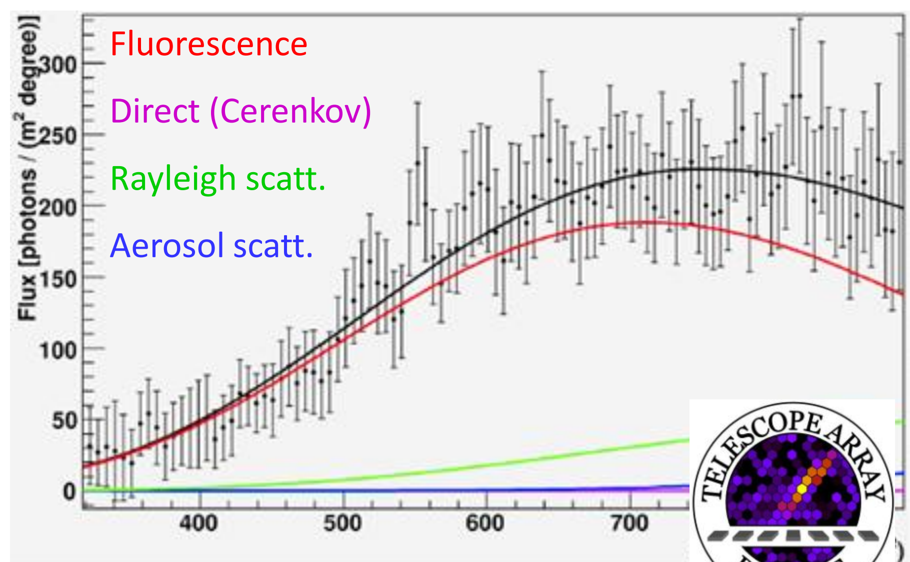
A typical fluorescent-detector event



Event Display
Black Rock Mesa



Monocular timing fit



Reconstructed Shower Profile

TA fluorescence detectors working together

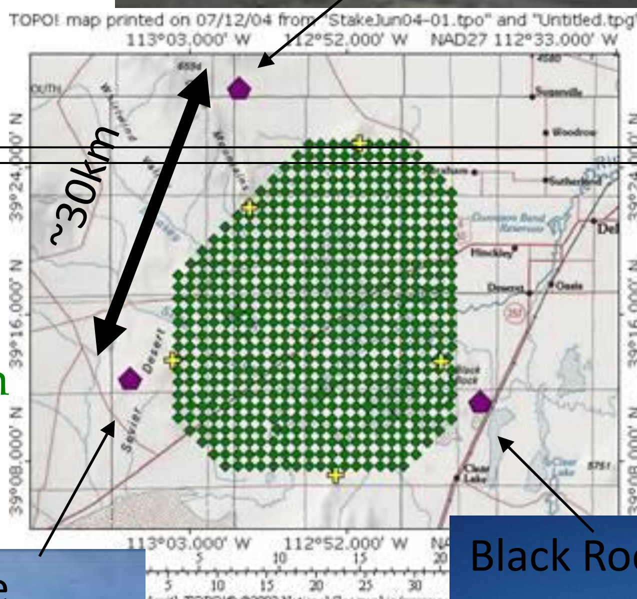
Refurbished from HiRes-I

Observations since ~10/2007

Middle Drum

14 telescopes@station
256 PMTs/camera

5.2 m²



New FDs

Observation since ~11/2007

Long Ridge

Observation since ~6/2007

Black Rock Mesa

12 telescopes/station
256 PMTs/camera
Hamamatsu R9508
FOV~15x18deg

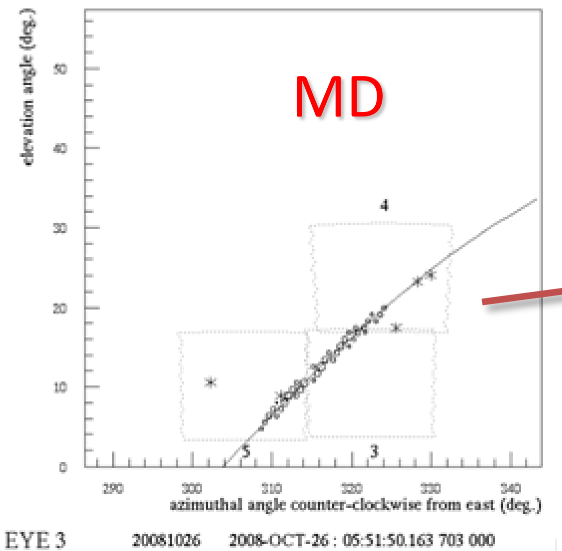
~1 m²

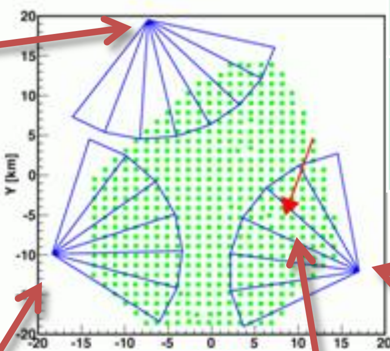
6.8 m²

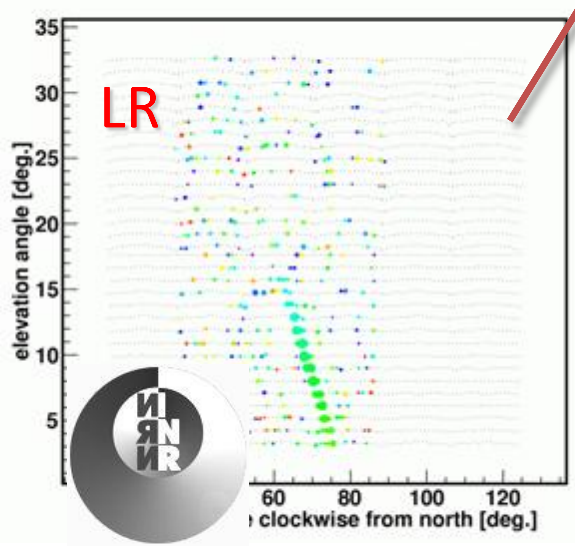
Example of a TRIPLE STEREO HYBRID event

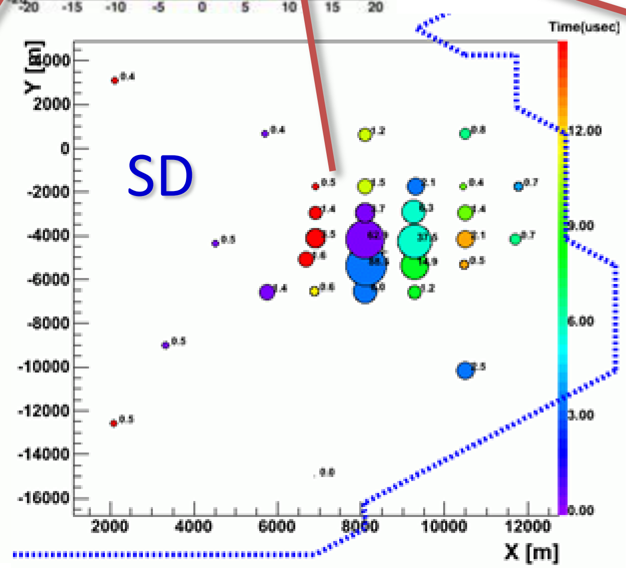
2008-10-26

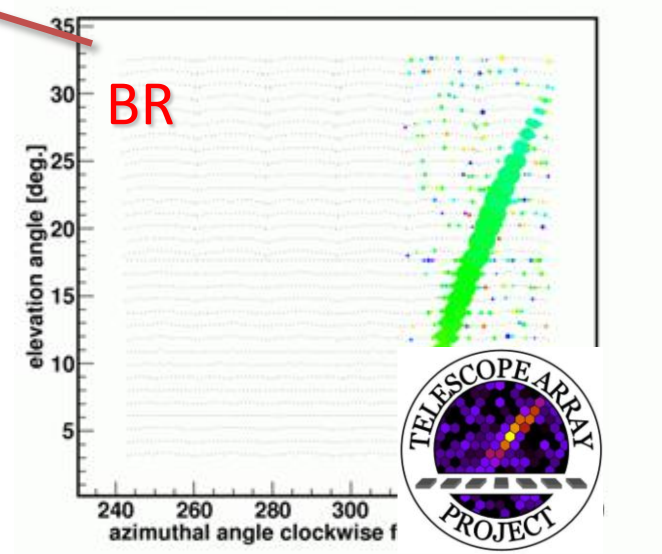
	θ[°]	ϕ[°]	x[km]	y[km]
MD mono	**51.43**	**73.76**	**7.83**	**-3.10**
BR mono	**51.50**	**77.09**	**7.67**	**-4.14**
Stereo BR&LR	**50.21**	**71.30**	**8.55**	**-4.88**









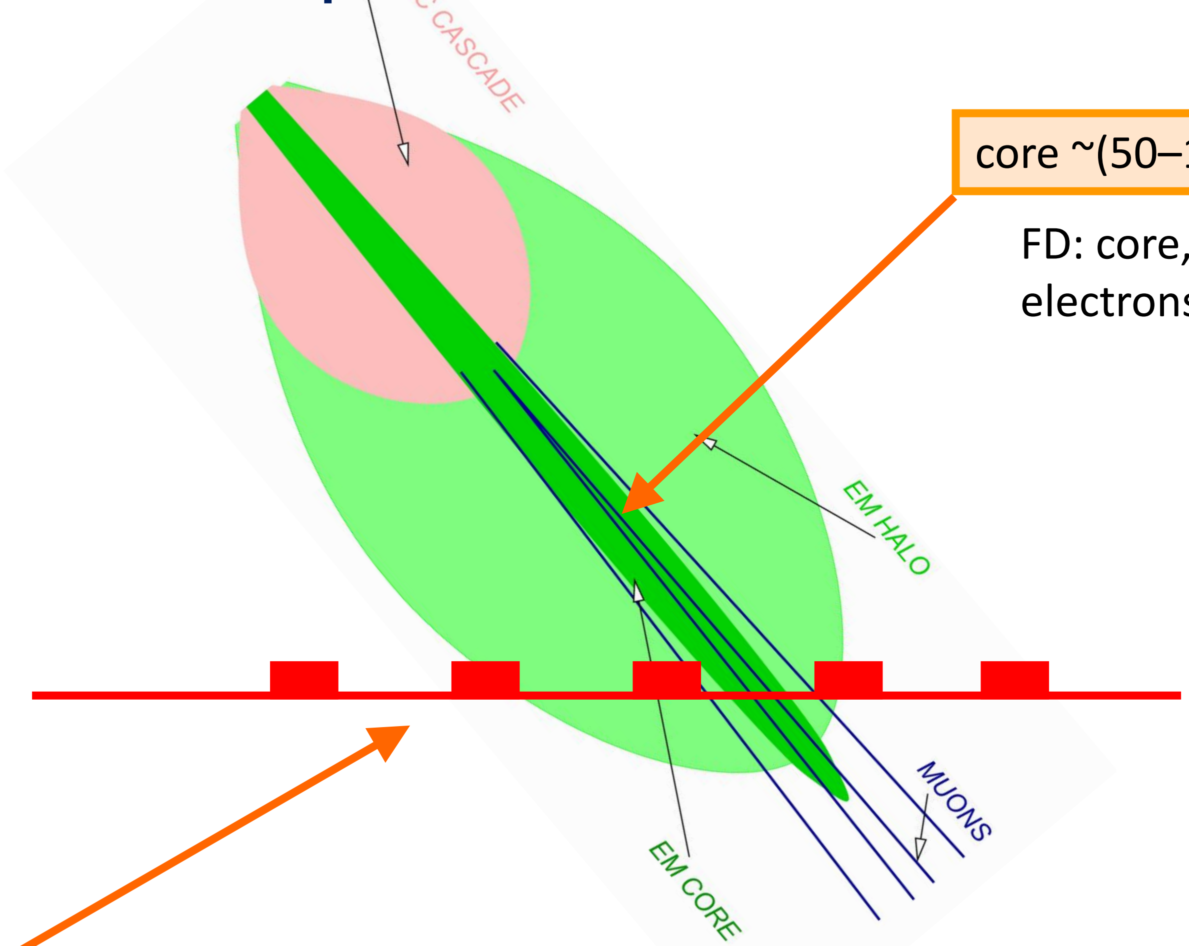


energy estimation

Energy estimation:
SD and FD see different parts of the shower

core ~(50–100) m

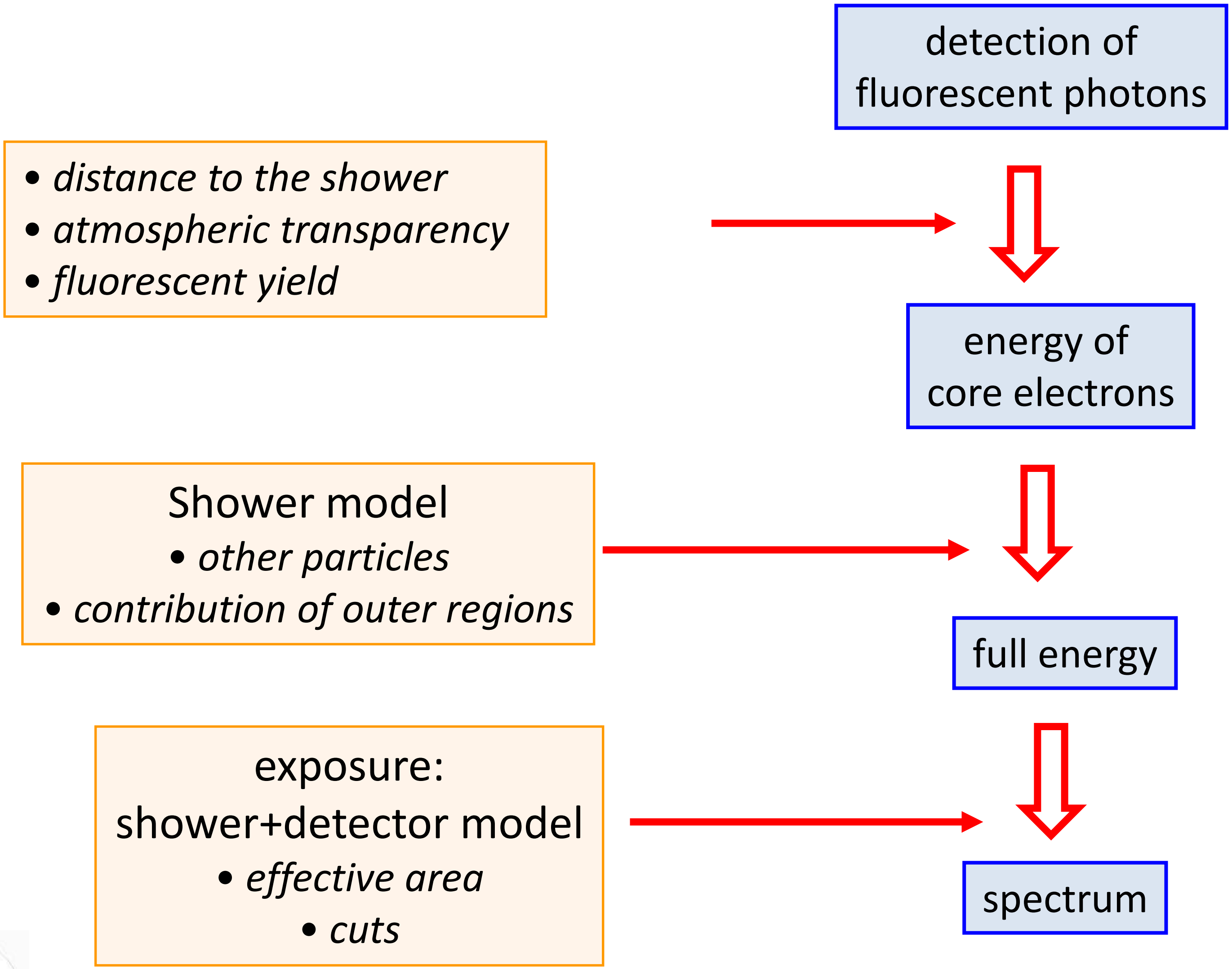
FD: core,
electrons only



distance between stations ~(1000–1500) m

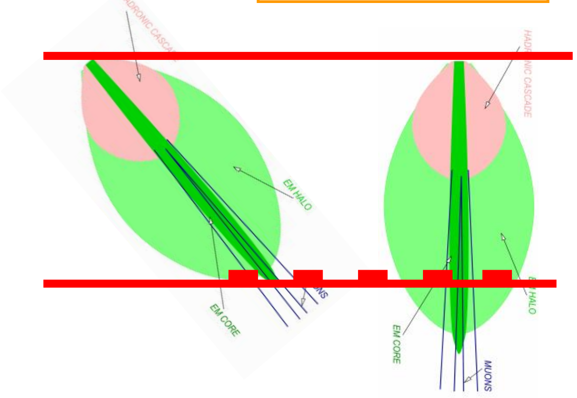
SD: periphery of the shower, sums up all particles

FD energy estimation



SD energy estimation: traditional (“the CIC method”)

experiment



signal at detector
as a function of zenith angle
for identical showers

⇩

effective signal
«if the shower
were vertical»

⇩

Monte-Carlo
depends of the shower model
and primary particle type

OR

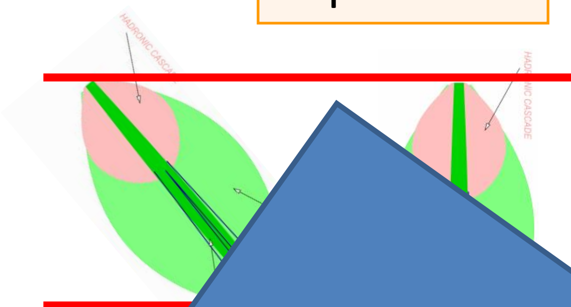
calibration to
a different method
(FD, air Cerenkov)
averaging,
systematics

energy
corresponding to
this effective signal

SD energy estimation: TA

experiment

signal at detector
as a function of zenith angle
for identical showers



cal»

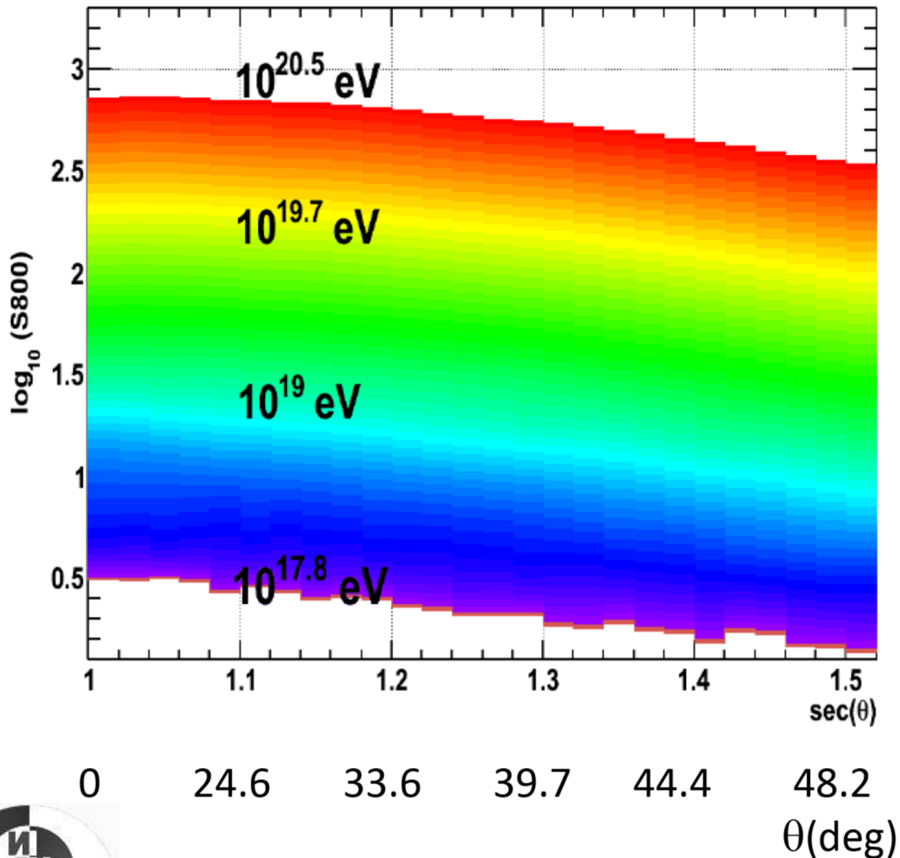
Monte-Carl
depends of the s
and prima

ca
a differ od
(FD, air C enkov)
averaging,
systematics

ial

SD energy estimation: TA

FULL MONTE-CARLO!   QGSJET II PROTONS



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

SD energy estimation: why not CIC?

because of excellent data/MC agreement!

Haverah Park, AGASA, Yakutsk, Pierre Auger: CIC method
Their motivation: MC does not describe well the shower development

WHY WORKS in TA [at least for (0-45) degree zenith angles]?

yet to be understood…

- a bit of luck (relatively high altitude + plastic scintillators)??
  - Haverah Park: water tanks low altitude
  - Yakutsk, AGASA: plastic scintillators low altitude
  - Pierre Auger: water tanks high altitude

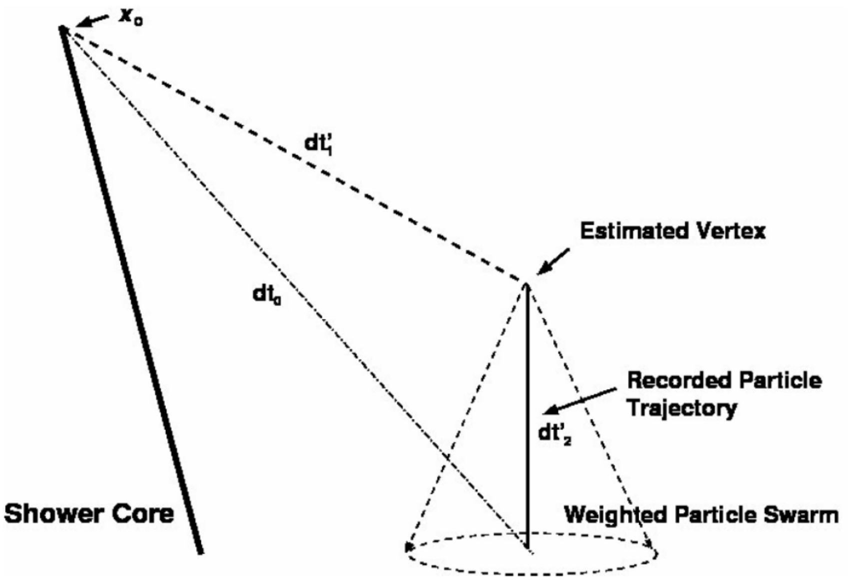
- sophisticated MC (shower+detector, dethinning etc.)?

SD simulations: summary

- CORSIKA 6.960 QGSJET-II/FLUKA
  - Parallelization
  - Dethinning
- GEANT4
- Superb detail
- Very computationally intensive

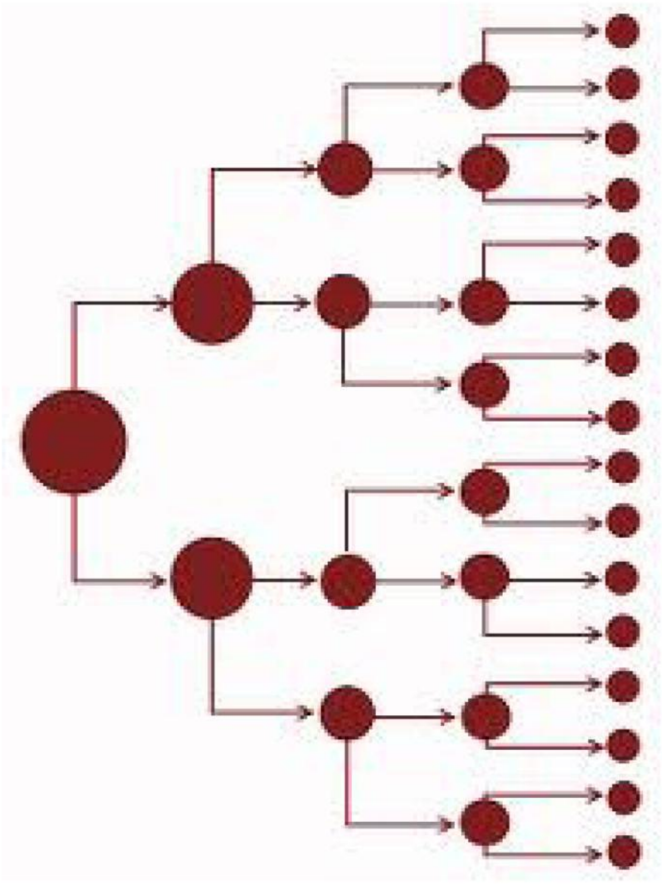
SD simulations: dethinning

- Dethinning
  - Change each CORSIKA output particle of weight *w* to *w* particles with similar characteristics to the original particle
  - Adjust dethinning parameters to agree with full CORSIKA generated via parallelization



SD simulations: no-thinning

- Parallelization
  - Wrapper scripts and binaries
  - CORSIKA itself left untouched
  - 100+ showers
    - $10^{18.5}$ to $10^{19.5}$ eV
    - 0^o to 60^o zenith
    - *p*, Fe

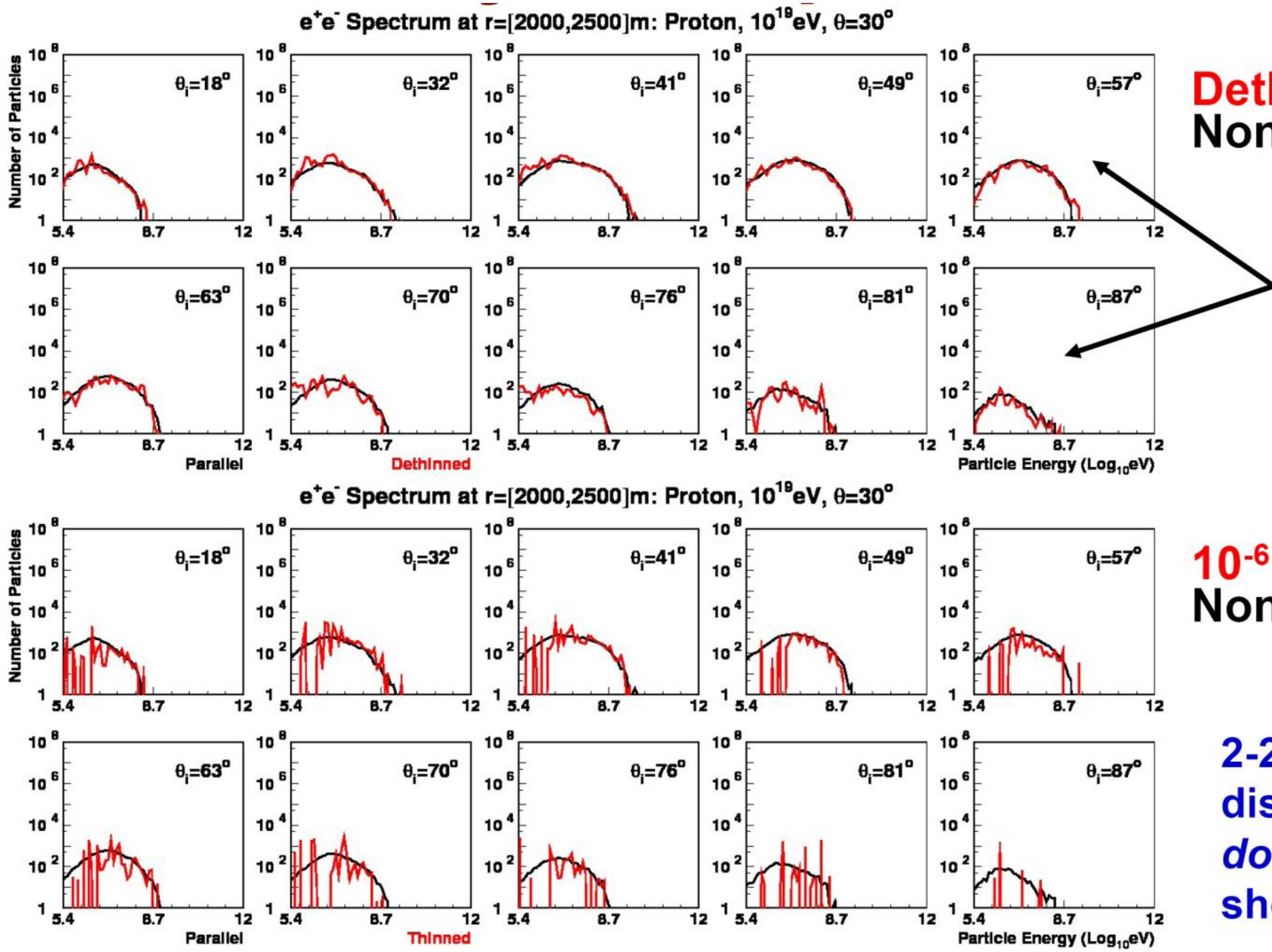


SD simulations: no-thinning

Livni - the public database of artificial extensive air showers generated without thinning

- The library currently contains 90 showers, with primary energies 10^{17}—10^{18} eV, different zenith angles and interaction models.
- QGSJET, QGSJET II, EPOS, GHEISHA and EGS4 models are used for simulation of library showers
- Shower library is available at `http://livni.inr.ac.ru/` you may register to use

SD simulations: dethinning



Dethinned
Non-thinned

Different Incident Angles

10^{-6} Thinning
Non-thinned

2-2.5km lateral distance *downstream* from shower core

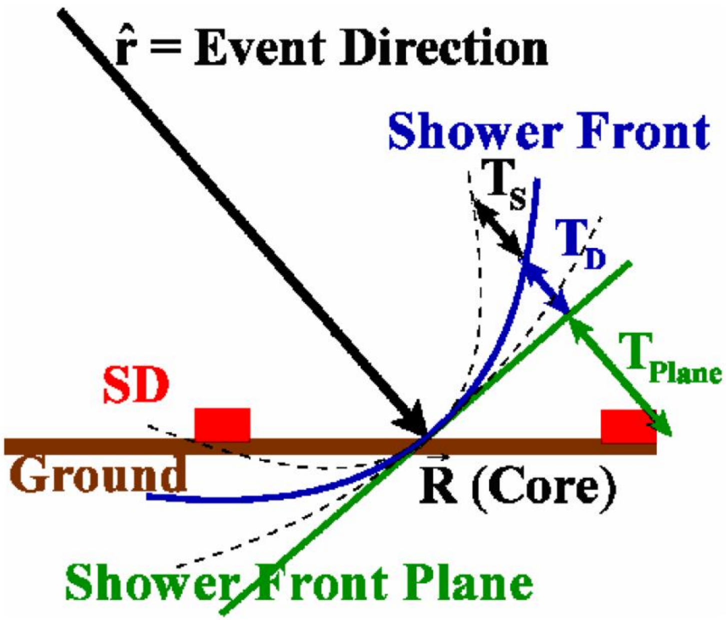
Secondary Particle Energy: 250keV to 1 TeV

SD simulations summary

- CORSIKA shower library:
  - 33,000 dethinned showers
  - $10^{17.1}$ to $10^{20.5}$ eV
  - Isotropic distribution
- Calculate energy deposition for entire shower
  - GEANT4
- Simulate SD electronics repeatedly for each library element
- Select events for data set with respect to previously measured energy spectrum

SD energy estimation: TA

$$\chi^2 = \sum_{i=1}^{\text{nSDs}} \frac{\left(t_i - T_0 - T_{\text{Plane}} - T_{\text{D}}\right)^2}{T_{\text{S}}^{\,2}} + \frac{\left(\vec{\mathbf{R}} - \vec{\mathbf{R}}_{\text{COG}}\right)^2}{(180\text{m})^2}$$



T_0 Time of the core hitting ground

T_{Plane} Time of the shower front plane

T_{D} Time delay (Modified Linsley)

T_{S} Fluctuation of time delay (Modified Linsley)

$\vec{\mathbf{R}}$ (Fitted) core position

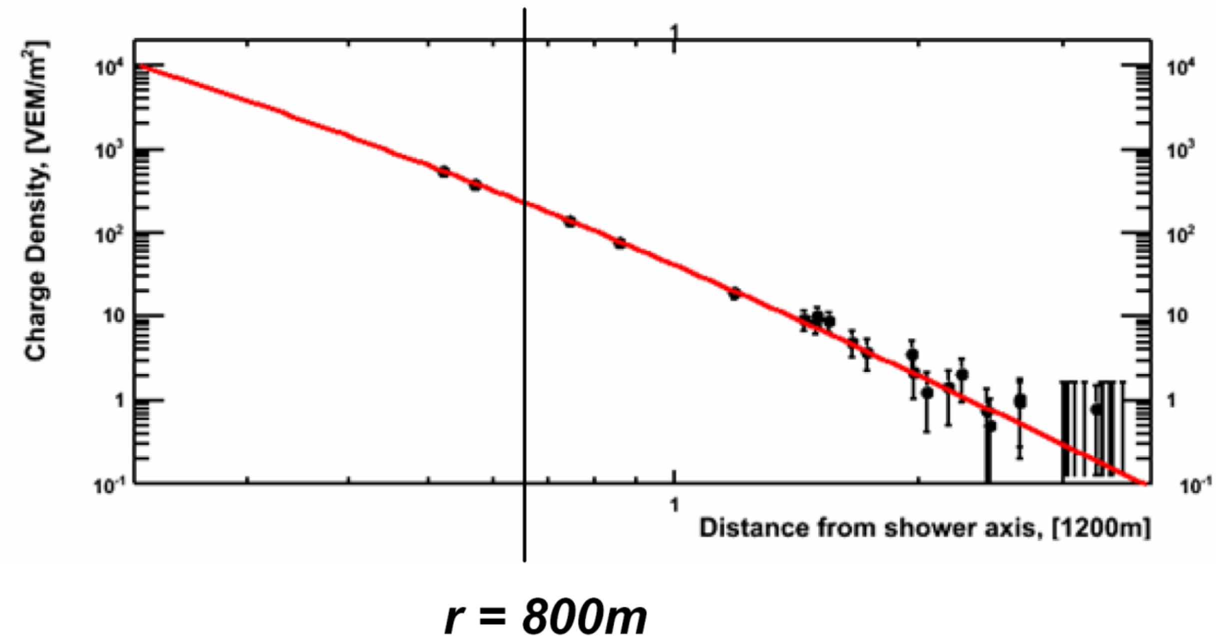
$\vec{\mathbf{R}}_{\text{COG}}$ Core position found from the center of gravity of charge

SD energy estimation

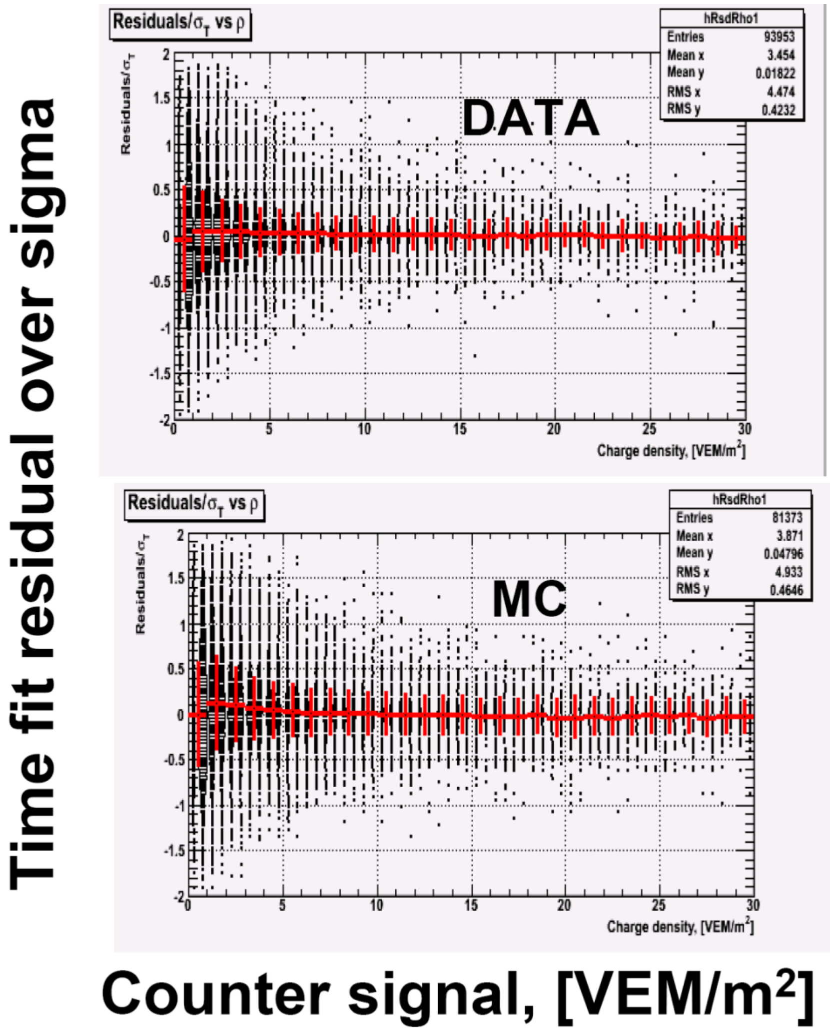
- **Fit with AGASA LDF**

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

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



SD data/MC comparison



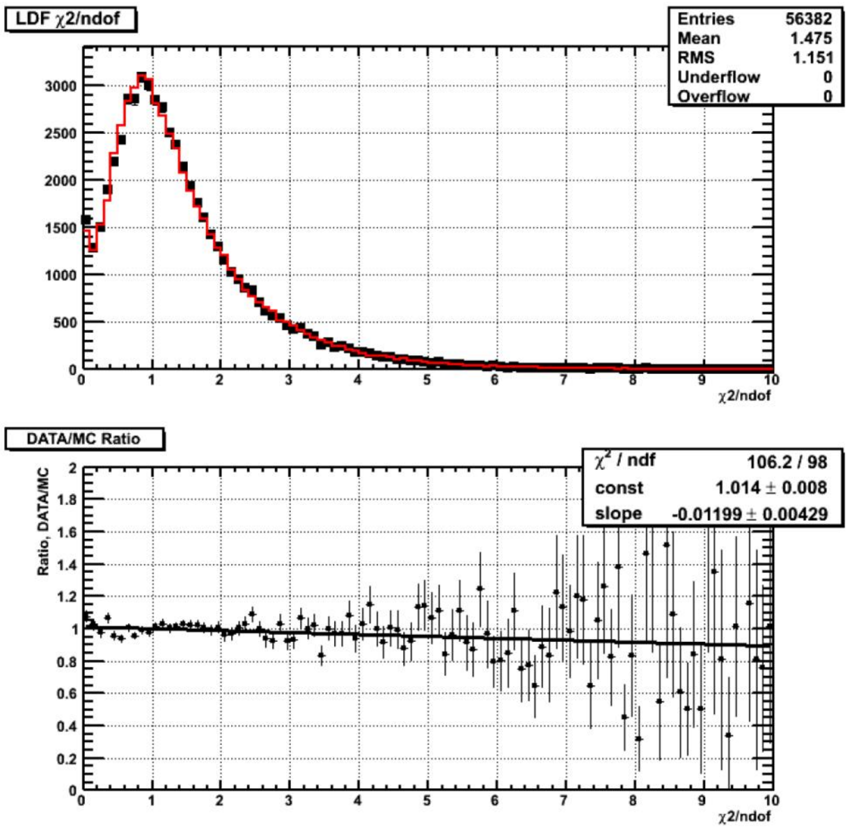
- Identical analysis routines are applied to data and Monte Carlo
- Fit results are compared between real and simulated events
- Monte Carlo fits the exact same way as the real data.
- Consistent for both geometric and lateral density fits.

SD quality cuts

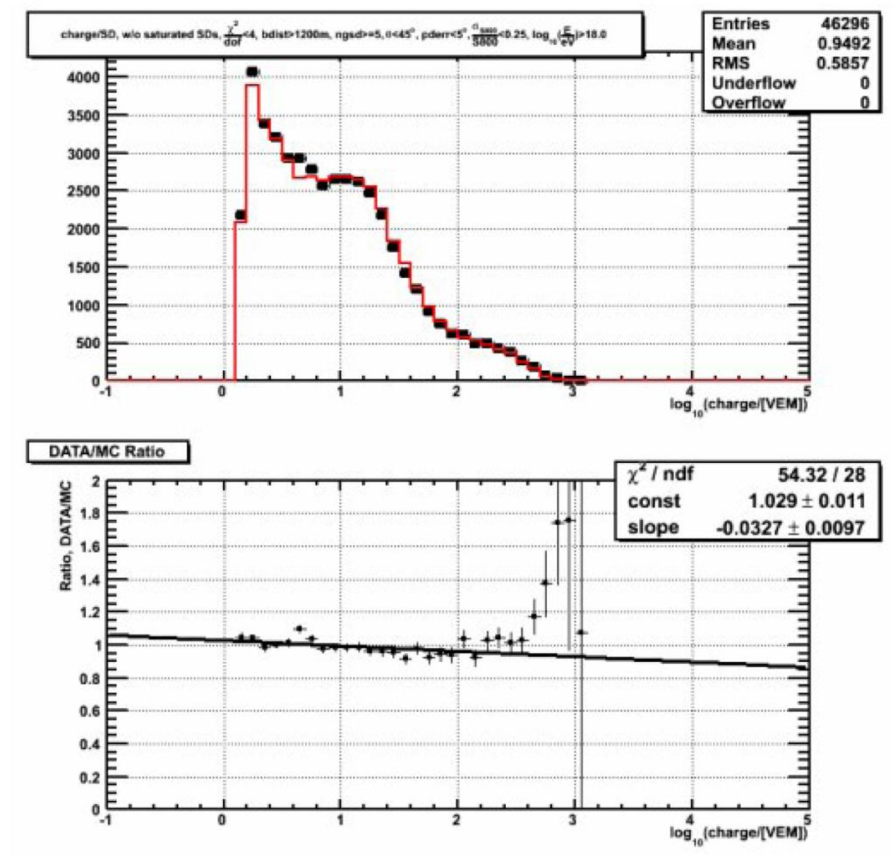
- Good data fits:
  - ❑ χ^2/d.o.f. > 4.0
  - ❑ Pointing direction resolution <5°
  - ❑ Fractional S(800) uncertainty <25%
- Good shower geometry:
  - ❑ Border cut >1200 m
  - ❑ Zenith angle cut <45°

- 1.75 years, 6264 events

SD data/MC comparison

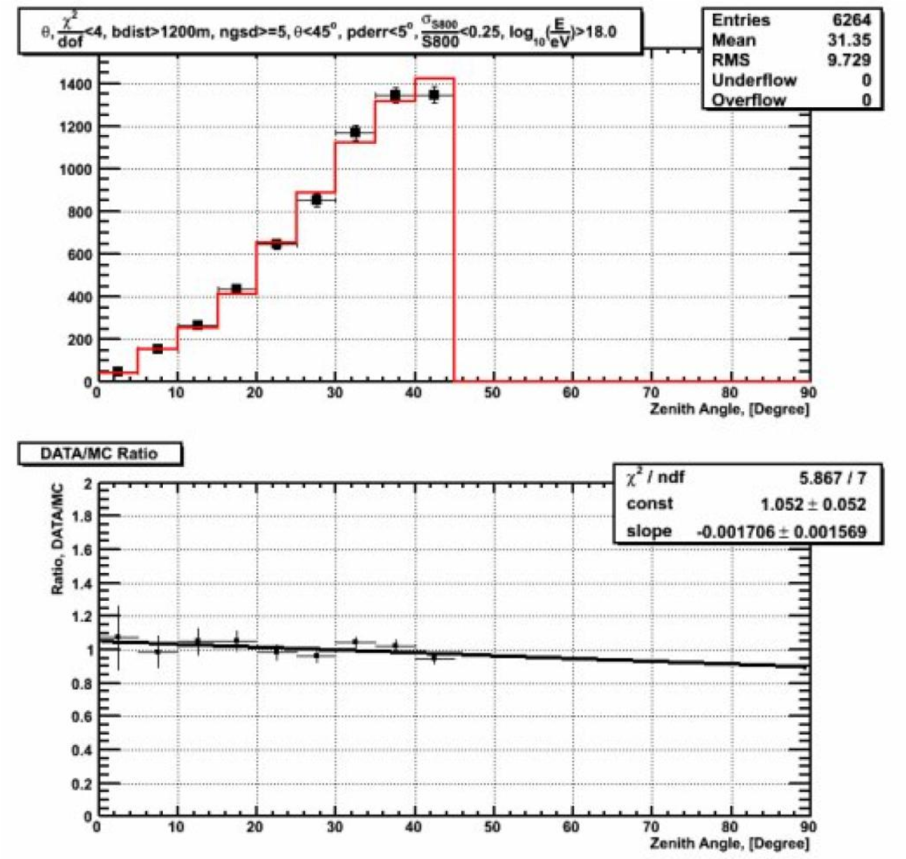


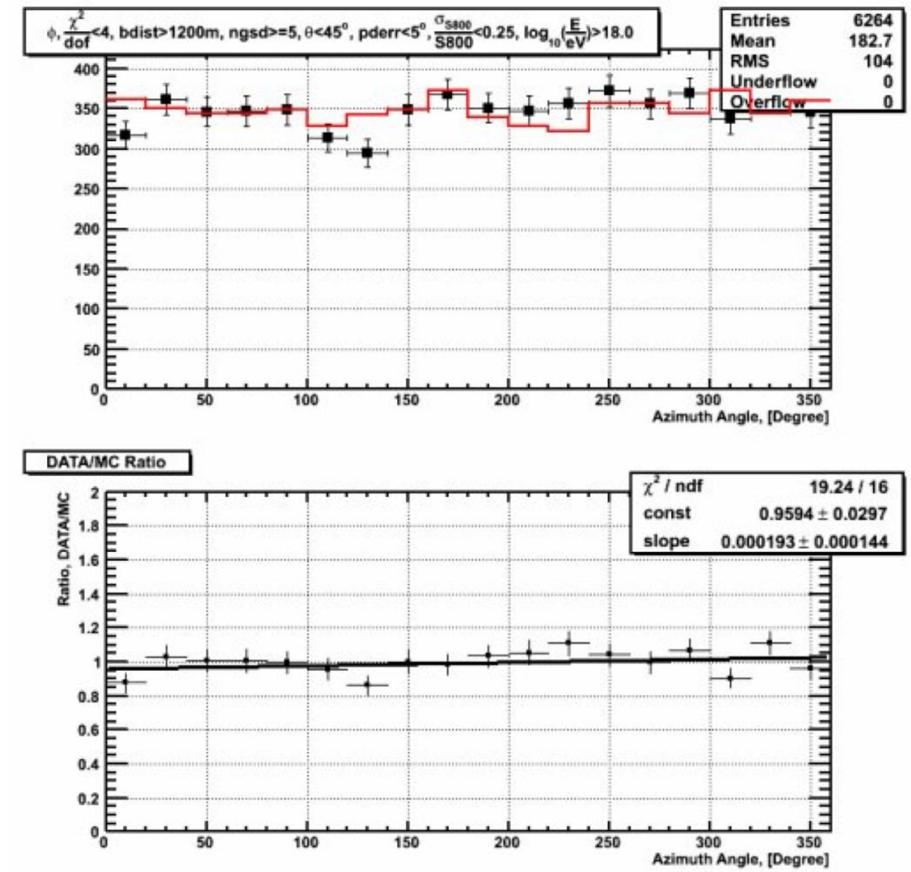
LDF fit χ^2/dof



VEM / counter

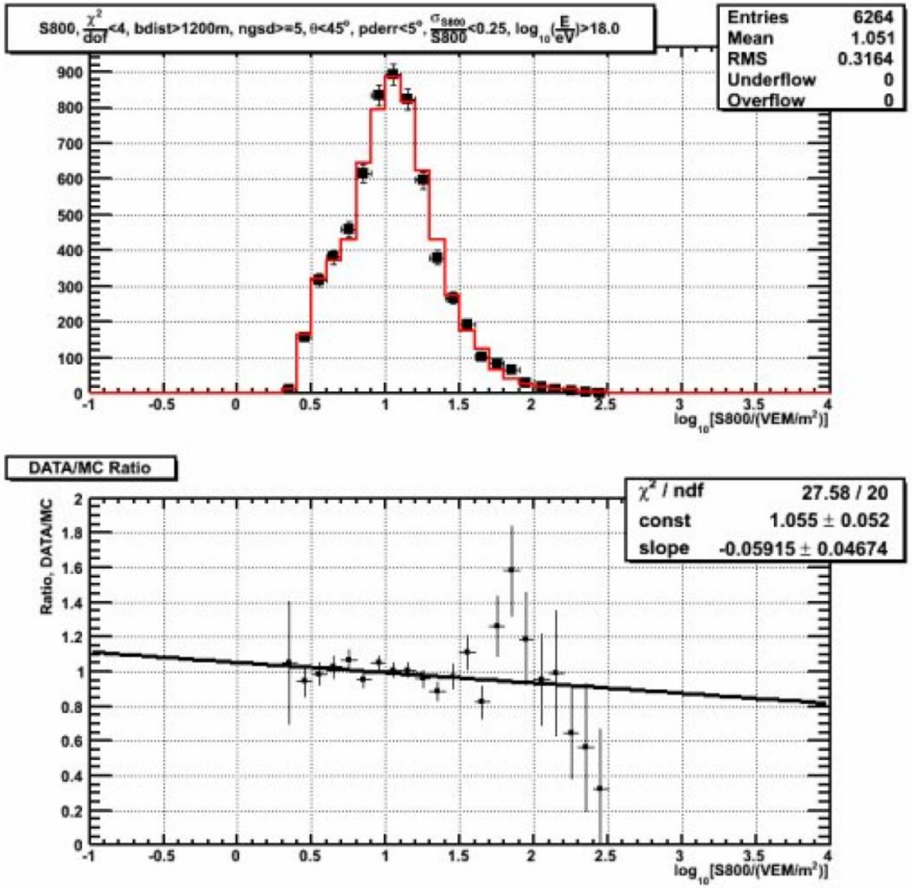
SD data/MC comparison



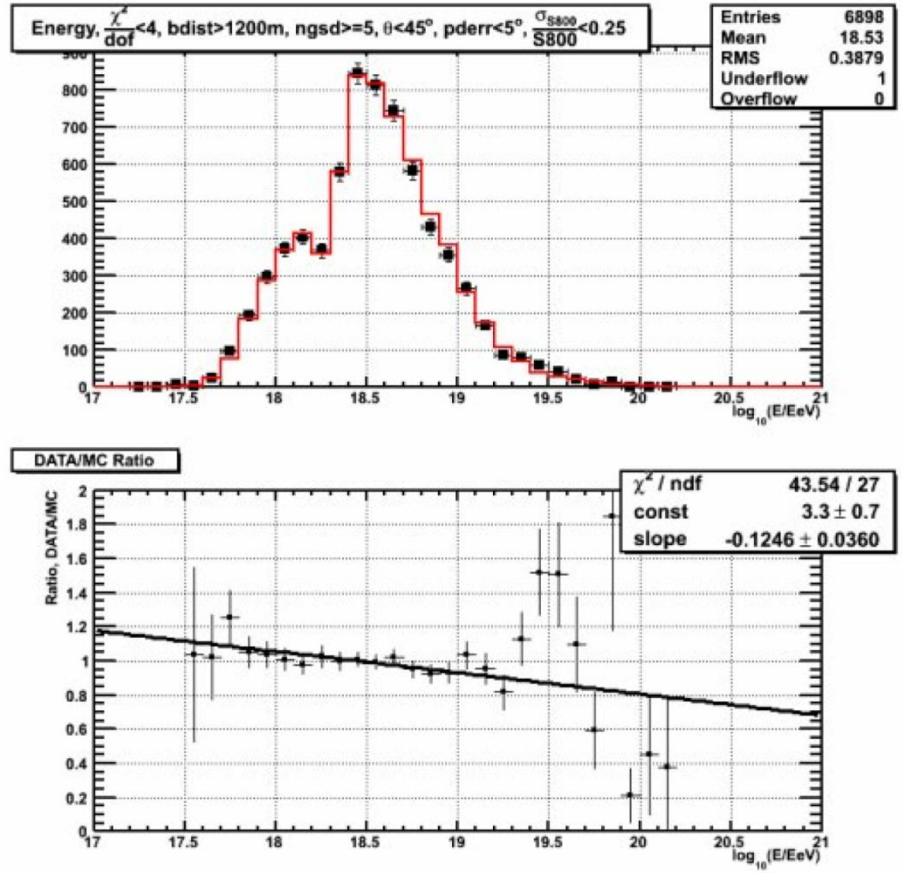


Zenith angle **Azimuthal angle**

SD data/MC comparison

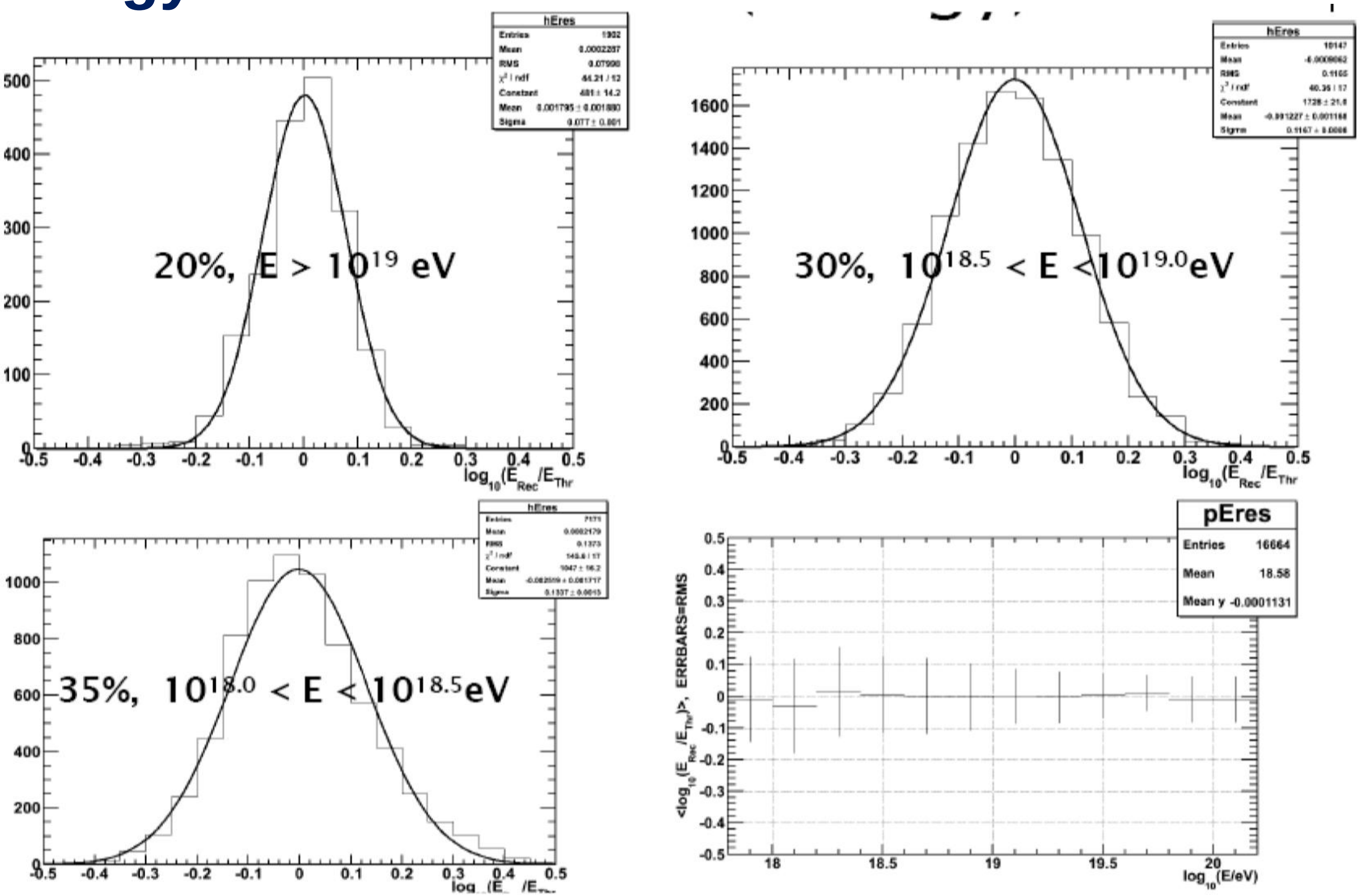


S_{800}

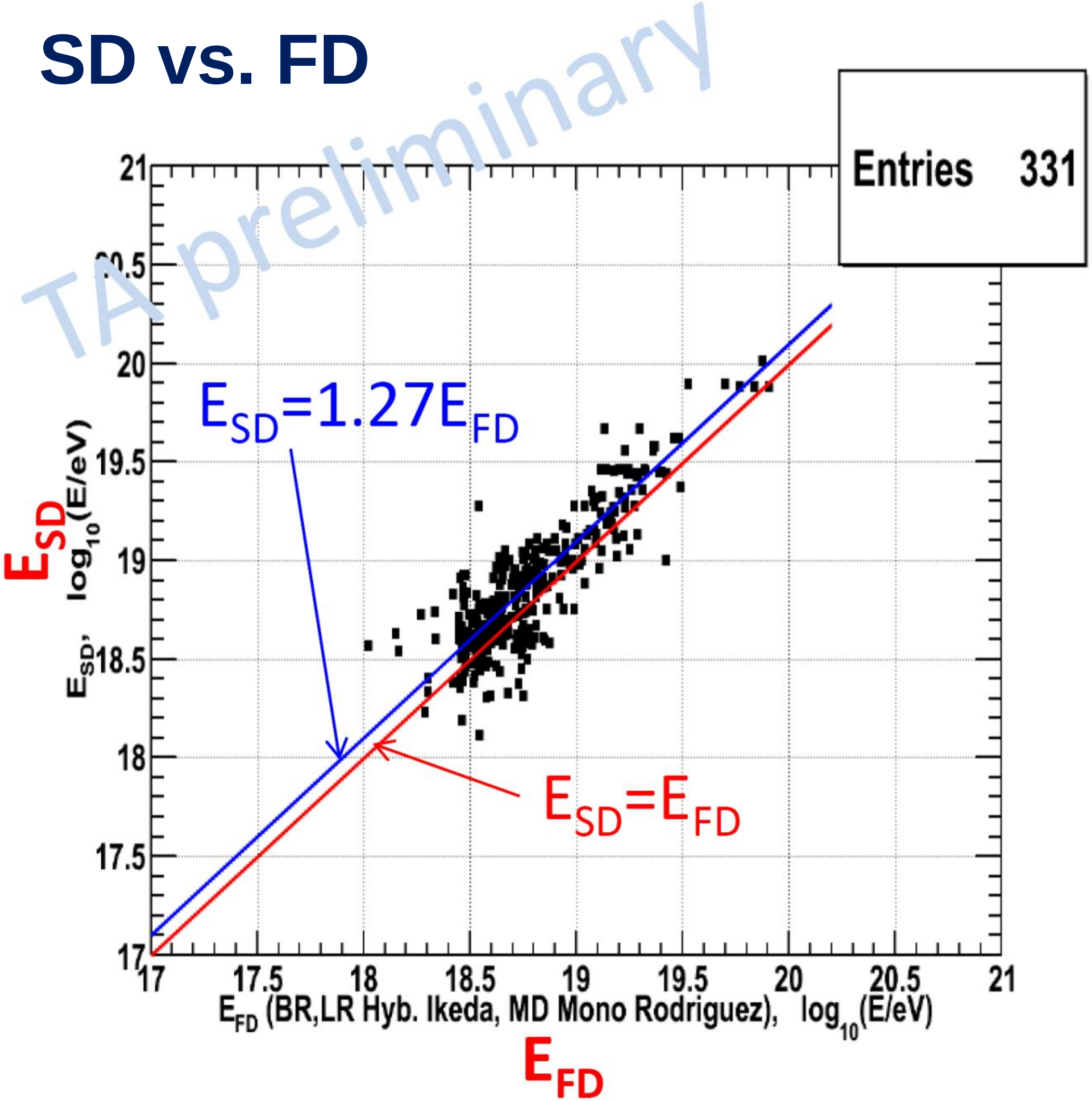


Energy

SD energy resolution



SD vs. FD



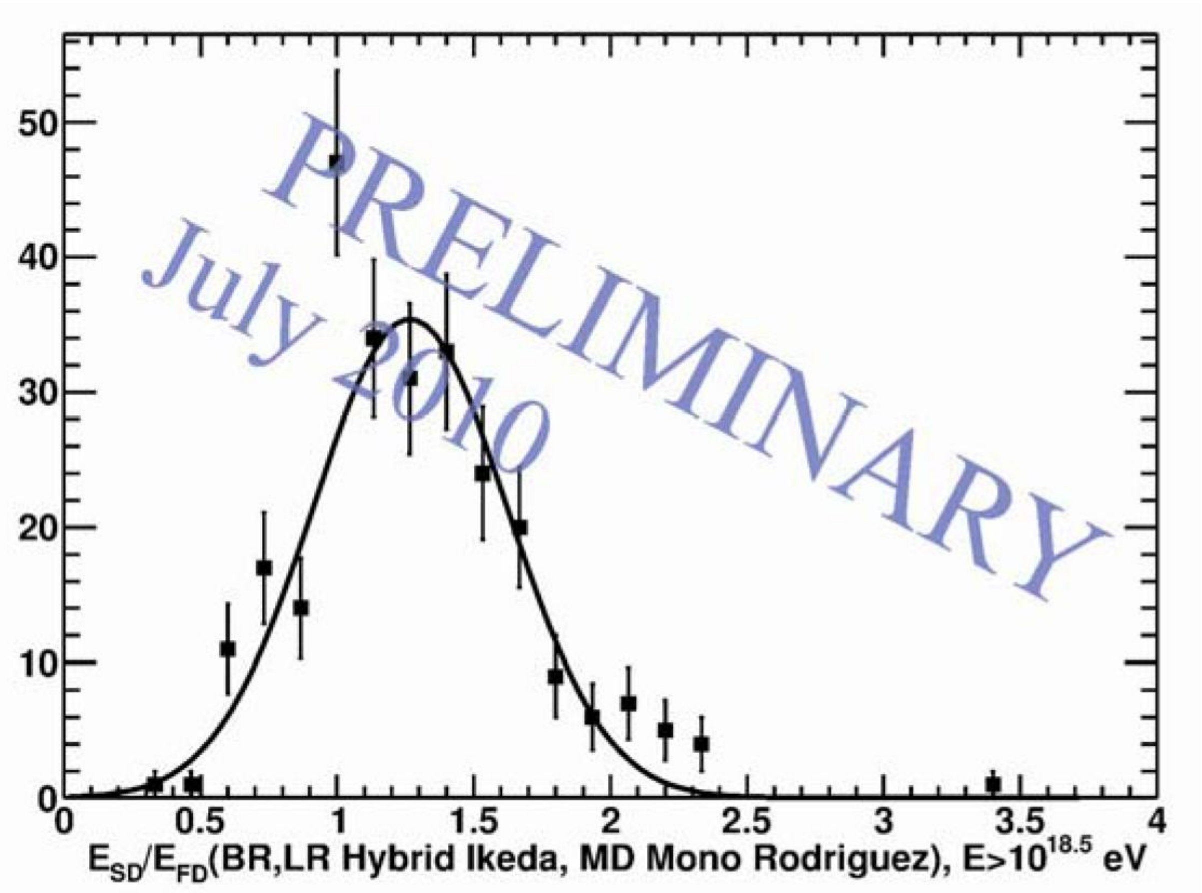
SD energy: CORSIKA
QGSJET-II protons
full MC

FD energy:
MD mono,
BRM, LR hybrid

$$\text{Result: } E = E_{SD}/1.27$$

Note: 19% systematic uncertainty

SD vs. FD


PRELIMINARY
July 2010
0
10
20
30
40
50
0
0.5
1
1.5
2
2.5
3
3.5
4
E_{SD}/E_{FD}(BR,LR Hybrid Ikeda, MD Mono Rodriguez), $E>10^{18.5}$ eV

SD vs. FD energies:

approaches to the contradiction

Auger:

correct method=FD
use FD normalization for SD events

Telescope Array:

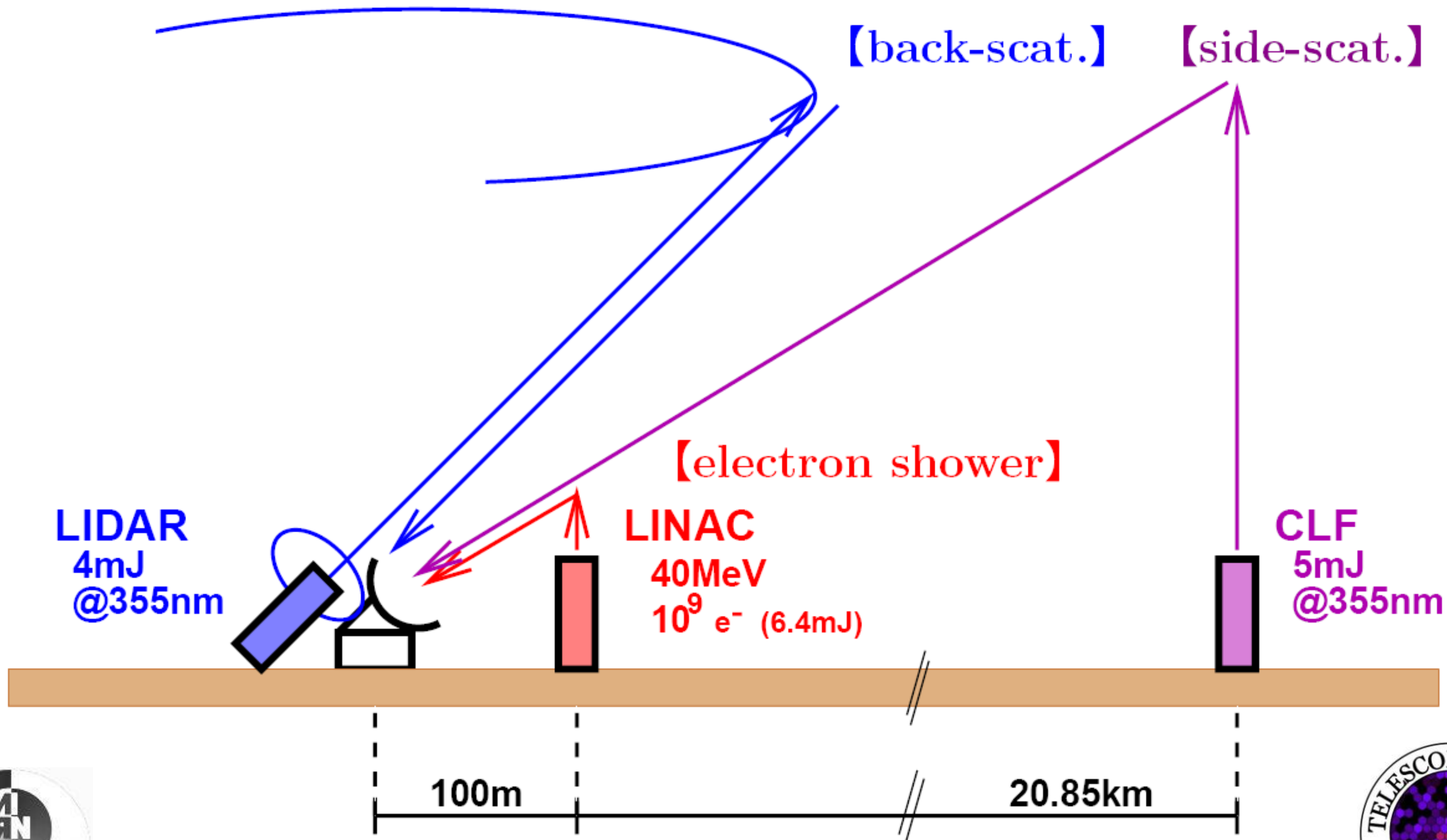
study hybrids (work in progress)
calibrate FD to electron beam from an accelerator (work in progress)
currently use FD normalization for SD events…

theory:

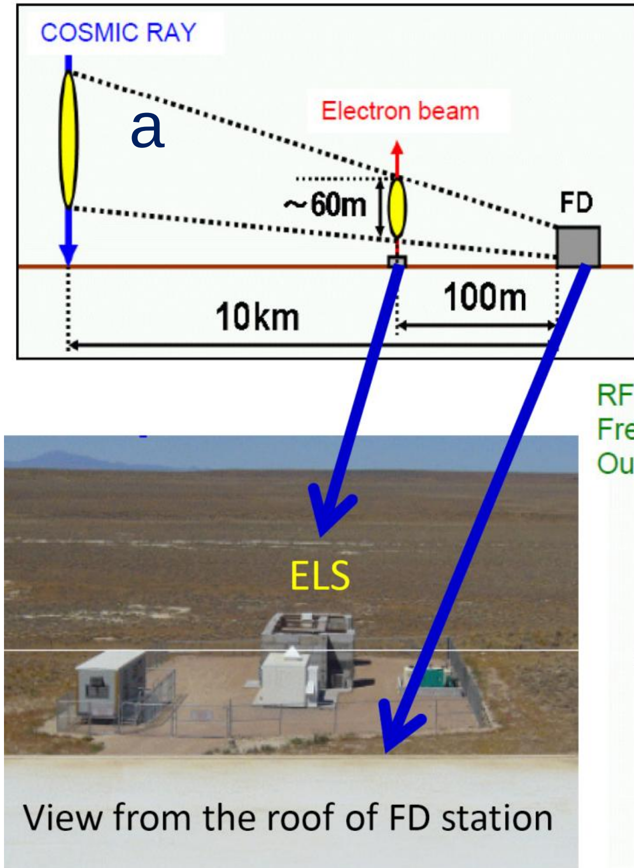
new models of hadronic interactions?
new models of electromagnetic cascades???
details of systematics of the FD method

Telescope Array: FD calibration

< Atmospheric Monitor (LIDAR, CLF) & LINAC >



Telescope Array: FD calibration
ELS (electron light source = LINAC)

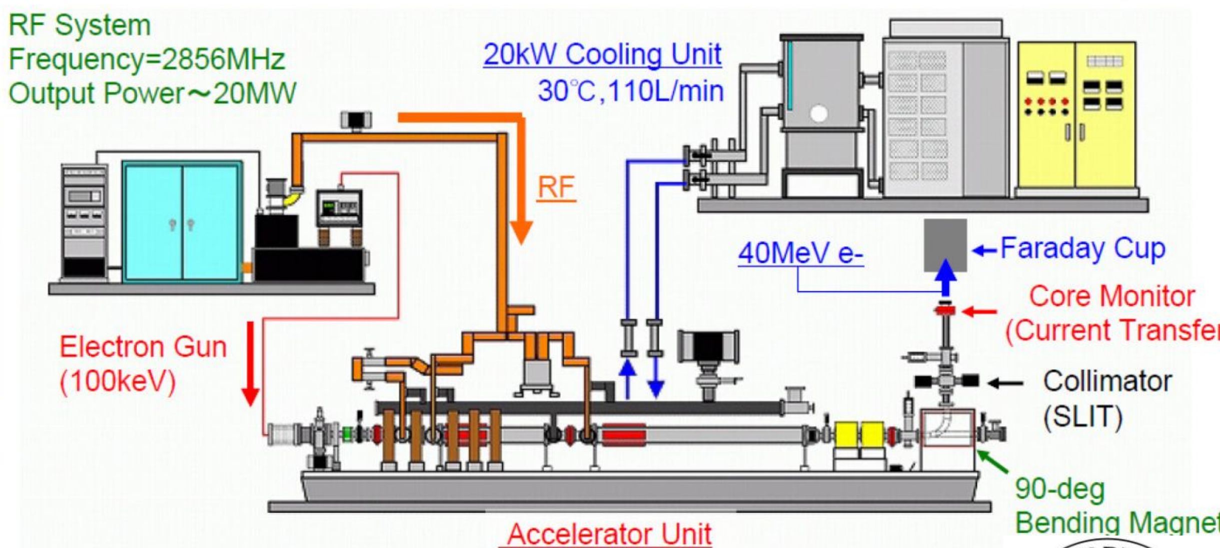


View from the roof of FD station

Specification

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

0.5Hz

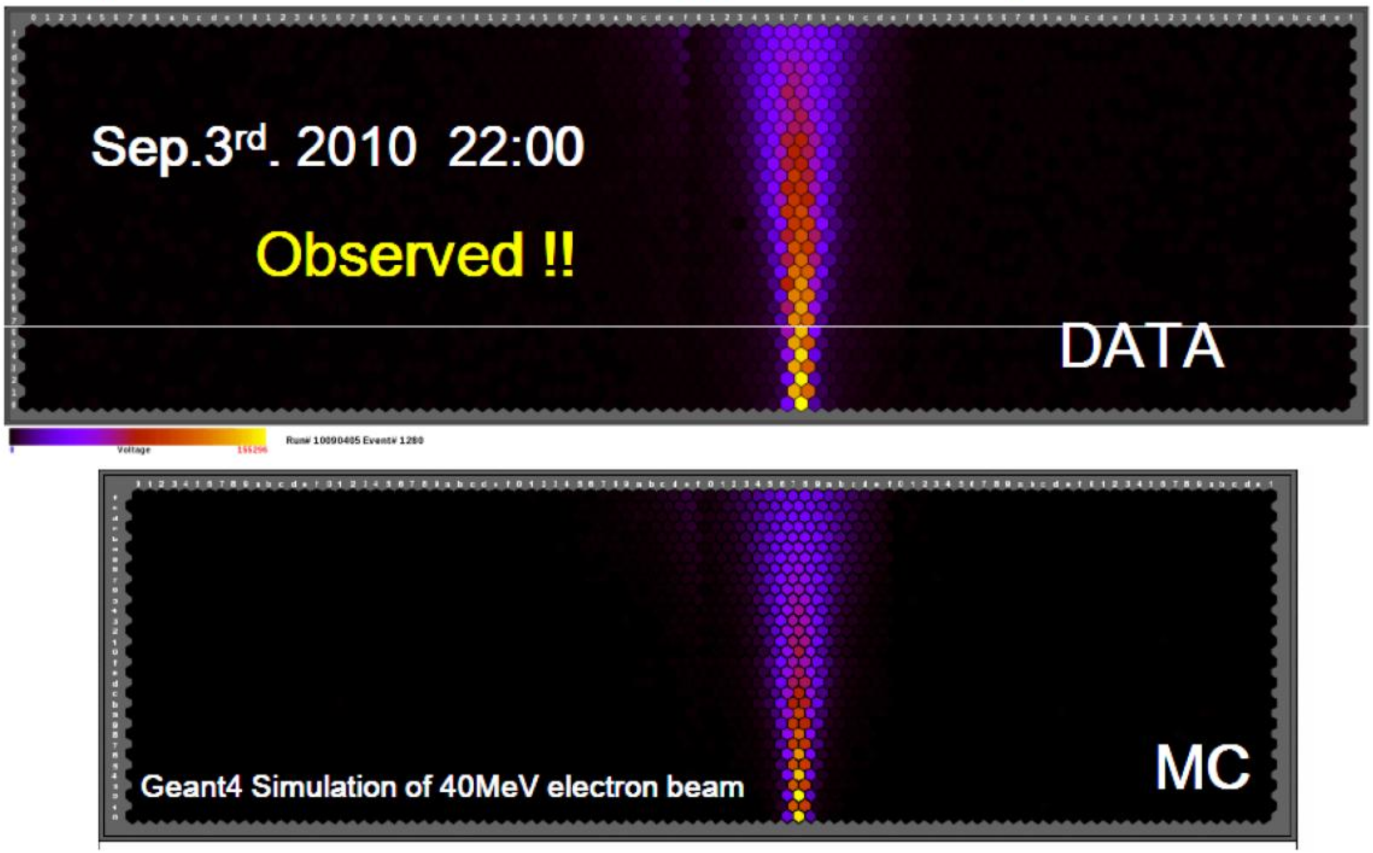


Telescope Array: FD calibration

ELS works!

FD Observation

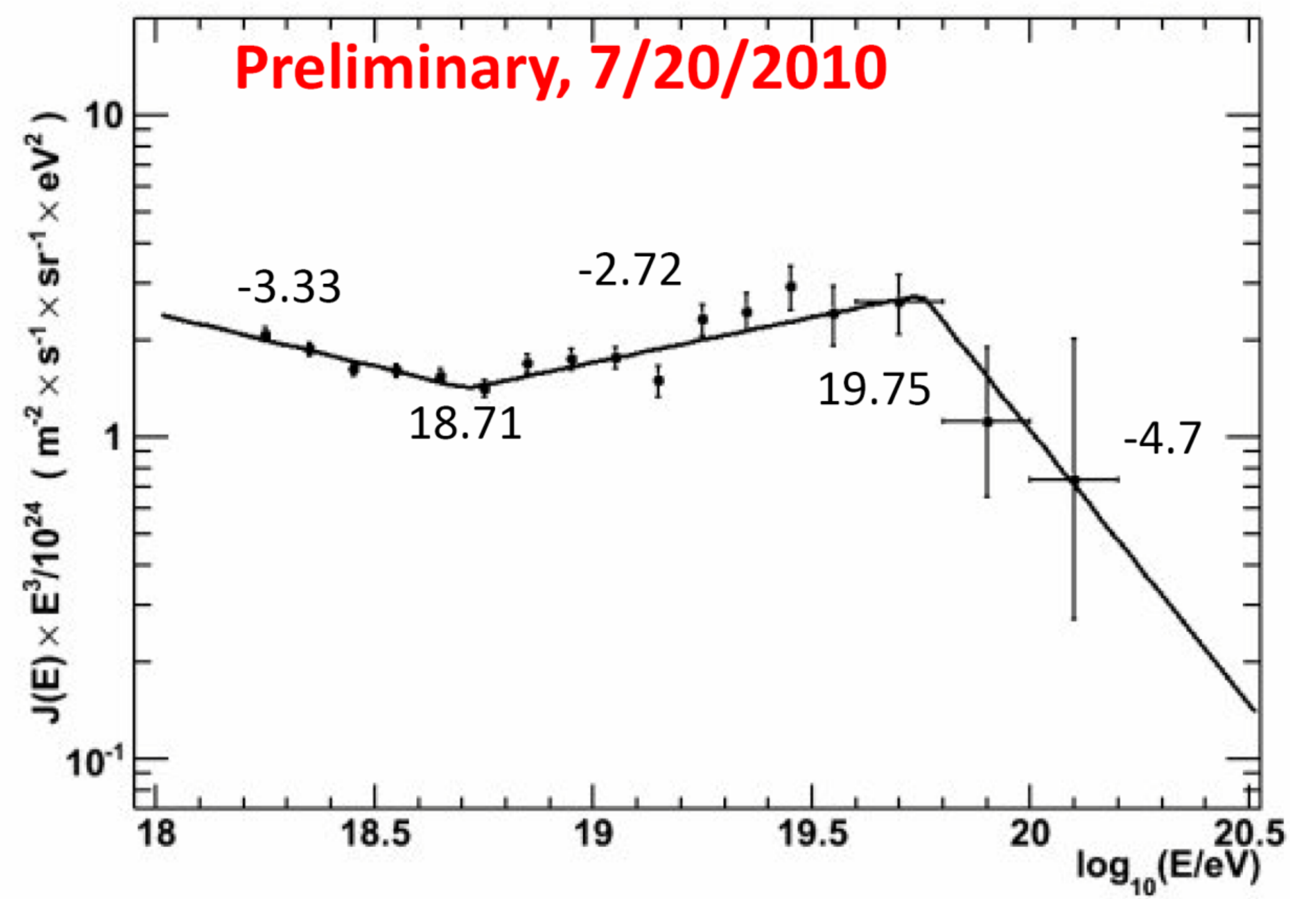
Sep.3rd.2010   Beam Shot into the Sky, and Observed by FD



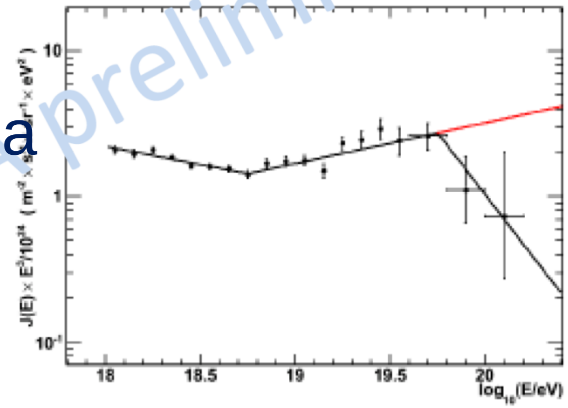
RESULTS: COSMIC-RAY ENERGY SPECTRUM

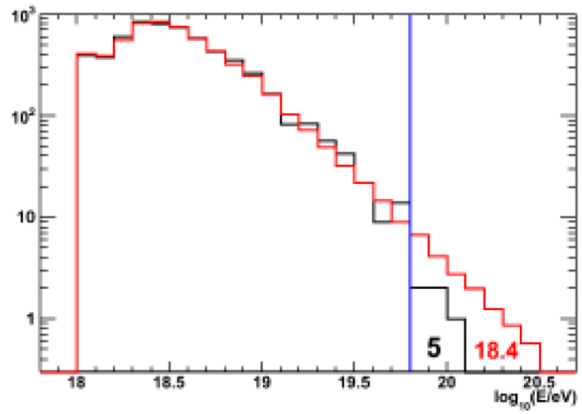
TA SD spectrum

SD energy recaled to FD energy



TA sees the GZK-like suppression





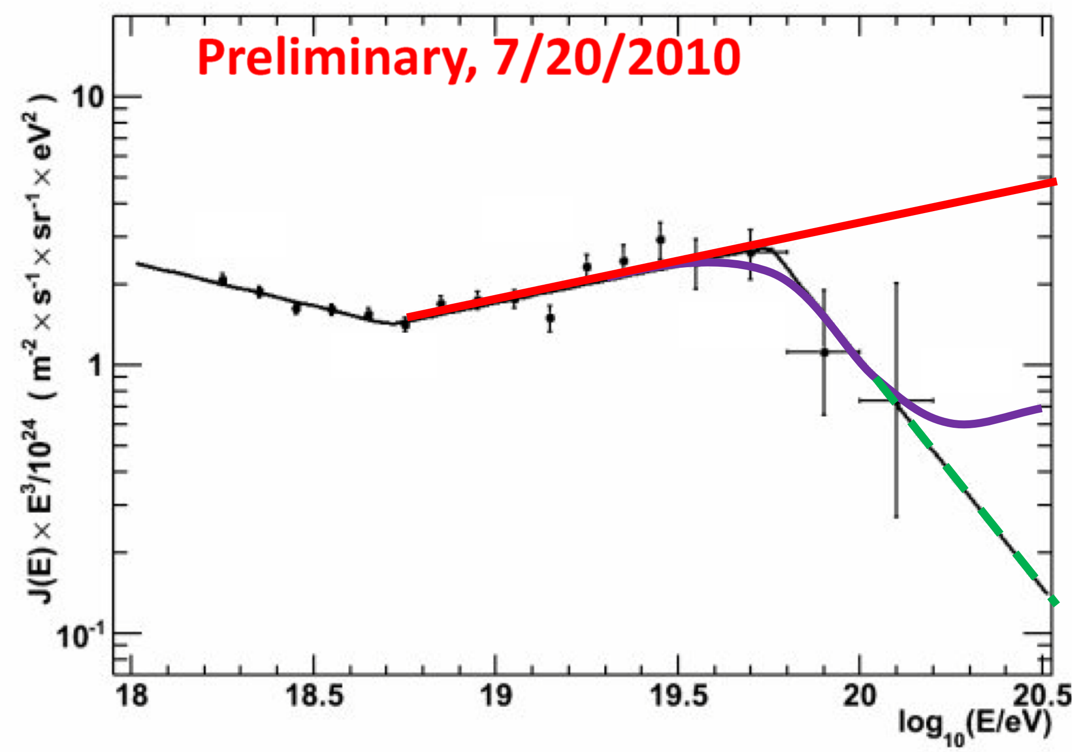
- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TASD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}E$ bins after $10^{19.8}$eV bin:
  - $N_{EXPECT} = 18.4$
  - $N_{OBSERVE}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

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

(3.5σ)

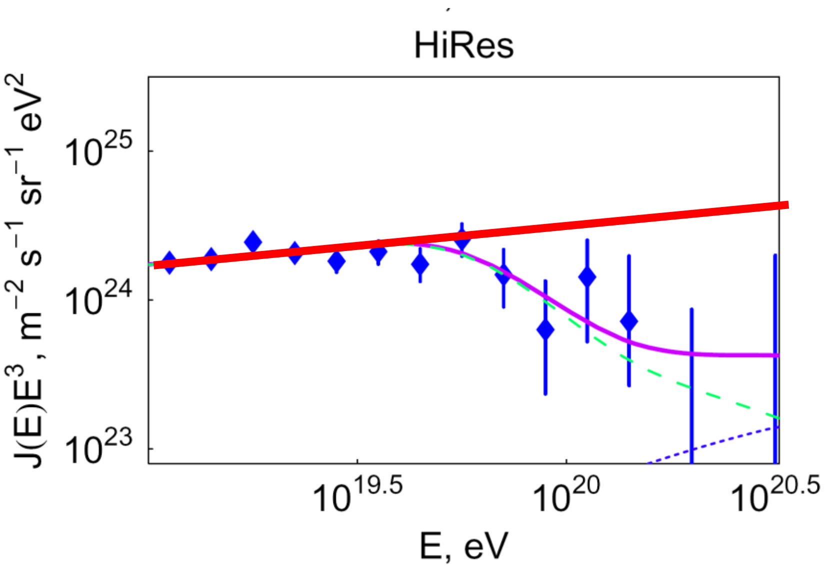
TA sees the GZK-like suppression

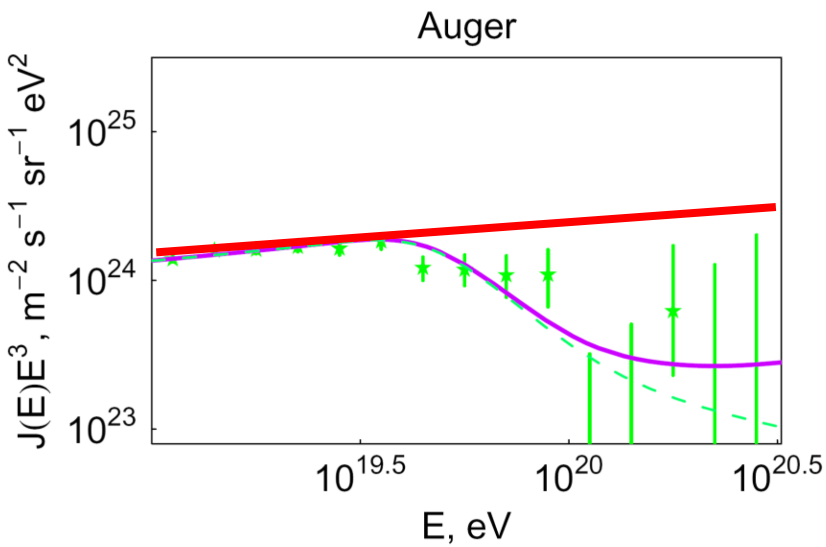
a cutoff or a step? not enough statistics



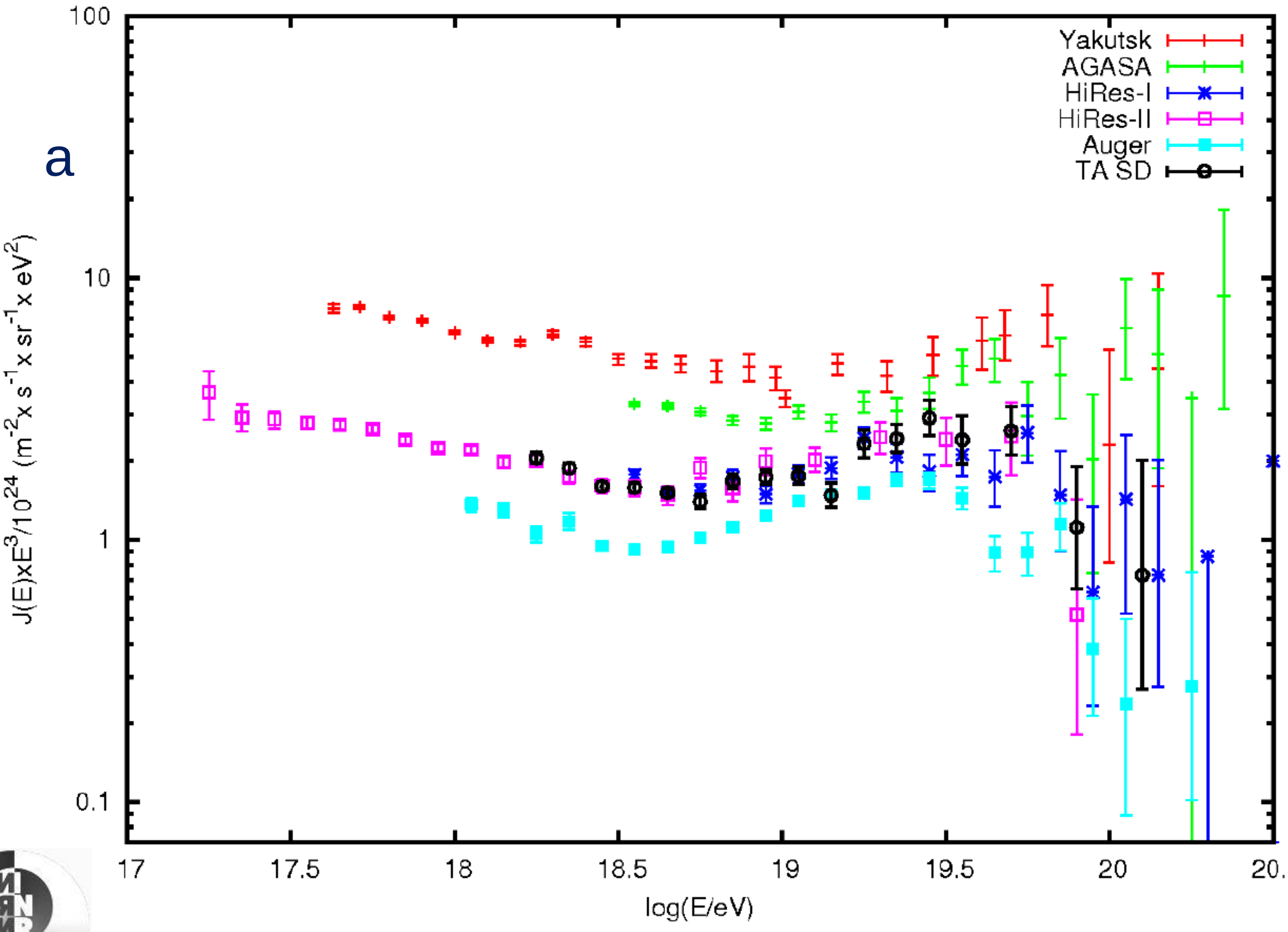
Other experiments see the GZK-like suppression

spectrum continuation excluded at
6σ (HiRes), 10σ (Pierre Auger), 3.5σ (TA)

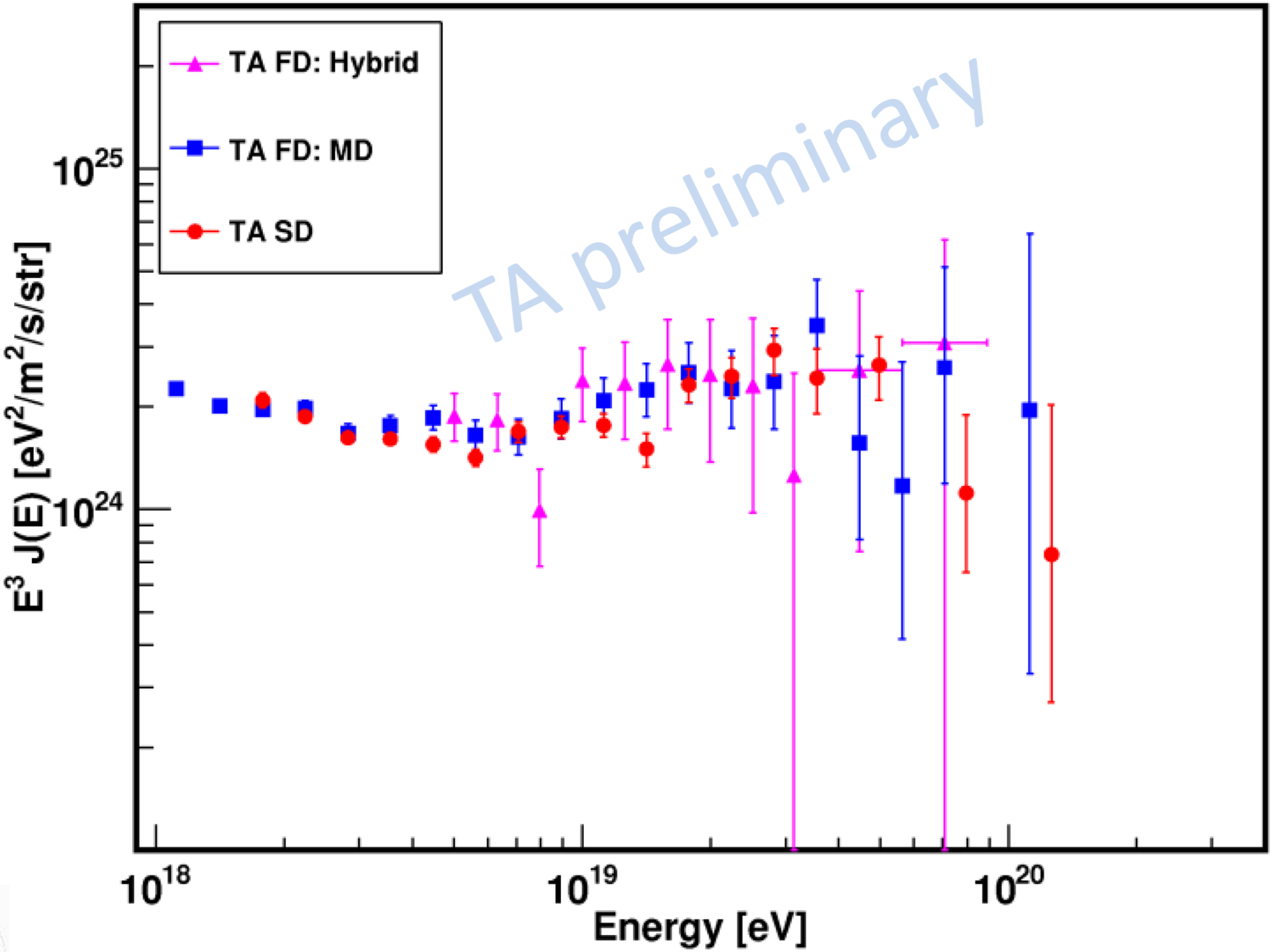




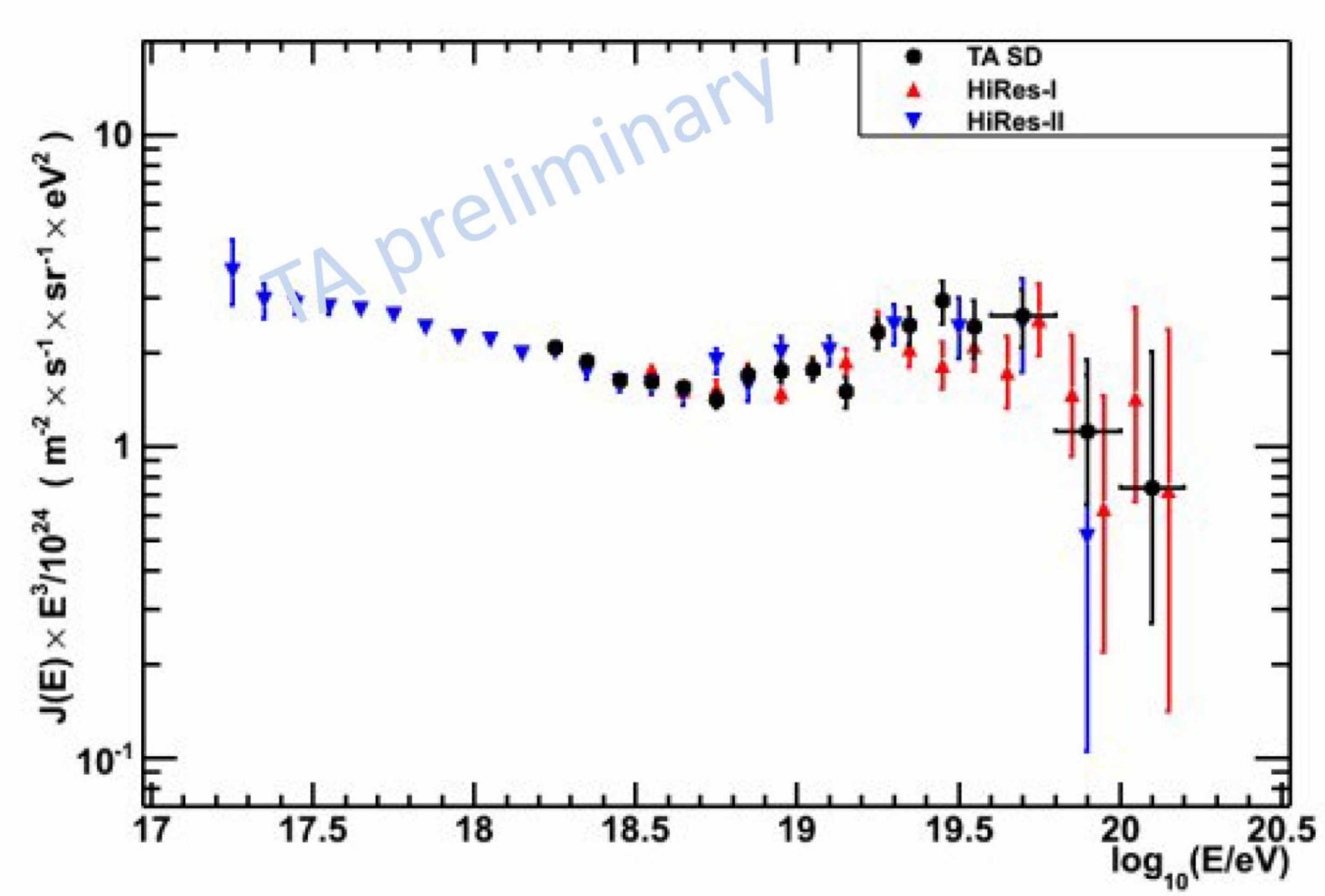
Spectra measured in various experiments



TA spectra (different techniques)



TA spectrum agrees with HiRes

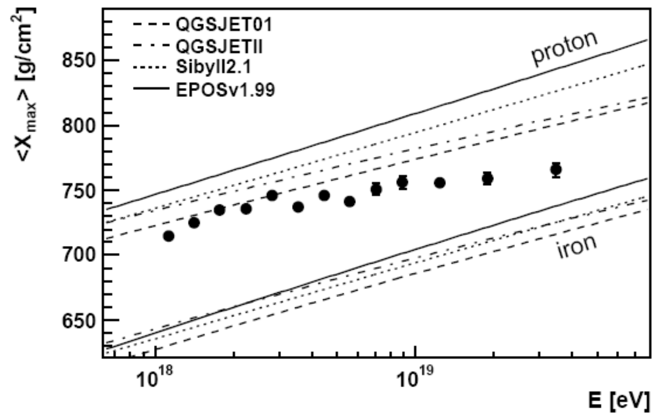


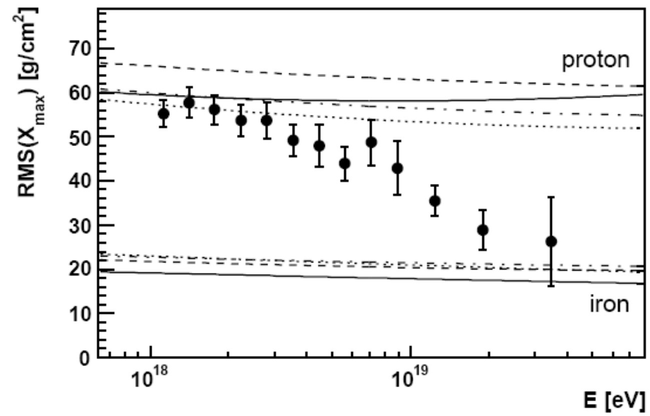
RESULTS: PRIMARY COMPOSITION

Primary composition: protons or heavy nuclei?

Auger

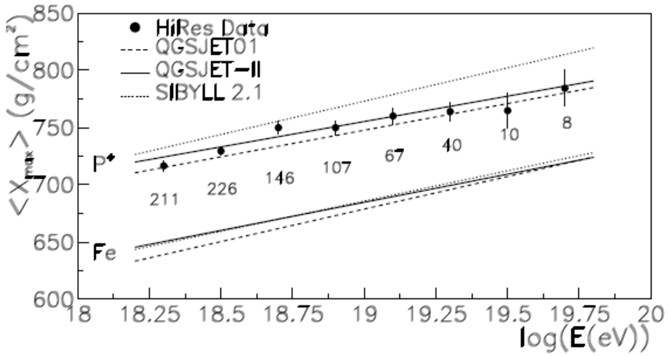
Phys.Rev.Lett.104.091101

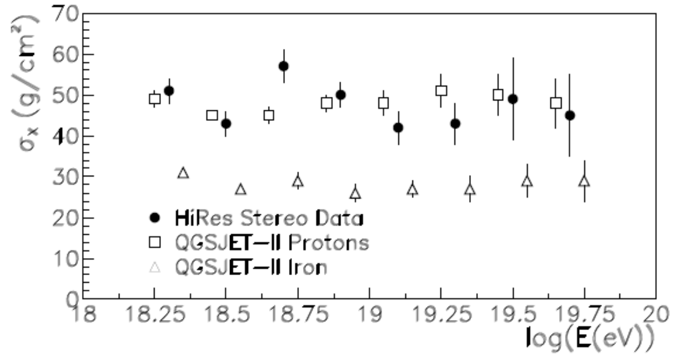




HiRES

Phys.Rev.Lett.104.161101





Yakutsk (muons):

$$0.29 \leq \epsilon_{Fe} \leq 0.68 \quad (95\%\mathrm{CL}), \qquad E > 10^{19}\ \mathrm{eV}$$

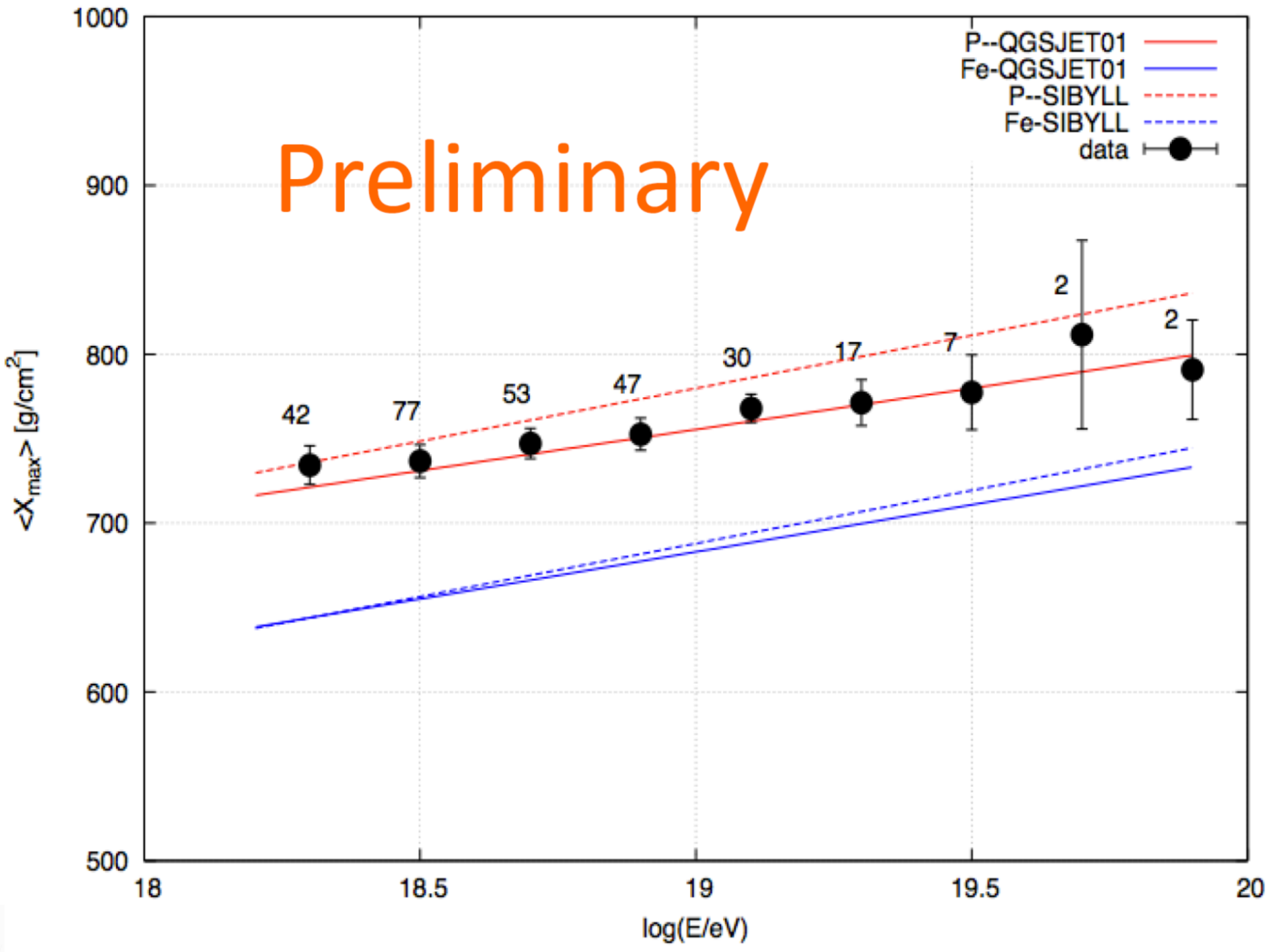
Primary composition: protons or heavy nuclei?

HiRes:
Northern hemisphere, protons

Auger:
Southern hemisphere, mix

Yakutsk:
Northern hemisphere, mix

TA composition results:



Primary composition: protons or heavy nuclei?

HiRes:
Northern hemisphere, protons

Auger:
Southern hemisphere, mix

Yakutsk:
Northern hemisphere, mix

TA:
Northern hemisphere, protons

RESULTS: ARRIVAL DIRECTIONS

Anisotropy: data

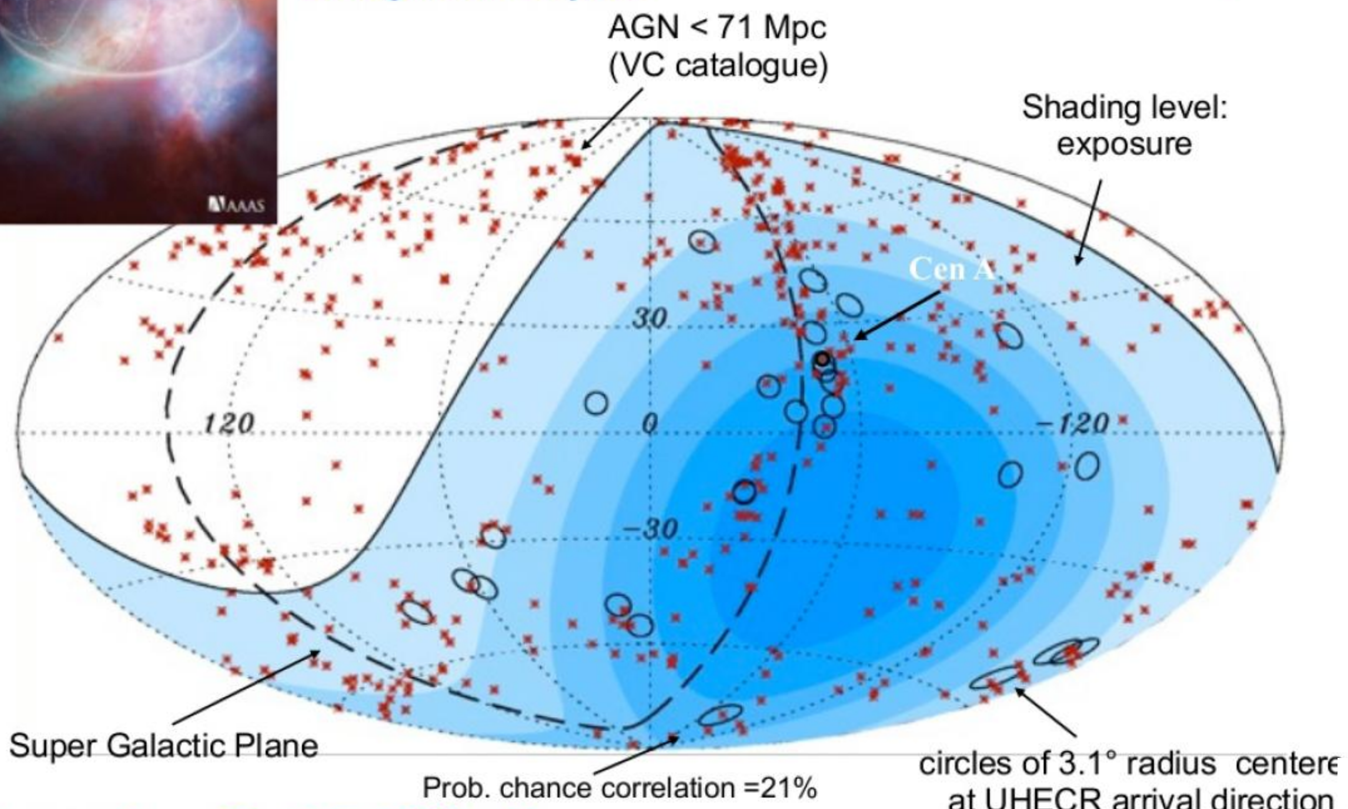
- 28 months (May 2008 $\rightarrow$ September 2010) of surface detector data
- 655 events above 10 EeV
  35 events above 40 EeV
  15 events above 57 EeV
- angular resolution 1.5°
- geometrical acceptance

Auger: AGN correlations

November 9, 2007

"Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

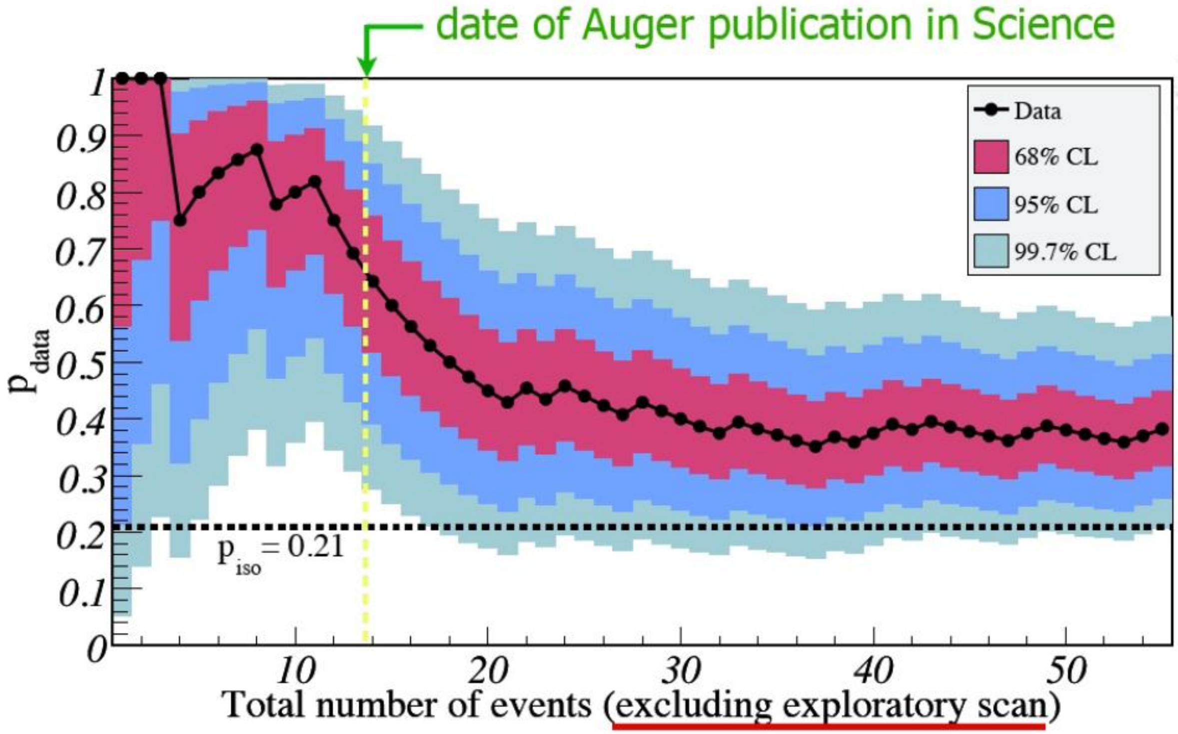
Anisotropy of the UHECR sky



27 events E> $5.7 \cdot 10^{19}$ eV

Angular resolution < 1°

Auger: AGN correlations weakened

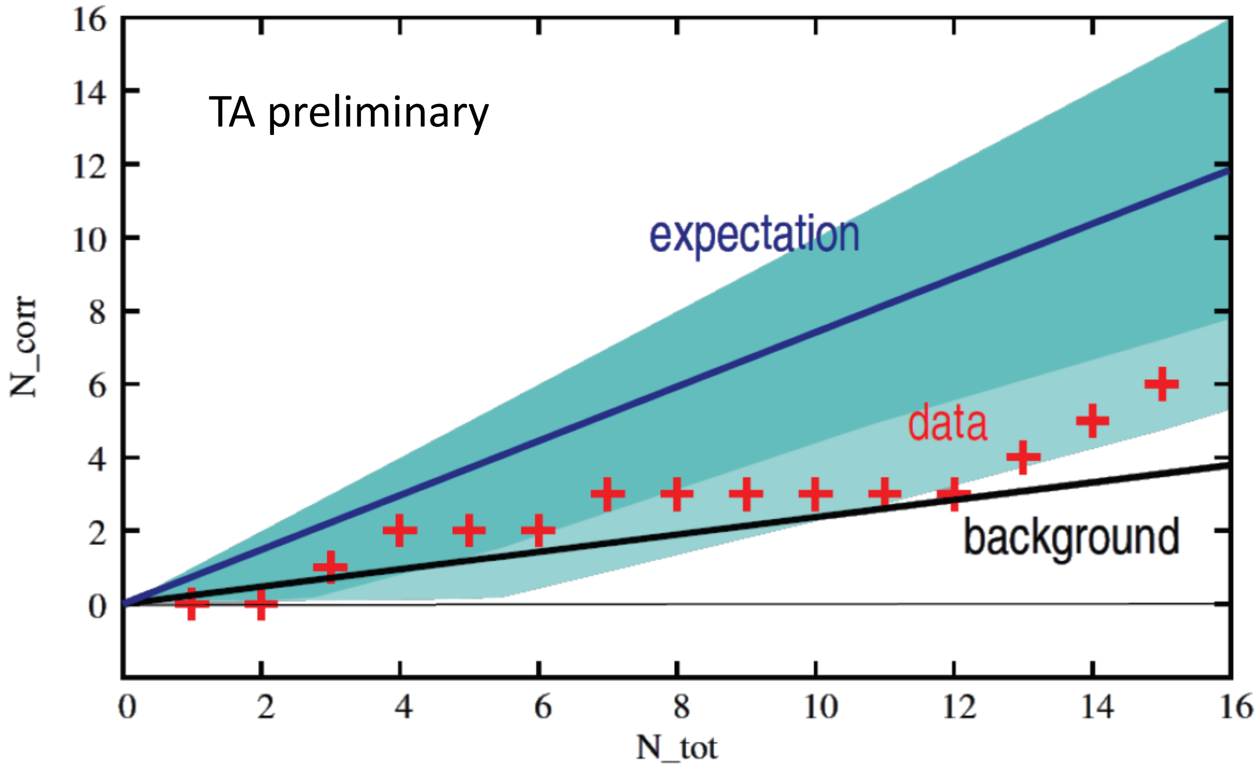


Pierre Auger collaboration, Astropart. Phys. 34 (2010)

Before publication date: 9/13 correlate. Background: 2.7 ± 1.6

After publication date: 12/42 correlate. Background: 8.9 ± 3.0

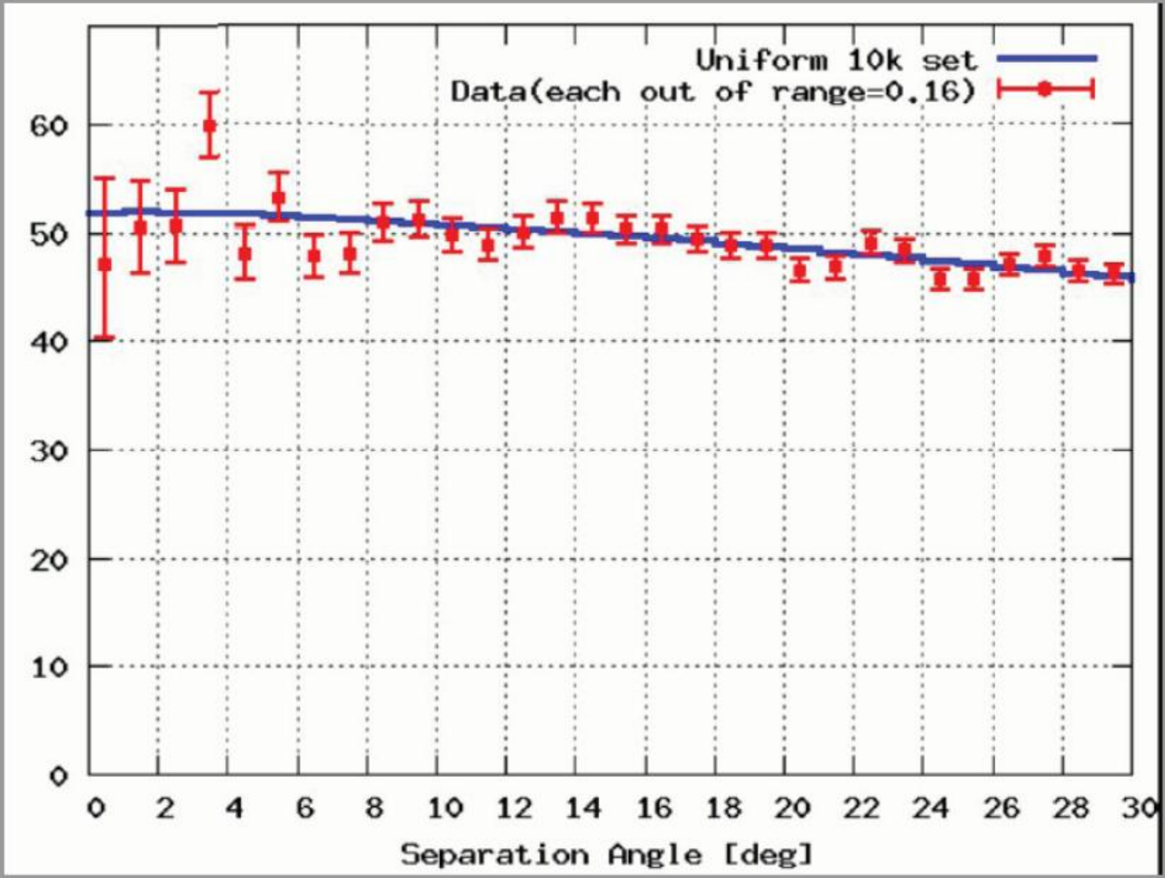
TA AGN correlations



correlate: 6 of 15, bg: 3.6

TA autocorrelation

$E > 10$ EeV



⟹ no excess over background

TA correlations with the large-scale structure

matter in the Universe distributed anisotropically
at the scales of UHECR propagation

astrophysical sources should follow the matter distribution

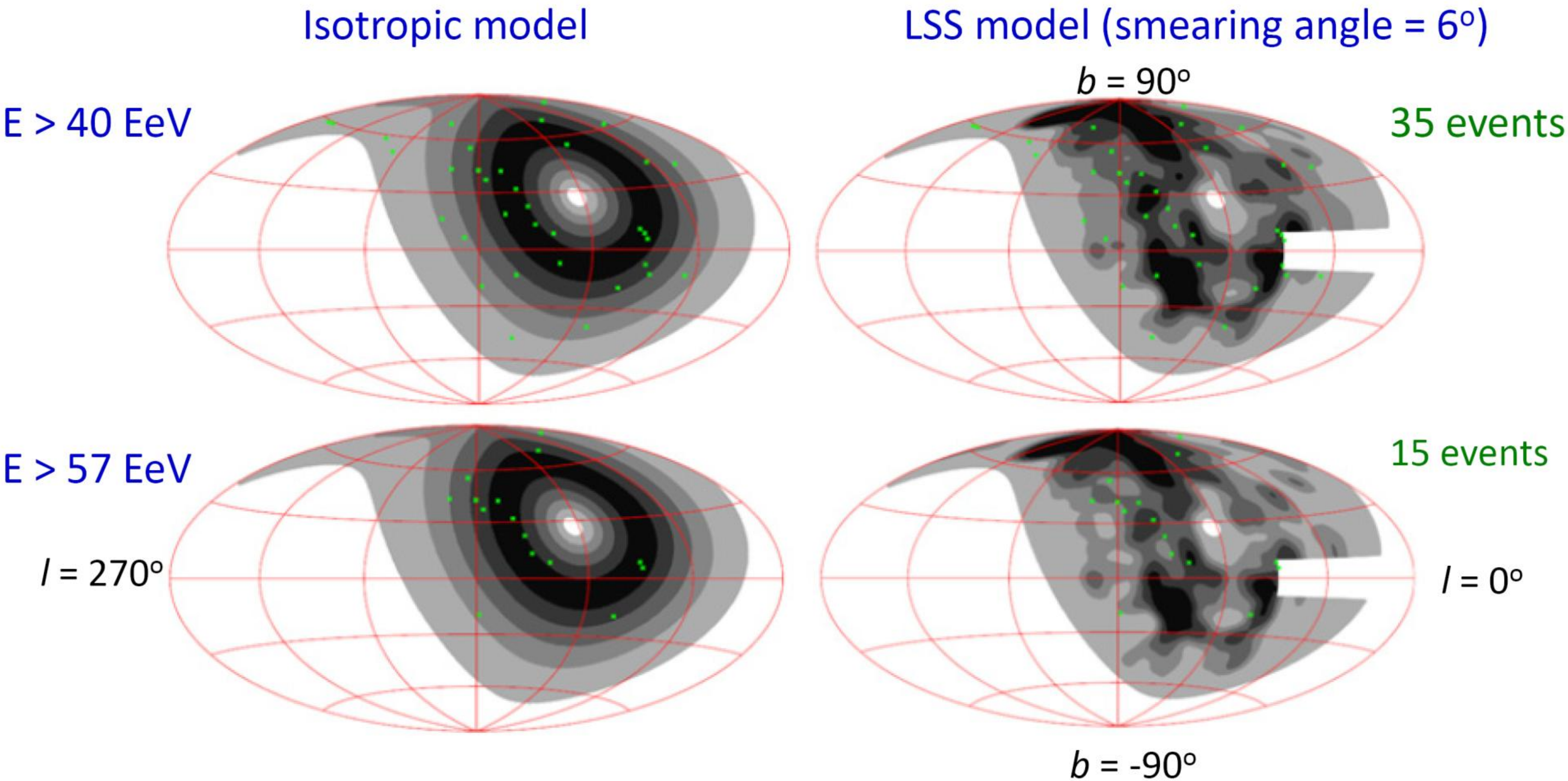
- **arrival directions follow the matter distribution?**

  - trace the distribution of galaxies (2MASS XSCz)
  - assume injection spectrum
  - account for propagation
  - get expected skymap
  - compare with data

- first observed in 1990s in Yakutsk data
- may explain Auger AGN correlations without AGNs

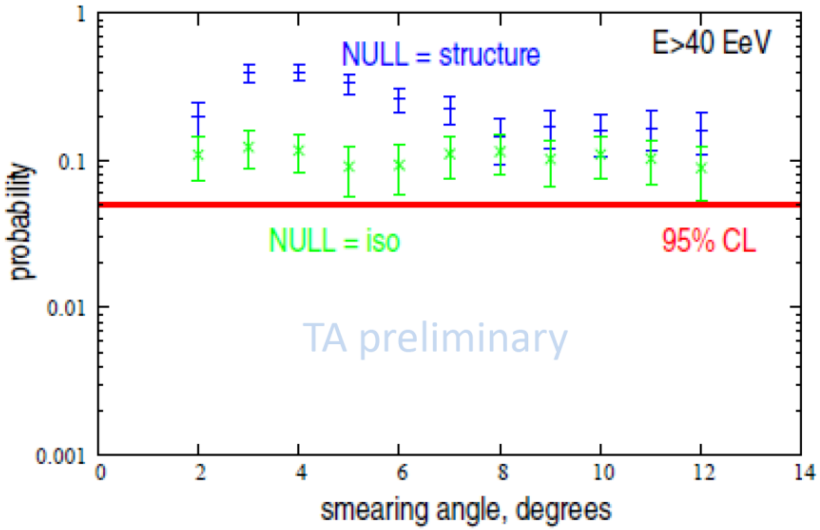
TA correlations with the large-scale structure

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

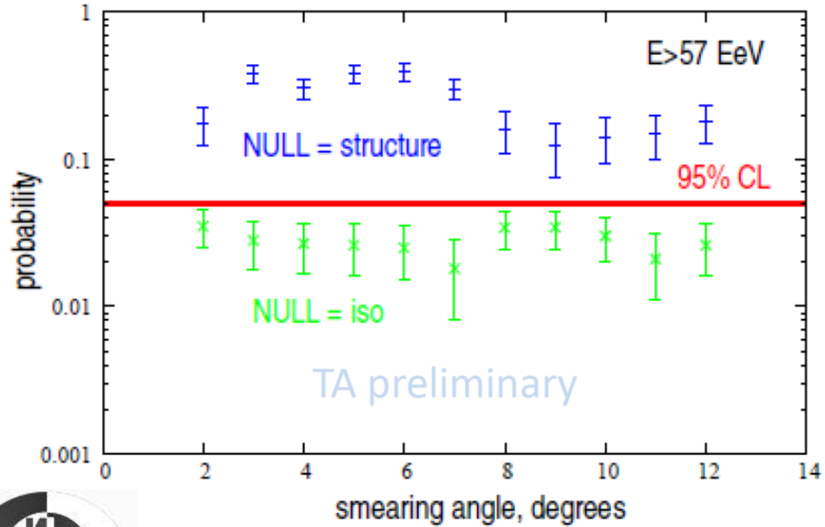


the galactic coordinates

TA correlations with the large-scale structure



Data with E > 40 EeV is compatible with LSS and isotropy models.



Data with E > 57 EeV is compatible with LSS model, and is not compatible with isotropic model at 95% CL.

RESULTS: SEARCH for PHOTONS

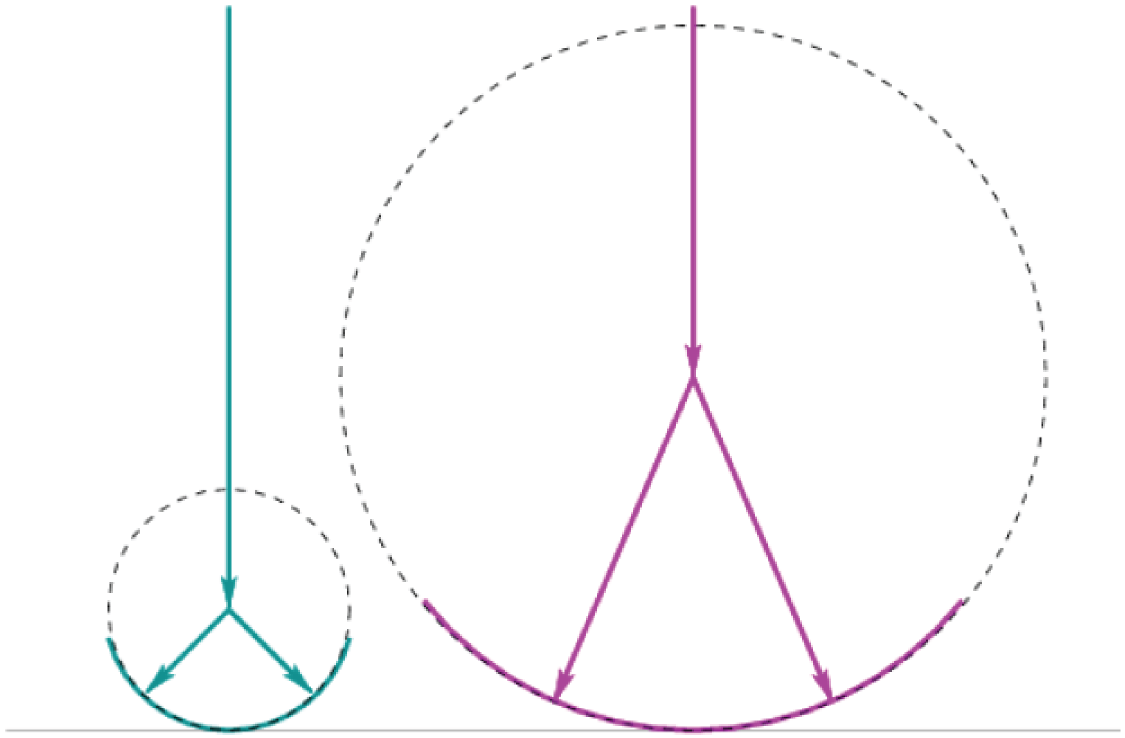
TA photon search

Photon-sensitive parameter:

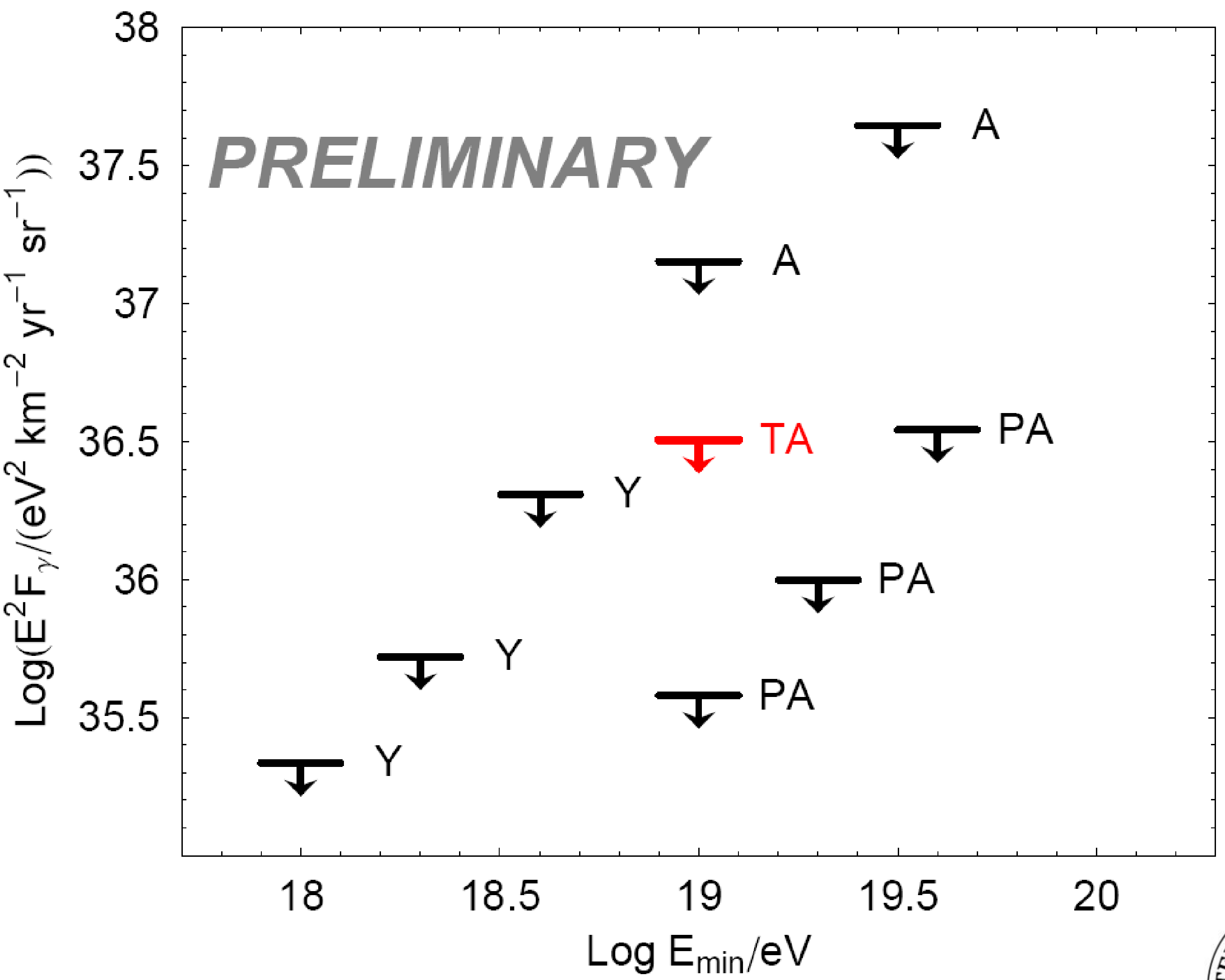
AGASA, Yakutsk	muon density (strongest discrimination)
Pierre Auger SD	shower front curvature and thinkness
Pierre Auger hybrid	XMAX
Telescope Array SD	shower front curvature

TA photon search

deep shower maximum = curved front



TA photon search



TA future plans…

1. **Low Energy Extension = “TALE”**
   - Large elevation angle FD + SD array = Hybrid
   - Energy range extend down to 10^{17} eV

2. **Extension of area = “Next TA”** (tentative name)
   - (Phase 1 TA) X 5 SD array = 3,400 km^2
   - Concentrate to anisotropy/point source study

3. **Further extension**
   - Hybrid or Stereo FD array

And new detection methods (Bistatic Radar, ….)

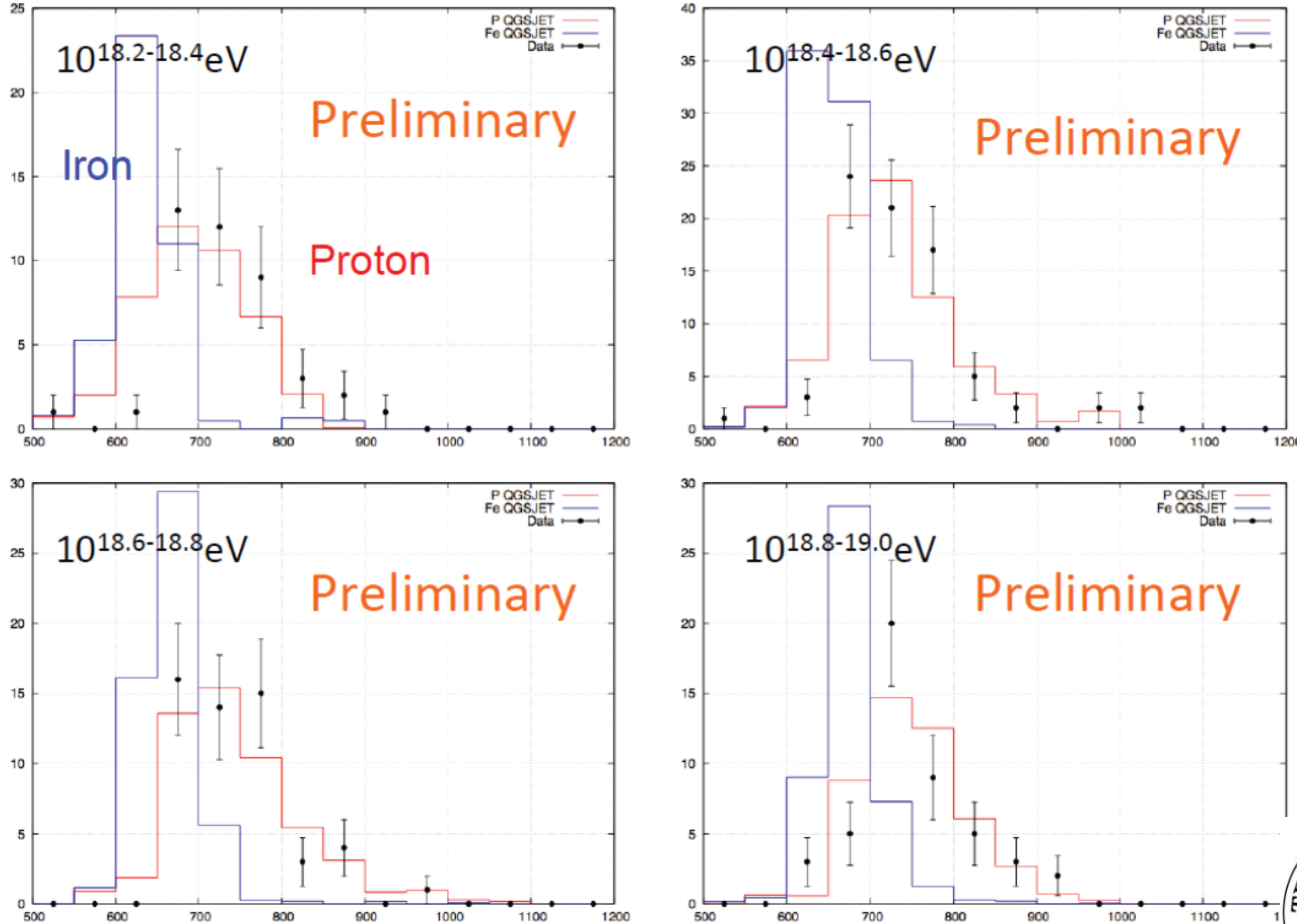
CONCLUSIONS

CONCLUSIONS

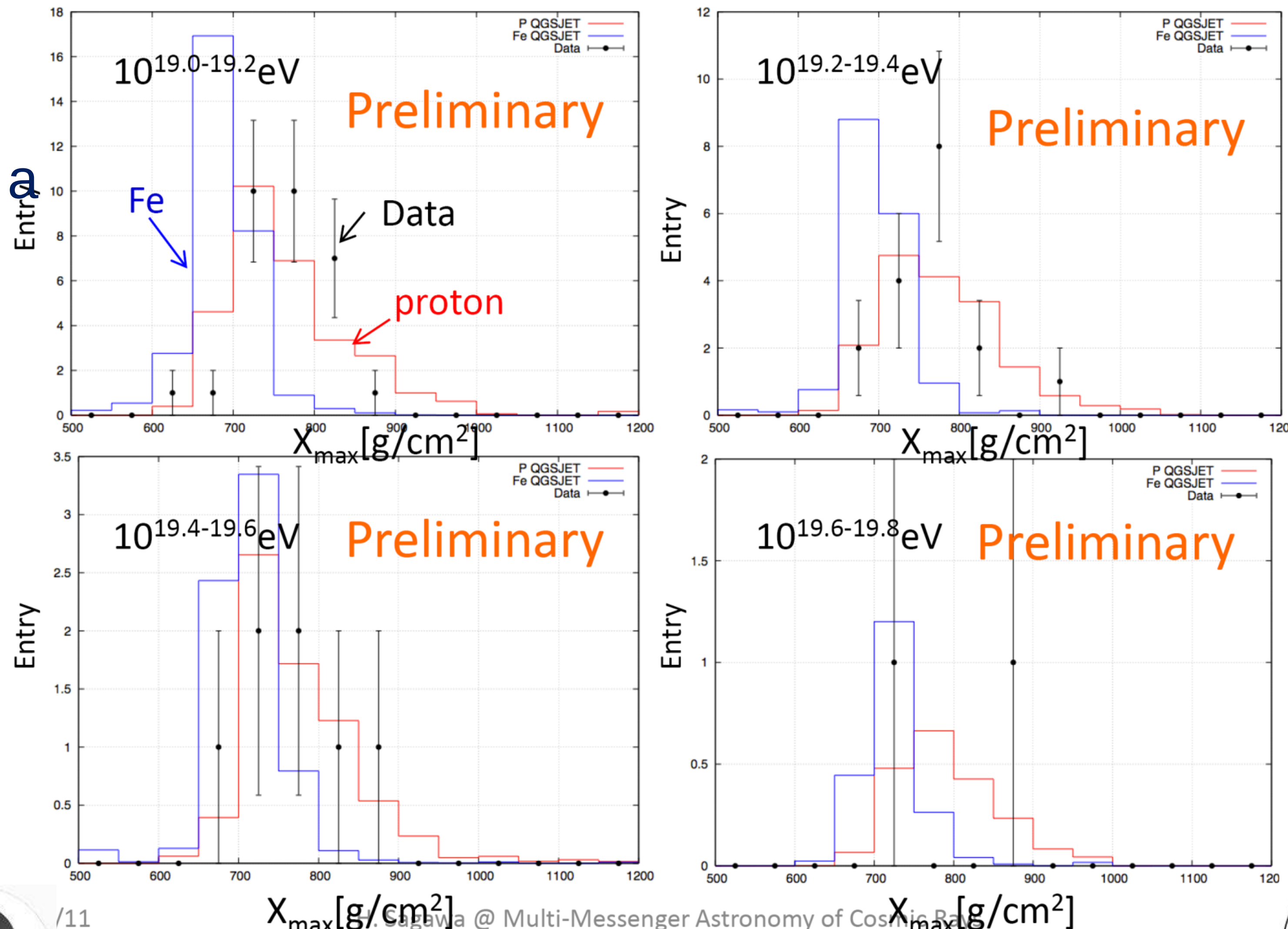
- PRIMARY ENERGIES:
  - FD/SD disagreement (TA: 27%), origin to be studied
  - TA uses a new SD energy method (MC, not CIC)
- SPECTRUM:
  - TA=HiRes
  - Auger vs. TA vs. Yakutsk disagree in normalization
  - HiRes, Auger, TA agree on the GZK-like suppression
  - insufficient statistics to study the shape at $E>10^{20}$ eV
- COMPOSITION: contradictory results
  - TA, HiRes : protons
  - Auger, Yakutsk : mix
- ANISOTROPY:
  - Auger AGN correlations weak, TA AGN: consistent with isotropy
  - Autocorrelations: consistent with isotropy
  - Large-scale structure: weak evidence at $E>57$ EeV
- NO PHOTONS FOUND

stereo: protons or nuclei?

Xmax Distribution (QGSJET01)

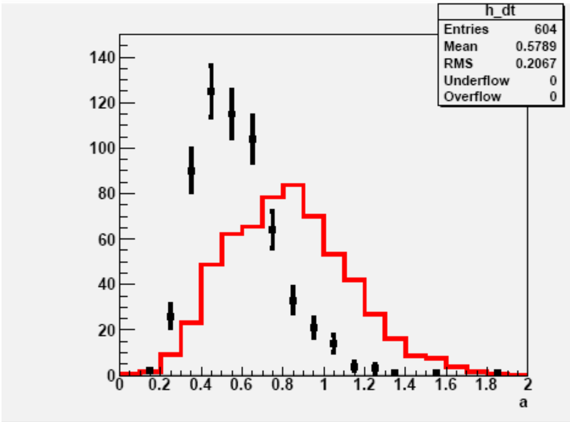


stereo: protons or nuclei?

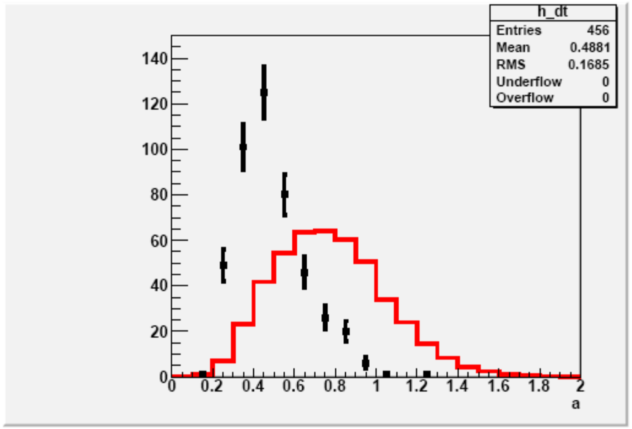


Photons?

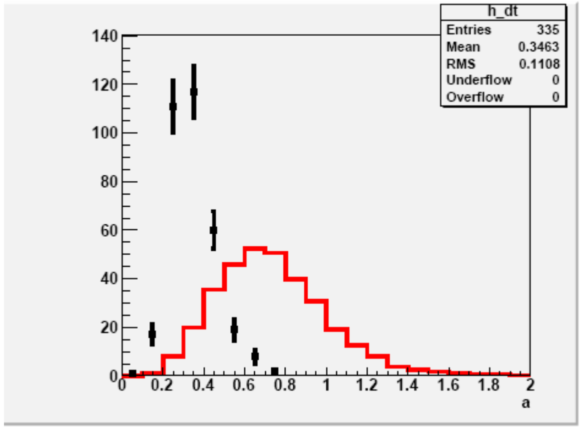
$0^\circ - 30^\circ$



$30^\circ - 45^\circ$



$45^\circ - 60^\circ$



$E_\gamma > 10^{19}$ eV

data

photon MC, E^{-2} spectrum