

# *Measurement of Ultra-high Energy Cosmic Rays*

*- First Results from Telescope Array (TA) -*

*May 7, 2010 @ ULB*

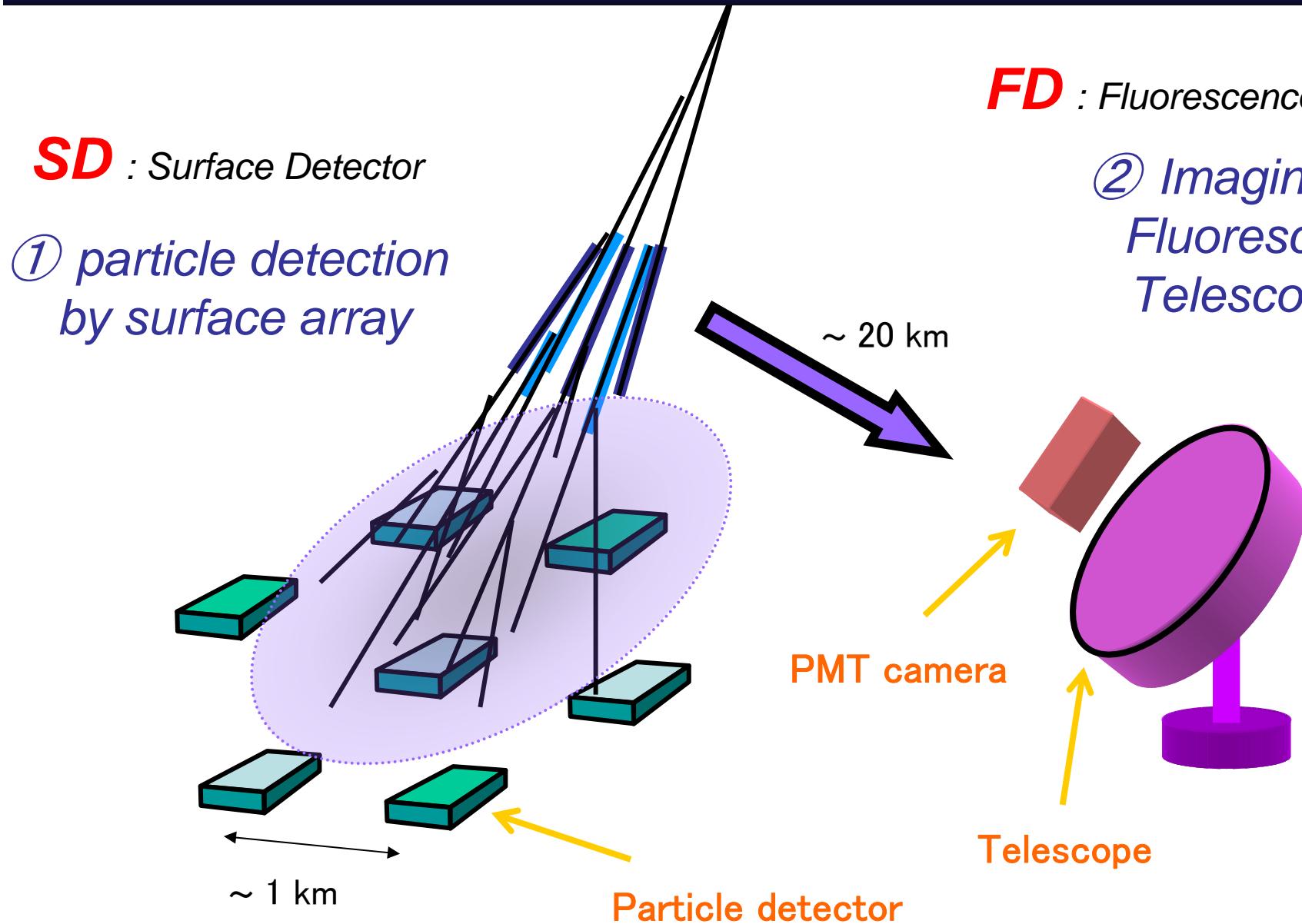
*M. Fukushima, ICRR, Univ. Tokyo*

# *The Telescope Array (TA) Collaboration*

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*~120 Scientists from Japan, US, Korea, Russia and Belgium  
ICRR/Tokyo, Tokyo Tech., Osaka-City, Univ. of Utah, Rutgers,  
INR/RAS, ULB & others*

# Detection of Air Shower

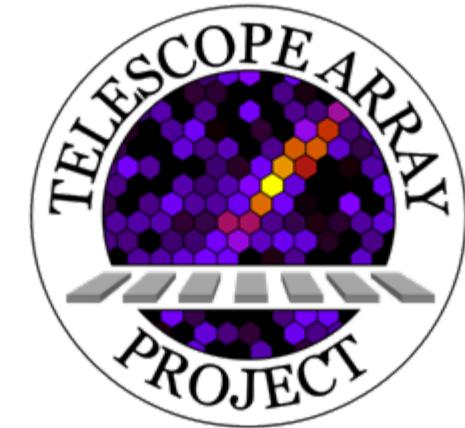
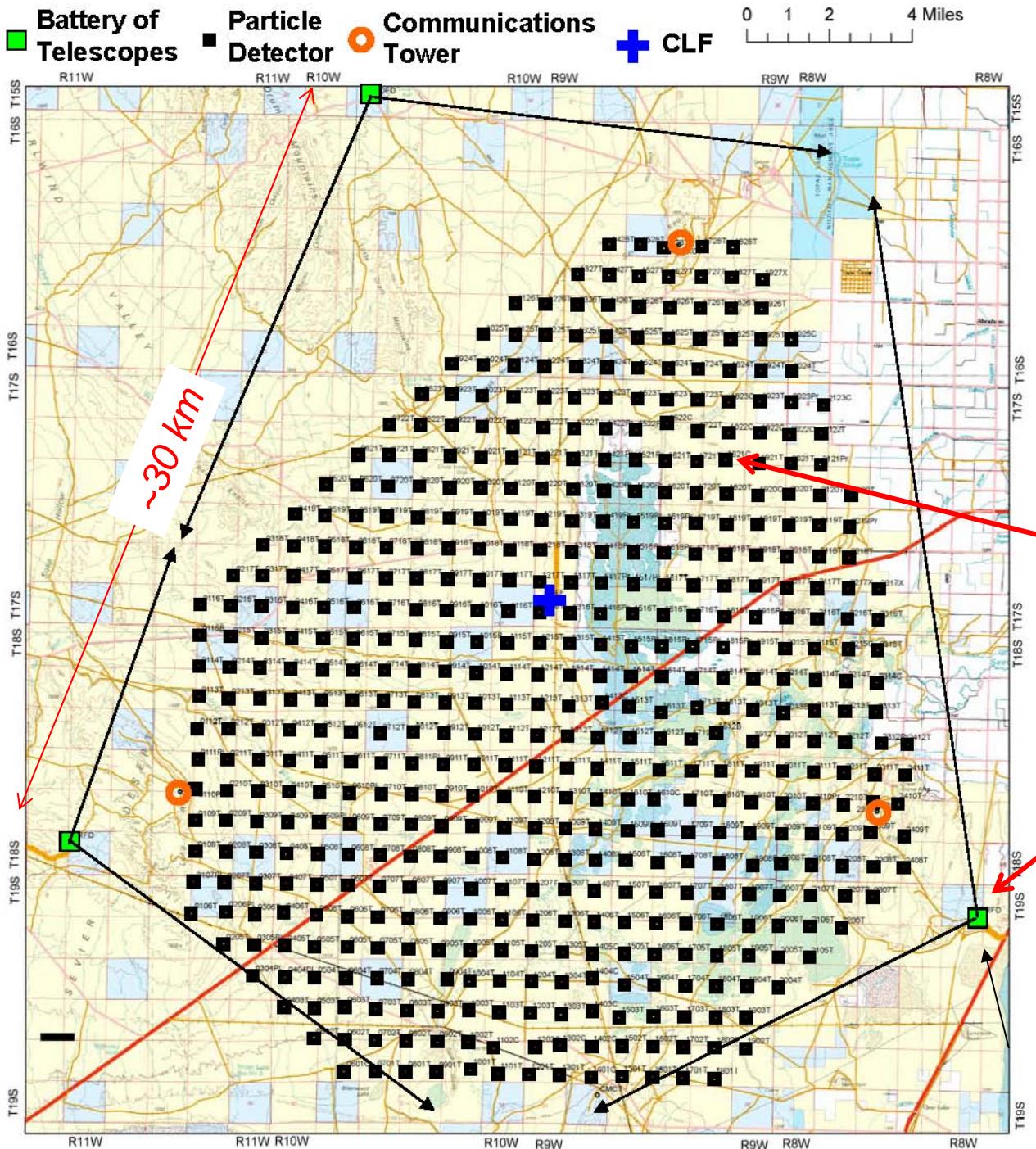


**FD** : Fluorescence Detector

**SD** : Surface Detector

① particle detection  
by surface array

② Imaging by  
Fluorescence  
Telescope



507 Surface Particle Detectors  
cover 680 km<sup>2</sup>

3 Fluores. Telescope stations  
overlook the array.

Utah, USA  
 $39.3^{\circ} N$   
 $112.9^{\circ} W$   
 Alt. 1400 m

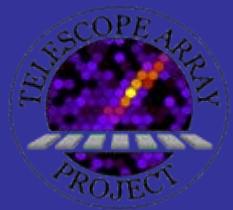


# *Middle Drum telescope station*

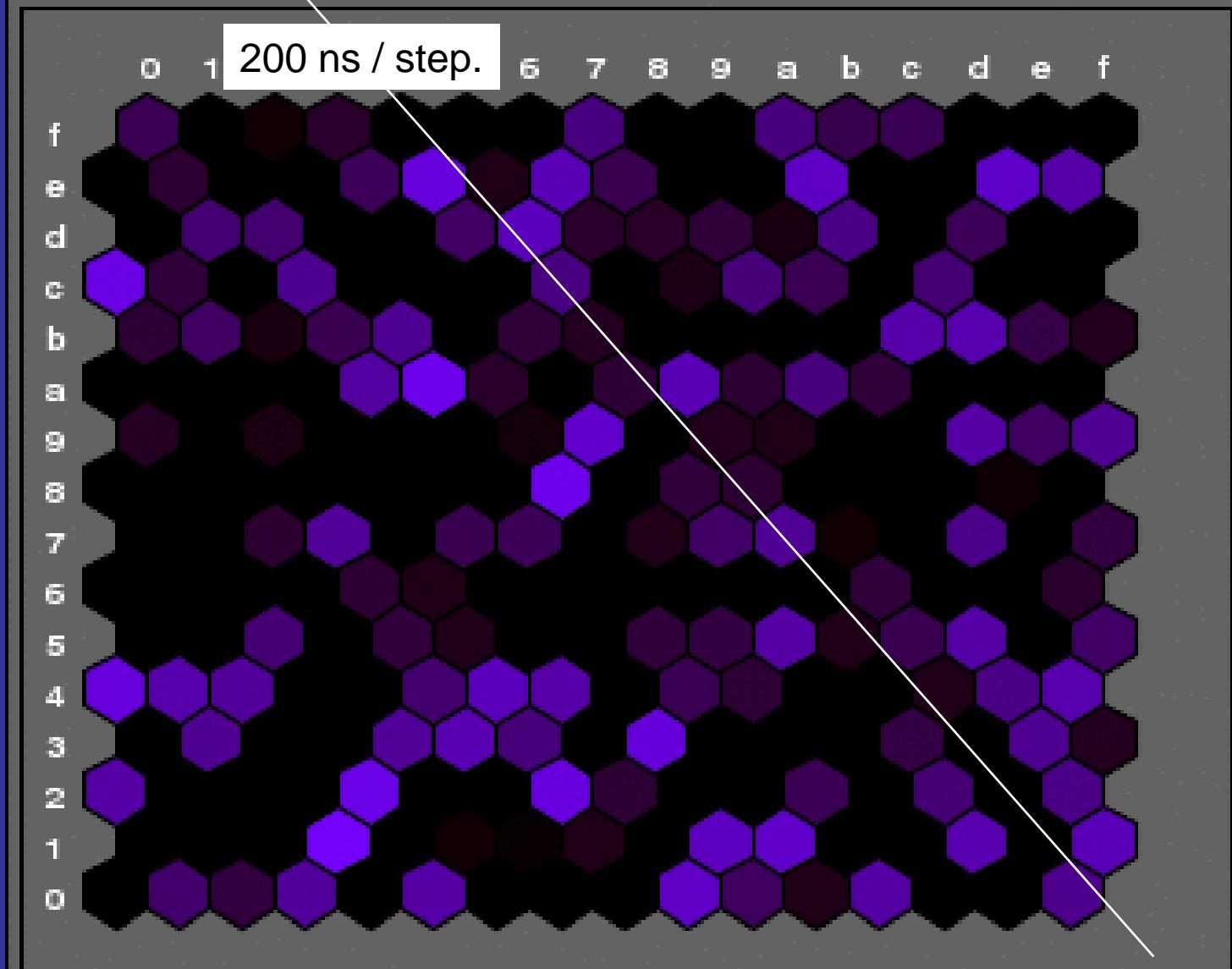




*Transfer of HiRes – 1  
and adjustment*



One of the first events of TA: 2005/07/12, 2:52 am, Utah.



top / bottom & left / right of camera view reversed.

# *FD is a Total Absorption Calorimetry* for absolute energy measurement

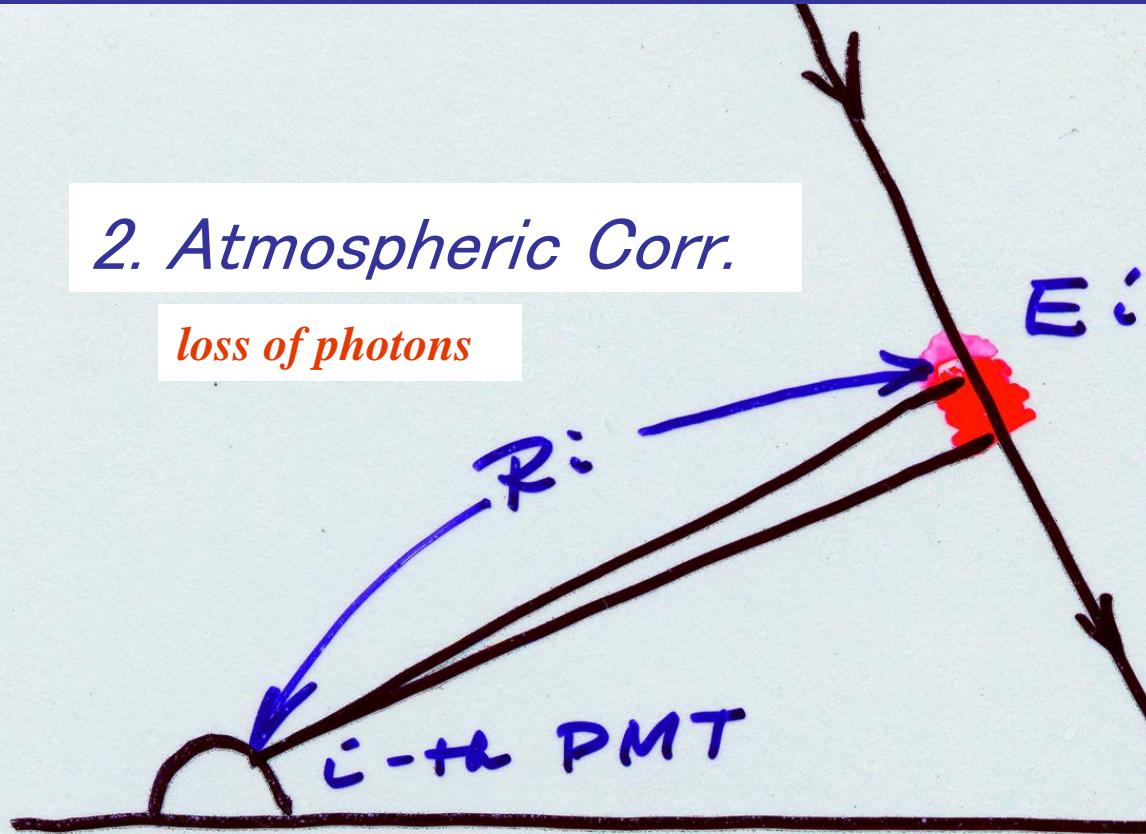
## 2. Atmospheric Corr.

*loss of photons*

*E:*

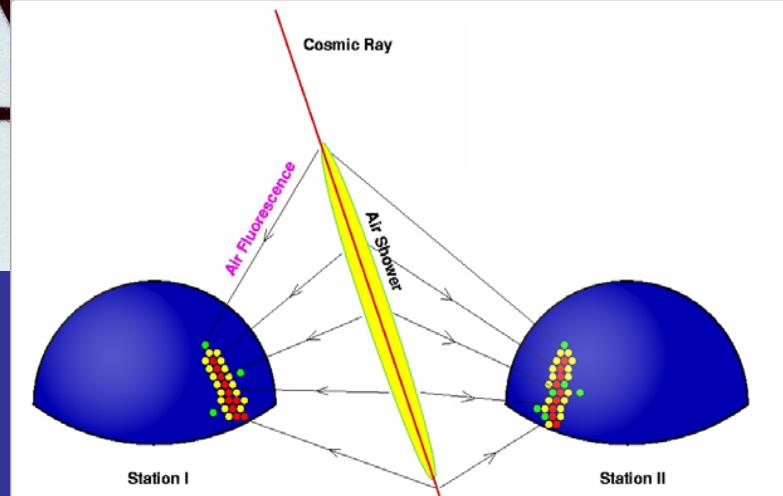
## 1. Fluores. Eff.

$\Delta E \rightarrow \# \text{ of photons}$

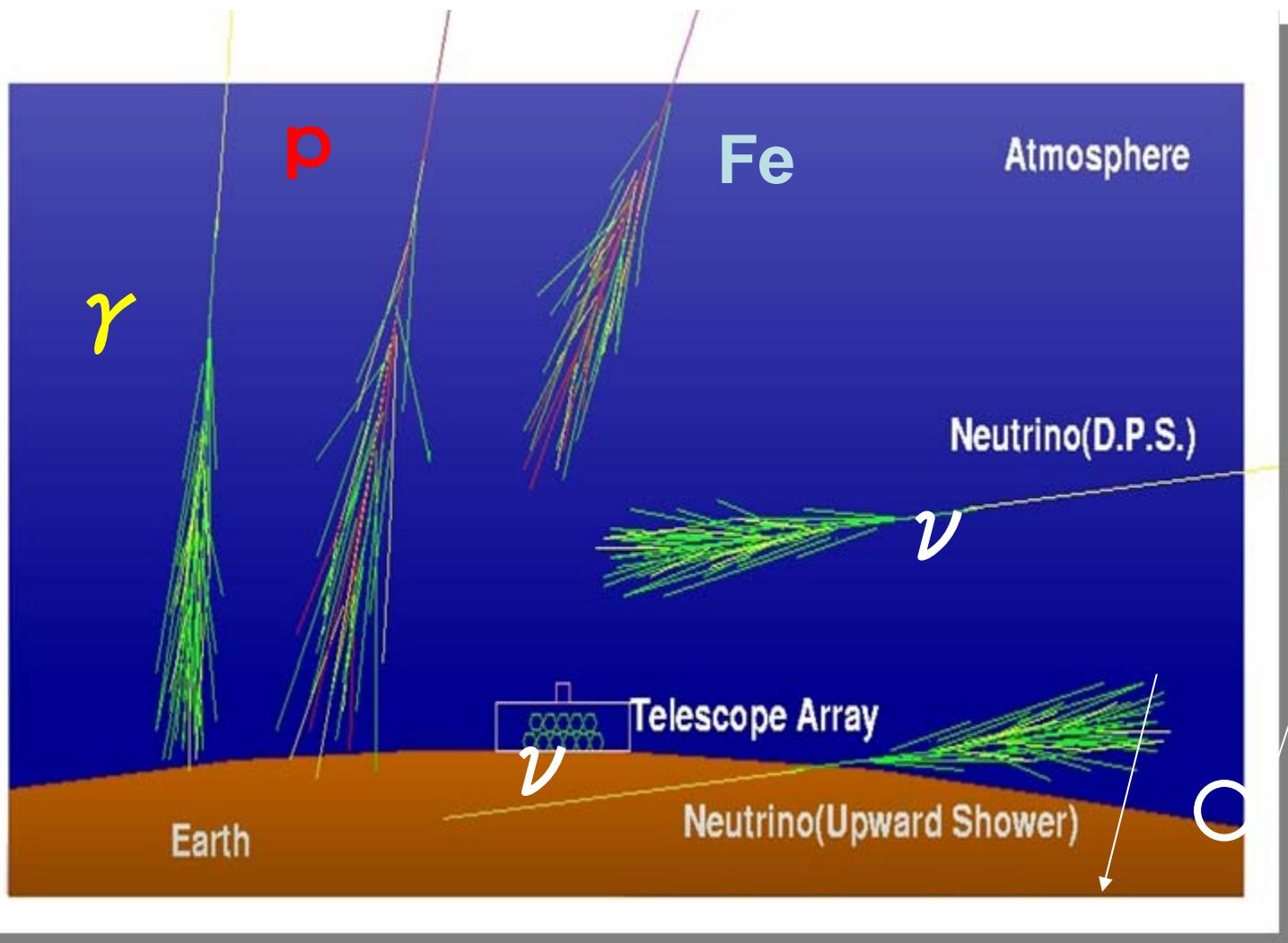


## 3. Telescope Calib.

*# of photons*  $\rightarrow$  *ADC ch*

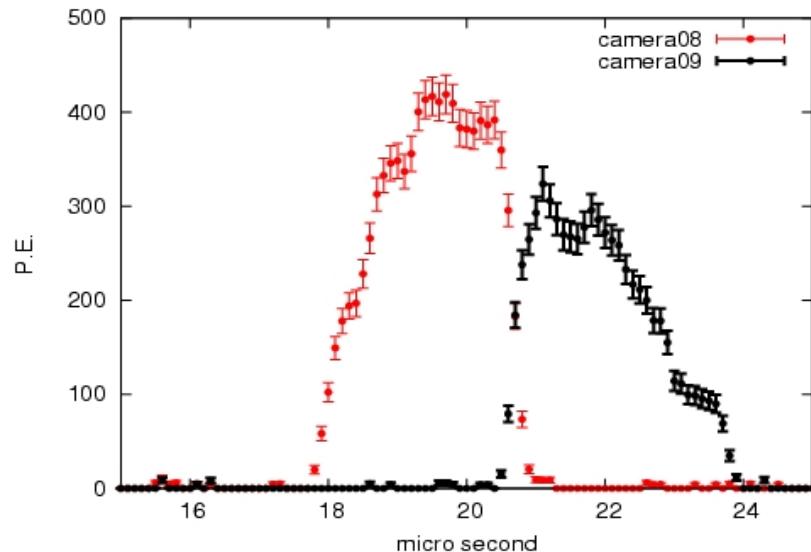
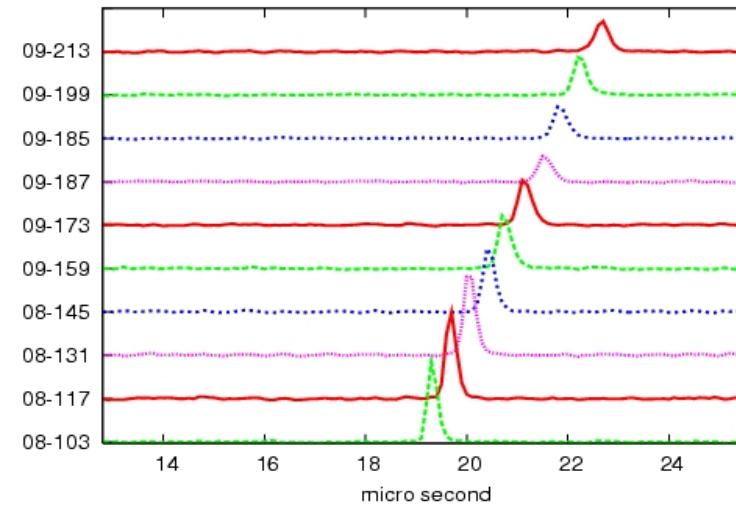
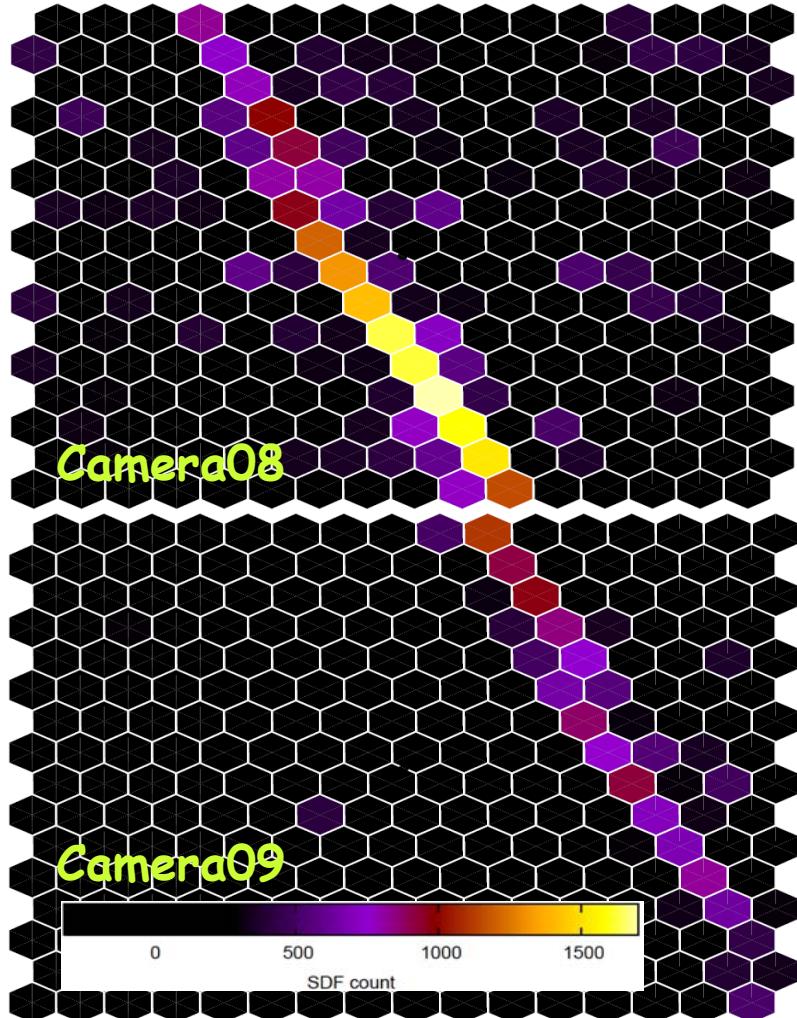


# *Primary composition and Xmax*



# Example of FD Event

June 20, 08:18:21(UTC), trigger ID 0000169





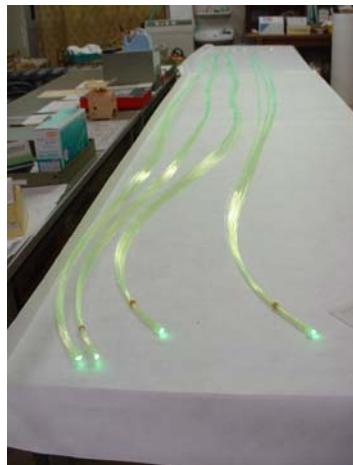
*TA Surface Detector  
(Plastic Scintillator)*



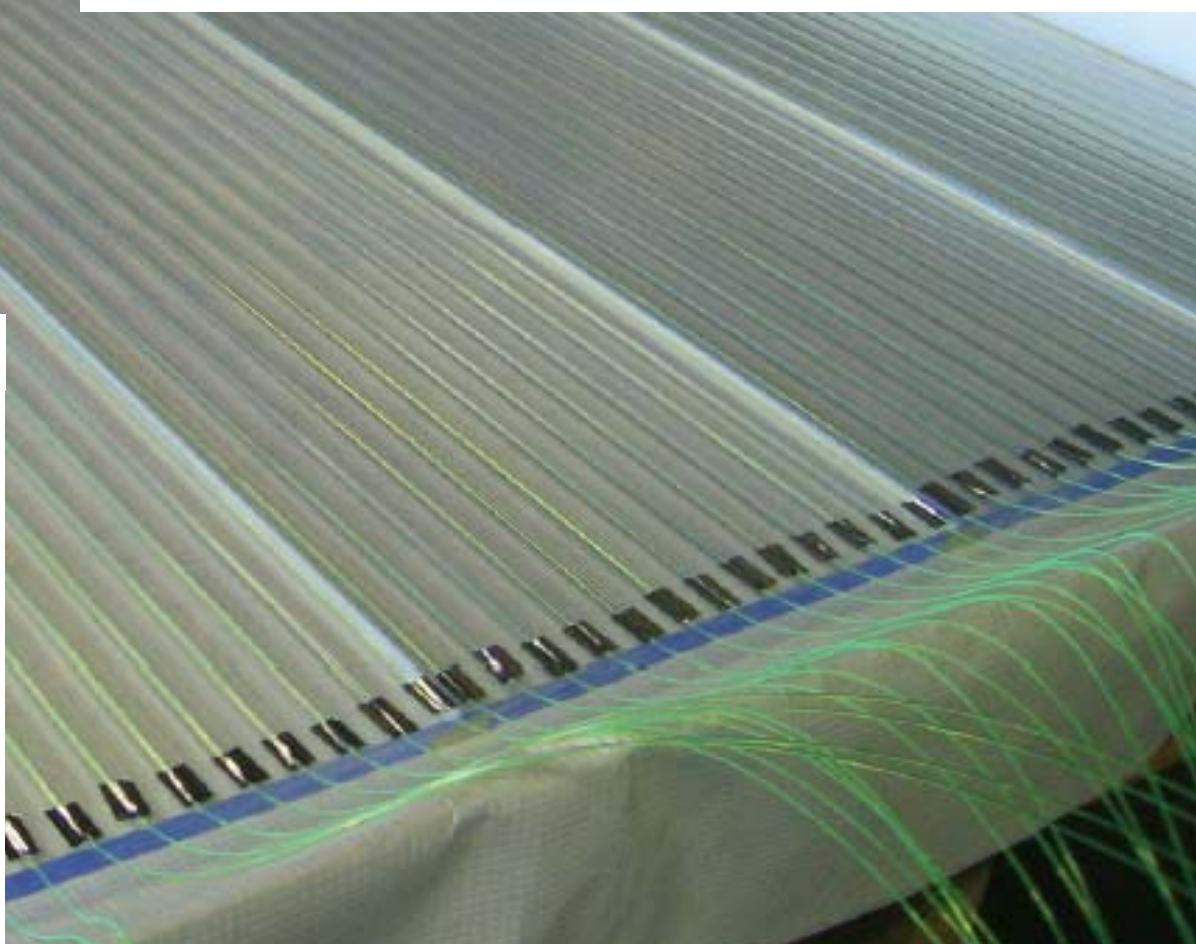
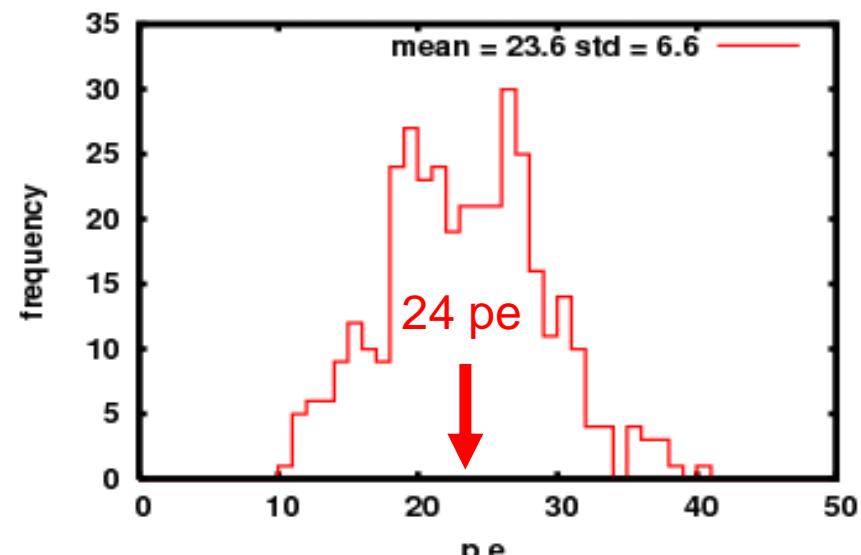
# Plastic Scintillator

3 m<sup>2</sup>, 12 mm t

WLSF readout, 2 layers overlaid



1 MIP photo-electron distribution

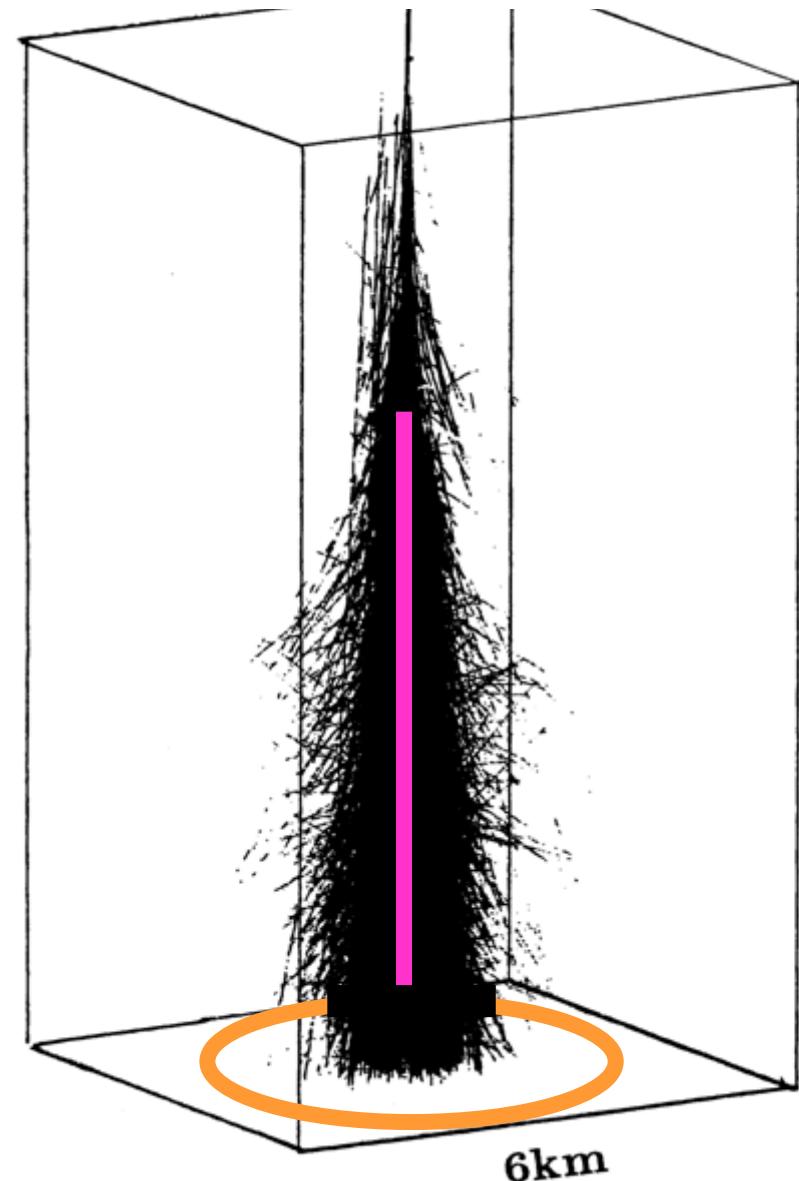
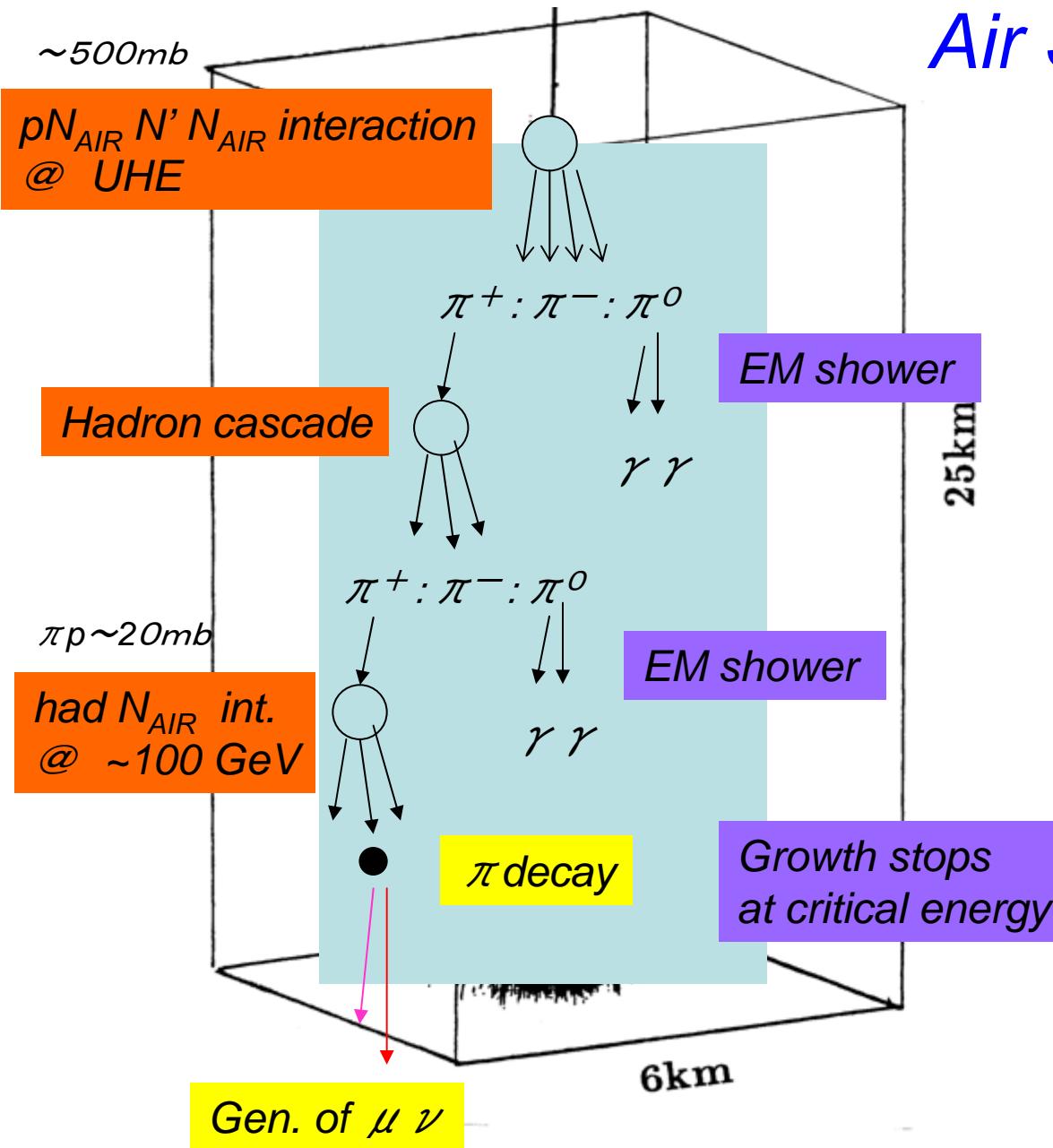


*Lifted by helicopter*  
 $\sim 510 \text{ kG}$

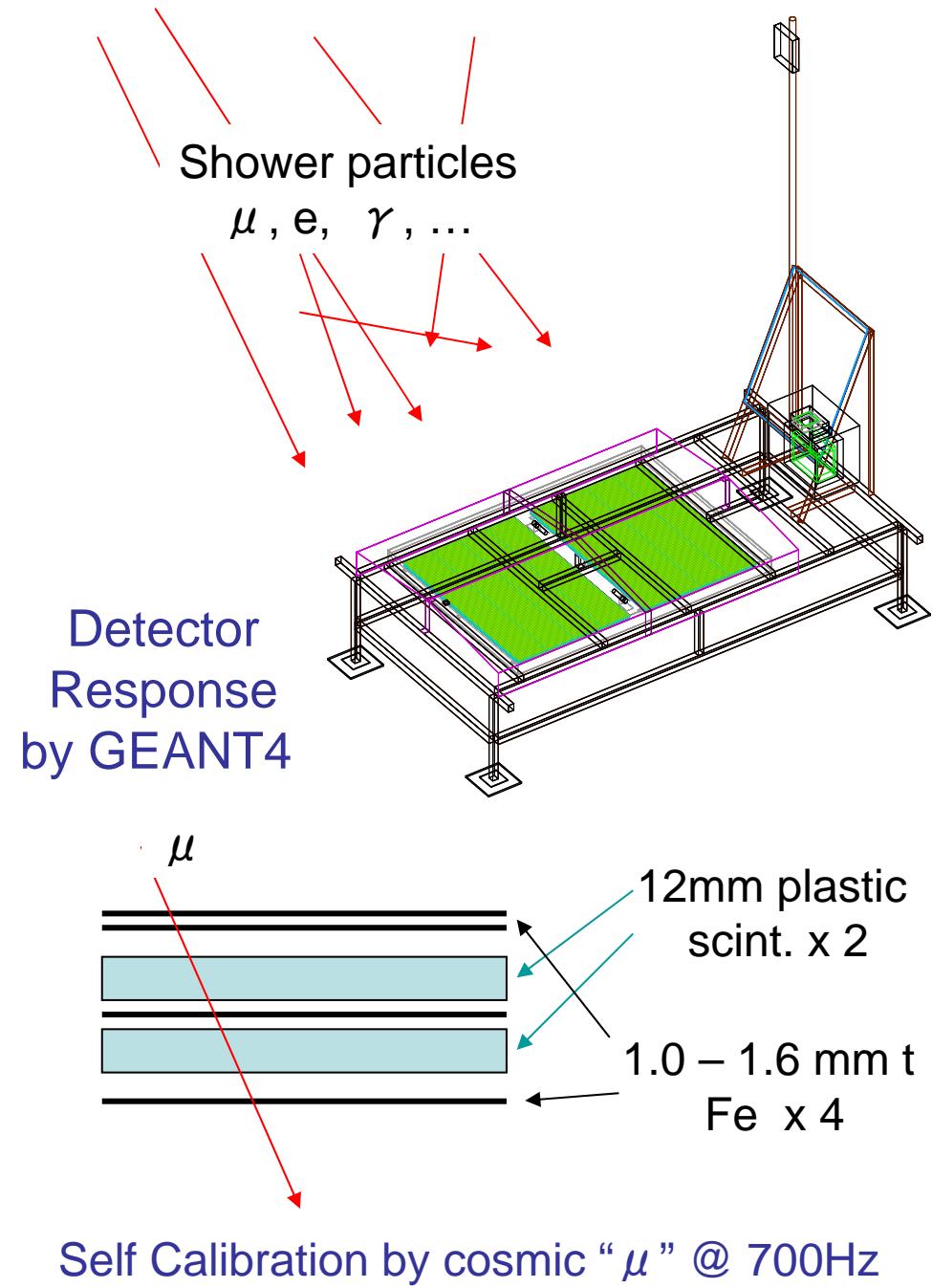




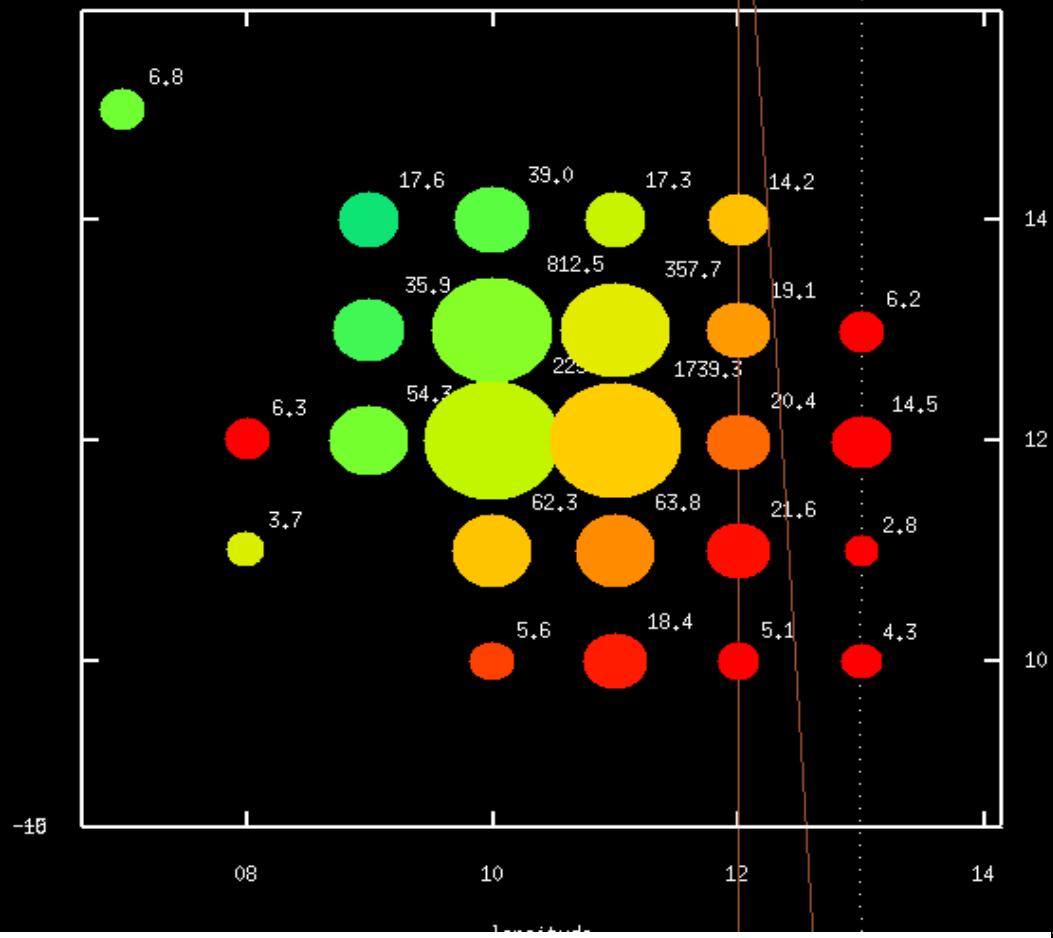
# Air Shower generation



# Air Shower Detection

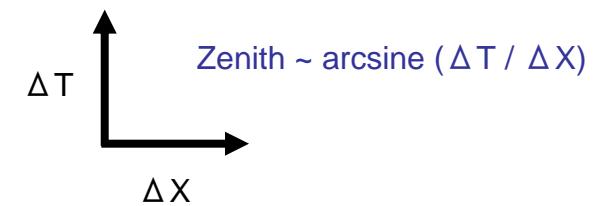
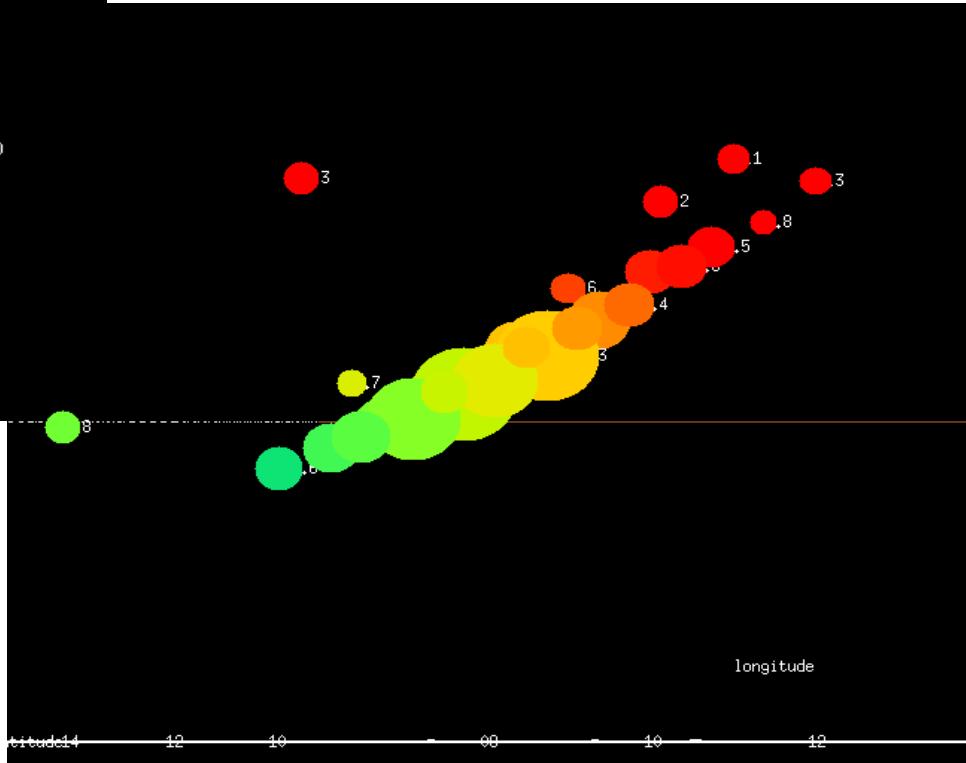


090122-225422  
TH~38<sup>0</sup>



## Event Top View

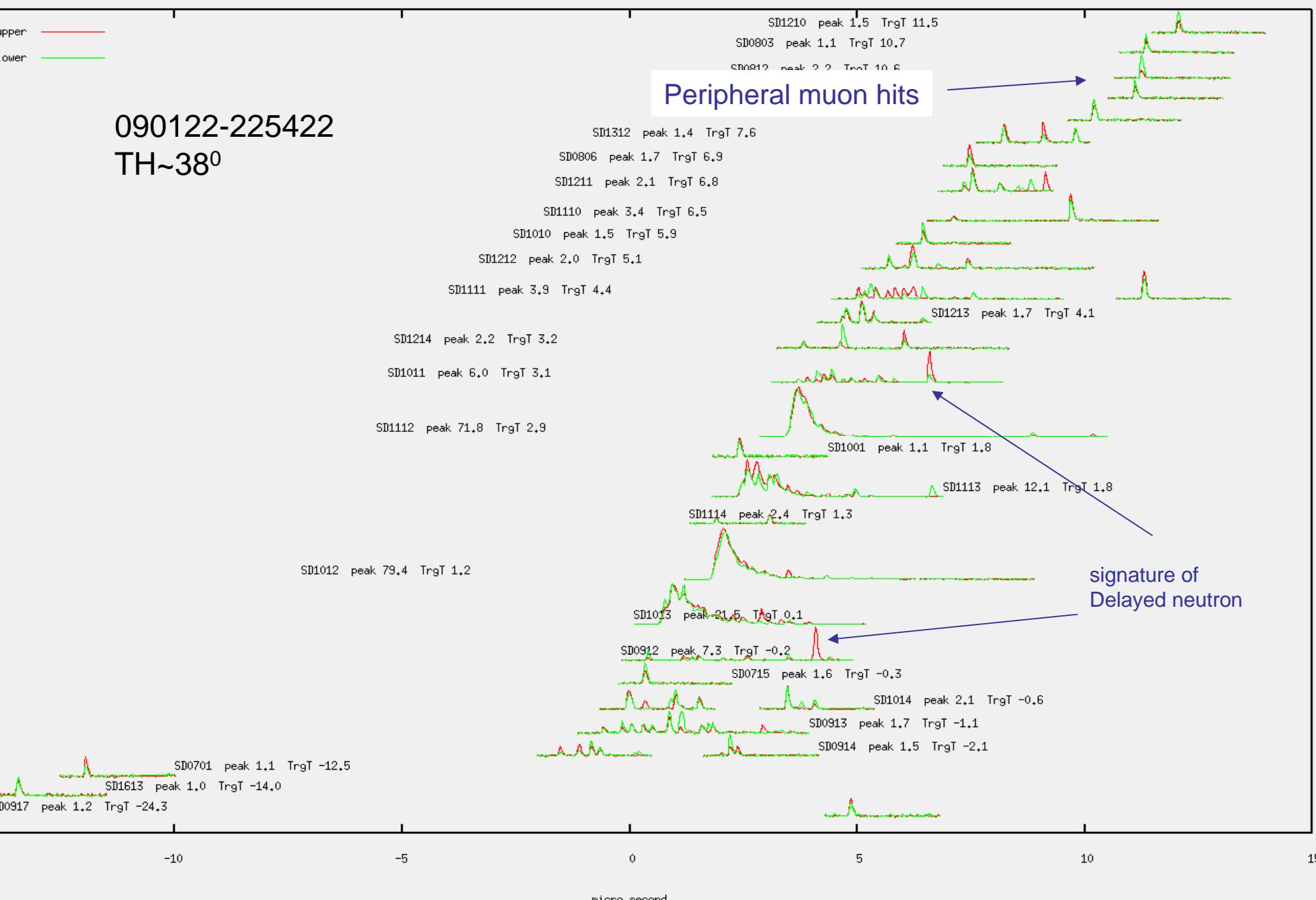
X,Y = counter #  
number = MeV energy deposit (av U+D)  
~ 2.5 MeV for vertical mu



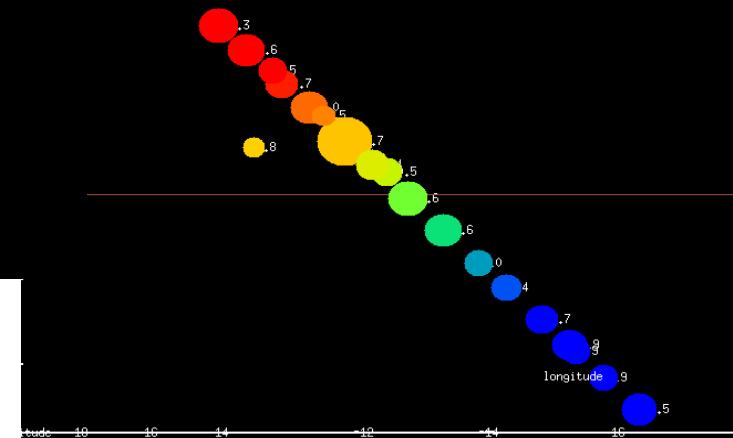
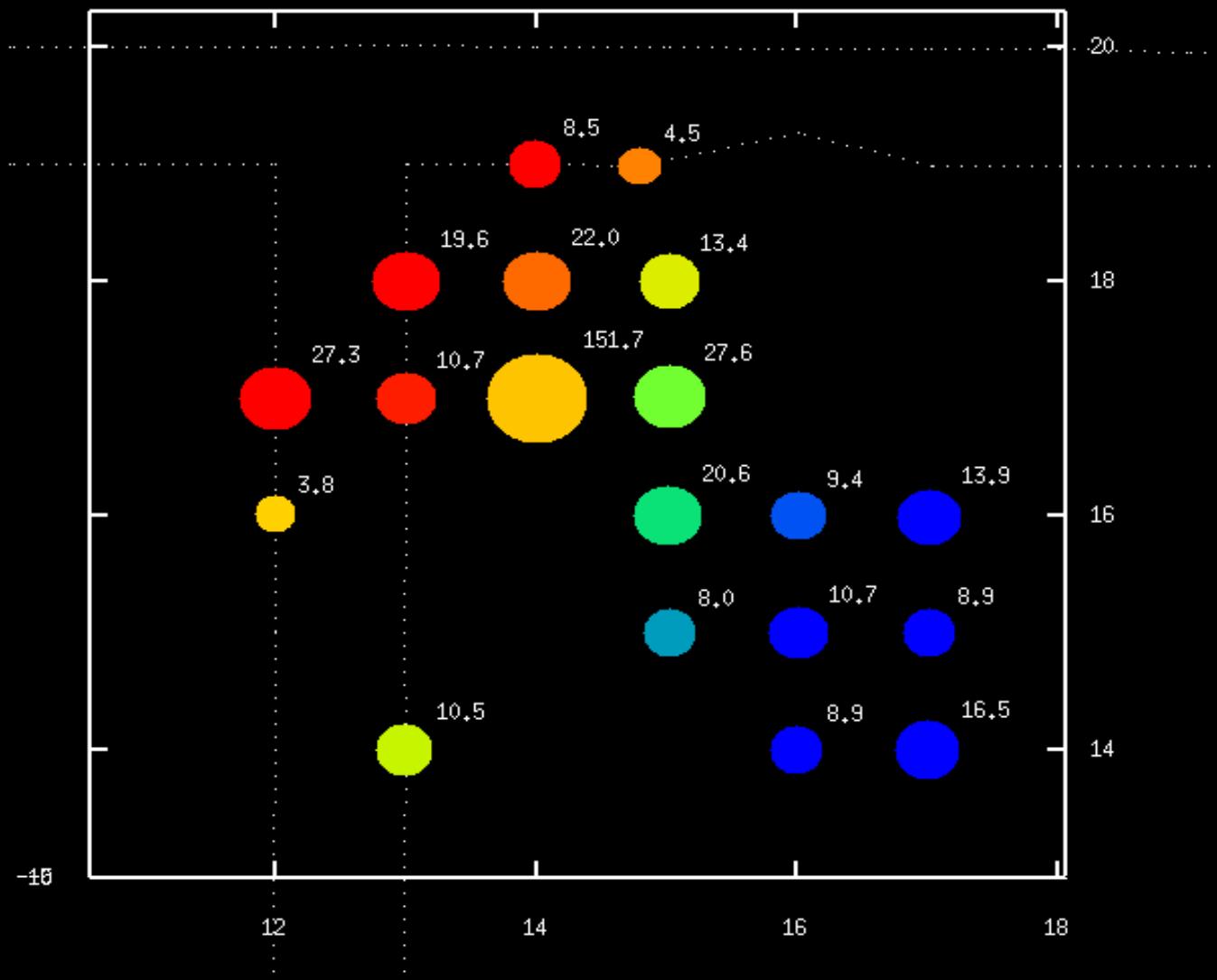
## Event “Side” View

Upper  
Lower

090122-225422  
TH~38°

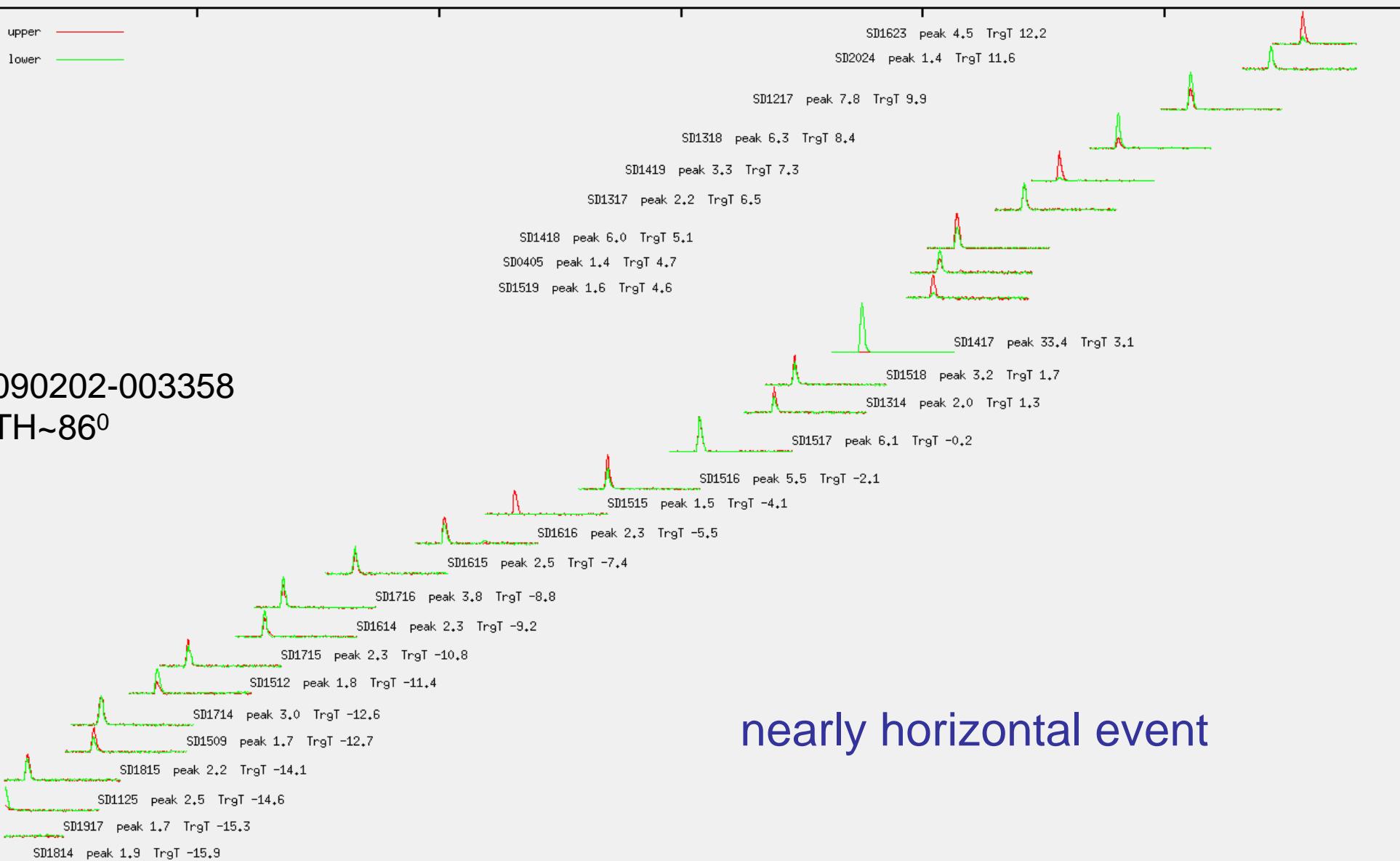


090202-003358  
TH~86°



upper  
lower

090202-003358  
TH~86°



nearly horizontal event

# *Event Reconstruction by SD*

*Geometry*

*\* by core location + arrival timing*

*Energy  $\propto$  energy deposit on the ground  
? estimate of zenith attenuation*

*Composition by shower front curvature + muon*

- + Flat acceptance, uniform exposure
- Abs. energy : by shower MC

# *Event Reconstruction by FD*

## *Geometry (direction + distance)*

- \* Monocular: 1 FD by angular speed
- \* Stereo: intersect of 2-3 FDs
- \* Hybrid: + SD timing (+ core location)

*Energy  $\propto$  # of detected photons,  
? atmospheric transparency etc..*

## *Composition by Xmax (shower max.)*

- Variable acceptance (energy, angle, distance, weather...) & change of exposure (seasonal sky coverage)
- + Abs. energy : experimental

*SD and FD of TA are independent.  
Each by itself is a complete detector.*

*Numerous cross checks possible.*

*(No Calib. & no detector monitor in this talk )*

# *TA measures*

*Primary Composition: what is the UHECR ?*

*Spectrum: dip and cutoff ?*

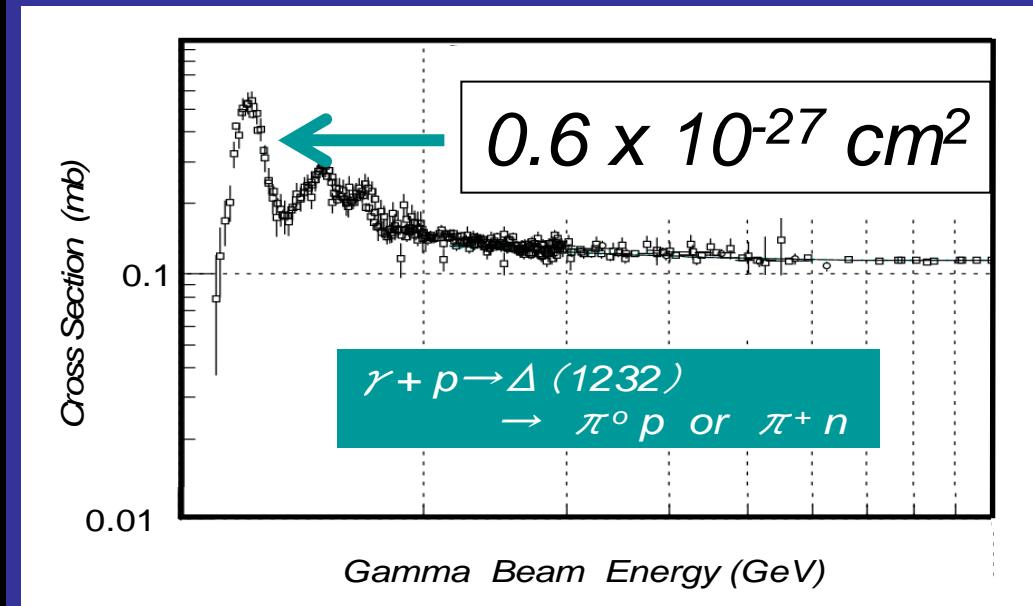
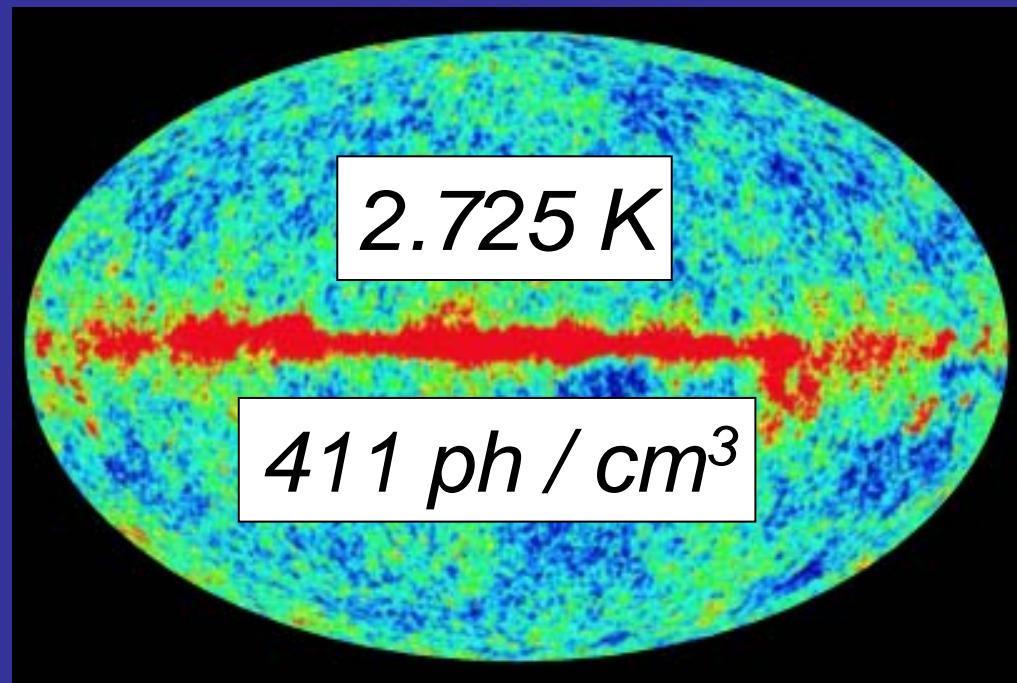
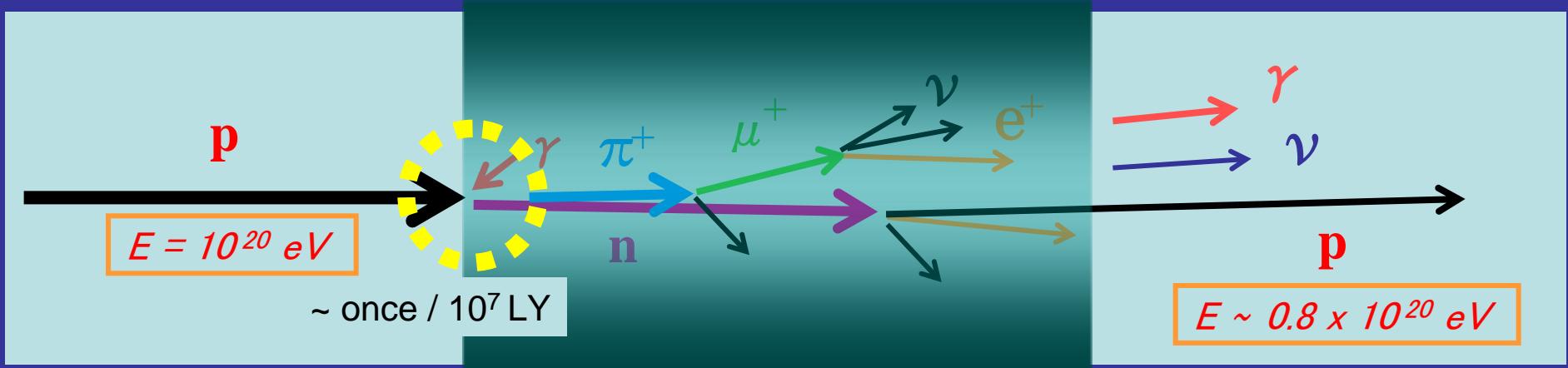
*Source + Anisotropy: From where it is coming ?*

*UHE  $\gamma$  and  $\nu$  : Exotic origin ?*

*Today's talk covers analyses of*

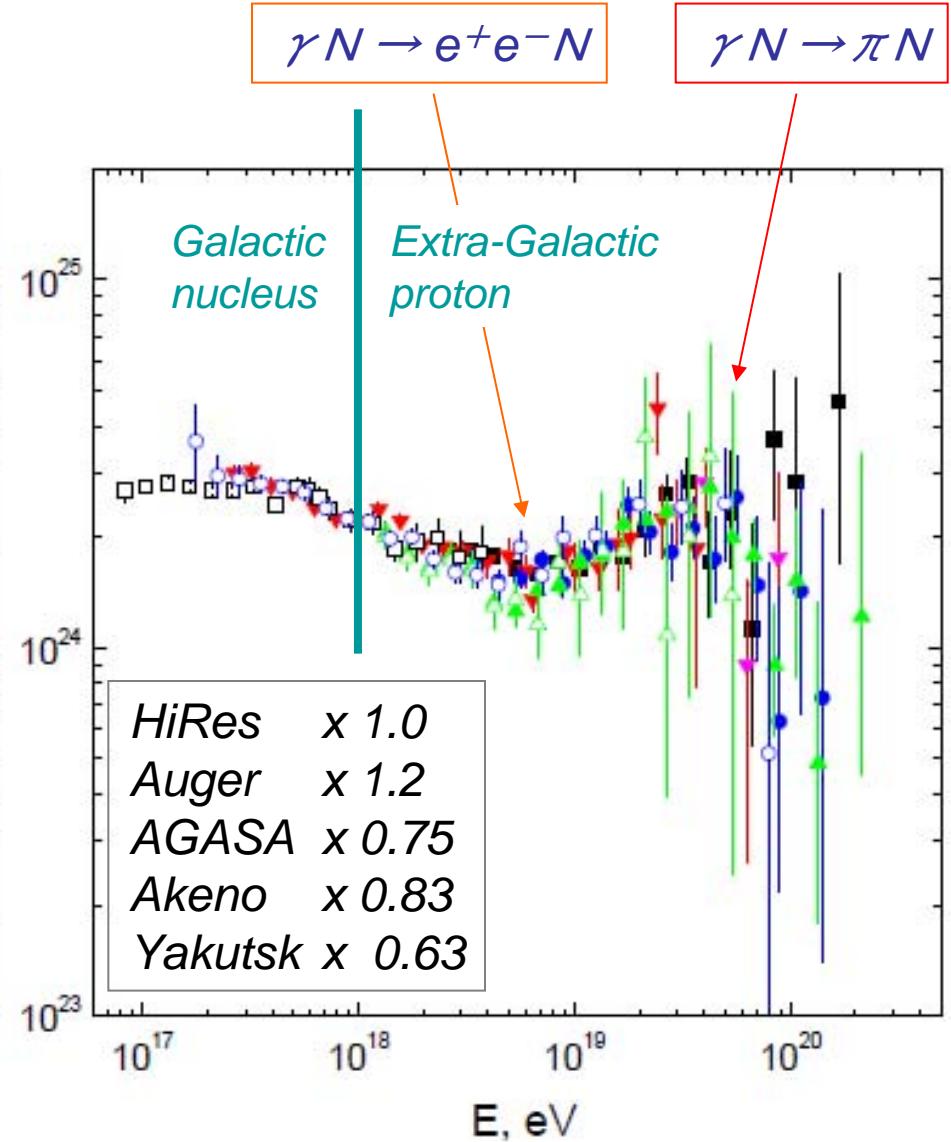
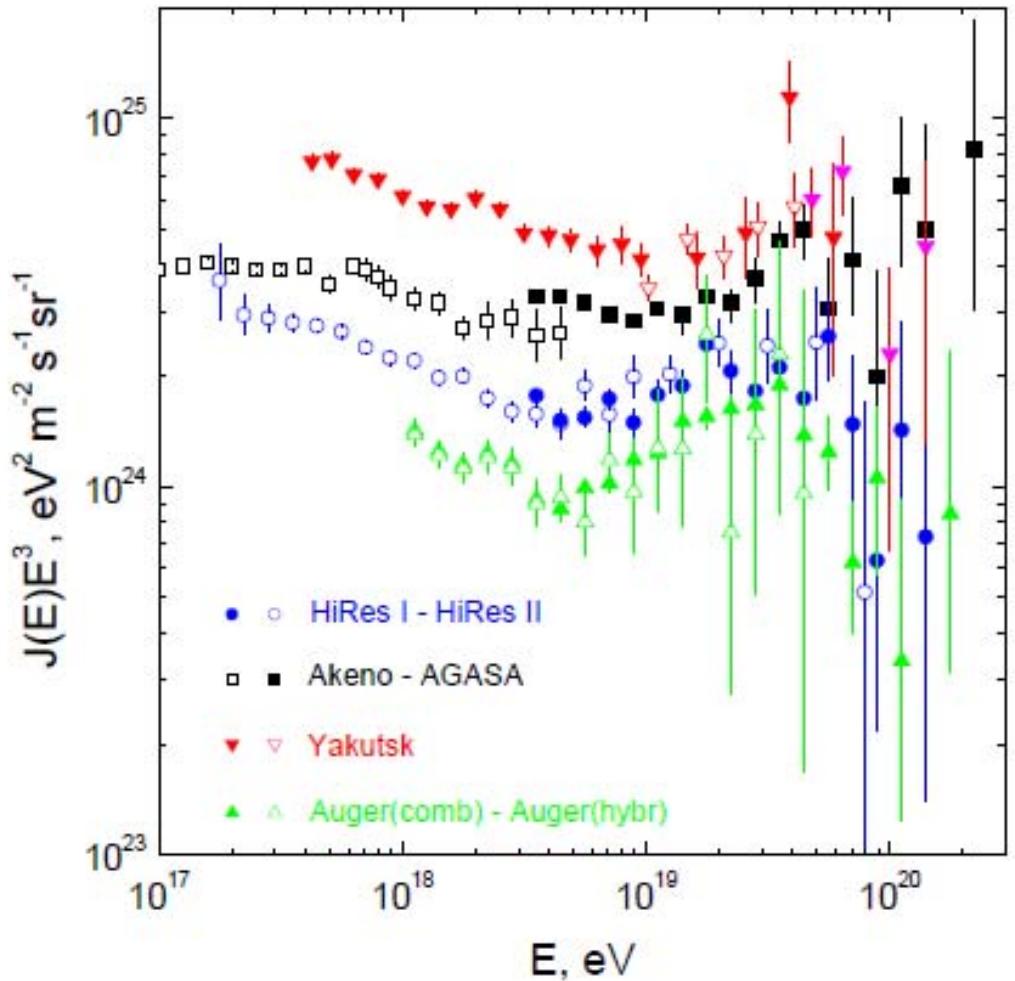
- *Xmax by stereo FD (by Y.Tameda)*
  - *Spectrum by FD/SD hybrid (by D.Ikeda)*
  - *UHE  $\gamma$  limit (by G.Rubtsov)*
- 
- *[SD spectrum]*
  - *[LSS association, Point sources etc.]*
  - *[UHE  $\nu$  search]*

# Greisen - Zatsepin - Kuzmin (GZK) Cutoff



*Cosmic rays exceeding  $\sim 10^{20} \text{ eV}$  must have origins nearby*

*At the highest energy region*



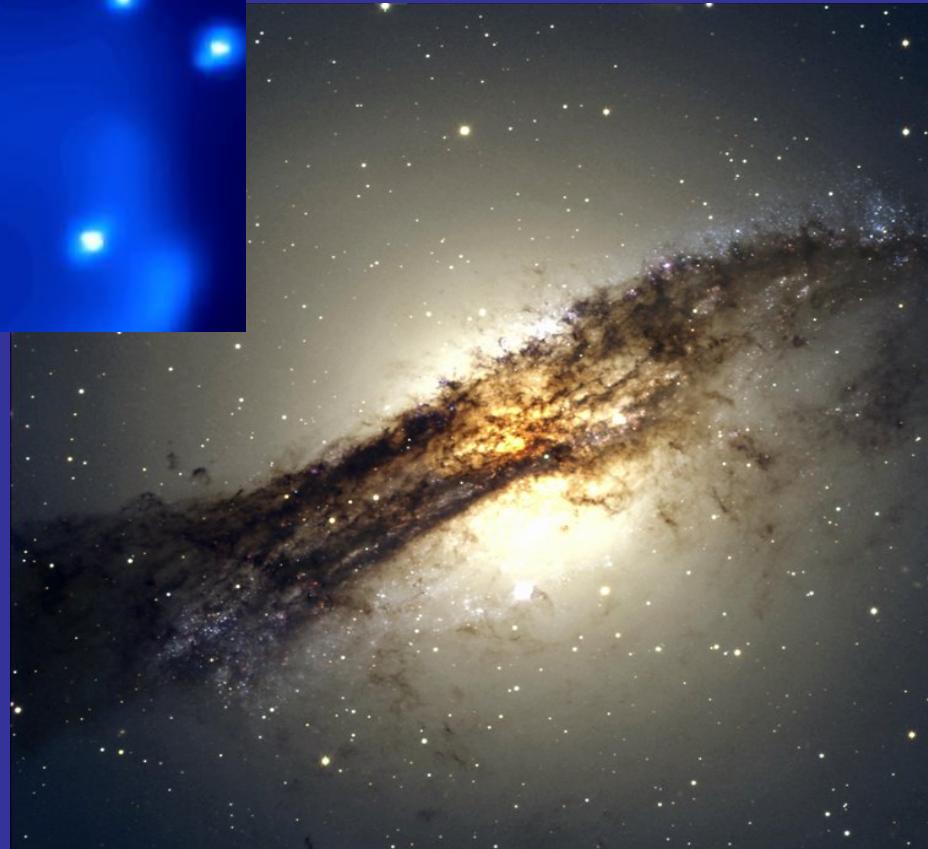
If particles are protons at  $E > 10^{18}$ eV, we may be observing pair creation dip (uncle) and pion production (GZK) cutoff .

by Berezinsky Jun08



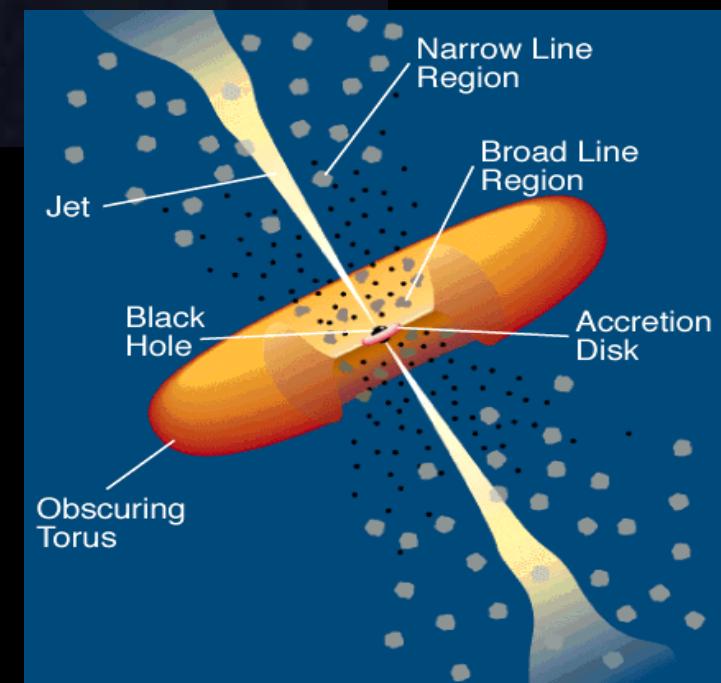
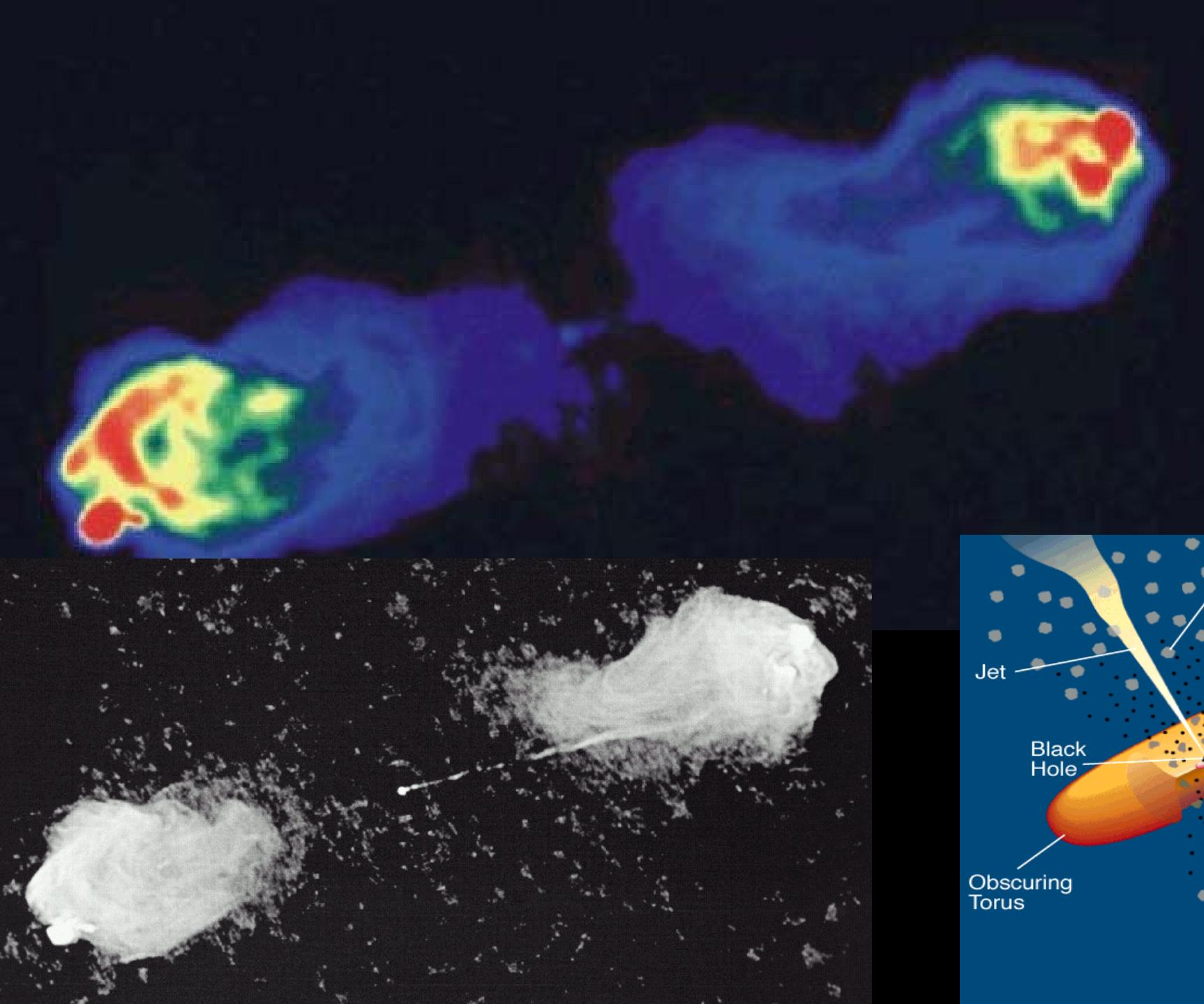
*Xray picture*

*Cen A*  
 $\sim 4 \text{ Mpc}$



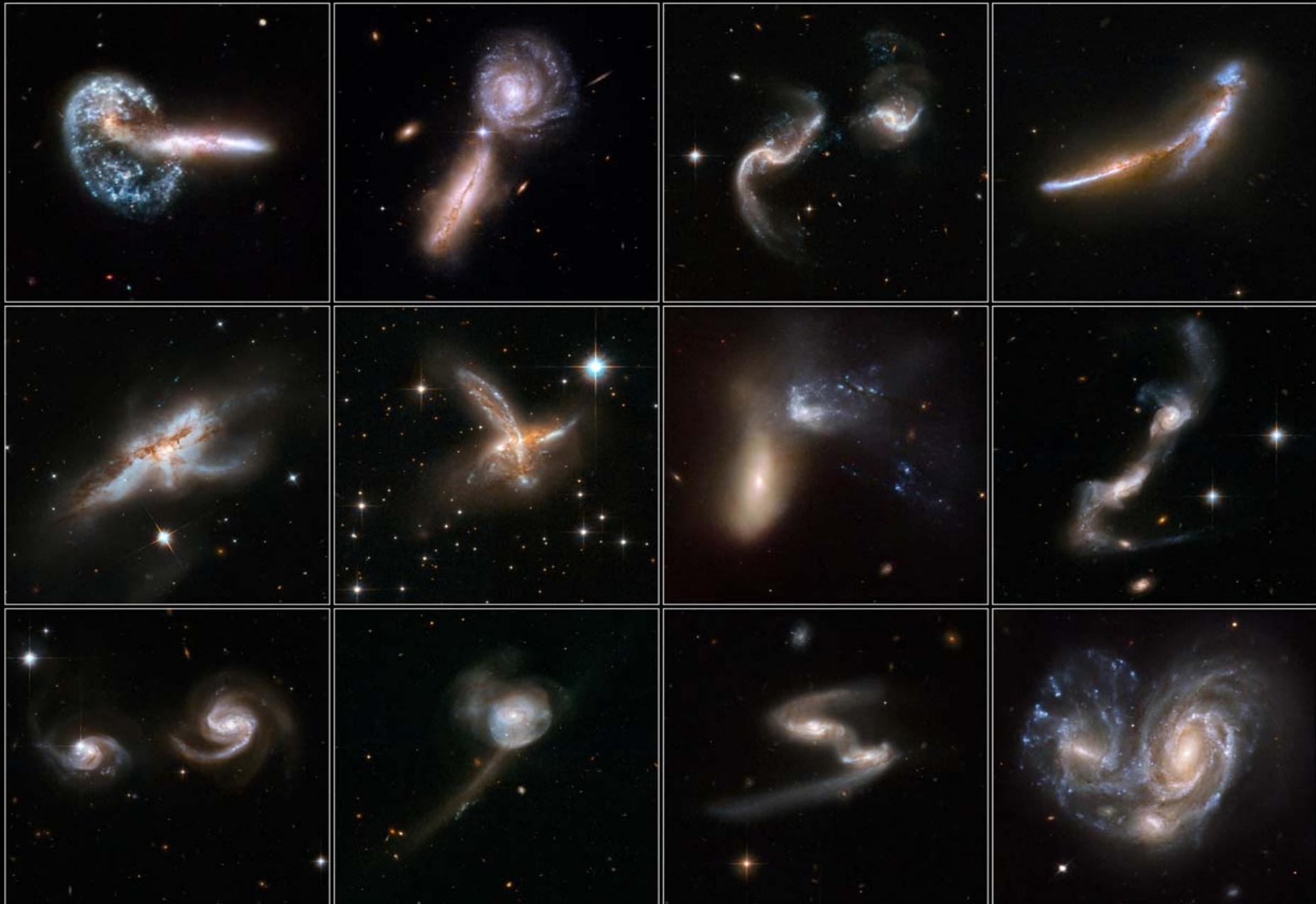
*Optical picture*

*Cyg A*

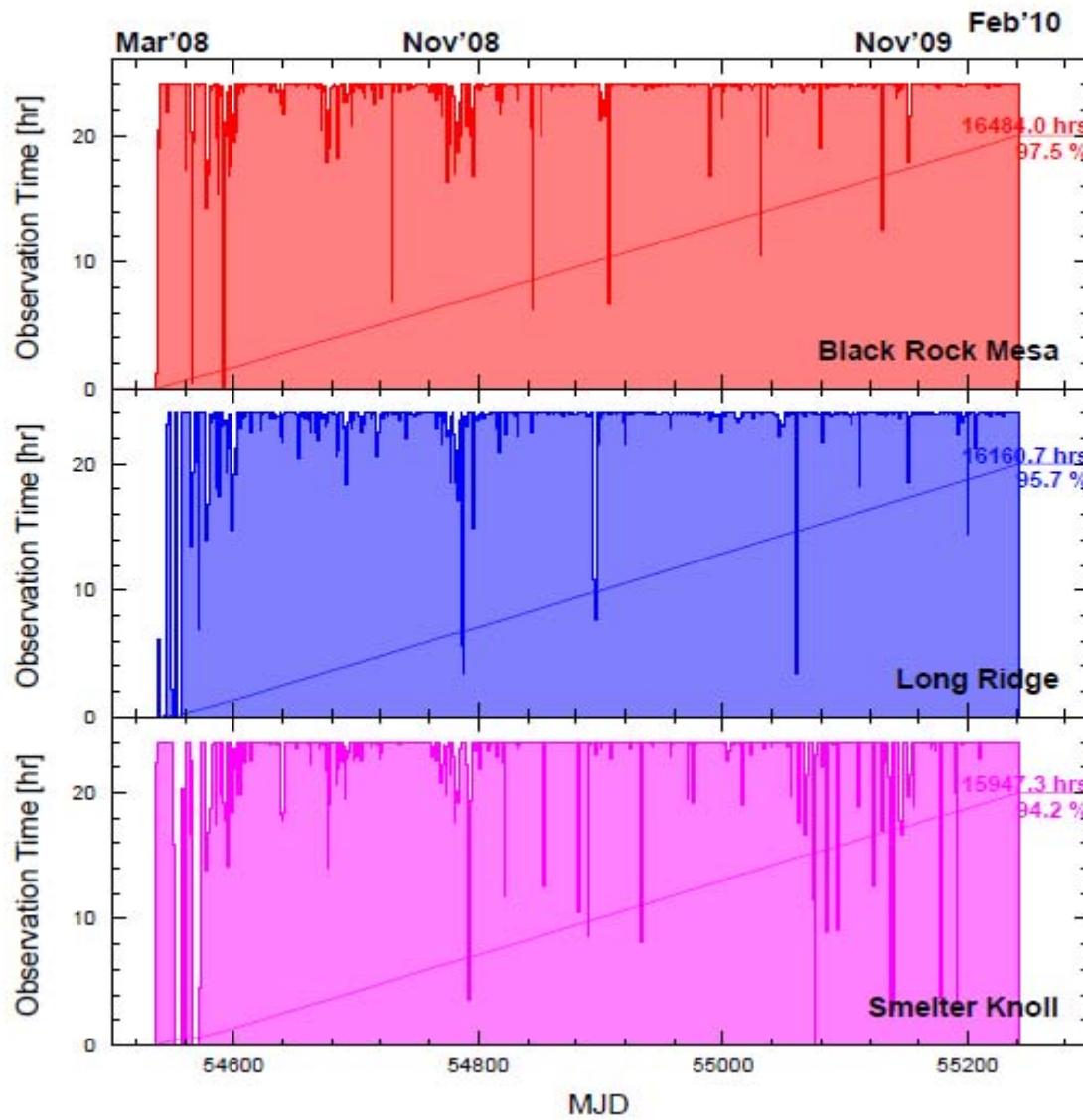


# Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2



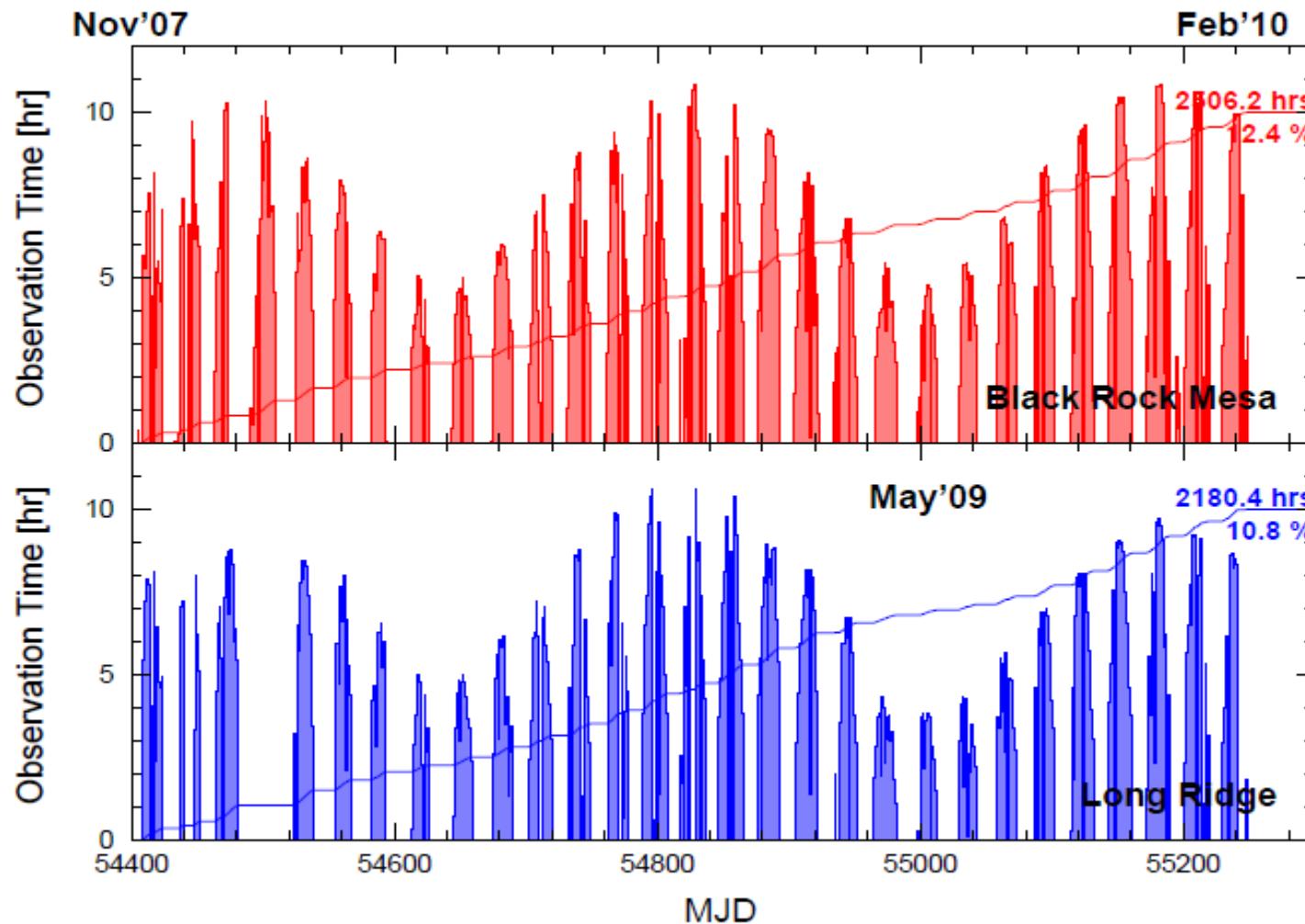
## < SD Observation Status >



- operation in stable  
   $\gtrsim 95\%$   
   $\gtrsim 16k$  hours
- wLAN interference  
  in early stage
- thunder storms  
  in summer
- maintenance access  
  in autumn
- low temperature &  
  snow in winter

## < FD Observation Status >

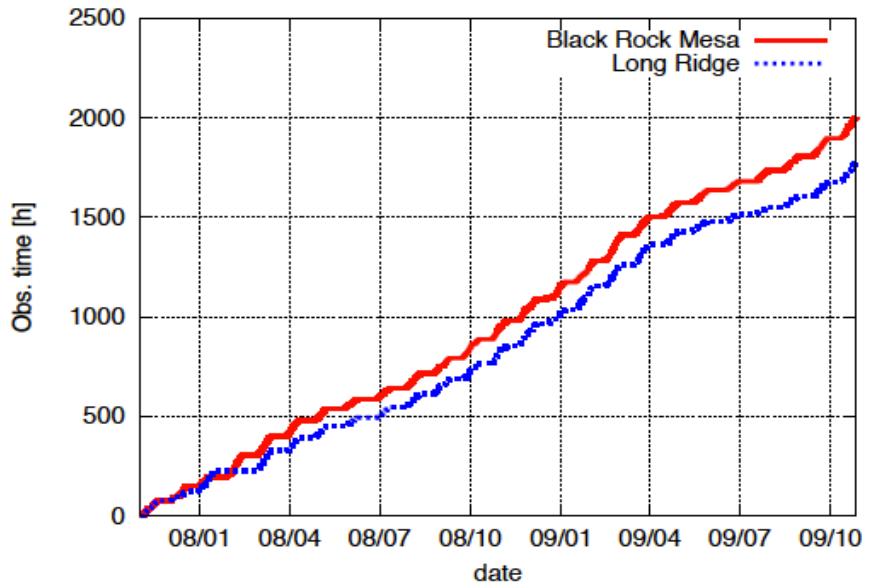
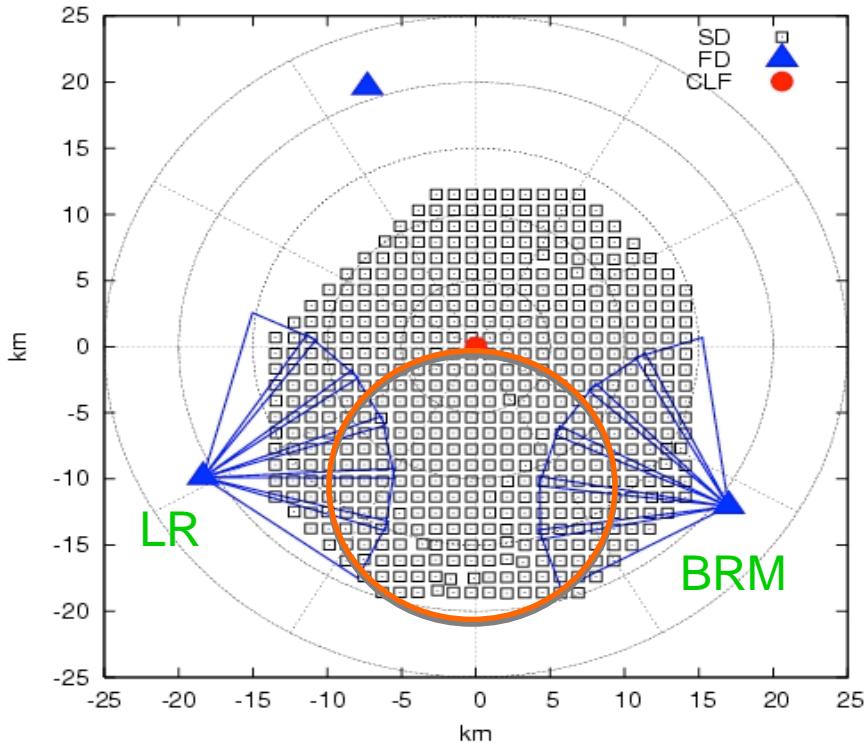
- Full operation since Nov '07



- Long Ridge remote operation since May '09

# (1) FD Stereo Analysis for Xmax

Nov. 2007 – Oct. 2009  
BRM-LR Stereo Event



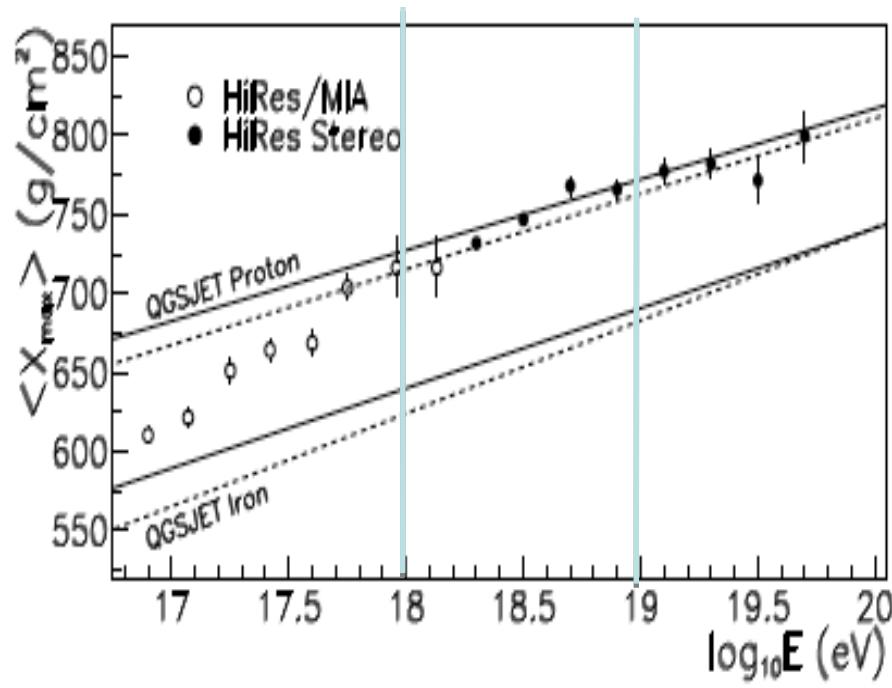
## Event Selection

- Xmax within FoV
- Zenith Angle  $< 56^\circ$
- Shower Core in R=9.6km circle
- $E > 10^{18.6} \text{ eV}$
- good  $\chi^2$

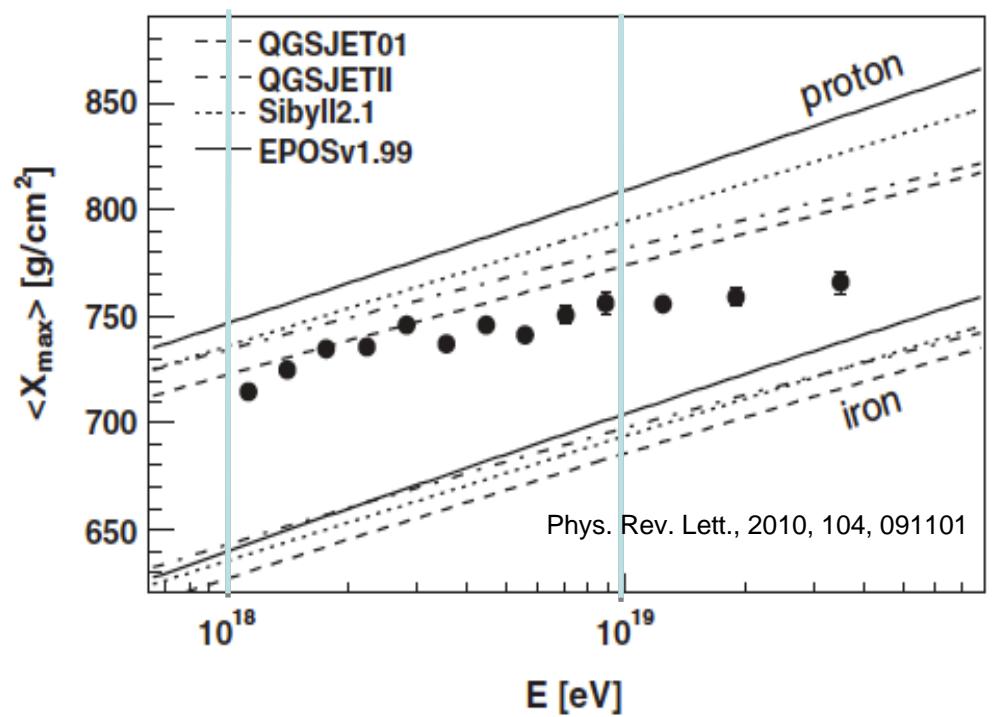
Check with MC expectation

# Existing Xmax data

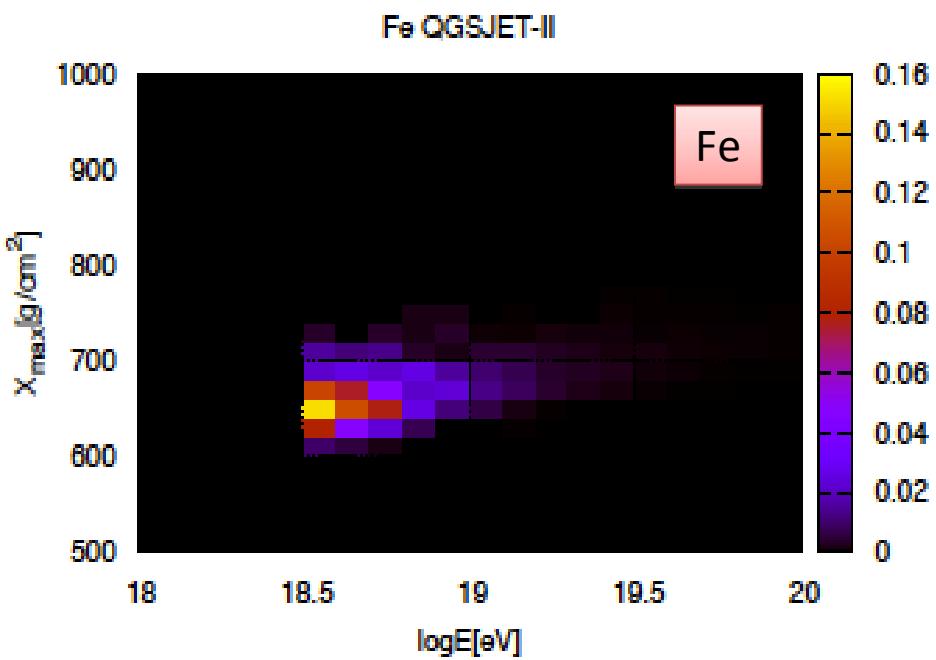
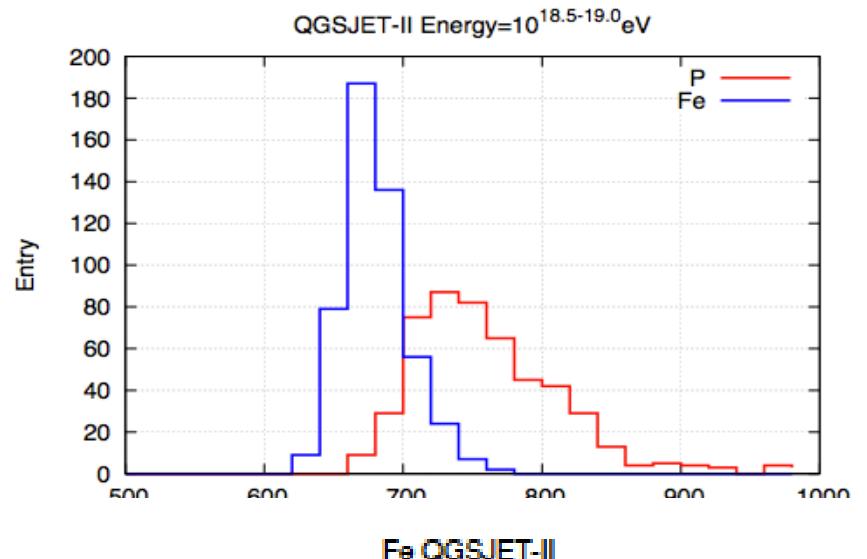
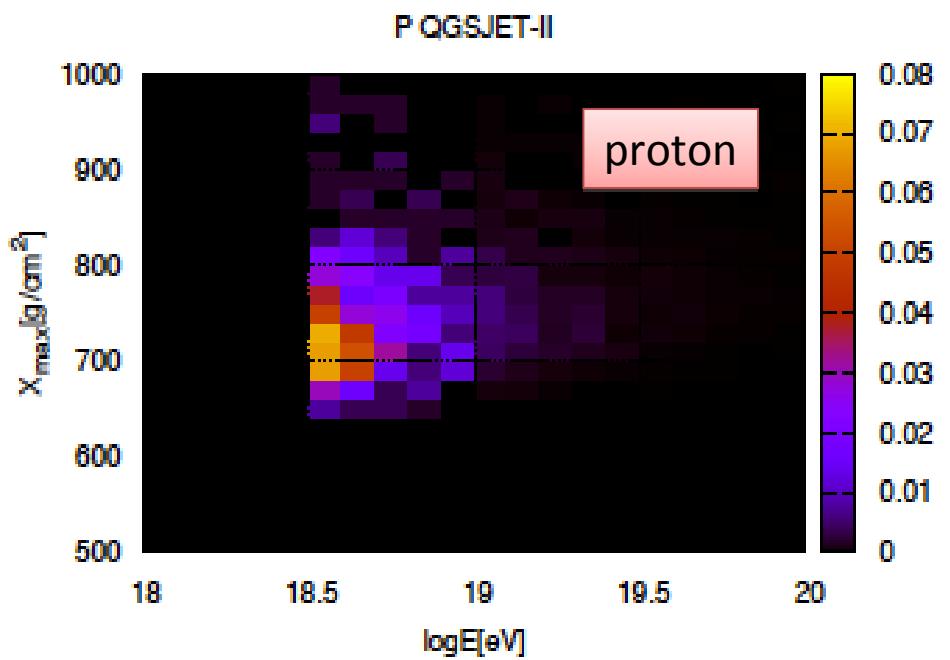
HiRes: stereo FD



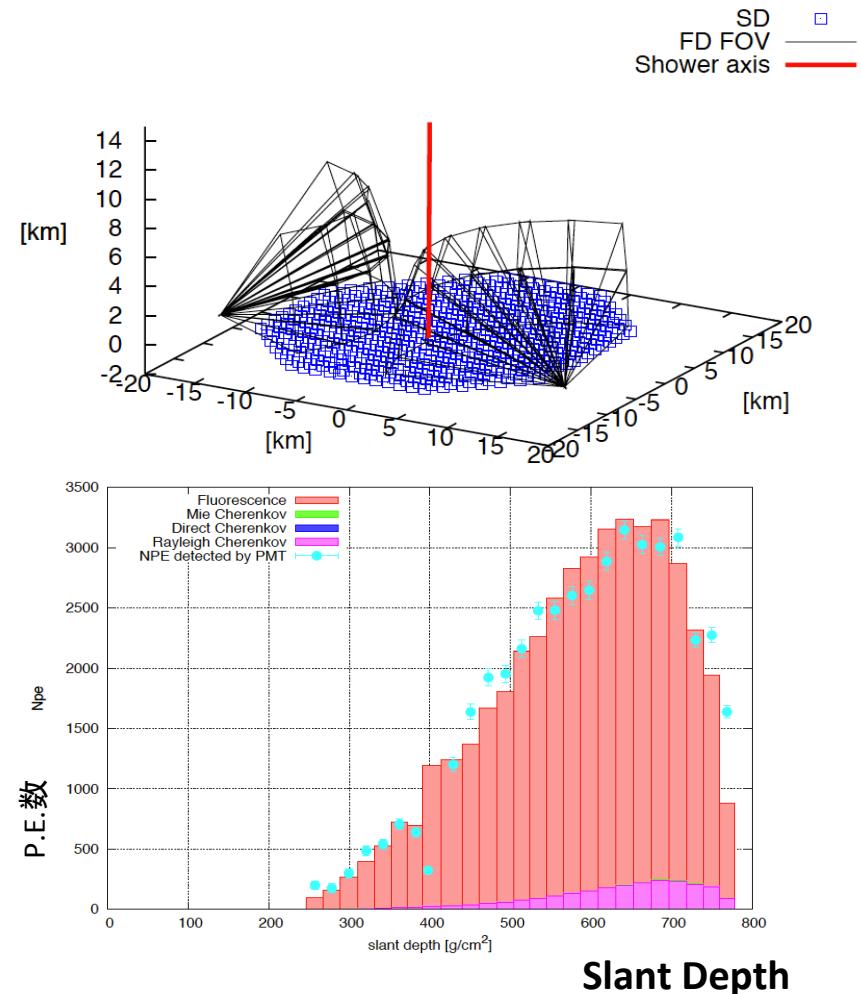
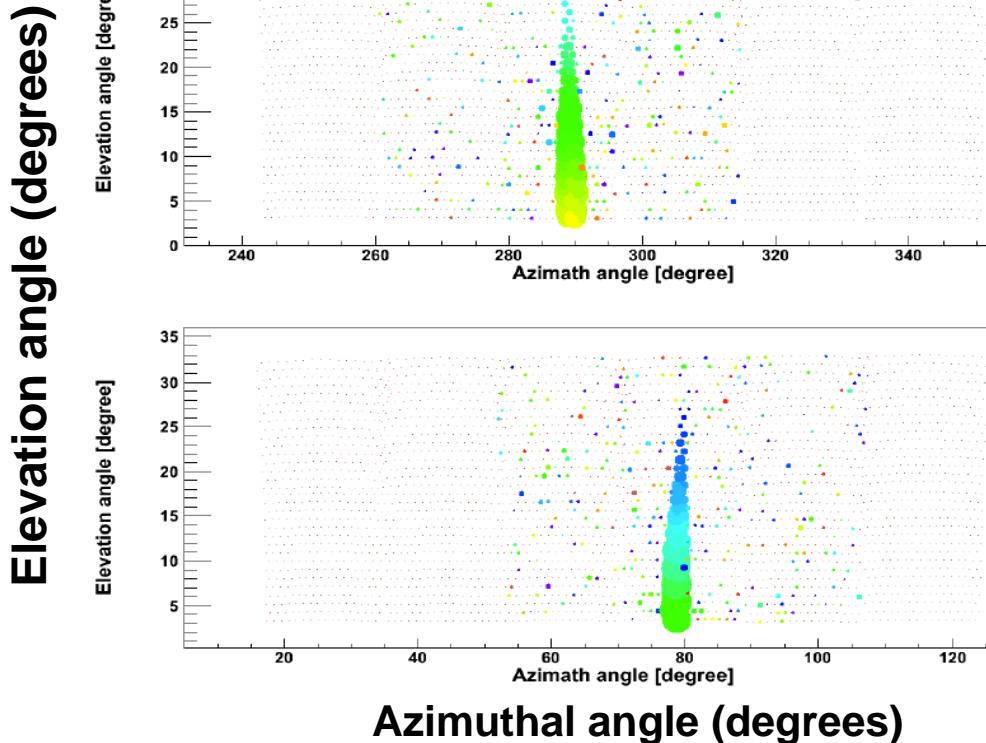
Auger: FD/SD hybrid



# Xmax by MC (Raw)



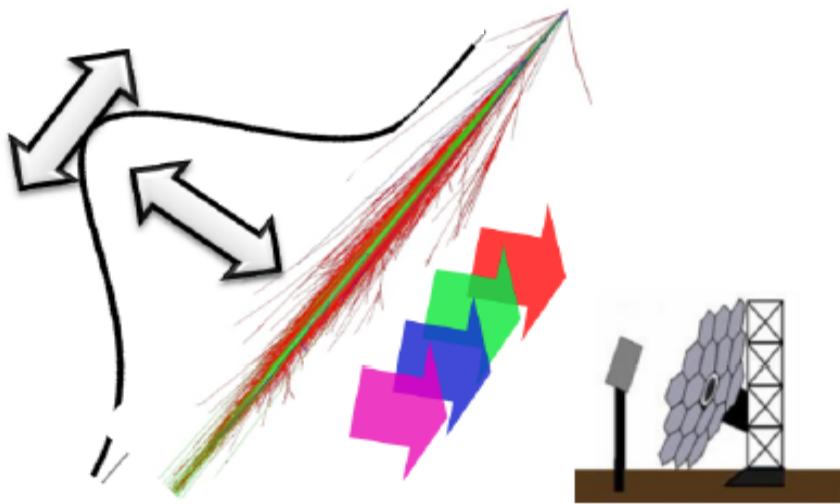
# Example of Stereo Event



zenith	azimuth	core [km]
$3.23^\circ$	$145.9^\circ$	0.09, -6.10

# Reconstruction

- 1) Core and Direction by Stereo Geometry
- 2) E and Xmax by Inverse MC



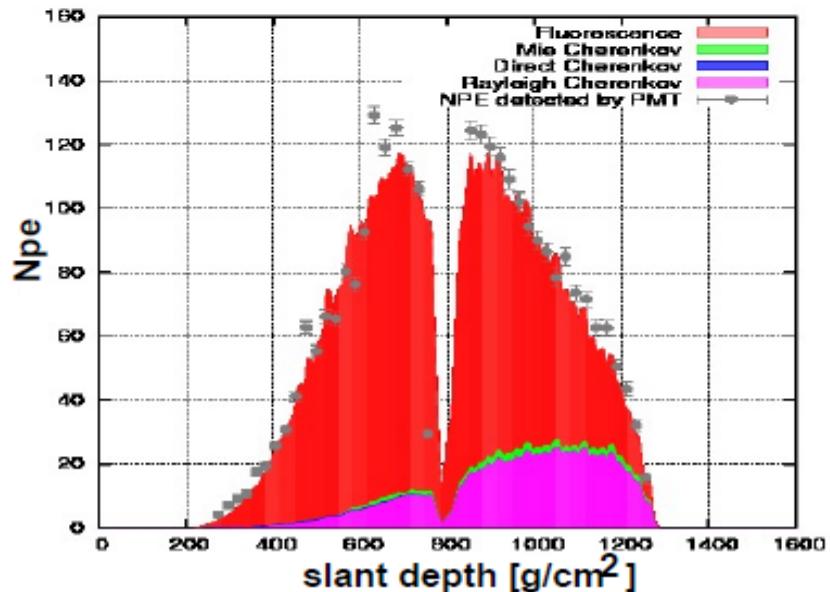
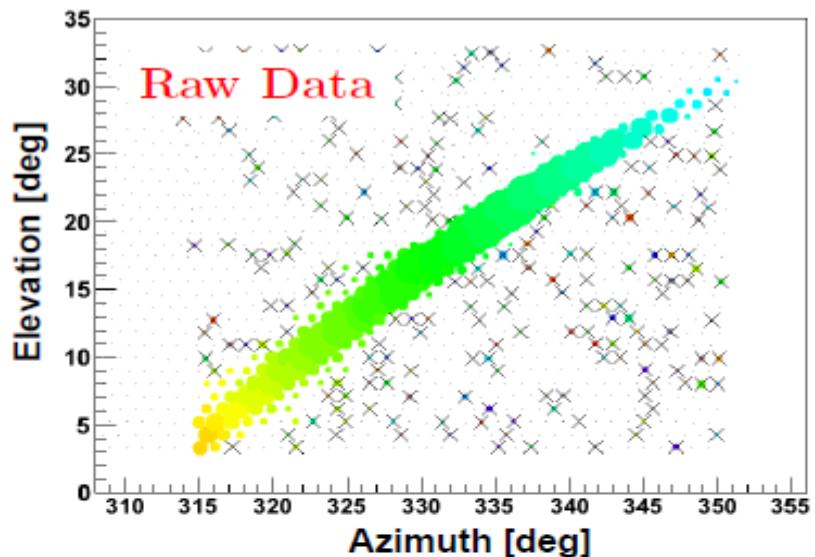
Accuracy @  $10^{19}$ eV

Direction : < 1.6 deg

shower core location :  $\pm 180$  m

Energy :  $-5.4 \pm 5.8$  %

Xmax :  $-9.7 \pm 16$  g/cm<sup>2</sup>



728.5 g/cm<sup>2</sup>

$1.76 \times 10^{19}$  eV

# Making Simulated Events

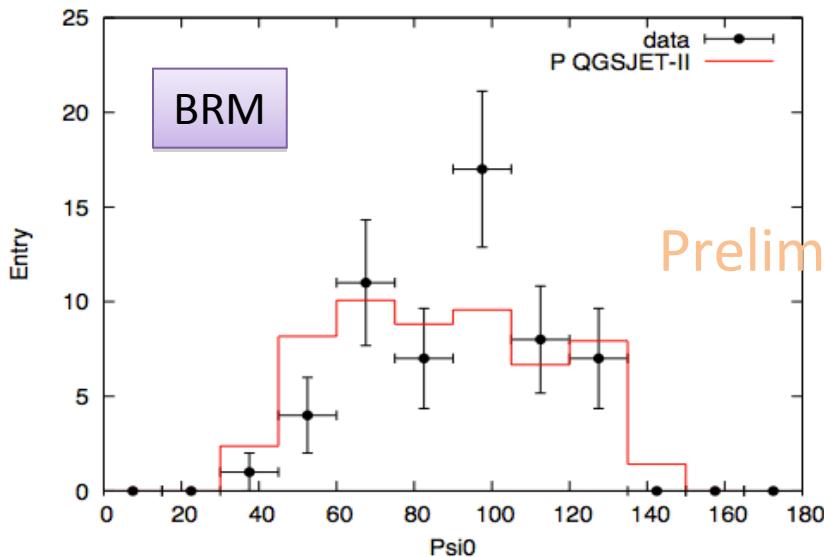
## Shower Simulation

- CORSIKA v6.9
- Hadronic Int. Model
  - QGSjet-II, QGSjet-01, SIBYLL
- Proton or Fe Nuclei
- Energy:
  - $\log E = 18.5-19, 19-19.5, 19.5-20$
  - Power index : - 3.1
- Zenith Angle : 0 – 60 deg
- thinning factor :  $10^{-4}$
- Ecut: EM:100keV, hadron:100MeV
- Core:  $r < 10$  km
- Each 500 events

## Detector Simulation

- Atmosph. by nearby Radio Sonde
- Typical measured Mie attenuation by lidar ( $h=1.0$ km,  $\lambda = 29$ km)
- Fluorescence yield
  - Normalization by Kakimoto et al.,
  - Spectrum by FLASH

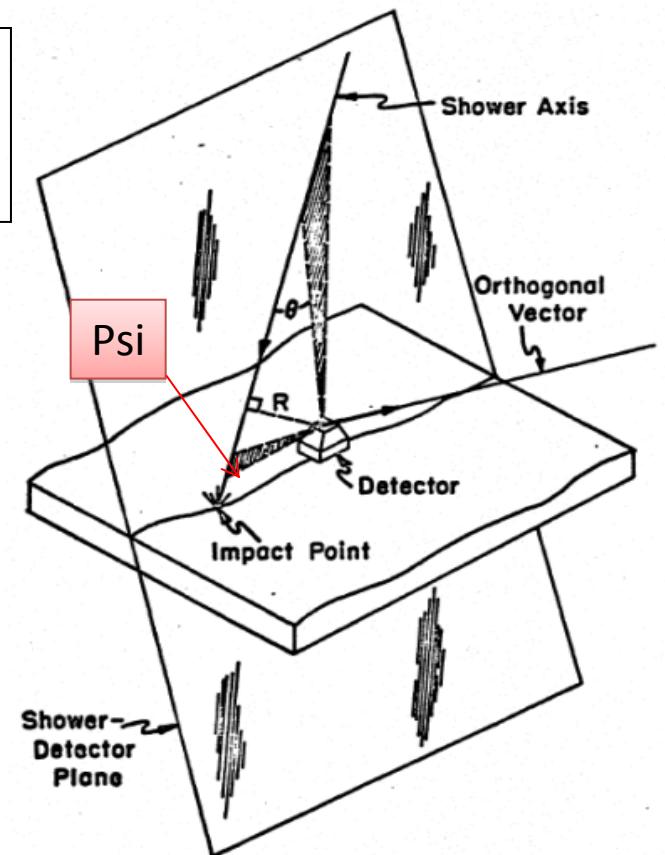
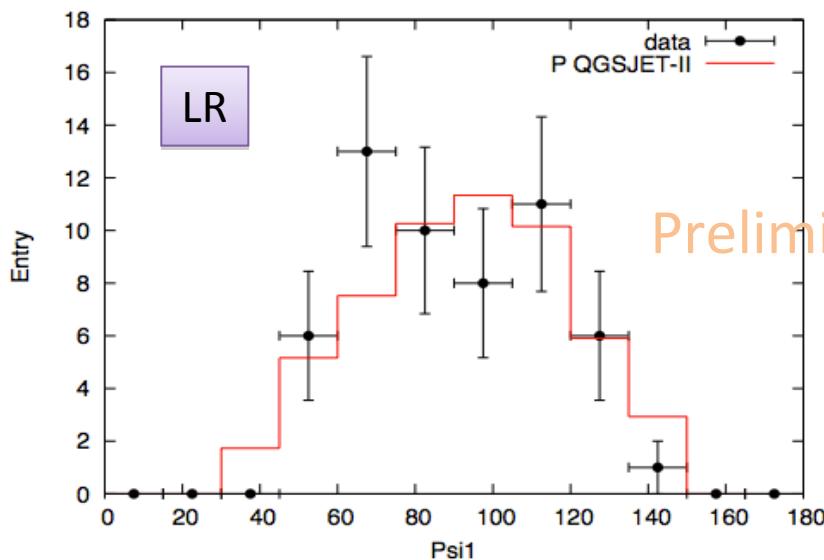
# Psi angle (deg)



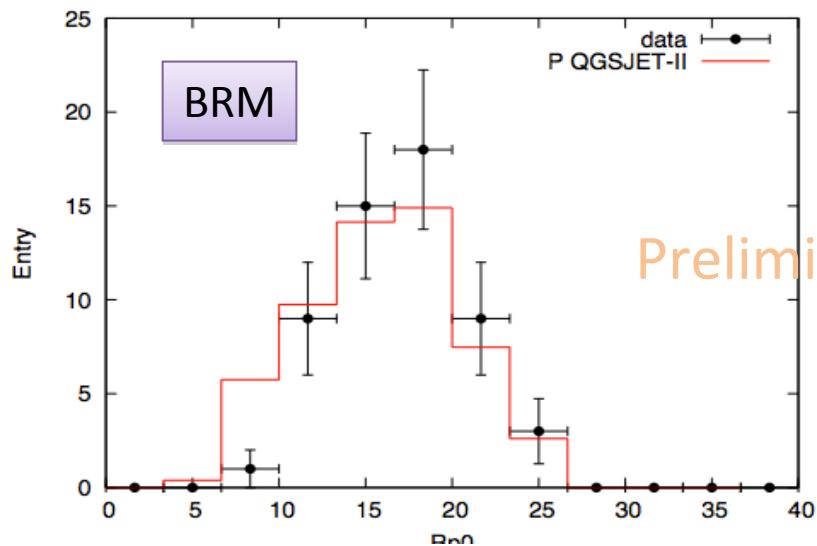
MC: CORSIKA QGSjet-II proton  
 $E^{-3.1}$

Preliminary

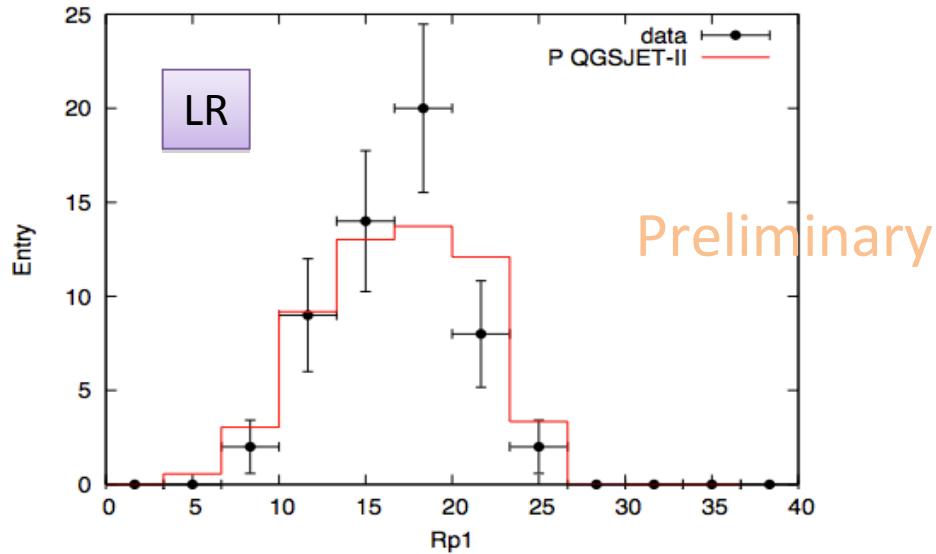
Cuts:  
 $E > 10^{18.6} \text{ eV}$   
 $\theta < 56^\circ$



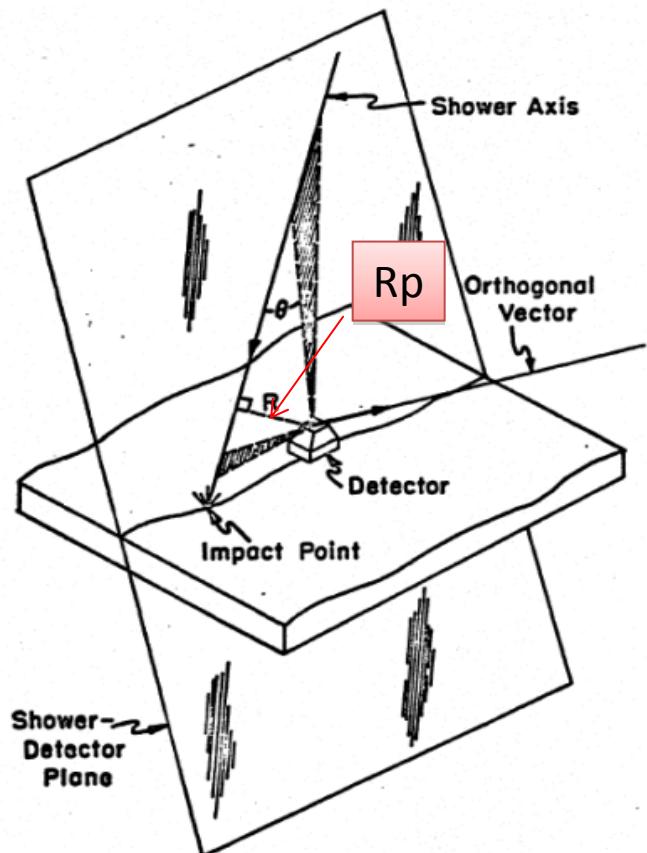
# $R_p$ (km)



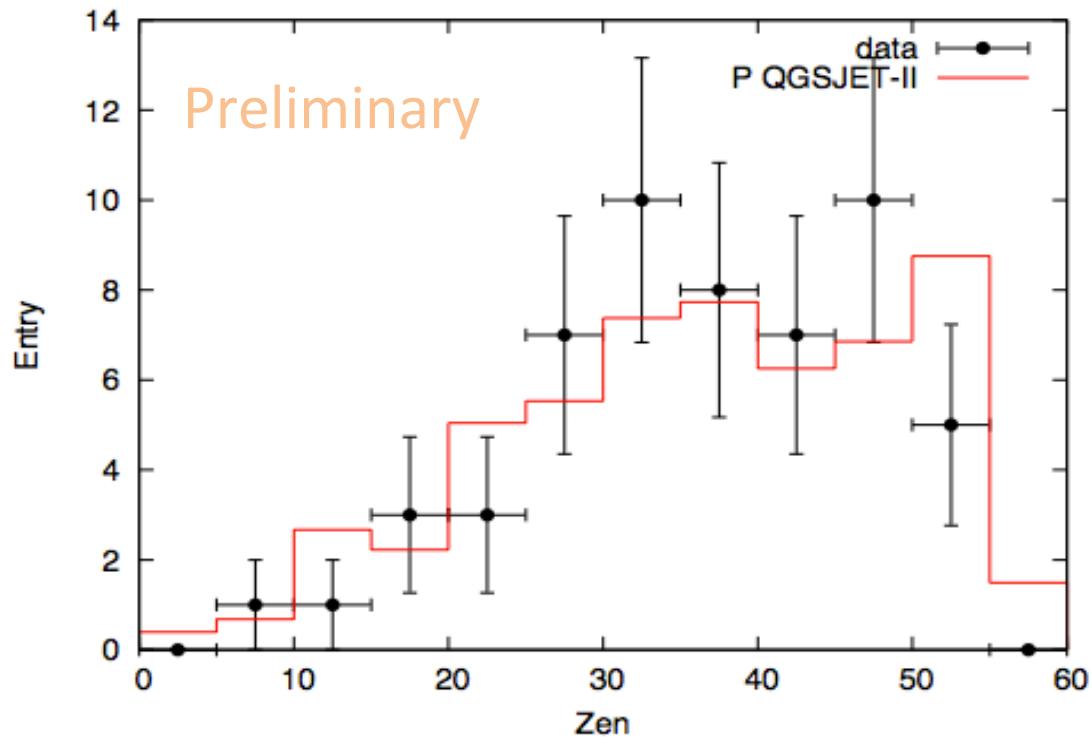
Preliminary



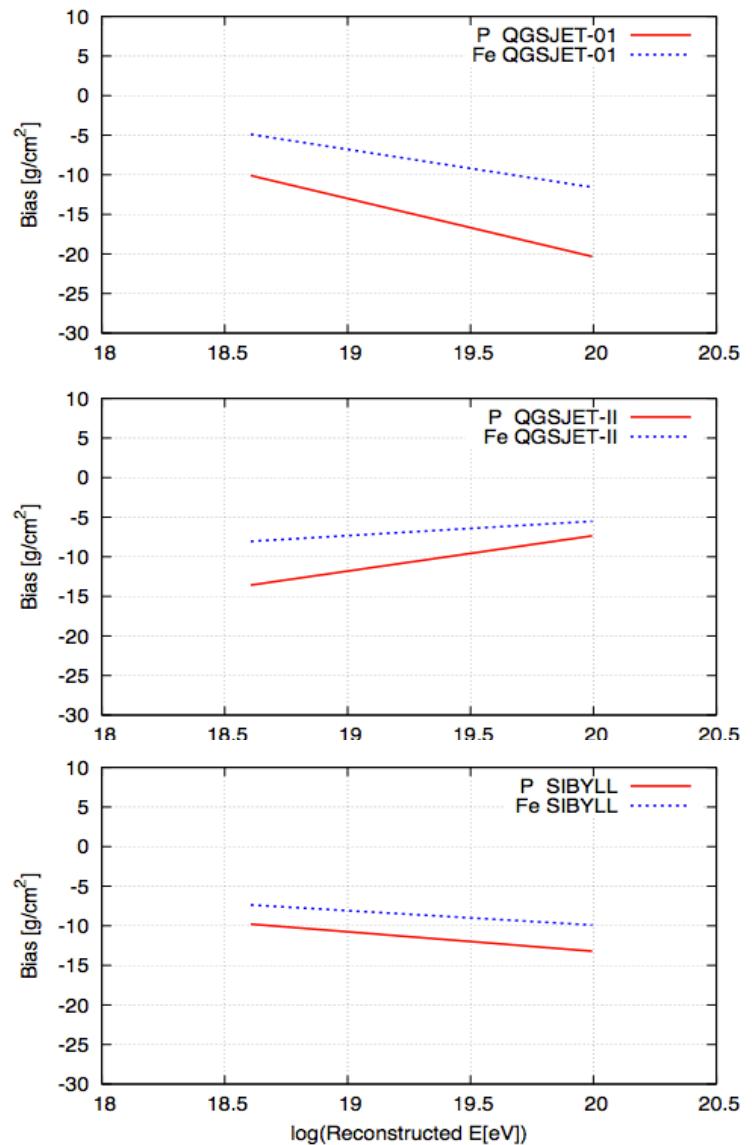
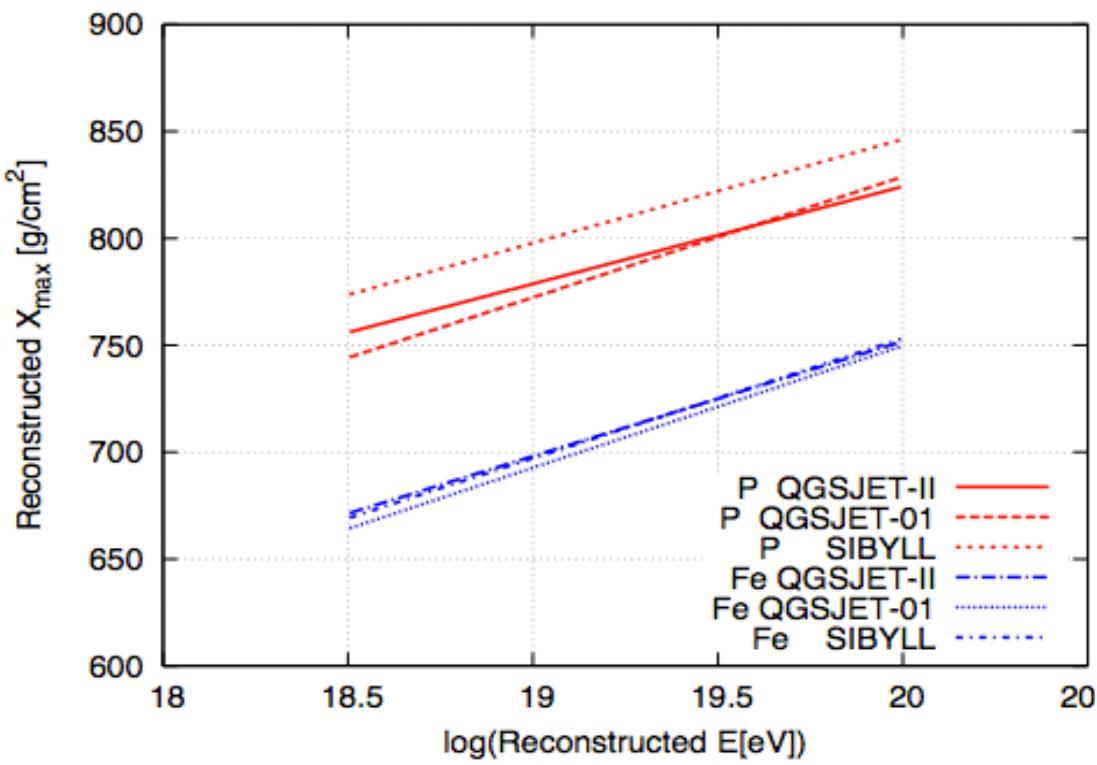
Preliminary



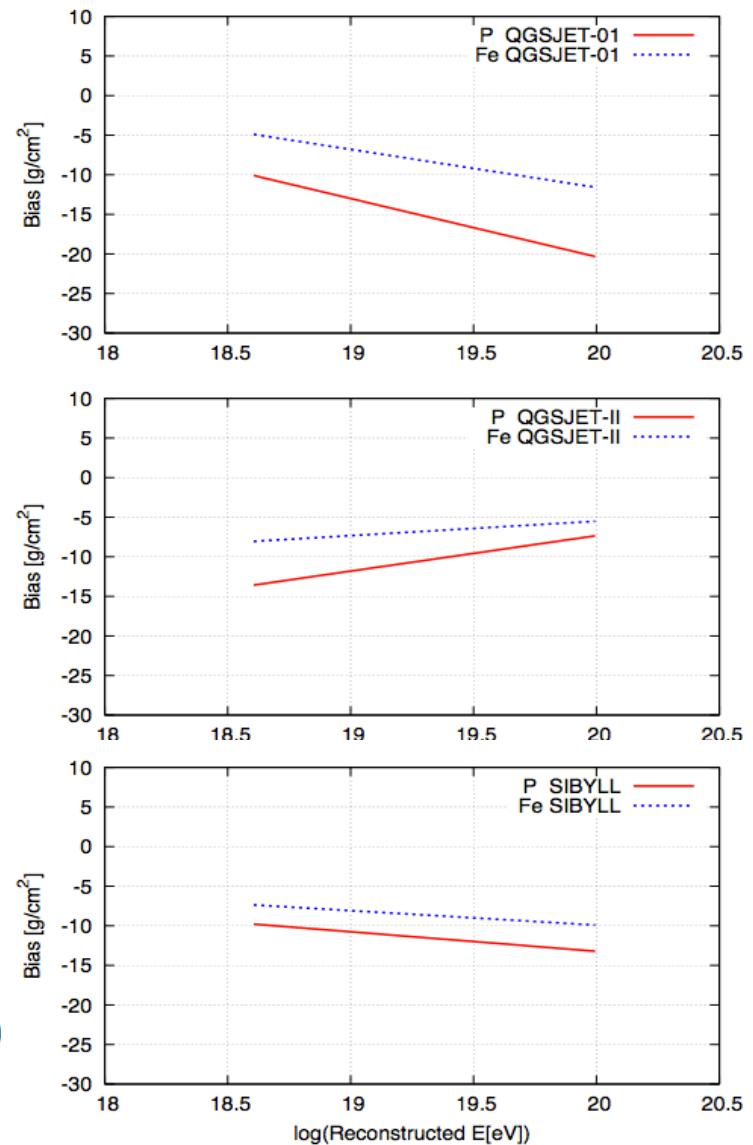
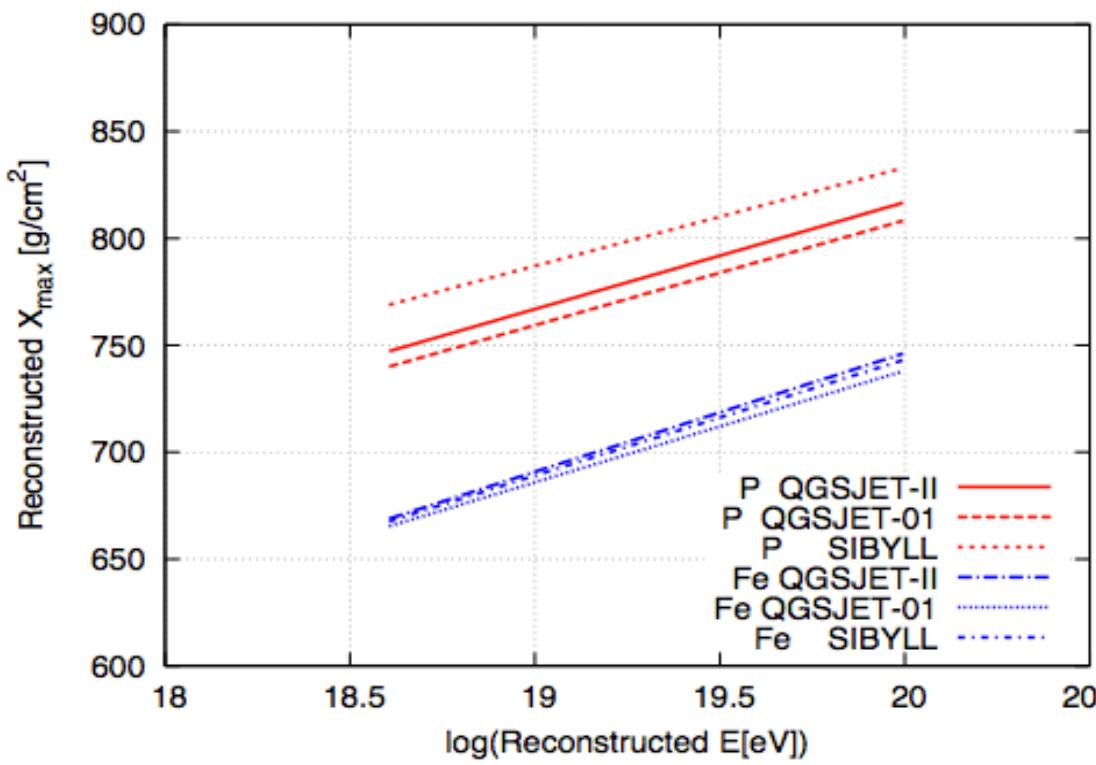
# Zenith angle (deg)



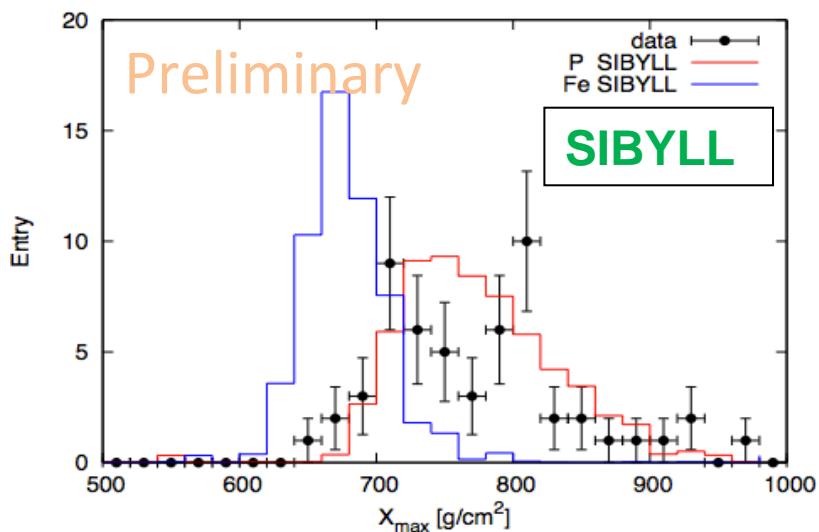
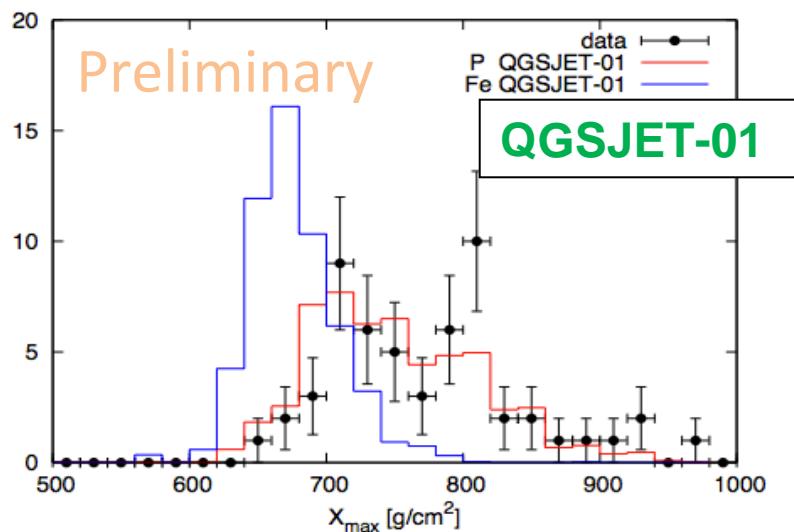
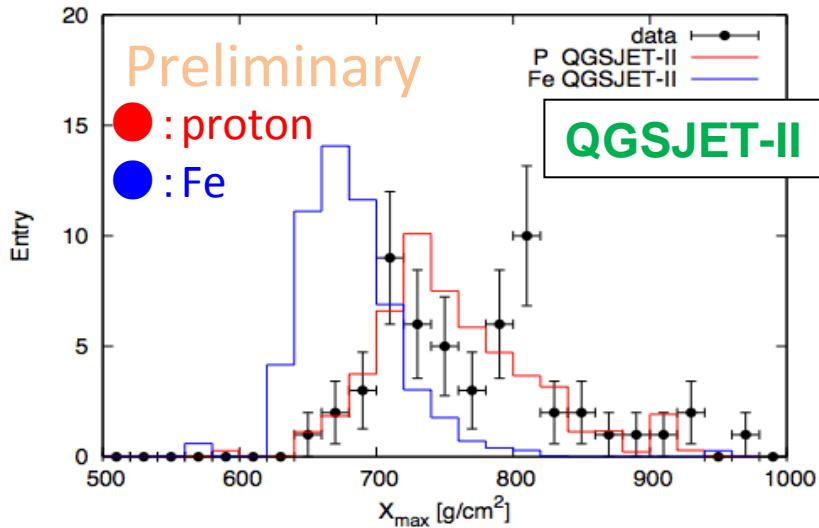
# Xmax “bias” by recons. + selection



# Xmax “bias” by recons. + selection



# Comparison of reconstructed $X_{\max}$ between data and MC

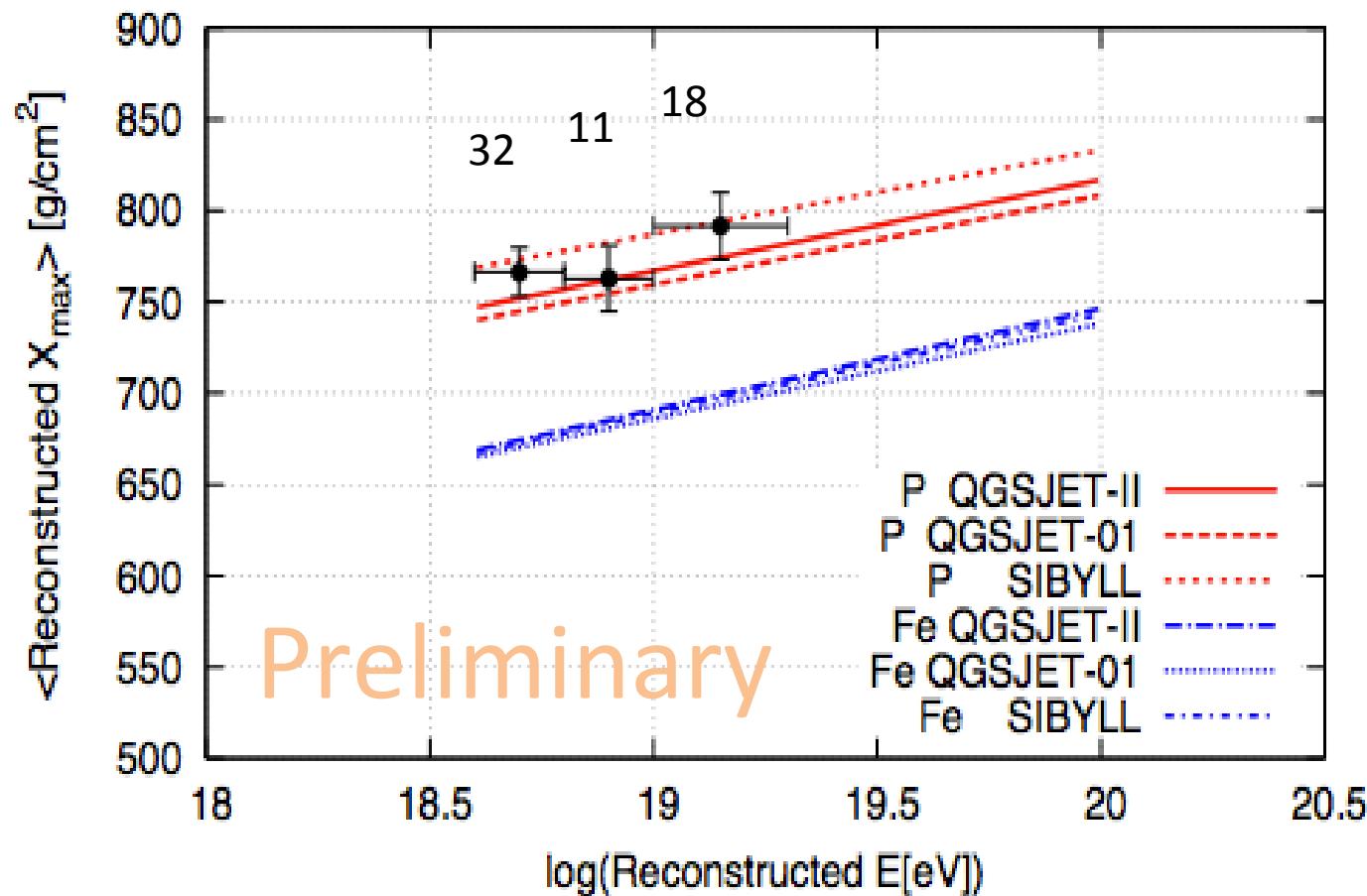


$E > 10^{18.6} \text{ eV}$

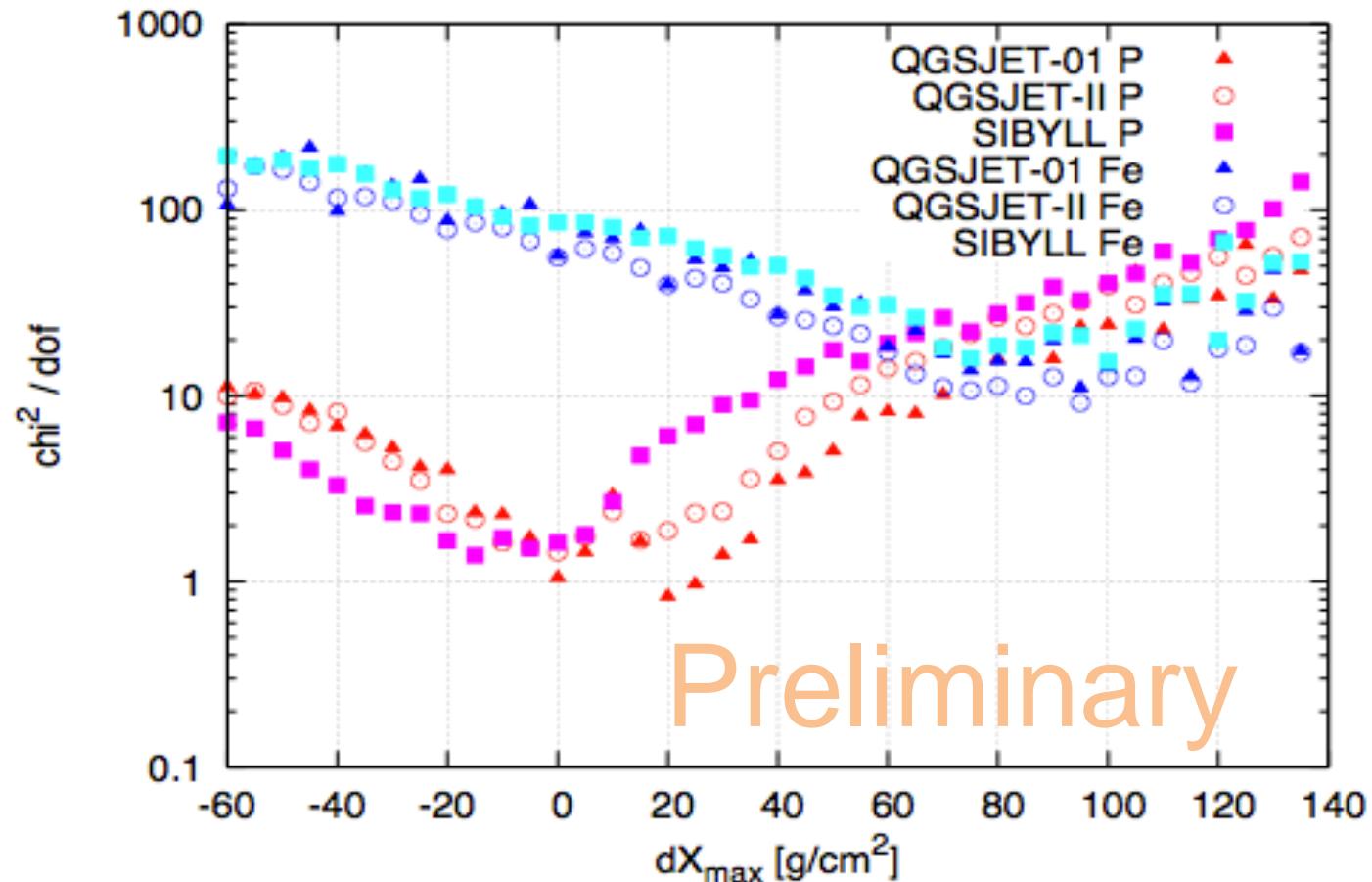
$\chi^2 / \text{dof}$

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

# $\langle \text{Reconstructed } X_{\max} \rangle$ vs. $E$



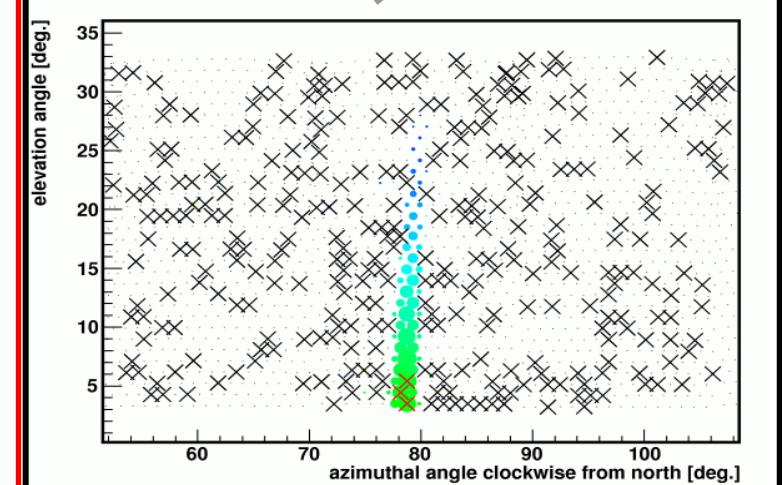
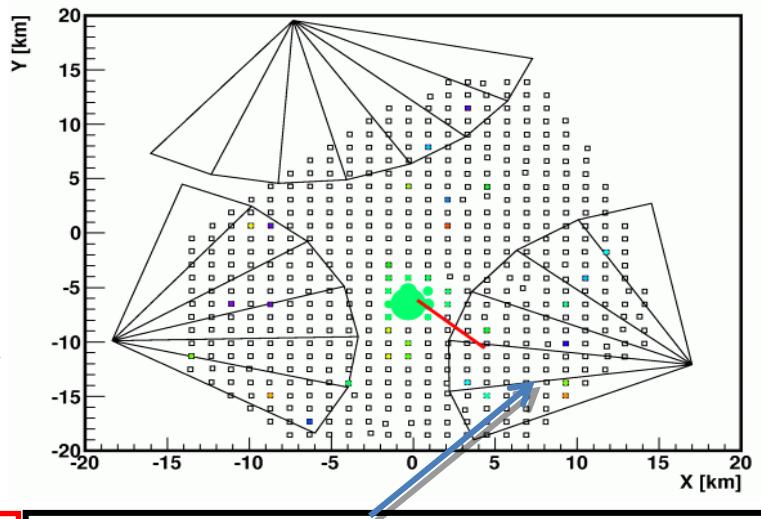
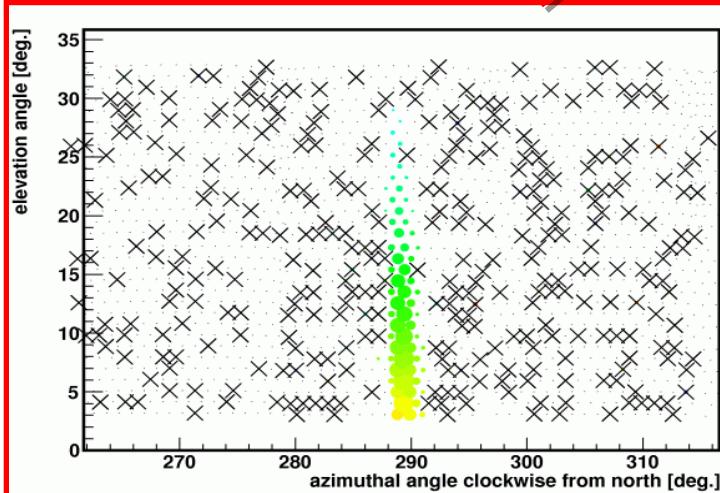
# Chi2 vs shift of dXmax



## (2) Hybrid Analysis for Spectrum

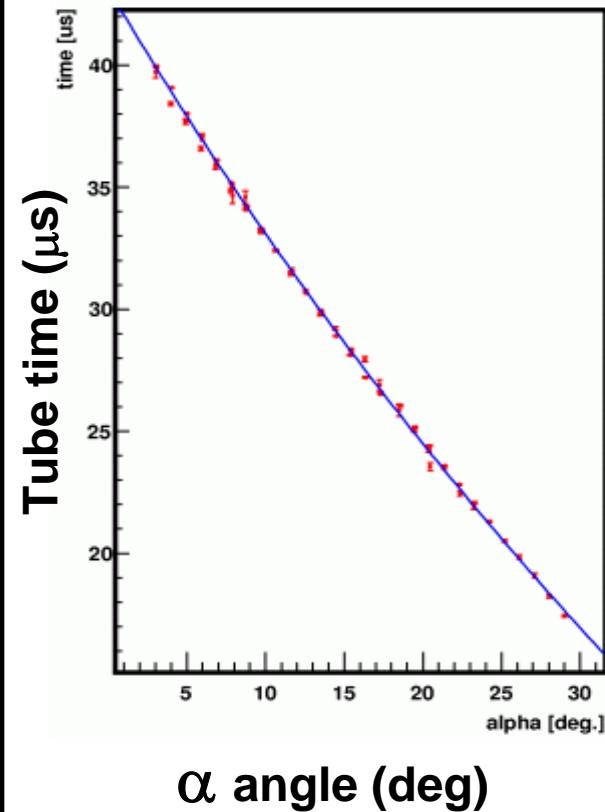
- FD geom. reconst. with SD timing
- Energy determined by FD
- Acceptance determined by “SD”

Example of hybrid event



# Geometrical reconstruction

FD mono analysis + timing of one (best) SD



Mono reconstruction

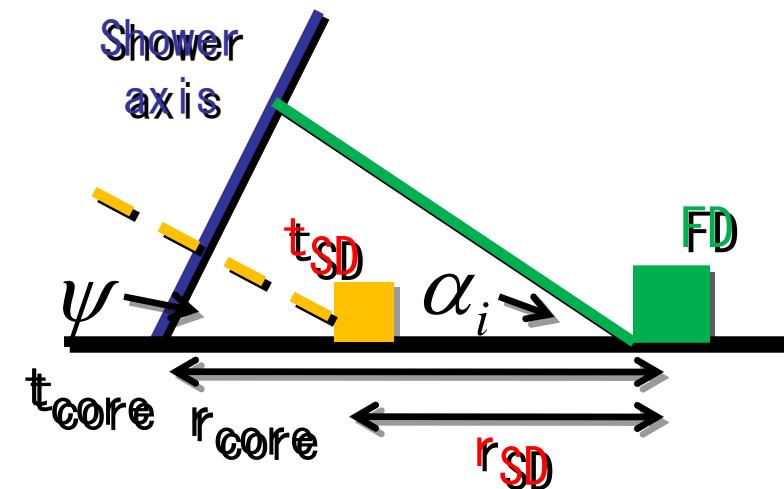
$$t_i = t_{core} + \frac{1}{c} \frac{\sin \psi - \sin \alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$



Hybrid reconstruction

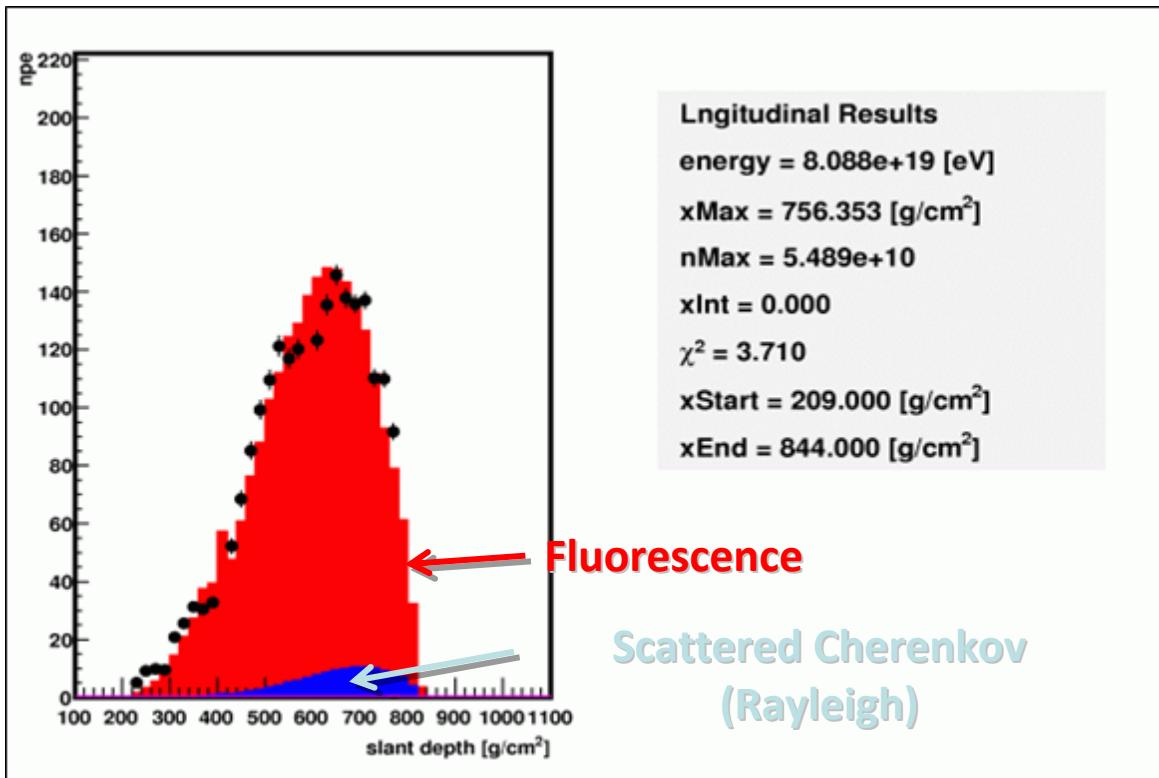
$$t_i = t_{core} + \frac{1}{c} \frac{\sin \psi - \sin \alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

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



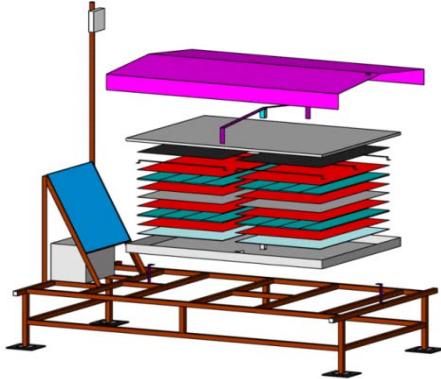
# Shower profile reconstruction

- Xmax has to be observed
- Energy  $> 10^{18.65}$  eV
- Zenith angle  $< 45$  degree



# MC simulation

## Air shower simulation: COSMOS



SD

- Time dep. Calib.
- Same as SD analysis

FD

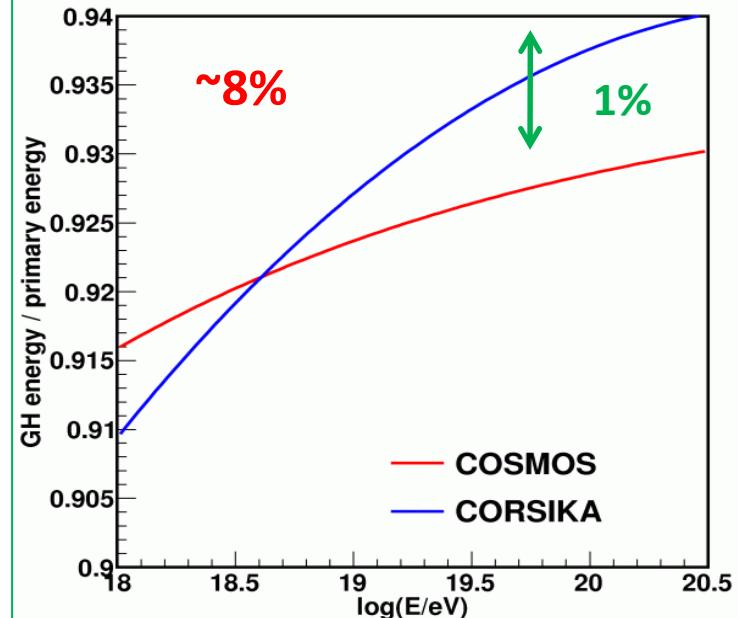
- Time dep. Calib.
- BG by real data.
- Geom. corrected by star.
- Measured atmosphere

## Hybrid MC data:

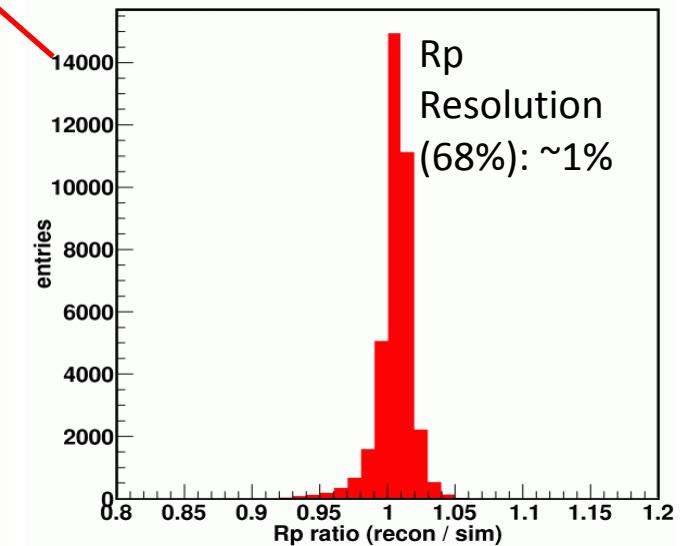
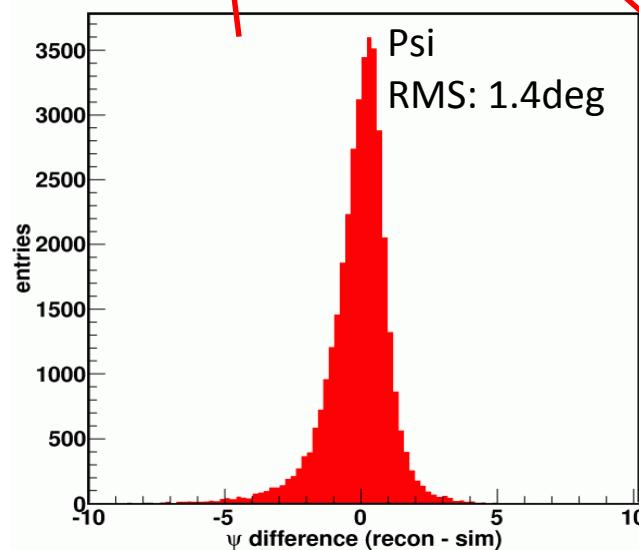
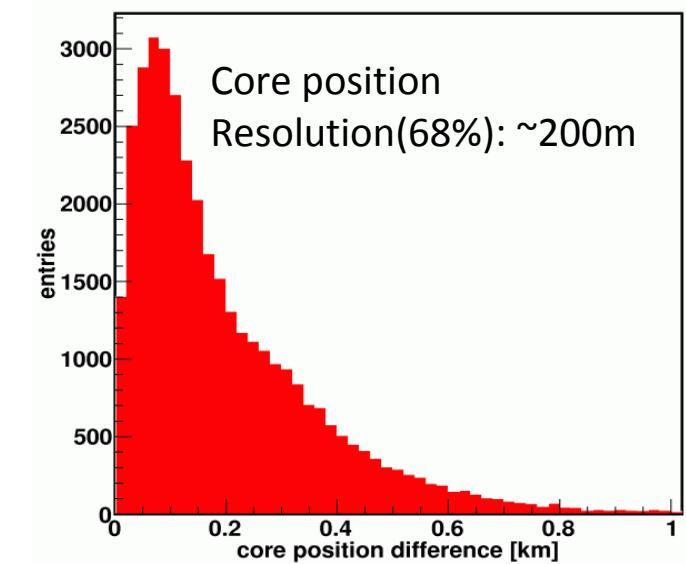
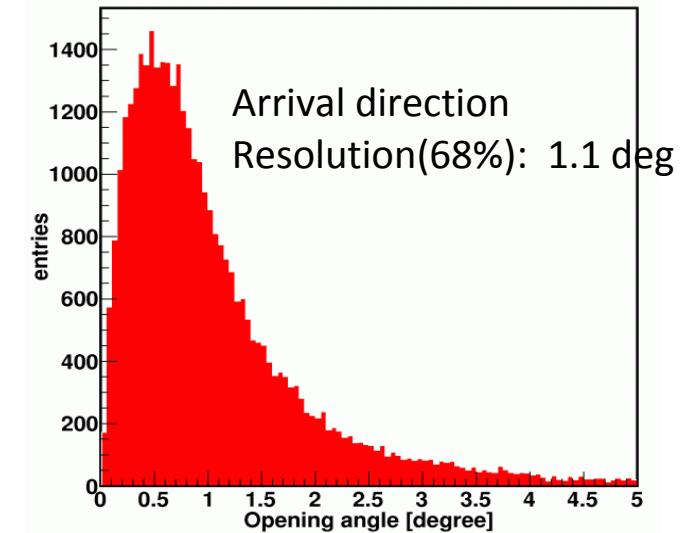
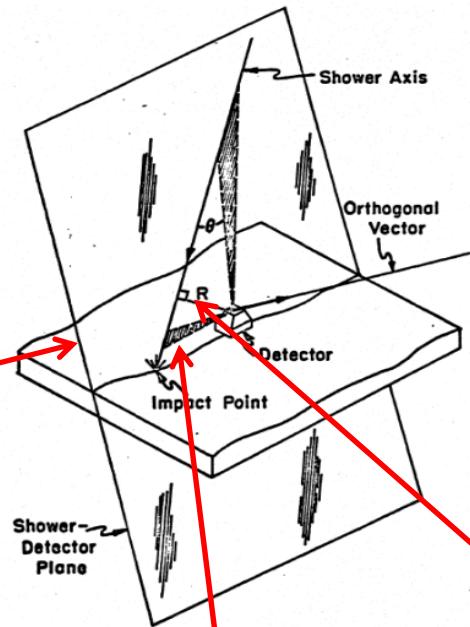
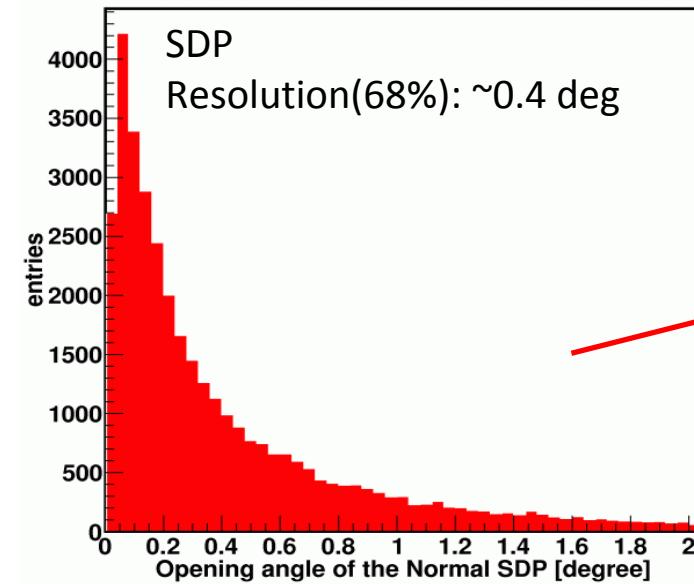
- Date: Random in FD observation period
- Core: 25km radius from CLF
- Slope data: ~2.5M events with  $E^{-3.1}$
- Flat data: ~20k events for each energy

Items	Values
Primary energy	$10^{18}\text{eV} \sim 10^{20.5}\text{eV}$
Zenith angle	$\cos \theta = 0.65 (\doteq 50\text{degree}) \sim 1$
Primary particle	Proton
Thinning ratio	$10^{-4} (\leq 10^{20}\text{eV}), 10^{-5} (> 10^{20}\text{eV})$
Interaction model	QGSJET II
Cut threshold	100keV

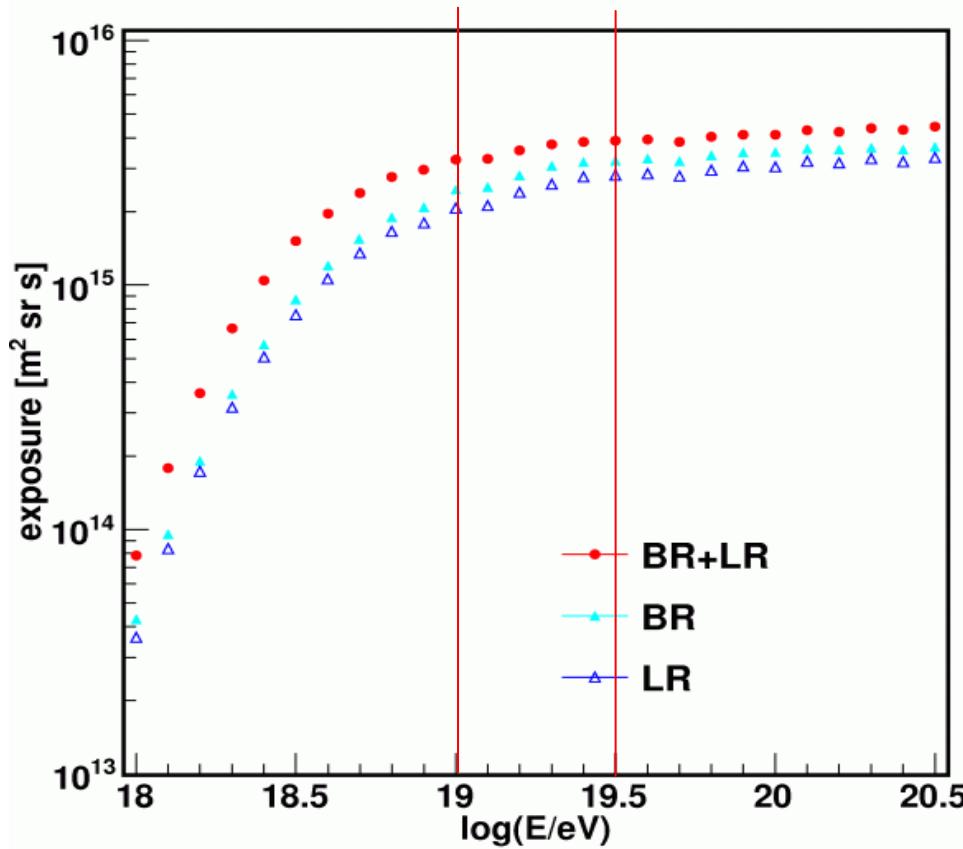
Missing energy



# Resolution (Geometry)



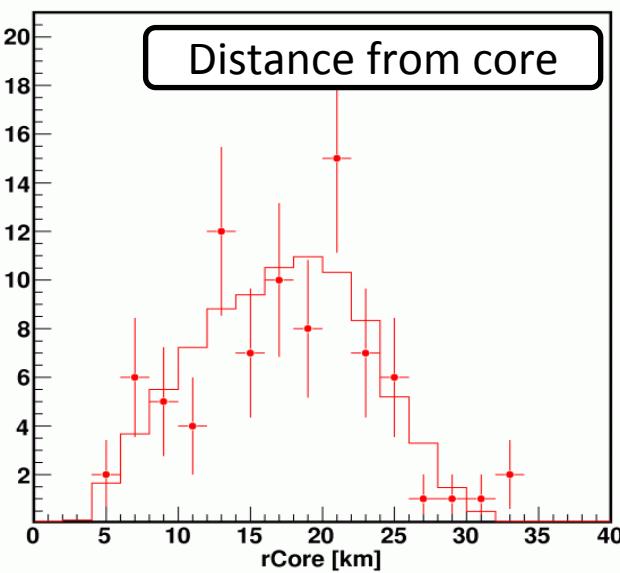
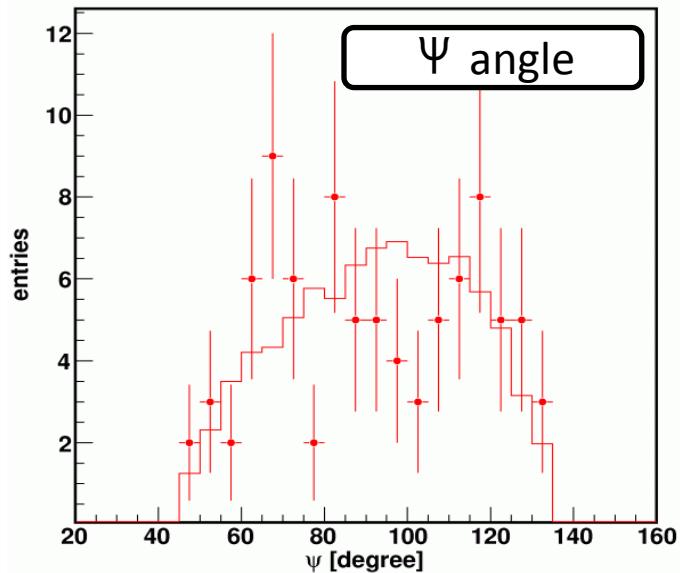
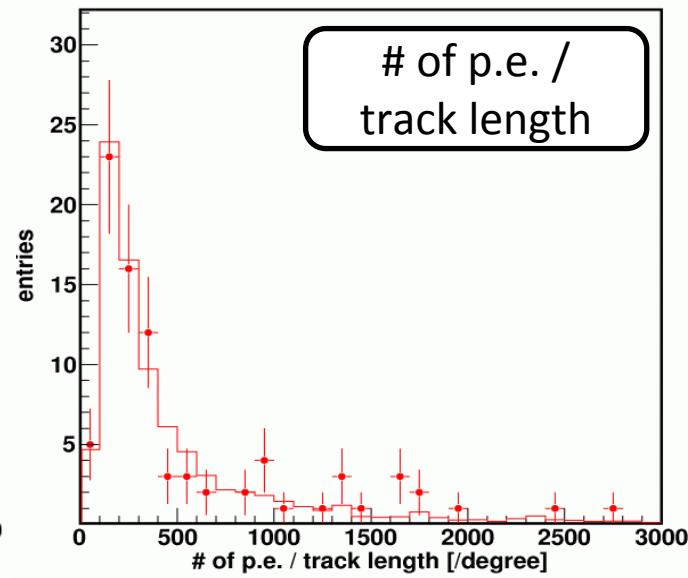
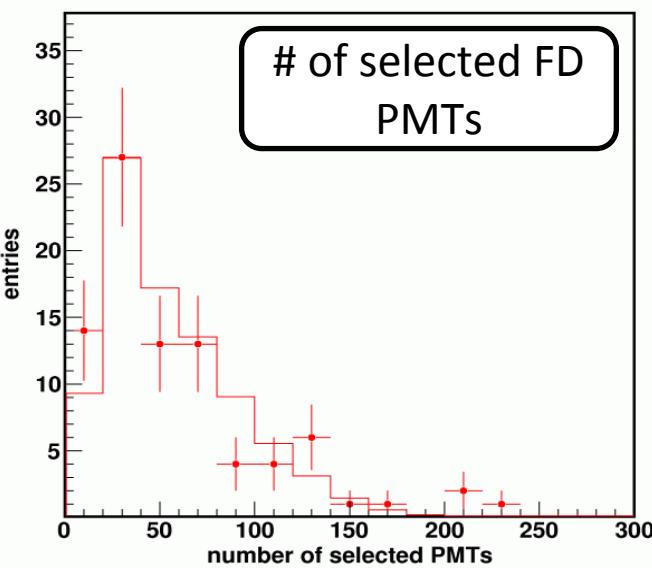
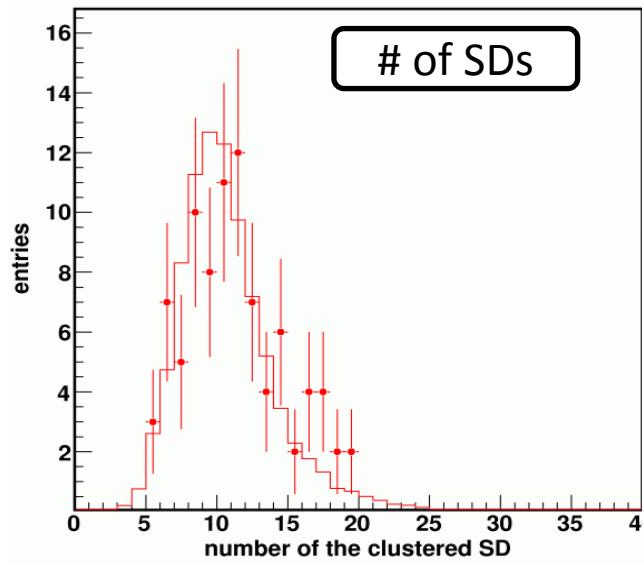
# Exposure



The aperture is calculated from MC simulation.

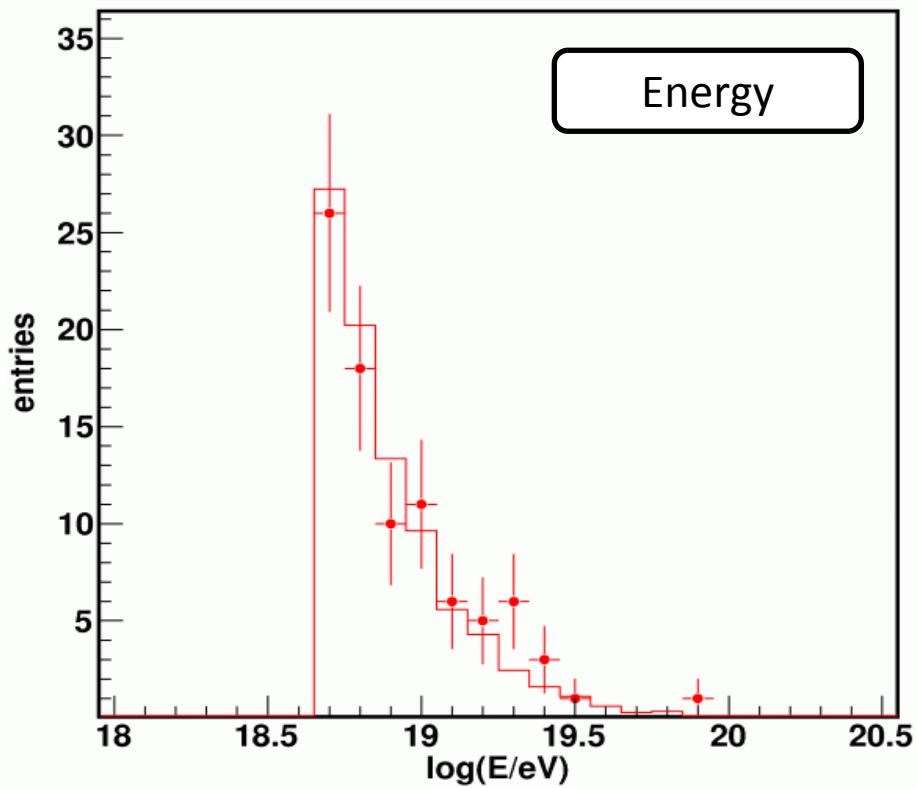
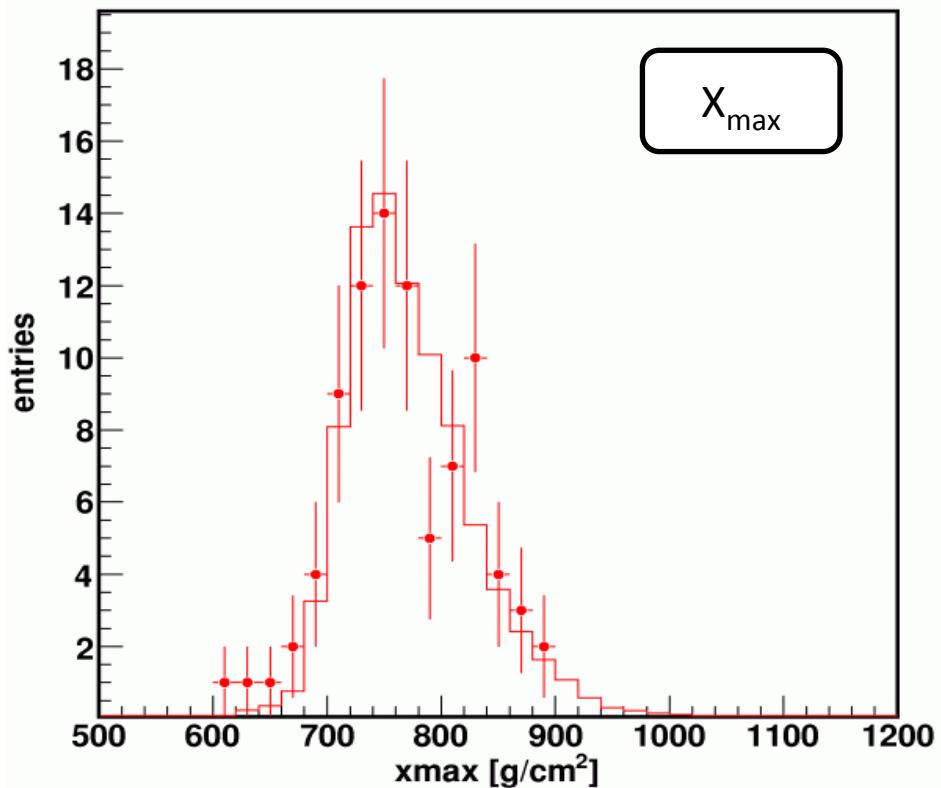
Exposure:  $\sim 3 \times 10^{15} \text{ m}^2 \text{ sr s}$  ( $> \sim 10^{19} \text{ eV}$ )

# Data/MC comparison - 1



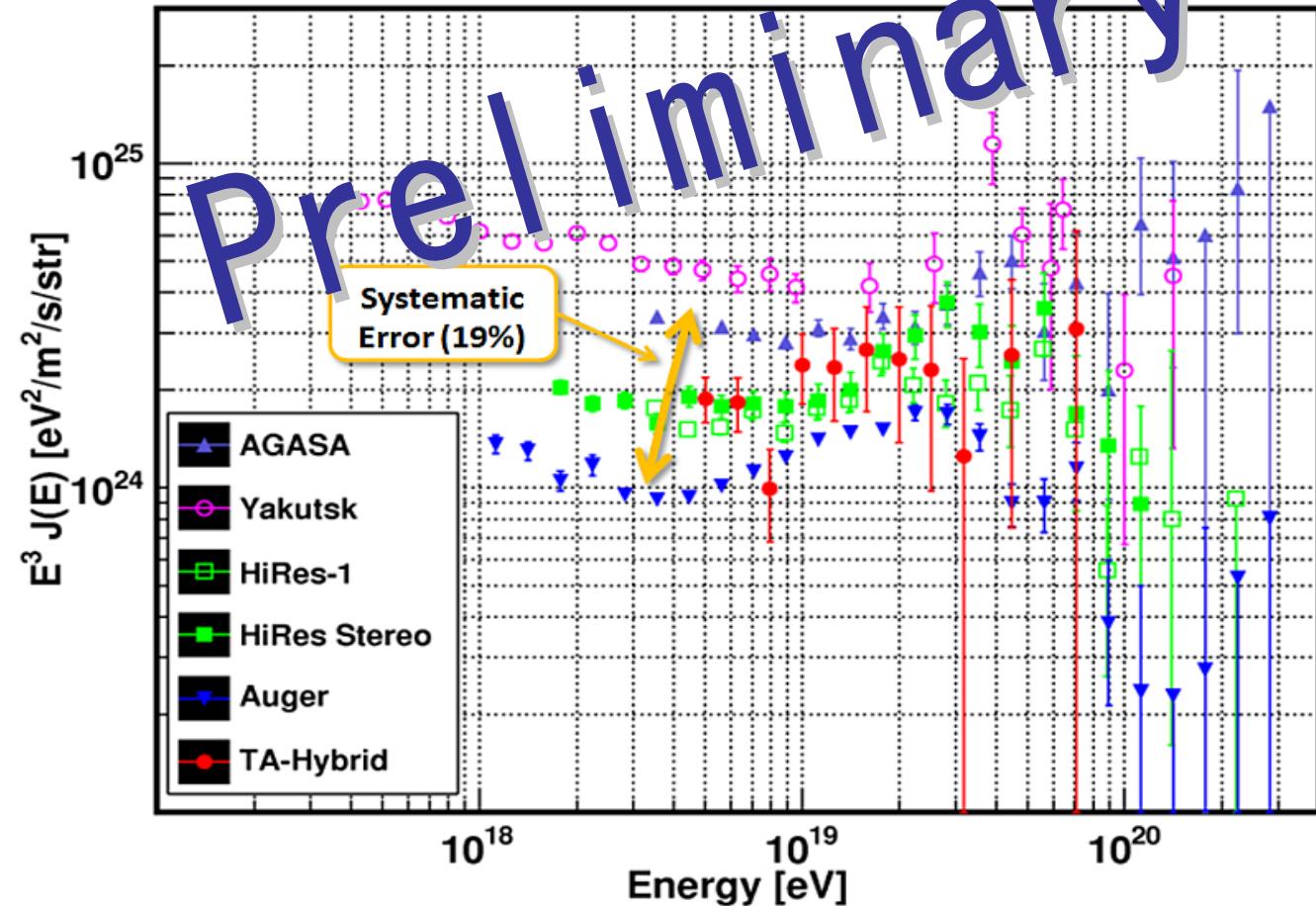
- BR station
- Filled circles : data
- Histograms : MC

# Data/MC comparison - 2



# Energy spectrum

Preliminary



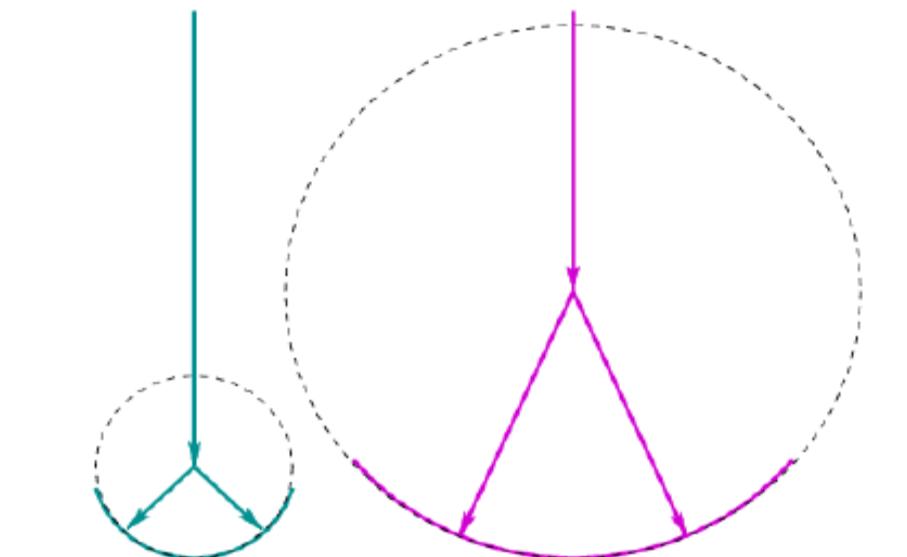
## Systematic errors

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

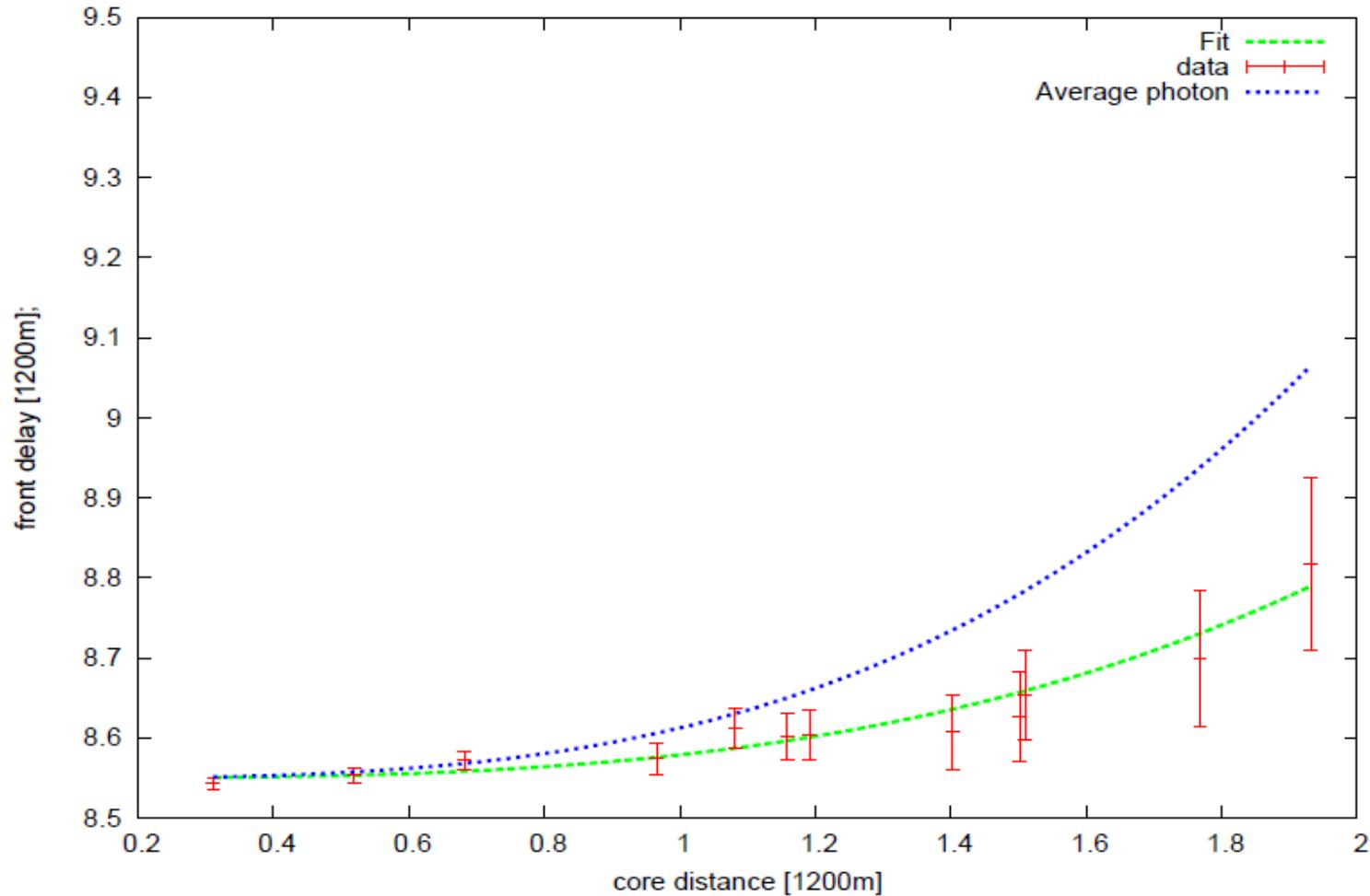
## (3) UHE Photon Search

Shower front curvature

**deep shower maximum = curved front**



# Example of front curvature



# Event reconstruction

- ▶ Joint fit of LDF and shower front profile
- ▶ 7-parameters:
  - ▶  $x_{core}, y_{core}$  – shower core location at the ground level
  - ▶  $\theta, \phi$  – 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

$$t(r) = t_0 + t_{plane}(r) + a t_L(r)$$

$$t_L(r) = (r/39m)^{1.5} LDF(r, \theta)^{-0.5}$$

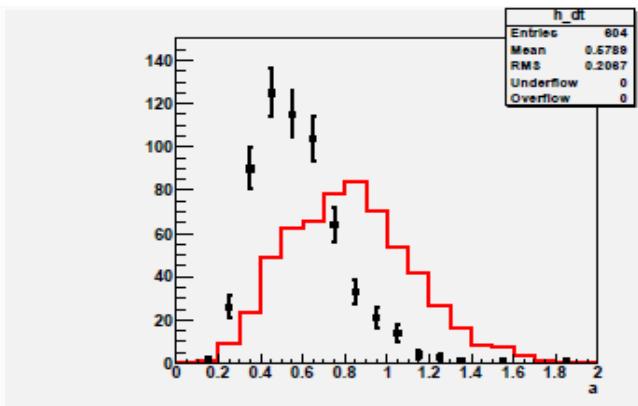
$$S(r) = S_{800} LDF(r, \theta), \quad LDF(800m, \theta) = 1$$

$LDF(r)$  – modified AGASA function

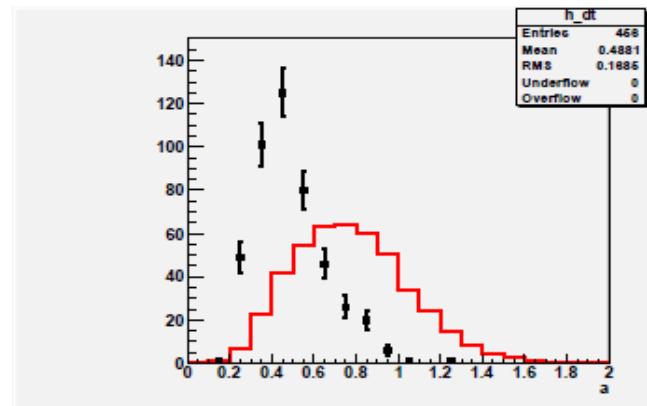
$r$  – core distance in shower plane

# Linsley curvature “a”: data vs. photon MC

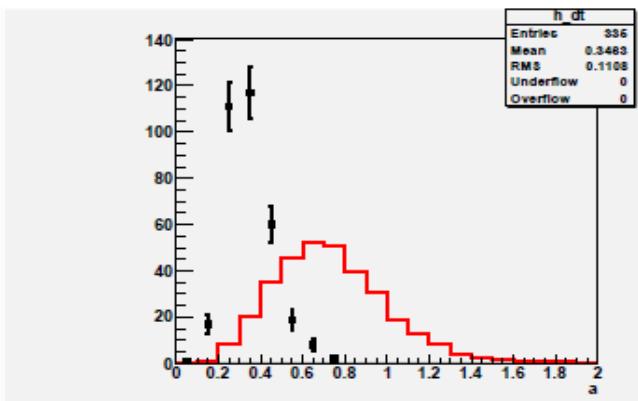
$0^\circ - 30^\circ$



$30^\circ - 45^\circ$



$45^\circ - 60^\circ$



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

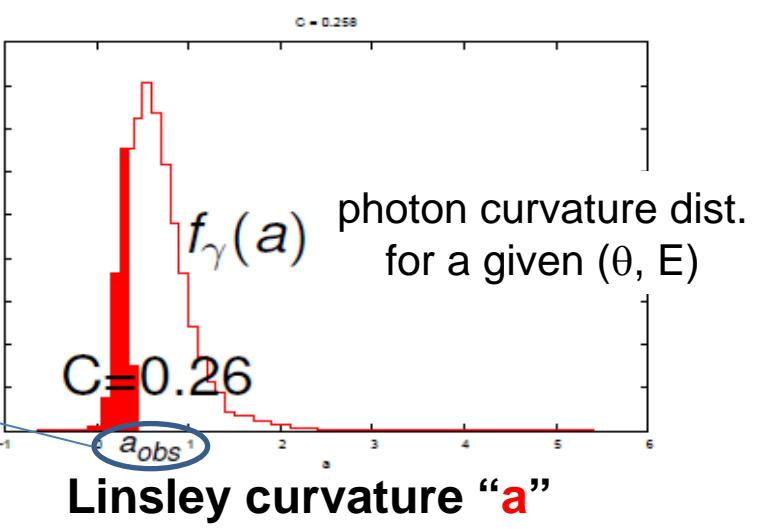
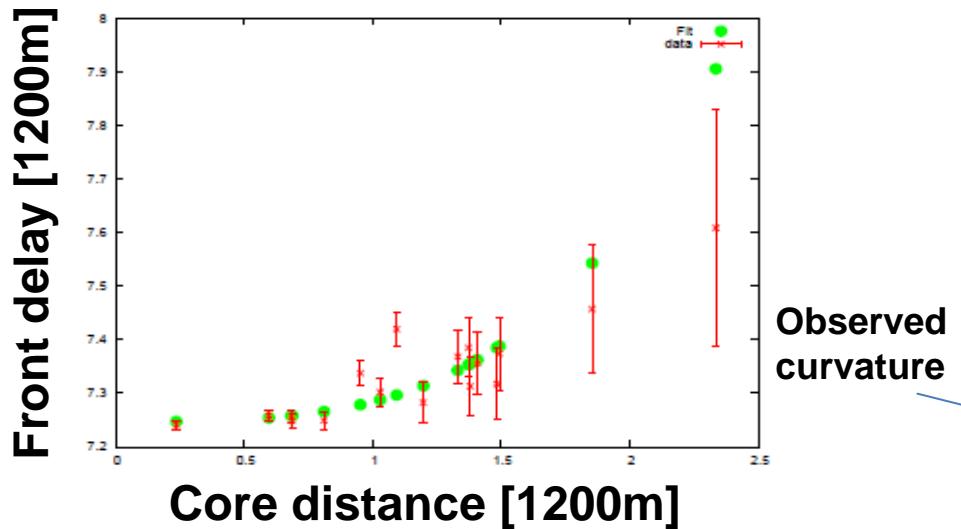
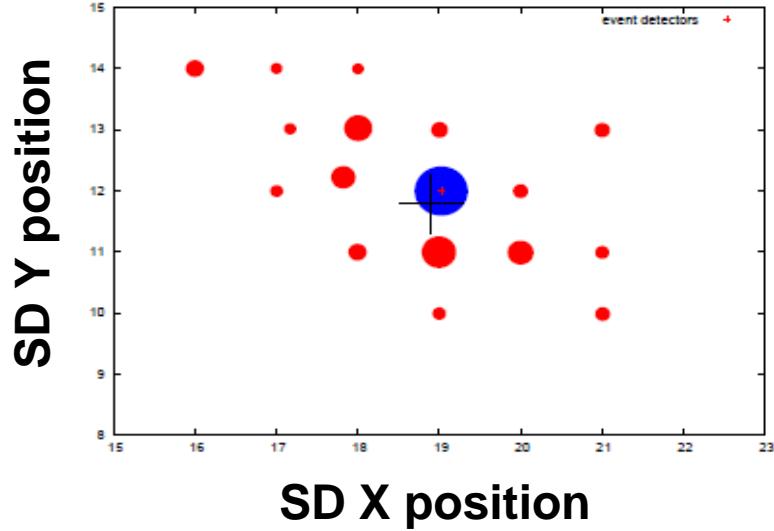
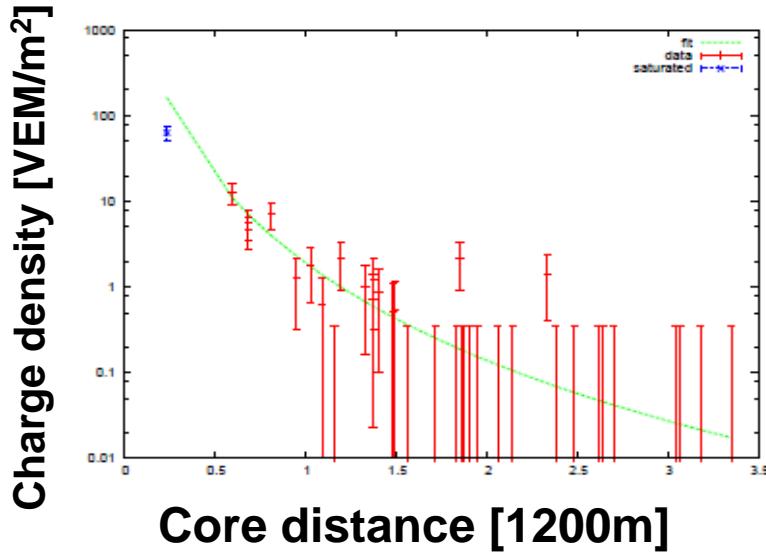
**data**  
**photon MC,  $E^{-2}$  spectrum**  
Corsika with QGSJET-II



Larger curvature

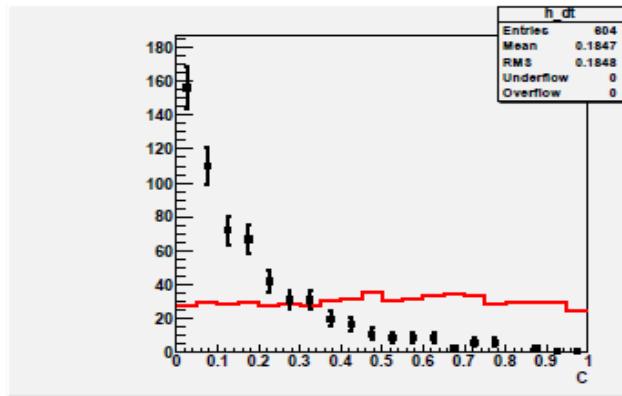
# Example of analysis of one event

$$\theta = 59.9^\circ, E_\gamma = 3.2 \times 10^{19} \text{ eV}, C = 0.26$$

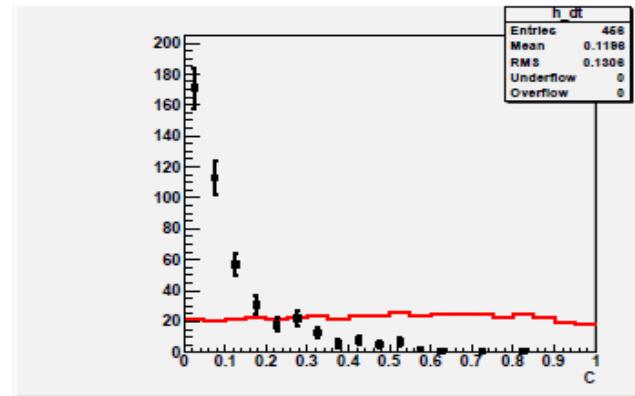


# C distribution: data vs photon MC

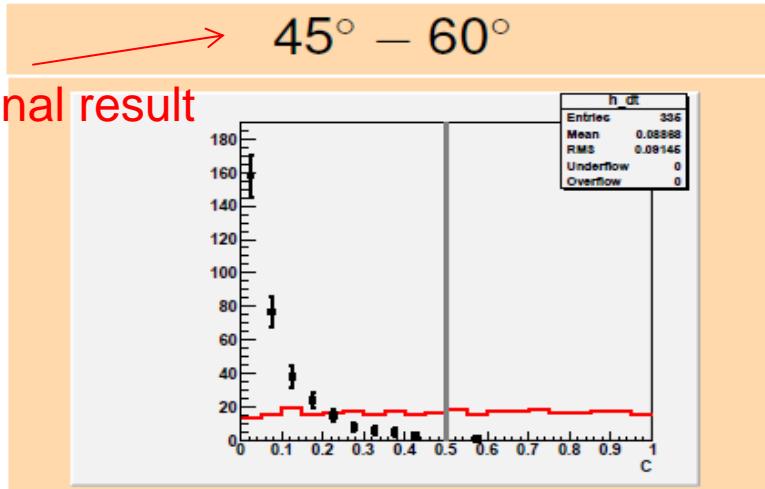
$0^\circ - 30^\circ$



$30^\circ - 45^\circ$



$45^\circ - 60^\circ$



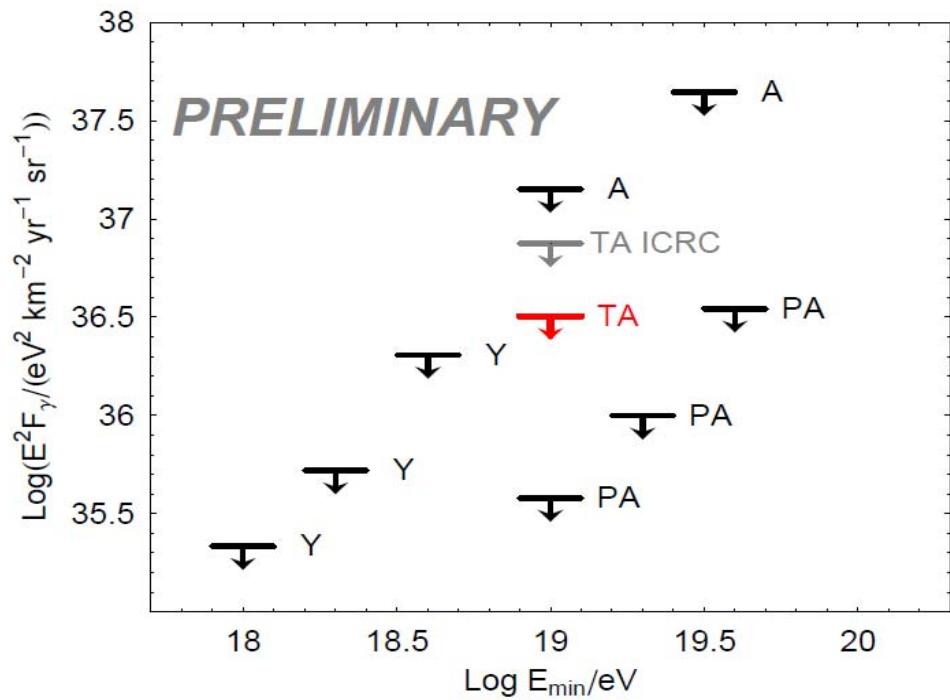
$$E_\gamma > 10^{19} \text{ eV}$$

**data**  
**photon MC,  $E^{-2}$  spectrum**

C is distributed uniformly between 0 and 1 for photon events.

# Photon Flux Limit Conclusion

- $E_\gamma > 10^{19}$  eV
- $45^\circ < \theta < 60^\circ$
- $C > 0.5$ 
  - One event remain.
- Total exposure:
  - $158 \text{ km}^2 \text{ sr yr}$
- $F_\gamma < 3.3 \times 10^{-2} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$   
(95%CL) preliminary



# SUMMARY

*TA measures*

*Primary Composition: what is the UHECR ?*

*Spectrum: dip and cutoff ?*

*Source + Anisotropy: From where it is coming ?*

*UHE  $\gamma$  and  $\nu$  : Exotic origin ?*

*Today's talk covered*

- *Xmax by stereo FD -----* ~ proton for  $E=10^{18.5} \sim 10^{19.3}$  eV
- *Spectrum by FD/SD hybrid -----* ~ consistent with HiRes
- *UHE  $\gamma$  limit -----* ~ no  $\gamma$   $E < 10^{19}$  eV
- *[SD spectrum]*
- *[LSS association, Point sources etc.]*
- *[UHE  $\nu$  search]*

*Coming soon*