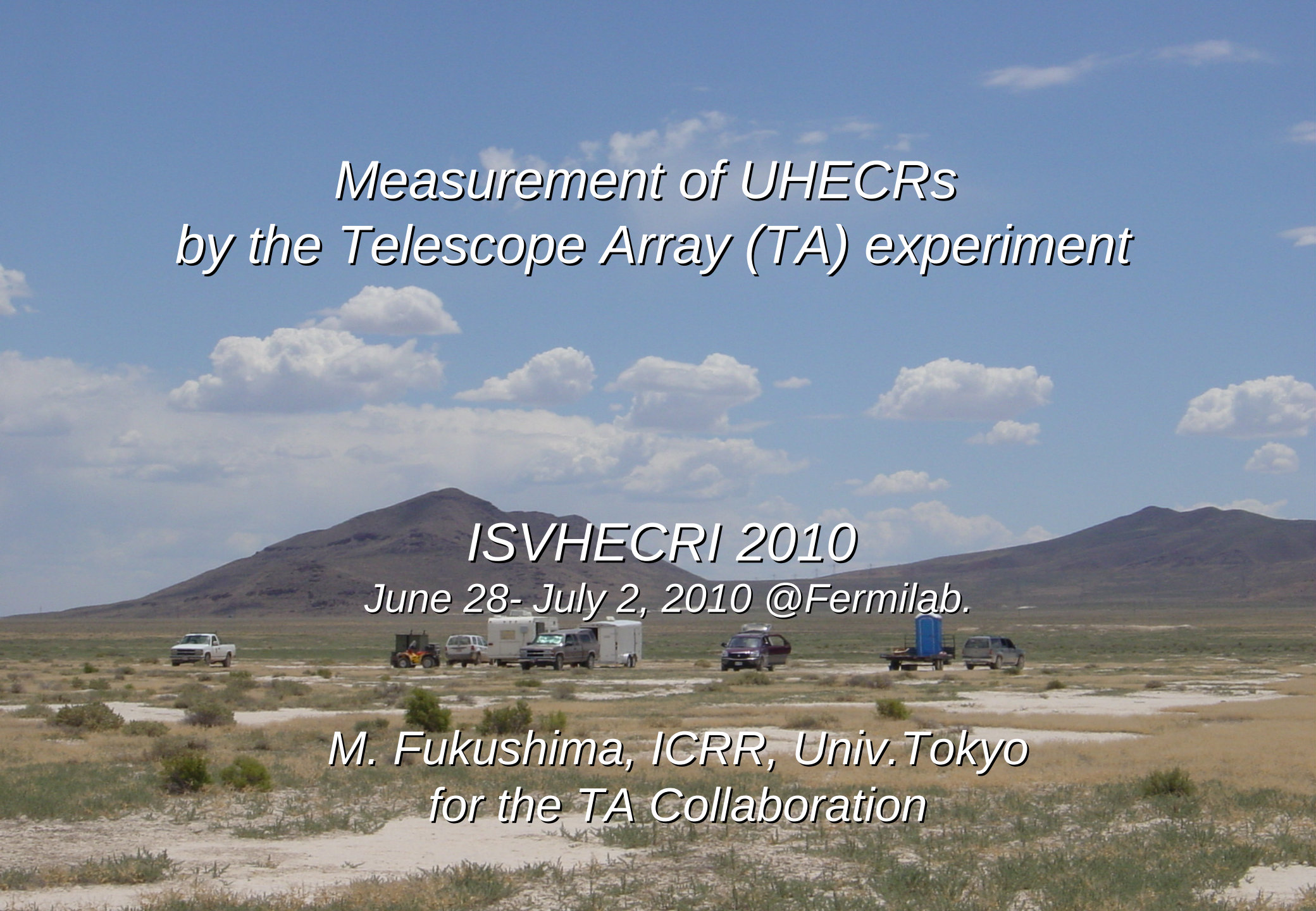


The background of the slide is a photograph of a desert landscape. In the foreground, there is a sandy area with sparse green and yellow vegetation. A small campsite is visible with several vehicles: a white pickup truck on the left, a yellow and black utility vehicle, a white van, a white trailer, a dark SUV, a dark minivan, a blue portable toilet on a trailer, and a silver SUV on the right. In the background, there are large, dark, rounded mountains under a blue sky with scattered white clouds.

Measurement of UHECRs by the Telescope Array (TA) experiment

*ISVHECRI 2010
June 28- July 2, 2010 @Fermilab.*

*M. Fukushima, ICRR, Univ.Tokyo
for the TA Collaboration*

The Telescope Array (TA) Collaboration



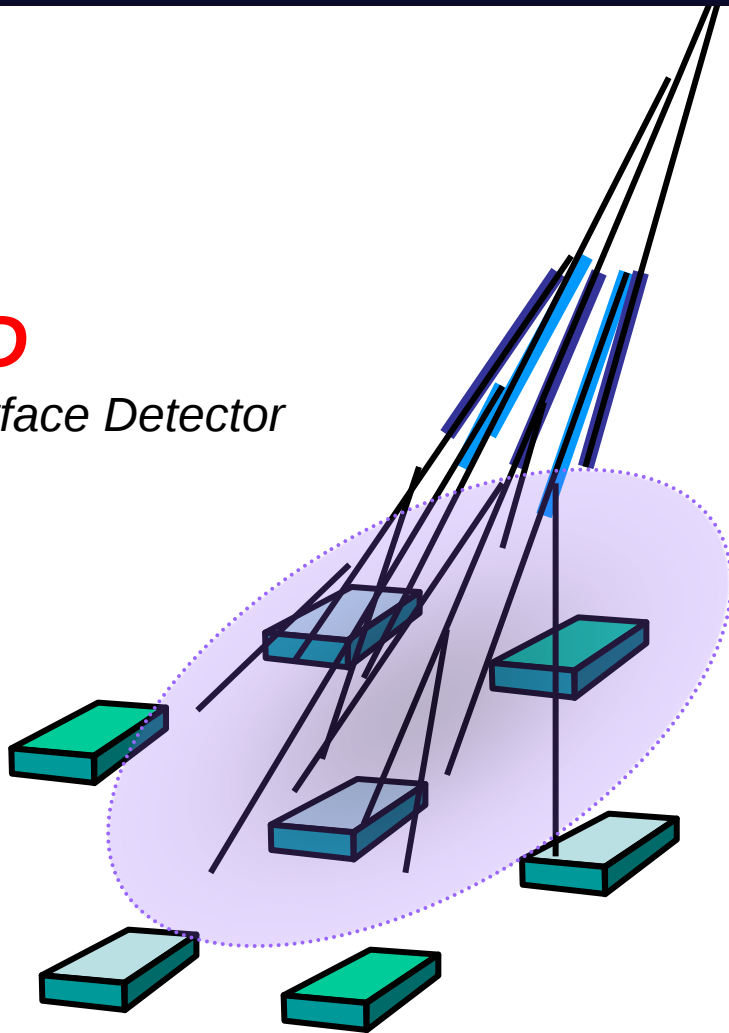
T. Abu-Zayyad¹, R. Aida², M. Allen¹, R. Azuma³, E. Barcikowski¹, J.W. Belz¹,
T. Benno⁴, D.R. Bergman⁵, S.A. Blake¹, O. Brusova¹, R. Cady¹, B.G. Cheon⁶,
J. Chiba⁷, M. Chikawa⁴, E.J. Cho⁶, L.S. Cho⁸, W.R. Cho⁸, F. Cohen⁹,
K. Doura⁴, C. Ebeling¹, H. Fujii¹⁰, T. Fujii¹¹, T. Fukuda³, M. Fukushima^{9,22},
D. Gorbunov¹², W. Hanlon¹, K. Hayashi³, Y. Hayashi¹¹, N. Hayashida⁹, K. Hibino¹³,
K. Hiyama⁹, K. Honda², G. Hughes⁵, T. Iguchi³, D. Ikeda⁹, K. Ikuta²,
S.J.J. Innemee⁵, N. Inoue¹⁴, T. Ishii², R. Ishimori³, D. Ivanov⁵, S. Iwamoto²,
C.C.H. Jui¹, K. Kadota¹⁵, F. Kakimoto³, O. Kalashev¹², T. Kanbe², H. Kang¹⁶,
K. Kasahara¹⁷, H. Kawai¹⁸, S. Kawakami¹¹, S. Kawana¹⁴, E. Kido⁹, B.G. Kim¹⁹,
H.B. Kim⁶, J.H. Kim⁶, J.H. Kim²⁰, A. Kitsugi⁹, K. Kobayashi⁷, H. Koers²¹,
Y. Kondo⁹, V. Kuzmin¹², Y.J. Kwon⁸, J.H. Lim¹⁶, S.I. Lim¹⁹, S. Machida³,
K. Martens²², J. Martineau¹, T. Matsuda¹⁰, T. Matsuyama¹¹, J.N. Matthews¹, M. Minamino¹¹,
K. Miyata⁷, H. Miyauchi¹¹, Y. Murano³, T. Nakamura²³, S.W. Nam¹⁹, T. Nonaka⁹,
S. Ogio¹¹, M. Ohnishi⁹, H. Ohoka⁹, T. Okuda¹¹, A. Oshima¹¹, S. Ozawa¹⁷,
I.H. Park¹⁹, D. Rodriguez¹, S.Y. Roh²⁰, G. Rubtsov¹², D. Ryu²⁰, H. Sagawa⁹,
N. Sakurai⁹, L.M. Scott⁵, P.D. Shah¹, T. Shibata⁹, H. Shimodaira⁹, B.K. Shin⁶,
J.D. Smith¹, P. Sokolsky¹, T.J. Sonley¹, R.W. Springer¹, B.T. Stokes⁵, S.R. Stratton⁵,
S. Suzuki¹⁰, Y. Takahashi⁹, M. Takeda⁹, A. Taketa⁹, M. Takita⁹, Y. Tameda³,
H. Tanaka¹¹, K. Tanaka²⁴, M. Tanaka¹⁰, J.R. Thomas¹, S.B. Thomas¹, G.B. Thomson⁵,
P. Tinyakov^{12,21}, I. Tkachev¹², H. Tokuno⁹, T. Tomida², R. Torii⁹, S. Troitsky¹²,
Y. Tsunesada³, Y. Tsuyuguchi², Y. Uchihori²⁵, S. Udo¹³, H. Uka², B. Van Klaveren¹,
Y. Wada¹⁴, M. Wood¹, T. Yamakawa⁹, Y. Yamakawa⁹, H. Yamaoka¹⁰, J. Yang¹⁹,
S. Yoshida¹⁸, H. Yoshii²⁶, Z. Zundel¹

~120 Scientists from Japan, US, Korea, Russia and Belgium

TA : SD / FD hybrid experiment

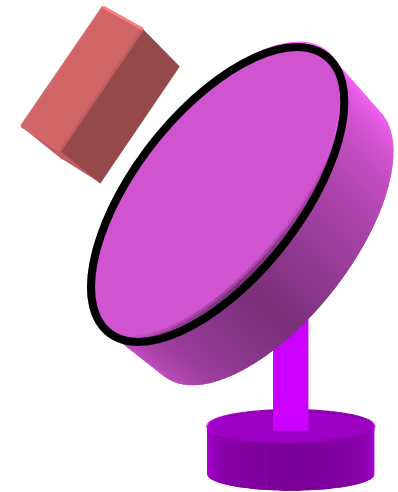
SD

Surface Detector



FD

Fluorescence Detector



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

■ Battery of Telescopes
 ■ Particle Detector
 ○ Communications Tower
 + CLF

0 1 2 4 Miles



Utah, USA

39.3°N

112.9°W

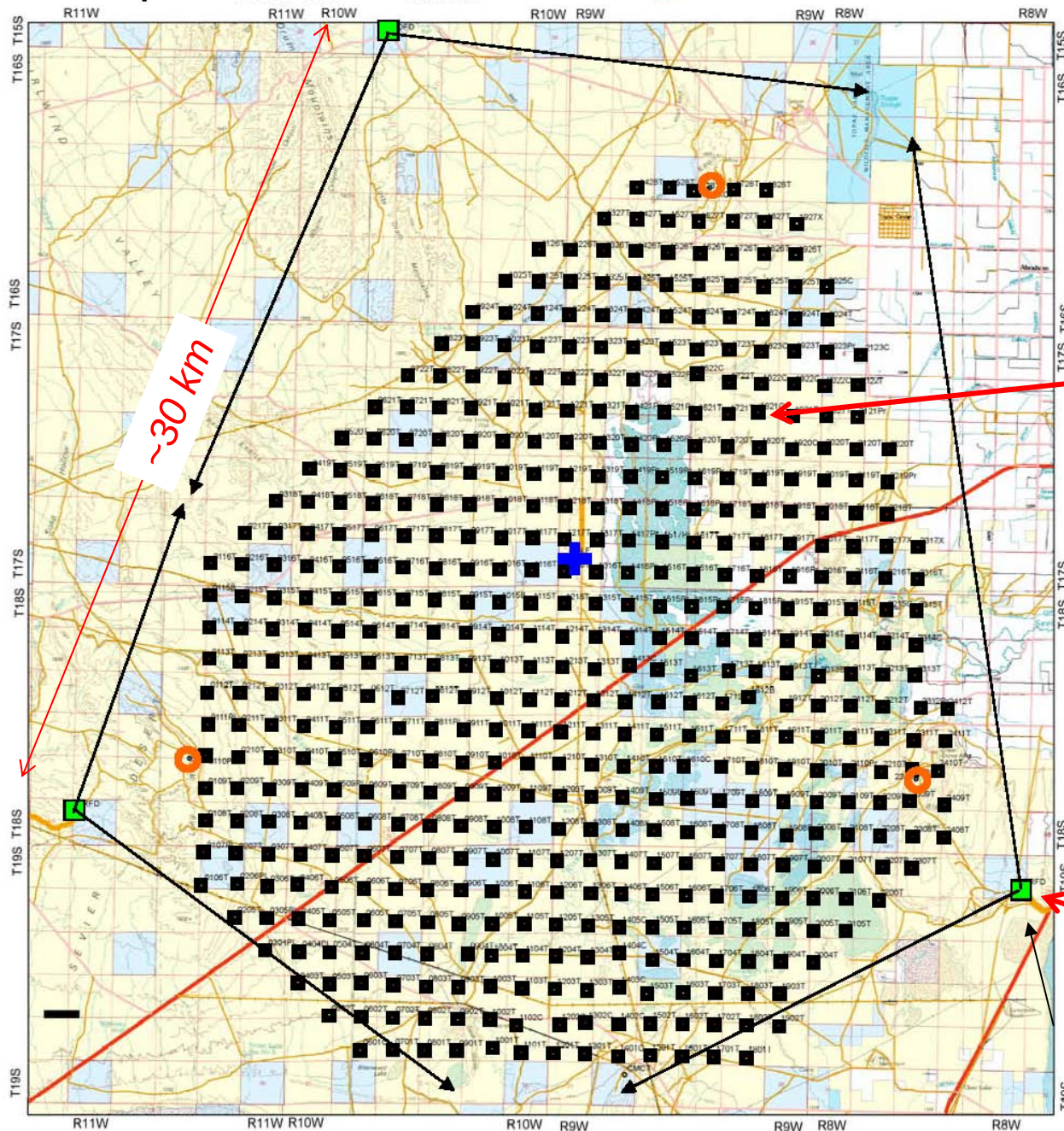
Alt. 1400 m

507 SDs cover 680 km²

Calibration Facilities

- Lidar, IR camera
- Central Laser
- Electron Light Source

3 FD stations





Two FD stations in the south

9.4 m² mirror

3⁰-34⁰ elevation

with 1⁰ pixel

Wave form sampling

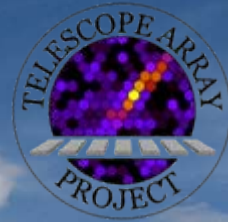


*One FD station in the north
transferred from HiRes-1*



*5.2 m² mirror
3⁰-34⁰ elevation
with 1⁰ pixel
S/H electronics*

Calibration by Electron Beam



40 MeV electron
 10^9 ppp
 $1 \mu s$ duration
@ 0.5Hz

$= 6.4 \times 10^{16}$ eV shower
100m from FD





←
1.2km grid

Plastic Scintillator

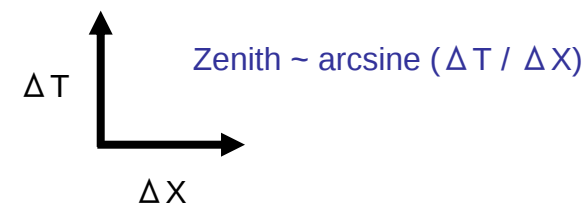
3 m², 12 mm t

WLSF readout, 2 layers overlaid

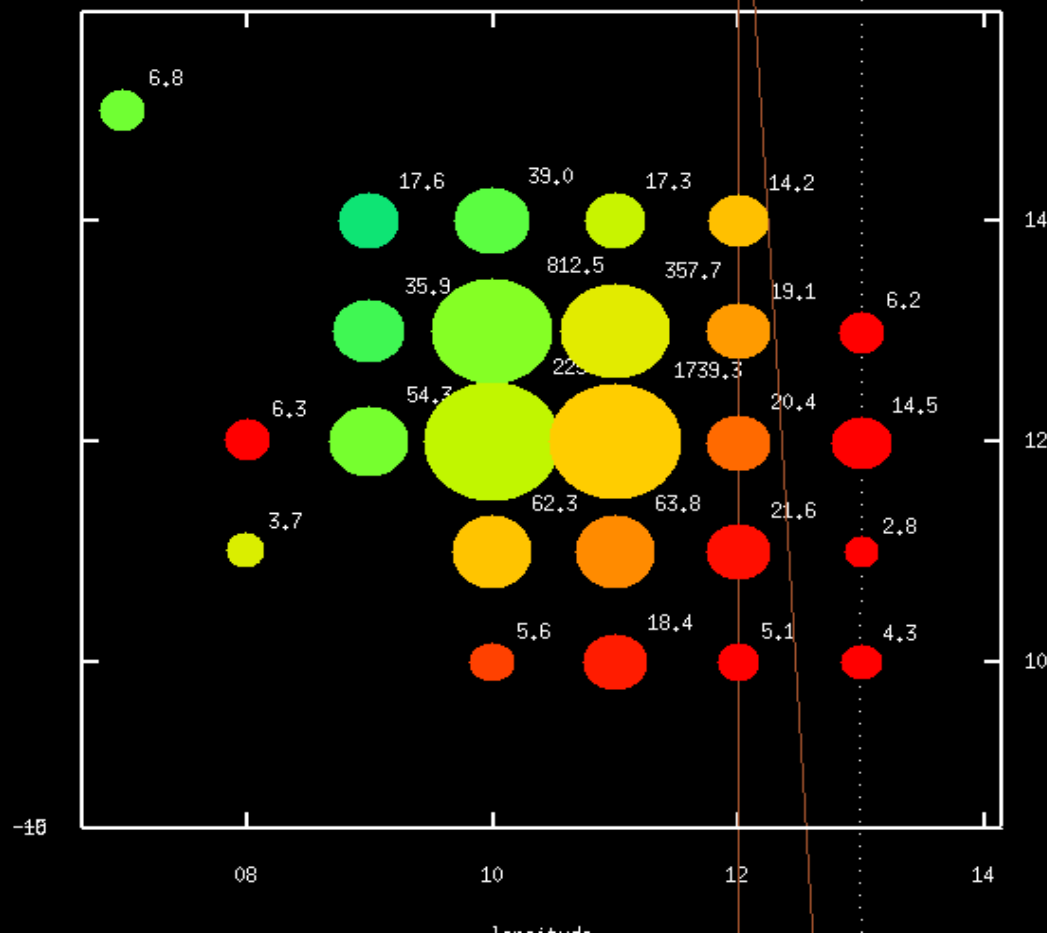
50MHz, 12bit waveform rec.

090122-225422

TH~38°

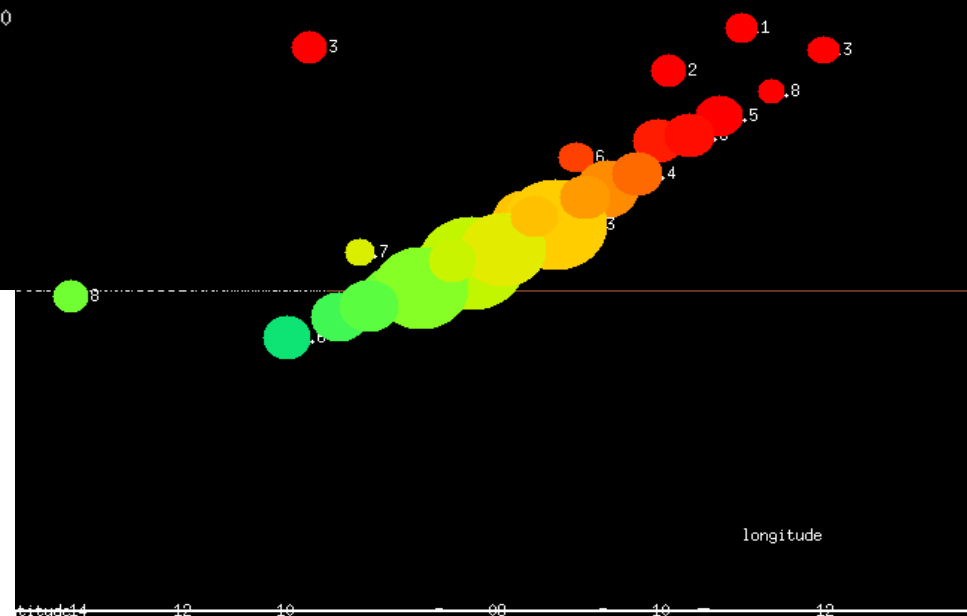


Event "Side" View

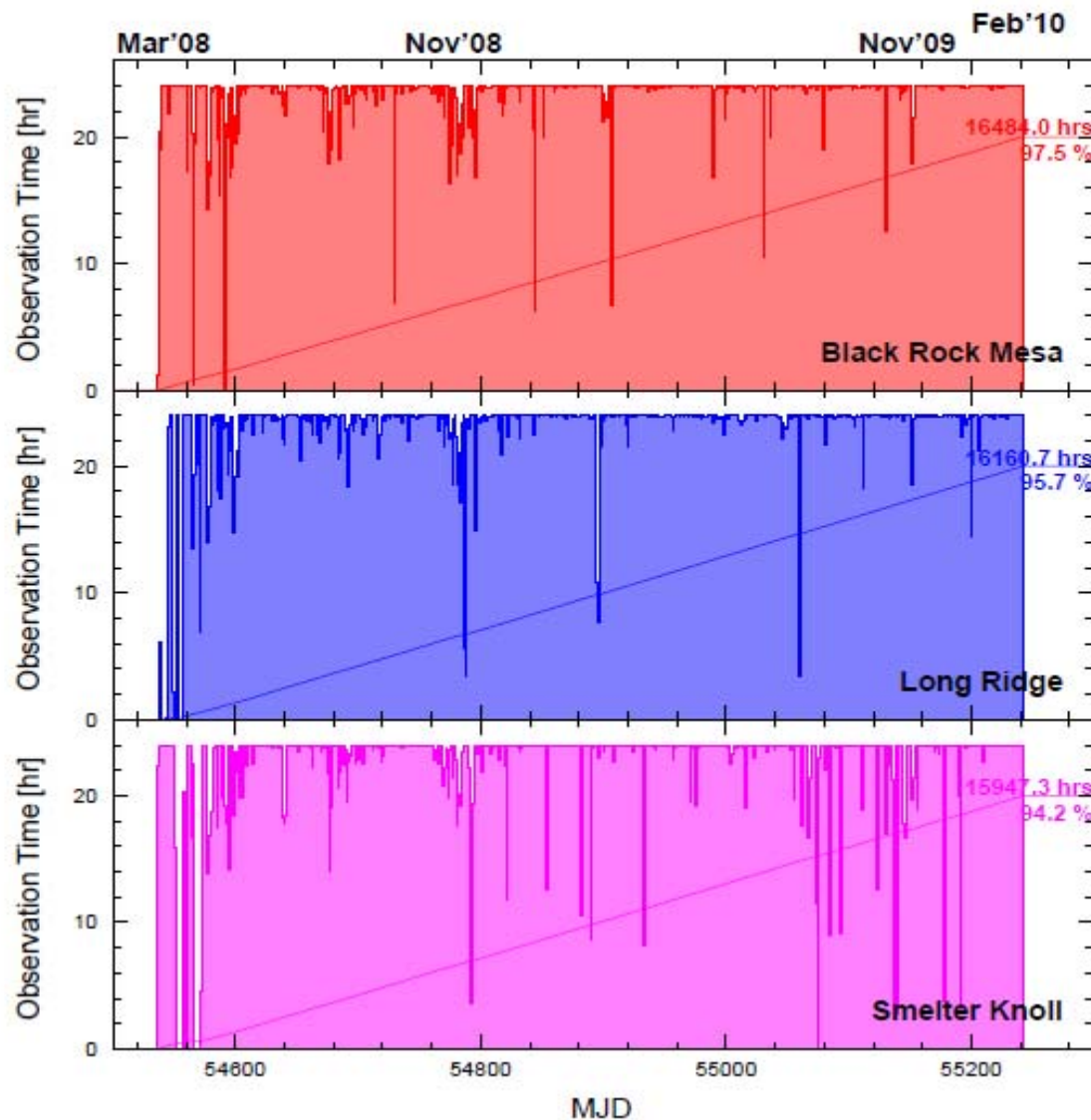


Event Top View

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



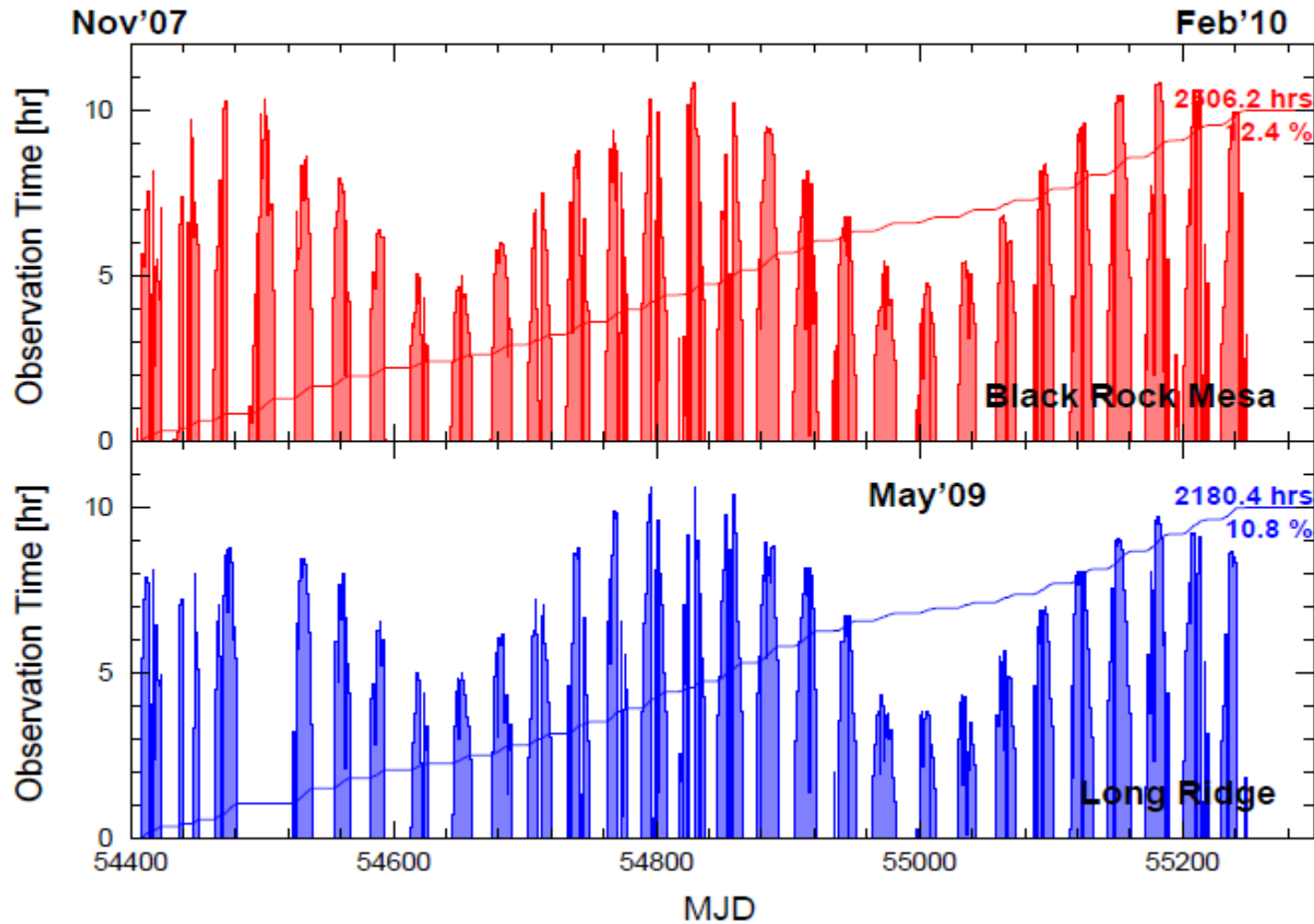
> SD Observation Status >



*DAQ @ 3 sub-arrays
+ boarder crossing trig.
No deadtime (pipelined)*

*~99% of SDs functional
~5% down time
~16 k hours of run
since Mar. 2008*

< FD Observation Status >



~6% dead time
@ 2Hz trig

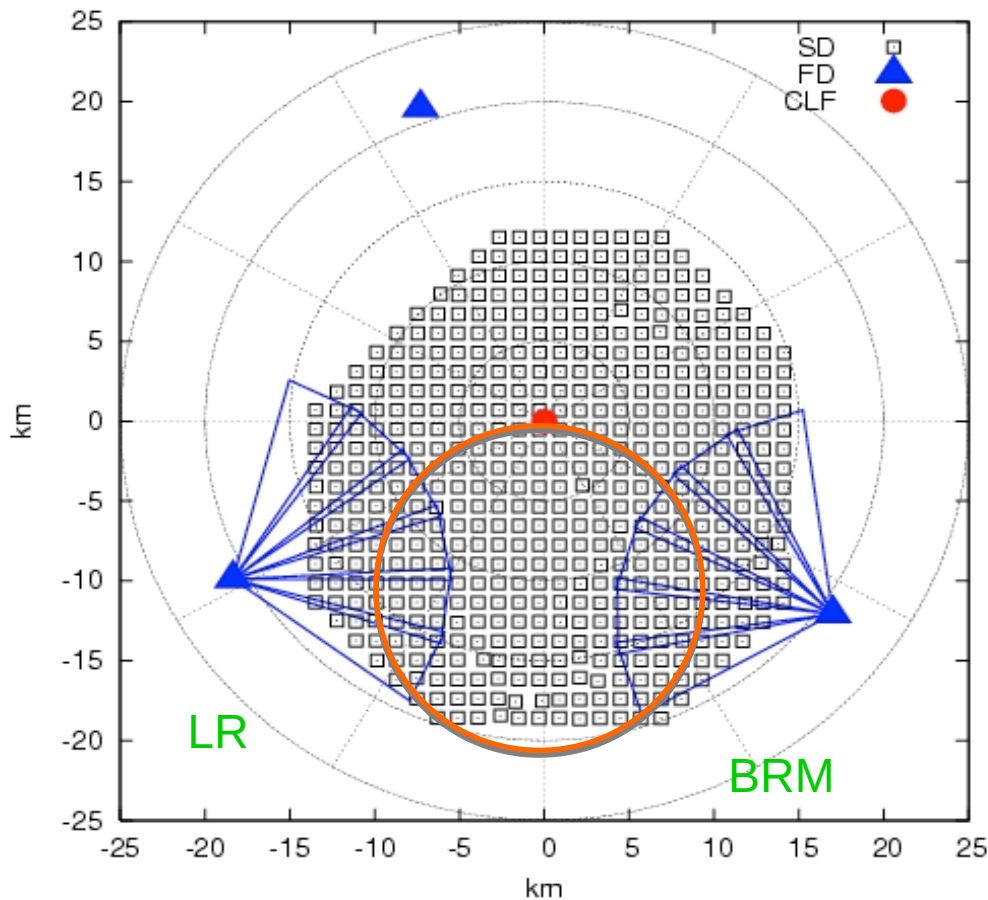
• $\gtrsim$ 2.5k hrs
since Nov. 2007

Remote op.
since May. 2009

• $\gtrsim$ 2.1k hrs

Hybrid trig.
planned in 2010

(1) FD Stereo Analysis for Xmax



Nov. 2007 – Oct. 2009

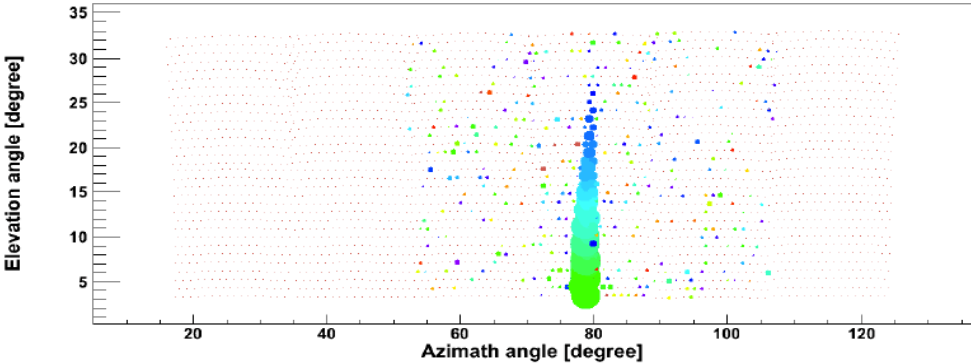
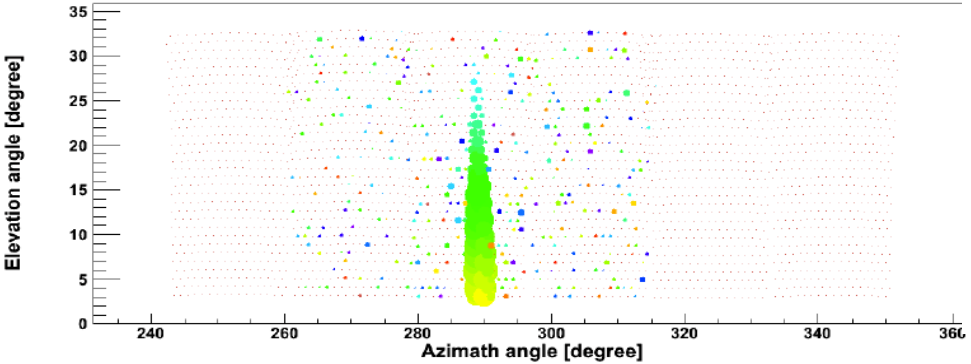
BRM-LR Stereo Event

Event Selection

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

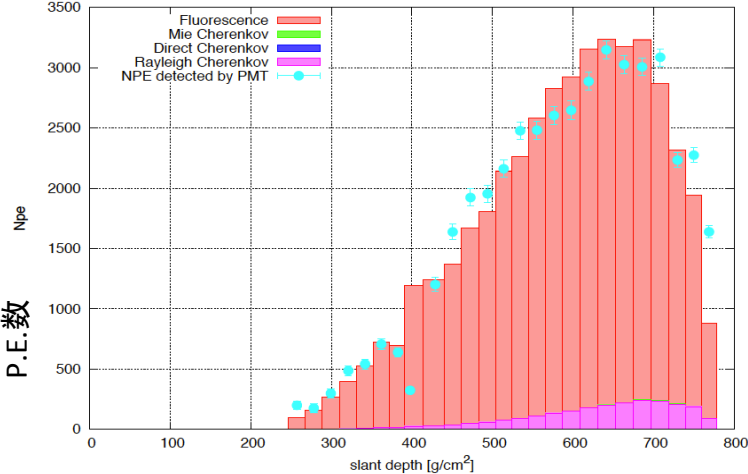
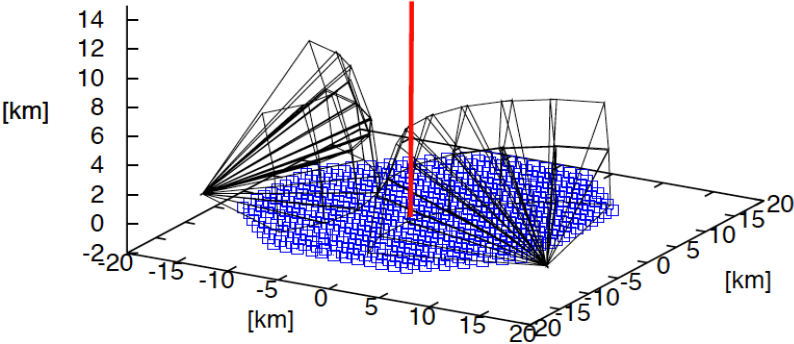
Example of Stereo Event

Elevation angle (degrees)



Azimuthal angle (degrees)

SD
FD FOV
Shower axis

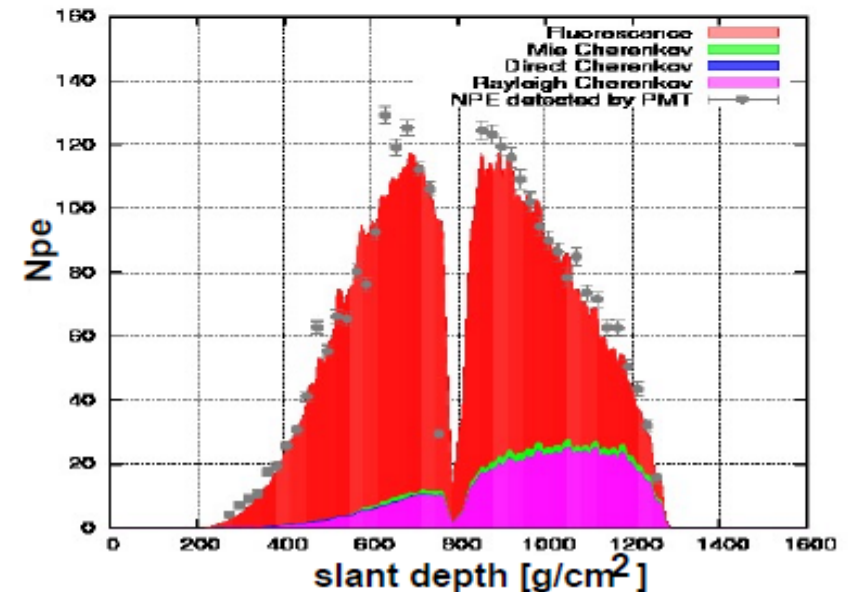
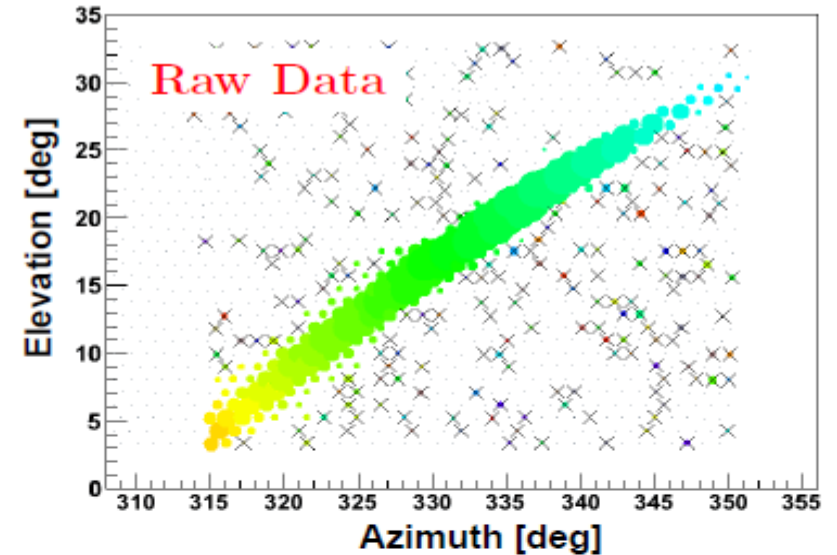
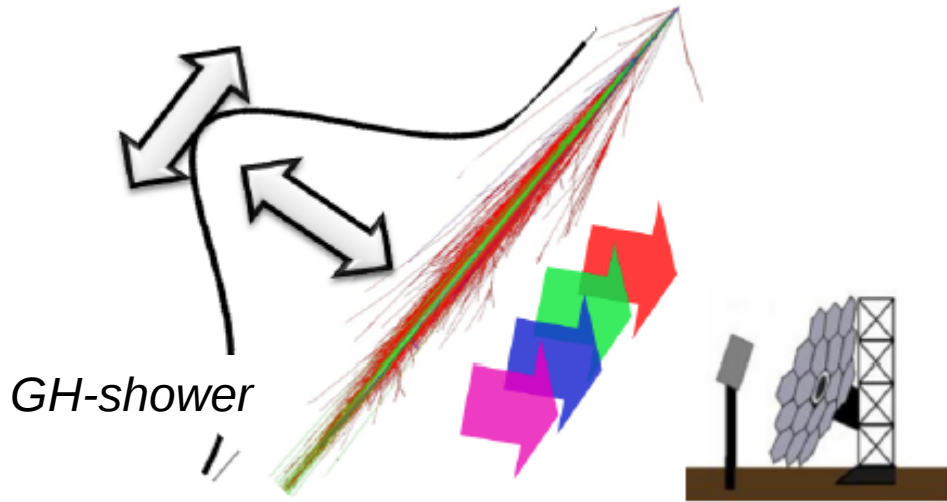


Slant Depth

zenith	azimuth	core [km]
3.23°	145.9°	0.09, -6.10

Event Reconstruction

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



Accuracy @ 10^{19} eV

Direction :	< 1.6 deg
core location :	± 180 m
Energy :	-5.4 ± 5.8 %
Xmax :	-9.7 ± 16 g/cm ²

Making MC spectral set

Shower simulation

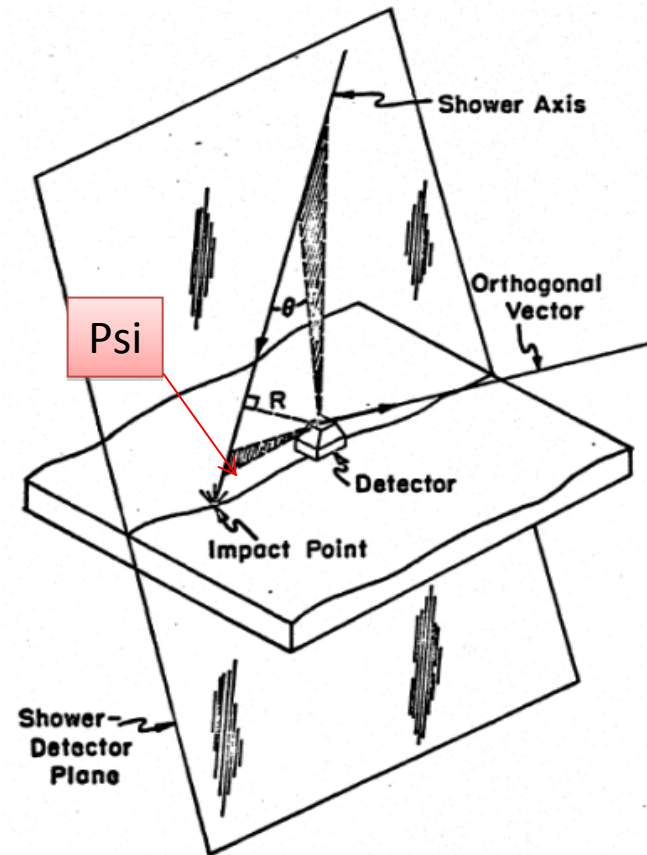
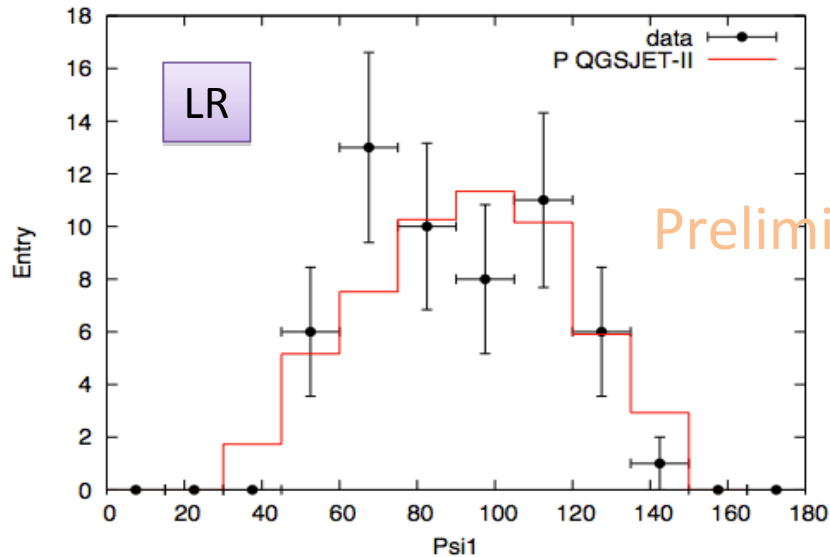
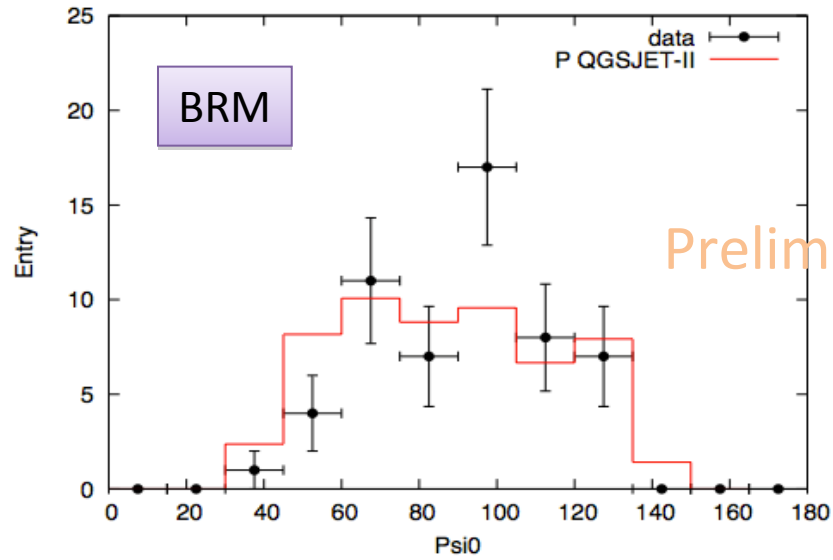
- CORSIKA v6.9
- Hadronic Int. Model
 - QGSjet-II, QGSjet-01, SIBYLL
- Proton or Fe Nuclei
- Energy:
 - $\log E = 18.5-19, 19-19.5, 19.5-20$
 - Power index : - 3.1
- Zenith Angle : 0 – 60 deg
- thinning factor : 10^{-4}
- Ecut: EM:100keV, hadron:100MeV
- Core: $r < 10$ km
- Each 500 events

Fluorescence & Atten.

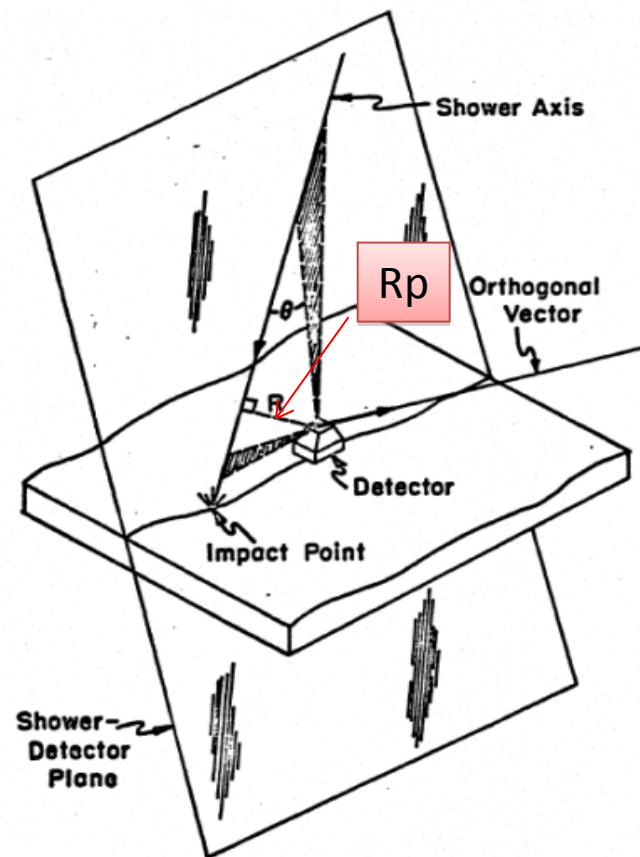
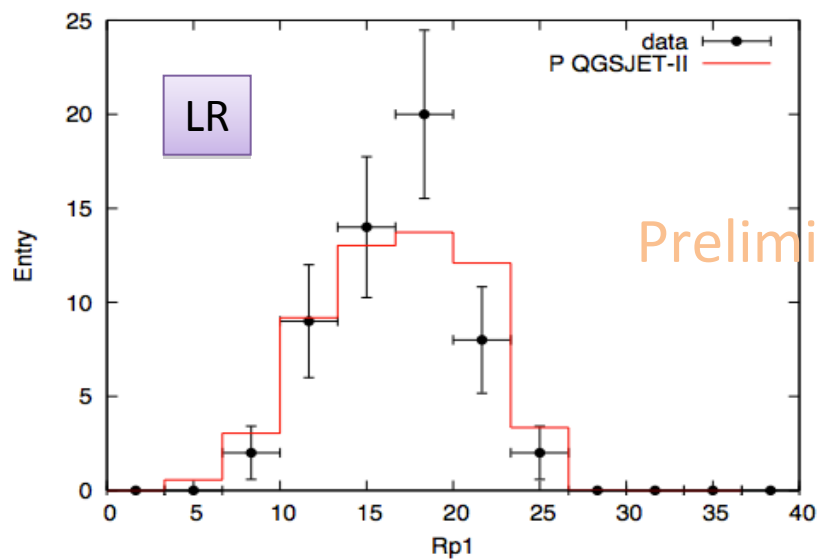
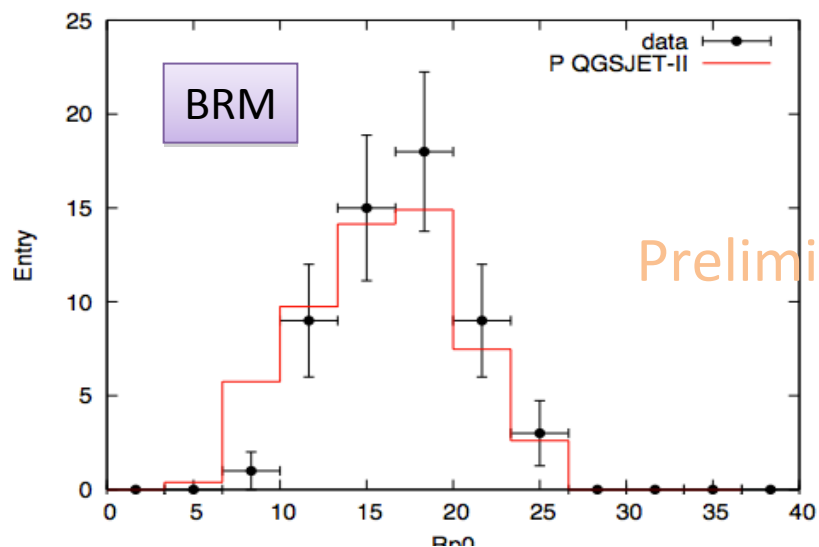
- Fluorescence yield
 - FLASH spectrum
 - Kakimoto et al. normalization
- Atmosphere by nearby Radio Sonde
- Typical measured Mie att. By lidar
 - $h=1.0\text{km}, \lambda = 29\text{km} @ 355\text{nm}$

also used by inv-MC reconst.

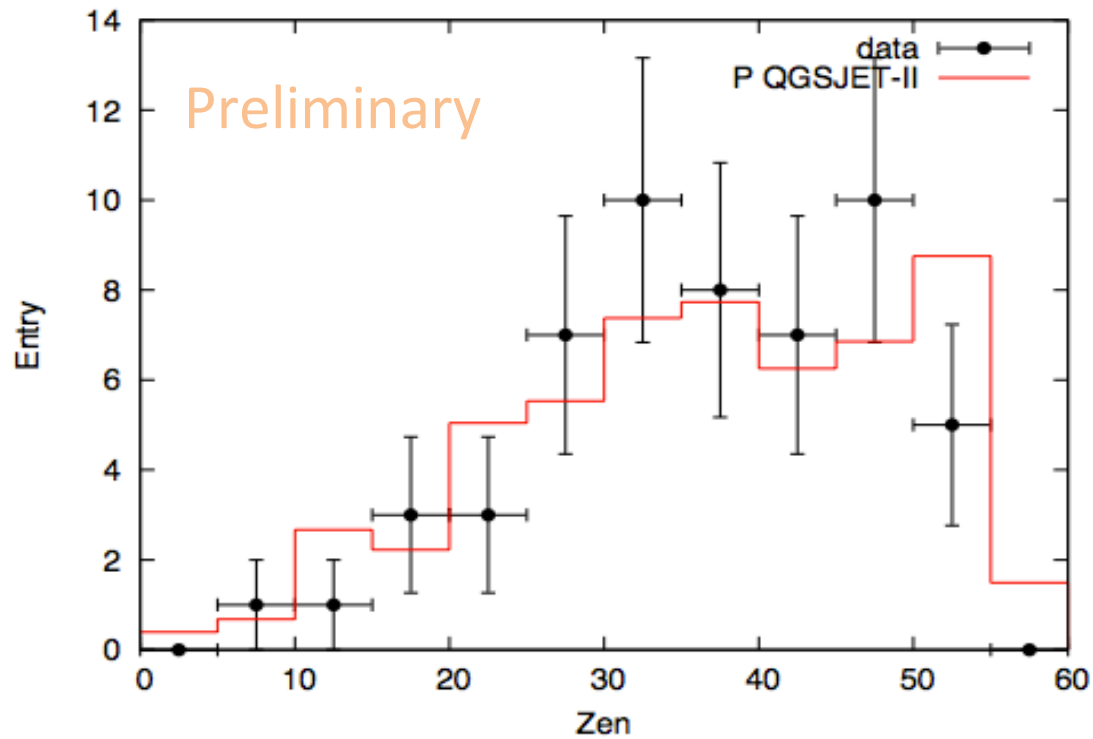
Psi angle (deg)



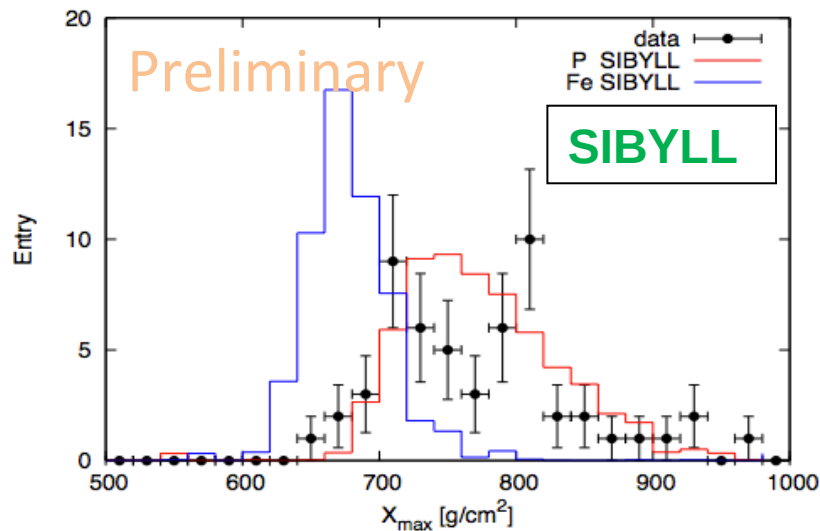
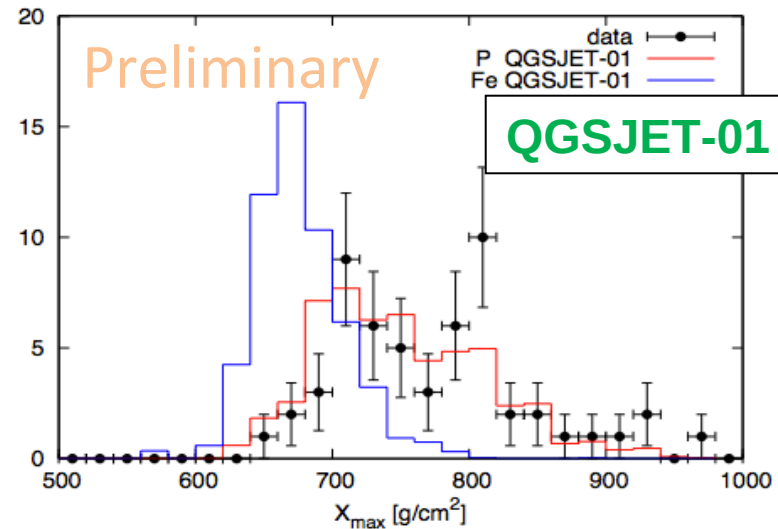
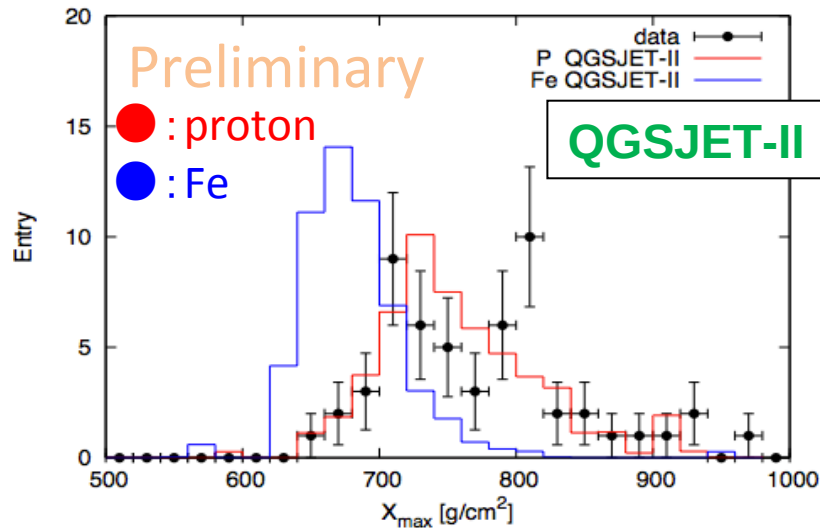
Rp (km)



Zenith angle (deg)



Comparison of reconstructed $X_{\max}$ (data and MC)

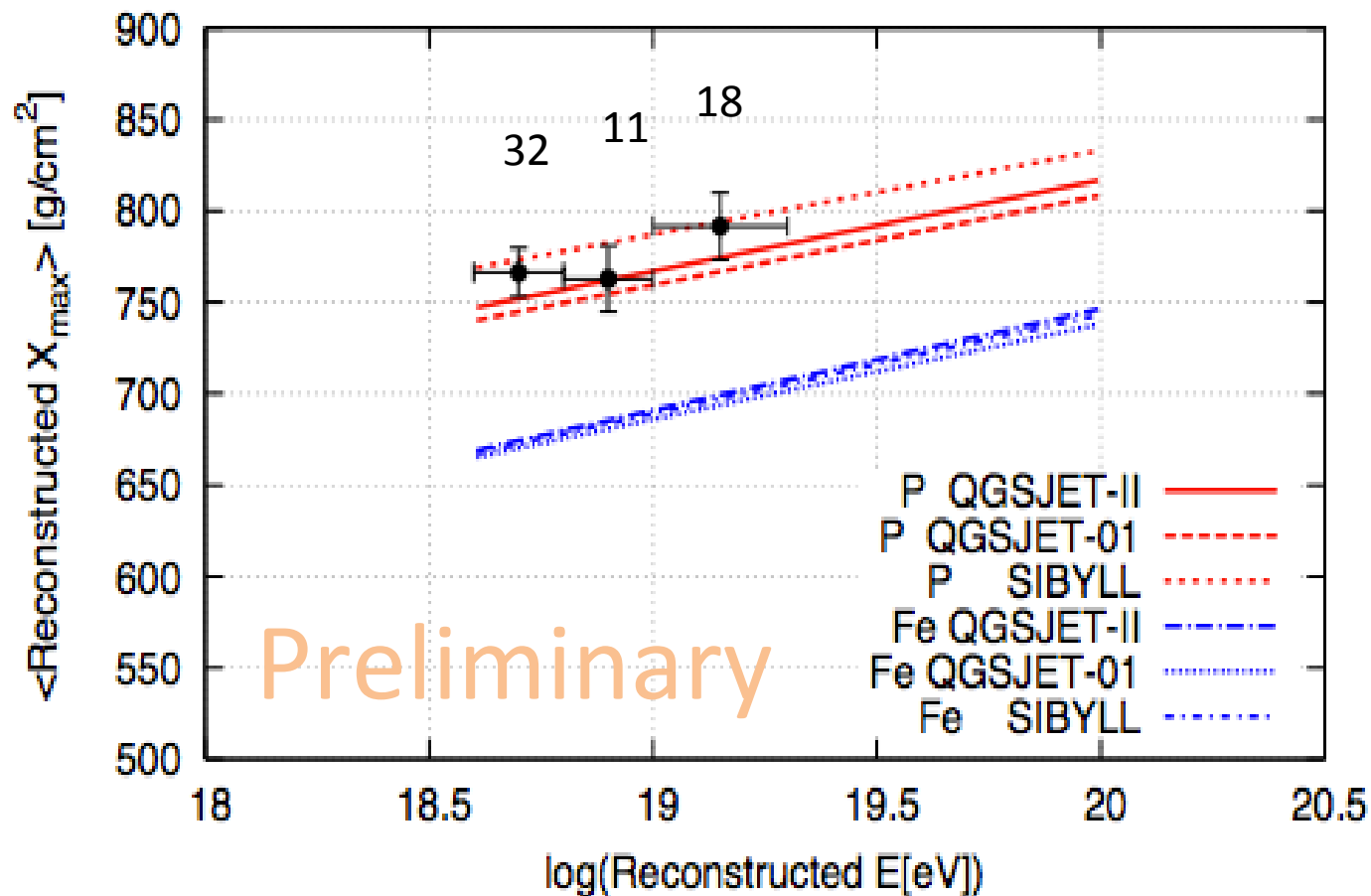


$E > 10^{18.6}$ eV

Chi² / dof

	QGSJET-II	QGSJET-01	SIBYLL
P	1.4	1.0	1.6
Fe	55	57	86

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



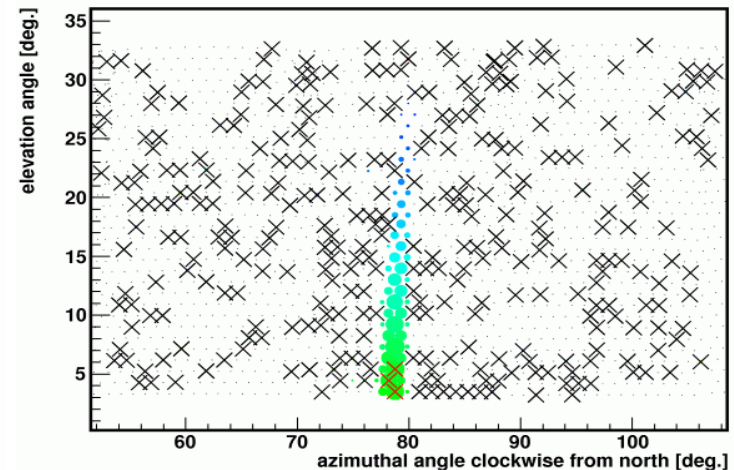
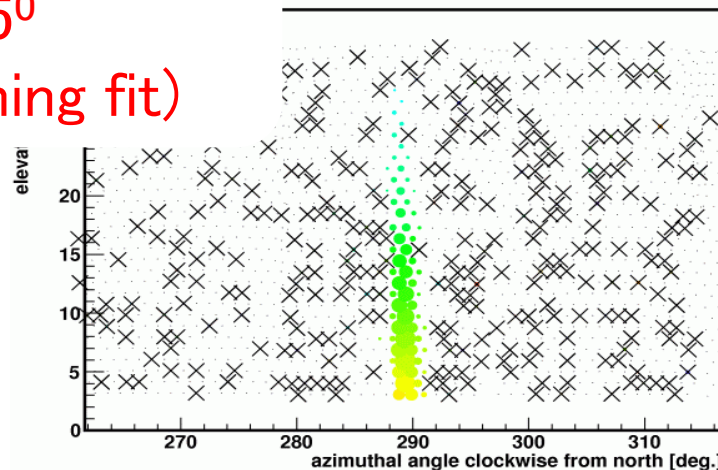
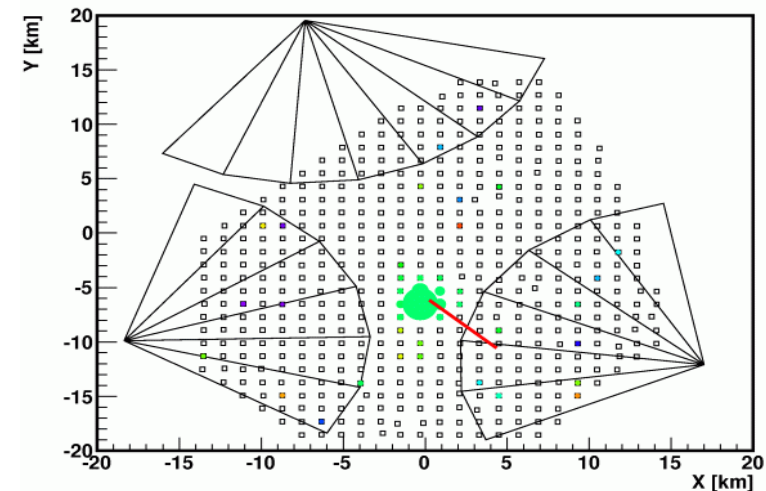
(2) Hybrid Analysis for Spectrum

- Triggered by SD and FD (indep.)
- FD geometry with SD timing
- Energy determined by FD
- Acceptance determined by “SD”

Event Selection

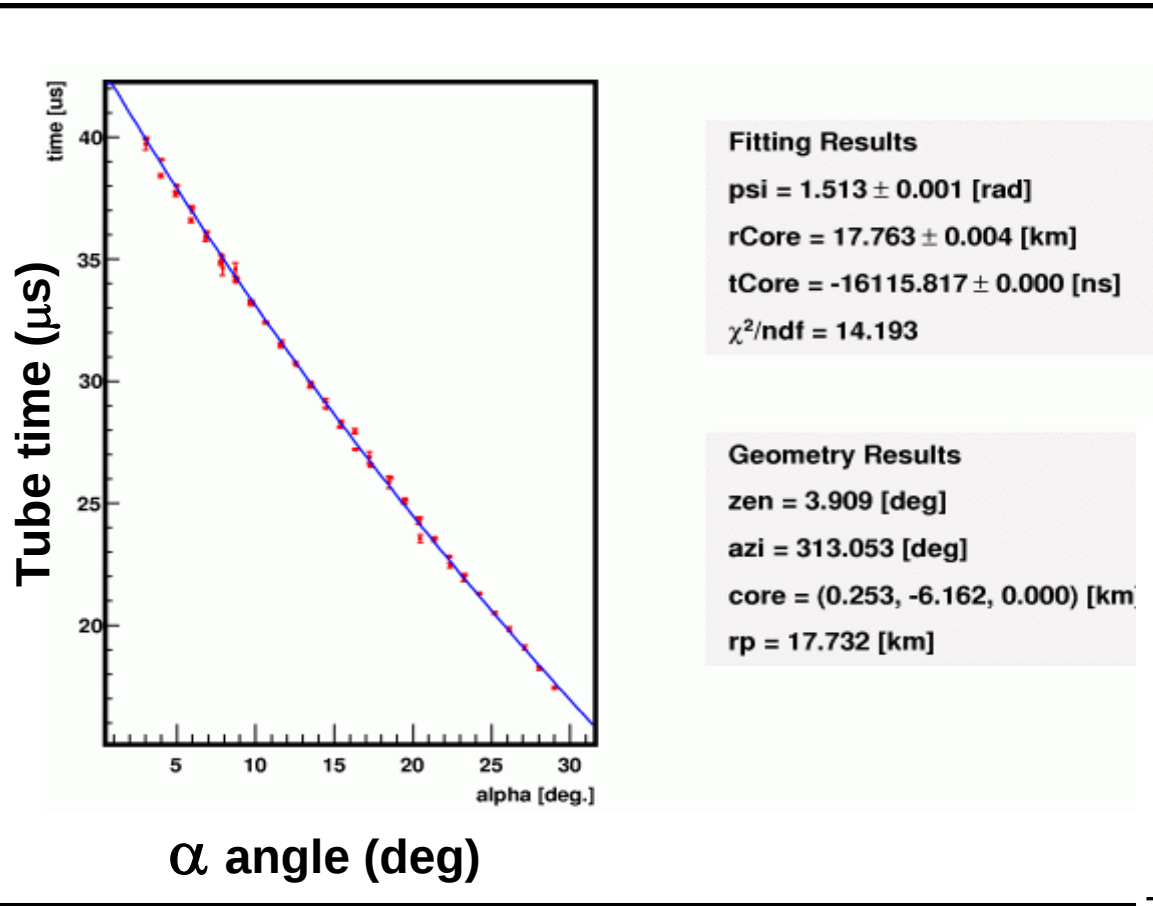
- Xmax in FoV
- Zenith $< 45^\circ$
- one SD (timing fit)

Example of hybrid event



Hybrid Geometry Reconst.

FD mono analysis + timing of one (best) SD



Mono reconstruction

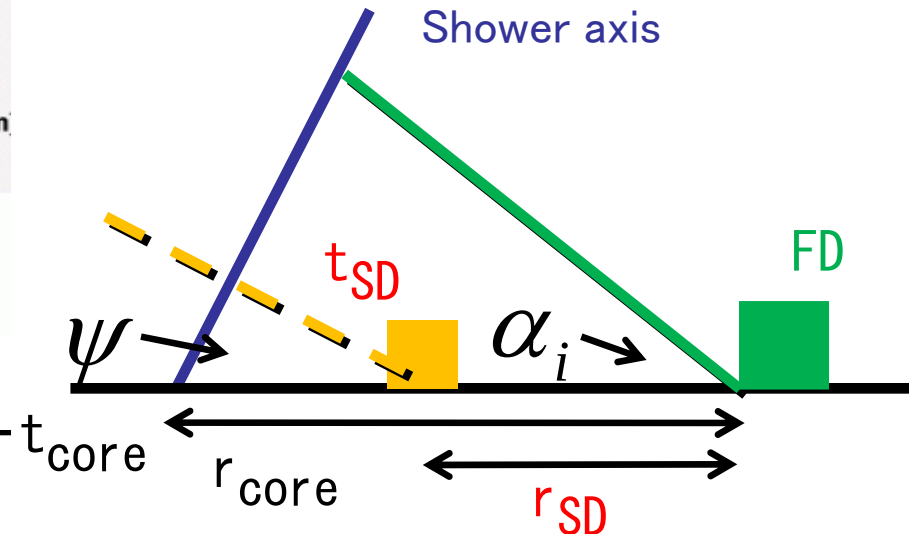
$$t_i = t_{core} + \frac{1}{c} \frac{\sin \psi - \sin \alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$



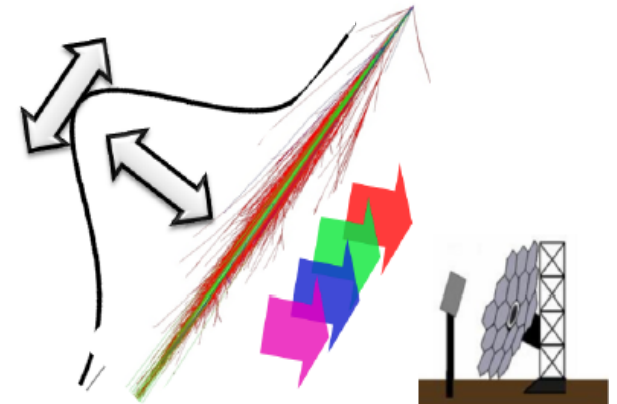
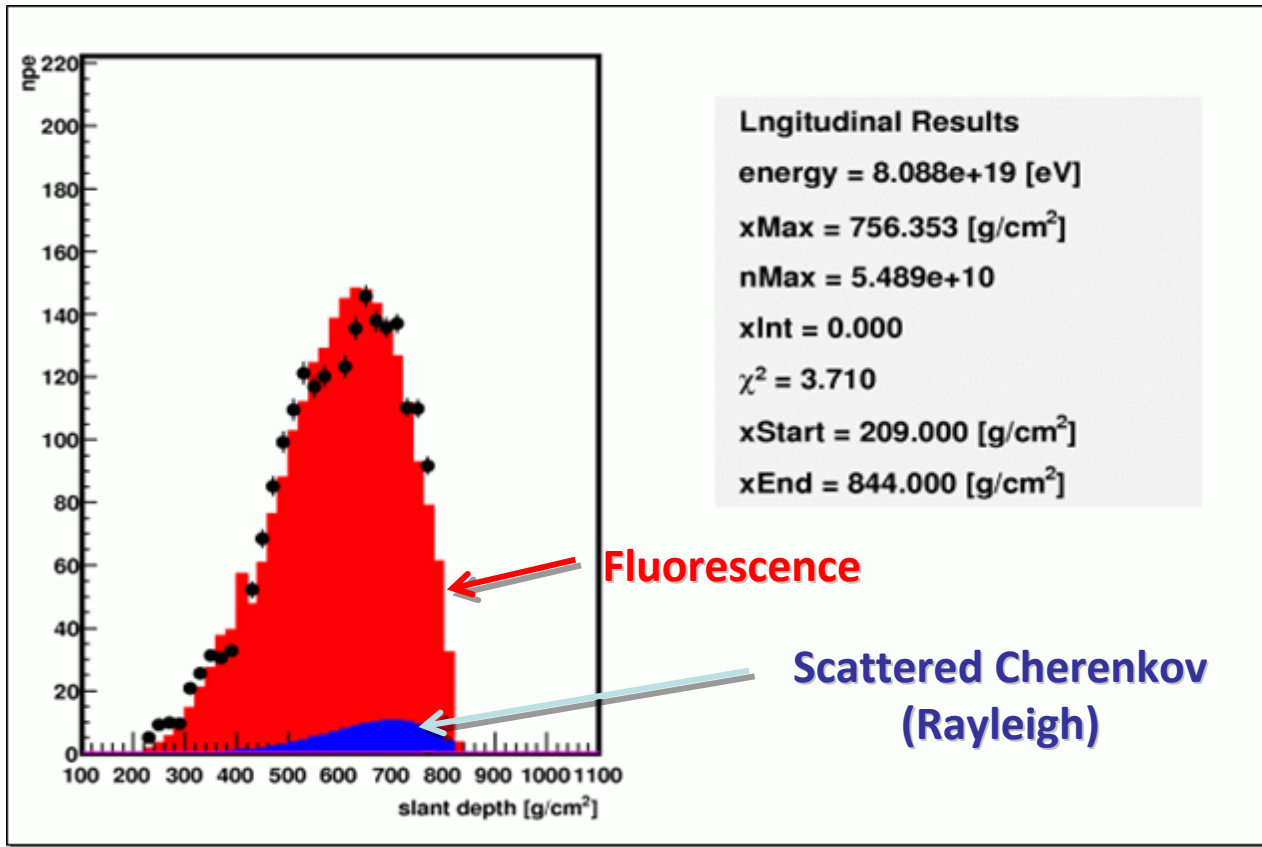
Hybrid reconstruction

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

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

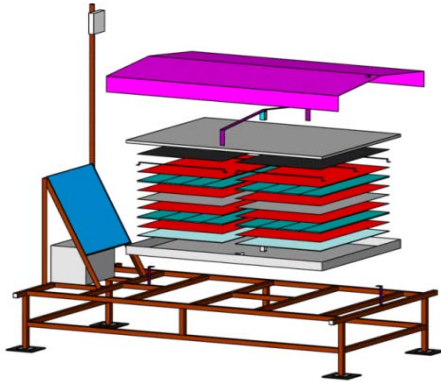


Shower profile & Energy determination



Making MC spectral set

Air shower simulation: COSMOS



SD

- Time dep. Calib.
- Same as SD analysis

FD

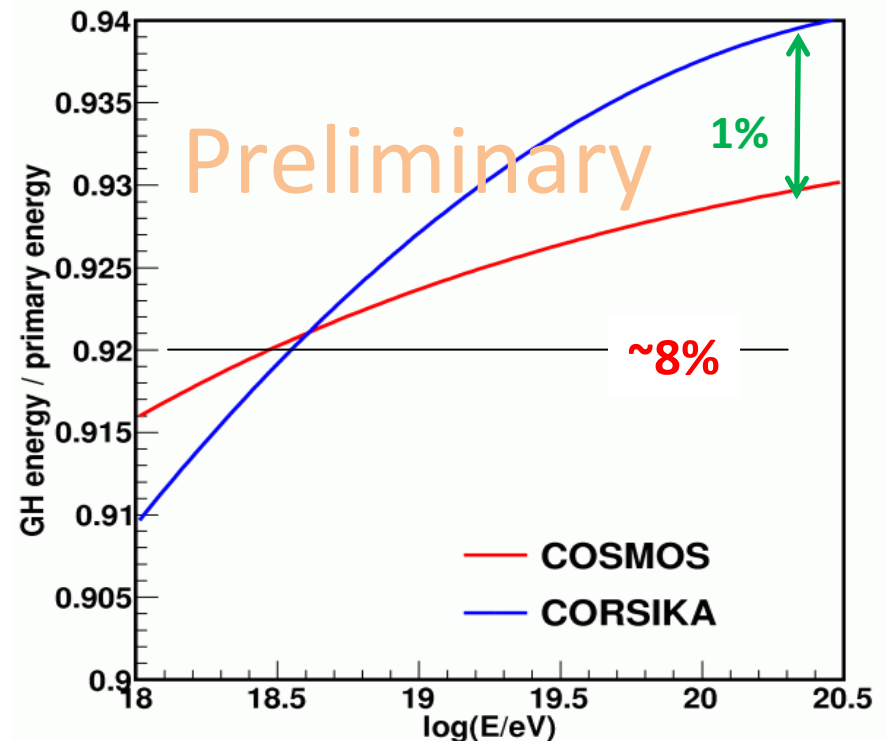
- Time dep. Calib.
- BG by real data.
- Geom. corrected by star.
- Measured atmosphere

Hybrid MC data:

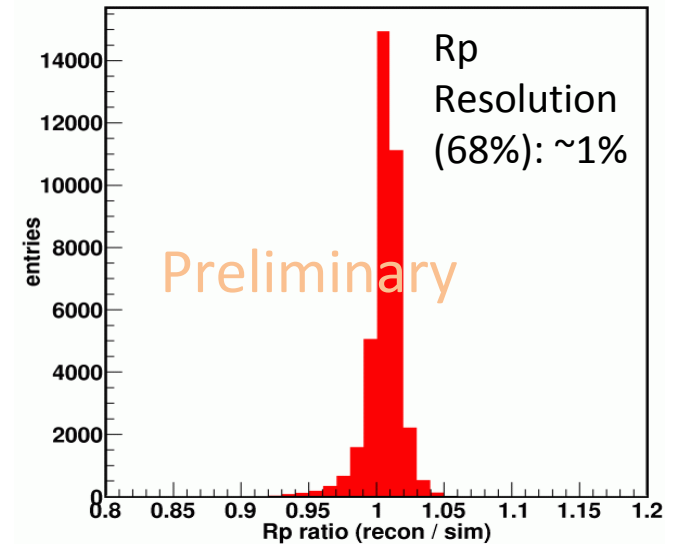
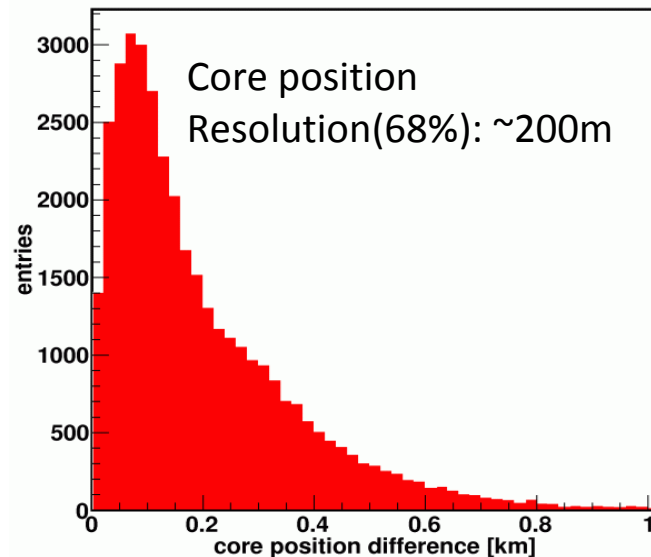
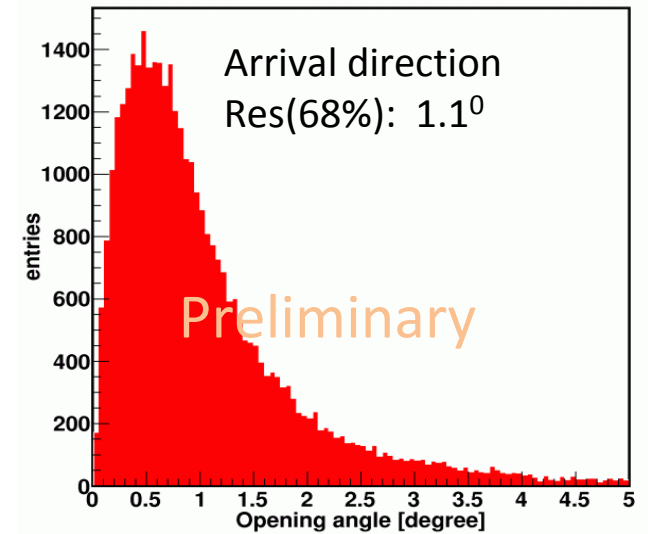
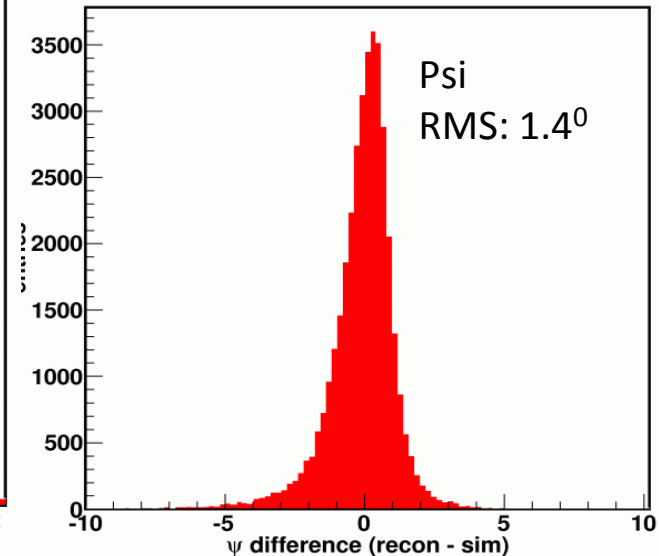
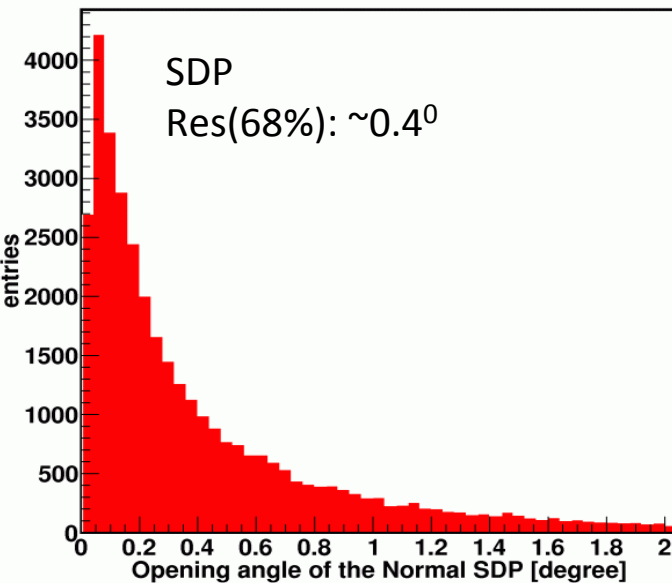
- Date: Random in FD observation period
- Core: 25km radius from CLF
- Slope data: ~2.5M events with $E^{-3.1}$
- Flat data: ~20k events for each energy

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

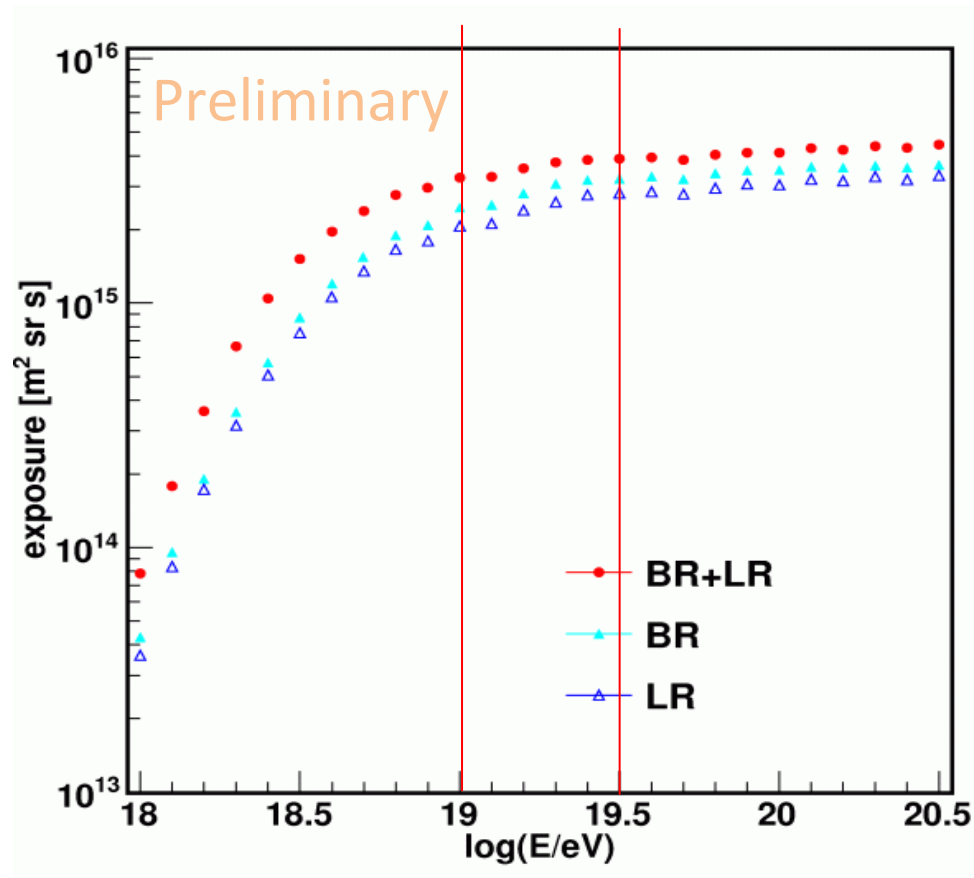
Missing Energy = GH_E_{dep} / E_0



Accuracy of Reconstruction (MC study)



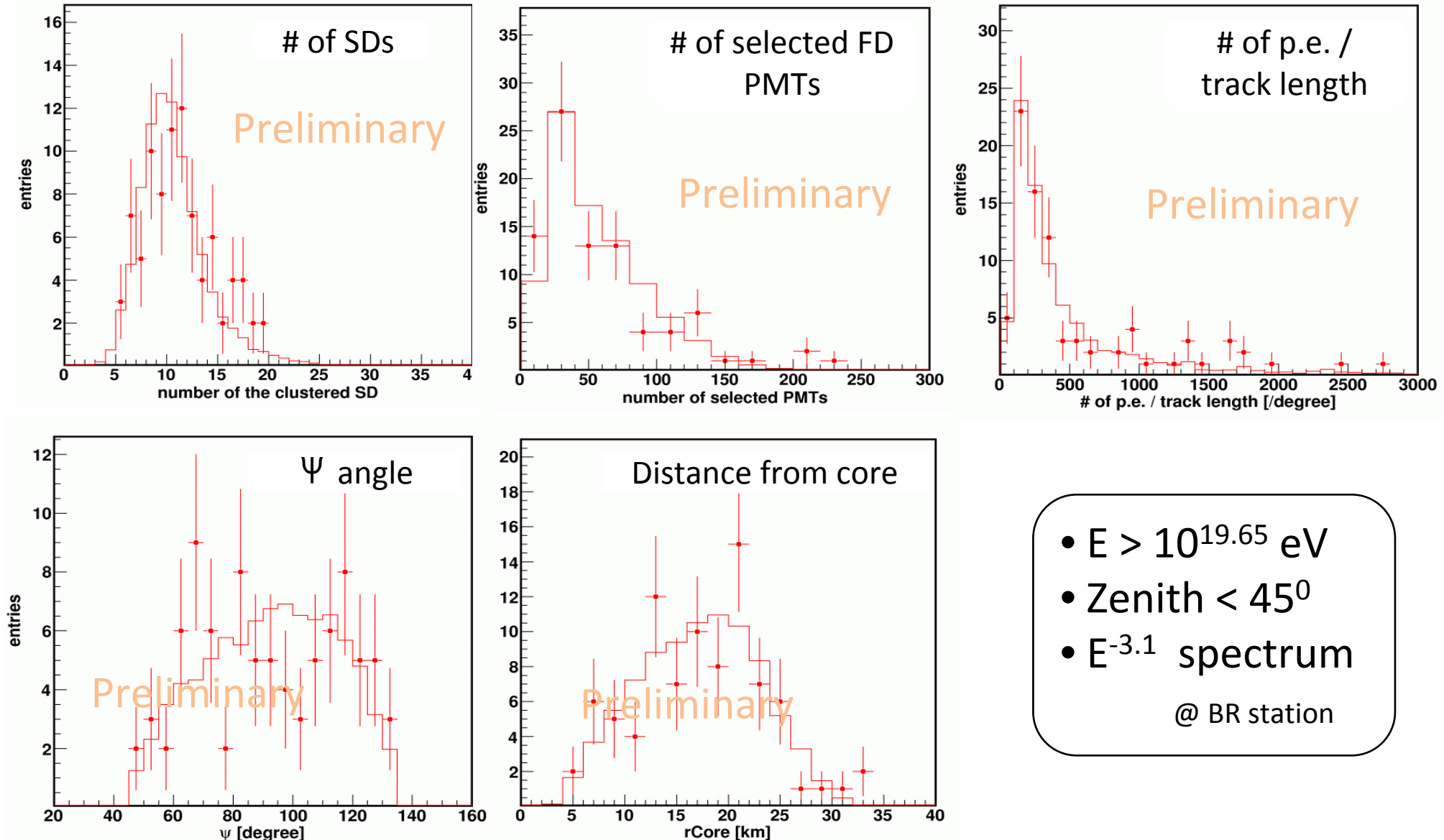
Exposure



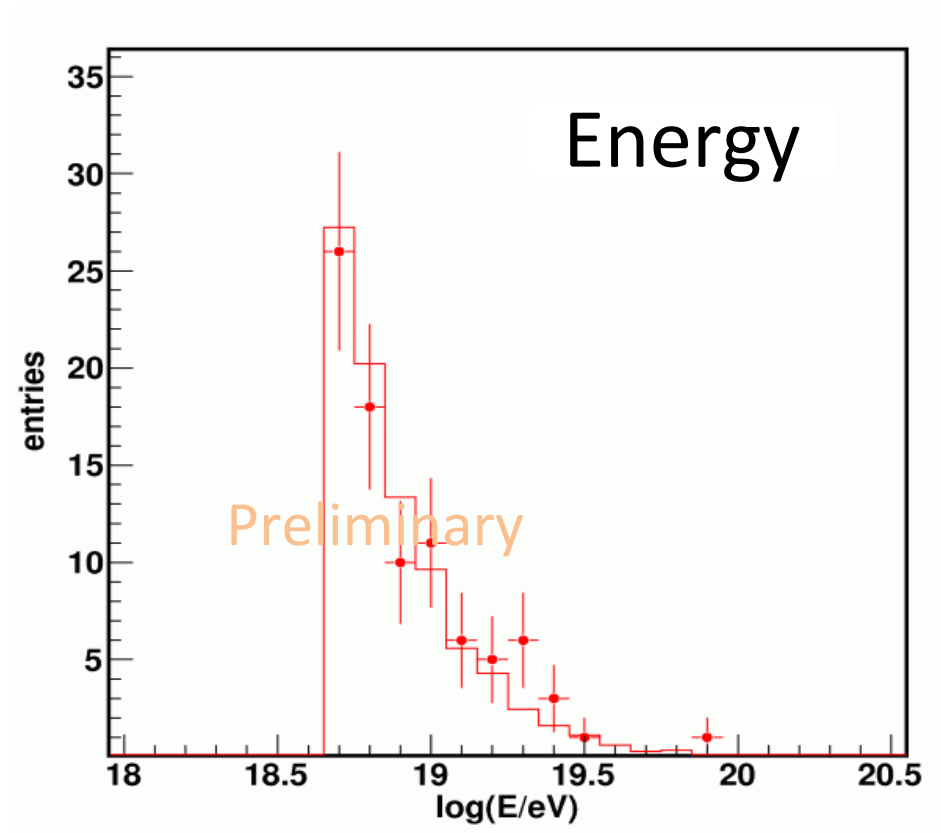
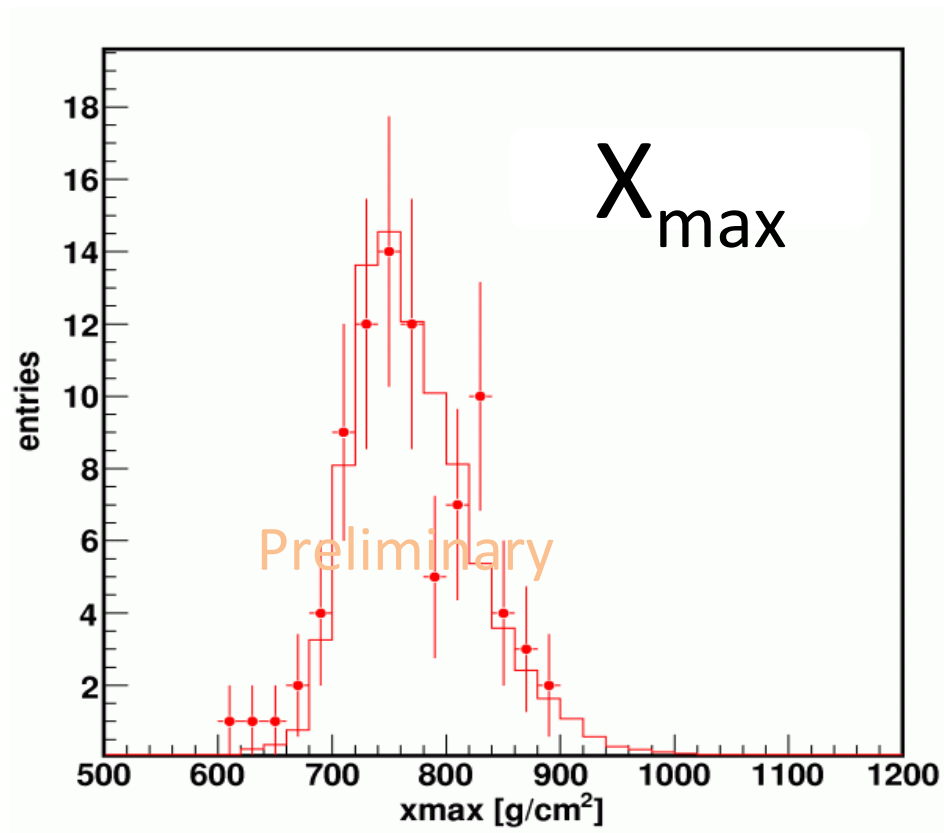
The aperture is calculated by MC.

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

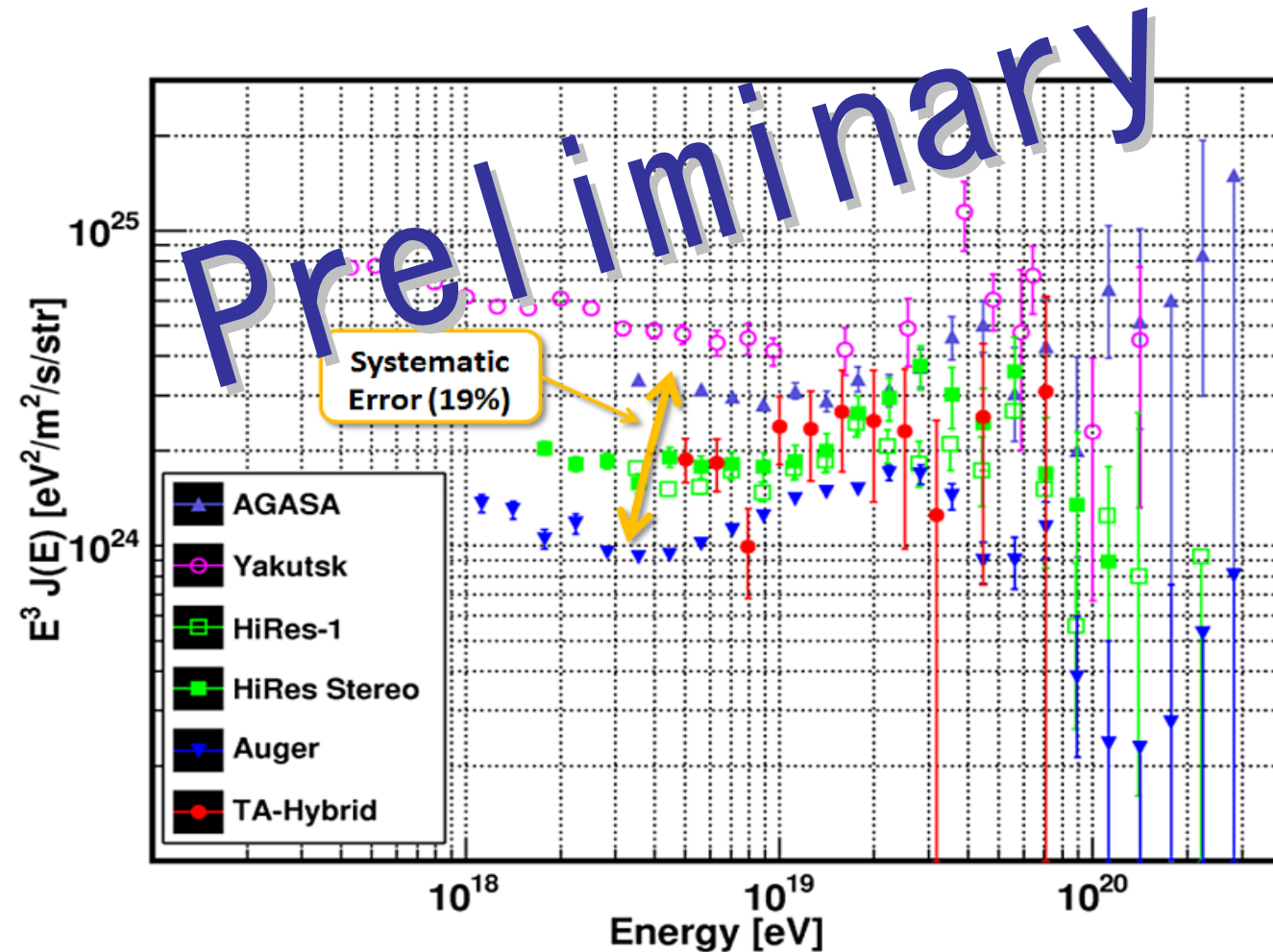
Data vs MC (spectral set) comparison



Data vs MC



Energy spectrum



Systematic errors

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

Summary

*TA operation: >16k hours (SD), > 2k hours (FD) since 2007
Detectors and DAQ in good condition.
Calibration and performance being understood.*

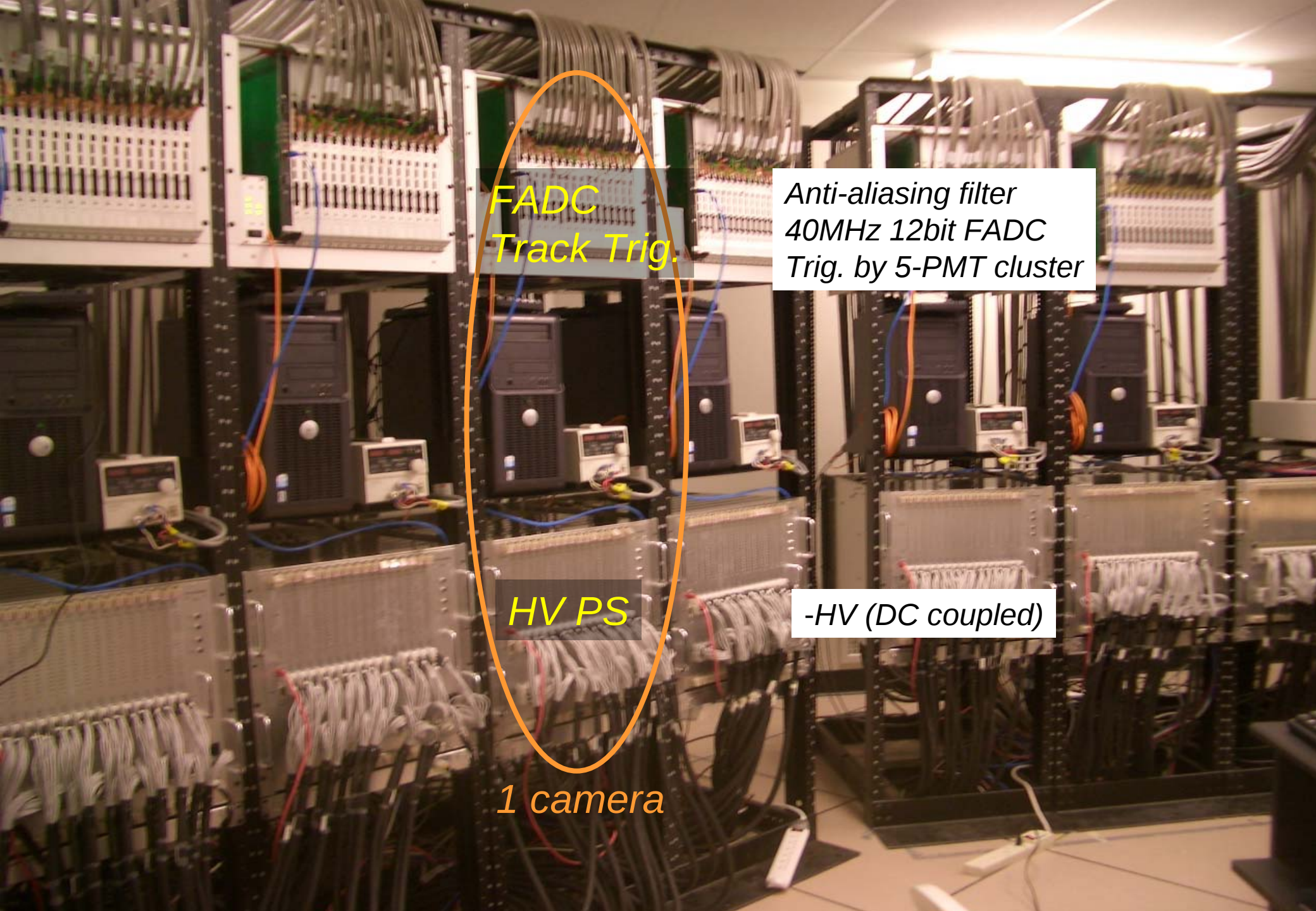
Preliminary results

*FD stereo analysis: Primary composition is consistent with proton
for $10^{18.6} - 10^{19.3}$ eV*

*Hybrid analysis: Spectrum for $10^{18.7} \sim 10^{19.5}$ eV is obtained.
Flux is consistent with HiRes.*

*New FD calibration by electron beam is soon to come.
Other analyses are on-going.*

Reserved



*FADC
Track Trig.*

*Anti-aliasing filter
40MHz 12bit FADC
Trig. by 5-PMT cluster*

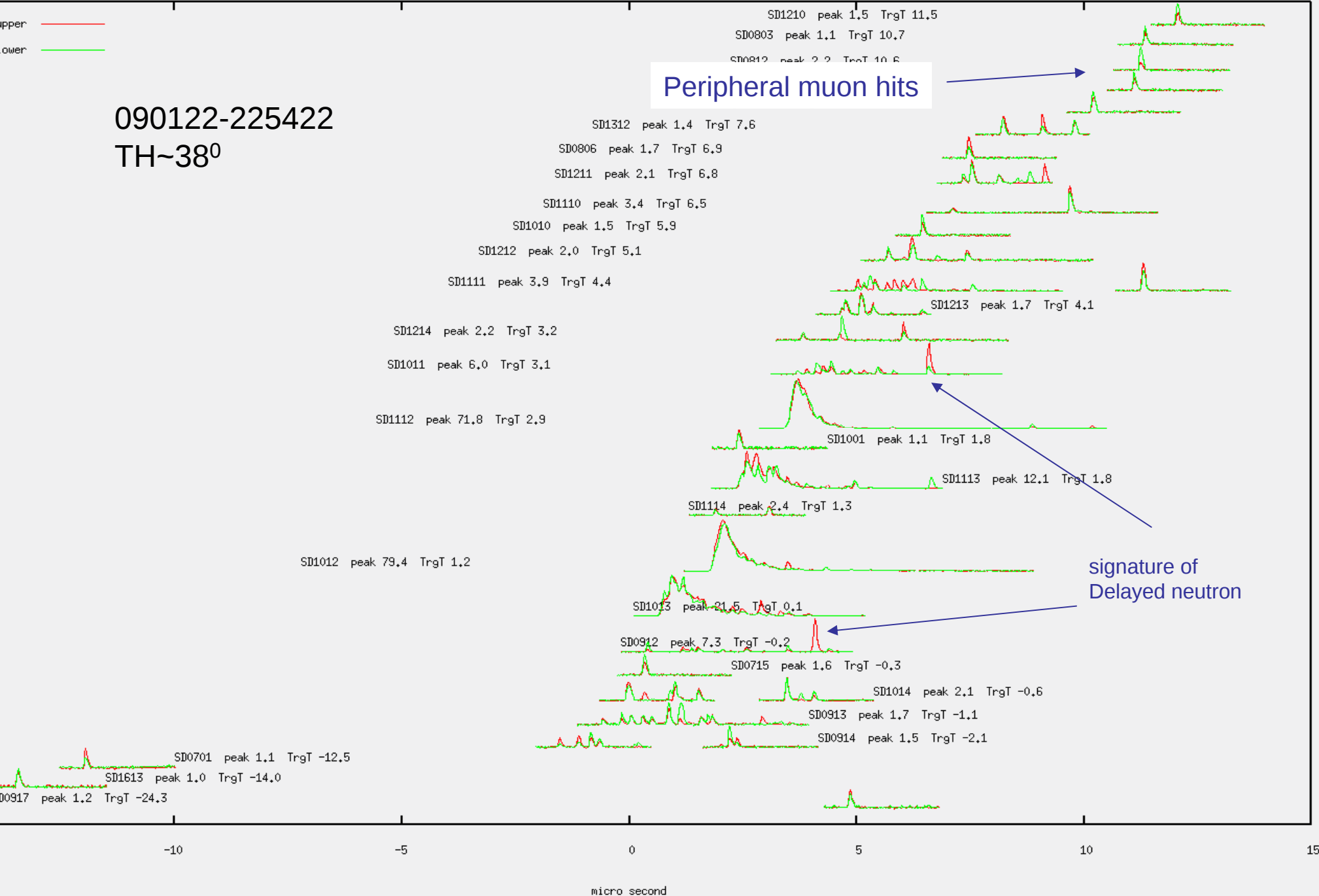
HV PS

-HV (DC coupled)

1 camera

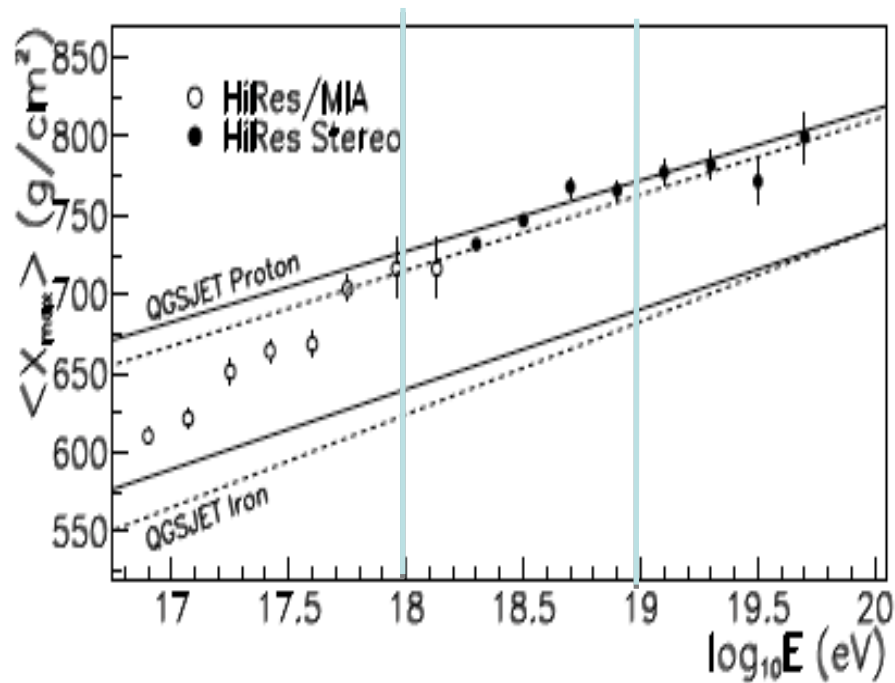
upper
lower090122-225422
TH~38°

Peripheral muon hits

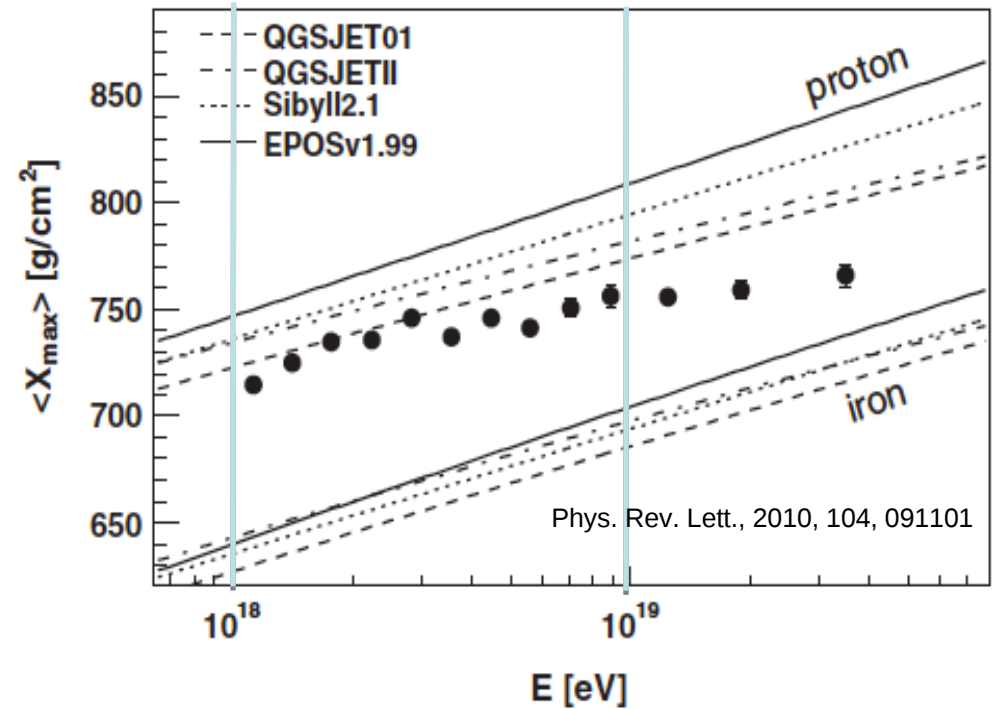


Existing Xmax data

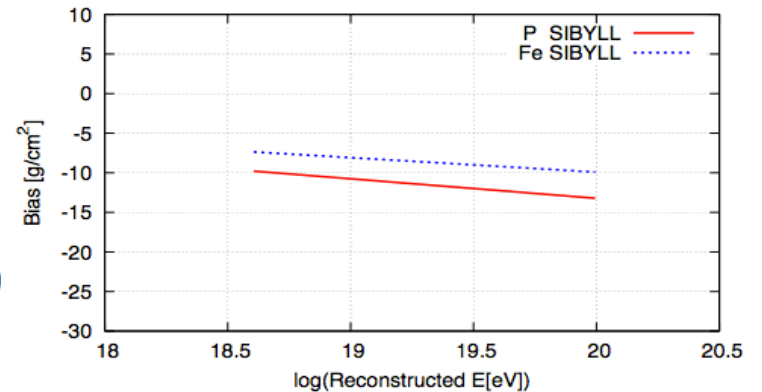
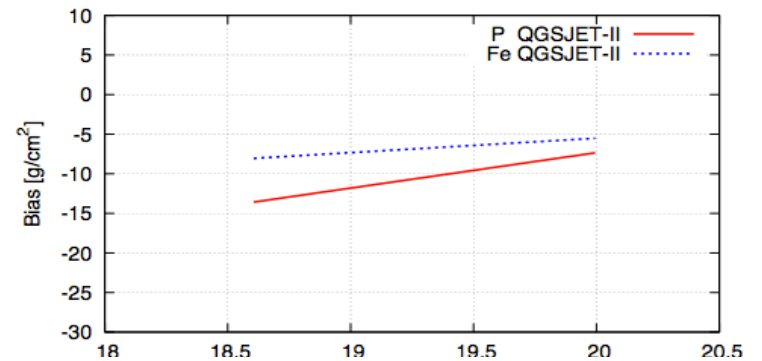
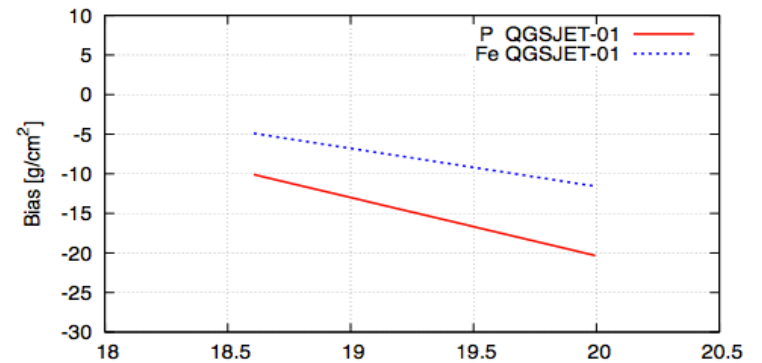
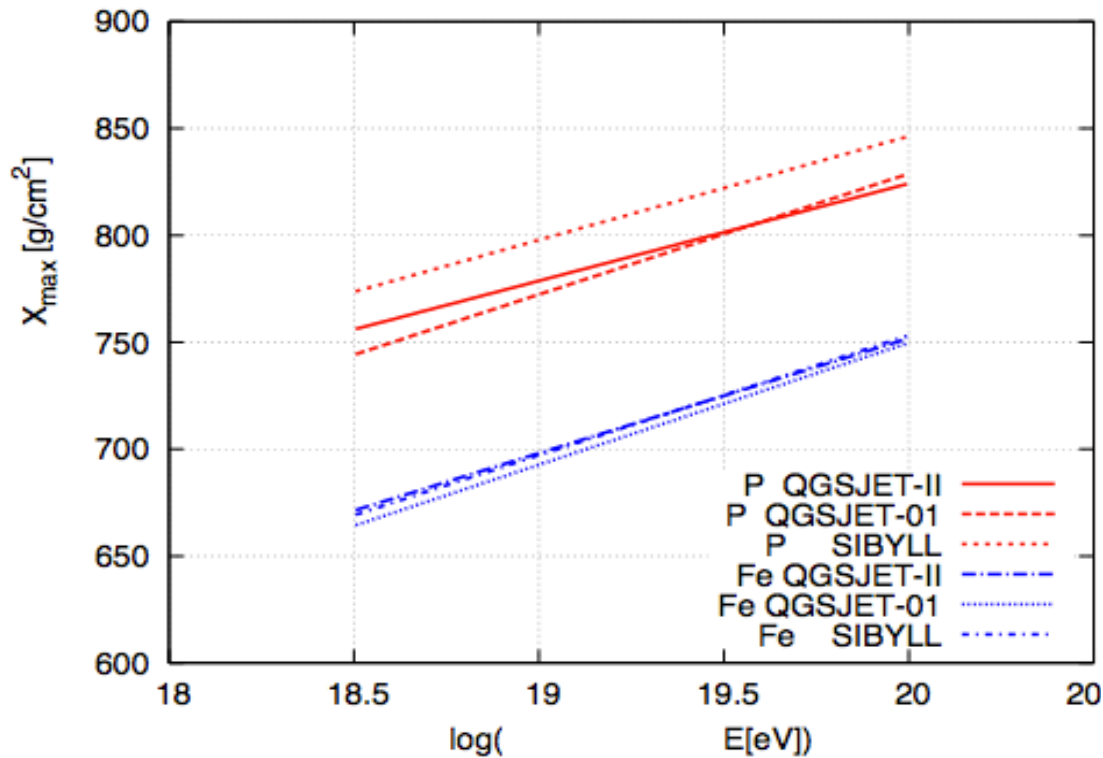
HiRes: stereo FD



Auger: FD/SD hybrid



Xmax “bias” by recons. + selection



Xmax “bias” by recons. + selection

