Ultra high energy cosmic ray and LHCf data

Nobuyuki Sakurai

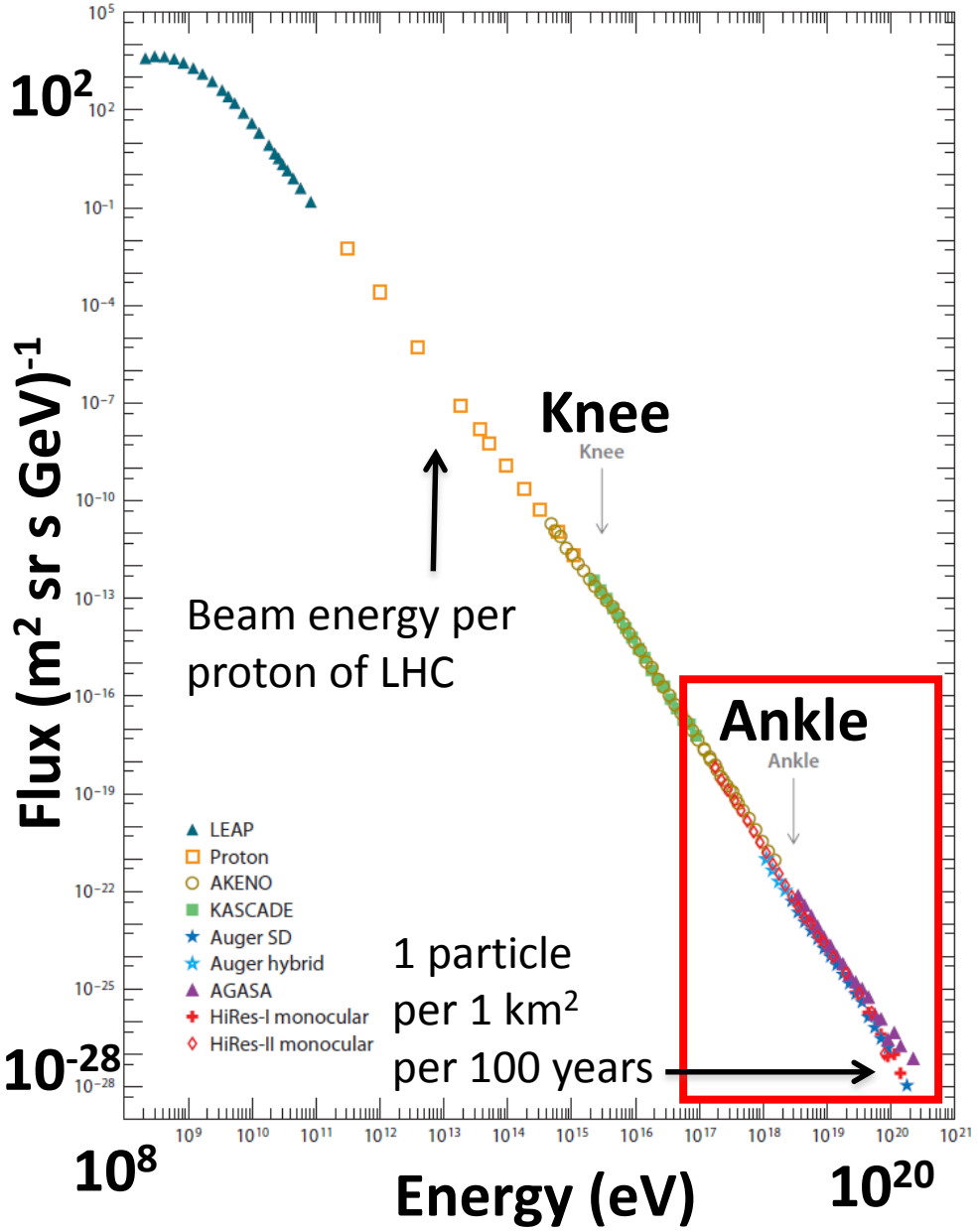
Outline

- Ultra high energy cosmic ray (UHECR)
- Observation of UHECRs
- Hadronic interaction and UHECR observation
- Collider experiment dedicated UHECR study

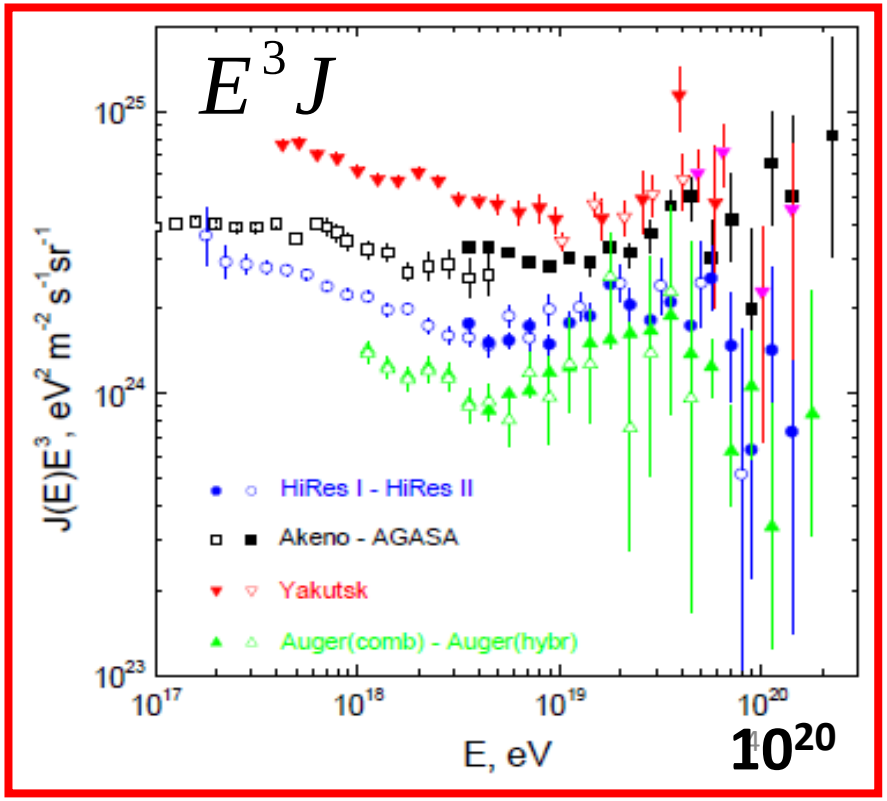
  ~ LHCf ~
- Summary

Ultra high energy cosmic ray (UHECR)

Ultra High Energy Cosmic Ray

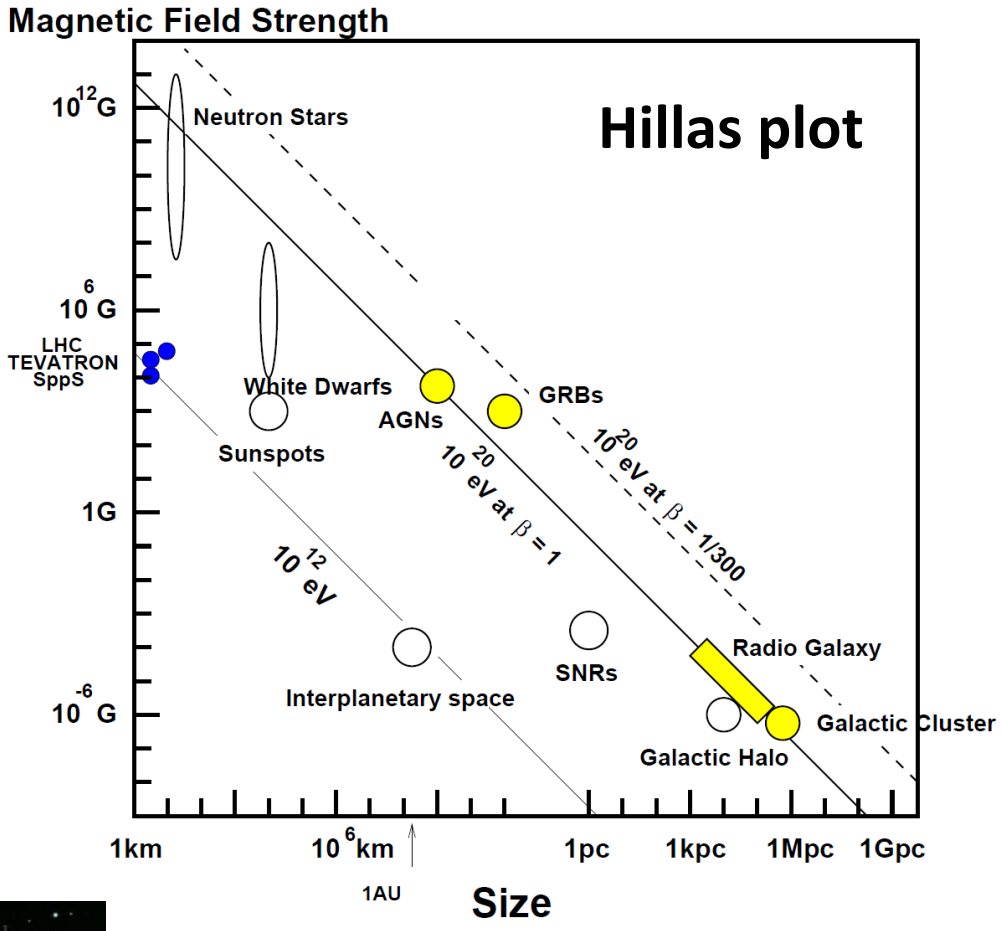


Ultra high energy cosmic ray



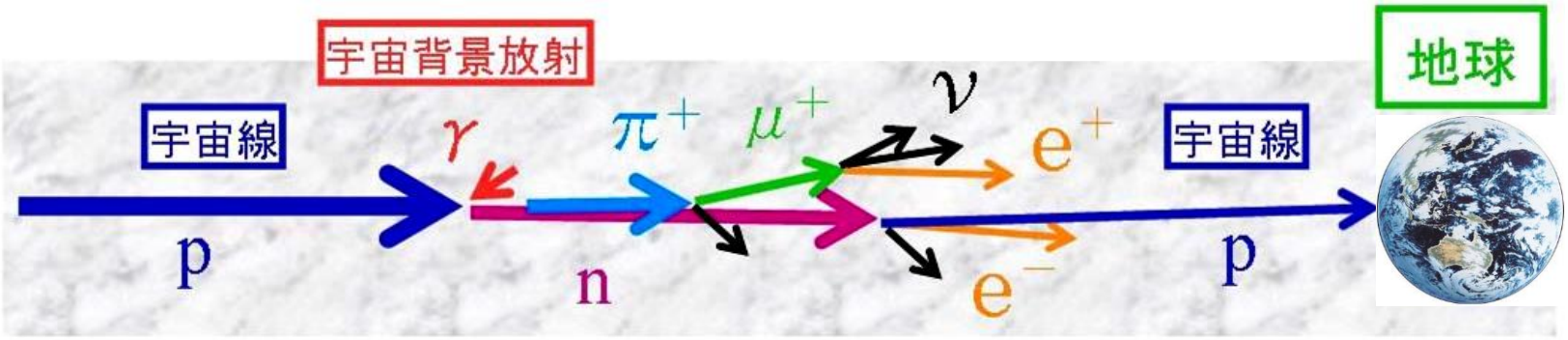
CR source candidates of UHECRs

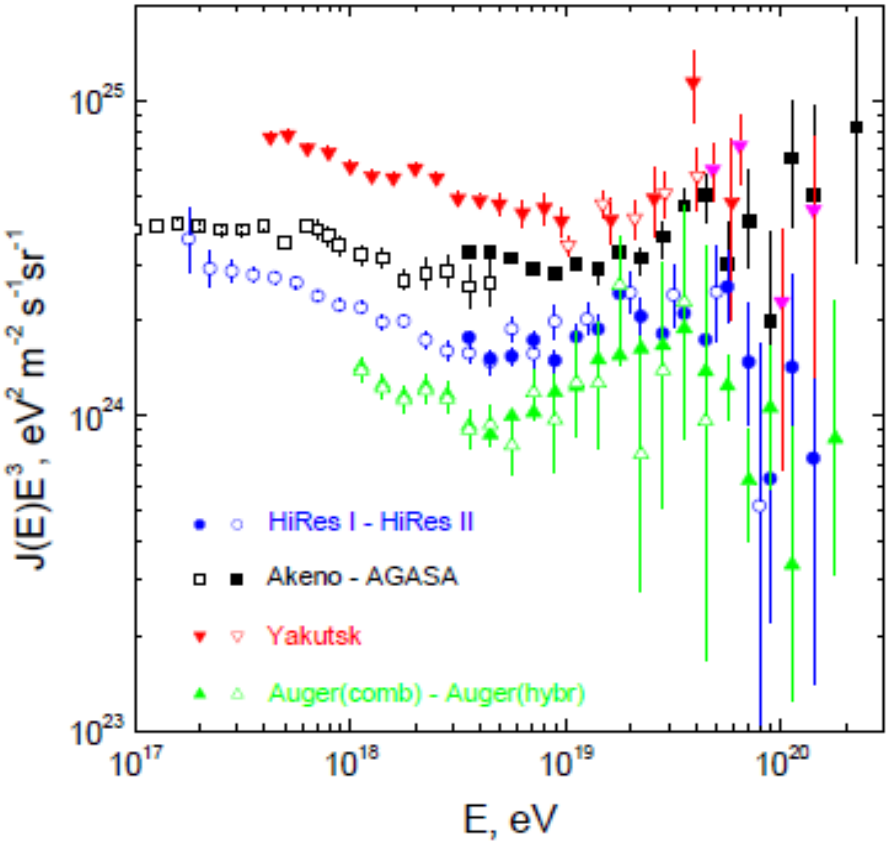
- Top-down model
  - Decay or annihilation of super heavy particle
  - Z burst
  - Topological defect
- Bottom up model
  - Neutron star
  - Active galactic nuclei
  - Gamma ray burst
  - Galactic cluster
  - Radio galaxy



$$E_{\max} \leq \gamma e Z B R$$

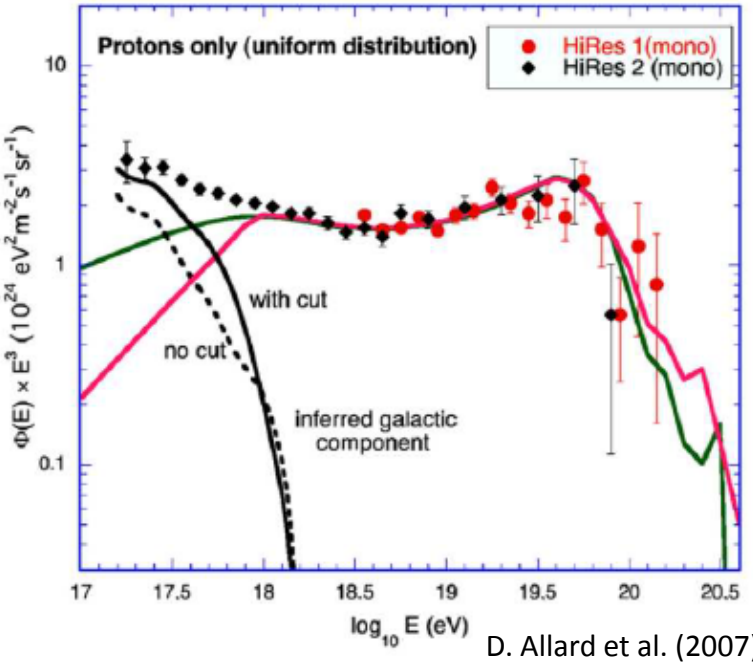
Greisen, Zatsepin and Kuzmin (GZK) Cutoff



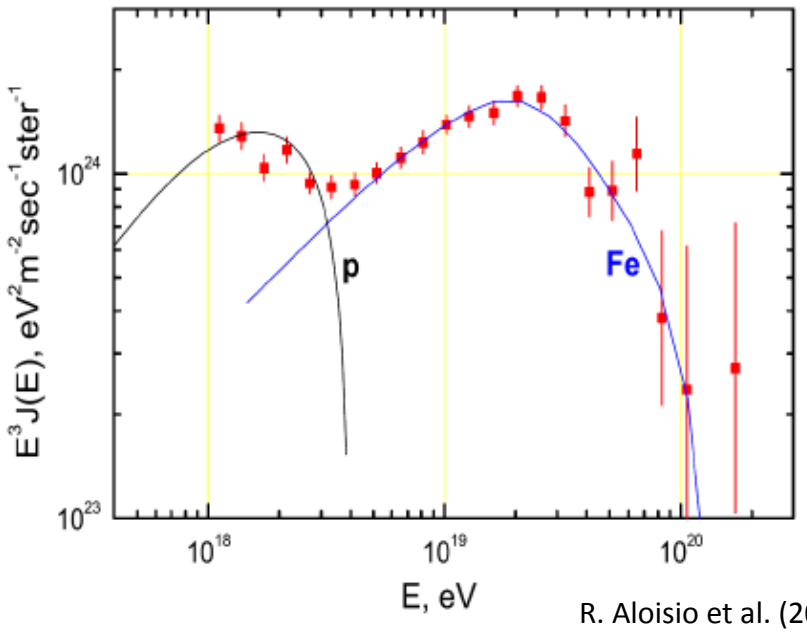


- Interaction mechanism between CMB and UHE proton.
  - ✓ Mean free path ~ 50 Mpc
- Flux suppression above 5×10^{19} eV is expected.
  - ✓ AGASA → beyond
  - ✓ HiRes, Auger → suppression
- Large systematic error
  - ✓ AGASA 18%, HiRes 17%, Auger 22%

Models of spectrum structure



D. Allard et al. (2007)



R. Aloisio et al. (2011)

- Suppression = GZK cutoff
- "ankle"
  = "dip" by pair-creation
  $p + \gamma_{CMBR} \rightarrow p + e^+ + e^-$
- Transition of the primary composition before "ankle"

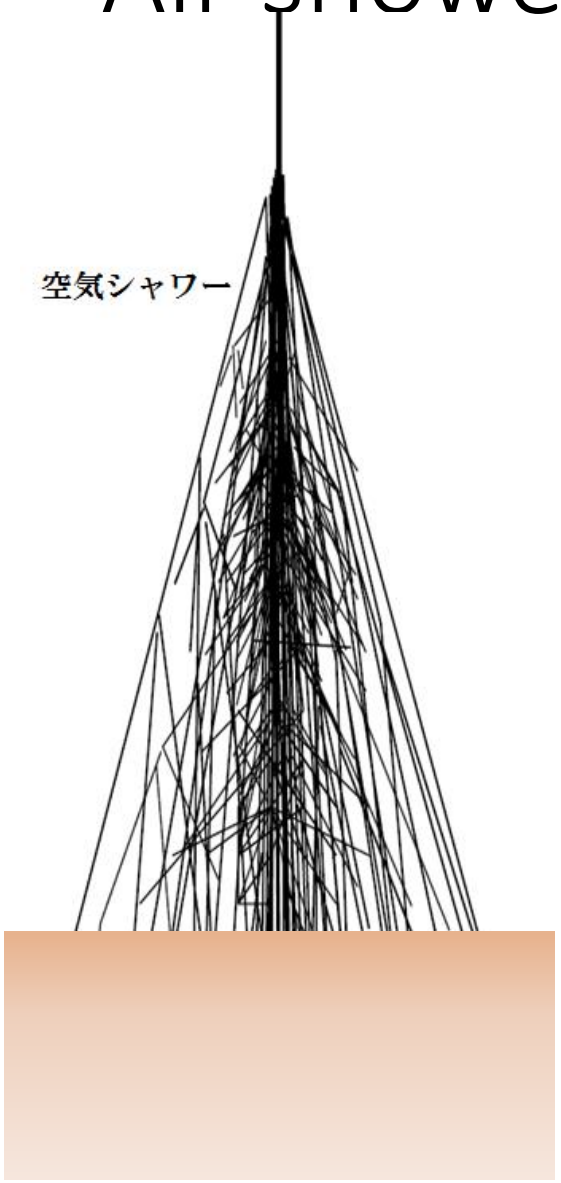
- Suppression = Accerelation limit
- "ankle" = Different CR source
- "ankle" is not "dip"

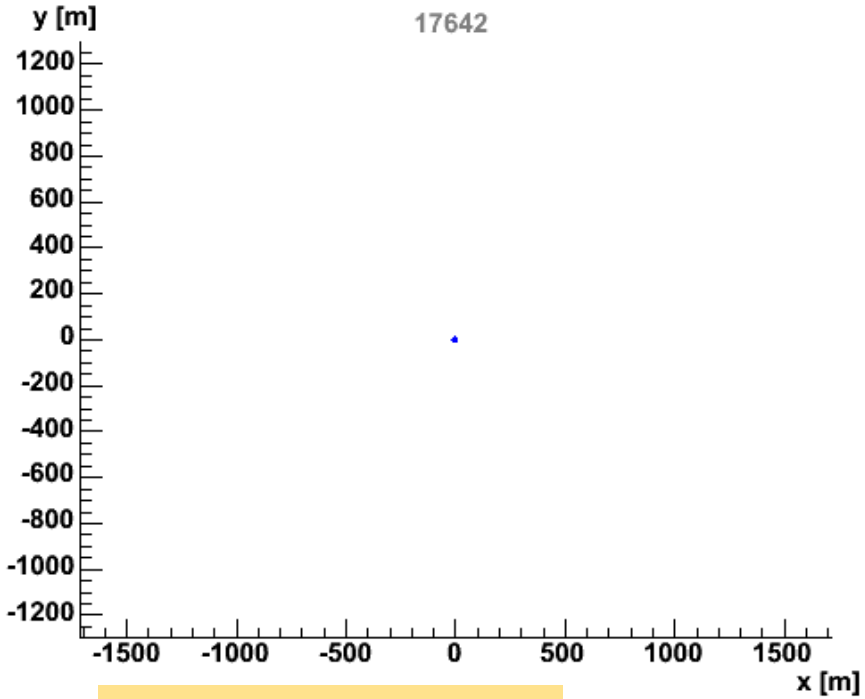
Key is "composition measurement"

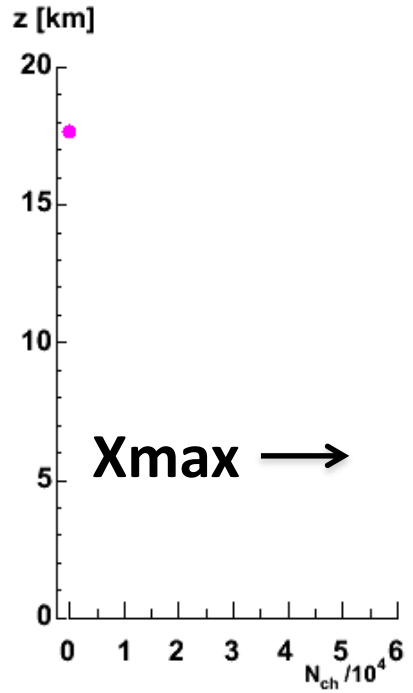
Observation of UHECRs

Air shower phenomena

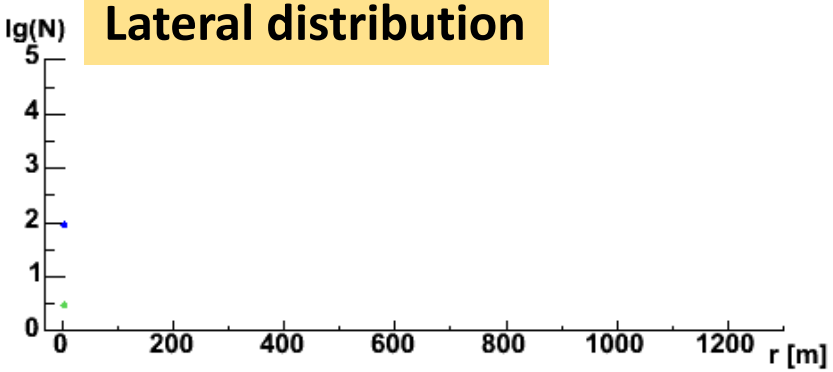
Longitudinal development







Lateral distribution



Proton 10^{14} eV

h^{1st} = 17642 m

hadrons muons

neutrons electrs

J.Oehlschlaeger,R.Engel,FZKarlsruhe

Made by A. Oshima (Chubu U.)

Surface detector array (SD)

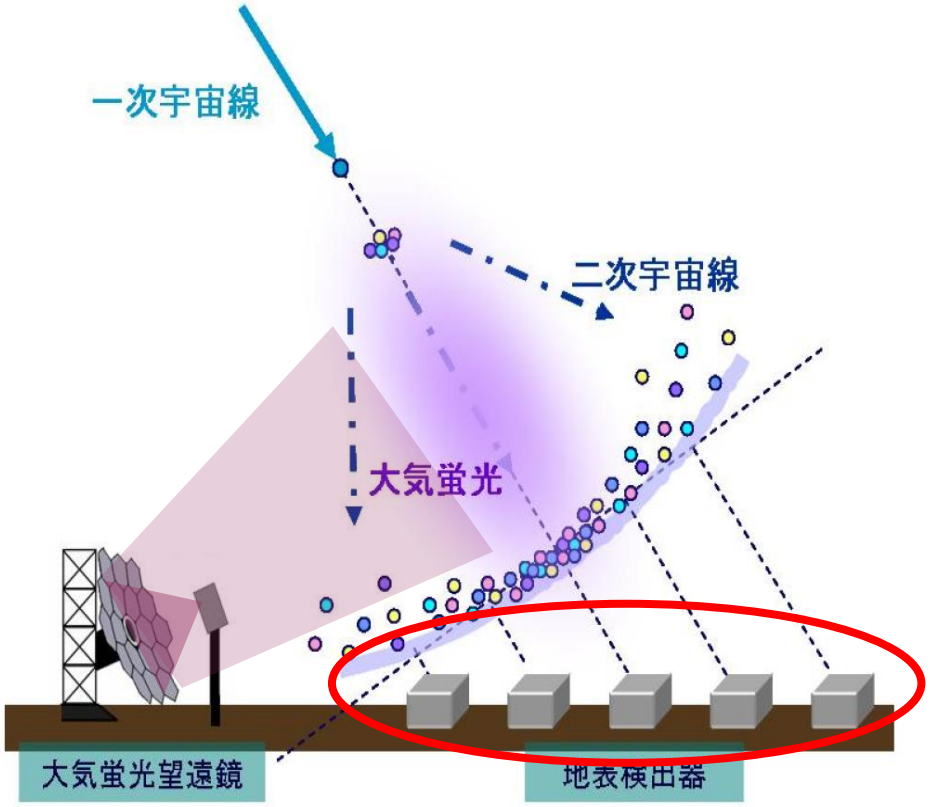
Detect secondary particles by counter array on the ground.

Strong point

- **100% duty**
- **Relatively cheap**
- Lateral distributions of particle density and timing.

Weak point

- Energy reconstruction depends upon the hadron interaction largely.



Fluorescence Detector (FD)

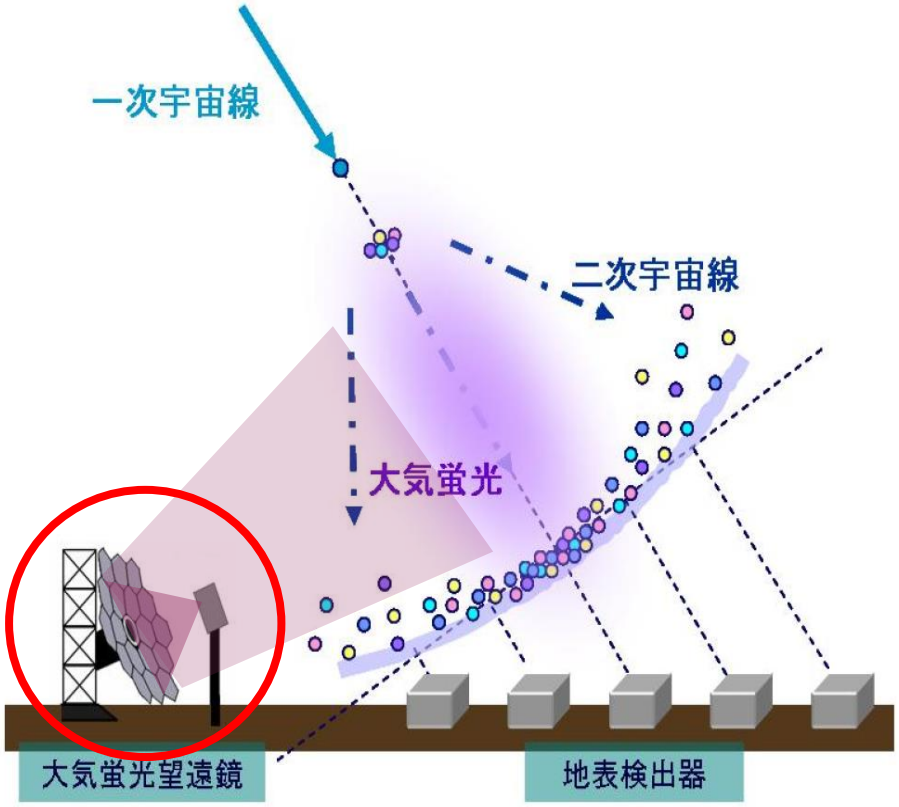
Detect air fluorescence light by telescope.

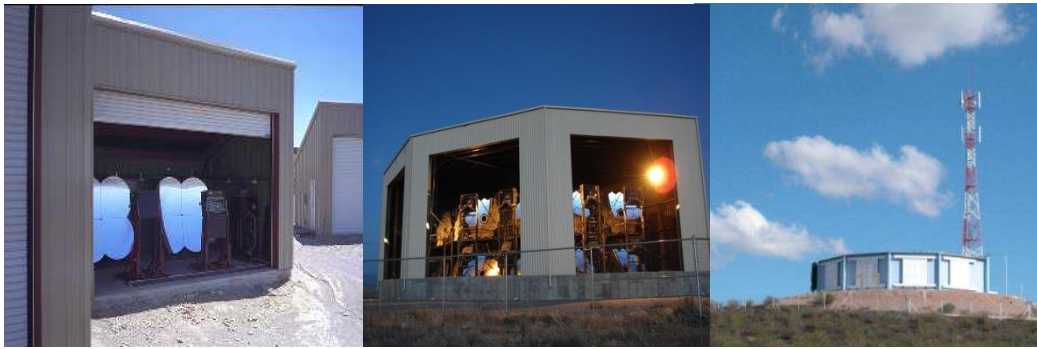
Strong point

- Longitudinal development of air shower = Primary composition
- Energy can be measured calorimetrically.

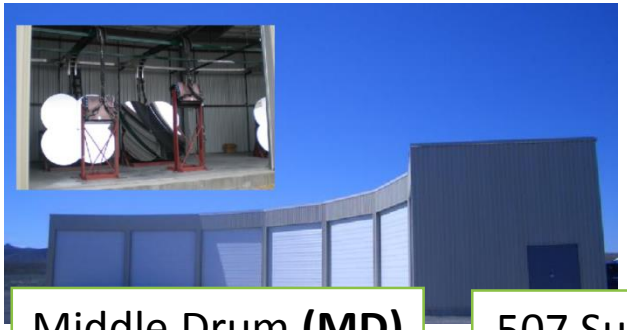
Weak point

- Duty is less than 10%
- Depends on the atmospheric conditions.





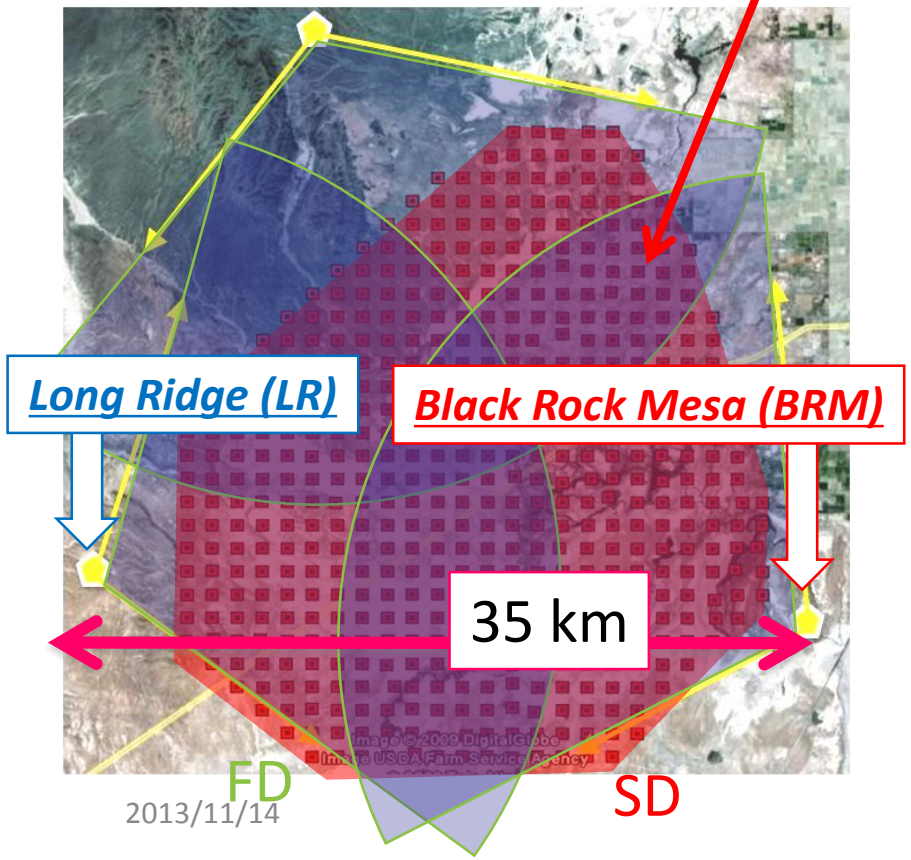
Telescope Array experiment(TA)



Middle Drum **(MD)**

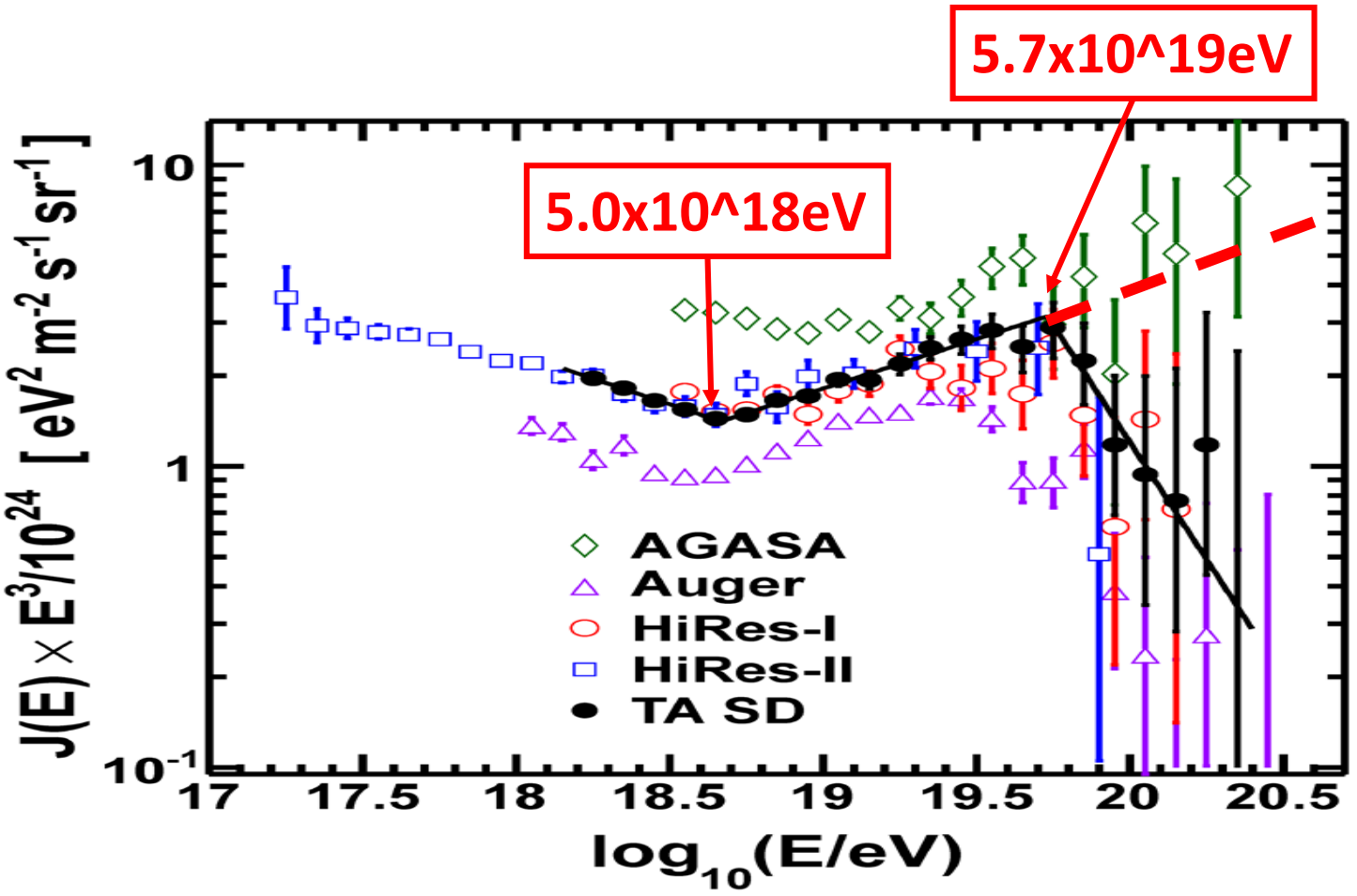
507 Surface detectors **(SD)**

- Western desert of Utah, USA
- Detection area ~ 700 km^2
- Largest detector in northern hemisphere
- Opereation : 2008 Mar.～

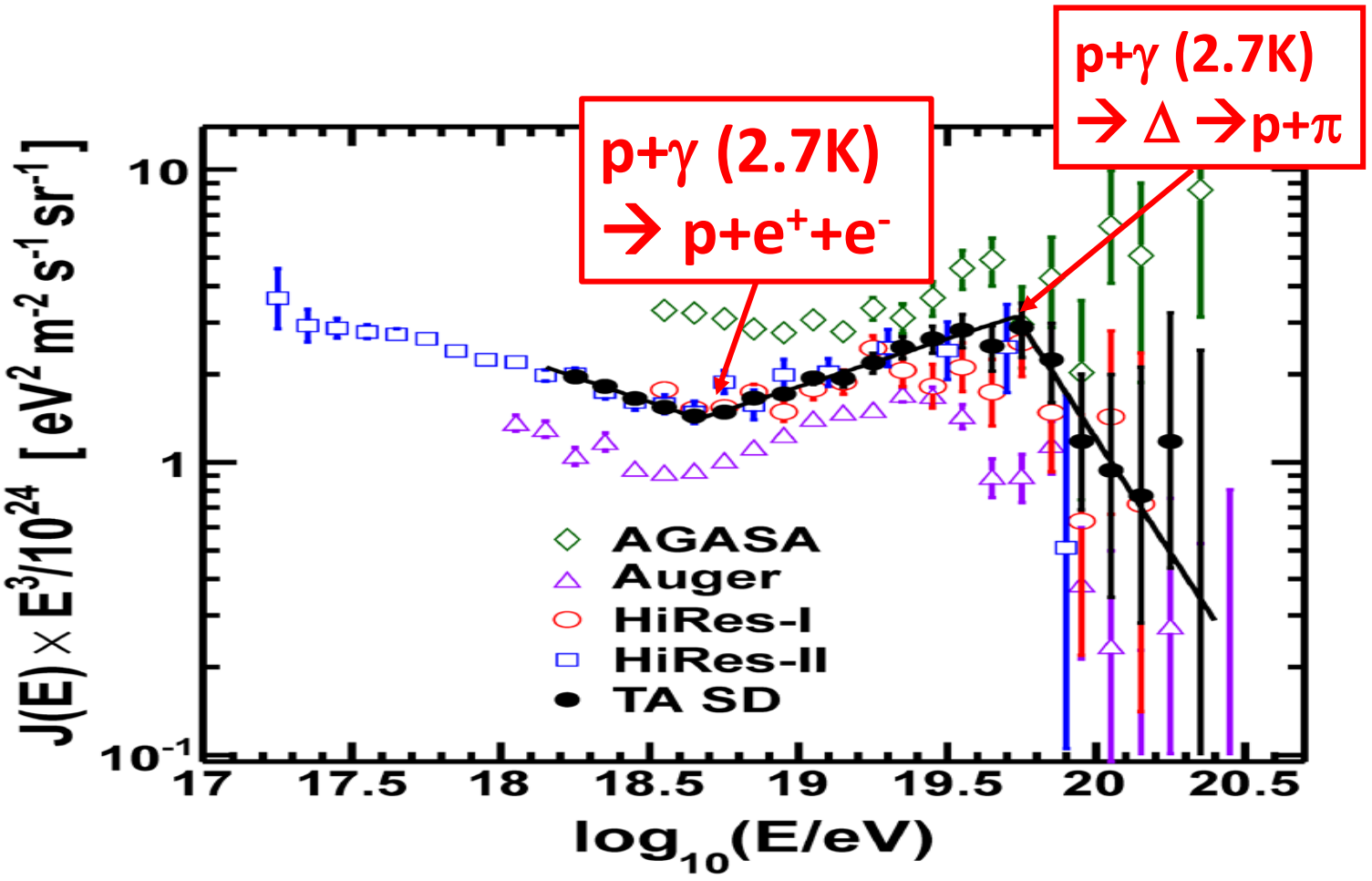


Fluorescence detector**(FD)** Station (BRM&LR)

Energy spectrum of UHECRs



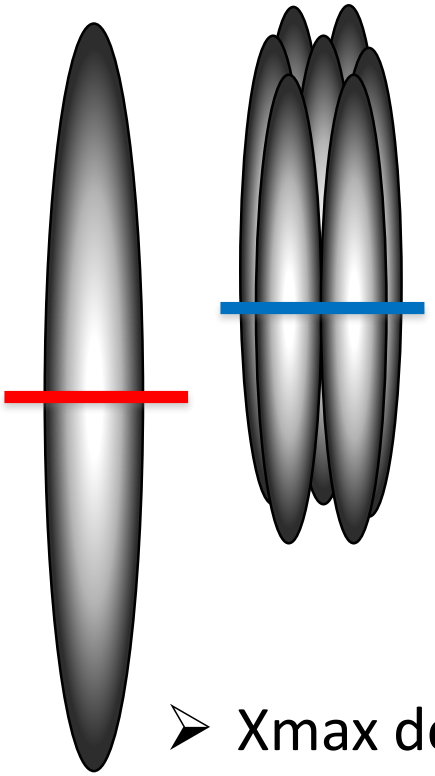
Energy spectrum of UHECRs



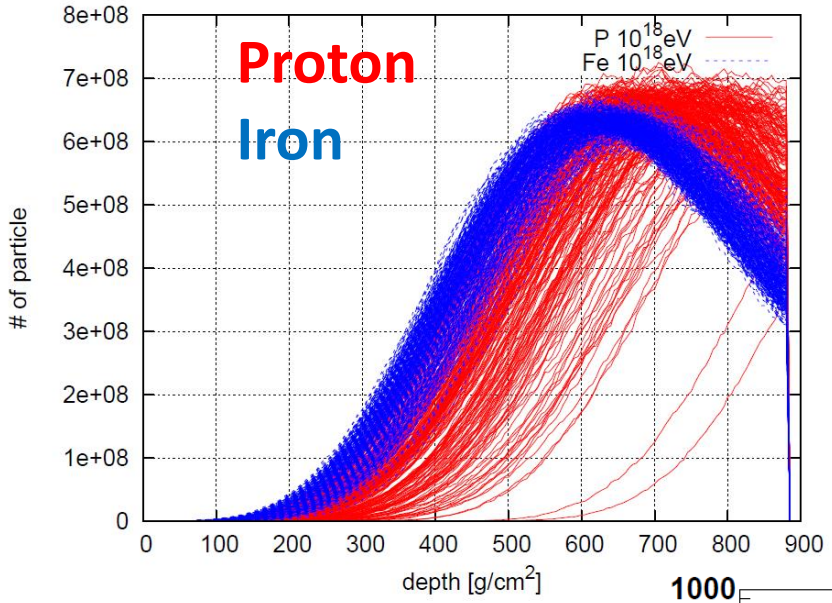
Xmax : Primary composition

For same energy…

Proton **iron**

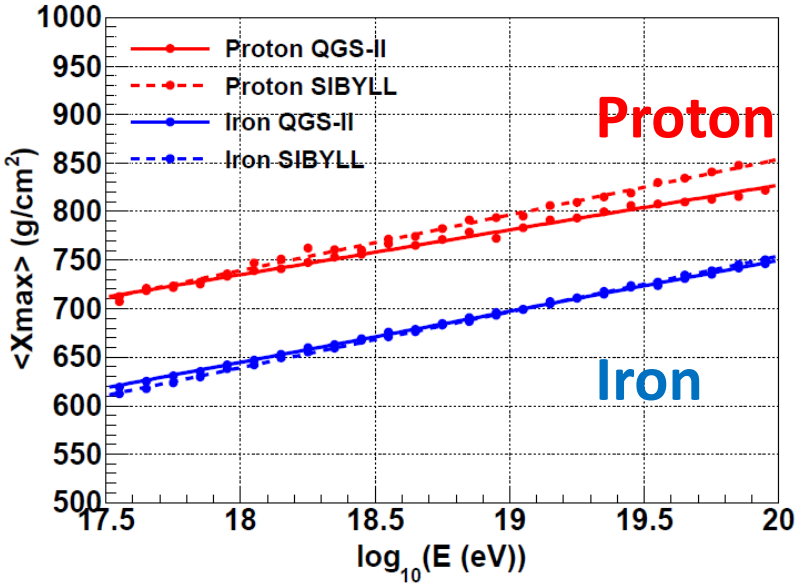


Longitudinal development



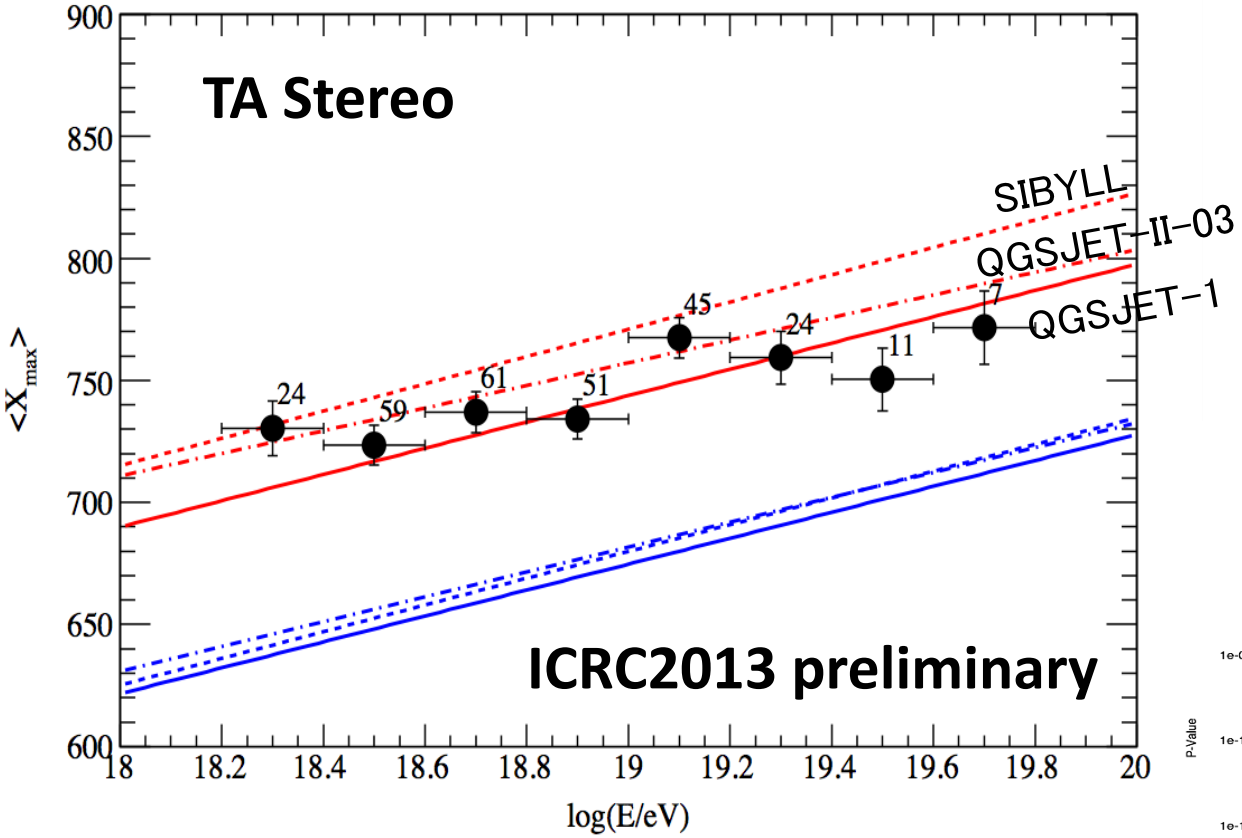
Primary particle can be estimated by long. development information.

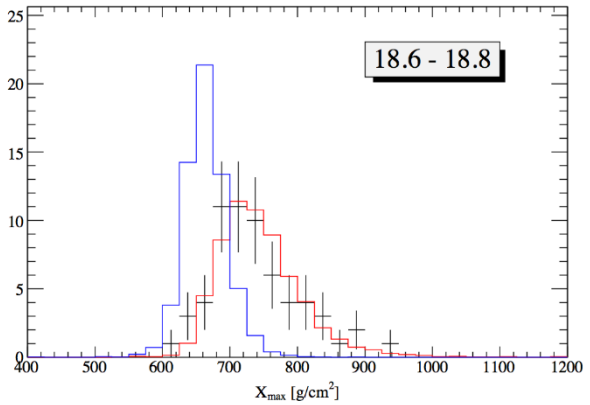
Averaged Xmax

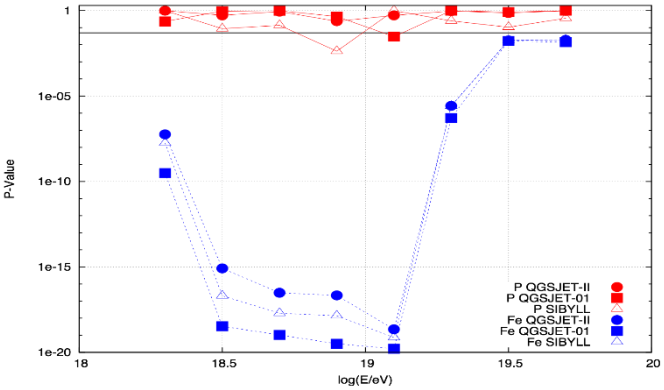


- Xmax depends on primary energy.
- Xmax difference between proton and iron is about 100 g/cm^2.

Primary composition of UHECRs

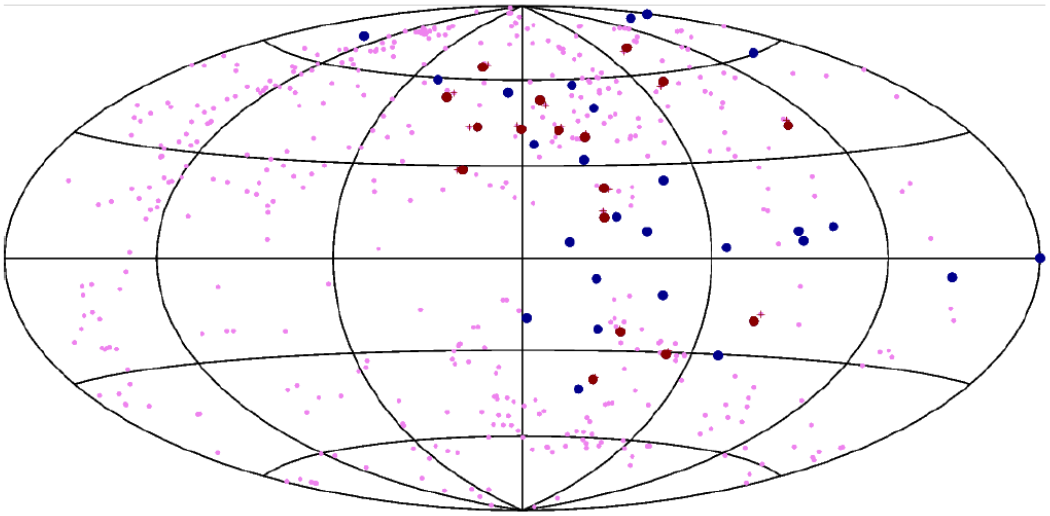






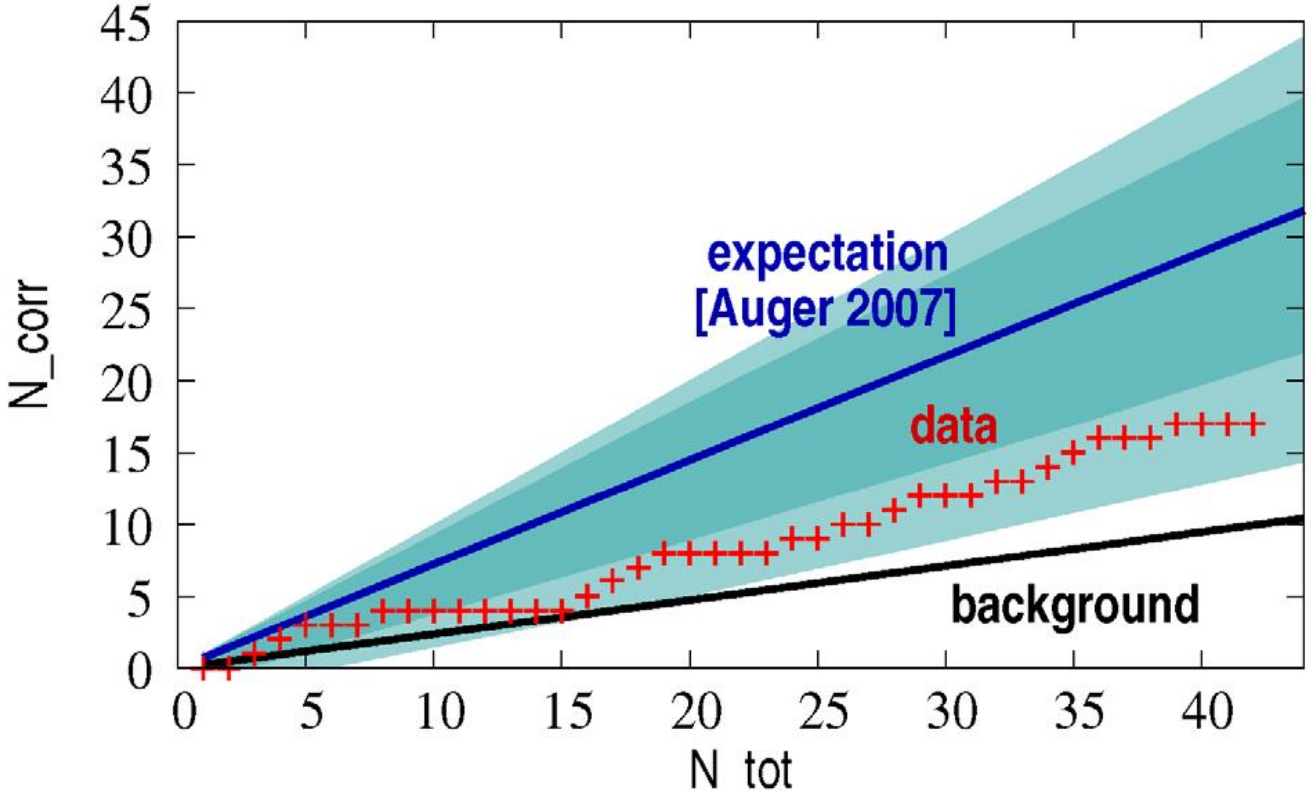
Correlation with AGN

- 472 AGN from 2006 Veron catalog with z<0.018
- E>57EeV, zenith angle<45deg, N=42(5yr)
- Separation angle < 3.1deg



Correlation with AGN

- 17 events correlate out of 42 → p=0.014



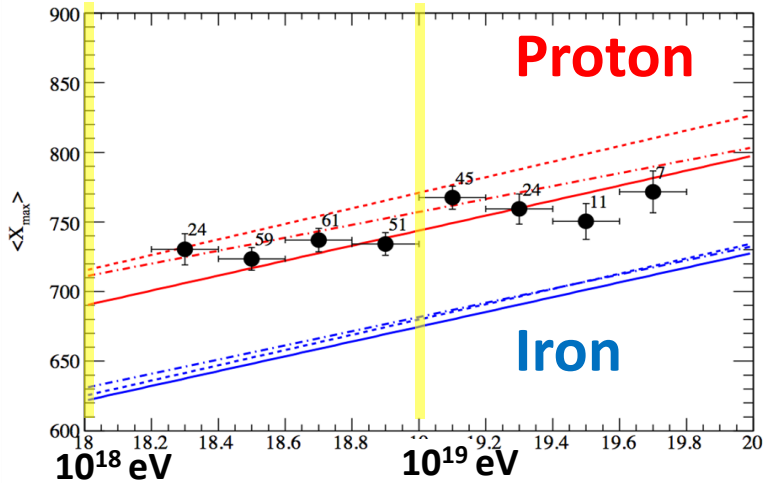
Summary of TA latest results

- Results of 5 years TA operation was presented.
- Energy spectrum
  - Significance of the suppression is 5.7σ above 5.4x10^19eV.
- Composition
  - Consistent with proton above 1.6x10^18eV.
- Arrival direction
  - Some hints?

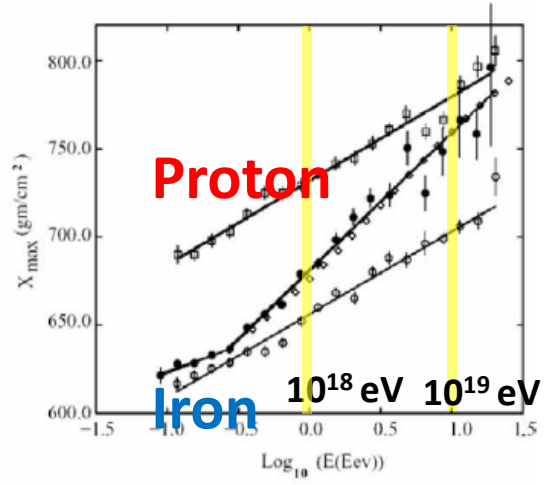
Hadronic interaction & UHECR observation

Summary of composition studies

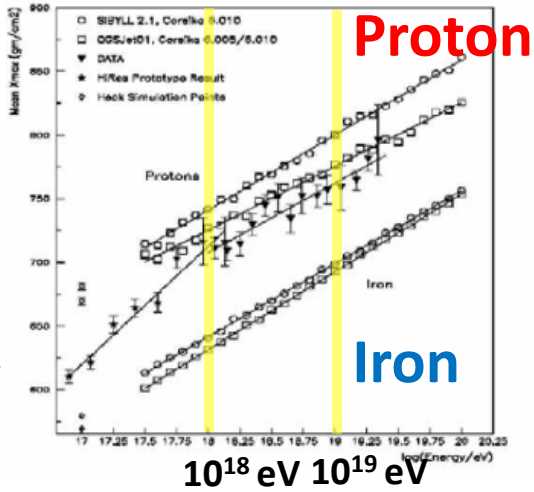
- Around 10^{18} eV, composition is changing. (Stereo Fly's Eye, HiRes/MIA)
- Above $10^{18.5}$ eV,
  - Proton (TA & HiRes)
  - Light nuclei (Auger)



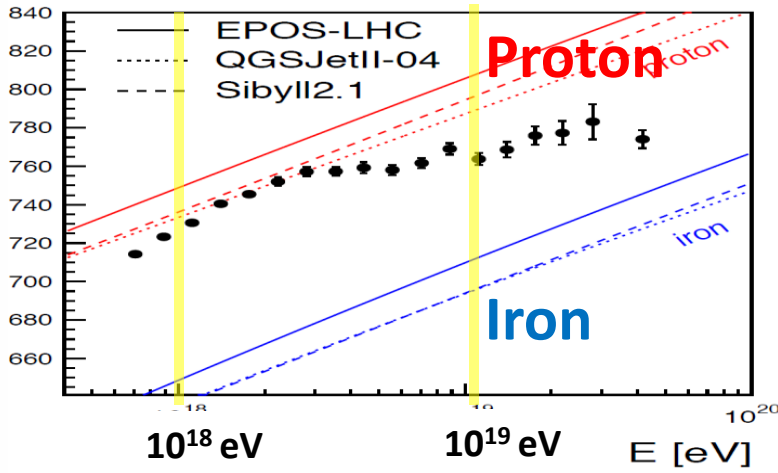
Telescope Array (TA)



Stereo Fly's Eye



HiRes/MIA and HiRes (High Resolution Fly's Eye)



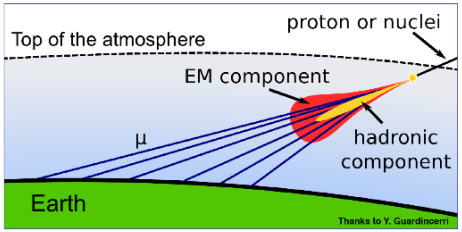
Pierre Auger Observatory (Auger)

Known anomalies of air shower observables(1)

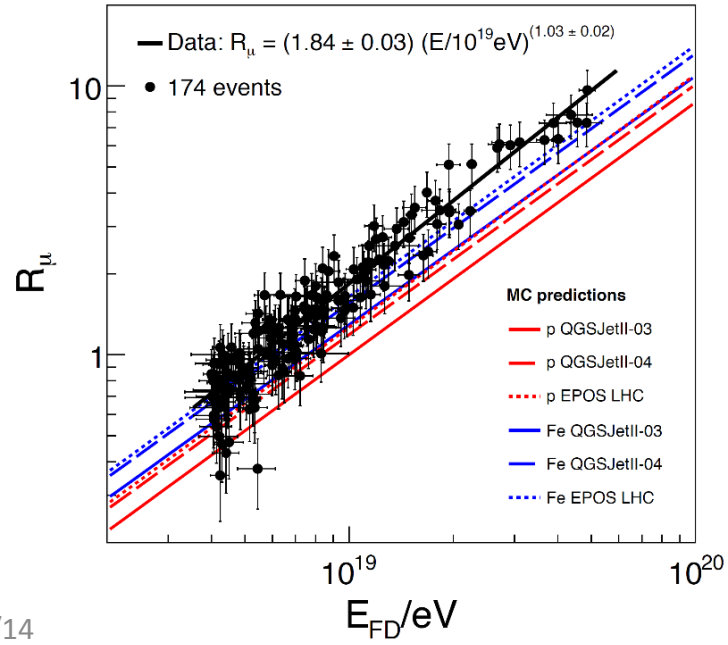
- # of muons on the ground is too much.

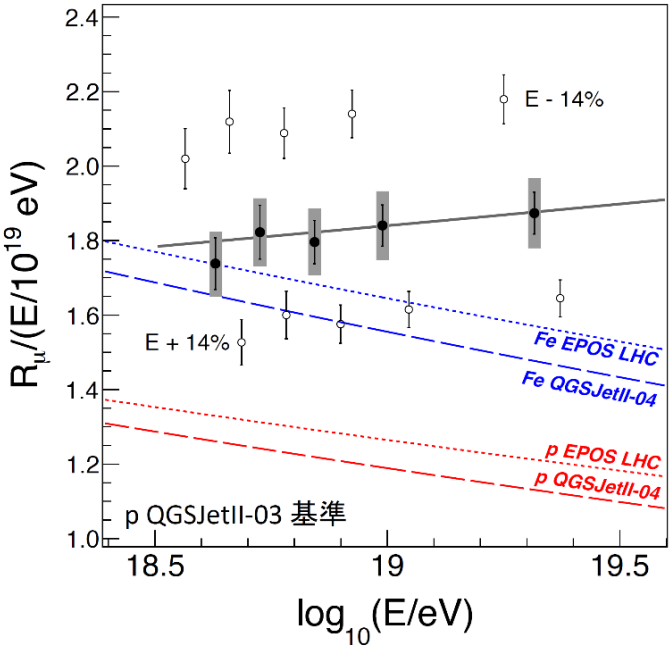
$N_{19}=N_{\mu}/N_{\mu,19} \rightarrow R_{\mu}$

(corrected the bias < 5% based on MC)



$62^{o}<\theta<80^{o}$
#SD >= 4
Golden hybrid





Known anomalies of air shower observables(2)

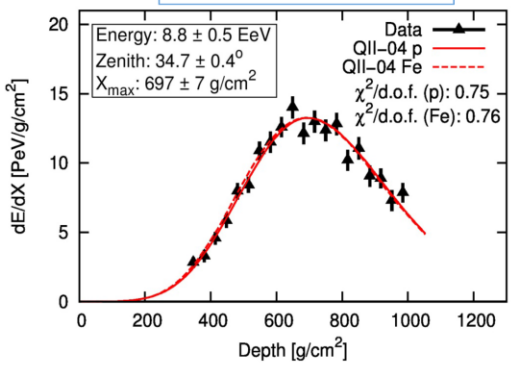
- E.M component of secondary particle on the ground is also too mach.

Auger

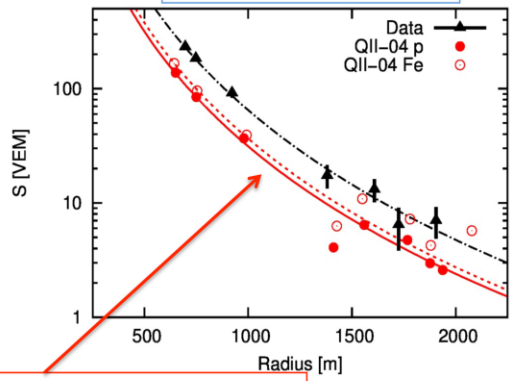
Method

- Find simulations which match measured FD profile, ***for each event***
- Compare the ground signals between the simulations and data
- Rescale muon content (R_μ) so that simulated ground showers best-match observed ones; also allow for energy calibration rescaling (R_E).

FD: longitudinal profile

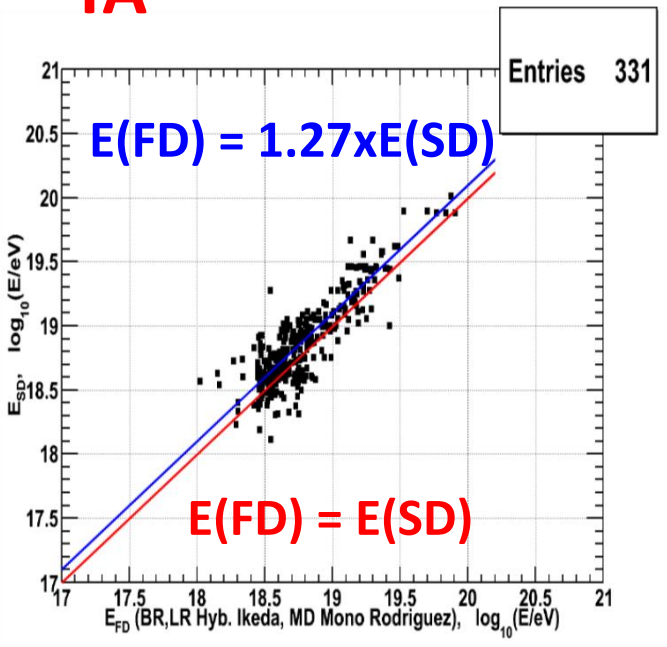


SD: lateral distribution



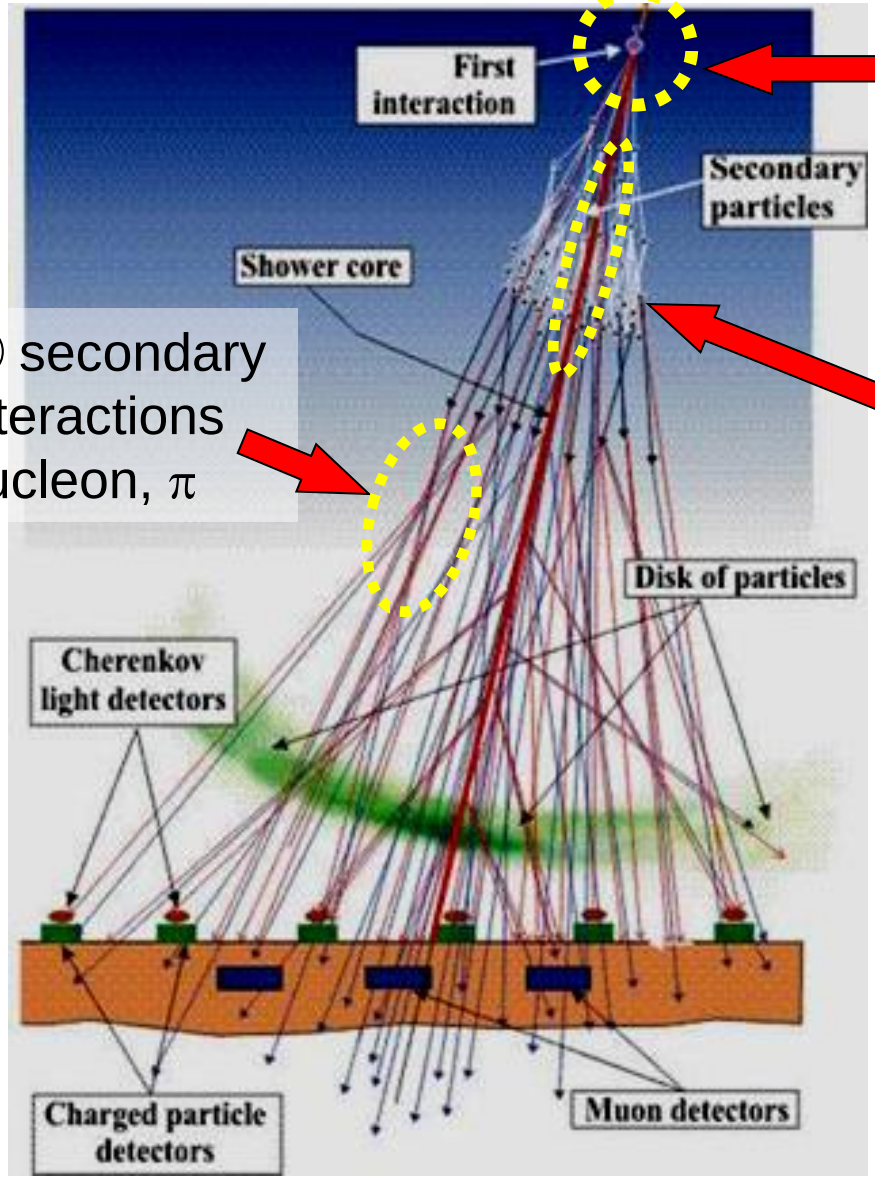
Typical example: model ground signal is too low

TA



Collider experiment dedicated UHECR study (LHCf)

Air Shower study using collder



④ secondary interactions nucleon, π

① Inelastic cross section

If large σ: rapid development
If small σ: deep penetrating

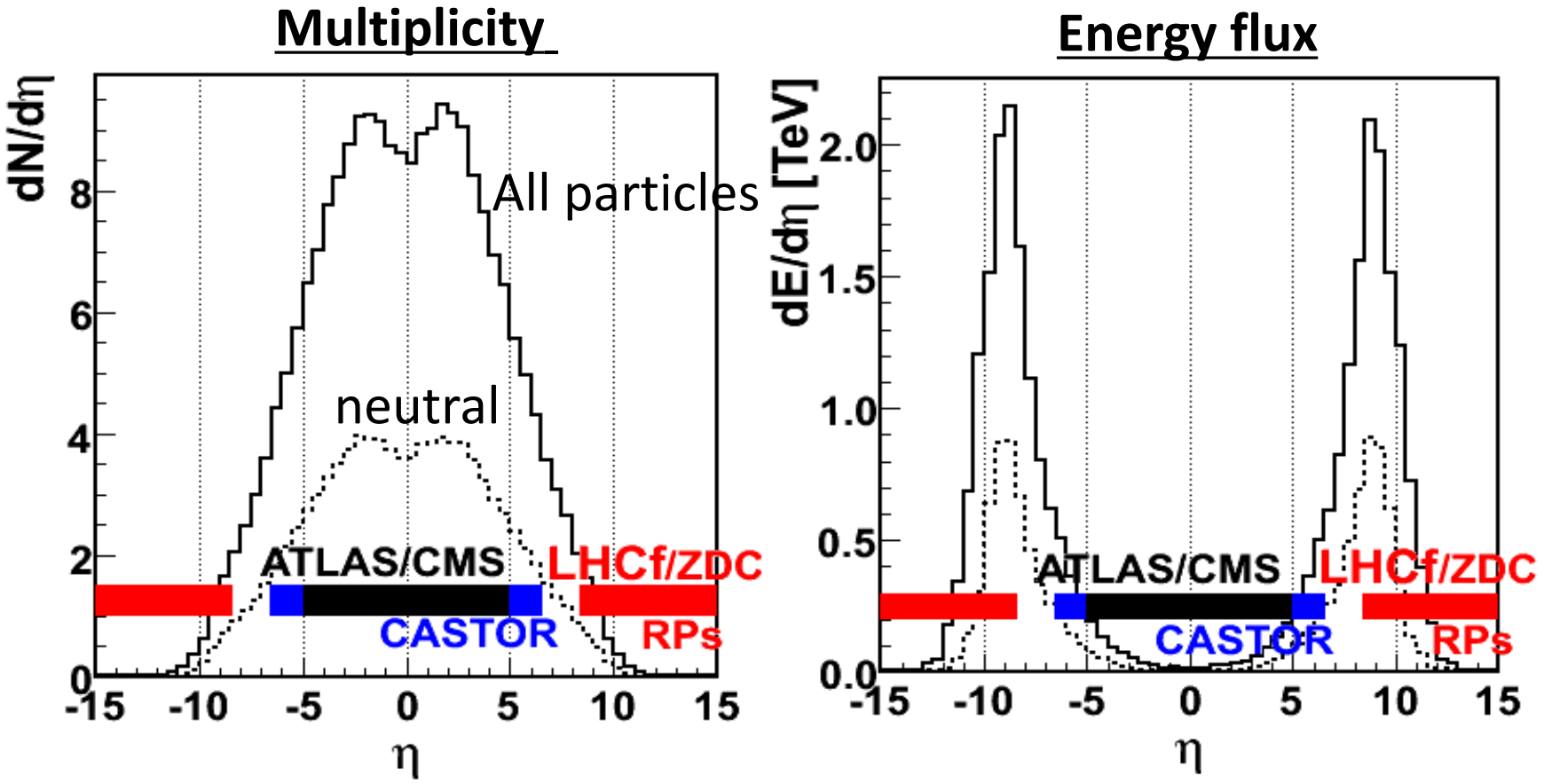
② **Forward energy spectrum**

If softer shallow development
If harder deep penetrating

③ **Inelasticity** $k = 1 - \frac{E_{lead}}{E_{avail}}$

If large k (π^0s carry more energy)
rapid development
If small k (baryons carry more energy)
deep penetrating

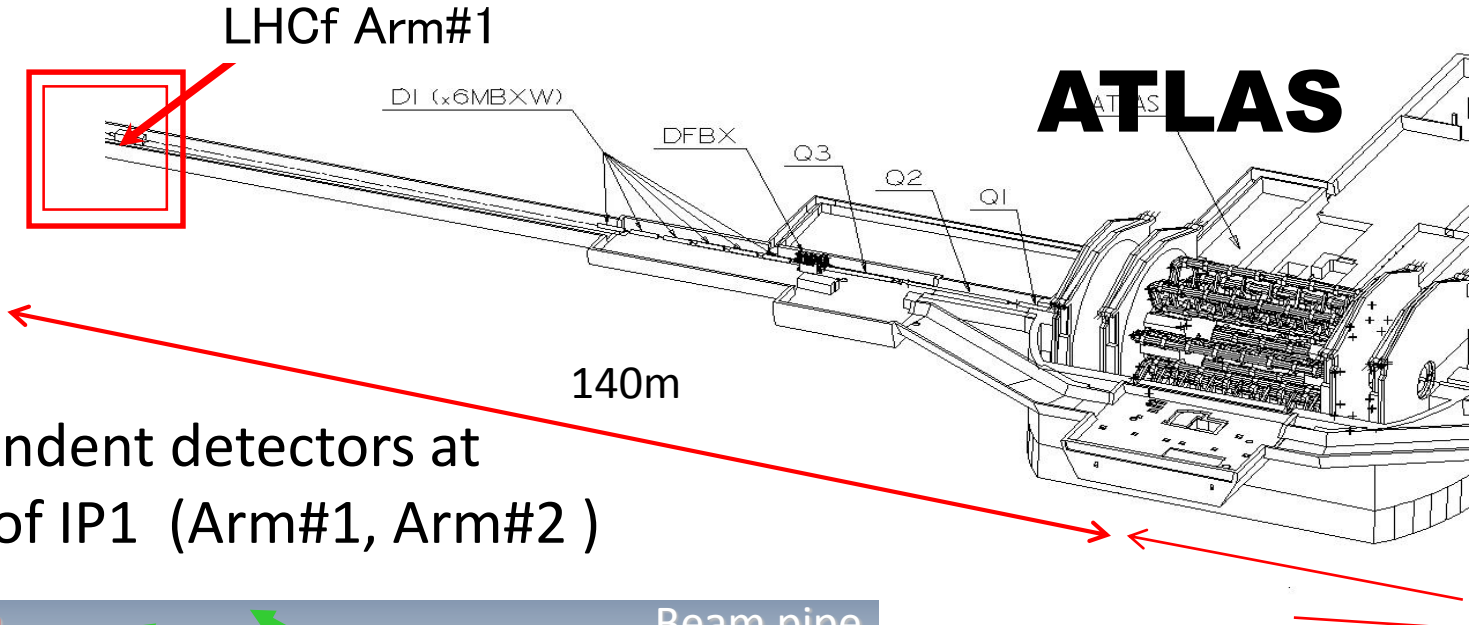
Where to be measured at colliders



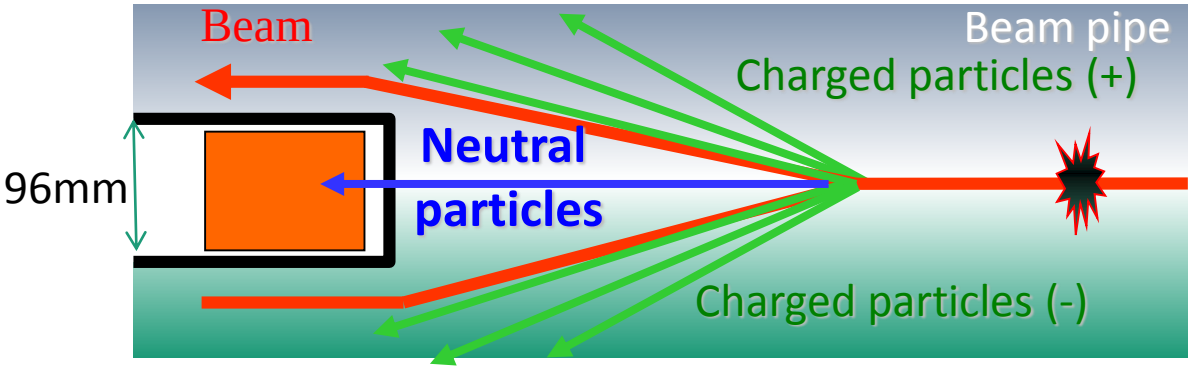
Most of the particles produced into central,

Most of the energy flows into **forward**

The LHC forward experiment



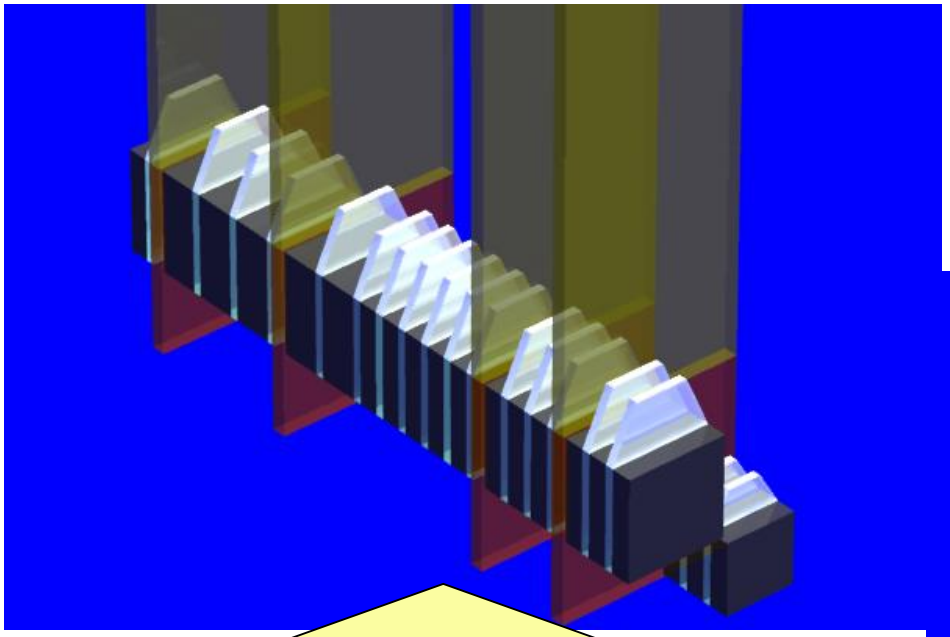
Two independent detectors at either side of IP1 (Arm#1, Arm#2)



- All charged particles are swept by dipole magnet
- Neutral particles (photons and neutrons) arrive at LHCf
- 0 degree is covered

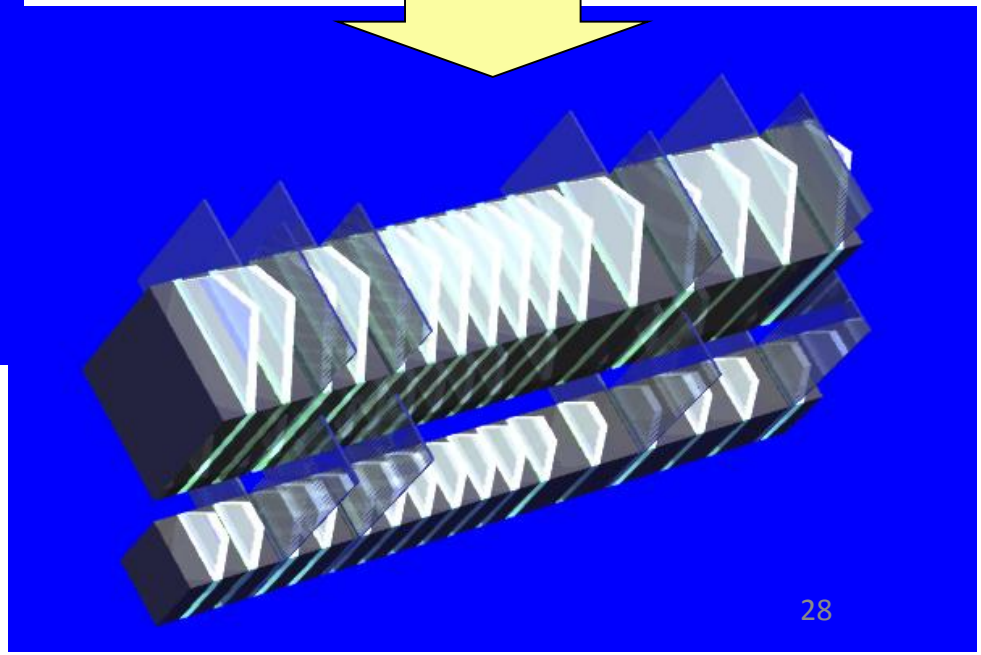
LHCf Detectors

- ✓ Imaging sampling shower calorimeters
- ✓ Two calorimeter towers in each of Arm1 and Arm2
- ✓ Each tower has 44 r.l. of Tungsten,16 sampling scintillator and 4 position sensitive layers

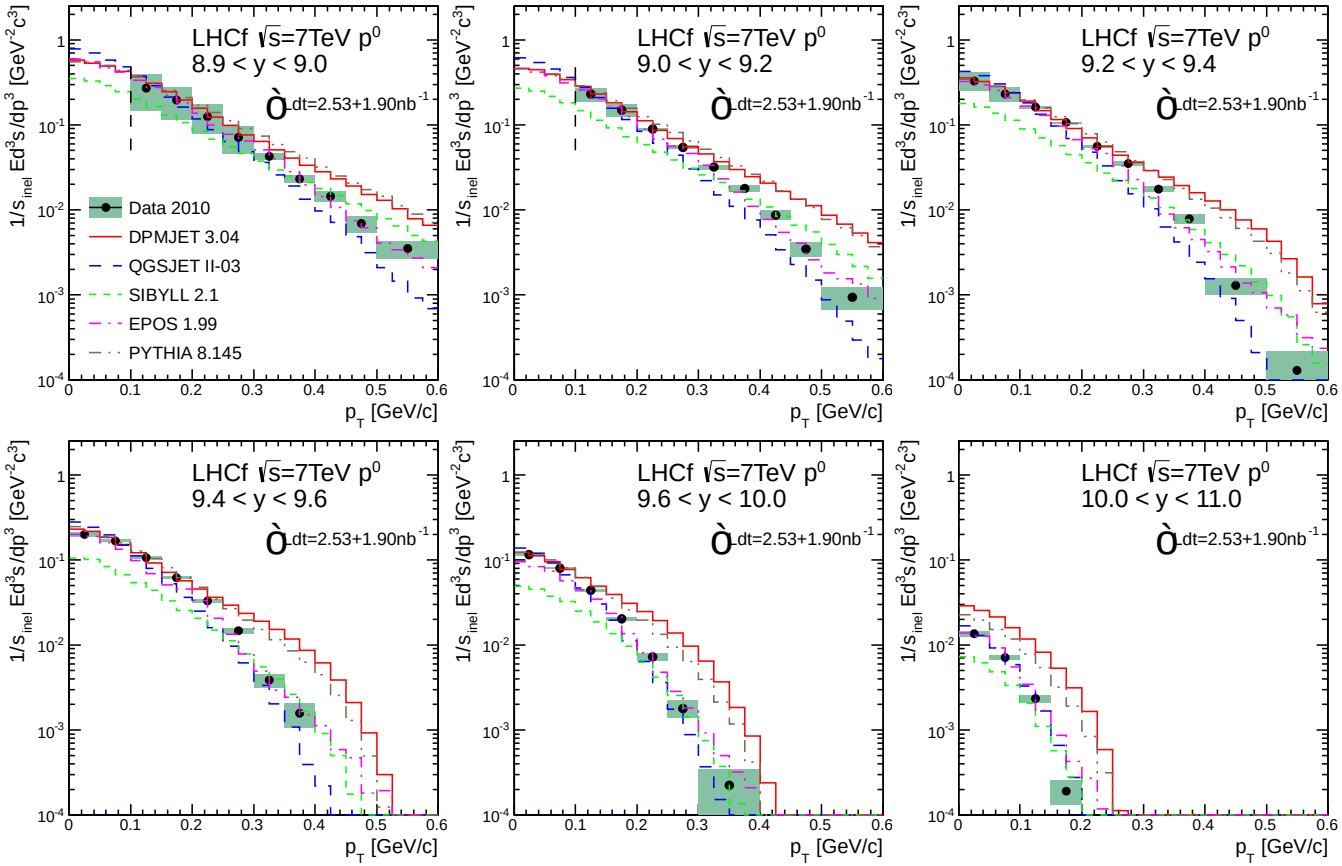


Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

Arm#1 Detector
20mmx20mm+40mmx40mm
4 XY SciFi+MAPMT



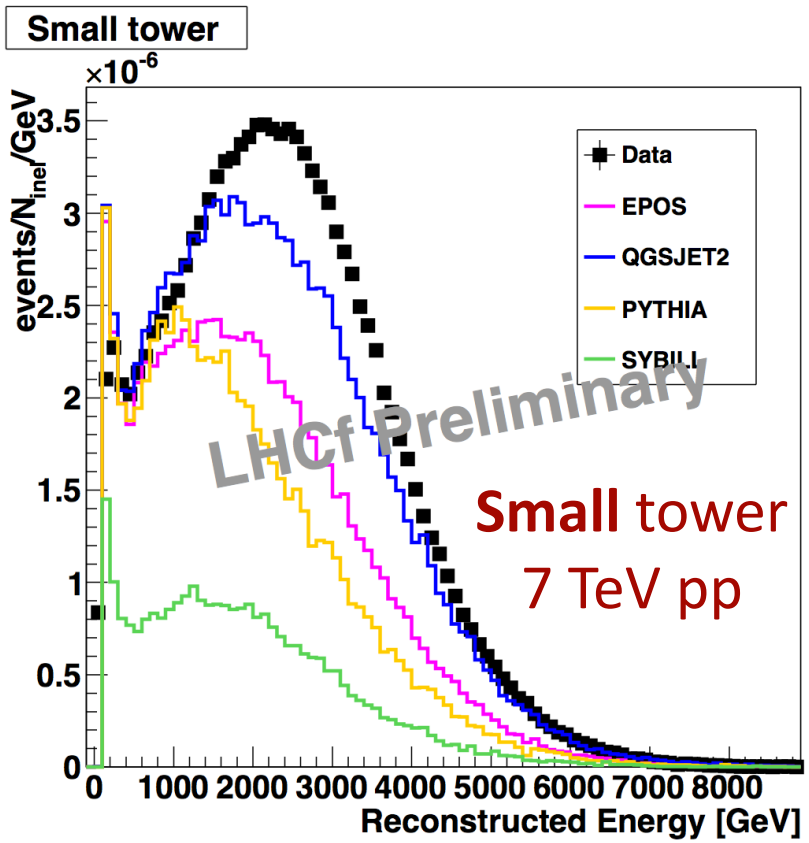
Comparison of π^0 data at $\sqrt{s} = 7\text{TeV}$ w/ hadronic interaction models

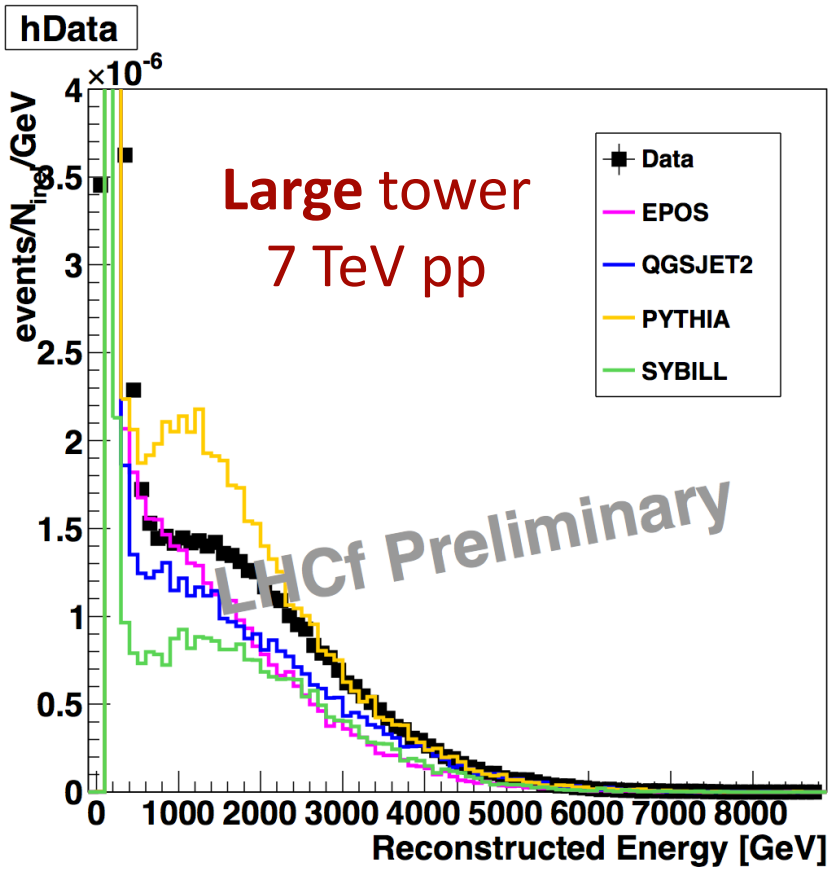


"$\sqrt{s} = 7\text{TeV}$"→ CR energy of 2.6x10^16eV

- **EPOS1.99** show the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder spectra than data ("popcorn model")
- **QGSJET** has softer spectrum than data (only one quark exchange is allowed)

Comparison of neutron data at $\sqrt{s} = 7\text{TeV}$ w/ hadronic interaction models

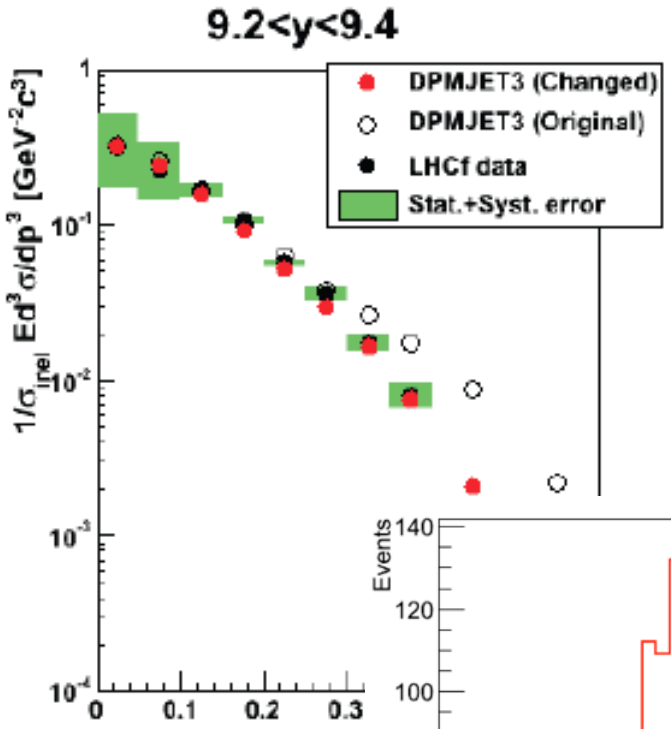




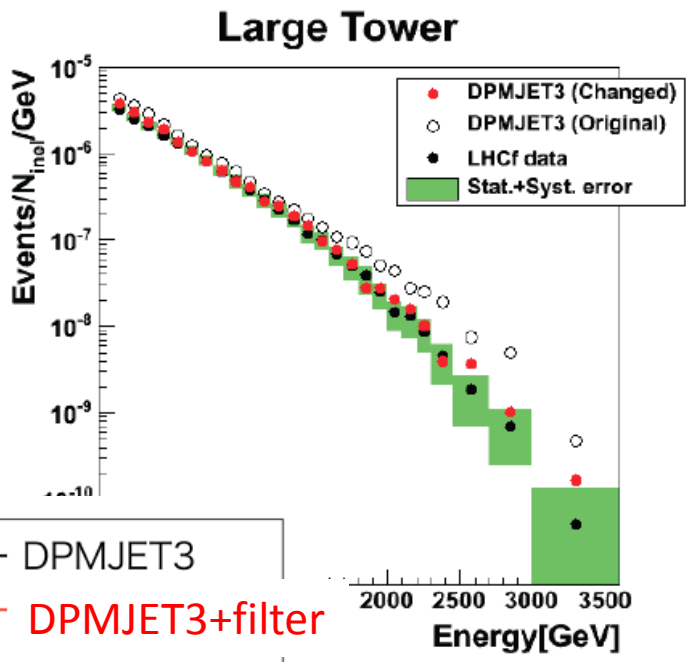
Courtesy of K. Kawade (Nagoya U, STE lab.)

No rapidity selection
No efficiency correction
Only statistical error

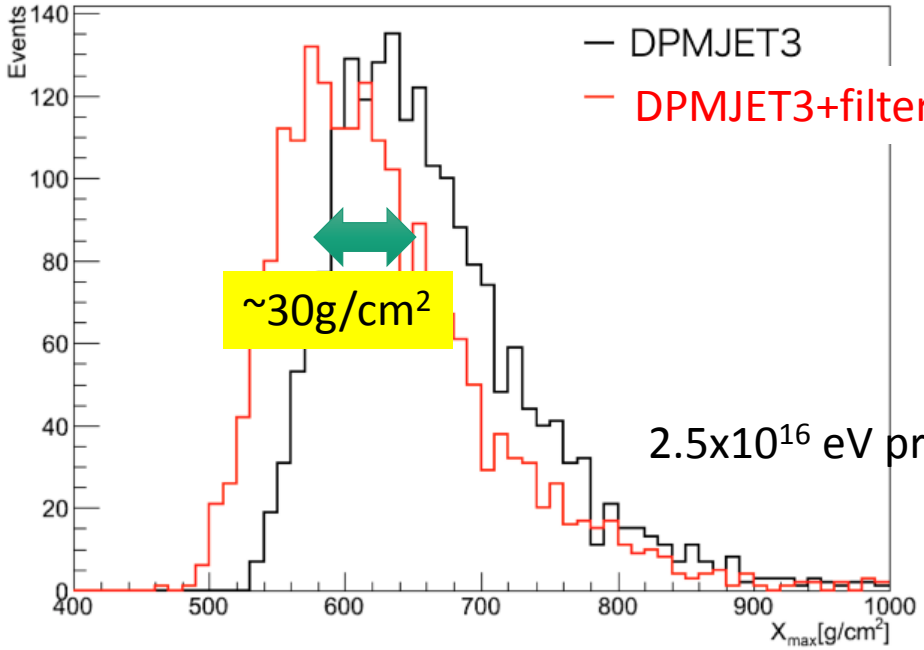
Example of model modification(1)



π^0 spectrum



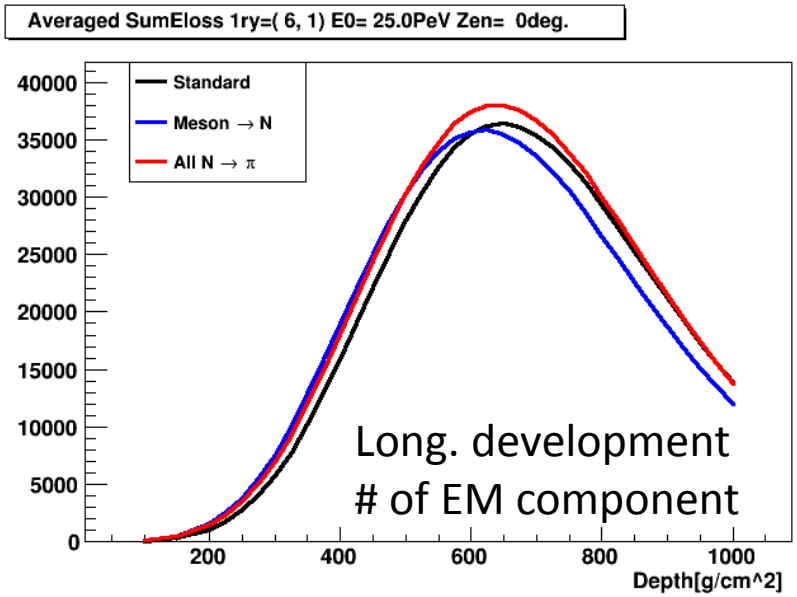
photon spectrum

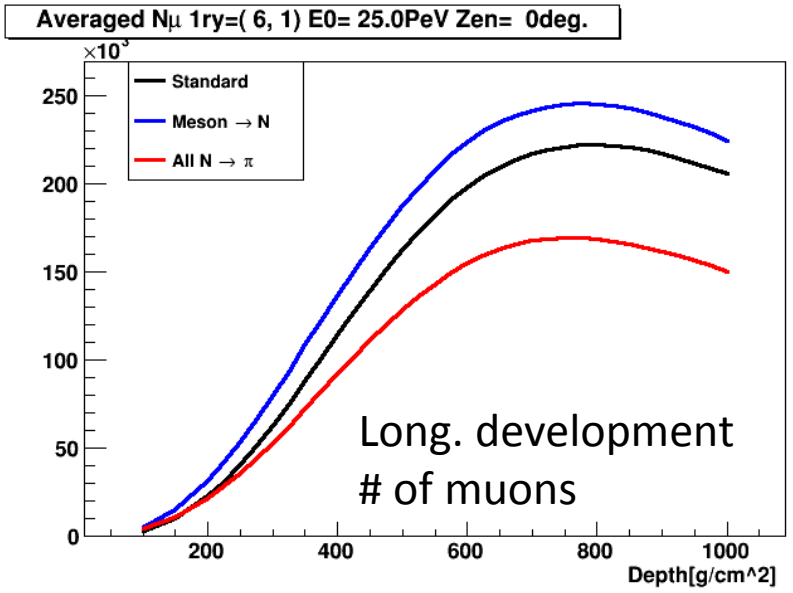


2.5x10^{16} eV proton

Example of model modification(2)

- Toy model study of nucleon contribution
  - High rapidity & high energy pions are changed to nucleon (Blue case).
  - All nucleons are changed to pions (Red case).





More realistic modification studies are going on now.

Summary

- Latest results of TA shows
  - Spectrum shape & Xmax study are consistent with proton primary case.
  - There is some hint of source in arrival direction distribution.
- Hadronic interaction study is very important for interpretations of UHECR observation.
  - Uncertainty of composition study.
  - Anomalies of air shower observables.
- Hadrons in very forward region affects the air shower development.
  - LHCf data will improve the UHECR observation.