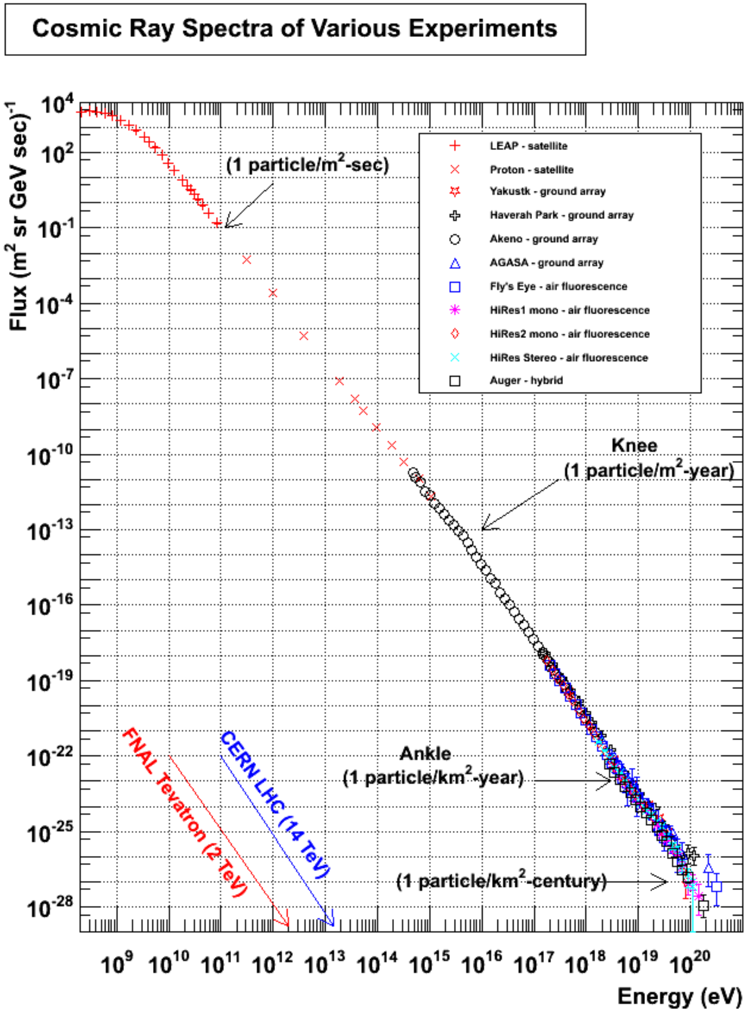
The Composition of Ultra High Energy Cosmic Rays Through Hybrid Analysis at Telescope Array

Elliott Barcikowski
PhD Defense
University of Utah, Department of Physics and Astronomy
Thursday, September 29th, 2011

What are cosmic rays?

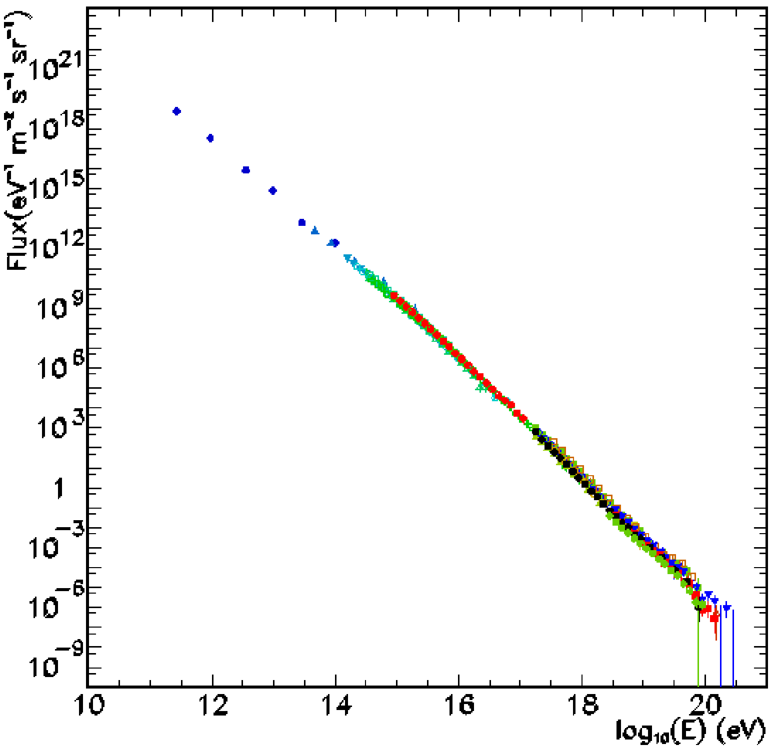
- Relativistic atomic nuclei originating outside the Solar System
  - "Ultra High Energy" → $E > 10^{17}$eV
- First discovered by Victor Hess by measuring radiation in high altitude balloon flights (1911-1913)
  - Awarded the Nobel Prize in physics in 1936
- Produced by the most energetic processes in the Universe
  - Galactic: Super novae
  - Extragalactic: Active Galactic Nuclei

The All-Particle Spectrum



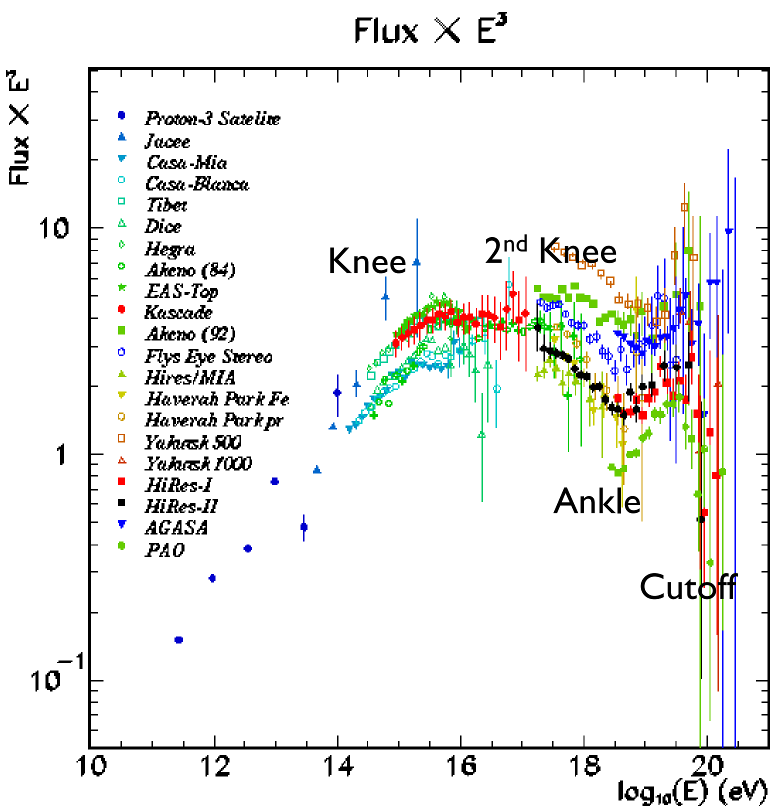
- Steady power law over many decades in energy
- Large flux at low energies
- Low flux for Ultra High Energies
- Much higher in energy than may be produced in an accelerator

The All-Particle Spectrum



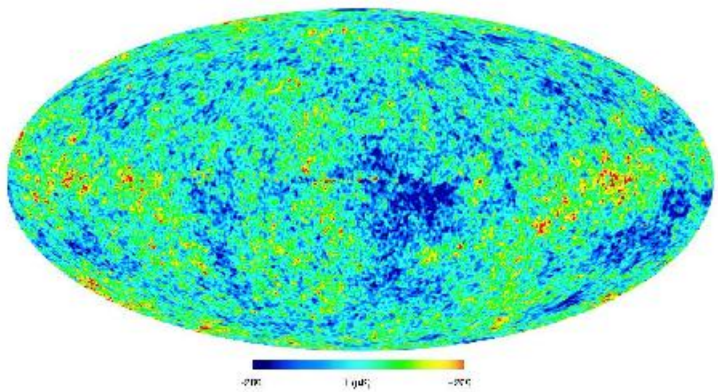
- Four clearly defined spectral features
  - Knee
  - 2nd Knee
  - Ankle
  - Cutoff

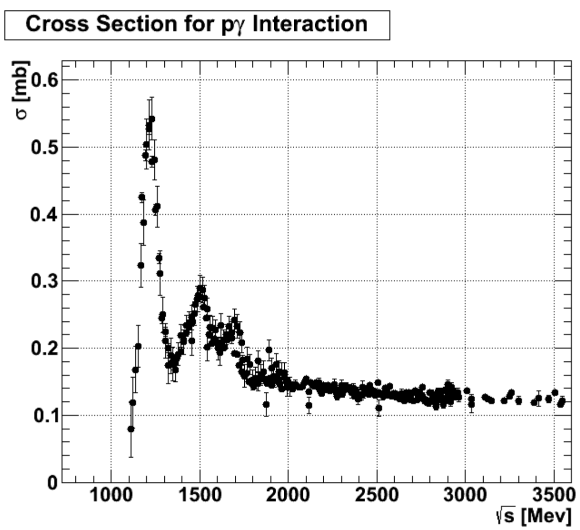
The All-Particle Spectrum



- Four clearly defined spectral features
  - Knee
  - 2nd Knee
  - Ankle
  - Cutoff

Cutoff



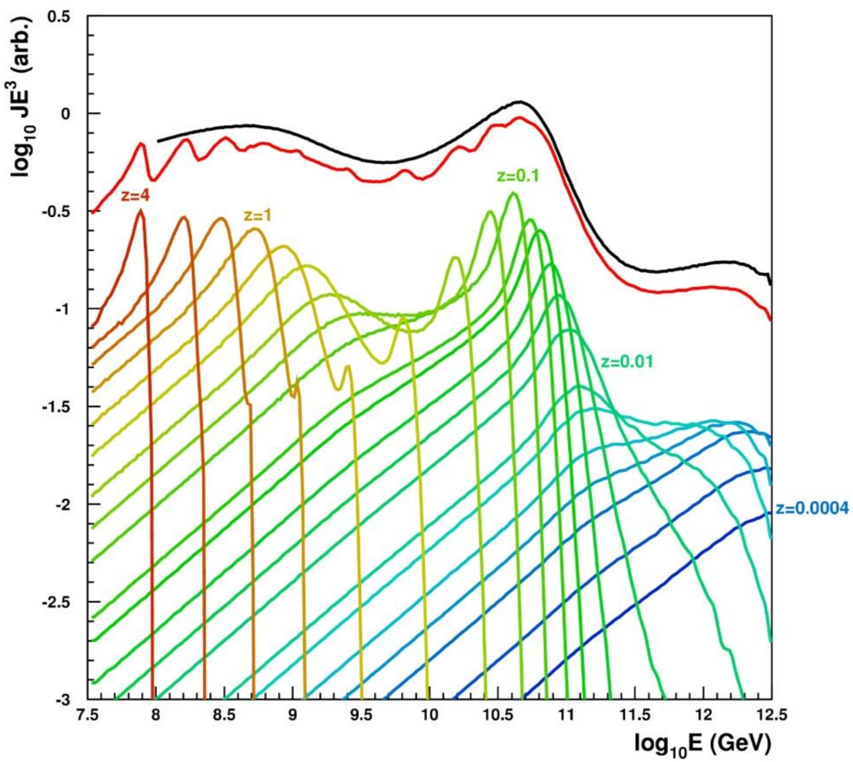


- Predicted in 1966 by Greisen, Kuzmin, and Zatsepin
  - Coined the "GZK" Cutoff

$$p^{+} + \gamma \rightarrow \Delta^{(1232)} \rightarrow \begin{cases} p^{+} + \pi^{0} \\ n + \pi^{+} \end{cases}$$

- First observed by HiRes
- Requires protons
- Alternative: acceleration limit?

Ankle



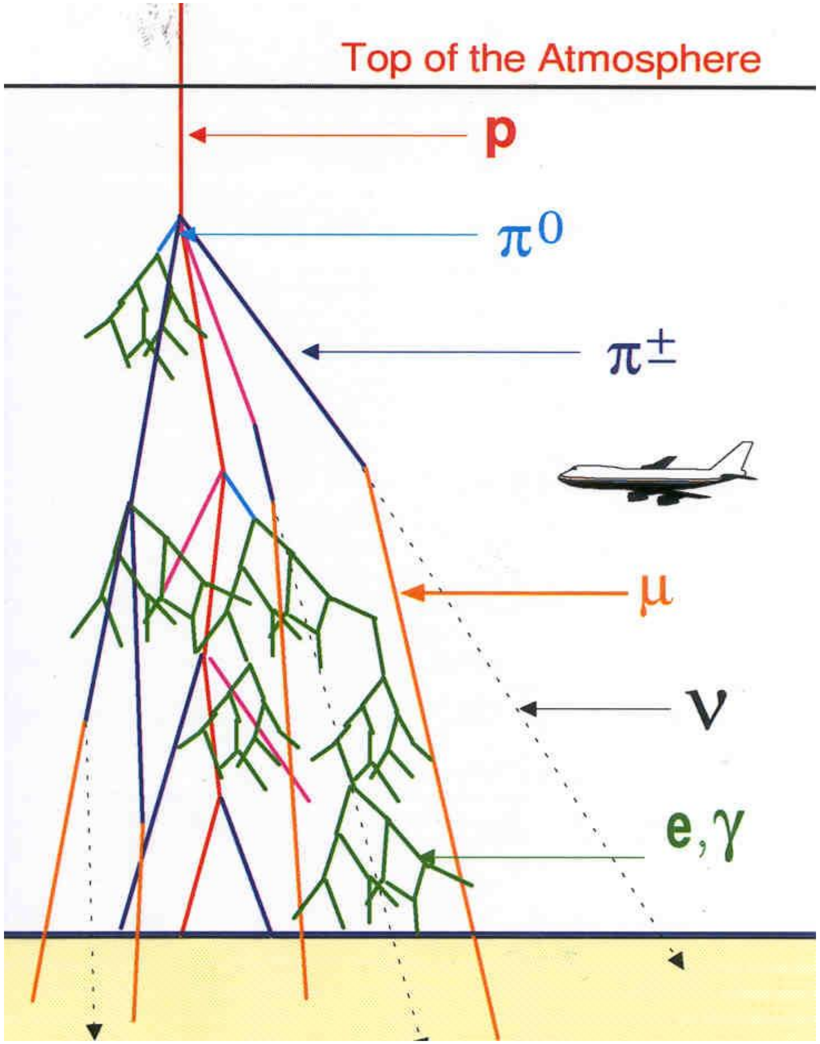
Reproduction of Berezinsky's modeled comic ray spectrum by D. Bergman

- Produced by pair production combined with GZK "pile up"
  - First shown by Berezinsky, 1988

$$p^{+} + \gamma \rightarrow p^{+} + e^{+} + e^{-}$$

- Requires protons
- Alternative: extra-Galactic transition?

The Extensive Air Shower



- Primary cosmic rays interact high in the Earth's atmosphere
  - EASs result in billions of secondary particles
- Fluorescence photons produced at core
  - May be observed with telescopes in the UV
- Many particles reach the ground
  - May be observed with ground arrays

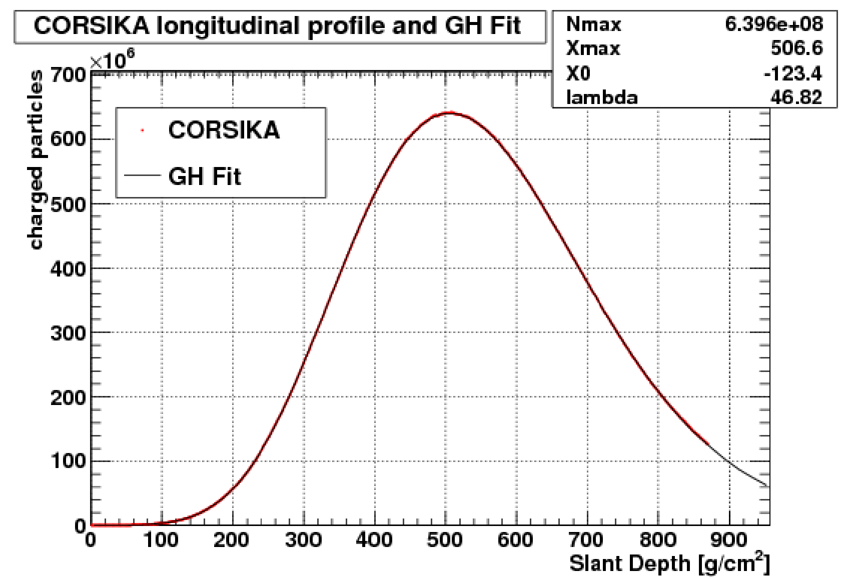
Air Shower Simulations (CORSIKA)

Simulated air shower – E = 10^{15} eV proton, $\theta = 45^\circ$

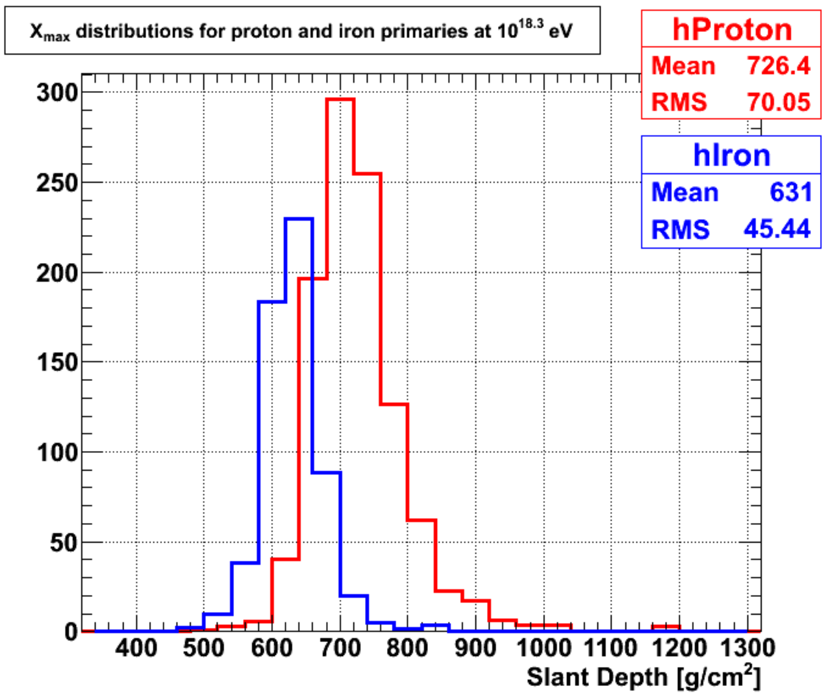
red – $e^{+/-}$, γ
green – $\mu^{+/-}$
blue – hadrons ($\pi^{0/+/-}$, $K^{0/+/-}$, p, n)

Gaisser-Hillas parameterization

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

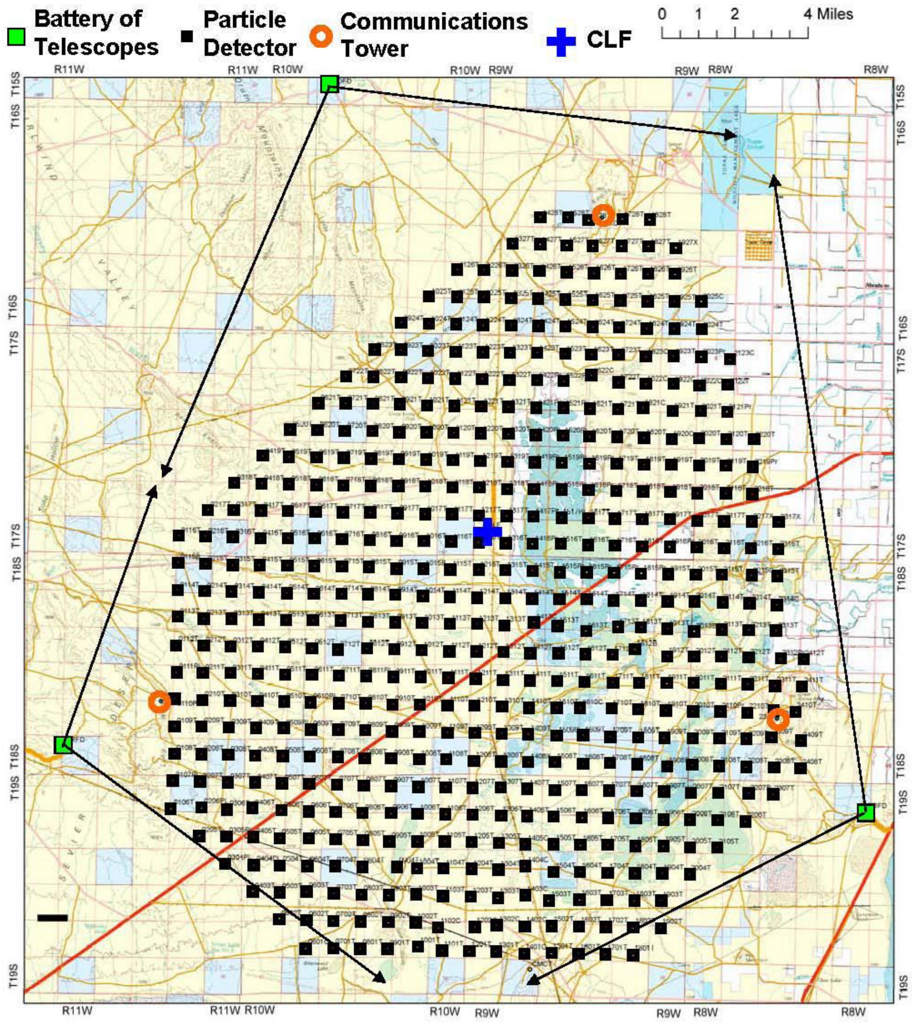


Proton and Iron X_{max} Distributions



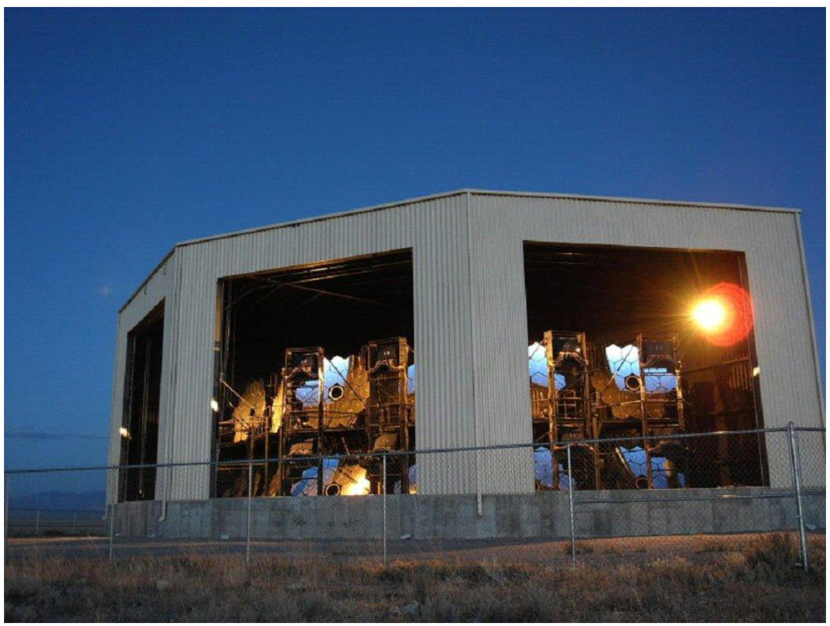
- Proton X_{max} distributions are deeper and wider than iron distributions
- Resulting iron X_{max} is narrower than that from proton primaries
- The distributions overlap
  - Good resolution in X_{max} is critical to successfully resolve composition

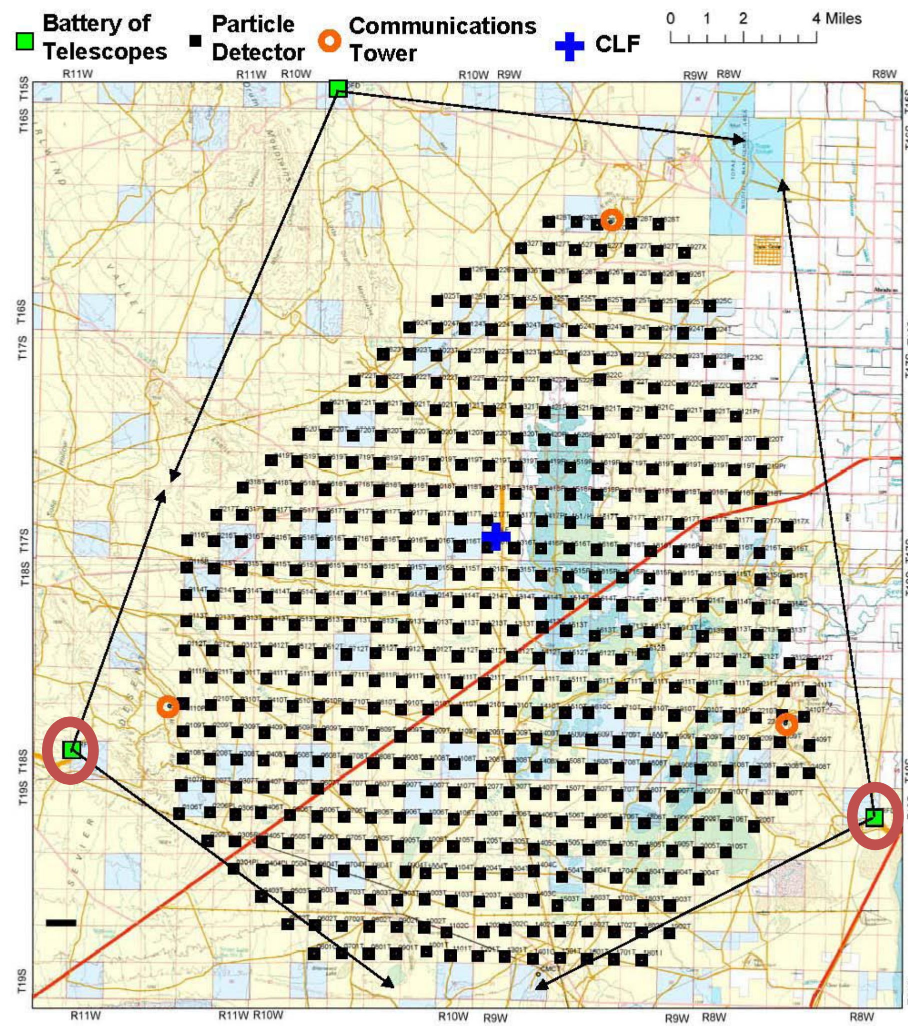
The Telescope Array Experiment



The Telescope Array Experiment

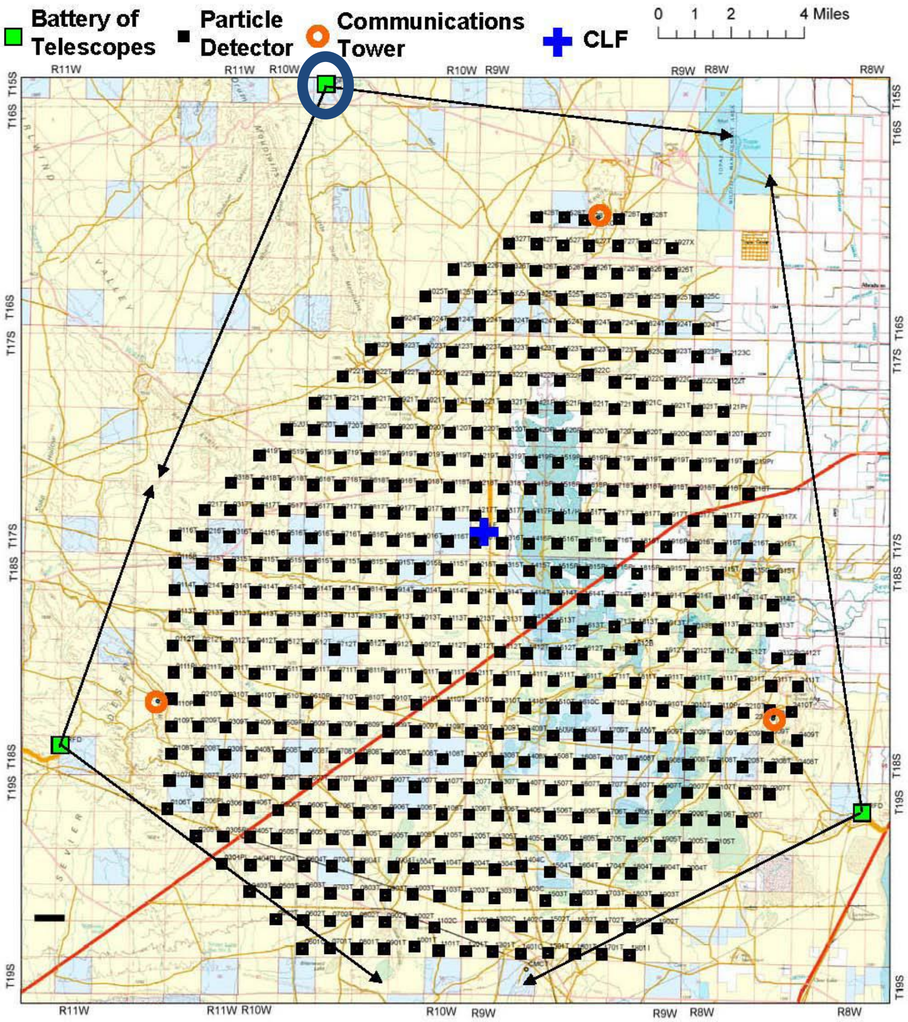
Black Rock Mesa and
Long Ridge Fluorescence
Detectors





The Telescope Array Experiment

Middle Drum
Fluorescence Detector

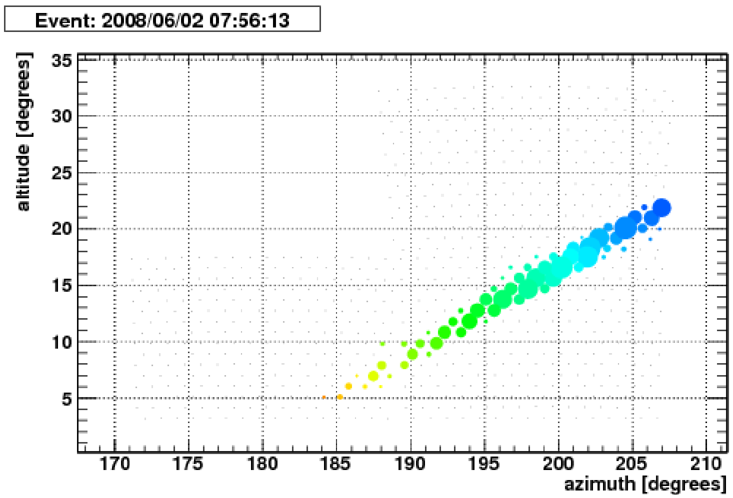


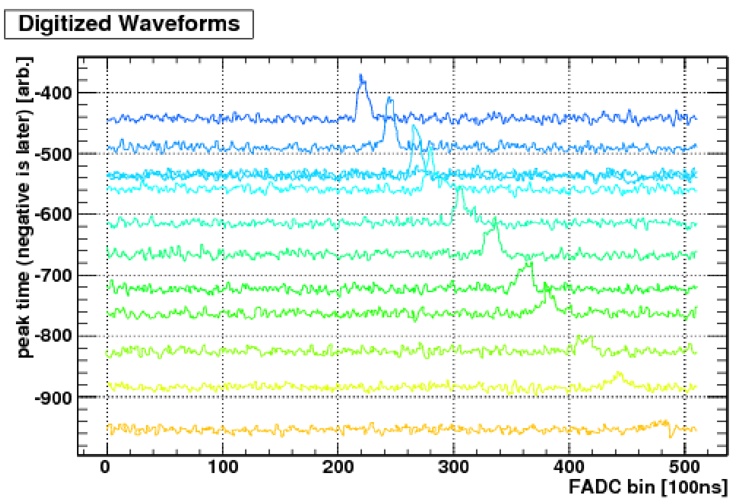
BRM/LR Fluorescence Detectors (I)

Image produced by 16x16 PMT "Cluster Box"

3.3 m diameter mirrors collect light and focus it on the cluster box

BRM/LR Fluorescence Detectors (II)



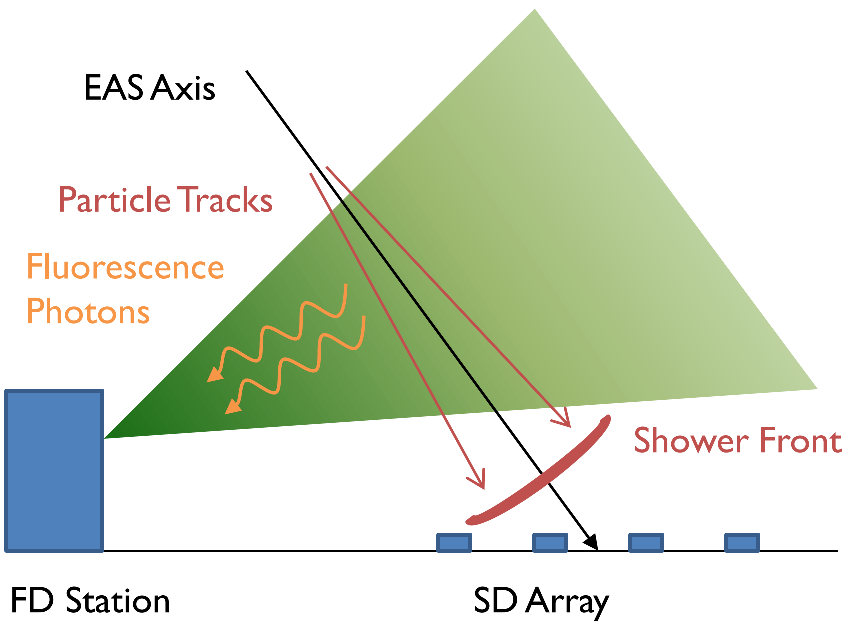


- PMT provide 2D image with ~1° angular resolution
- FADC digitization provides a PMT "trace" with 100 ns binning

Surface Array

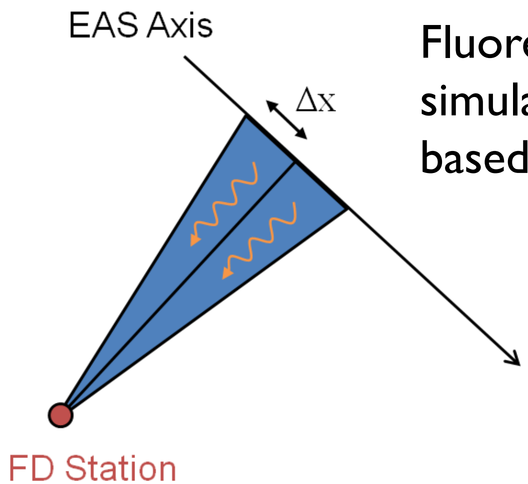
- 2 x 3 m^2 scintillator plastic
- 2 photo-multiplier tubes
  - 1 per scintillator layer
- Self powered with solar panels
- Radio communication facilitates data acquisition and trigger

The Telescope Array Hybrid Detector



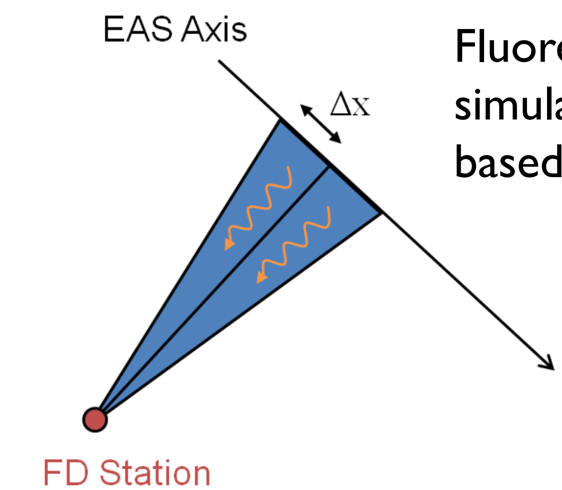
- FD observes longitudinal development close to shower core
- SD observes lateral distributions of particles
- Hybrid data allows for the observation of X_{max} with well constrained geometries.

Detector Simulation

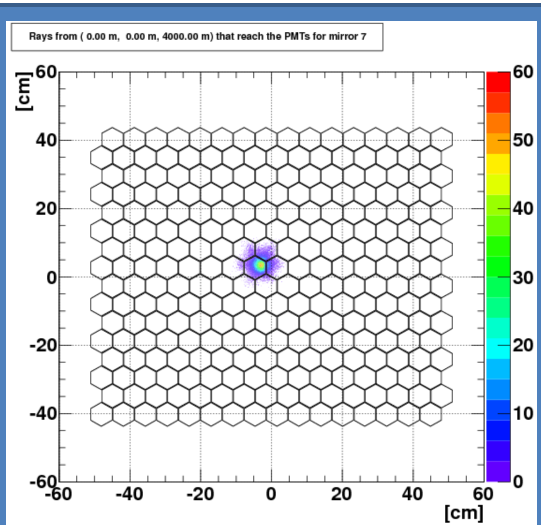


Fluorescence photons are simulated on shower axis based on GH parameters

Detector Simulation

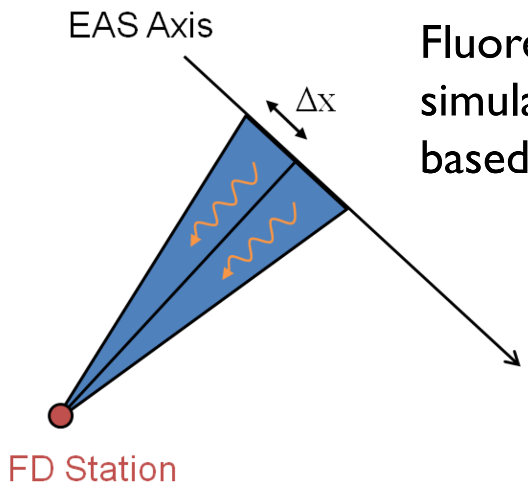


Fluorescence photons are simulated on shower axis based on GH parameters

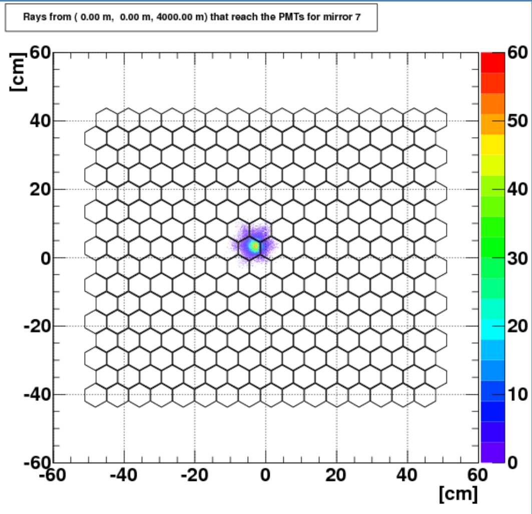


Ray-tracing ensures correct treatment of optics

Detector Simulation

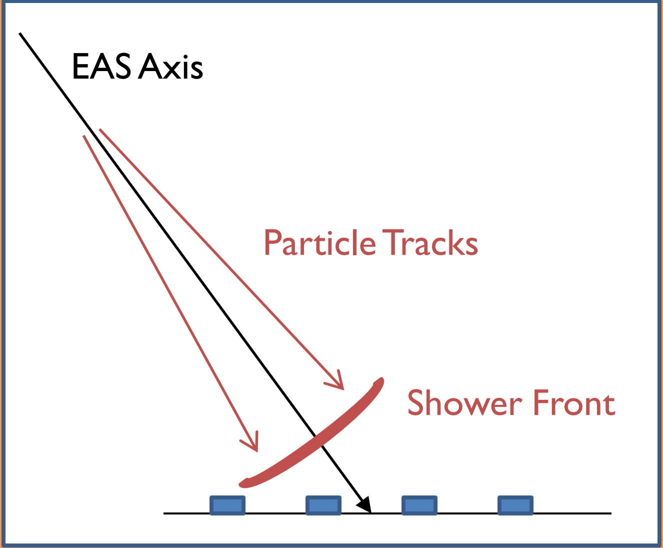


Fluorescence photons are simulated on shower axis based on GH parameters

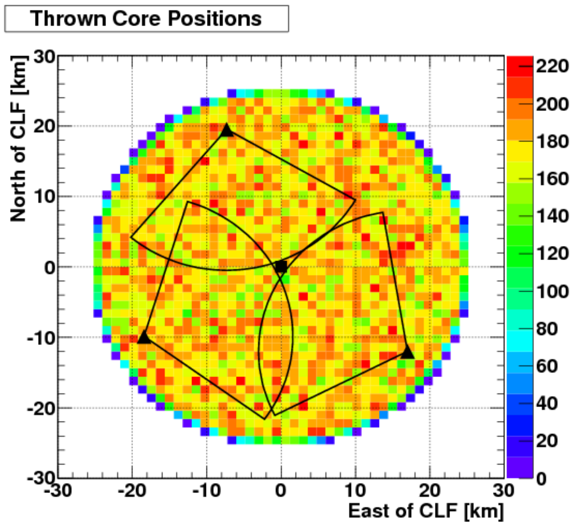


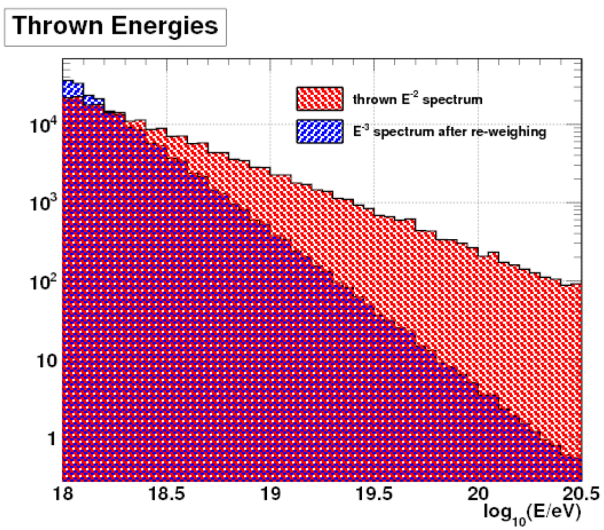
Ray-tracing ensures correct treatment of optics

Secondary particles from CORSIKA simulations are thrown against a simulated SD array



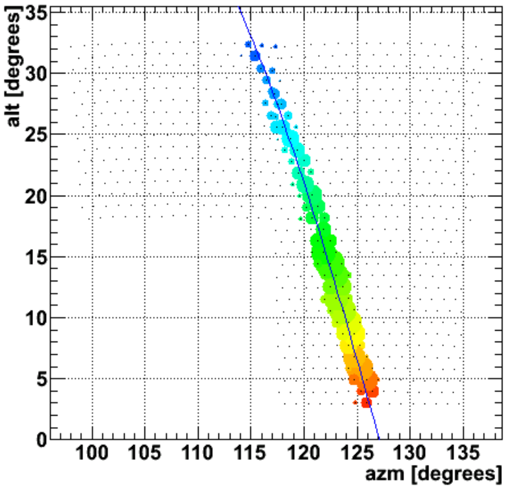
Thrown MC Distributions





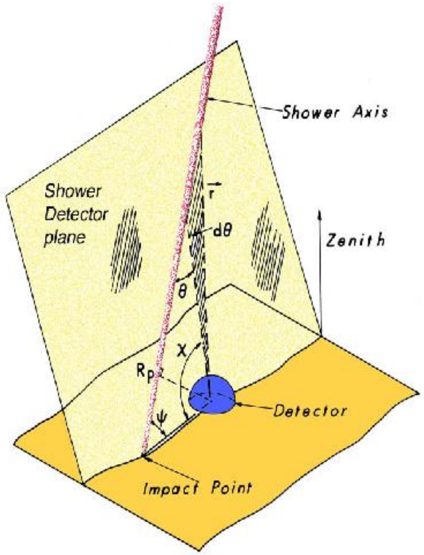
- Simulated MC distributions must reflect underlining physics
- Must test the boundaries of the detector
- Data and MC are identical
  - Both are reconstructed with the SAME programs
- Distributions from MC must match those in the data!

Hybrid Geometry Reconstruction (I)



Directions of triggered FD PMTs constrain event geometry to a Shower Detector Plane (SDP)

$$\chi^2_{SDP} = \sum_i \vec{n} \cdot \vec{t}_i w_i$$



Cosmic ray event geometries:

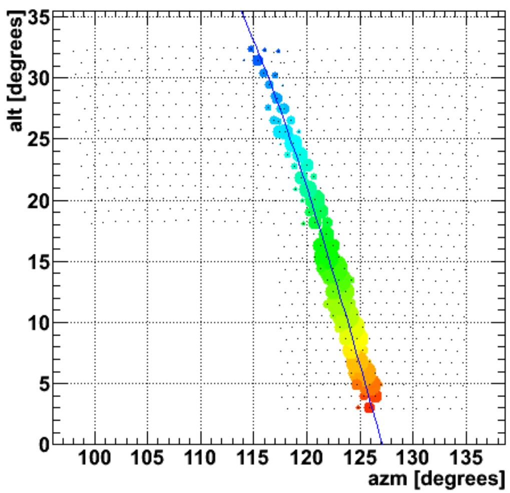
R_p -- distance of closest approach

ψ -- Angle inside SPD

t_0 -- Time at R_p

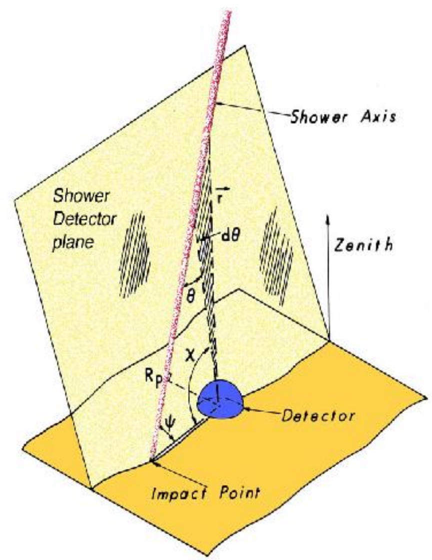
$$t(\chi) = t_0 + \frac{R_p}{c} \tan\left(\frac{\pi - \psi - \chi}{2}\right)$$

Hybrid Geometry Reconstruction (I)



Directions of triggered FD PMTs constrain event geometry to a Shower Detector Plane (SDP)

$$\chi^2_{SDP} = \sum_i \vec{n} \cdot \vec{t}_i w_i$$



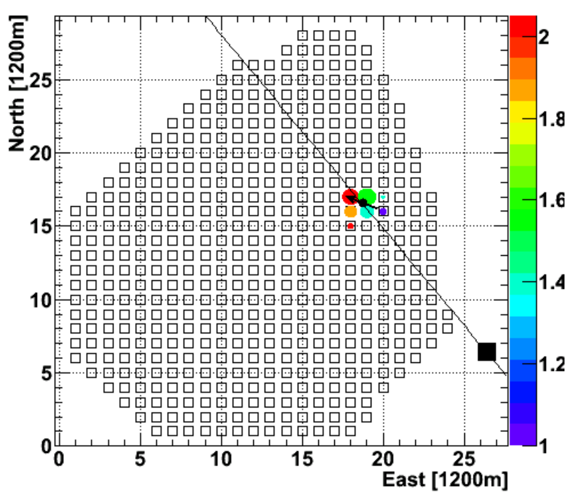
Cosmic ray event geometries:

R_p -- distance of closest approach

ψ -- Angle inside SPD

t_0 -- Time at R_p

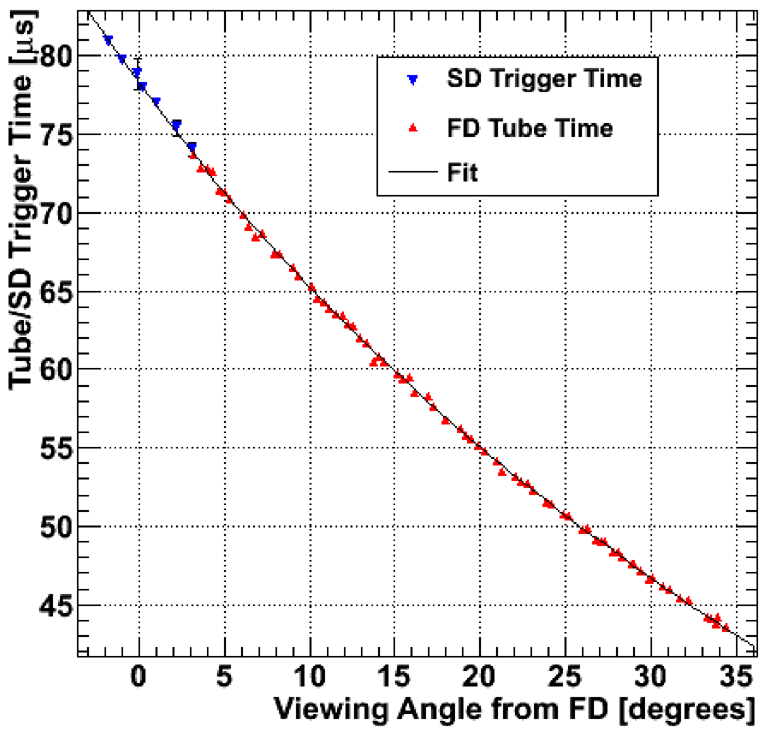
$$t(\chi) = t_0 + \frac{R_p}{c} \tan\left(\frac{\pi - \psi - \chi}{2}\right)$$



Center of charge of triggered SDs constrains the core to a center of charge

$$\chi^2_{COC} = \left(\frac{|\vec{x} - \vec{c}|}{\sigma}\right)^2$$

Hybrid Geometry Reconstruction (II)



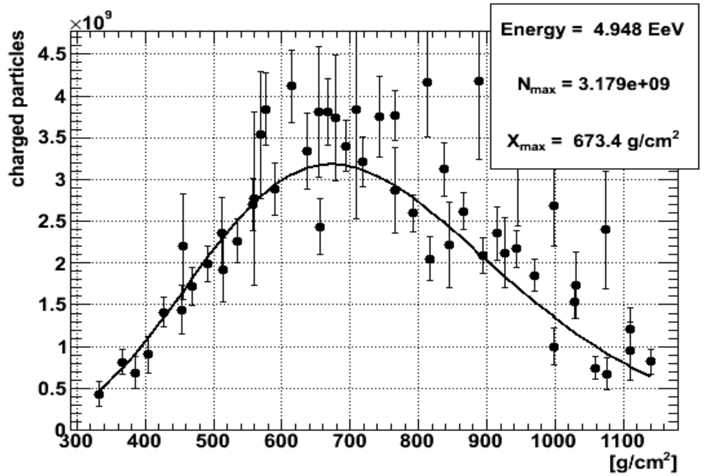
$$\chi^2_{FD} = \chi^2_{SD} = \sum_i \left(\frac{t_i - f(\chi_i)}{\sigma_i} \right)^2$$

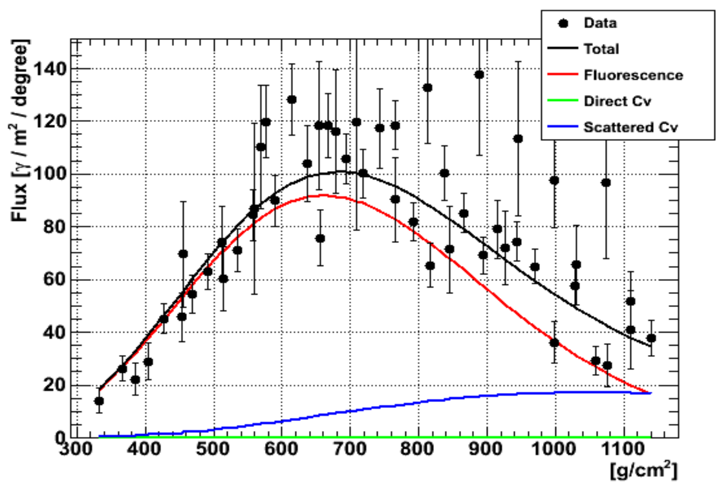
- Each triggered FD PMT and SD detector provides timing data
- Construct a 4 component χ^2 function using all available information

$$\chi^2_{GEOM}(x, y, \theta, \varphi, t_c) = \chi^2_{COC} + \chi^2_{SDP} + \chi^2_{SD} + \chi^2_{FD}$$

- Minimize in 5 parameters

Longitudinal Profile Reconstruction





- Using reconstructed geometry use Inverse Monte Carlo to find the best N_{max}, X_{max}.

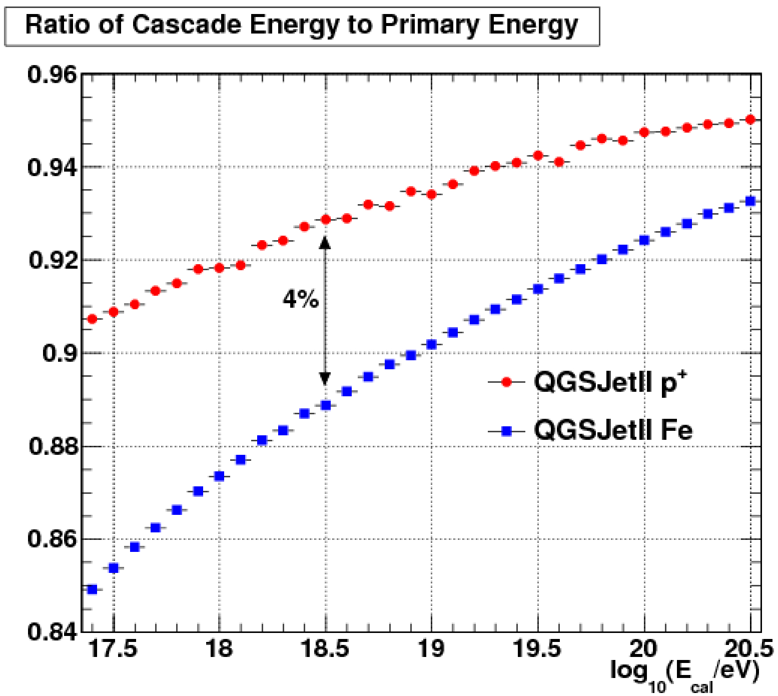
$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max} - X_0}{\lambda}} \exp\left(\frac{X_{max} - X}{\lambda}\right)$$

$$\chi^2_{PRFL}(N_{max}, X_{max}) = \sum_i \left(\frac{n_i - \Phi_i A_i}{\sigma_i}\right)^2$$

- GH fit leads to calculation of the shower energy

$$E_{cal} = \int < \frac{dE}{dX} > N(X)dx$$

Missing Energy Correction



4% difference between proton and iron simulation

- Some shower energy results in μ and ν particles and does not result in fluorescence
- This "Missing Energy" must be corrected for in reconstruction
- CORSIKA is used estimate the average missing energy

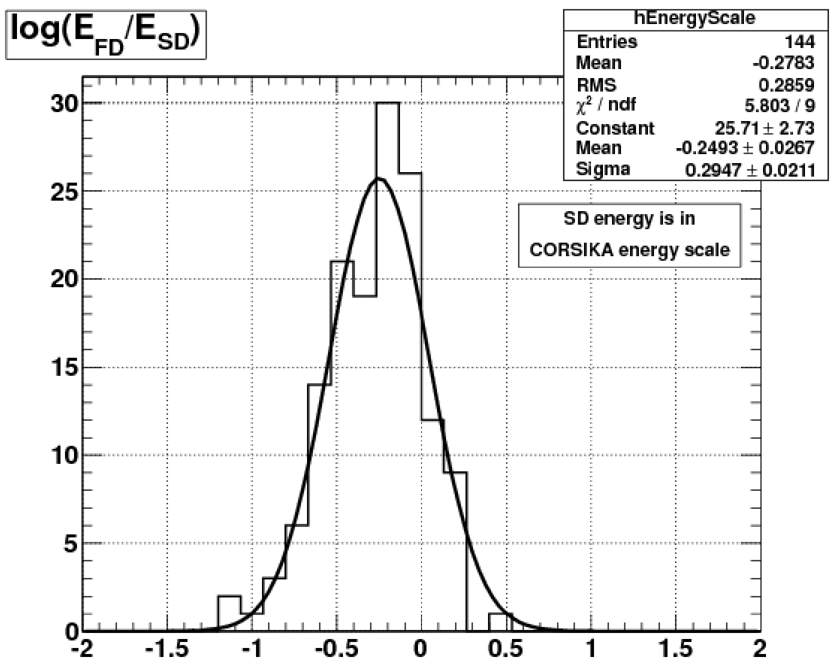
Data Set and Quality Cuts

- All hybrid data before implementation of hybrid trigger
  - May 2008 – September 2010
- Results in 454 hybrid events and 74 hybrid-stereo events

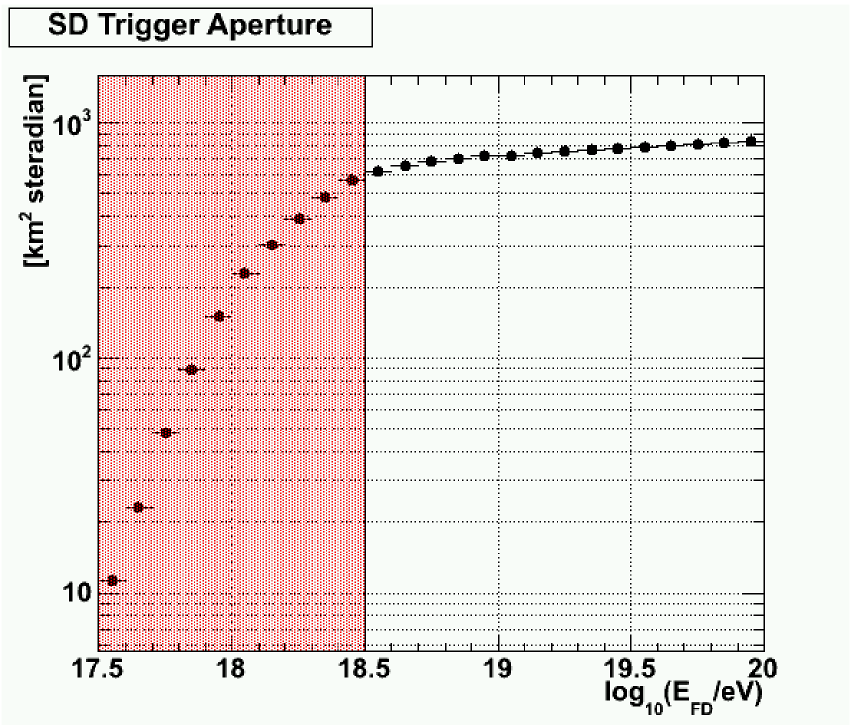
Cut	BR Events	LR Events
None	3085	2720
Good Weather	1933	1696
$E > 10^{18.5}$ eV	521	439
$\theta < 55^{\circ}$	432	327
χ^2_{geom} / DOF < 5	429	367
χ^2_{prfl} / DOF < 5	350	327
$X_{low} < X_{max} < X_{high}$	324	291
$\psi < 130^{\circ}$ && track time > $7\mu s$	294	269
core inside SD array	276	252

Energy Scale Treatment

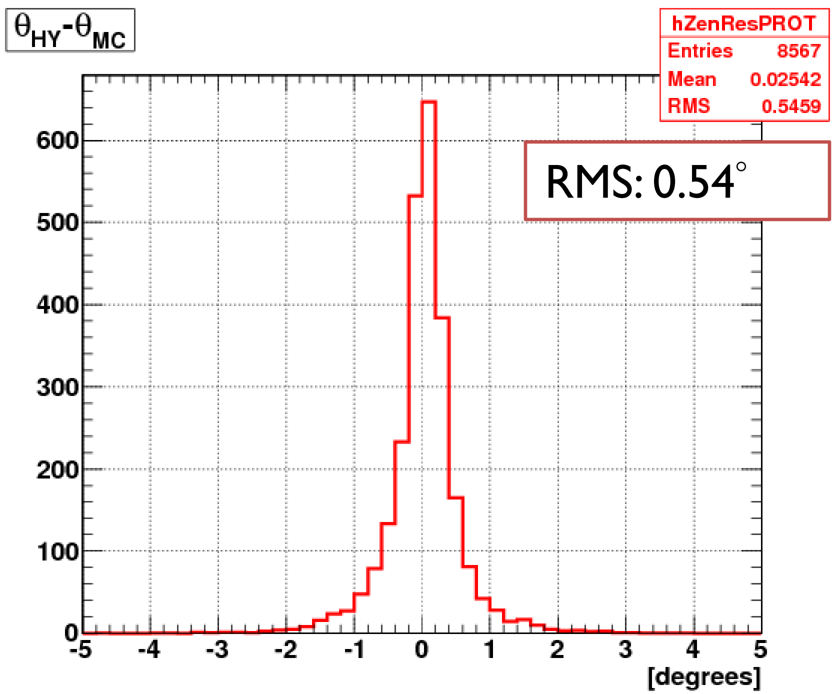
27% difference between FD and SD energies

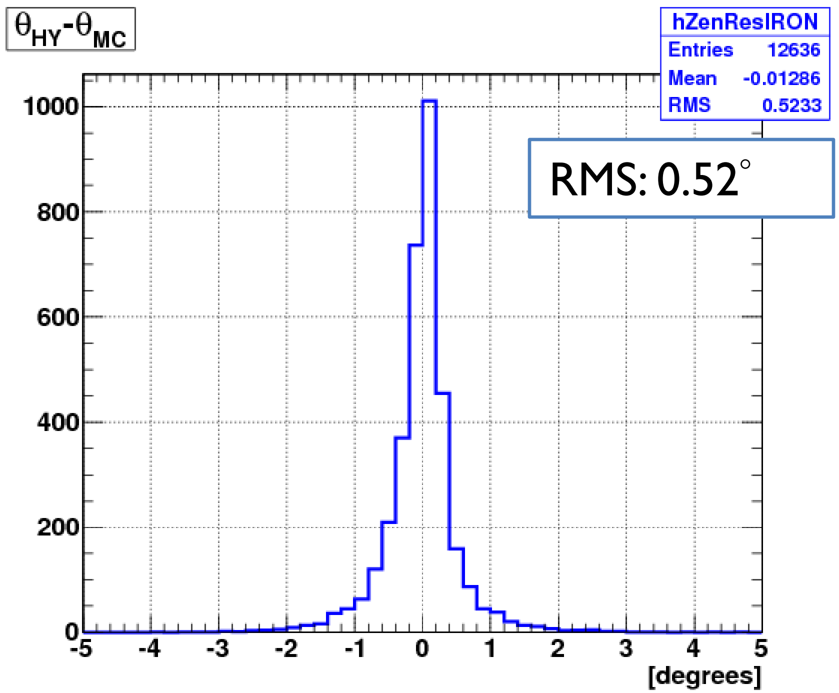


Use hybrid events where the SD trigger aperture is flat

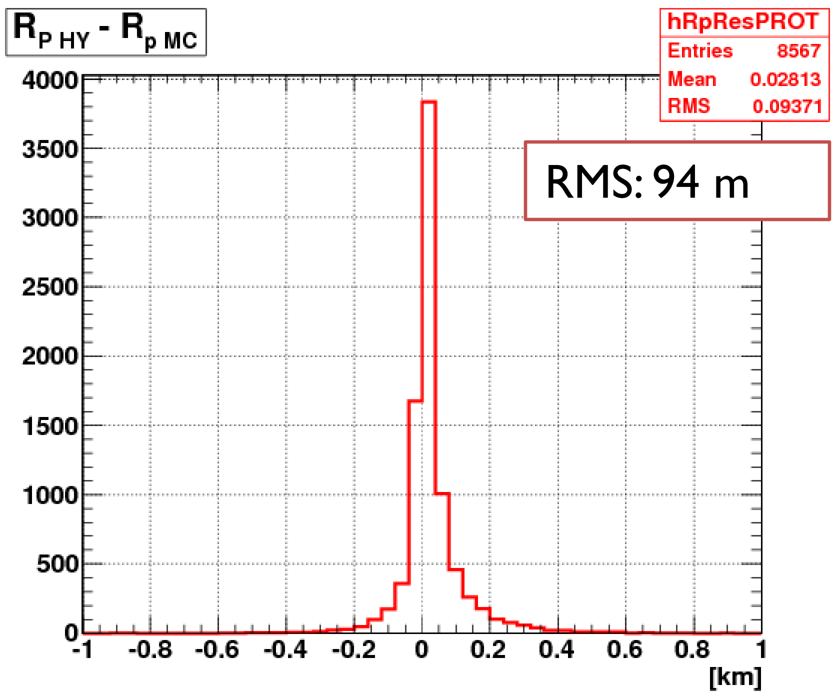


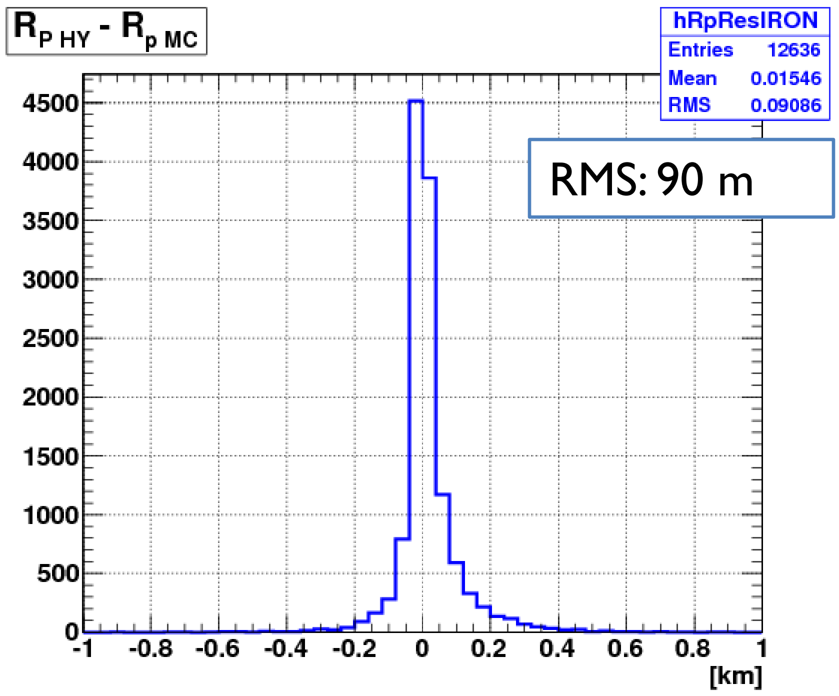
Resolution Studies (Zenith)



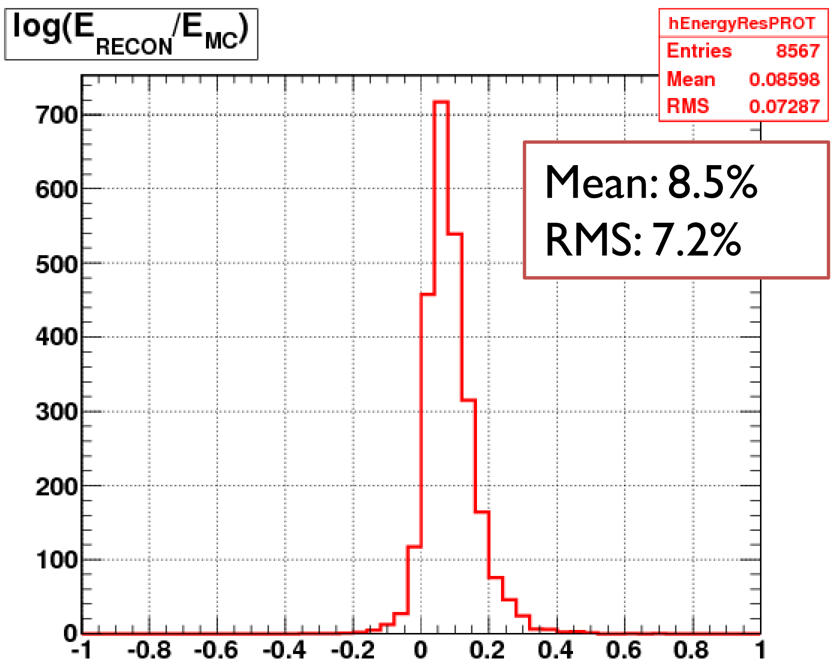


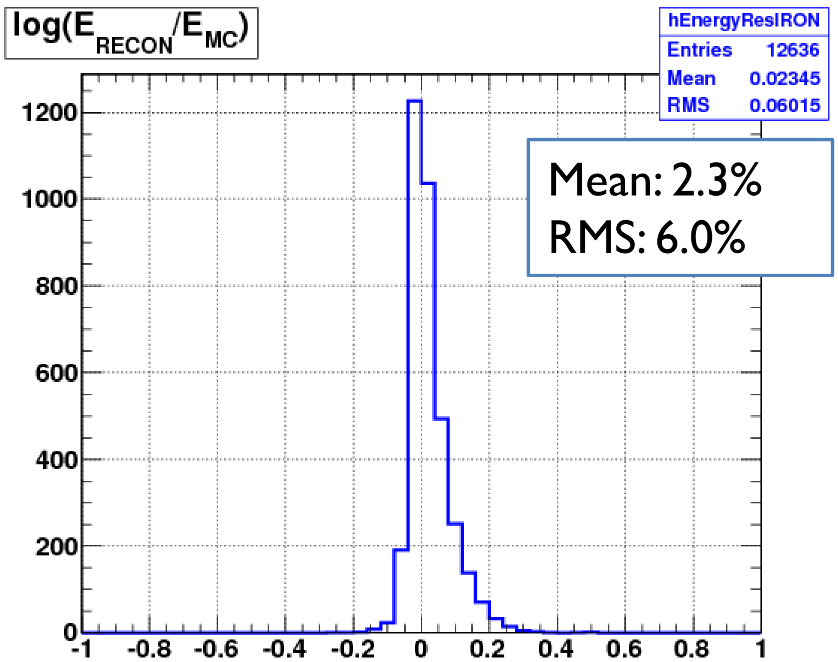
Resolution Studies (R_p)



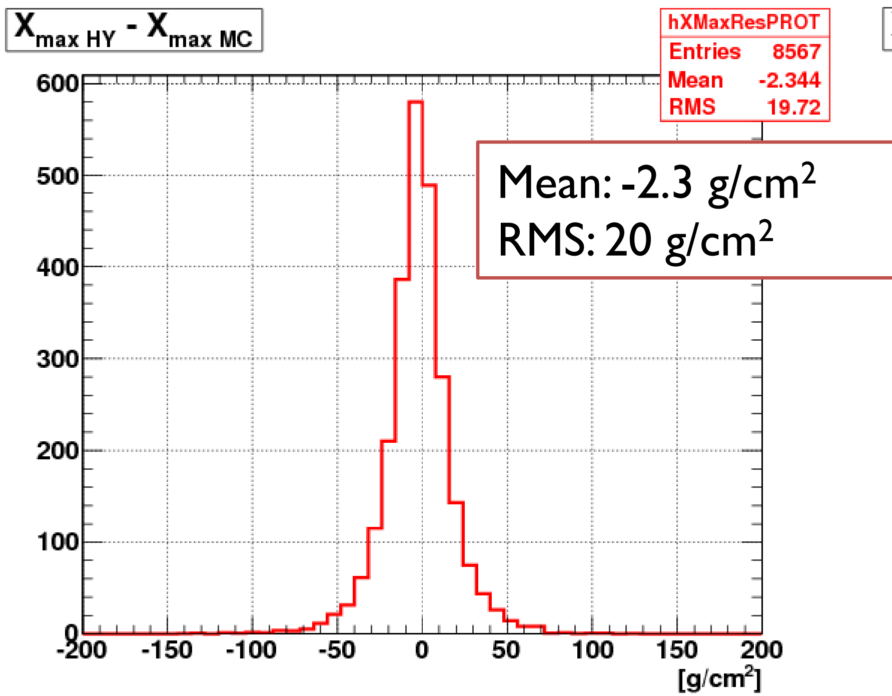


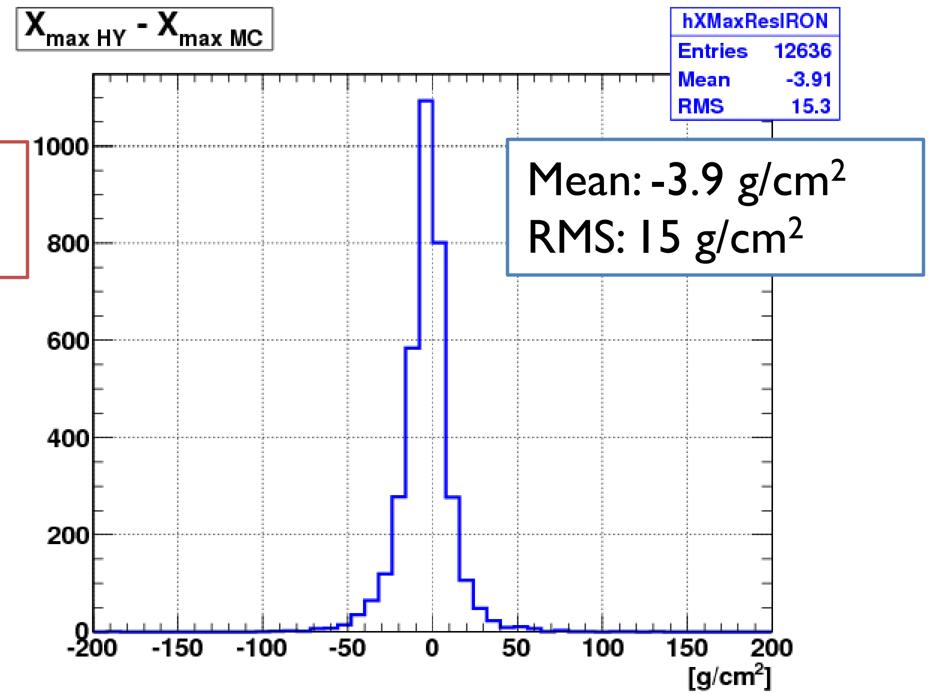
Resolution Studies (Energy)



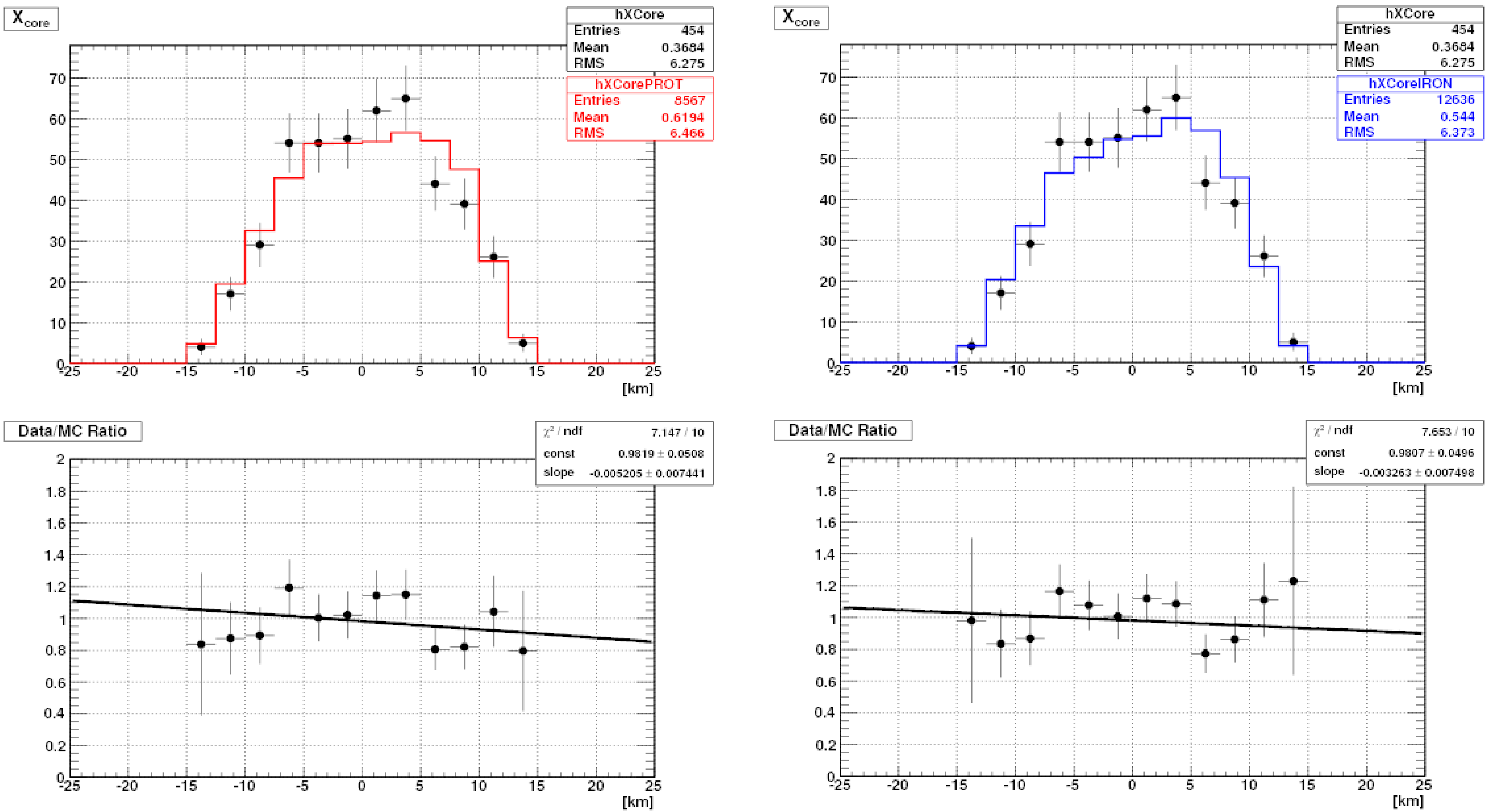


Resolution Studies (X_{max})

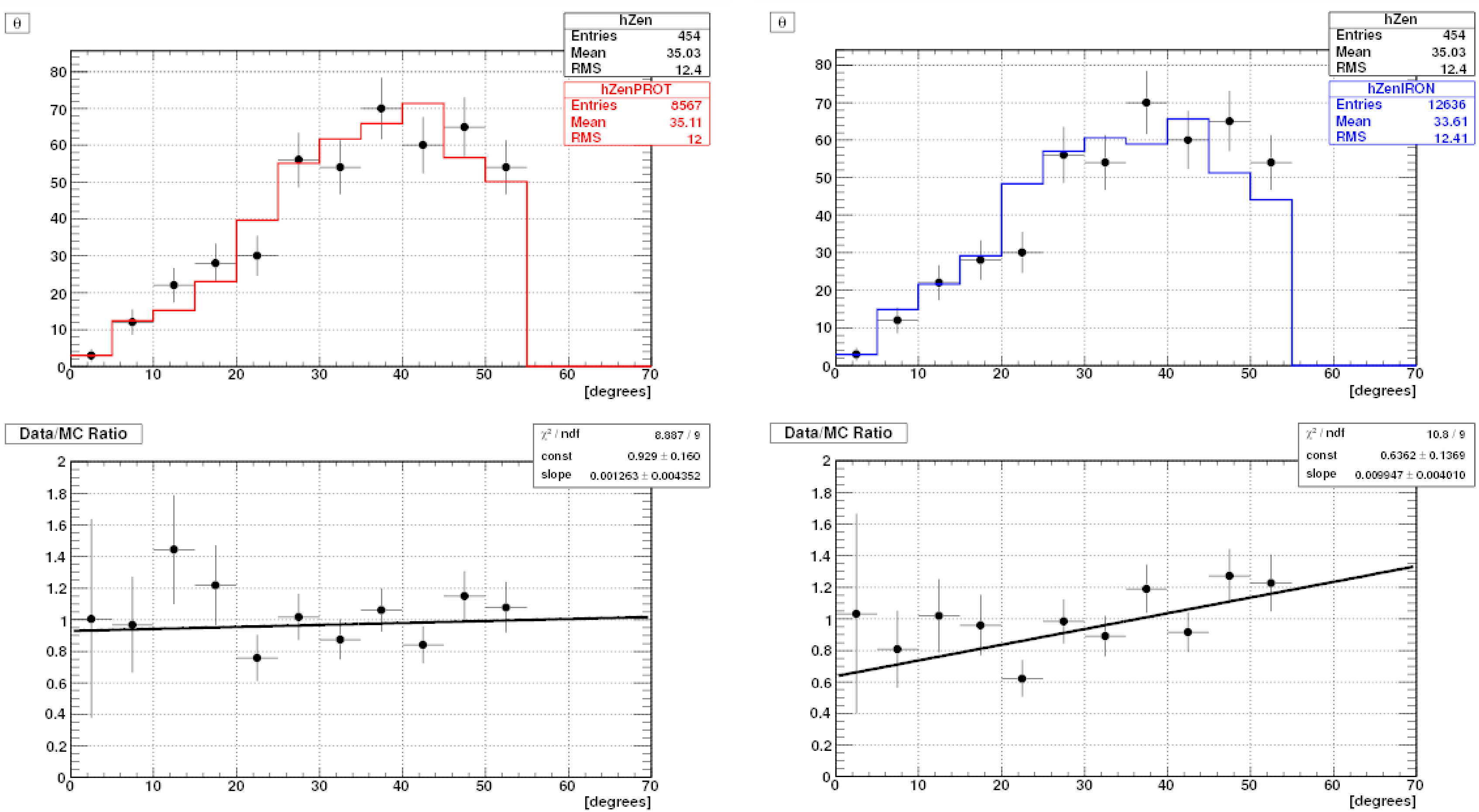




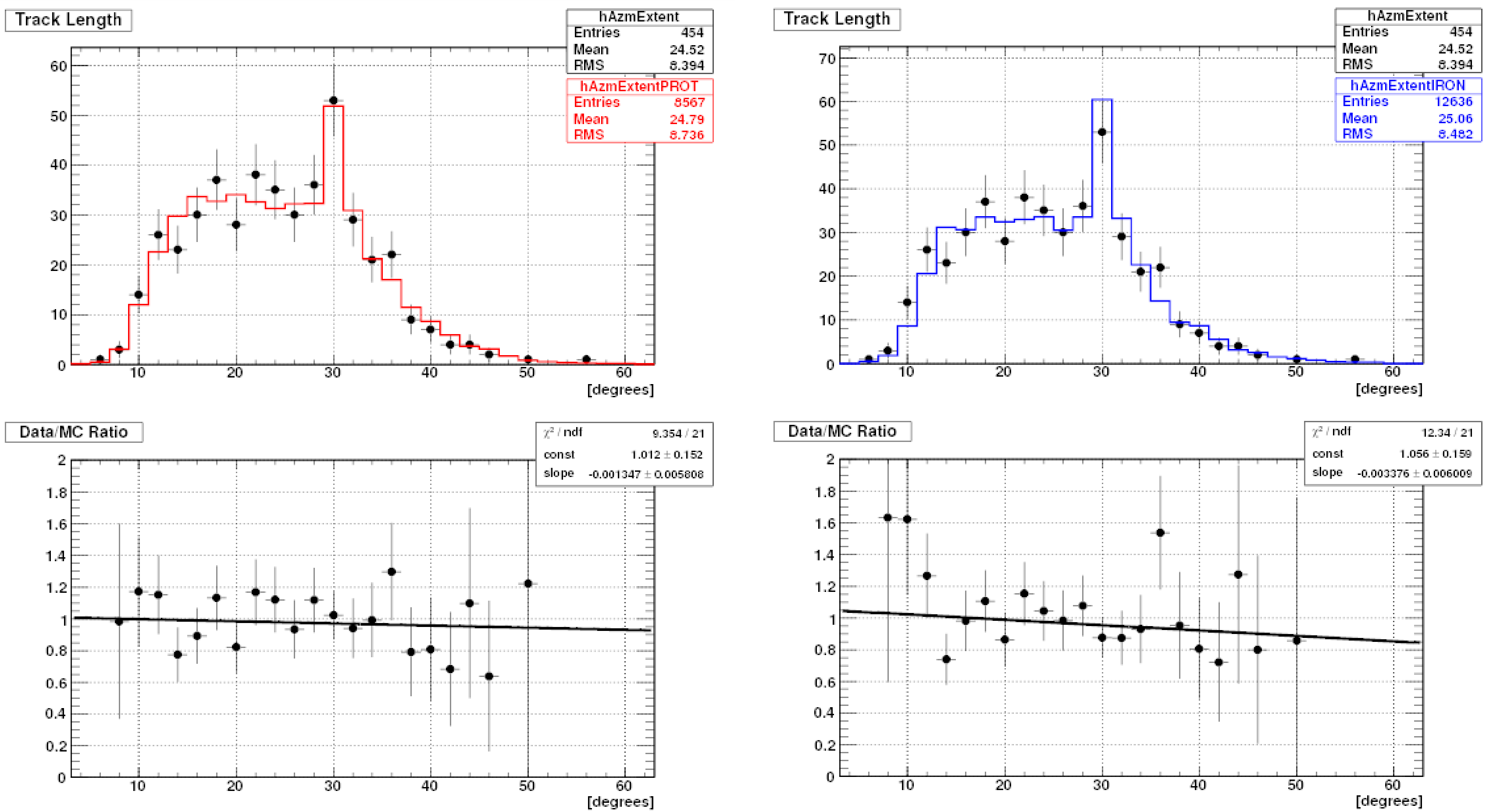
Data/Monte Carlo (X_{core})



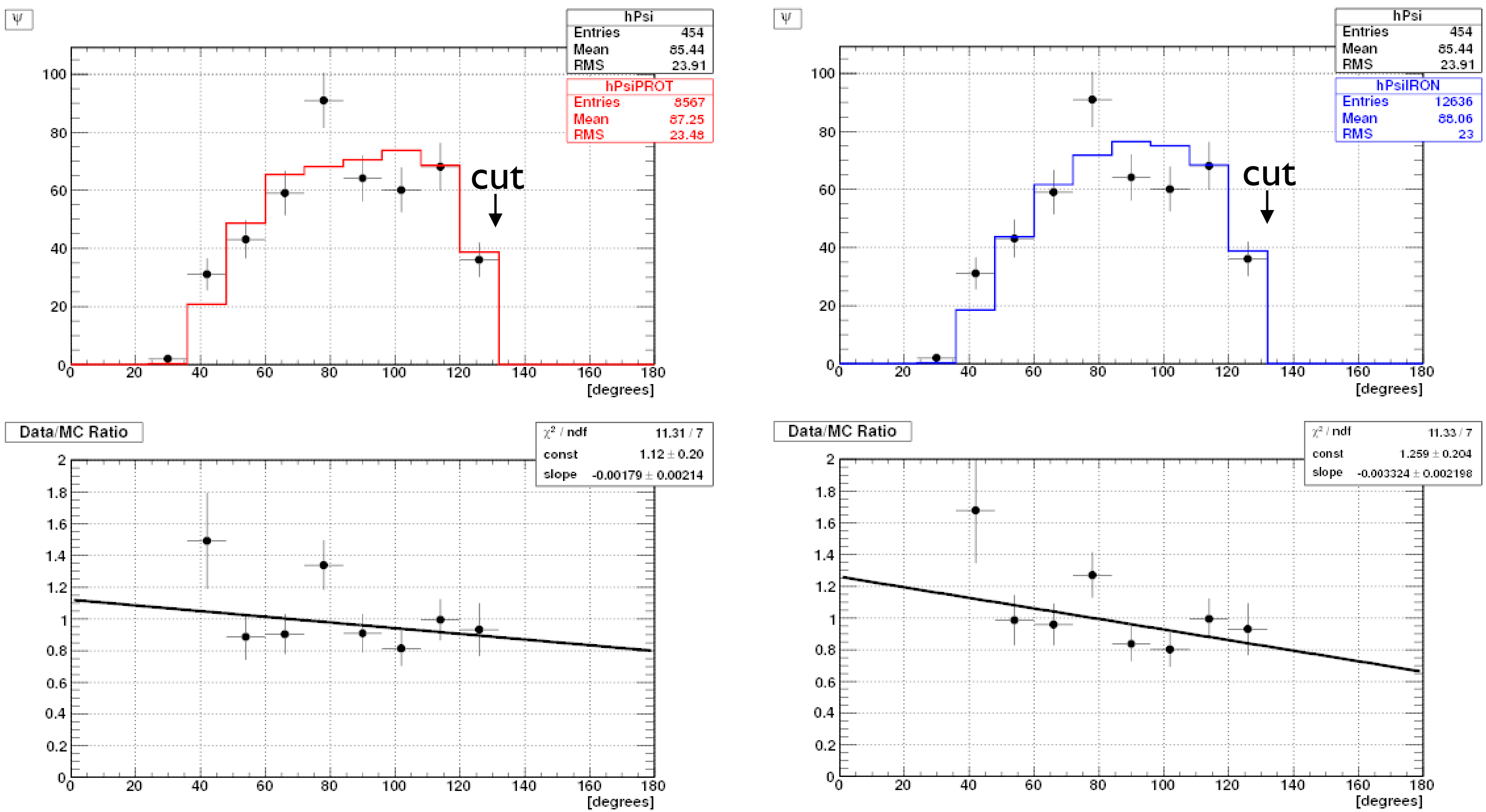
Data/Monte Carlo (Zenith Angle)



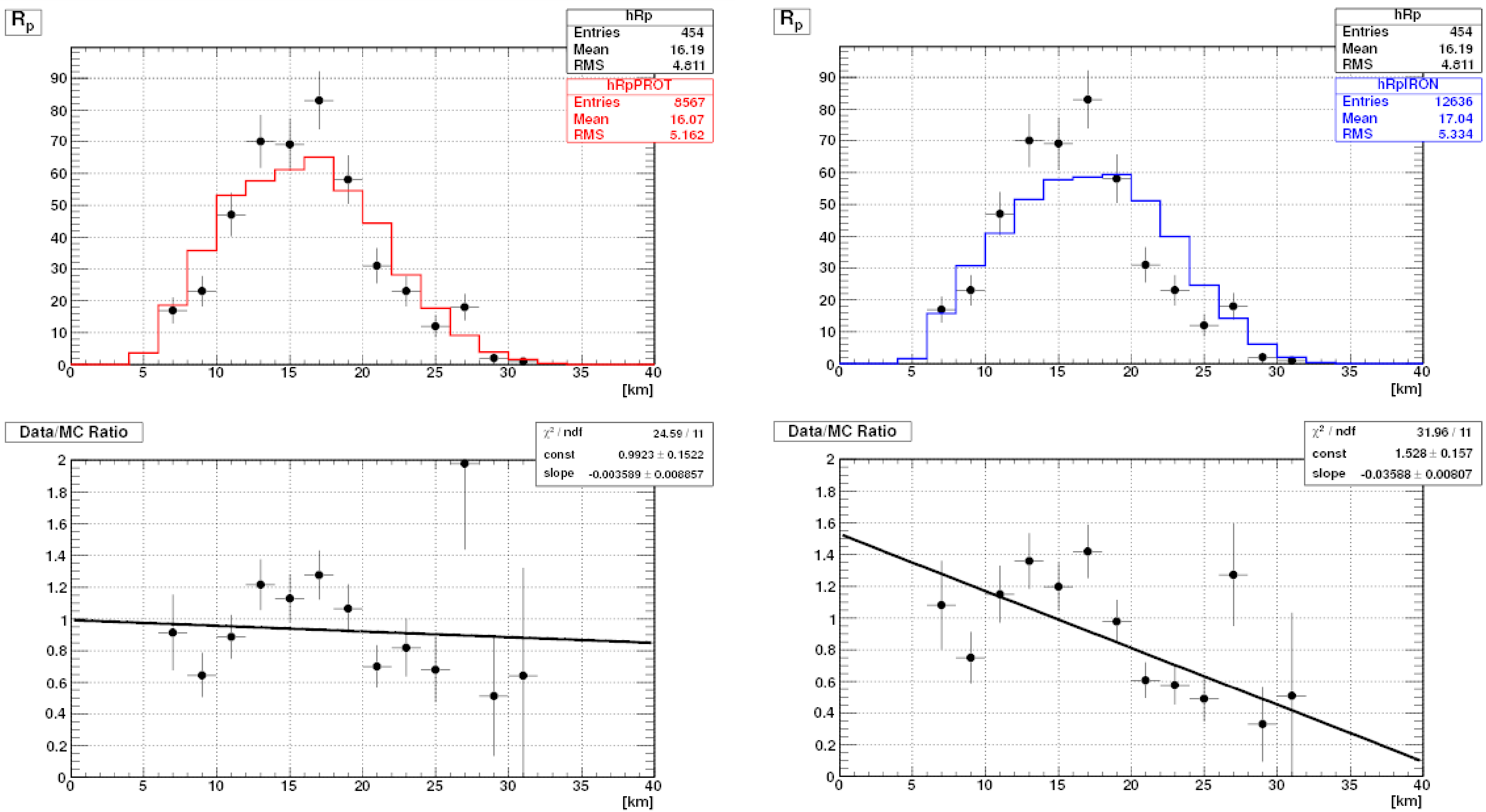
Data/Monte Carlo (Track Length)



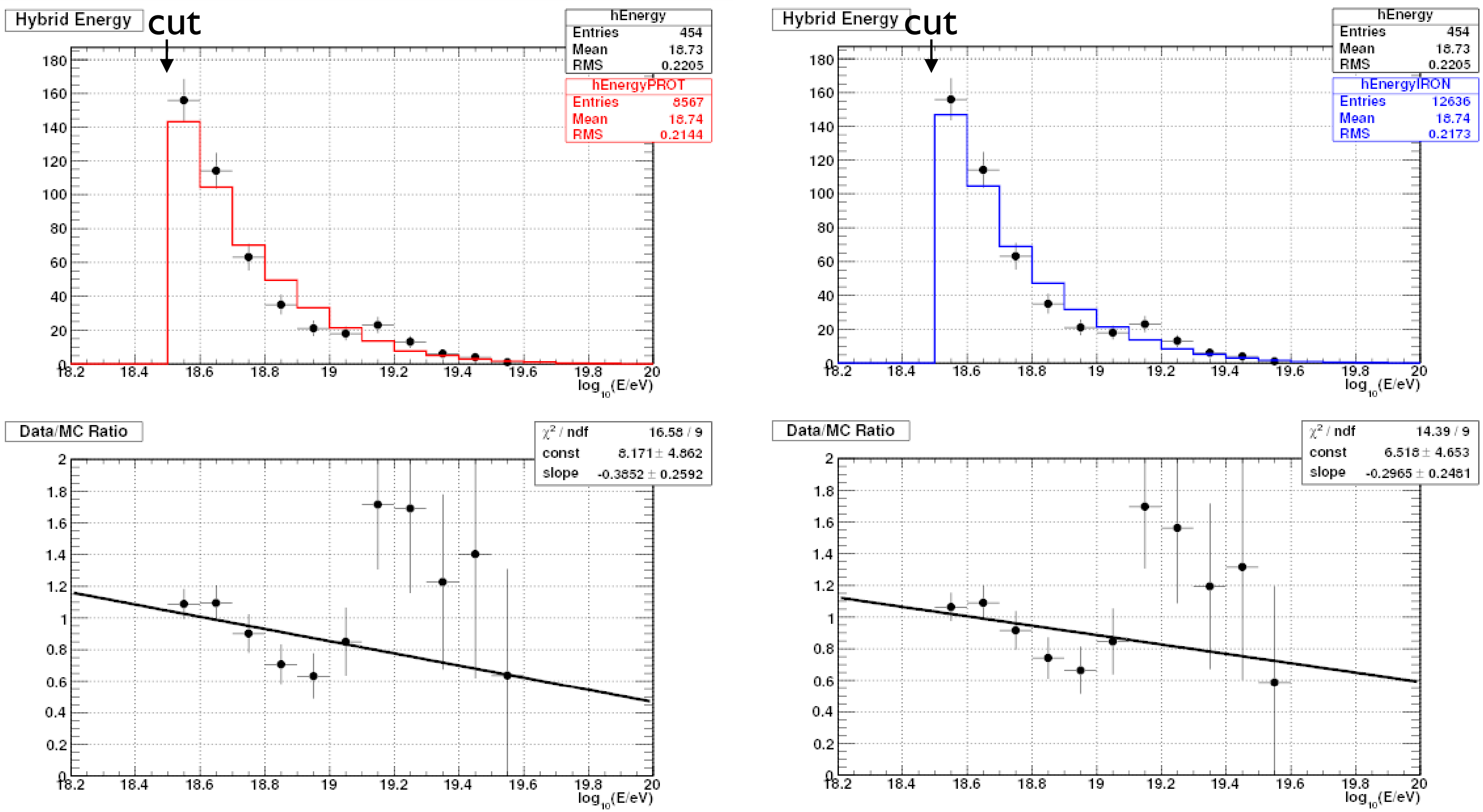
Data/Monte Carlo (ψ)



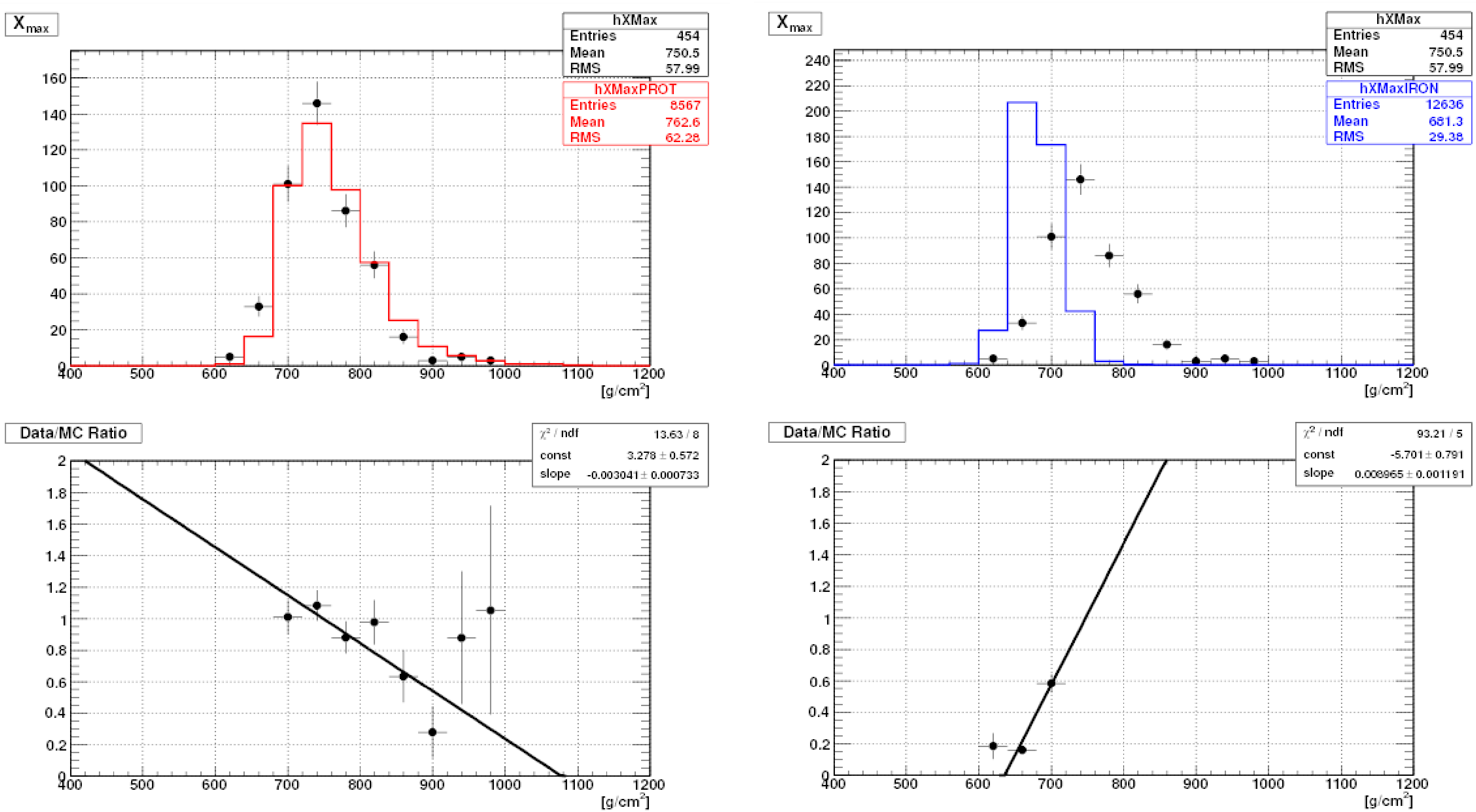
Data/Monte Carlo (R_p)



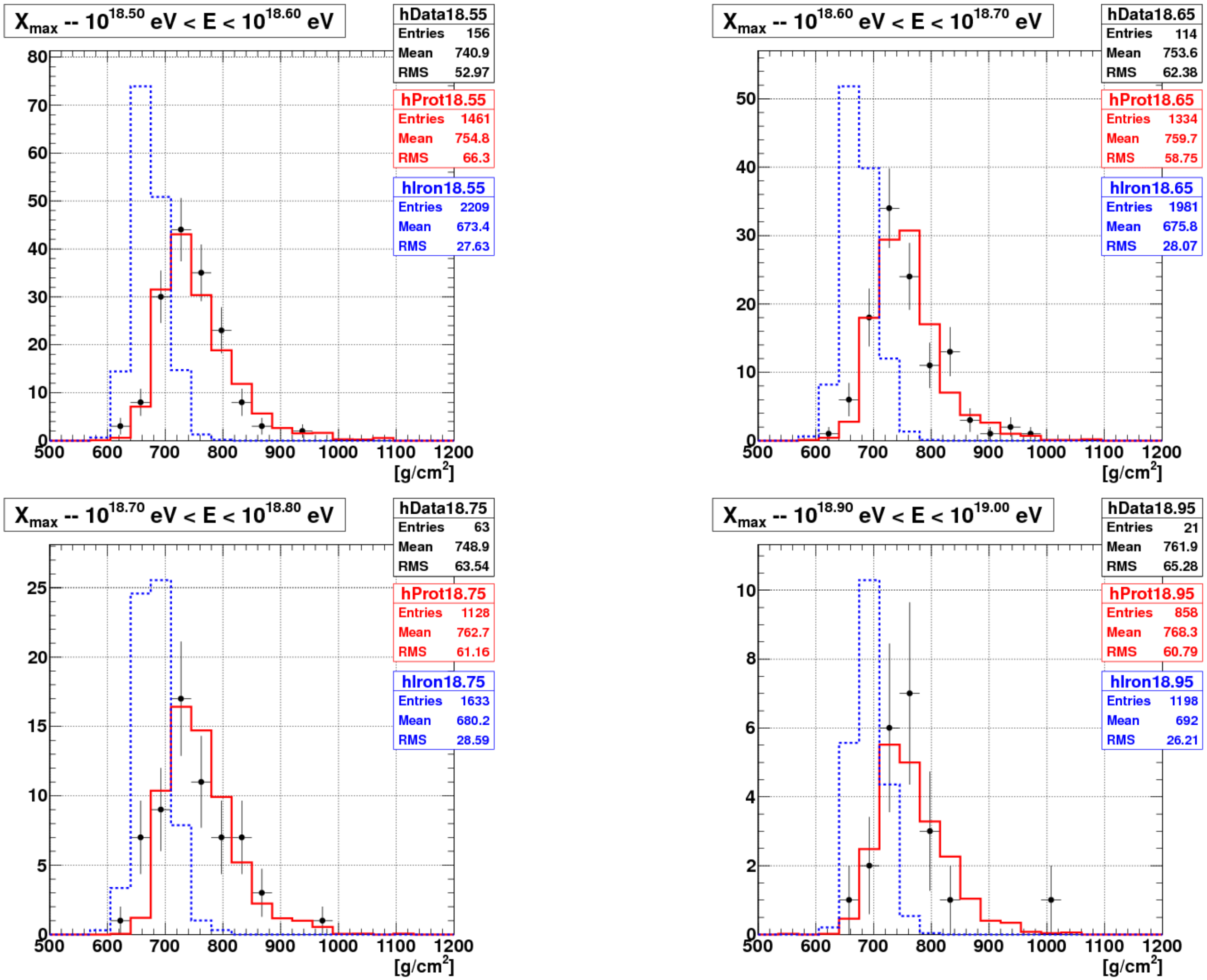
Data/Monte Carlo (Energy)



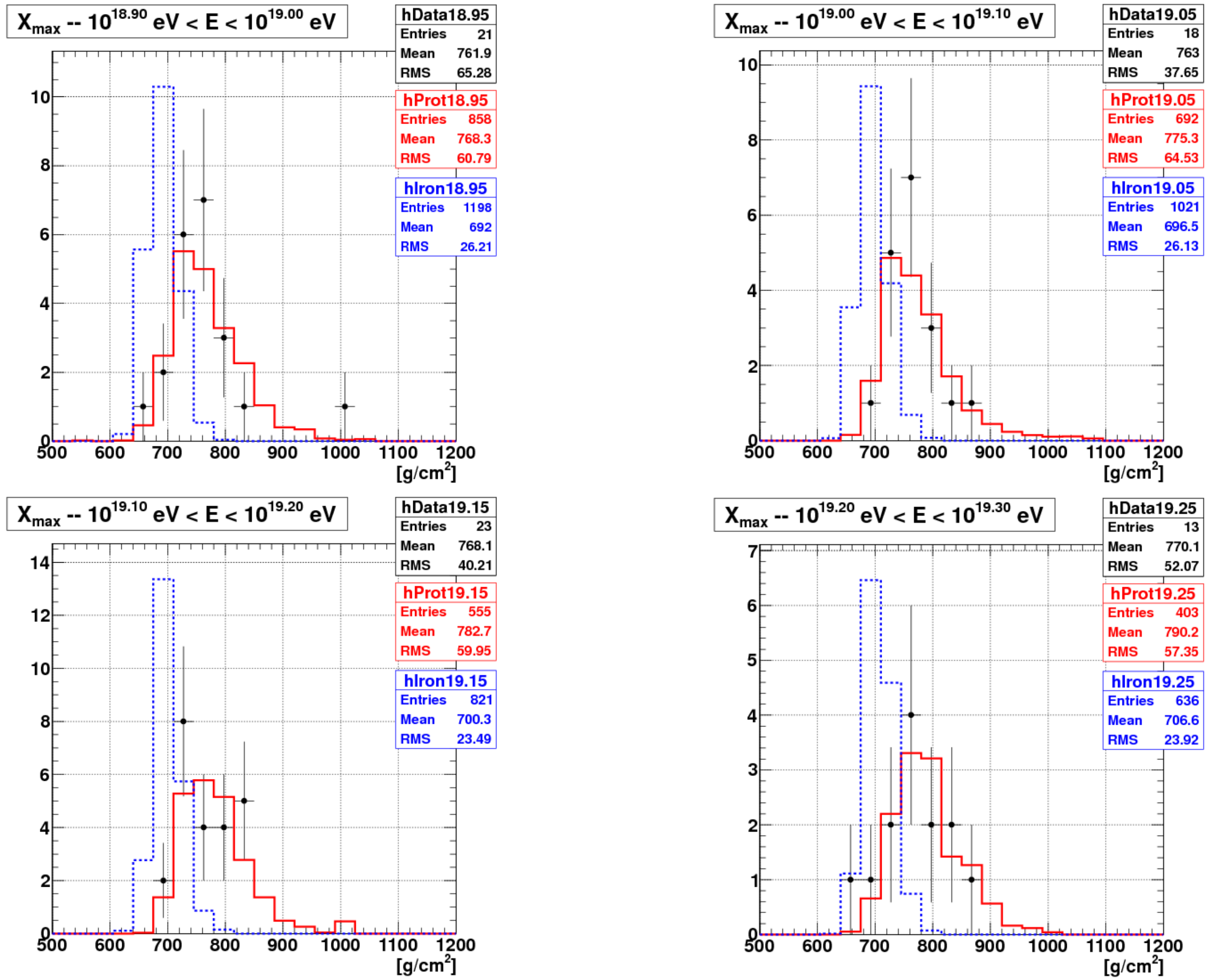
Data/Monte Carlo (X_{max})



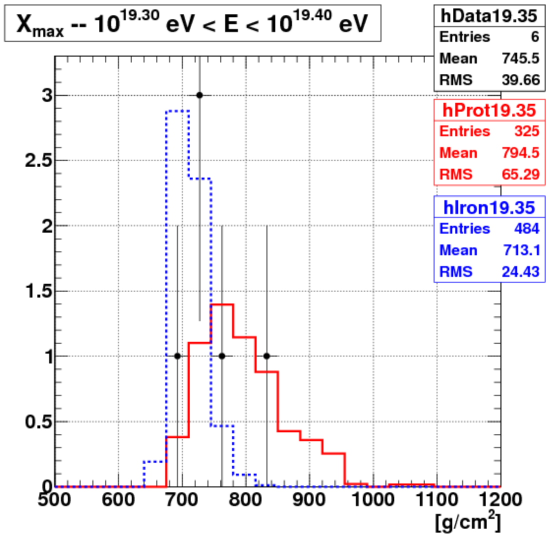
X_{max} ($10^{18.5}$ eV < E < $10^{18.9}$ eV)

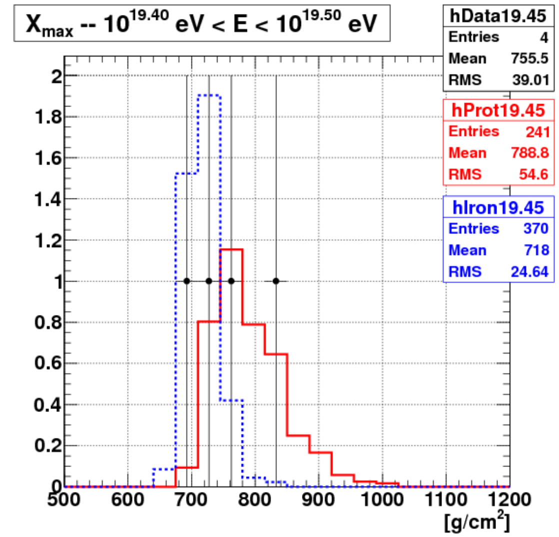


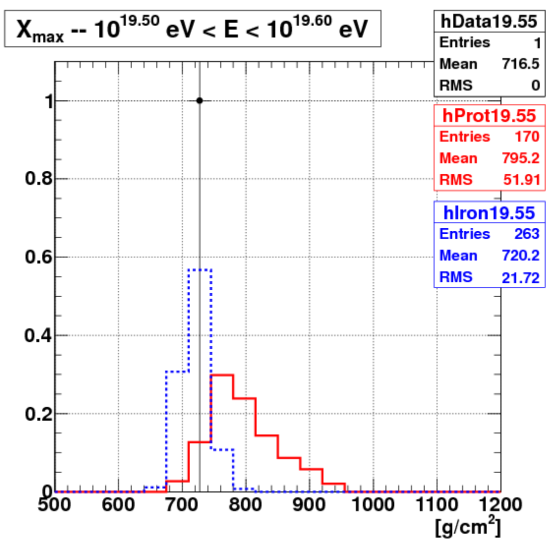
X_{max} ($10^{18.9}$ eV < E < $10^{19.3}$ eV)



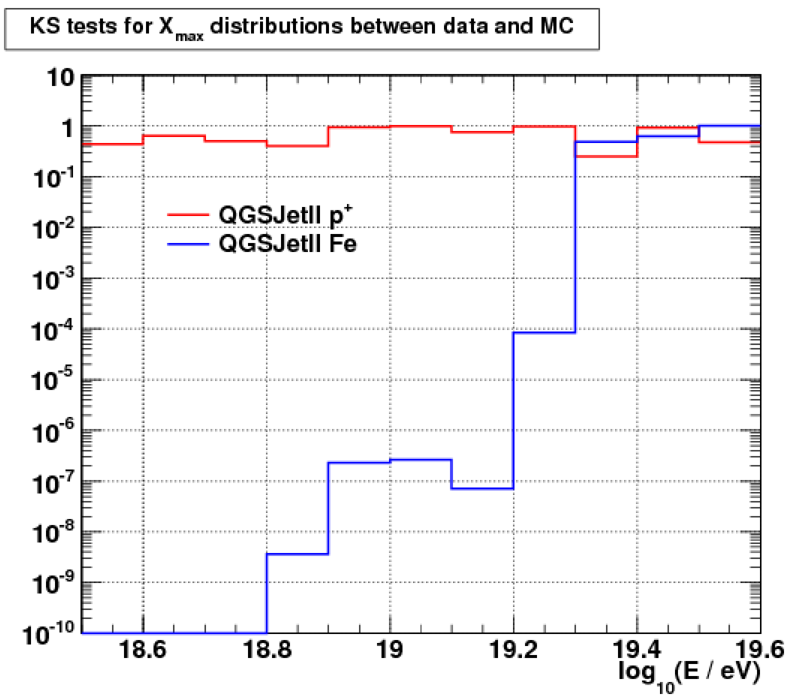
X_{max} (E > $10^{19.3}$ eV)





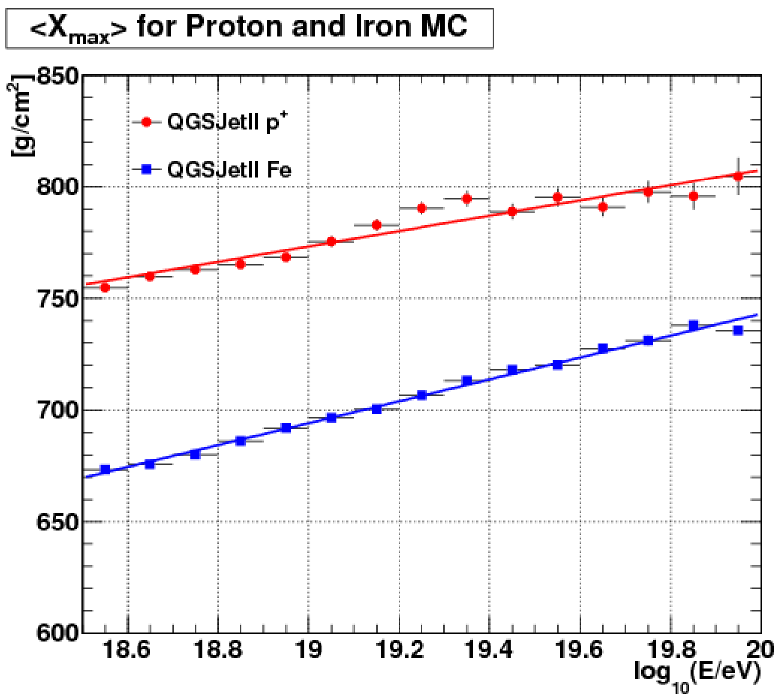


Compatibility with MC



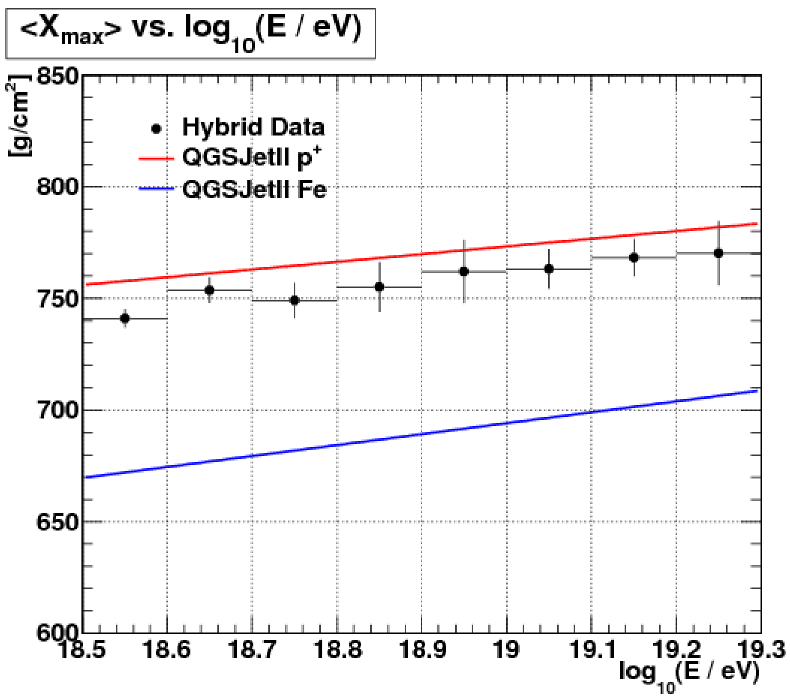
- Using the binned X_{max} distributions (slides 55-57) we may use statistical tests to compare the distributions
- Completely excludes iron MC until $10^{19.3}$ eV

MC Study: Mean X_{max}



- The $\langle X_{max} \rangle$ can provide a single measurement to quantify the distributions in each energy bin
- The fits shown here for proton and iron MC will be used to compare against the data

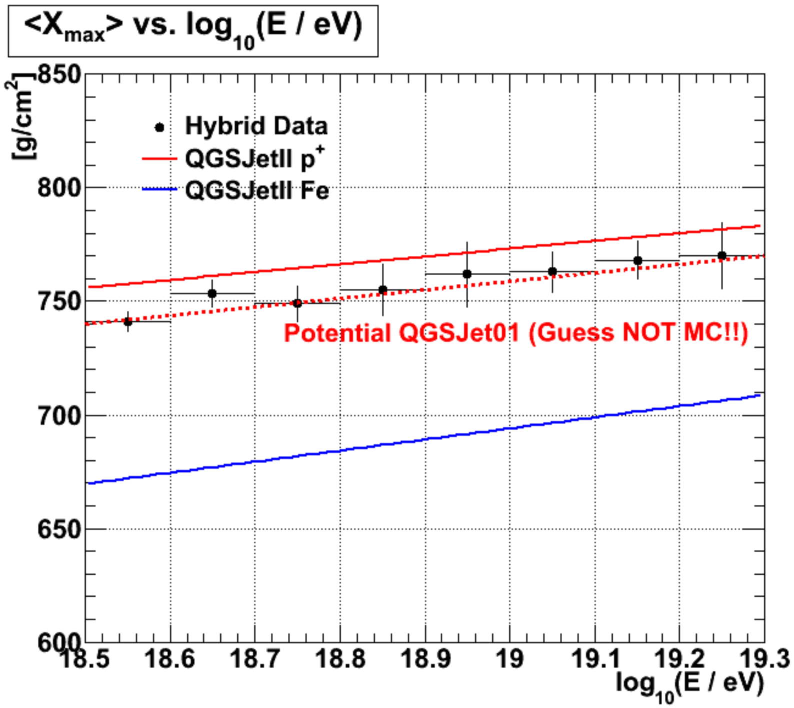
Mean X_{max}



- The mean X_{max} from the data agrees with proton MC
- The data is shifted 10 g/cm^2 shallower than the MC
- Would find better agreement with different hadronic model
  - QGSJet01

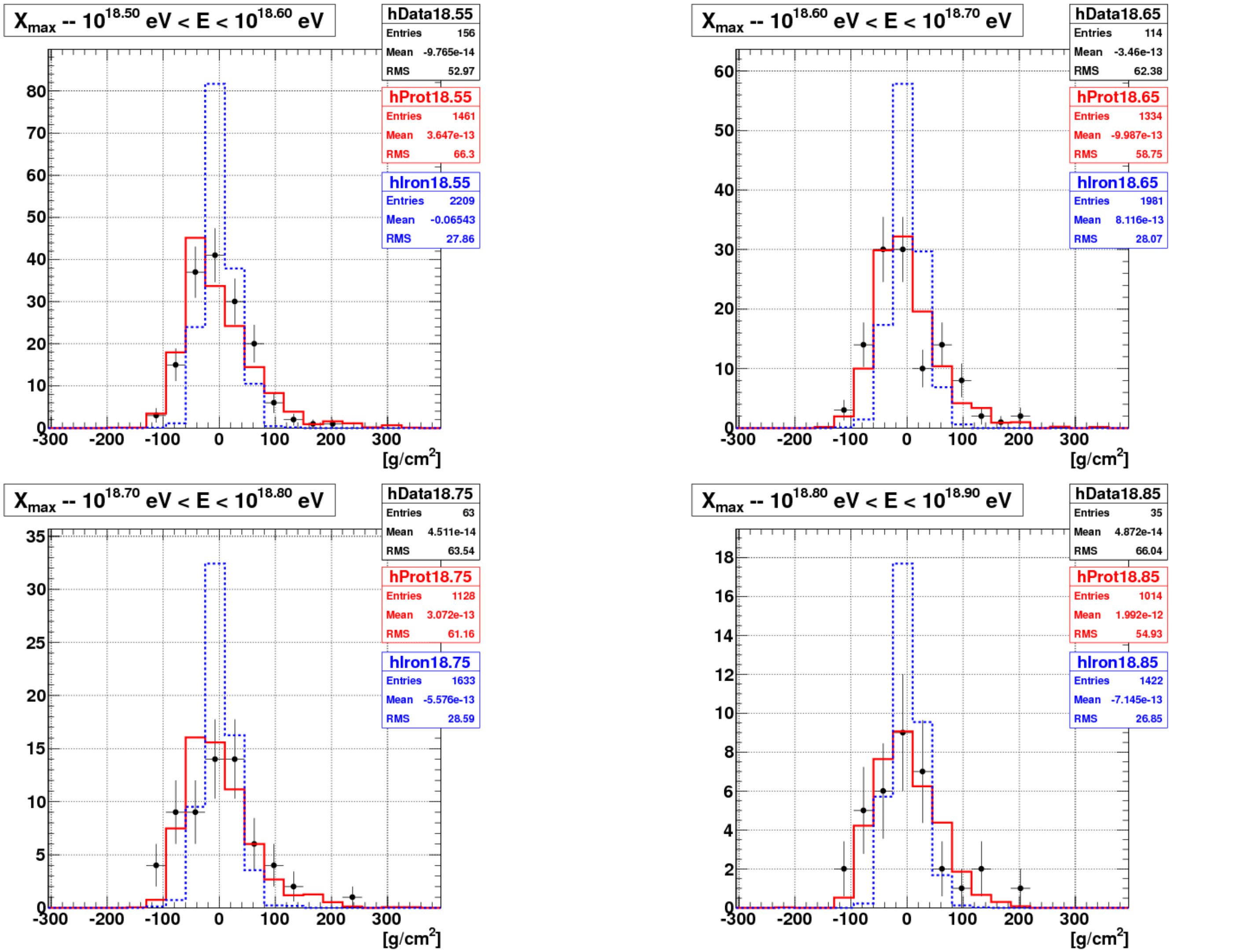
Mean X_{max}

QGSJet01??

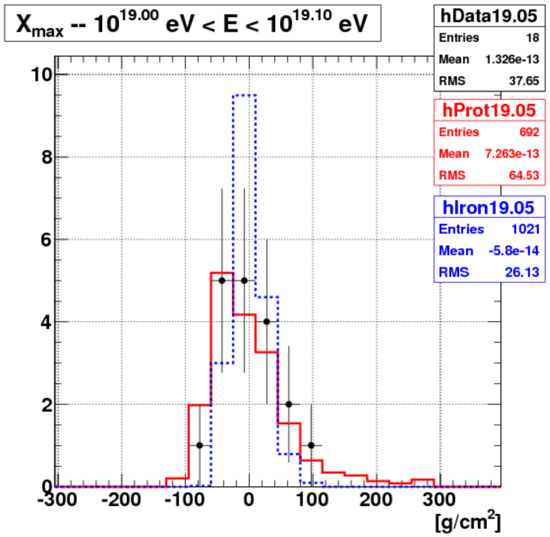


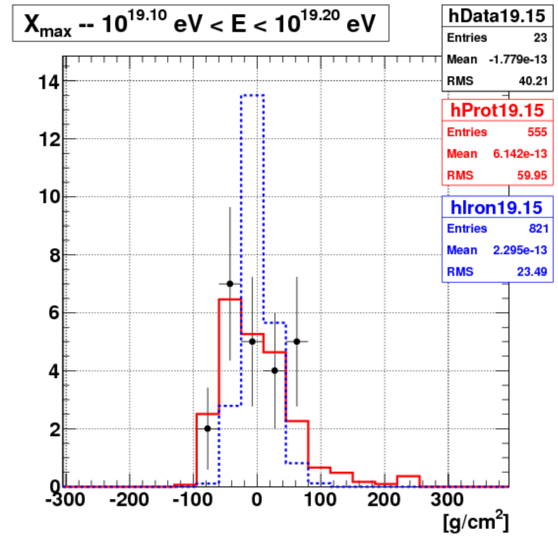
- The mean X_{max} from the data agrees with proton MC
- The data is shifted 10 g/cm^2 shallower than the MC
- Would find better agreement with different hadronic model
  - QGSJet01

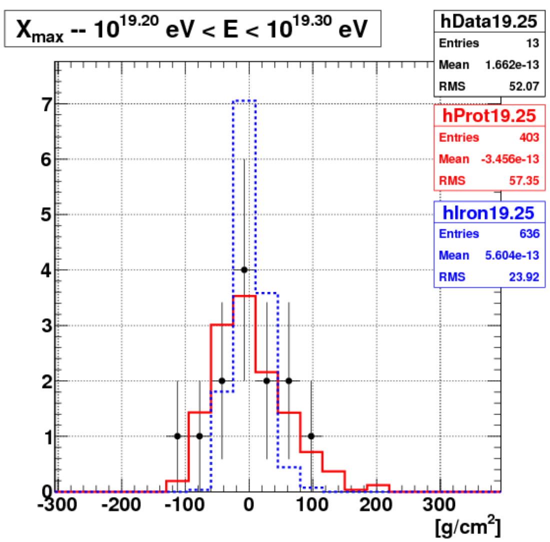
Shifted X_{max} ($10^{18.5}$ eV < E < $10^{18.8}$ eV)

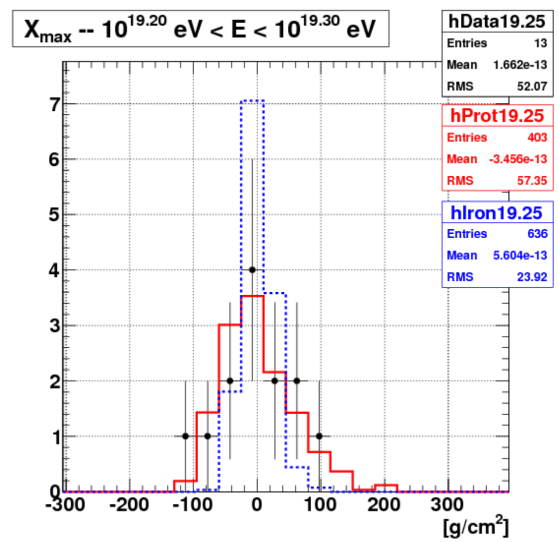


Shifted X_{max} ($10^{18.8}$ eV < E < $10^{19.3}$ eV)

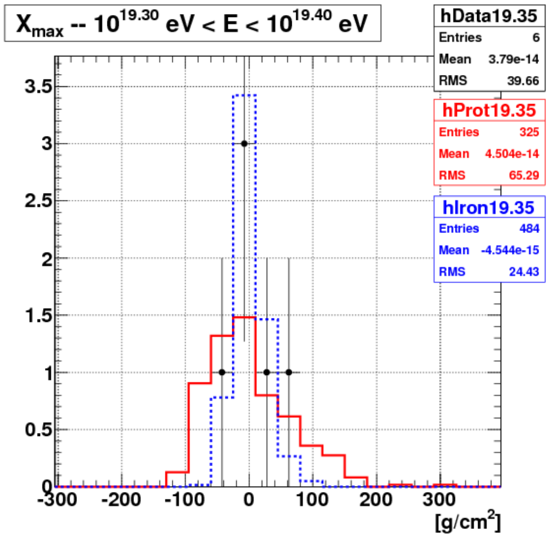


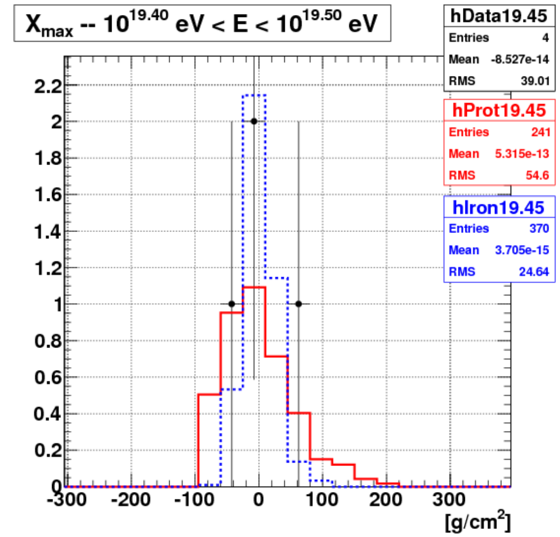


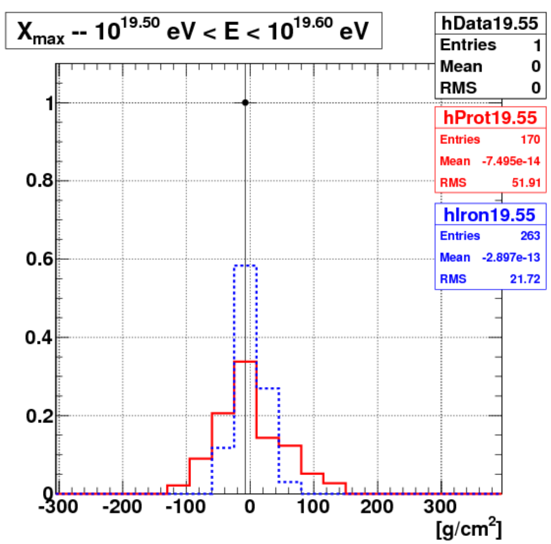




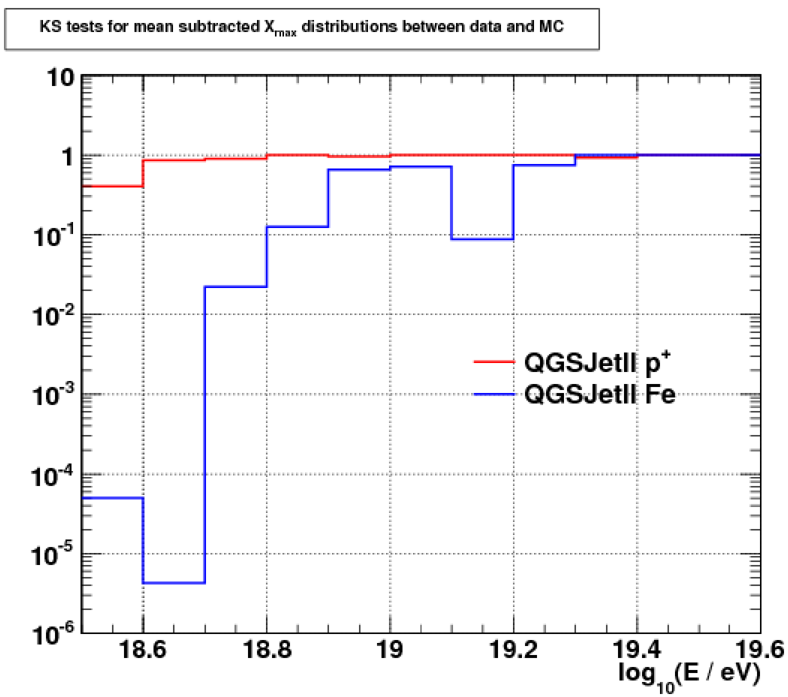
Shifted Xmax (E > $10^{19.3}$ eV)







Compatibility of shifted X_{max} with MC



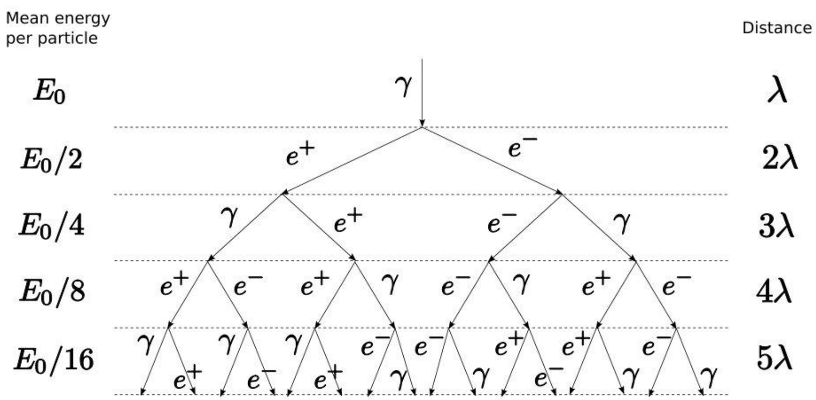
- Statistical tests of the shifted distributions provide compatibility of the shape
- Iron MC is excluded below $10^{18.8}$ eV
- Otherwise the statistical power is limited above $10^{18.8}$ eV

Conclusions

- This study shows very clear compatibility with proton MC and exclude iron MC below $10^{19.3}$ eV
- Data shows a 10 g/cm^2 shift in X_{max} from QGSJetII protons
- Measurement of width and "shape" of X_{max} distributions corroborate the proton compatibility below $10^{18.8}$ eV
- This result supports the GZK cutoff and pair-production theories to explain features of the cosmic ray spectrum

Support Slides

Electromagnetic Cascade (Heitler Model)



$$N(X) = 2^n = 2^{X/\lambda}$$

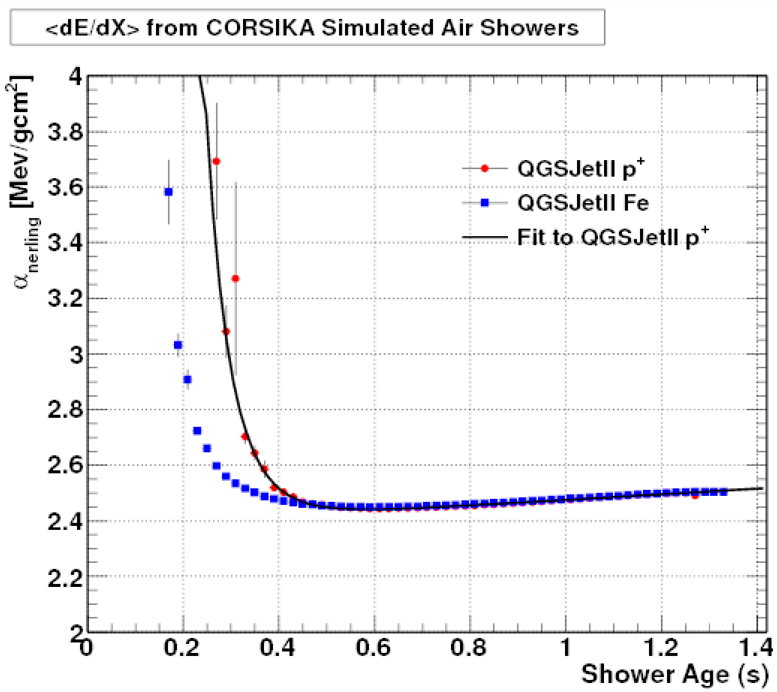
$$E_p(X) = \frac{E_0}{N(X)} = \frac{E_0}{2^{X/\lambda}}$$

$$N_{\max} = E_0 / E_c$$

$$X_{\max} = \lambda \frac{\ln(E_0 / E_c)}{\ln(2)} \rightarrow \lambda \frac{\ln(E_0 /(AE_c))}{\ln(2)}$$

- High energy photons pair produce producing $e^{+/-}$
- $e^{+/-}$ bremsstrahlung producing photons
- Critical energy when electrons lost to ionization is dominate
  - 84 MeV in the atmosphere
- X_{max} may be observed with UV sensitive telescopes

Average Energy Deposited in CORSIKA

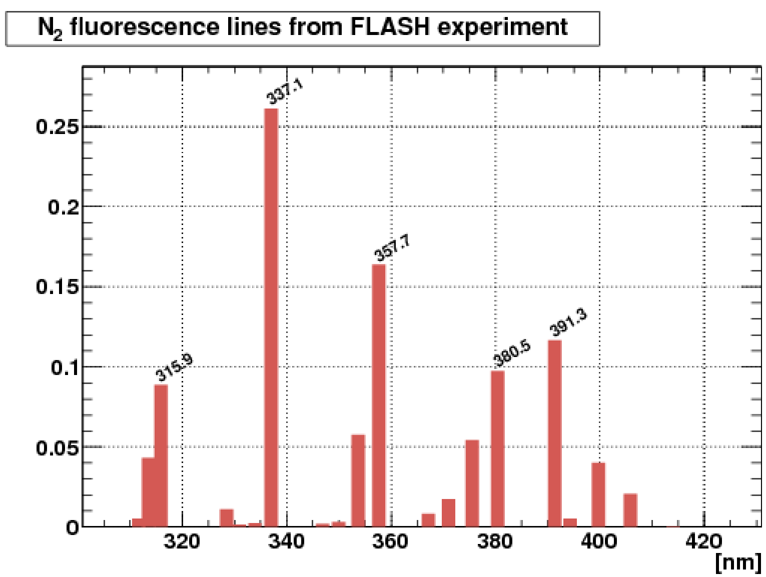


- CORSIKA simulations are used to calculate the average energy deposited by air shower
- Proton and iron simulations agree above s = 0.4
- "age" is related to X as

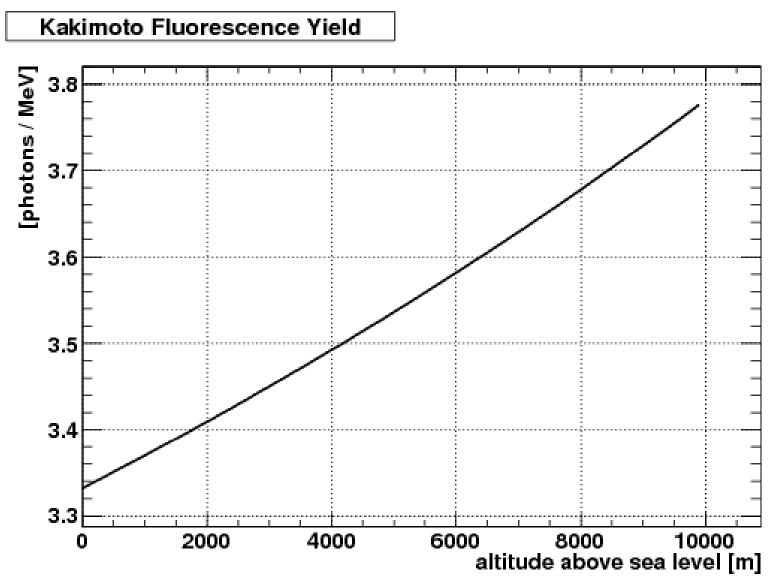
$$s = \frac{3X}{2X + X_{\max}}$$

Fluorescence Yield

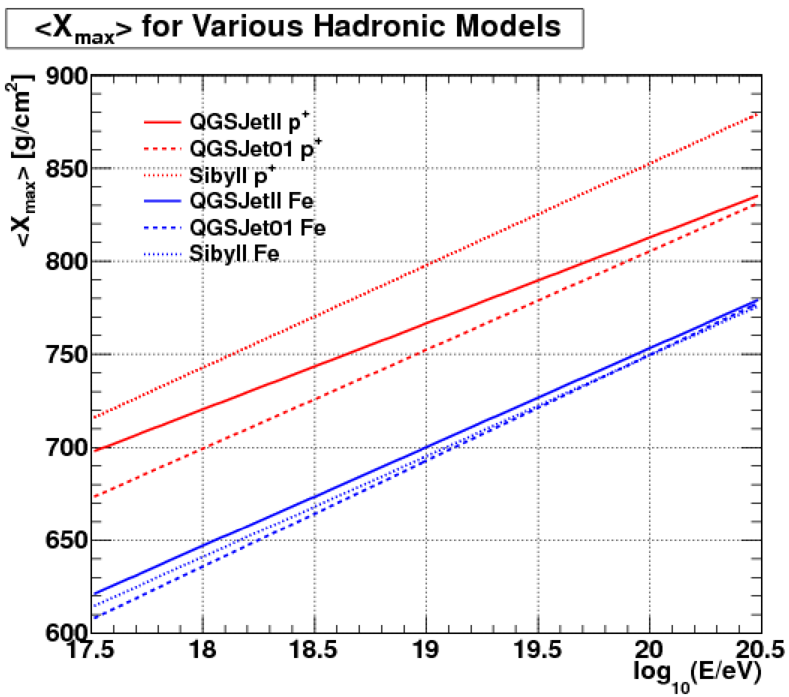
N_2 fluorescence lines as measured by the FLASH experiment



Kakimoto fluorescence yield provides the number of photons per energy deposited



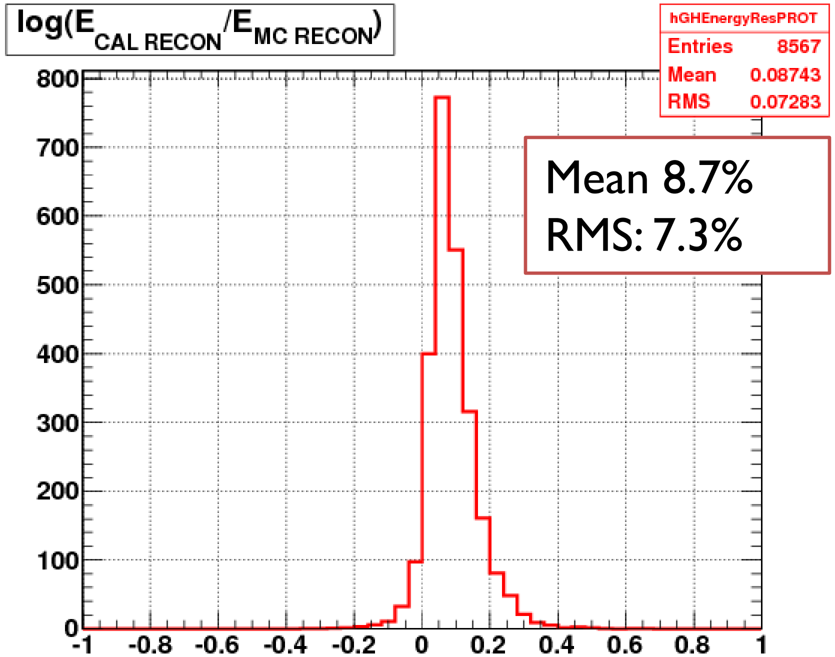
Model Dependence of X_{max}

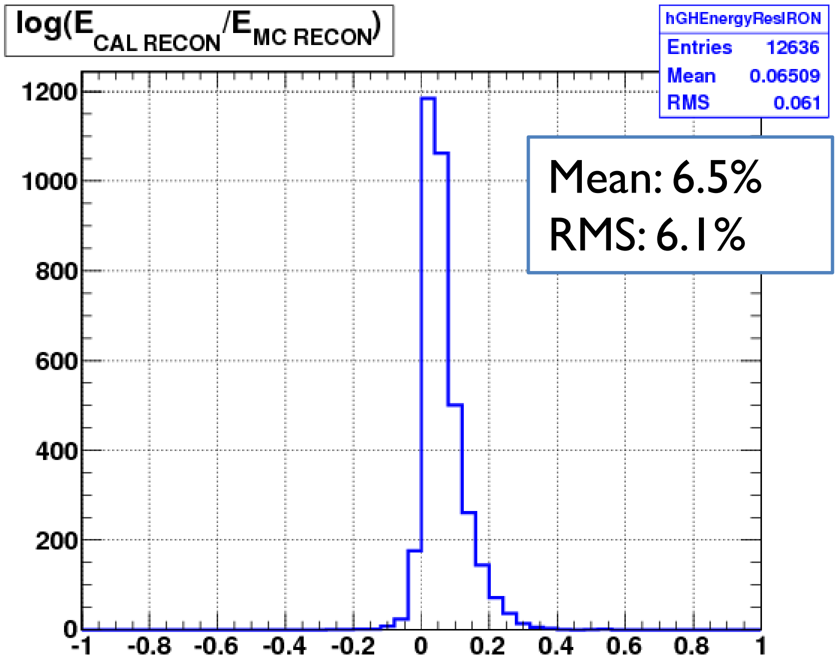


- Difference models of hadronic physics produce slightly different X_{max}
- Model parameters must be extrapolated from accelerator results

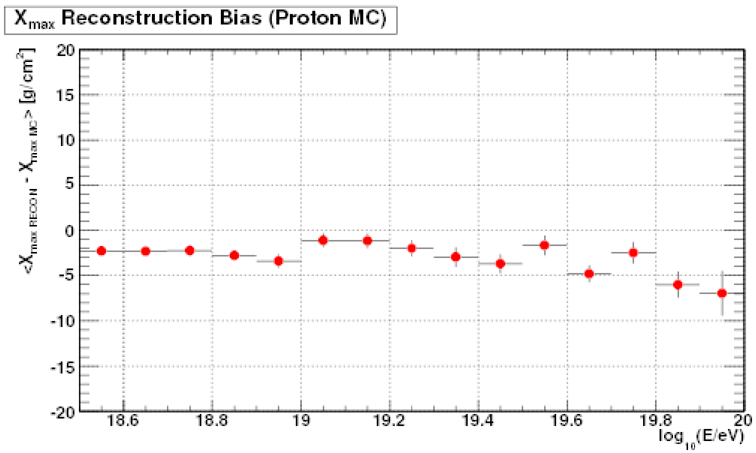
Extra Resolutions

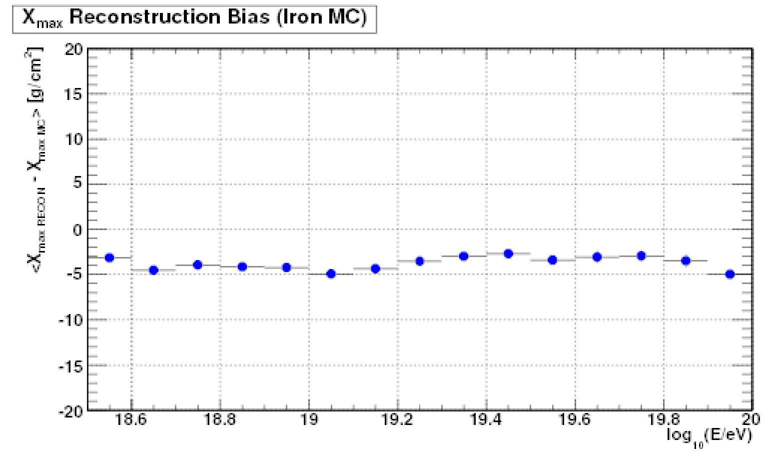
Resolution Studies (Cascade Energy)

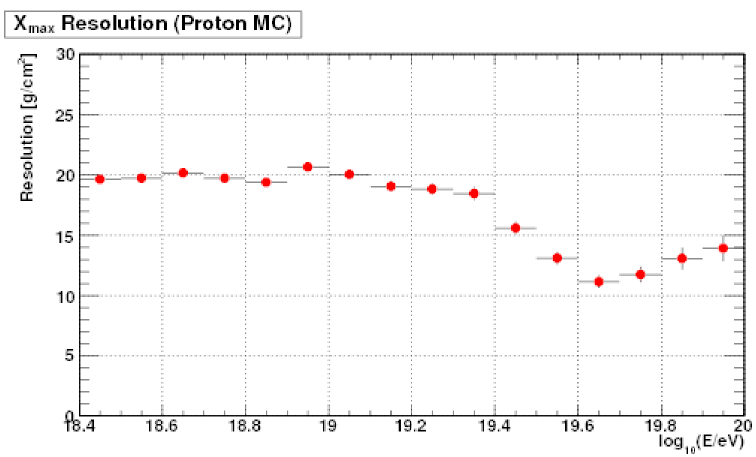


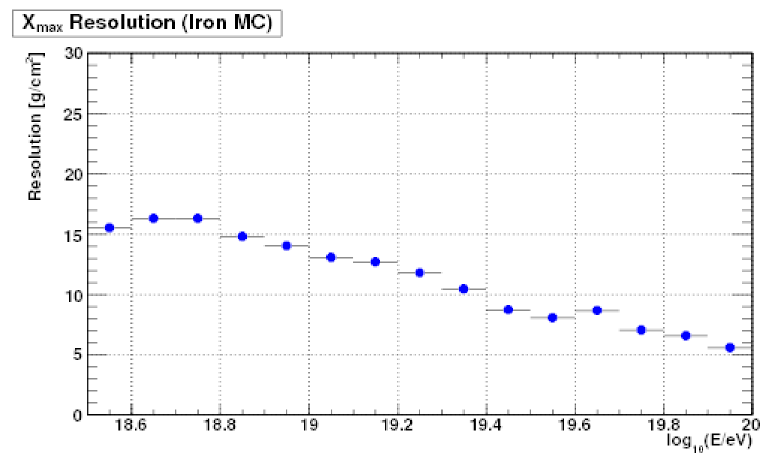


Resolution Studies (X_{max} in Energy)



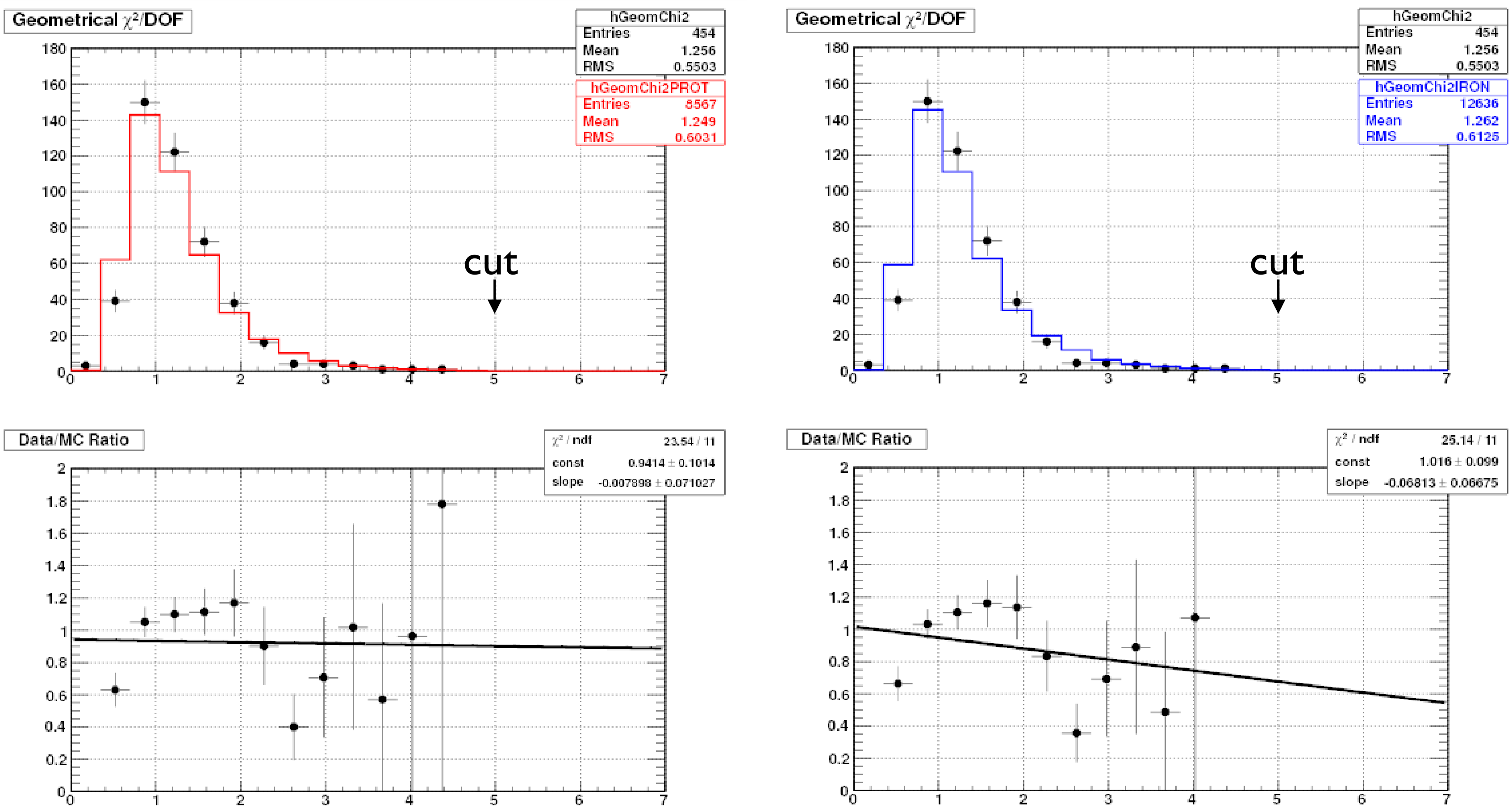




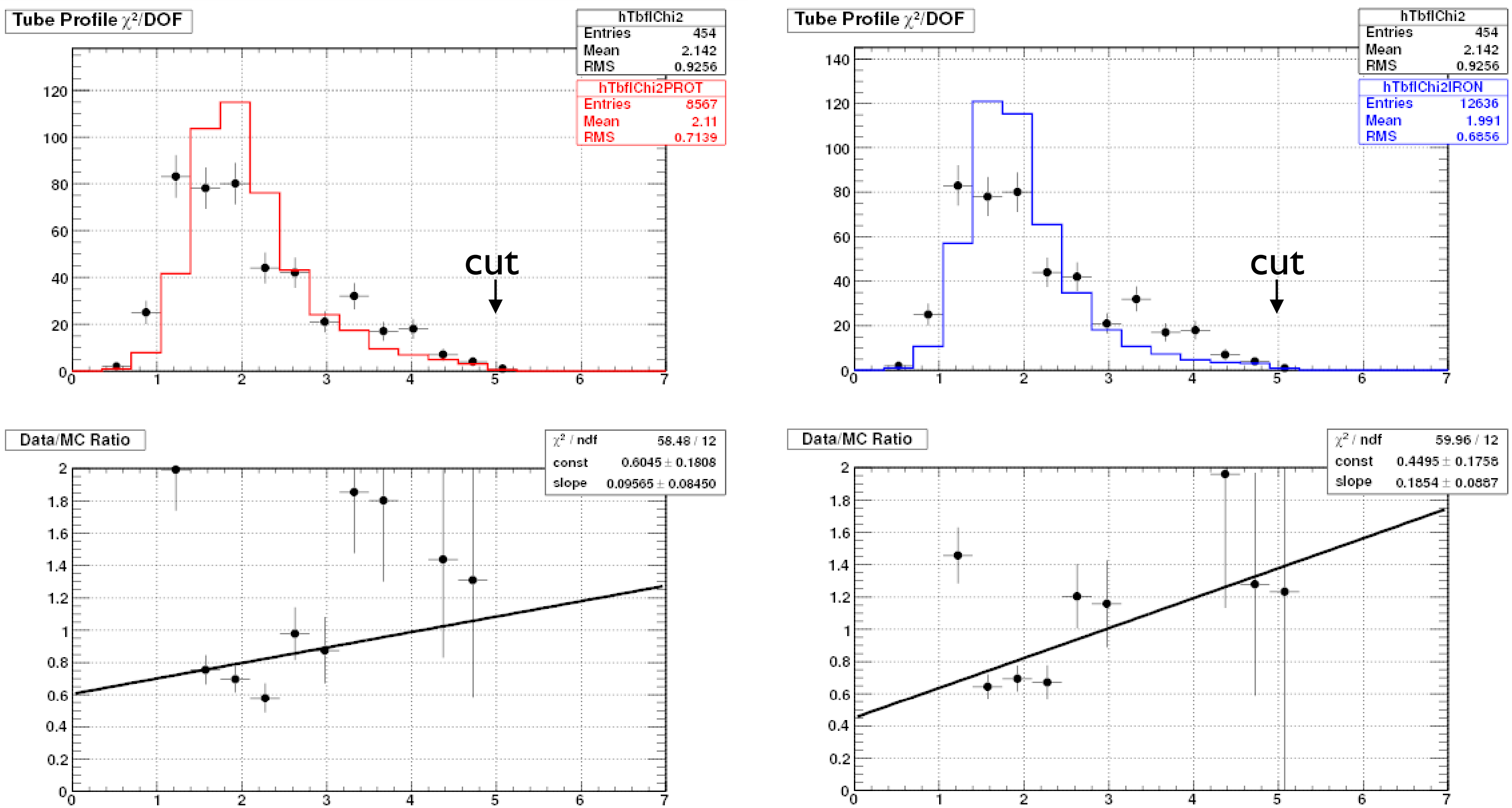


Extra Comparison Plots

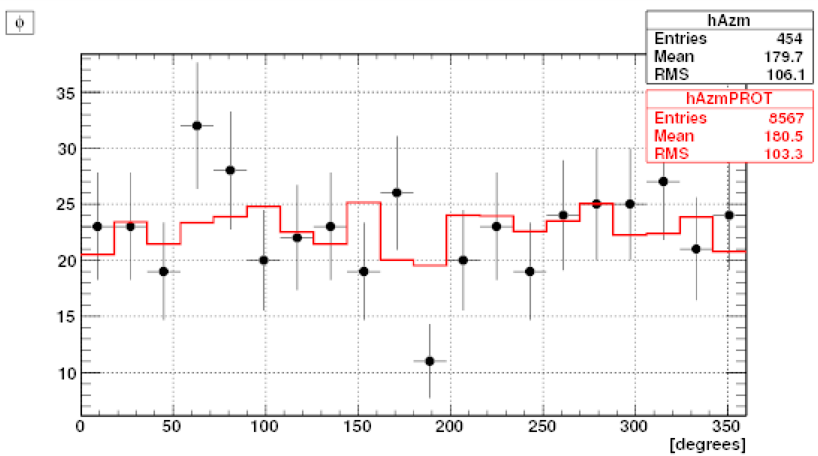
Data/Monte Carlo (χ_{GEOM}/DOF)

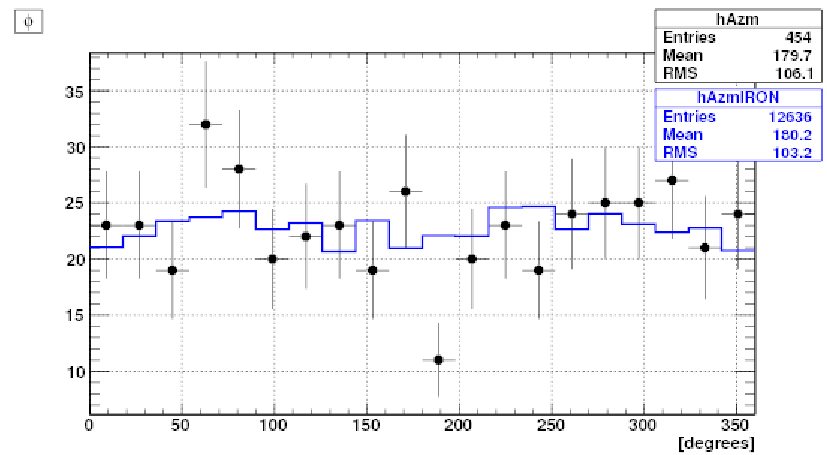


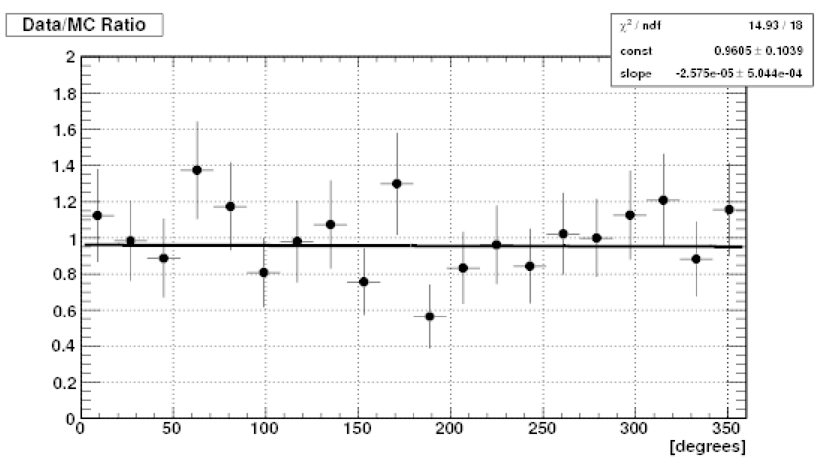
Data/Monte Carlo (χ_{PRFL}/DOF)

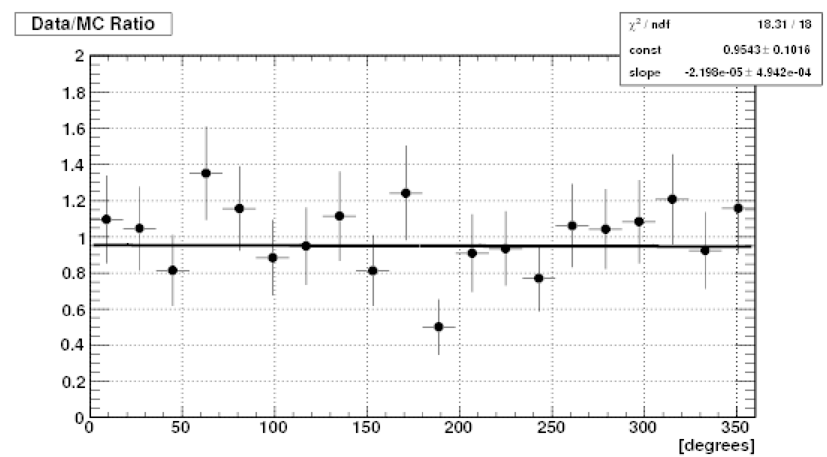


Data/Monte Carlo (Azimuth)

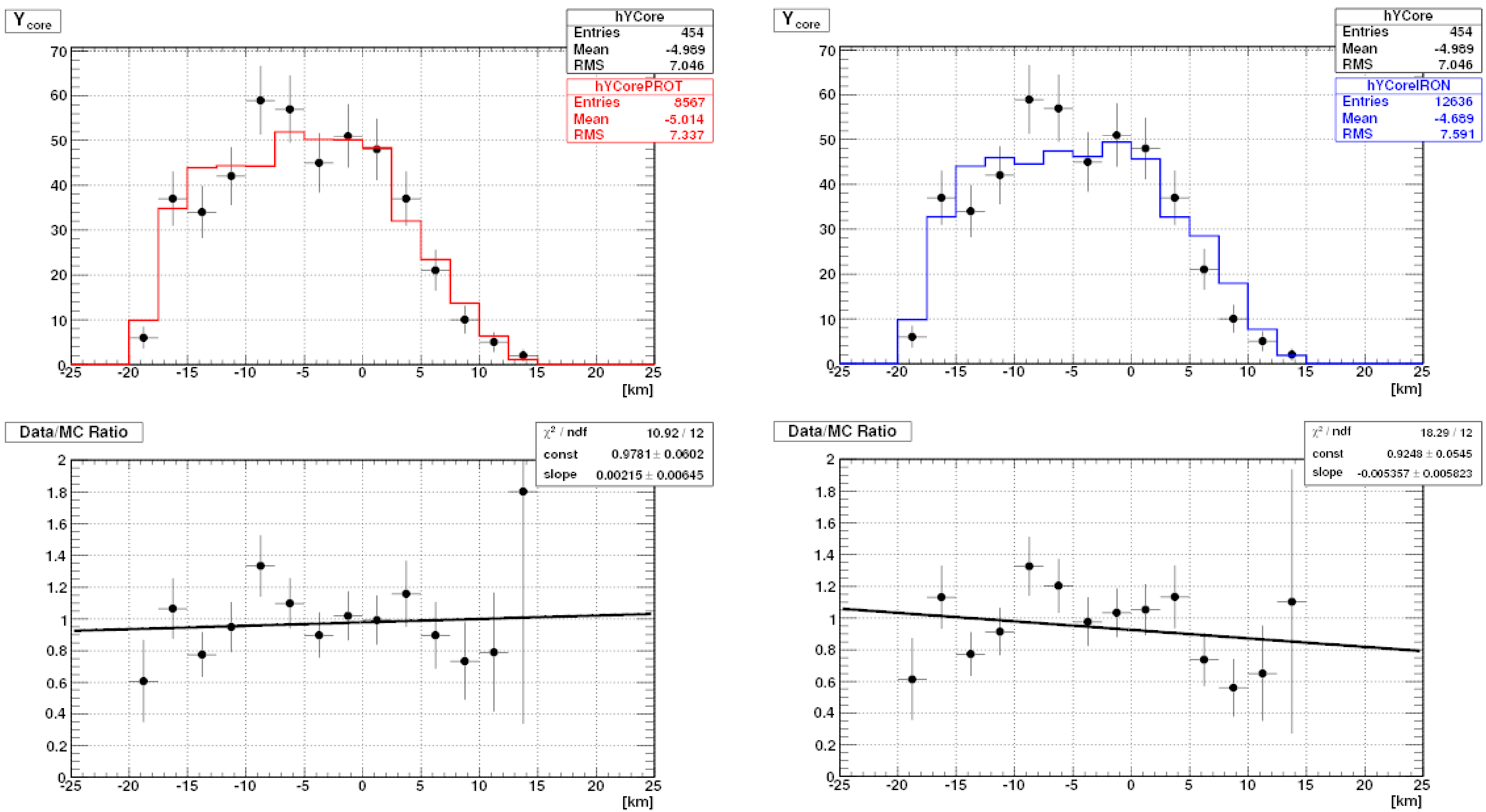




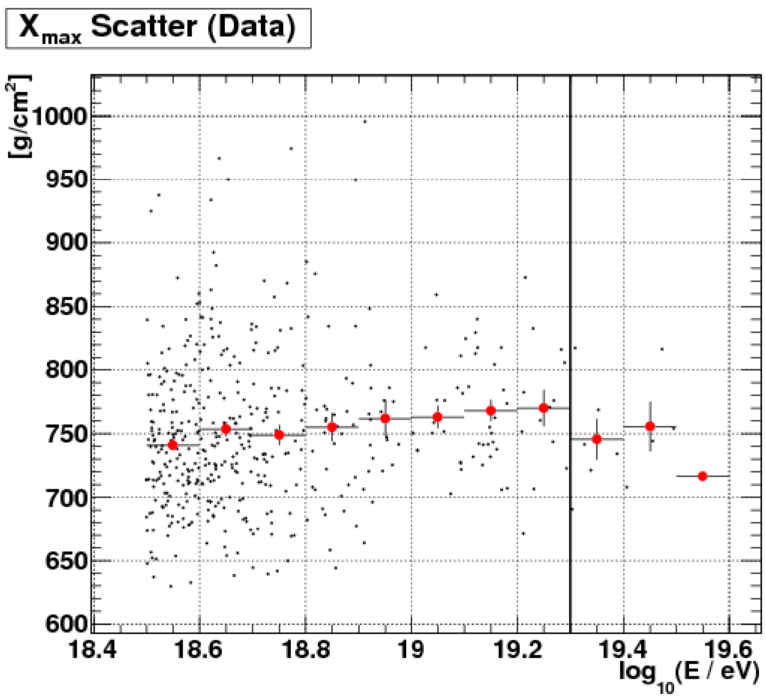




Data/Monte Carlo (Y_{core})



X_{max} Data After Cuts



- Clear elongation rate in the mean (red circles)
- Statistics are too poor to draw any conclusions above $10^{19.3}$ eV
  - Marked with solid line
- MC is used to aid in interpretation of physics