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First results from the Telescope Array

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The Telescope Array Project is a successor to the High Resolution Fly's Eye (HiRes) and AGASA (Akeno Giant Air Shower Array) experiments. It is the largest ultra high energy cosmic ray experiment in the northern hemisphere. The Telescope Array observatory has been collecting data since 2008 using a hybrid of fluorescence telescopes and scintillator surface detectors. Some of the first results from the experiment are presented including the monocular spectrum from the Middle Drum fluorescence site and the spectrum from the scintillator array. These are in good agreement with the spectrum from the High Resolution Fly's Eye. In addition, a first pass at a composition measurement is made and indicates a predominantly light composition in the 10^{19}eV region. Finally, some of the ongoing work of the group is presented including a novel technique for an end to end calibration of the telescopes involving a 40 MeV linear accelerator.

The Telescope Array Collaboration was forged by members of the High Resolution Fly's Eye (HiRes) and the Akeno Giant Air Shower Array (AGASA) to study Ultra High Energy Cosmic Rays. The purpose of Telescope Array is to: (a) understand the differences between the results of HiRes and AGASA, (b) to study the spectrum, composition, and anisotropy of ultra high energy cosmic rays, and (c) to study the galactic to extra-galactic transition of cosmic rays. Over time, the collaboration has grown to include groups from the US, Japan, South Korea, Russia, and Belgium.

The Telescope Array Observatory is located about 2.5 hours south of Salt Lake City, Utah in the USA, just west of the town of Delta. (Figure 1). The high energy component (Phase-I) of the Telescope Array consists of 38 fluorescence telescopes (9728 PMTs) located in three batteries at the corners of a triangle which is approximately 30 km on each leg. The fluorescence telescopes (FD) overlook an array of 507 scintillator surface detectors (SD). The Telescope Array is complete and has been operational since about 1/2008.

The north-most telescope station is composed of 14 refurbished telescopes from the HiRes-I observatory which was previously located at Dugway Proving Ground, Utah. The spheri-

cal mirrors are 5.2 m^2 in area and the cameras each have 256 pixels which are 40mm hexagonal Philips/Photonis XP3062-FL PMTs. Each pixel subtends about 1° of sky. The PMTs are in a 16×16 hexagonal close pack array, so that the site has a view which subtends about 120° in azimuth and from 3° to 31° in elevation. The telescopes are running the same Sample and Hold data acquisition system that they were running for HiRes. The site saw first light in 5/2007 and it has been making routine observations since 10/2007. The two southern telescope stations are each instrumented with 12 new telescopes. These have 6.8 m^2 spherical mirrors and cameras with 256 hexagonal Hamamatsu R9508 PMTs. These also subtend about 1° of sky. Each of these sites has a view which subtends about 112° in azimuth and from 3° to 33° in elevation. The data acquisition electronics of these new telescopes stations is similar in concept to those of the HiRes systems. However, each PMT channel is digitized by a 14 bit FADC system operating at 10 MHz. The eastern site saw first light in 6/2007 and the western site followed in 11/2007.

Each scintillator detector has a solar power panel with deep-cycle batteries for power, a GPS timing system, and a radio system to communicate with a control tower. (There are three radio
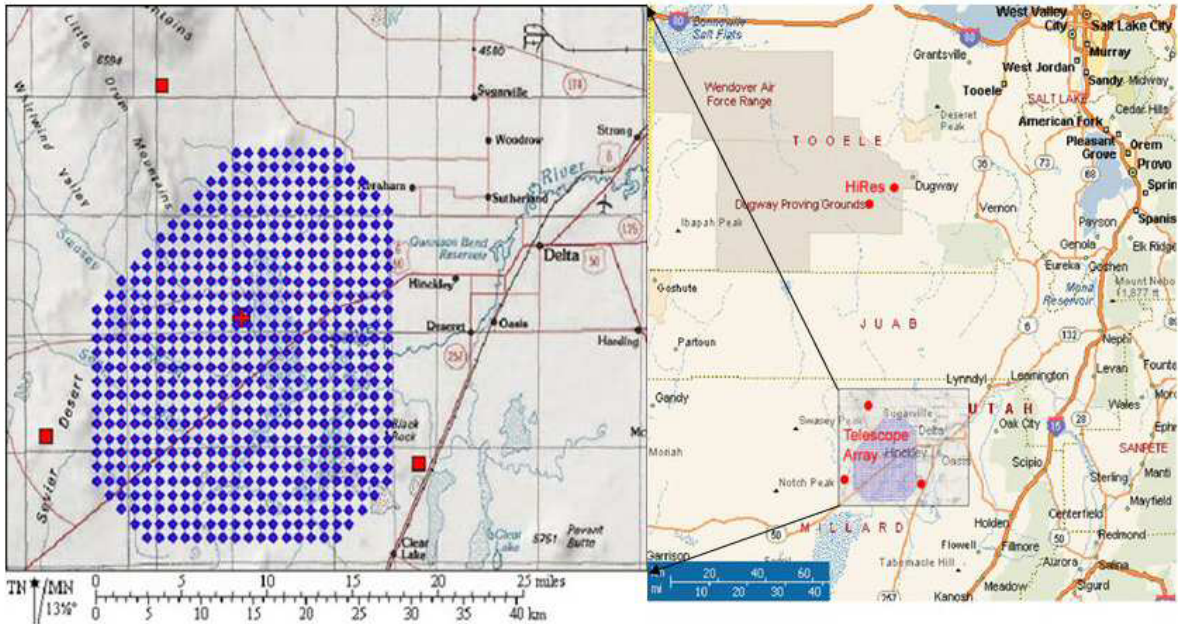
Figure 1. Map of the Telescope Array observatory. At right, the location of the Telescope Array is shown with respect to Salt Lake City and the HiRes experiment. At left right, the layout of the detectors is shown. The red boxes at the three corners indicate the locations of the three batteries of fluorescence telescopes, the blue diamonds show the scintillator detectors, and the red + at the center indicates the Central Laser Facility (CLF).

control towers, each located near one of the fluorescence stations.) The detectors are composed of two layers of half inch scintillator and each detector has an area of 3 m^2. Light collection is accomplished using wavelength-shifting fibers that are embedded in extruded grooves on the surface of the plastic. The fibers guide the light to two Electron Tube Ltd. 9124SA PMTs (one per layer). This arrangement gives pulse height uniformity within about 7% across the scintillator surface. The two layers are read out independently by PMT's, giving redundant measurements of particle pulse heights. The analog signal from each PMT is digitized by a 50 MHz, 12-bit flash analog-to-digital converter (FADC). Each counter is set to trigger at a signal equivalent to 1/3 of a Minimum Ionizing Particle (MIP), and when a coincidence occurs between the two scintillator layers. Every second the radio control towers poll the ground array stations to enquire if they have any signals above 3 MIPs. An array

trigger is formed when, within 8 μsec, three neighboring counters each have 3 MIP signals in both of their scintillator layers. For each detector level trigger, the sum of 20 FADC bins is saved for self-calibration purposes. A histogram of such sums is read out and saved every 10 minutes for later use during analysis. Signals shared among the three radio communication towers ensure that there are no cracks in the array efficiency along boundaries among the radio tower catchment areas. The scintillator surface detector array occupies a total of about 750 square km and has been operational since 3/2008. Thus far, each of the detector systems is independently operated, however a hybrid trigger system (FD to SD) is currently being installed and will be operational in the fall of 2010. In addition, many events are already observed by multiple detector systems. Events observed in monocular by a telescope station have an average of 5° resolution in ψ, the angle of the shower within the shower-detector plane. If one is able
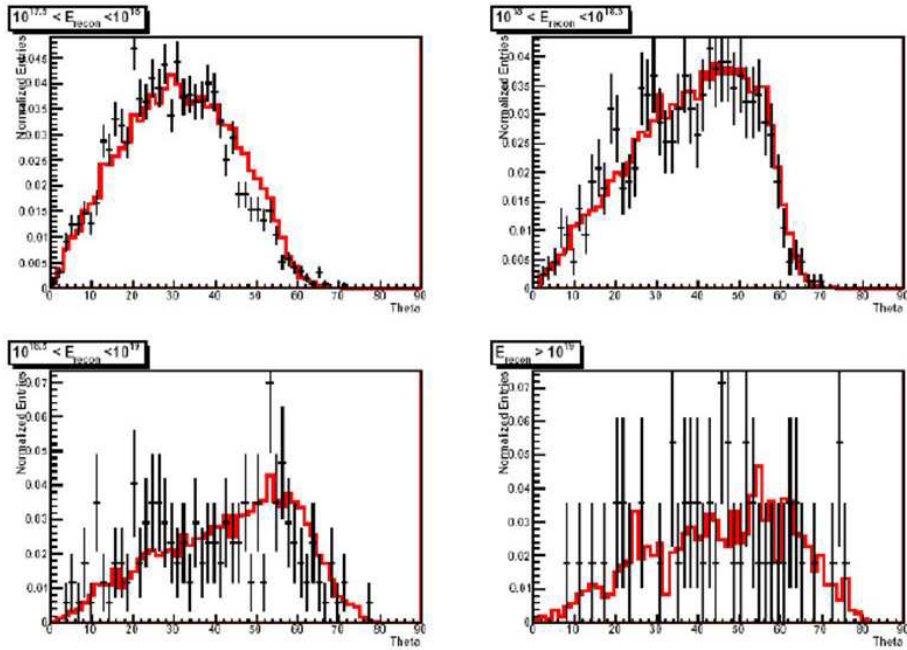
Figure 2. Zenith Angle Distributions for the Middle Drum Fluorescence Site. Data (Black Points) and Monte Carlo (Red Histogram) zenith angle distributions for four energy ranges - from top left - a) $10^{17.5}$ to 10^{18} eV, b) 10^{18} to $10^{18.5}$ eV, c) $10^{18.5}$ to 10^{19} eV, and d) $>10^{19}$ eV. There is good agreement between the data and the Monte Carlo. Note that the lowest energy range, $<10^{17.5}$eV, is NOT used in the spectrum.

to add SD information, or if the event is observed in stereo (two FD stations), then the resolution is about 0.5°. In addition, some events are being collected which are observed by all detector systems - all three telescope stations as well as the scintillator array. In comparing with the High Resolution Fly's Eye (HiRes) experiment with the Telescope Array, the spectrum from the northern fluorescence site (Middle Drum) is a natural place to start. The 14 telescopes at the site used to be part of the HiRes-I detector. They have simply been refurbished. We can use the same average atmosphere (VAOD = 0.04), same cuts and (almost) the same analysis programs. There are, however, some differences. The telescopes are now pointing in different directions. In particular, they observe over a broader range of elevation angles, making longer tracks in the cameras. Another difference is that the night sky in

Delta is darker than that in Dugway, resulting in thresholds which are about 20% lower. We use the Monte Carlo method to test our understanding of the physics and detector. We start with the previously measured spectrum and composition and use Corsika/QGSjet to generate events with an isotropic distribution. Atmospheric scattering is taken into account and these events are then fed into detector simulations which include the front end electronics, trigger, and DAQ. We write the events out in the same format as the real data and analyze the MC simulated data with the same programs as are used for the real data. We then validate the Monte Carlo by comparing data and Monte Carlo distributions of various physical measurables. Figure 2 compares data and Monte Carlo distributions for the zenith angle of cosmic ray events. The distributions are shown for four energy different energy ranges. Figure 3 shows
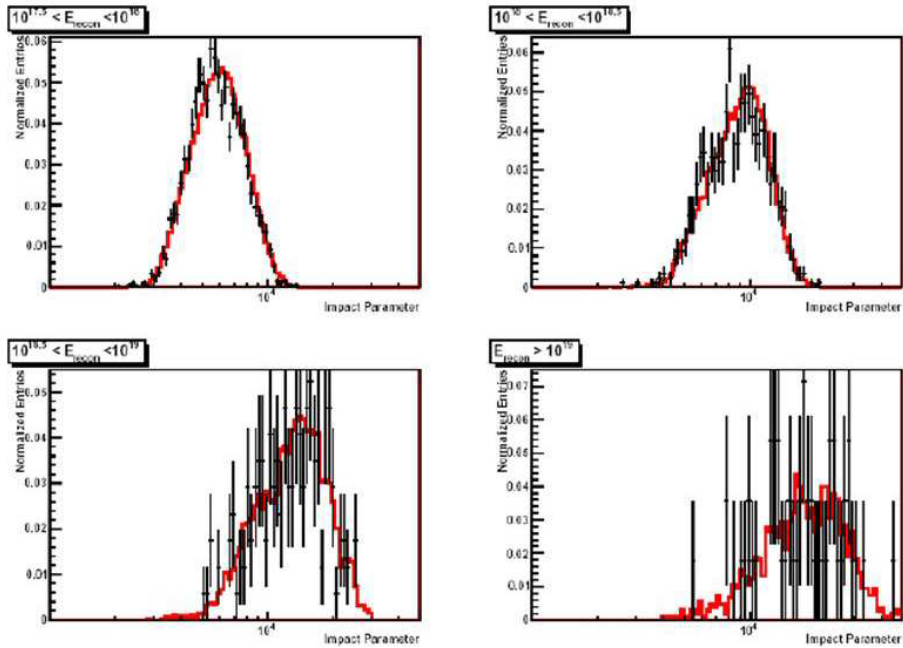
Figure 3. Impact Parameter Distributions for the Middle Drum Fluorescence Site. Data (Black Points) and Monte Carlo (Red Histogram) impact parameter (distance of closest approach) distributions for four energy ranges - from top left - a) $10^{17.5}$ to 10^{18} eV, b) 10^{18} to $10^{18.5}$ eV, c) $10^{18.5}$ to 10^{19} eV, and d) $>10^{19}$ eV. There is good agreement between the data and the Monte Carlo. Note that the lowest energy range, $<10^{17.5}$eV, is NOT used in the spectrum.

the data - Monte Carlo comparison of the impact parameter (Rp) for the same four energy ranges. The lowest energy range is not used in making a cosmic ray energy spectrum. In both cases there is good agreement between the data and the Monte Carlo simulations. These plots are indicative of many such comparisons and give us confidence that the Monte Carlo is doing a good job of simulating the data as well as giving us confidence in the aperture calculation. Figure 4 shows the preliminary Middle Drum energy spectrum made using the first year of data is overlaid with the monocular spectra from HiRes-I and HiRes-II (highest statistics). There is excellent agreement between the Telescope Array and HiRes spectra. Similar analyses are ongoing with the other two fluorescence telescope sites and they are making good progress.

Next, we consider the scintillator surface detector array. Events with bad resolution must be cut and this will affect the aperture. Therefore, we calculate the aperture by Monte Carlo. We use the same techniques as for the fluorescence detectors, folding in all that we know about the showers and the detectors before writing the data out in the same format as the real data. The Monte Carlo simulated data is then analyzed using the same programs as for the real data and again we validate the Monte Carlo by comparing with the data distributions. In reconstructing the events we use two fits. The first is the timing fit which compares the time vs. the distance along the shower axis on the ground to determine the event geometry. For this fit, we use a modified Linsley function. The second fit if the Lateral Distribution Fit. It compares the charge density
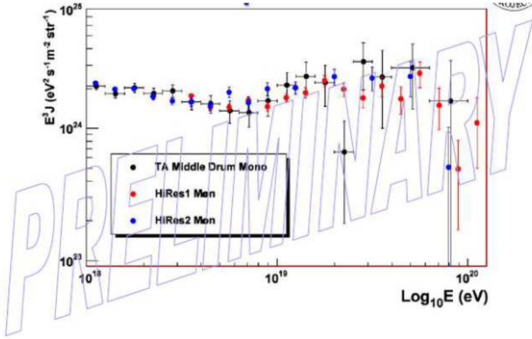
Figure 4. Energy Spectrum the Middle Drum Fluorescence Site. The energy spectrum from the first year of data from Middle Drum fluorescence site (black) is overlaid with the HiRes-I (red) and HiRes-II (blue) monocular spectra. There is good agreement between the Middle Drum and HiRes spectra.

in a detector to the perpendicular distance from the shower axis. This is fit, using the AGASA fitting function, to determine the signal size at a distance of 800 m from the shower core (S800). Figure 5 shows the data - Monte Carlo comparison for the geometrical distributions of zenith and azimuthal angle of events. Figure 6 shows the comparison for the signal (S800) and raw energy distributions of events. In all cases, the Monte Carlo simulation is in very good agreement with the data. Again these plots are representative of many distributions which we have tested and they all are in good agreement. This gives confidence that the data is well simulated by the Monte Carlo and that we can trust it with calculations such as the aperture calculation. Next we use the Monte Carlo to construct a table of S800 and $\sec(\theta)$, where θ is the zenith angle, for each energy. The first estimation of an event's energy is made using this table, interpolating between S800 and $\sec(\theta)$ lines. After data quality cuts, we have resolutions of 20% in energy and about 1° each in zenith and azimuth for events with energy greater than 10^{19}eV. We note that the data - Monte Carlo overlays above are made with this

energy estimation. The final energy scale of the scintillator array data is determined experimentally by using the fluorescence telescopes. We use events that are well reconstructed by both detector systems (fluorescence telescopes and scintillator array) to do this. The scatter plot of SD vs. FD energy is well represented by a straight line with a slope of one, however there is an off-set of 1.27 in the energy scales. Hence, we renormalize the scintillator array energy measurements by this. Without this renormalization, the energy scale of the scintillator array is similar to that of AGASA. However, the Telescope Array scintillator spectrum differs from that of AGASA in that we have fit the TA scintillator spectrum to a broken line fit and it observes the GZK suppression at the 3.5σ level. (Using a broken line fit we observe 5 events above the cutoff where we would have expected 18.4 events.) Figure 7 shows the spectrum from the Telescope Array scintillator array overlayed with the monocular spectra from HiRes-I and HiRes-II. There is excellent agreement between the Telescope Array scintillator and HiRes spectra.

As previously noted, many events are observed by multiple detector systems. We have examined some of the stereo data from the two southern fluorescence sites. The reconstructed geometrical parameters (such as zenith angle, azimuthal angle, and impact parameter) of the data are all well modeled by QGSjet-II protons. Next we compared the Xmax distribution of the data to those of iron and protons of various models including QGSjet-I, QGSjet-II, and SIBYLL. In all cases, the data looks much more like protons than iron. The best fit is to QGSjet-I protons. These comparisons are shown in Figure 8. The data is shown as a function of energy (elongation rate) in comparison to the models in Figure 9. Meanwhile, other activities are underway at the Telescope Array. One of these is the installation of a small linear accelerator. The 40 MeV accelerator was built at KEK (the Japanese accelerator laboratory) and transported to Utah. It has been installed 100 m in front of the central telescopes at the south east (Black Rock Mesa) fluorescence telescope site.

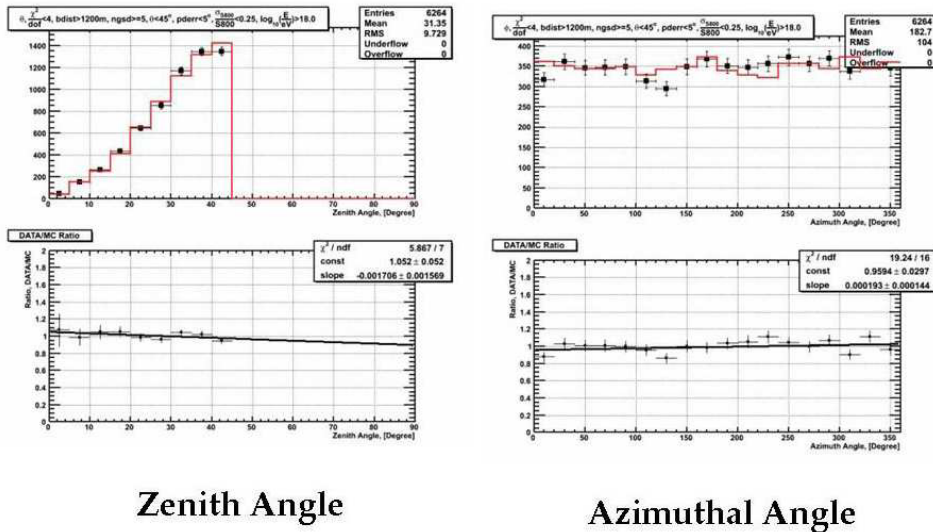**Zenith Angle**   **Azimuthal Angle**

Figure 5. Data - Monte Carlo Geometrical Comparison. Left top shows the zenith angle distribution, number of events as a function of angle, for data (black points) and Monte Carlo (red histogram). Top right is a similar comparison for the azimuthal angle distributions. Below the overlays are the ratios (data/Monte Carlo) as a function of angle. The plots indicate good agreement between the data and Monte Carlo in geometrical distributions.

The accelerator fires pulses of 10^9 electrons at 0.5 Hz. In doing so, it excites the nitrogen in the atmosphere just like an air shower. It has the same wavelength dependant fluorescence yield and this goes through the air, is reflected off of the mirrors, goes through the optical filters, and has the PMT quantum efficiency taken into account just like an air shower. In this way, the accelerator provides an end-to-end calibration of the telescopes and of the technique. The accelerator fired its first pulses of electrons into the Utah sky in September 2010. In conclusion, the Telescope Array has picked up where HiRes left off. It is the largest ultra high energy cosmic ray observatory in the northern hemisphere and is actively collecting data. Though the statistics are limited and the analyses are still preliminary, the task of analyzing the Telescope Array data in a variety of ways is well underway. The results above are meant to give a flavor of the on-going work and its status. Data collection and analysis will continue for the next several years.
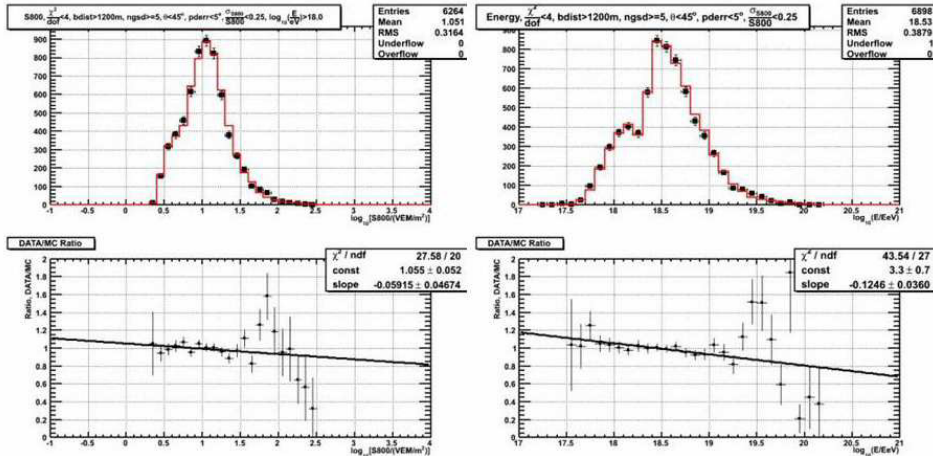
Figure 6. Data - Monte Carlo Signal and Energy Comparison. Left top shows the S800 distribution, signal at a distance of 800 m from the core, for data (black points) and Monte Carlo (red histogram). Top right is a similar comparison for the raw energy distributions. Below the overlays are the ratios (data/Monte Carlo). In the energy plot, a cut eliminating events with $E < 10^{18}$ eV has been relaxed. The plots indicate very good agreement between the data and Monte Carlo.
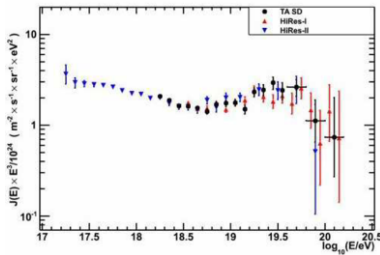

Figure 7. Energy Spectrum the Scintillator Surface Array. The energy spectrum from 1.75 years of scintillator array data (black) is overlaid with the HiRes-I (red) and HiRes-II (blue) monocular spectra. There is excellent agreement between the Middle Drum and HiRes spectra.
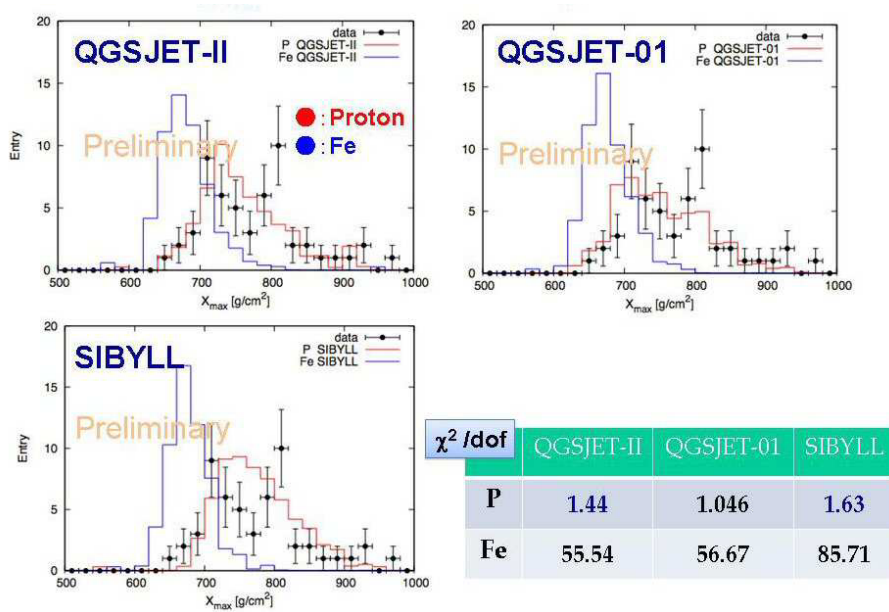
Figure 8. Xmax Data/Monte Carlo Comparison. The stereo Xmax distribution (black points) is compared to the iron/Fe (blue) and proton (red) distribution for QGSjet-II (top left), QGSjet-I (top right) and SIBYLL (bottom left). In all cases the data looks much more like protons than iron. Bottom right is a table of the χ^2/dof for each of the comparisons, quantifying the comparisons. The data looks most like QGSjet-I protons.
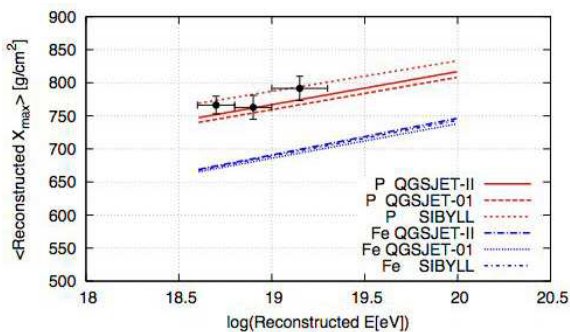

Figure 9. Xmax Data/Monte Carlo Elongation Rate Comparison. The stereo Xmax distribution as a function of energy (black points) is compared to the iron/Fe (blue) and proton (red) distribution for QGSjet-II, QGSjet-I and SIBYLL. The data looks much more like protons than iron.