Experimental/Observational Summary - Very High Energy Cosmic Rays and their Interactions

Paul Sommers
Institute for Gravitation and the Cosmos and Penn State Physics, University Park, PA 16802, USA

Observations of cosmic rays have been improving at all energies, with higher statistics and reduced systematics. Fundamental questions remain regarding the origins of cosmic rays both within the Galaxy and in extragalactic sources, and new puzzles have arisen at ultra-high energies. A key issue is determining the elemental composition based on air shower measurements. Accelerator experiments at the LHC, with comprehensive measurements in the forward direction and high interaction energies, will greatly reduce the uncertainty in air shower simulations. Ultra-high energy air showers may reveal properties of particle interactions at energies far beyond the reach of the LHC.

1. INTRODUCTION

The Sixteenth International Symposium on Very High Energy Cosmic Ray Interactions has brought together high energy physicists from the domains of collider experiments and cosmic ray observatories. Fermilab is a natural setting for this interaction, as it now has strong participation in both communities. The instrumentation of high energy particle physics is common to all.

Close cooperation and dialog between the communities is now especially timely, as data from LHC collider experiments begin to establish particle interaction properties up to higher energy, and measurements of air showers produced by ultra-high energy cosmic rays offer constraints on interactions at still higher energies. Collider experiments make and measure individual collisions between particles of known energy and type. Observations of cosmic ray interactions are indirect, and the energy and particle type of the incident cosmic ray must be inferred. Cosmic accelerators provide an uncontrolled beam, but that cosmic beam provides access to interactions with energies far beyond what can be reached in laboratories.

In his colloquium during the conference, Dietrich Mueller emphasized the two persistent questions about cosmic rays: What are these particles? And where do they come from? Direct measurements of cosmic rays at the top of the atmosphere have established the distribution of nuclear masses at low energies. These cosmic rays are known to be of galactic origin from the abundances of radioactive nuclei, and the column density (g/cm^2) of matter which they traverse in the disk of the Galaxy before escaping is determined for different energies from the relative abundance of isotopes that are produced by spallation. GeV and Tev gamma ray observations provide evidence supporting the hypothesis that supernovae and pulsar wind nebulae produce these cosmic rays in the Galaxy, although observational proof is still lacking that those gamma rays are produced by cosmic ray interactions rather than electromagnetic processes.

Direct measurements of electrons and positrons (ATIC and PAMELA) have found excesses that have prompted widespread speculation that they could be evidence for dark matter annihilation or decay. Alternatively, the overdensities relative to expectation might be due to one or more nearby sources. Curious anisotropy features observed both by Milagro and ARGO might also be evidence of cosmic ray particles from nearby sources.

The answers to Mueller's questions are even less clear at energies where the low flux requires indirect measurements by air showers. This includes the especially interesting region of the spectrum's knee near 3 PeV. Open questions remain as to what causes the knee. Is it a rigidity limit of supernova shock acceleration, with the spectrum for each nuclear type breaking at an energy proportional to its charge? Does the knee result from an abrupt change in the rigidity dependence of the time needed for escape from the Galaxy? Or could it be a measurement artifact stemming from an interaction energy threshold effect that would create a spectral break at a particular value of E/A rather than E/Z? Is the sharpness of the knee indicative of a single prominent source?

Of particular interest is the energy of transition where the low energy cosmic rays of galactic origin give way to a different population that come from extragalactic sources. A transition between two power law spectra would necessarily be concave upward in the transition region (on a log-log plot of the spectrum). The only prominent upward concavity in the spectrum is at the ankle near 5 EeV. (1 EeV = 10^{18} eV.) Dominance by galactic cosmic rays to such high energy requires something other than supernova accelerators, i.e. the galactic "source B" of Hillas (cf. Gaisser's talk [1]). Another popular picture is that the ankle is a feature carved from an extragalactic proton spectrum by $e^{\pm}$ pair production, with the transition energy being somewhere below the ankle [2]. In that case, the challenge is to find evidence for the transition in the energy spectrum or composition at some energy below the ankle. KASCADE Grande extended upward the energy range of the KASCADE array for this purpose. The TALE extension of the Telescope Array and the HEAT enhancement of Auger are extending downward their energy ranges for this search. Evidence for upward concavity just before a "second knee" was shown in talks by Arteaga-Velzquez [3] and Martirosov [4]. See section 5.

Ironically, the answers to Mueller's questions may be easier for the extremely rare trans-GZK [5] particles with energy above 6×10^{19} eV. Cosmic rays cannot retain such high energy for more than roughly 100 Mpc due to pion photoproduction (protons) or nuclear photodisintegration. Their sources must therefore lie within that "GZK sphere," and protons can arrive from those sources with magnetic deflections of only a few degrees. Also, except for heavy nuclei like iron, photodisintegration is so rapid that any contributing sources of nuclei must be within just tens of Mpc. Unless there are one or more strong sources very close, the composition can only be protons, heavy nuclei like iron, or some mixture of just those two types. Heavy nuclei are deflected much more than protons by magnetic fields (both galactic and extragalactic). Compelling evidence for small deflections from candidate sources would identify the sources and also establish a population of extremely high energy protons. That leads to the next questions: How are the protons accelerated in those sources? And what do we learn about high energy hadronic interactions from air shower development properties using that proton beam? Intriguing results from the Auger Observatory are suggesting some exciting results in this direction. Analyses of HiRes data, however, do not confirm trans-GZK anisotropy, and there are differences in measured properties of air shower developments between HiRes and Auger.

There were a large number of exciting talks about experiments and observations – too many to summarize here. The written versions are available in these proceedings. This summary is an eclectic selection of topics and results from the presentations.

2. Accelerator experiments

The exciting fact is that the LHC is operational. Proton collisions are occurring at 7 TeV center-of-mass energy. Detectors are collecting lots of data and results are being published.

Mike Albrow [6] gave a helpful introduction to accelerator data for purposes of cosmic ray physics with a historical perspective. He focused on hadronic collision results in the forward region above about 20 GeV center-of-mass energy.

Rajendran Raja [7] explained the importance of the MIPP upgrade for cosmic ray physics. It will study interactions of six different beam particles (protons, kaons, and pions) on a large number of nuclei, with full acceptance over phase space, including nuclear fragmentation. The plan is to change the target nucleus each day and collect about 5 million events in a day.

Baha Balantekin [8] summarized results from heavy ion collisions at RHIC that should be relevant for cosmic ray nuclei interacting with atmospheric nuclei. The quark-gluon state is almost a perfect fluid, and RHIC has measured its temperature in gold-gold collisions.

Mary Convery [9] reviewed recent results from D0 and CDF at the Tevatron. These include single top measurements, new heavy baryons, a possible signature of CP violation beyond the standard model in di-muon charge asymmetry, and constraints on the Higgs mass.

Switching to LHC, Georges Azuelos [10] reported on ATLAS. It was tested on cosmic rays and is collecting quality LHC data, validating the detector simulations. It is poised to measure cross sections, efficiencies, and rare processes, and to look for unexpected phenomena.

Ambra Gresele [11] presented early results from CMS. Papers have reported rapidity and transverse momentum distributions at several energies, including 7 TeV and Bose-Einstein correlations. Single-diffractive events have been observed in the calorimeters.

TOTEM is potentially one of the most important detector systems for cosmic rays as it is designed to measure the total cross section and forward charged particle multiplicity distributions. Emilio Radicioni [12] talked about its construction and readiness. It is still in a commissioning state until after the winter shutdown.

In conjunction with ATLAS, LHCf studies very forward neutral particles. Takashi Sako [13] reported on the performance of LHCf and preliminary results at 900 GeV and 7 TeV. They have almost enough statistics and will focus on systematics before finalizing results. The detectors will be removed for radiation hardening ahead of the 14 TeV runs.

At 14.4 meters from the CMS interaction point, CASTOR is a Cherenkov calorimeter that surrounds the beam pipe and is sensitive to forward particles $-6.6 < \eta < -5.2$. Edwin Norbeck [14] presented its status and performance, emphasizing searches for exotic events like cosmic ray centauros, strangelets, and long penetrating particles.

Christian Linn [15] reported on early performance and results from LHCb. It specializes in precision measurements of B decays. The K_S differential production cross section is slightly harder than in Monte Carlo models. $\bar{\Lambda}/\Lambda$ production ratio is lower than MC tunings at 900 GeV, but agreement with predictions is good at 7 TeV.

Results from ALICE were reported by Henner Buesching [16]. These include multiplicity distributions at 900 GeV, 2.6 and 7 TeV, transverse momentum distribution at 900 GeV and mean p_T as a function of multiplicity, and the anti-baryon/baryon ratio at 900 GeV and 7 TeV. Figure 1 shows a comparison of data with some model expectations. Although

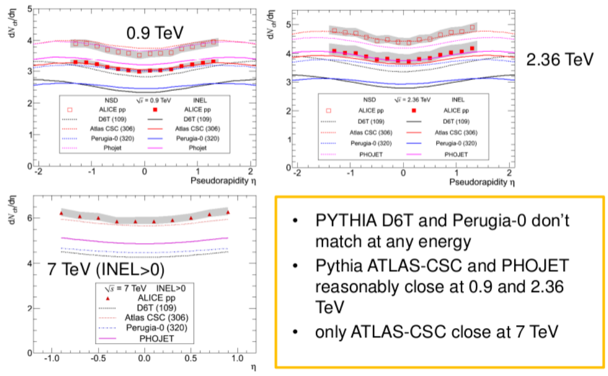

Figure 1: ALICE results for $dN_{ch}/d\eta$ and comparison to model predictions.

PYTHIA does not provide a good fit to the data, the models used in cosmic ray physics comfortably bracket the data, and Sibyll 2.1 gives good agreement, as shown in the talk of Tanguy Pierog.

3. Muon measurements with laboratory detectors

Detectors built for studies of particle collisions and neutrino beams have been used also to detect cosmic ray muons. Those muons are helpful in analyzing detector performance, but the measurements can also be used for cosmic ray physics.

Yuqian Ma [17] reported on results from the L3+C collaboration. They have measured the atmospheric muon energy spectrum, the muon charge ratio; the moon's shadow, the anti-proton/proton ratio, and properties of muon bundles. They have not found any muon excess from candidate point sources, but they identified a hot spot as a candidate unknown source. They do not detect anisotropy in sidereal time.

CMS results for muon measurements were reported by Gavin Hesketh [18]. Measurements were made above ground and in the cavern underground. The charge ratio has been measured carefully as a function of energy, and results are consistent with cosmic ray shower models [19].

Philip Schreiner [20] reported results from MINOS on atmospheric muons. They make careful corrections for temperature, which affects their muon detection rates. They have been able to determine several meson production rate ratios for primary cosmic rays above 7 TeV: π^+/π^-, K^+/K^-, and also $(K^+ + K^-)/(\pi^+ + \pi^-$.

4. Direct cosmic ray measurements

The direct measurements were divided according to whether or not the detectors used magnetic spectrometers.

John Mitchell [21] reviewed the missions with detectors that include magnetic spectrometers. Those include both missions in space as well as balloon payloads. The magnet allows charge separation for particles of the same mass and energy, so in conjunction with other detectors these can distinguish matter from anti-matter. The talk focused primarily on four different missions: (1) the two balloon flights of Bess-Polar (Balloon-Borne Experiment with a Superconducting Spectrometer), (2) PAMELA satellite (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics), (3) AMS (Alpha Magnetic Spectrometer), its first ride on the space station and plans for the upcoming AMS-02, (4) the future PEBS (Positron Electron Balloon Spectrometer).

Results on the energy dependence of the positron/electron ratio from PAMELA have attracted enormous attention due to possible explanations in terms of dark matter annihilations. The updated PAMELA plot is shown in Figure 2. Mitchell's talk included not only a discussion of various dark matter scenarios, but also astrophysical explanations in terms of a nearby source (supernova or pulsar).

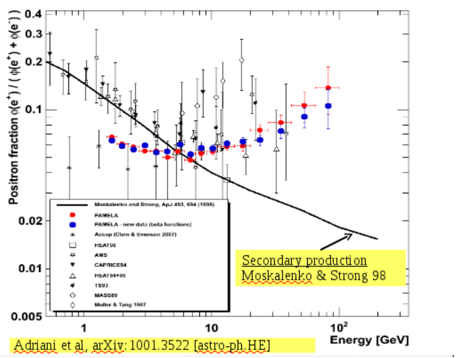

Figure 2: Positron to electron fraction measured by PAMELA as a function of energy. This figure includes data taken through the end of 2008.

Andrei Kounine [22] presented details about the AMS mission. In particular, he explained the reason for the recent announcement that the permanent magnet used in AMS-01 would be used also in AMS-02 instead of the planned superconducting magnet. The hope is to collect data until 2020 or 2028. With the superconducting magnet, the lifetime would be limited to less than 3 years by the cryogenics, without an option to refill. The detector has been reconfigured to work with the weaker field of the permanent magnet, and launch is expected in November of this year.

Eun-Suk Seo [23] reviewed the missions that measure cosmic rays directly without a magnetic spectrometer. These include ATIC (Advanced Thin Ionization Calorimeter), Fermi Gamma-ray Space Telescope, CALET (Calorimetric Electron Telescope), CREST (Cosmic Ray Electron-Synchrotron Telescope), TRACER (Transition Radiation Array for Cosmic Energetic Radiation), TIGER (Trans-Iron Galactic Element Recorder), and CREAM (Cosmic Ray Energetics and Mass). The ATIC collaboration reported a significant excess electron intensity near 500 GeV in 2008 (relative to model expectations), which, taken along with the PAMELA result, ignited interest in the interpretation of dark matter annihilating to a light boson. Astrophysically the excess flux can be attributed to the presence of individual sources [24]

Seo emphasized results from the five flights of CREAM: the boron/carbon ratio up to TeV/nucleon, and elemental spectra over four decades of energy. The energy spectra show a distinct hardening near 200 GeV/nucleon (Figure 3), and a variety of explanations have been proposed to account for it.

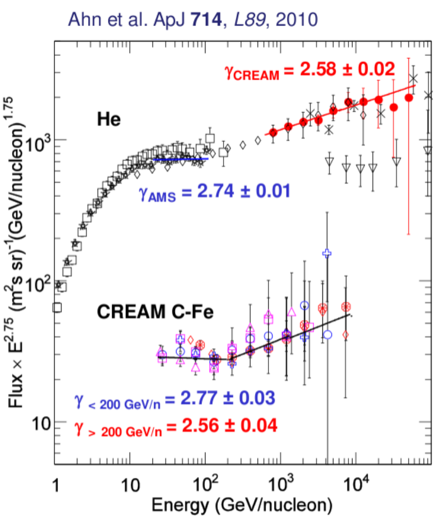

Figure 3: CREAM energy spectra showing an upward concavity near 200 GeV.

Satoru Takahashi [25] presented plans for a balloon-borne gamma-ray telescope with nuclear emulsions. It is expected to have excellent angular resolution (Figure 4) and polarization sensitivity.

5. Air shower measurements below the ankle

Although direct measurements of cosmic rays have provided rich details about the energy spectra of individual components up to energies exceeding 100 TeV, important additional information about anisotropy of

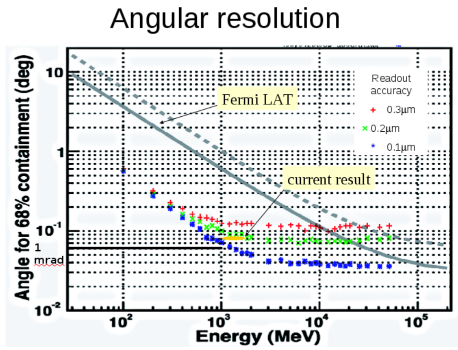

Figure 4: Angular resolution of the balloon-borne nuclear emulsions for gamma rays.

those cosmic rays is coming from air shower detectors and large muon detectors. In particular, Jordan Goodman [26] summarized anisotropy results from Milagro, IceCube, ARGO, and the Tibet Air Shower Array that show a consistent large scale anisotropy pattern. Figure 5 shows a full-sky anisotropy map using IceCube (muon) data for the southern sky and Milagro cosmic ray data for the north. A one-

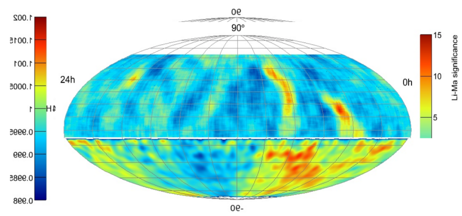

Figure 5: Color-coded map of celestial excess and deficit regions. The northern hemisphere is derived from Milagro data, and the southern sky from IceCube.

dimensional plot of the intensity variation with right ascension is shown in Figure 6 for a strip of declinations between 10° and 20°. The large-scale varia-

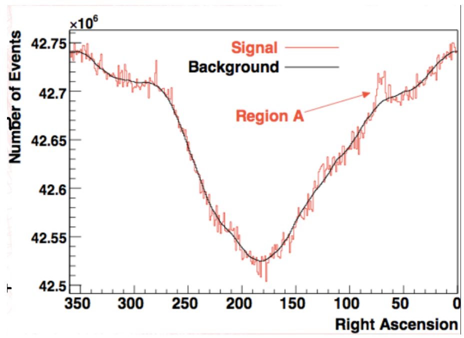

Figure 6: Milagro cosmic ray intensity variation with right ascension for declination between 10 and 20 degrees.

tion with right ascension is statistically unquestionable. The amplitude (0.1% is less than the Compton-Getting [27] effect (0.5%) which would be expected if our motion relative to the cosmic rays were that of our motion relative to the CMB, and the dipole component is not in the direction of that motion. It is interesting that Milagro has measured a modest time dependence of the anisotropy that is not confirmed by Tibet AS. Figure 6 shows a narrow feature marked as “Region A” in that declination strip. It is seen, along with “Region B” in Figure 7, where the same narrow features are clear also in the ARGO data. These features are due to cosmic rays, not gamma rays, in the Milagro data, and it is a fascinating open question how charged particles with such small Larmor orbits in the galactic magnetic field can produce these narrow features on the sky.

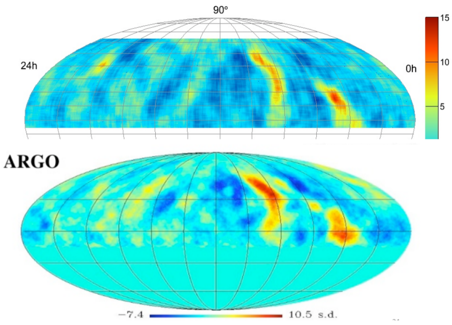

Figure 7: Milagro (top) and ARGO data show the same two narrow features (regions A and B) of excess cosmic ray arrivals.

Results above the knee of the spectrum were reported from KASCADE-Grande by J.C. Arteaga-Velzquez [3]. Inferences about the composition based on separate measurements of muons and electromagnetic particles have dependence on which hadronic interaction model is used (QGSJET or Sibyll). The all-particle spectrum cannot be fit by a simple power law above the knee. Figure 8 shows a region of upward concavity followed by a steepening that might be interpreted as an “iron knee.” The upward concavity was not proposed as a transition to extragalactic cosmic rays. Like the spectral hardening seen at lower energy by CREAM, favored interpretations are shock broadening by the accelerating particles themselves [28] or the effect of a nearby source.

The KASCADE collaboration is pursuing multiple avenues for determining the elemental composition of the cosmic rays. One particularly interesting approach is muon tracking, as presented by Paul Doll [29]. The idea is to use the muon arrival directions to determine the heights of muon production and the muon pseudorapidity distribution.

As reported by Romen Martirosov [4], the GAMMA experiment on Mt. Aragats has also found an upward concavity followed by a steepening of the energy spectrum just below 10^{17} eV. The bump, shown in Figure 9 may be consistent with the KASCADE features of Figure 8.

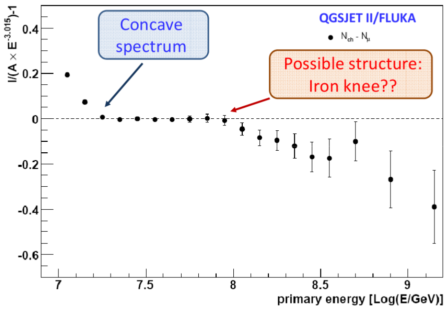

Figure 8: The KASCADE-Grande all-particle spectrum is not described by a single power law.

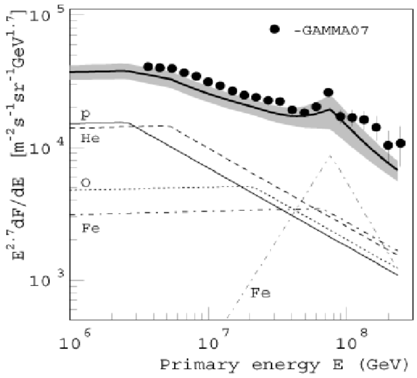

Figure 9: Data from Mt. Aragats also deviates from a simple power law with a bump-like feature that includes a narrow region of upward concavity.

IceTop is an air shower array built directly above the IceCube Observatory at the South Pole, with a pair of ice Cherenkov tanks deployed above each IceCube string. Serap Tilav [30] presented the status of the array as IceCube nears the end of its construction. The high elevation is favorable for detecting air showers near maximum development with an energy threshold near 100 TeV, and the ability to study high energy muon bundles with IceCube will be a powerful tool for analyzing the composition in the region of the knee. The build-up of snow on older detectors affects the trigger rate and signal levels and must be considered in the analysis. A raw energy distribution shows the spectral steepening at the knee.

Sunil Gupta [31] presented results from the GRAPES-3 detector at Ooty. It also has a low energy threshold and can compare its composition analyses based on air showers against direct measurements. They have measured their angular resolution using the shadow of the moon. They have studied in detail the trigger rate dependence on atmospheric pressure and temperature. In addition, the rates respond to space weather, and they track the effects of coronal mass ejections.

A presentation by Jing Huang [32] for the Tibet Air

Shower γ Collaboration was given by Yuqian Ma. The results focused on the spectrum and composition at the knee. The Tibet results indicate that the knee is produced by nuclei heavier than helium, as they dominate the lightest elements by that energy. Beyond the knee the composition is expected to be heavy. To check these results in detail, they plan to construct, in three stages, the YAC: Yangbajing Air shower Core array. Its goal is to study spectra of individual components at the knee. YAC-I is already operational, and some early results were shown.

6. Ultra-high energy cosmic rays

The study of the highest energy cosmic rays is challenged by the extremely small flux of particles. The Auger Observatory in Argentina runs continuously with an aperture of 7000 km^2sr. Despite that large size, the results on anisotropy and composition are limited primarily by inadequate statistics. Paolo Privitera described plans for Auger North, which would operate with 47,000 km^2sr, increasing the aperture by almost a factor of eight, while retaining good control of systematics with hybrid detections at night and careful atmospheric monitoring.

Jim Adams [33] presented plans for JEM-EUSO, a space-based air fluorescence telescope to be flown on the International Space Station. Expected to launch in 2015, it will have an enormous aperture by virtue of a wide field of view (60°) and its large distance from the air showers. Its duty cycle is limited by sunlight, moonlight, high clouds, and city lights. Its energy threshold will be approximately 70 EeV, roughly the energy above which Auger has reported cosmic ray anisotropy. It will have full sky coverage, and it is expected to distinguish neutrinos, gamma rays, and hadronic cosmic rays.

Chris Williams [34] spoke about MIDAS, an experimental study of the feasibility of observing air shower longitudinal developments day and night by using molecular brhemsstruhlung radiation instead of air fluorescence. Overcoming the limited duty cycle of air fluorescence telescopes would be a major advance for the study of ultra-high energy cosmic rays.

Fred Kuehn [35] reported on the status of the AirFly measurements of the air fluorescence yield. That yield is an important normalizing constant for air fluorescence detectors that is the basis of the energy scale for ultra-high energy cosmic ray observatories. Relative yield dependence on atmospheric pressure, temperature, and humidity, on photon wavelength and electron energy have all been published already. A final result for the absolute yield is expected by the end of 2010 with uncertainty less than 5%.

Masaki Fukushima [36] presented preliminary results obtained with the Telescope Array in Utah, including a hybrid energy spectrum and composition analysis using stereoscopic measurements. The results are consistent with published HiRes results. In particular, the mean depths of maximum X_{max} in three energy bins below and above 10 EeV are at least as deep as expected for protons using conventional air shower models. Of special interest is an upcoming end-to-end calibration of their fluorescence detector using a linac to accelerate electrons in an upward-going beam at a distance of 100 meters from a TA telescope.

TALE is a proposed low-energy extension of the TA which would permit air fluorescence measurements of cosmic ray shower longitudinal profiles down to energies below 100 PeV. Charlie Jui [37] presented plans for 15 additional telescopes to cover an elevation angle range from 31° to 73° over a 90° azimuthal range. At those lower energies, air showers can only be measured relatively nearby, and the depth of maximum is therefore viewed at a high elevation angle.

Pierre Sokolsky [38] reported "Final Results from the High Resolution Fly's Eye (HiRes) Experiment." Those results include the stereo energy spectrum, anisotropy, and composition analysis. The energy spectrum was shown to agree well with the Auger energy spectrum by a shift of energies commensurate with the combined systematic uncertainty of the two observatories. No significant anisotropy is found - not the clustering reported by AGASA, not the AGN correlation reported by Auger, not any detected correlation with nearby large scale structure represented in the 2MRS catalog, and no confirmation of a tentative HiRes correlation with BL Lacs reported earlier. The HiRes analysis of depths of maximum is shown in Figure 10. The results are consistent with simulations of proton-initiated air showers.

Paolo Privitera [39] presented results from the Pierre Auger Observatory. The energy spectrum shows a clear steepening at the energy expected for the GZK pion photoproduction by protons or photodisintegration of iron. The structure is very similar to the HiRes spectrum, differing only by about a 20% shift in energy. The status of the correlation of arrival directions above 55 EeV with AGN locations was updated with new data. The correlation has decreased from roughly 70% to 40%. However, the 2.5σ statistical significance of the deviation from the 21% isotropic expectation is the same as when the correlation was first reported in 2007. Figure 11 shows the history and present status of the AGN correlation.

The Auger X_{max} results appear different from those of HiRes, as can be seen by comparing Figure 12 with Figure 10. Of special interest is the trend toward narrow X_{max} distributions in the decade from 4 to 40 EeV. Using customary extrapolations of hadronic models to these energies, the narrow distribution near 20 EeV is not consistent with a mixture of heavy nuclei and protons, and it is significantly narrower than expected for a pure proton composition. It is suggestive of a purely heavy composition and, in view of

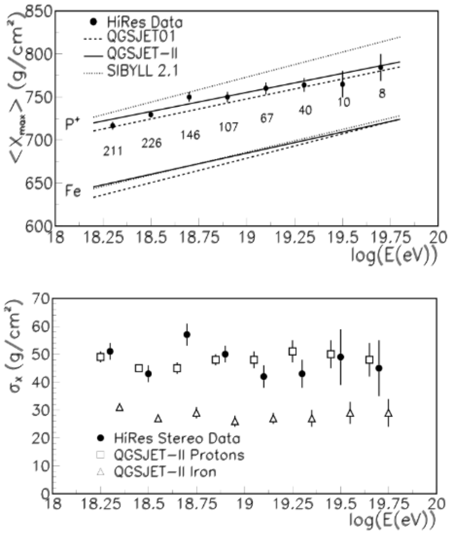

Figure 10: HiRes results on air shower depths of maximum X_{max}. The upper plot shows the mean X_{max} as a function of energy. The lower plot shows the width of the X_{max} distribution at each energy. In both plots the data are compared with expectations from customary models for protons and for iron.

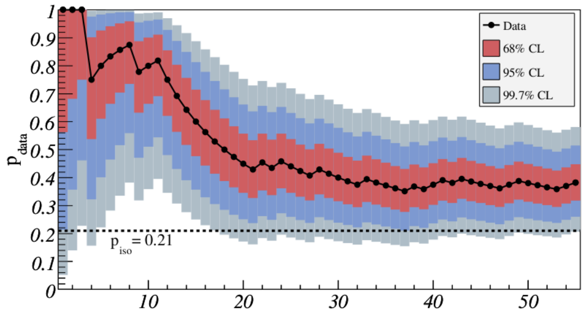

Figure 11: Fraction of correlating Auger events above 55 EeV as a function of the cumulative number collected *after* the exploratory scan. As originally prescribed, an arrival direction correlates if it is less than 3.1 degrees from one of the AGNs with redshift less than 0.018 in the 12th Veron-Cetty and Veron AGN catalog.

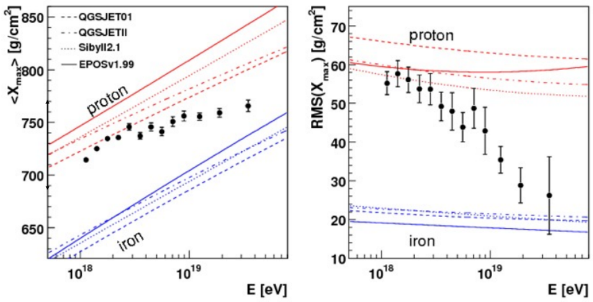

Figure 12: Auger X_{max} results. The left plot shows the mean X_{max} as a function of energy, and the right plot shows the width of the X_{max} distribution for each energy bin.

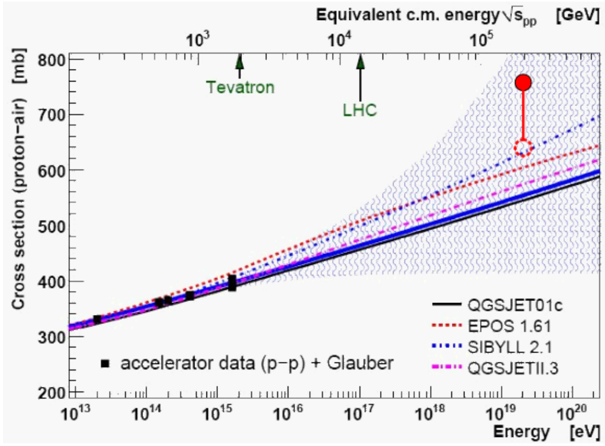

Figure 13: The red dot is a conservative lower limit for the proton-air cross section based on the narrow distribution of X_{max} values near 20 EeV *if the primary particles are protons*. The dotted circle is the upper limit obtained from the "1-sigma" upper limit on that X_{max} distribution width.

the magnetic field of the Galaxy, not easily reconciled with the correlation of arrival directions with AGNs at somewhat higher energy. If the narrow distribution is assumed to be protons at the next-to-highest energy bin, for example, a conservative minimum proton-air cross section is obtained by assuming that the spread in X_{max} is entirely due to the spread in first interaction depths. Figure 13 shows this lower limit in relation to some standard models of how the proton-air cross section may rise with energy.

7. Summary and discussion

Accelerator experiments and cosmic ray observations are two arenas of high energy physics that have been intertwined since particle accelerators came into existence in the second half of the last century. The high energy frontier always belongs to cosmic rays, but measurements with controlled conditions belong to the accelerators. Indirect (air shower) studies of cosmic rays rely on models of particle interactions, and presently the models extrapolate interaction properties to energies which have not been investigated experimentally. For example, different extrapolations result in different composition inferences near the knee using KASCADE data. It is therefore exciting that detectors like TOTEM, LHCf, and CASTOR will be providing data in the essential forward region. The center of mass interaction energy is now 7 TeV and will increase to 14 TeV. As seen in Figure 13, a measured cross section at the LHC energy will be a powerful constraint on extrapolations to the regime of ultra-high energy cosmic rays. Air shower simulations also require accurate modeling of secondary interactions. The MIPP measurements, with its variety of beam particles and nuclear targets and with its measurements over all of phase space, will provide vital data for this.

Cosmic ray observations are now rich in details over the entire energy spectrum of ten decades. Satellite and balloon missions have measured spectra of individual elements or groups of elements almost up to the knee. Anisotropy has been mapped by Milagro, IceCube, Tibet AS array, and ARGO. KASCADE-Grande continues to refine measurements up to 100 PeV in order to determine the spectra of individual element groups in the region of the knee and above. Ultra-high energy cosmic ray observatories, Auger and TA, are pushing down to 100 PeV from above. At the same time, they are looking to the highest energy cosmic rays for clues about the ultra-high energy extragalactic sources as well as the nature of particle interactions above 300 TeV center-of-mass energy. Fundamental questions about the origins and propagation of cosmic rays persist at all energies. The measurements have improved in statistics and systematics. Interpreting the air shower measurements requires knowledge of particle interactions that must be obtained from accelerator experiments. These ISVHECRI meetings play an important role.

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