Results from the High-Resolution Fly’s Eye (HiRes) Experiment

Physics at the End of the Galactic Cosmic Ray Spectrum

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Outline

• Brief introduction of the High-Resolution Fly’s Eye (HiRes) Experiment
• Energy spectrum
• Anisotropy
• Composition
• Proton-air cross-section measurement
The High Resolution Fly’s Eye (HiRes)

HiRes Collaboration:

- University of Utah
- Columbia University
- Rutgers University
- University of New Mexico
- University of Montana
- University of Adelaide
- Los Alamos National Laboratory (LANL)
- University of Tokyo
- IHEP (Beijing, China)
HiRes Location

• HiRes is located on the U.S. Army Dugway Proving Ground, ~2 hours from The University of Utah campus.

• The two detector sites are located 12.6 km apart at Little Granite Mountain and Camel’s Back Ridge.
Detector Design

- Each HiRes detector unit ("mirror") consists of:
  - spherical mirror w/ 3.72m² unobstructed collection area
  - 16x16 array (hexagonally close-packed) of PMT pixels each viewing 1° cone of sky: giving ×5 improvement in S:N over FE (5° pixels)
  - UV-transmitting filter to reduce sky+ambient background light
  - Steel housing (2 mirrors each) with motorized garage doors
Typical HiRes Event

~2×10^9 eV event seen in 1999
(3× vertical scale)
Reconstruction of EAS from HiRes Data

- The trajectory of the EAS can be determined in one of two ways:
  1. Monocular reconstruction using the arrival time of light signal at the detector.
  2. By intersecting the shower-detector planes (SDP) seen from the two detector sites.

\[ t_i = t_0 + \frac{R_P}{c} \tan \frac{\theta_i}{2} \]
**HiRes Operations**

- Continuous operation of HiRes-1 detector since 1997 with 4 major down period (7 months off after anthrax episode)
- Currently running at 10% duty cycle

<table>
<thead>
<tr>
<th>Experiment/ Data Set</th>
<th>Exposure (km$^2$sr-yr)</th>
</tr>
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<tbody>
<tr>
<td>AGASA (100 km$^2$)</td>
<td>$\sim$1000</td>
</tr>
<tr>
<td>Fly’s Eye (stereo)</td>
<td>150</td>
</tr>
<tr>
<td>Fly’s Eye (monocular)</td>
<td>930</td>
</tr>
<tr>
<td>Haverah Park (12 km$^2$)</td>
<td>270</td>
</tr>
<tr>
<td>Yakutsk (25 km$^2$)</td>
<td>490</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2,740</td>
</tr>
<tr>
<td>HiRes-1 monocular</td>
<td>$\sim$5,000</td>
</tr>
<tr>
<td>HiRes Stereo</td>
<td>$\sim$2,500</td>
</tr>
</tbody>
</table>
Physics with HiRes Data

- **Stereo data**: best resolution, optimized for $E > 3 \times 10^{18} eV$
- **HiRes-2 monocular**: can reach down to as low as $10^{17.2} eV$
- **HiRes-1 monocular** data began ~3 years earlier: largest statistics,
  - Uses profile constrained fit (PFC) unreliable $< 10^{18.5} eV$
  - No possibility of composition analysis with $X_{max}$

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Monocular Spectrum

- HiRes-1 monocular requires “profile constrained Fit” (PCF)
- Combined HiRes-1 and HiRes-2 monocular spectra published:
  *Phys. Rev. Lett. 92, 151101 (2004)*
- HiRes-2 monocular spectrum (updated Summer 2004)
Cross checks

• PCF reconstruction and spectrum checked against:
  – stereo reconstruction
  – geometrically restricted aperture
Atmospheric Correction

- Average Aerosol VAOD at Dugway ~0.04

- Reconstructing energy of **vertical laser at 34 km** from HiRes-2 using hour-to-hour correction

Energy Reconstruction of 34 km vertical Laser: Nov 2003 – April 2004
**FLASH (SLAC E-165)**

- Undertaking detailed fluorescence measurements
- Also measure light yield from simulated showers (alumina)

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**Figure:** Spectrum In Dry Air Measured On North Side
HiRes

- Located west of the City of Delta: Now under construction
- TA Phase-1 (Standatd TA)
  - Ground array of 576 (1.2km spacing) scintillation counters
  - Three fluorescence sites looking inward
Power Law Fits

- Topic of another presentation later by Doug Bergman

- Triple Power Law Fit (TPLF)
  - Finds GZK suppression

- Hires-II sees the same features by itself:
  - Also finds GZK suppression
Monocular Spectrum Update

- Latest update HiRes-2 monocular spectrum continues to be in good agreement with HiRes-1 monocular in the region of overlap (which is expanding as more data is analyzed)
Monocular Anisotropy

- HiRes-1 mono ang. resolution: \(~8^\circ\) within the SD plane.
- Asymmetric error ellipses but with area comparable to AGASA angular resolution
- Both are null results from HiRes

*Autocorrelation functions* (histogram of \(\cos \theta\) between all possible pairs) for HiRes-1 monocular (left) and AGASA (right) events above \(~4\times 10^{19}\)eV


Search for dipole enhancement in the direction of nearby a-priori sources: *null results* for the Galactic Center, Centaurs A, and M87

**Astropart. Phys. 21, 111 (2004)**
Monocular Anisotropy

- Point source search: null result
- Search for cross-correlation with AGASA doublets and triplet:
  - treated the six AGASA "clusters" as *a priori* candidates
  - Observed overlap with these clusters is no greater than that expected by chance from an isotropic background distribution.
  - The fluctuation required for these sources to have yielded both the HiRes and AGASA event counts would occur with a probability of less than 3%.
Prelim. Stereo Spectrum

- Stereo data has best energy resolution
- Statistics poorer than HiRes I monocular
- Present stereo data can be used to confirm the spectrum normalization from 3 to 100 EeV.
- Continue to accumulate Stereo Data to match monocular sensitivity at highest energies.
- New stereo spectrum by summer 2005
Stereo Anisotropy

- Stereo data has angular resolution **better than 0.6°**: significantly better than that of AGASA
Stereo Anisotropy

- Analysis on small scale anisotropy:
- Count number of pairs $N_p$ with separation $< \theta$. 
- Use Monte Carlo with isotropic distribution to:
  - find probability of observing $N_p$
  - determine expected value for $<N_p>$

$w = N_p / <N_p> - 1$

- HiRes ($E > 10^{19}$ eV) is consistent with isotropy at all small angular scales.

Stereo Anisotropy

- Work also in progress on search for enhancement about the Super-Galactic Plane
- Joint point source search with AGASA data
- Apply likelihood analysis to random isotropic data sets with identical number of events.
- 47 out of $10^4$ have $\ln(R) > 12.98$.
- Actual chance probability is higher because of ad hoc changes in Hires threshold and a posteriori nature of the AGASA cuts.
Stereo Anisotropy

- BL-Lac Correlations
  Gorbunov et al., astro-ph/0406654
  - Set of 156 BL Lacs, with
  - no cuts on $z$, $m < 18$, no cuts on $F_6$
  - no criteria for correlation with EGRET catalog.
  - Set of HiRes events with $E > 10^{19}$ eV (271 events)
  - 11 events within $0.8^\circ$ of these BL Lacs.
  - chance probability $\sim 10^{-3}$
Composition


- Higher statistics needed to extend analysis up to the GZK Threshold!
Stereo Xmax Measurement

- Two simultaneous measurements of the Xmax allows for direct verification of the MC resolution
Systematic Uncertainty in Xmax

- Effect of pointing accuracy – 15 gm/cm²
- Effect of atmospheric variation – 10 gm/cm²
- Effect of using Std Atmosphere – 10 gm/cm²
- Reconstruction bias – 5 gm/cm²
- Sum in quadrature – 21.2 gm/cm²
- Will use 3-season-model in future work with composition
Nuclear & Particle Physics

- First HiRes measurement of *Inelastic proton-air cross-section* Paper in preparation (K. Belov)

J. Hörandel QGSJET corrections using CDF (Abe at al. 1994), and E-710, E-810 (Amos at al., 1990, Avila at al., 1999).

*Aspen*

4/06/05
\( \Delta X_{\text{max}} \approx 21 \text{ g/cm}^2 \)

shift of \( \langle X_{\text{max}} \rangle \approx 2 \text{ g/cm}^2 \)

\( \Delta E = 12\% \)
Composition influence – Fe & CNO.

- 20% Fe is shown as dotted line.
- Heavier nuclei influence can be reduced by only using a part of the distribution deeper than 700 g/cm$^2$. 
Utah (continued)

- The atmosphere over Utah appears much more stable and in good agreement with seasonal “Standard atmosphere” Models.
- Residuals between measurements and model are typically less than ~10 mBar in the troposphere.
How much does the reconstructed shower $X_{\text{max}}$ shift using Radiosonde data (SLC) vs. using the US standard atmosphere model?
Summary

- HiRes has been operating in monocular mode since 1997 and stereo mode since late 2000
- Monocular spectrum is consistent with GZK suppression and shows an ankle near $\sim 4 \times 10^{18} \text{ eV}$
- In good agreement with FE stereo spectrum
- HiRes mono and stereo spectra are consistent
- Results in monocular and stereo anisotropy:
  - No point sources in HiRes data
  - Apparent overlap of one HiRes stereo event with AGASA triplet
  - Possible BL-Lac correlation
- Xmax composition result published
- P-air cross section