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

From Colliders to Cosmic Rays

Prague

Sep 11, 2005

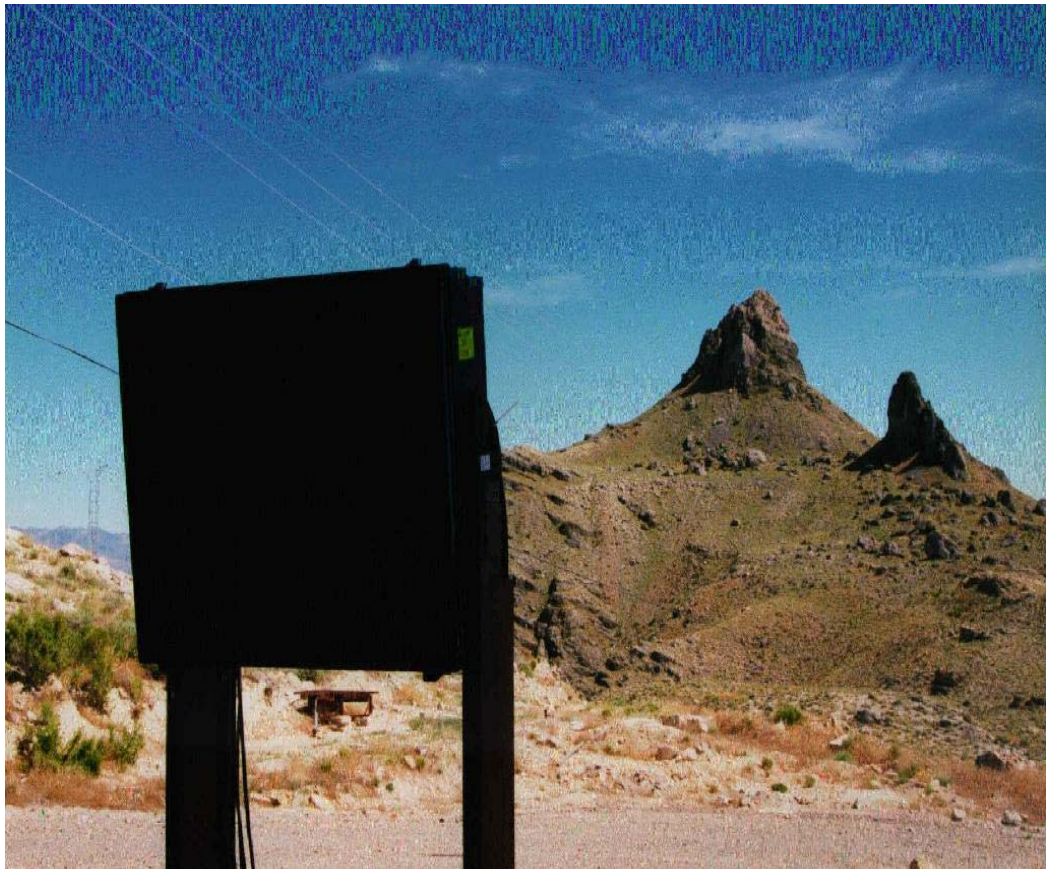
Charles Jui

University of Utah

Outline

- Introduction of the High-Resolution Fly's Eye (HiRes) Experiment
- Composition and p-air cross-section measurements (*abbreviated: more details from K. Belov on Mon Sep. 12 @ C2CR*)
- Energy spectrum and features
- Anisotropy
- The Future: TA and TALE … + ?

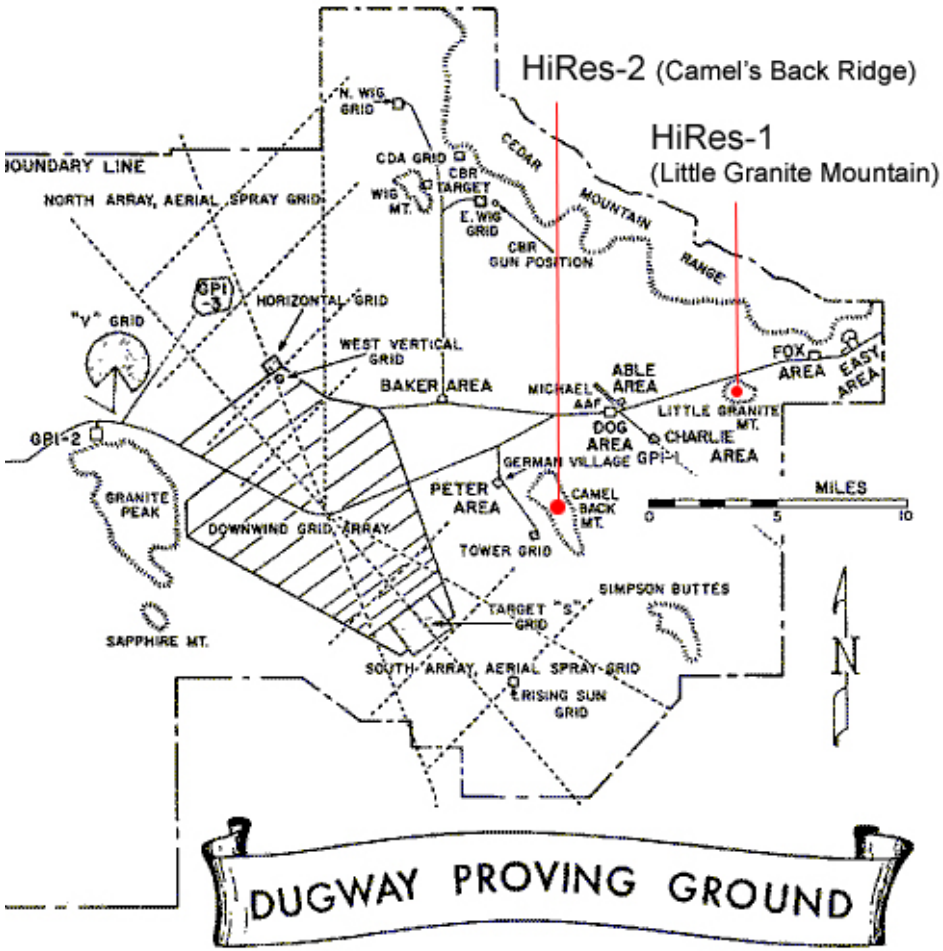
Introduction to the High Resolution Fly's Eye (HiRes)



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)*

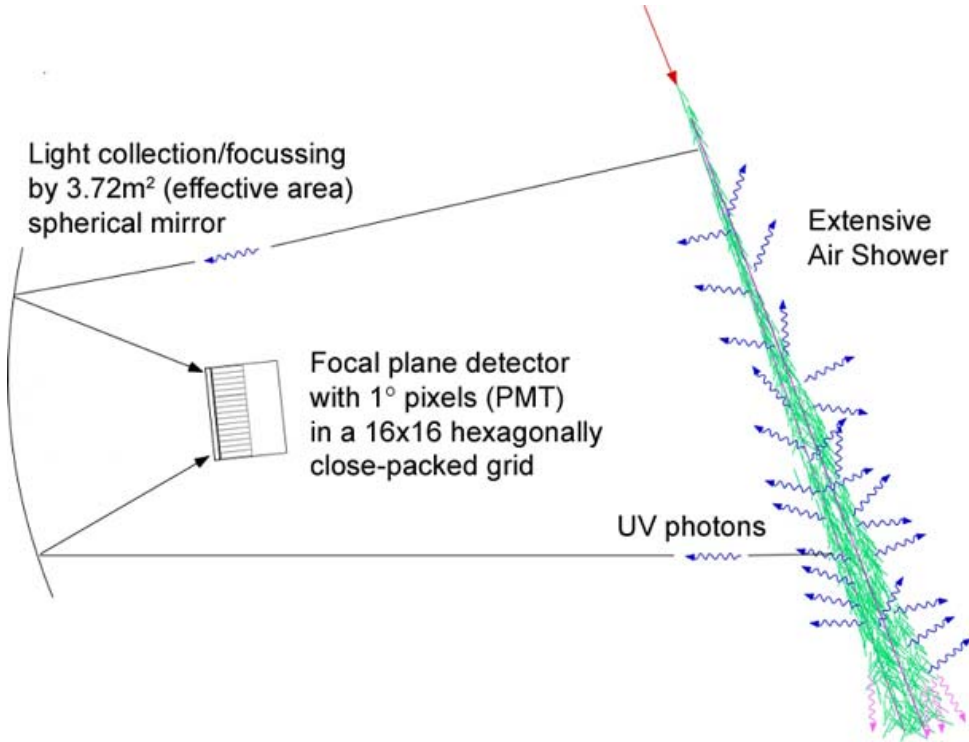
HiRes Location



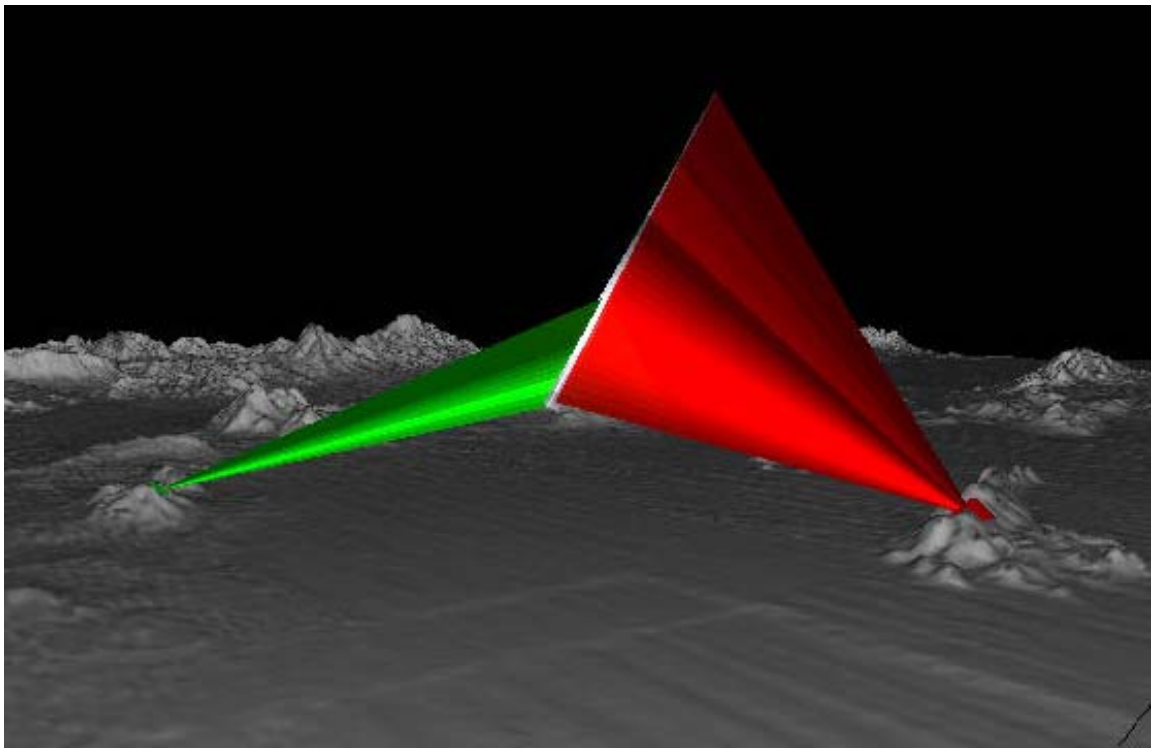
- HiRes is located on the U.S. Army Dugway Proving Ground, ~2 hours from The University of Utah campus.
- The two detector sites are located 12.6 km apart at Little Granite Mountain and Camel's Back Ridge

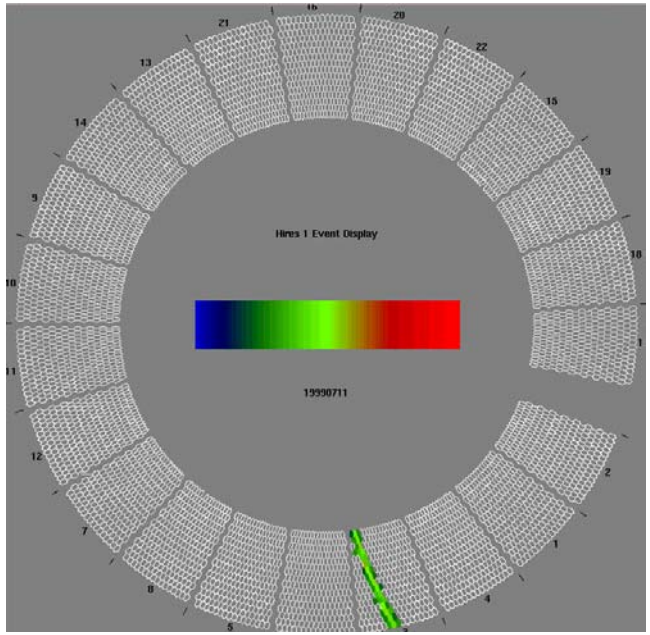
Detector Design

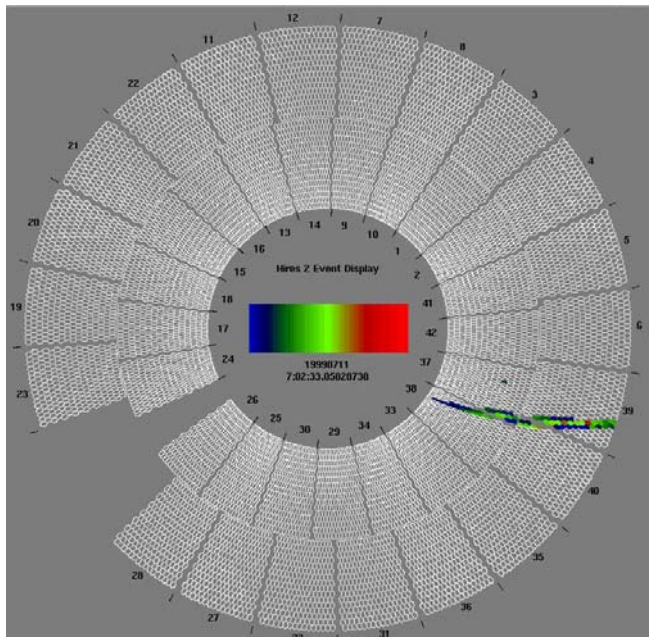
- Each HiRes detector unit ("*mirror*") consists of:
  - spherical mirror w/ ***3.72m²*** unobstructed collection area
  - 16x16 array (hexagonally close-packed) of PMT pixels each viewing ***1° cone*** of sky: giving ×5 improvement in S:N over FE (5° pixels)
  - UV-transmitting filter to reduce sky+ambient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



Typical HiRes Event





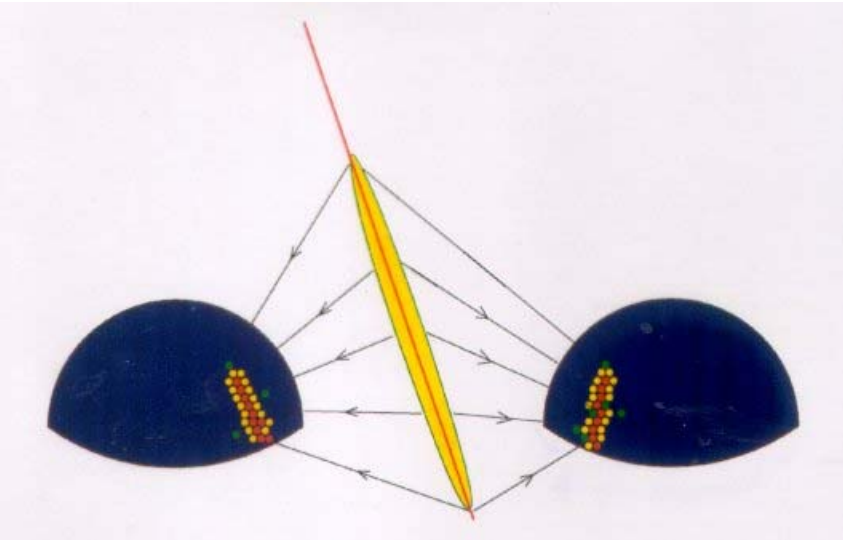


~2×10^9eV event seen in 1999

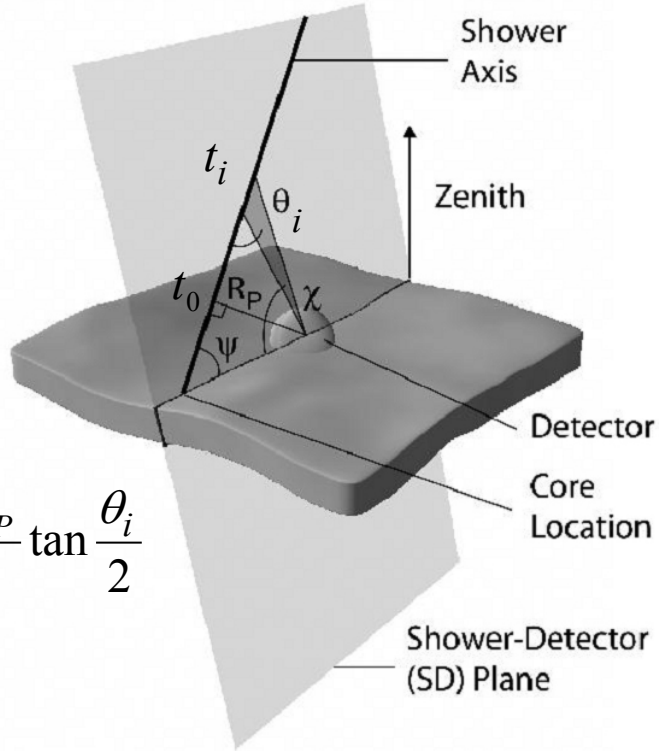
(3× vertical scale)

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.

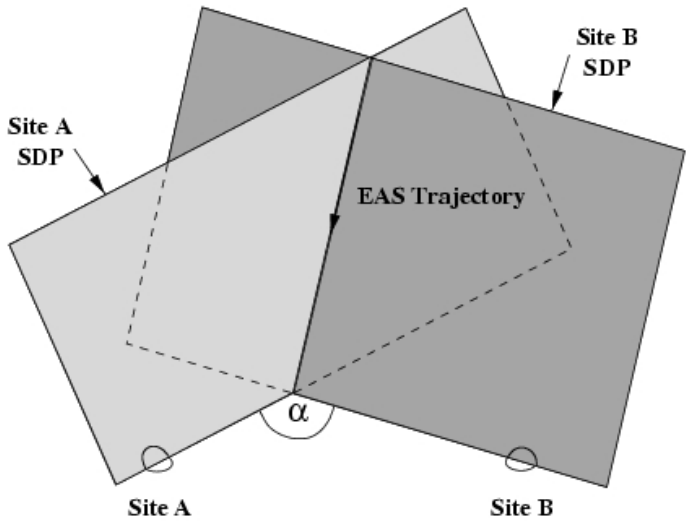


1.)



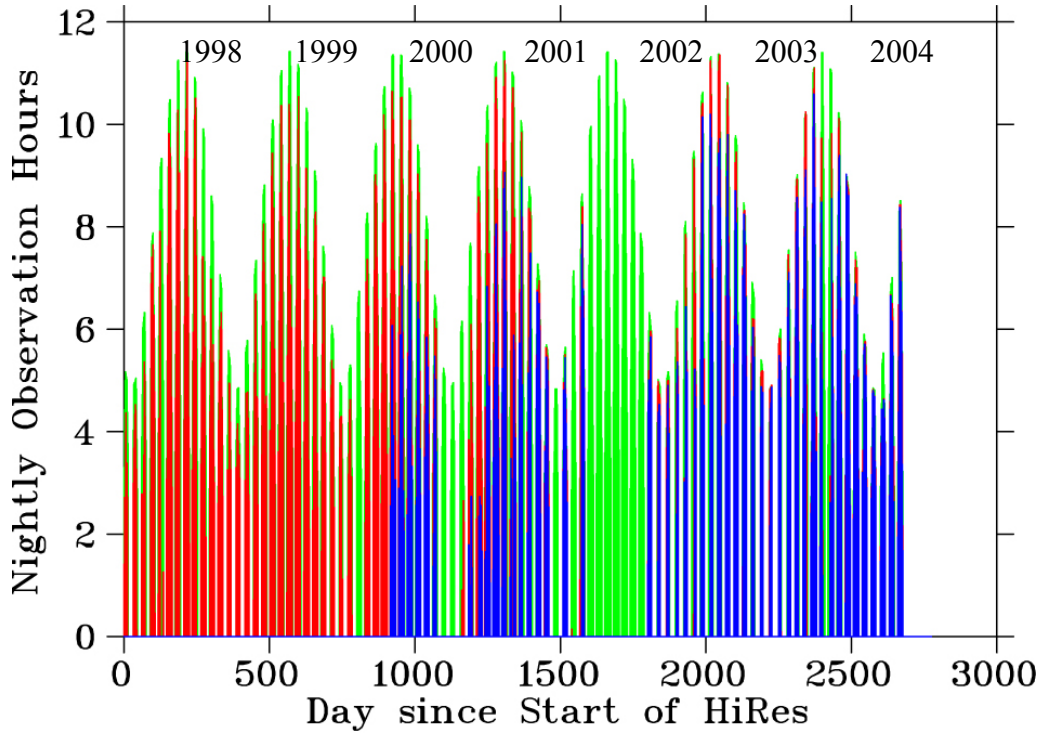
$$t_i = t_0 + \frac{R_P}{c} \tan\frac{\theta_i}{2}$$

2.)



HiRes Operations

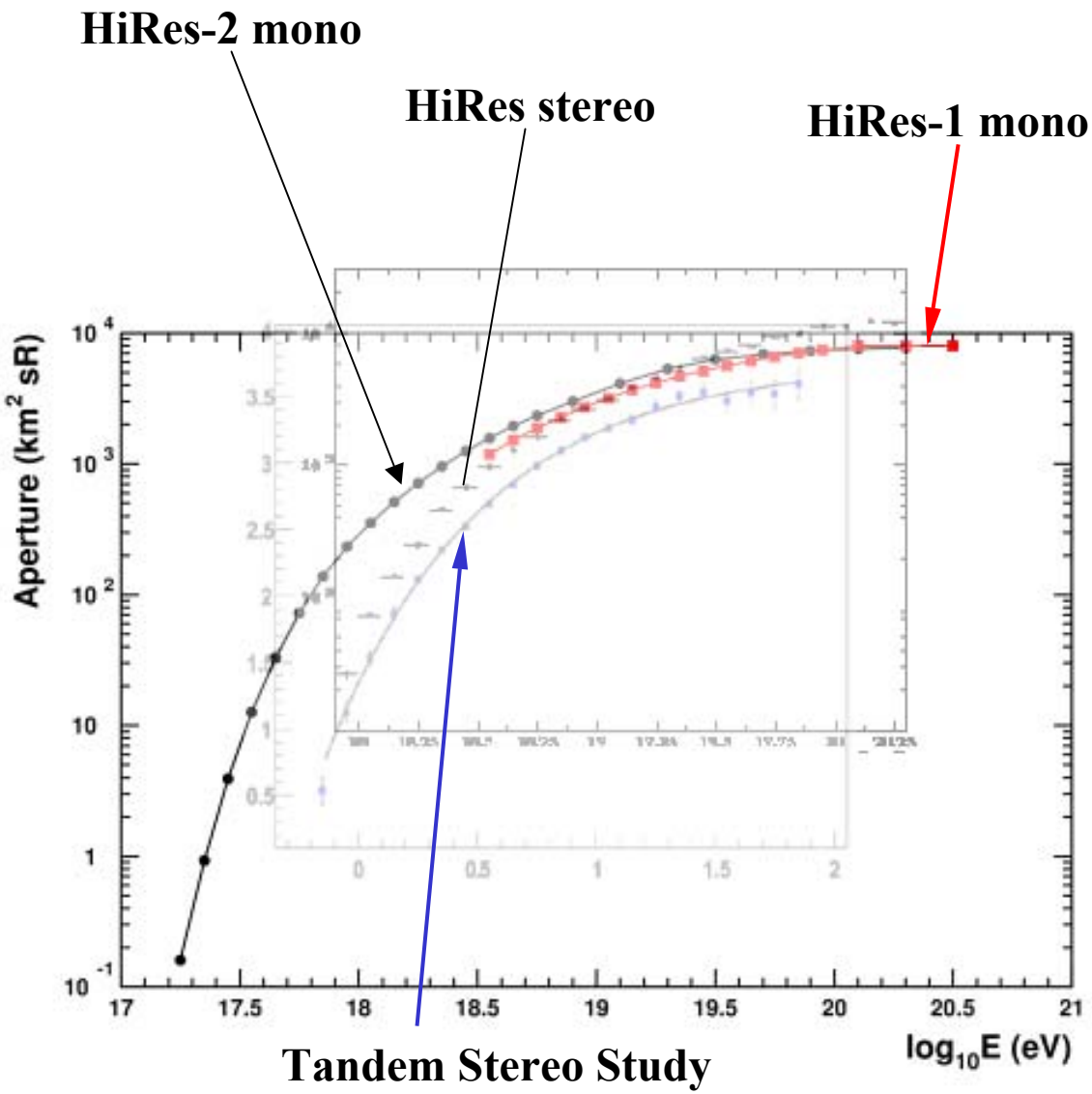
- Continuous operation of HiRes-1 detector since 1997 with 4 major down periods (7 months off after anthrax episode)
- Has been operating at 10% duty cycle since 2001-2002 shutdown



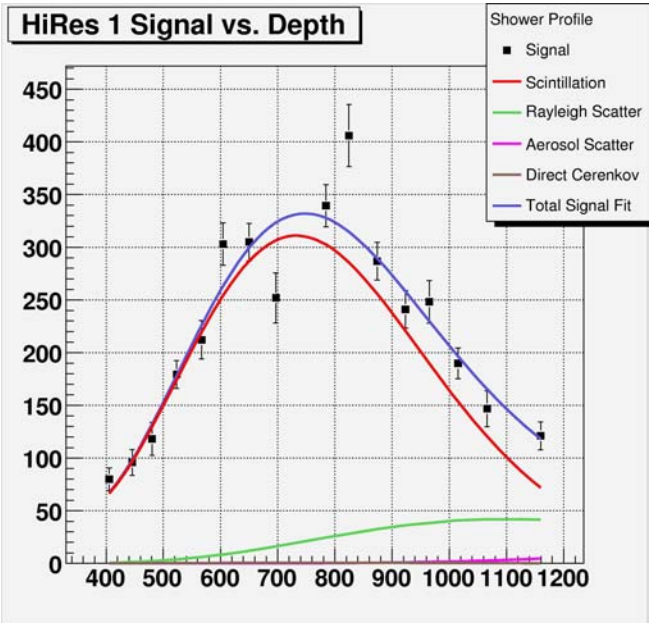
Experiment/ Data Set	Exposure(km^2sr-yr)
AGASA (100 km^2)	~1000
Fly's Eye (stereo)	150
Fly's Eye (monocular)	930
Haverah Park (12 km^2)	270
Yakutsk (25 km^2)	490
Total	2,740
HiRes-1 monocular	**~5,000**
HiRes Stereo	**~3,000**

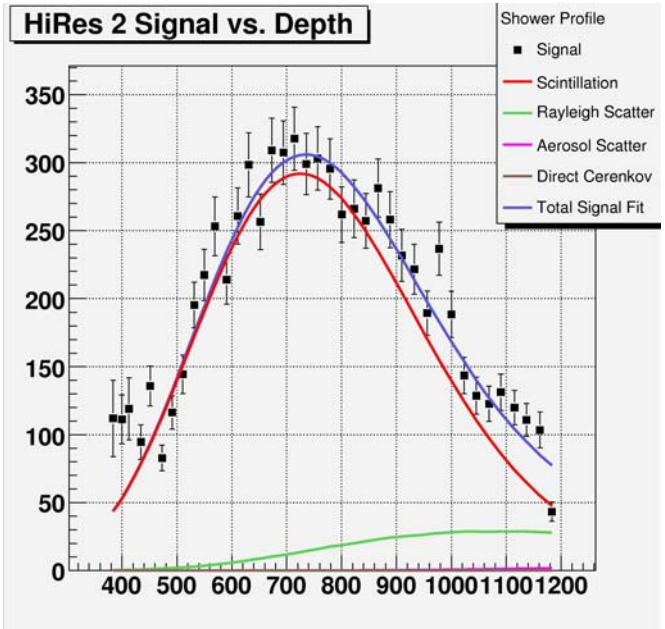
Physics with HiRes Data

- ***Stereo data***: best resolution, optimized for $E>3\times10^{18}eV$
- ***HiRes-2 monocular***: can reach down to as low as $10^{17.2}eV$
- ***HiRes-1 monocular*** data began ~3 years earlier: ***largest statistics***,



Measured shower profile.





Measured shower parameters.

Event by event:

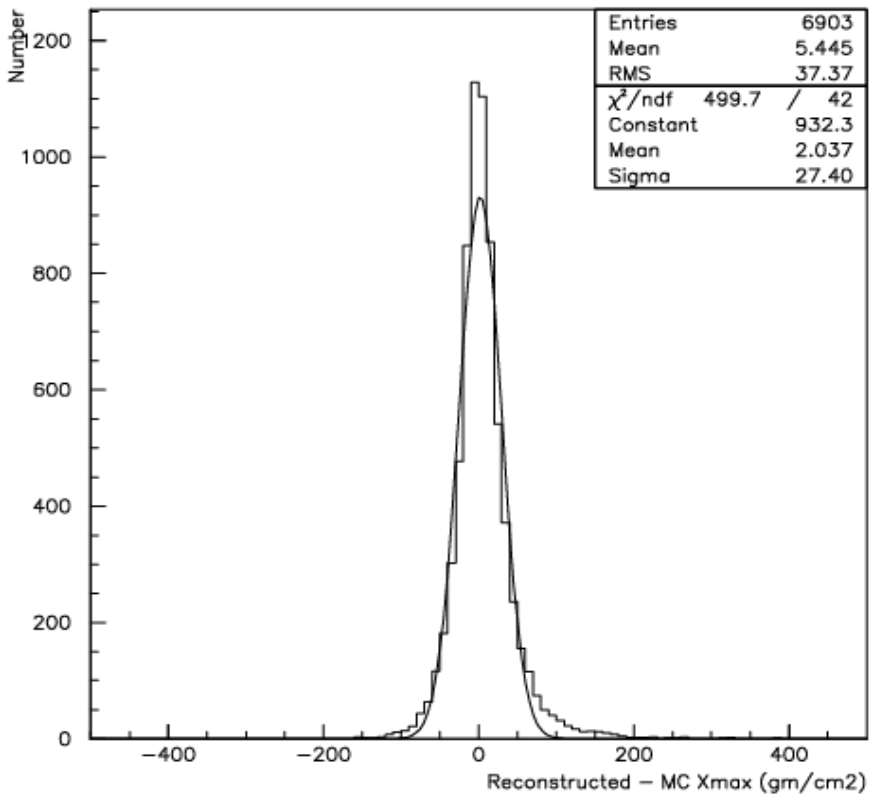
- X_{max} in g/cm^2;
- Total energy of the primary particle:
- Arrival direction

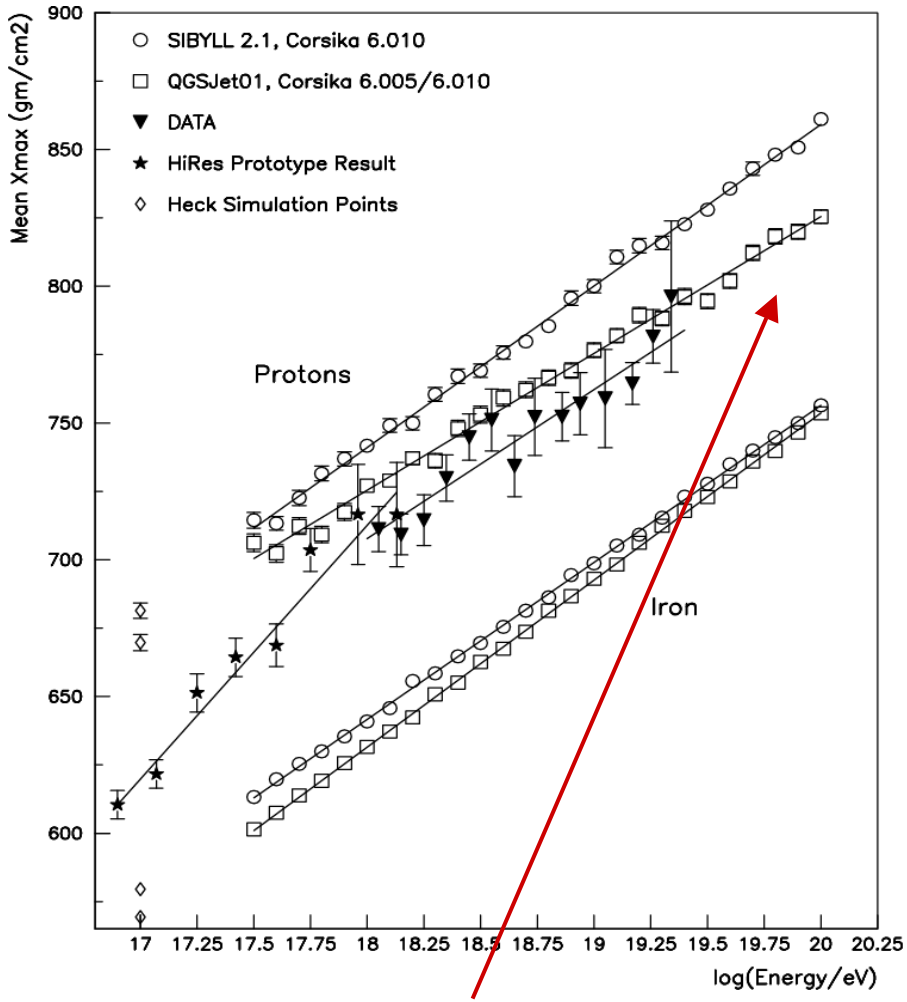
Statistically:

- composition.
- *p*-air inelastic cross-section;

HiRes Composition Measurement

- **Astrophysical Journal 622 (2005) 910-926**

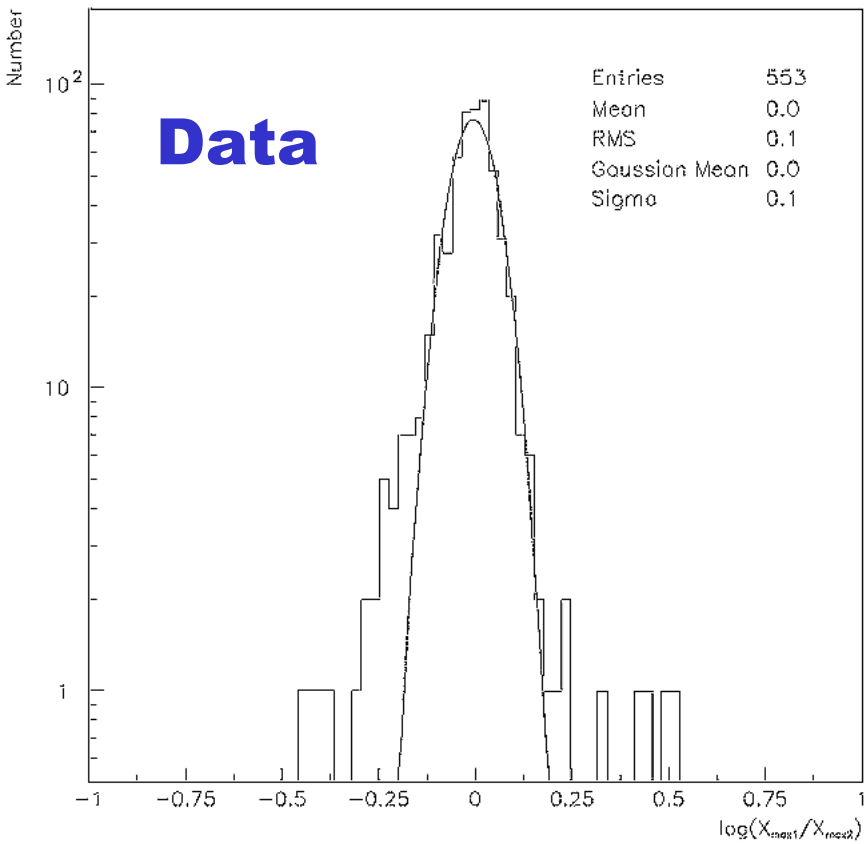


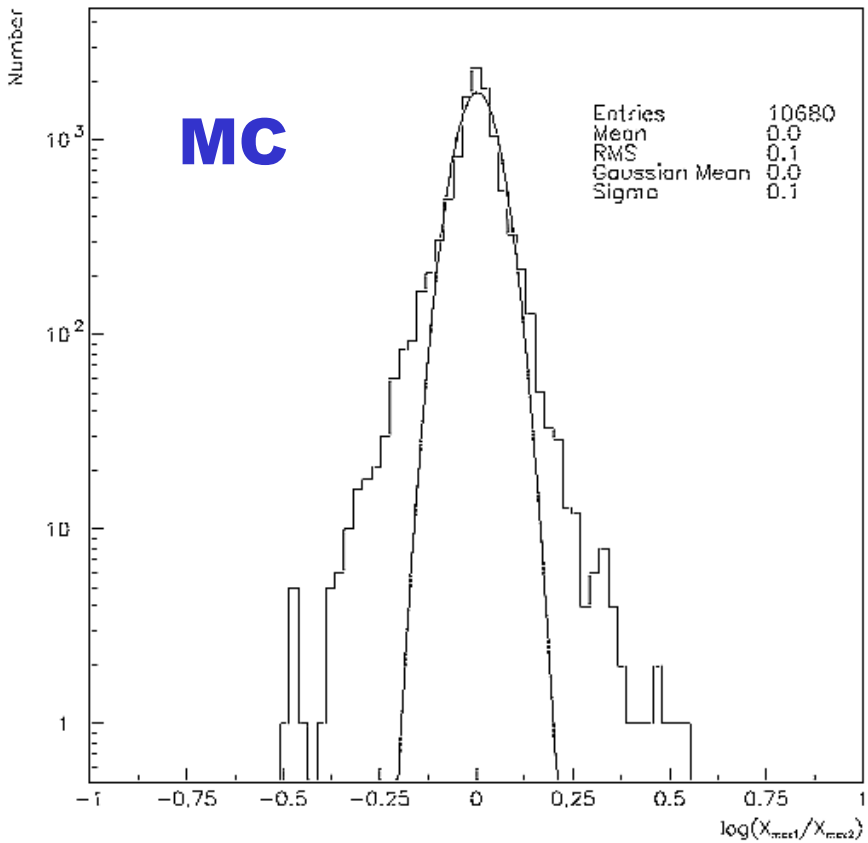


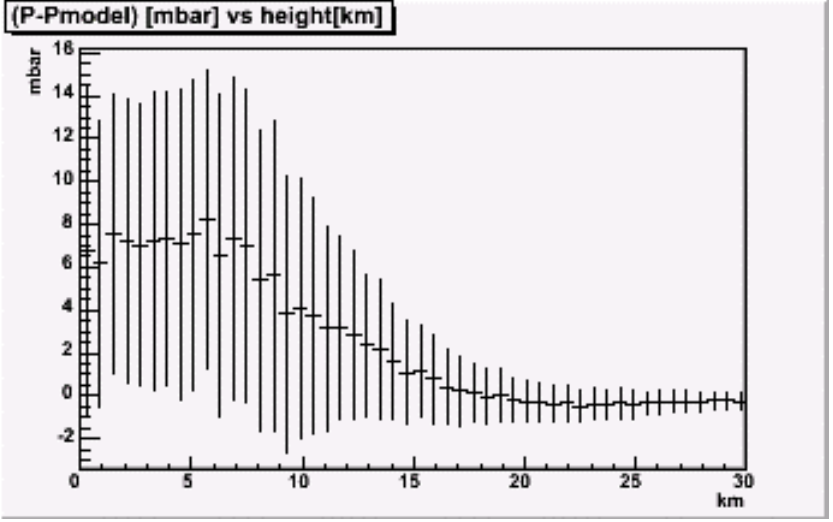
- ***Higher statistics needed to extend analysis up to the GZK Threshold!***

Stereo Xmax Measurement

- Two simultaneous measurements of the Xmax allows for ***direct verification*** of the MC resolution

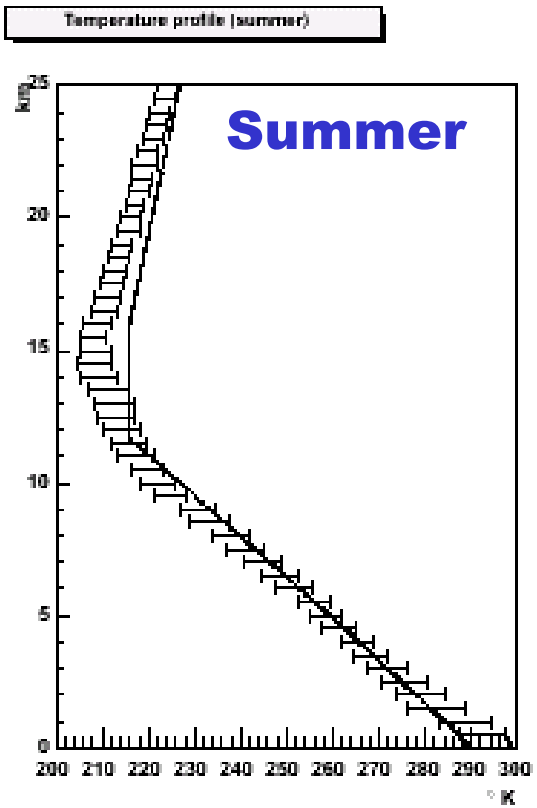


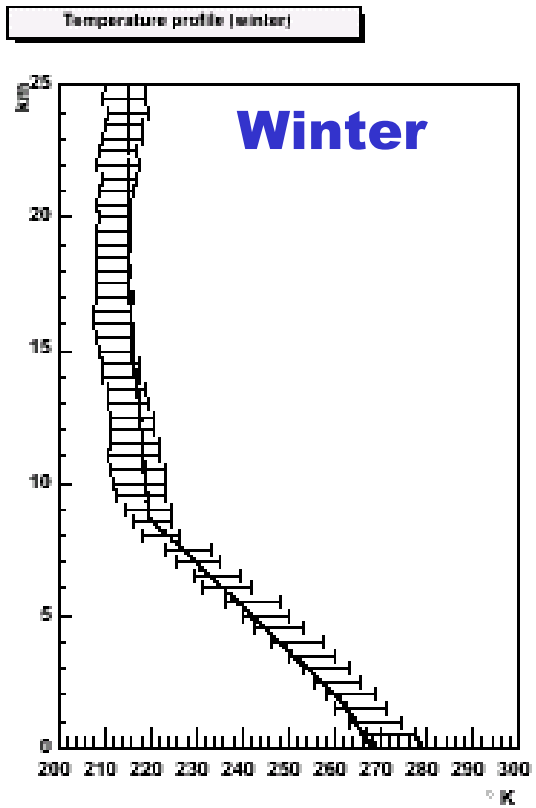


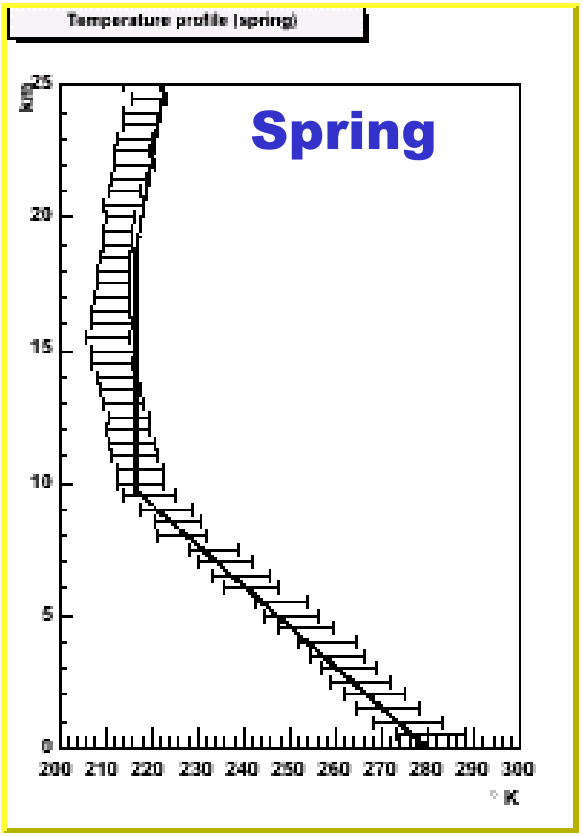


Updated Atmospherics

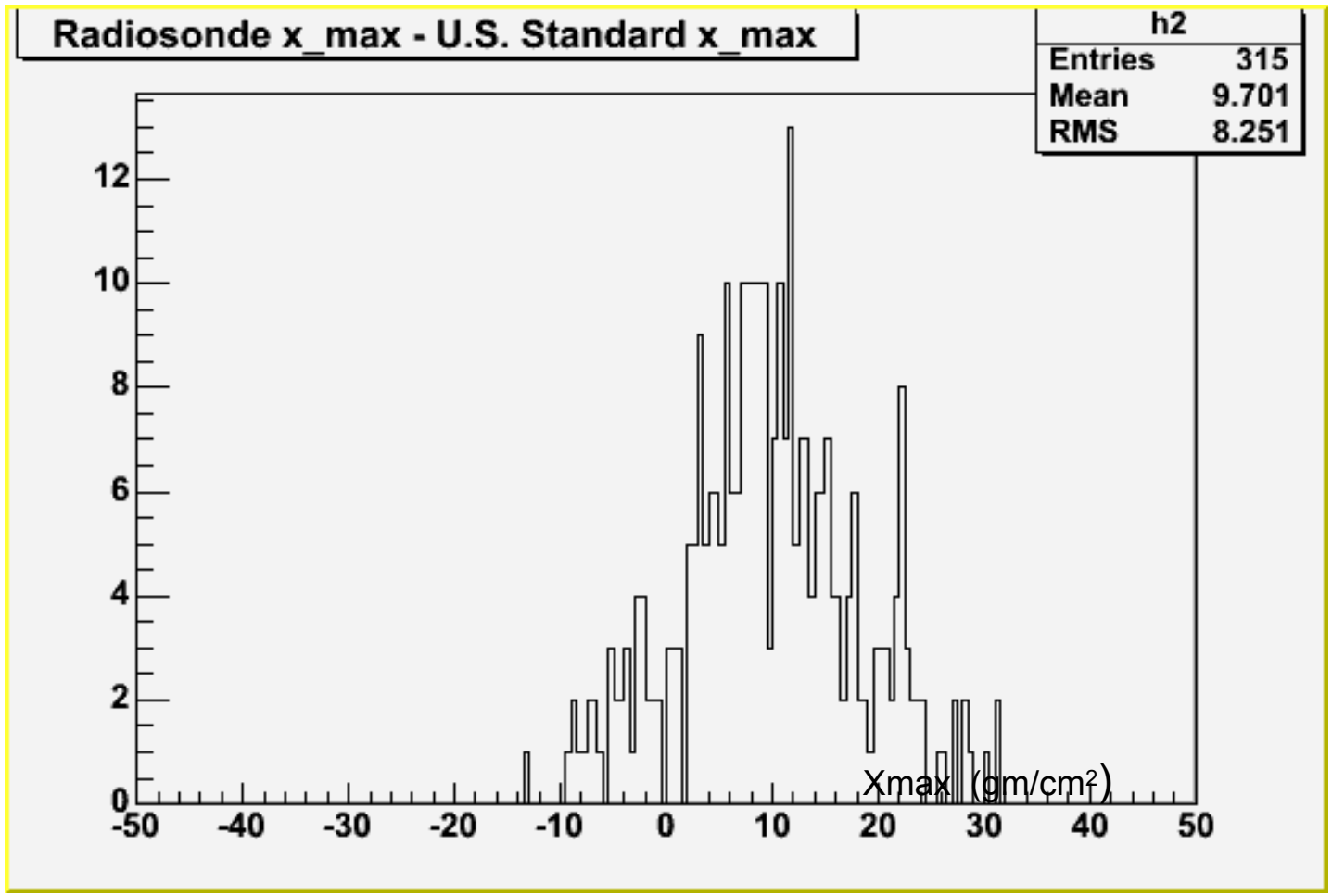
- The atmosphere over Utah appears stable and in good agreement with seasonal "Standard atmosphere" Models
- Residuals between measurements and model are typically less than ~10 mBar in the troposphere.







How much does the reconstructed shower X_{max} shift using Radiosonde data (SLC) vs. using the US standard atmosphere model?



Systematic Uncertainty in Xmax

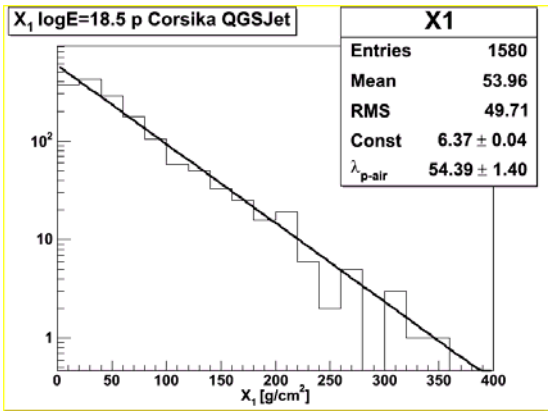
- Effect of pointing accuracy – 15 gm/cm^2
- Effect of atmospheric variation – 10 gm/cm^2
- Effect of using Std Atmosphere –10 gm/cm^2
- Reconstruction bias – 5 gm/cm^2
- Sum in quadrature – 21.2 gm/cm^2
- 3-season model shifts published Xmax vs E results 10 gm/cm^2 larger/deeper
- Will use 3-season-model in future work with composition:

Measuring Cross-Section: De-convolution Method.

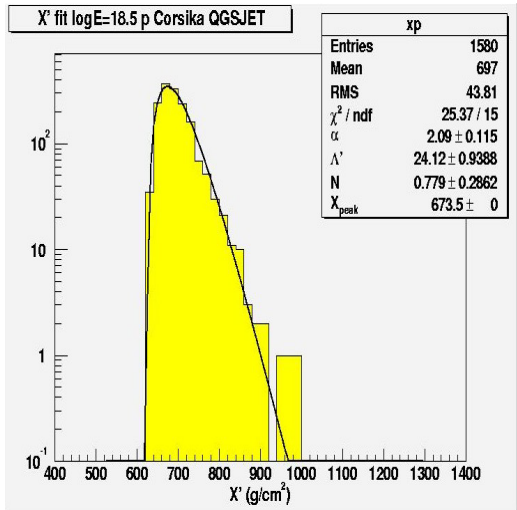
Point of first interaction distribution. Exponential index reflects inelastic Cross-section

Atmospheric part of air shower fluctuations

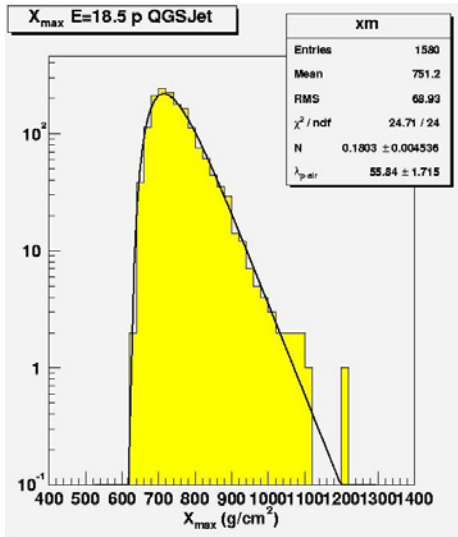
X_{max} distribution



$\otimes$



$=$



$$f_{\text{int}} = e^{-\frac{x_1}{\lambda_{p-Air}}};$$

$$\lambda_{p-Air} = \frac{1}{\tilde{n}\,\sigma^{inel}_{p-air}};$$

$$X' = X_{\max} - X_1$$

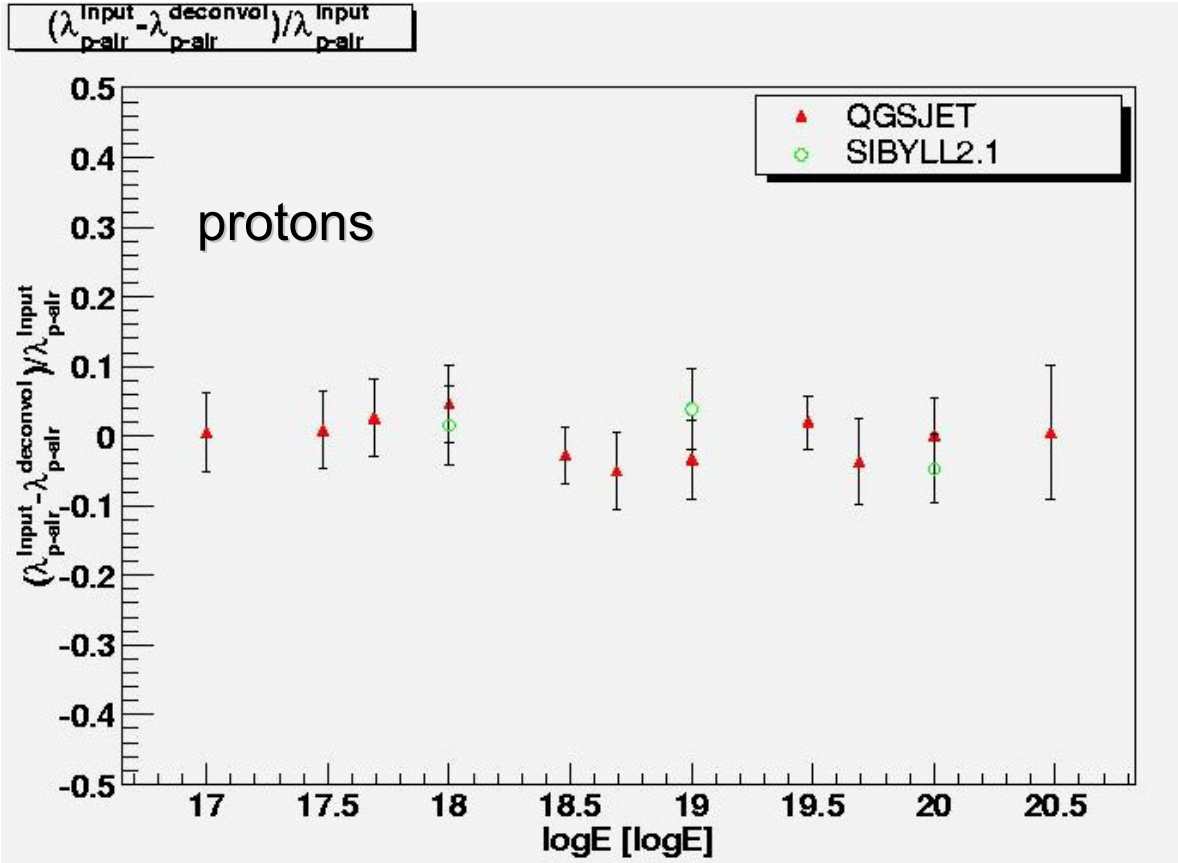
$$f_{fluct} = \left[\frac{x_{\max} - x_{peak} - x_1 + \Lambda'\alpha}{e}\right]^{\alpha} e^{-\frac{x_{\max}-x_1-x_{peak}}{\Lambda'}}$$

$$f_{fluct}(x_{peak}(E), \Lambda'(E), \alpha(E)) \Rightarrow f_{fluct}(E)$$

$$P_m(x_m) = N \int_0^{x_m - x_{peak} + \Lambda'\alpha} e^{\frac{-x_1}{\lambda_{p-Air}}} \left[\frac{x_{\max} - x_{peak} - x_1 + \Lambda'\alpha}{e}\right]^{\alpha} e^{-\frac{x_{\max}-x_1-x_{peak}}{\Lambda'}} dx_1;$$

Test of De-convolution Method

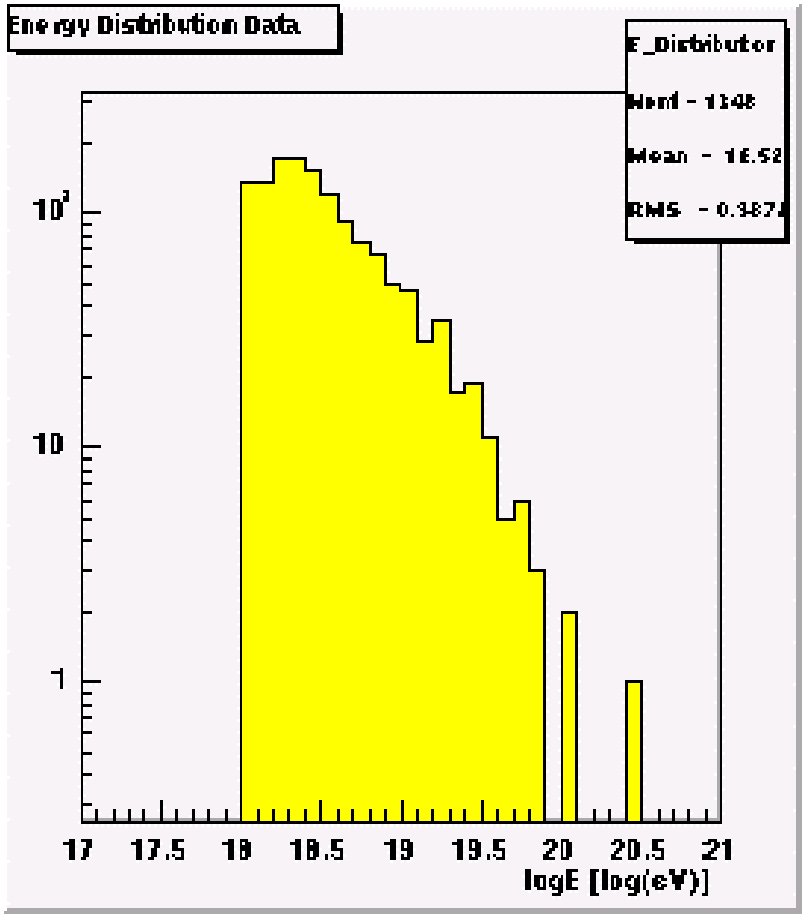
$$\frac{\lambda^{input}_{p-air} - \lambda^{deconvol}_{p-air}}{\lambda^{input}_{p-air}}$$



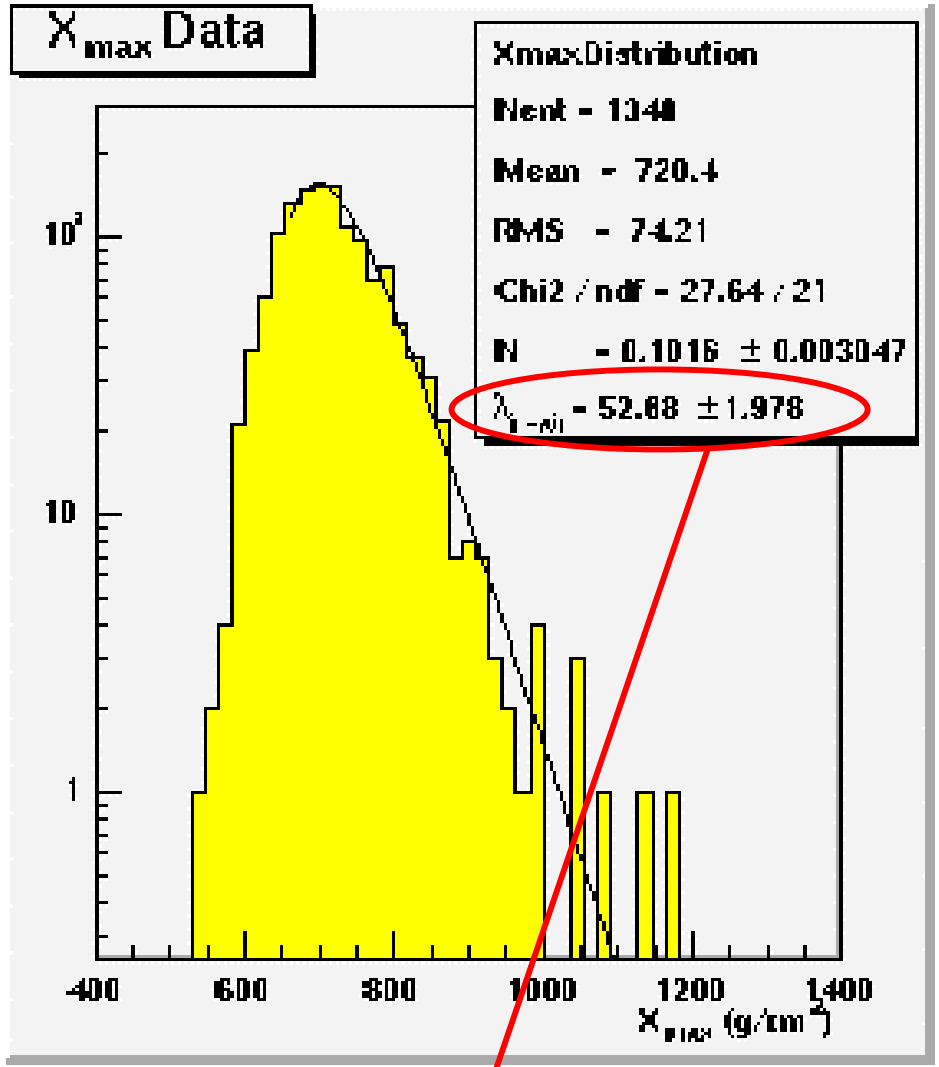
Correct within fitting errors

Deconvolution is identical for QGSJet and SIBYLL. (events through detector simulation)

Data and Deconvolution Result

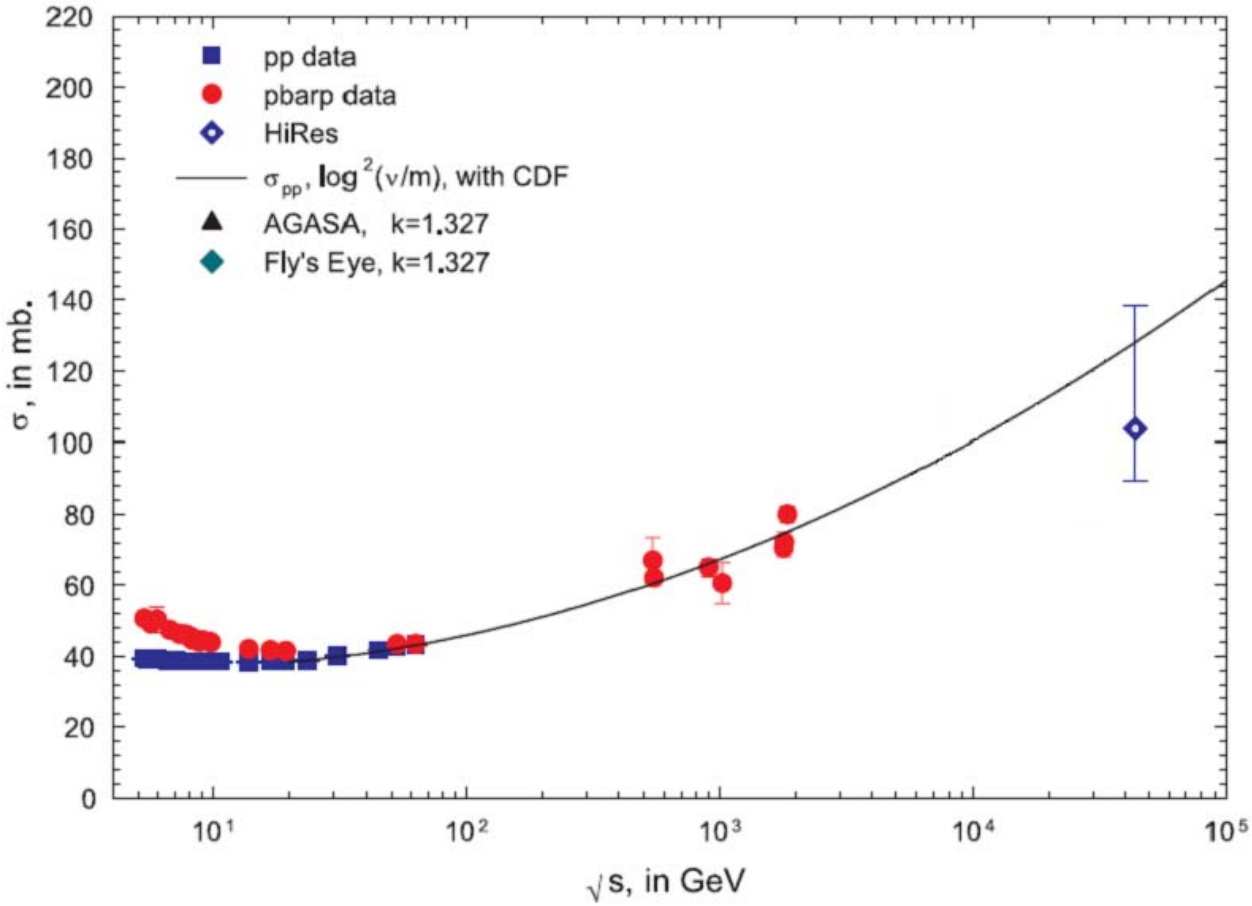


- 1348 out of 3346 stereo events pass the quality cuts (data:12/1999-3/2003)



$$\sigma_{in}^{p-Air} = 456 \pm 17\ mb$$

HiRes Measurement

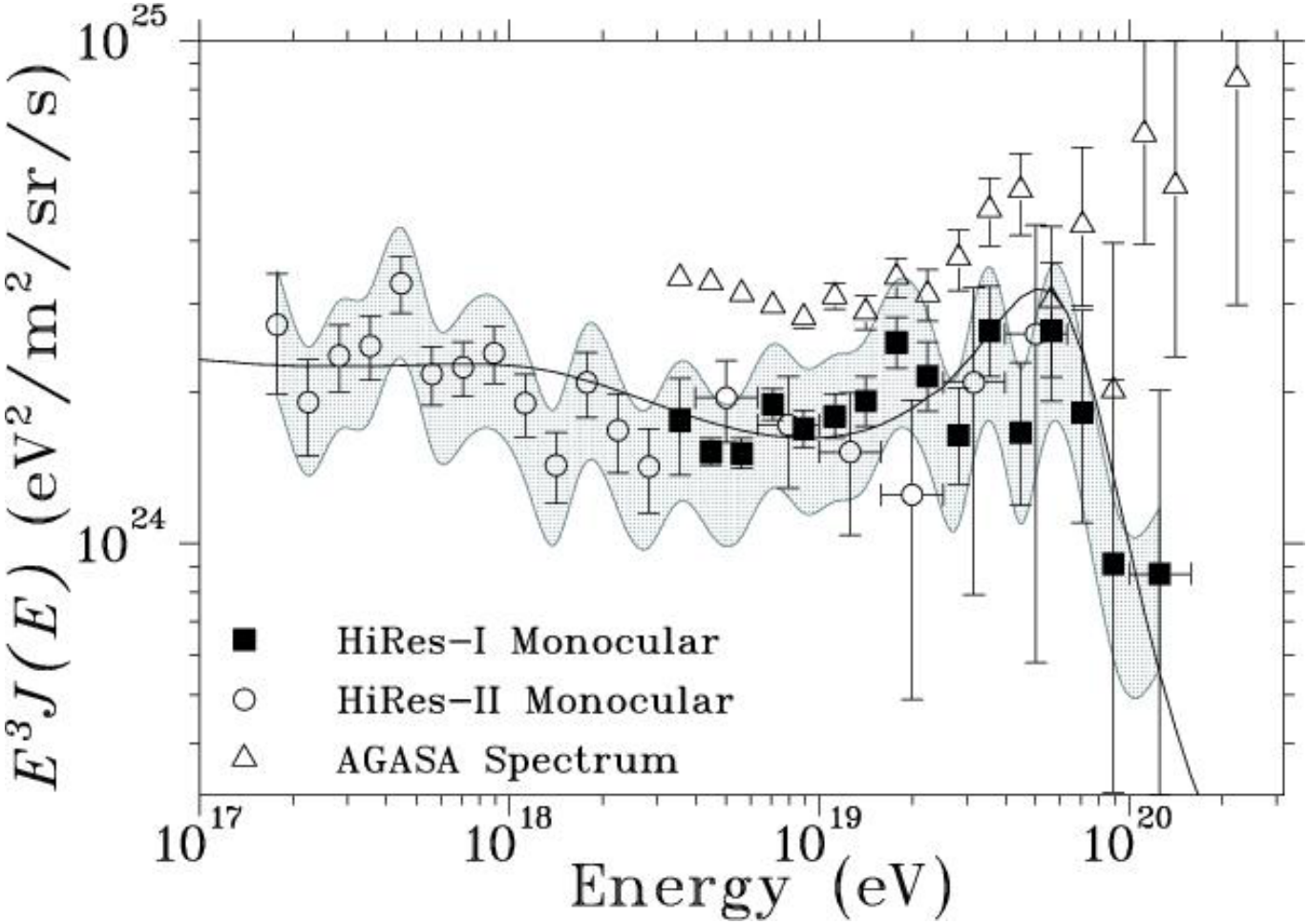


- HiRes: $\sigma_{in}^{p-Air} = 456 \pm 17(stat) + 39(sys) - 11(sys)\ mb \text{ at } 10^{18.5}\ eV$

Measurement of UHECR Energy Spectrum

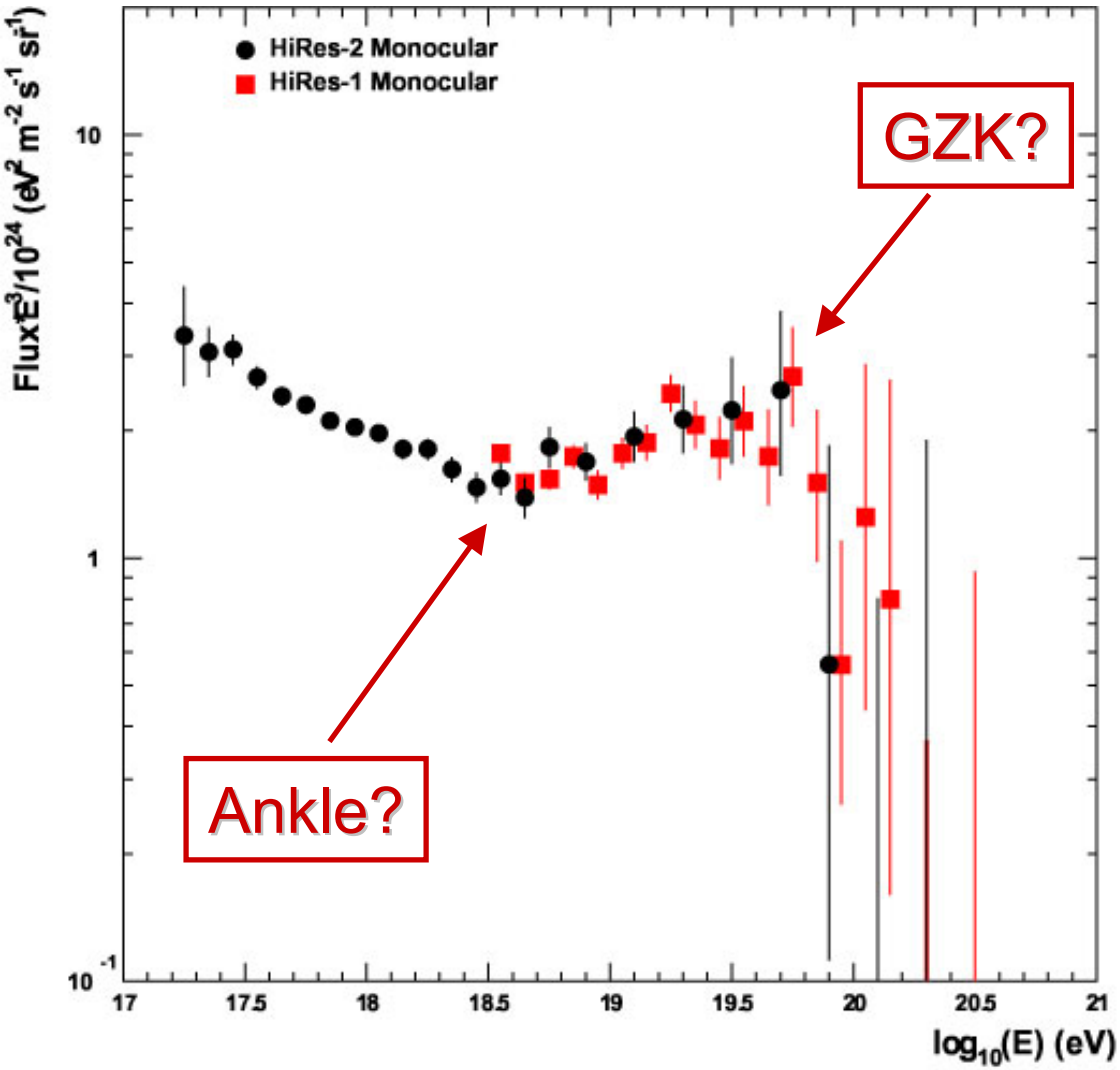
- Combined HiRes-1 and HiRes-2 monocular spectra published:

Phys. Rev. Lett. 92, 151101 (2004)

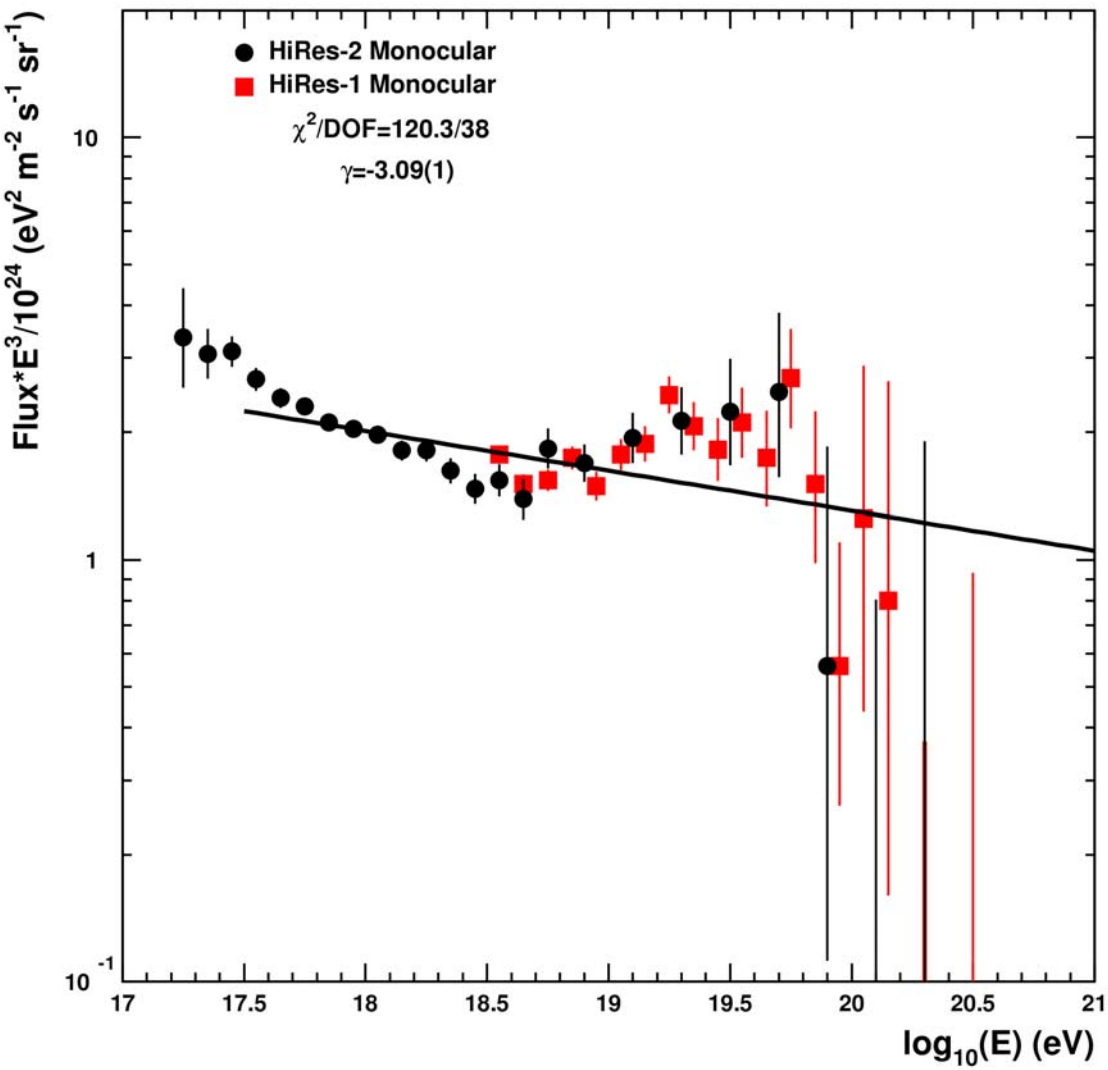


Updated monocular spectrum:

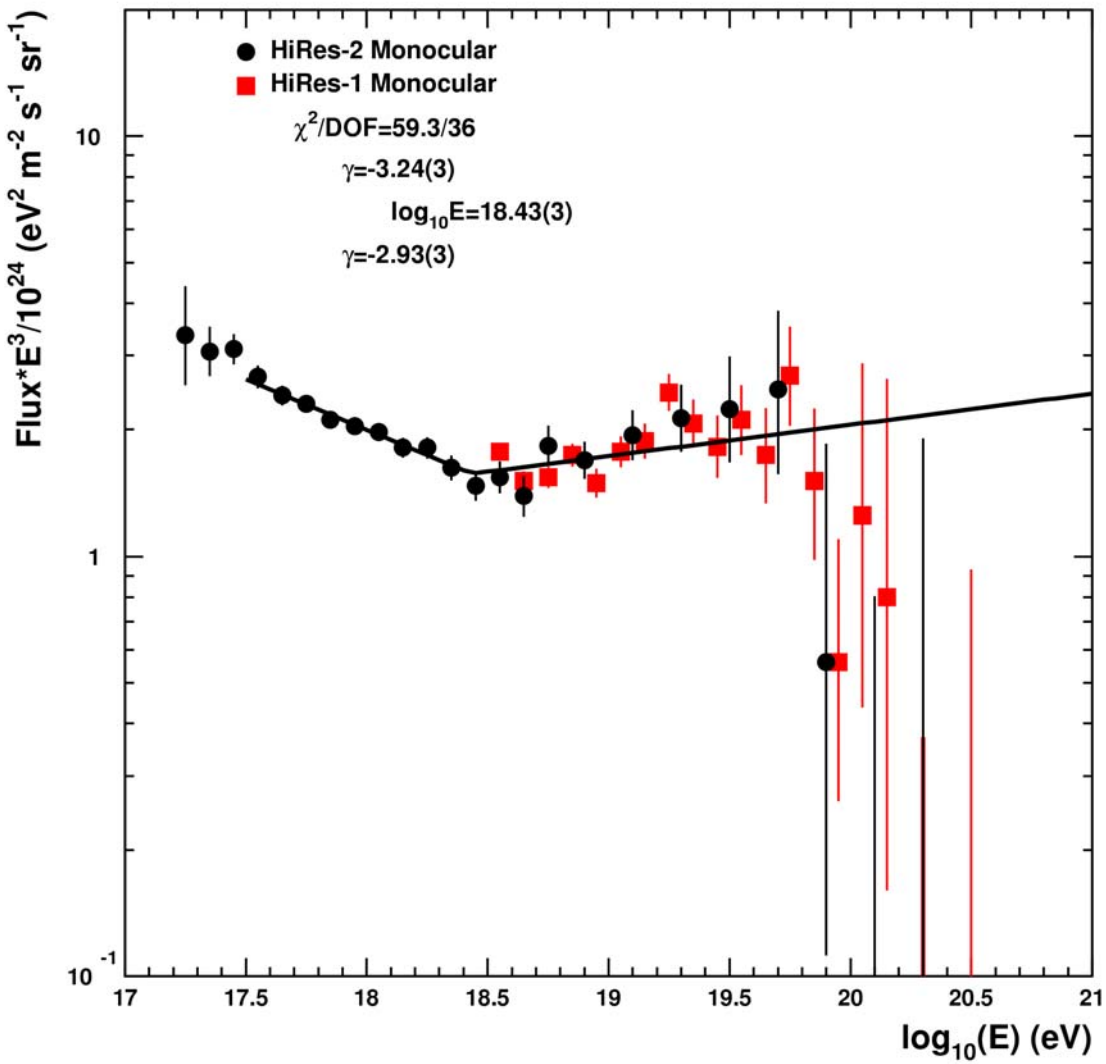
Are spectral features seen?



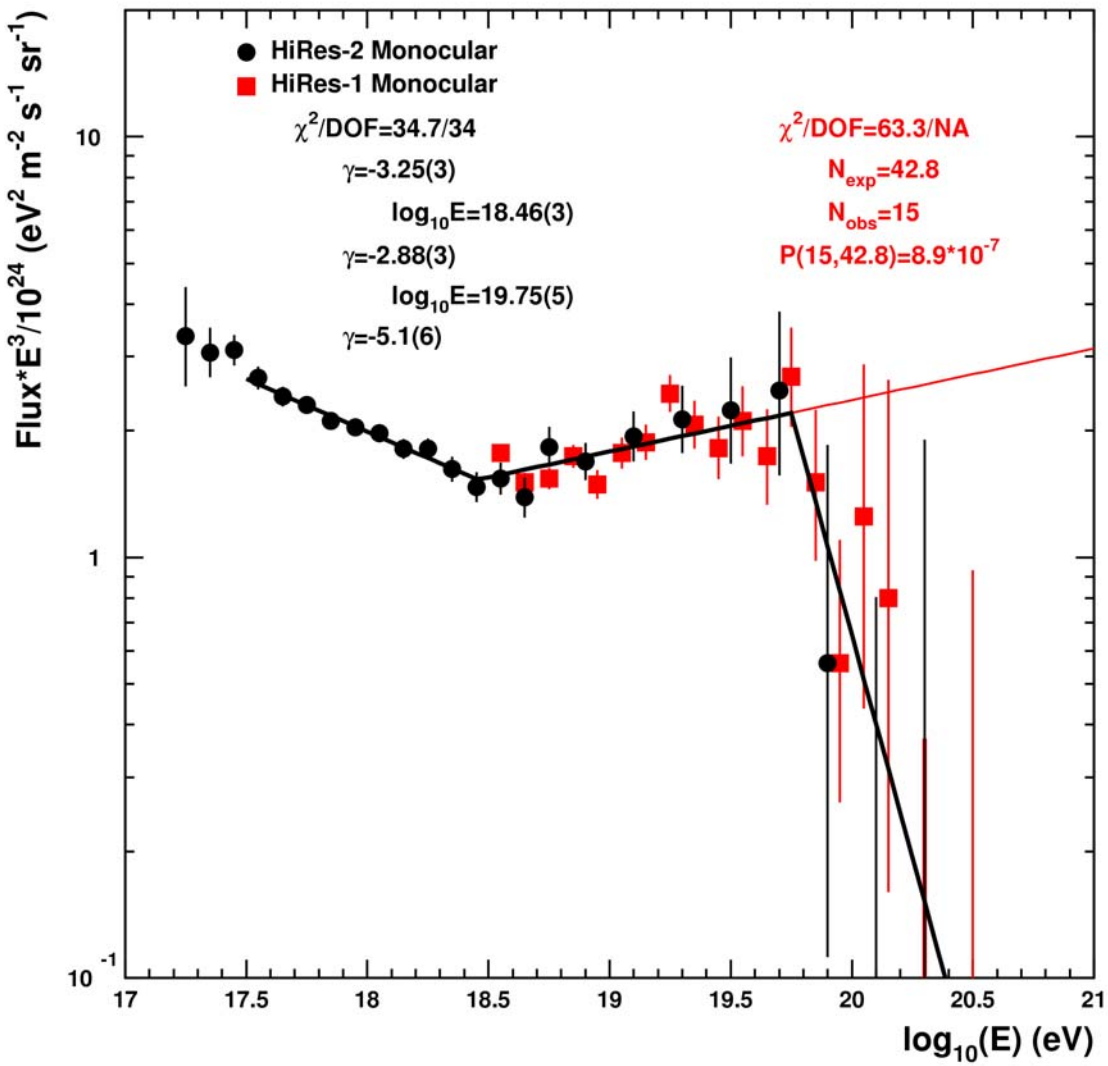
1. Single power law fit:



2. Improved fit using two-power laws with a single floating break



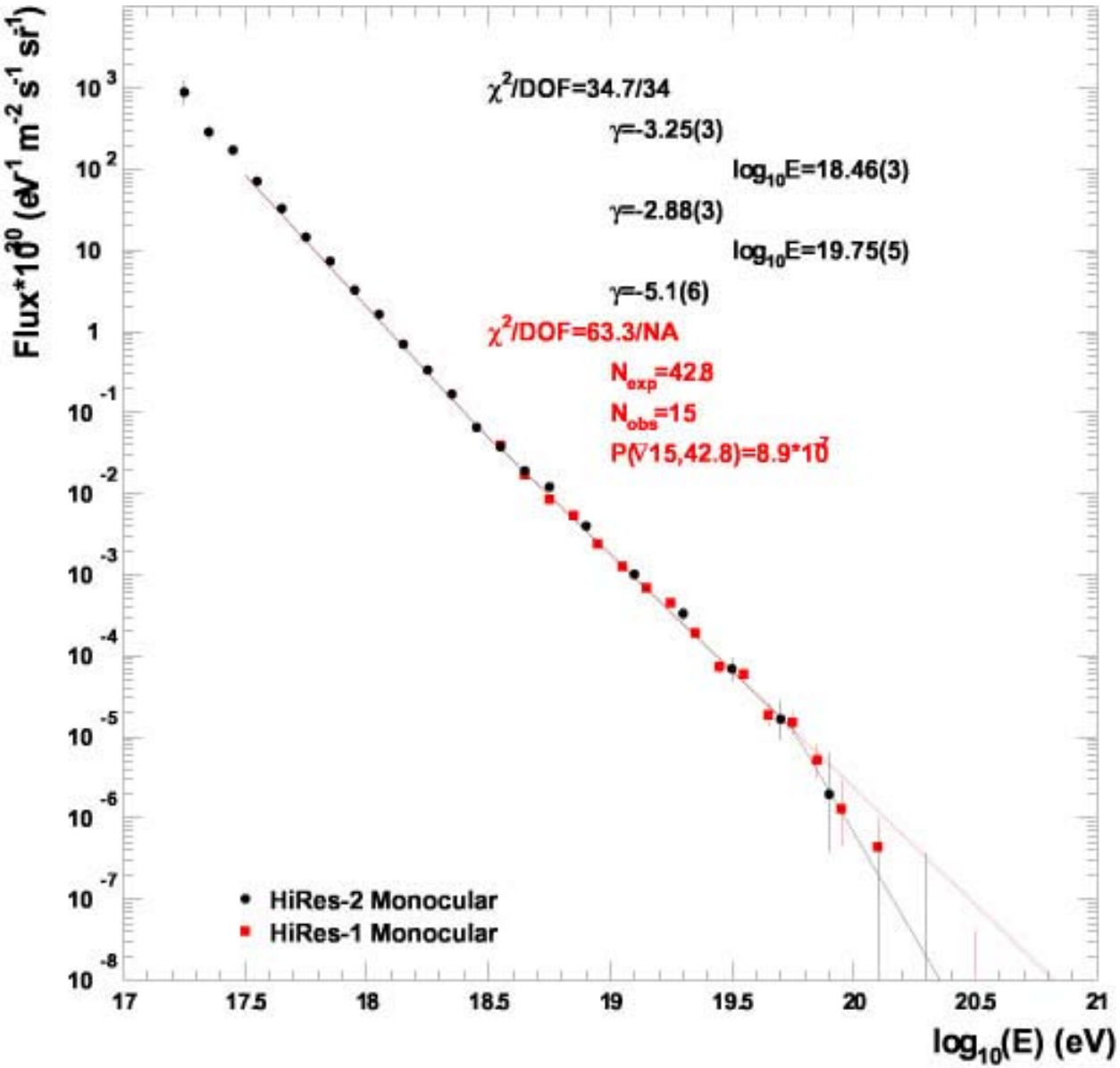
3. Still better fit using three power laws with two floating breaks



- Significance of the deficit at high energy end relative to continuation of power law ?
- Extrapolate middle section:
  - Expect 42.8 events
  - Observe 15
  - Poisson
    $p = \sim 10^{-6}$

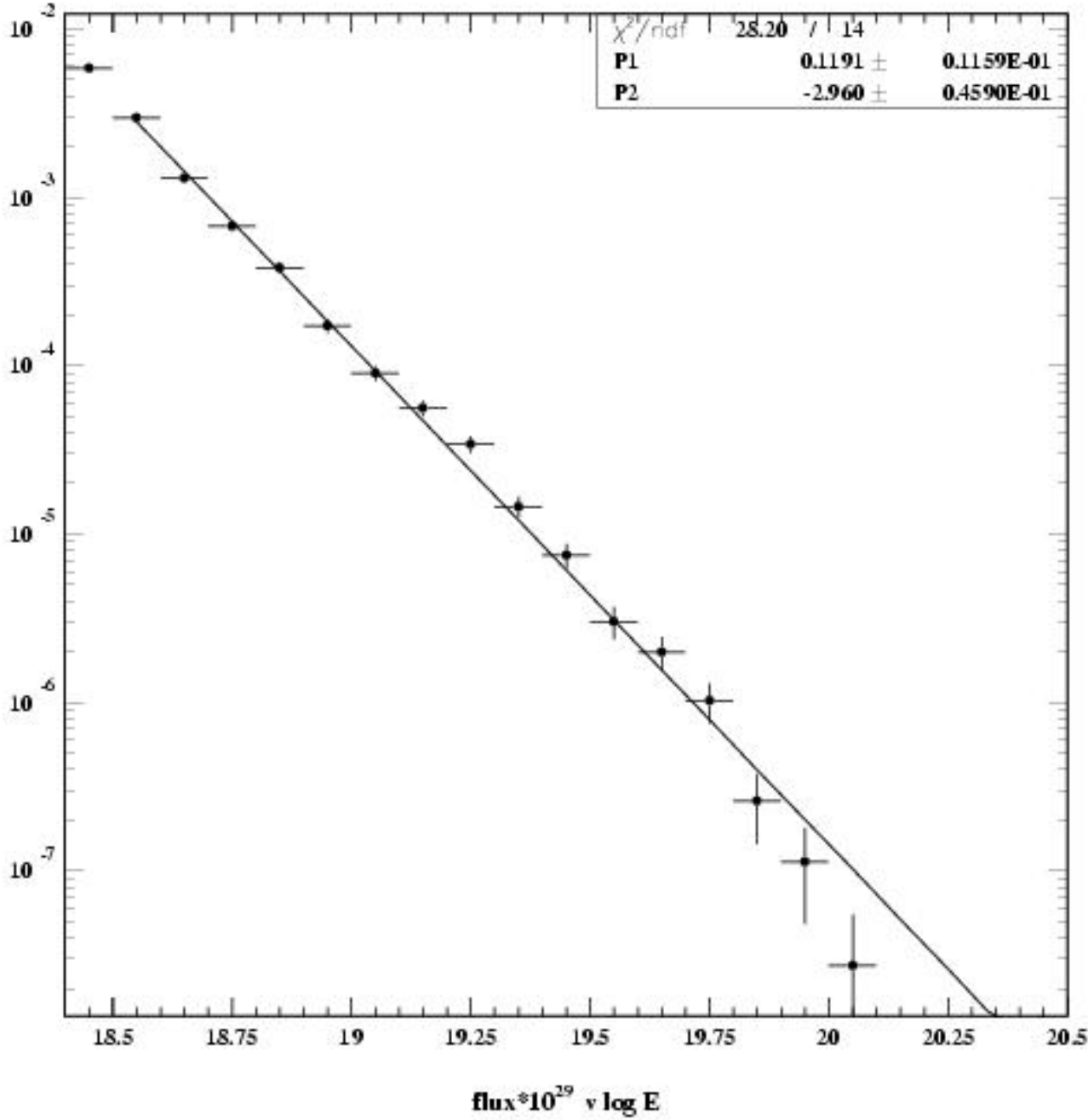
4σ is 3×10^{-5}

5σ is 3×10^{-7}



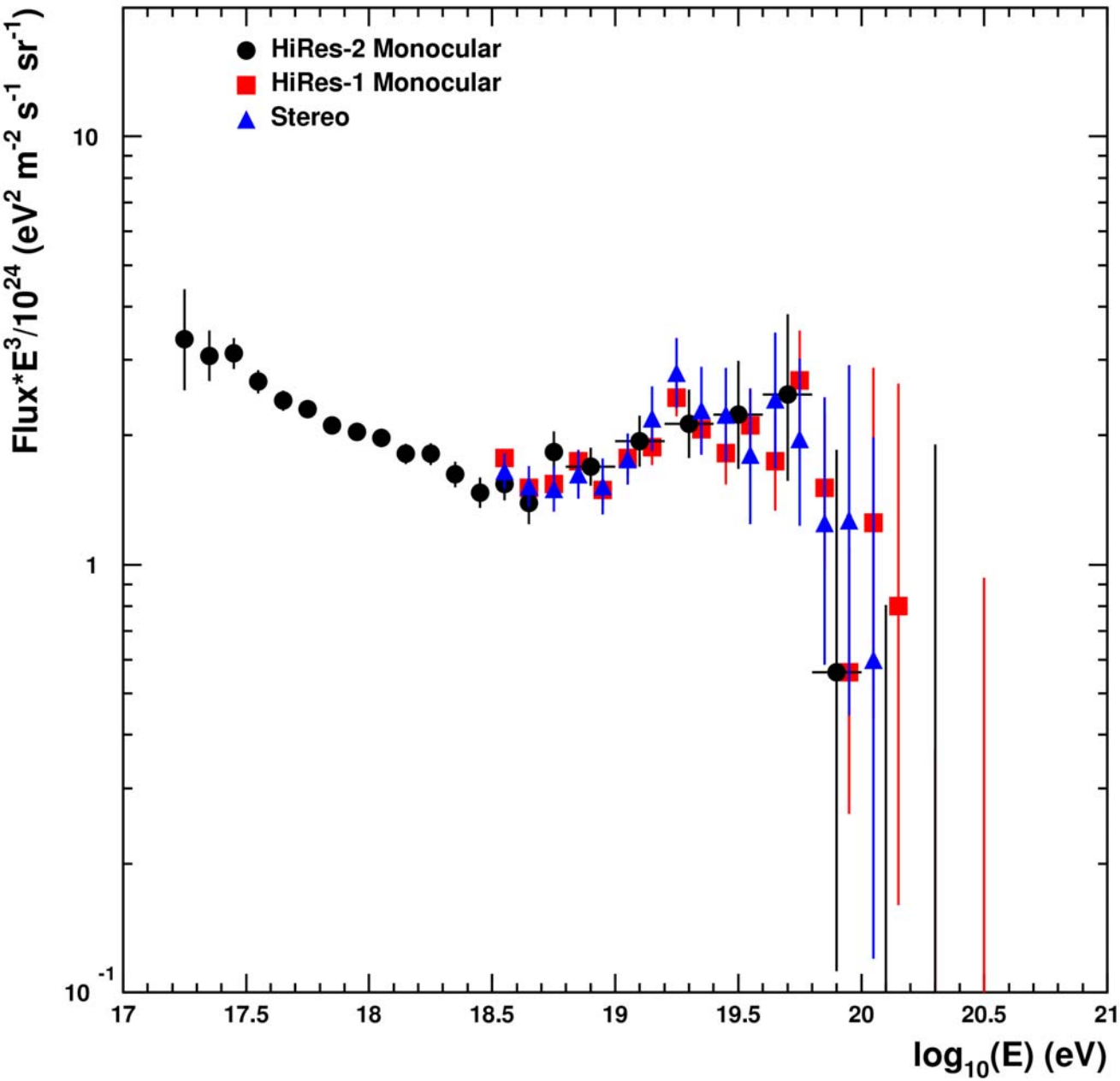
Preliminary Stereo Spectrum

- Fit to power law.
- Single index gives poor χ^2
- Evidence for changing index near ~$10^{19.8}$ eV



HiRes Monocular & Prelim Stereo Spectra

(Stereo Normalized to Monocular)



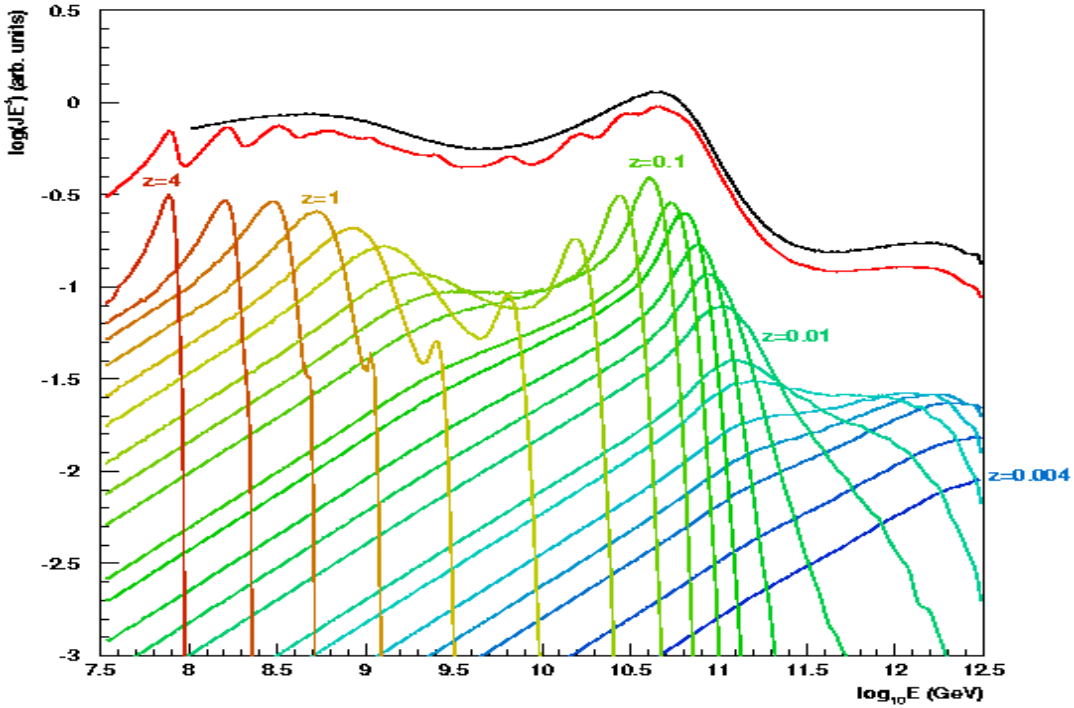
Stereo GZK sensitivity

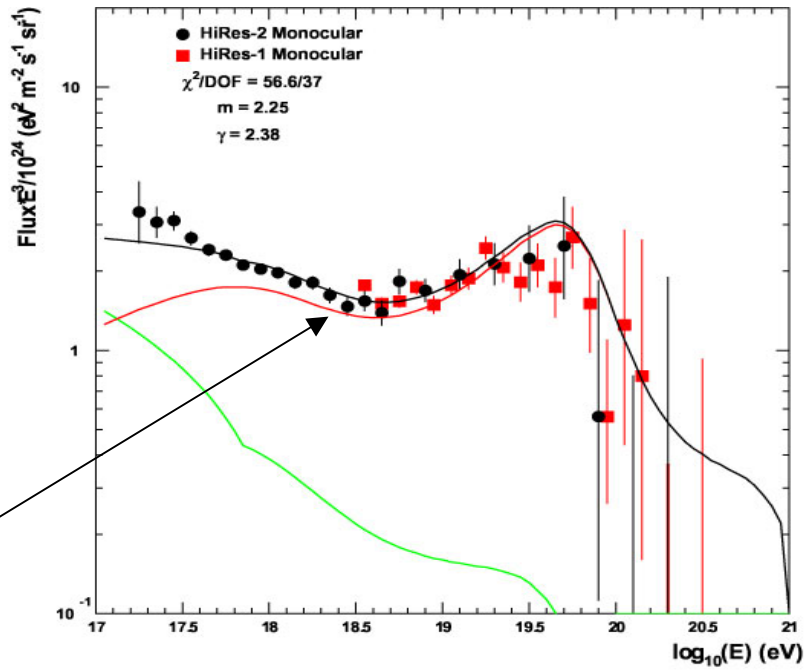
- Assume 3900 hours
- Assume Stereo Aperture
- Consider 2 possible spectral models
  - Fly's Eye with no GZK cutoff: expect ~34 events
  - Fly's Eye with GZK cutoff: expect ~9 events

Interpretation of the UHE Spectrum

- Interaction with the CMBR fractionates the extragalactic flux of protons by red-shift/age
- Observed structures can be attributed to this process
- Pile-up from pion-production causes the bump at $10^{19.5}$ eV.
- e^+e^- pair production excavates the ankle.

see **Phys. Letters B, in press (2005)** (arXiv:astro-ph/0501317) update shown





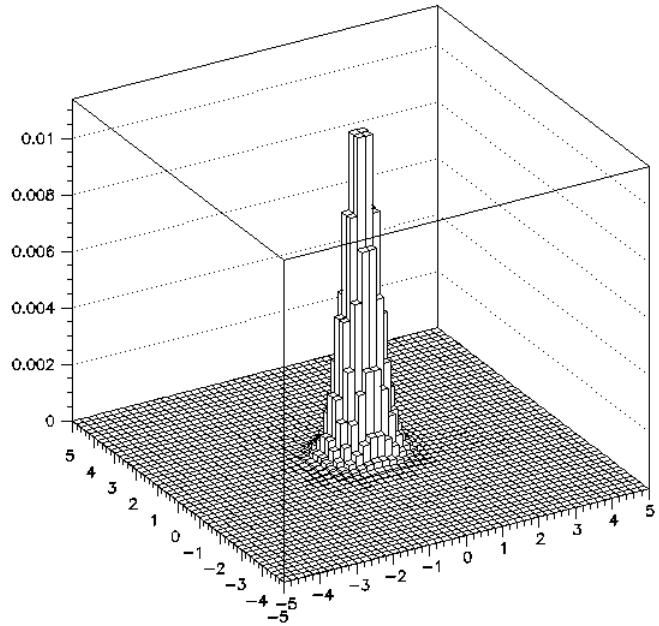
Summary of Spectrum Results

- **Monocular Spectrum**
  - Using the latest monocular data, HiRes has observed the GZK suppression
  - Ankle at ~$10^{18.6}$eV

- **Stereo Spectrum**
  - Shape consistent with monocular spectrum at 2.5x AGASA statistics
  - GZK suppression seen in stereo
  - Studies to understand absolute normalization in progress

HiRes Anistropy Results

Stereo point spread function



Monocular Anisotrpy Results

- ***Autocorrelation functions*** (histogram of $\cos\theta$ between all possible pairs) for HiRes-1 monocular (left) and AGASA (right) events above ~4x10^{19}eV
  Astropart. Phys. 22, 139 (2004)
- 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)
- Point source search: null result

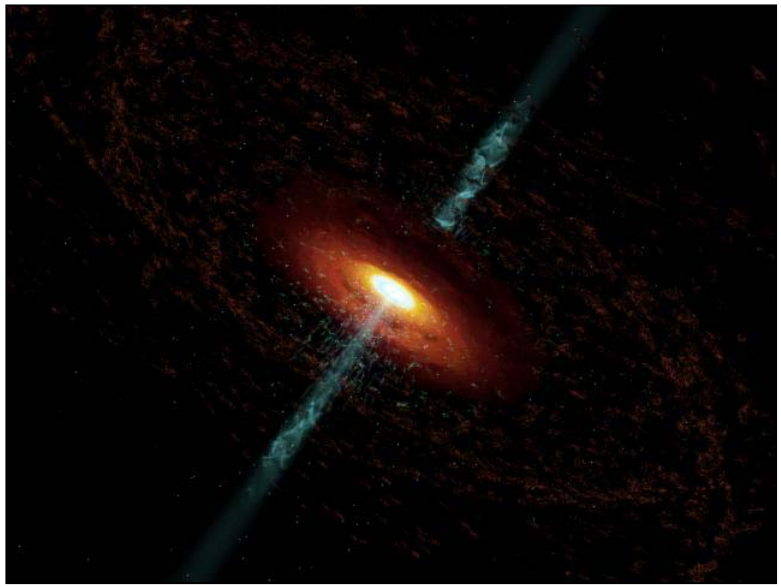
  Submitted to Astropart Phys.
- Search for cross-correlation with AGASA doublets and triplet:
  - Observed overlap no greater than that expected by chance from an isotropic

  Submitted to Astropart Phys.

Stereo Anisotrpy Results

- Stereo angular resolution ***~0.6°***
- HiRes stereo data ($E > 10^{19}$ eV) is consistent with isotropy at all small angular scales
  Astrophys. J. Lett. 610 (2004) L73
- Search for Point Sources of Ultra-High Energy Cosmic Rays above 4.0 10^{19} eV Using a Maximum Likelihood Ratio Test
  Astrophys. Journal 623 (2005) 164

Corrlation with BL Lacertae Objects



- BL Lacertae Object - special type of blazar, active galaxy with jet axis aligned with our line of sight.
- Blazars are established sources of TeV g-rays
- Candidates for accelerating cosmic rays to EeV energies

Somewhat controversial recent history regarding correlations of UHECR with BL Lac objects:

Tinyakov and Tkachev, JETP 74 (2001) 445.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., ApJ 577 (2002) L93.
Evans, Ferrer, and Sarkar, Phys.Rev. D67 (2003) 103005.
Torres et al., Astrophys.J. 595 (2003) L13.
Gorbunov et al., JETP Lett. 80 (2004) 145.
Stern and Poutanen, ApJ 623 (2005) L33.

BL Lac Correlation: Previous Claims

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	$< 10^{-4}$
m < 18	z > 0.1 or unknown	S_{6cm} > 0.17 Jy		HiRes > 24 EeV	66	2.5°	0	1.00
Catalog: Veron (10th Ed.) BL Lacs correlated with EGRET sources			14	AGASA >48 EeV Yakutsk >24 EeV	65	2.9°	8	10^{-4}
no cut	no cut	no cut		HiRes > 24 EeV	66	2.9°	1	.70
Catalog: Veron (10th Ed.) BL Lacs			156	AGASA > 40 EeV	57	2.5°	12	.02
m < 18	no cut	no cut		HiRes > 40 EeV	27	2.5°	2	.78
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut						

Tinyakov & Tkachev, JETP 74 (2001) 445.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., ApJ 577 (2002) L93.

BL Lac Correlation: New Claim

Most recent claim by Gorbunov is based on published HiRes data. It uses a 10 EeV threshold, so it is a new claim.

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	$< 10^{-4}$
m < 18	z > 0.1 or unknown	S_{6cm} > 0.17 Jy		HiRes > 24 EeV	66	2.5°	0	1.00
Catalog: Veron (10th Ed.) BL Lacs correlated with EGRET sources			14	AGASA >48 EeV Yakutsk >24 EeV	65	2.9°	8	10^{-4}
no cut	no cut	no cut		HiRes > 24 EeV	66	2.9°	1	.70
Catalog: Veron (10th Ed.) BL Lacs			156	AGASA > 40 EeV	57	2.5°	12	.02
m < 18	no cut	no cut		HiRes > 40 EeV	27	2.5°	2	.78
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut						

Gorbunov et al., JETP Lett. 80 (2004) 145.

BL Lac Correlation: New Claim

The 0.8º angular bin size was optimized by Gorbunov et al.

It is preferable to perform an ***unbinned*** maximum likelihood analysis, using the individual errors of each event.

We performed an analysis similar to that used in the point source search (described in usa-westerhoff-S-abs1-he14-oral), modified for a multiple-source hypothesis. We find:

Estimated number of source events: $n_s = 8.0$

(~ *excess* of events correlating with BL Lacs)

Fraction *F* of isotropic MC sets with stronger signal: $F = 2\times10^{-4}$

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut		Need to test with new data				

BL Lac Correlation: New Claim

- Charged primaries with energies ~ 10^{19} eV are expected to be deflected many degrees by the galactic magnetic field.
- Correlations on the scale of the HiRes angular resolution (0.6º) imply that primary must be neutral (at least over most of its path). But neutrons and photons have a very short mean path (~ few Mpc) at this energy...
- Arrival directions have not been examined for the data taken since 2004 January.
- **Use current sample to decide *a priori* what will be tested with new data.**

BL Lac Correlation: Energy Dependence

- Modify Energy Threshold:

  10^{19} eV threshold is due to the fact that HiRes originally published only the arrival directions of events above this energy.

  If we perform the analysis on all the events below 10^{19} eV , there is a weaker correlation: $n_s = 22$ with ln R = 3.10.

  The fraction of isotropic MC sets with stronger signal is $F = 6\times10^{-3}$.

  For the combined HiRes data set (all energies), the result is: $n_s = 31$, $F = 2\times10^{-4}$

BL Lac Correlation: Source Sample

- Confirmed BL Lacs in the Veron Catalog are classified as "BL" or "HP" (latter for relatively high degree of polarization).
- So far, only "BL" have been considered.
- If we perform the analysis on the 47 "HP" BL Lacs (using the same m<18 cut as was used for "BL") and HiRes events above 10^{19} eV , we find: $n_s = 3.0$, with $F = 6\times10^{-3}$.
- For the complete set of confirmed BL Lacs (i.e. "BL" + "HP") with m<18, and HiRes events above 10^{19} eV , we find: $n_s = 10.5$, with $F = 10^{-5}$.
- The m<18 was originally tuned to optimize correlations with AGASA data. We have performed all of the same tests using BL Lacs with m>18, and no correlation is found.

TeV BL Lac Correlation

- Six BL Lacs are confirmed sources of TeV g-rays. Five are in the northern hemisphere and well observed by HiRes.
- We perform the maximum likelihood analysis on each source individually using all HiRes events:

Name	z	V Mag	n_s	*F*
Mrk 421	0.03	12.9	0.3	0.2
H1426+428	0.13	16.5	0	0.4
Mrk 501	0.03	13.8	3.3	6×10^{-4}
1ES1959+650	0.05	12.8	2.0	8×10^{-3}
1ES2344+514	0.04	15.5	0	0.7

- For the TeV blazars taken as a set, the ML analysis yields:

All energies: ns = 5.6 with *F* = 10-3

Summary of BL Lac Correlation:

- "BL", m<18, all HiRes events (no E cut): $F = 2\times10^{-4}$
- "BL+HP" with m<18, HiRes E>10 EeV: $F = 10^{-5}$
- Confirmed TeV blazars, all HiRes events (no E cut): $F = 10^{-3}$
- **These are not independent results: the samples overlap.**
- Analysis has been *a posteriori*, so above *F* values are not true chance probabilities.
- **Correlations must be tested with independent data before any claim can be made.**
- Arrival directions of past year of data have not been analyzed. Data taking through March 2006 will yield an independent data set ~70% of the current sample size: Independent test of BL Lac correlations should be possible

Future Prospects

- HiRes will cease operation at the end of March 2006
- Analysis of major topics to be completed by summer of 2007 (30th ICRC)
- Subgroups of HiRes have joined the Telescope Array (Delta, UT, USA)
  - Grond array of 576 (1.2km spacing) scintillation counters
  - Three fluorescence sites looking inward
- US contribution: low-energy extension down to $10^{16.5}$ eV
- TALE will also make TA into a fully stereo-hybrid detector