Hadronic interactions in modeling atmospheric cascades

The atmospheric cascade equation

Heavy flavor production (atmospheric ν)

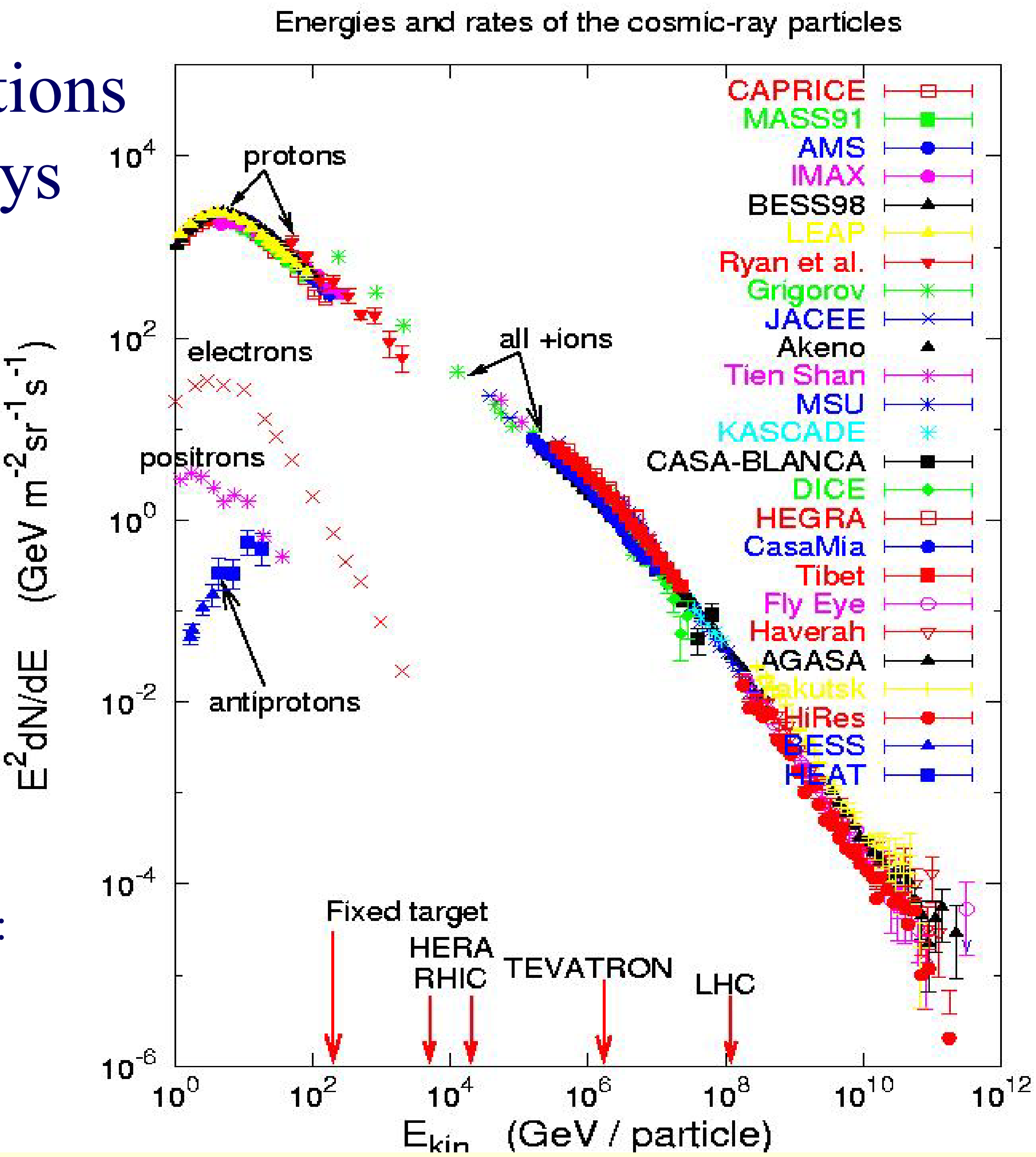
Inelasticity in ultra-high energy showers

QCD at Cosmic Energies
Erice, Aug 30, 2004

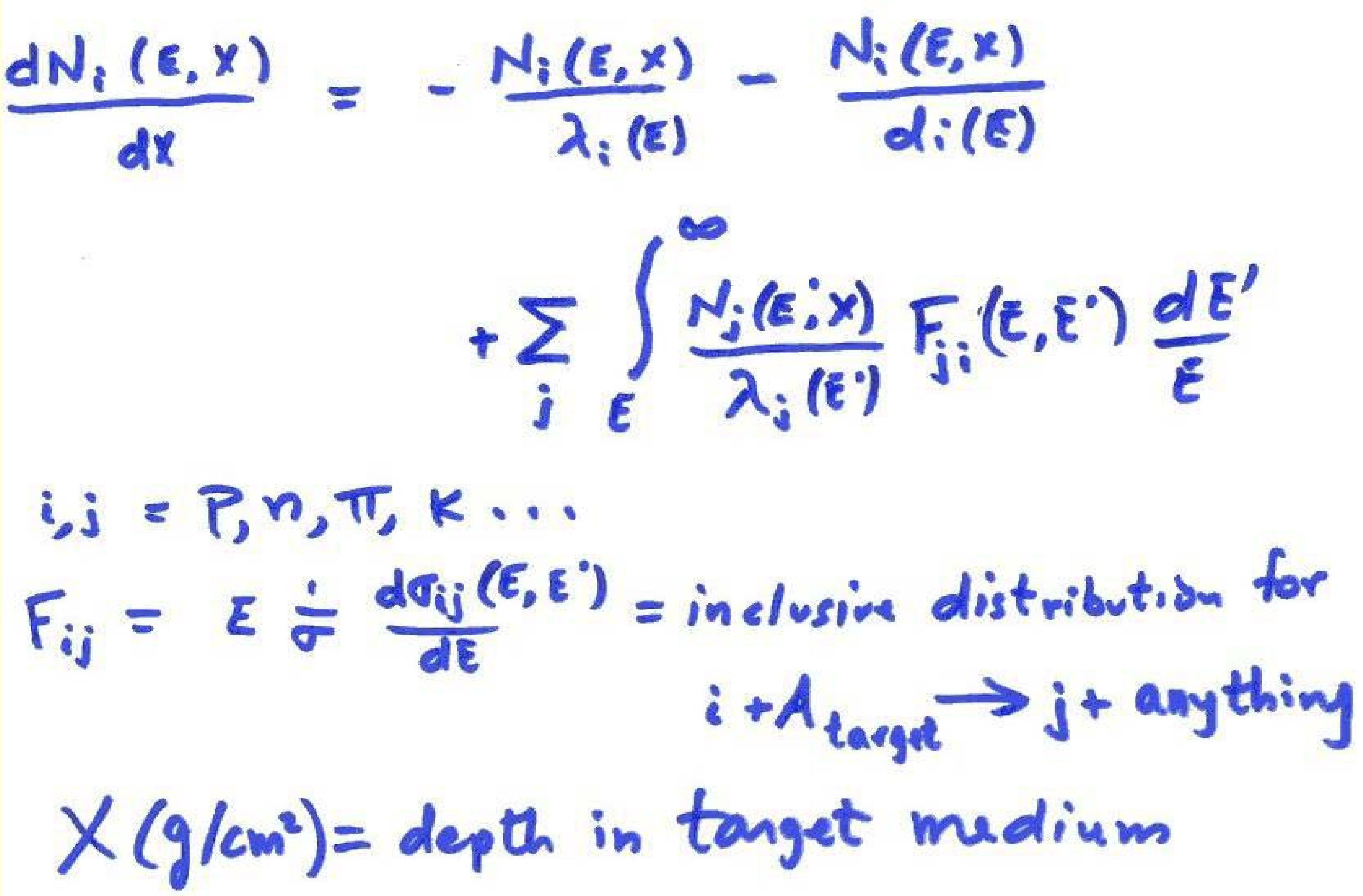
Thomas K. Gaisser

Particle interactions for cosmic rays

- Atmosphere
  - Nuclear targets
  - Nuclear projectiles
  - Forward region
  - High energy
  - “Minimum bias”
  - Limited guidance from accelerator data
- Astrophysics
  - Astrophysical uncertainties are even more severe & limited
  - Main information flow: Particle physics → astrophysics
  - Rather than vice versa



Cascades in the atmosphere



$$\frac{dN_i(E,X)}{dX} = -\frac{N_i(E,X)}{\lambda_i(E)} - \frac{N_i(E,X)}{d_i(E)} + \sum_j \int_E^\infty \frac{N_j(E',X)}{\lambda_j(E')} F_{ji}(E,E') \frac{dE'}{E}$$

$i,j = p, n, \pi, K \ldots$

$F_{ij} = E \frac{1}{\sigma} \frac{d\sigma_{ij}(E,E')}{dE}$ = inclusive distribution for $i + A_{target} \rightarrow j +$ anything

$X\,(g/cm^2)$ = depth in target medium

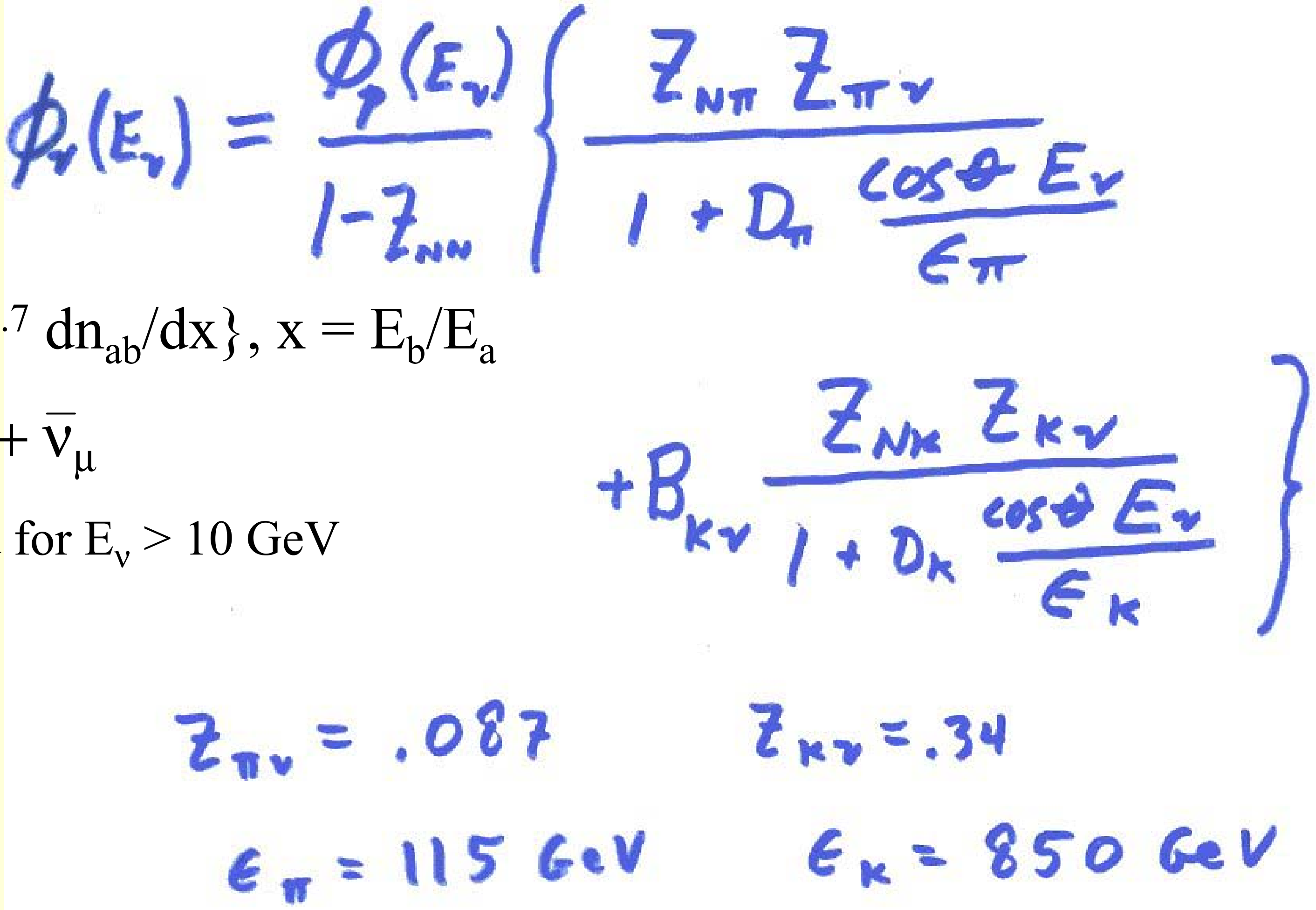
Two boundary conditions

- **Air shower**, primary of mass A, energy E_0 :
  - $N(X=0) = A\,\delta\,(E - E_0/A)$ for nucleons
  - $N(X=0) = 0$ for all other particles

- **Uncorrelated flux** from power-law spectrum:
  - $N(X=0) = \phi_p(E) = K\,E^{-(\gamma+1)}$
  - $\sim 1.7\,E^{-2.7}$ ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$), top of atmosphere

- $F_{ji}(E_i,E_j)$ has no explicit dimension, $F \rightarrow F(\xi)$
  - $\xi = E_i/E_j$ & $\int \ldots F(E_i,E_j)\,dE_j / E_i \rightarrow \int \ldots F(\xi)\,d\xi / \xi^2$
  - Expect scaling violations from m_i, $\Lambda_{QCD} \sim \mathrm{GeV}$

Uncorrelated flux of atmospheric ν



$$\phi_\nu(E_\nu) = \frac{\phi_p(E_\nu)}{1-Z_{NN}}\left\{\frac{Z_{N\pi}\,Z_{\pi\nu}}{1+D_\pi\frac{\cos\theta\,E_\nu}{\epsilon_\pi}} + B_{K\nu}\frac{Z_{NK}\,Z_{K\nu}}{1+D_K\frac{\cos\theta\,E_\nu}{\epsilon_K}}\right\}$$

$Z_{ab} = \int dx\,\{x^{1.7}\, dn_{ab}/dx\}$, $x = E_b/E_a$

$\nu = \nu_\mu + \bar{\nu}_\mu$

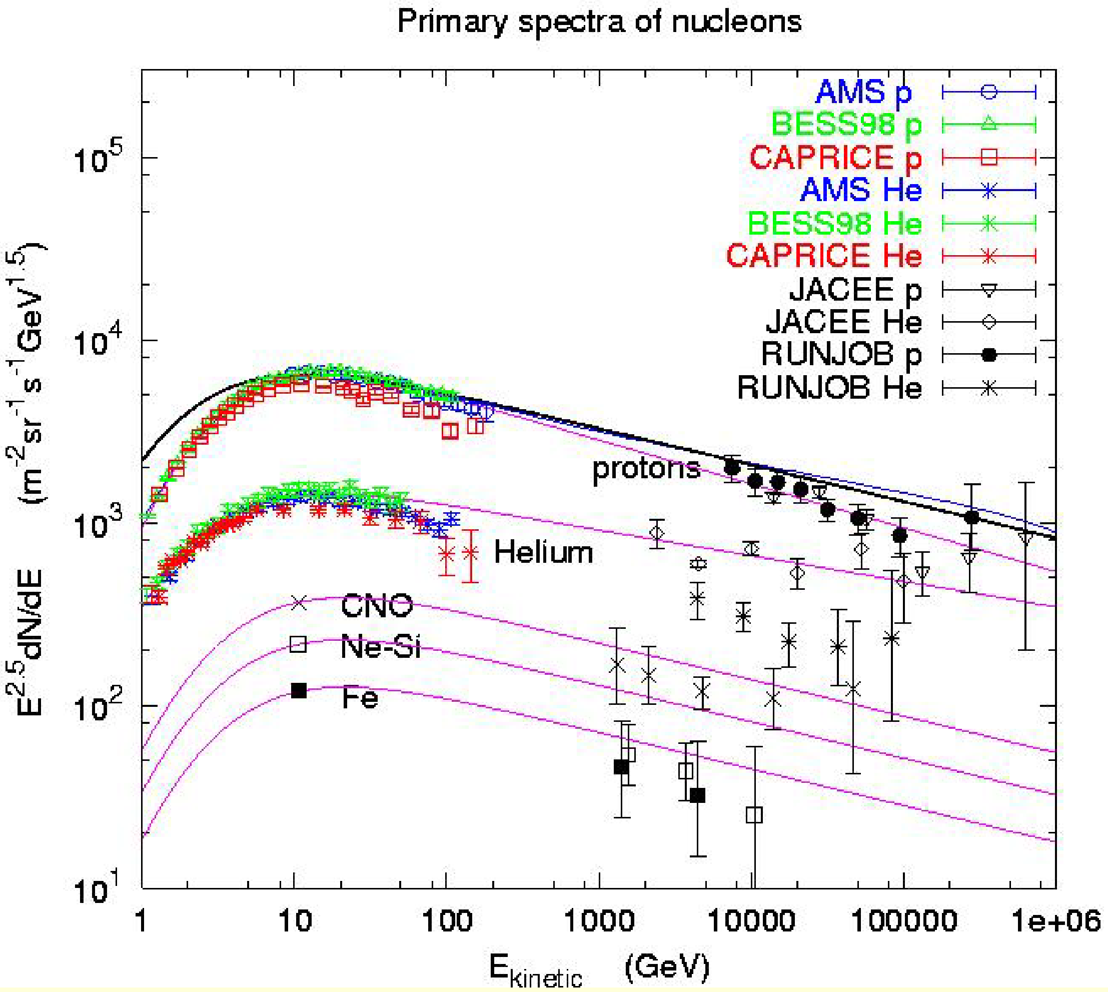
-- good for $E_\nu > 10$ GeV

$Z_{\pi\nu} = .087$ $Z_{K\nu} = .34$

$\epsilon_\pi = 115$ GeV $\epsilon_K = 850$ GeV

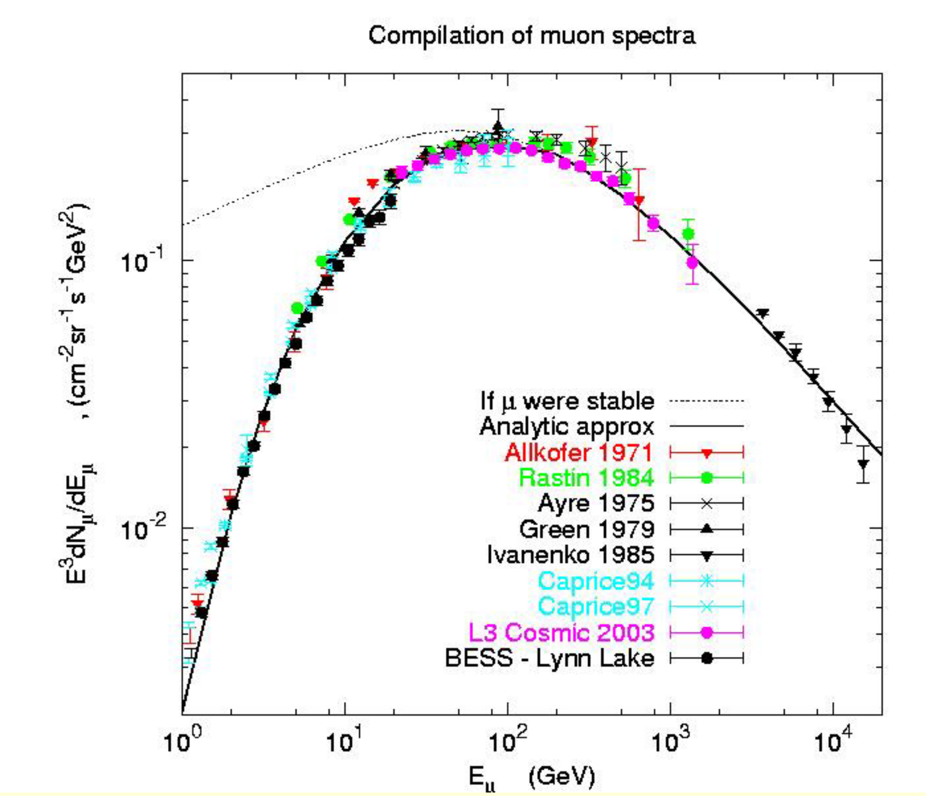
Primary spectrum of nucleons

- Plot shows
  - 5 groups of nuclei plotted as nucleons
  - Heavy line is $E^{-2.7}$ fit to protons
  - Add up all components to get primary spectrum of nucleons ~ $E^{-2.7}$



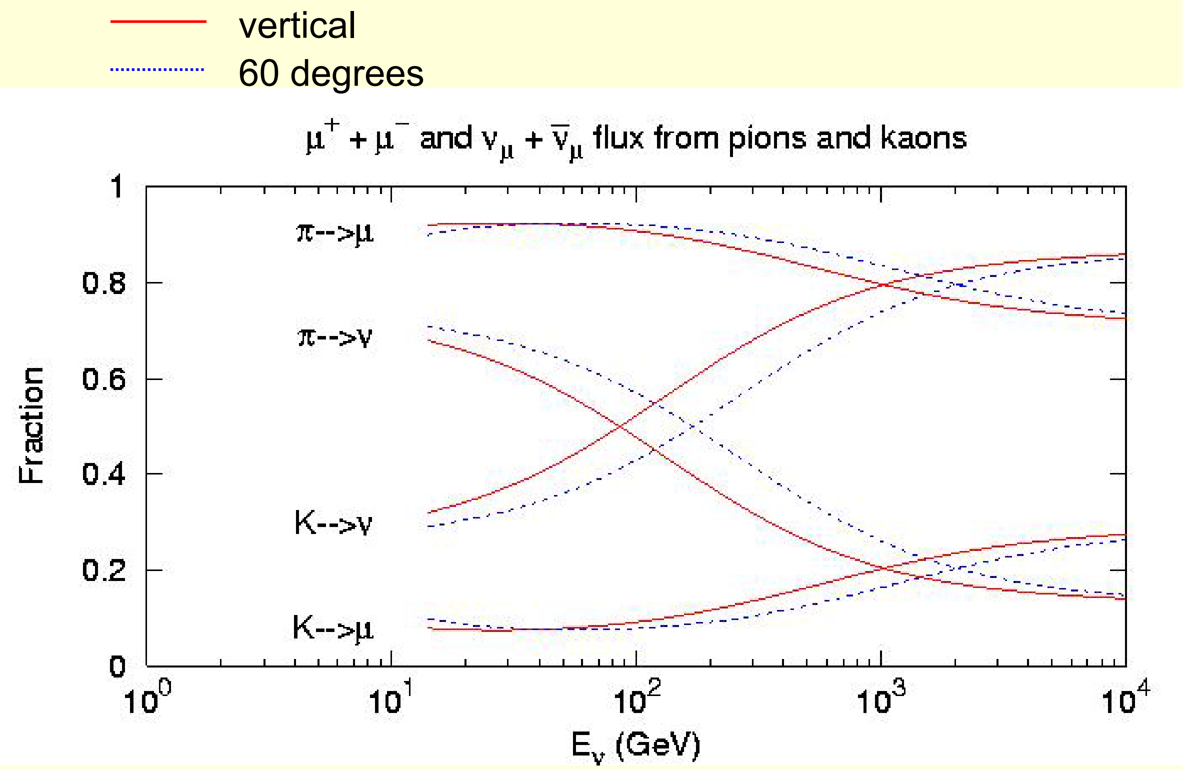
Comparison to measured μ flux

- Input nucleon spectrum:
  - $1.7\ E^{-2.7}$ (GeV cm s sr)$^{-1}$
- High-energy analysis
  - o.k. for E_μ > TeV
- Low-energy:
  - dashed line neglects μ decay and energy loss
  - solid line includes an analytic approximation of decay and energy loss by muons

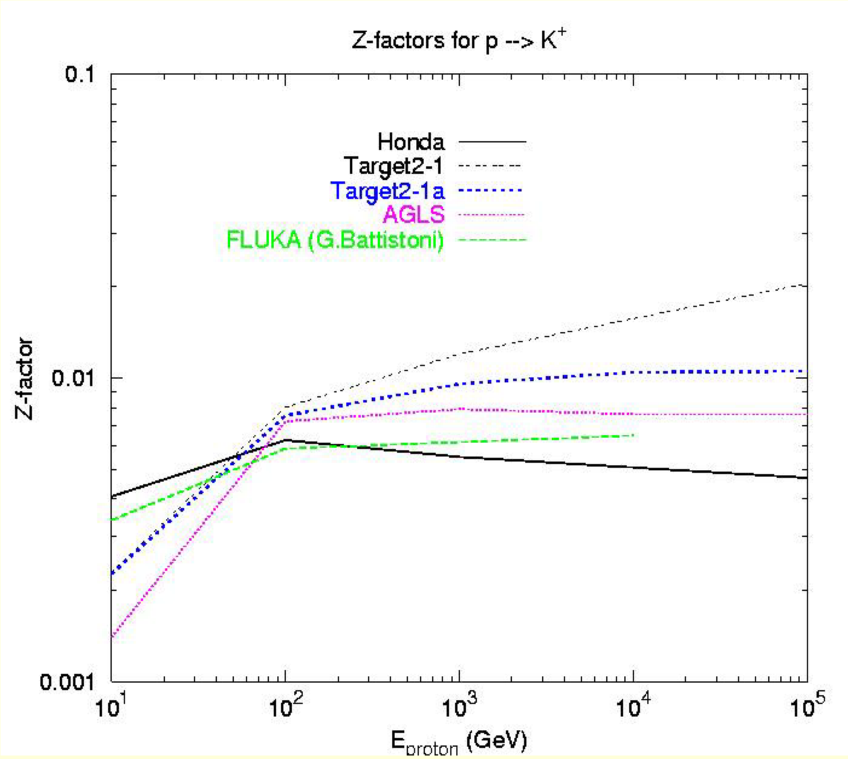


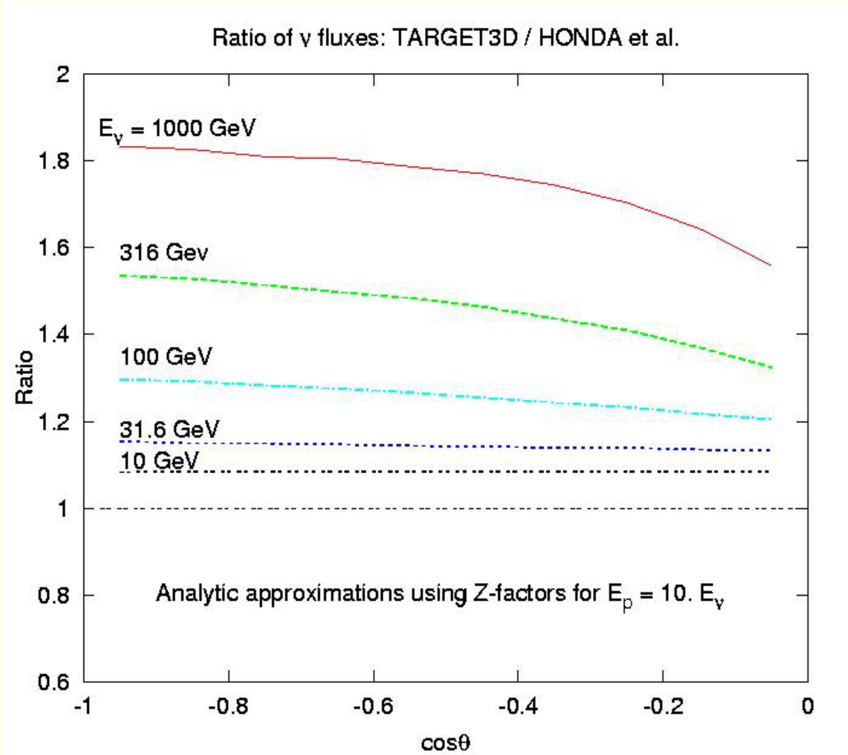
High energy (e.g. $\nu_\mu \rightarrow \mu$)

- Importance of kaons
  - main source of ν > 100 GeV
  - p → $K^+ + \Lambda$ important
  - Charmed analog important for prompt leptons



Importance of kaon production for atmospheric neutrinos



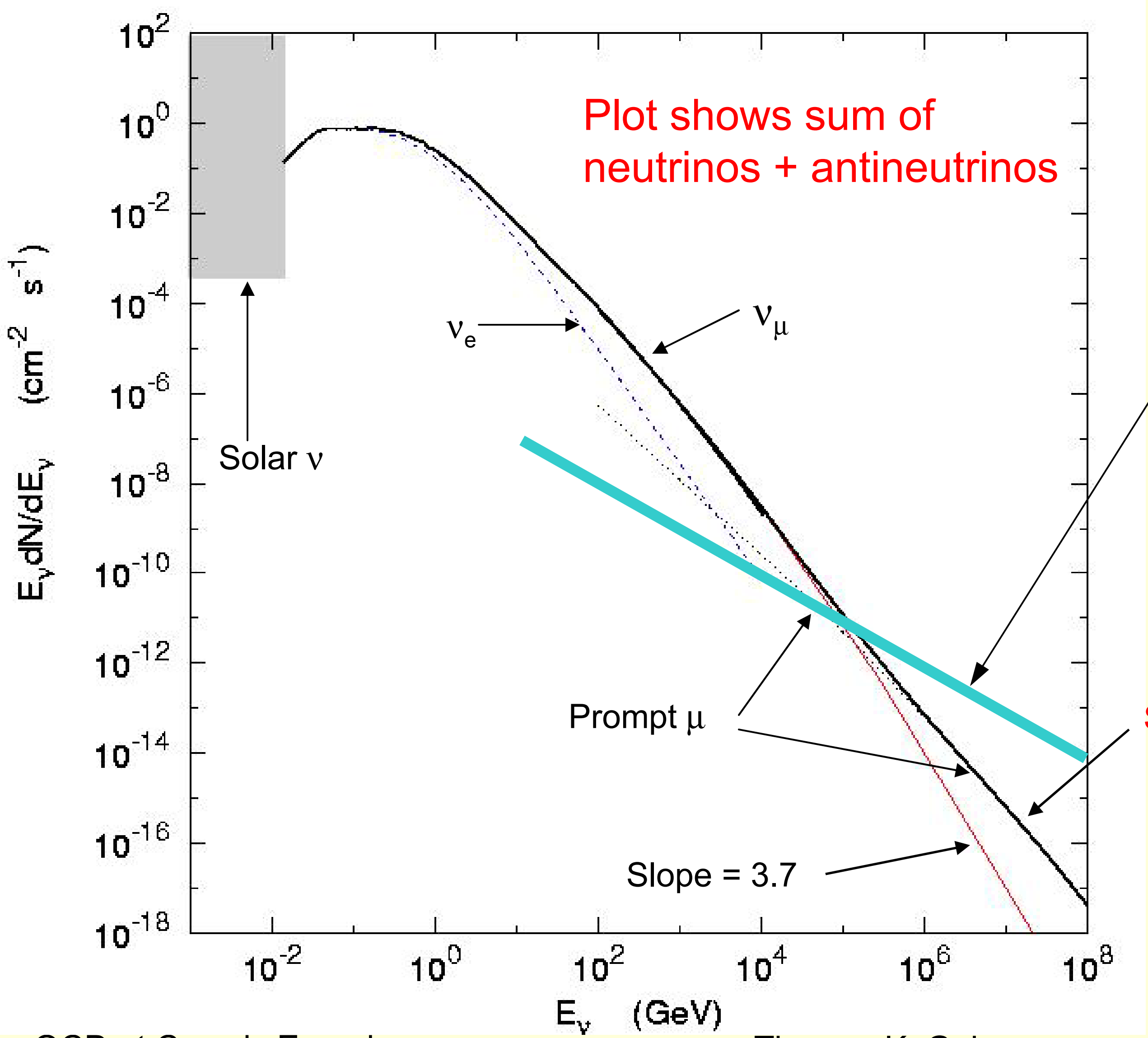


Uncertainties for uncorrelated spectra

- p → $K^+ \Lambda$ gives dominant contribution to atmospheric neutrino flux for $E_\nu > 100$ GeV

- p → charm gives dominant contribution to neutrino flux for $E_\nu > 10$ or 100 or ? TeV
  - Important as background for diffuse astrophysical neutrino flux because of harder spectrum

Global view of atmospheric ν spectrum



Possible E^{-2} diffuse astrophysical spectrum (WB bound)

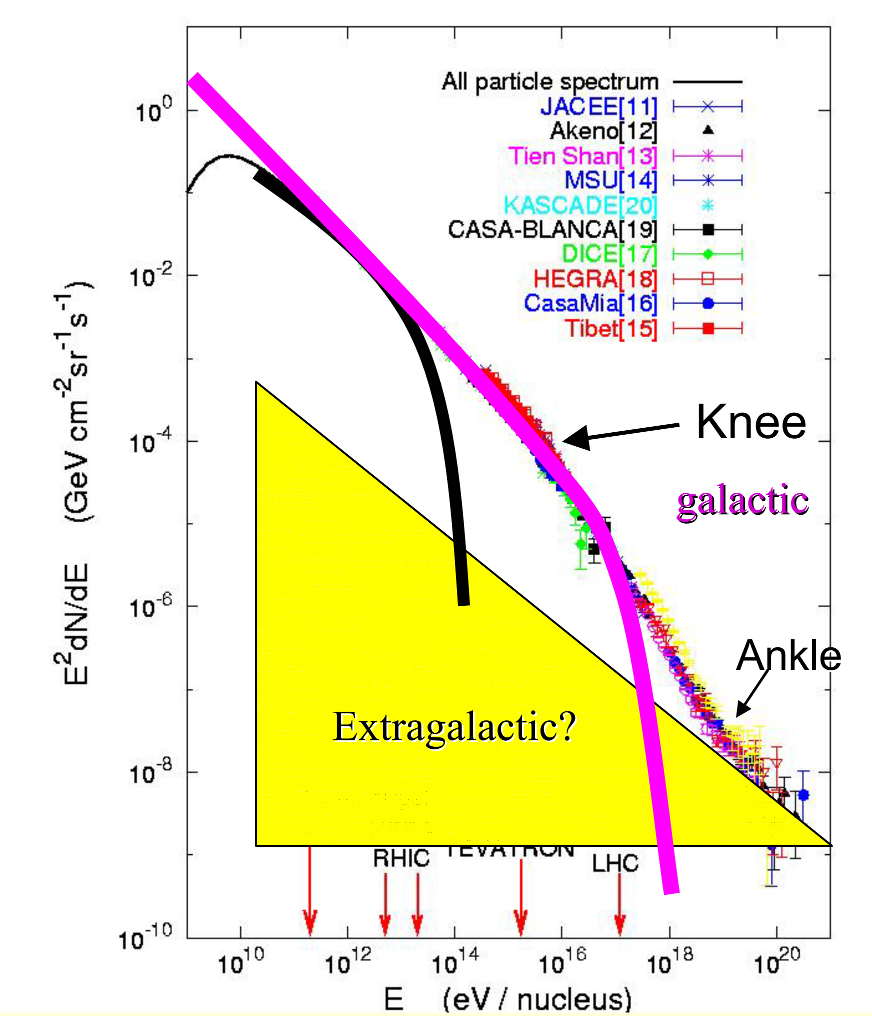
Uncertainty in level of charm a potential problem for finding diffuse neutrinos

Slope = 2.7

Highest energy cosmic rays

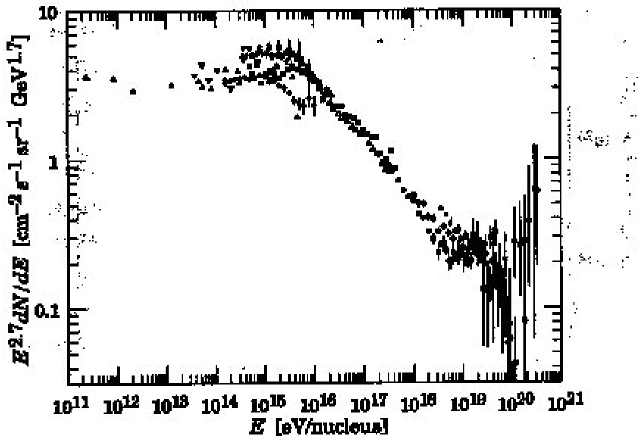
- $E_{max} \sim \beta_{shock}$ Ze x B x R_{shock} for SNR
  - → $E_{max} \sim$ Z x 100 TeV
- Knee:
  - Differential spectral index changes at ~ 3 x 10^{15}eV
  - $\alpha = 2.7 \rightarrow \alpha = 3.0$
  - Some SNR can accelerate protons to ~10^{15} eV (Berezhko)
  - How to explain 10^{17} to >10^{18} eV ?
- Ankle at ~ 3 x 10^{18} eV:
  - Flatter spectrum
  - Suggestion of change in composition
  - New population of particles, possibly extragalactic?

- Look for composition signatures of "knee" and "ankle"

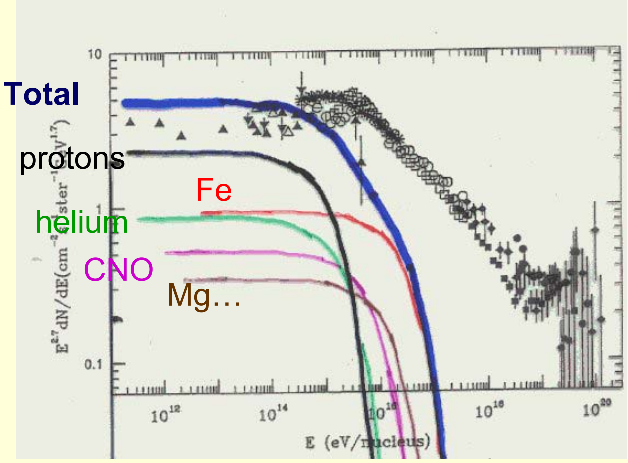


Complex composition around “knee”?

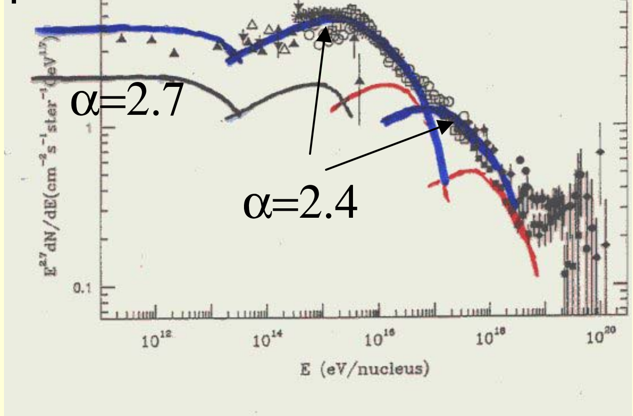
Blow-up of knee region

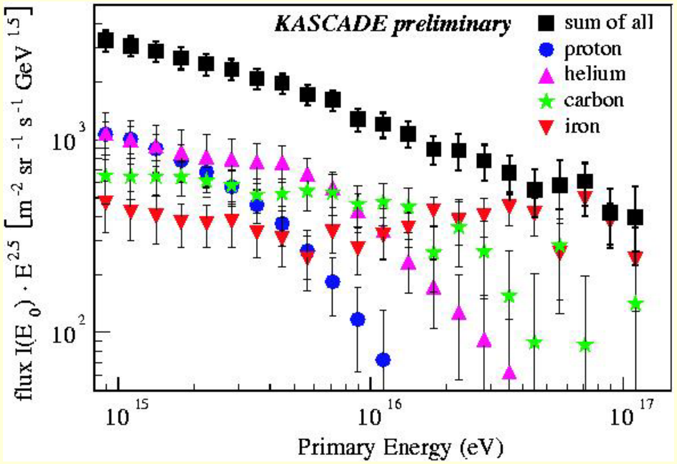


Emax = Z x 1 PeV

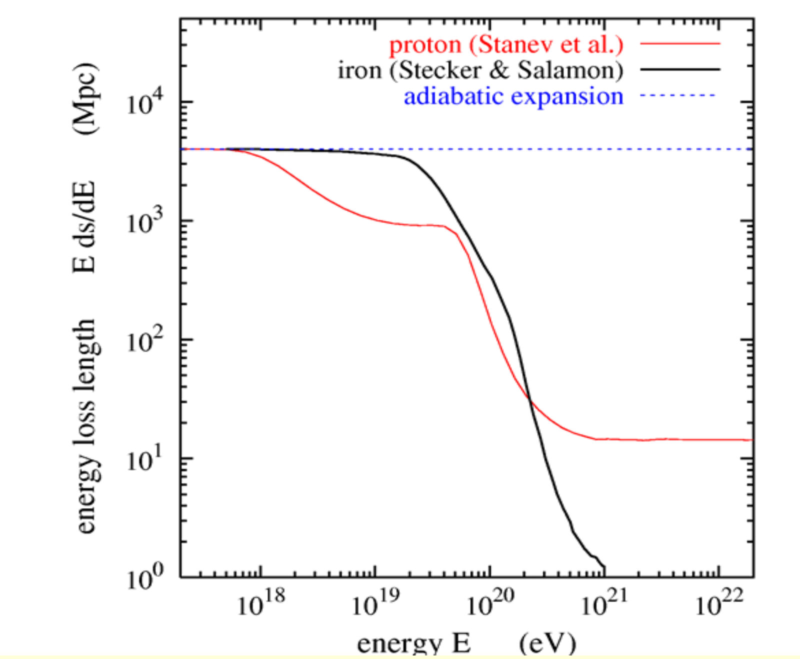


3 components

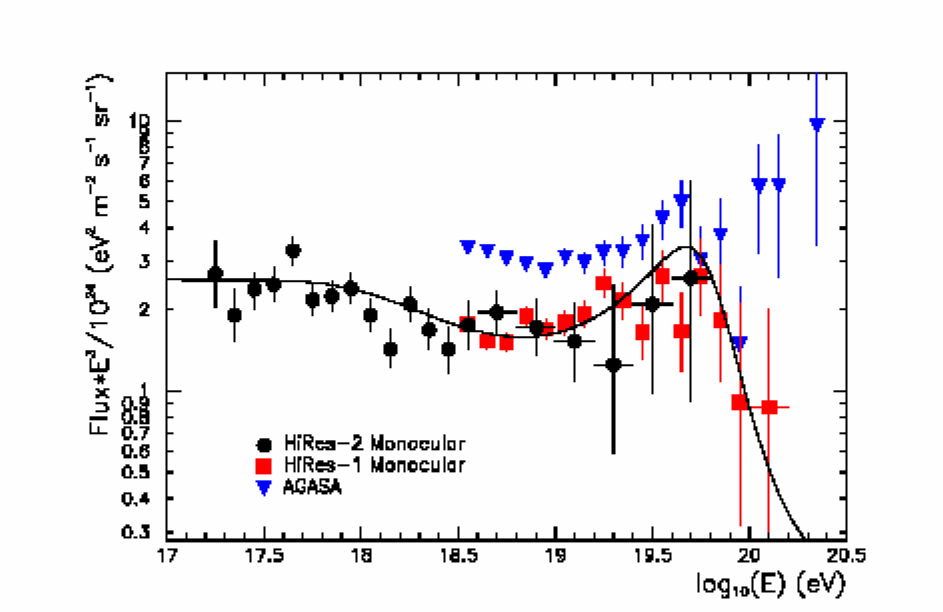




K-H Kampert et al., astro-ph/0204205
derived from μ / e ratio in EAS



Attenuation length in 2.7° background

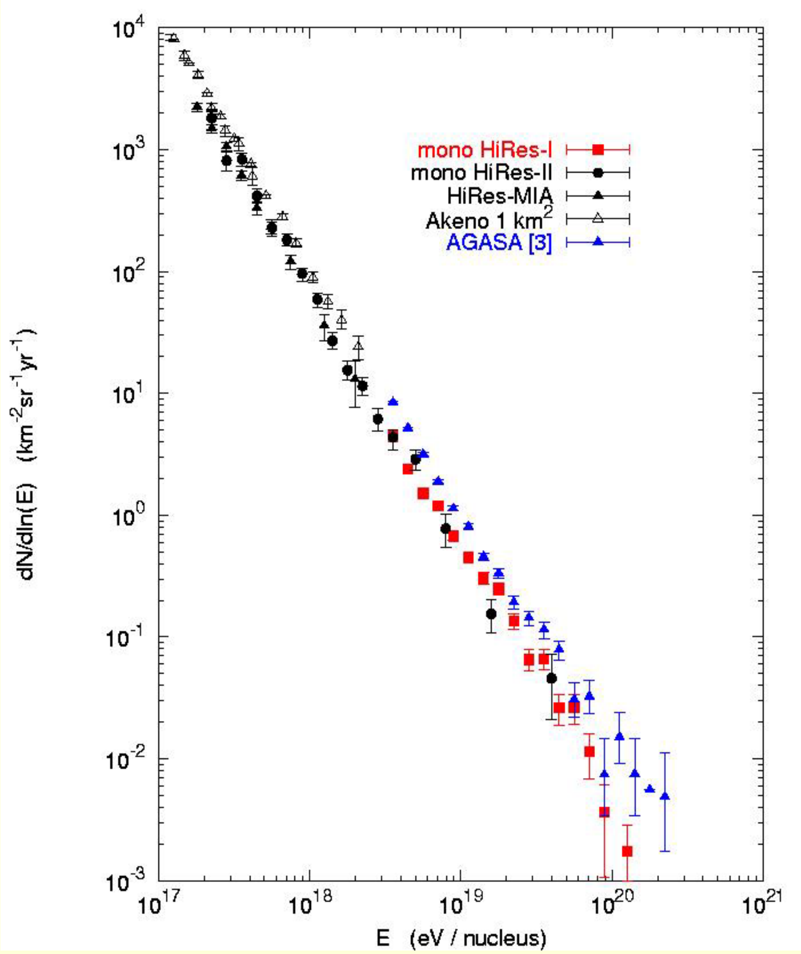


HiRes monocular spectrum compared to AGASA

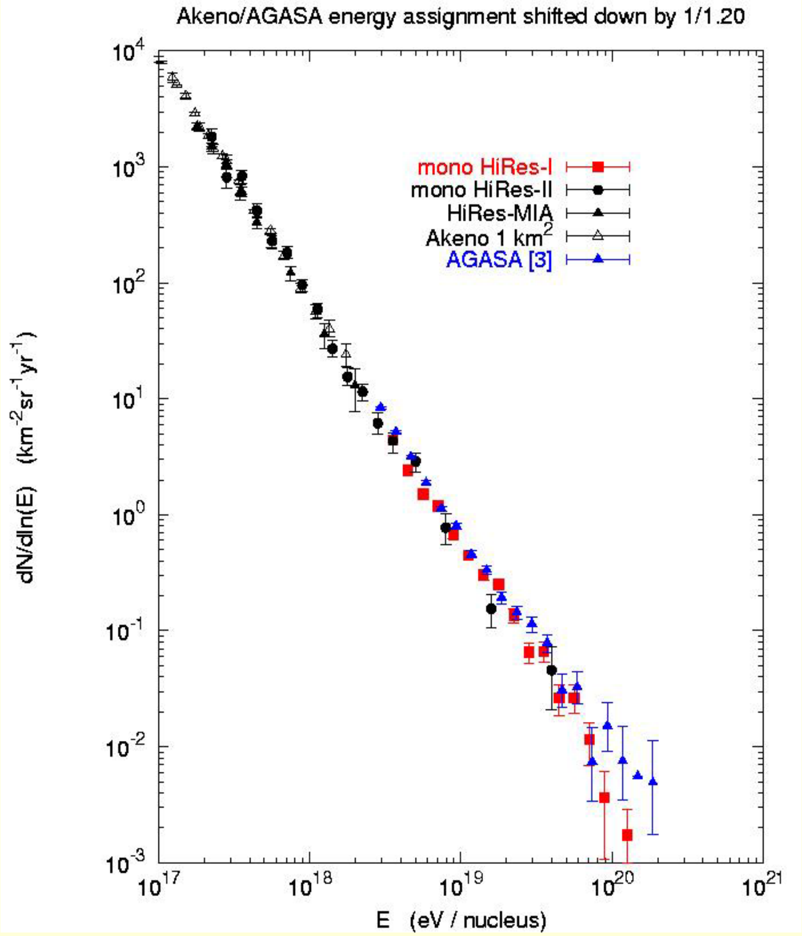
--*D. Bergman et al., Proc. 28th ICRC, Tsukuba, Aug. 2003*

Akeno-AGASA / HiRes: comparison of what is measured

As measured



Akeno-AGASA shifted down by 1 / 1.20



Energy content of extra-galactic component depends on location of transition

- Energy content determines possible sources

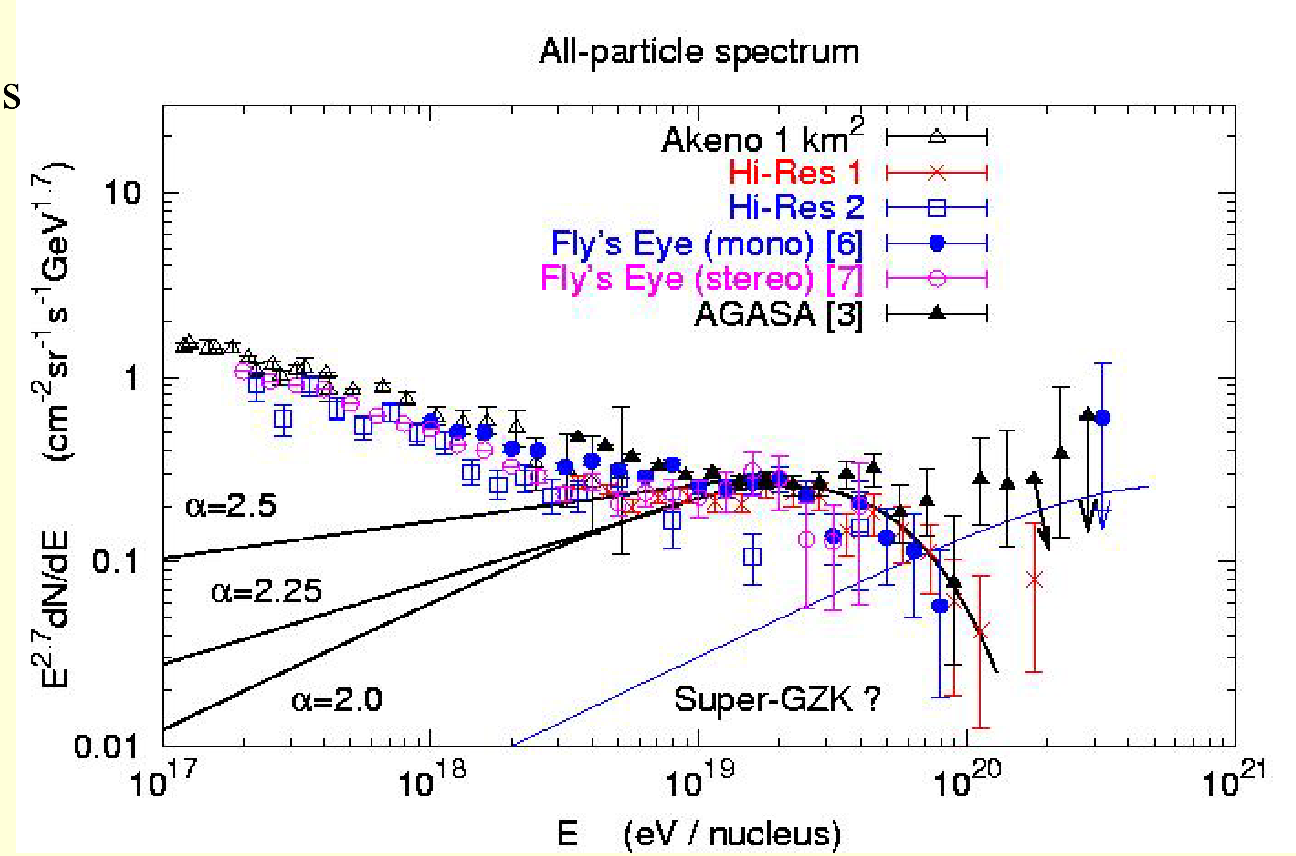
Uncertainties:

- Normalization point:
  10^{18} to $10^{19.5}$ used
  Factor 10 / decade

- Spectral slope
  $\alpha = 2.3$ for rel. shock
  $= 2.0$ non-rel.

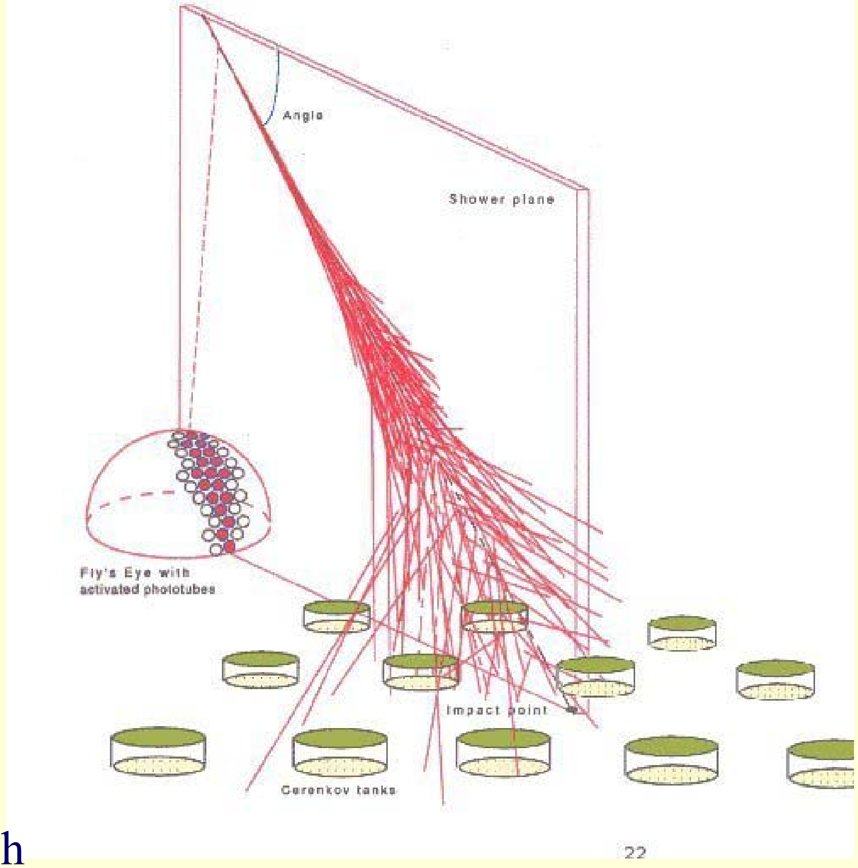
Composition signature:

- transition back to protons



Composition with air showers

- Cascade of nucleus
  - mass A, total energy E_0
  - X = depth in atmosphere along shower axis
  - $N(X) \sim A \exp(X/\lambda)$, number of subshowers
  - $E_N \sim E_0 / N(X)$, energy/subshower at X
  - Shower maximum when $E_N = E_{critical}$
  - $N(X_{max}) \sim E_0 / E_{critical}$
  - $X_{max} \sim \lambda \ln \{ (E_0/\mathbf{A}) / E_{critical} \}$
  - Most particles are electrons/positrons
- μ from π-decay a distinct component
  - decay vs interaction depends on depth
  - $N_\mu \sim (\mathbf{A}/E_\mu)_*(E_0/\mathbf{A}E_\mu)^{0.78} \sim \mathbf{A}^{0.22}$
- Showers past max at ground (except UHE)
  - → **large fluctuations**
  - → poor resolution for E, A
  - Situation improves at high energy and/or high altitude
  - Fluorescence detection > 10^{17} eV



Schematic view of air shower detection: ground array and Fly's Eye

Shower profiles from Auger

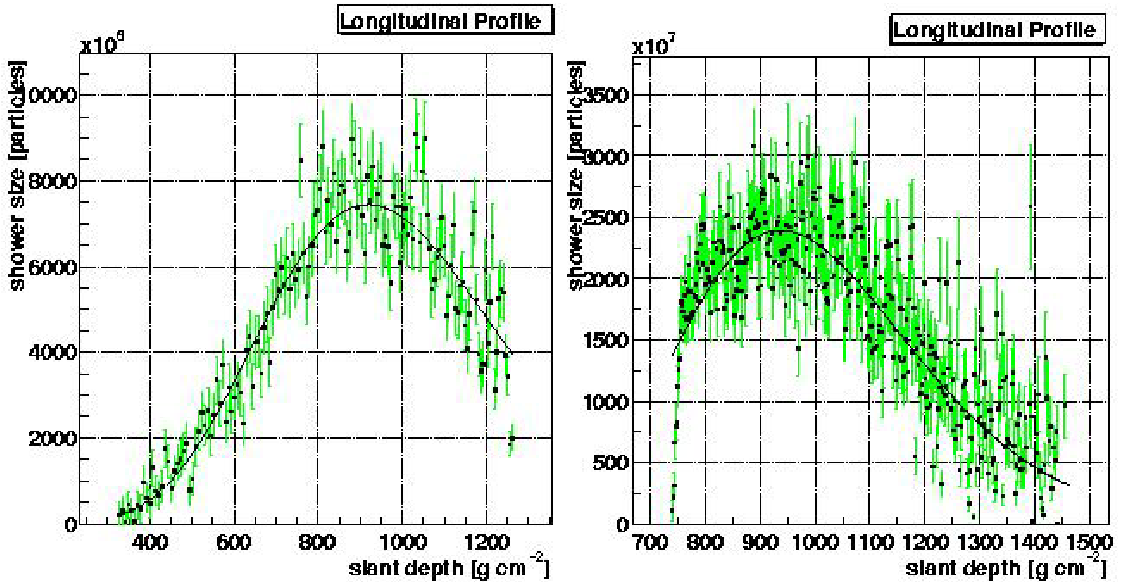
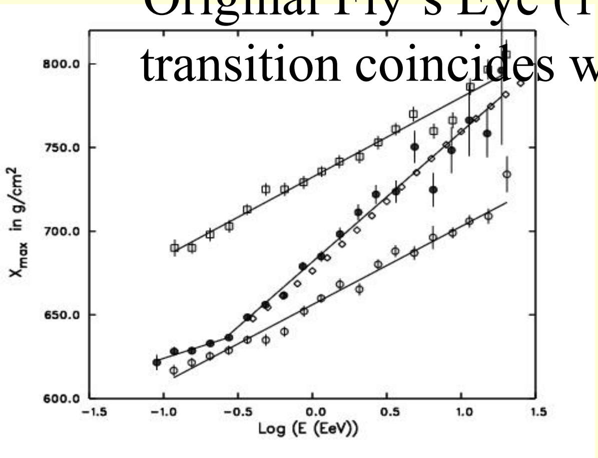
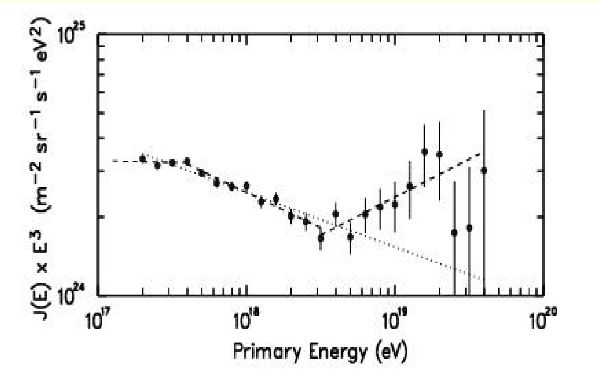


Fig. 2. *Left:* Reconstructed longitudinal profile of a shower landing about 13 km from the detector. The estimated energy is around 1.3×10^{19} eV. The line is a fit to a Gaisser-Hillas function. *Right:* Same for an inclined shower landing about 20 km from the detector, with energy around 3.3×10^{19} eV

Change of composition at the ankle? If so, at what energy?

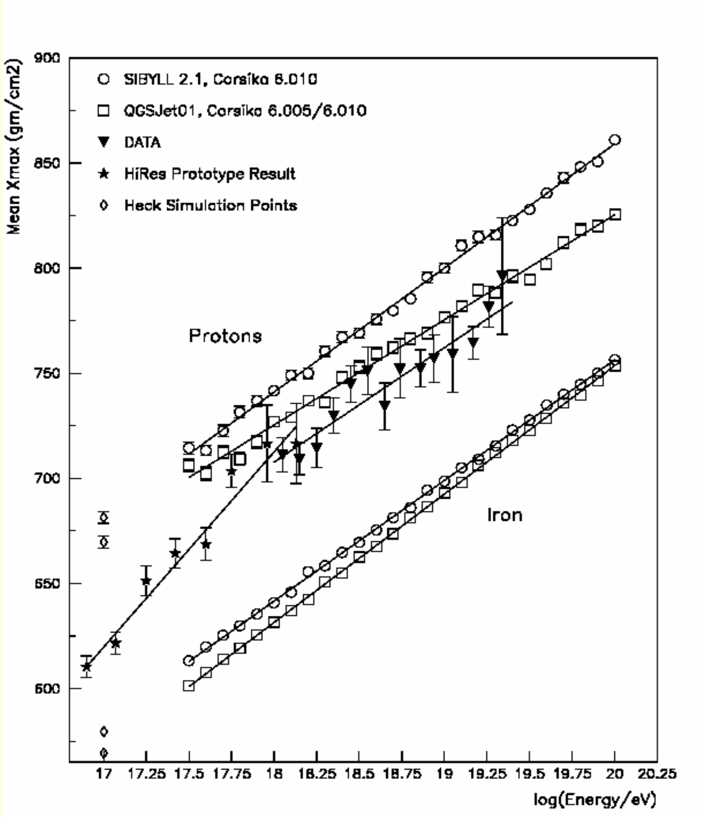
Original Fly's Eye (1993): transition coincides with ankle





Stereo

HiRes new composition result: transition occurs before ankle



G. Archbold, P. Sokolsky, et al., Proc. 28th ICRC, Tsukuba, 2003

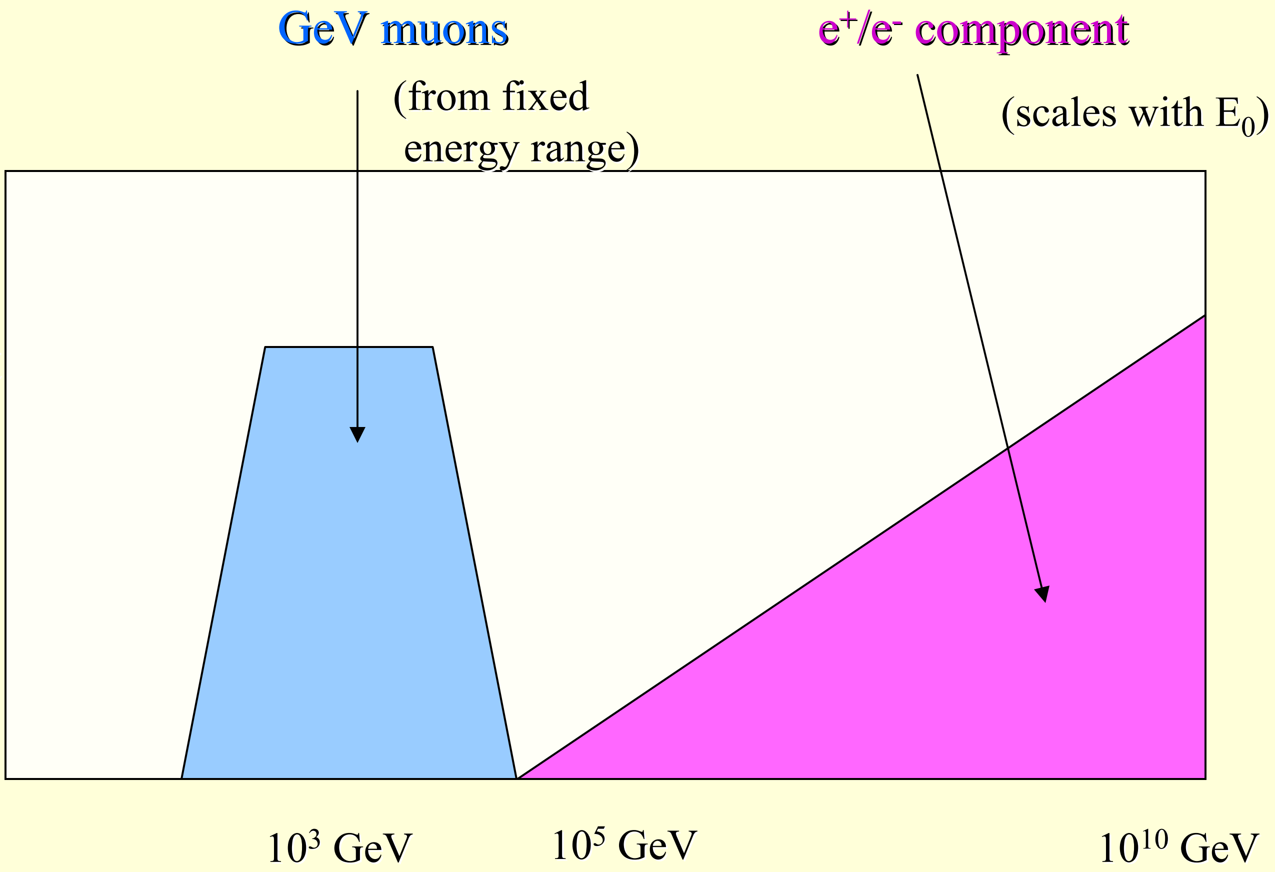
Calculations of air showers

- Cascade programs
  - *Corsika*: full air-shower simulation is the standard
  - Hybrid calculations:
    - CASC (R. Engel, T. Stanev et al.) uses libraries of presimulated showers at lower energy to construct a higher-energy event
    - SENECA (H-J. Drescher et al.) solves CR transport Eq. numerically in intermediate region
- Event generators plugged into cascade codes:
  - DPMjet, QGSjet, SIBYLL, VENUS, Nexus

What energies are important?

Example: 10^{10} GeV primary proton:

- ~ TeV interactions produce most GeV μ, independent of primary E_0; need $< N_\pi(\text{TeV}) >$
- For dominant e^+e^- component, E_{int} scales with E_0



GeV muons

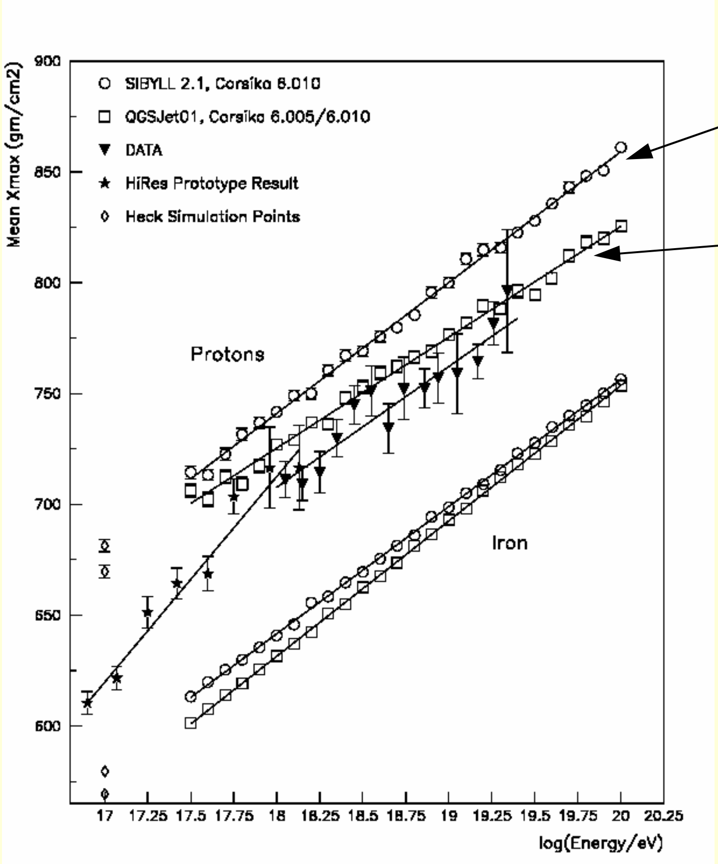
(from fixed energy range)

e^+/e^- component

(scales with E_0)

Model-dependence of X_{max}

HiRes new composition result:
transition occurs before ankle



G. Archbold, P. Sokolsky, et al.,
Proc. 28th ICRC, Tsukuba, 2003

Sybil 2.1 (some screening of gluons at small x)

QGSjet (strong increase of gluon multiplicity at small x)

- **$X_{max} \sim \lambda \log(E_0 / A)$ with scaling**
- **With increase of inelasticity,**
  - **Primary energy is further subdivided:**
  - **$X_{max} \sim \lambda \log\{ E_0 / (A * (1 - \langle x(E) \rangle)) \}$**

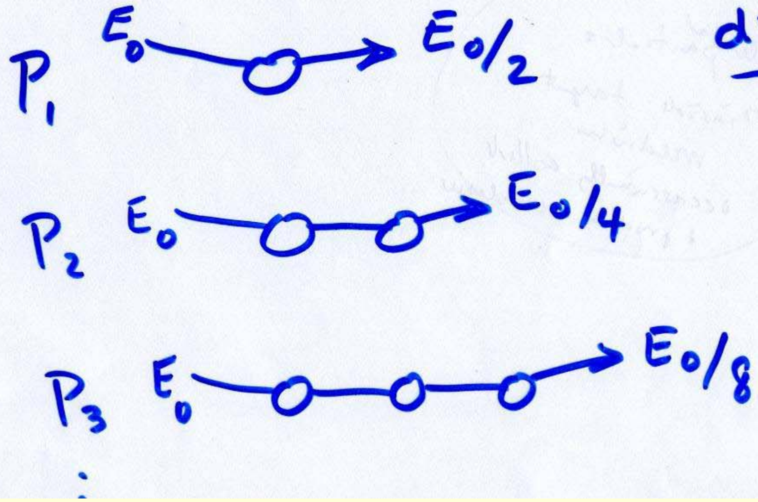
Wounded nucleons & inelasticity in p-air interactions

Mean number of wounded nucleons:

$$\langle N_w \rangle = \frac{\sum_{N=1}^{\infty} N\sigma_N}{\sigma_{pA}} = \frac{A\sigma}{\sigma_{pA}}$$

$$\sigma_{pA} \sim A^{2/3}, \text{ so } \langle N_w \rangle \sim A^{1/3}$$

Assume fast pions materialize outside nucleus, so only "leading" hadron suffers further losses inside nucleus



$$\frac{dn(E,E_0)}{dE} = \frac{1}{E_0}$$

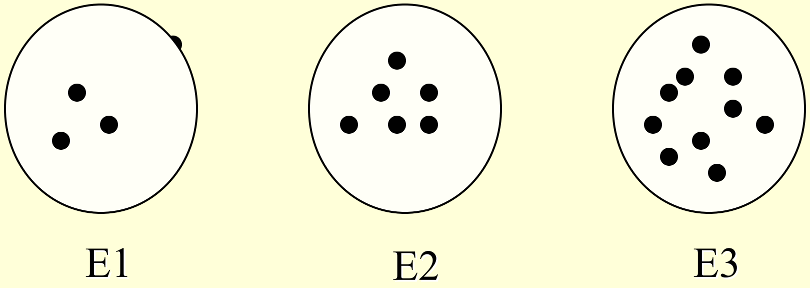
$$= \frac{1}{E_0} \ln\frac{E_0}{E}$$

$$= \frac{1}{2}\frac{1}{E_0} \ln^2\frac{E_0}{E}$$

Hadronic interactions at UHE

- Most important is “leading” particle distribution
- At higher energy more complex interactions may be important, leading to increase of inelasticity (Drescher, Dumitru, Strikman hep-ph/0408073)

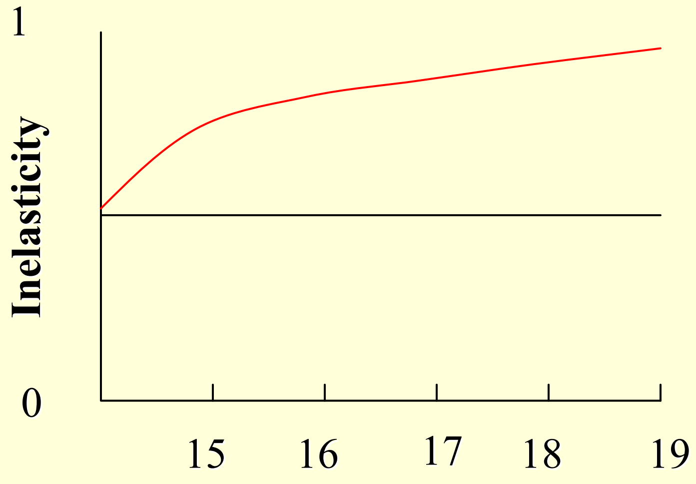
$s_{12} = x_1x_2s = 2mx_1x_{2\mathrm{Elab}} >$ few GeV
resolves quarks/gluons in target;
Gluon structure function:
$g(x) \sim (1/x_2)^p$, $p \sim 0.2 \ldots 0.4$

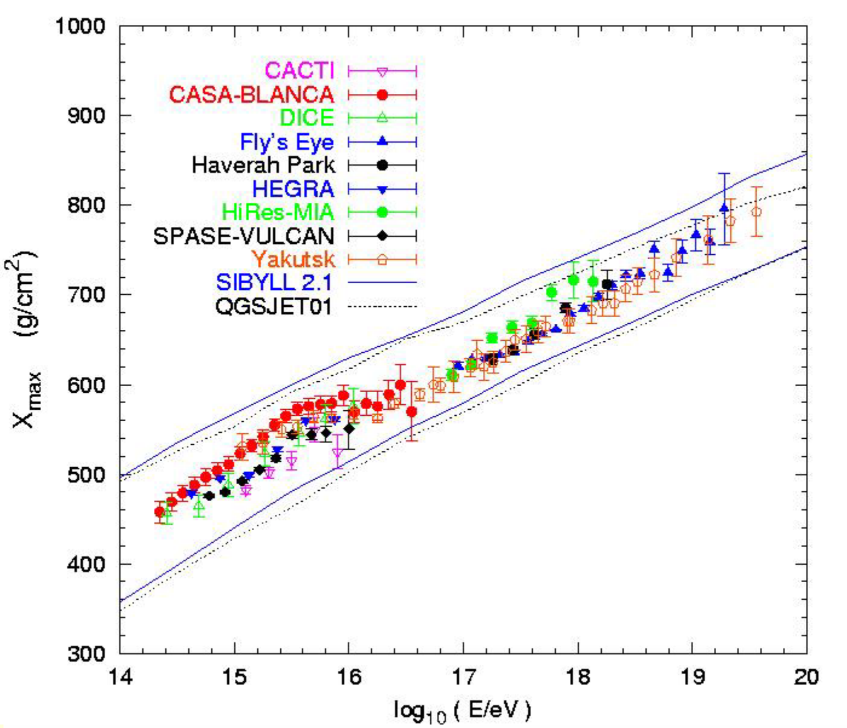


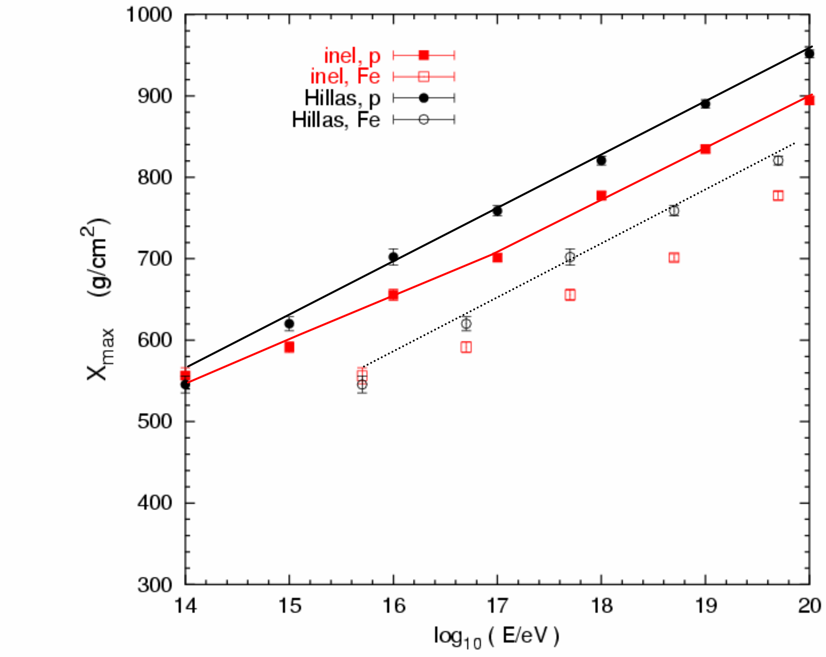
Example of increasing inelasticity

I have assumed effect is limited because energy not carried by leading nucleon is divided among pions, which materialize outside the target.

Such a large change would have
a significant effect on interpretation
-in terms of composition
-of energy in a ground array







Agenda for discussion

- Hans-Joachim Drescher: "Black Body Limit in Cosmic Ray Air Showers"
- Giuseppe Battistoni: "Atmospheric cascades with FLUKA"
- Sergej Ostapchenko: "Non-linear effects in high energy hadronic interactions"
- Comments
  - Francis Halzen: Heavy flavor production
  - Ralph Engel: Comparison of models
  - Mike Albrow: "The White Pomeron, Color Sextet Quarks and Cosmic Ray Anomalies"
  - Spencer Klein: Electromagnetic effects
- Further discussion