

THE KNEE : THEORY AND EXPERIMENT

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- I. Introduction and Overview of the Problem of the Knee
- II. Review of Direct Measurements : Mixed Composition
- III. Indirect Experiments:
Air Shower Exp Sensitivity to Primary Mass, Energy
- IV. Results from Current Air shower Experiments of Energy Spectra and Composition.
 - (a) Cherenkov based experiments
 - (b) Air Shower based experiments
- V. Conclusions ?

I. INTRODUCTION

Relating Observed Events to the Source of Cosmic Rays

The Onion

Assume you can measure Energy, E, Atomic Mass M and Charge Z of each event, then the observed quantities C(E,A,Z) can be related to the cosmic ray source by:

$$C(E,A,Z) = D[M \{P (A (I (S (E', A', Z')))) \} \}]$$

D = Detector characteristics

M = Modulation due to local magnetic fields

P = Propagation outside the acceleration region

A = Acceleration, for example by SN shocks

I = Injection from ISM or from some other source into Acceleration

S = Source Kernel – composition of the source

Lingenfelter, Kyoto 1979

Any Theory of the Knee must address the following :

Sources have to supply energy content of CR.

Accelerators have to produce non-thermal spectra of CR.

Acceleration mechanism should accelerate up to the knee at least.

Acceleration must overcome injection problems.

Propagation in the galaxy must lead to high degree of isotropy of CR

Spectra below and above the knee should “ match “.

Sources could be detected by observing high energy gamma rays or neutrinos from likely sources.

To generate gamma rays one needs to introduce a target for pion production for origin in sources which accelerate nuclei or or B field for self synchrotron Compton origin via electrons.

May be we are seeing some SNR as source of cosmic rays.

Current theory Paradigm:

- SN explosions supply the energy of CR
- SN shocks provide acceleration with universal spectral index of ~ -2.1
- SN shock acceleration terminates at about $\sim Z$ (100s of TeV)
- SN shock acceleration and leakage out of the galaxy leads to Rigidity dependent cut off.
- Observed spectrum is the source spectrum modified by energy dependence of the CR path length distribution.
- Source has the elemental abundance of ISM or of some stellar wind, into which the shock wave travels.
- The sharpness of the cut off and magnitude of change of slope is subject of current investigations.

Three theoretical problems need explanation:

- (1) The origin and energy of the knee?
- (2) The origin of the smooth transition to a steeper spectrum beyond the knee
- (3) The smallness of anisotropy above the knee

One model invokes two sites (Bierman et al) : (a) normal SN explosions into the approximately homogeneous ISM, (b) SN explosions into stellar winds. Another model invokes a **recent local SNR** source which adds a small component on the top of a smooth galactic CR spectrum (Erlykin and Wolfendale). The first 'predicts' the desired change of slope below above the knee and the latter has to avoid 'kinks' or 'bumps'.

A bothersome question is: if the knee is due to presence of different types of sources why do they 'match up' so smoothly at the knee?

Some modellers invoke 'change' in hadronic interactions to explain the knee – not likely at these energies in my opinion.

General consequences of this paradigm:

Primary Cosmic Rays have a mixed composition which is energy dependent.

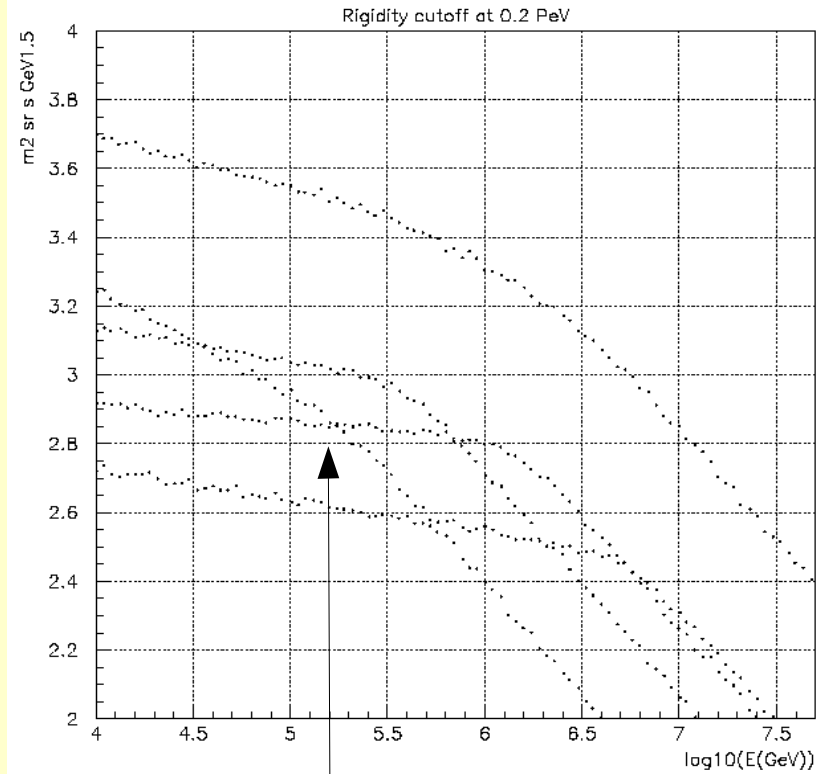
The composition becomes “ heavier “ as one approaches the cut off.

The knee should be around a PeV

The isotropy of CR is due to pitch angle scattering during propagation off magnetic field fluctuations in the galaxy.

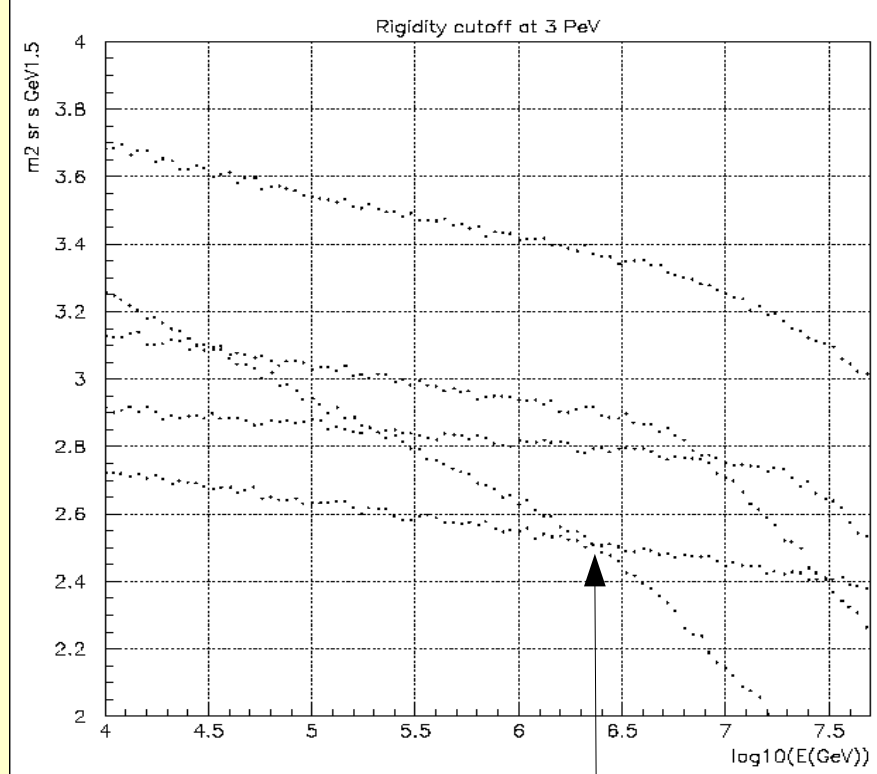
Next I show two models currently in ' fashion'.

Rigidity Cutoff 0.2 PeV



Proton cutoff

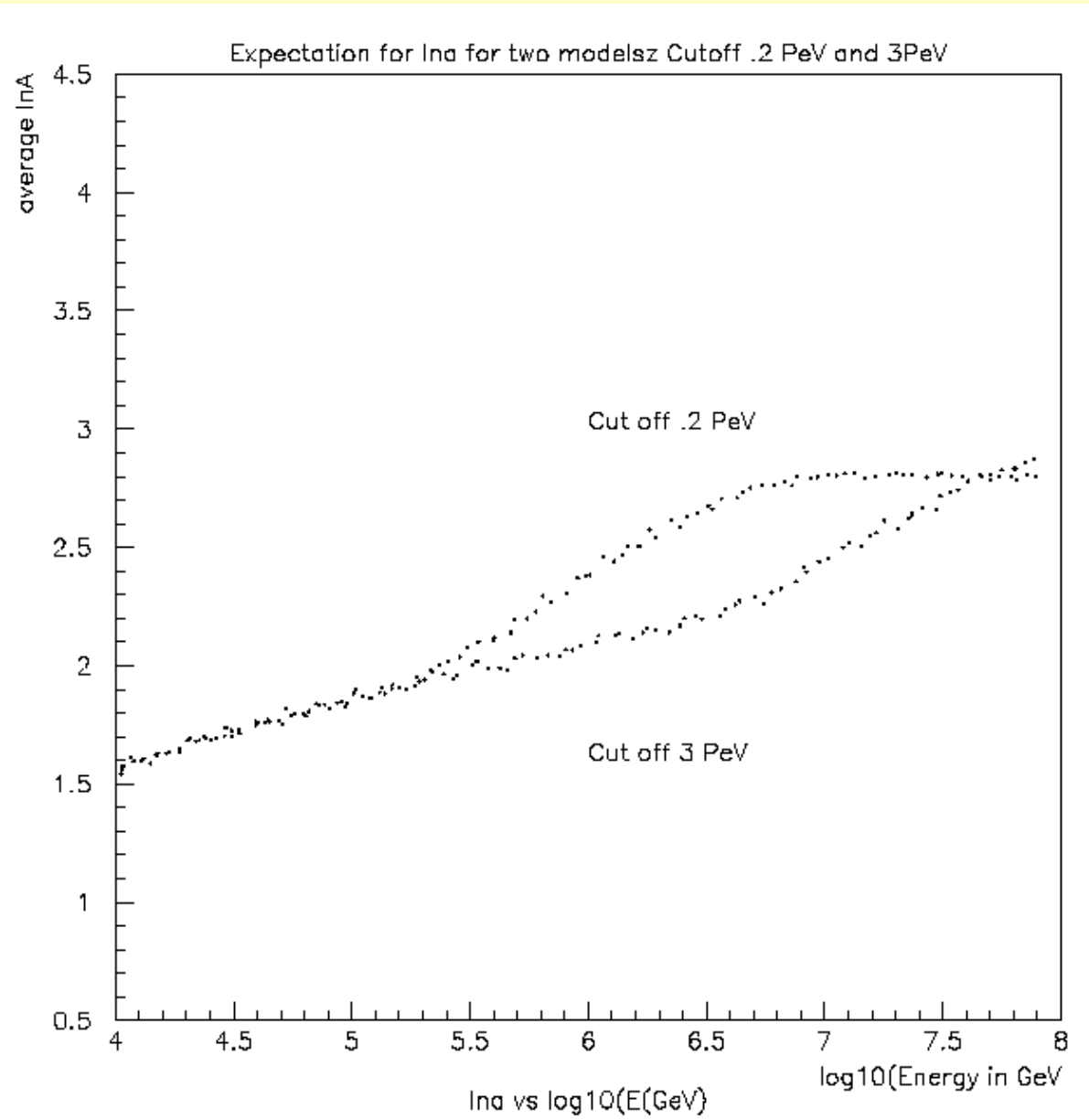
Rigidity Cutoff 3 PeV



Proton cutoff

Note that the cutoff changes spectral indices of all components by different amounts so that after cutoff the indices become all equal and about -3.1.

How does mean $\ln A$ vary with energy for these two models ?



Max difference
in average $\ln A$
for the two models

0.45

How well can we
measure it?

Such a difference
in $\ln A$ corresponds
to only 30 gm/cm^2
in X_{max} !

Some early History

First suggestion of a two source model with one source having a sharp rigidity cutoff was made by Peters(1961). This model supplemented with a 'simple' shower analysis gave a 'natural' explanation of Nikolski's (1956) observation of a sharp increase in nuclear active particles in air showers as a function of energy.

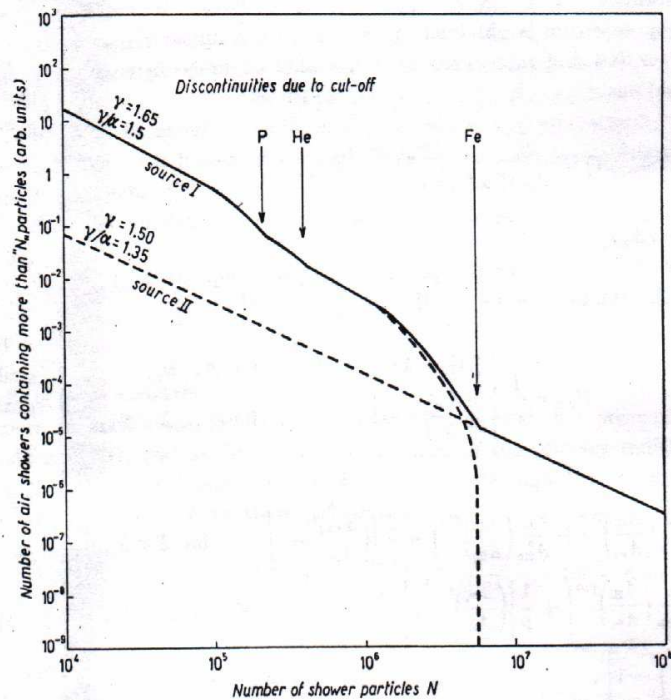
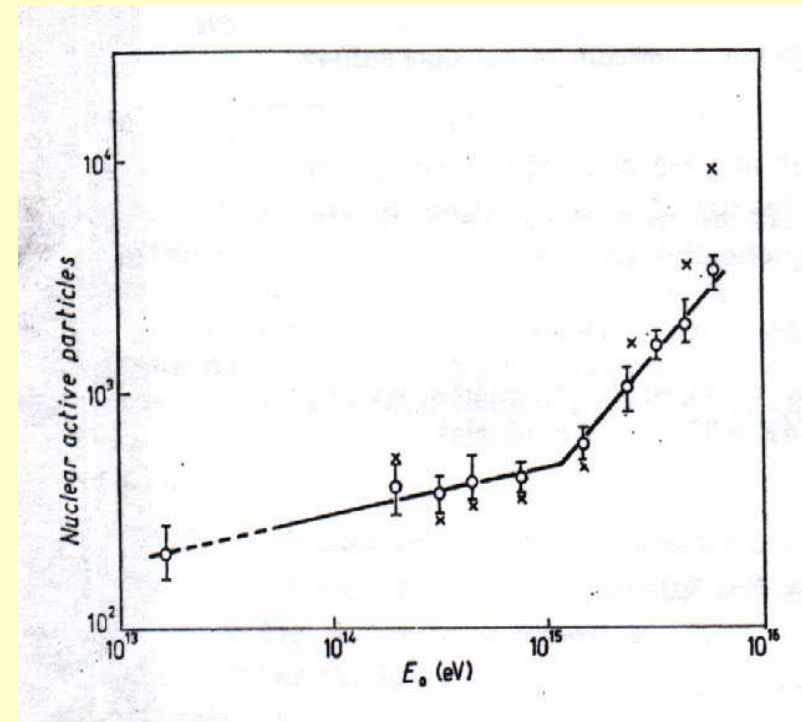
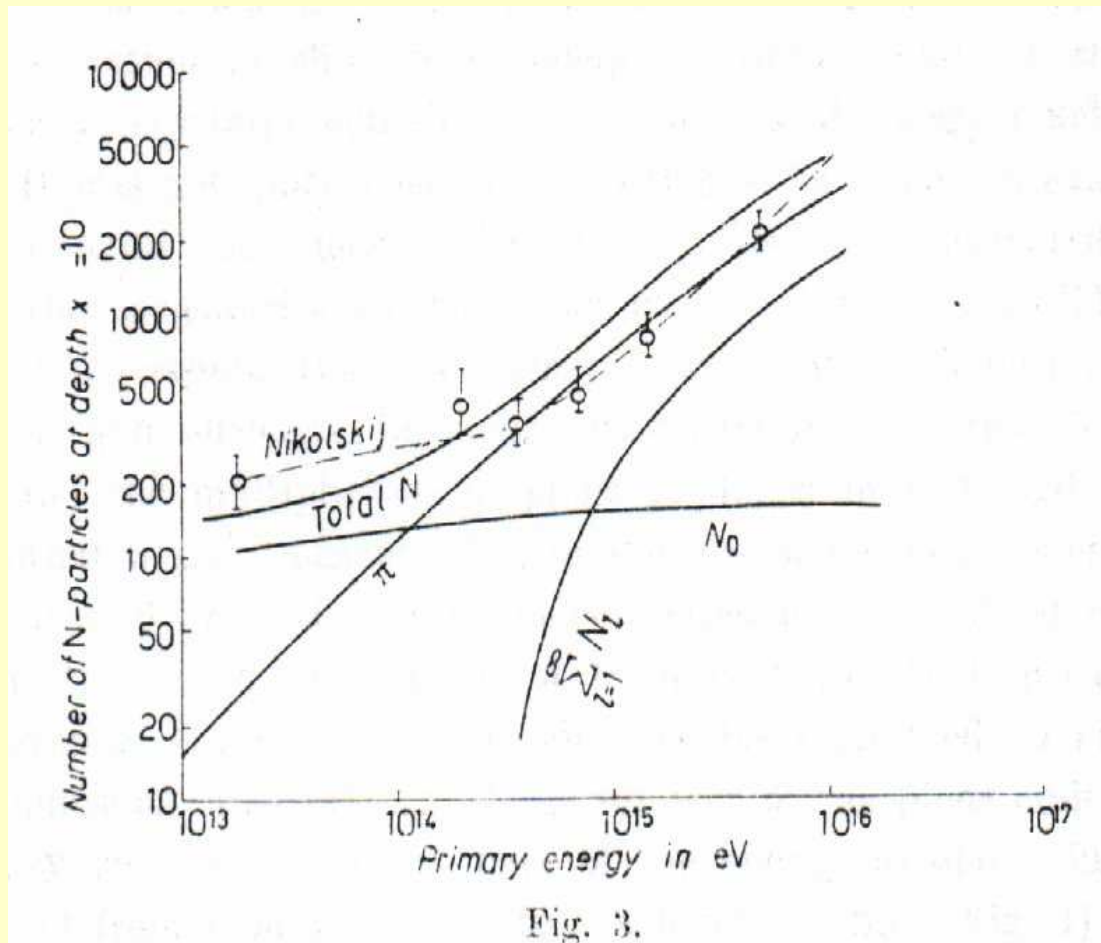


Fig. 2. - Curve I represents the integral size-frequency distribution of air showers, corresponding to the differential distribution of Fig. 1. Curve II represents the distribution contributed by a hypothetical and different source with the following properties: 1) an energy spectrum proportional to $E^{-\gamma}$ with $\gamma=1.5$; 2) an energy output which is one thousand times smaller than that of source no. 1; 3) a cut-off which lies much higher than that of source no. 1. The solid line represents the combined effect of the two sources.



Peters introduced me to this problem and I was not satisfied with his hadronic model for shower generation. So with D.S. Narayan I did a more realistic model.

Narayan and Yodh (1960) with one of the first air shower calculation including pion cascades showed that the increase does not prove a rigidity cut off !!



A blow by blow Monte Carlo simulation was developed by the Maryland group to interpret delayed hadron experiments in the late 1970s and early 1980s. Similar simulations were done by Hillas, Turver and others. A modular program, “SHOWERSIM”, was written by Andrez Wrotniak.

Scale breaking leading to rising cross sections were deduced from Cosmic Rays in early 1970s (YPT). This had a singular effect on shower development in the PeV region.

These simulations were applied to understand results obtained by EC at mountain altitudes regarding spectra and interactions and to the interpretation of observations of shower max in the 70s and 80s.

Next I discuss elemental composition of cosmic rays at high energies:

Some Quotes from EAS experimental papers on composition near the knee :

...the composition of cosmic rays is varying with energy ... from being dominated by protons and lighter nuclei below 10^4 GeV to becoming dominated by heavy nuclei between 10^5 and 10^7 GeV
.... Goodman et al 1982 (Delayed hadrons)

No Evidence for a large change in mean mass of cosmic rays across the kneeSwordy and Kieda 1999 (DICE experiment)

.. there is no doubt about the general trend: the mass composition gets heavier at energies above the knee observed in the all particle spectrum, and the knee originates from the vanishing light component ... Haungs, Rebel and Roth , 2003 (KASKADE experiment)

II. REVIEW OF DIRECT EXPERIMENTS:

Cosmic Ray spectra from direct measurements above the atmosphere.

All these experiments measure the charge and energy or momentum of the cosmic ray particle in their detectors.

In these experiments generally

(1) The charge is measured to $\frac{(\Delta Z)}{Z} \leq 0.2$

This resolution is sufficient to do element or element group identification.

(2) Nuclei are made to interact in a target layer and sampled by

Emulsion Chambers giving Energy Resolution $\frac{(\Delta E)}{E} \leq 0.2$

(3) In other experiments TRD or Cherenkov radiation is used for Energy measurement.

Circumvents the problem of using hadronic interaction properties to simulate hadron calorimeter response.

Pioneering Experiments for direct Measurements:

Proton Satellite, Calorimeter(1960s) Grigorov et al : up to PeV total energy
All particle and protons and/or helium. First indication of knee.

JACEE (2 decades) EC Calorimeter: Again up to about PeV/particle: Elemental composition – energy varying mixed composition.

CRNE, Gas Cherenkov and TRD up to about a TeV/amu. Energy measured electromagnetically using Cherenkov and TRD.

Newer and Current Experiments:

RUNJOB: EC and Fragmentation technique: up to 1 PeV/particle

ATIC: Tracking Calorimeter: up to few 100 GeV/amu

TRACER: Cherenkov, TRD : up to 1 TeV/amu

CREAM: TRD + Calorimeter : up to a PeV/particle

Results from Current Experiments (Tsukuba 2003) are shown next:

Chamber Structure for RUNJOB'95

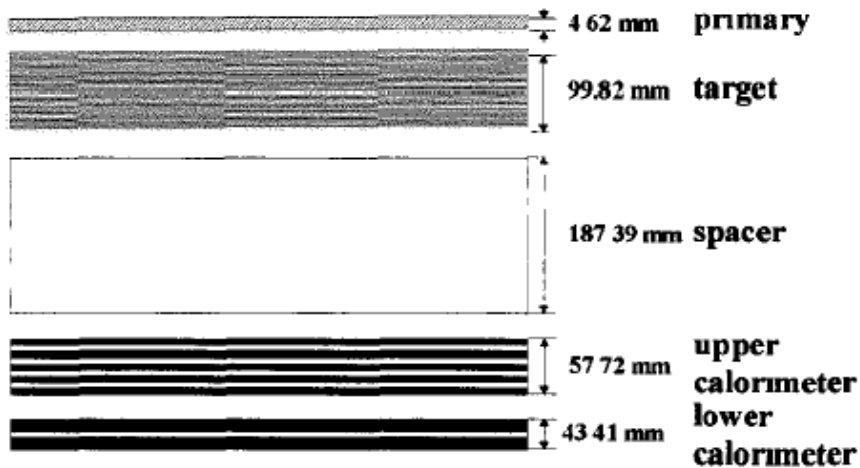
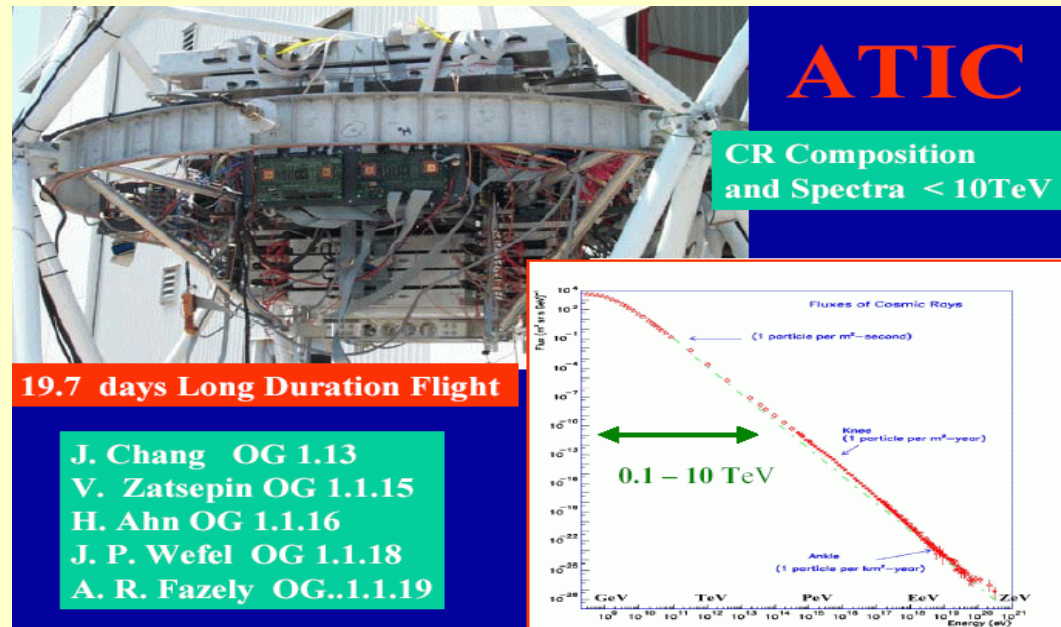


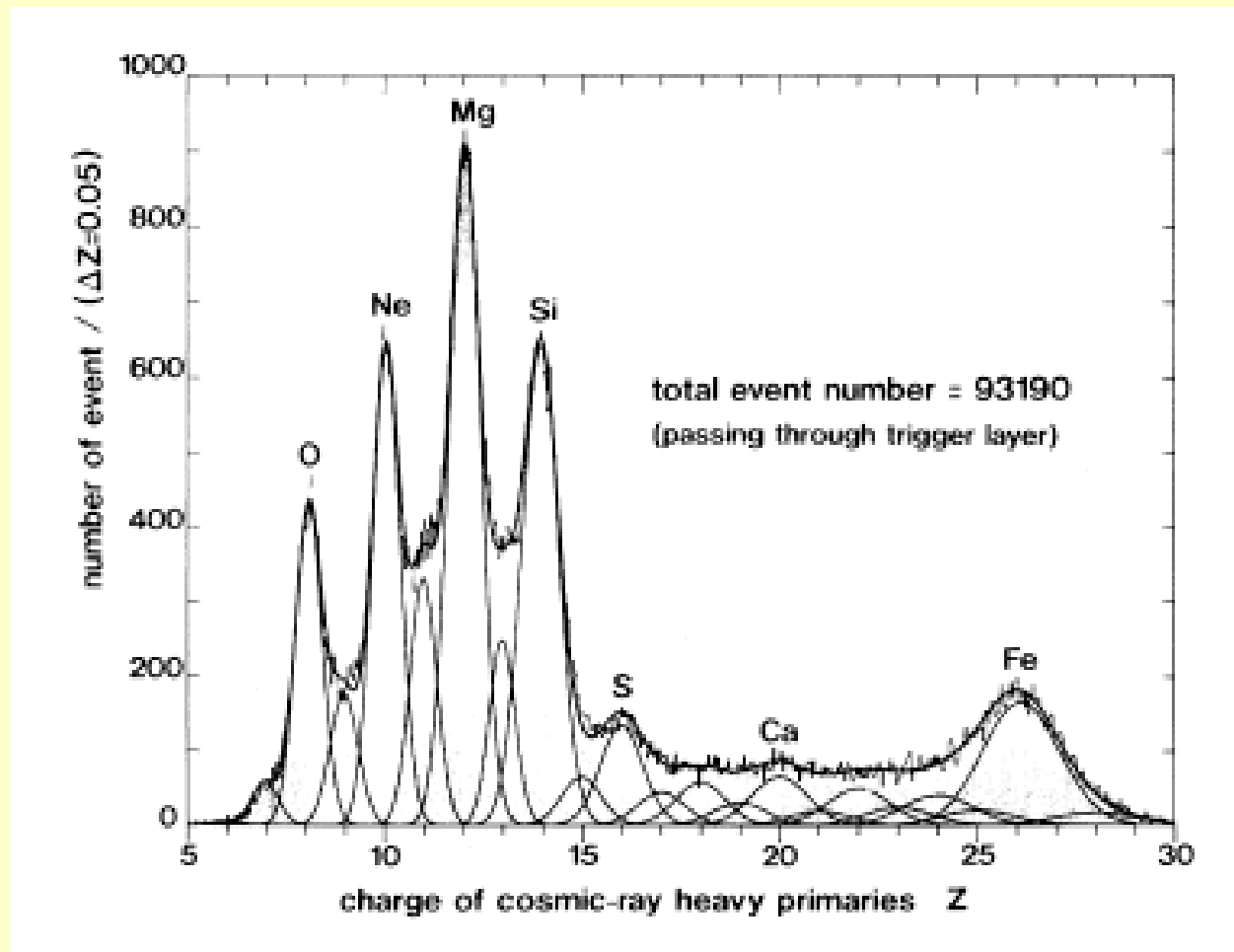
Fig. 2. Chamber structure for RUNJOB in 1995.

Primary interacts in a target and energies and angles of secondary jets measured in the lower chamber. Large effective acceptance. Primary Charge measured.

Energy of primary measured with calorimeter and charge measured.

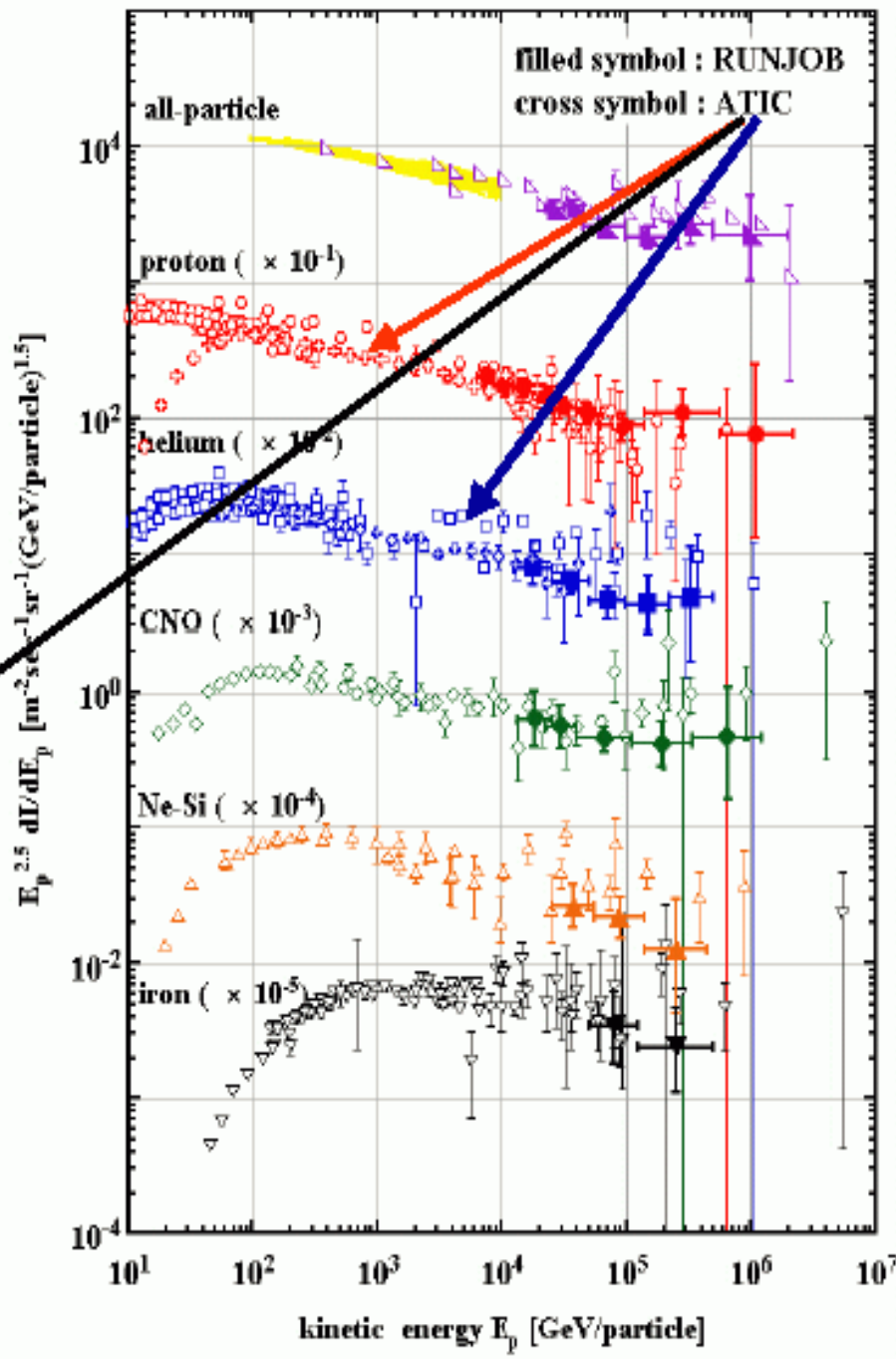
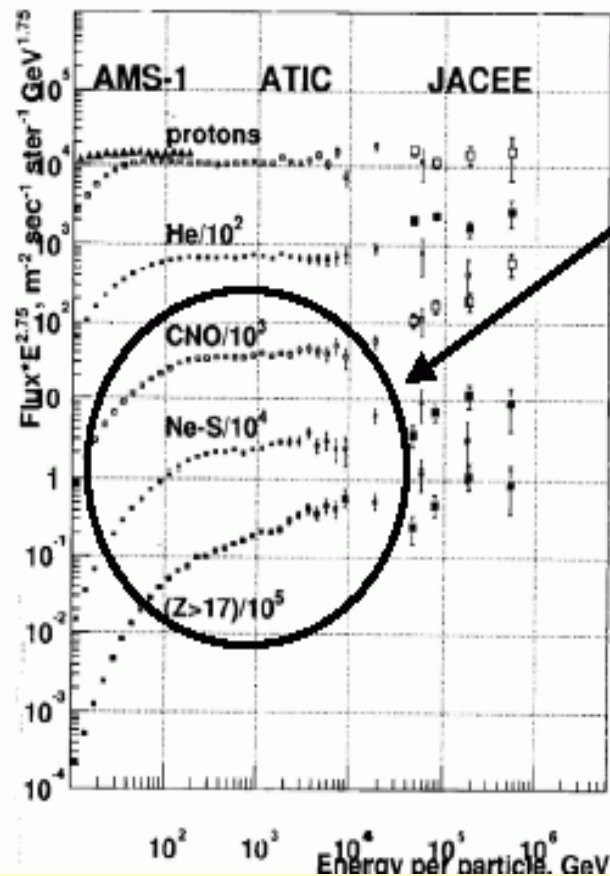


Charge resolution of RUNJOB for M and H elements

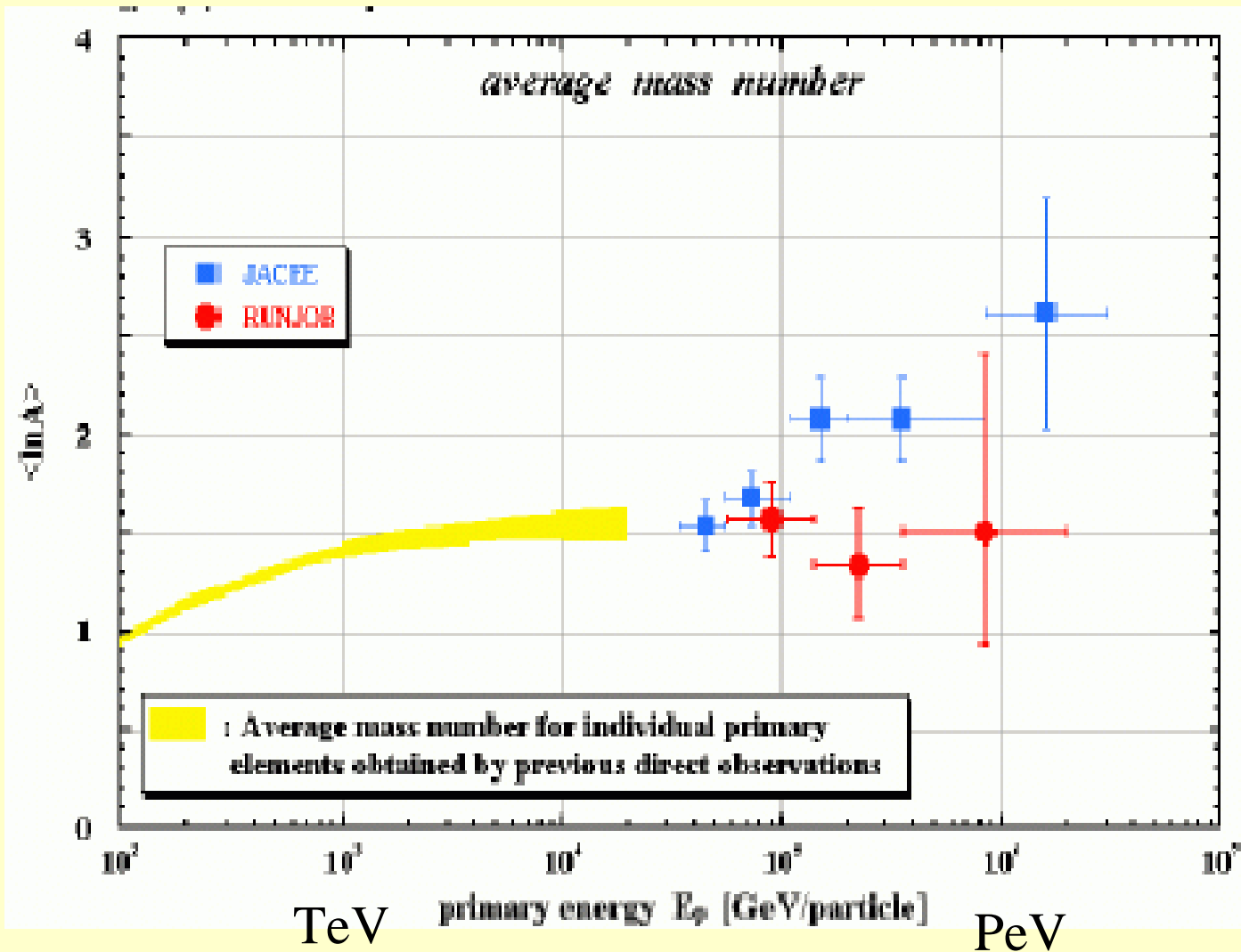


2

Better understanding of the CR composition approaching the knee region



$$E^{2.5} \left(\frac{dJ}{dE_p} \right)$$



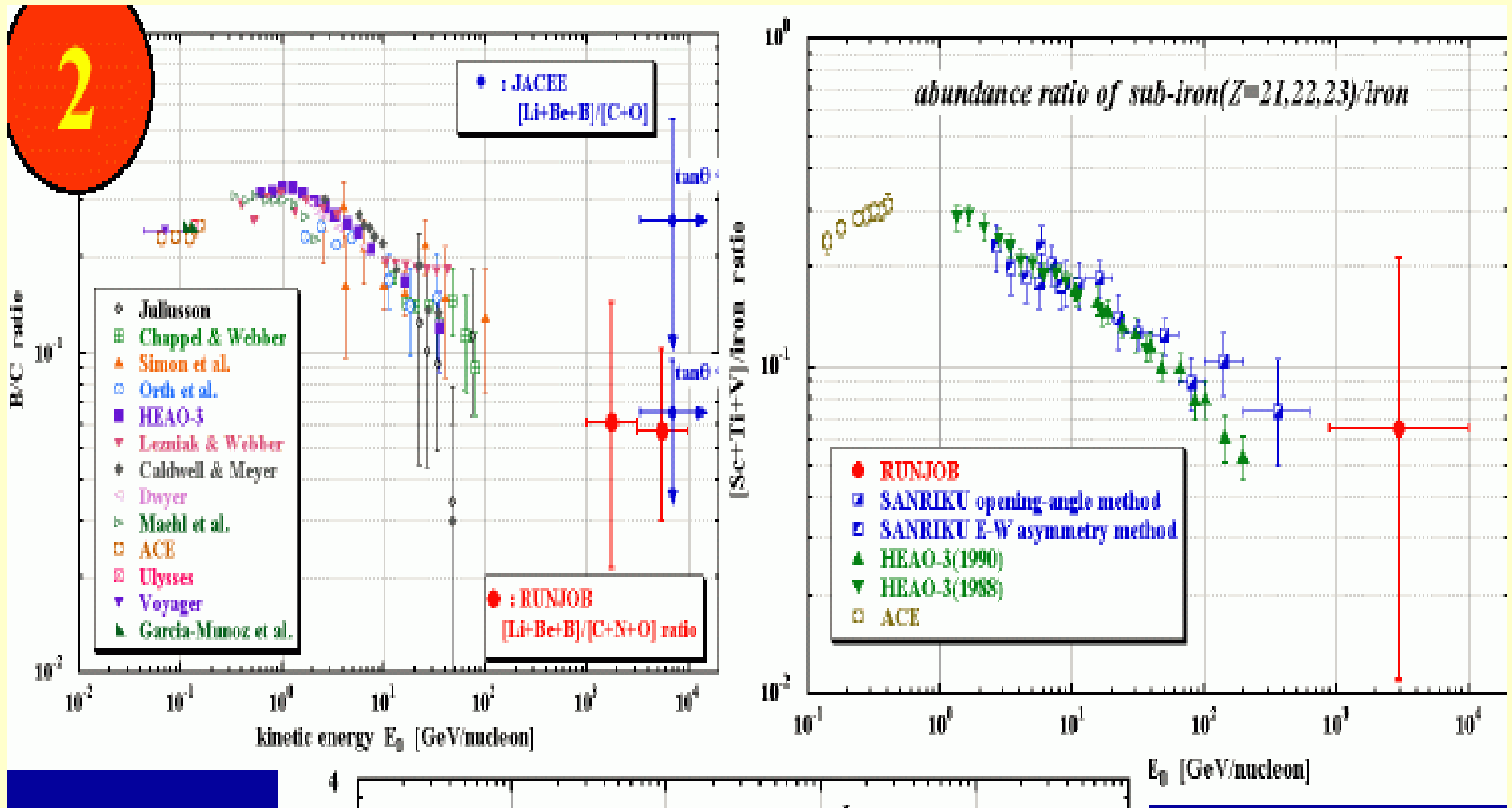
Fe

P

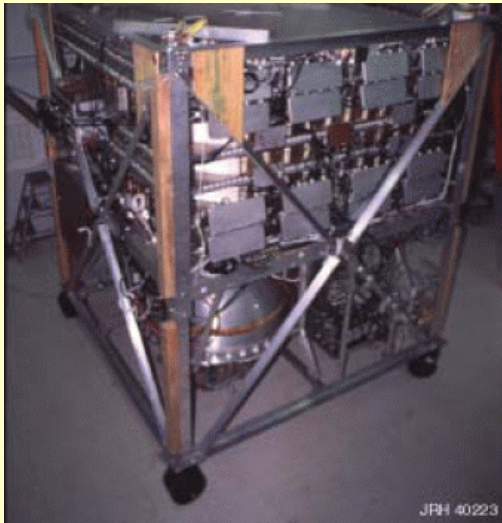
Mixed Composition. Is it Changing as we approach the knee?
 If you average the two sets the composition is getting heavier.

Takita, Tsukuba 2003

Data relevant to propagation and anisotropy:

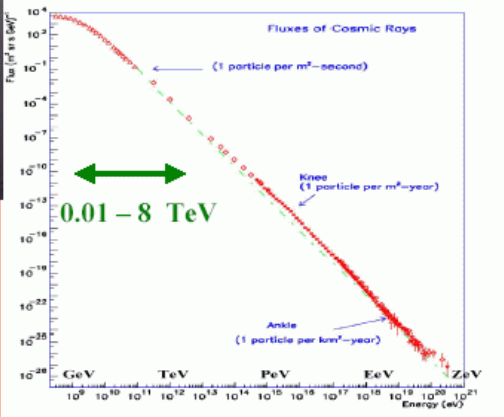


S/P ratio as a function of energy – Path length distributions from Direct measurements. **Need better higher energy measurements.**



TRACER

~ 1 day long test flight

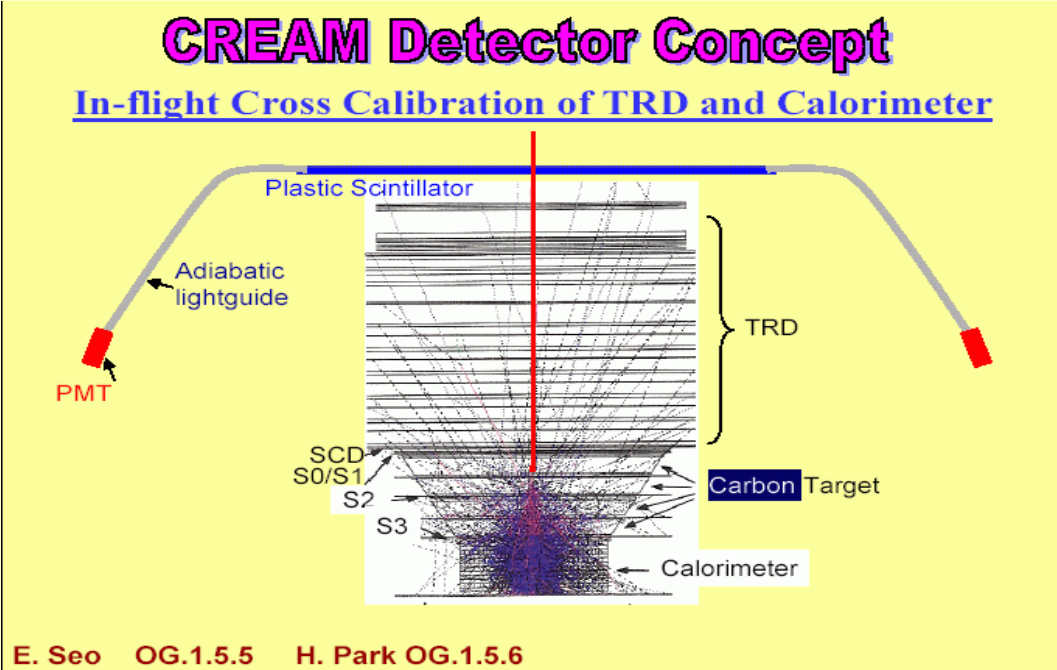


D.Muller OG 1.1.20

O, Ne, Mg, Si, Fe spectra
 $E_{kin} \sim 0.010 - 8 \text{ TeV}$

Had a test flight

Had a long flight :



III. INDIRECT EXPERIMENTS

No longer do we measure $C(E,Z,A)$ as for direct measurements.

Indirect measurements involve Sampling Air Showers:

Calorimetric Measurements – Cherenkov light or Fluorescence

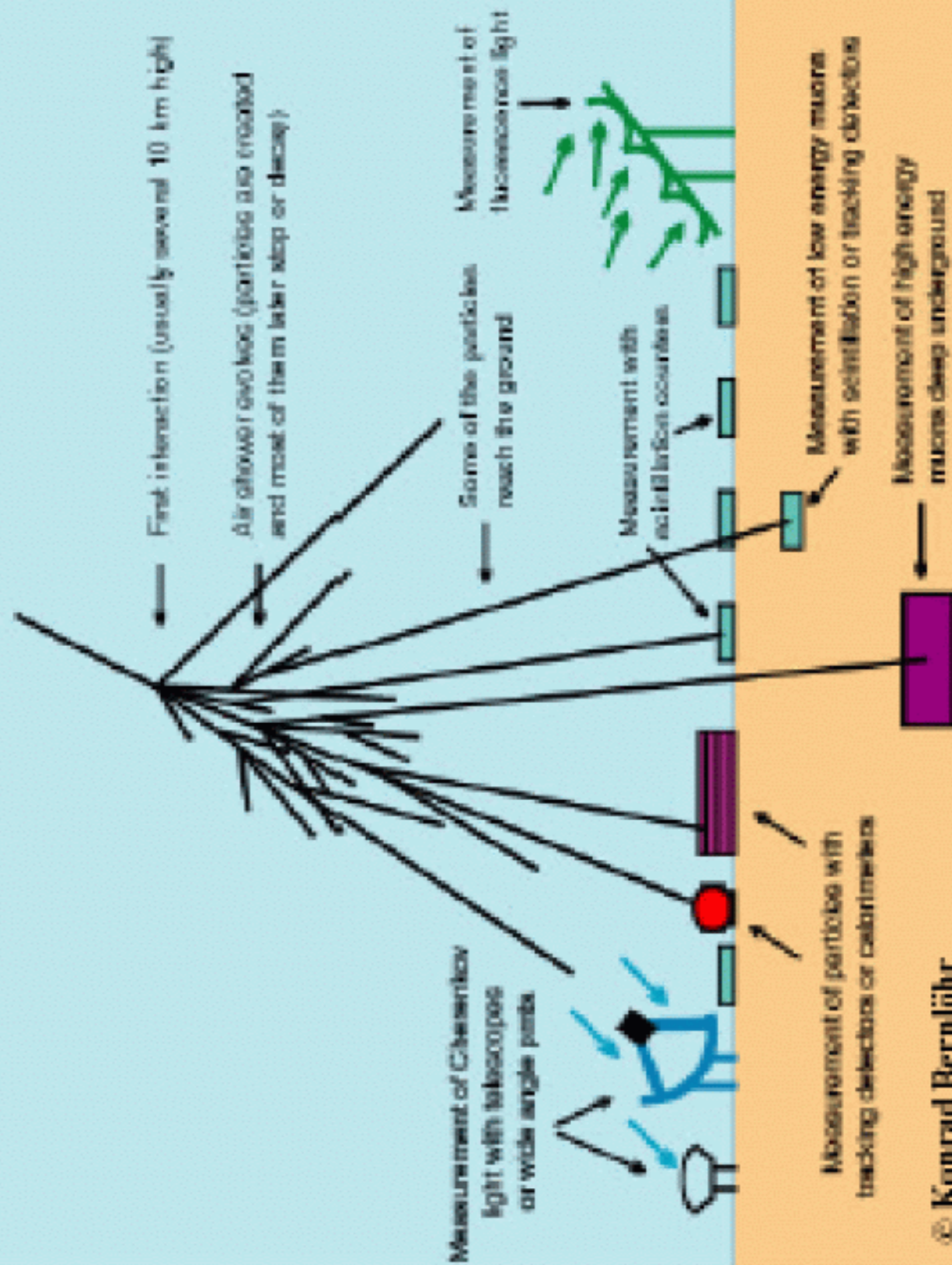
Others:

Single layer sampling of electron, muon, hadron components

Or for some experiments a combination of the above two.

Mountain level EC experiments to measure $\sum E_y$
for energetic hadrons and gammas interacting in a target layer.

Need detailed shower simulations to extract $C(E,Z,A)$ from observed data.



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A full description of an air shower produced by a primary of energy E_0 and atomic mass A requires the knowledge of the multi-dimensional functions (at depth slant depth $x = h \sec \theta$)

electrons and positrons	$\rho_e(E_0, A, x, E_e, r, t)$	
gamma rays	$\rho_\gamma(E_0, A, x, E_\gamma, r, t)$	
muons	$\rho_\mu(E_0, A, x, E_\mu, r, t, \theta_\mu)$	
hadrons	$\rho_h(E_0, A, x, E_h, r, t)$	
neutrinos	$\rho_\nu(E_0, A, x, E_\nu, r, t)$	not measured
Cherenkov photons	$\rho_{cherekov}(E_0, A, x, r, t)$	Low duty factor
Fluorescence photons	$\rho_{fluor}(E_0, A, x, r, t)$	

They represent lateral and longitudinal variation of these densities

$x =$ depth along the shower axis

$r =$ distance from the axis of the shower

$t =$ arrival time of particles at a given slant depth

If we had a true calorimeter which contained the shower then the energy could be measured as follows

Calling each of the distribution functions ρ_i

And integrating over r and x we should get

$$E_0 = \sum_i \int \int \int E_i \rho_i dE_i dx d^2 r$$

Air shower experiments, however, measure only some of the components :

Cherenkov Exp: Longitudinal profiles and lateral distributions of Cherenkov light X_{max} , $E_{cherenkov}$, A

Fluorescence Exp: Longitudinal profiles : X_{max} , E_{fluor}

Air Shower Exp: ρ_e , $\rho_{mu}(E_\mu)$, $\rho_{had}(E_{had})$ at a fixed depth x .

Need simulations to relate Observed Quantities to Primary energy and Primary Mass and a judicious choice of variables.

Detector response must be simulated.

Steep energy spectrum must be input.

SIMULATION PROCEDURES:

Primary spectra approximated by a few groups:

Protons and Helium – Light group

CNO – Medium group

Fe group – Heavy component

Typical input parameters are 3 intensities, 6 slopes and 3 cutoff energies.

Hadronic interaction models have to be extrapolated to energies and into kinematic regions where direct accelerator measurements do not exist.

Sensitivities of various measured parameters to atomic mass (or charge) are best illustrated by using the superposition model:

Primary of mass A and energy E is approximated by A independent nucleons each of energy E/A . In simulations the nucleus is fragmented in successive interactions.

SENSITIVE PARAMETERS TO MASS AND ENERGY:

Energy and longitudinal development best measured by Cherenkov yield and longitudinal profile : E and Xmax

Nucleon content of primary (A) best measured by

Position of shower maximum

Muon to electron ratio (as a function of muon energy)

Hadron content and hadron timing

Cherenkov lateral distribution.

Important to know shower core position – to measure lateral distributions.

Major cause of difficulty of interpretation: **Fluctuations of the depth of first interaction of the shower.**

From superposition model or detailed simulation one can find:

$$(1) \frac{N_{(\mu(A))}}{N_{(\mu(P))}} \propto \ln(A)$$

(2) Number of delayed hadrons (low energy) is a function of A

(3) Number of energetic hadrons should depend on A
for fixed energy showers

(4) Cherenkov photon density lateral distribution is sensitive
to $\ln(A)$ for fixed energy showers

$$(5) \sigma(N_{\mu} / \overline{N_{\mu}})$$

(6) Air shower experiments are most sensitive to $\ln(A)$
if energy per particle is known

(7) Over limited shower size ranges energy of shower can
estimated from N_{μ} and N_e measurements,

Dependence of Shower Parameters on A and hadronic interactions:

For Proton Showers

$$\text{Shower max } X_{max}^P = X_0 + X_m \log(E)$$

$$\text{Muon Size } N_{\mu}^P = N_{(\mu_0)} E^{\alpha}$$

For Nuclei mass A Shower max $X_{max}^A = X_0 + X_m \log(E) - X_m \log(A)$

$$\text{Muon size } \log_{10} \left(\frac{N_{\mu}^A}{N_{(\mu_0)}^P} \right) = \log(A) + \alpha \log(E/A)$$

From simulations using CORSIKA and VENUS

Cherenkov yield at distances > 75 m from the core

can be represented as: $N_{ch} = C_0 E^{\gamma} A^{-\epsilon} e^{-\beta r}$

where γ is a function of $\ln A$ and β is functions of $\ln A$ and $\ln E$

Swordy and Kieda 2000.

Energy and A dependence of position of shower maximum

Consider only protons first (constant composition) then

ELONGATION RATE depends on energy variation of hadron interactions

$$\text{Linsley Formula } D_e = \frac{d(X_{max})}{d \ln E} = (1 - B) X_0$$

The quantity B can be written as sum of terms:

B depends on energy variation of hadronic properties $B = B_g + B_\lambda + \dots$

Relevant energy dependence of multiplicity: $B_g = \frac{d(\ln g)}{d(\ln E)} \sim 0.23$

Relevant energy dependence of cross section $B_\lambda = -\beta \frac{d(\lambda_N + \lambda_\pi)}{d(\ln E)} \sim 0.11$

Next consider composition dependence:

Linsley and Watson , Phys. Rev. Letters 46, 459,1981 and references therein.

Using a superposition model for nuclei one gets

$$\text{For } X_{\text{max}}: X_m = X_1 + (1 - B) X_0 (\ln E - \ln A)$$

where X_1 is model dependent but does not depend on E or A

For a variable mixed composition $\ln A$ is replaced by $\langle \ln A \rangle$ giving

$$\text{For } X_{\text{max}}: \langle X_m \rangle = X_1 + (1 - B) X_0 (\ln E - \langle \ln A \rangle)$$

$$\text{ER: } D_e = (1 - B) X_0 \left(1 - \frac{d \langle \ln A \rangle}{d \ln E} \right)$$

To give a feel for these numbers we take: $B = 0.23$; $X_0 = 37 \text{ gm/cm}^2$;

The ER with no composition change is : $D_{10} = 66 \text{ gm/cm}^2$

The ER with composition change from pure O to P

per decade in energy is : $D_{10} = 84 \text{ gm/cm}^2$

Elongation rate can also be measured by studying fluctuations in measured shower quantities, such as muon rise time.

Walker and Watson, J Phys G, 7,(1981)1297 and 8,(1982) 1131

The **sensitivity** of experiments which measure X_{\max} to determine **average atomic weight and its change with energy** can be studied by noting that:

If B is a slowly varying function of E , then one can normalize X_{\max} to that for protons from the best simulation model and ask what is the sensitivity of X_{\max} to composition using the Linsley relationship.

$$\langle X_{\max} \rangle = X_1 + (1 - B) X_0 (\ln E - \langle \ln A \rangle)$$

$$ER = (1 - B) X_0 \left(1 - \frac{d\langle \ln A \rangle}{d \ln E} \right)$$

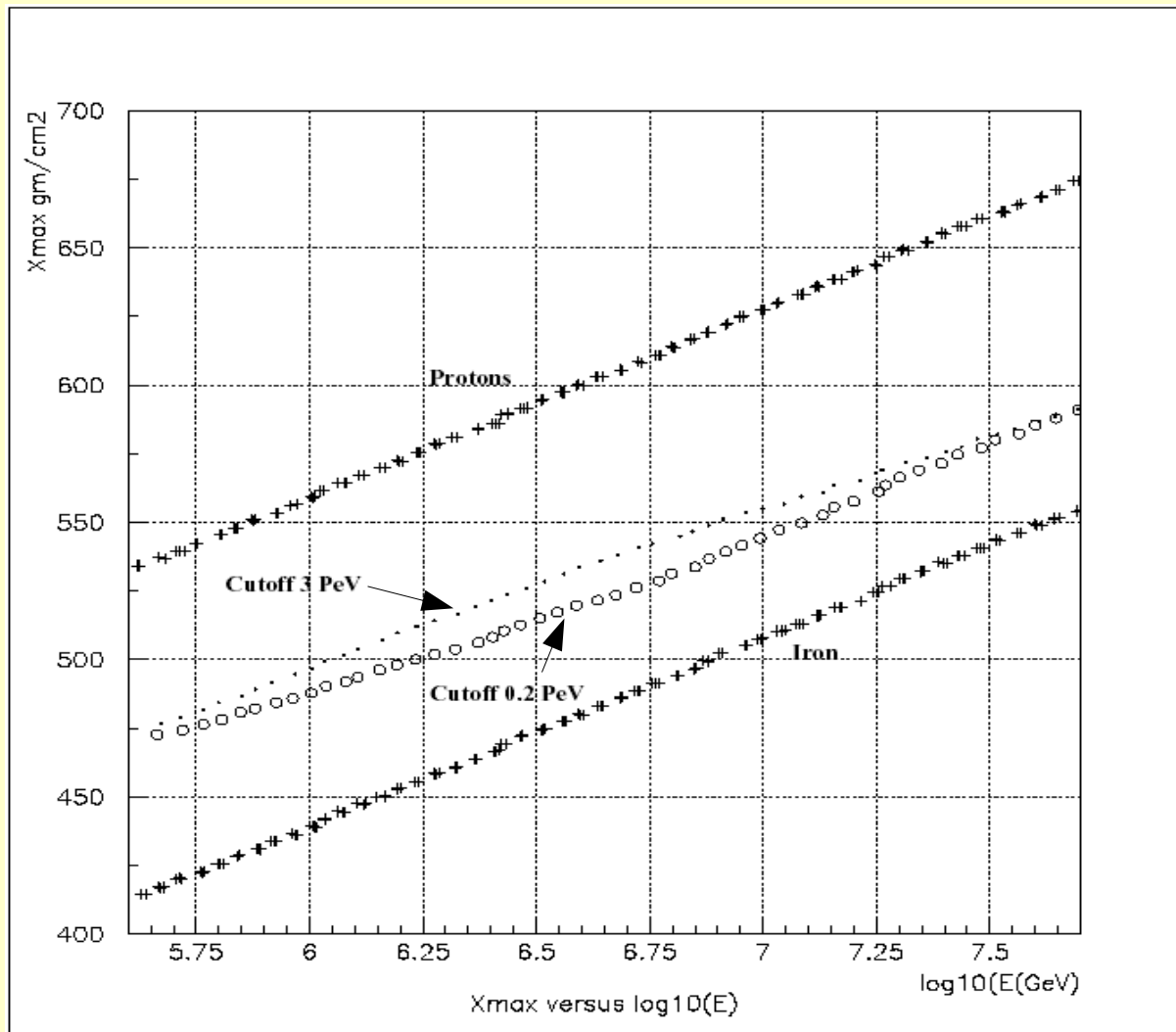
Note: ER is constant if $\langle \ln A \rangle = \text{constant}$

X_{\max} should **generally** increase with energy unless $\langle \ln A \rangle$ increases faster than increase of $\ln E$.

This is shown in the next graph for two scenarios:

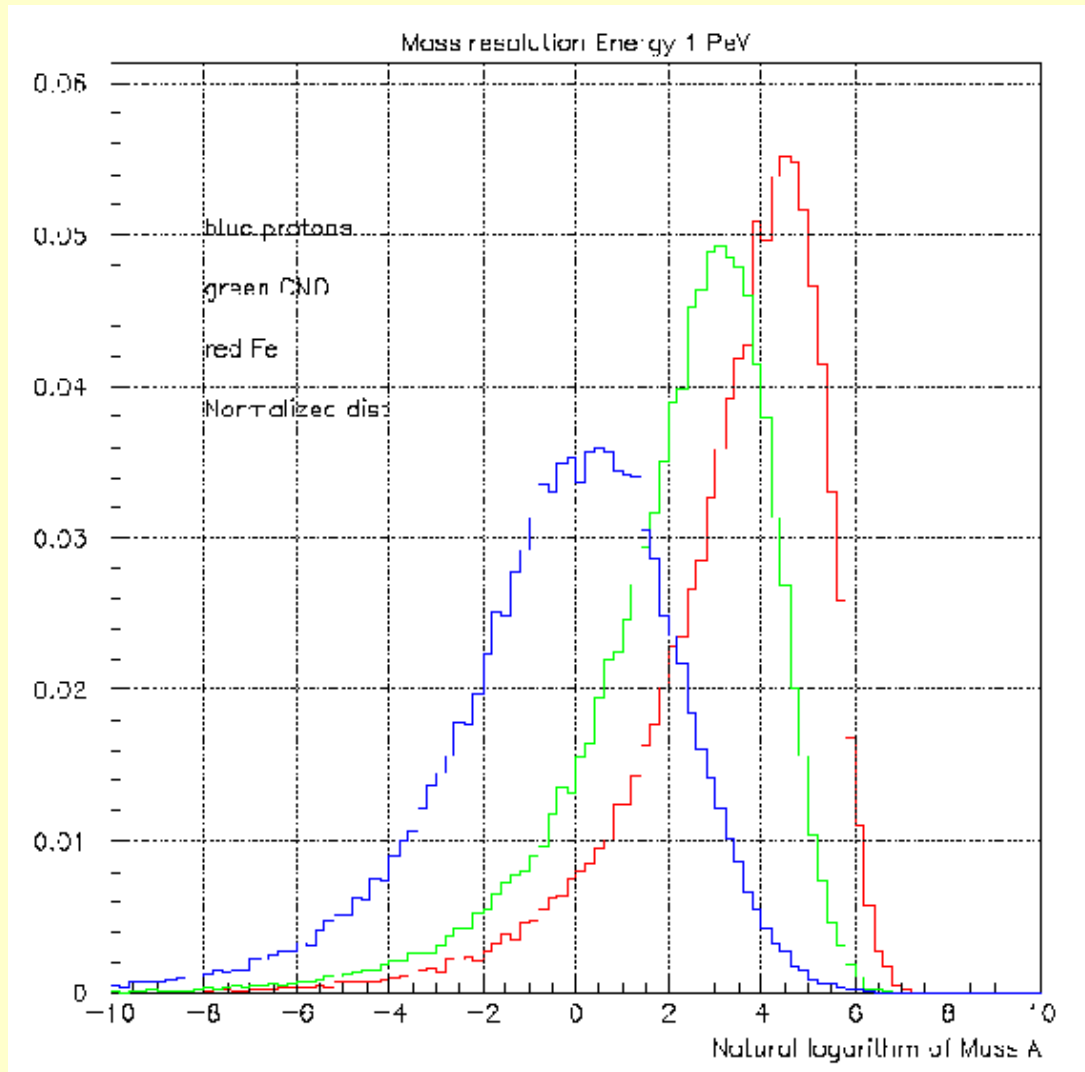
(a) Rigidity cutoff at 0.2 PeV and

(b) Rigidity cutoff at 3 PeV.



The difference in X_{max} in the cutoff region between the two quite different models is at best 30 gm/cm^2 . The elongation rate, however can be an indication of changing composition. **Zero elongation rate implies a decrease of $\langle \ln A \rangle$ faster than $\langle \ln E \rangle$.**

Mass resolution of Xmax experiments:



Assume 20% energy resolution, superposition model, xmax determination : 50 gm/cm² for P ,
20 gm/cm² for iron.

IV. Results from Current Air shower Experiments for Energy Spectra and Composition.

Air shower experiments in the Knee region:

(a) **Cherenkov based:** DICE, BLANCA, HEGRA, CACTI, TUNKA

These use air shower array to provide shower core and shower size

(b) **Air shower based:**

Pioneering Experiments: Chacaltaya, MSU, Tien Shan, KGF,
Delayed Hadrons ...

Current Experiments: Tibet, KASKADE, SPASE-AMANDA

IV (a) Cherenkov / Airshower Measurements:

CACTI: Cygnus array and six Cherenkov Detectors

S. Paling, M. Hillas and CYGNUS collaboration: Nuclear Physics B.(Proc. Suppl) 122,(2203) 239-242.

DICE : CASA-MIA and Two Cherenkov Imaging telescopes

Swordy and Kieda: Astroparticle physics13,(2000) 137.

BLANCA: CASA-MIA and 144 Cherenkov detecting PMTS

Fowler J, et al ; Astroparticle Physics 15(2001)49

In these experiments X_{\max} is either obtained directly from the shower profile or by studying fluctuations in lateral distribution of Cherenkov light. Energy is estimated either by shower sizes or by total Cherenkov light collection.

CACTI -CYGNUS

Cherenkov lat distributions (Paling, Hillas)

Shower size and core from CYGNUS

Energy range $1 = 10$ PeV

Mass Resolution

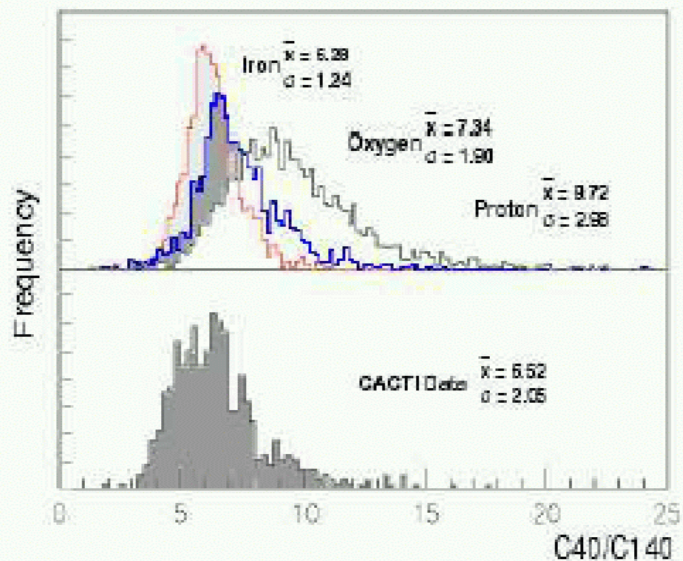
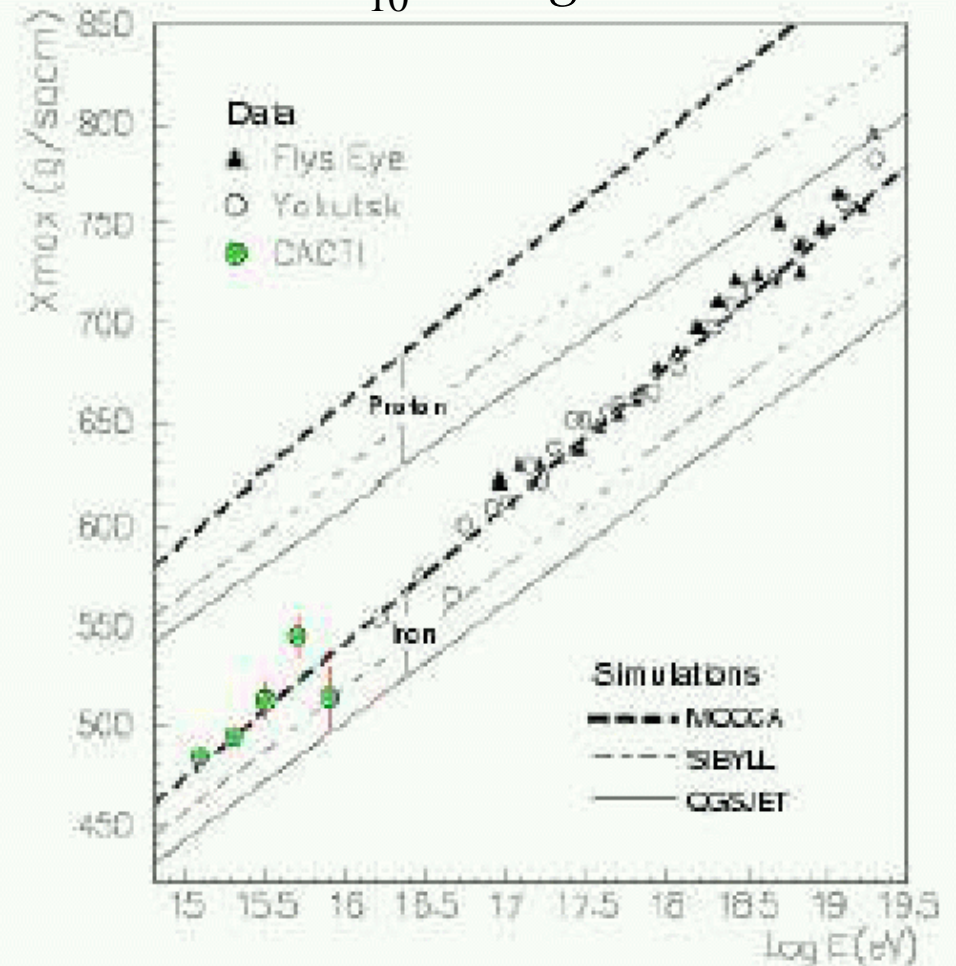


Fig. 4. Comparison of Data and simulations for the C40/C140 ratio distributions.

ER $D_{10} \sim 75 \text{ gm/cm}^2$



Xmax from all Cherenkov Experiments:

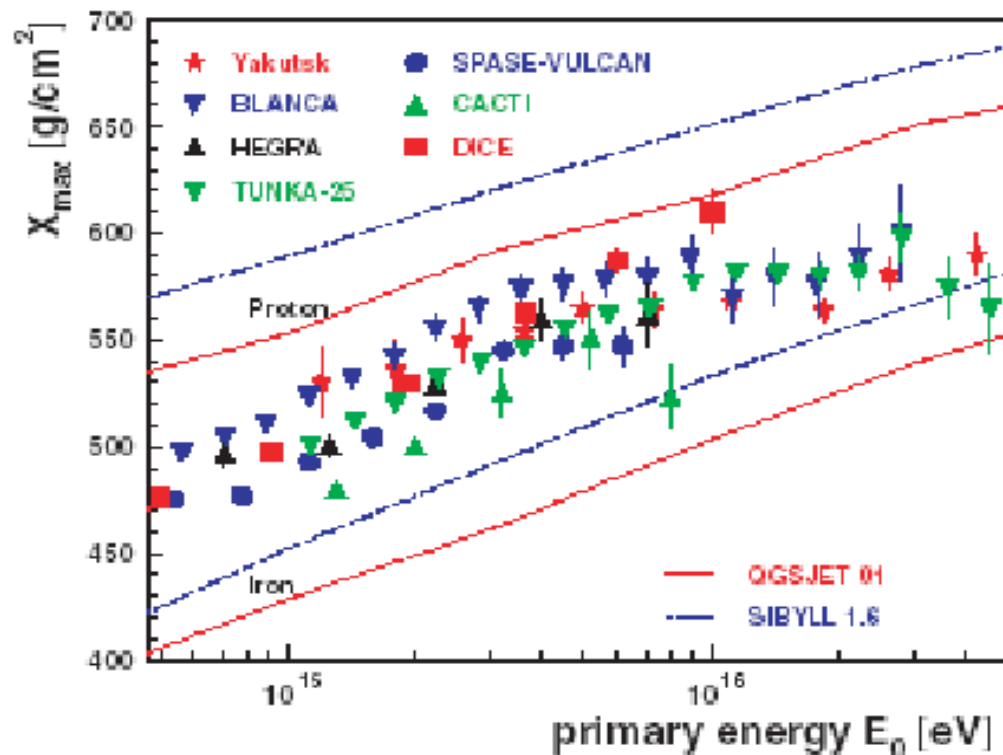


Figure 30. Compilation of different experimental results on the estimation of the shower maximum by measuring the air Cherenkov light (Yakutsk [159], BLANCA [22], HEGRA [24], TUNKA-25 [140], SPASE [48], CACTI [141], DICE [142]). Predictions by MC simulations [15] for two different models are also shown.

CACTI agrees with HEGRA AIROBIC and these two have lower Xmax with respect to DICE and BLANCA measurements below 10 PeV.

Note TUNKA has a constant Xmax above 10^{16} eV .

The spread in $\langle X_{max} \rangle$ from these different experiments is much larger than estimates of systematic errors in these experiments. Systematic errors on $\langle X_{max} \rangle$ are of estimated to be of the order of few 10s of g/cm^2 , while spread from experiment to experiment is about $50 \text{ g}/\text{cm}^2$!

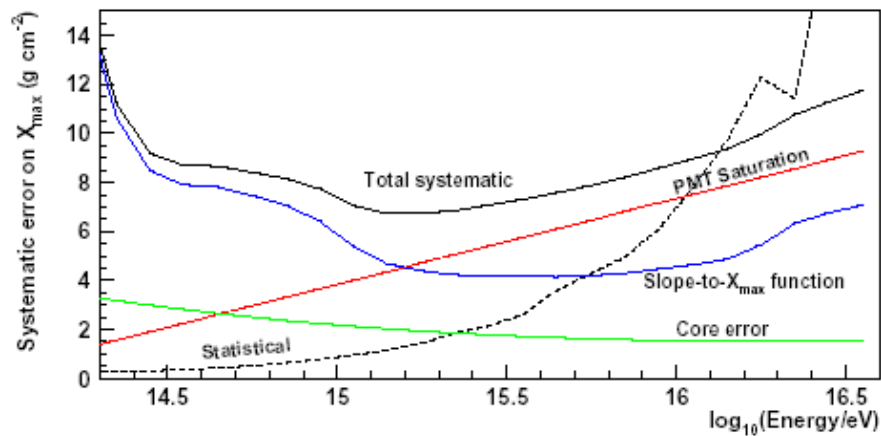


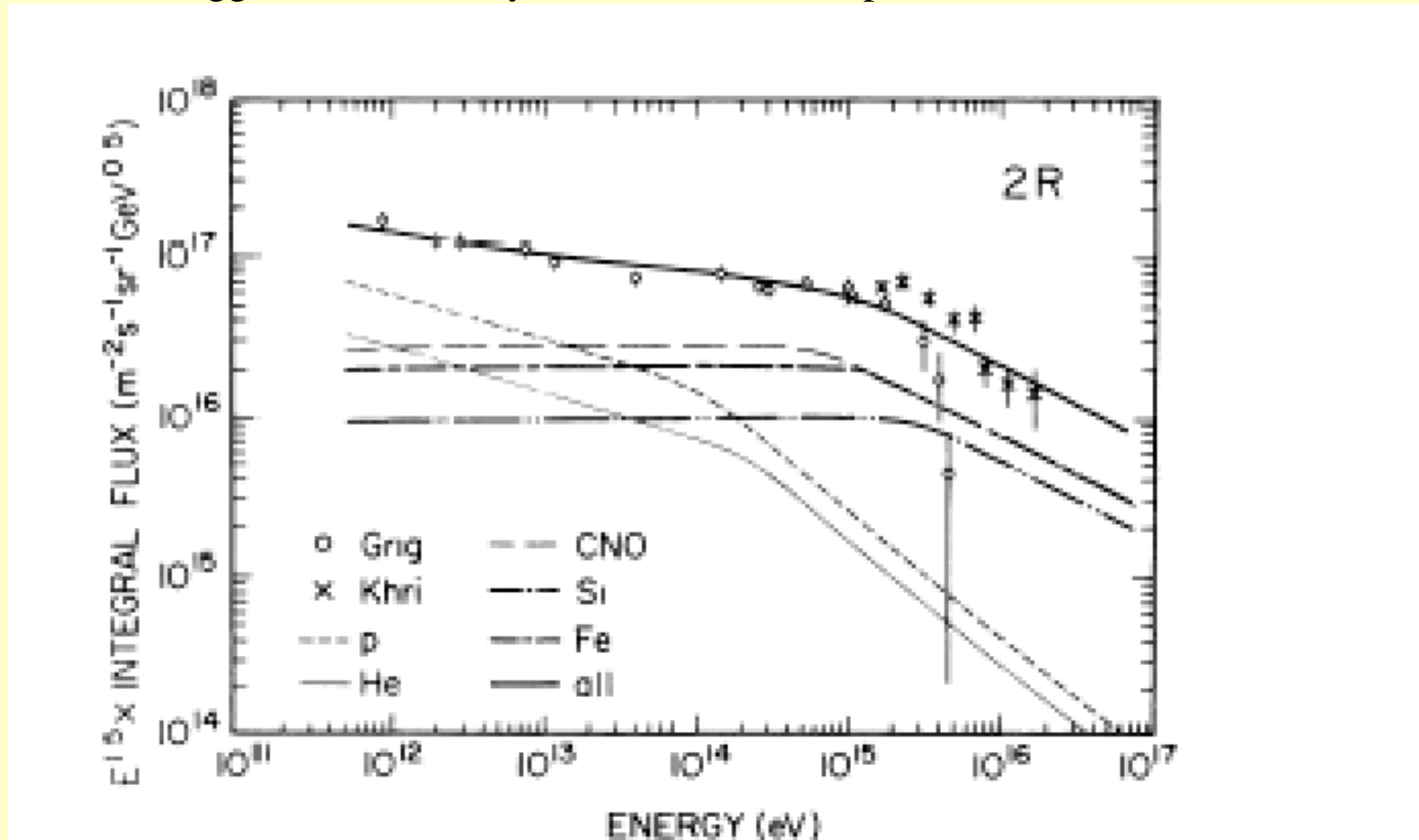
Fig. 6. Systematic uncertainties on CASA-BLANCA X_{max} estimates. At low energies, the dominant error comes from the slope-to- X_{max} conversion function; at high energies, the uncertain photomultiplier linearity is more important. For comparison, the statistical error on the CASA-BLANCA mean X_{max} measurements is also shown (dashed line), assuming a bin width of 0.1 decades.

BLANCA paper

(b) Air Shower Experiments:

Delayed hadrons experiment (Freudenreich et al Phys. Rev. D41,2732,1990)

Measure trigger rate and delayed fraction and compared with simulations.



A rigidity cutoff model which fits Md delayed hadron experiment, compared with Grigorov's all particle spectrum. MSU spectrum also shown.

This model represents one of the cases of Horandel's polygonato model.

A list of Air Shower experiments:

Experiment	site		g/cm ²	e	μ	h	✓ C
AKENO	Japan (35.5N, 138.5E)		930	○	1 GeV		
BLANCA	Utah (40.2N, 112.8W)		870	○			○
CASA-MIA	Utah (40.2N, 112.8W)		870	○	800 MeV		
DICE			860	○	800 MeV		○
EAS-Top	Italy (42.5N, 13.6E)		820	○	1 GeV		
HEGRA	La Palma (28.8N, 17.9W)		790	○			○
KASCADE (electrons/muons)	Karlsruhe Germany (49.N, 8.E)		1022	○	230 MeV		
KASCADE (hadrons/muons)	Karlsruhe		1022		230 MeV	50 GeV	
KASCADE (neural network)	Moscow		1022	○	230 MeV		
MSU			1020	○			
Mt. Norikura	Japan		735	○			
Tibet	Tibet (30.1N, 90.5E)		606	○			
Tunka-13			680				○
Yakutsk (low energy)	Russia		1020				○

SPASE – AMANDA -VULCAN (Not in the previous list)

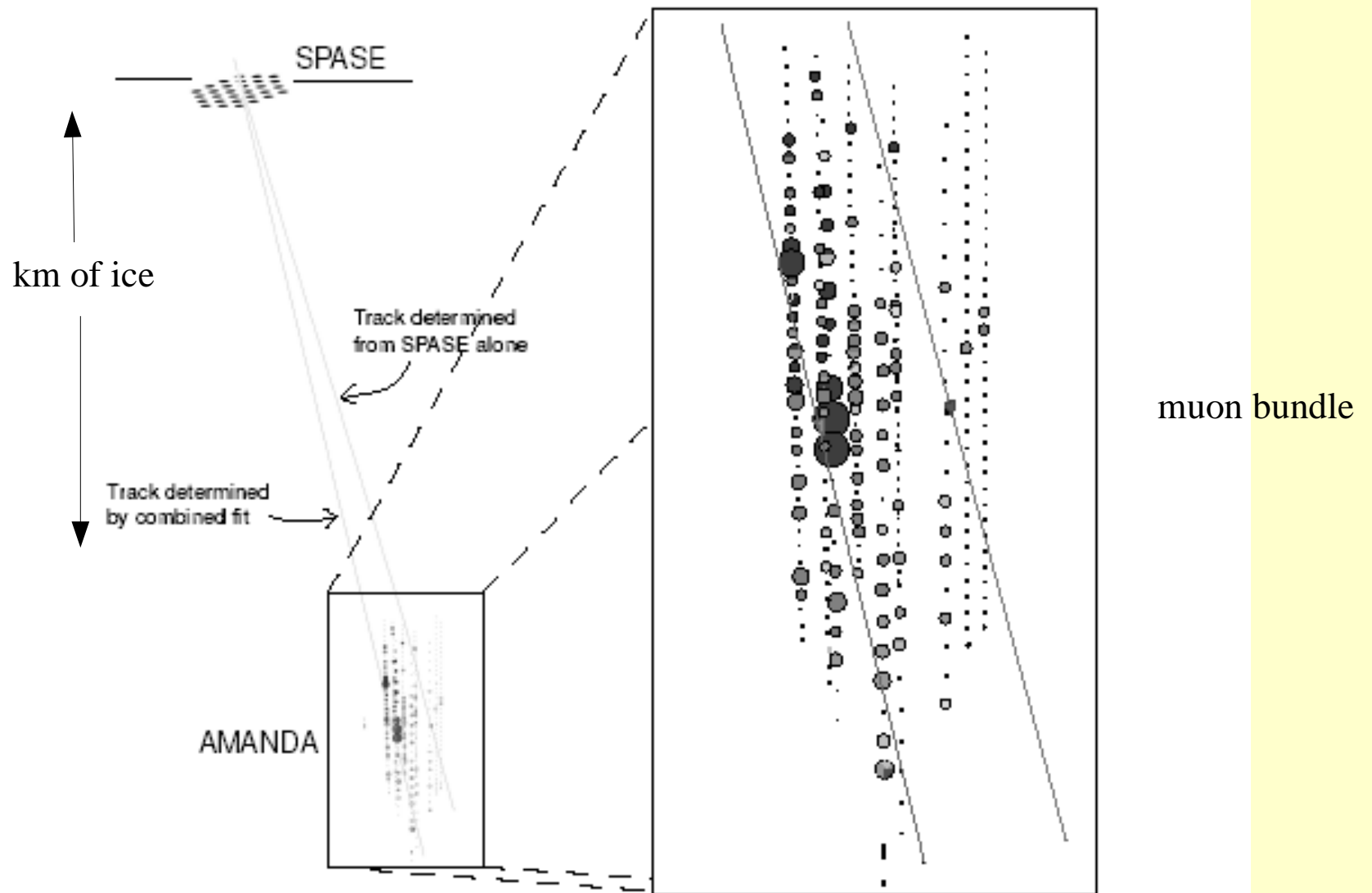


Fig. 1. SPASE/AMANDA coincidence event from 1997 data

KASKADE EXPERIMENT:

Sample shower components at “ sea level”

N_e , N_{μ} (Several energies) and $N_{had>(>E)$

Best Estimator of Energy: N_{μ}^{trunc} and N_e combination

Estimators for A: $\log N_{\mu}^{trunc}$ versus $\log N_e$.

This distribution is analyzed as an inverse problem to determine the energy spectra for individual species.

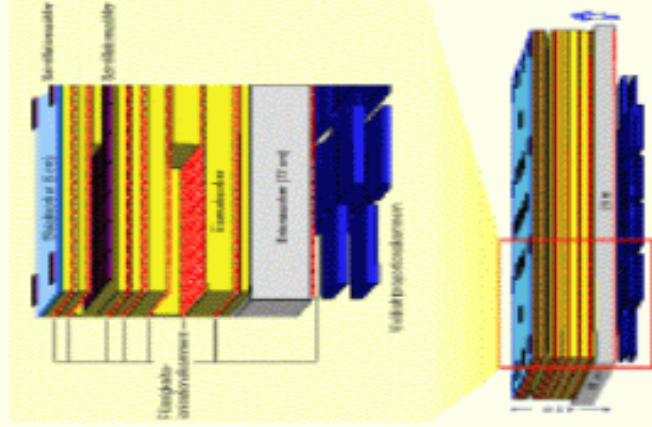
Hadron distributions also used to determine $\ln A$

N_{μ}^{trunc} is relatively insensitive to first interaction fluctuations



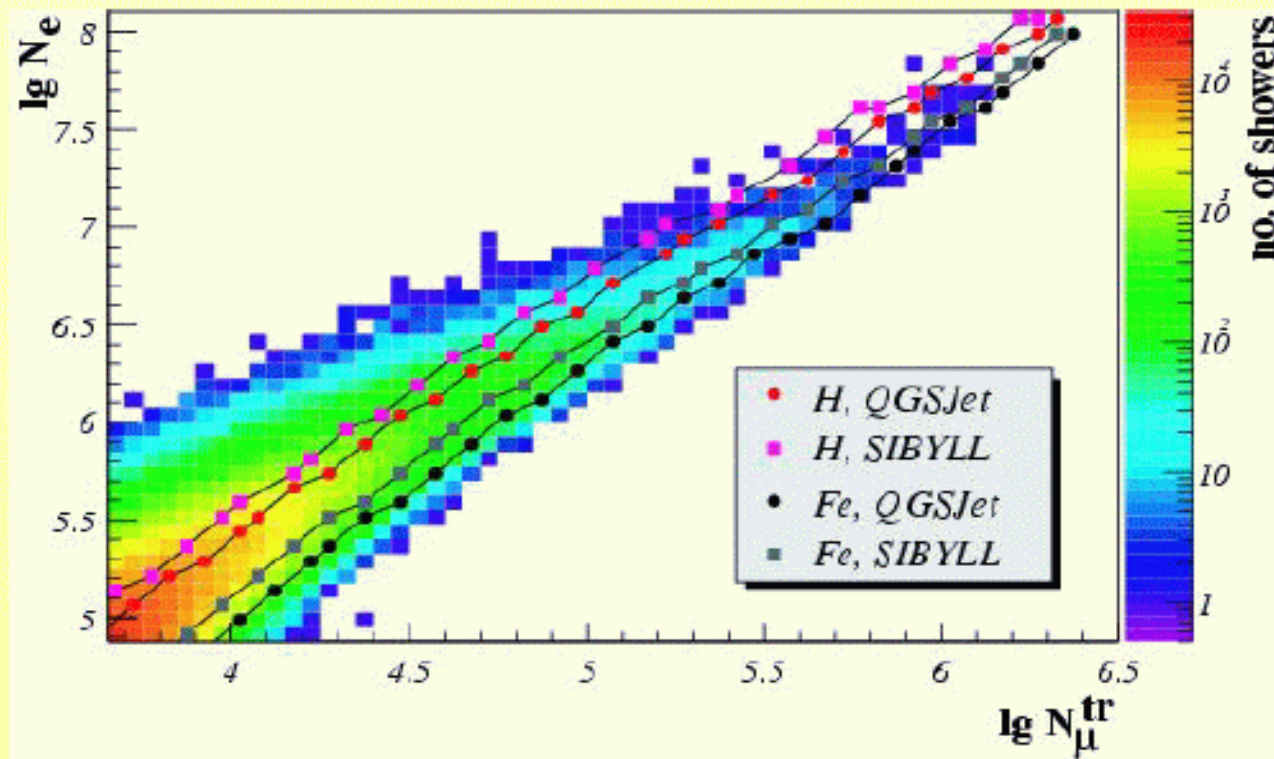
e/μ

Hadron



Energy spectra KASCADE:

Influence of hadronic interaction model

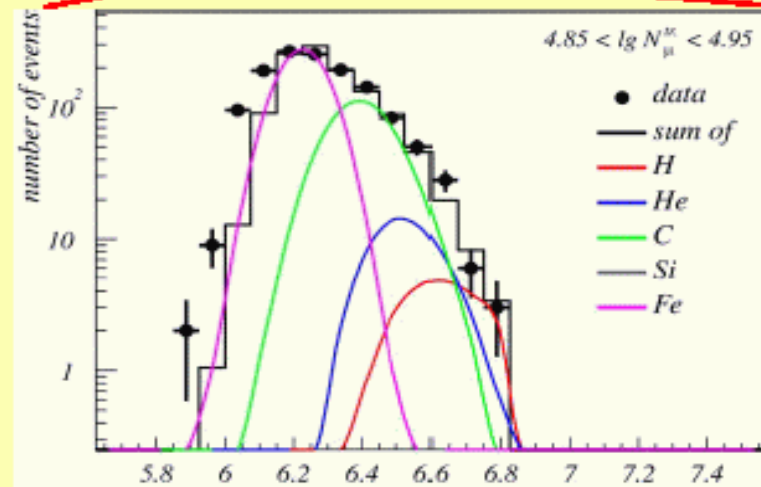
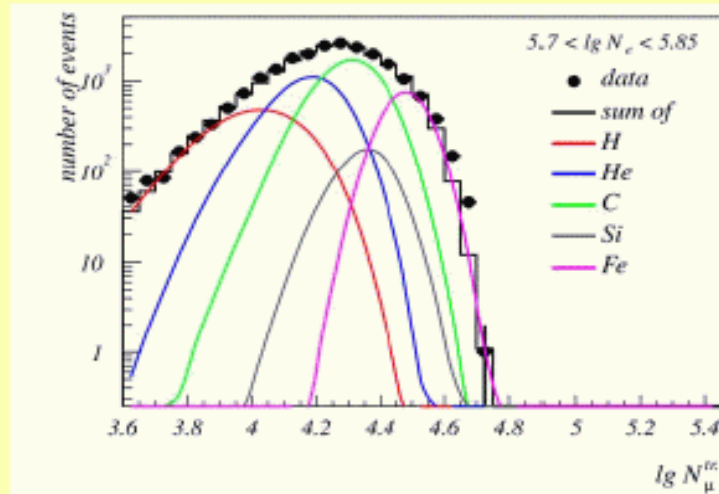
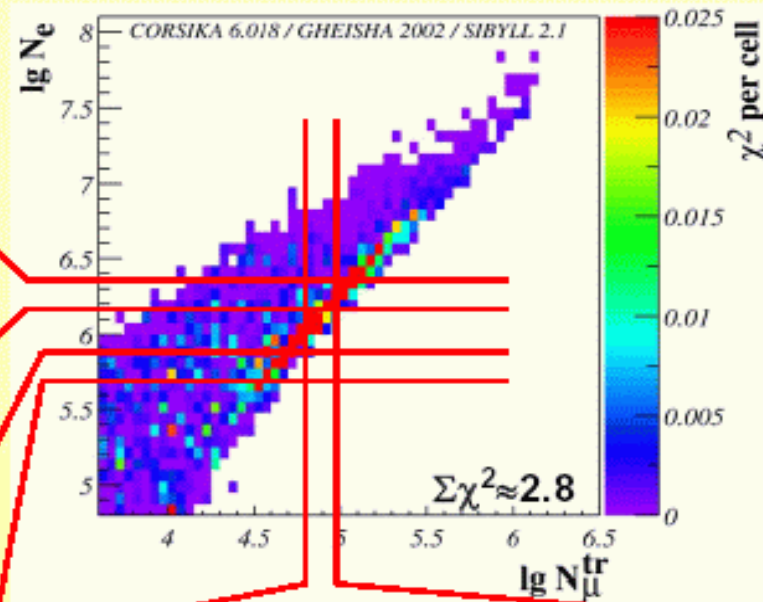
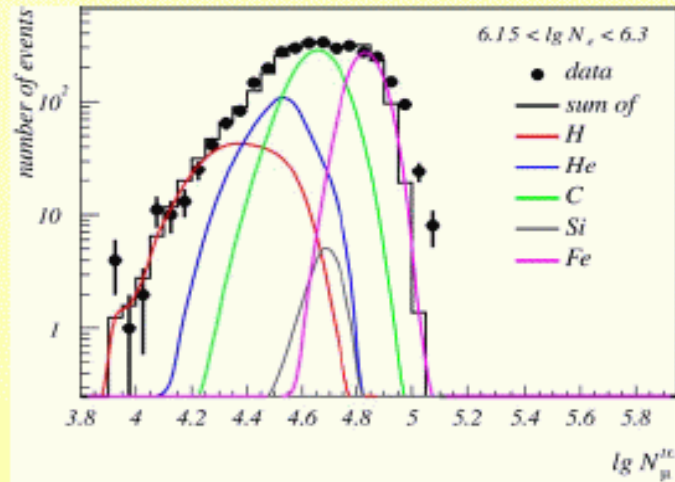


Main results keep stable independent of method or model:

-) knee caused by light primaries
-) positions of knee vary with primary elemental group
-) no (interaction) model can describe the data consistently

Energy spectra KASCADE:

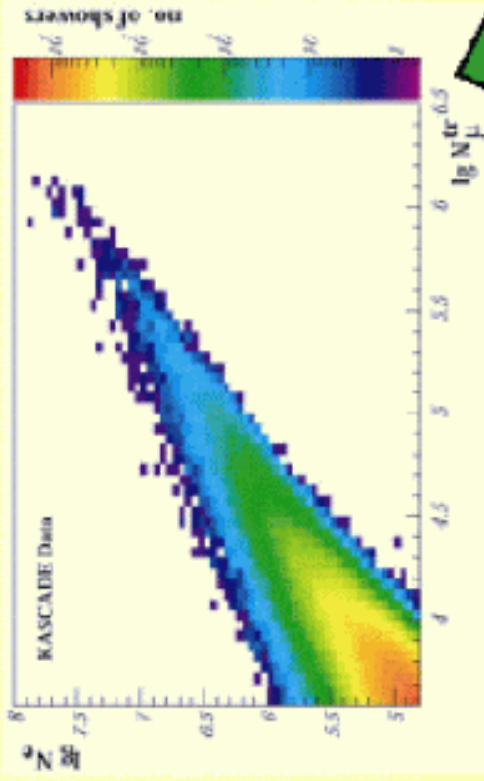
quality of description of data: SIBYLL



Nmu distributions for fixed Ne

Ne distributions for fixed Nmu

Energy spectra KASCADE:



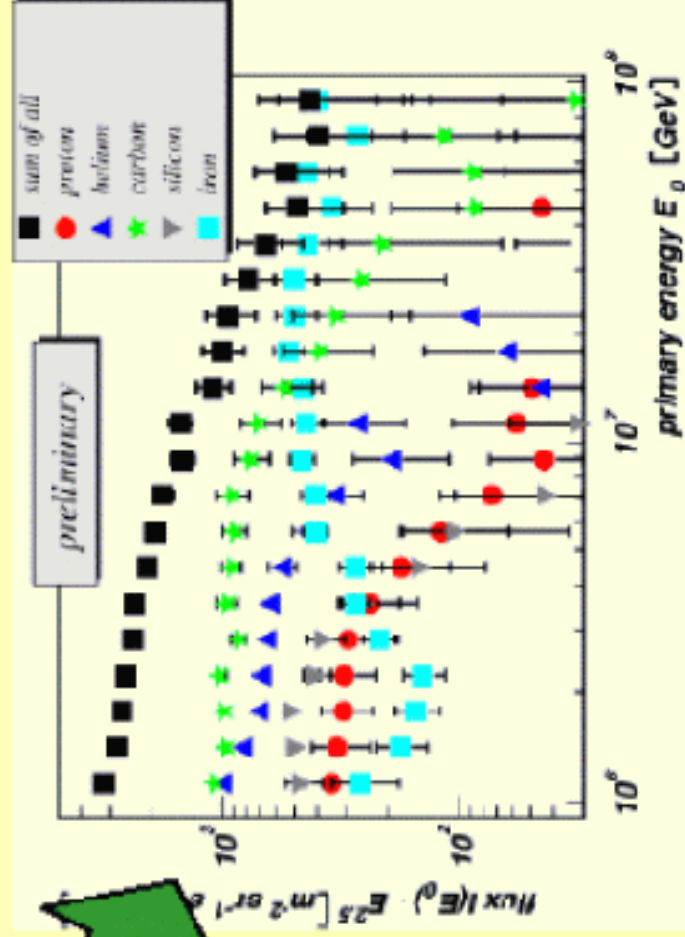
Searched:
E and **A** of the Cosmic Ray Particles

Given:
N_e and **N_μ** for each single event

→ solve the inverse problem

$$g(y) = \int K(y, x) p(x) dx$$

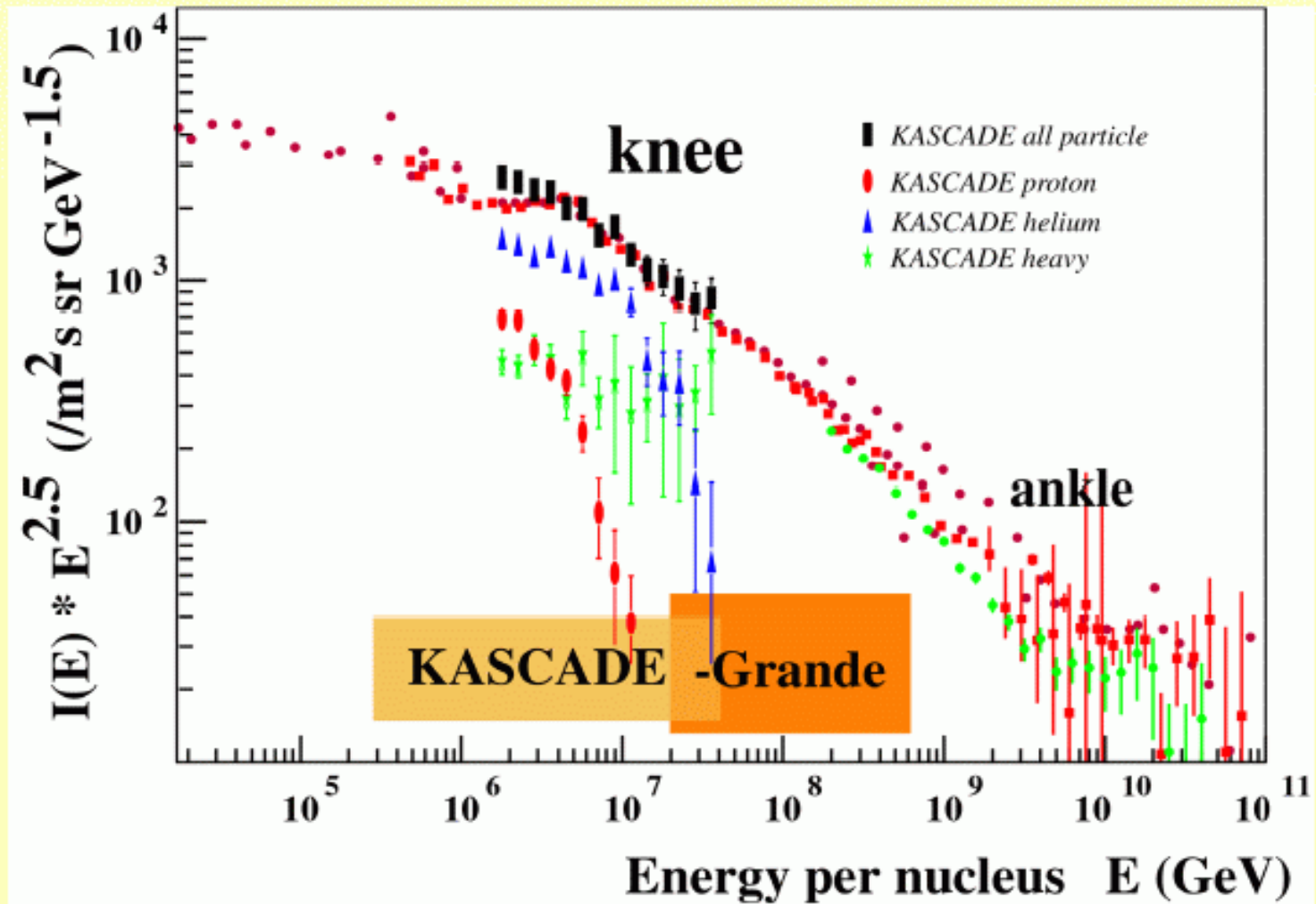
with $y=(N_e, N_\mu^{tr})$ and $x=(E, A)$



Monte Carlo simulations using
CORSIKA
 with **GHEISHA 2002** and
QGSJet2001 / SIBYLL 2.1

H. Ulrich PhD,
 KASCADE: Astrop. Phys., in preparation

Cosmic Rays around the Knee



KASCADE : “ Proof “ of rigidity cut off. P and He spectra

142 —

KASCADE Ne vs. N_{μ}

HE 1.1-18 Markus Roth and H. Ulrich

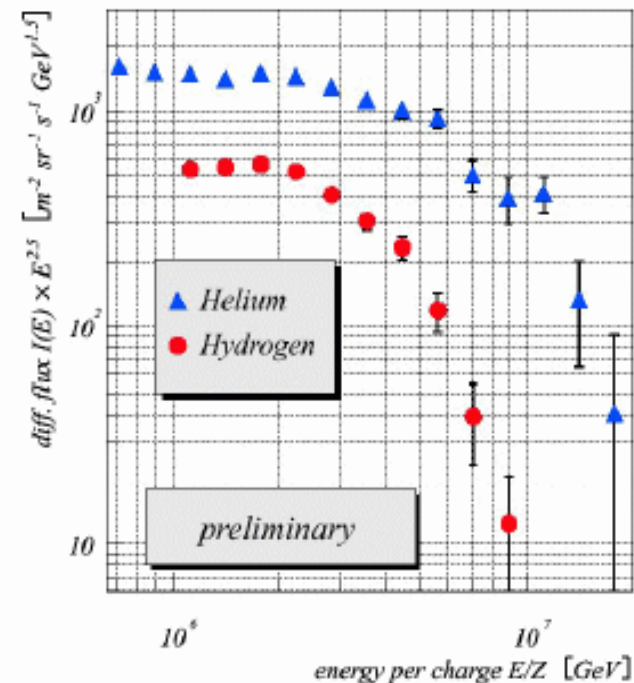
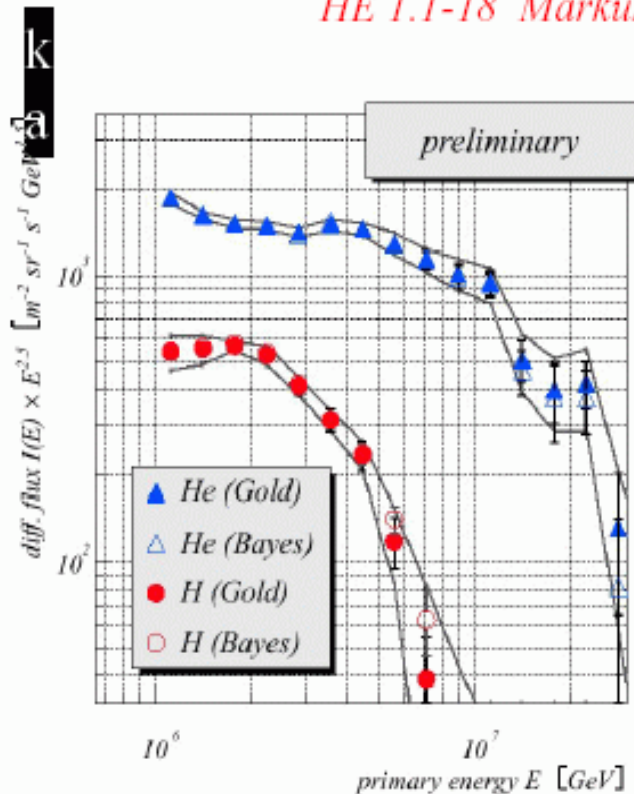


Fig. 3. Comparison of the deconvoluted H and He spectra using Bayesian [2] and Gold [3] unfolding. The solid lines mark the systematic uncertainty of the Gold algorithm.

Fig. 4. Individual spectra as a function of the rigidity $R \propto E/Z$. The knee positions of the H and He spectra are nearly at the same position.

KASCADE Proton Spectrum (UH)

Strong model dependence & systematic errors under study!

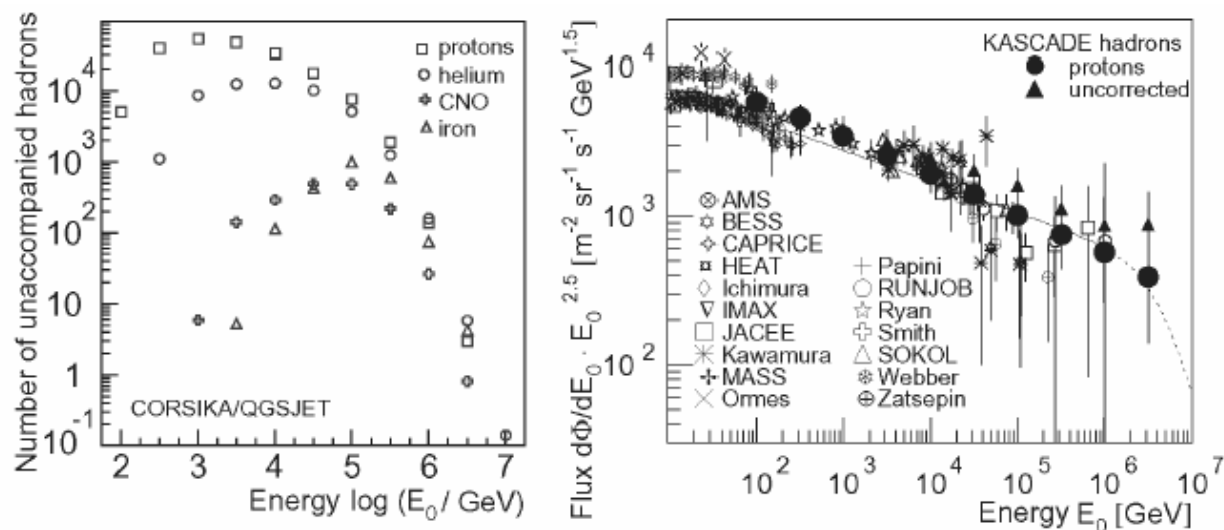
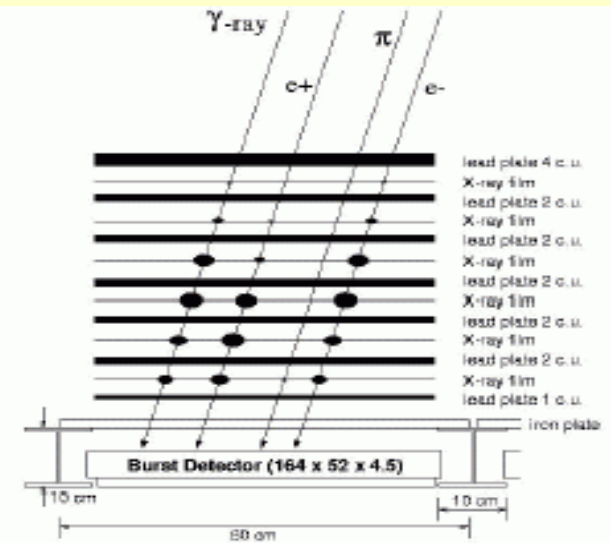
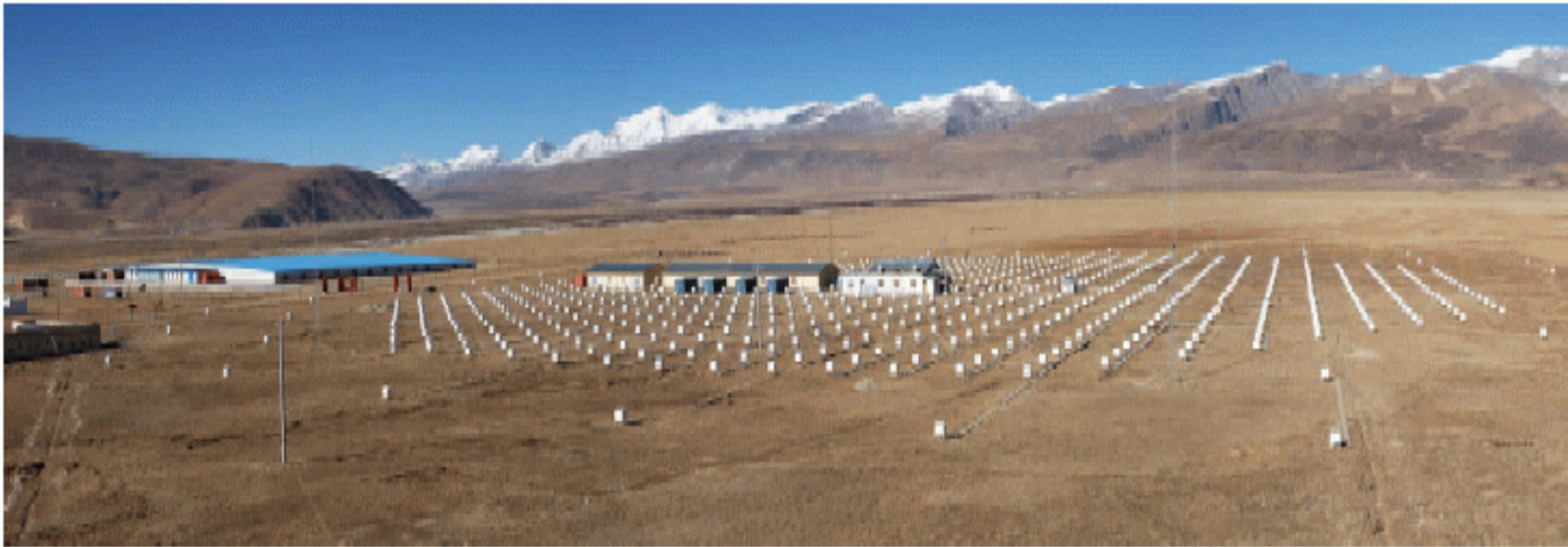


Fig. 3. Left: Number of unaccompanied hadrons versus primary energy for different elemental groups. Right: Primary proton flux reconstructed from unaccompanied hadrons compared to results of direct measurements, for references see [6]. The line represents a fit to the measurements [6].

S

Proton spectrum derived from unaccompanied hadrons at KASCADE. Values agree with direct measurements. Statistics insufficient to establish the proton knee.

TIBET YANBAJING AIR SHOWER EXPERIMENT



TIBET Experiment: Derived proton spectrum

From simulation analysis of high energy hadrons in showers.

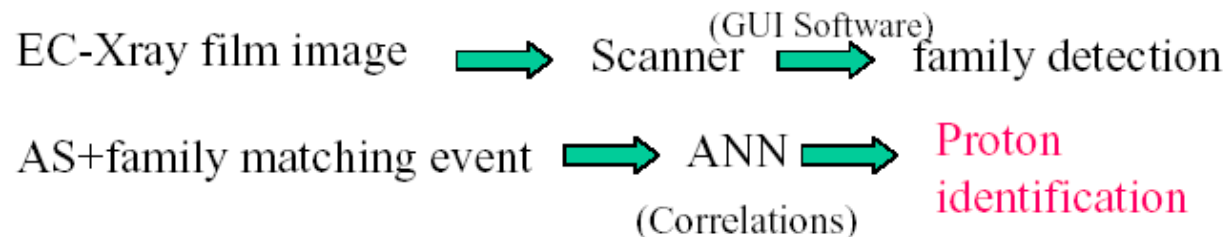
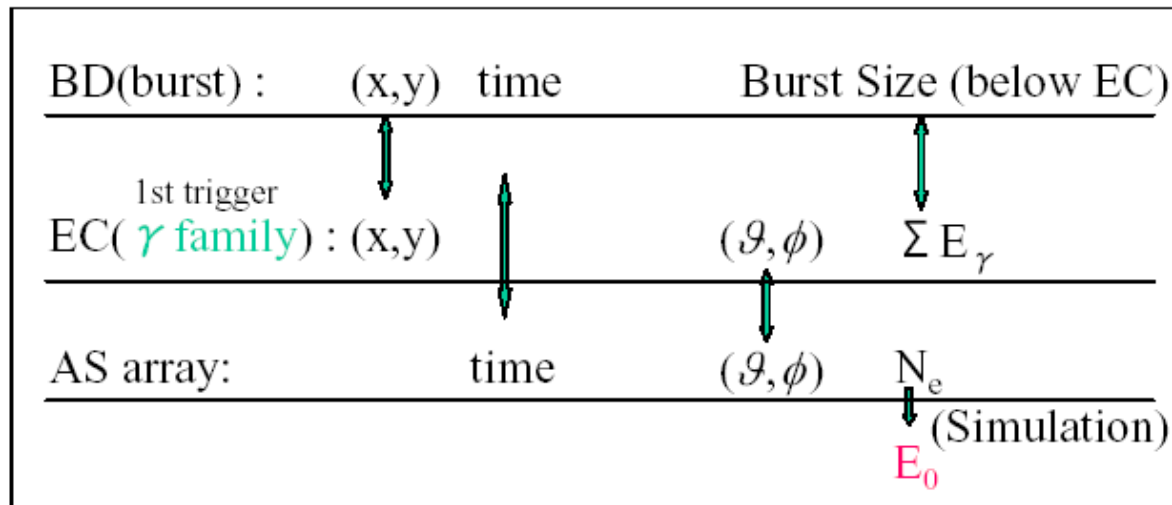
AS was triggered by 100 Burst detectors (BD) and gamma family events measured in EC s placed above the Burst detectors. A neural network analysis was made of these events and a target variable was used to identify proton induced showers. Analysis was done for two different assumed composition simulations to pick out proton showers, which showed that the neural net target variable correctly picked out proton showers.

An outline of the procedure is shown in the next slide.

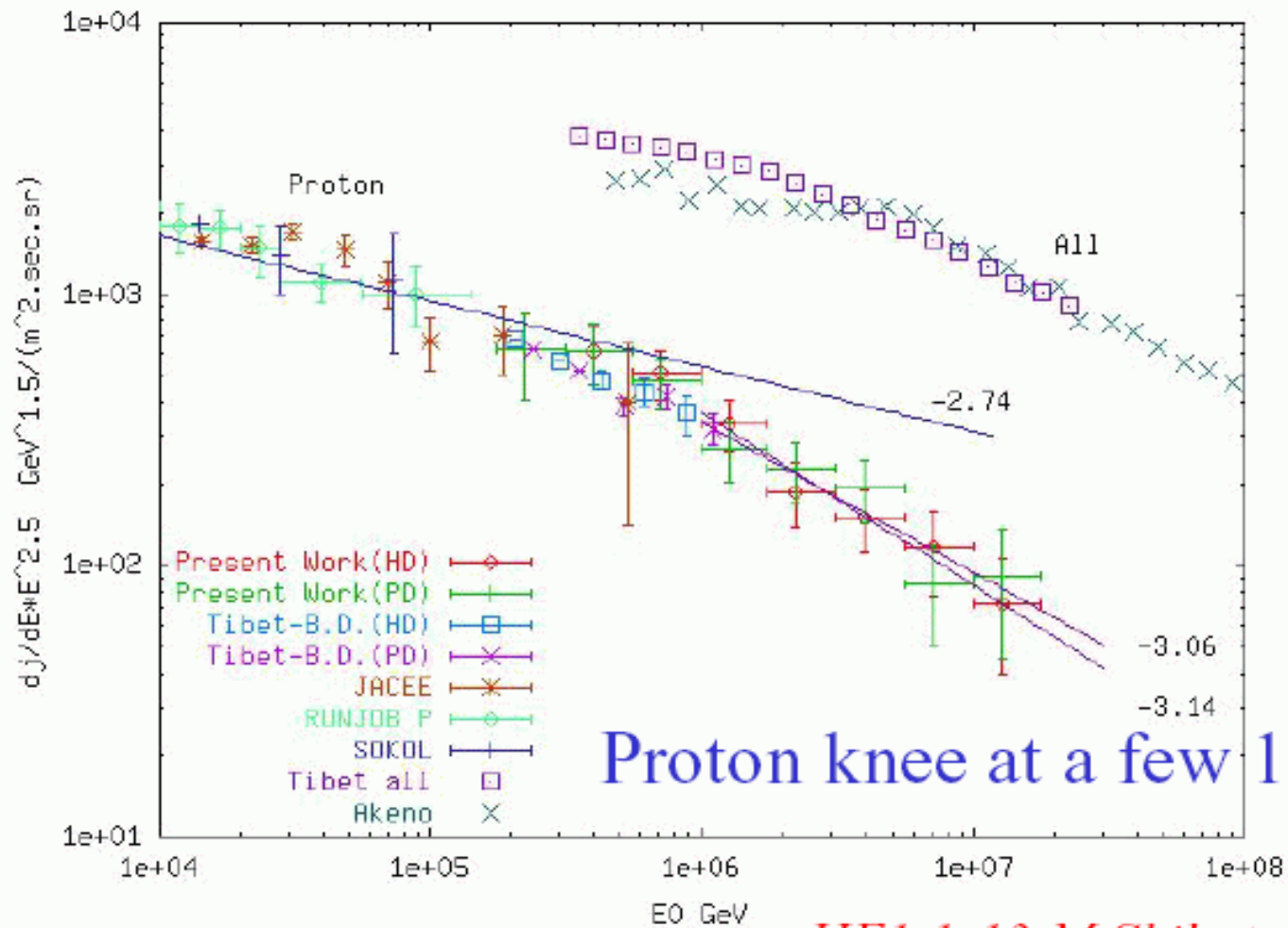
Tibet Proton: *HE1.1-13 M. Shibata* (2003)

How to obtain proton spectrum?

Hybrid system



Tibet Proton spectrum

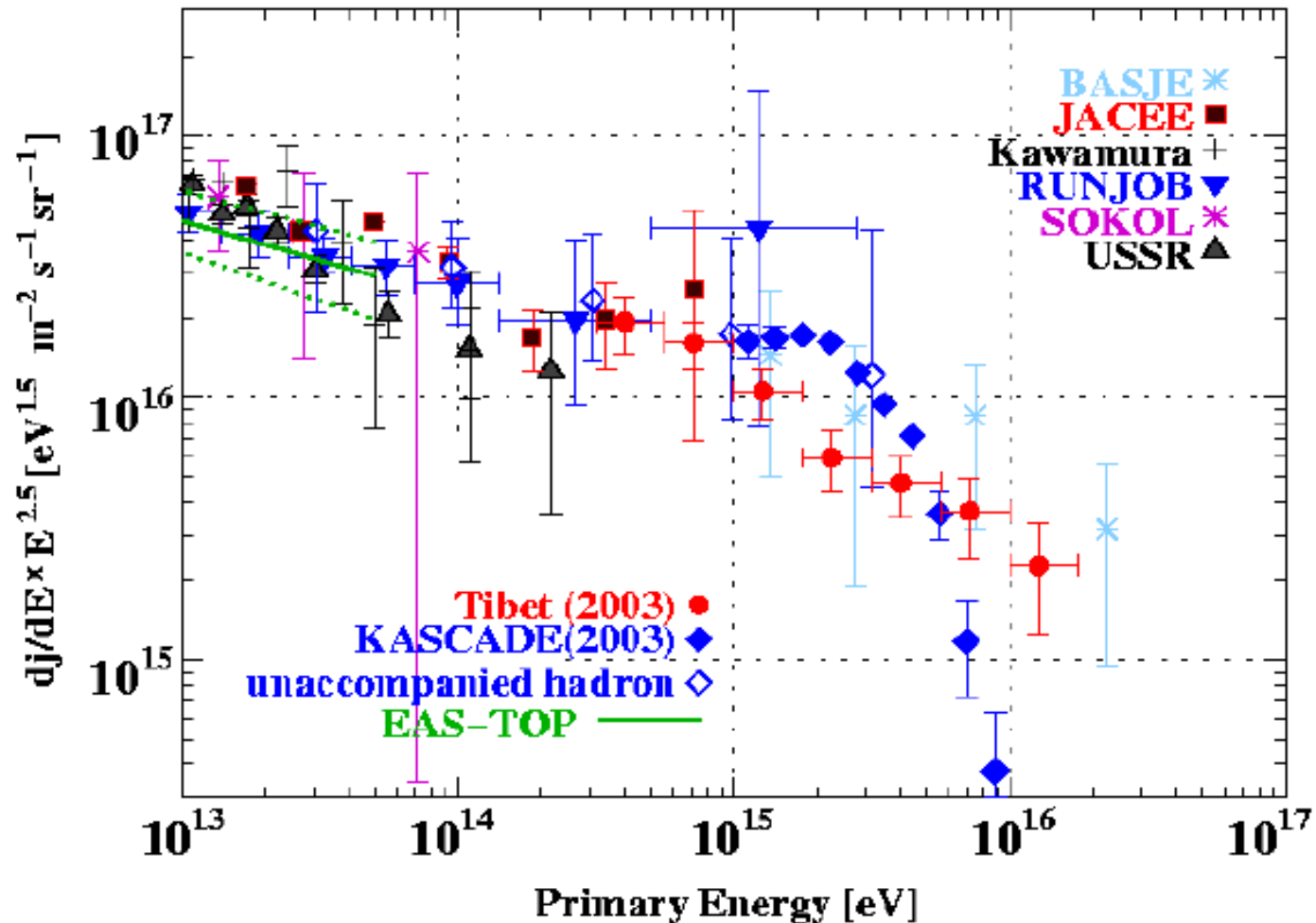


Proton knee at a few 100 TeV

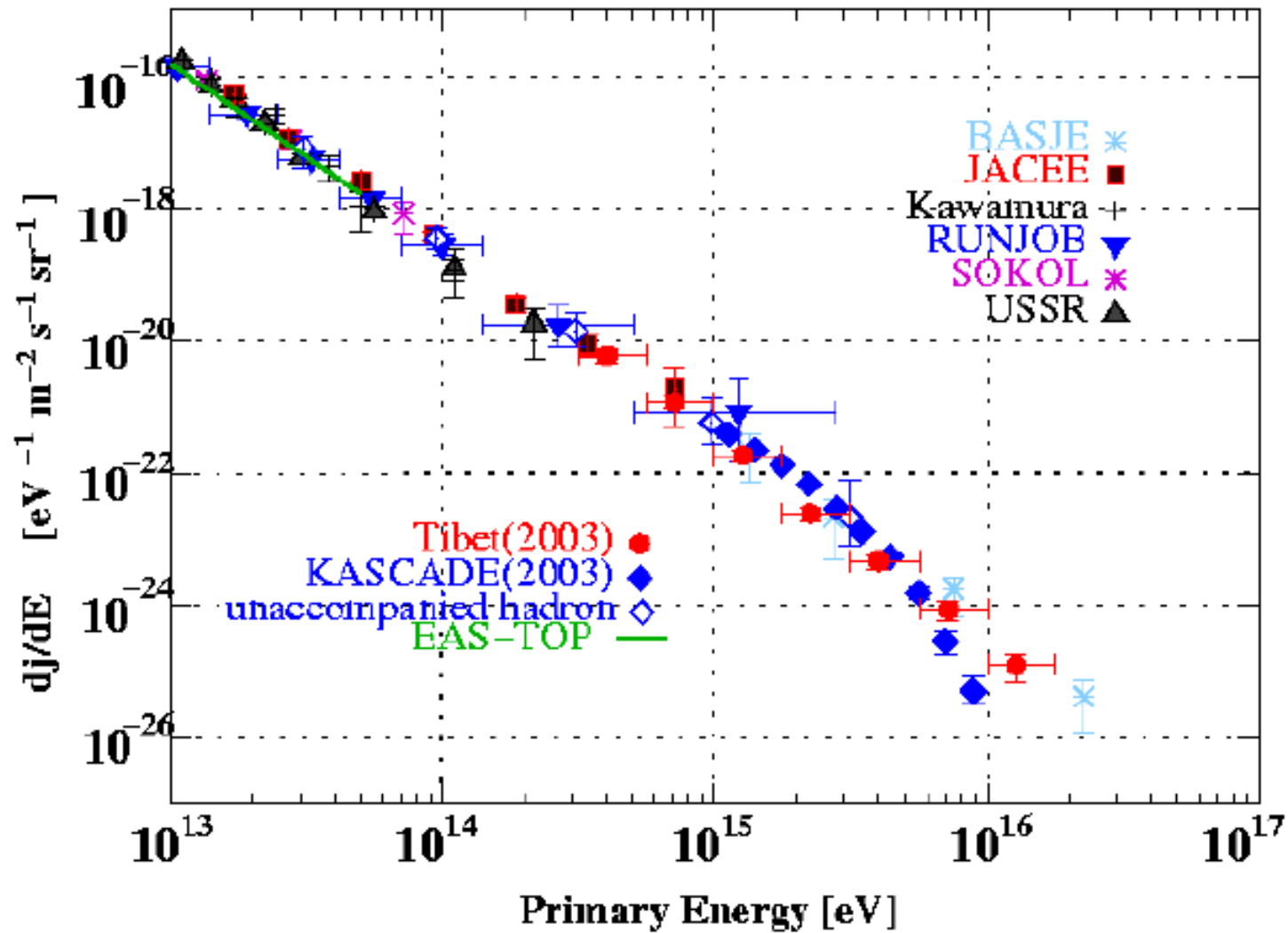
HE1.1-13 M.Shibata (2003)

Comparison of proton spectra derived by Tibet and KASCADE Experiments. Difference exaggerated by multiplication by $E^{2.5}$.

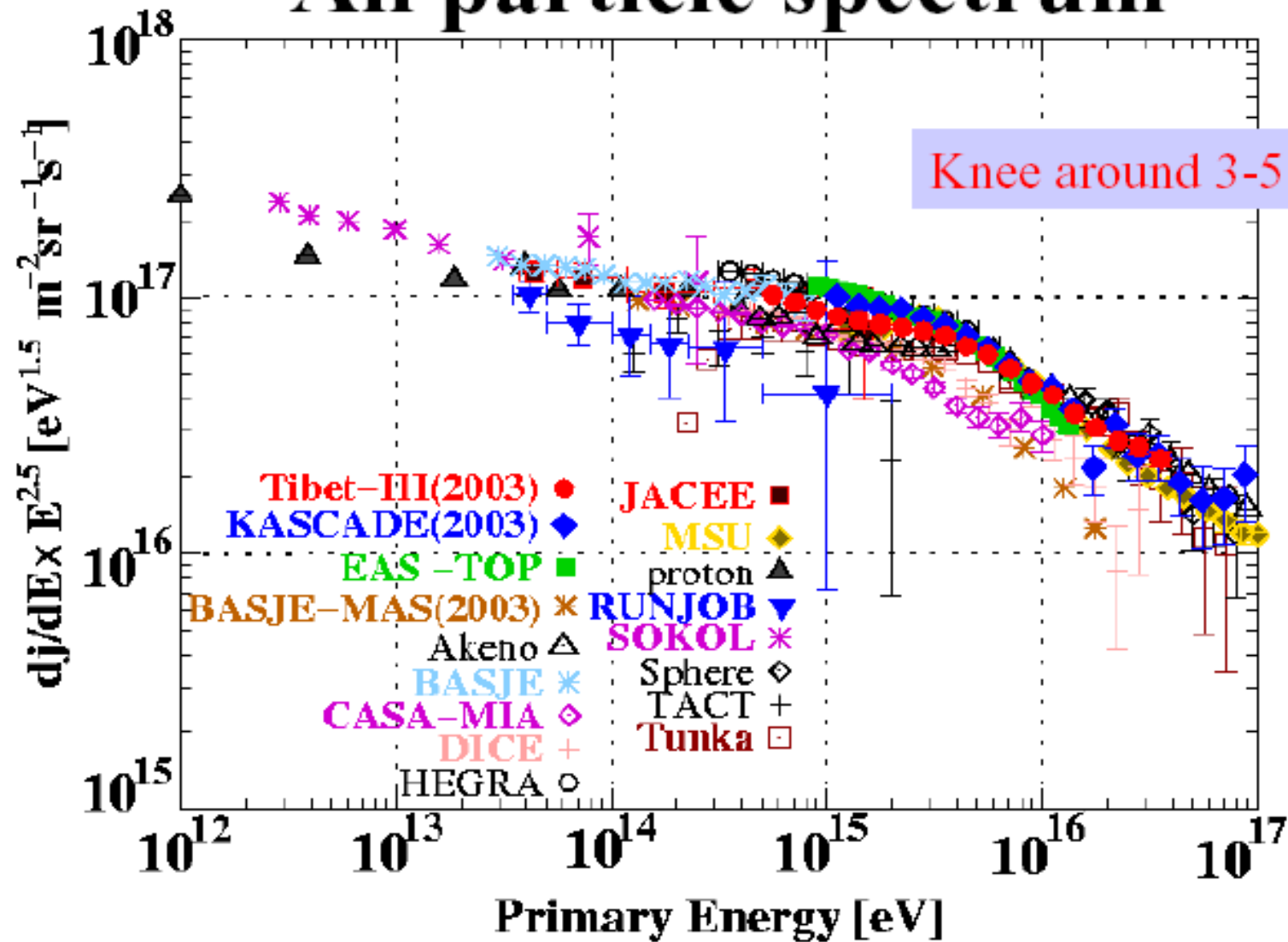
Proton spectrum



Proton spectrum



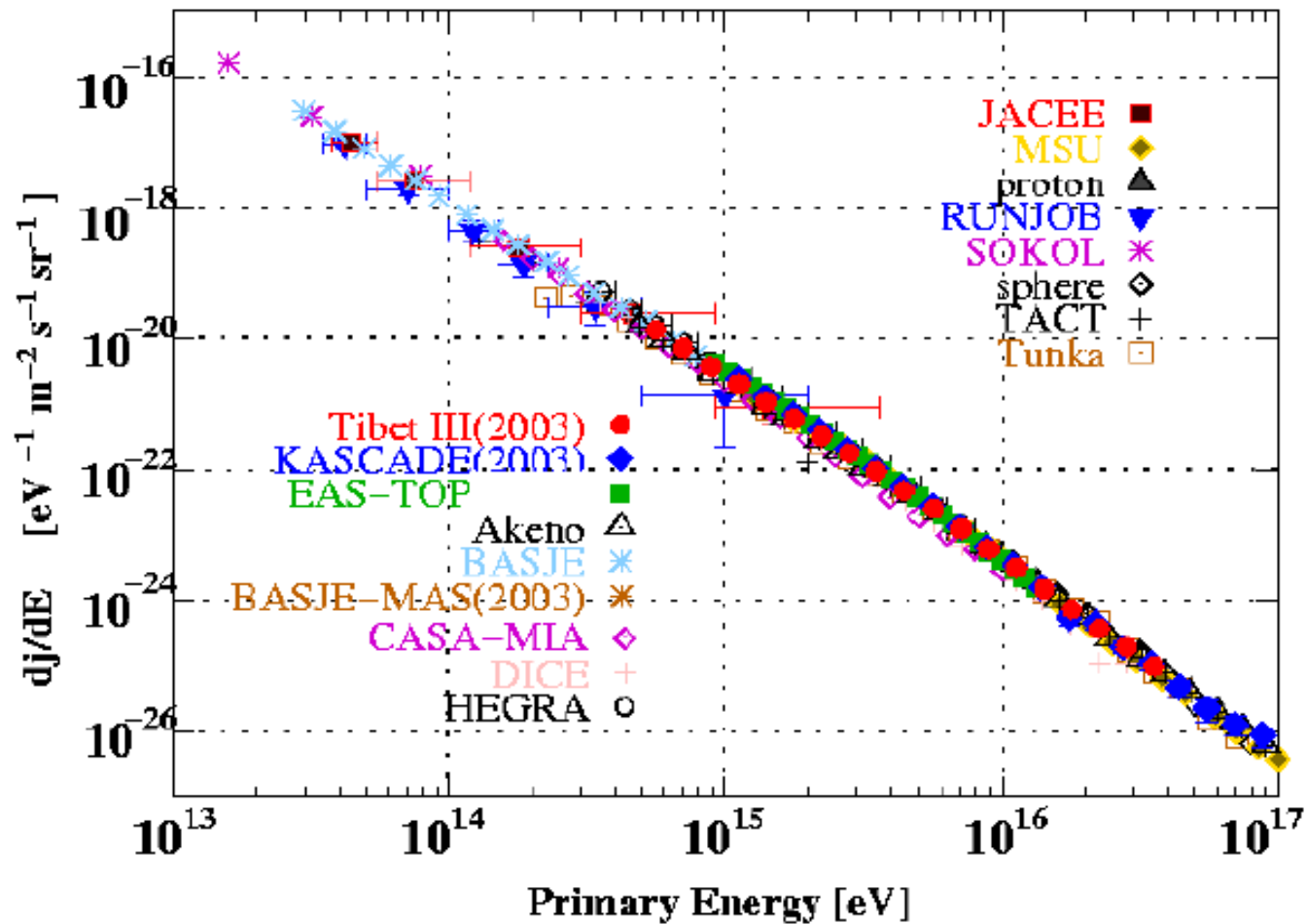
All particle spectrum



Takita (Rapporteur) 2003

Note that indirect experiments use different simulations. At Tibet altitudes the shower maximum is close to observation level, in the knee region.

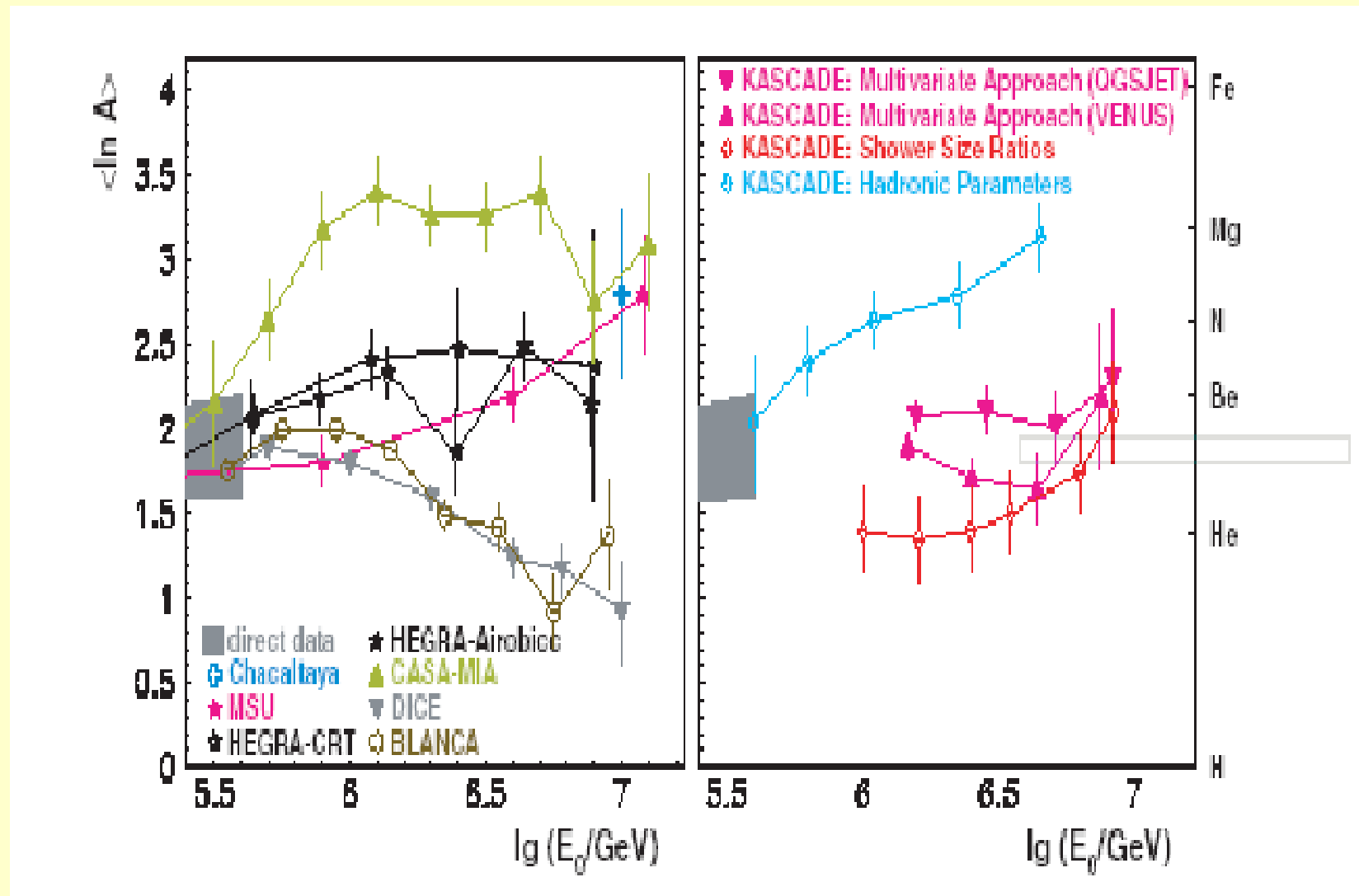
All particle spectrum



By judicious energy shifts all particle spectra can be made consistent .

Takita (Rapporteur) 2003

Average $\ln A$ in the knee region: A partial summary



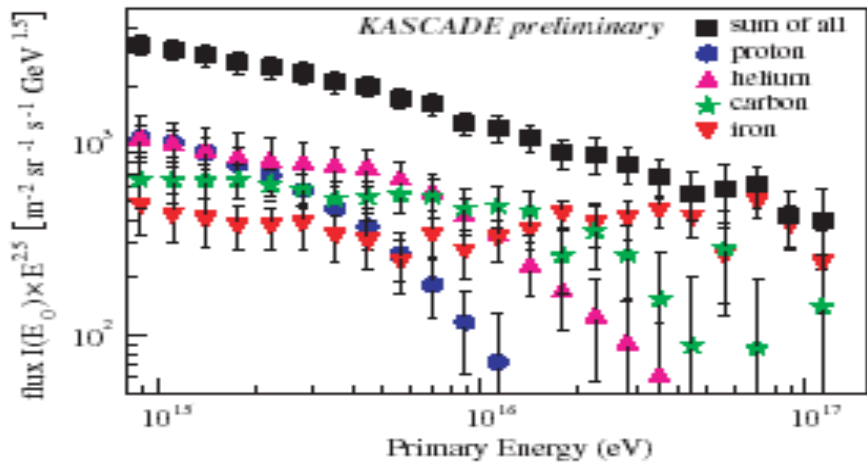


Figure 35. Energy spectra of four primary mass groups as obtained from an unfolding procedure applied to the KASCADE size spectra (from [149]).

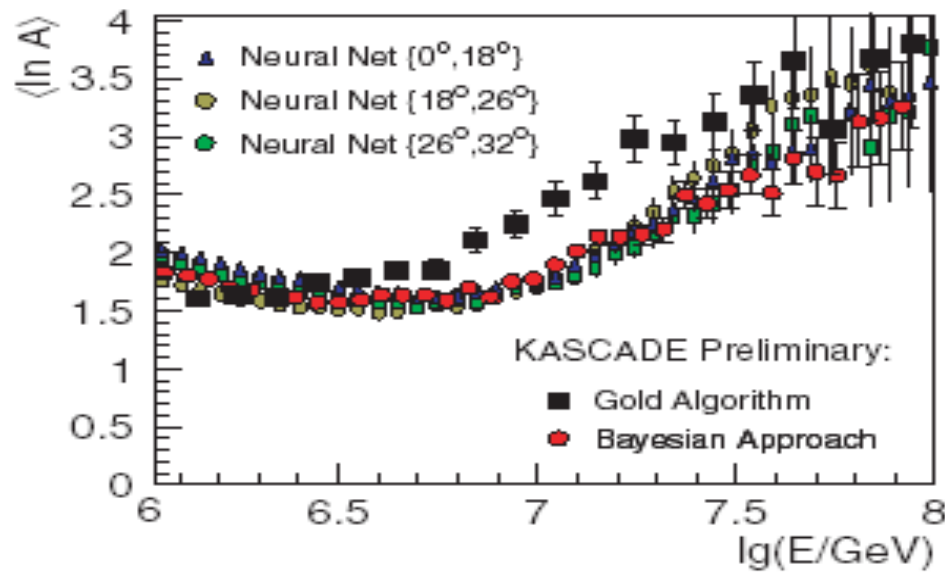
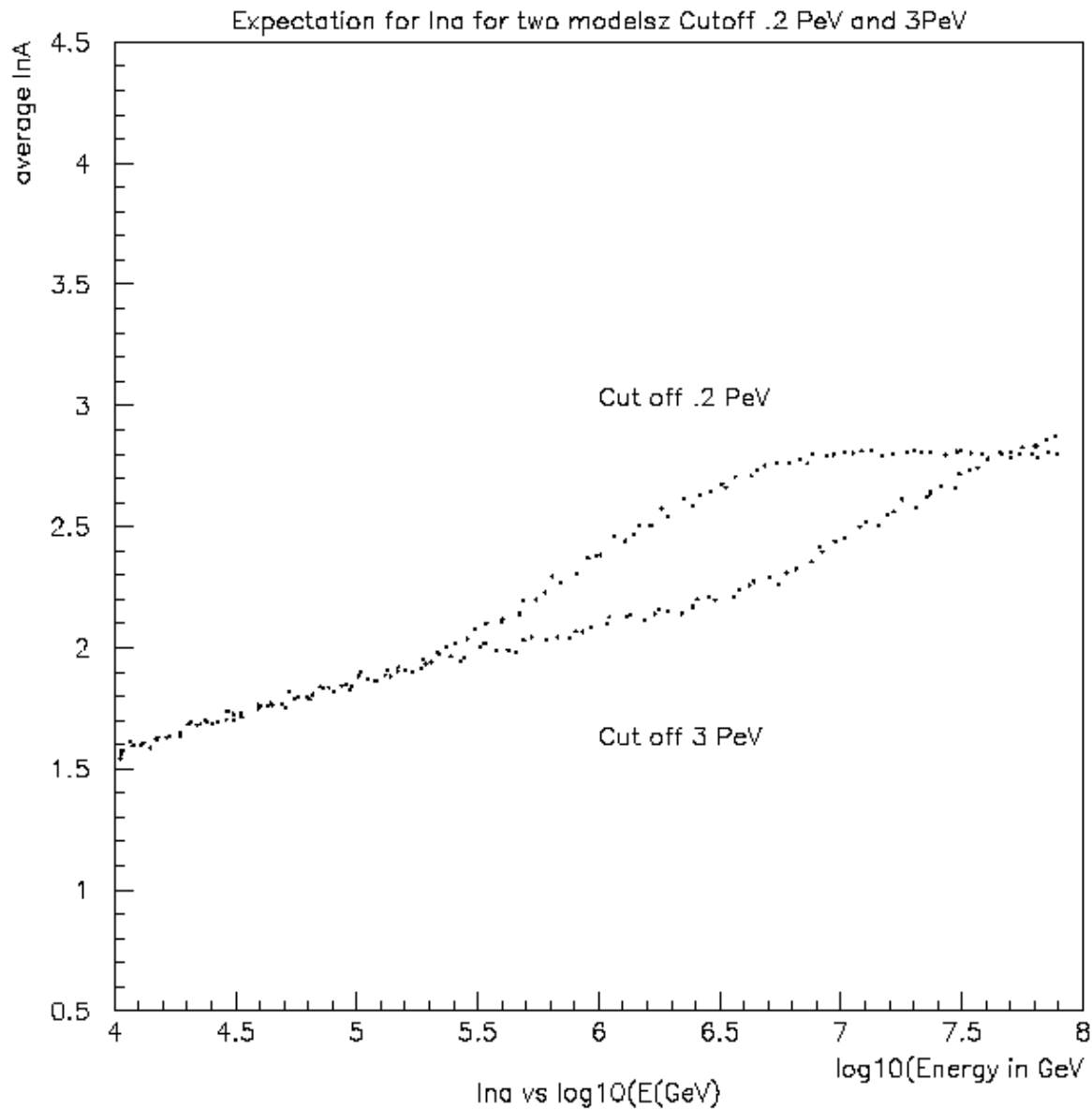


Figure 36. Mean logarithmic mass as obtained from unfolding procedures and a neural network applied to the KASCADE size spectra (from [117, 138, 151]).

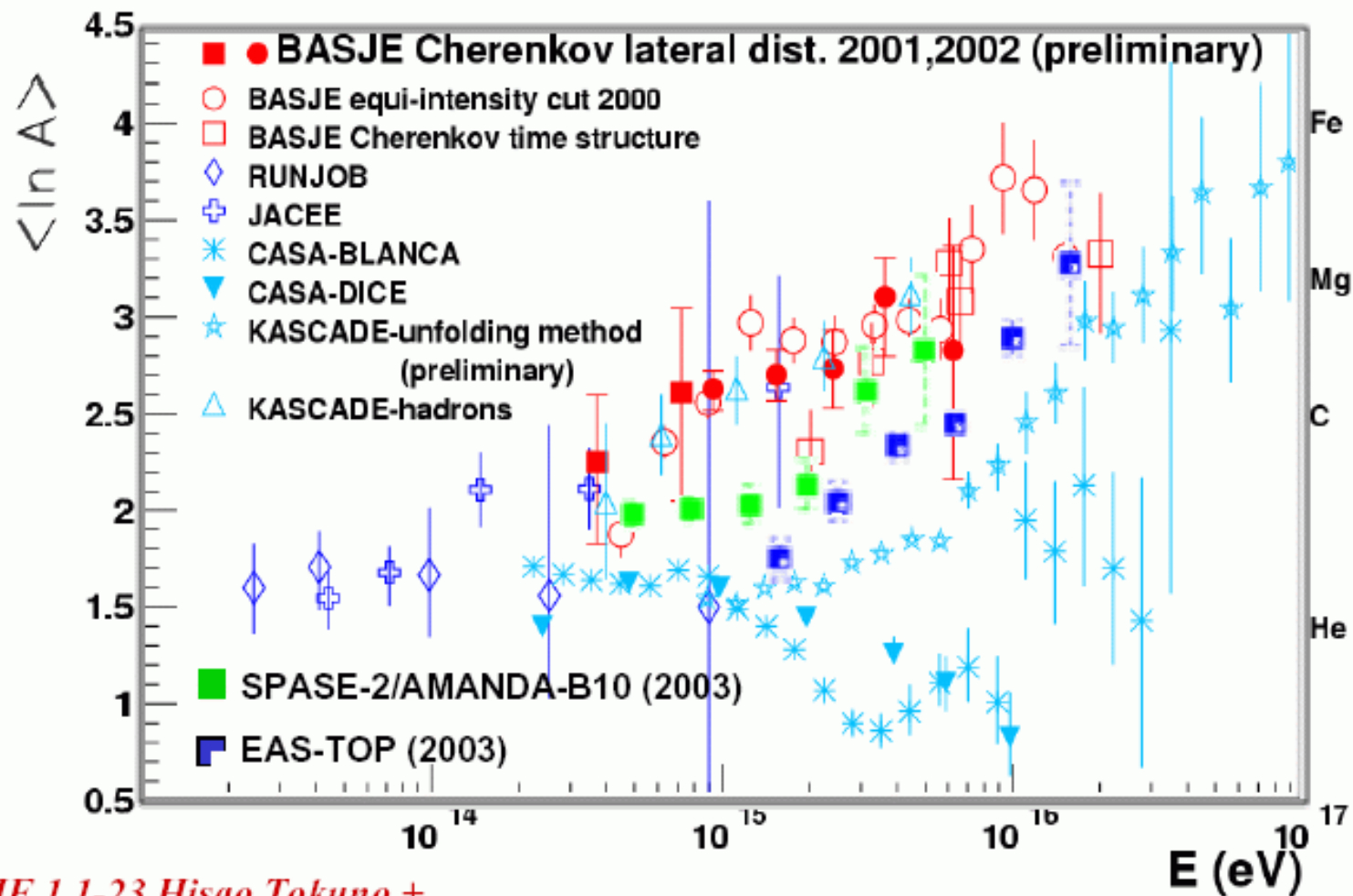


Max difference
in average $\ln A$
for the two models

0.45

How well can we
measure it?

Cosmic Ray Composition $\langle \ln A \rangle$



HE 1.1-23 Hisao Tokuno +

HE 1.1-25 Katherine Rawlins for the SPASE and the AMANDA Collaboration

HE 1.1-21 Gianni Navarra for the EAS-TOP Collaboration

Takita compilation 2003.

Clearly there are systematic effects and differences between different techniques and different experiments. It shows that the “ inverse “ problem to find the primary spectra is **very difficult**.

Is it possible to improve the mass resolution of indirect experiments sufficiently to rectify this confused situation ?

Detailed reviews of the measurements and problems can be found in

Haungs, Rebel and Roth: Rep.Prog.Phys. 66 (2003) 1145

Horandel: Astroparticle Physics 19 (2003) 193

CONCLUSIONS:

1. There is general agreement that the knee in the all particle spectrum is between 3 and 5 PeV. (First pointed out by MSU experiments in the 1950s)
2. RUNJOB sees no steepening of proton or helium spectra and generally agrees with JACEE and CRN and is good continuation of ATIC.
3. TIBET experiment sees a “steepening” of the proton spectrum around few hundred TeV.
4. KASKADE experiment does not see a proton “knee” before a PeV and shows rigidity dependent cutoff of P and He.
5. KASKADE, SPASE-AMANDA, HEGRA-Airobic, CACTI and TIBET favor “Heavy” composition knee and beyond up to 10 PeV.
6. Blanca, DICE, RUNJOB favor very little composition change.

COMMENTS !

The knee is still there but its details are still elusive. Rigidity cutoff is likely scenario but far from understood, both experimentally and theoretically. Further progress needs a modern version of Proton experiment orbiting the earth for many years and in ground based experiments one needs knowledge of hadron interactions in the forward region to be able to make robust simulations.

Will these become available in the future ?

Need experiments which can determine longitudinal development and lateral distributions event by event with sufficient redundancy and precision to be able to identify the A of the primary for each event.

Mass resolution has to be much better than so far achieved. Need $\frac{\Delta A}{A} \ll 1$ to separate the elements. Can it be done ?

If primary charge can be determined before the primary interacts in the atmosphere, it would be a much welcomed improvement in ground based experiments.

Kieda, Swordy and Wakeley, Astroparticle Physics 15,(2001) 287.

ARE WE
THERE YET?!



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