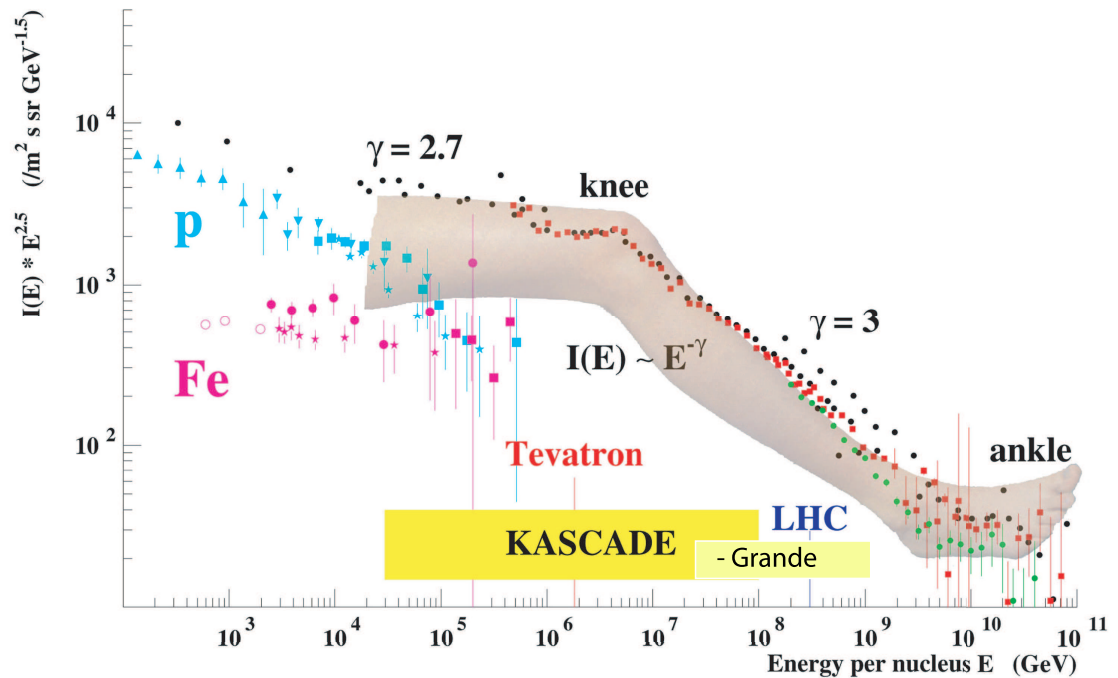
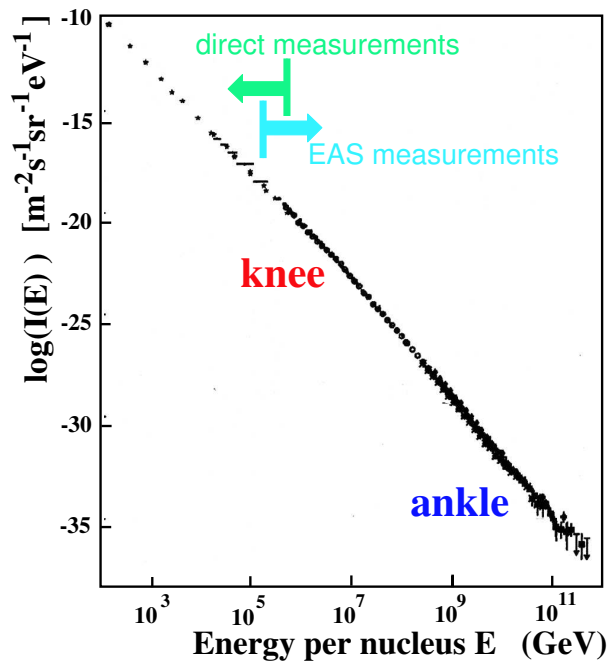


ASTROPHYSICS AROUND THE 'KNEE' OF PRIMARY COSMIC RAYS

Andreas Haungs

Forschungszentrum Karlsruhe, Germany

ISMD Krakow, September 2003

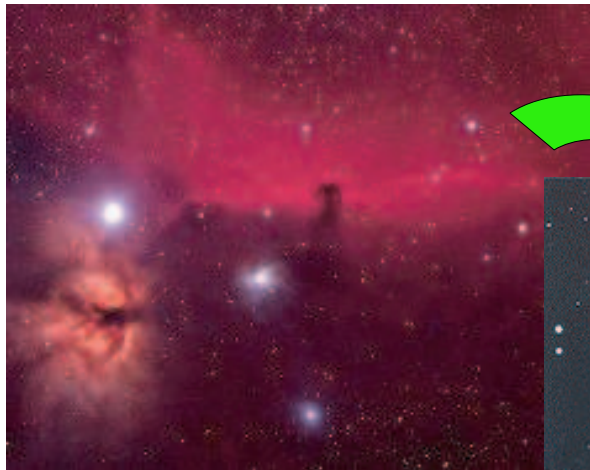


haungs@ik.fzk.de

KASCADE-Grande collaboration

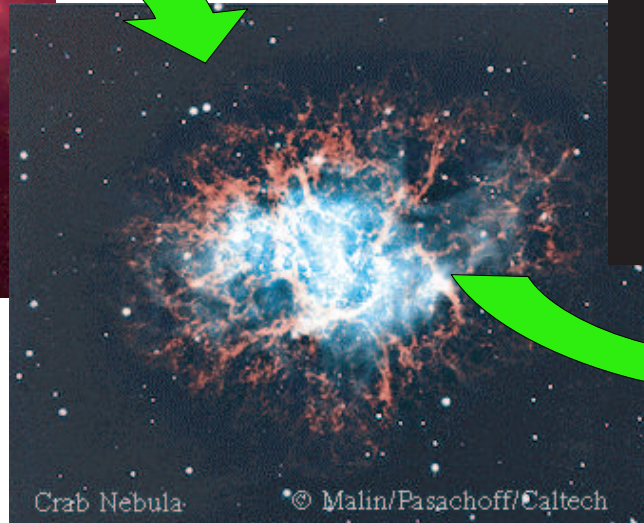
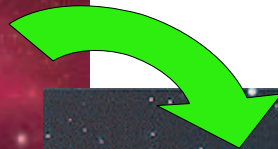
Cosmic rays

Source → Acceleration → Transport



Stellar matter

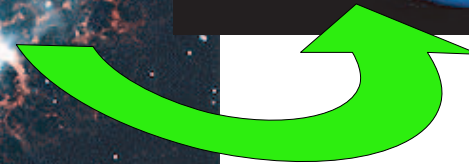
Injection



Supernovae

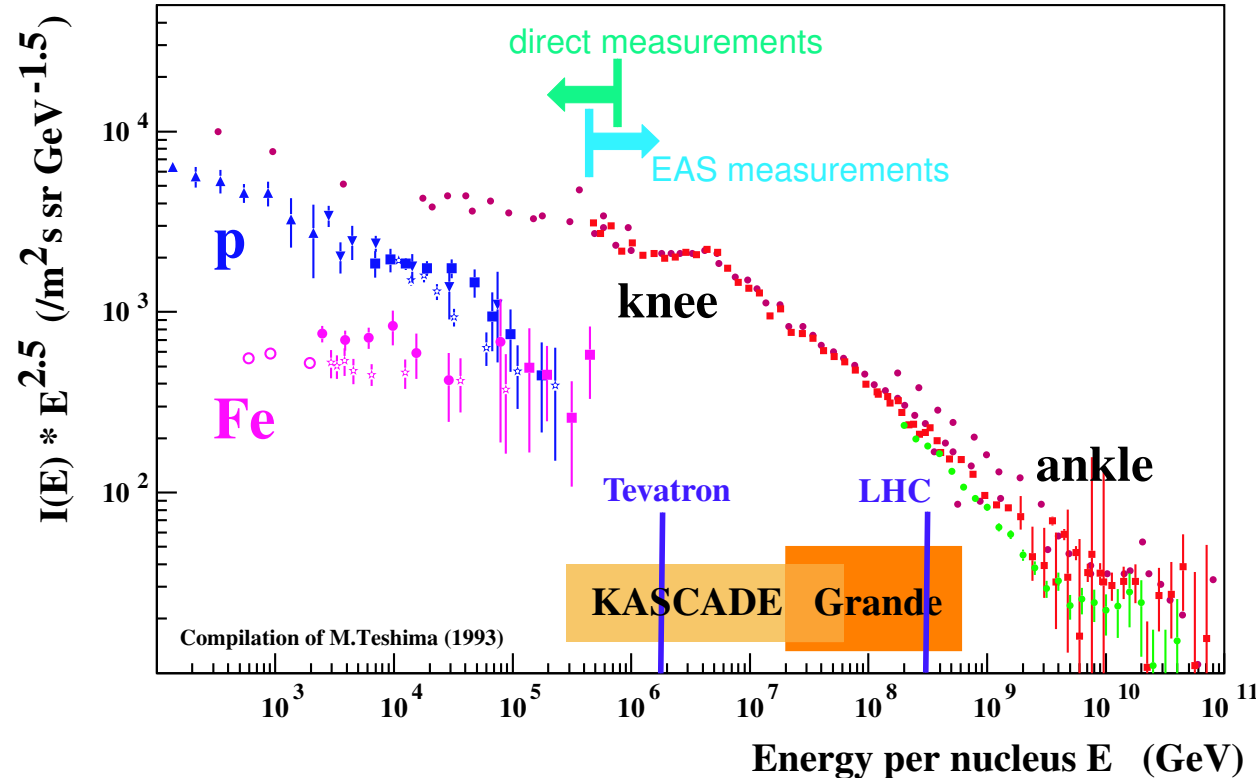


Spallation



Experiments

The Problem



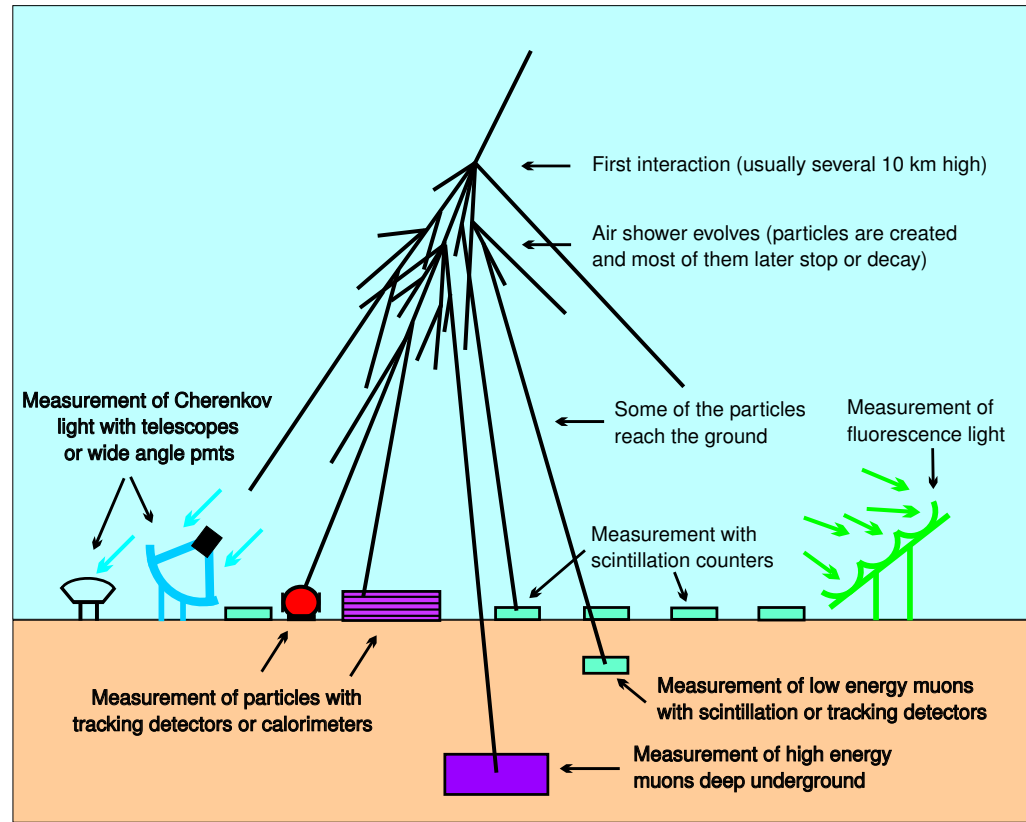
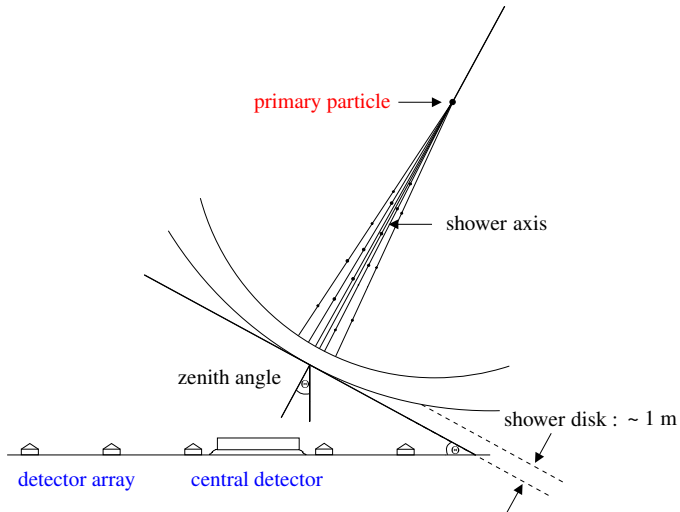
What is the origin of the "KNEE"?

- change of the cosmic ray sources ? (source, acceleration, composition)
- effect of transport mechanism ? (leaking from Galaxy)
- effect of interaction of CRs in the atmosphere ?

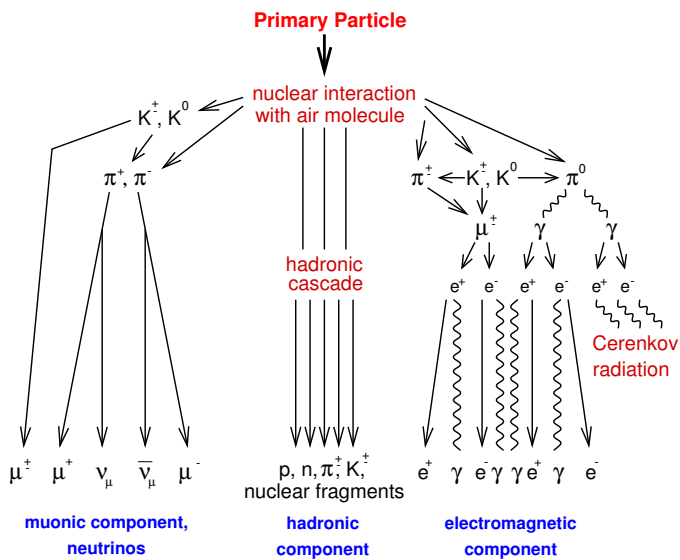
Experimental access:

- all-particle (single mass group) cosmic ray energy spectrum
 \implies knee position(s): $\propto Z$ or $\propto A$??
- elemental composition around the "knee"!
- anisotropy of cosmic rays around the "knee"!
- investigations of the hadronic interaction mechanisms !

Extensive Air Shower – EAS

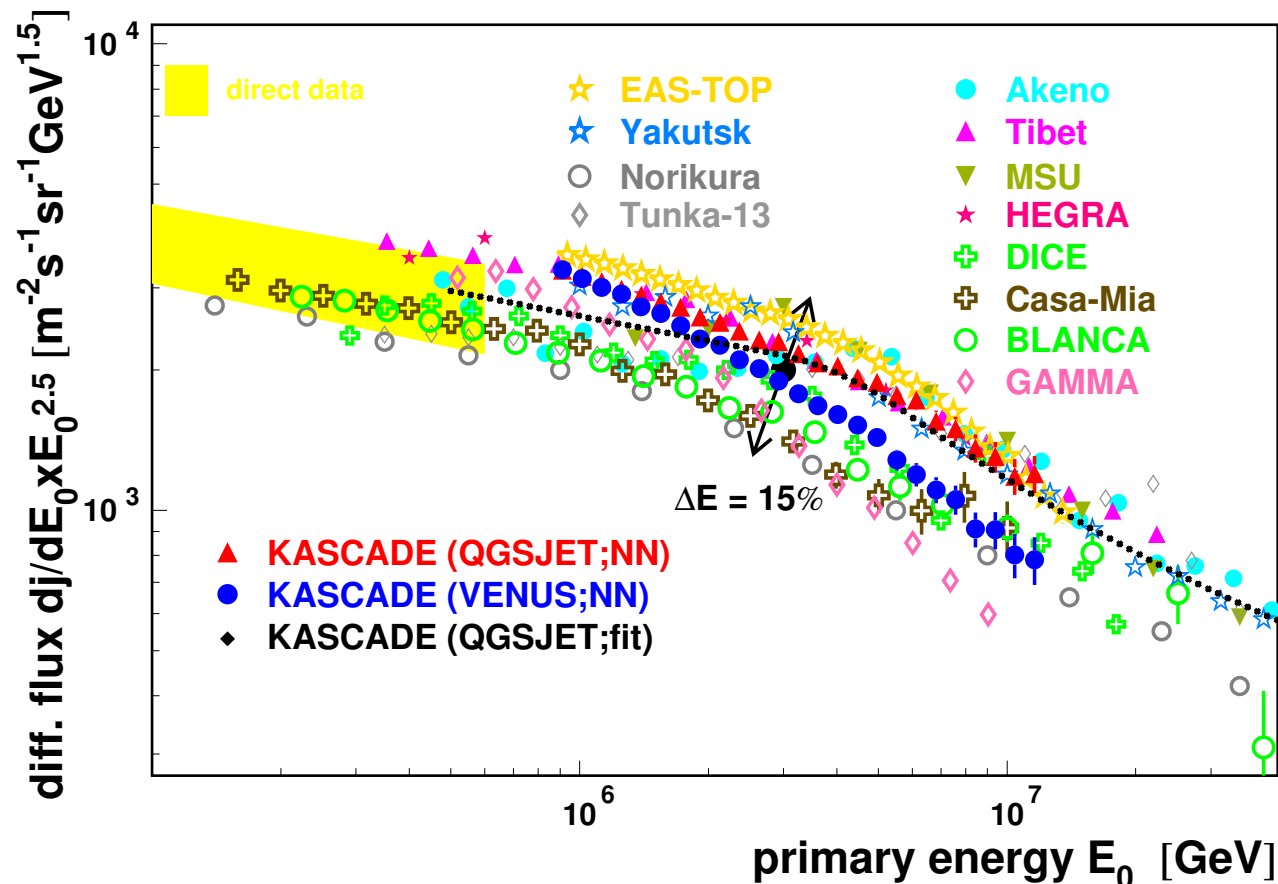


detection of EAS



schematic views of EAS

The all-particle energy spectrum



Average values from 14 measurements \pm variance:

$$E_k = (3.2 \pm 1.2) \cdot 10^{15} \text{ eV}$$

$$\text{slope below knee: } \gamma_1 = -(2.68 \pm 0.06)$$

$$\text{slope above knee: } \gamma_2 = -(3.06 \pm 0.08)$$

$$\text{flux at 1 PeV: } (2.73 \pm 0.70) \cdot 10^{-9} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ TeV}^{-1}$$

Origin of the knee ??

$$E_{\text{knee,A}} \propto Z \times E_{\text{knee,p}}$$

Maximum of acceleration process:

$$E_{\text{max}} < Z \times (L \times B)$$

$$E_{\text{max}} < Z \cdot 10^{15} \text{ eV}$$

e.g. in Supernova Remnants

Escape from our Galaxy:

e.g. magnetic rigidity corresponding to one crossing of the galactic disc relates to

$$E_{\text{max}} < Z \cdot 3 \cdot 10^{15} \text{ eV}$$

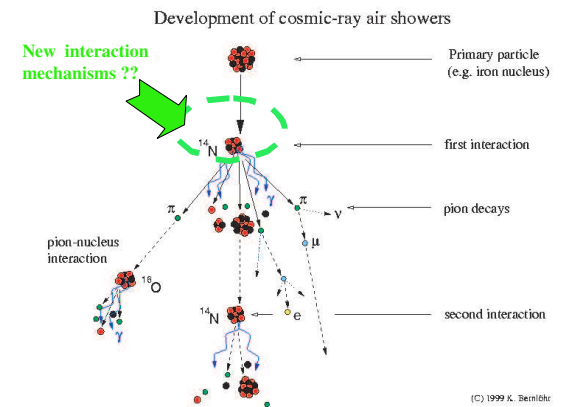
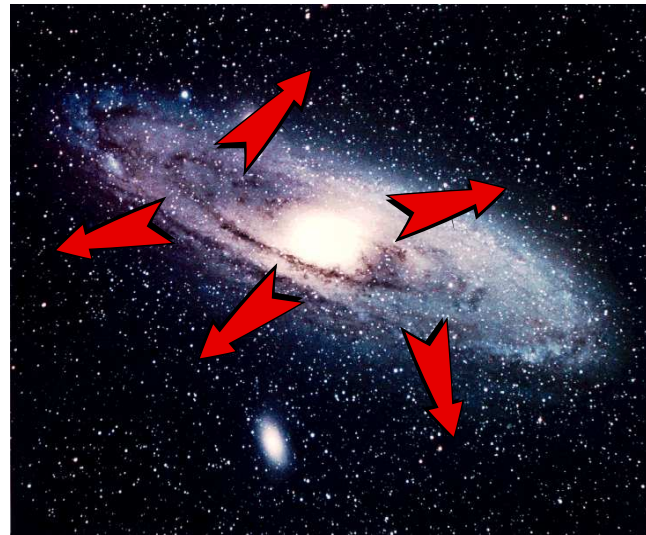
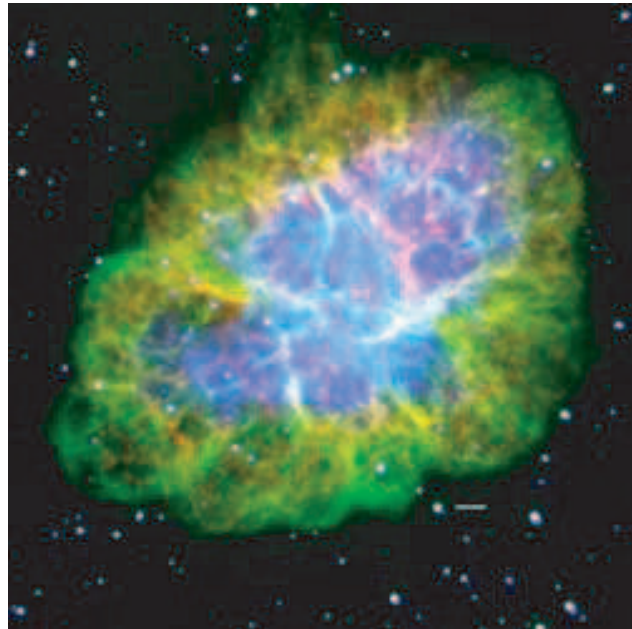
$$E_{\text{knee,A}} \propto A \times E_{\text{knee,p}}$$

New channel in high-energetic interactions:

e.g. Production of new heavy particle
or

Transformation of energy in gravitational energy
or

Interaction of primary with relic neutrino
or ...



Origin of the knee ??

example: knee by reaching maximum of acceleration

P.L.Biermann et al. 2003, preprint astro-ph/0302201

two component supernova acceleration

-) supernovae in interstellar medium

⇒ cutoff in the 100 TeV range

⇒ low energy protons

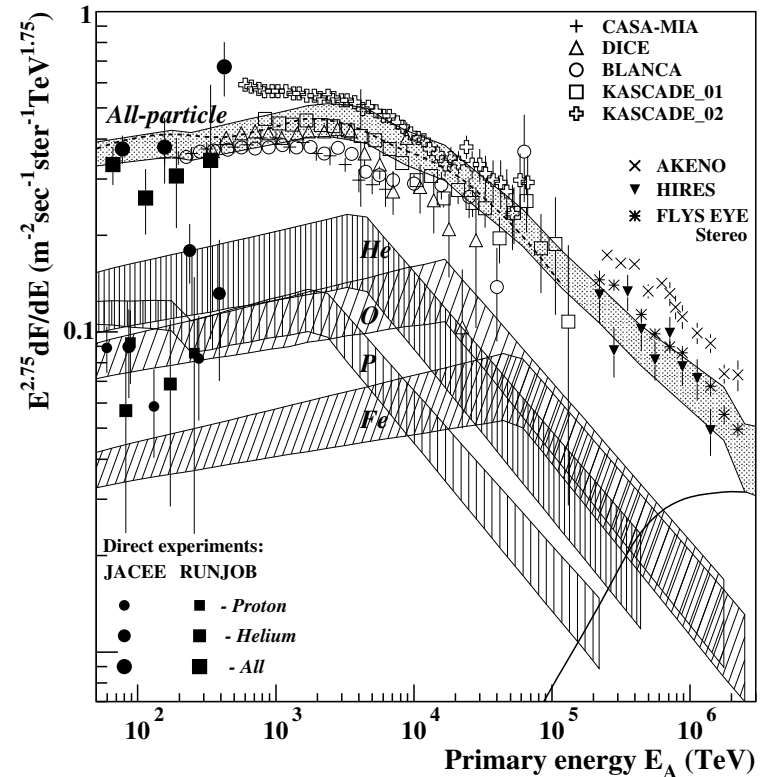
-) supernovae into their own stellar wind

⇒ cutoff at $Z \cdot 10^{15}$ eV

⇒ source composition heavier

⇒ final cutoff at $Z \cdot 3 \cdot 10^{17}$ eV

$$E_{\text{knee},A} \propto Z \times E_{\text{knee},p}$$



Source of galactic cosmic rays: SNR's ??

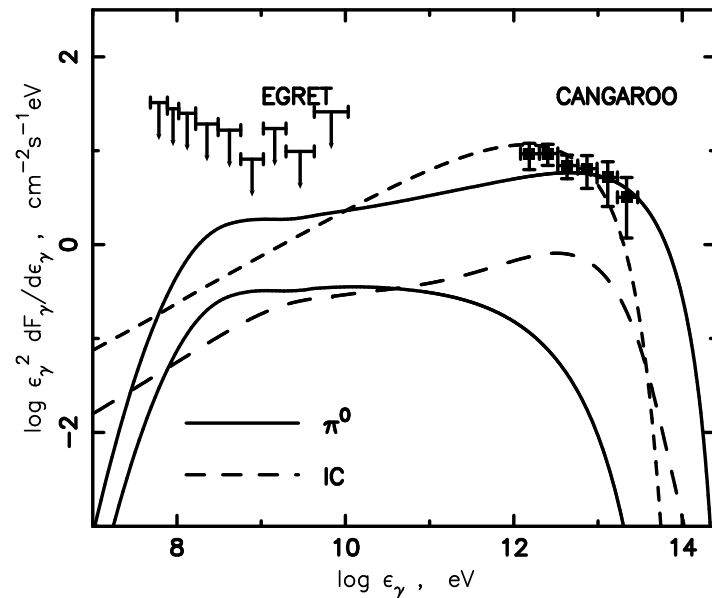
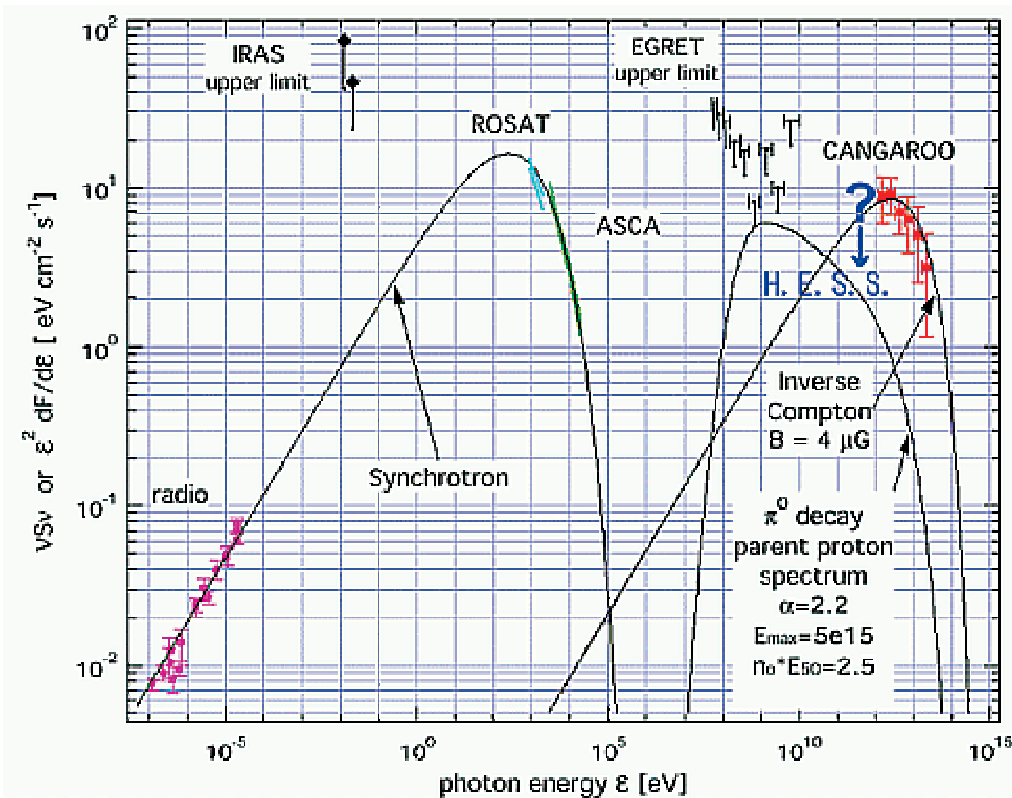
hints by: TeV γ -ray astronomy

H.J.Völk, 2003, highlight ICRC 2003, Tsukuba, Japan

E.G.Berezhko et al., 2002, A&A, preprint astro-ph/0204085

TeV γ -production by inverse compton effect of electrons which produce also synchrotron emission.

at source electron and proton acceleration !?
TeV γ -production by π^0 -decay.



Origin of the knee ??

example: knee by change of the efficiency of cosmic ray confinement in the Galaxy

J.Candia et al. 2003, JCAP, preprint astro-ph/0302082

Diffusion/drift model of cosmic rays inside the Galaxy

-) constant source spectrum according to direct measurements at 1 TeV
-) account for a regular magnetic field
-) account for a random turbulent field

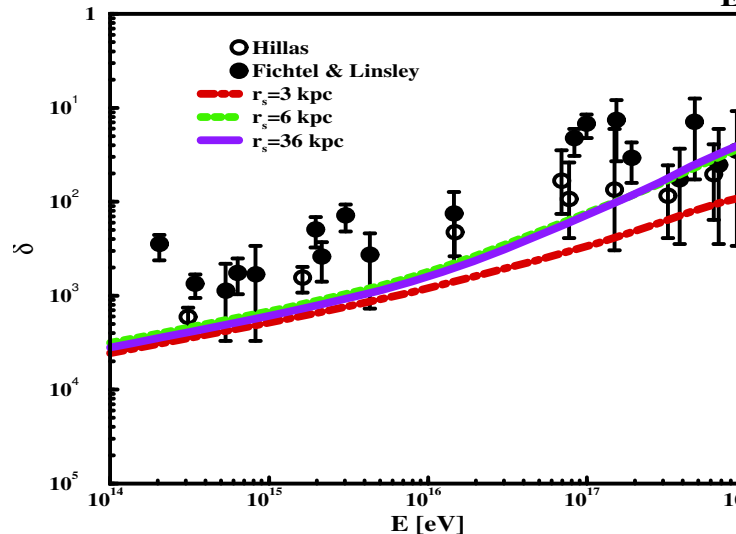
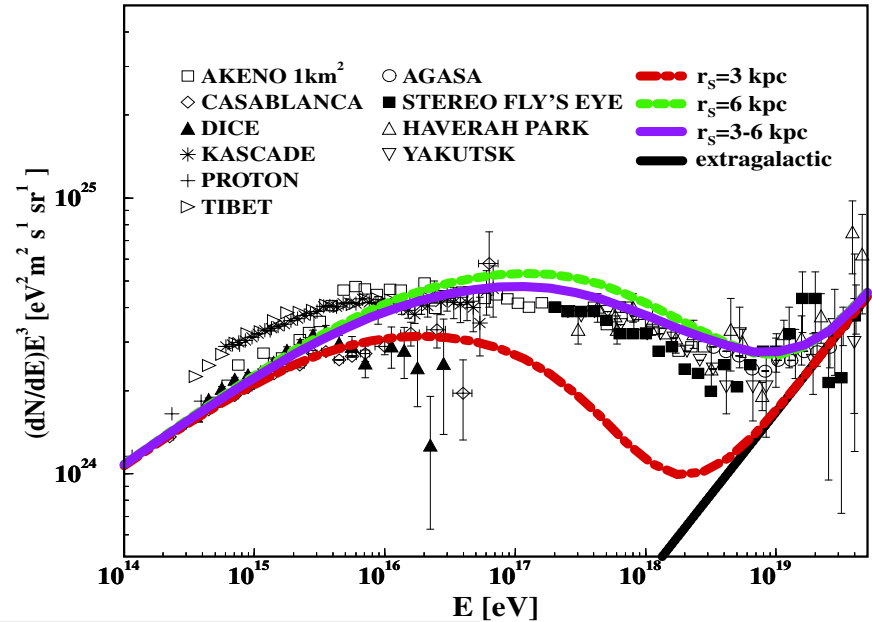
$$\Rightarrow E < Z \cdot E_{\text{knee,p}}:$$

$$dN/dE \propto E^{-\beta-0.33}$$

$$\Rightarrow E > Z \cdot E_{\text{knee,p}}:$$

$$dN/dE \propto E^{-\beta-1.0}$$

$$E_{\text{knee,A}} \propto Z \times E_{\text{knee,p}}$$



Origin of the knee ??

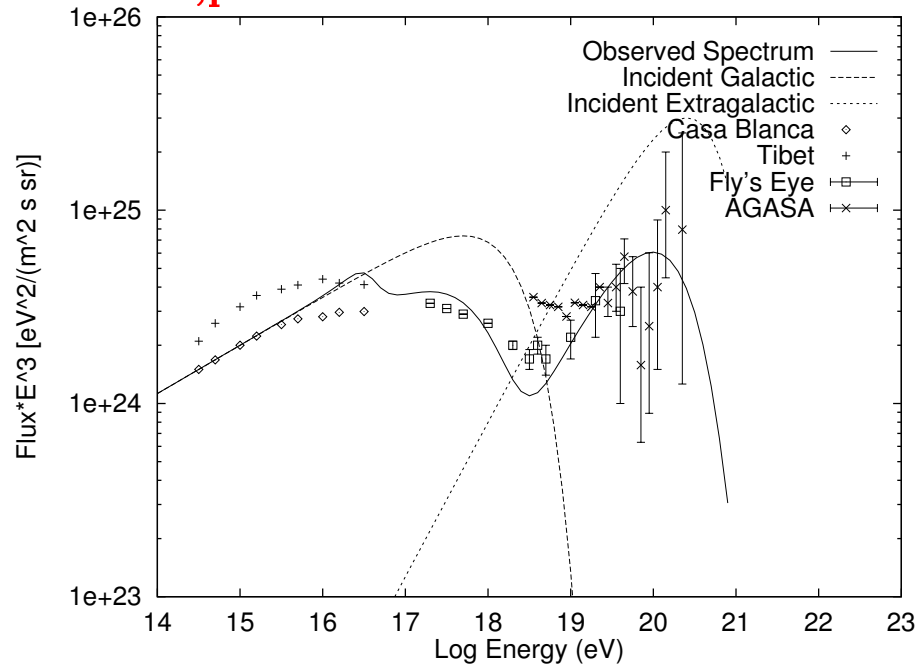
example: Cosmic Ray particles transform energy in gravitational energy

D.Kazanas, A.Nicolaidis 2001, preprint hep-ph/0109247

Graviton production in pp collisions

-) initial galactic and extragalactic components
-) probability of graviton production
-) free parameters: fundamental scale of gravity M_f in $4 + \delta$ dimensions
-) the graviton is unseen in air-shower
⇒ to fit measured CR spectrum: $M_f = 8 \text{ TeV}$, $\delta = 4$

$$E_{\text{knee},A} \propto A \times E_{\text{knee},p}$$

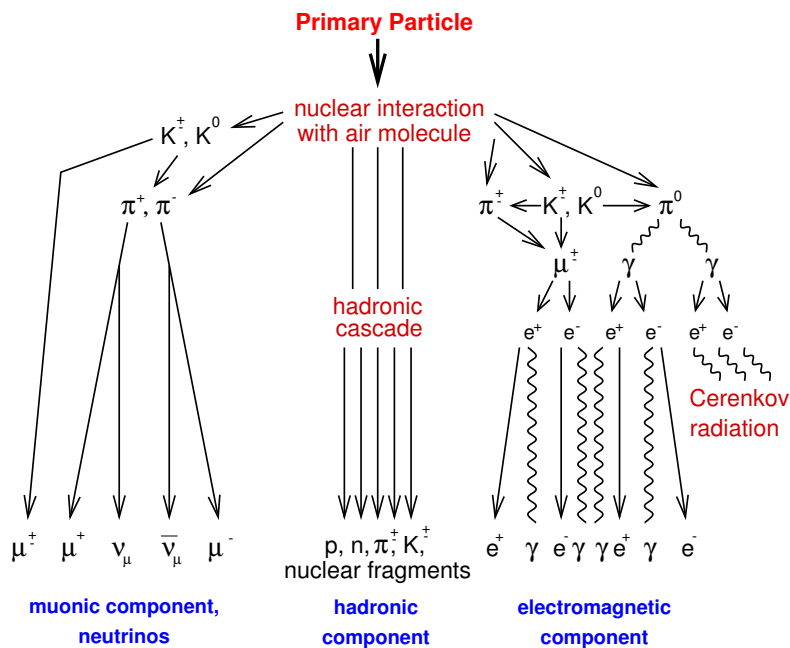


Measuring extensive air showers

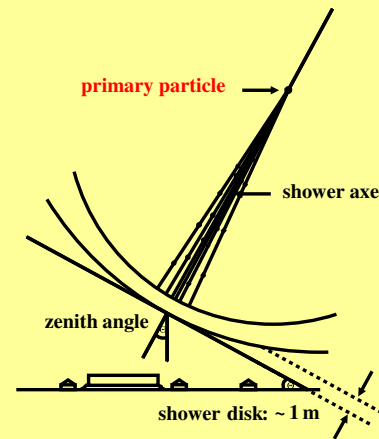
← disentangle 3-fold problem:
E, A, interactions !

⇒ measure as much as possible
redundant EAS informations !

⇒ multidetector system to get
information from different EAS particle
components !



KASCADE-Experiment



Data Acquisition

KRETA
Reconstruction of EAS-Observables
e.g. N_e, N_h, N_μ , Lateral Distributions, ...

Comparisons
of the distributions
Neural Nets, Bayes Classifier, ...

E_{est}, A_{est}
Energy Spectra
Chemical Composition

Tests of
High-Energy
Interaction Models

Monte-Carlo Simulation

Primary Energy **E**
Primary Particle **A**

CORSIKA
DPMJET
QGSJET
SYBILL
VENUS
...

CRES
Detector-Response

KRETA
Reconstruction of EAS-Observables
e.g. N_e, N_h, N_μ , Lateral Distributions, ...

Comparisons
of the distributions
Neural Nets, Bayes Classifier, ...

E_{est}, A_{est}
Energy Spectra
Chemical Composition

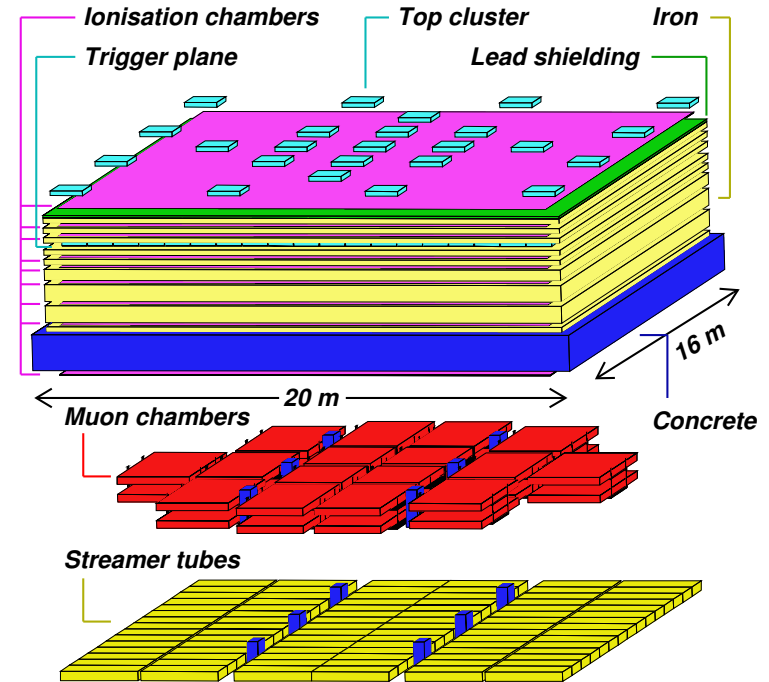
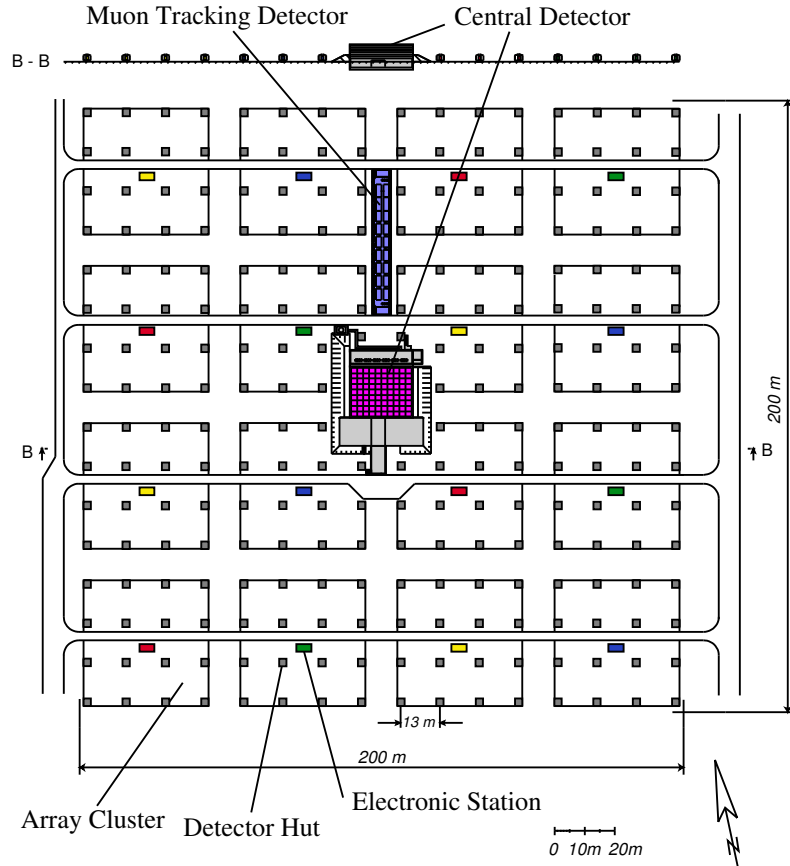
Tests of
High-Energy
Interaction Models

KASCADE

KARlsruhe Shower Core and Array DEtector



KASCADE



KASCADE Array

- electron detectors
- muon detectors ($E_{\mu} > 230 \text{ MeV}$)
- muon tracking detector ($E_{\mu} > 800 \text{ MeV}$)

KASCADE Central Detector

- hadron calorimeter ($E_h > 50 \text{ GeV}$)
- trigger plane ($E_{\mu} > 490 \text{ MeV}$)
- muon chambers ($E_{\mu} > 2400 \text{ MeV}$)

High-Energetic Hadronic Interactions

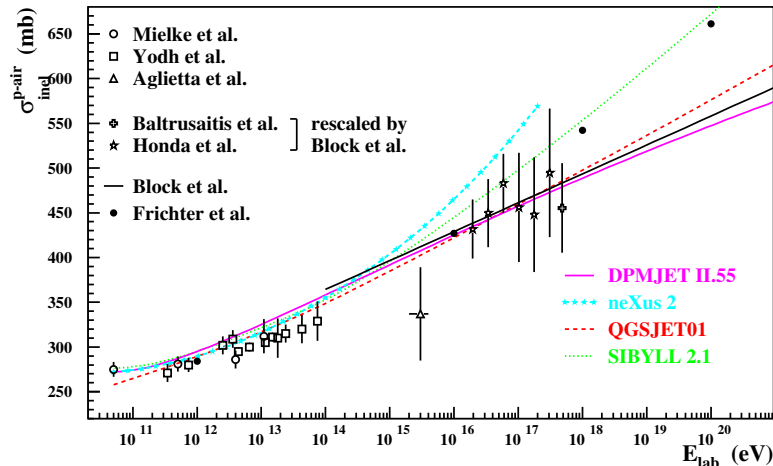
The problem

- extrapolation of cross-sections to 'unknown' energies
- multiplicity of secondary particles in high-energetic interactions
- extrapolation in extreme forward direction
- diffractive part of cross-sections

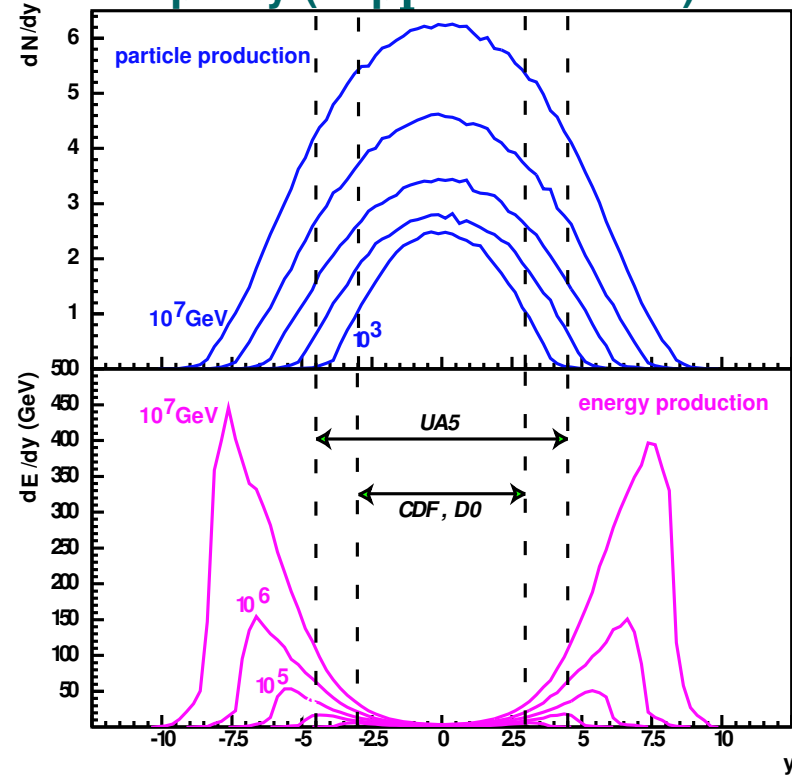
⇒ see talk Ralph Engel

⇒ see talk Jens Milke

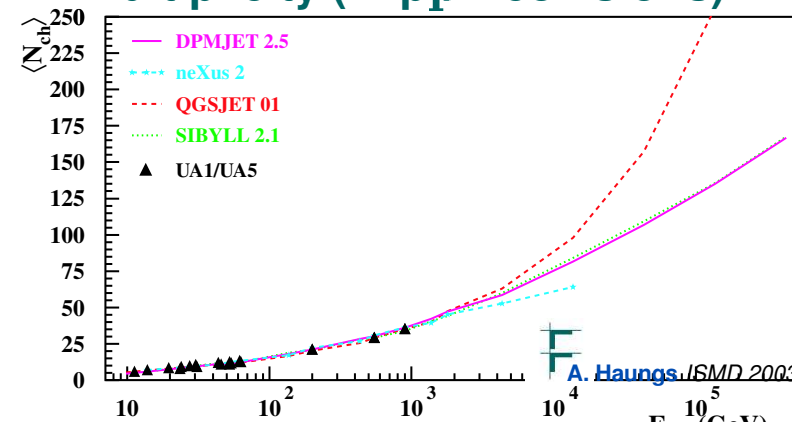
CORSIKA cross-sections



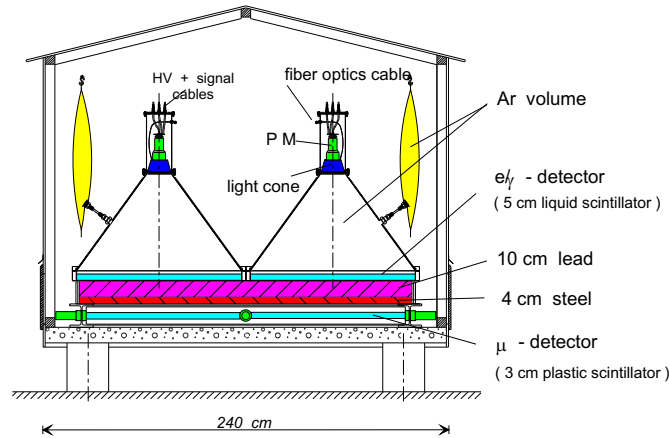
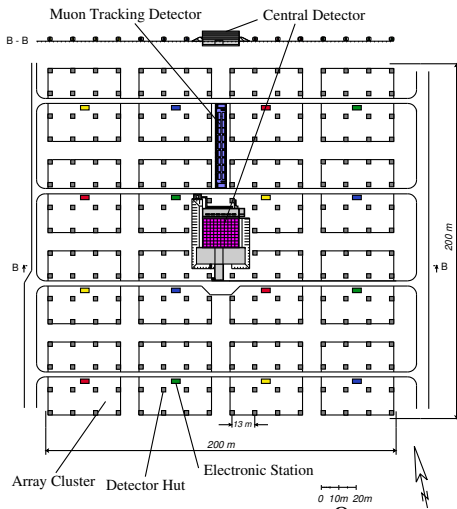
Rapidity (in $p\bar{p}$ - collisions)



Multiplicity (in $p\bar{p}$ - collisions)



Energy and Mass Reconstruction



Measurement:

KASCADE Array data

900 days

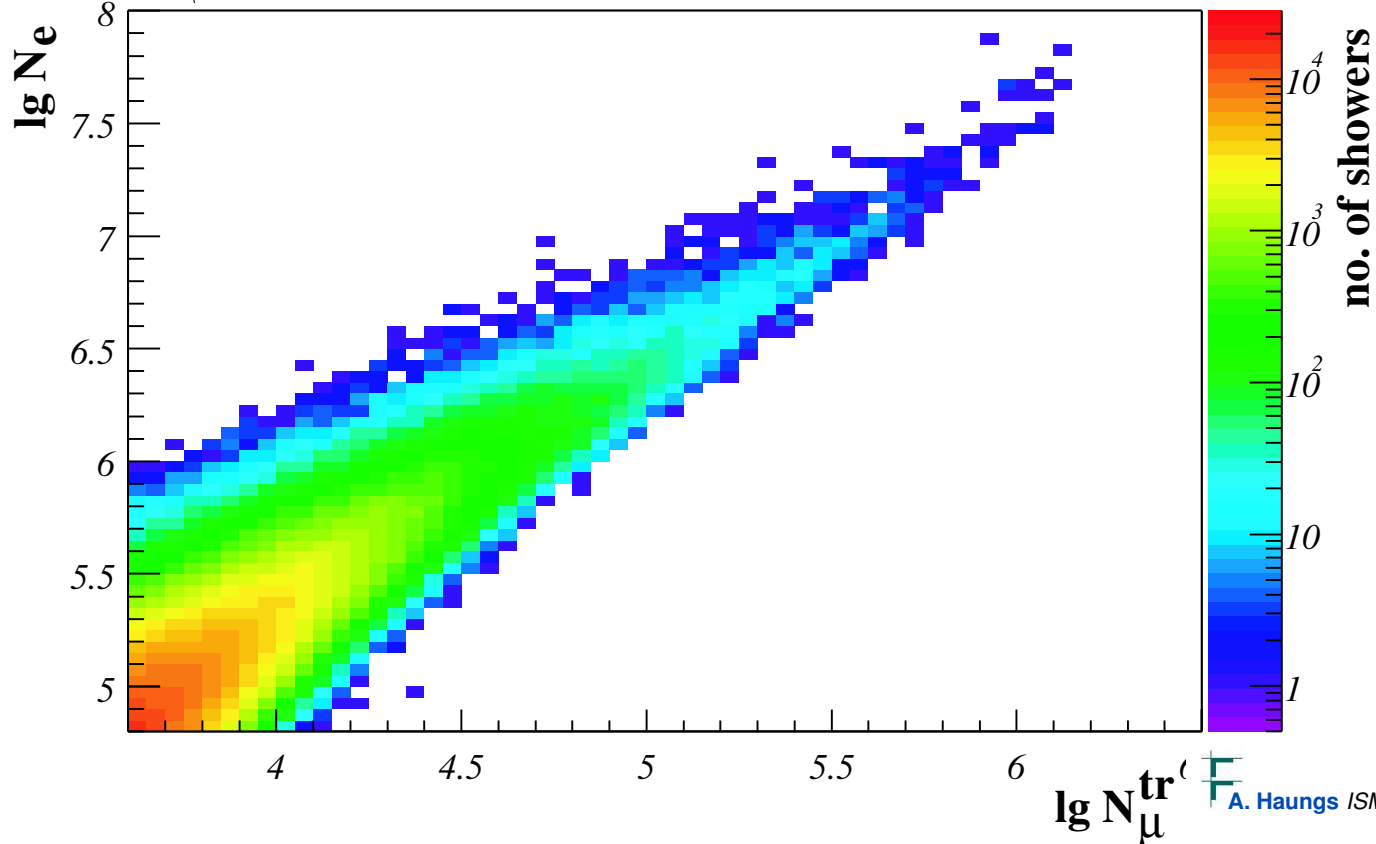
0 – 18° zenith angle

0 – 91 m core distance

$\lg N_e > 4.8$

$\lg N_\mu^{tr} > 3.6$

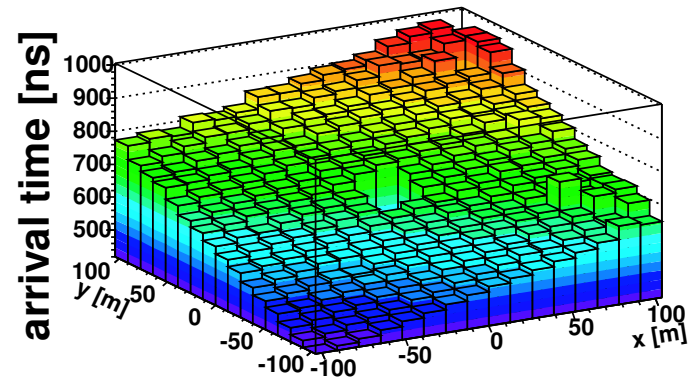
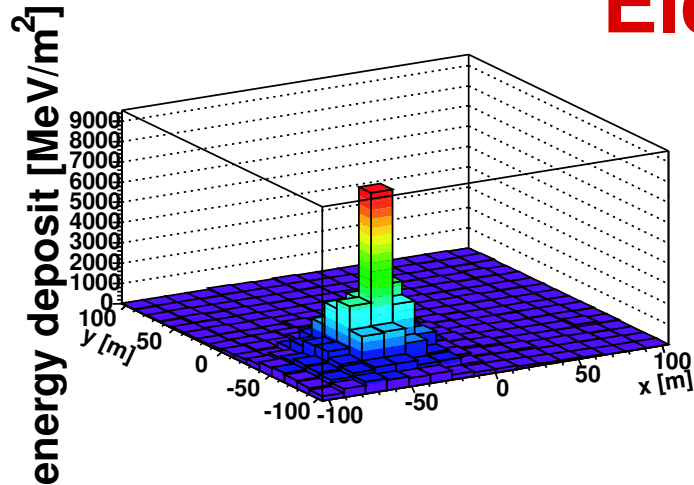
⇒ 685868 Events



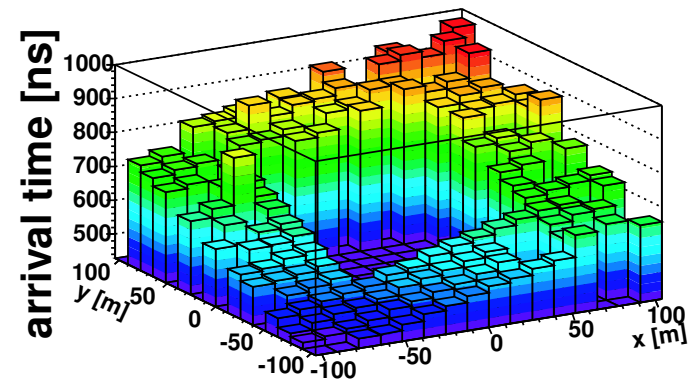
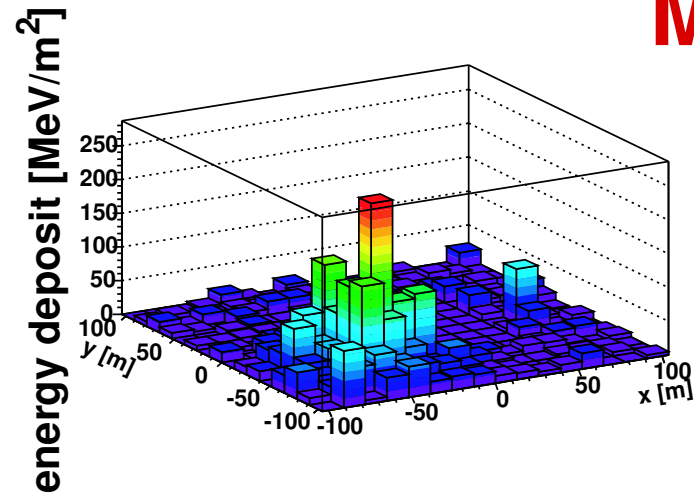
Examples

Array

Electrons



Muons



Run 3226, File 2, leve 65041, Ymd 10215, Hms 225810, Neds 250, Npds 138
(Xc,Yc) = (-45.4,-51.0), (Ze,Phi) = (36.7,228.6), log10(Ne)=6.14, log10(Lmuo)=4.66

Unfolding Methods at KASCADE

searched:

E and A of the Cosmic Rays

given:

N_e and N_μ^{tr} for each single event

\implies solve the inverse problem

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

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

Gold-Algorithm

$$\frac{dJ}{d \lg N} = \sum \int \frac{dJ_A(\lg E)}{d \lg E} \cdot p_A(\lg N | \lg E) \cdot d \lg E$$

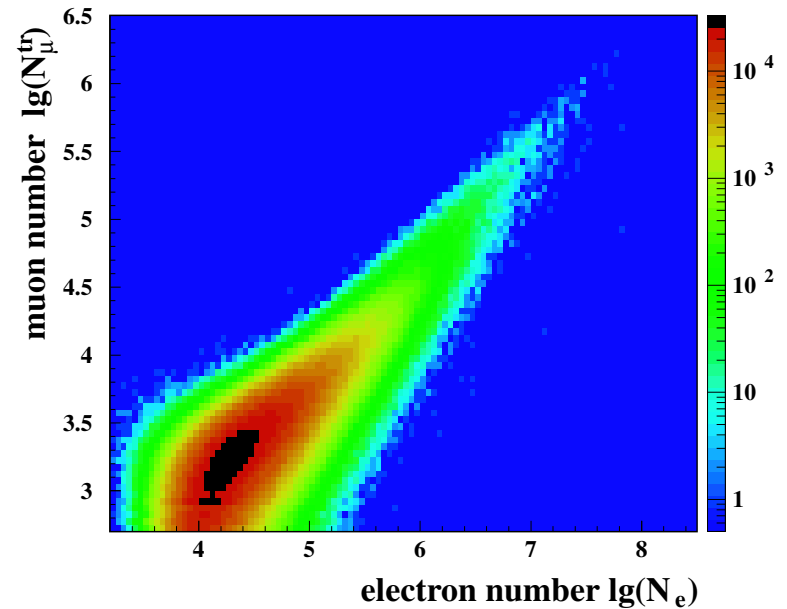
with p_A by Monte-Carlo simulations.

With response matrix R_A :

$$y_i = \sum_{j=1}^m R_{ij}^A \cdot x_j^A$$

\implies iterative minimization of χ^2 .

Monte Carlo simulations using CORSIKA
with GHEISHA2002 and QGSJet2001 / SIBYLL 2.1



Bayesian-Approach

Monte-Carlo Simulations:

$$P(y = (N_e, N_\mu^{\text{tr}}) | x = (E, A))$$

Bayes-Theorem:

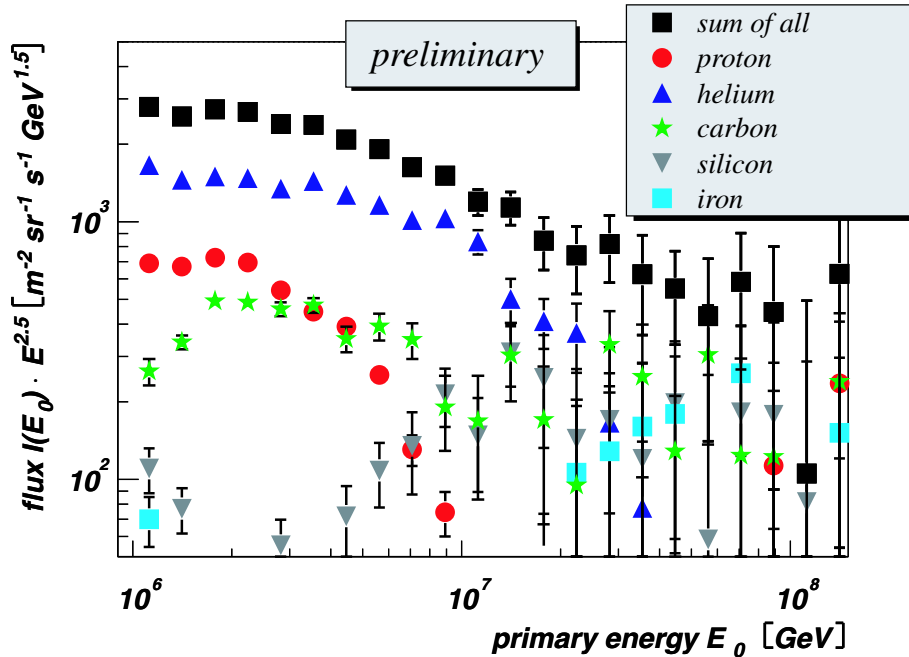
$$P(x | y) = \frac{P(y|x) \cdot P_0(x)}{\sum_{l=1}^m P(y|x_l) \cdot P_0(x_l)}$$

\implies

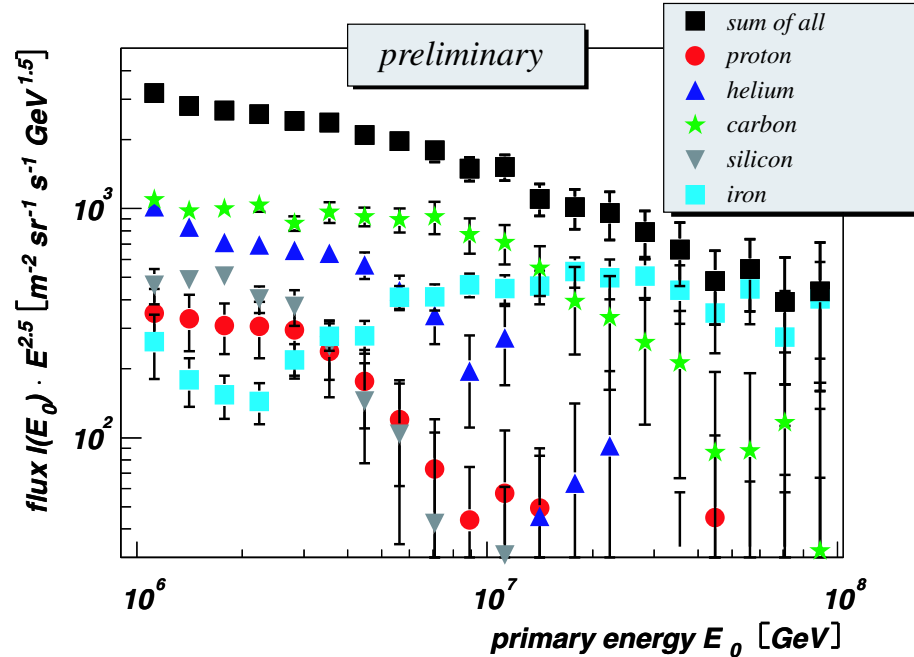
iterative procedure to get spectra

Results: Unfolding KASCADE Data

QGSJet



SIBYLL



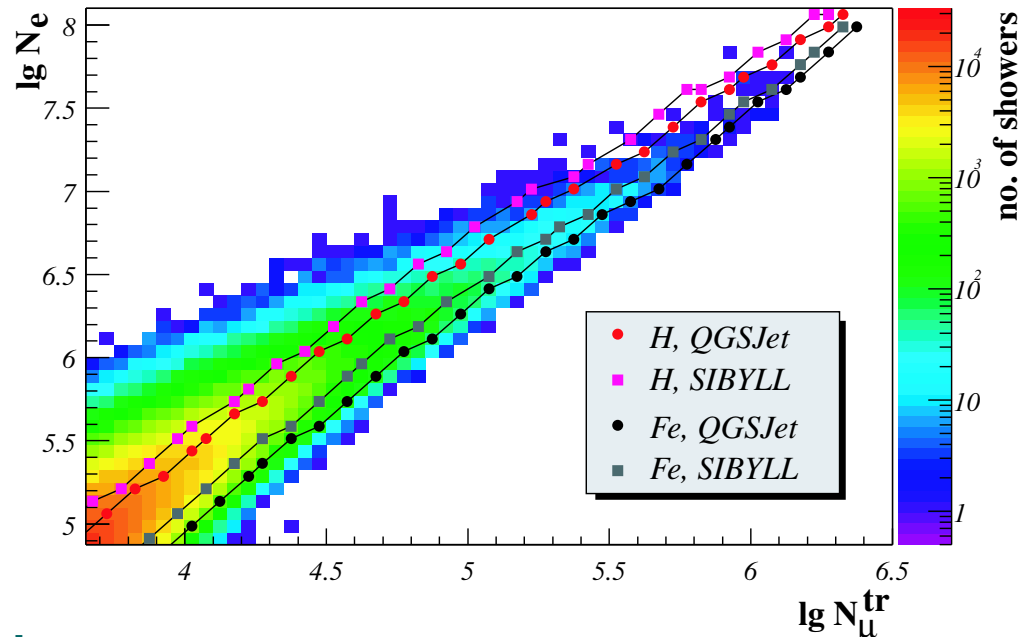
- knee caused by light elements
- $E_{\text{knee}}(A) \propto Z$ seems probable

but

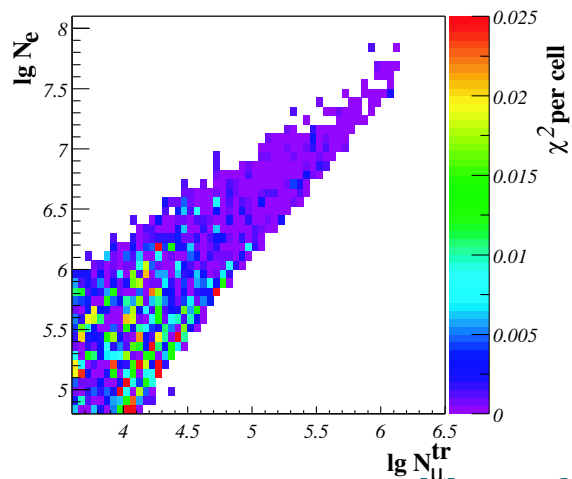
- strong model dependence for the relative dependencies of the various mass groups
- both models do not describe the data distribution sufficient enough

Influence of Interaction Models

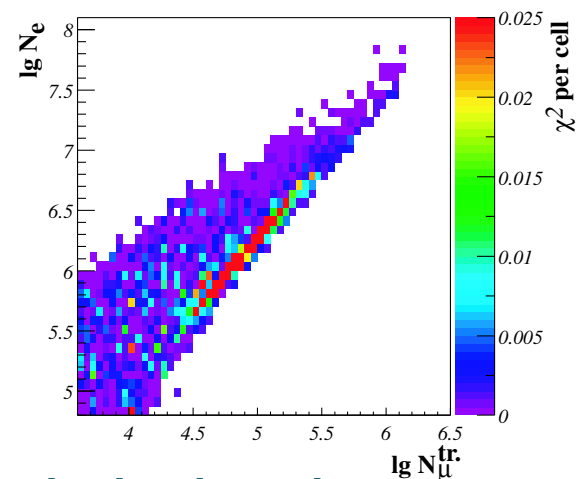
positions of maxima of $\lg N_e - \lg N_\mu^{tr}$ probability distribution



QGSJet



SIBYLL

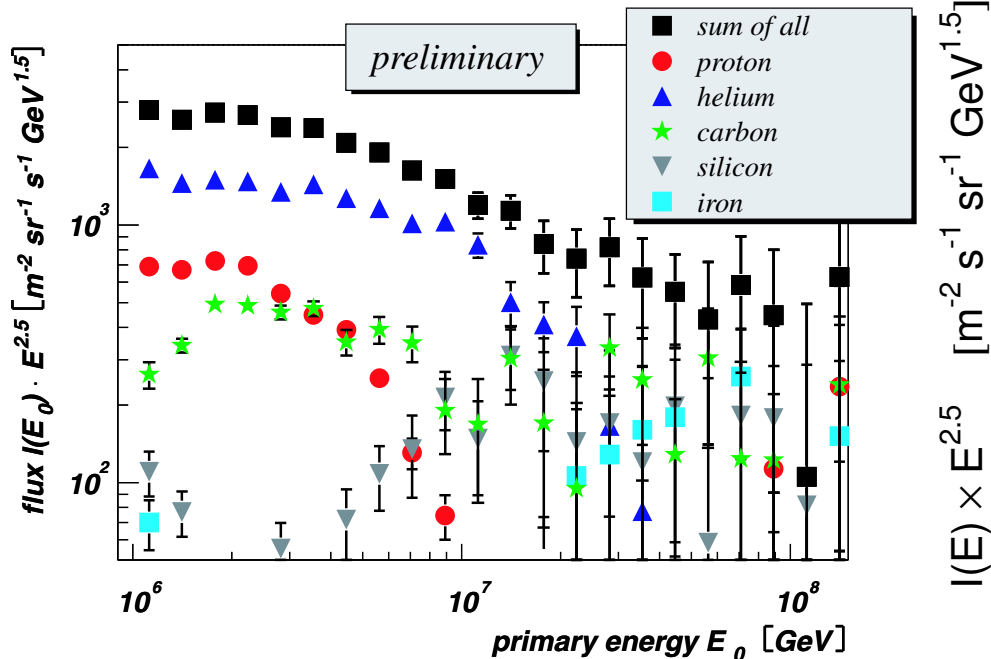


position of χ^2 -contributions in the data plane

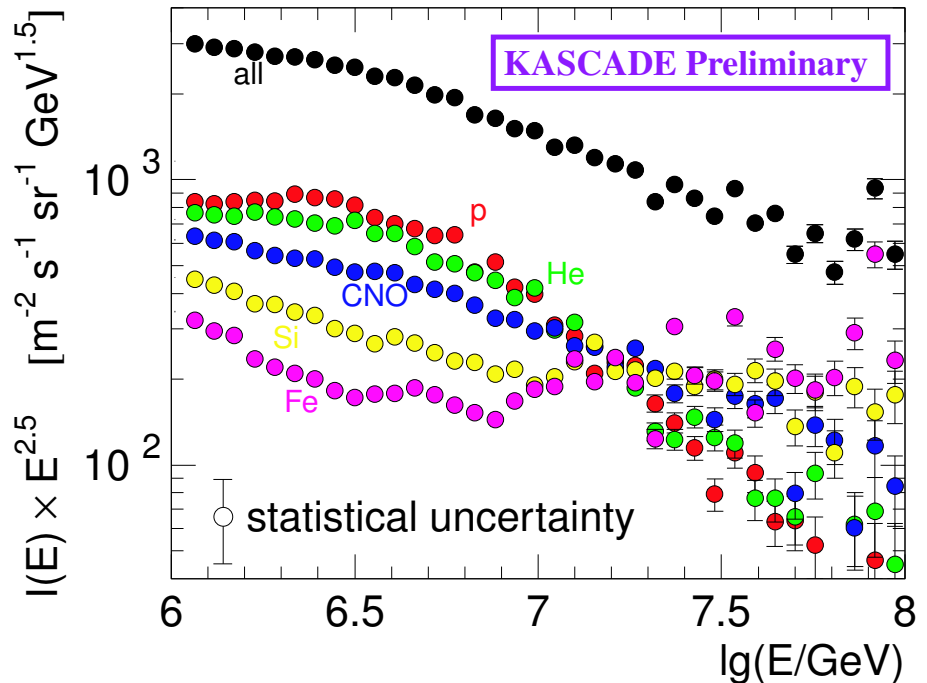
Sources of Uncertainties

- high-energy interaction models
- low-energy interaction models
- selection cuts ?
- Monte-Carlo input
- unfolding procedures

Gold algorithm - QGSJet



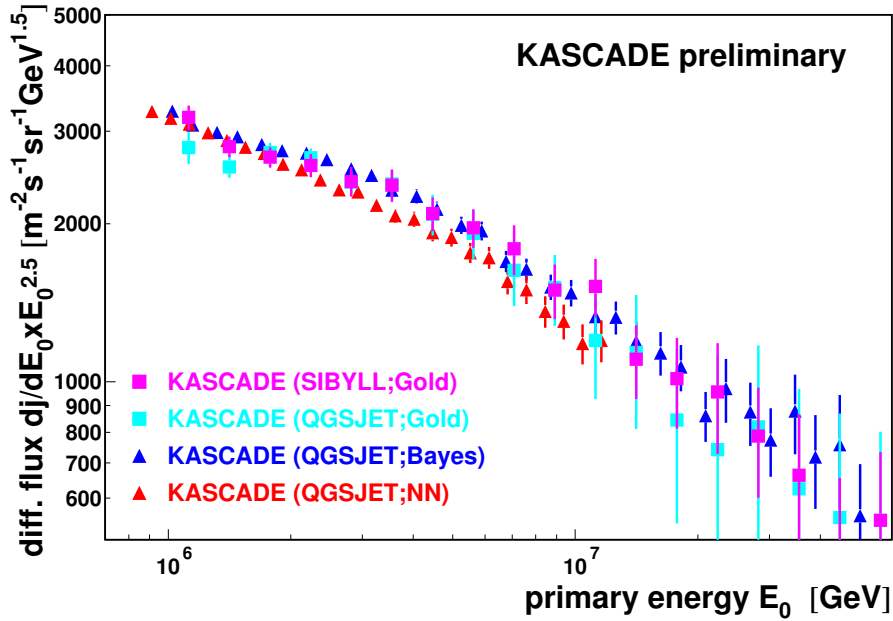
Bayesian approach - QGSJet



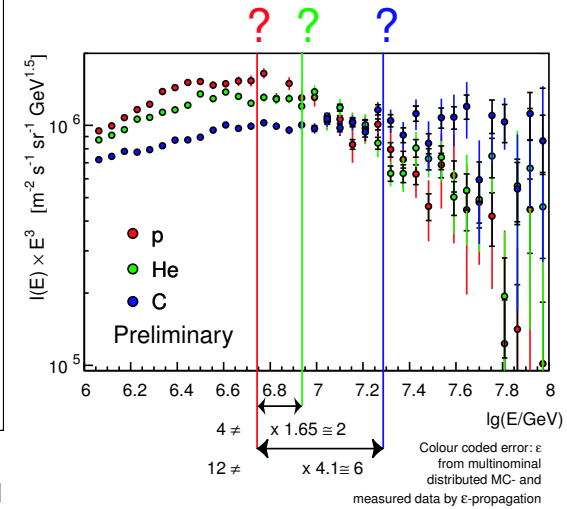
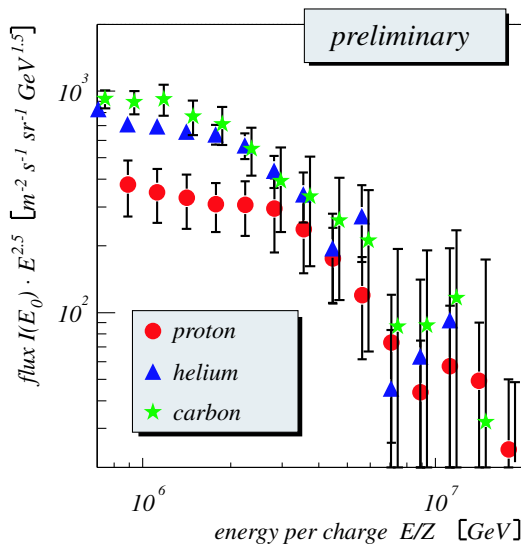
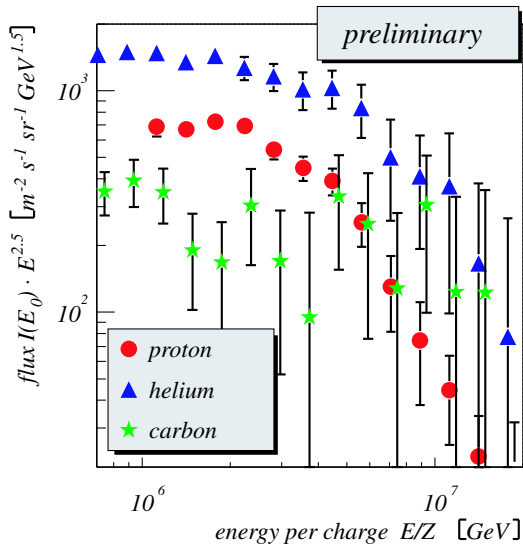
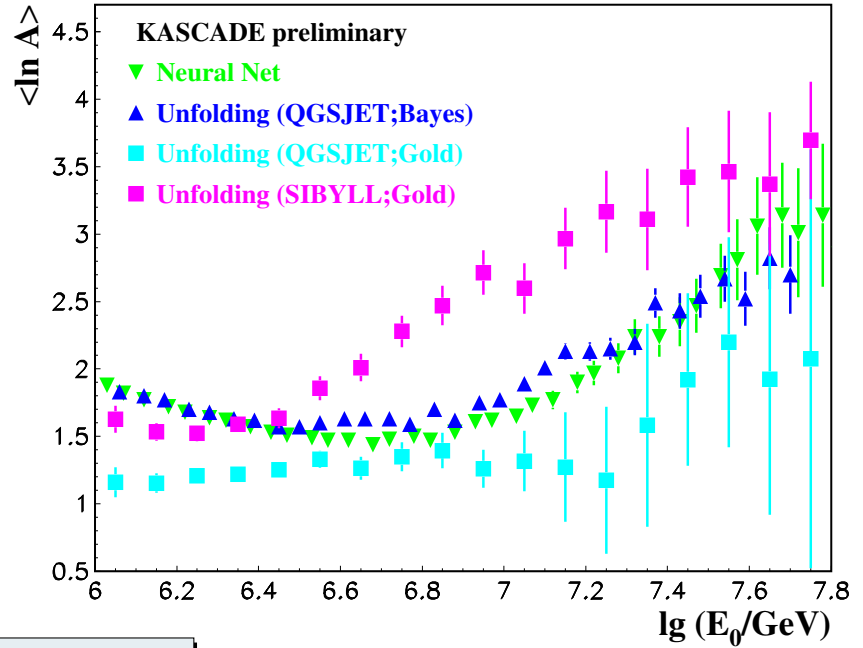
- Knee caused by light elements
- $E_{\text{knee}}(A) \propto Z$ seems probable

Comparisons

all-particle energy spectrum



mean logarithmic mass



Muon Density Measurements

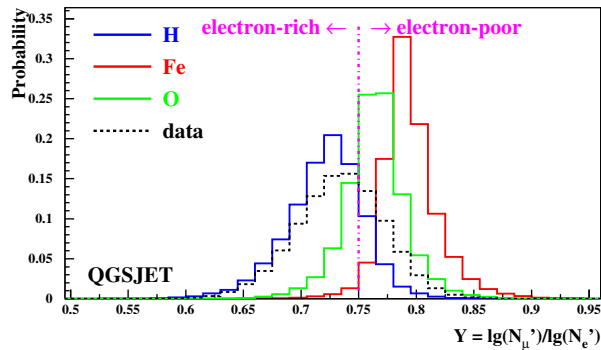
Ratio of muon to electron number is mass sensitive !:

$$Y = \lg(N'_\mu) / \lg(N'_e)$$

$$N'_\mu = f(N_\mu^{tr}, X_0, \lambda_\mu, \Theta)$$

$$N'_e = f(N_e, X_0, \lambda_e, \Theta)$$

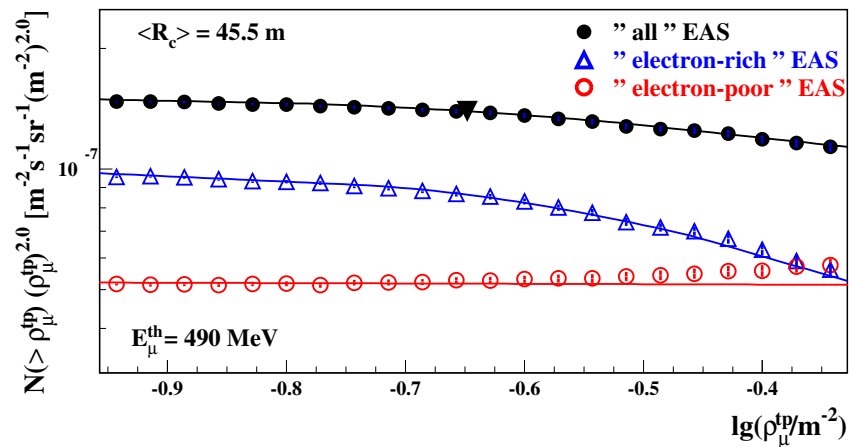
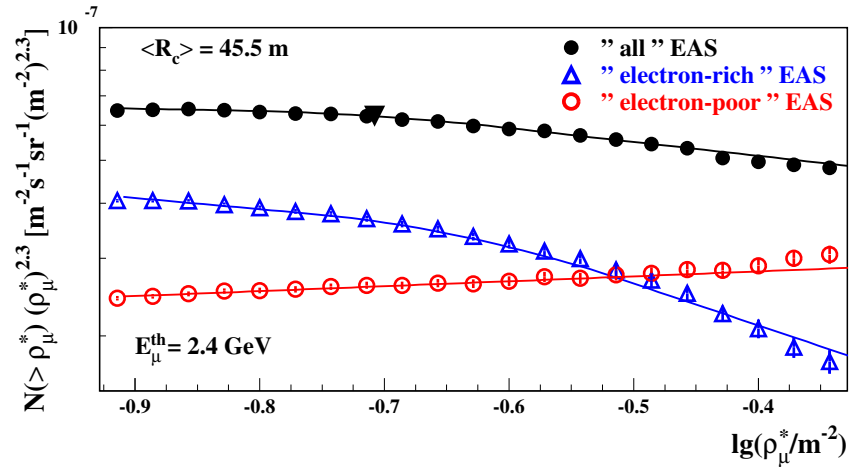
X_0 = observation level,
 λ = attenuation length



⇒
 Knee caused by decreasing flux of the light elements !

Muon Density Spectra

examples



KASCADE (A.Haungs), *Astrop.Phys.* 16(2002)373

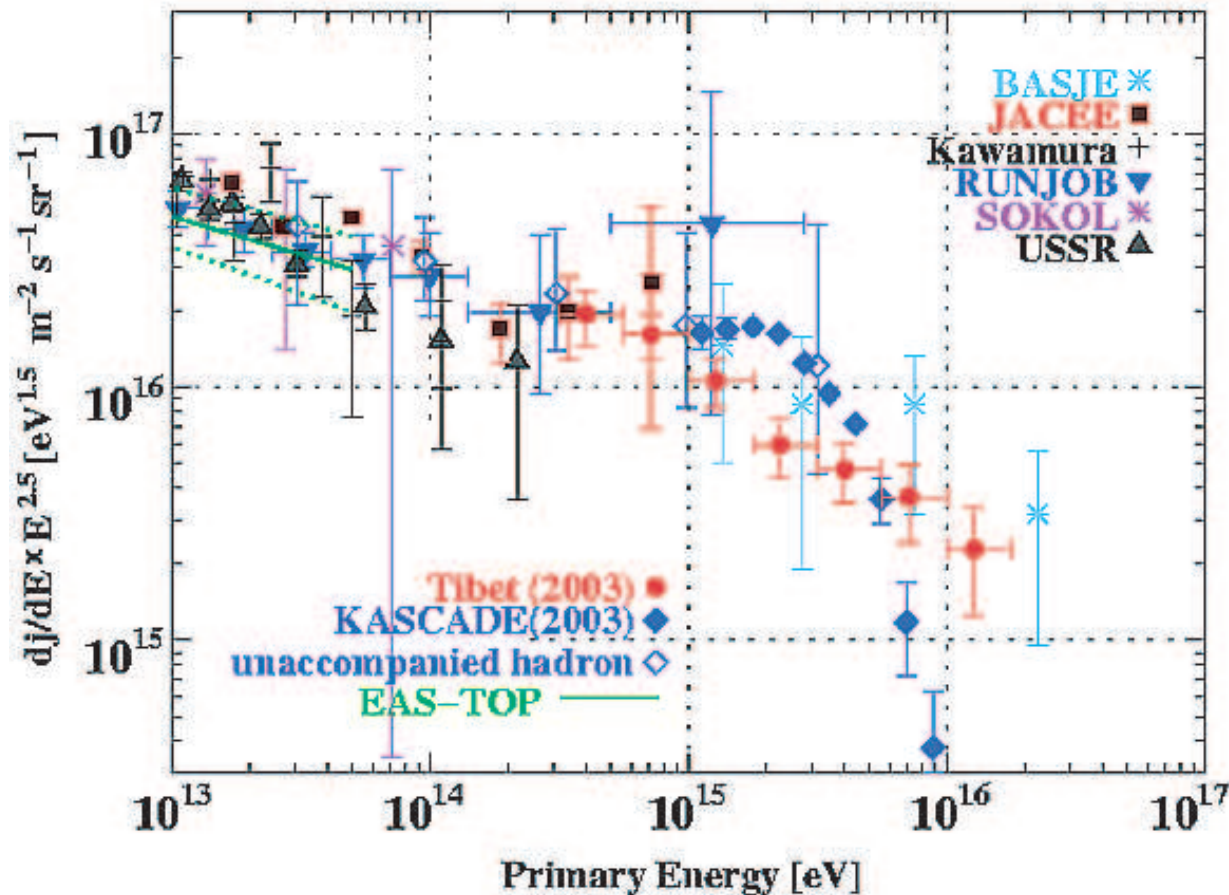
Where is the proton knee ?

different interpretations of the data

direct measurements (good proton identification, pure statistics)

TIBET experiment (163 events ! , proton selection model dependent)

KASCADE experiment (good statistics, proton selection model dependent)



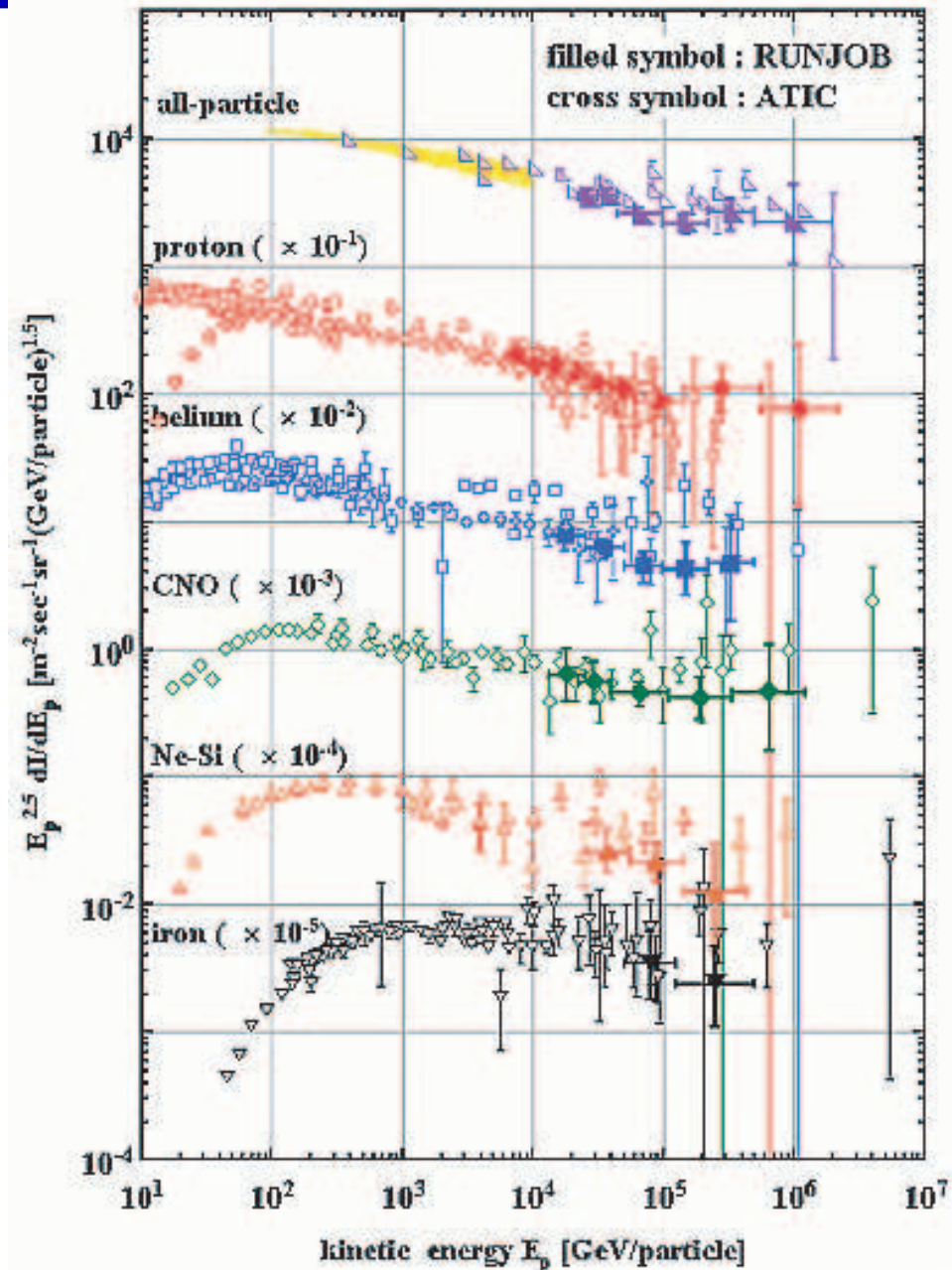
⇐ conclusion not possible with the present precision of the measurements

Direct measurements?

present situation of the knowledge:

⇐ conclusions not possible with the present uncertainties of the measurements

⇒ future: long flying balloons with larger sensitive areas (detectors of small weight)



Origin of the knee ??

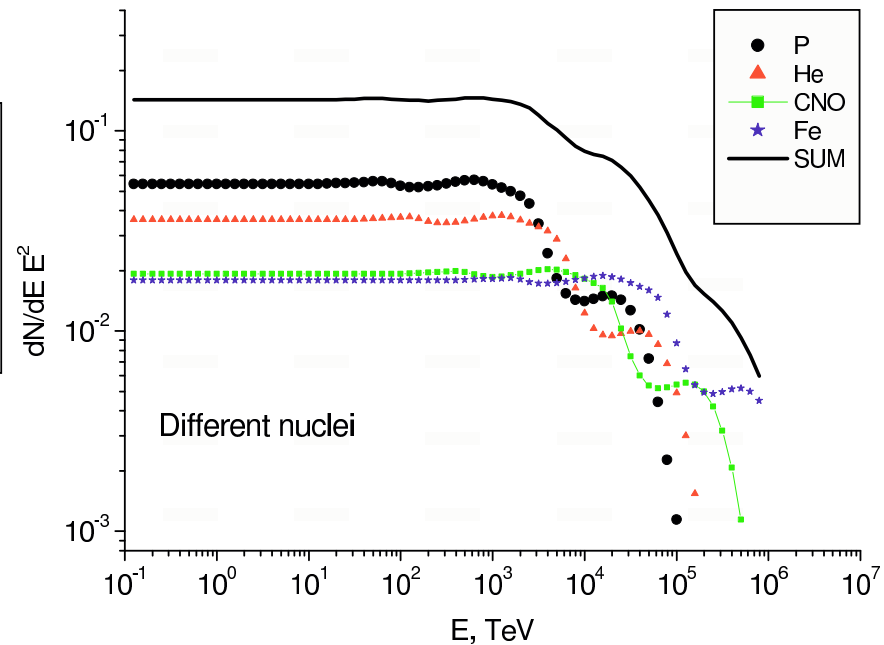
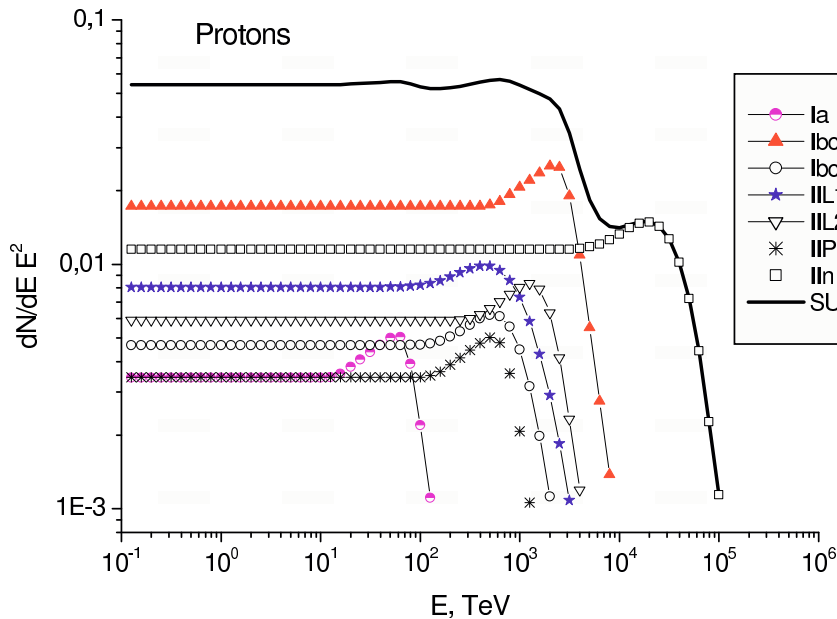
example: knee by different classes of Supernovae

L.G.Sveshnikova et al. 2003, preprint astro-ph/0303159

supernovae as source of cosmic rays

-) different classes of supernovae
-) different abundancies of the SN
 - ⇒ cutoffs at different energies
 - ⇒ source composition changes with energy

$$E_{\text{knee},A} \propto Z \times E_{\text{knee},p}$$



$$E_{\text{Knee}} \propto Z ?$$

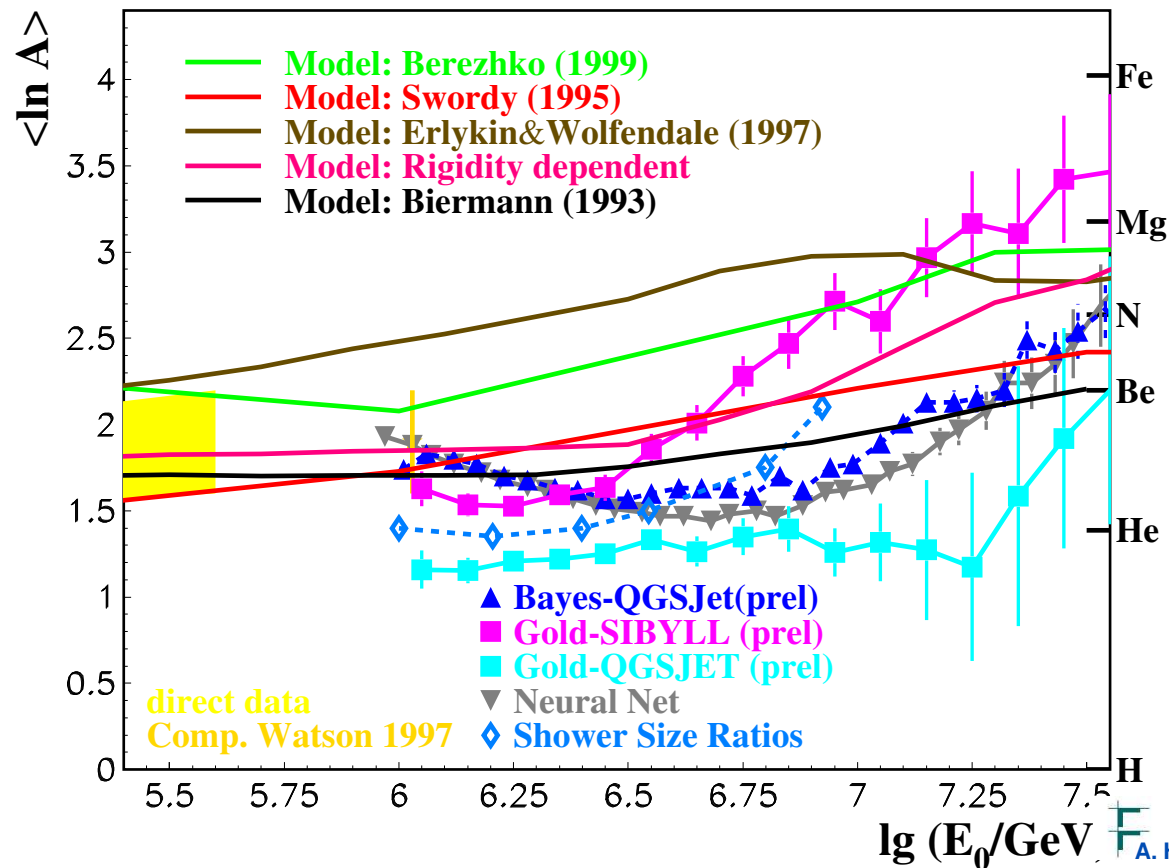
....this seems to be a reasonable supposition !

by Acceleration (max Energie at SNR) ??

or by Transport (escape from Milky Way) ??

or a mixture of both effects ??

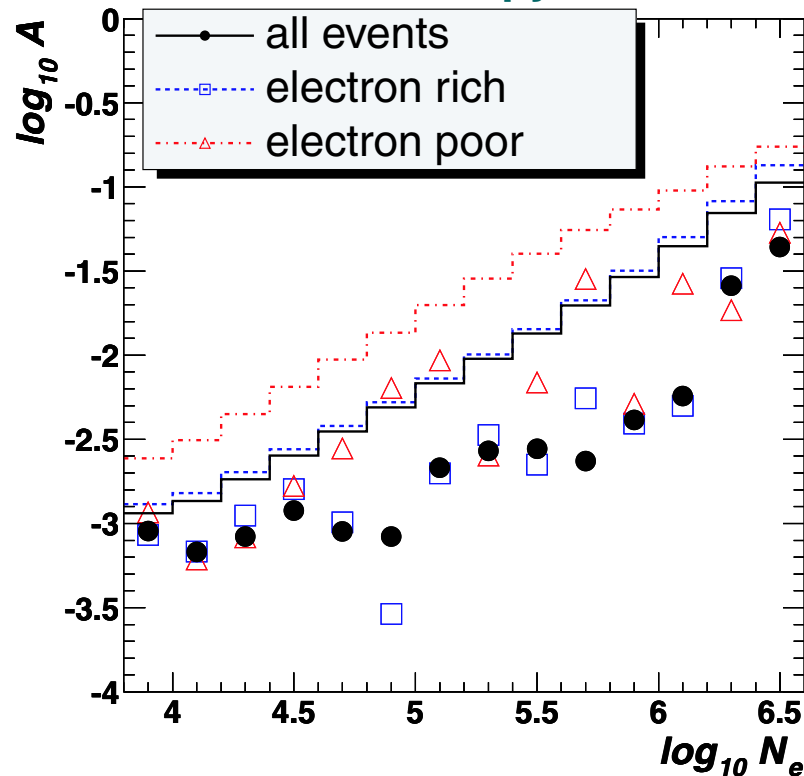
⇐ conclusion not possible without knowledge of the 'right' interaction model!



Anisotropy

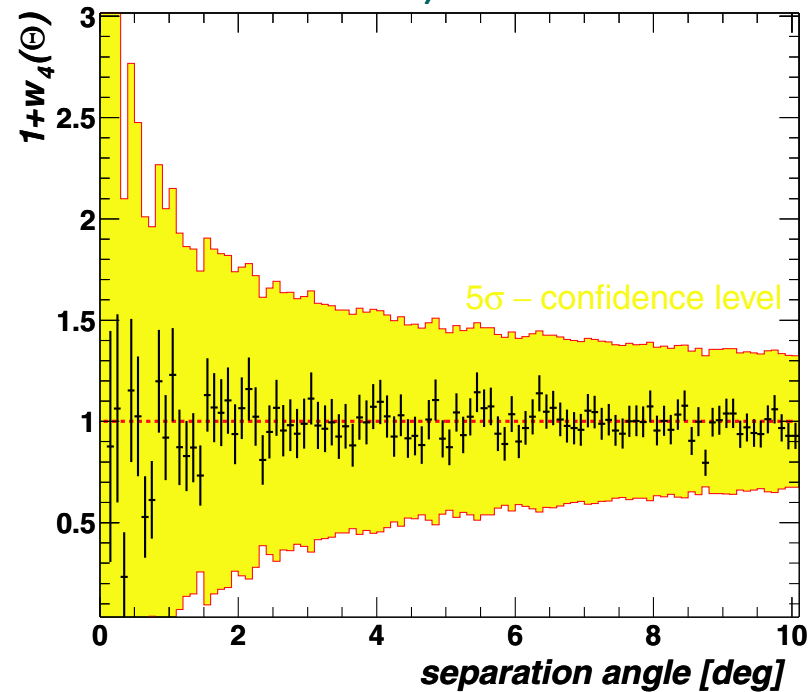
$\approx 10^8$ events are analyzed to find anisotropies separately for all events, enriched light and heavy samples, and for γ candidates (muon poor).

Large scale anisotropy:
Harmonic Analyses
 \Rightarrow no anisotropy seen



lines:
90% confidence limit of $1 - P_{fluc}$
(level of sensitivity)

Autocorrelation
of 1000 largest events
 \Rightarrow

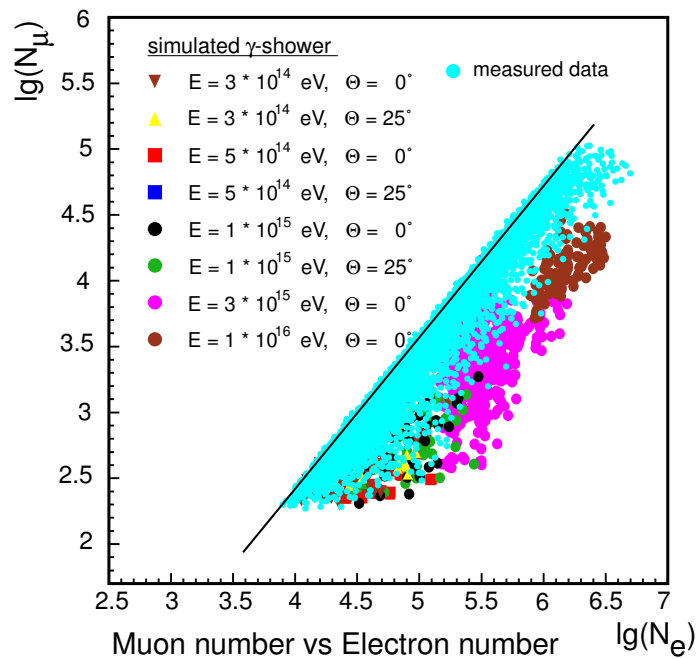


point source analysis:
 \Rightarrow no point sources seen

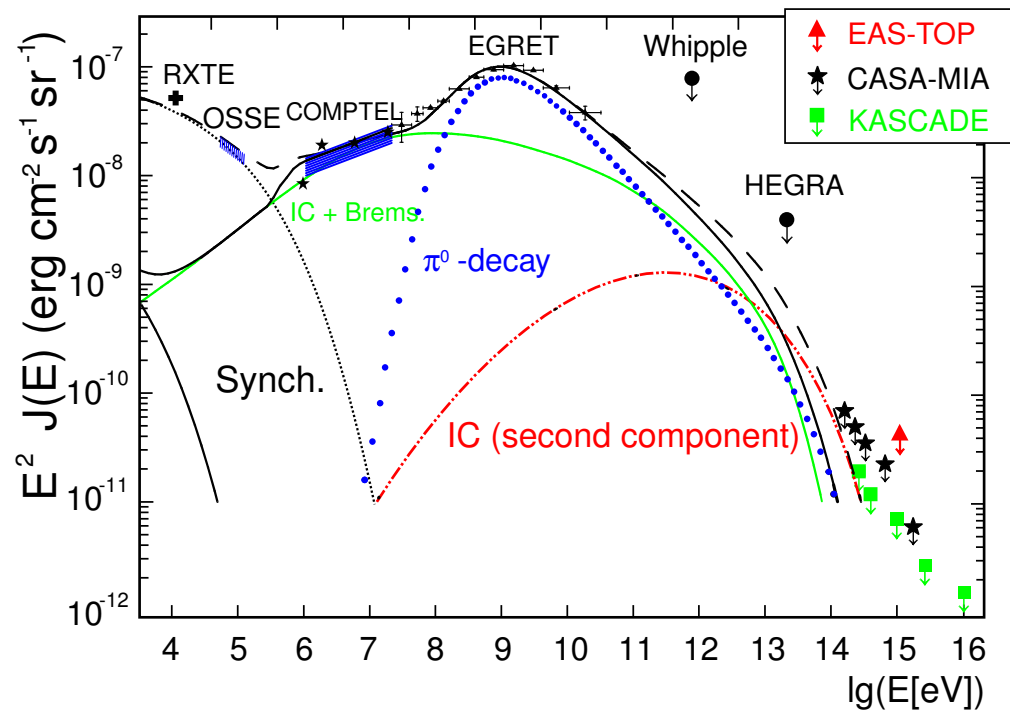
Gamma search

search for gamma induced EAS

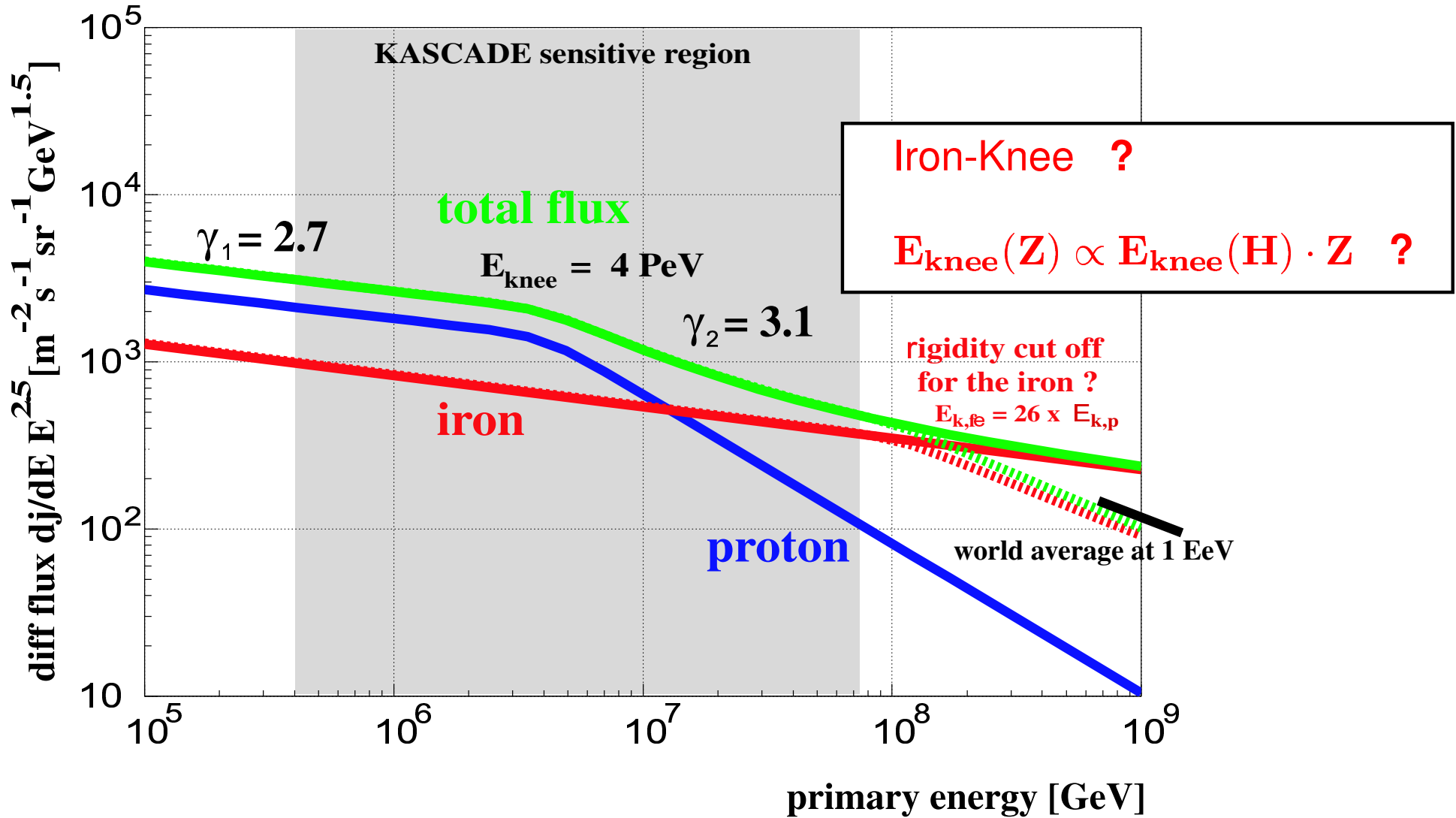
- N_μ/N_e -ratio
- slope parameter electrons
- smoothness of e-lateral distribution



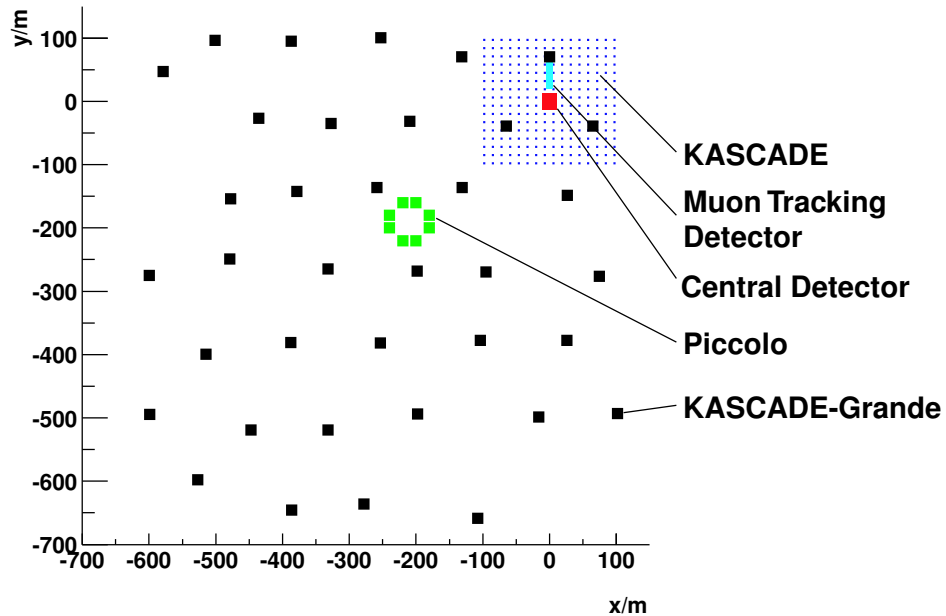
flux limits:



Motivation for KASCADE-Grande

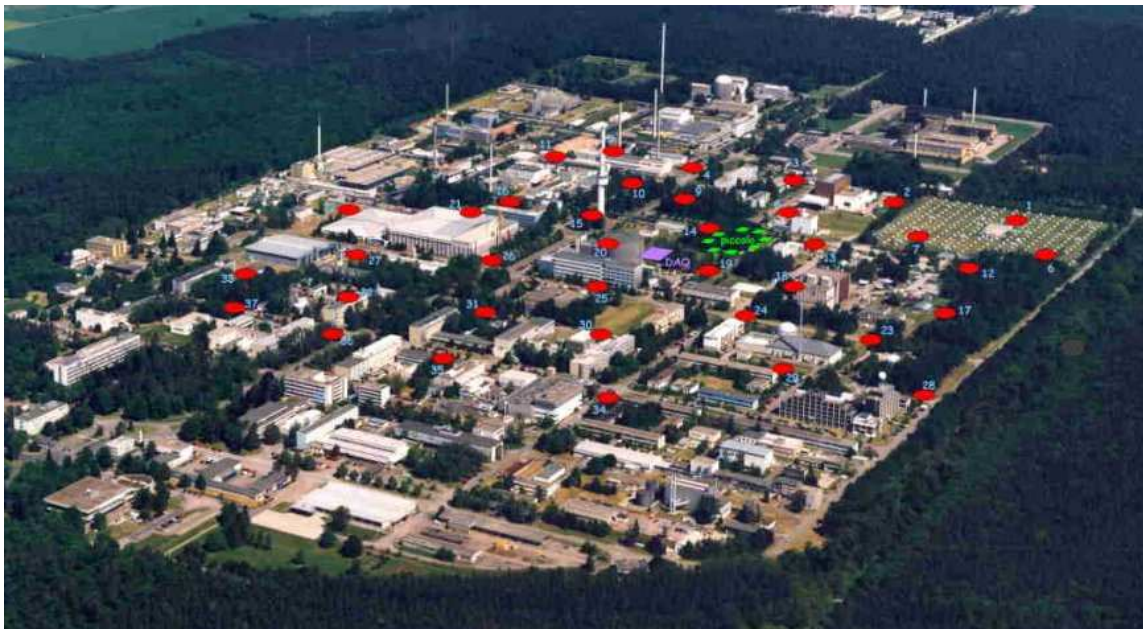


KASCADE-Grande



Grande Array:

- 37 x 10m² scintillator stations
- Piccolo: 8 x 10m² trigger stations
- + original KASCADE



Detector areas:

- 965m² for e/ γ
- 1070m² for μ (4 thresholds)
- 300m² for hadrons

KASCADE-Grande Collaboration

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Summary (personal view)

- knee is caused by light primary elements
- composition becomes heavier above the knee
- knee position most probable varying with charge Z
- **interaction models have to be further improved**
- interaction models do not need "new" physics
- knee is by a mixture of
acceleration, reacceleration, and diffusion effects

Summary (personal view)

- knee is caused by light primary elements
- composition becomes heavier above the knee
- knee position most probable varving with charge Z

