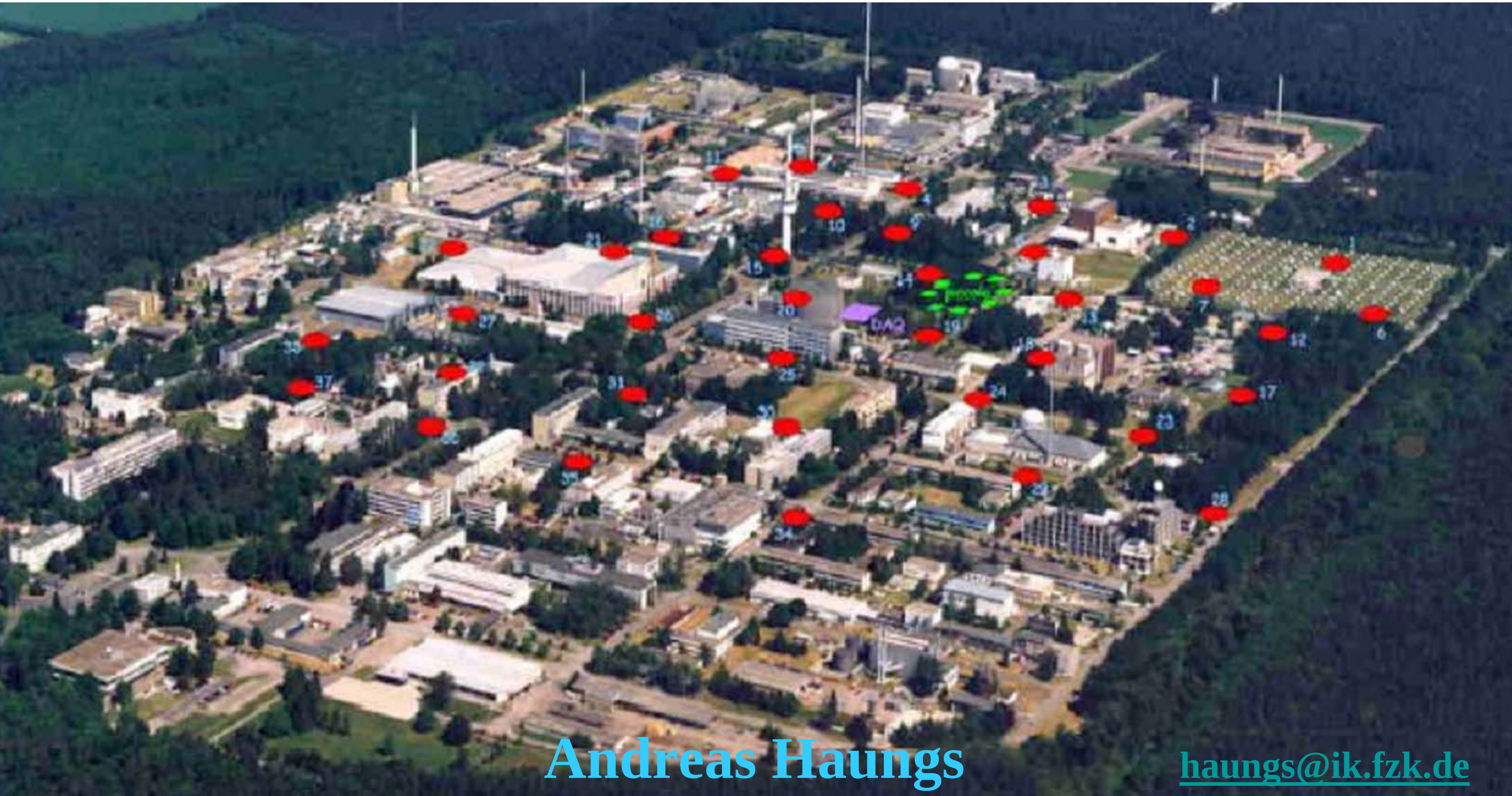
KASCADE-Grande: astrophysical results and tests of hadronic interaction models



Andreas Haungs

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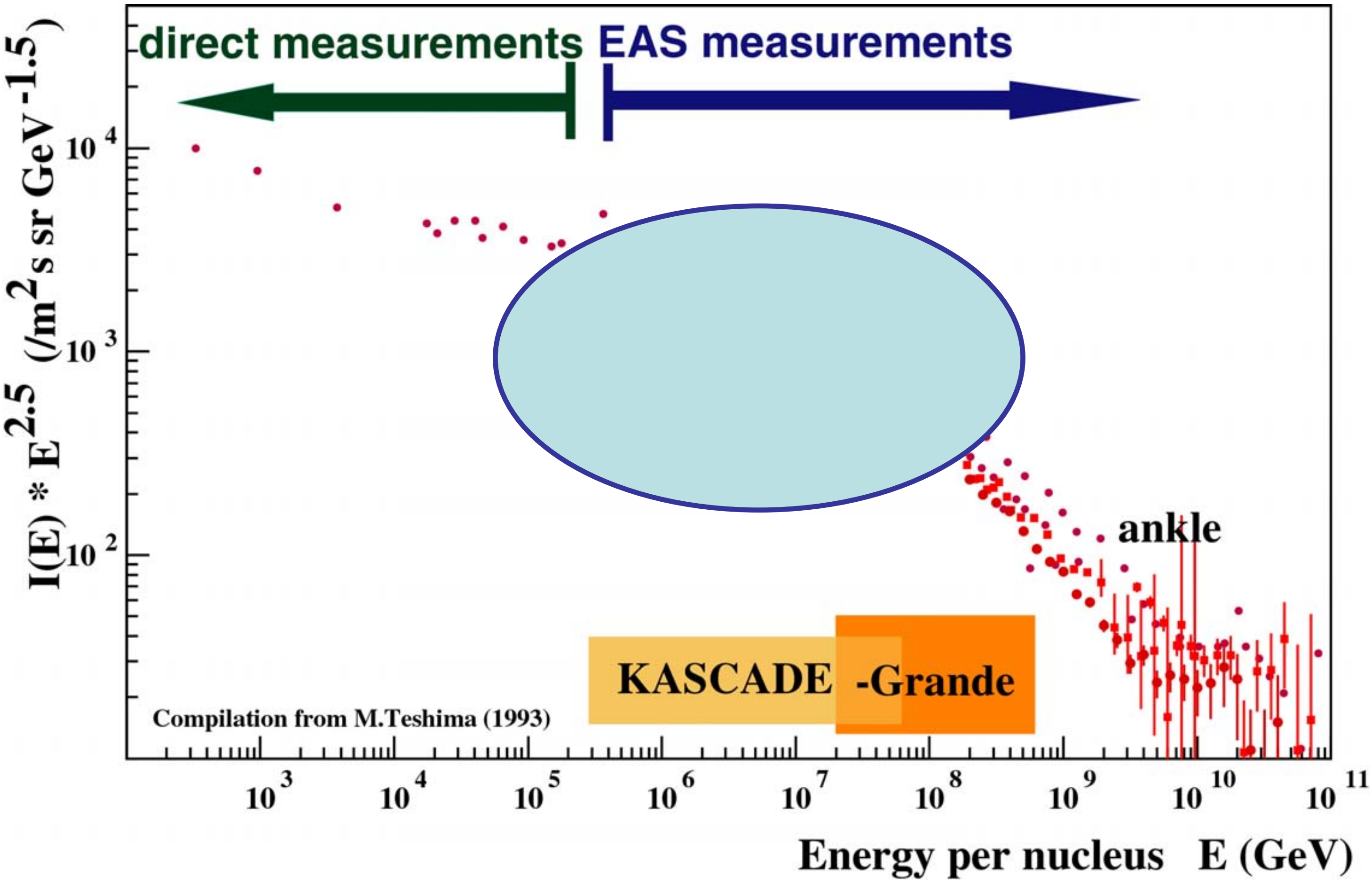
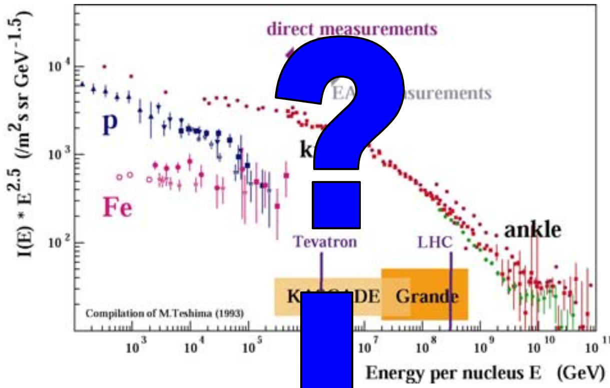
Cosmic Rays around the knee: What is the origin of the knee?

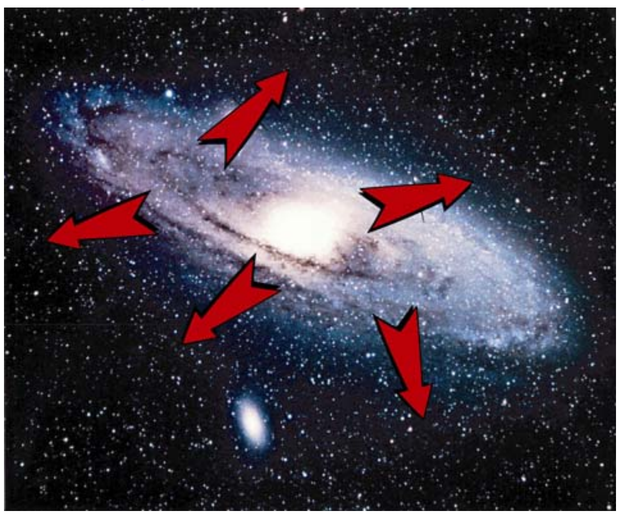


What is the origin of the knee?



various theories:

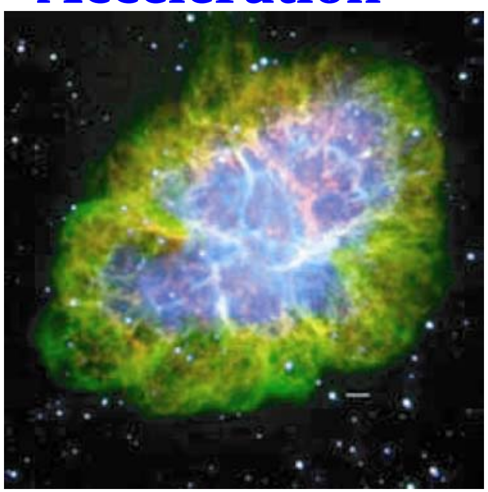
Diffusion



Escape from our Galaxy by diffusion

E(knee) ~ Z

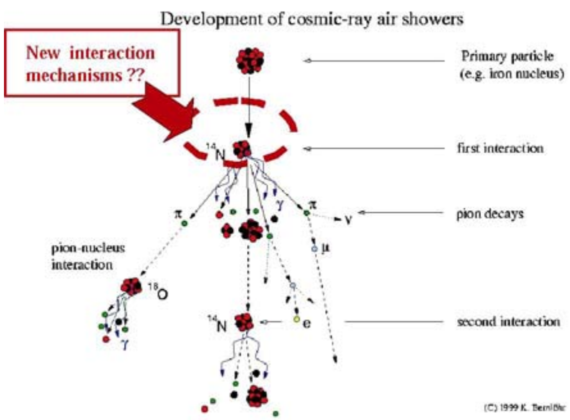
Acceleration



Reach of maximum energy at the acceleration

E(knee) ~ Z

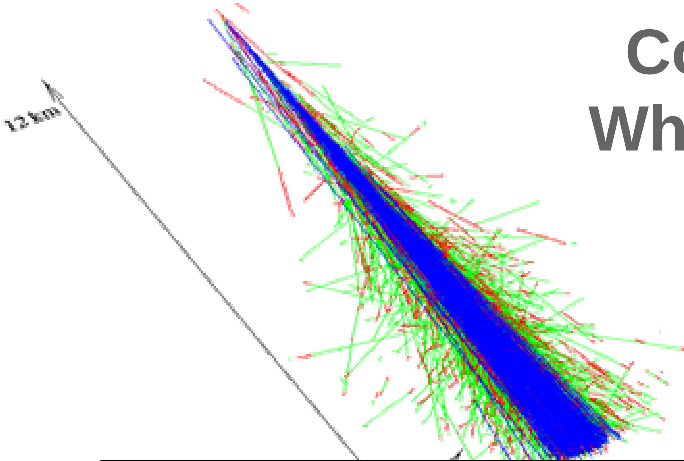
Interaction



Unknown effects of interactions at the air-shower development

E(knee) ~ A

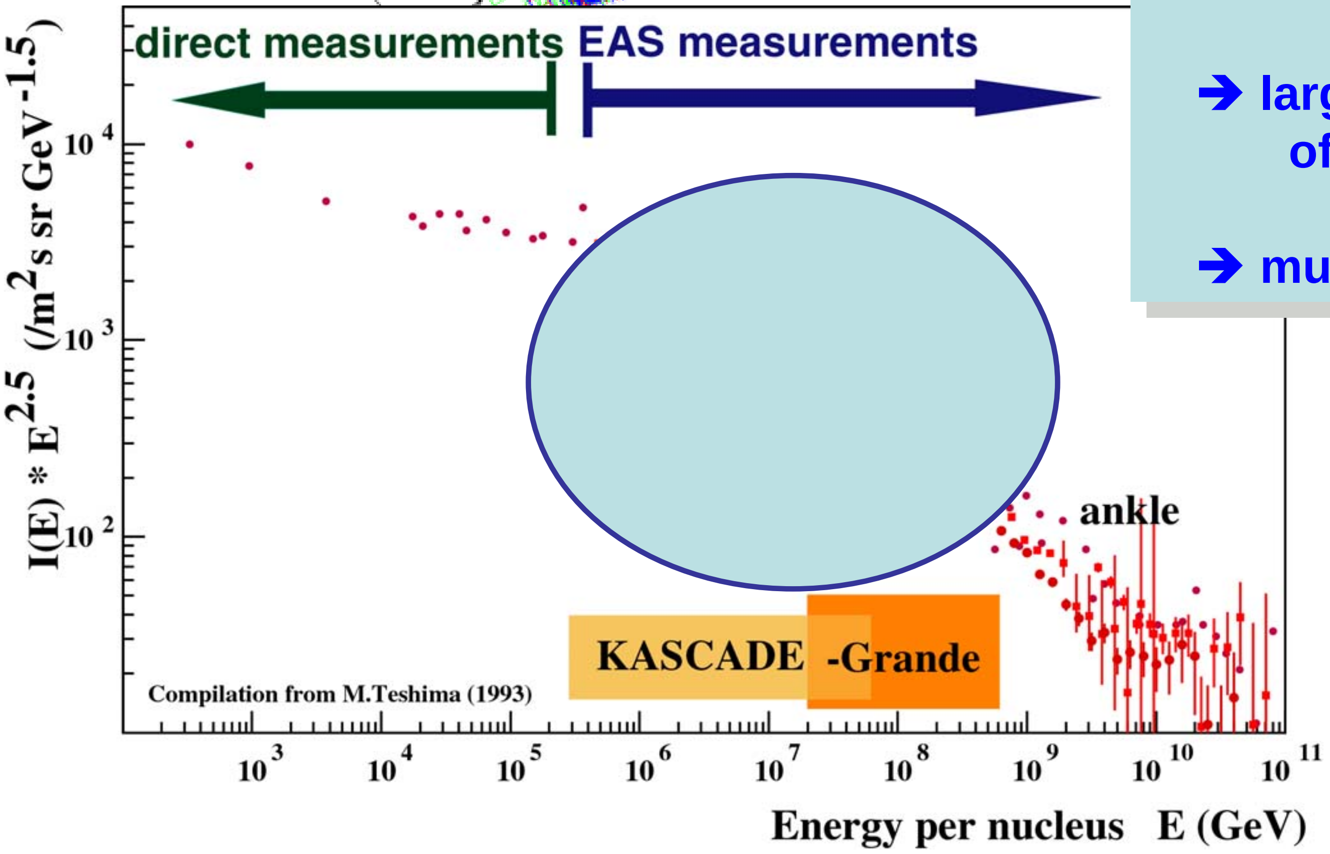
Cosmic Rays around the knee:
What is the origin of the knee(s)?



- energy ?
- mass ?
- arrival directions ?
- interaction mechanism ?

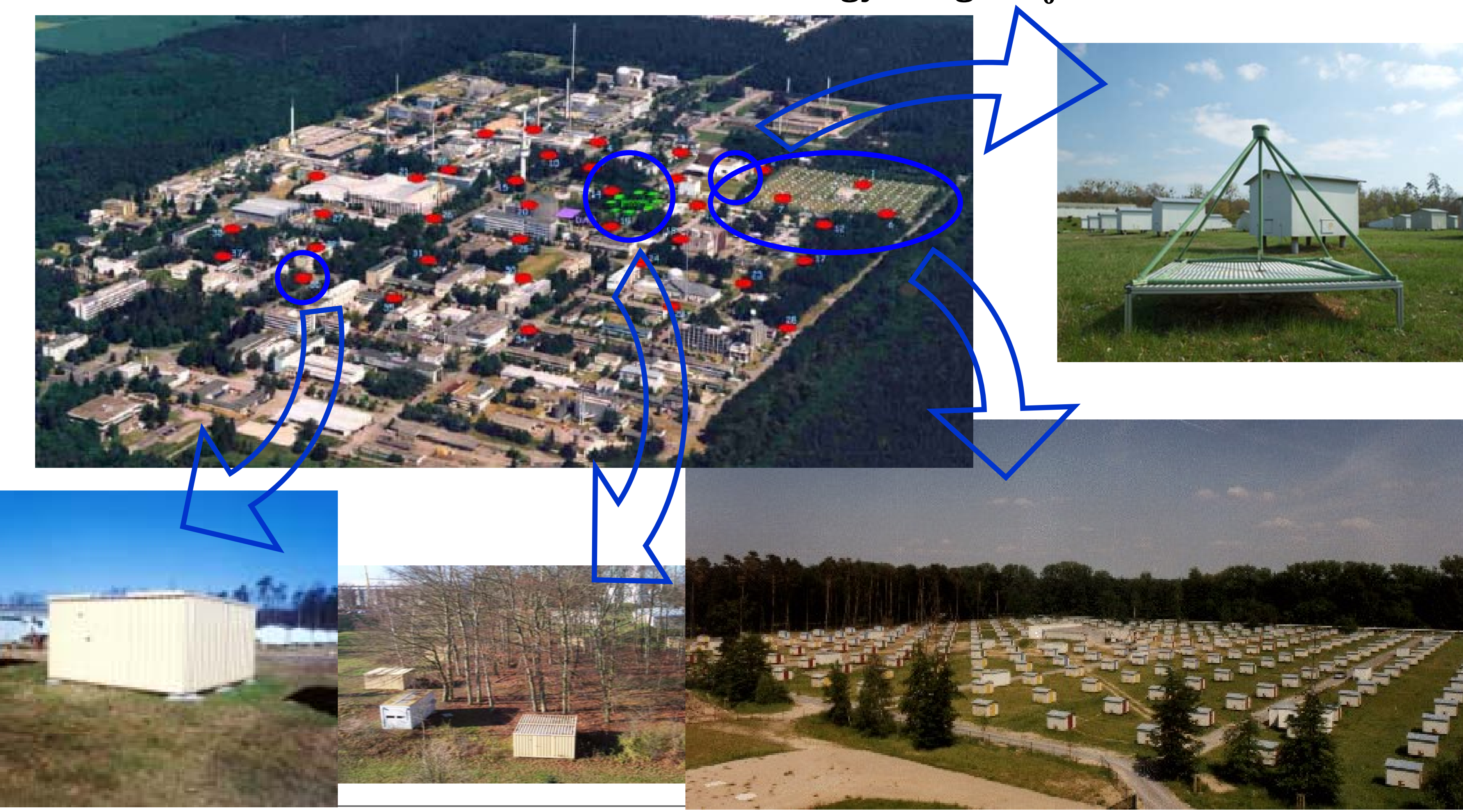
➔ large number of observables

➔ multi-detector system



KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV

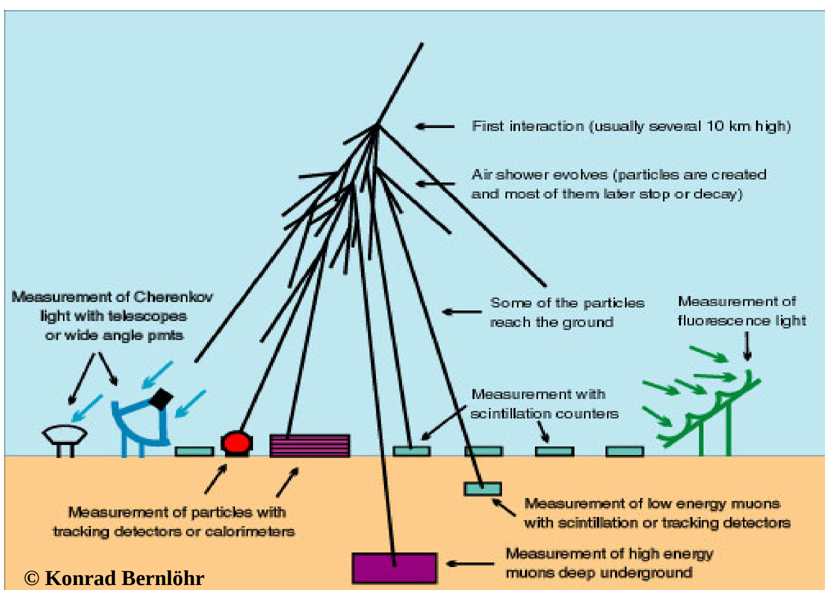


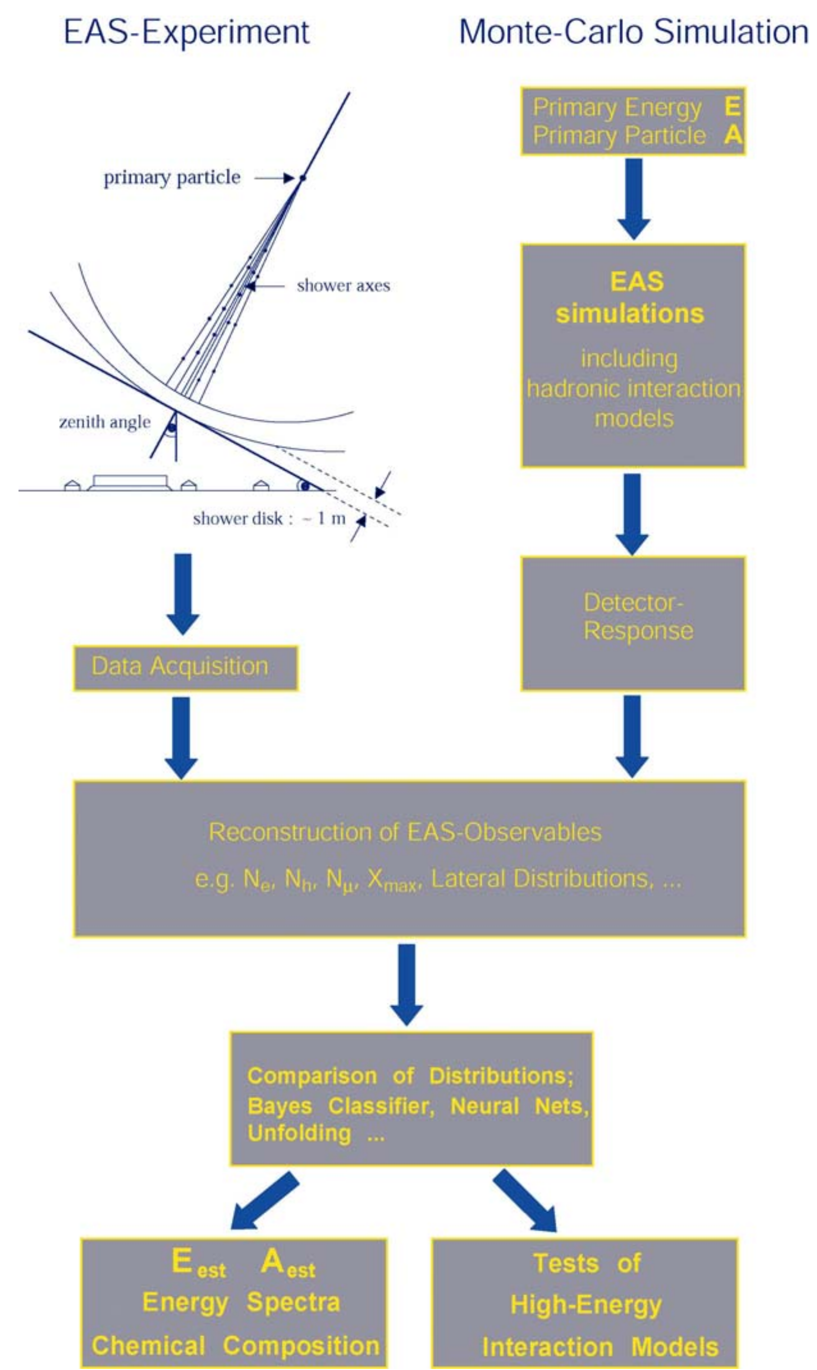
Concept KASCADE-Grande

Measure shower parameters as much as possible

Multi-detector system to get redundant information

Disententanglement of the threefold problem: E, A, interaction





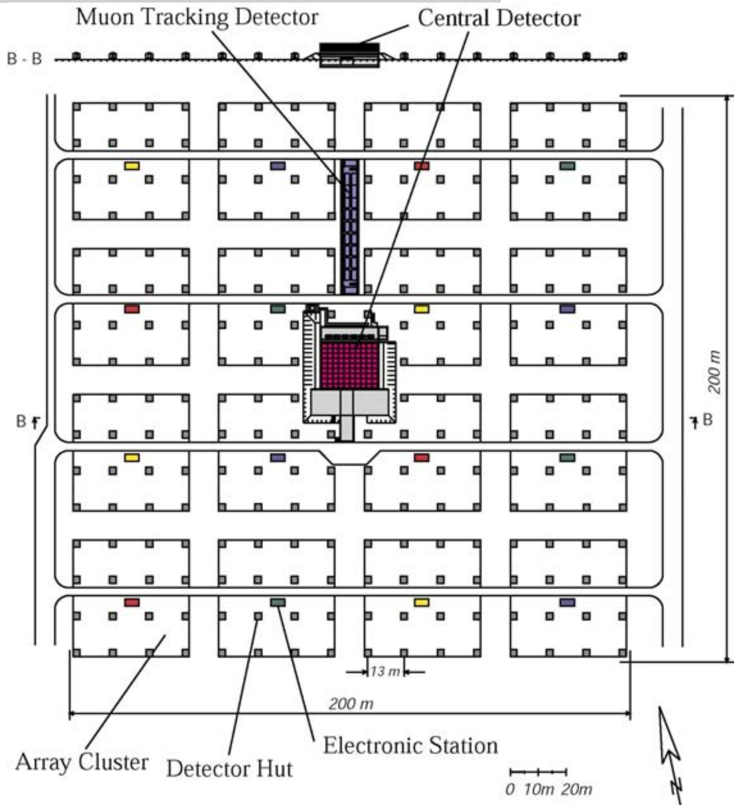
KASCADE :
multi-parameter measurements

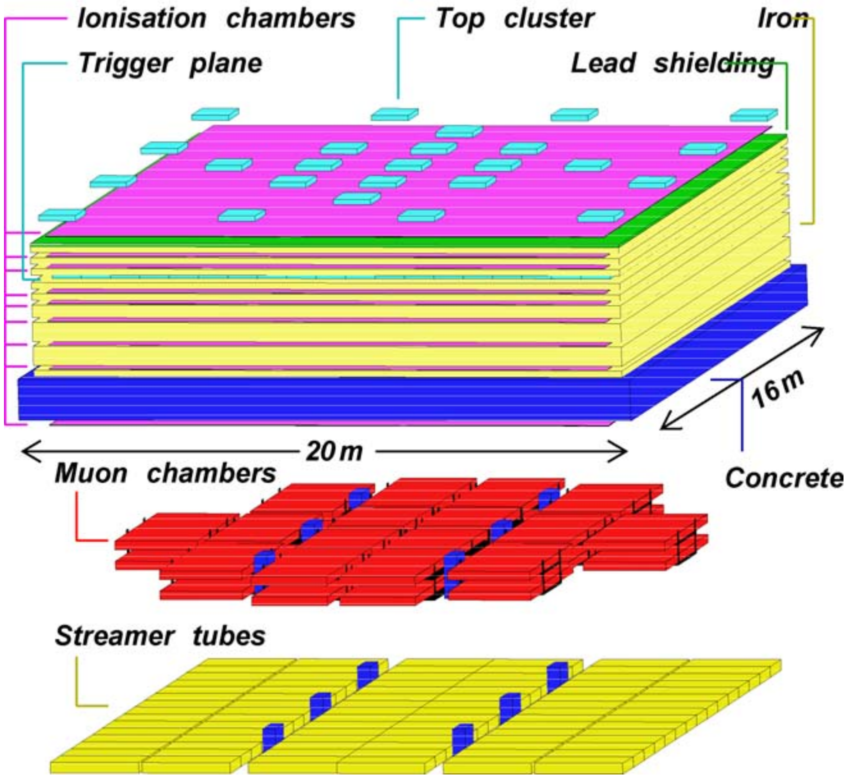
- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
  - ➔ electrons
  - ➔ muons (@ 4 threshold energies)
  - ➔ hadrons

KASCADE :

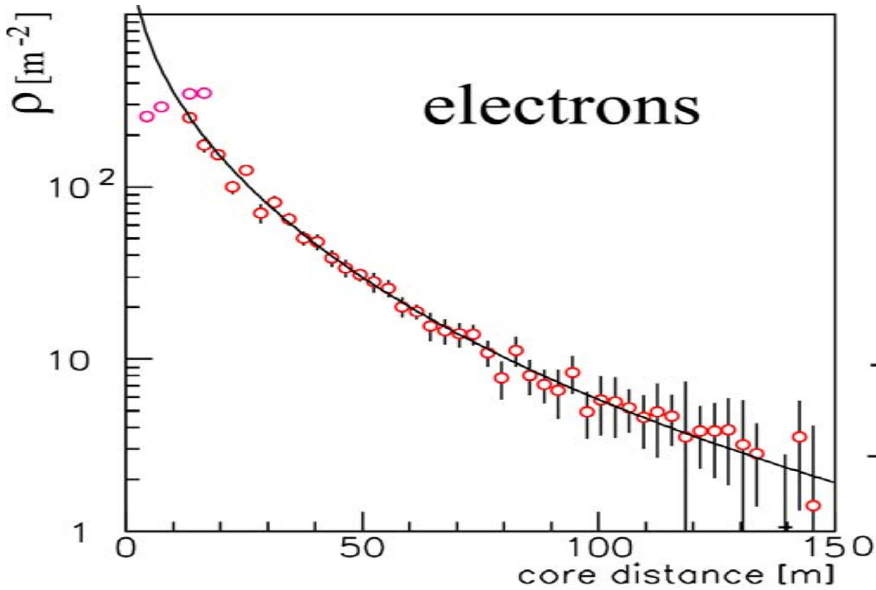
Array:
electrons
muons (230 MeV)
Tunnel:
muon tracking (800 MeV)

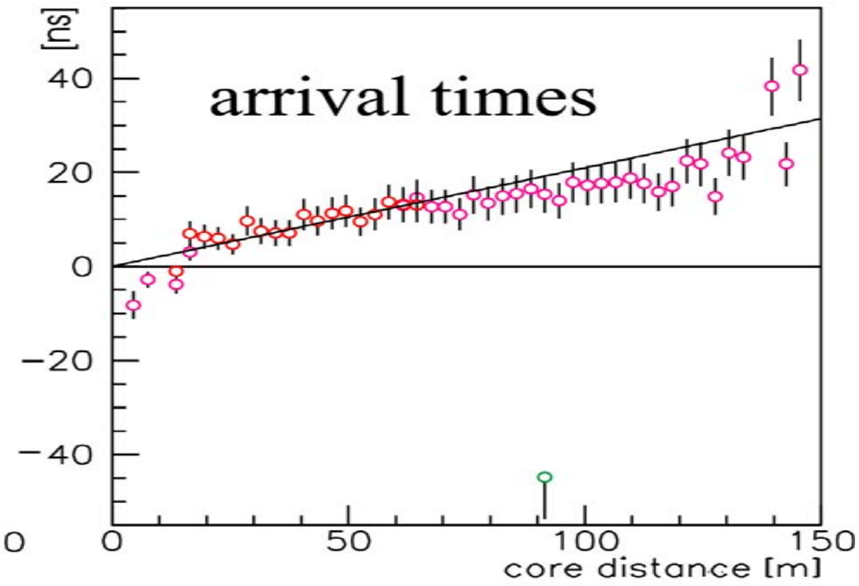
Central Detector:
hadron calorimeter
(hadrons, 50 GeV)
trigger plane
(muons, 490 MeV)
muon chambers, LST
(muons, 2.4 GeV)

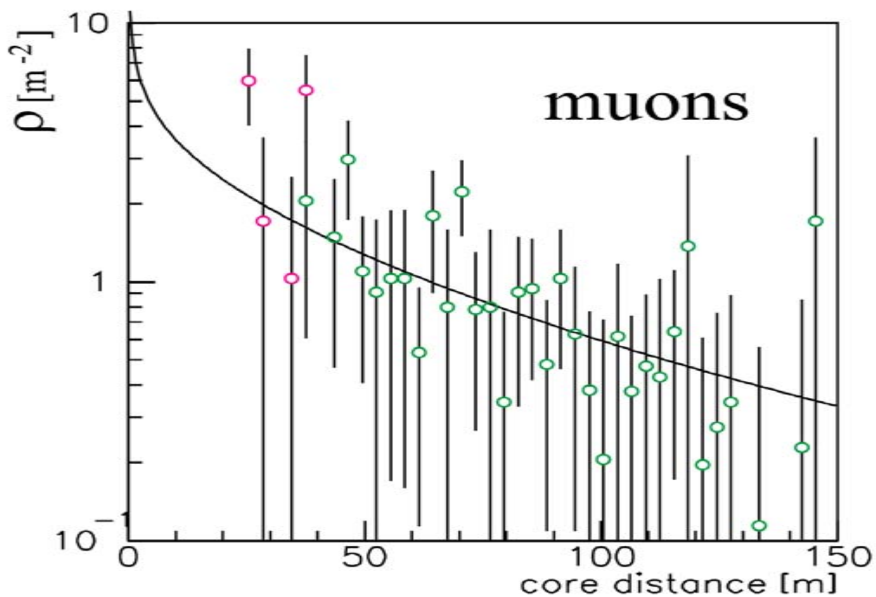




KASCADE :



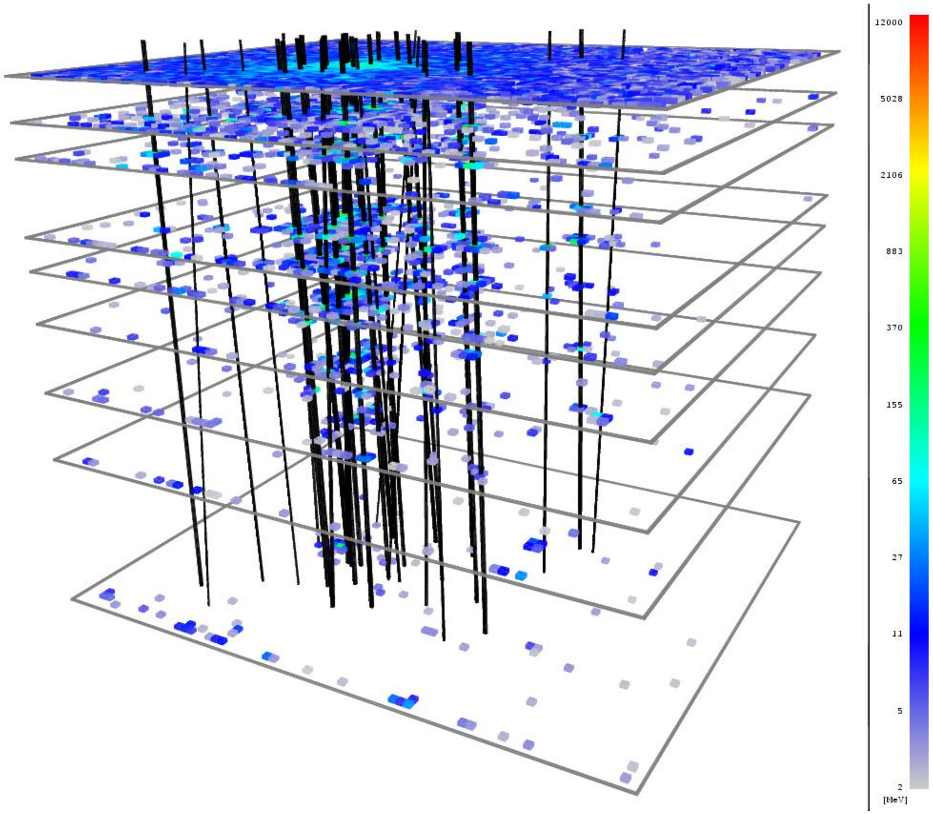




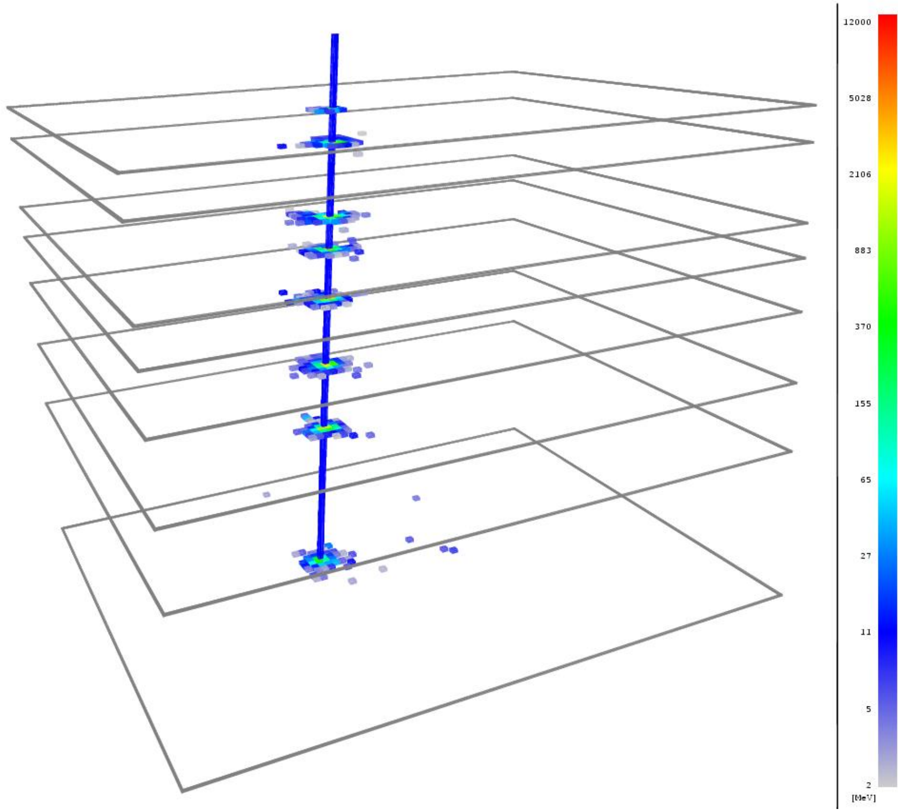
ANALYSIS RESULTS LEVEL 2			
X	Y	ϑ	φ
33.	11.	25.7	323.6

ANALYSIS RESULTS LEVEL 2				
Ne	s	N_μ^A	N_μ	s_μ
1.5E6	1.4	421	1.8E5	1.7

Eventdisplay KASCADE Calorimeter



EAS shower core



„single hadron“

observables: energy, position and direction for each reconstructed hadron

KASCADE : Observables per single air-shower !!

from detector array:

- shower direction Θ , ϕ
- shower core X_o , Y_o
- shower size N_e
- truncated (40m-200m) muon number N_μ^{tr}
- lateral particle distribution s, R_m

from calorimeter:

- number of reconstructed hadrons (E_h>100GeV) N_h^*
- sum of the reconstructed hadronic energy E_h^*
- energy of the leading hadron E_h^{max}
- parameters of the spatial hadron distributions λ,....

from MWPC-LST-system:

- number of reconstructed muons (E_μ>2.4GeV) N_μ^*
- local muon density ρ_μ^*
- parameters of hit pattern: multifractal moments D_6 , D_{-6}

from trigger plane:

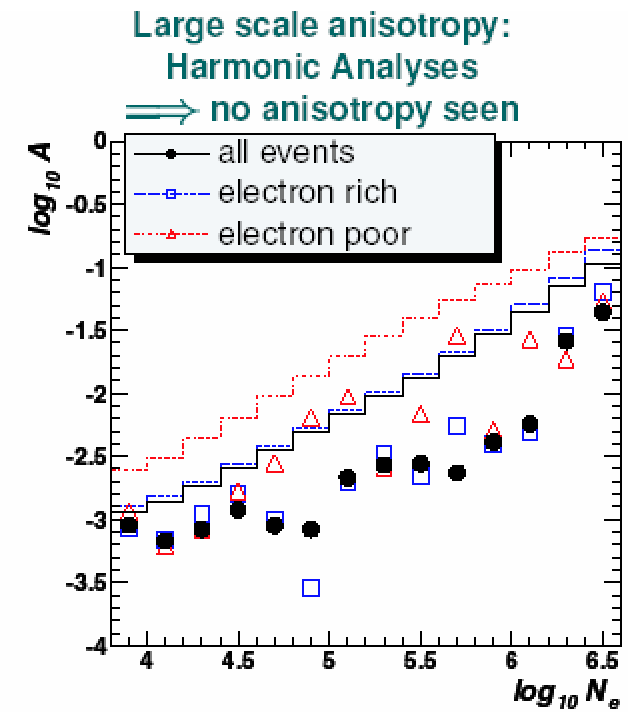
- number of reconstructed muons (E_μ>490MeV) N_μ^{tp} and ρ_μ^{tp}
- arrival times of muons τ_μ

from Muon Tracking Detector:

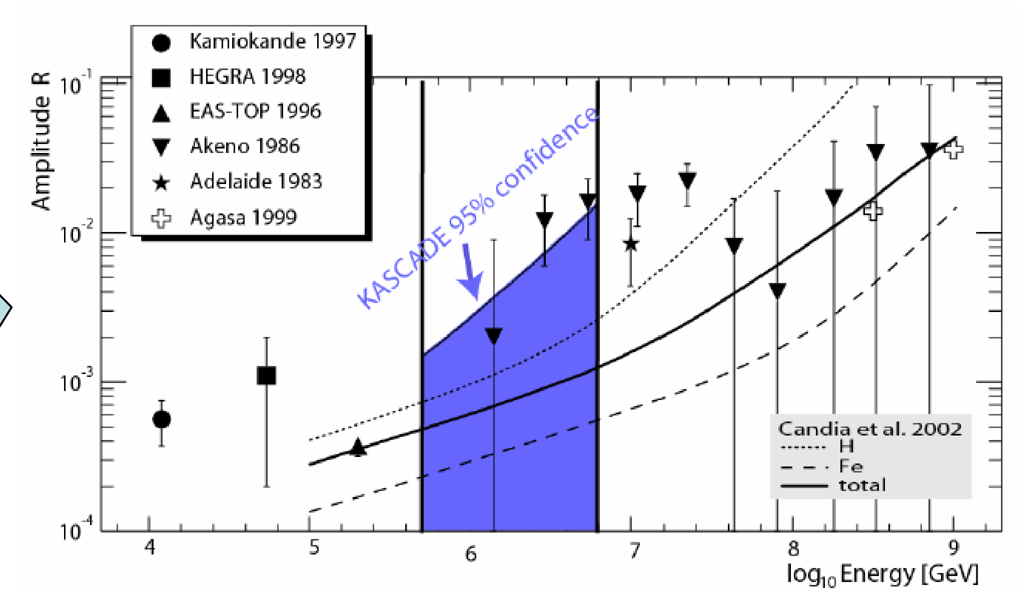
- number of reconstructed muons (E_μ>800MeV) N_μ^{mtd} and ρ_μ^{mtd}
- angel of muons: tangential and radial angle: τ_μ , ρ_μ

Analysis of large scale anisotropy of cosmic rays:

Anisotropy: different astrophysical models for the origin of the knee can be distinguished by their predictions of anisotropy



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



KASCADE (2004) Astrophysical Journal 604 p687

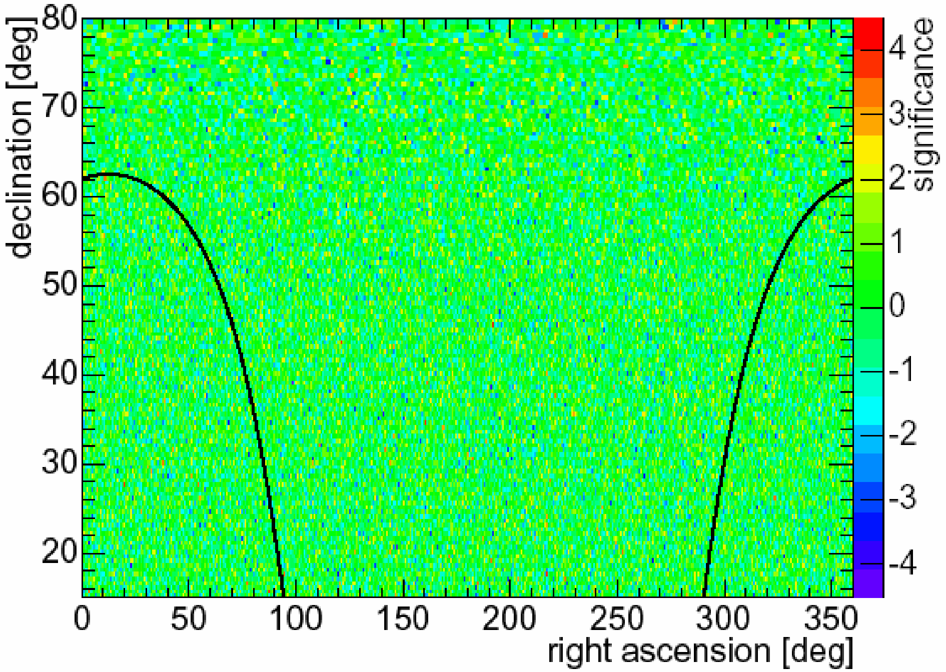
Result:
no large scale anisotropy observed
limits in Rayleigh amplitude

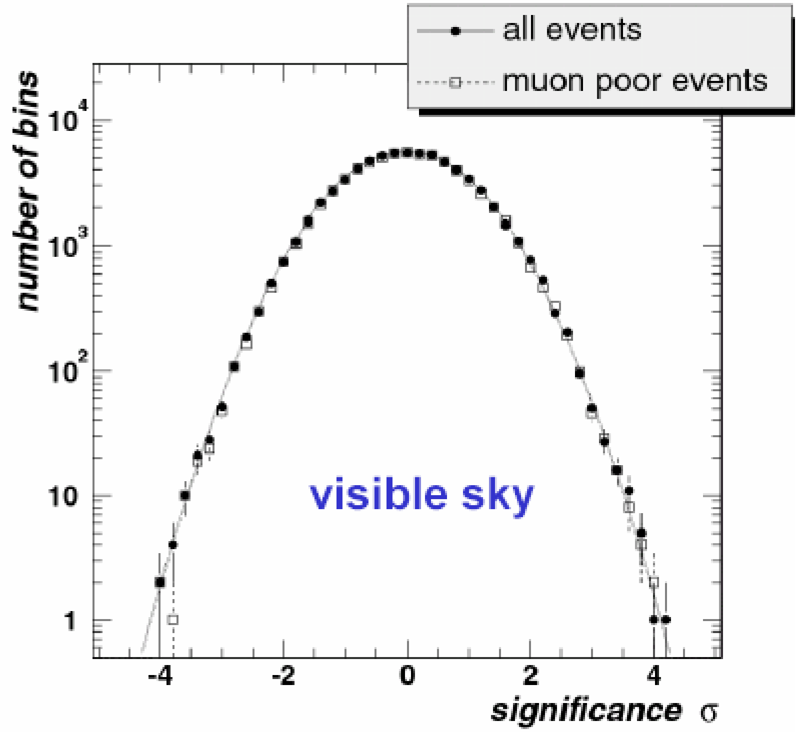
Search for point sources of cosmic rays:

Point sources: not expected at these energies, bur it have to be checked.
Muon poor events is a sample enriched by possible gamma induced showers.

$E_0 > 10^{14.5}$ eV

Li-Ma significances



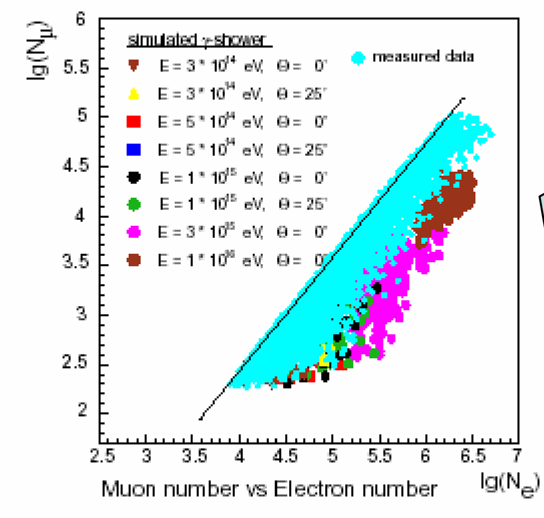


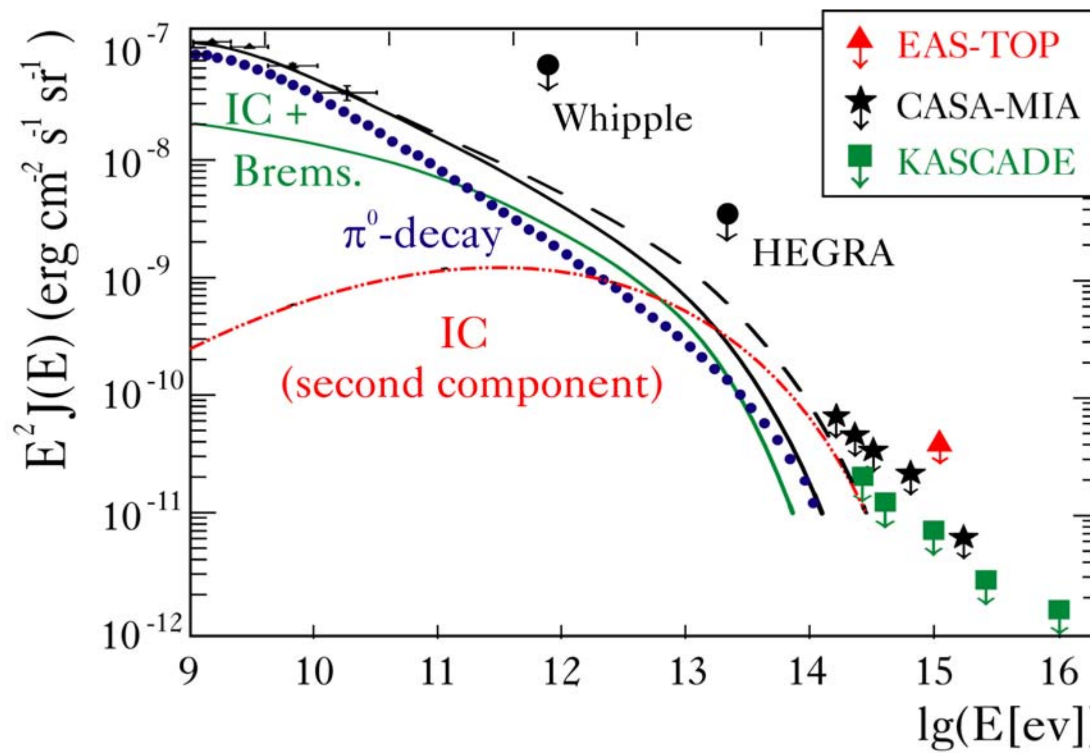
Results:
no positive signal from point sources

KASCADE (2004) Astrophysical Journal 608,p.865

Search for primary photons (diffuse Gamma-ray flux):

Primary photons: point directly to the source of cosmic rays
air-showers are muon-poor, i.e. small ratio of muon to electron number

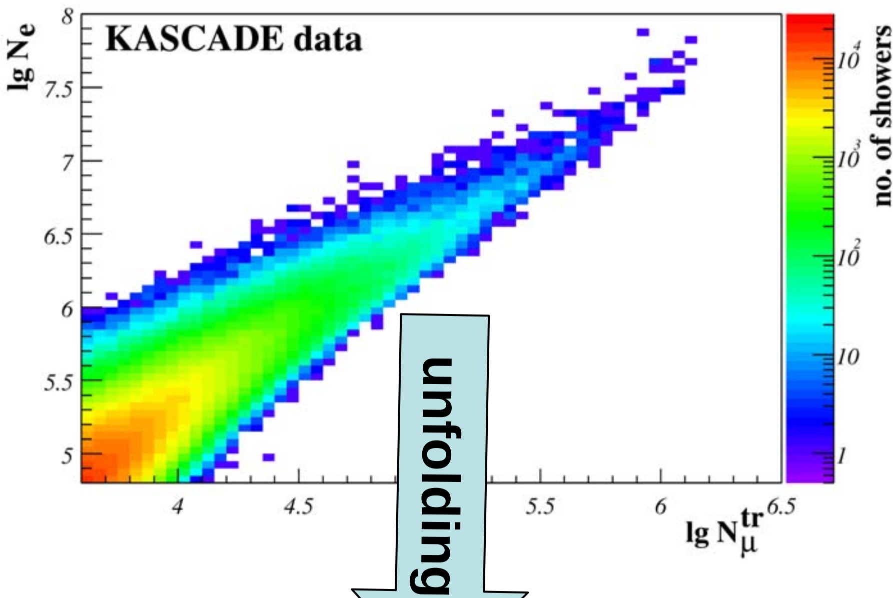


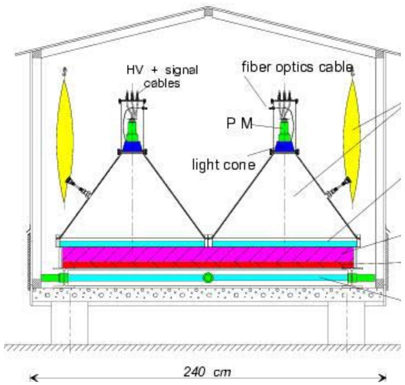


Results:
no positive signal observed
best limits for the diffuse flux

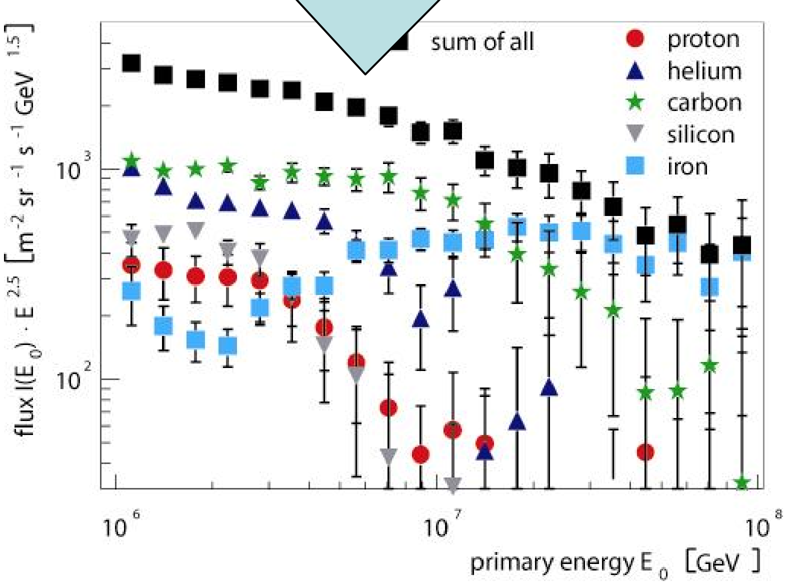
F.Feßler, PhD,
paper in preparation

KASCADE: energy spectra of single mass groups





Measurement:
KASCADE array data
900 days;
0-18º zenith angle
0-91m core distance
lg N_e > 4.8;
lg N_μ^{tr} > 3.6
➔ 685868 events



Searched:
E and **A** of the Cosmic Ray Particles
Given:
N_e and N_μ for each single event

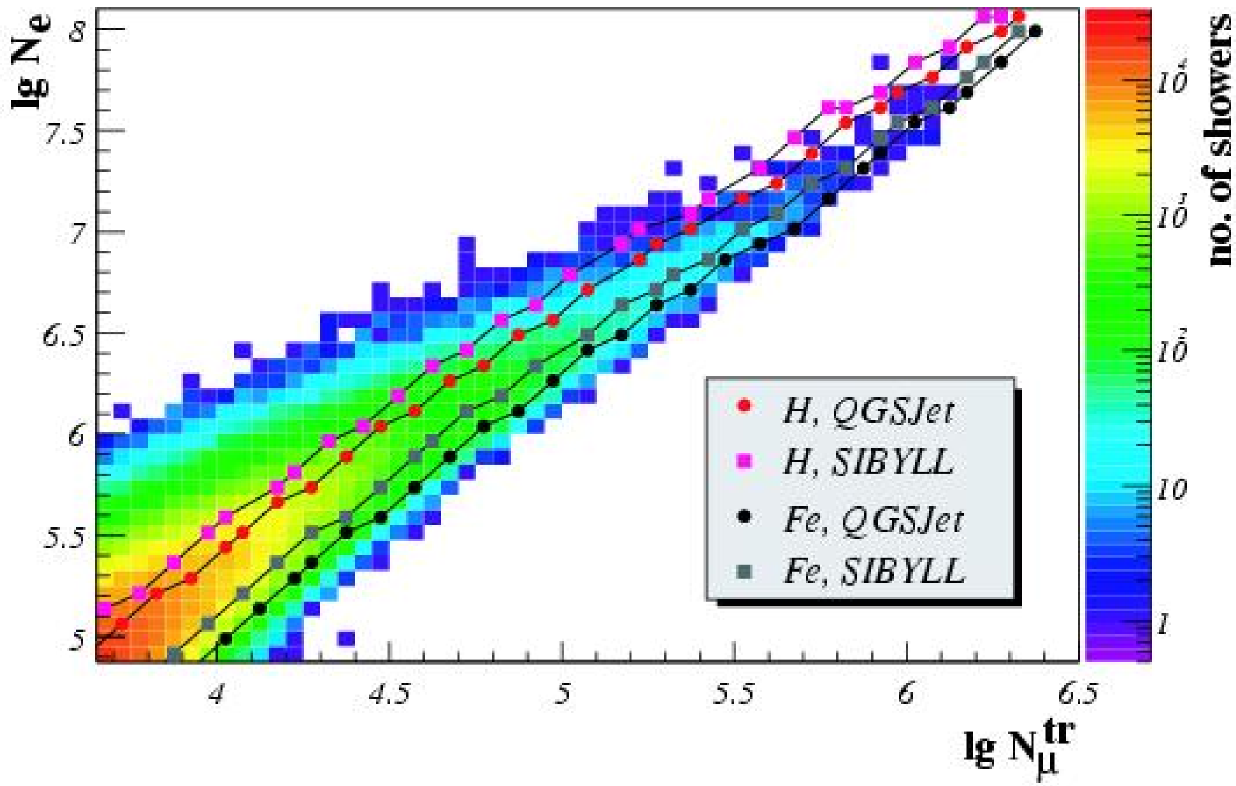
➔ solve the inverse problem

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

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

KASCADE result: sensitivity to hadronic interaction models

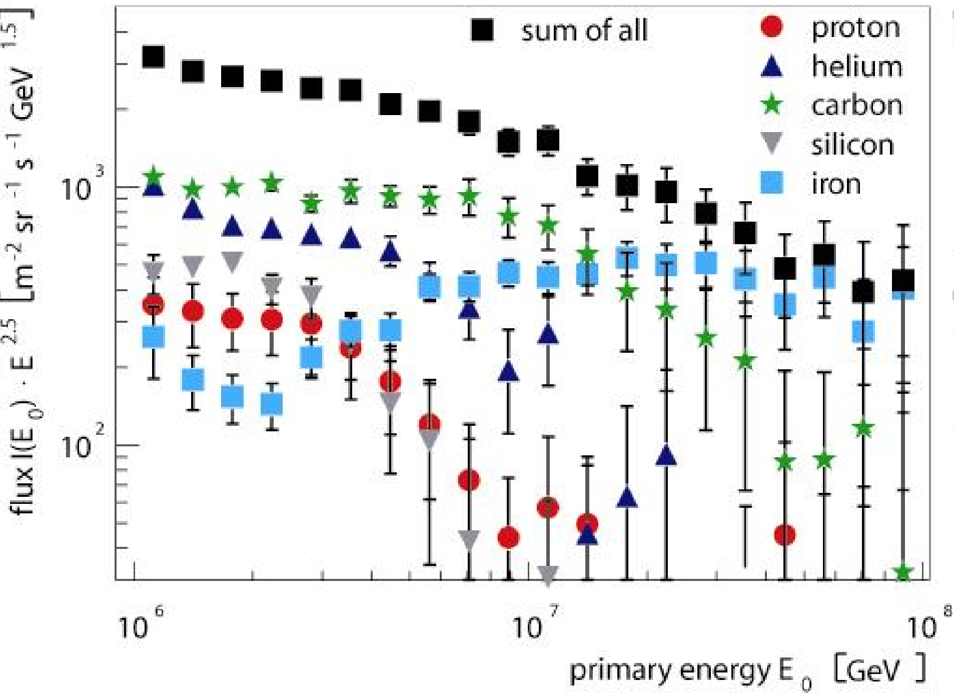
same unfolding but based on two different interaction models:
SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002)
and meanwhile also QGSJET II (with FLUKA)



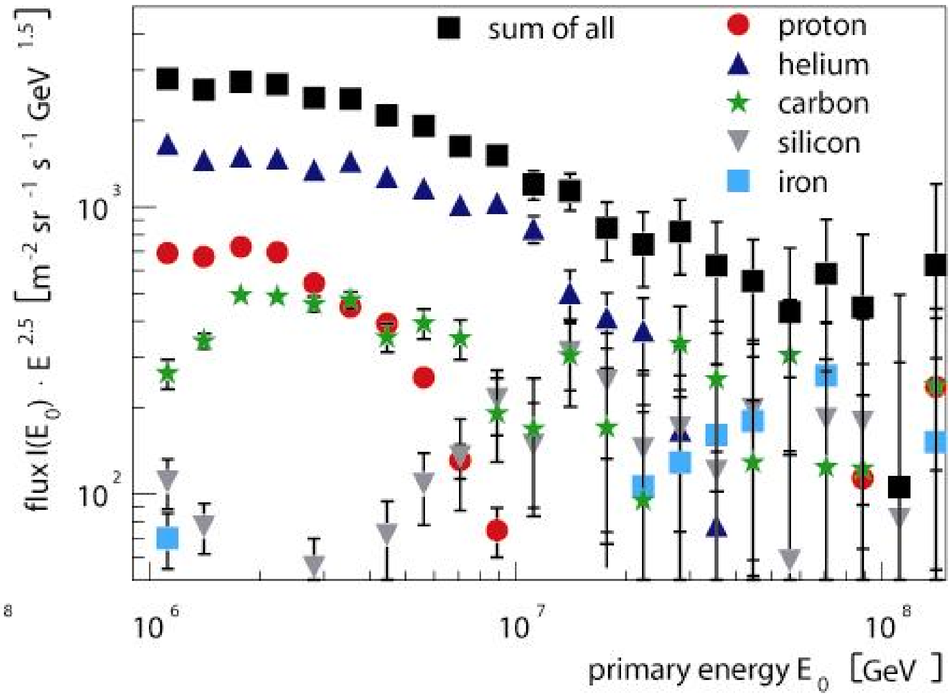
KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25

KASCADE result: influence on hadronic interaction model

SIBYLL



QGSJet



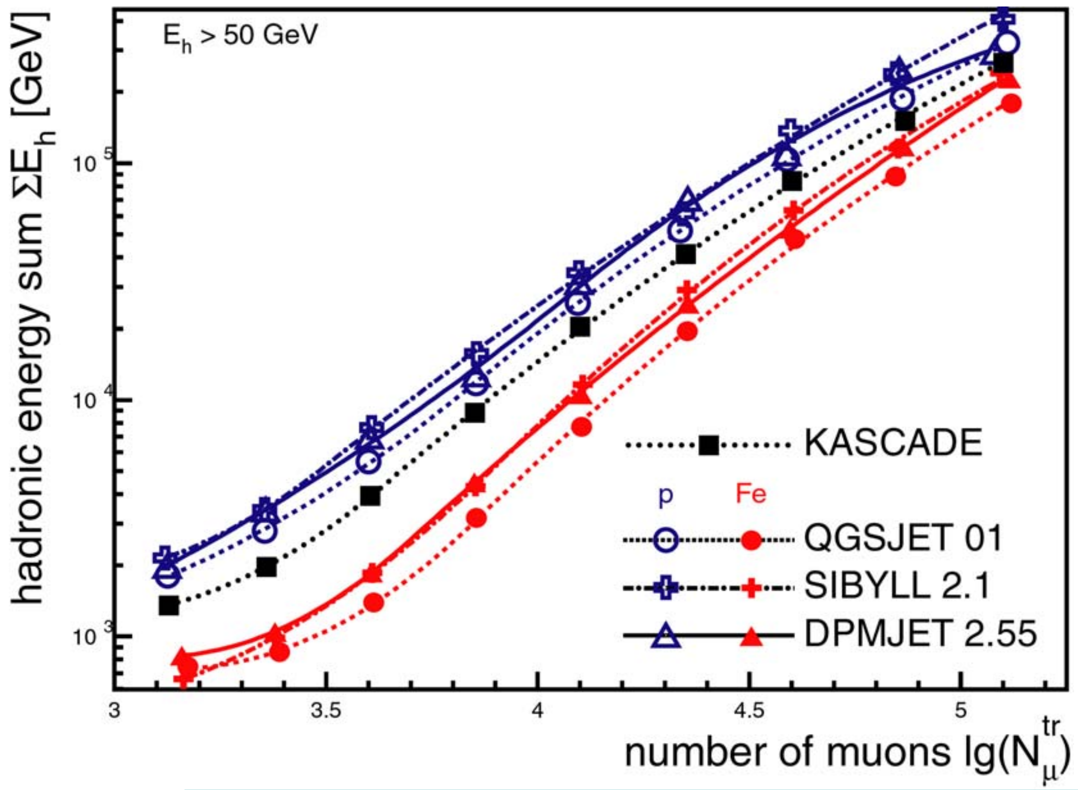
Main results keep stable independent of method or model:

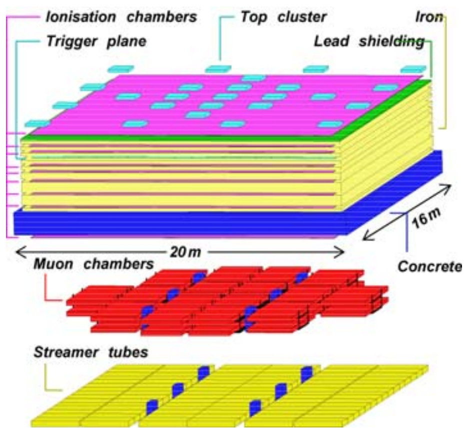
-) knee caused by light primaries

-) positions of knee vary with primary elemental group

-) no (interaction) model can describe the data consistently

KASCADE data analyses: shower observable correlations



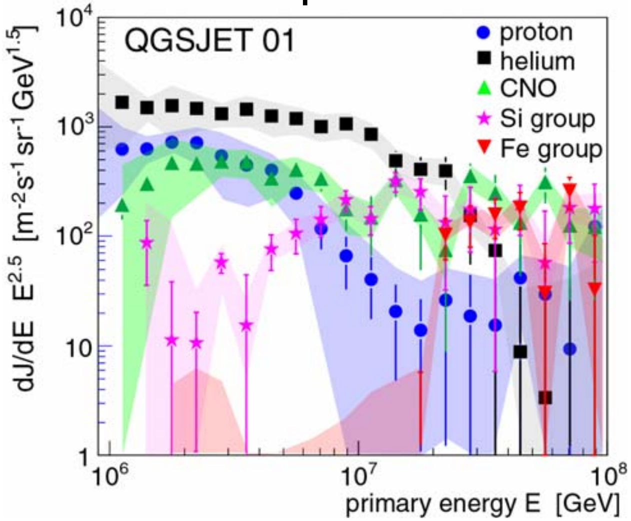


Example:
hadrons vs. muons

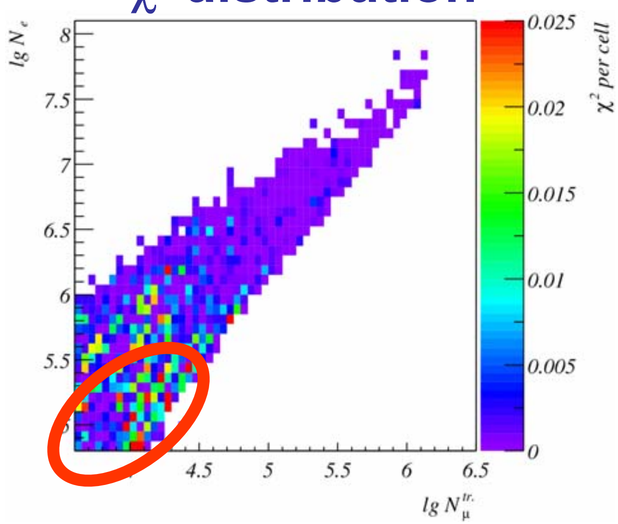
correlation of observables:
<u>no hadronic interaction model describes data consistently !</u>
➔ tests and tuning of hadronic interaction models !
➔ close co-operation with model builders

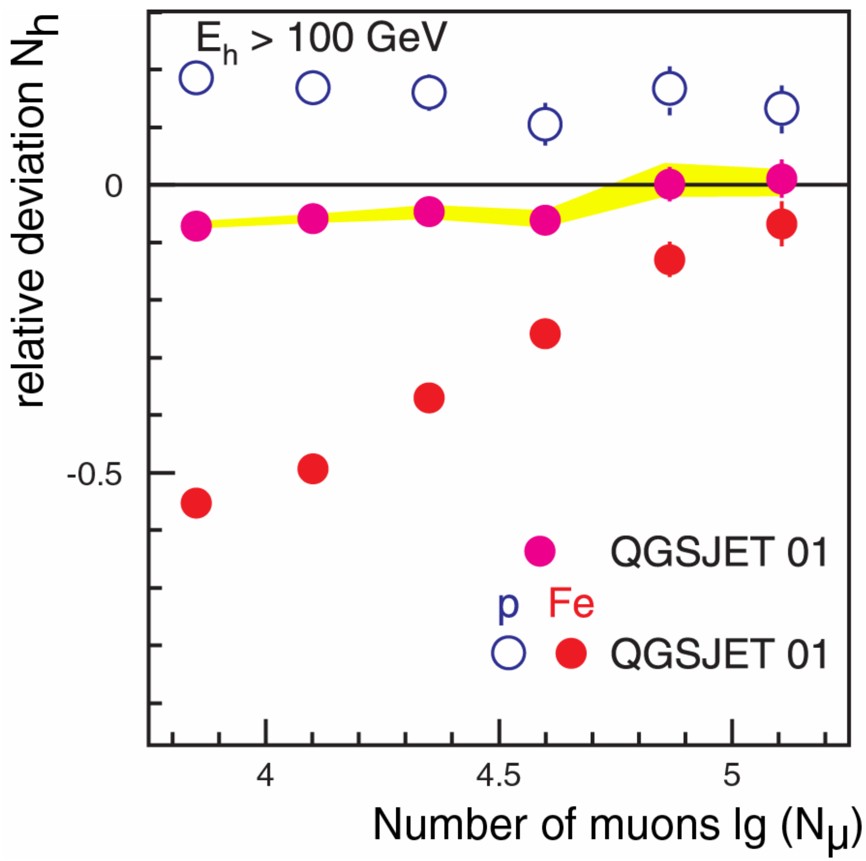
KASCADE data analyses: shower observable correlations

N_e-N_μ analysis



χ^2 distribution

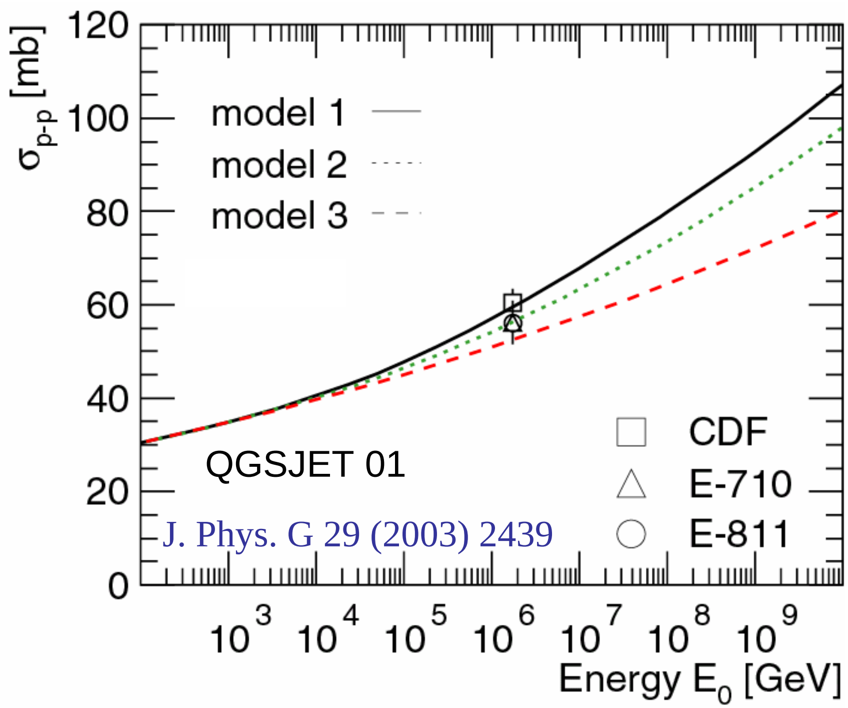


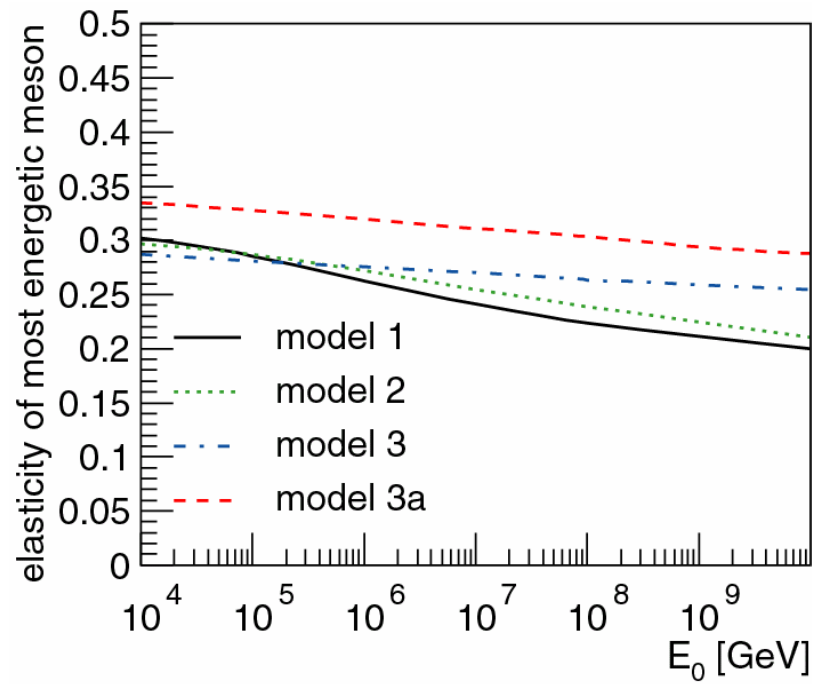


J. Milke - KASCADE-Grande, ICRC05, Pune

KASCADE: further model tests?

influence of model parameters! example: Corsika/QGSJet01/Fluka: change of cross-section and inelasticity





p-p cross section

π-N elasticity

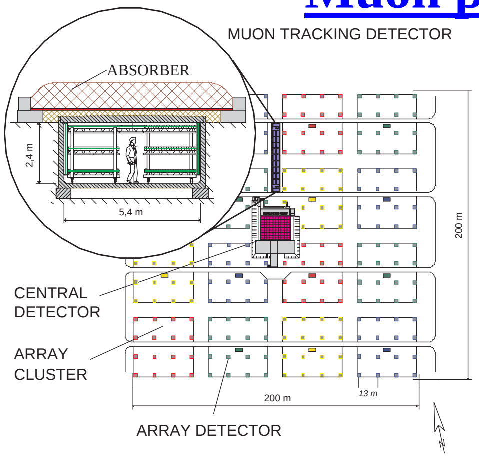
Results:

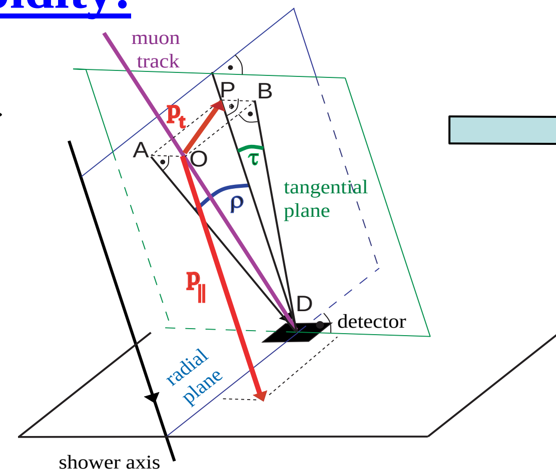
-) EAS observables change with modifications – but complex dependencies

J. Hörandel - KASCADE-Grande, ICRC05, Pune

KASCADE: further model tests?

Muon pseudorapidity!

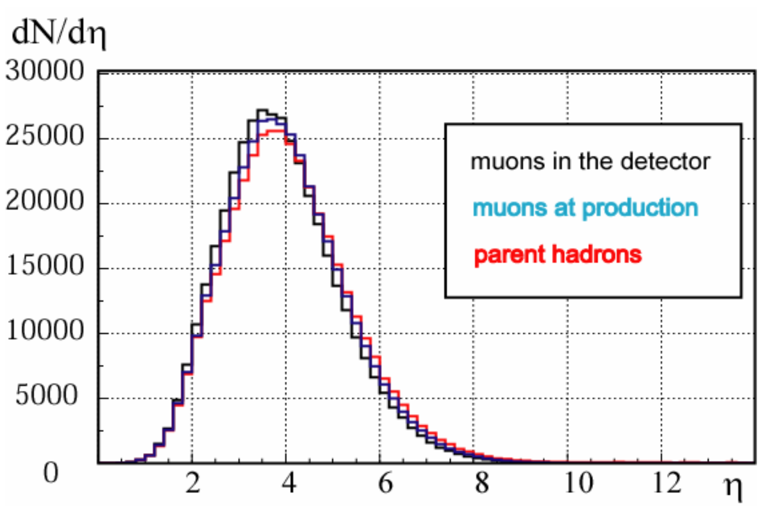




$$\zeta = \sqrt{\tau^2 + \rho^2} = \frac{p_t}{p_{\|}}$$

$$\eta = \ln \frac{2 \times p_{\|}}{p_t} = -\ln \frac{\zeta}{2}$$

pseudorapidity



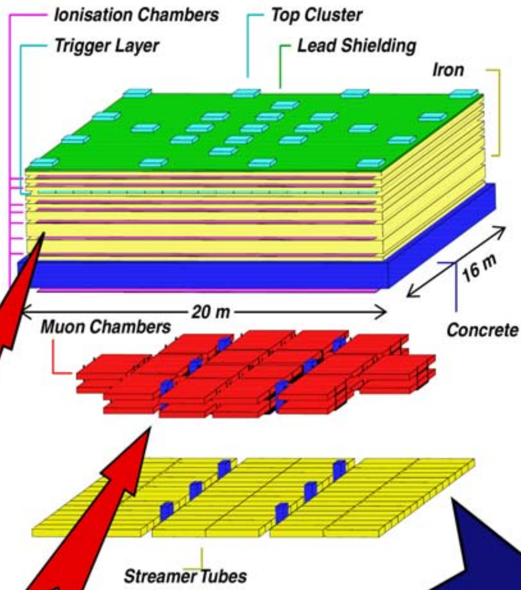
CORSIKA (QGSJet01 +Gheisha)

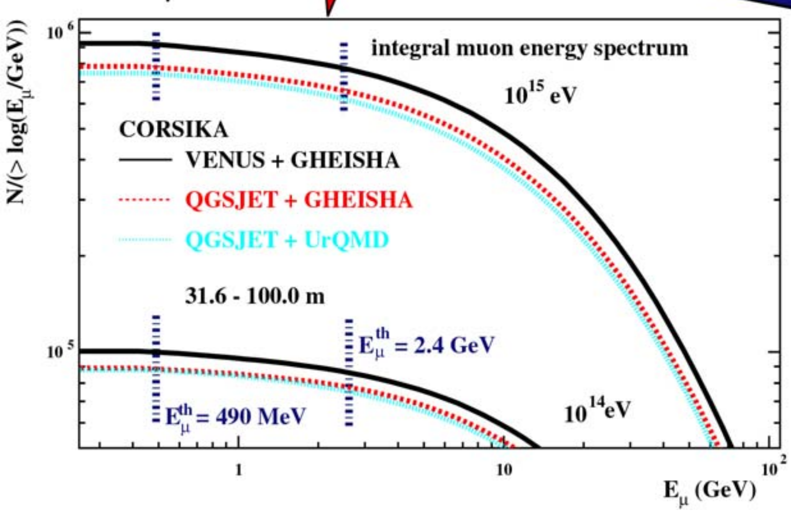
J. Zabierowski - KASCADE-Grande, ICRC05, Pune

Pseudorapidity of muons is correlated with η of parent hadrons ➔ sensitivity to hadronic interaction models

(better at KASCADE-Grande, due to larger distances)

Model tests at KASCADE by muon density measurements:

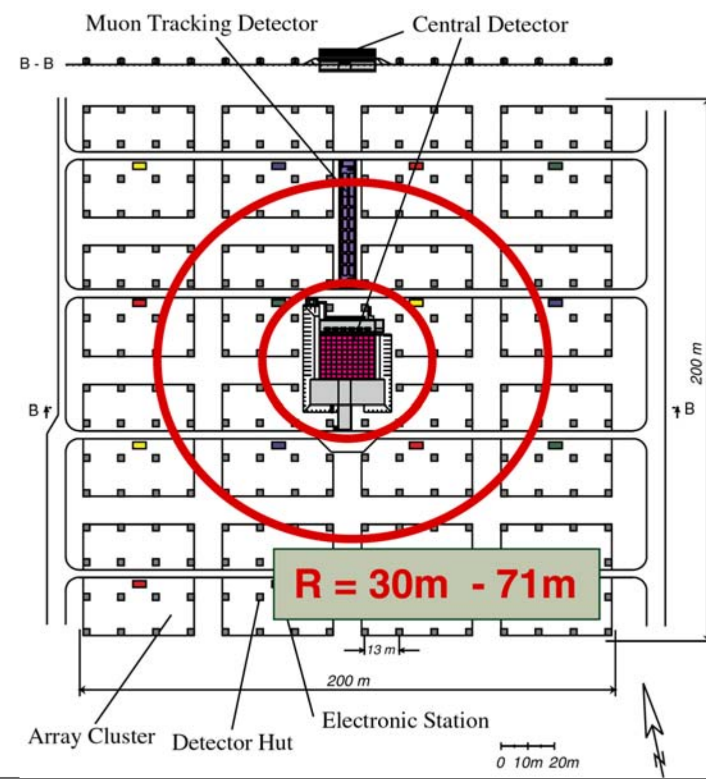




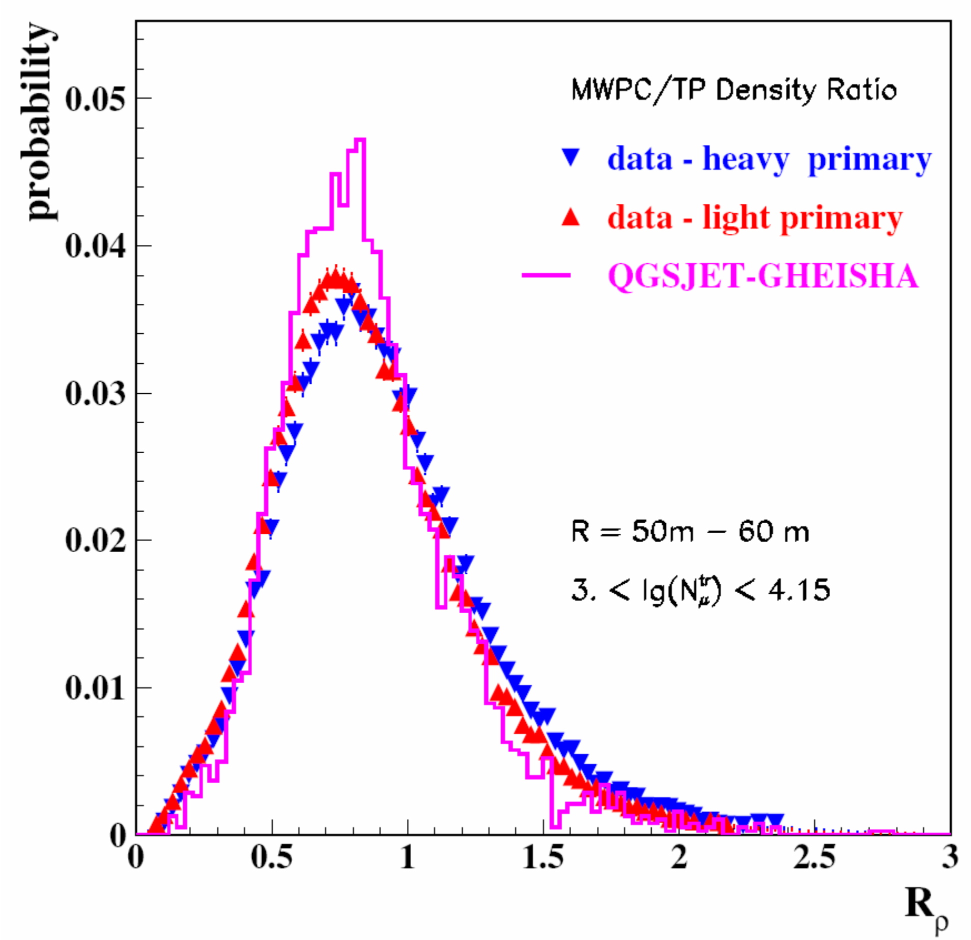
A. Haungs - KASCADE-Grande, ICRC05, Pune

model sensitive parameters:

$$R_\rho^{2.4/0.49} = \rho_\mu^{2.4GeV} / \rho_\mu^{0.49GeV}$$
$$R_\rho^{2.4/0.23} = \rho_\mu^{2.4GeV} / \rho_\mu^{0.23GeV}$$
$$R_\rho^{0.49/0.23} = \rho_\mu^{0.49GeV} / \rho_\mu^{0.23GeV}$$



Muon density ratio as model sensitive parameter:



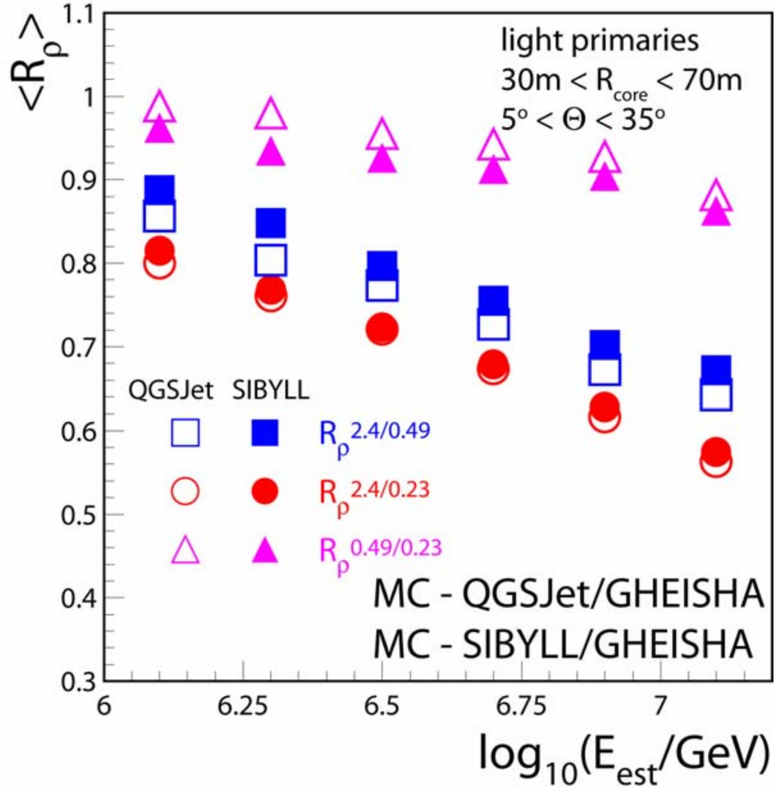
distribution of the muon density ratio for a certain range in distance and total EAS muon number.

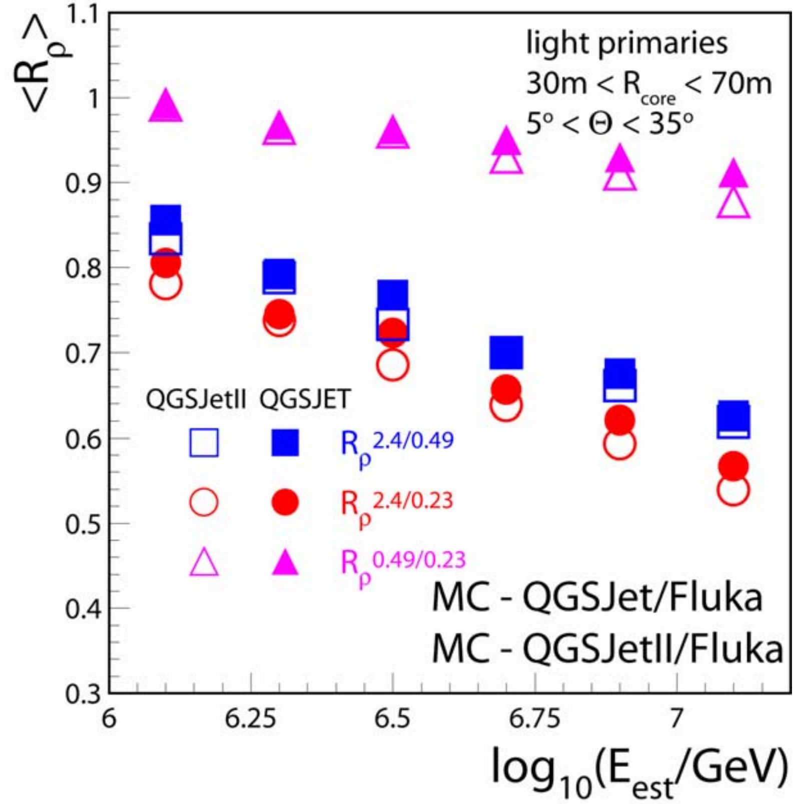
R_ρ were found to be insensitive
-to total muon number
-to the slope of the primary energy spectrum
-and nearly independent on composition
(investigation of subsamples)

investigated observables:
mean and rms of
R_ρ vs. primary energy
R_ρ vs. core distance

Model sensitivity?

Are there differences in the models, even after full simulations of the detector response?

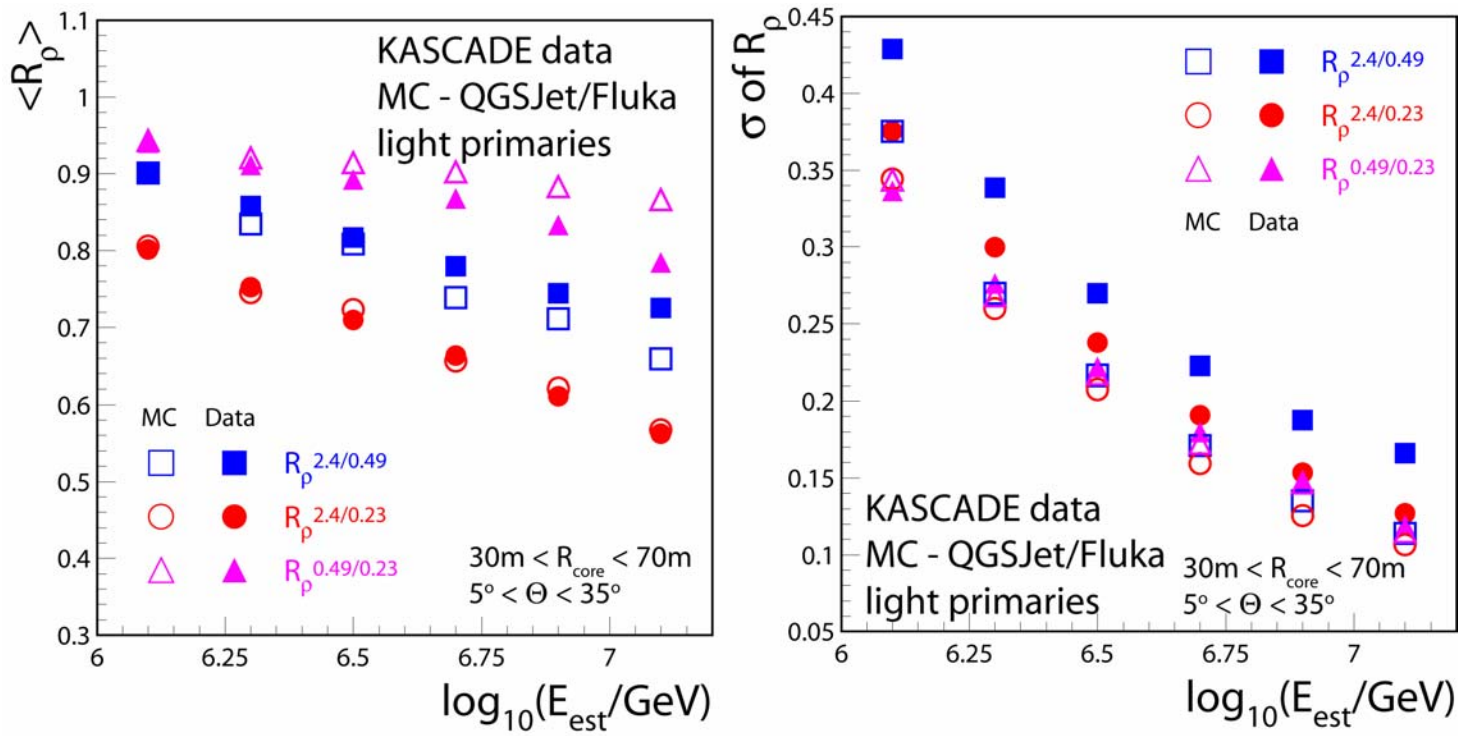




example:

mean of R_ρ vs. primary energy for different model combinations.

Muon density measurements at KASCADE as model test:



Results in terms of the muon energy spectrum in EAS:
-deviation between measurements and predictions increases with energy
-large deviations in the width of the distributions (shower to shower fluctuations)

A.Haungs - KASCADE-Grande, ICRC05, Pune

Help from Accelerator Experiments ?

present:

HERA: parton density measurements
➔important for multiplicity and cross-section extrapolations, leading baryon of high-energies

TEVATRON: high p_t - jets
➔hadron distributions at large Feynman x

RHIC: nucleus-nucleus interactions
➔particle densities, multiplicities

HARP, NA49: GeV-p,π,K ← → nucleus
➔ particle multiplicities in the full phase space

future:

HERA-B: particle production in p-C collisions
➔constraints for EAS simulations (e.g. muon flux)

LHC: cross sections at high energies
➔dedicated experiments to forward physics

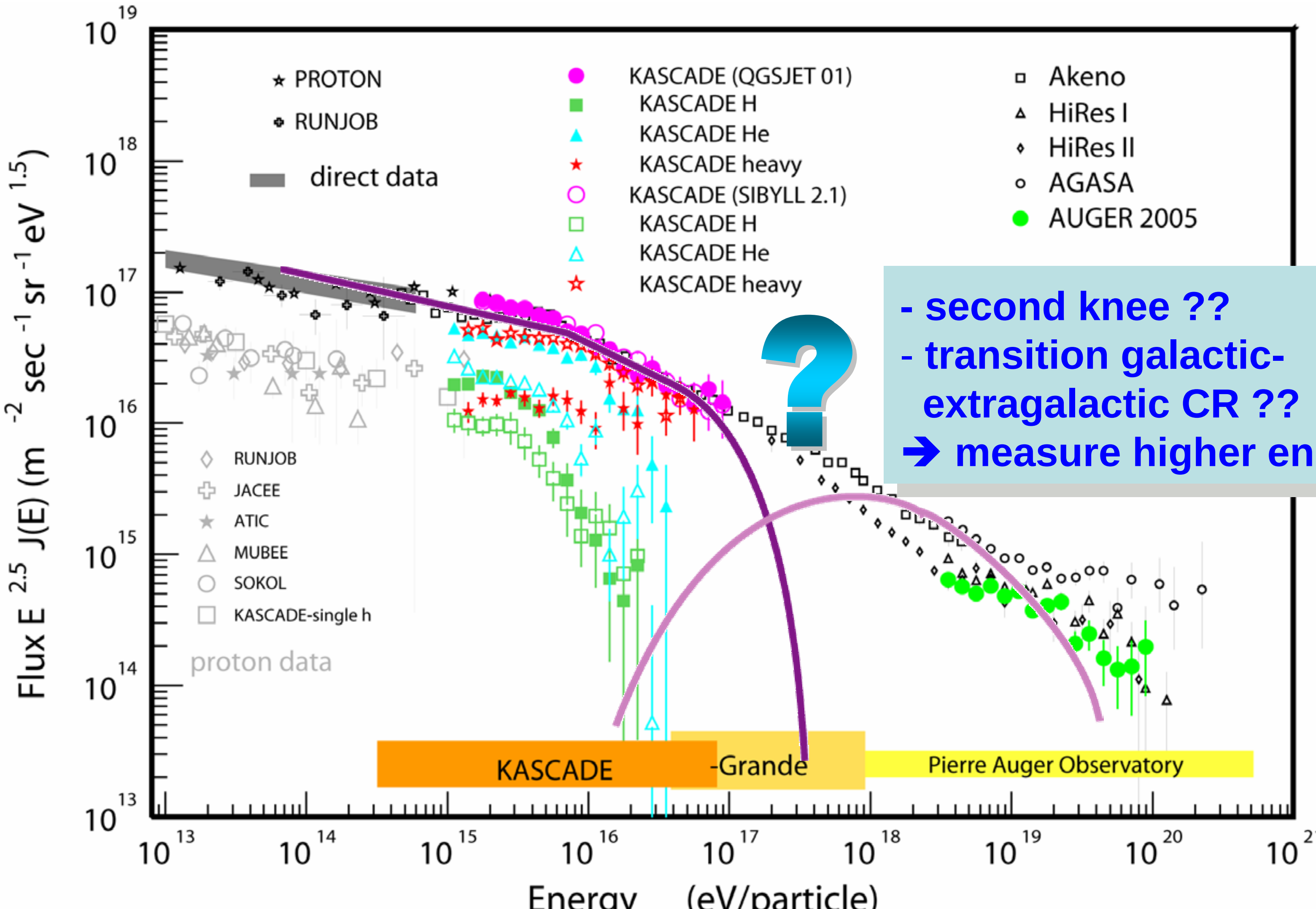
RHIC: nucleus-nucleus interactions
➔C or N targets

NA49 or other low energy experiments:
➔ π – interactions (dominate the EAS development)

- **measurements of properties of (forward) hadron production in EAS and at accelerators**
- **➔ closer collaboration of cosmic ray and high energy physics communities.**

see also NEEDS-workshop (http://www-ik.fzk.de/~needs) and XII ISVHECRI, Geneve 2003

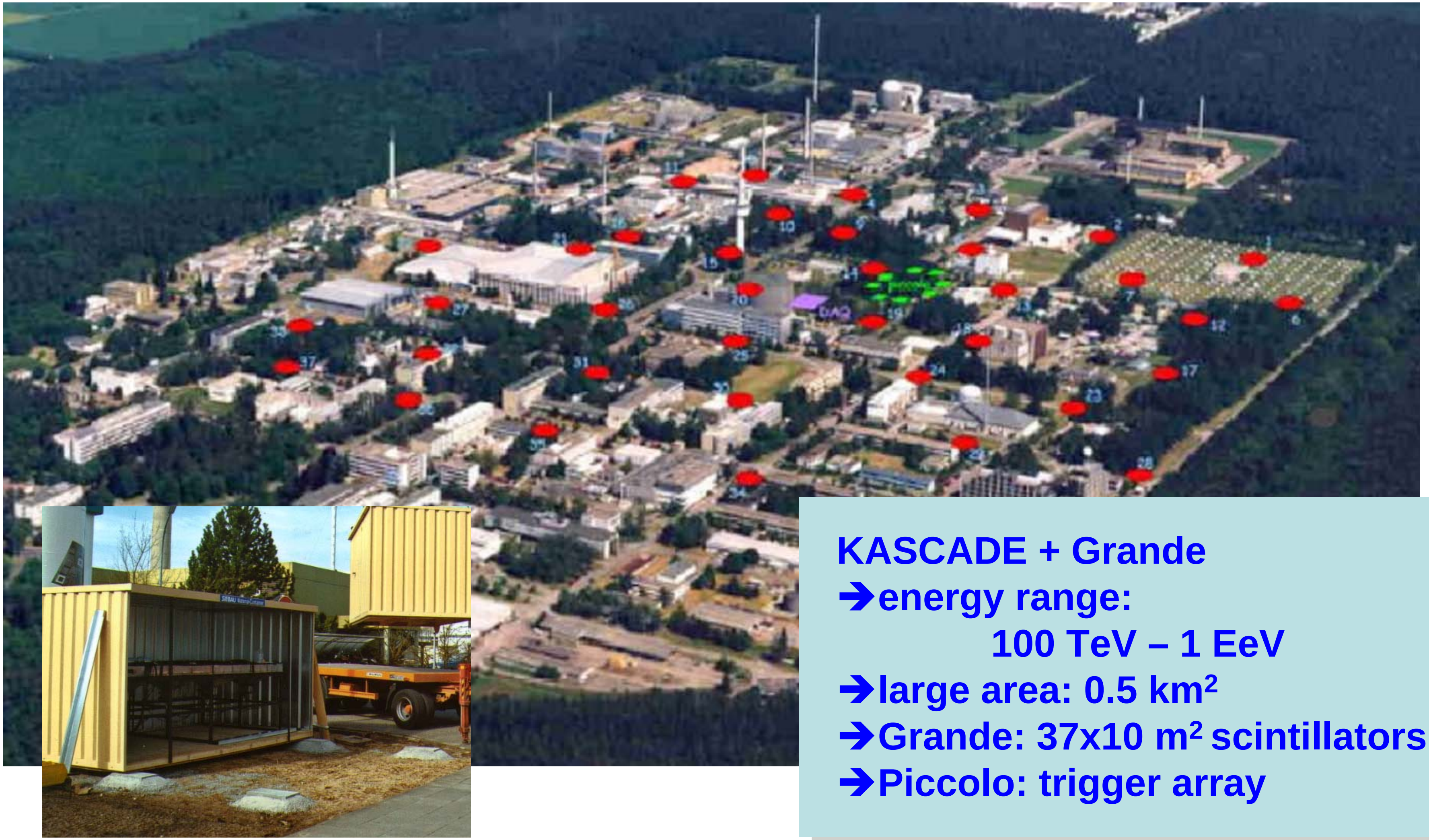
Motivation for KASCADE-Grande



- second knee ??
- transition galactic-extragalactic CR ??

➔ measure higher energies !

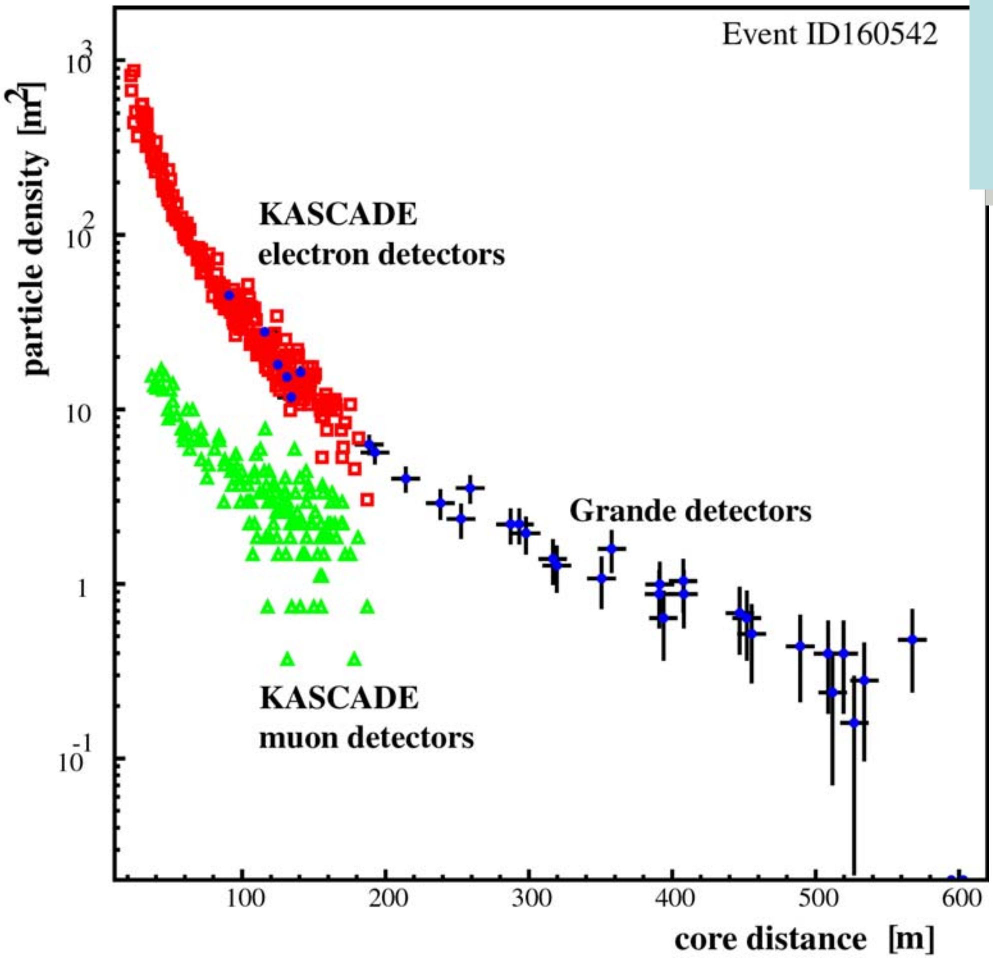
KASCADE-Grande : multi-parameter measurements

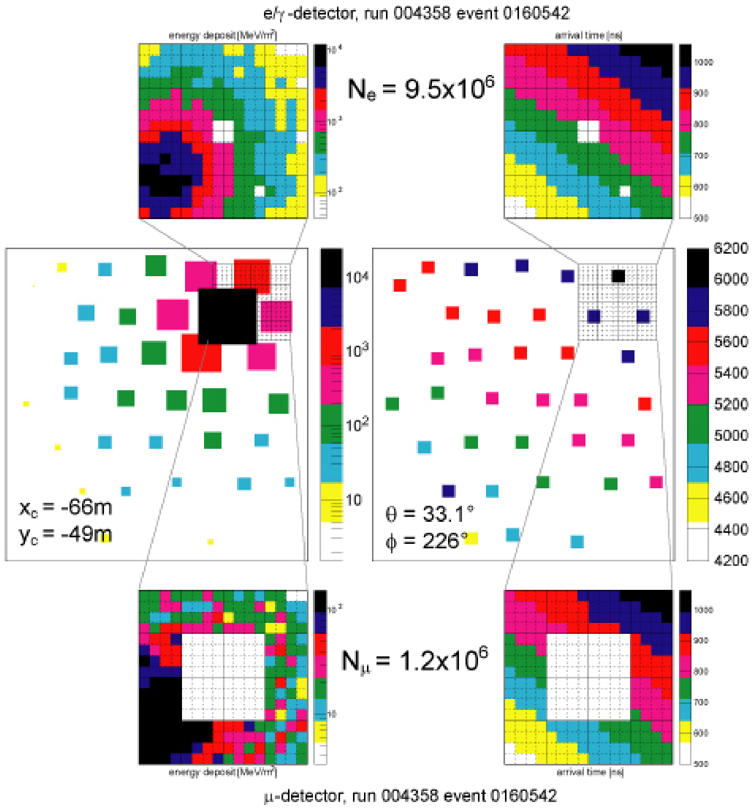


KASCADE + Grande
- ➔ **energy range: 100 TeV – 1 EeV**
- ➔ **large area: 0.5 km²**
- ➔ **Grande: 37x10 m² scintillators**
- ➔ **Piccolo: trigger array**

KASCADE-Grande : Status

lateral distribution of a single event measured by KASCADE-Grande: $E_0 \approx 2 \cdot 10^{17}$eV, $\Theta = 33^o$

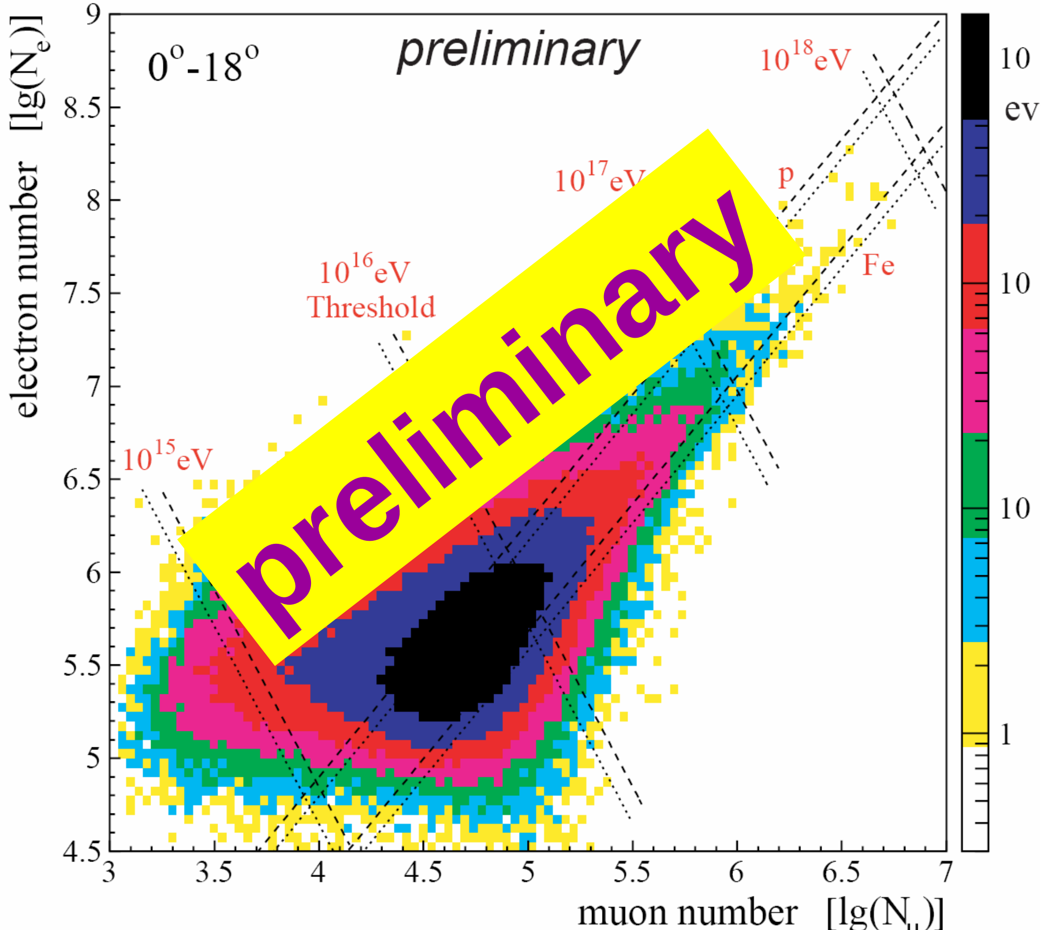




deposited energy [MeV/m^2] arrival time [ns]

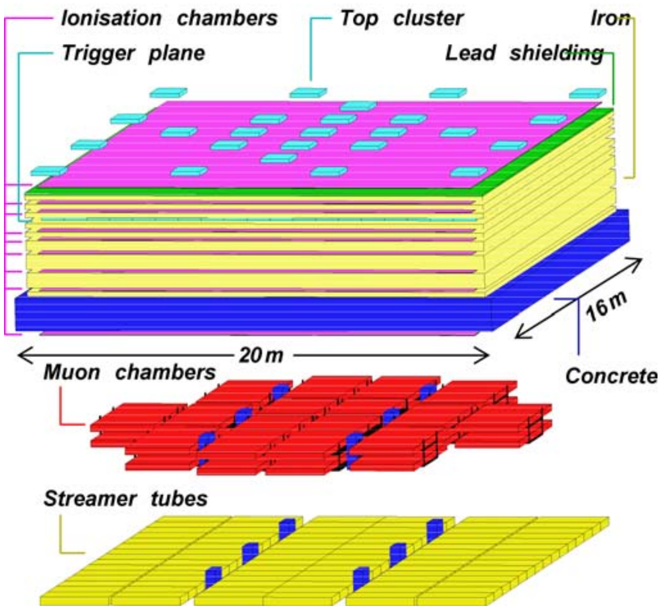
KASCADE-Grande : first analyses

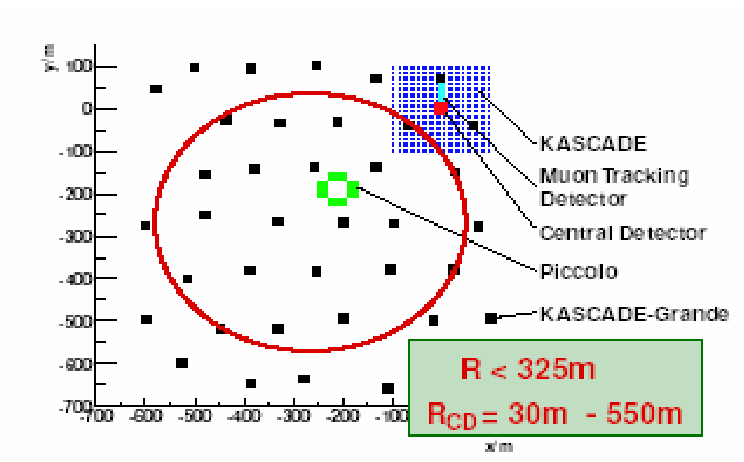
Unfolding of 2-dimensional shower size spectrum possible
➔ composition



Glasstetter et al. – KASCADE-Grande coll., ICRC (2005) Pune, India

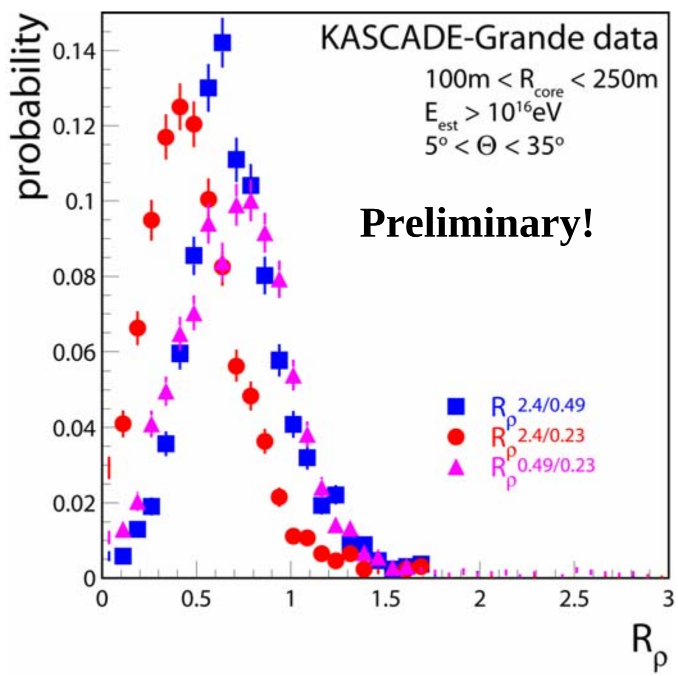
Model test at KASCADE-Grande by muon density measurements:





model sensitive parameters:

$$R_\rho^{2.4/0.49} = \rho_\mu^{2.4GeV} / \rho_\mu^{0.49GeV}$$
$$R_\rho^{2.4/0.23} = \rho_\mu^{2.4GeV} / \rho_\mu^{0.23GeV}$$
$$R_\rho^{0.49/0.23} = \rho_\mu^{0.49GeV} / \rho_\mu^{0.23GeV}$$



consistency check possible up to 10^{18} eV primary energy and 800 m core distance !

KASCADE-Grande : Summary

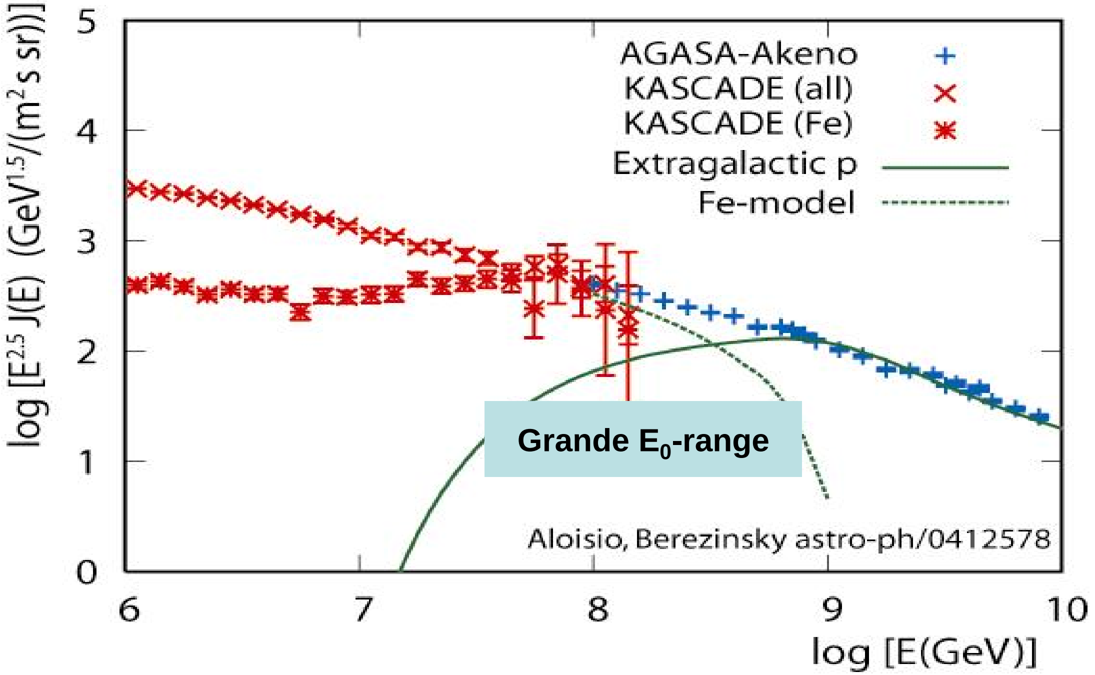
- **Single element spectra reconstruction is possible by EAS measurements (KASCADE)**

➔ Knee is caused by light primary elements, cosmic rays are isotropic around the knee

- **Data distributions are not consistent with Monte Carlo predictions**

➔ Correlation analyses of KASCADE-Grande data have to be continued

➔ Interaction models have to be further improved



- **KASCADE-Grande will cover whole „knee" range to find the „iron"-knee !**
- **Radio detection as new technique for UHECR measurements ?**

KASCADE-Grande Collaboration

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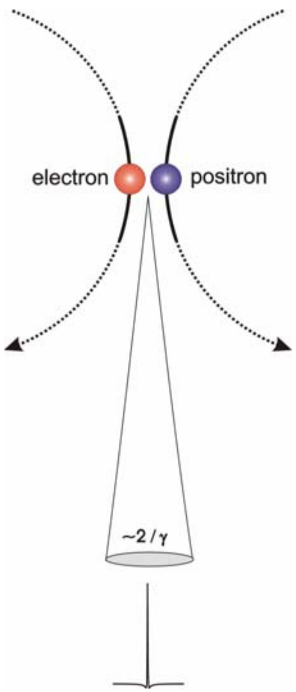
KASCADE-Grande : Radio shower detection



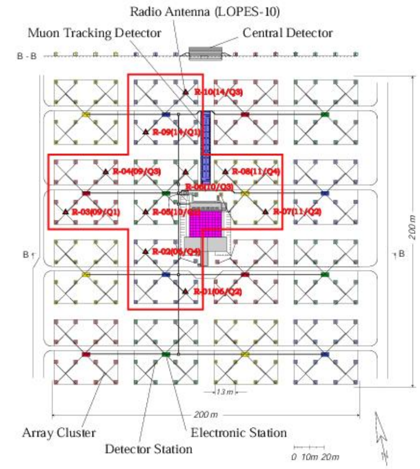
- deflection of electron-positron pairs in the Earth's magnetic field
  ➔ coherent emission at low frequencies

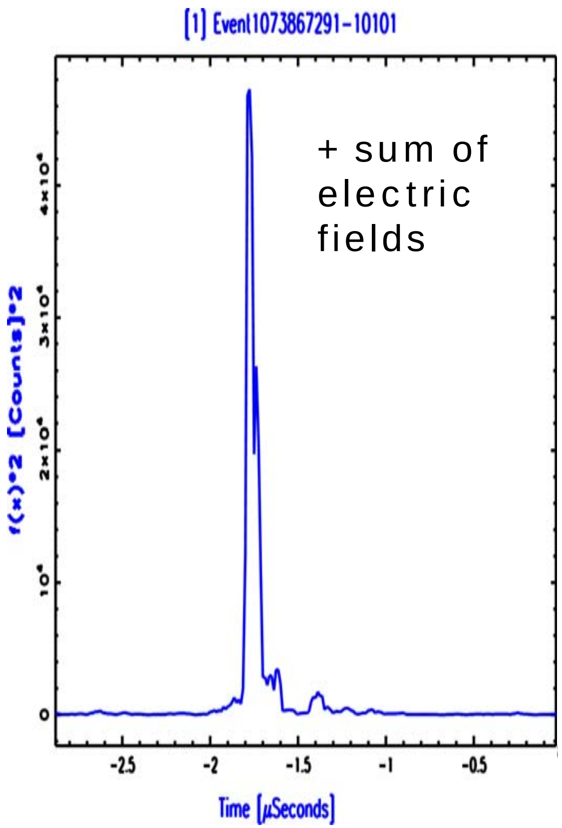
- with radio detection
  ➔ see shower development
  ➔ observe 24 hrs/day

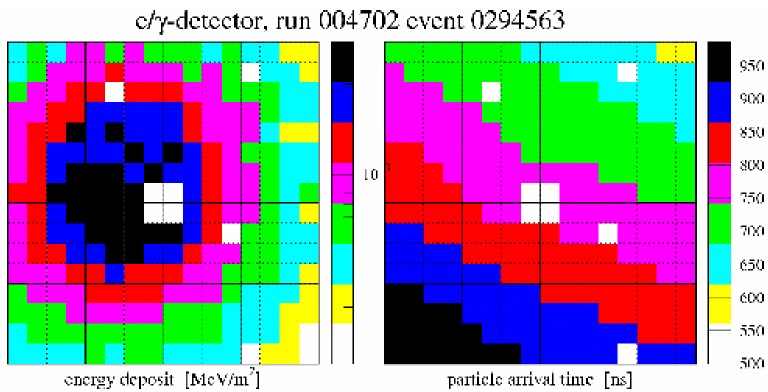
LOPES collaboration:
-) KASCADE-Grande
-) U Nijmegen, NL
-) MPIfR Bonn, D
-) Astron, NL
-) IPE, FZK, D

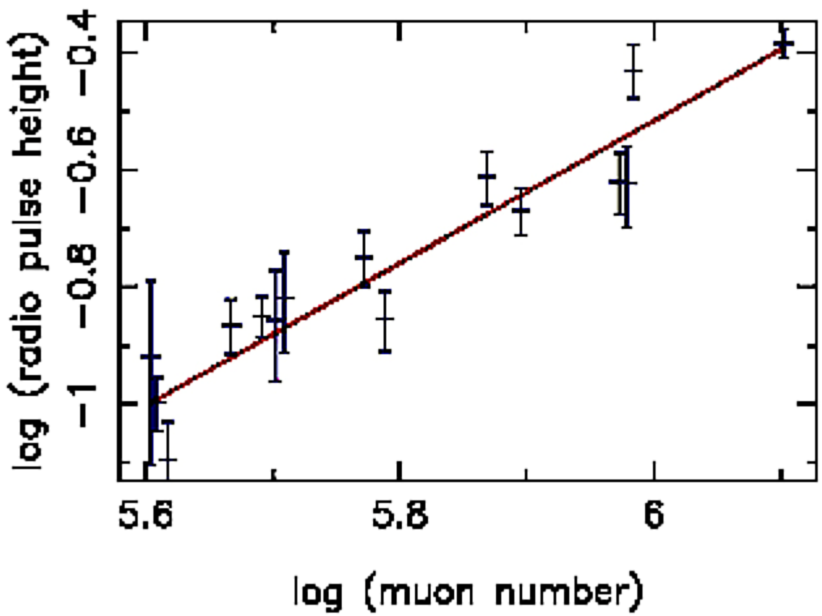
- 30 dipole antennas at KASCADE-Grande
- calibration of radio emission
- theory of radio emission and implementation in CORSIKA
- improvement/optimisation hardware (for application in Auger)

LOPES :
Radio shower detection





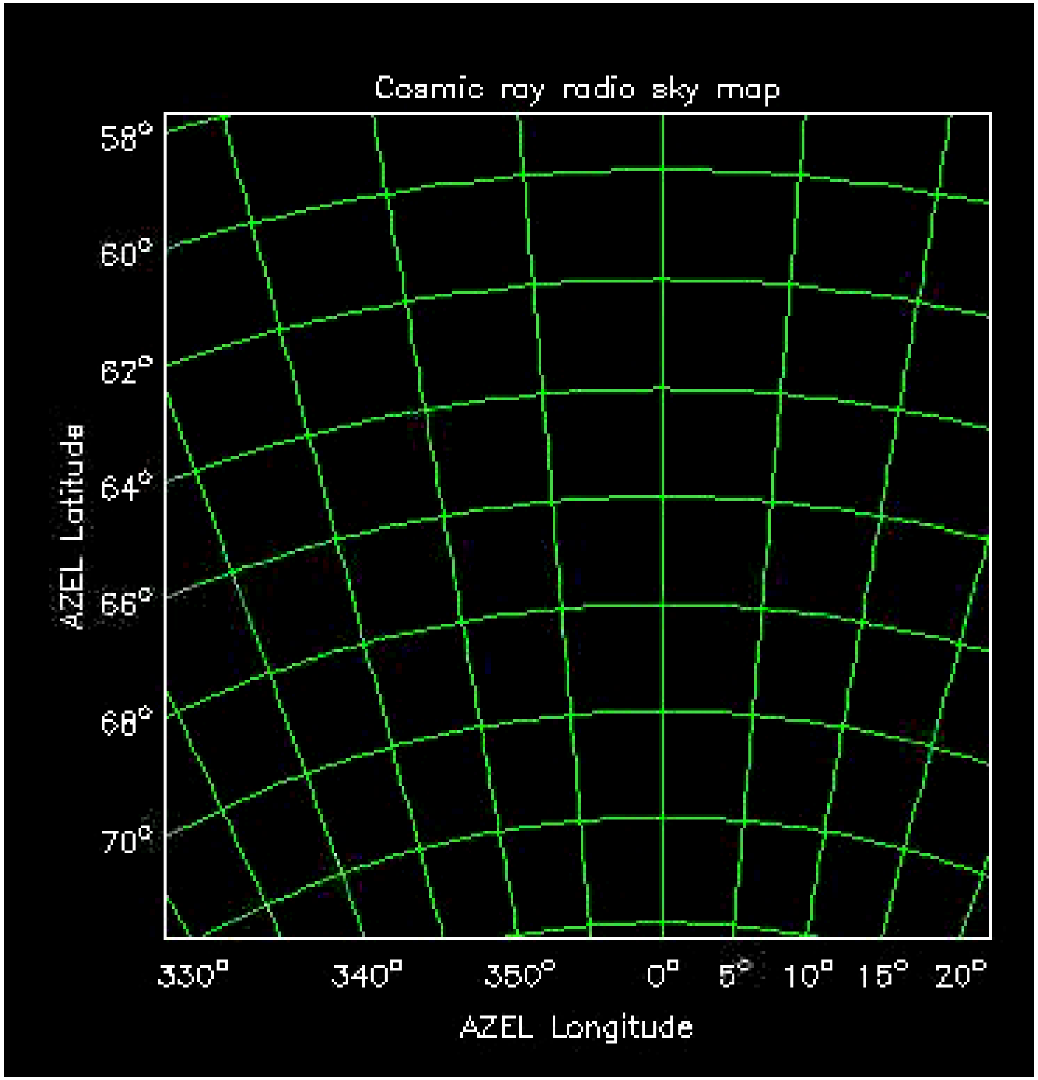




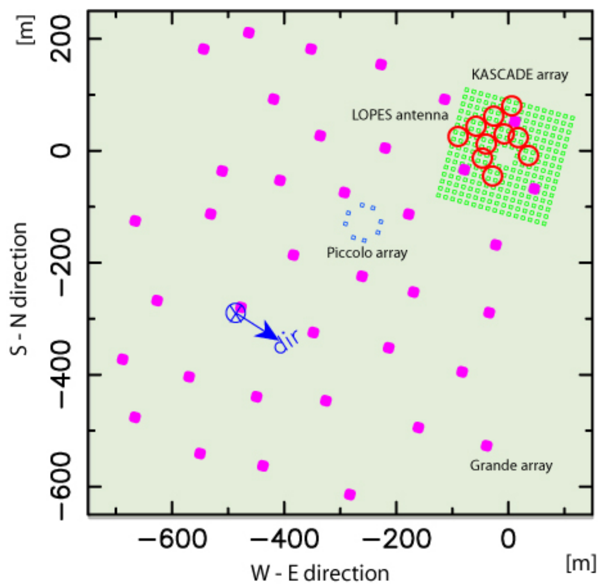
- **energy ≈ 10^{17} eV**
- **EAS core inside antennas**
- **Θ = 25.5º, Φ = 42.5º**
- **signal is coherent**

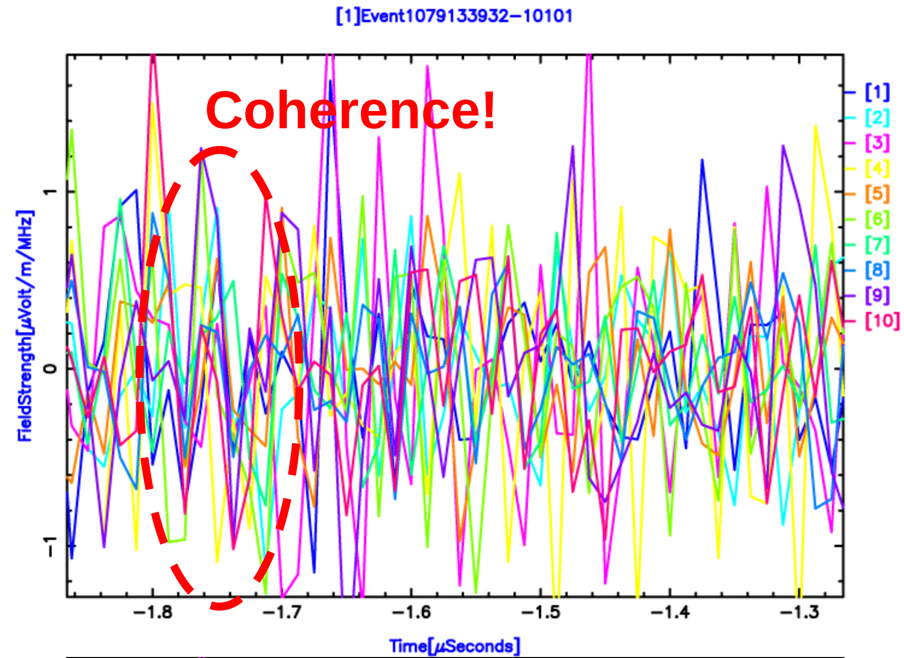
Falcke et al. – LOPES collaboration, NATURE 425 (2005) 313

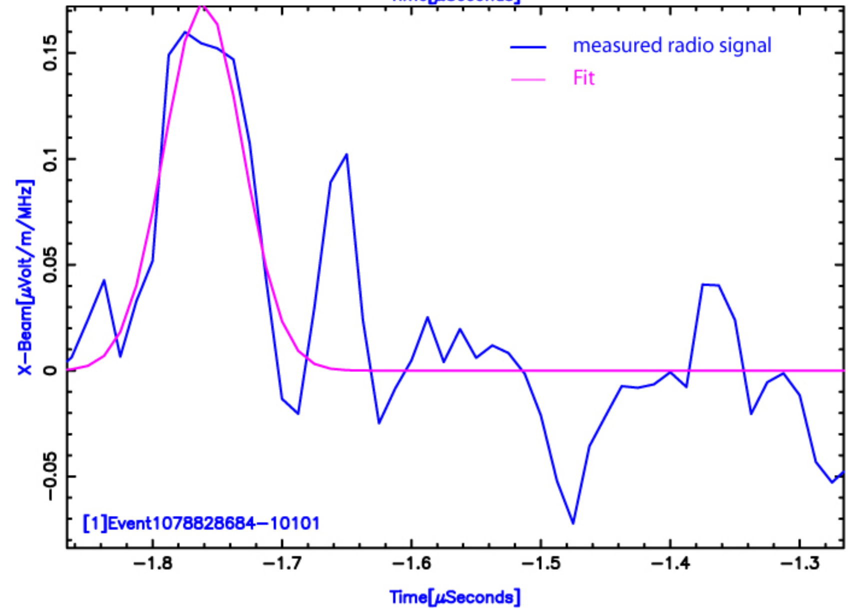
LOPES :
Radio shower detection



LOPES : Analysis of distant events







Event:

$\Phi = 122.65^o$	$\theta = 27.24^o$
$\alpha = 24.34^o$	R = 556 m
$lg(N_e) = 7.77$	$lg(N_\mu) = 6.48$
lg(E/eV) = 17.67	ln(A) = 1.73
curvature = 2250 m	

Badea et al. – LOPES collaboration, ICRC (2005) Pune, India

LOPES :
Analyses of inclined events

Event:

Φ = 74,4º　　　θ = 68º

core = outside

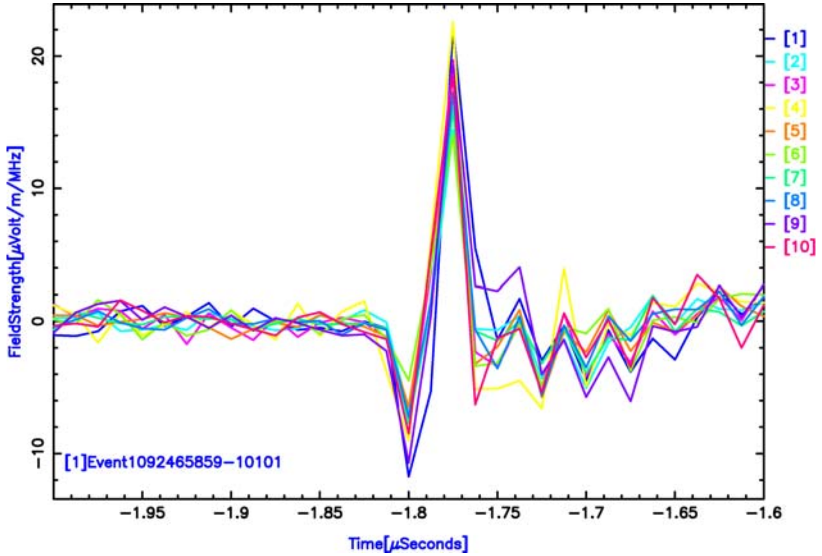
lg(N_e) ~ 6 ?　　　lg(N_μ) ~ 5.7 ?

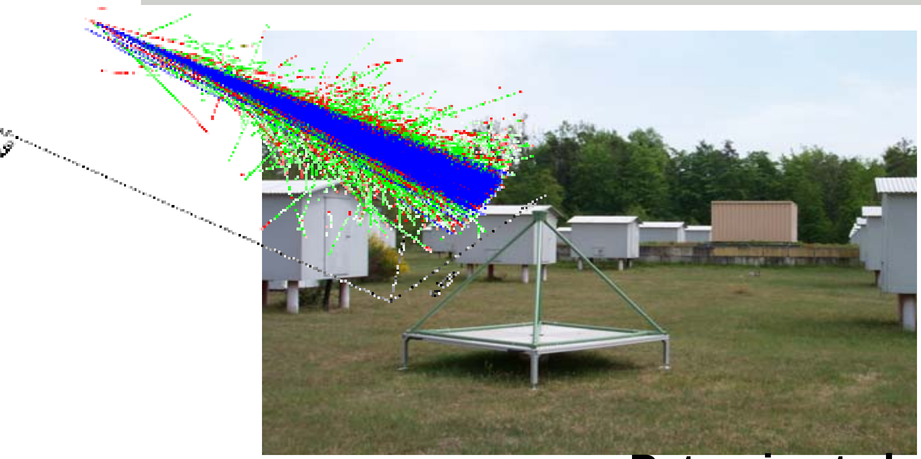
but clear radio signal !!

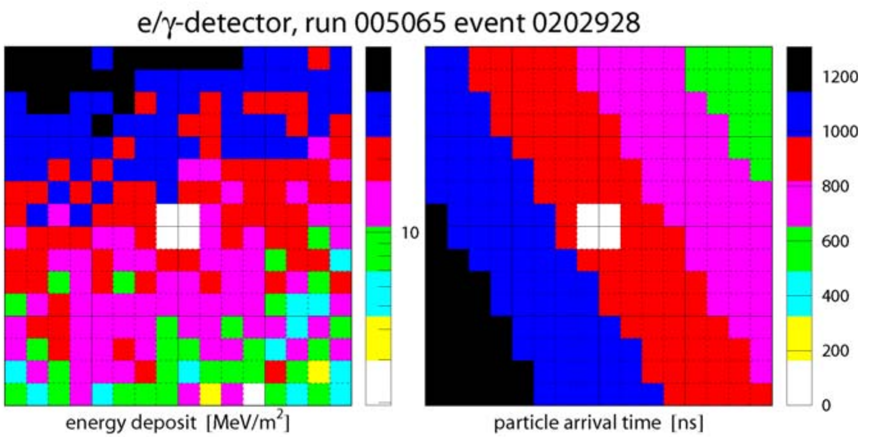
-reconstruction of shower by particle detectors difficult

-clear radio signals seen

-Grande reconstruction !







Petrovic et al. – LOPES collaboration, ICRC (2005) Pune, India