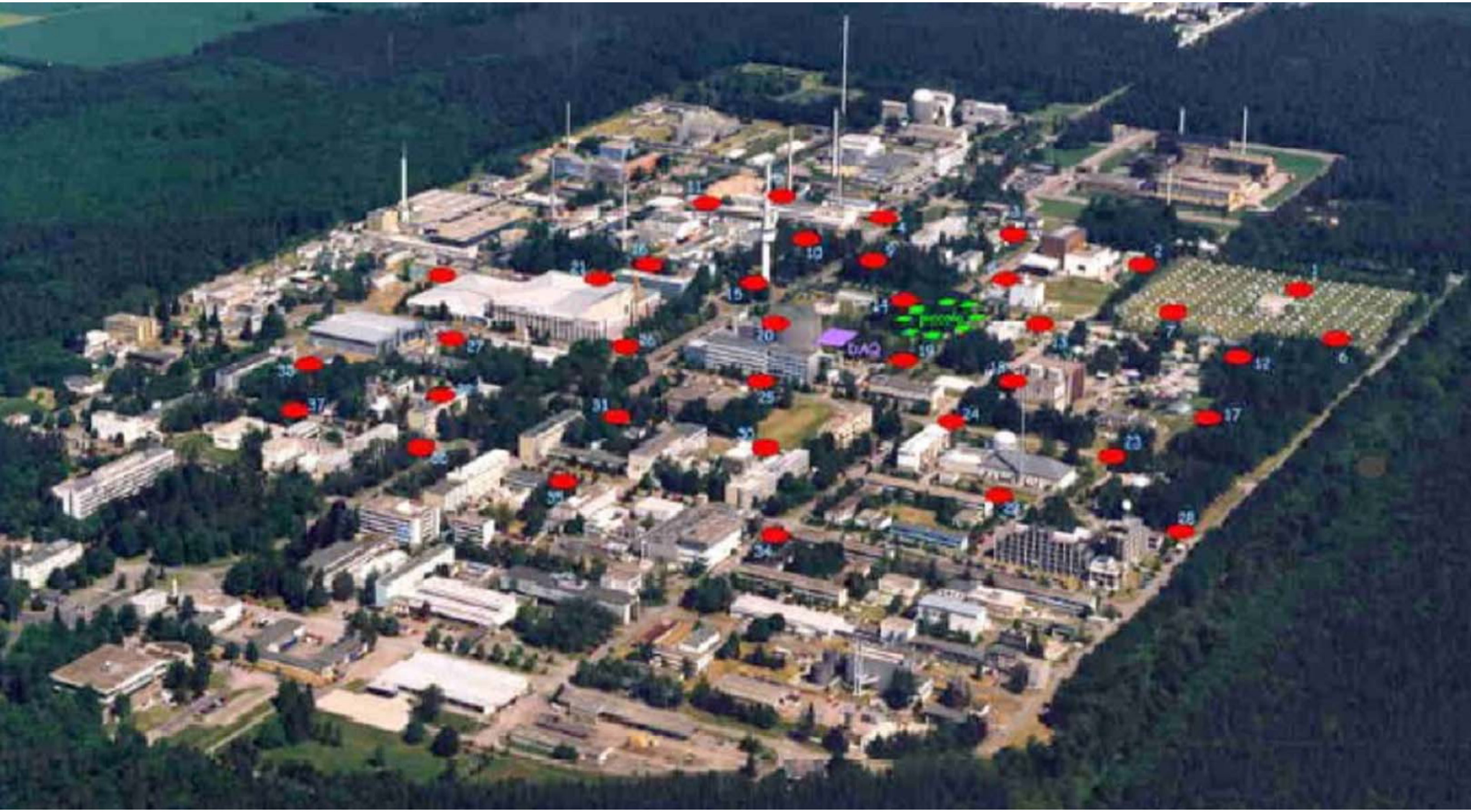
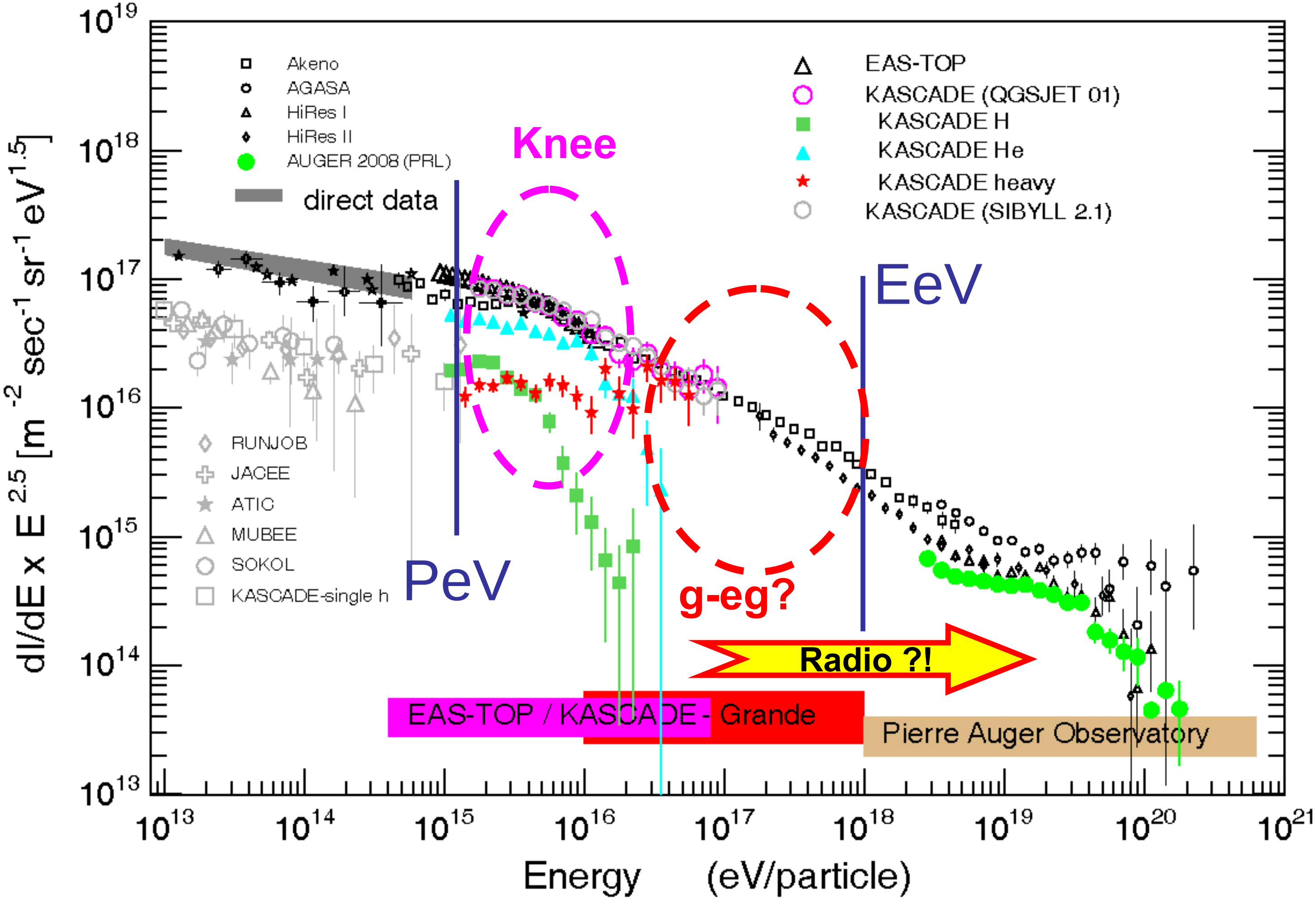
Latest results and perspectives of the KASCADE-Grande EAS facility



Motivation KASCADE-Grande

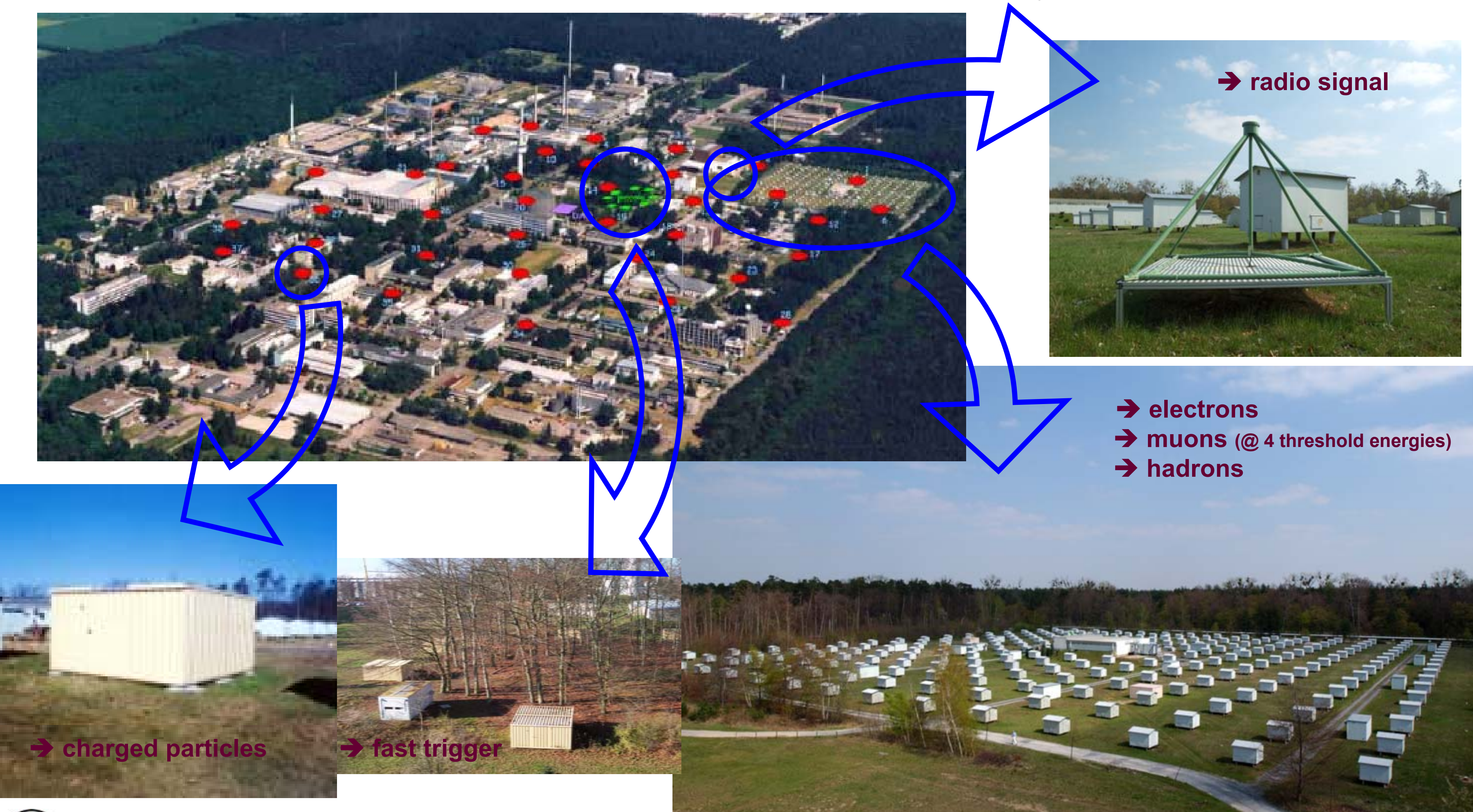


KASCADE	***10^{15}-10^{17}eV:***	**Origin of the knee?**
KASCADE-Grande	***10^{16}-10^{18}eV:***	**Iron knee (rigidity)?**
		Transition galactic-eg CR?
LOPES	***$10^{16.7}$-10^{18}eV:***	**New detection technique!**

KASCADE-Grande

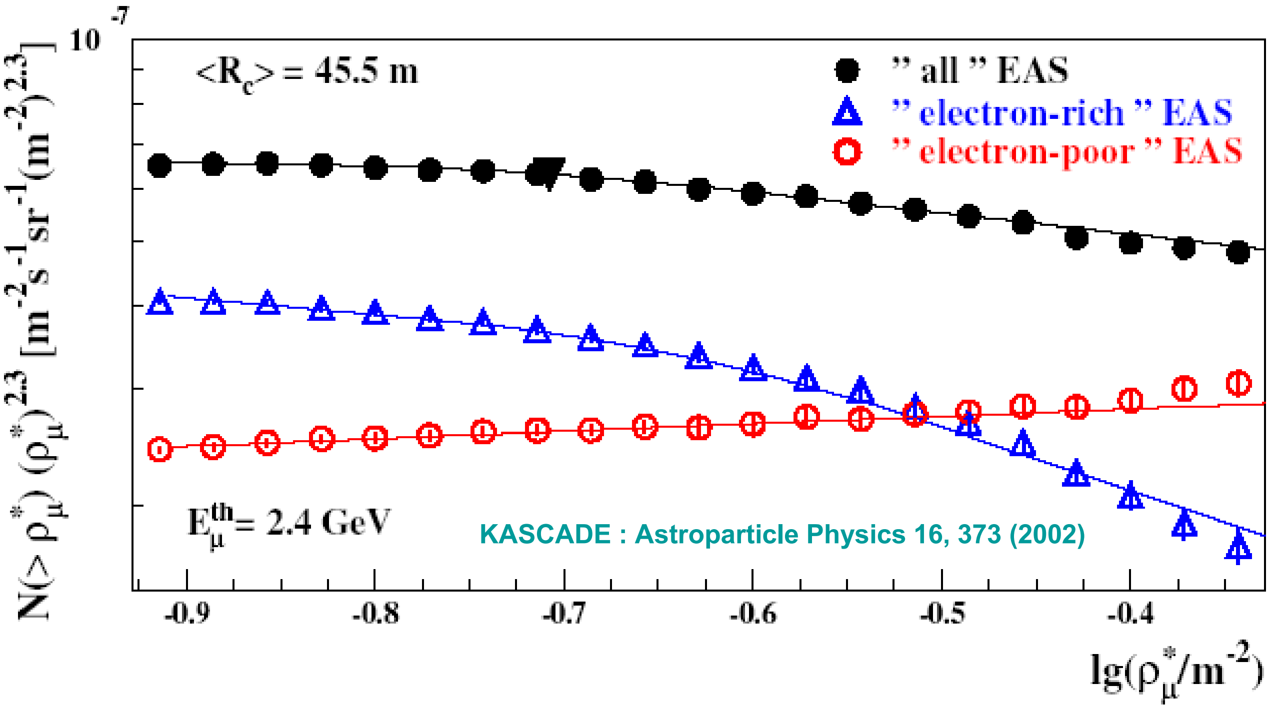
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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



Model independent multi-parameter analysis

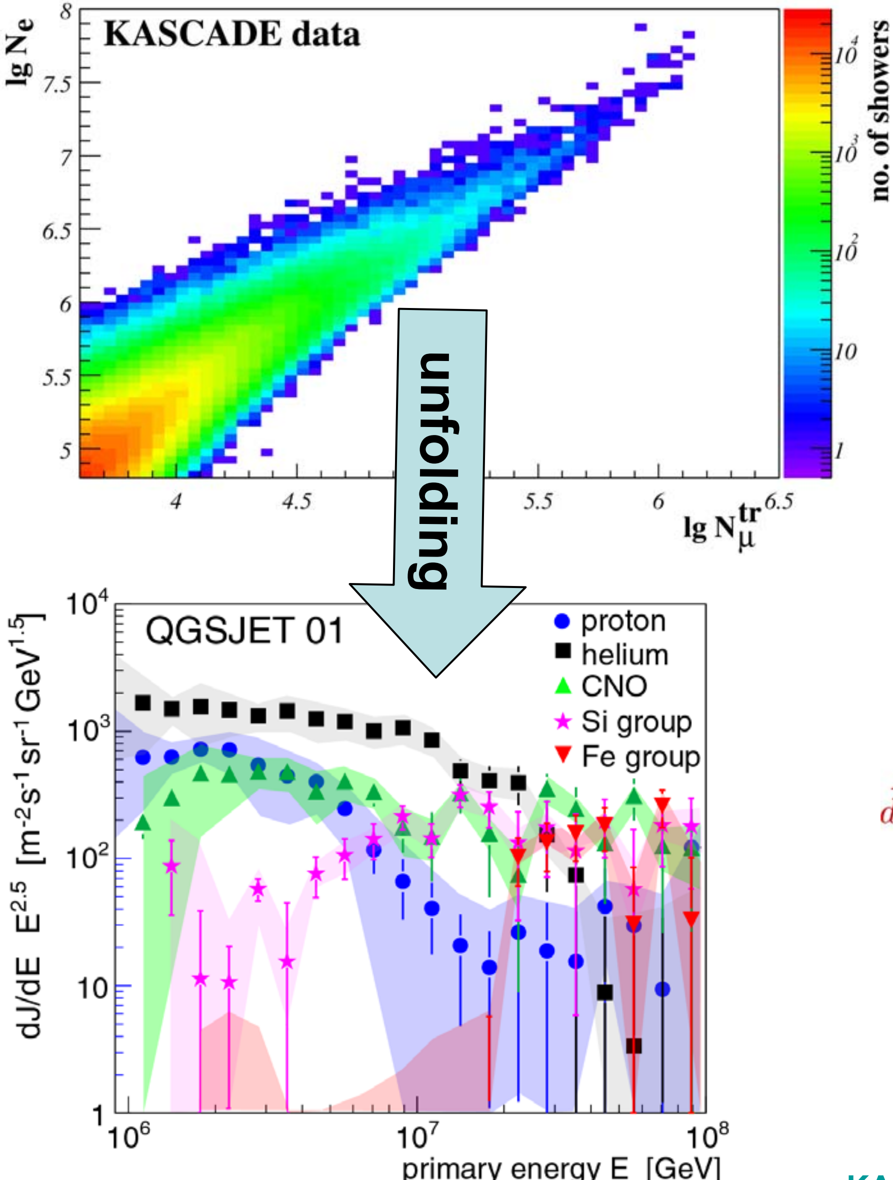
- **Total muon number and electron number ➔ mass estimator**
- **high-energy local muon density ➔ energy estimator**

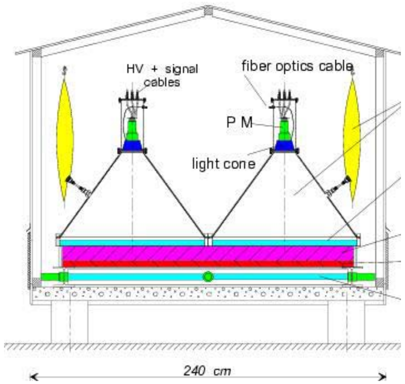


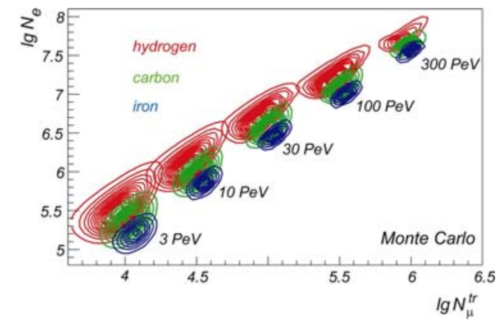
- **KNEE CAUSED BY DECREASING FLUX OF LIGHT ELEMENTS**
- **Do we need hadronic interaction models?**

  ➔ yes, for normalization of absolute energy and mass scale!!

KASCADE : energy spectra of single mass groups







Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ solve the inverse problem

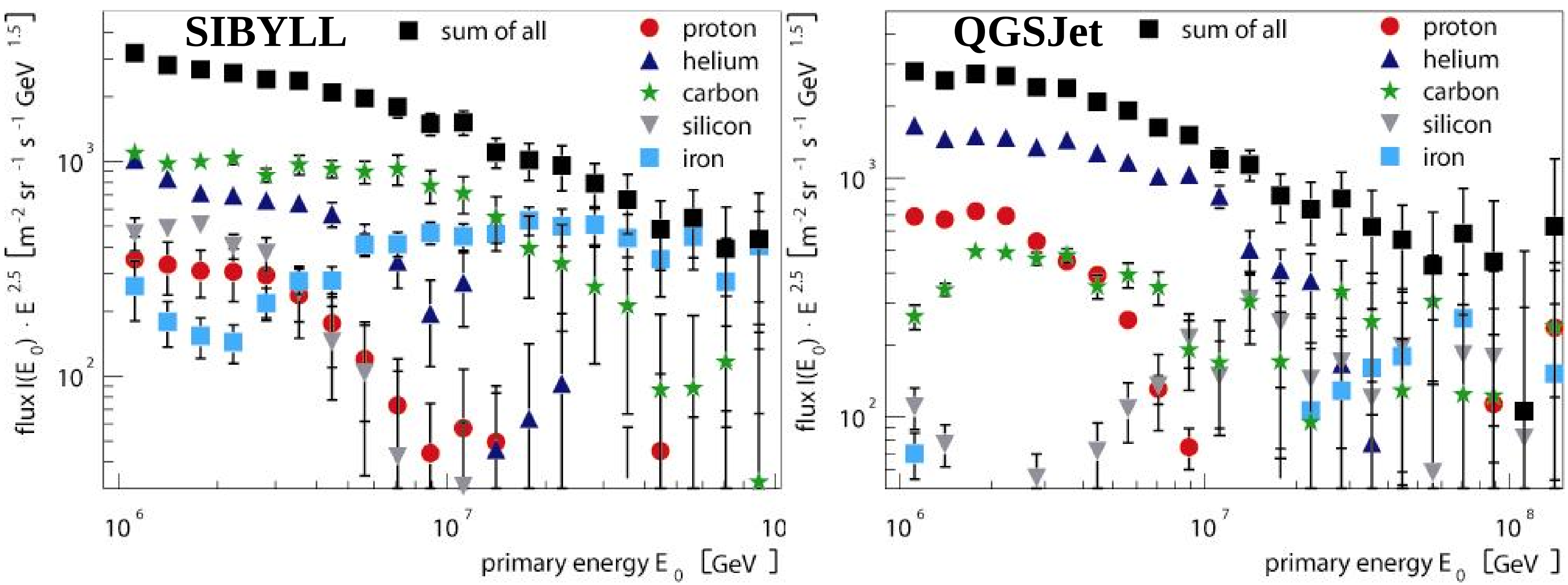
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

- **kernel function obtained by Monte Carlo simulations (CORSIKA)**
- **contains: shower fluctuations, efficiencies, reconstruction resolution**

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

KASCADE results

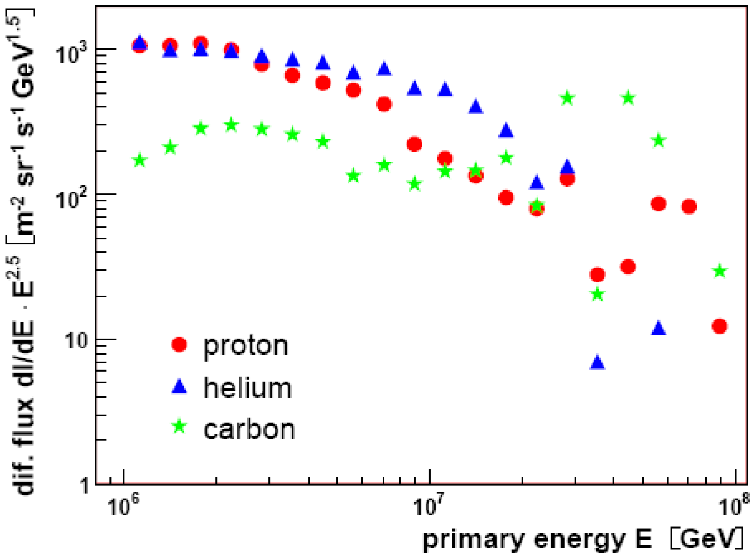
- same unfolding but based on different hadronic interaction models embedded in CORSIKA

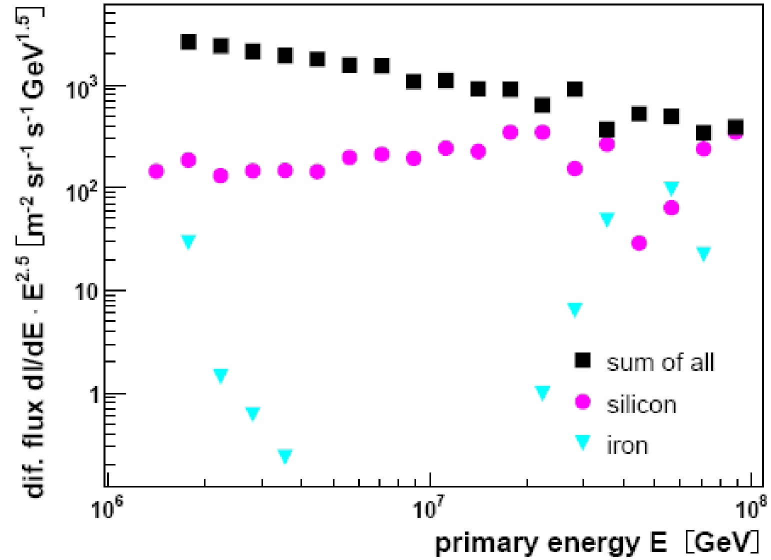


- all-particle spectrum similar
- general structure similar: knee by light component
- relative abundances very different **for different high-energy hadronic interaction models**

KASCADE collaboration, Astrop.Phys. 24 (2005) 1 , Astrop.Phys. 31 (2009) 86

KASCADE result: new model: EPOS 1.99



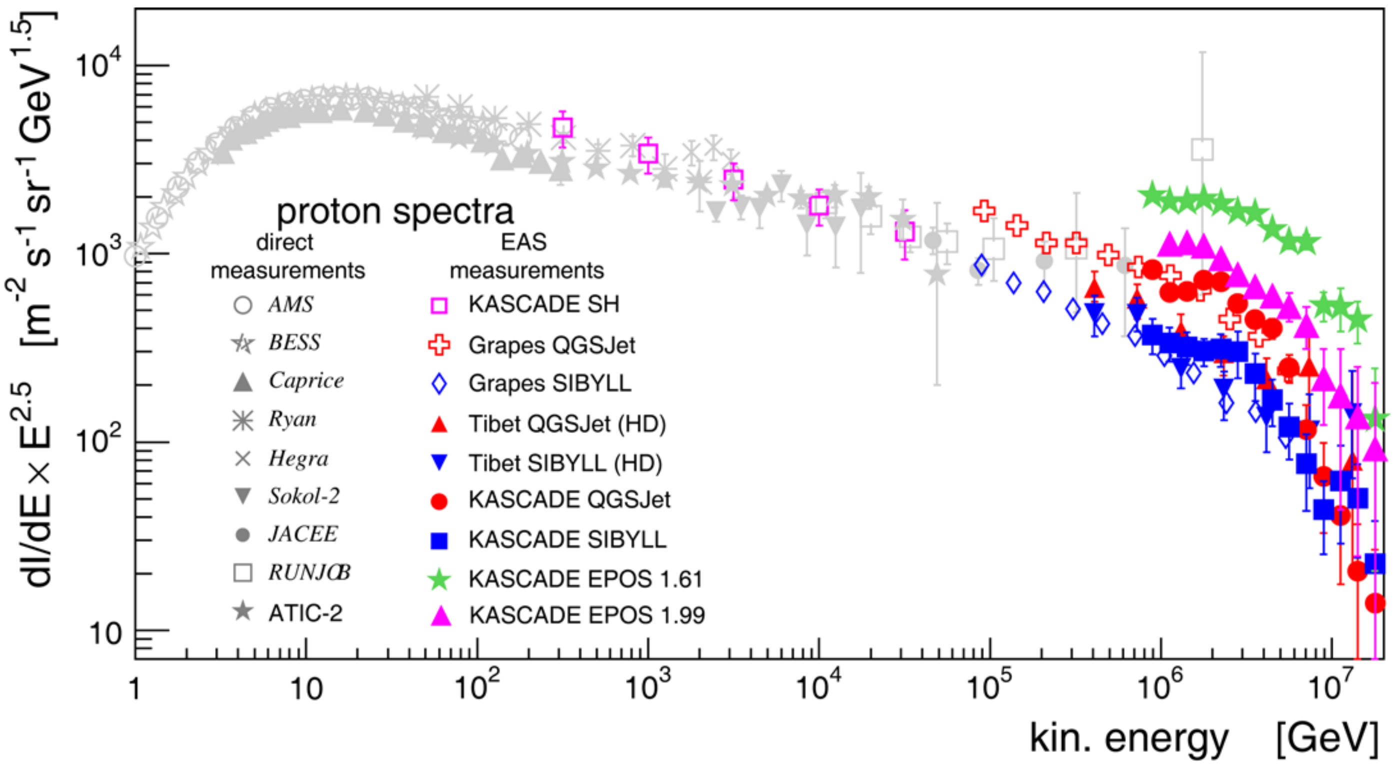


- EPOS 1.99 + FLUKA:
- **composition light dominant**
- **Knee caused by light elements**
- **all-particle spectrum okay**

- the case for EPOS 1.61:
all-particle spectrum not okay
very proton dominant

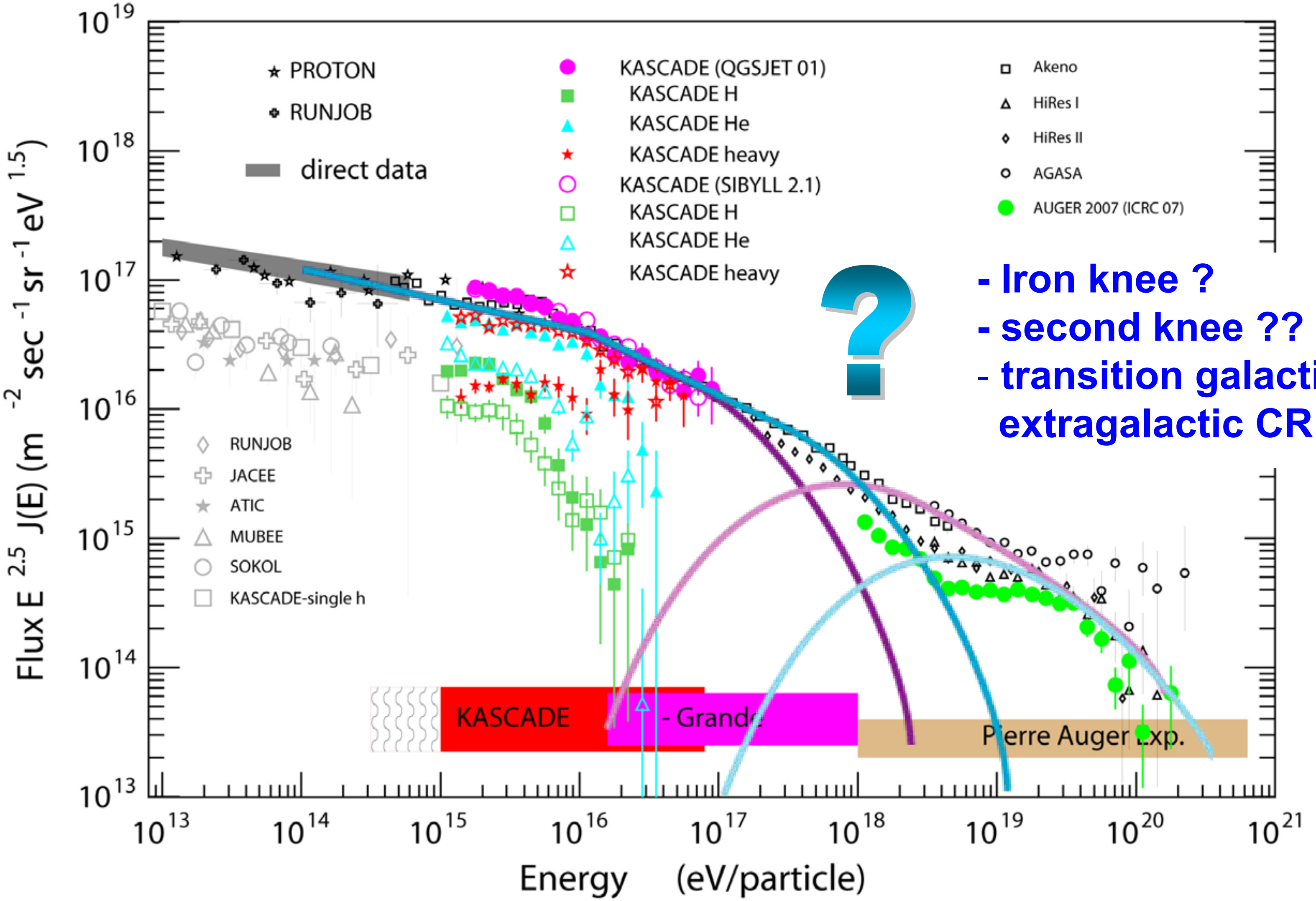
EPOS 1.99: Phys.Rev.C74(2006)044902 // KASCADE analysis: Marcel Finger PhD(2010)

KASCADE Summary



-) knee caused by light primaries ➔ composition gets heavier across knee
-) positions of knee vary with primary elemental group
-) relative abundancies depend strongly on high energy interaction model
-) no (interaction) model can describe the data consistently
-) all-particle spectra agree inside uncertainties (EPOS1.6 a bit lower)
-) proton spectra agree with direct measurements (not for EPOS1.6)

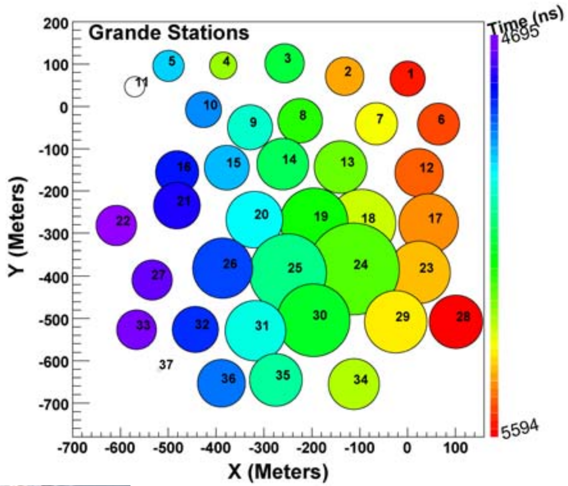
Motivation for measurements 100 – 1000 PeV

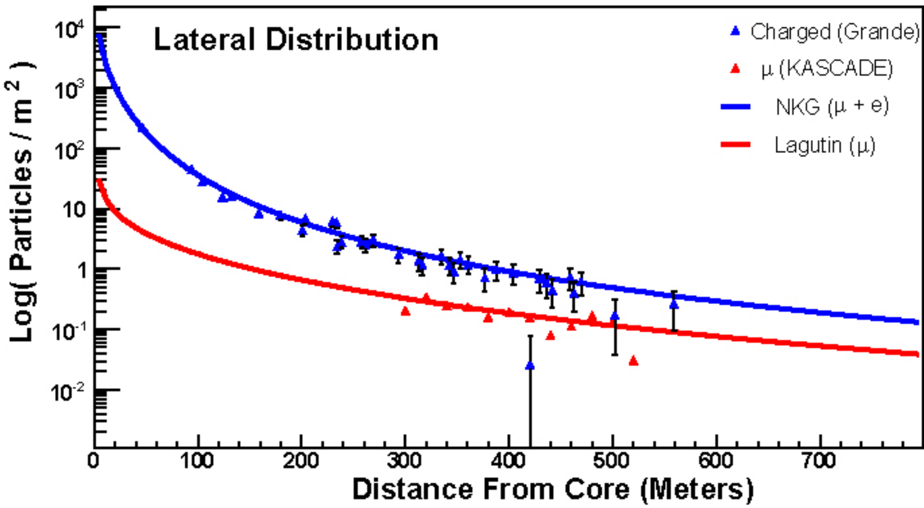


- Iron knee ?
- second knee ??
- transition galactic-extragalactic CR ??

Single event reconstruction

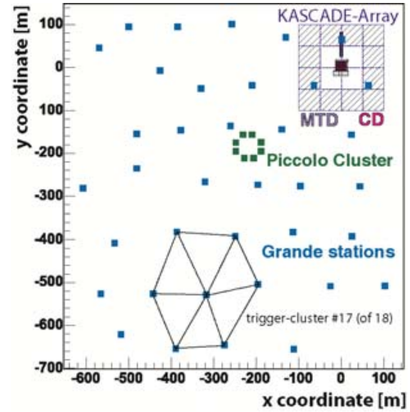
core (-155,- 401) m
$\log_{10}(N_{ch}) = 7.0$
$\log_{10}(N_{\mu}) = 5.7$
No saturation
Zenith: 24.2°
Azimuth: 284°
Recorded on
8 July 2005 at 12:11 (UTC)



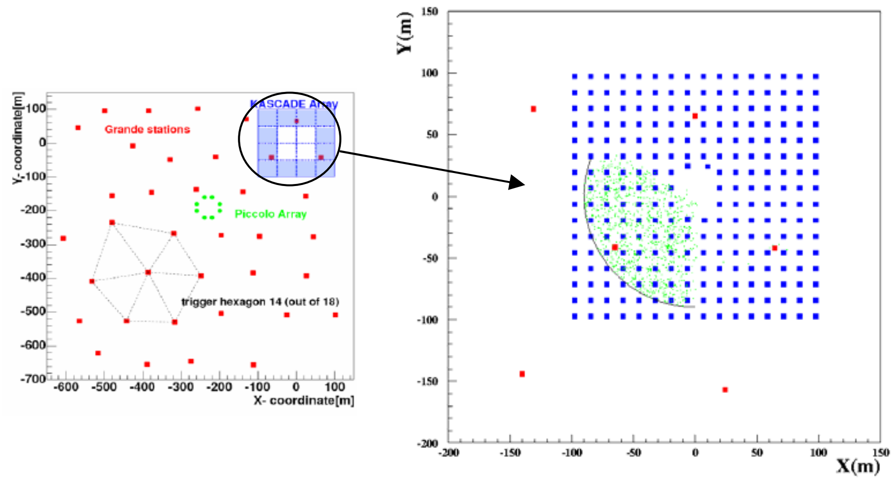


For each event:

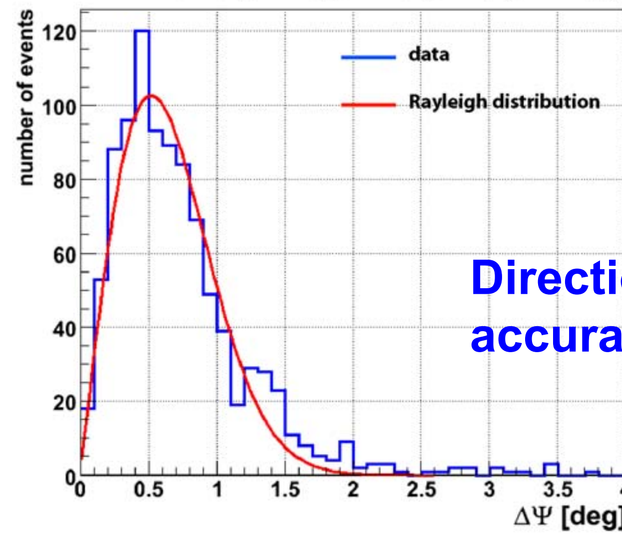
- **core and angle of incidence** (from Grande)
- **shower size** (charged particles)
- **muon number** (from KASCADE)
- **local muon density $\rho(r)$** (from KASCADE)
- **local charged density S(500)** (charged particles)
- …



KASCADE-Grande Accuracies
with subsample of common events KASCADE + Grande

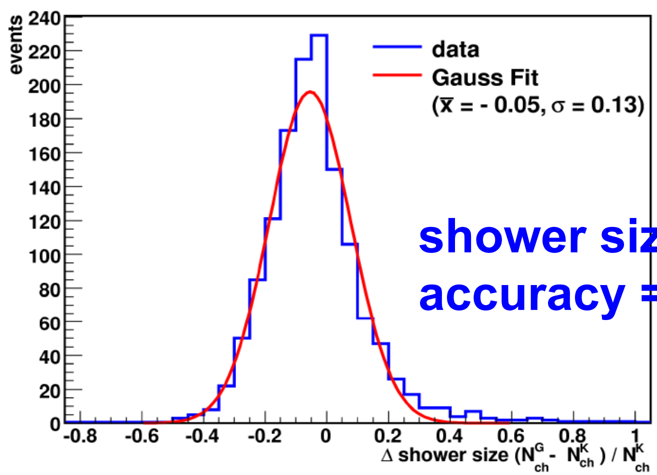


$$\Delta\psi = \arccos\left(\cos(\theta_K)\cdot\cos(\theta_G)+\sin(\theta_K)\cdot\sin(\theta_G)+\cos(\phi_K-\phi_G)\right)$$



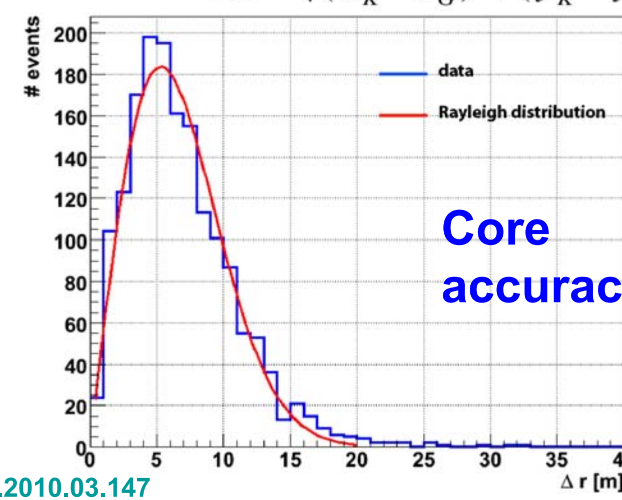
Direction accuracy = 0.6°

$$x = (N_{ch}^G - N_{ch}^K) / N_{ch}^K$$



shower size accuracy = 13%

$$\Delta r = \sqrt{(x_K - x_G)^2 + (y_K - y_G)^2}$$

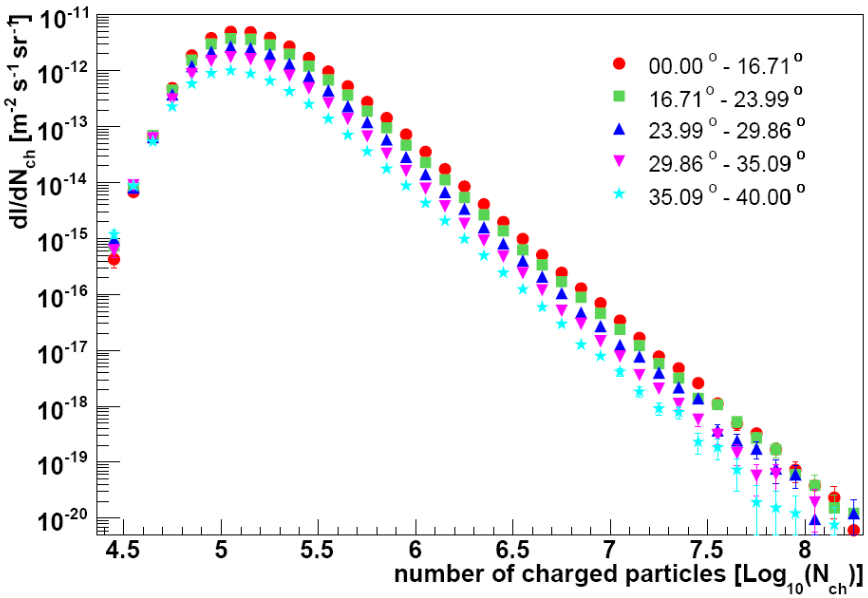


Core accuracy = 5m

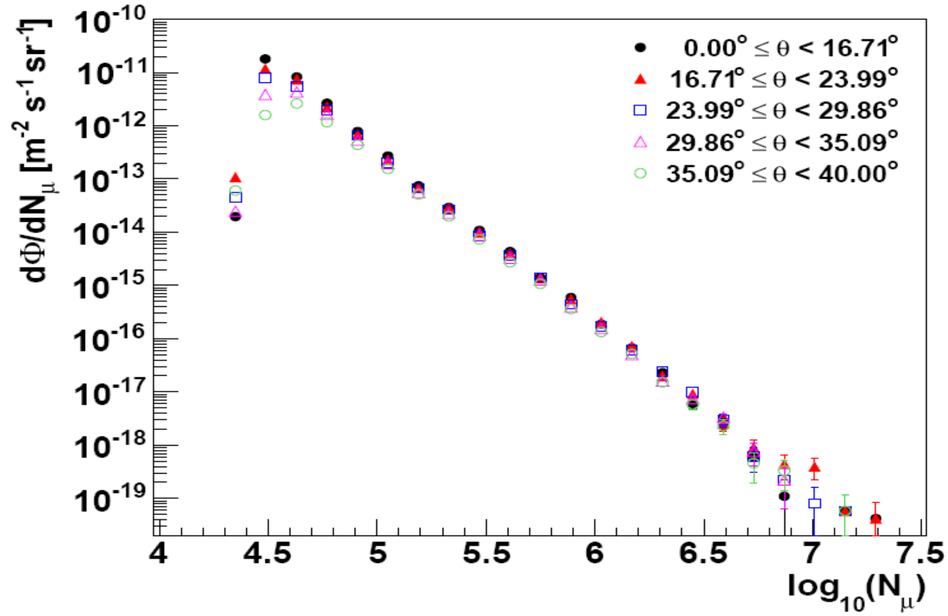
KASCADE-Grande coll., NIM A (2010) doi:10.1016/j.nima.2010.03.147

Reconstruction of the energy spectrum

size spectra (charged particles)

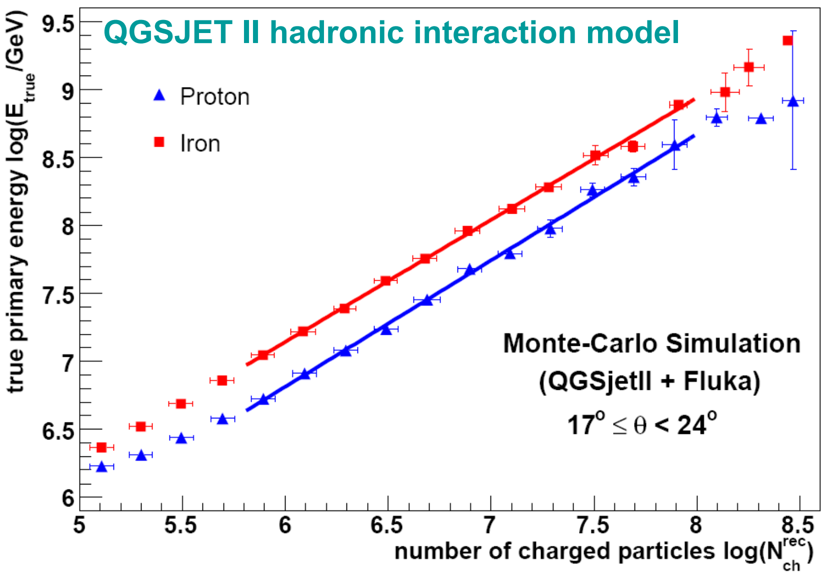


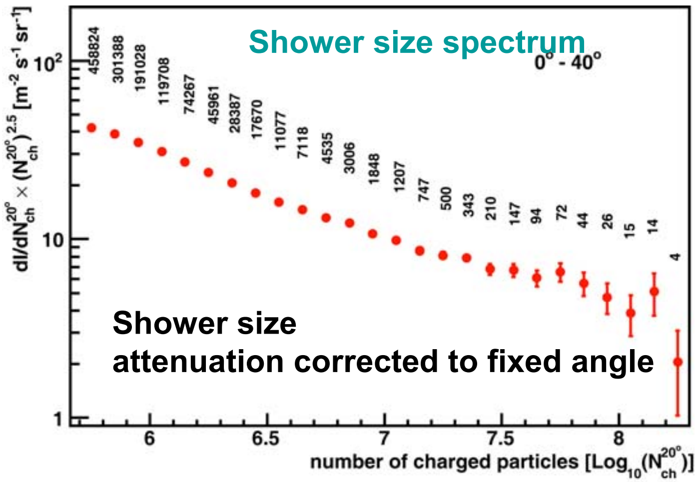
muon number spectra (N_μ ; E_μ>230MeV)



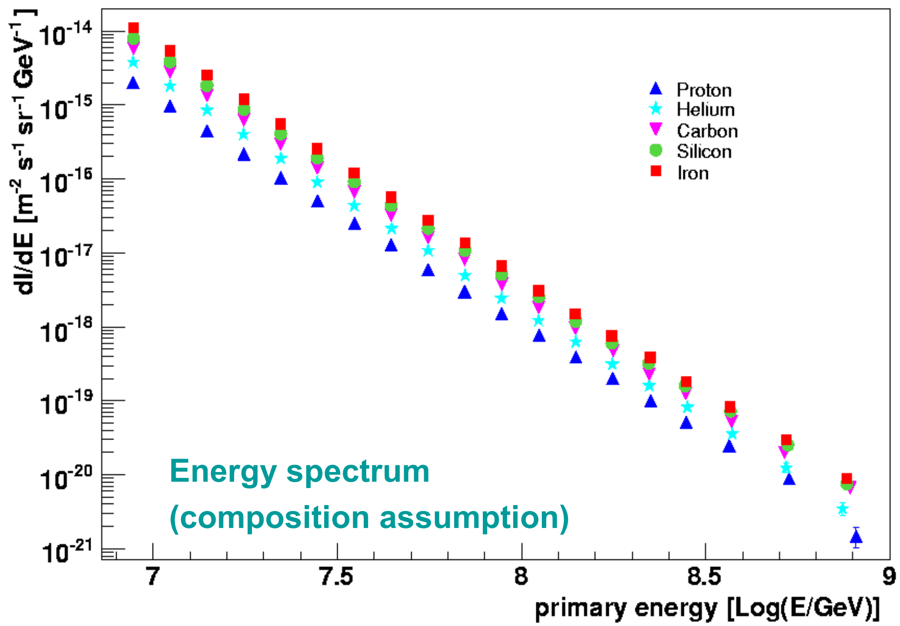
-stable data taking since 2004, c. 1173 days effective DAQ time
-performance of reconstruction (and detector) is stable

All-particle energy spectrum : via shower size (N_{ch})



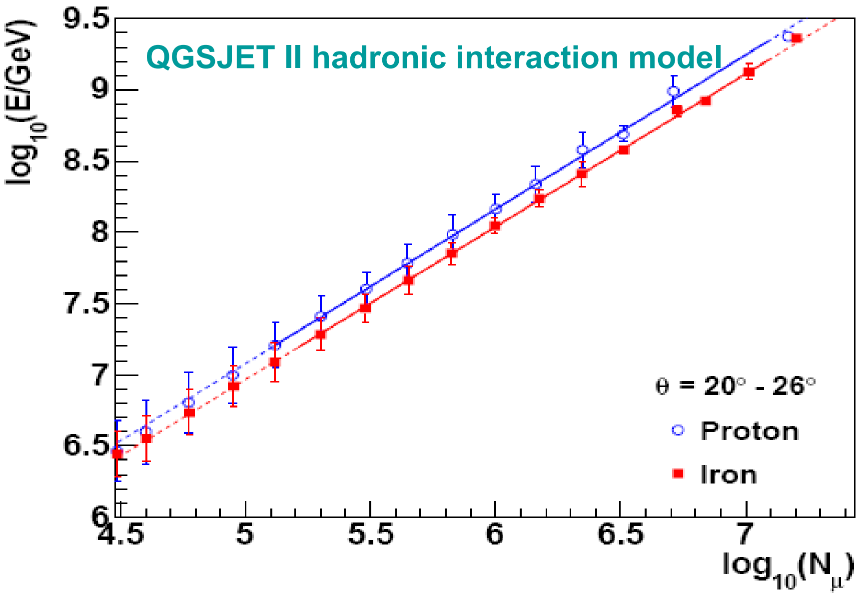


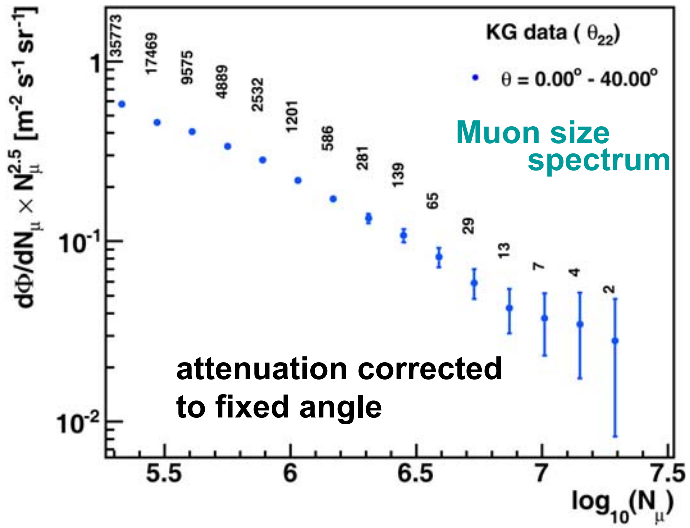
- Good reconstruction accuracy
- Application of a response matrix to correct bin-to-bin fluctuations
- Very composition dependent (need assumption of primary type)

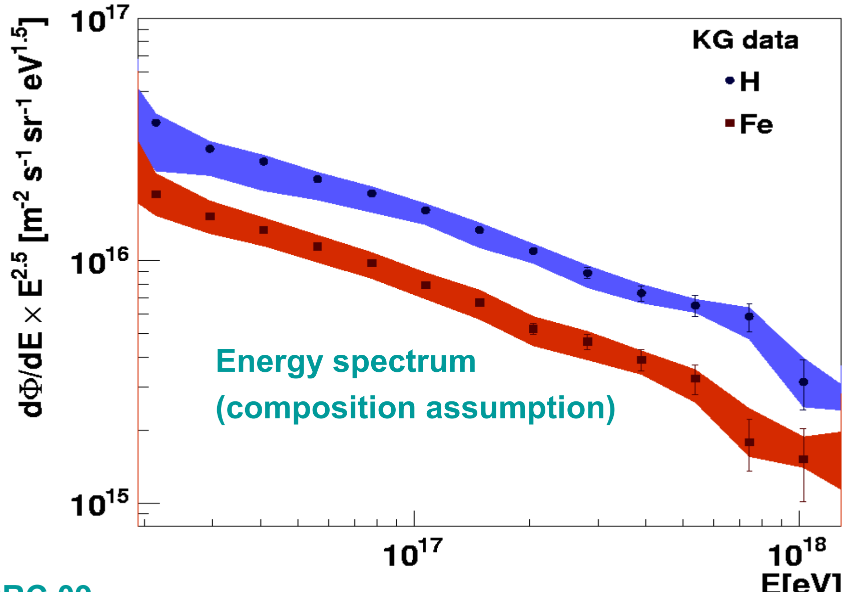


KASCADE-Grande collaboration, (D.Kang), ICRC 09

All–particle energy spectrum : via muon number (N_μ)







- Less good reconstruction accuracy
- Application of a response matrix to correct bin-to-bin fluctuations
- Less composition dependence

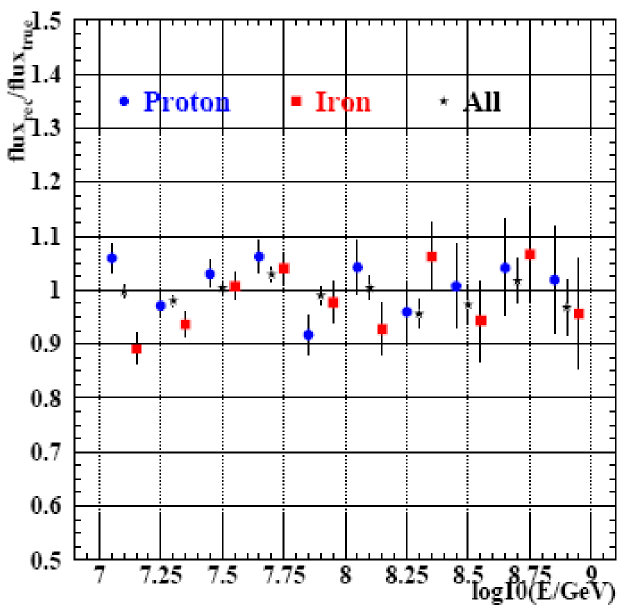
KASCADE-Grande collaboration (J.C.Arteaga-Velazquez), ICRC 09

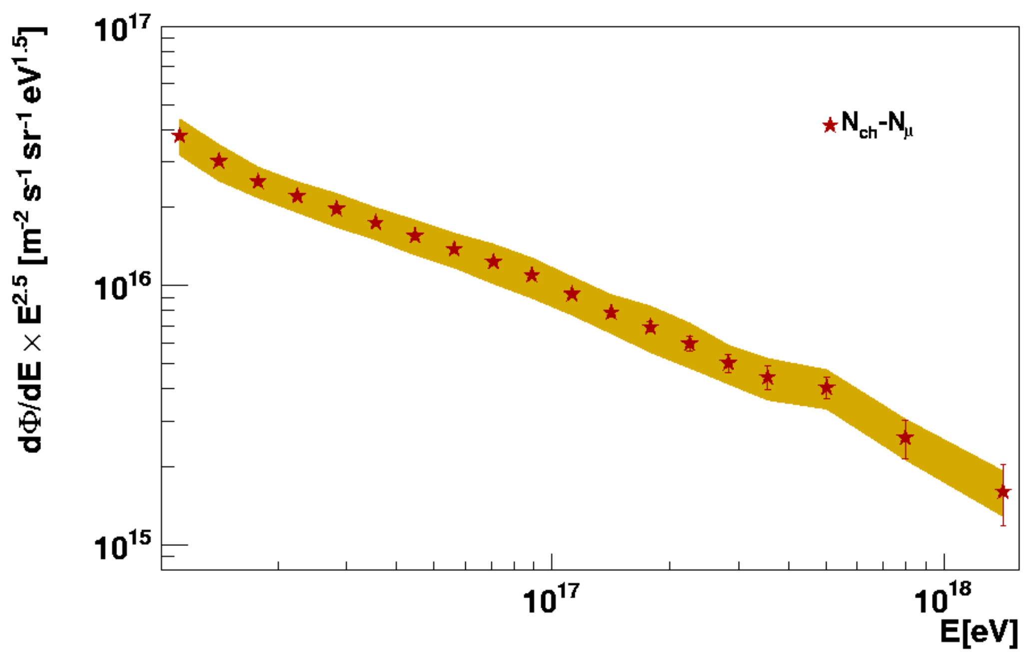
All-particle energy spectrum : via combination of N_μ and N_{ch}

$$\log_{10}(E) = [a_p + (a_{Fe}-a_p)\cdot k] \cdot\log_{10}(N_{ch}) + b_p + (b_{Fe}-b_p)\cdot k$$

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$

QGSJET II hadronic interaction model

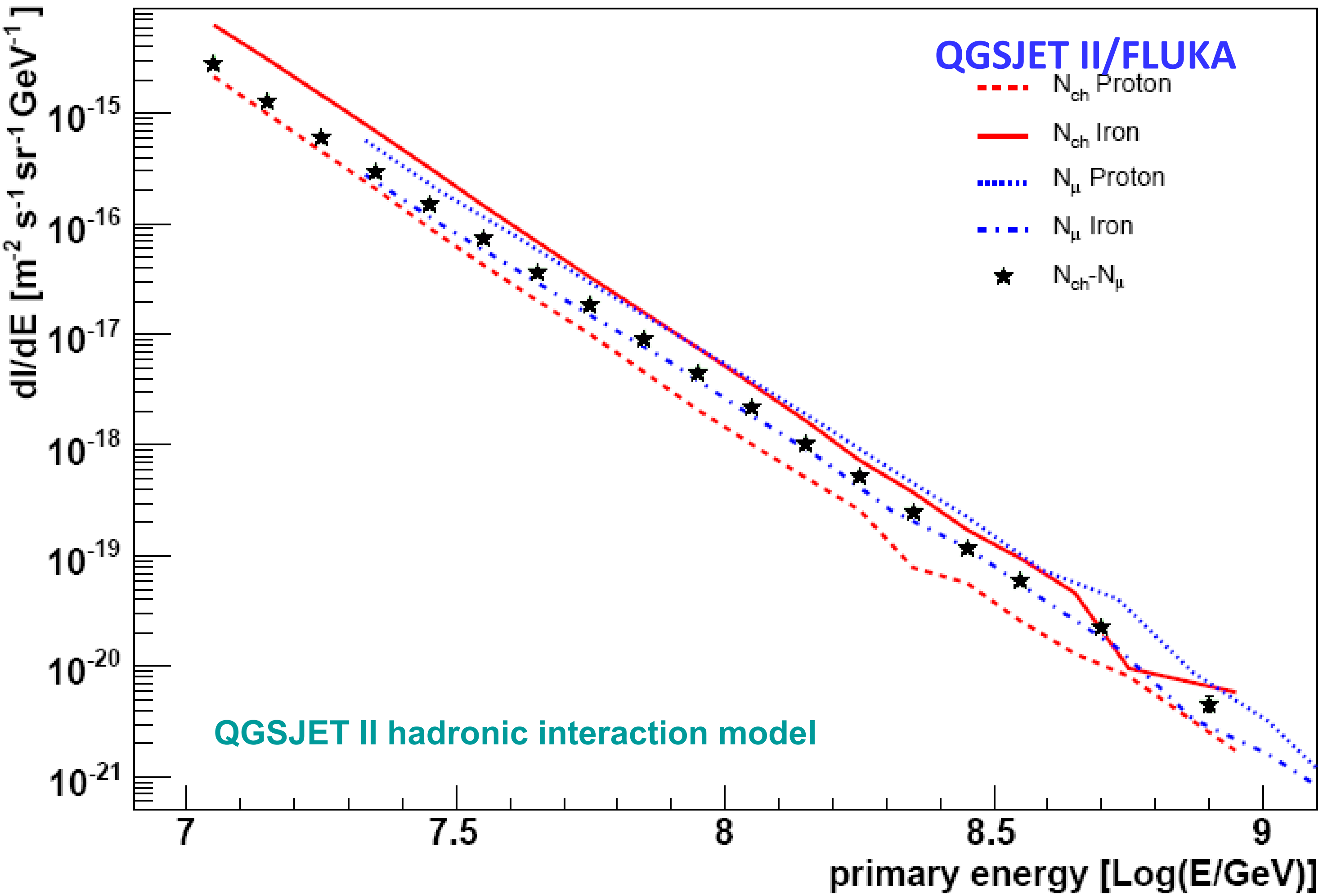




- different zenith angle bins
- no composition dependence

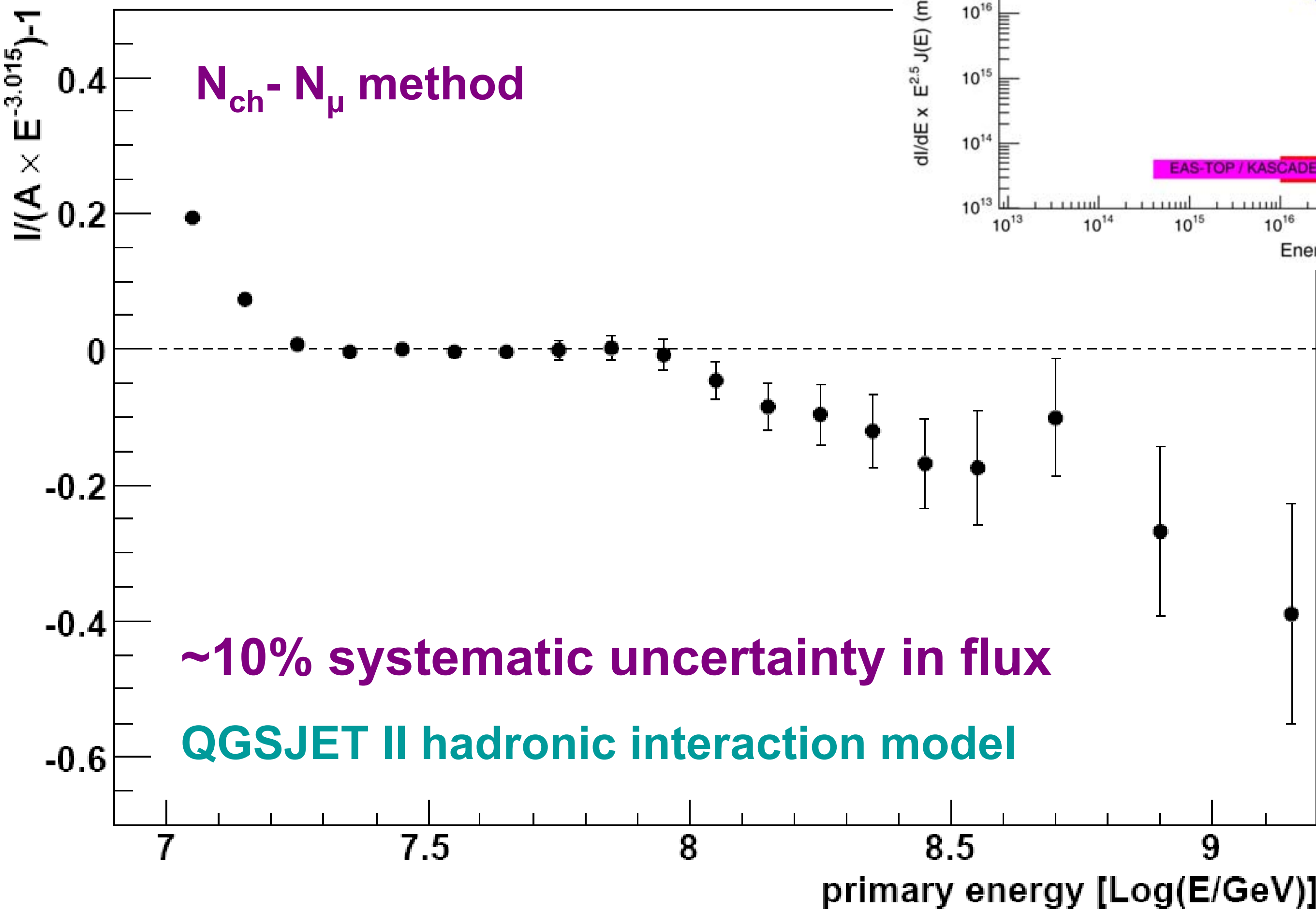
KASCADE-Grande collaboration (M.Bertaina), ICRC 09

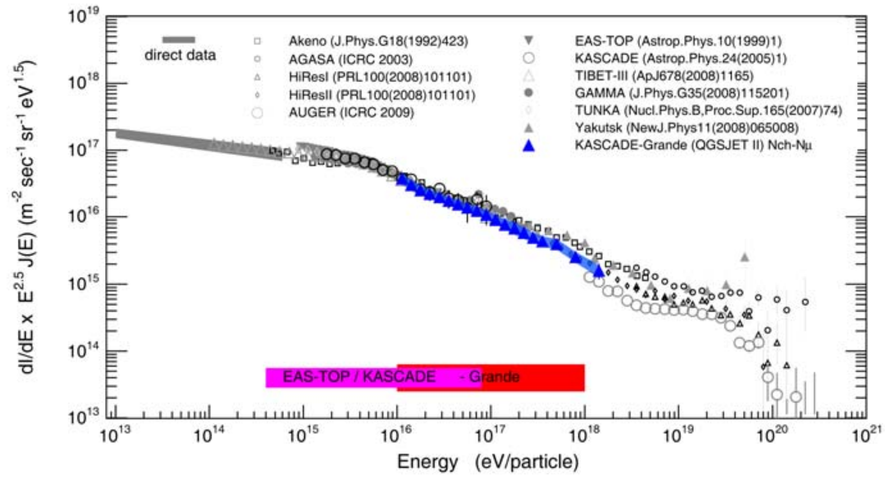
The all-particle energy spectrum



- very good agreement between results of different methods

The all-particle energy spectrum



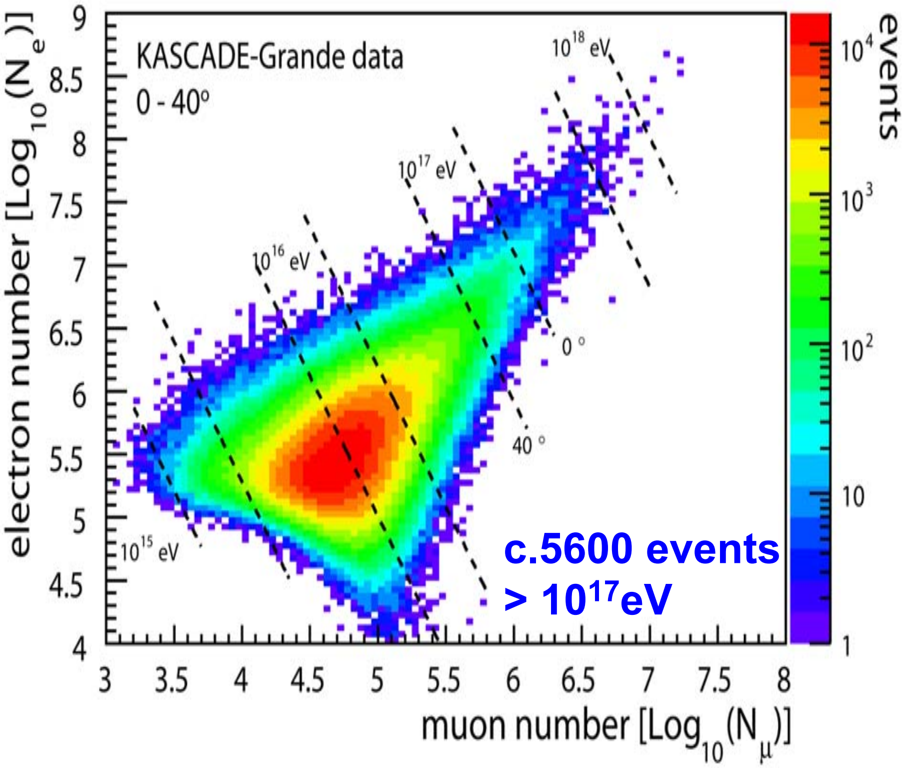


- spectrum not describable by a single power law at 10^{16}-10^{18}eV

Ways to elemental composition :

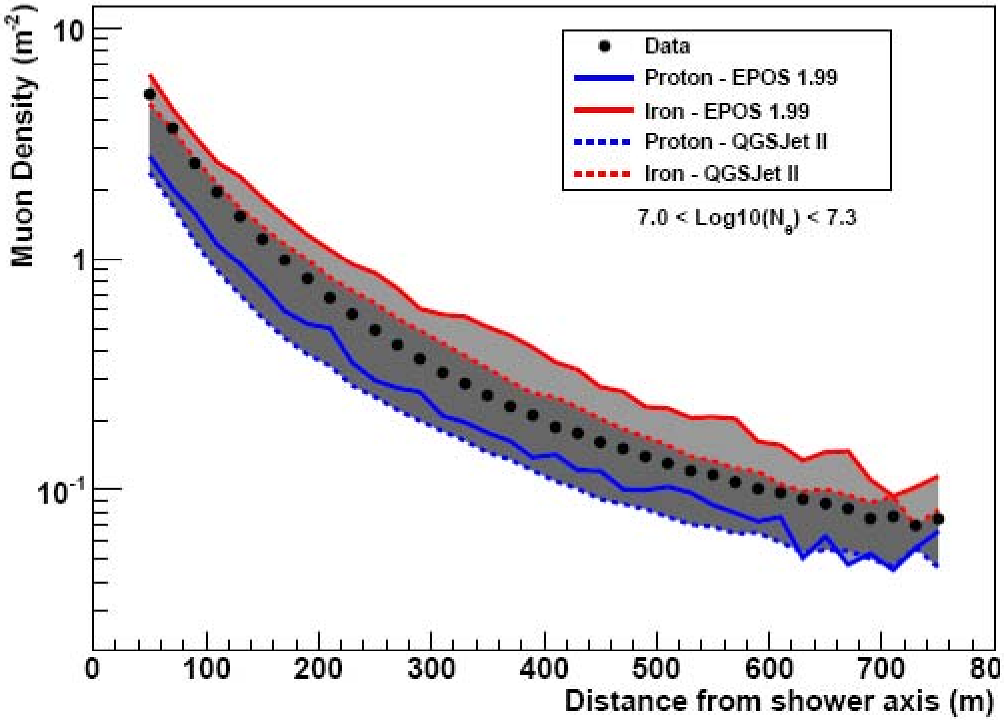
Application of different methods:

- **Local muon densities**
- **High-energy muon investigations**
- **Combination of N_{ch} , N_{μ}**
  (e.g., fit of N_{μ}/N_e -ratios in fixed size/ energy bins)
- **Unfolding of the 2-dimensional shower size spectrum**



Work in progress!

Way to elemental composition : muon density investigations



- **muon (local) density reconstruction for different, but fixed distances**

➔ composition sensitive

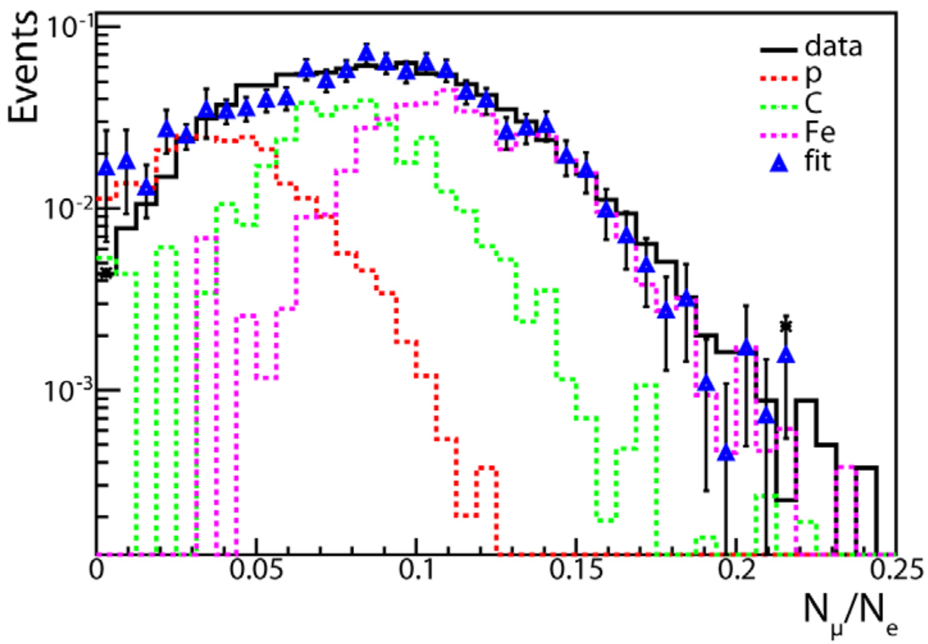
➔ model dependence: "heavy" for QGSJet, "light" for EPOS

➔ slope of LDF okay for EPOS 1.99

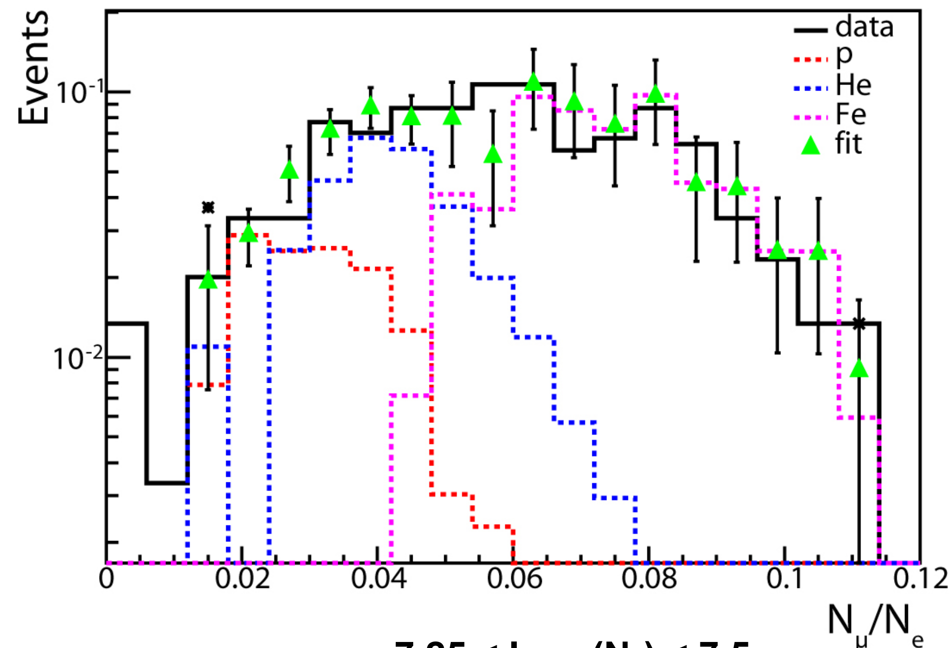
KASCADE-Grande collaboration (V. de Souza), ICRC 09

Way to elemental composition : N_μ / N_e-ratio

QGSJET II hadronic interaction model



6.5 < $\log_{10}(N_e)$ < 6.75



7.25 < $\log_{10}(N_e)$ < 7.5

- **shower size ratio: investigation of mean and rms**

➔ **rms of simulated distributions less model dependent than mean**

➔ **composition: more than 2 components needed; consistent with KASCADE in overlapping range**

KASCADE-Grande collaboration (E. Cantoni), ICRC 09

KASCADE-Grande Collaboration

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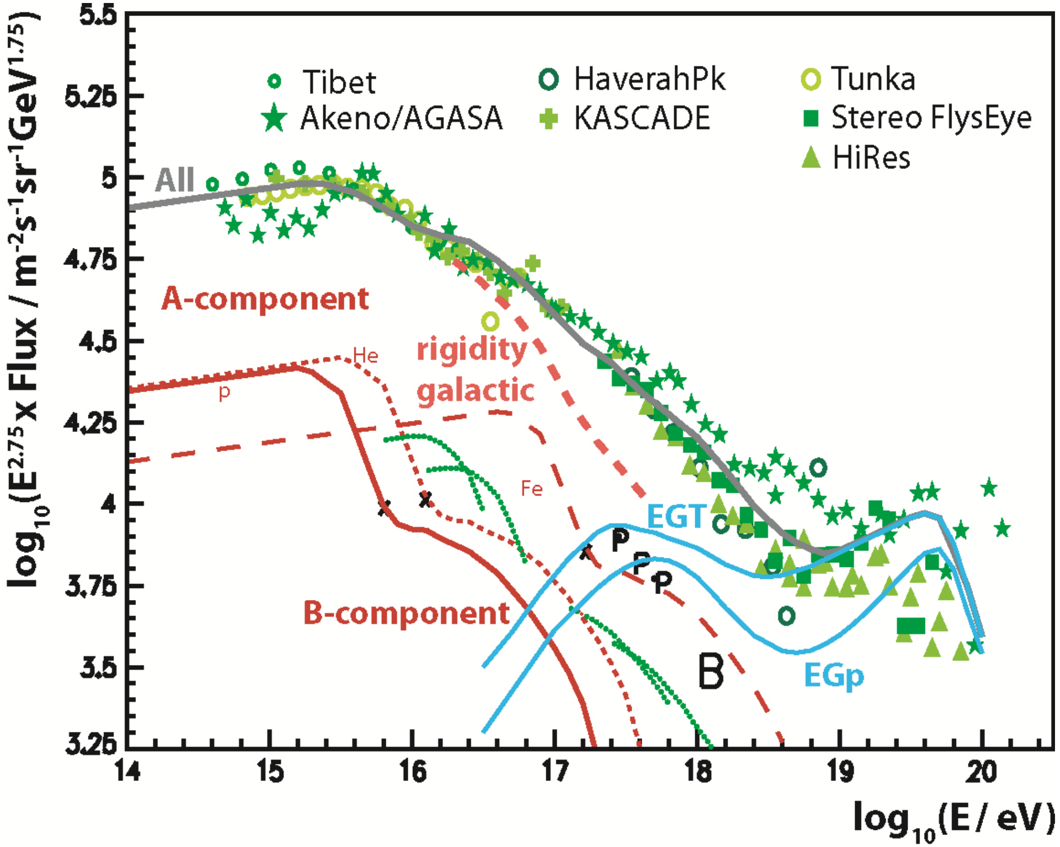
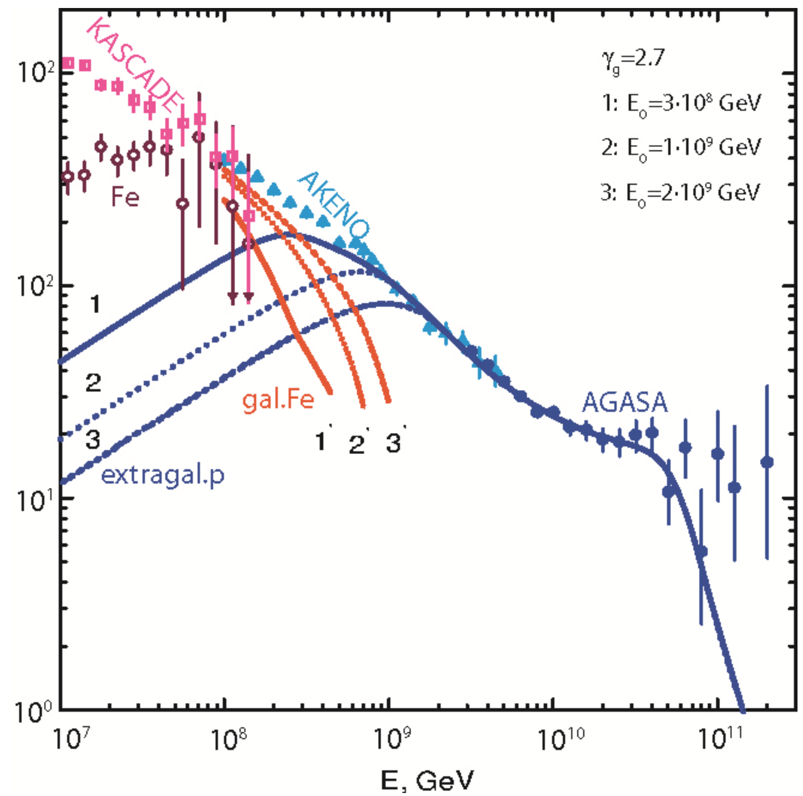
http://www-ik.fzk.de/KASCADE-Grande/

*deceased

Implications



A.M.Hillas, J. Phys. G: Nucl. Part. Phys. 31 (2005) R95



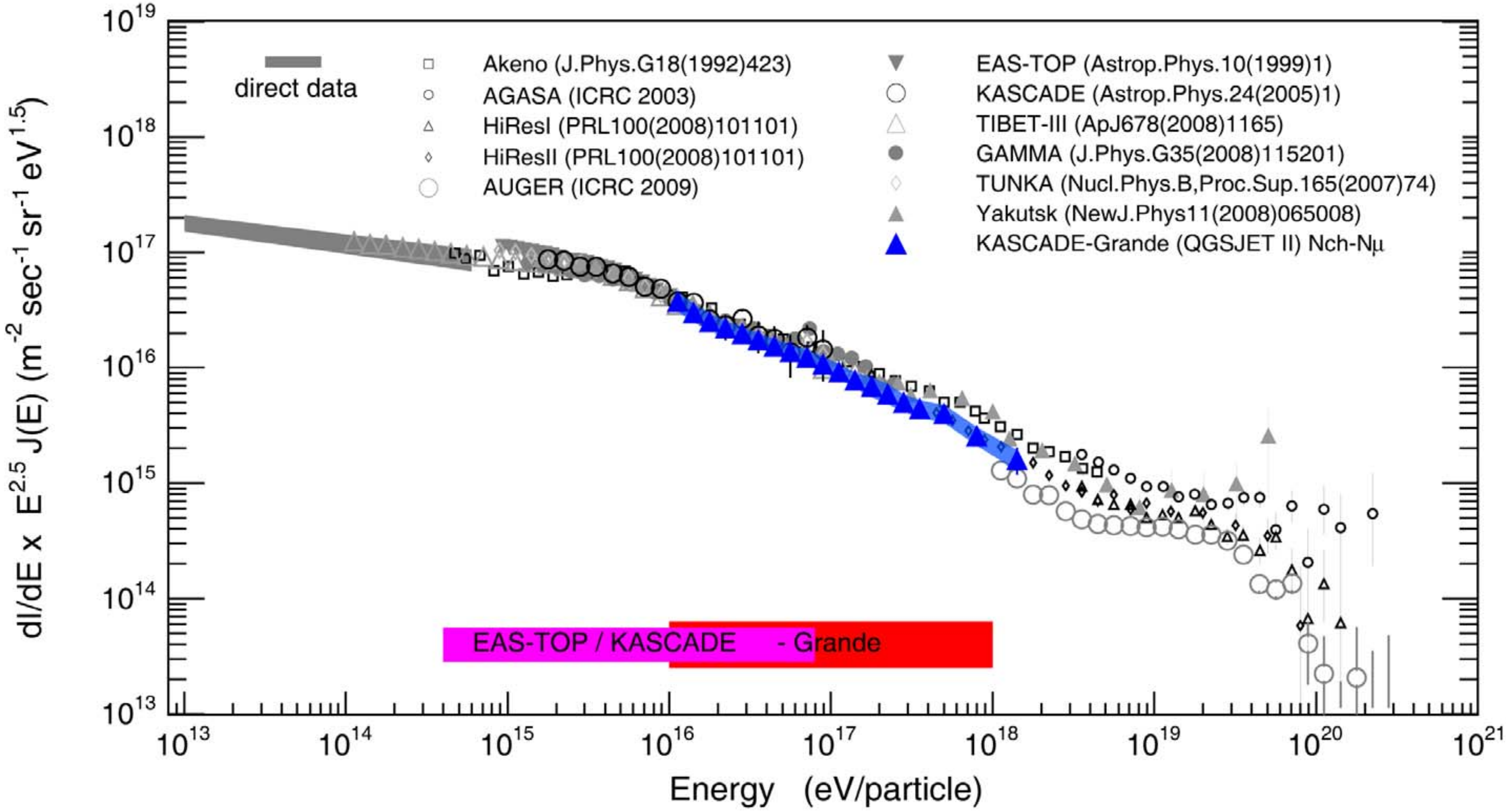
V.Berezinsky, astro-ph/0403477

KASCADE-Grande: spectrum concave at 10^{16}eV
small structure at 10^{17}eV
mixed composition

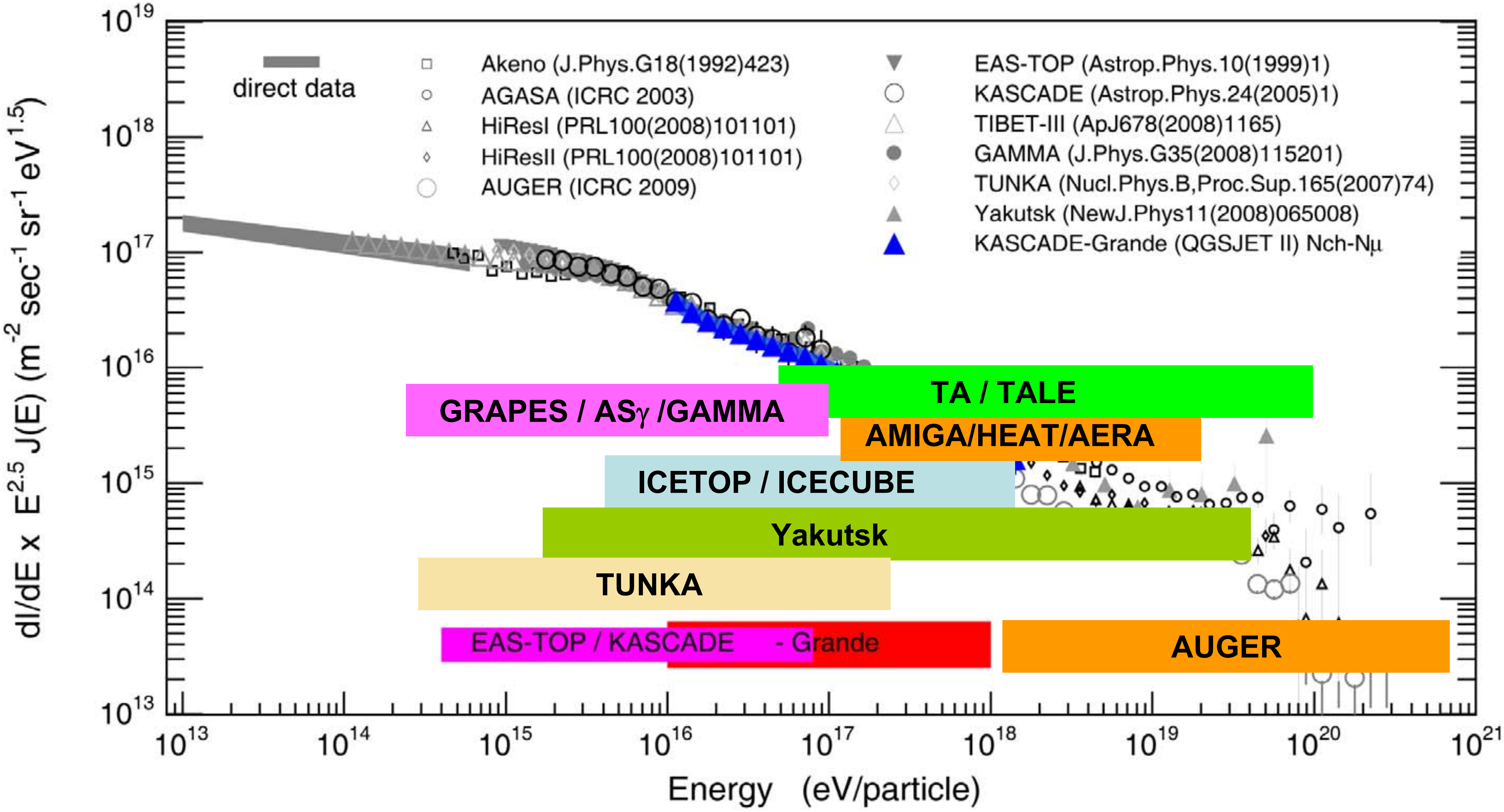
➔

- pure rigidity model unlikely
- at <10^{18}eV eg-protons only unlikely

KASCADE-Grande



KASCADE-Grande



30 March 2009 – official closure ceremony

➔ KASCADE-Grande EAS Test Facility

for internal and external users!

e.g. LOPES!

or HiSPARC

Connection particle array – radio array:

Radio detection technique is still in developing phase
hardware, software, analysis, emission mechanism(s?), … ➔
Calibration (understanding) radio emission
- Dependencies of radio signal
- Understanding emission mechanism(s)

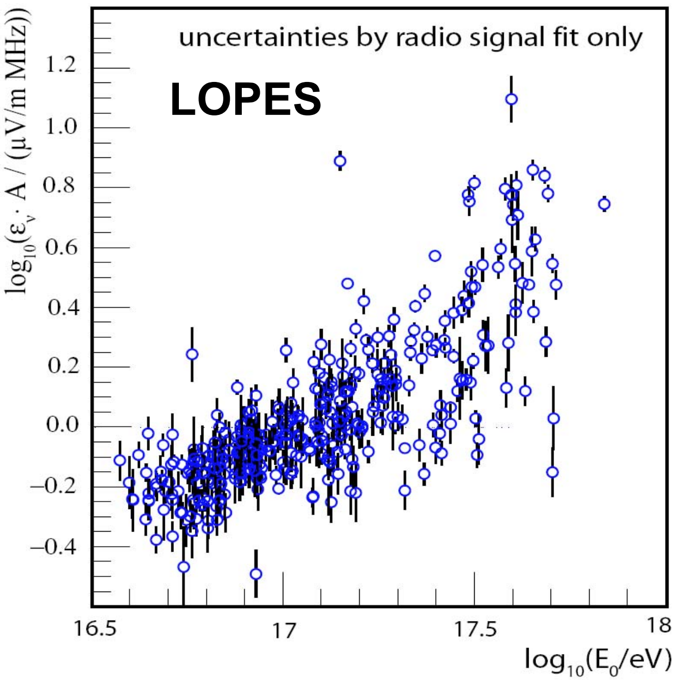
Capability of the radio detection technique?

Sensitivity and resolution to
- primary energy?
- arrival direction?
- composition ?

EAS radio detection for CR (and neutrino) measurements:
stand alone or hybrid technique?

Comparing with particle arrays, not fluorescence technique (duty cycle).

Primary Energy



- Radio-Emission seems coherent !
- Energy sensitivity via electric field strength
- Radio signal (electric field) scales with primary energy:

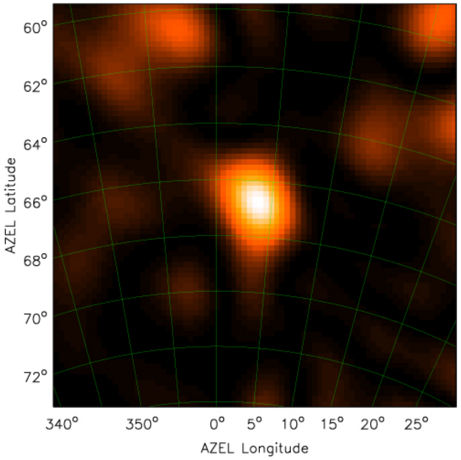
$$\varepsilon_\nu \sim E_0^{\approx 1}$$

➔ **Power of electric field scales approximately quadratically with primary energy !**

- Sensitivity and resolution $\Delta E/E \sim 20\text{-}25\%$
- Particle array: 10-20%

➔ is energy resolution really worse?
Model dependence?
Emission mechanism?
Geometry of shower?

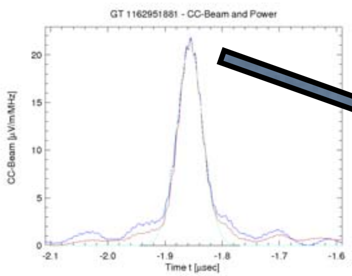
Arrival Direction

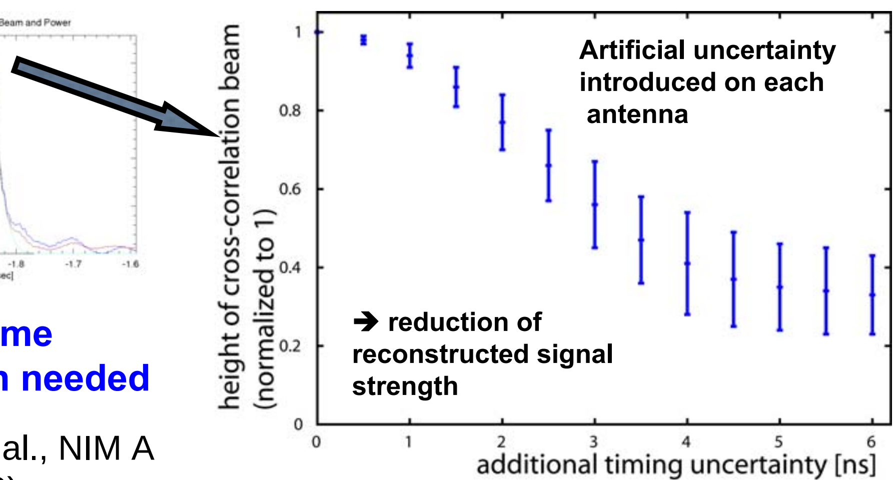


- sensitivity via pulse arrival time and phase
- systematic studies of direction resolution: KASCADE vs. LOPES: offset (1.3±0.8)°

➔ **resolution better 1°**

(by beam forming; Better with increasing field strength, but number of antennas?)



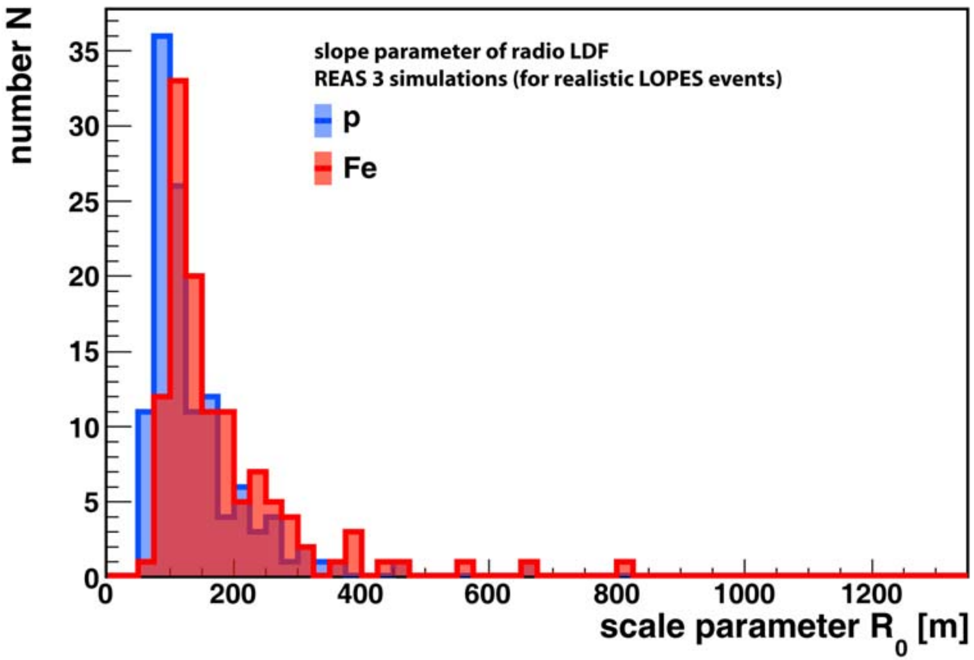


➔ ~1ns time resolution needed

F.Schröder et al., NIM A (2010)

\- **Sensitivity and resolution** σ(direction) << 1°

Composition



- Lateral distributions seems to have composition sensitivity!
- model dependence?

- Sensitivity and resolution ??
- Particle array: unknown (large) uncertainty (FD better)
  - ➔ by lateral sensitivity (pattern)
  - ➔ by longitudinal sensitivity
    - pulse shape
    - wave front
    - frequency spectrum
    - ….

= Xmax (shower maximum) sensitivity needed!!

EAS Radio detection

It works, but still many questions open:

- **Radio signal (electric field) scales with primary energy:** $\varepsilon \sim E_0^{\gamma}$ ($\gamma \sim 1$)
- **Radio signal scales with geomagnetic field:** $\varepsilon \sim v \times B$ (may be not all)
- **Radio signal scales with core distance:** $\varepsilon \sim \exp(-R/R_0)$ ($R_0 \sim$100-200m)
- **Frequency spectrum is a decreasing power law (or exp)** $\varepsilon \sim \nu^{\delta}$ ($\delta \sim -1$)
- **Radio signal is polarized (azimuth and observer position) dependent**

understanding of the radio emission and all its correlation with EAS parameters still important!

⇒

suitable for hybrid measurements!

LOPES 10 Analysis : Distant Events
Interplay of radio and shower particle analysis

Grande Event:

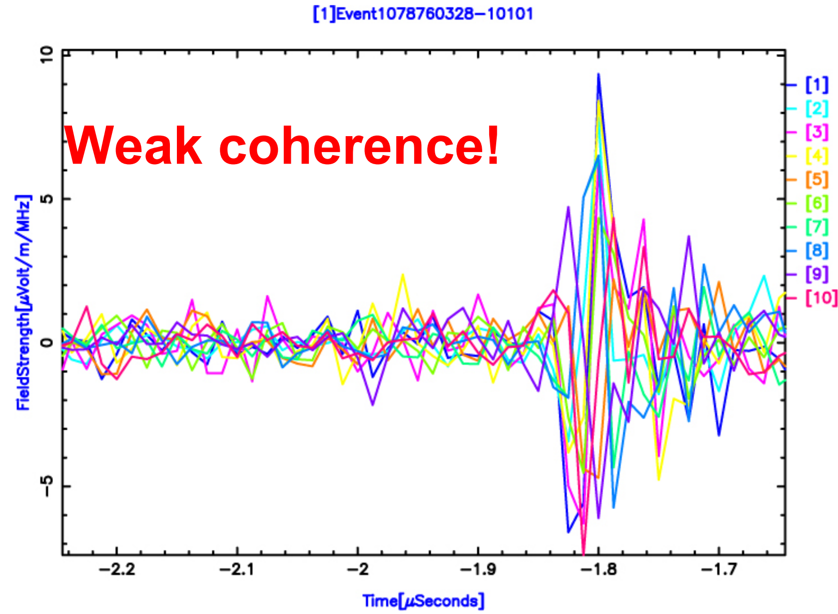
Φ = 302.18° θ = 41.01°

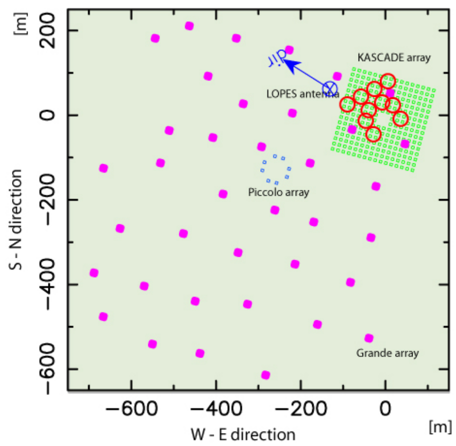
α = 57.91°

X_c = -142.85 m Y_c = 40.27 m

lg(E/eV) = 17.73 ln(A) = 3.16

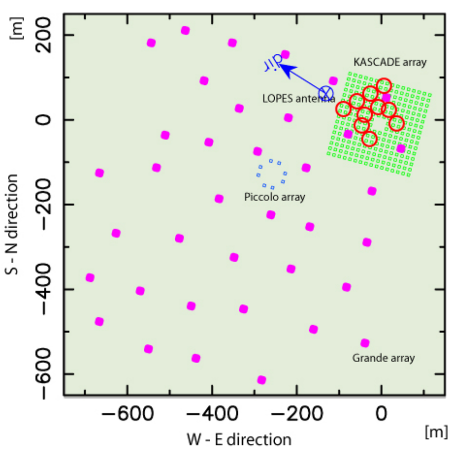
curvature = 3250 m

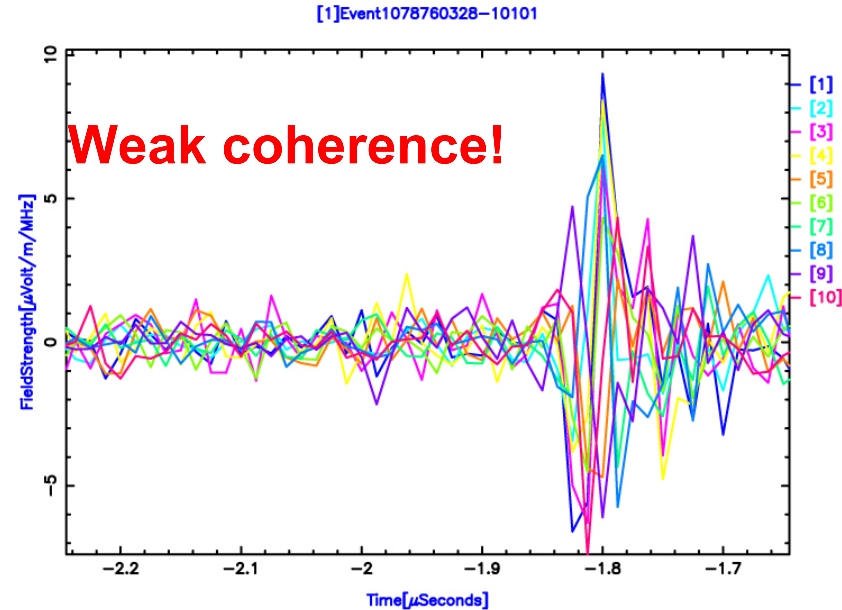


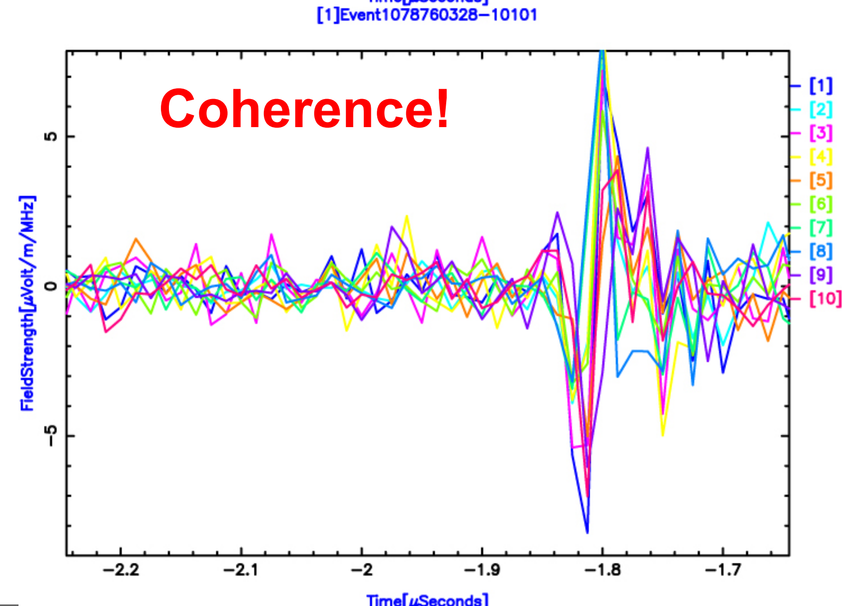


LOPES 10 Analysis : Distant Events
Interplay of radio and shower particle analysis

Event:	search for maximum coherence
Φ= 302.18°	= 301.58°
θ = 41.01°	= 40.61°
α = 57.91°	
X_c = -142.85 m	= -137.85 m
Y_c = 40.27 m	= 30.28 m
lg(E/eV) = 17.73	
ln(A) = 3.16	
curvature = 3250 m	= 4250 m







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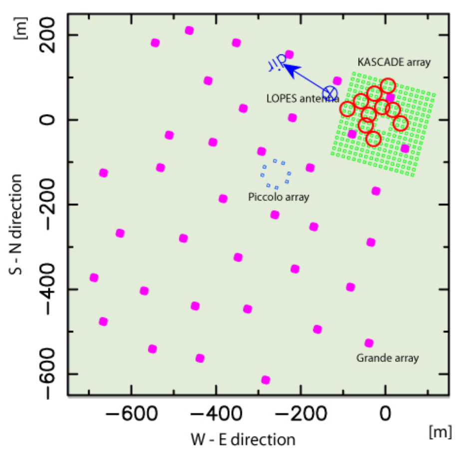
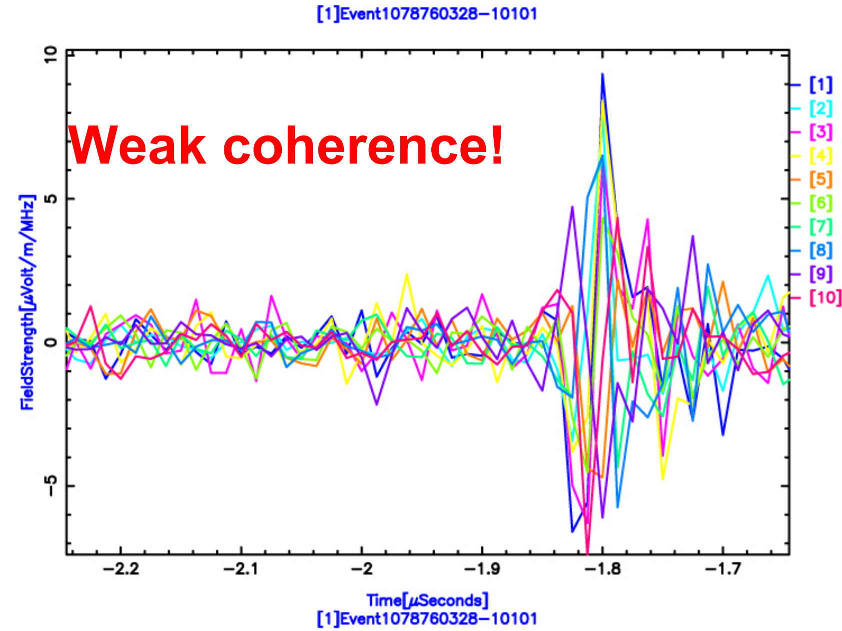
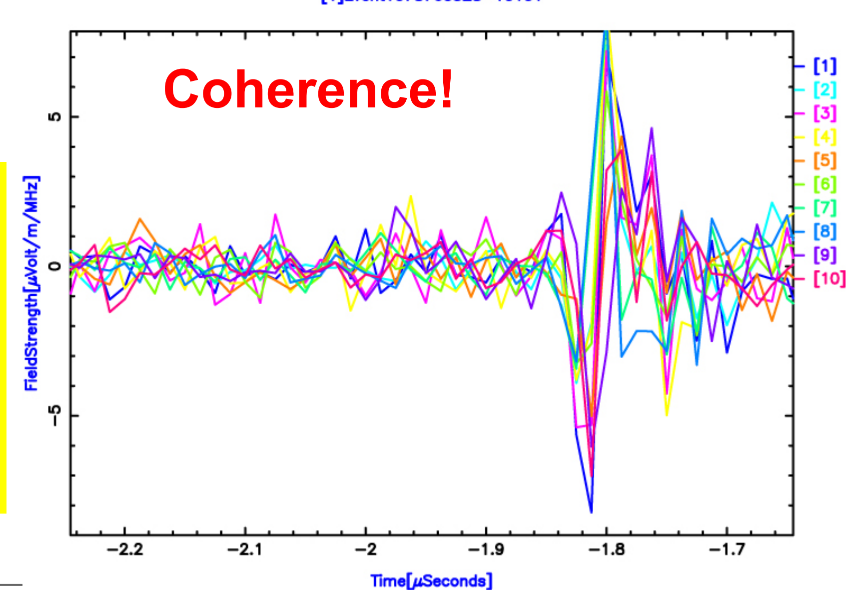
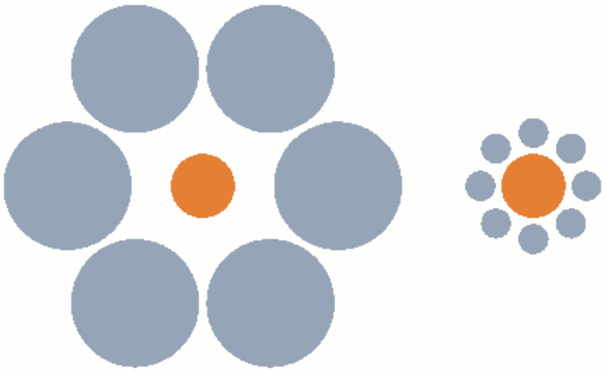


➔Improvement of shower core and arrival direction estimate in Grande by LOPES !

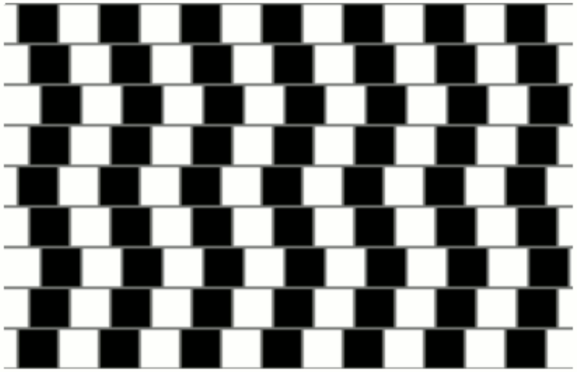




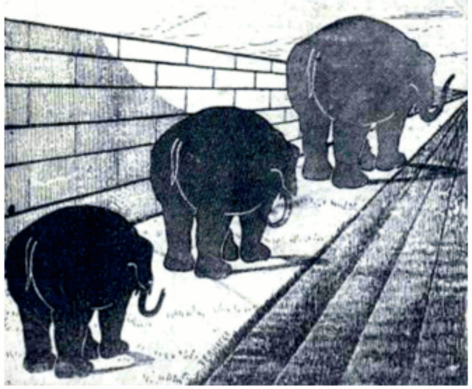
Lesson to be learned:
be careful that you are not fooled by sensors!



The right inner circle appears to be bigger



The horizontal lines look slanted



The elephants seem to be of different size

Lesson to be learned:
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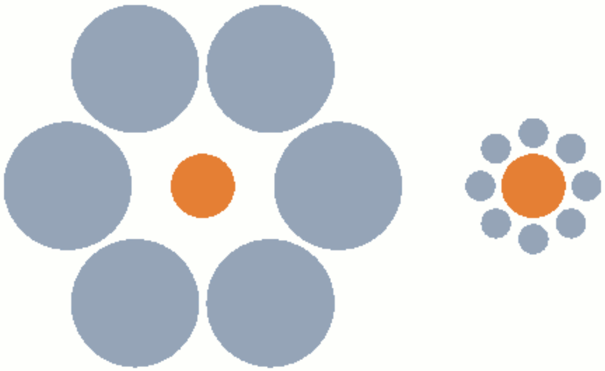

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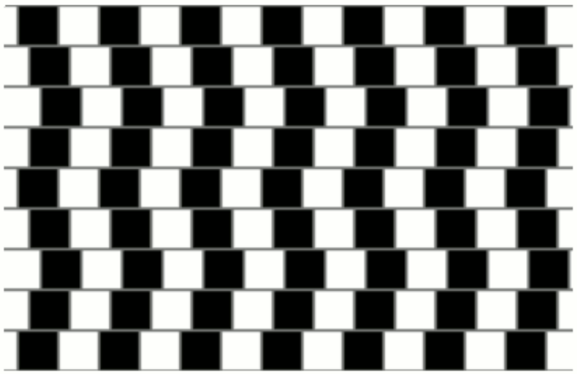
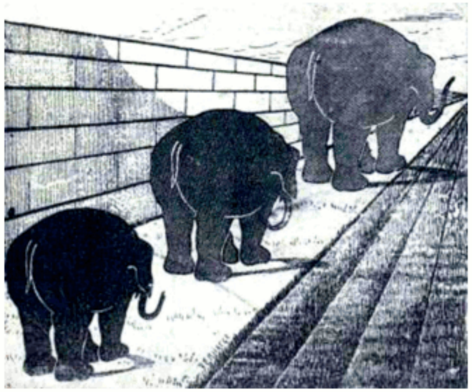


The horizontal lines look slanted



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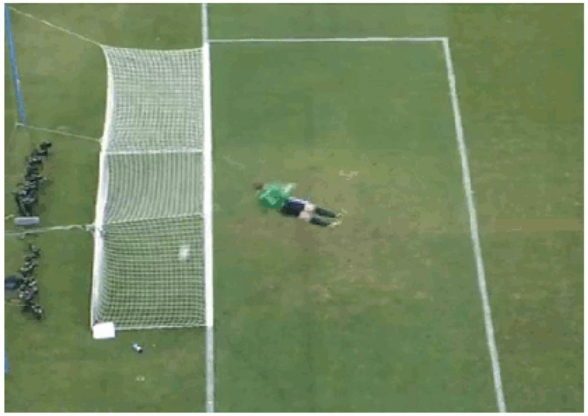

The ball appears to be in the goal.

Summary / Status

- high quality data at 10^{16} – 10^{18} eV by KASCADE-Grande to identify the „iron“- knee and transition galactic–extragalactic cosmic rays!
- first results KASCADE-Grande:
  - energy spectrum :
    - ➔ no single power law (concave form at 10^{16} eV)
  - elemental composition
    - ➔ more than two components needed around 10^{17}eV
  - anisotropy studies
    - ➔ no anisotropy seen
  - interaction models
    - ➔ muon attenuation, muon production height, etc…
- 30/03/2009: KASCADE-Grande closure symposium
  - KASCADE-Grande ➔ EAS test facility
  - ➔ data analysis continued…
- new detection techniques:
  - ➔ LOPES – radio detection of air showers
  - ➔ sensitivities of radio (hybrid performance!)