The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

2036-22

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

25 - 29 May 2009

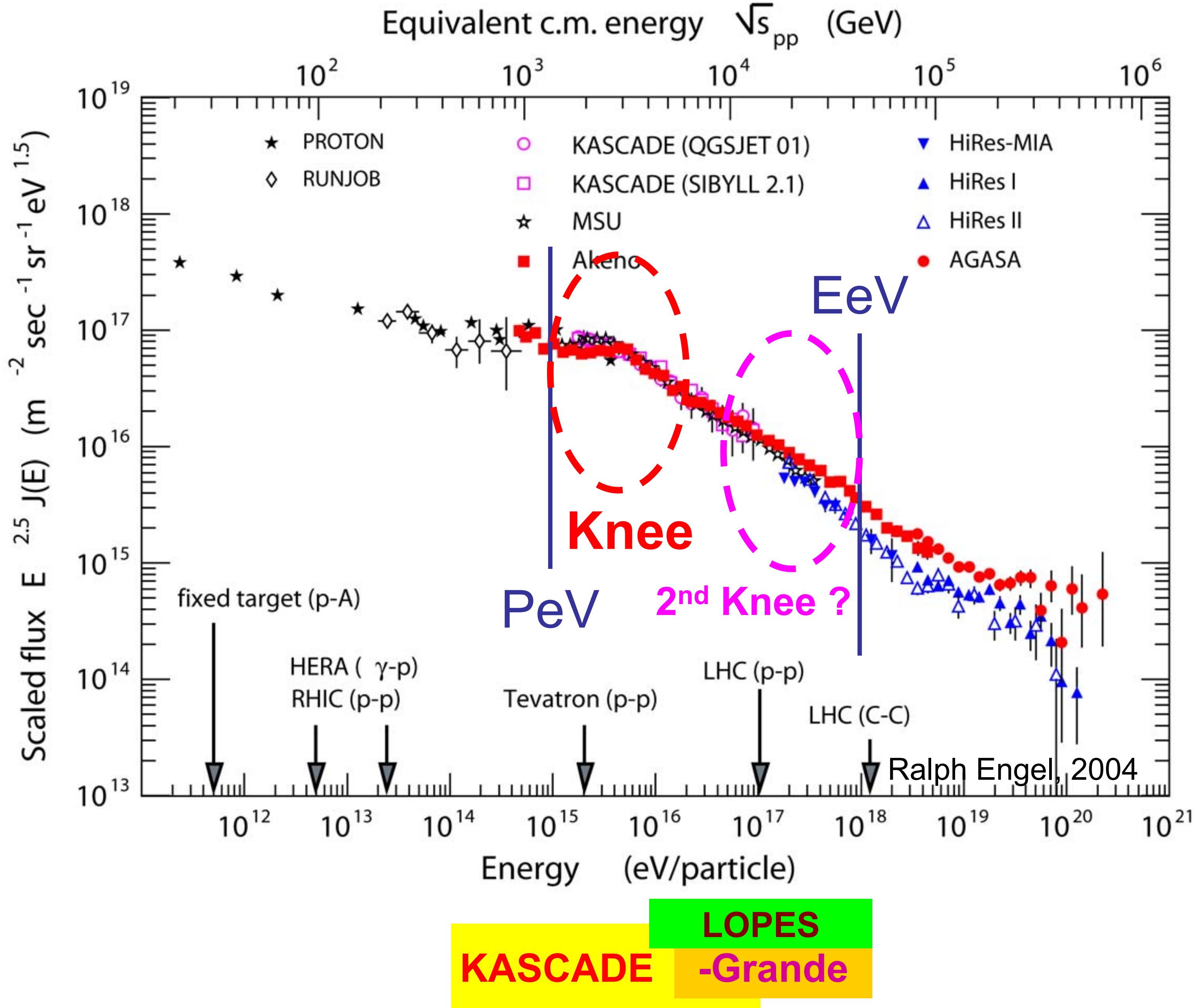
Air-shower measurements with KASCADE-Grande

Andreas Haungs
Kernforschungszentrum Karlsruhe G.M.B.H.
Germany

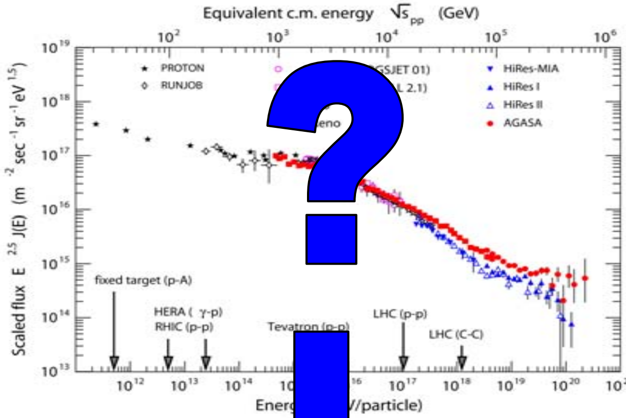
Air-shower measurements with KASCADE-Grande

Andreas Haungs haungs@ik.fzk.de

Cosmic Rays around the knee(s)

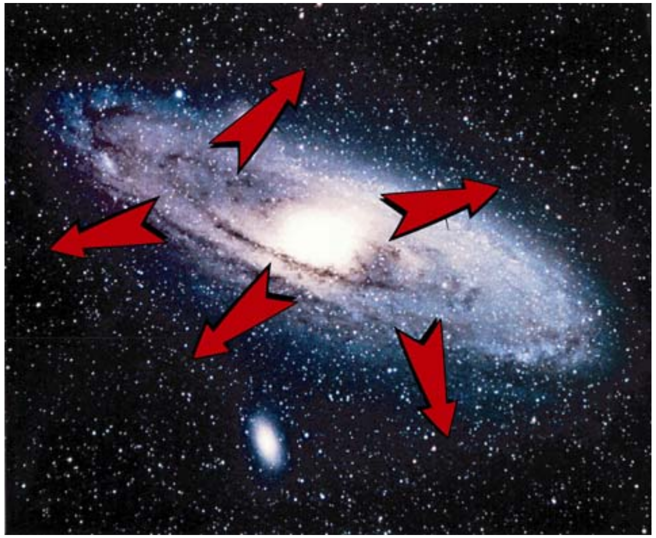


What is the origin of the (first) knee?



various theories:

Diffusion



Escape from our Galaxy by diffusion

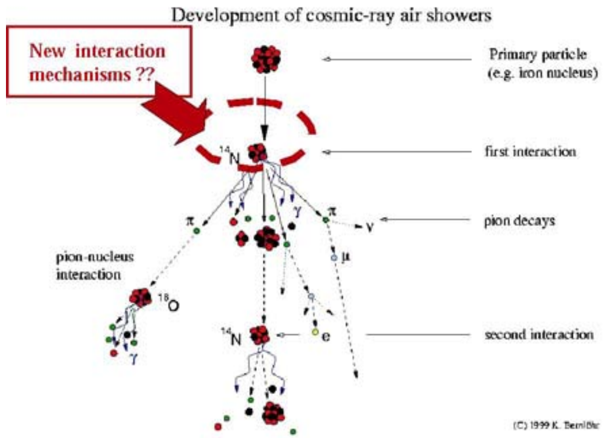
E(knee) ~ Z

Acceleration

Reach of maximum energy at the acceleration

E(knee) ~ Z

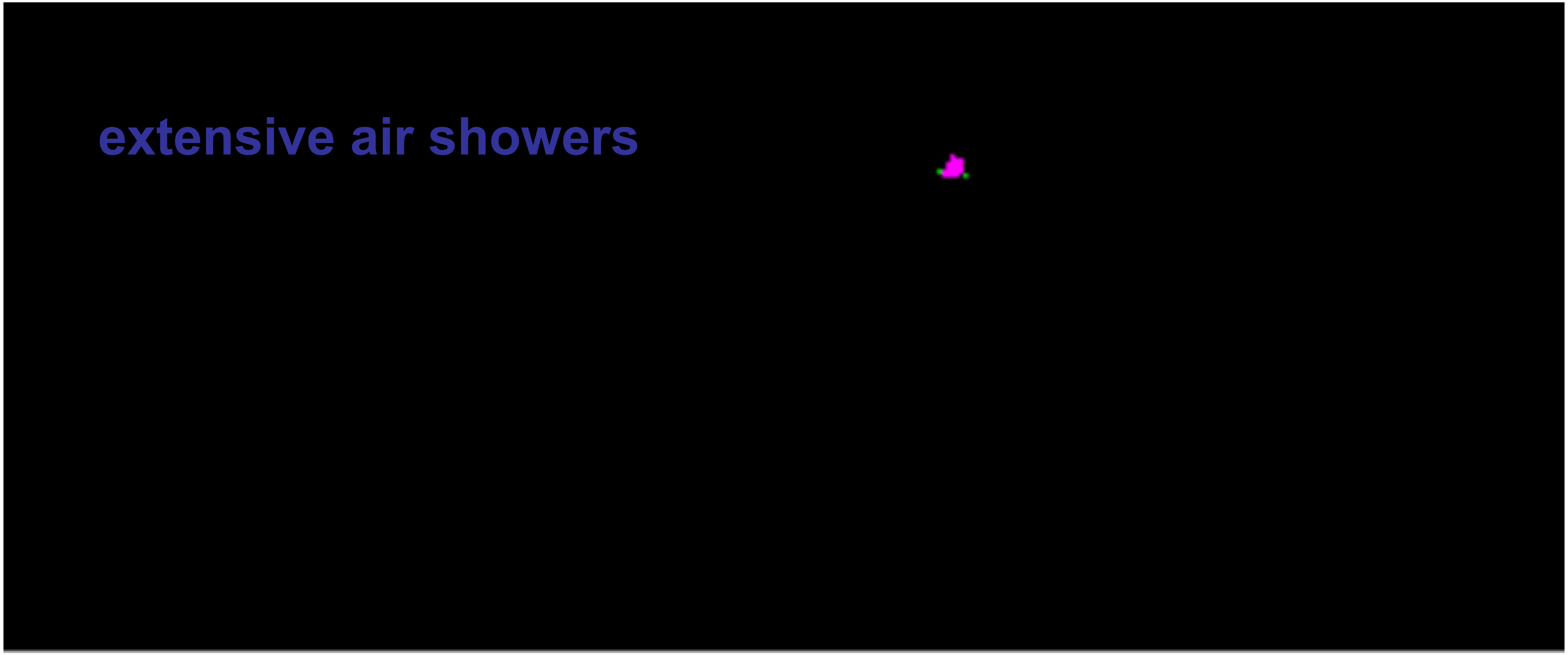
Interaction



Unknown effects of interactions at the air-shower development

E(knee) ~ A

extensive air showers



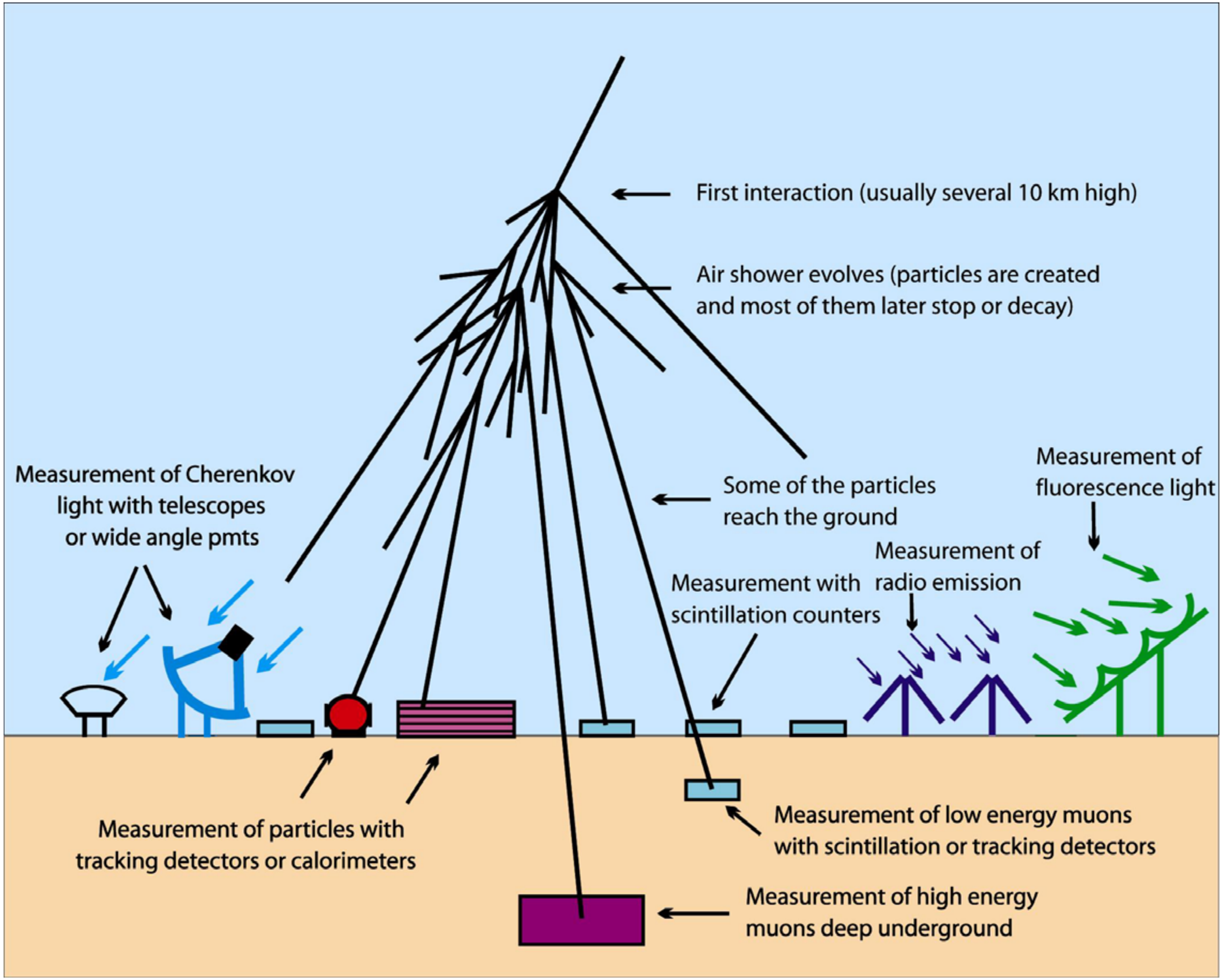
Differences in the shower development give hints to primary energy and mass

Measurement Techniques of Air Showers

energy ?
mass ?
direction ?
interaction ?

➔ large number of observables

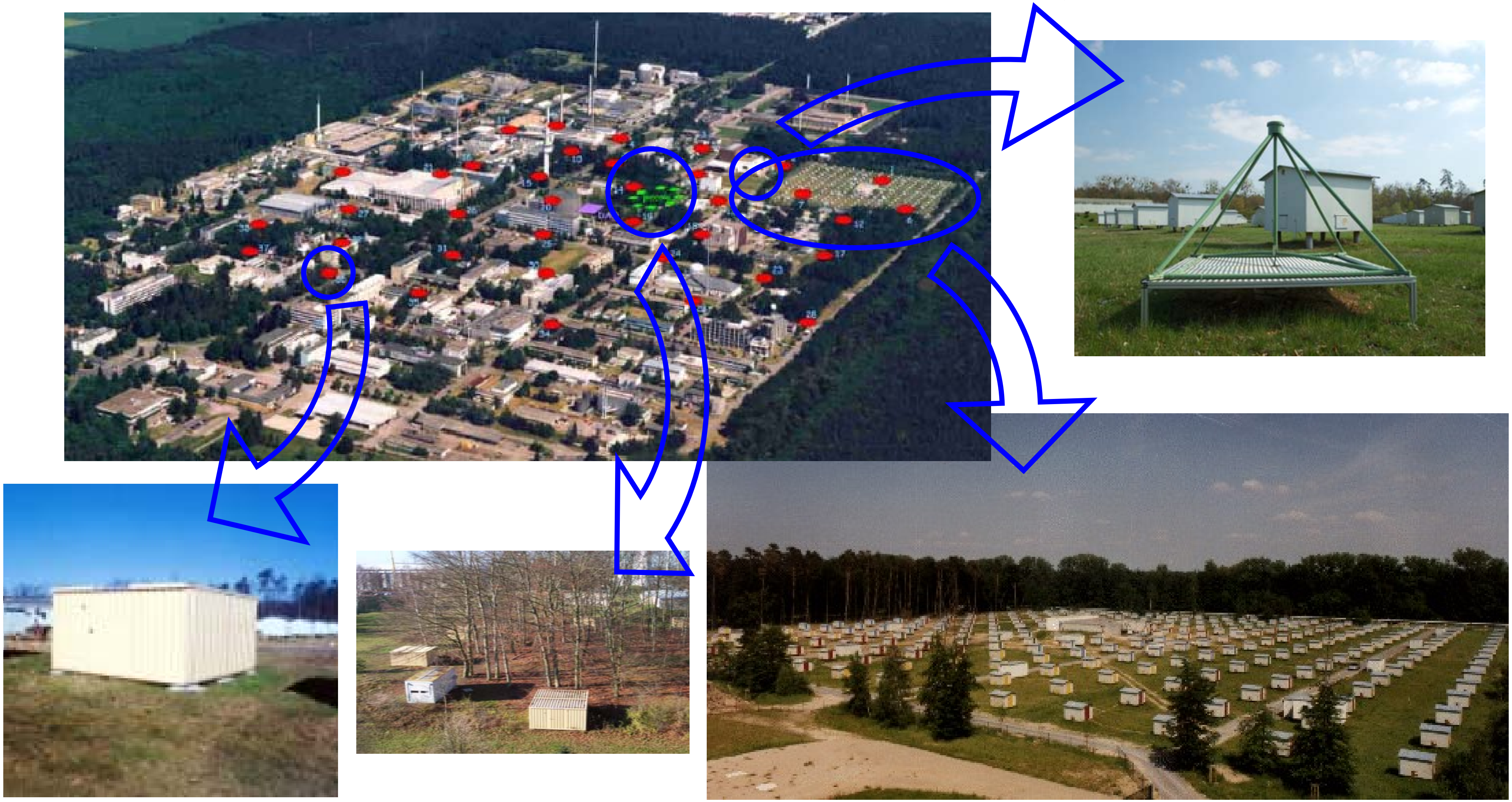
➔ multi-detector system



Experiment: KASCADE-Grande

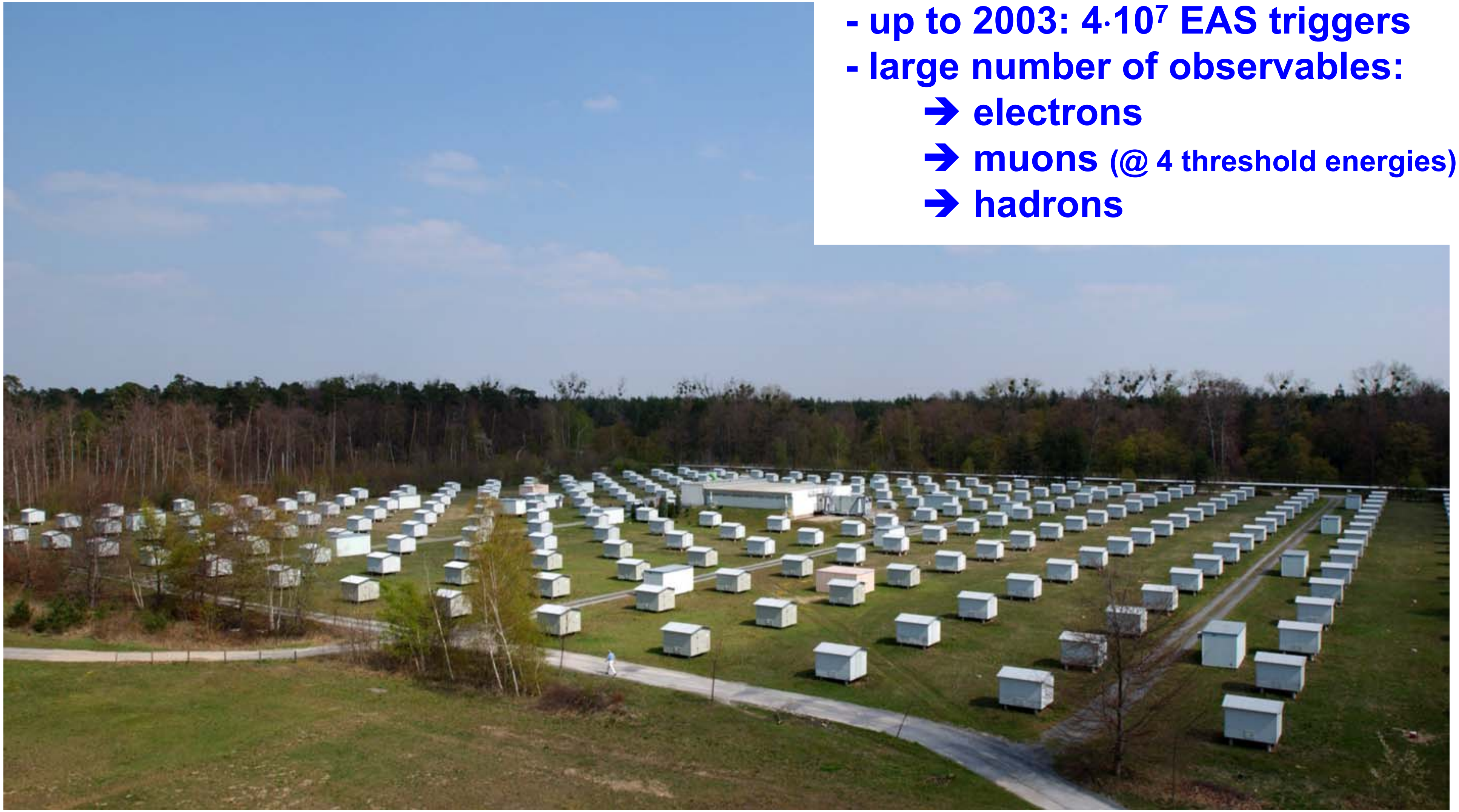
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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



KASCADE : multi-parameter measurements

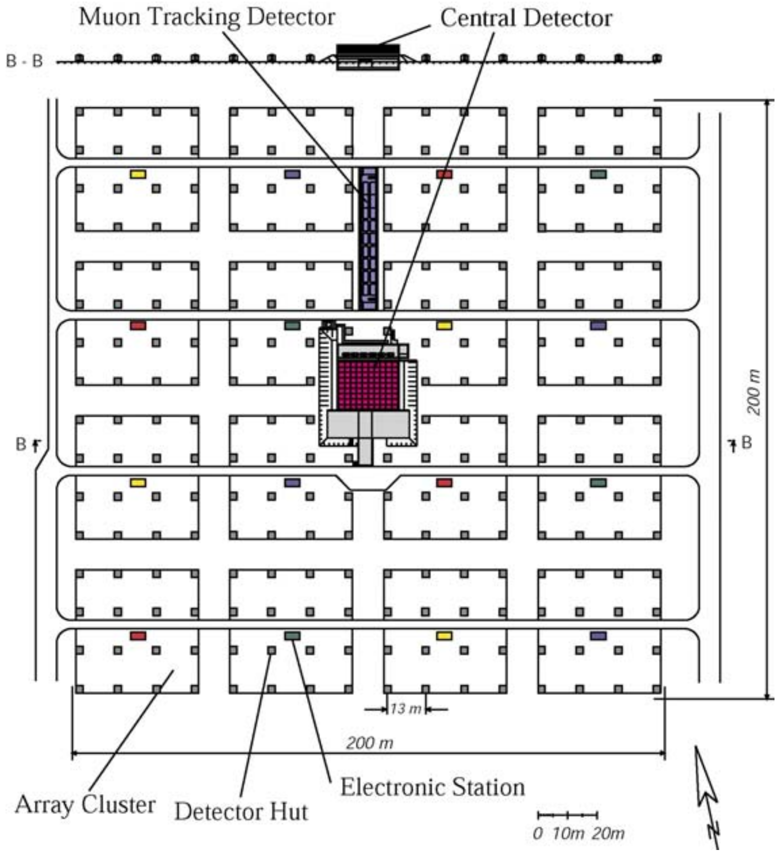
- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
  - ➔ electrons
  - ➔ muons (@ 4 threshold energies)
  - ➔ hadrons



KASCADE set-up

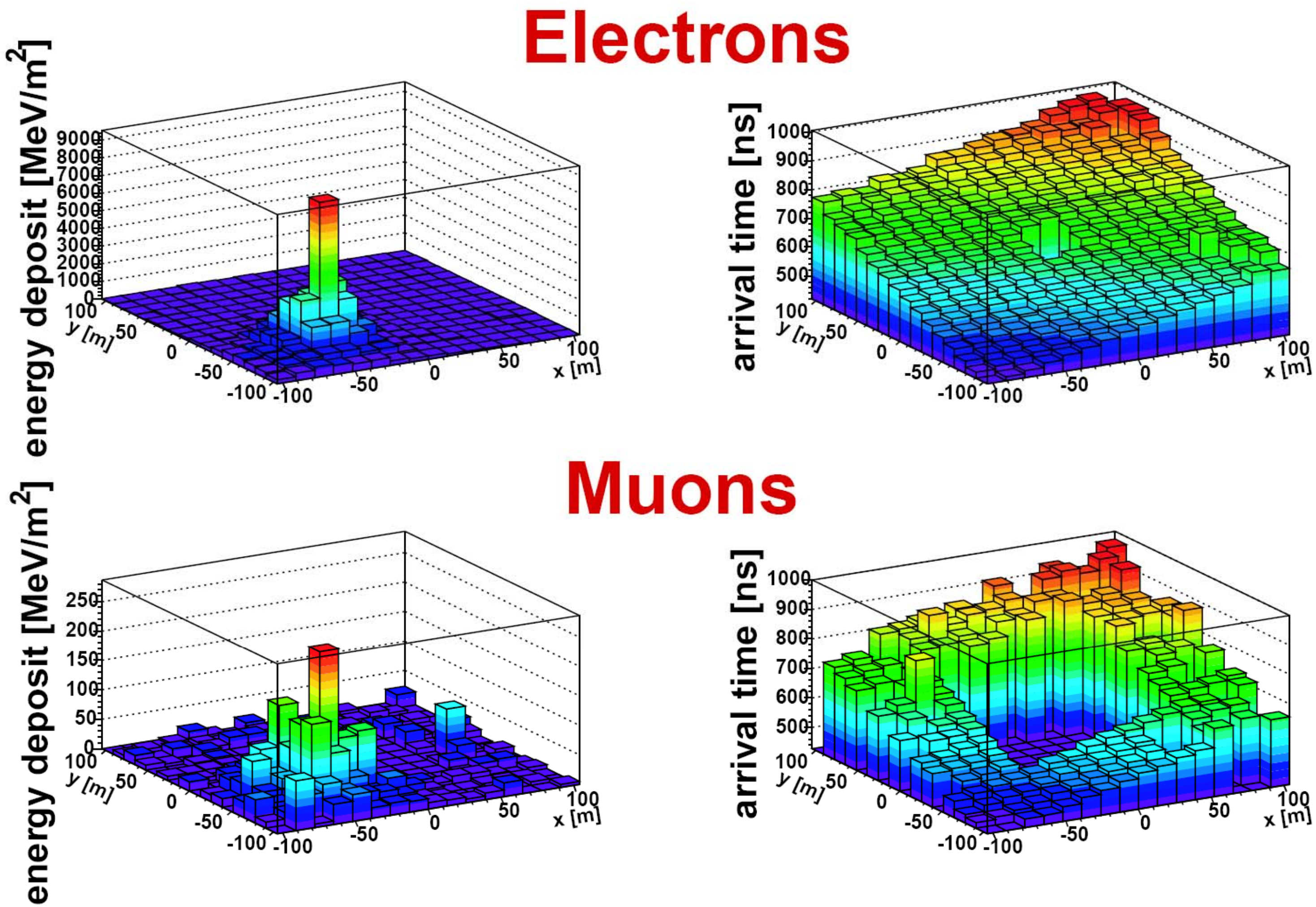
Multi-Detector-Setup !

Aim: measure as much as possible observables of the air-shower!



KASCADE – event example

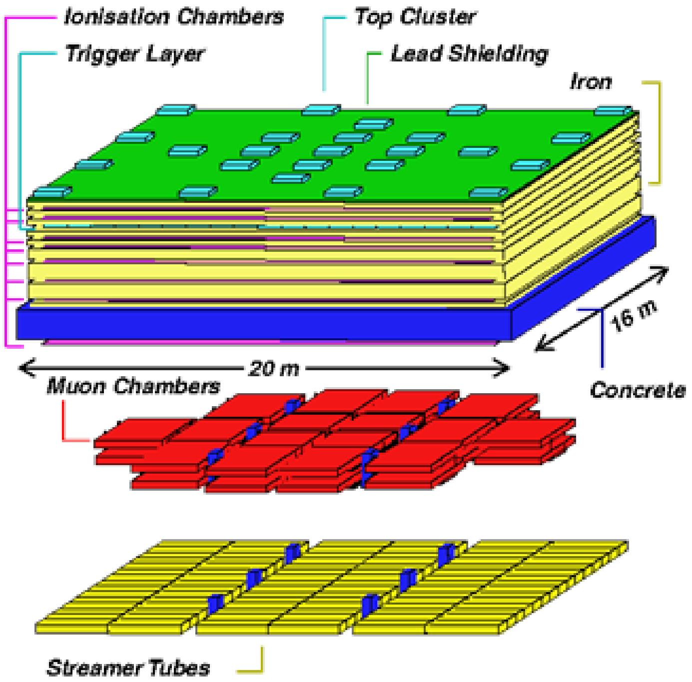
Array

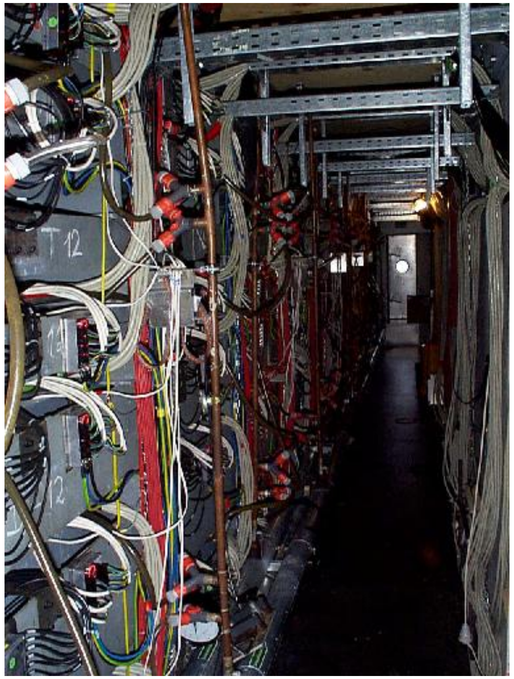


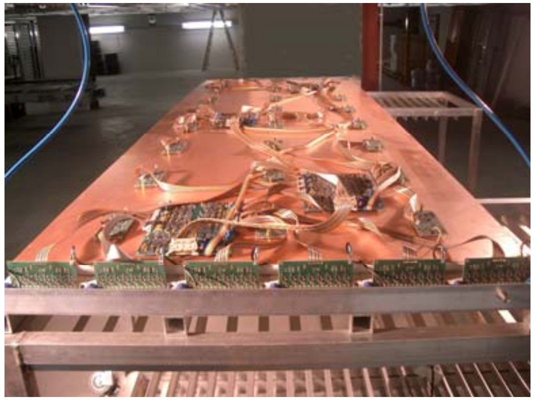
Run 3226, File 2, Ieve 65041, Ymd 10215, Hms 225810, Neds 250, Npds 138
(Xc,Yc) = (-45.4,-51.0), (Ze,Phi) = (36.7,228.6), log10(Ne)=6.14, log10(Lmuo)=4.66

KASCADE set-up

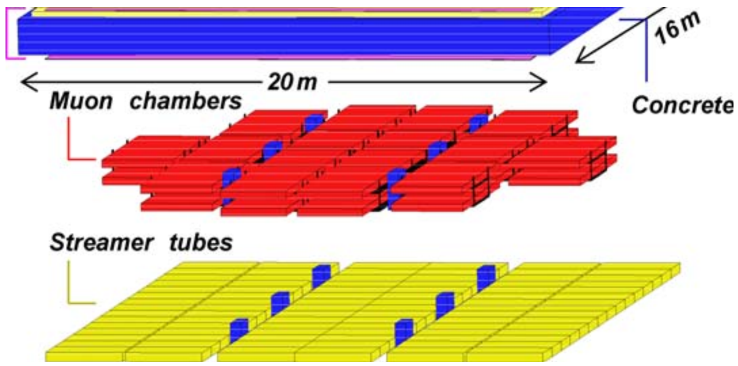
Multi-Detector-Setup !
Aim: measure as much as possible observables of the air-shower !

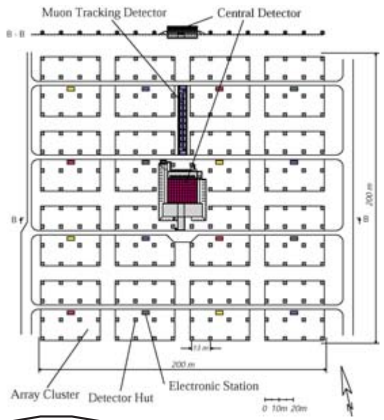


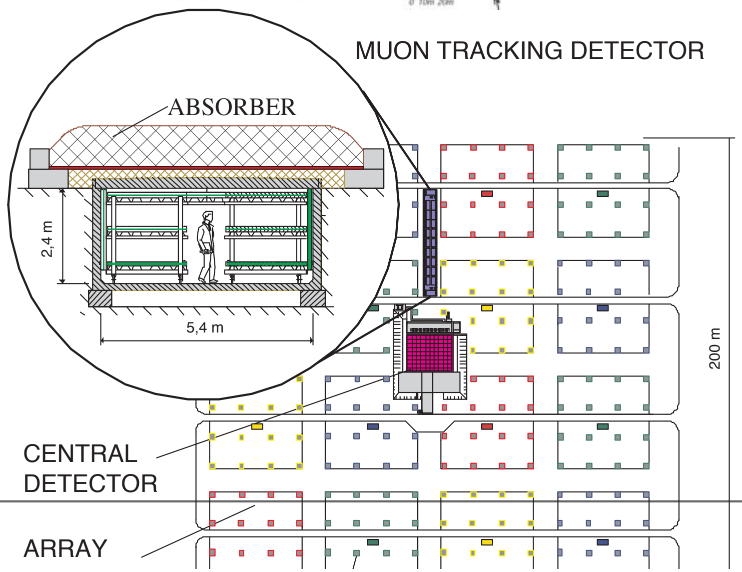




HE Muon Measurements at KASCADE







- **Central Detector muon facility**

  E_μ^{thresh} = 2400 MeV

  ➔ Muon Density measurements $\rho_\mu^{2.4GeV}$
  ➔ Lateral distributions
  ➔ Model tests (muon energy spectrum)

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

- **Muon Tracking Detector**

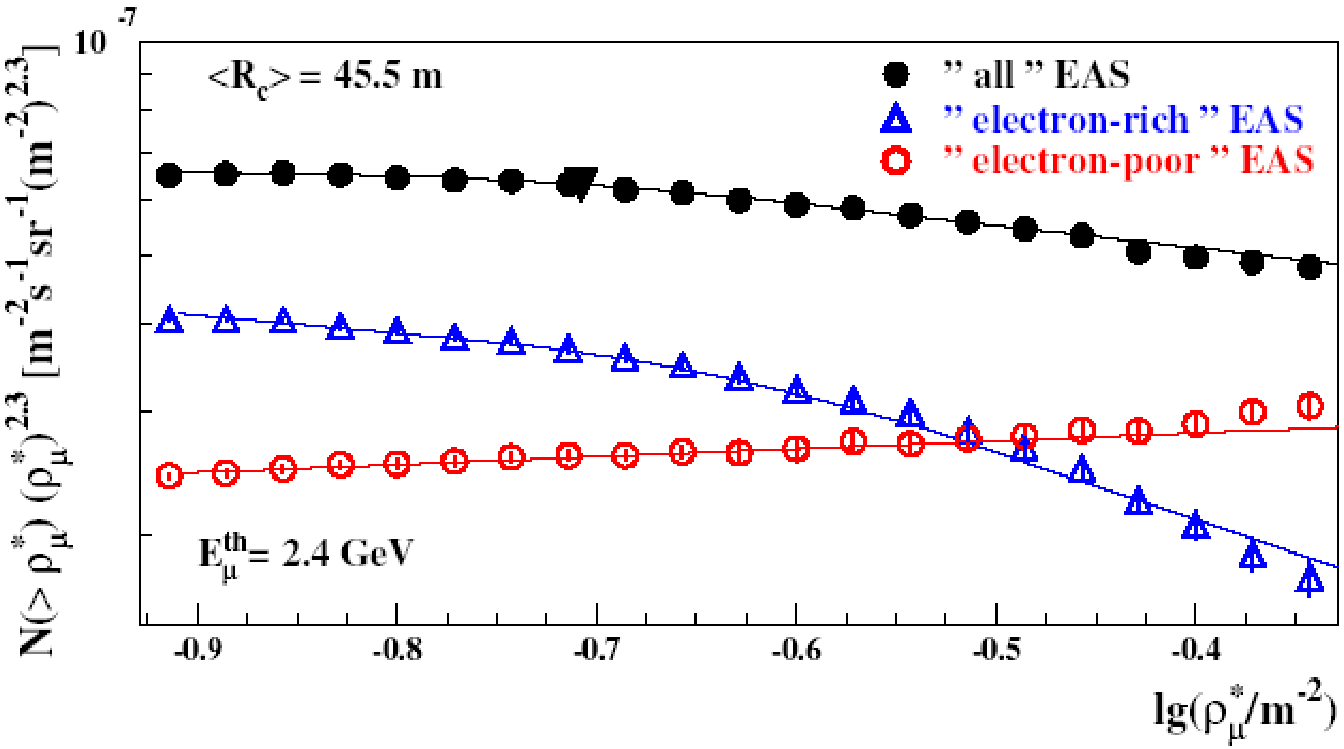
  E_μ^{thresh} = 800 MeV

  ➔ Measurement of radial and tangential angles ρ_μ, τ_μ
  ➔ Muon production height
  ➔ Lateral distributions
  ➔ Model tests (pseudorapidity)

  $$\eta_\mu = -\ln(\zeta/2) \quad \zeta = p_t/p_{||} = \mathrm{sqrt}(\rho^2 + \tau^2)$$

first: analysis of basic observable

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



KASCADE : Astroparticle Physics 16 373 2002

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

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

Concept KASCADE

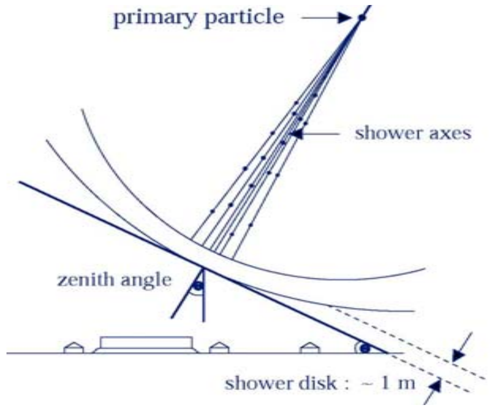
Disententanglement of the threefold problem: E, A, interaction

Measure shower parameters as much as possible

Multi-detector system to get redundant information

Experiment

Simulation



Primary Energy E
Primary Particle A

CORSIKA

DPMJET
QGSJET
SYBILL
VENUS
...

CRES

Detector-Response

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

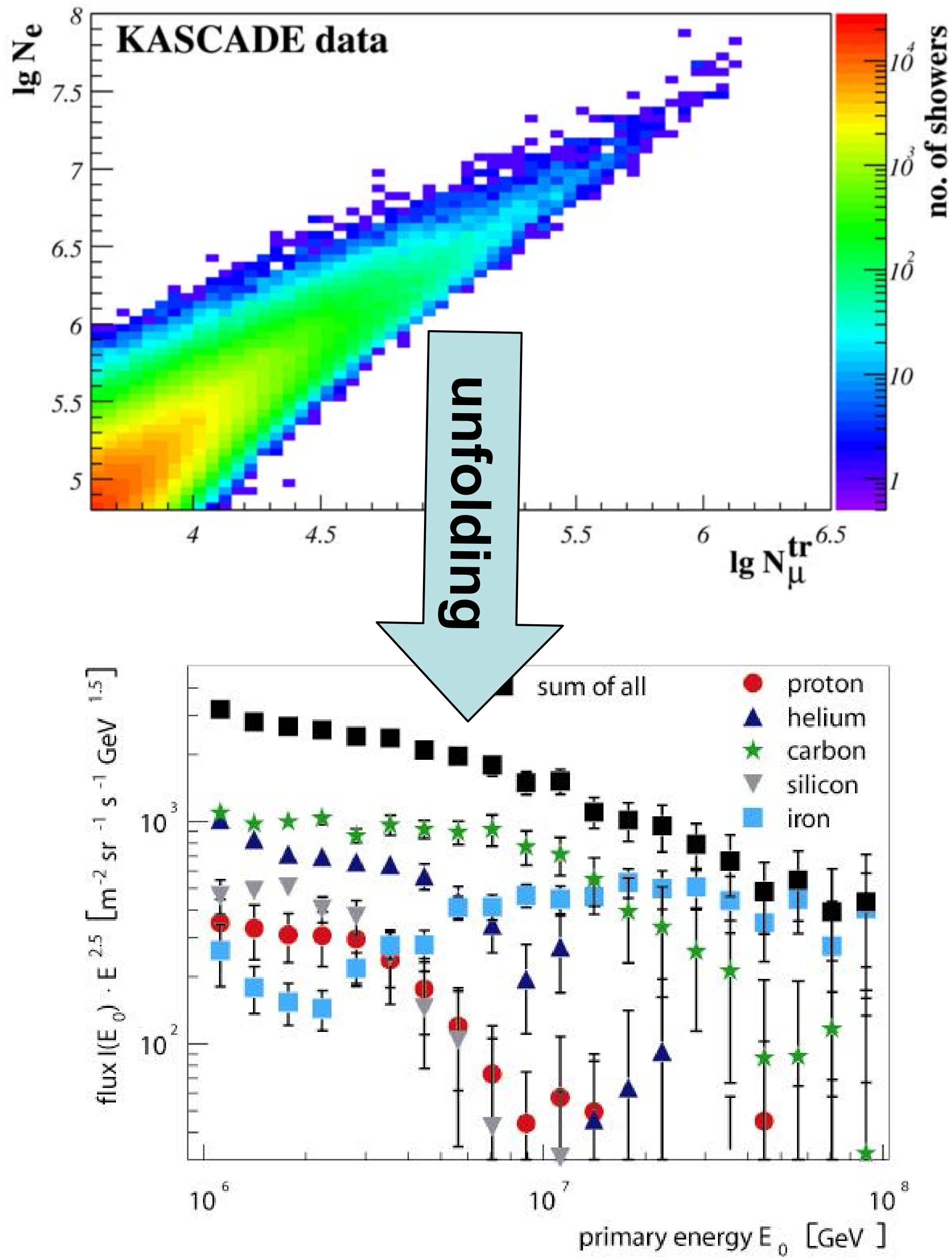
E_{est} A_{est}

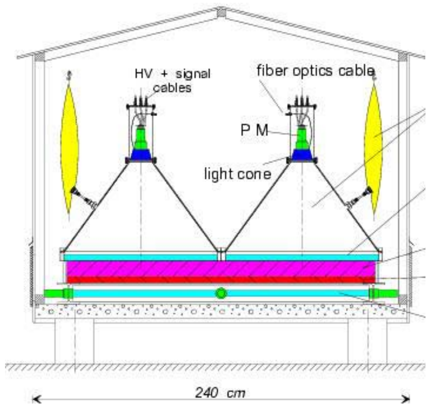
Energy Spectra
Chemical Composition

Tests of

High-Energy
Interaction Models

KASCADE : energy spectra of single mass groups





Measurement:
KASCADE array data
900 days;
0-18° 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

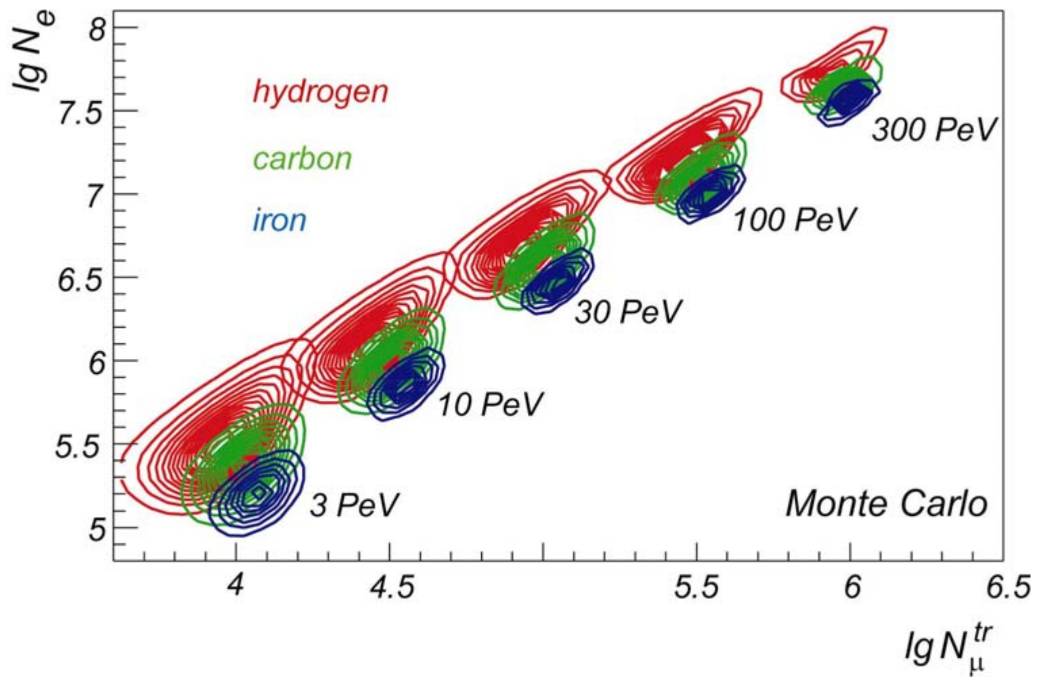
$$g(y) = \int K(y,x)p(x)dx$$

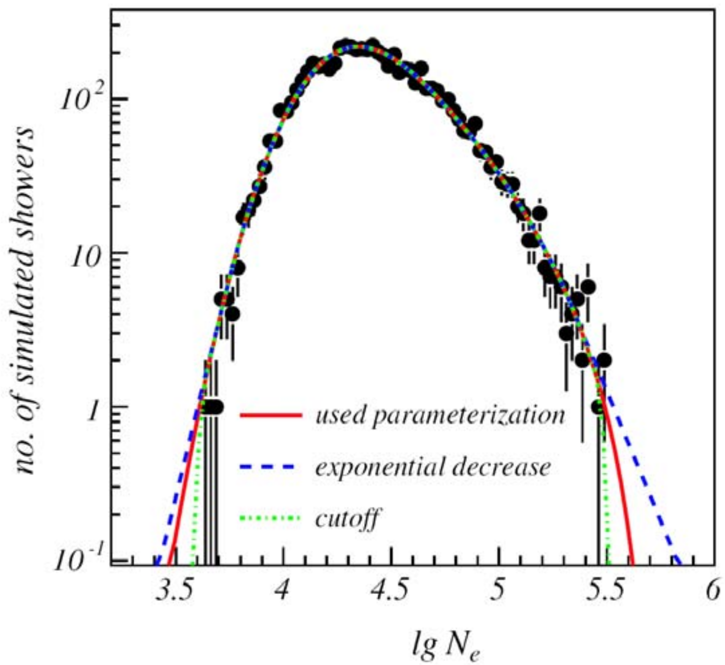
with $y=(N_e,N_\mu^{tr})$ and $x=(E,A)$

KASCADE Unfolding procedure

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

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



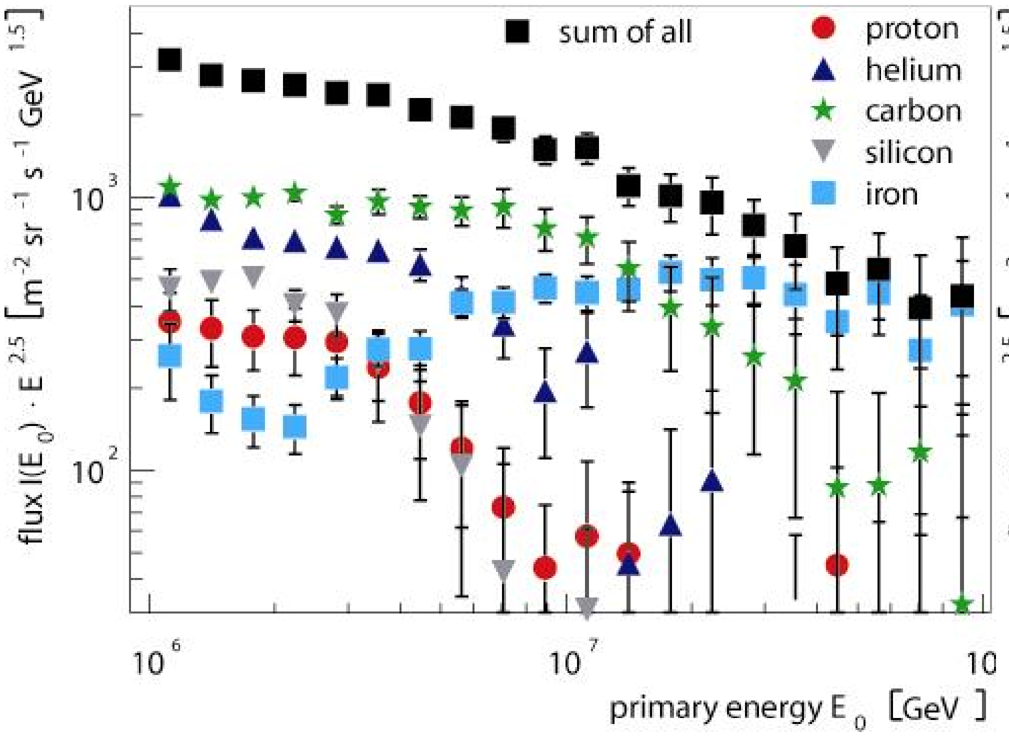


KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413

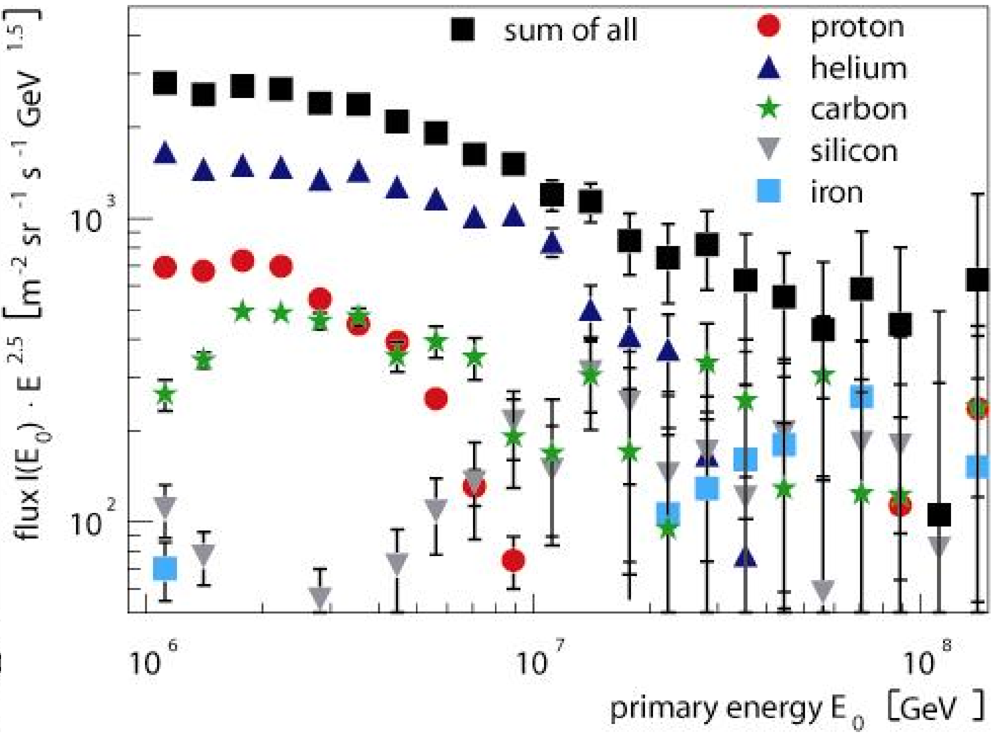
KASCADE results

- same unfolding but based on two different interaction models:
- SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002) all embedded in CORSIKA

SIBYLL

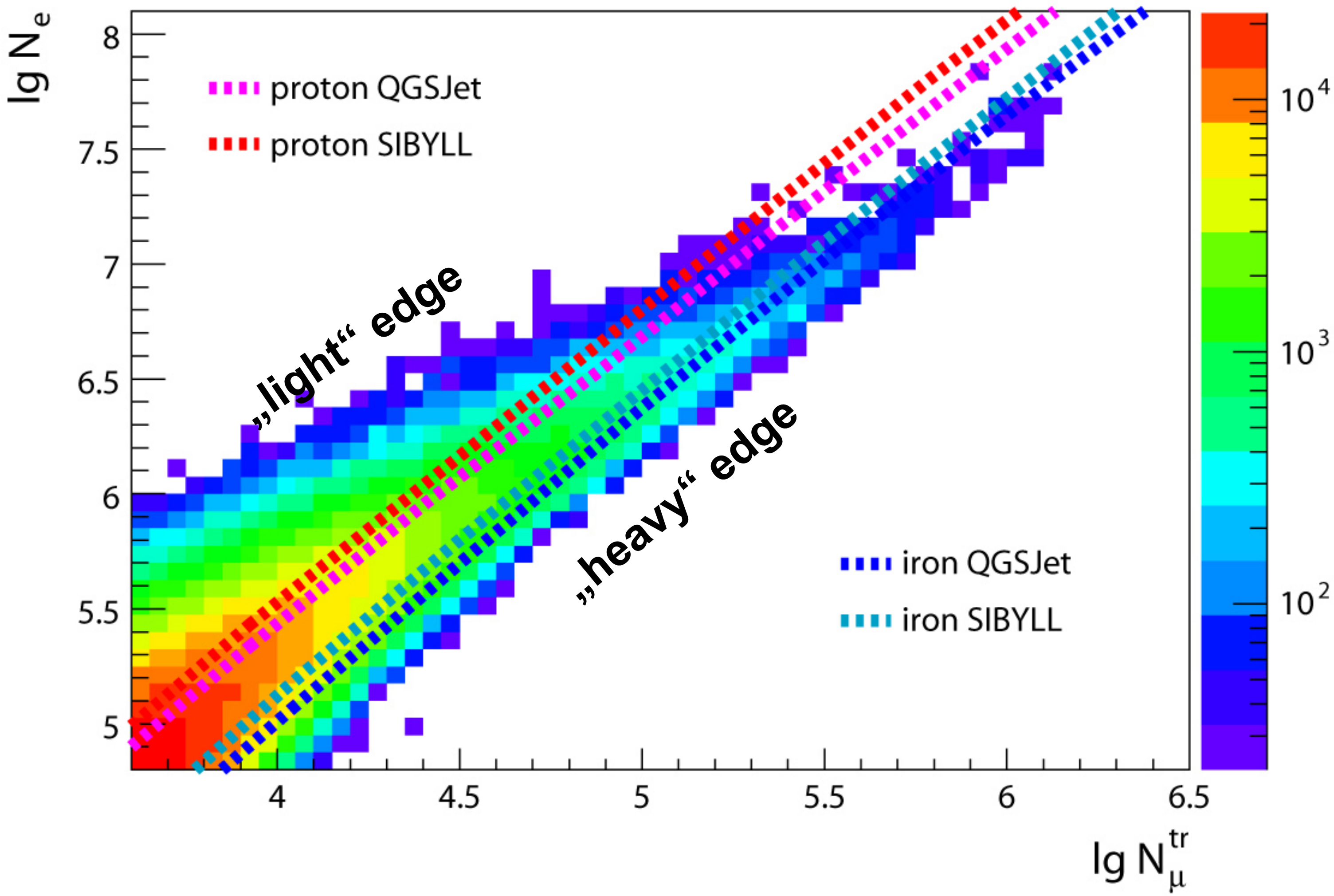


QGSJet

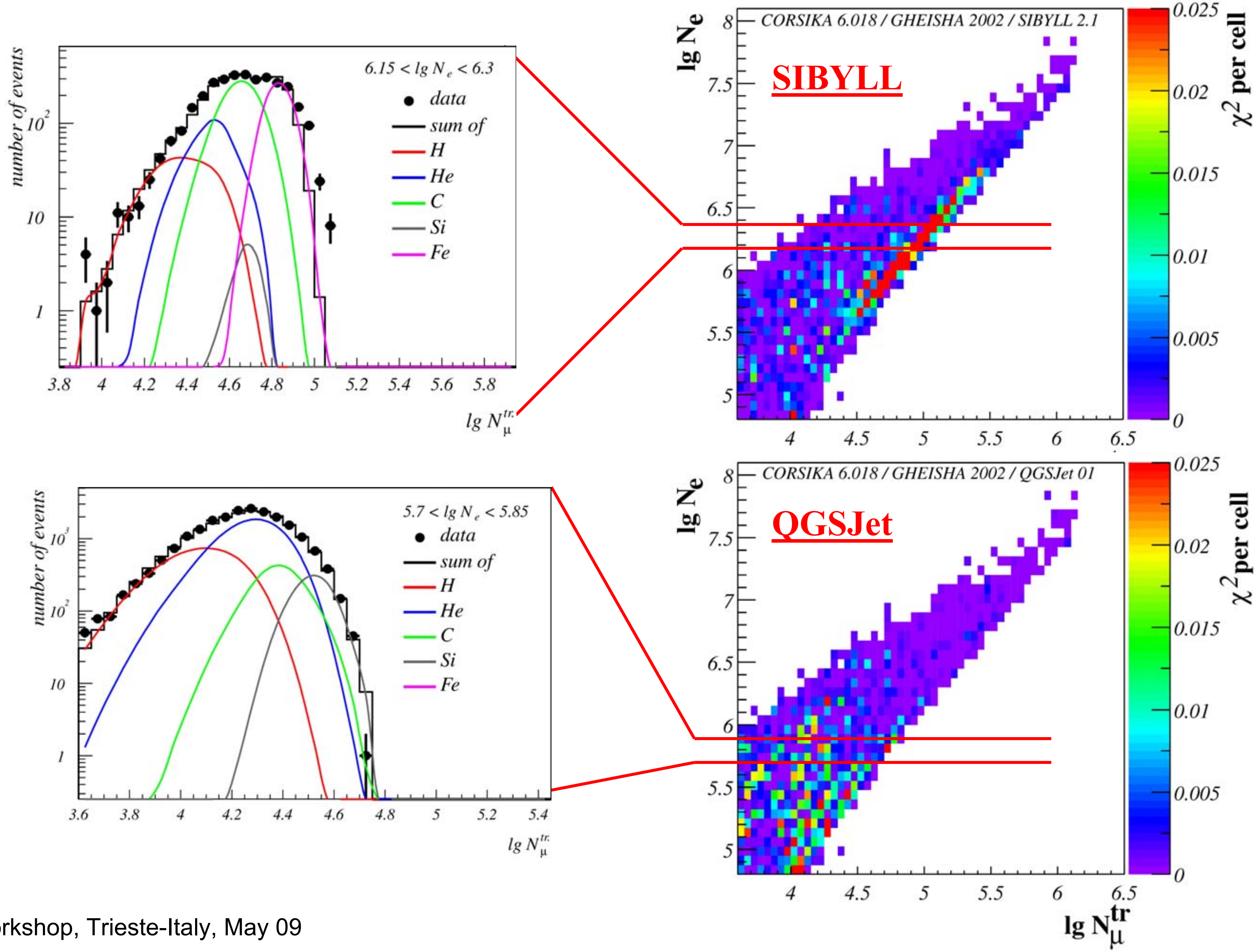


KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413

KASCADE : sensitivity to hadronic interaction models

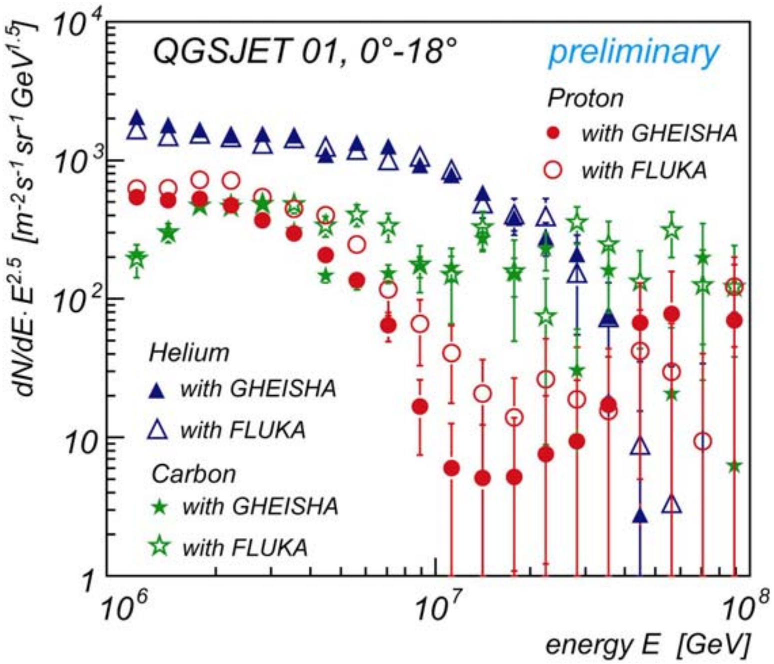


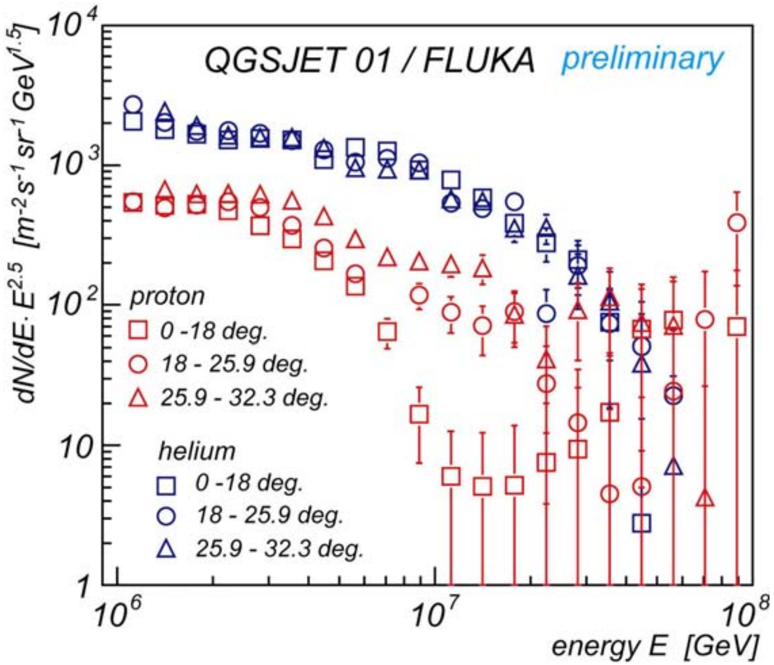
KASCADE: sensitivity to hadronic interaction models



KASCADE results: confirmation

- same unfolding but based on two different low energy interaction models and different zenith angle ranges:
- GHEISHA 2002 and FLUKA (both with QGSJET01)
- 0-18°, 18-25.9°, 25.9-32.3° (all with QGSJET01/FLUKA)





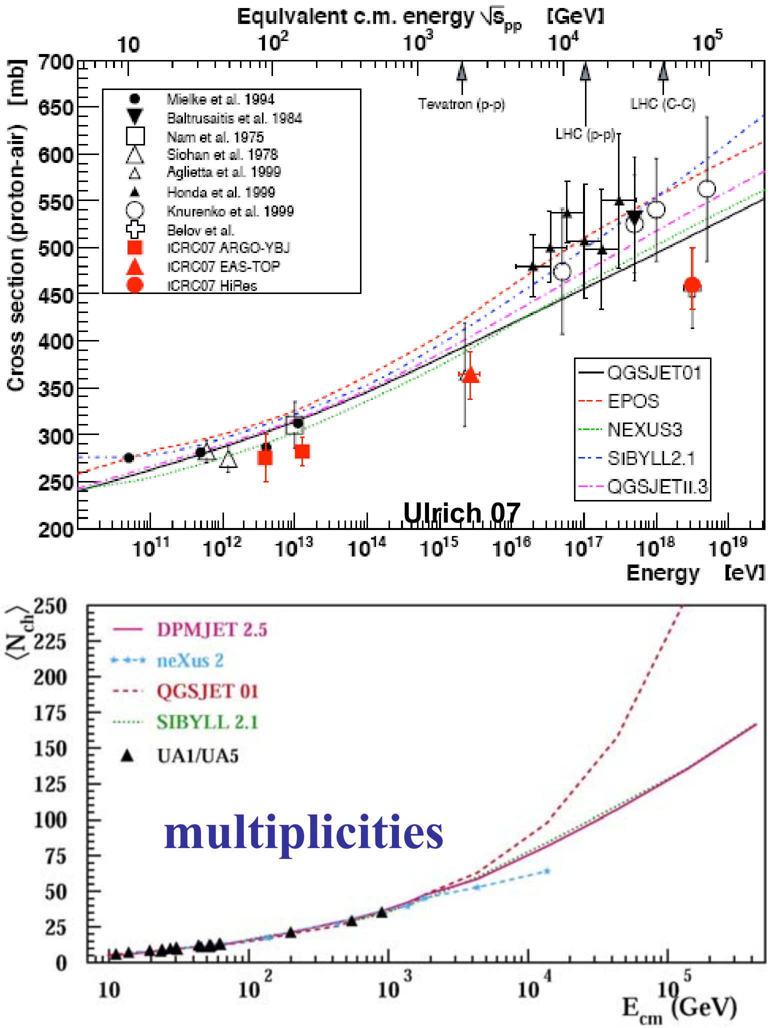
- Less dependence for unfolding based on different low energy hadronic interaction models
- Weak dependence on zenith angular binning (not significant)

KASCADE collaboration, Astroparticle Physics (2009), accepted

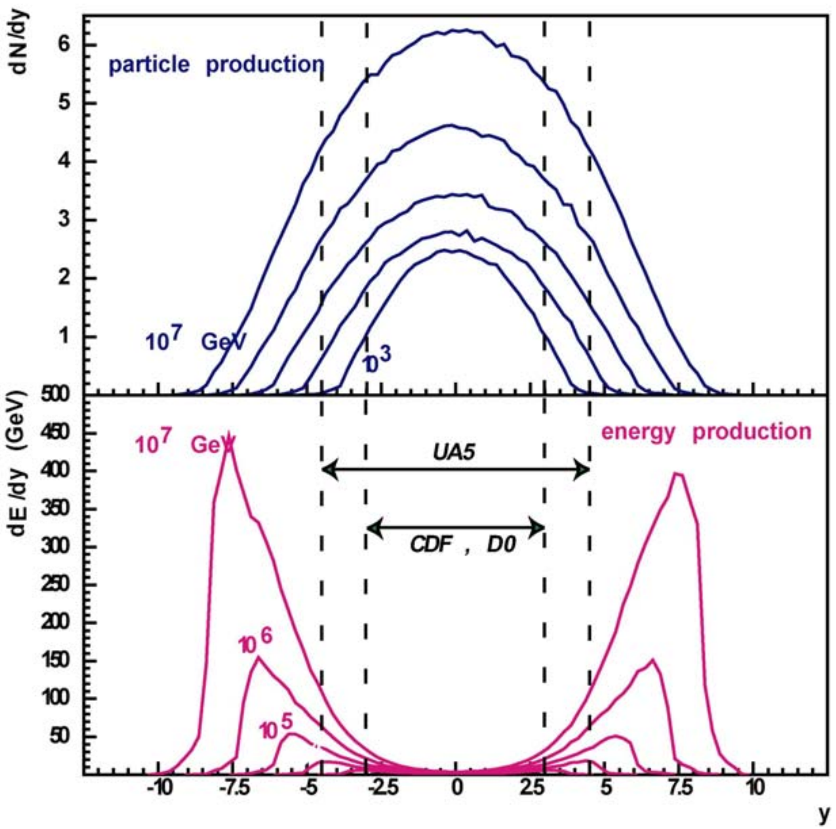
Hadronic Interactions: Problems

- Extrapolation of cross-sections to ultra-high energies
- Secondary particle multiplicity in high-energy interactions
- Extrapolation of kinematics to the extreme forward region (diffractive part of X-sections)

p-Air cross-section



rapidity distribution



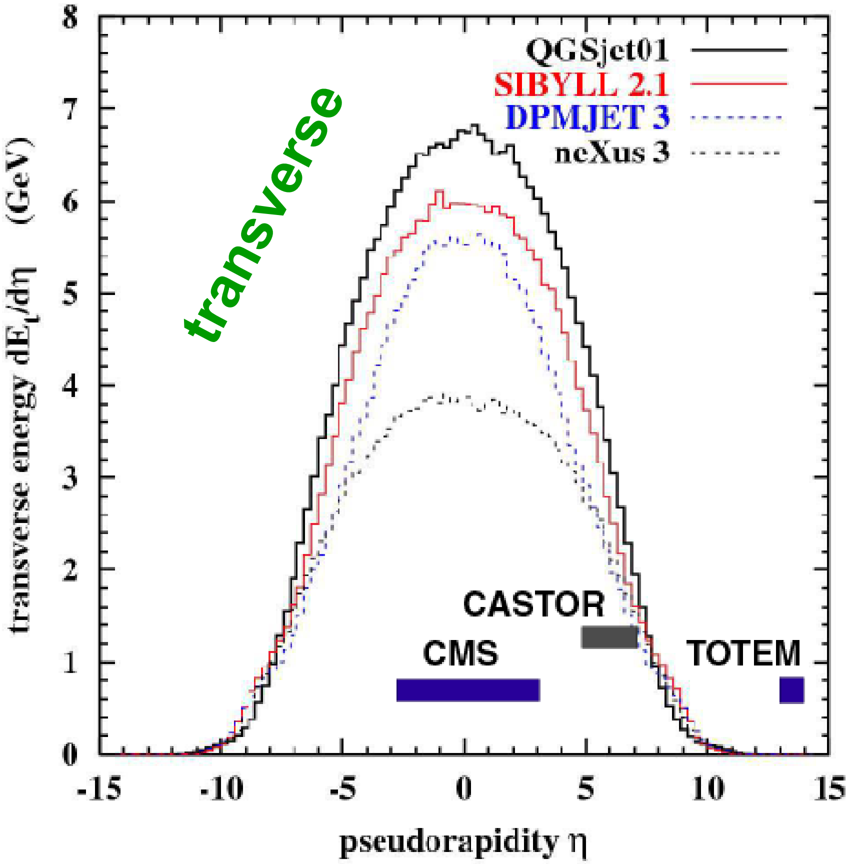
[CORSIKA (Heck et al) FZKA report 6019]

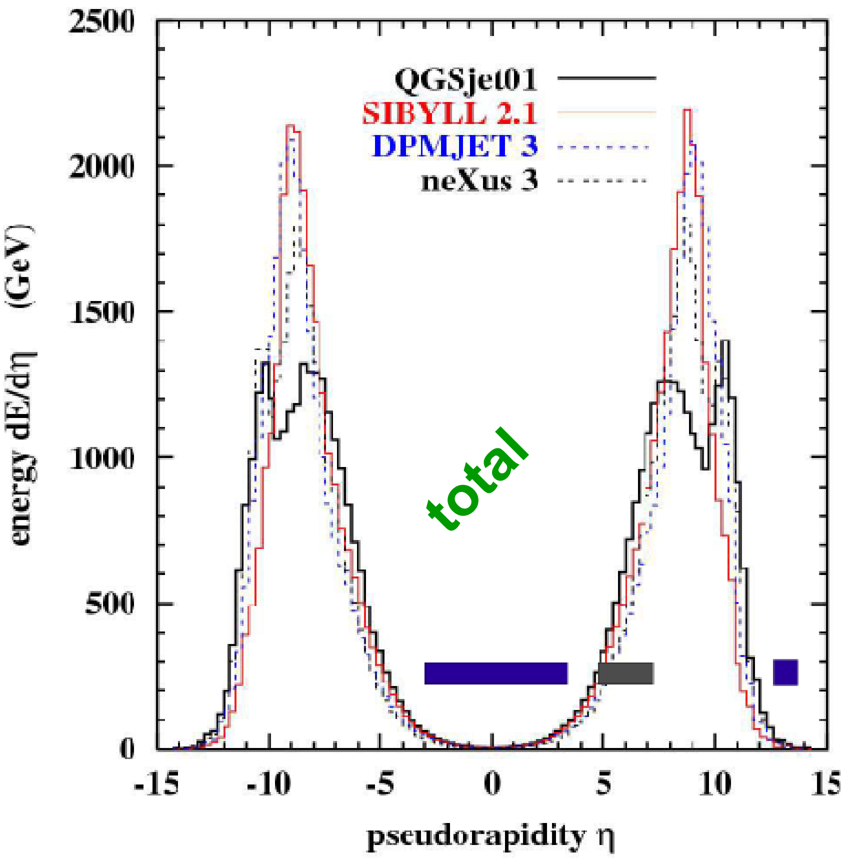
A.Haungs

Hadrons in EAS!

Hadronic interaction models and Energy flow in collider experiments

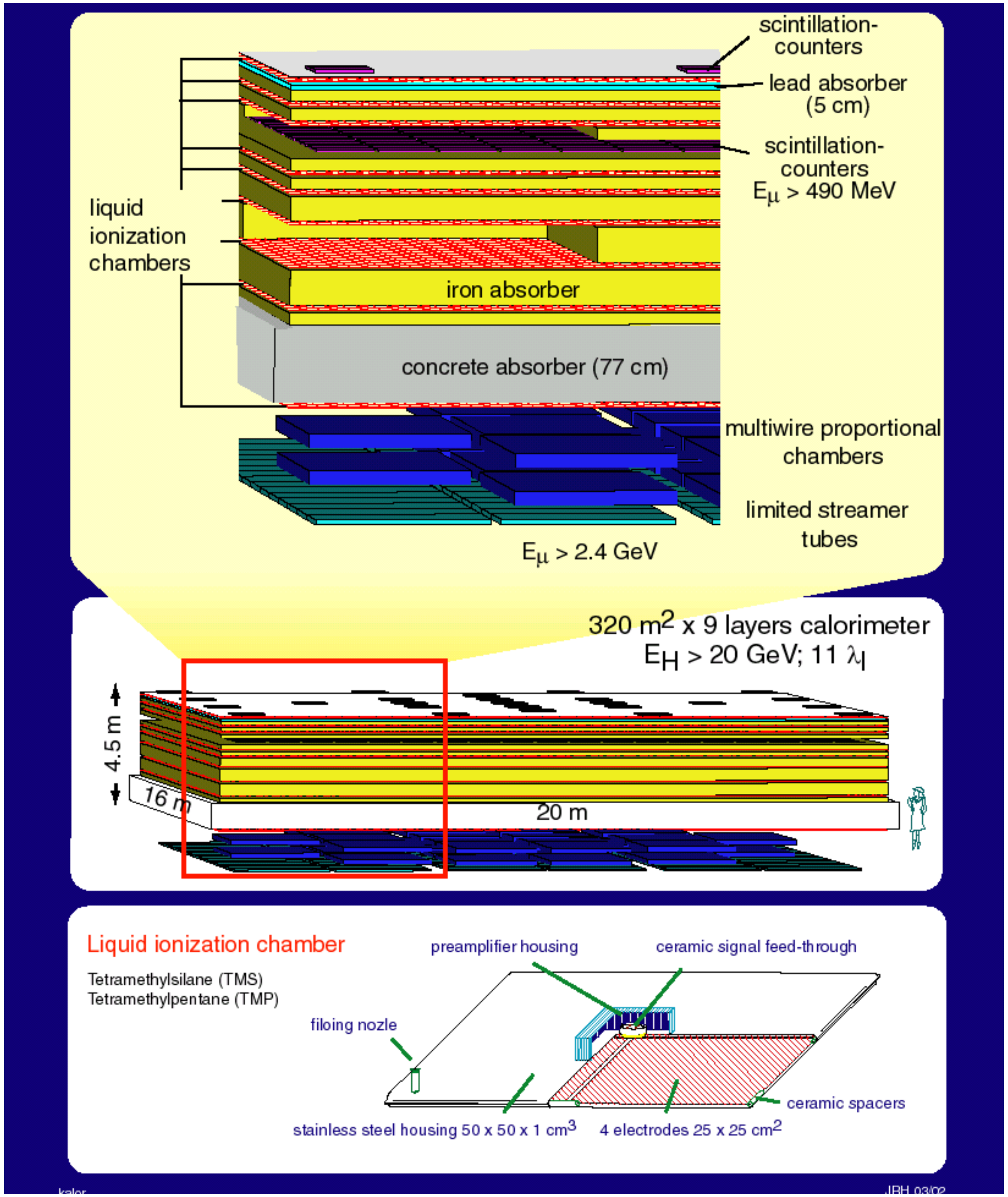
LHC (E_{cms}=17 TeV)
E_{lab}~ 10^{17} eV





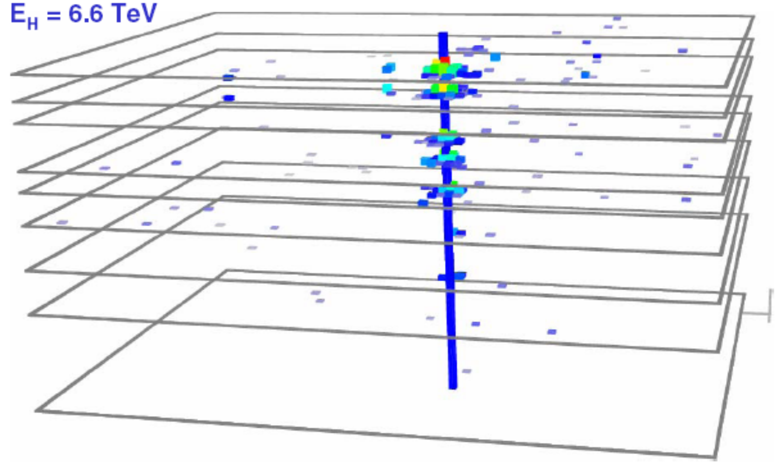
← Direct access by hadrons

hadrons in air shower cores



J. Engler et al., Nucl. Instr. Meth. A 427 (1999) 528

Unaccompanied hadron
E_H = 6.6 TeV



spatial resolution: $\sigma_x \sim 10 - 12$ cm

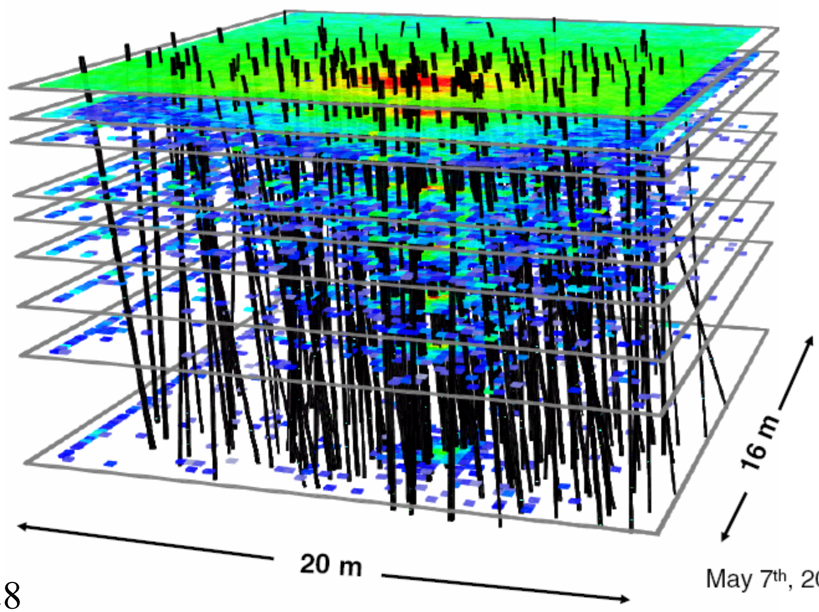
angular resolution: $\sigma_\Theta \sim 1^\circ - 3^\circ$

energy resolution:

$$\frac{\sigma(E)}{E}[\%] \sim \frac{250}{\sqrt{E/\mathrm{GeV}}}$$

$E_0 \sim 6$ PeV

Number of reconstructed hadrons $N_h = 143$



May 7th, 2002 9:45

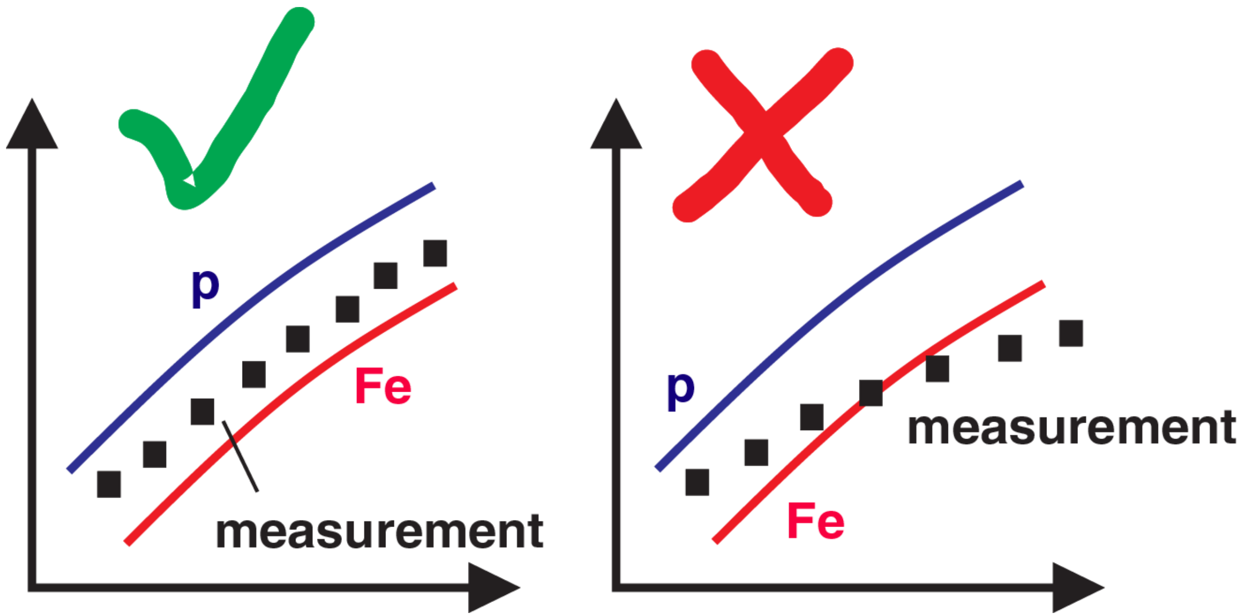
hadrons in air shower cores: test of hadronic interaction models

KASCADE observables per individual EAS:

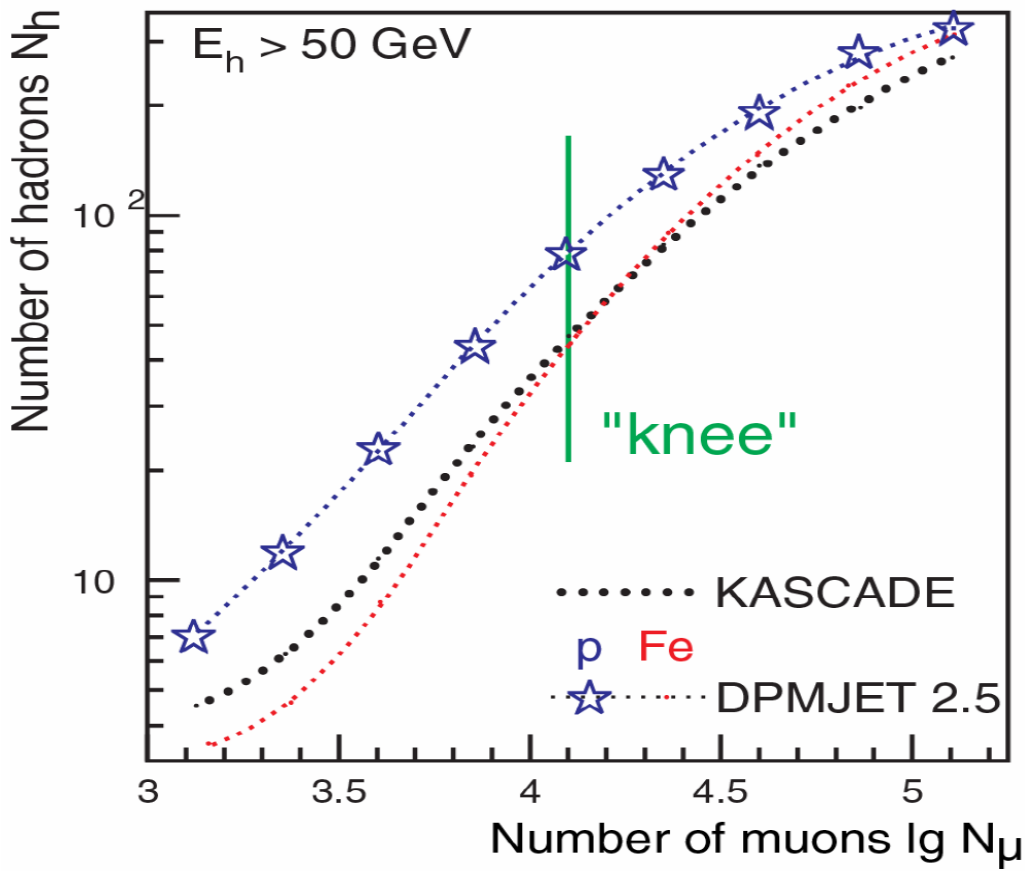
from detector array: general shower parameters

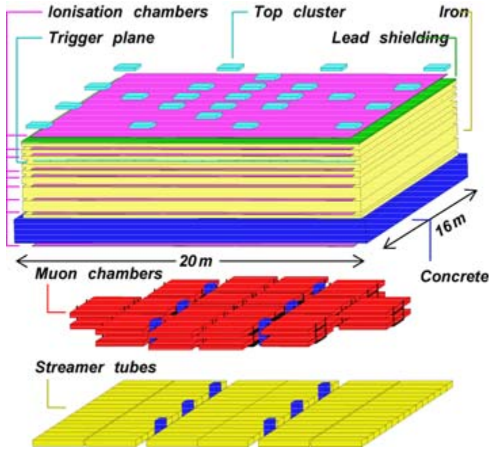
from calorimeter:

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



KASCADE data analyses: shower observable correlations





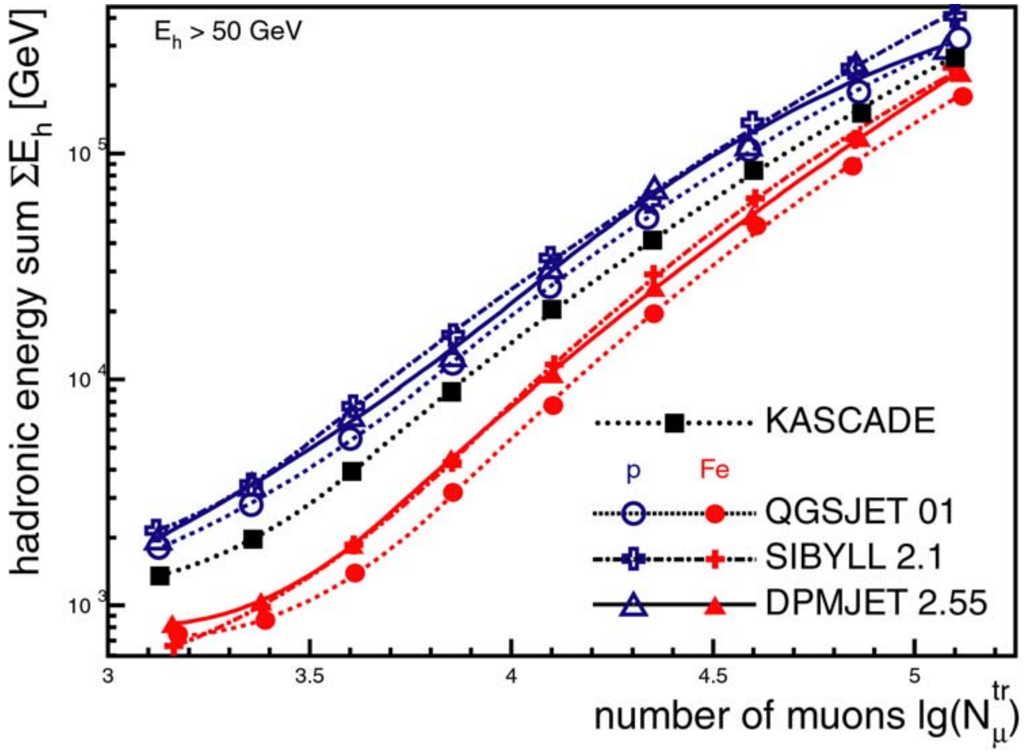
Example:
hadrons vs. muons

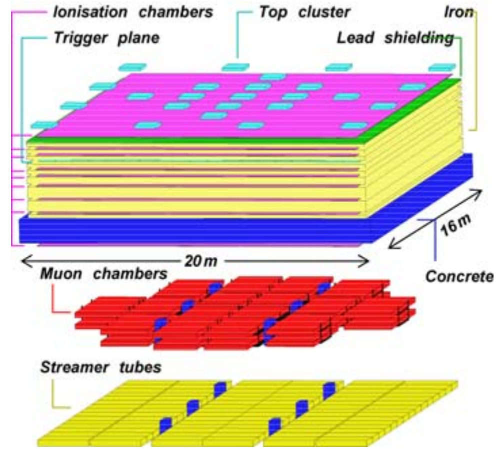
Investigated many correlation of observables of all three particle components

Electromagnetic Muonic Hadronic

By using full simulations (including detector response)

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 !

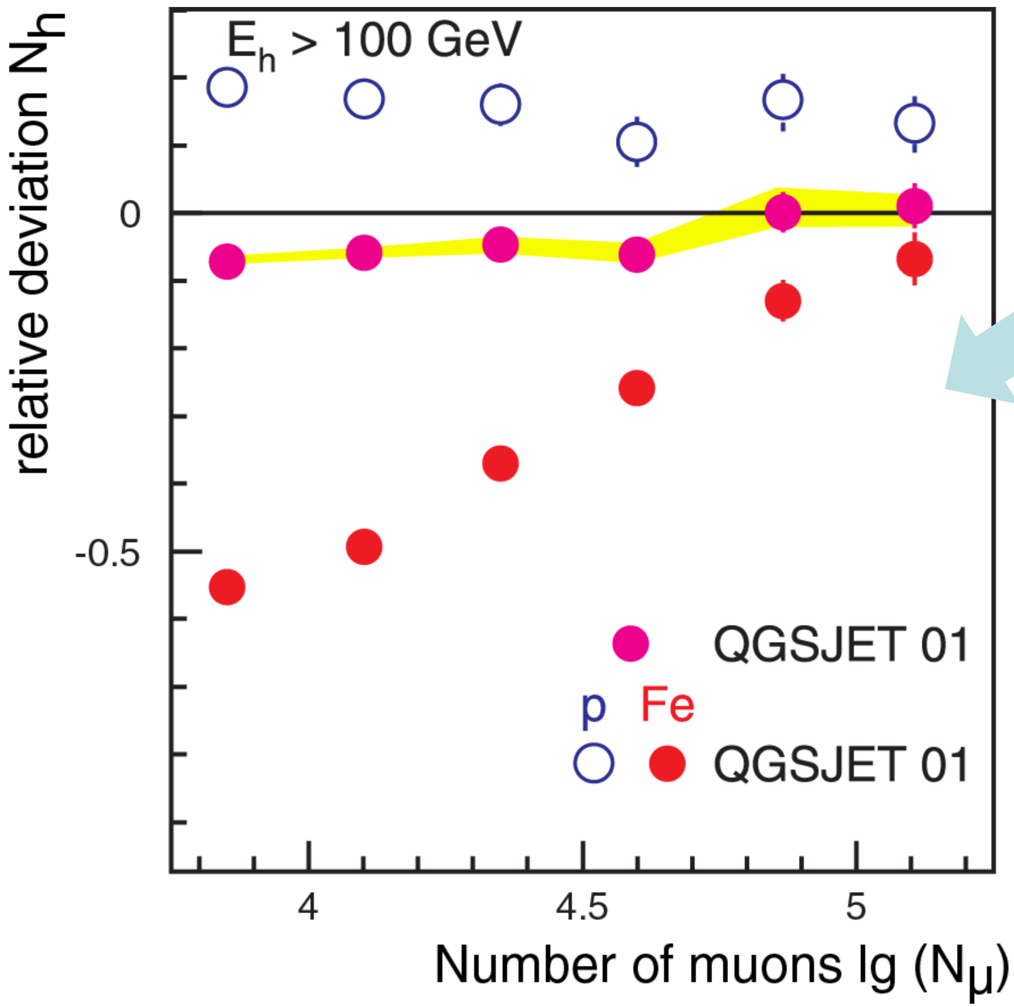
➔ close co-operation with theoreticians

(CORSIKA including QGSJET, SIBYLL, FLUKA, GHEISHA,…..)

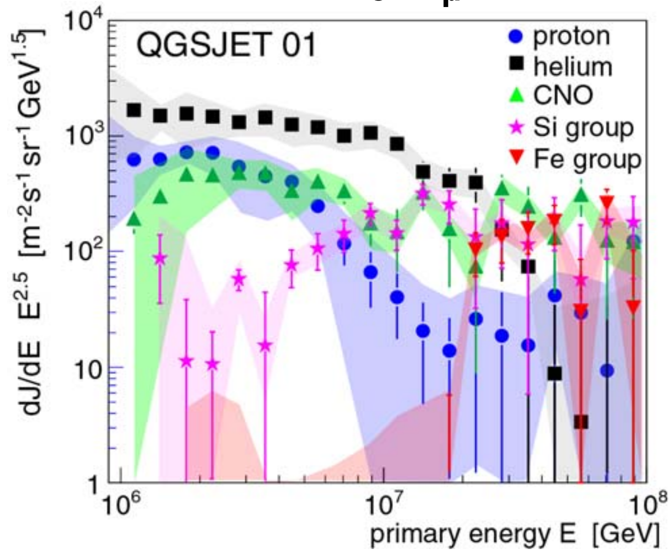
Shower observable correlations: Model tests with composition

QGSJET 01

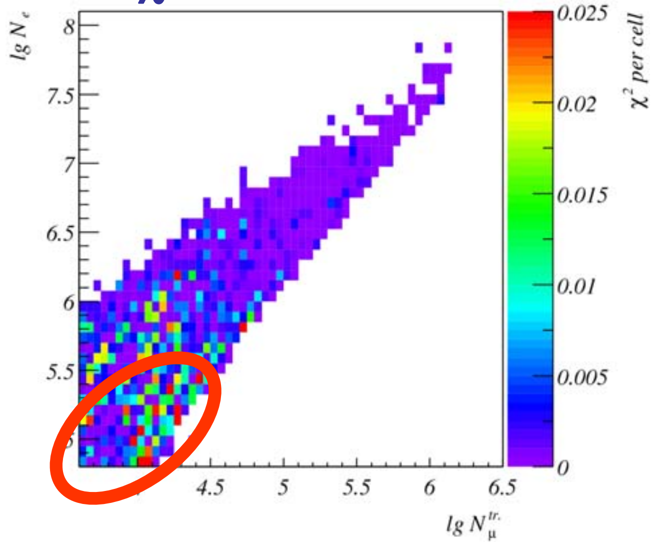
Number of hadrons vs. number of muons



N_e-N_μ analysis



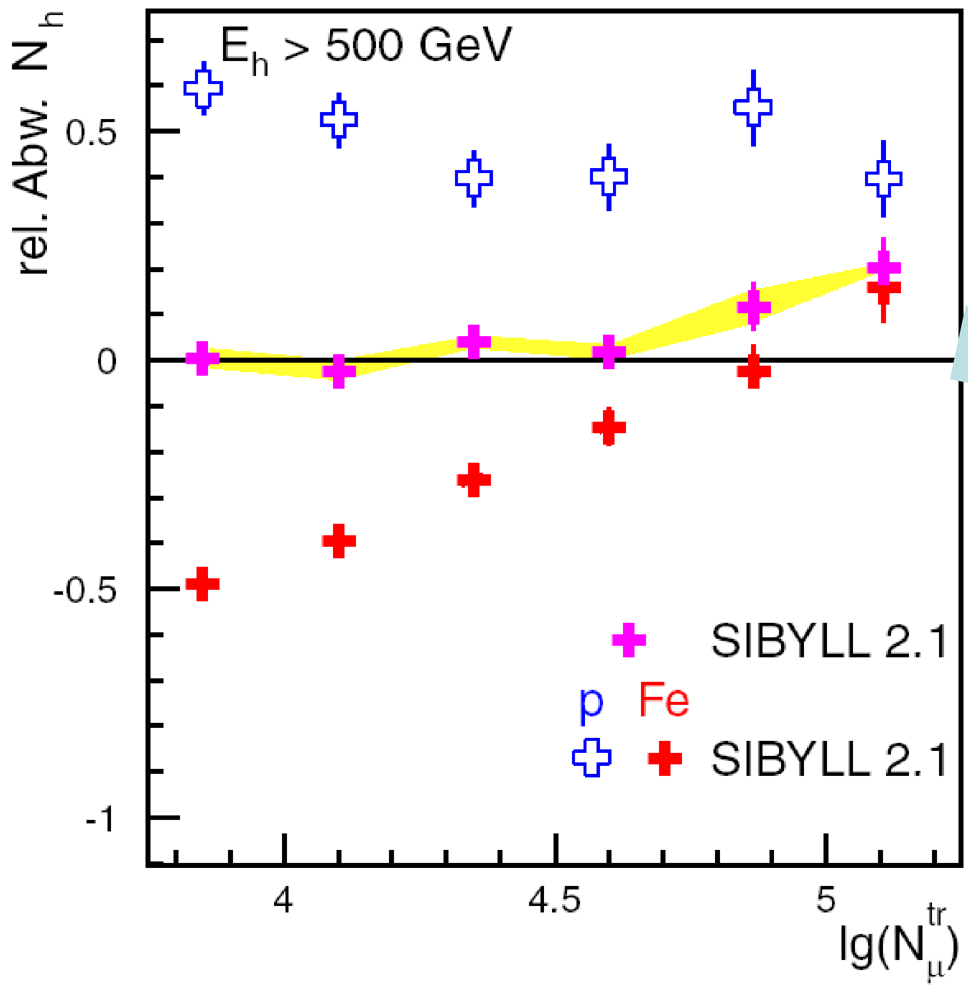
χ^2 distribution



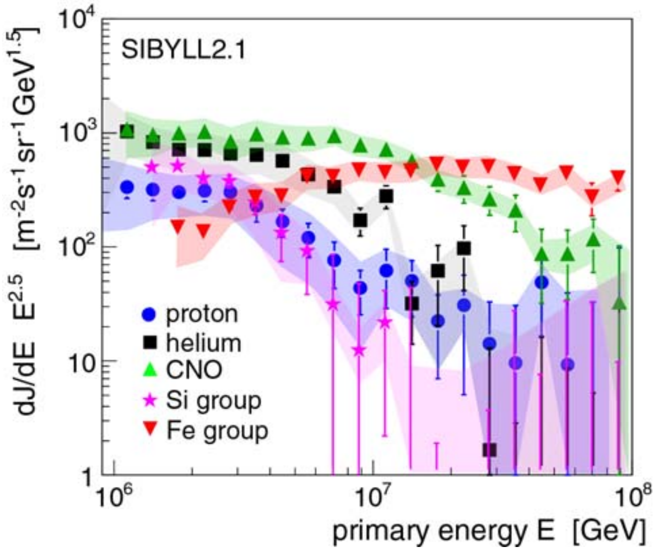
Shower observable correlations: Model tests with composition

SIBYLL 2.1

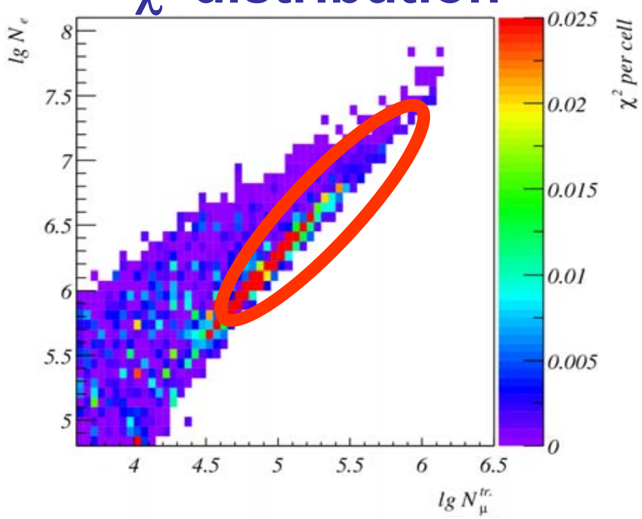
Number of hadrons vs. number of muons



N_e-N_μ analysis

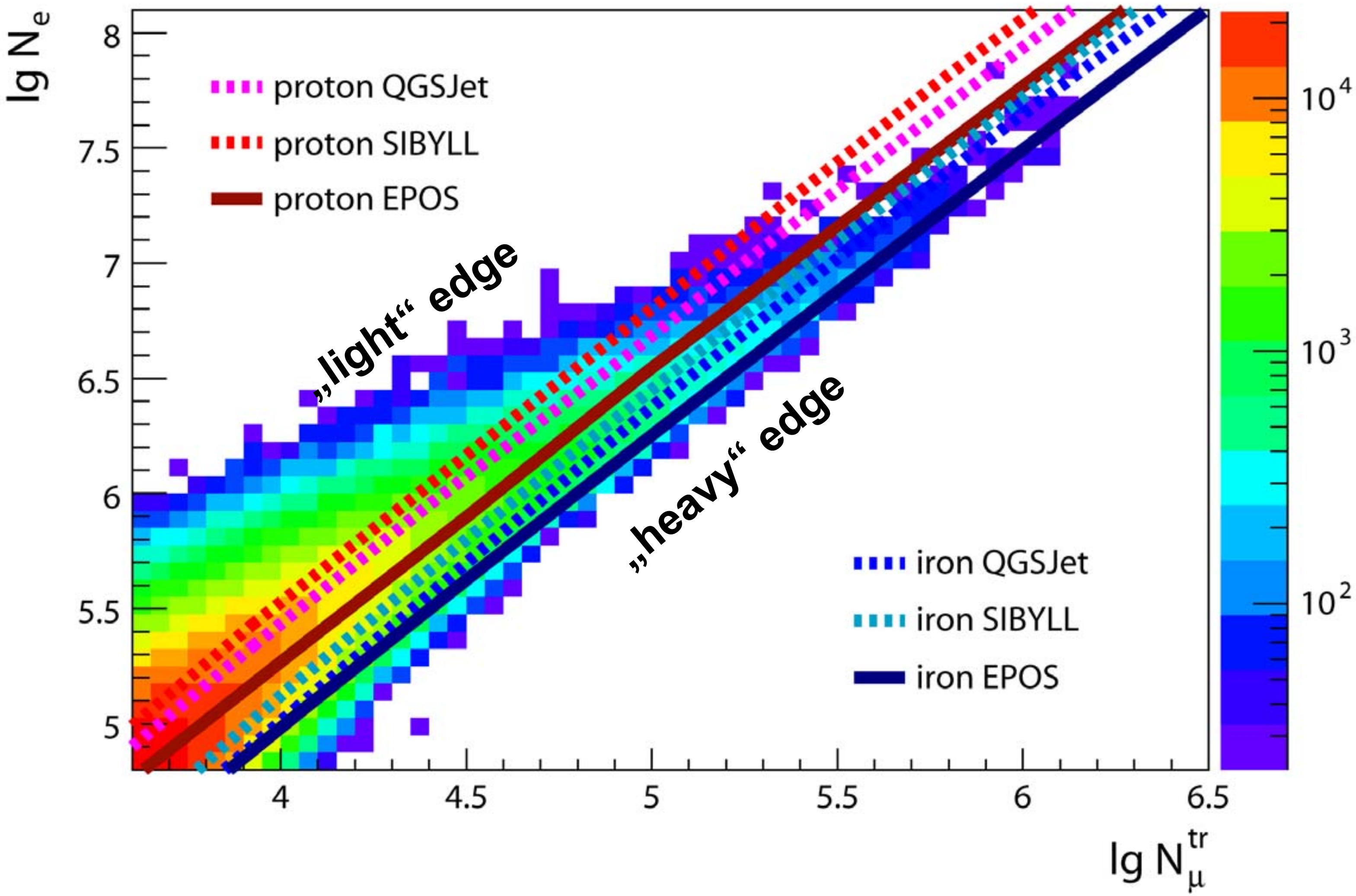


χ^2 distribution



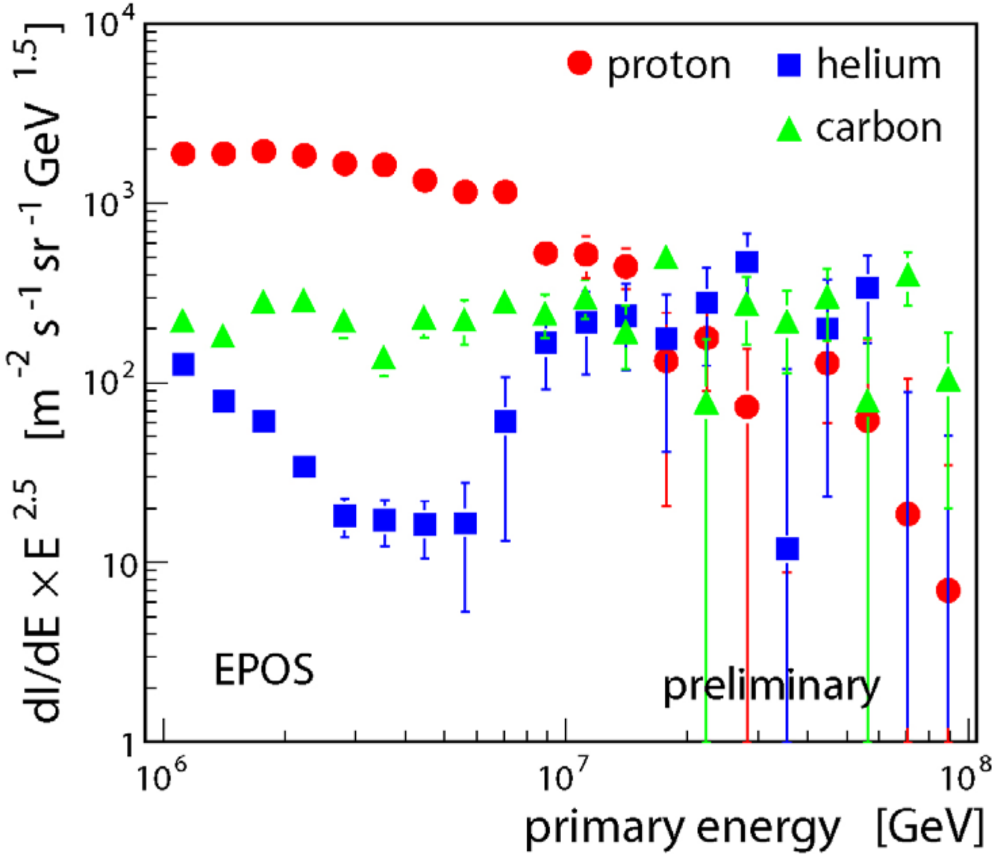
Inconsistencies at the level of 10% to 20%

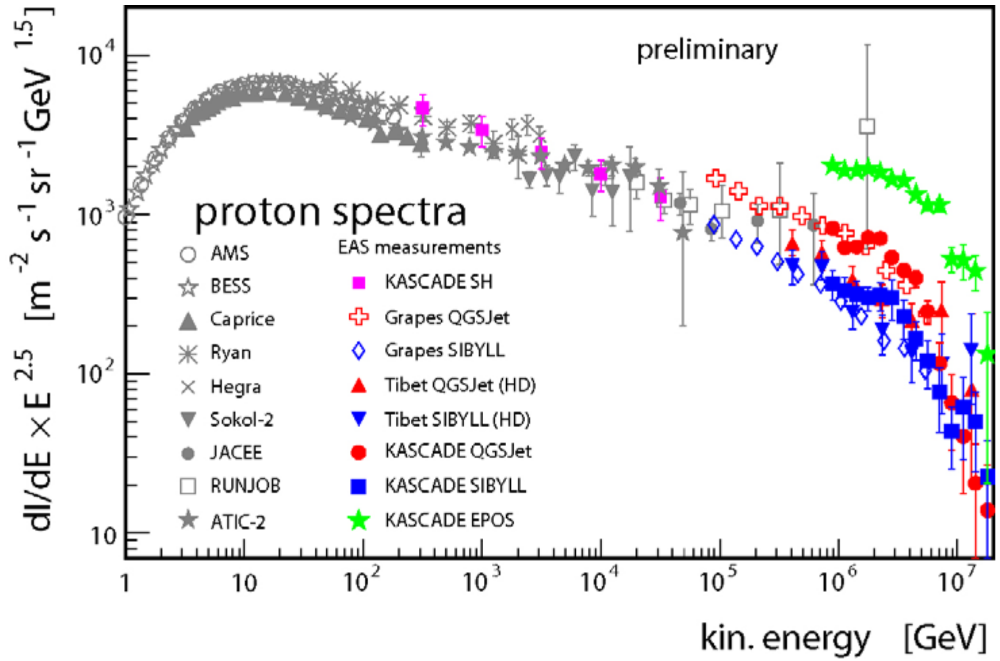
KASCADE : test of new hadronic interaction models
EPOS 1.61



KASCADE: new hadronic interaction model: EPOS

- unfolding based EPOS 1.61 and FLUKA (with CORSIKA 6.6)





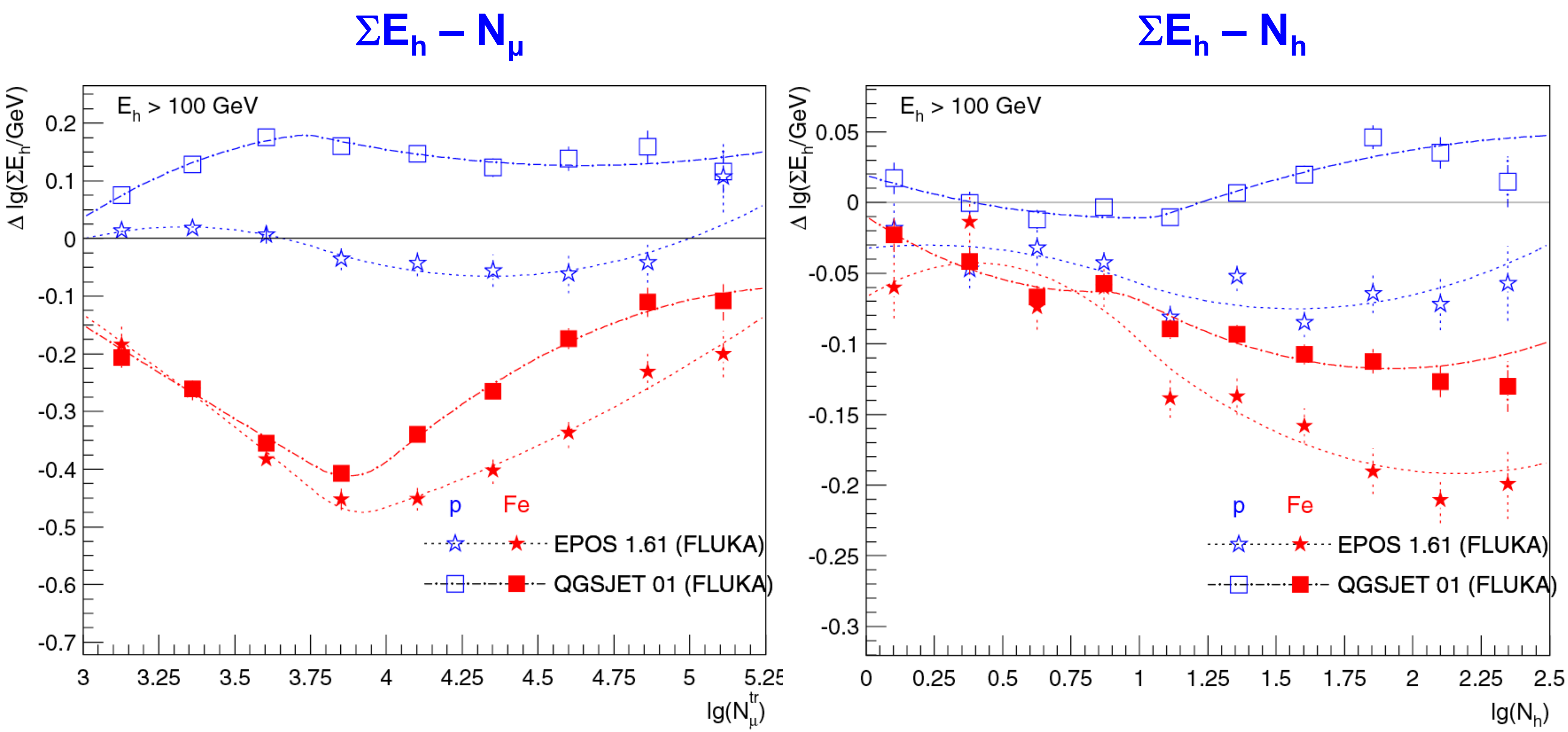
-) very proton dominant, but knee caused by light primaries

-) no iron needed

➔EPOS predict too many muons or too less electrons (for KASCADE)

KASCADE collaboration, ICRC 2007; J.Phys G (2008), in print

KASCADE – Test of EPOS 1.6 with hadrons



EPOS delivers not enough hadronic energy to the ground

→ energy per hadron too small

→ EPOS 1.6 is NOT CONSISTENT with KASCADE observations!

Shower observable correlations: Model tests

QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~

J. Phys. G: Nucl. Part. Phys. 25 (1999) 2161

DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~DPMJET II.5~~

J. Phys. G: Nucl. Part. Phys. 34 (2007) 2581

~~EPOS 1.6~~
QGSJET II

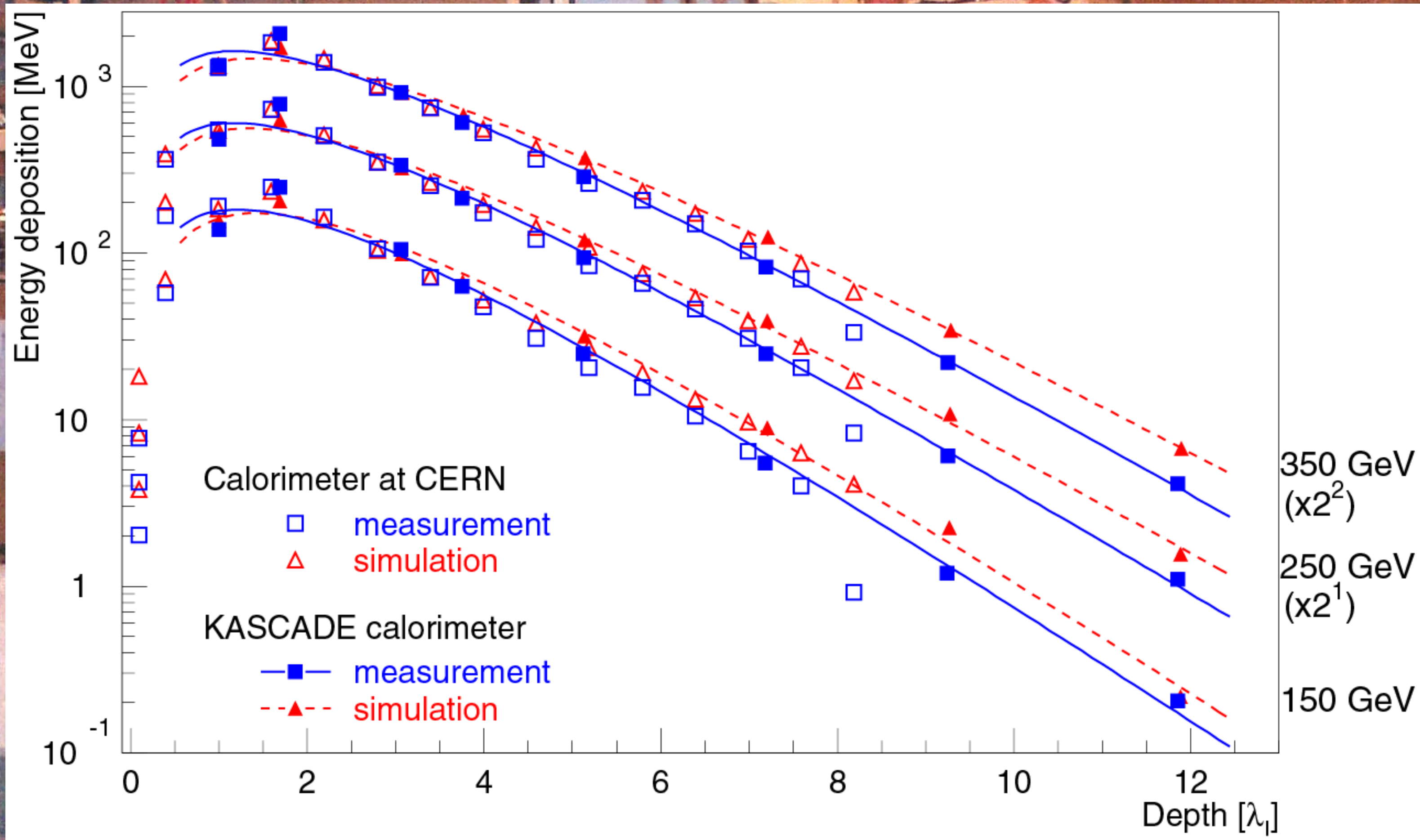
J. Phys. G: Nucl. Part. Phys. (2009) 035201

- EPOS 1.6 is not compatible with KASCADE measurements
- QGSJET-II has some deficiencies
- QGSJET 01and SIBYLL 2.1still most compatible models

➔ New models are welcome for cross - tests with KASCADE data

Calibration of the KASCADE hadron calorimeter at the CERN SPS

with hadrons up to 350 GeV



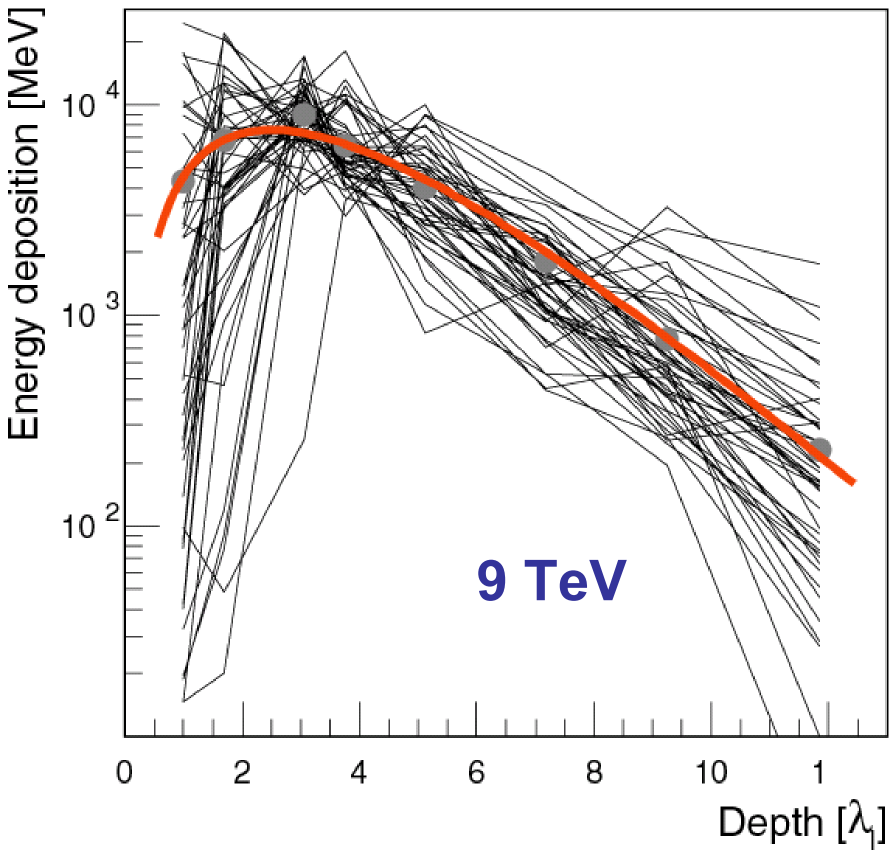
S. Plewnia et al., Nucl. Instr. & Meth. A 566 (2006) 422

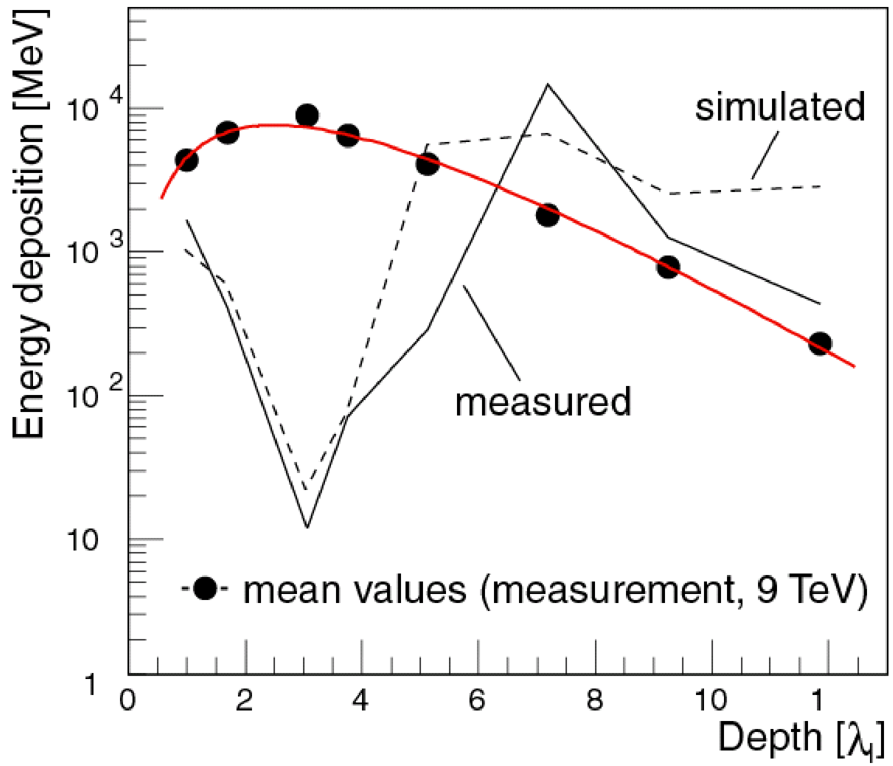
S. Plewnia et al., 29th ICRC, Pune 6 (2005) 17

Unusual events?

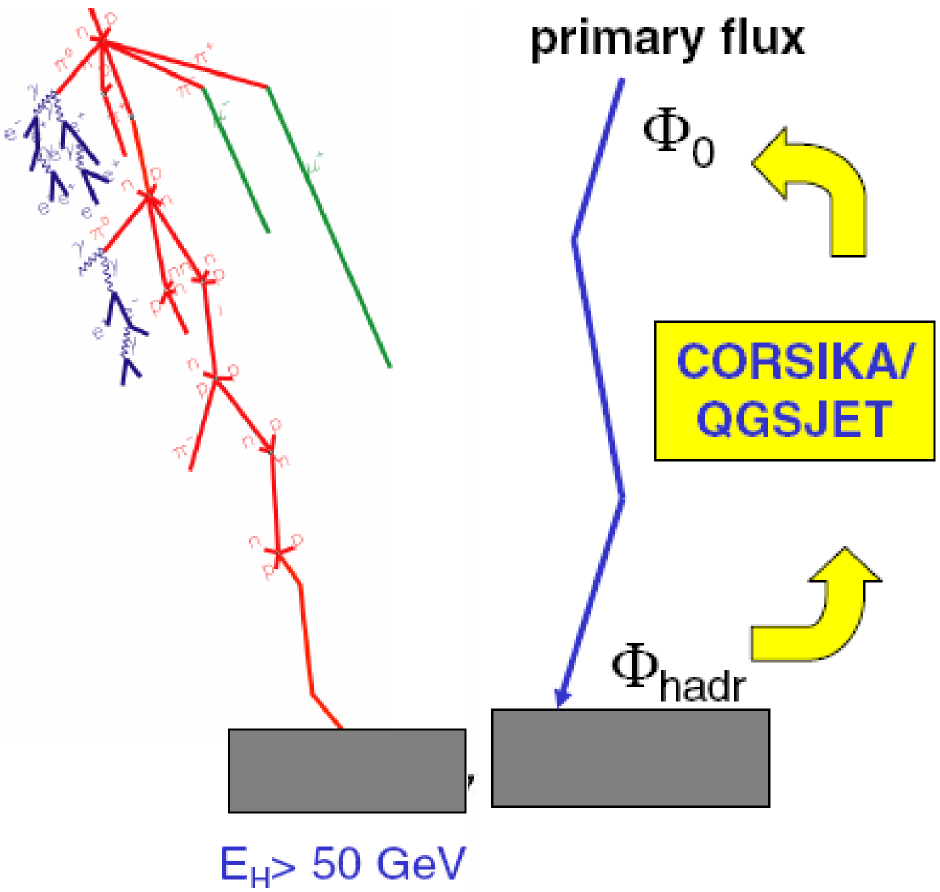
Hadrons measured in the calorimeter at an accelerator and in air showers

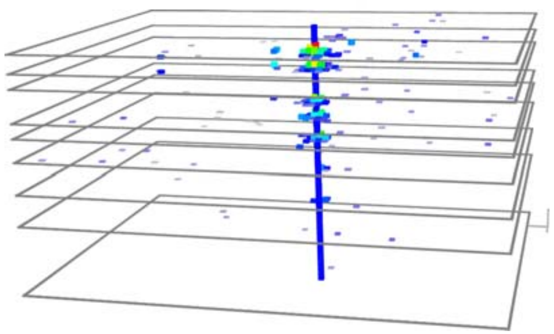
Fluctuations in shower development,
unusual events, long-flying component
🡐 In agreement with simulations





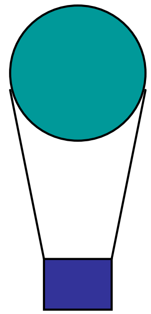
primary proton flux from hadron measurements

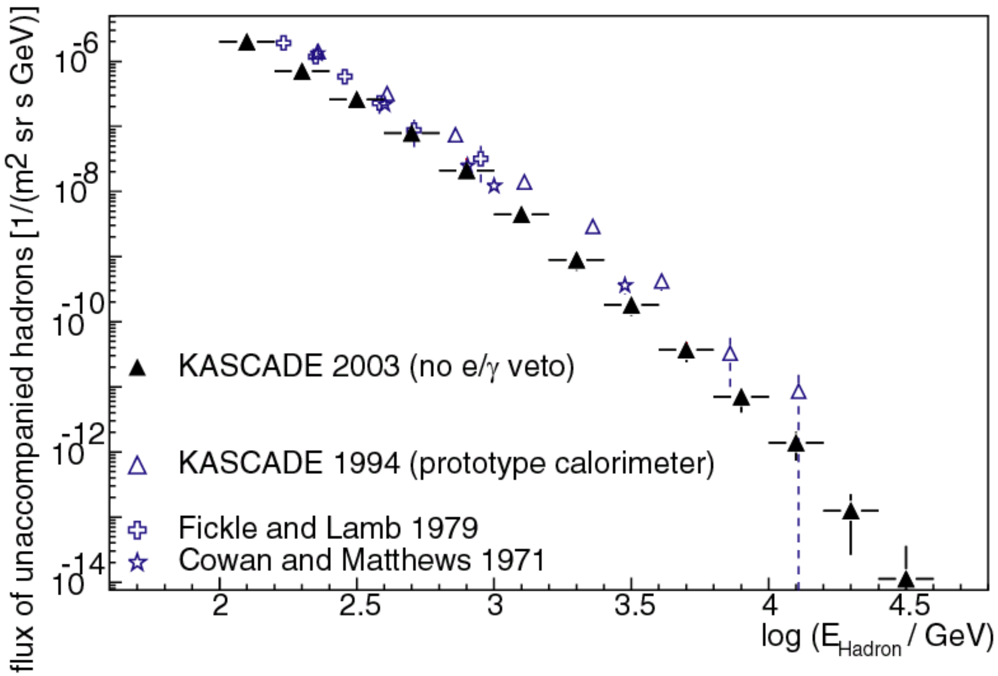




primary proton flux

$$\Phi_{hadr} = \Phi_0 \cdot \exp(-\frac{x}{\lambda_i})$$

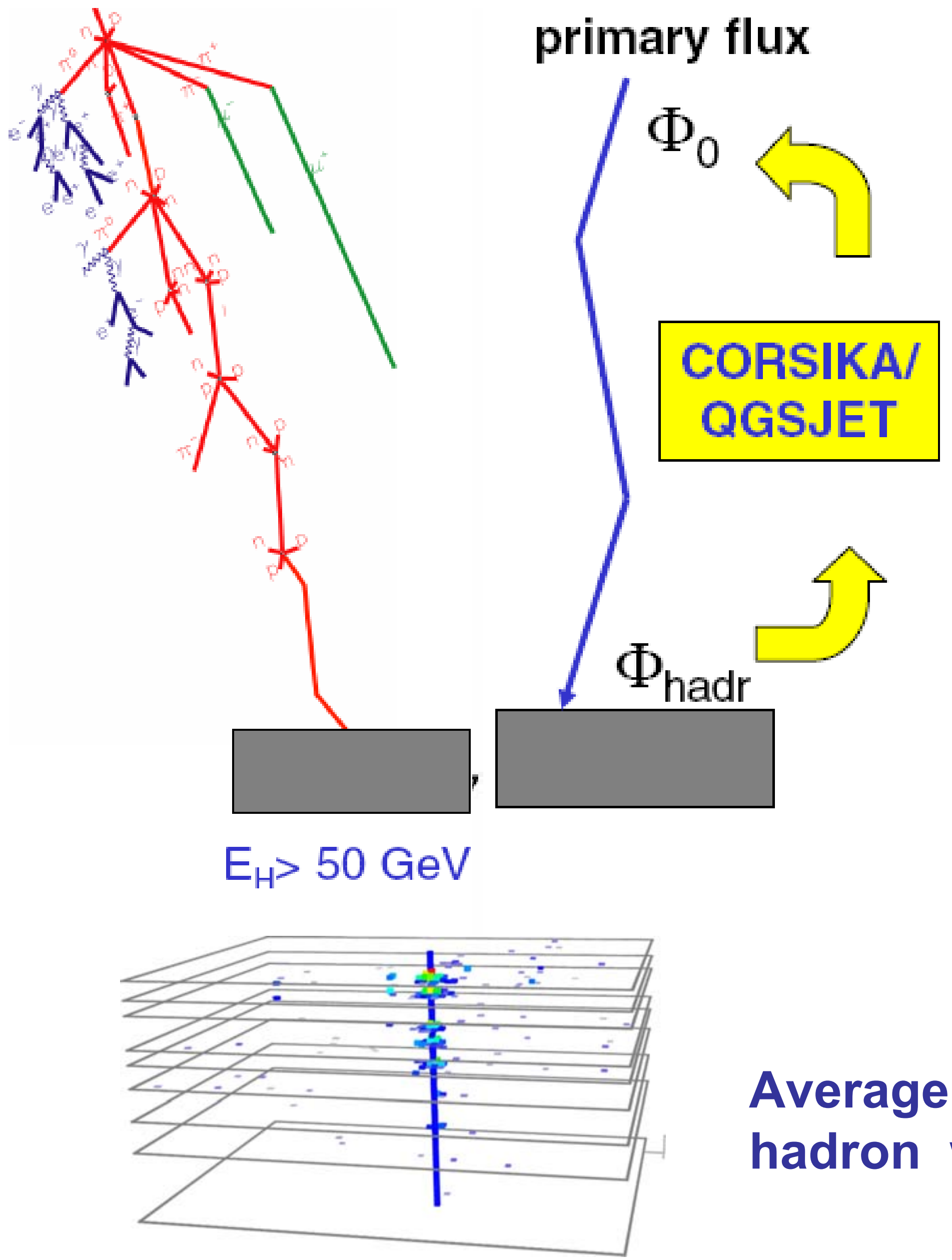


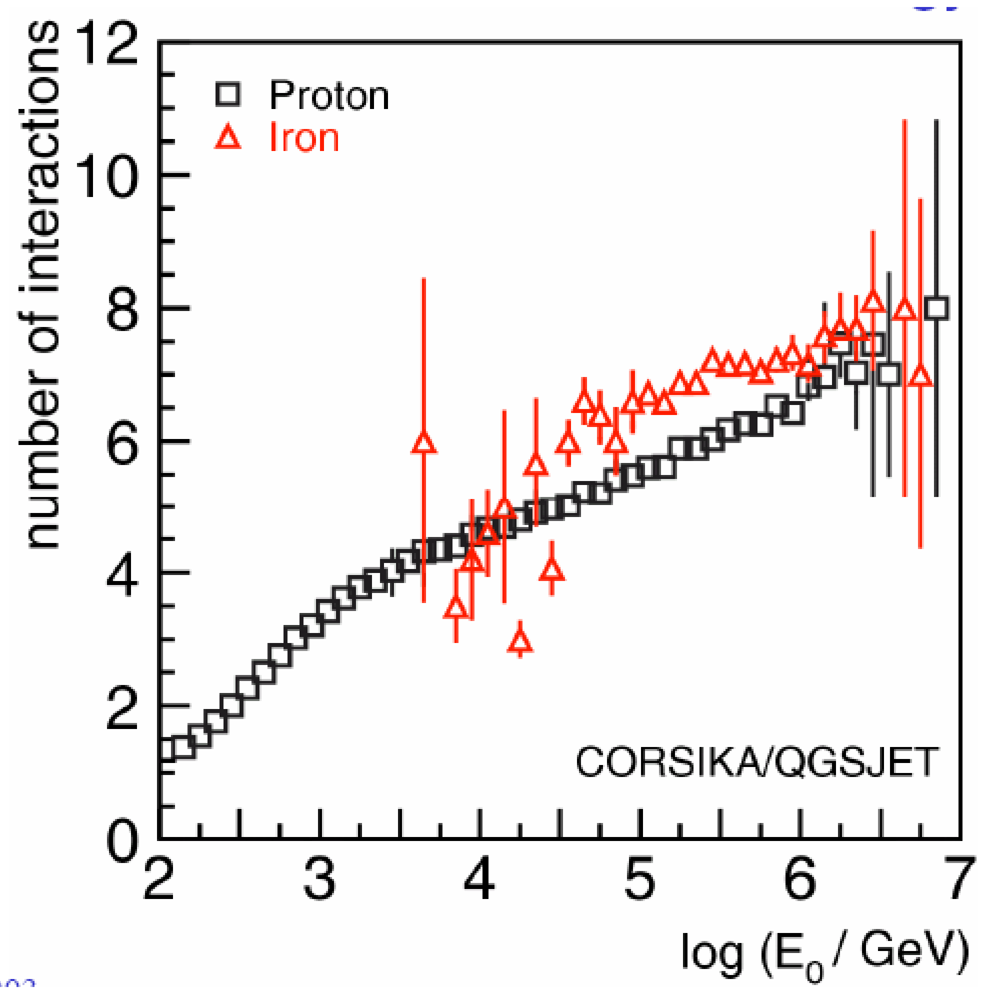


hadron spectrum at sea level

Single hadron: EAS did not trigger array

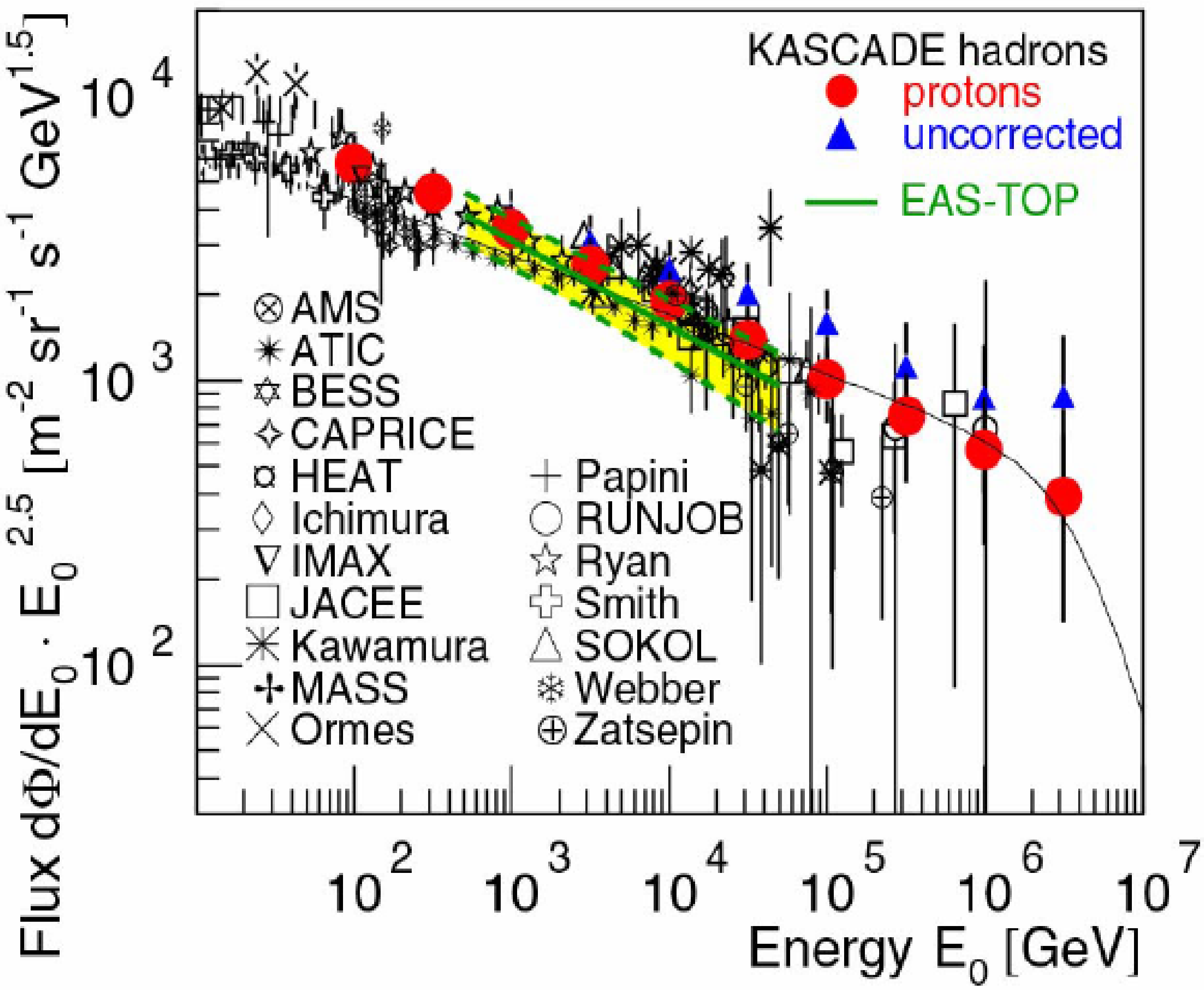
primary proton flux from hadron measurements



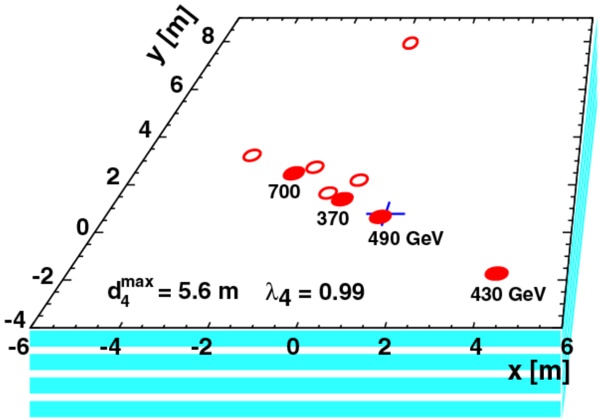


Average number of interactions when a single hadron was detected at KASCADE (simulations).

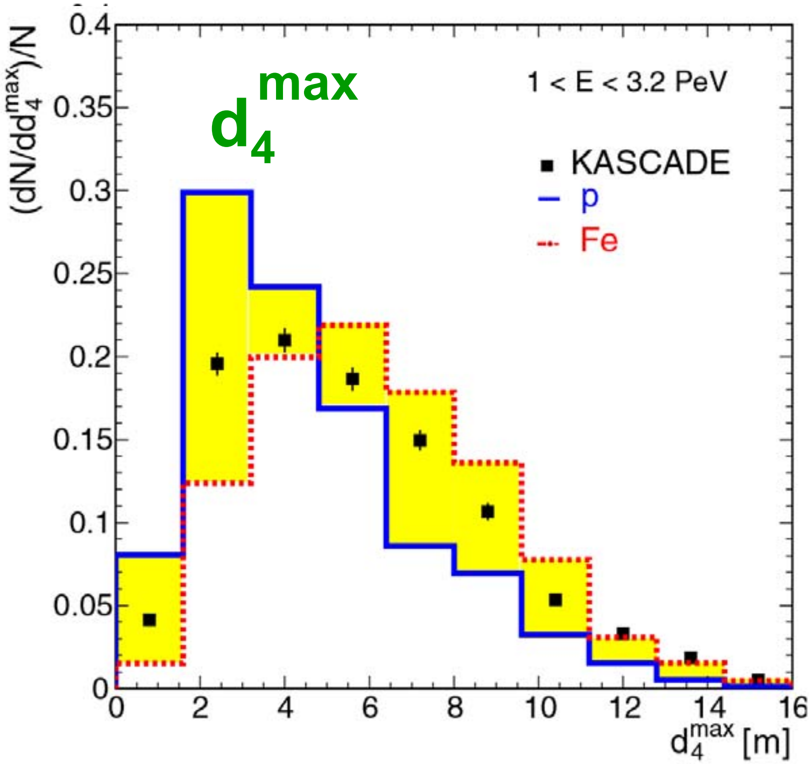
primary proton flux from hadron measurements

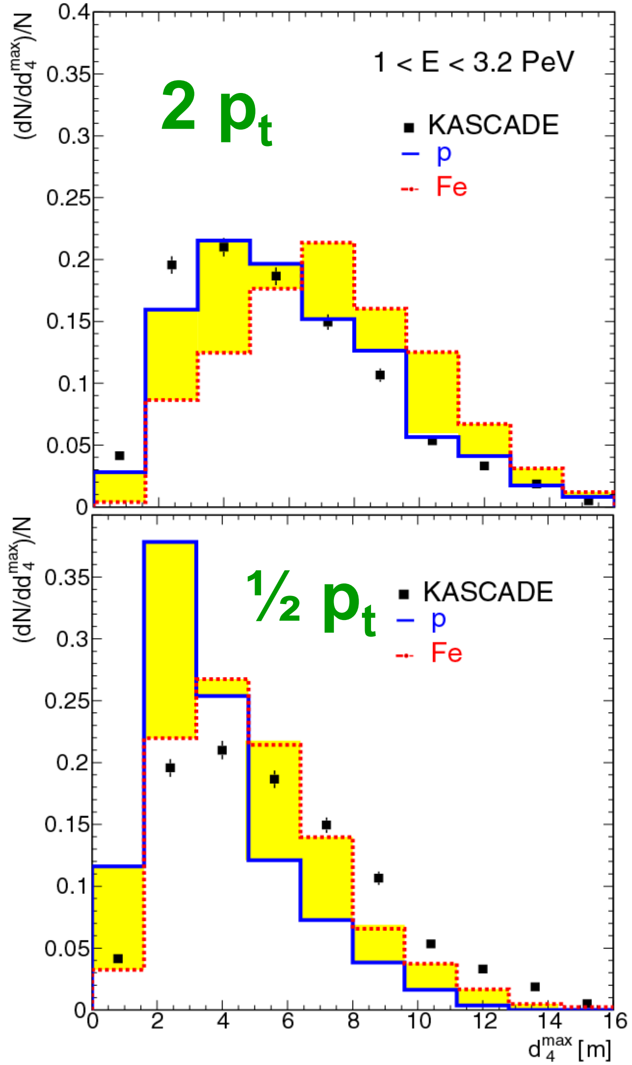


Spatial distribution: test of transverse momentum p_t in hadronic interaction



T. Antoni et al., Phys. Rev. D 71 (2005) 072002





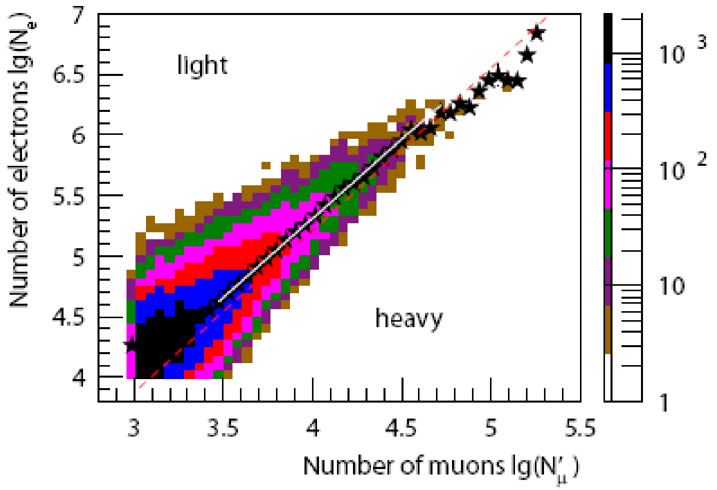
CORSIKA/QGSJET 01

Hadron Attenuation Length

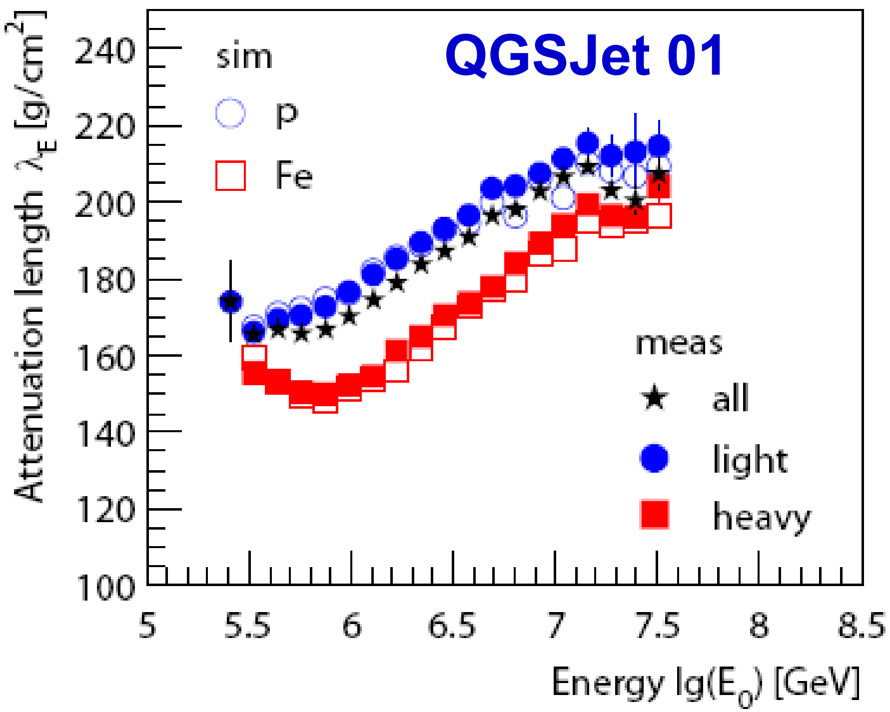
Method: measure hadronic energy sum at sea-level:

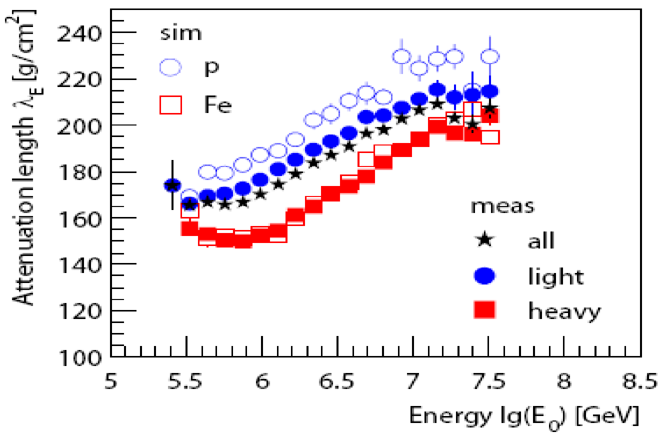
$$\Sigma E_H = E_0 \exp\left(-\frac{X_0}{\lambda_E}\right)$$

Divide data sample in light and heavy generated showers



Compare with simulations



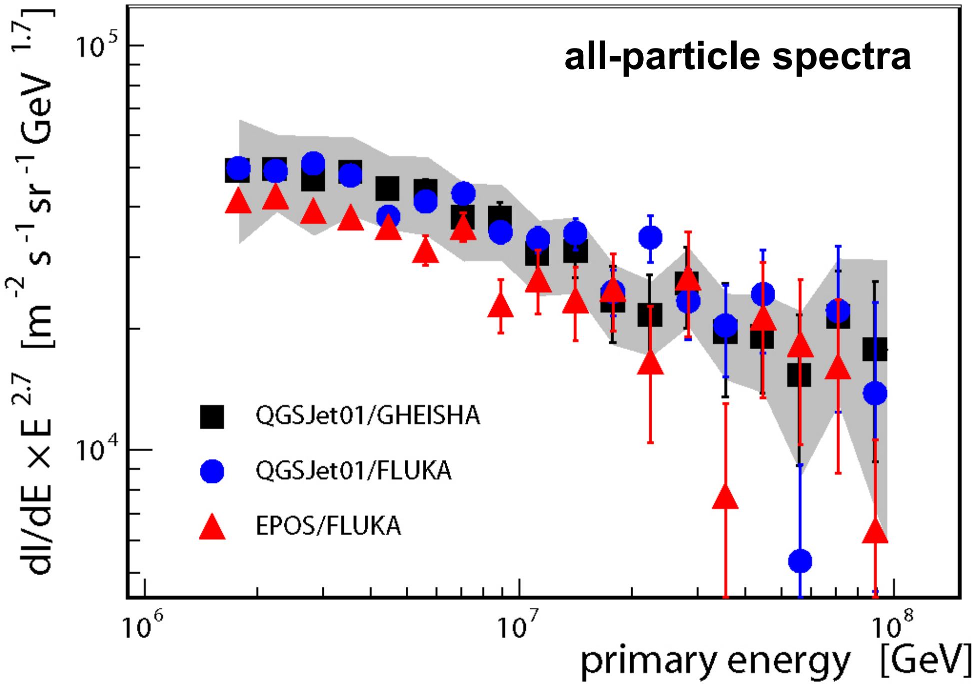


modified QGSJet 01: P-air cross-section: -5% Elasticity: +10%

KASCADE coll, submitted to PRD

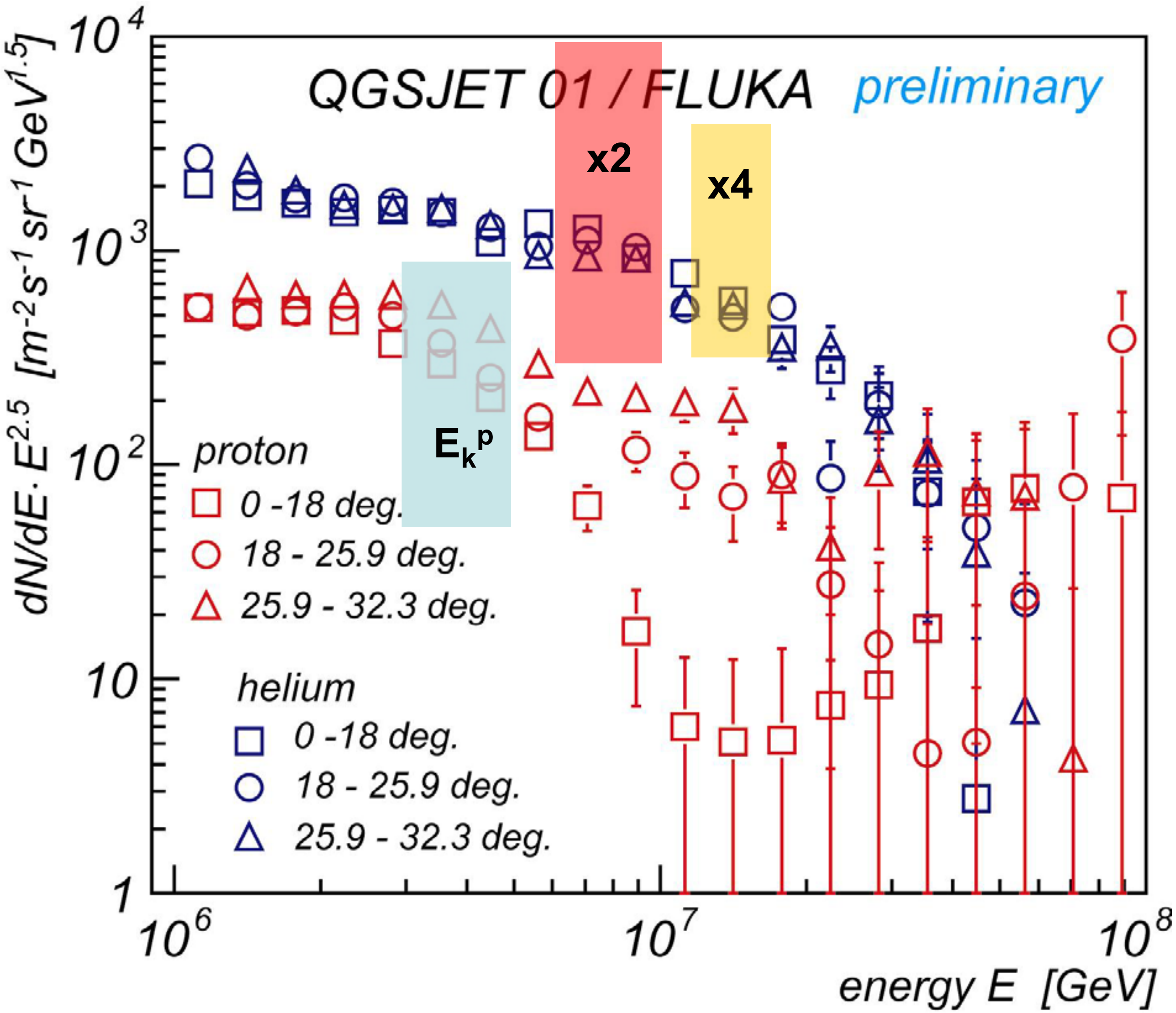
➔ **Hint for model builders??**

KASCADE Summary



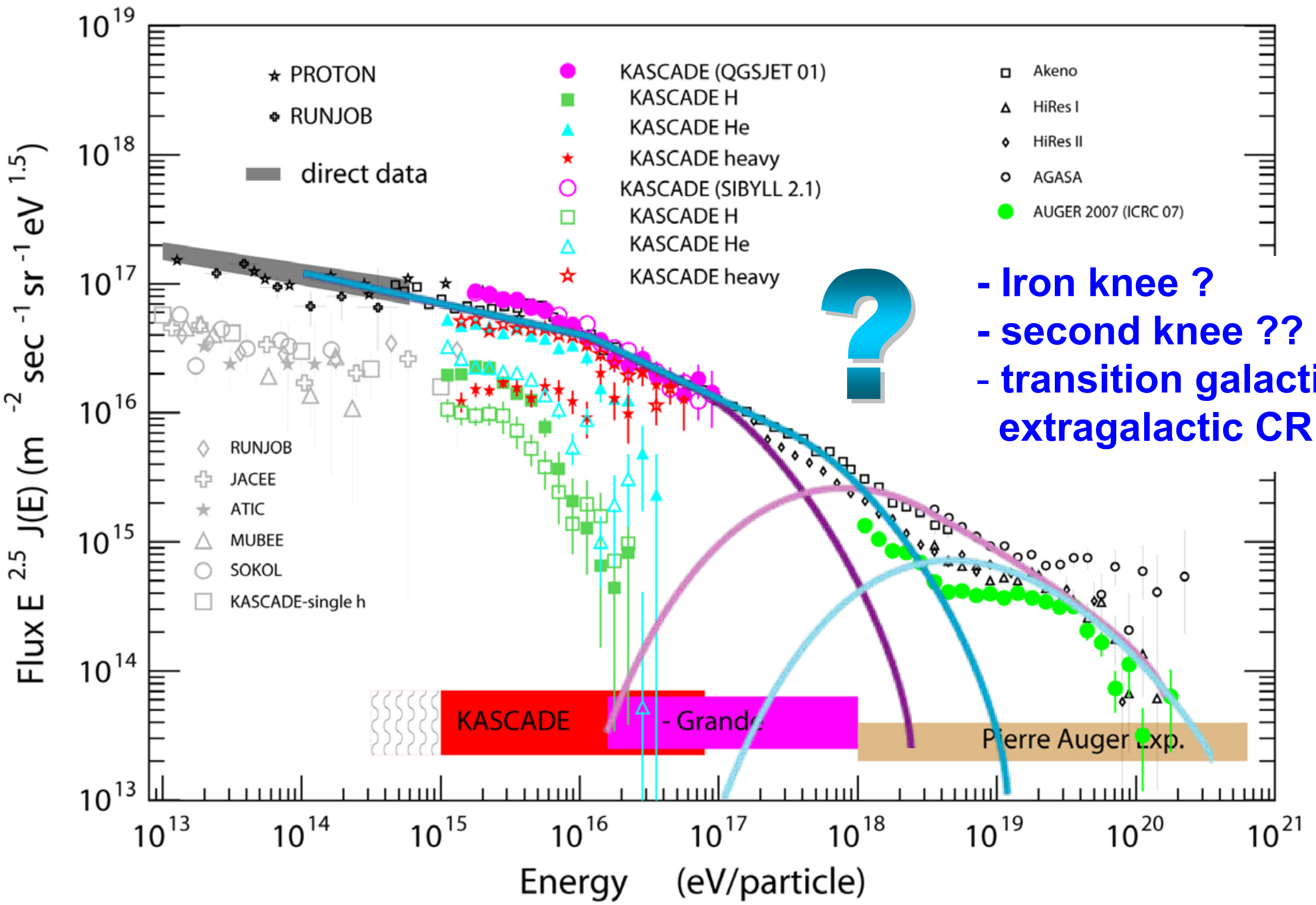
-) knee caused by light primaries ➔ composition gets heavier across knee
-) positions of knee vary with primary elemental group
-) relative abundancies depend strongly on high energy interaction model
-) result only weakly dependent on low energy interaction model
-) result consistent for different data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

A or Z ?



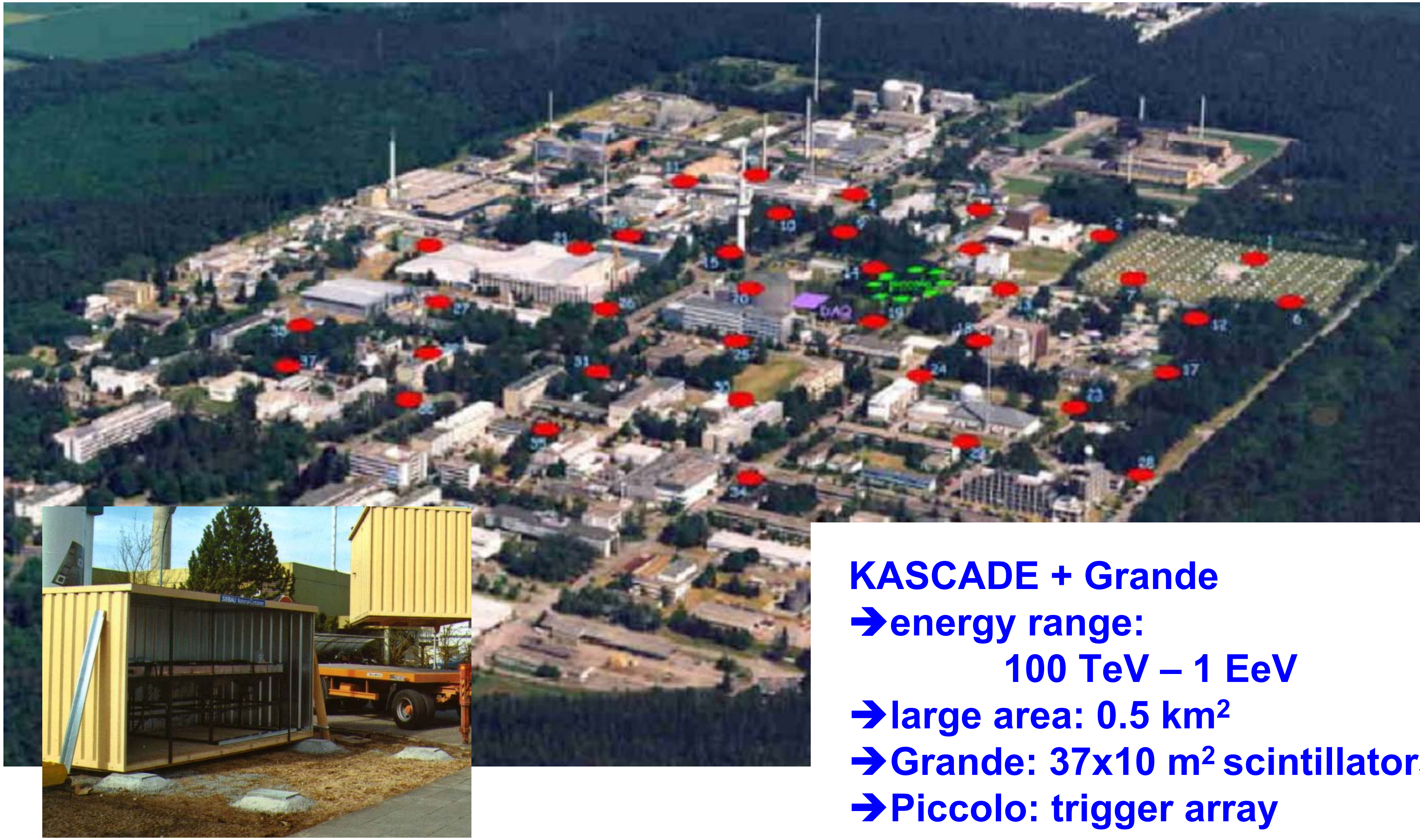
Data: KASCADE, H.Ulrich, XIV ISVHECRI, Weihai, China 2006

Motivation for measurements 100 – 1000 PeV



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

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: Reconstruction

1) core position and angle-of-incidence
   from Grande array data

➔

2a) shower size (charged particles)
   from Grande array data

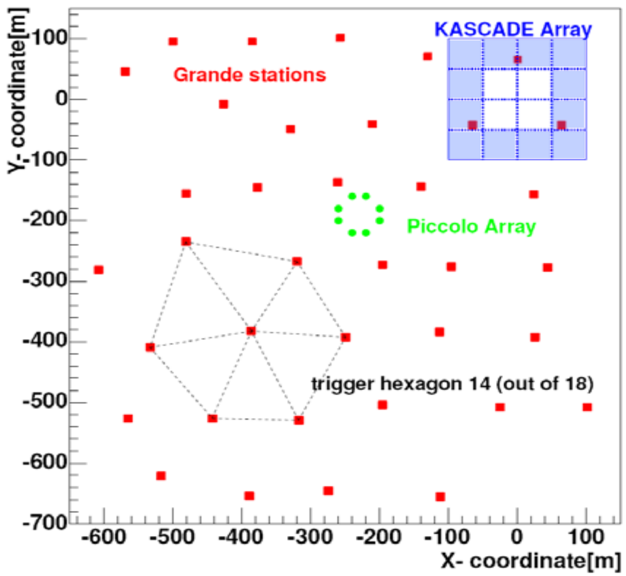
2b) muon number
   from KASCADE muon detectors

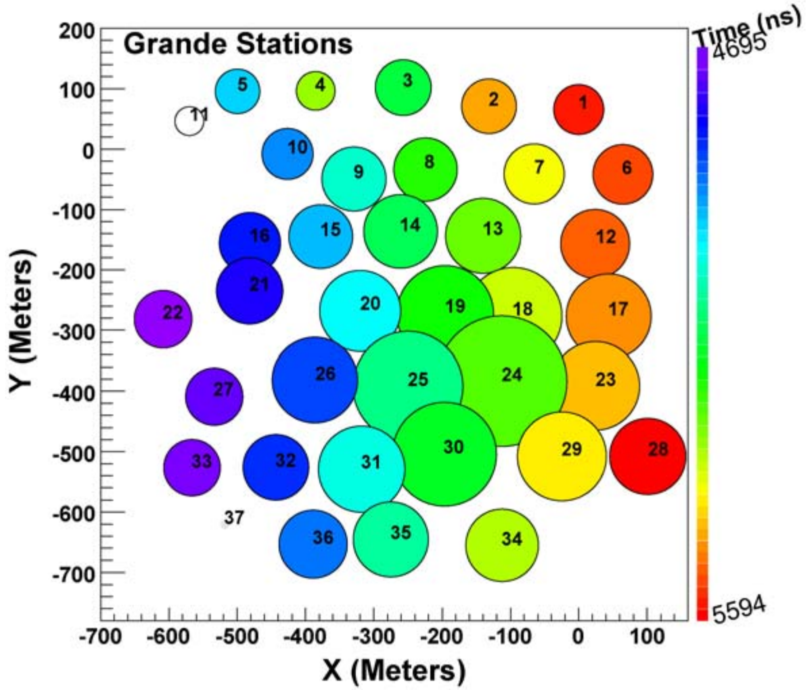
➔

3) electron number
   from Grande by subtraction of muon content

➔

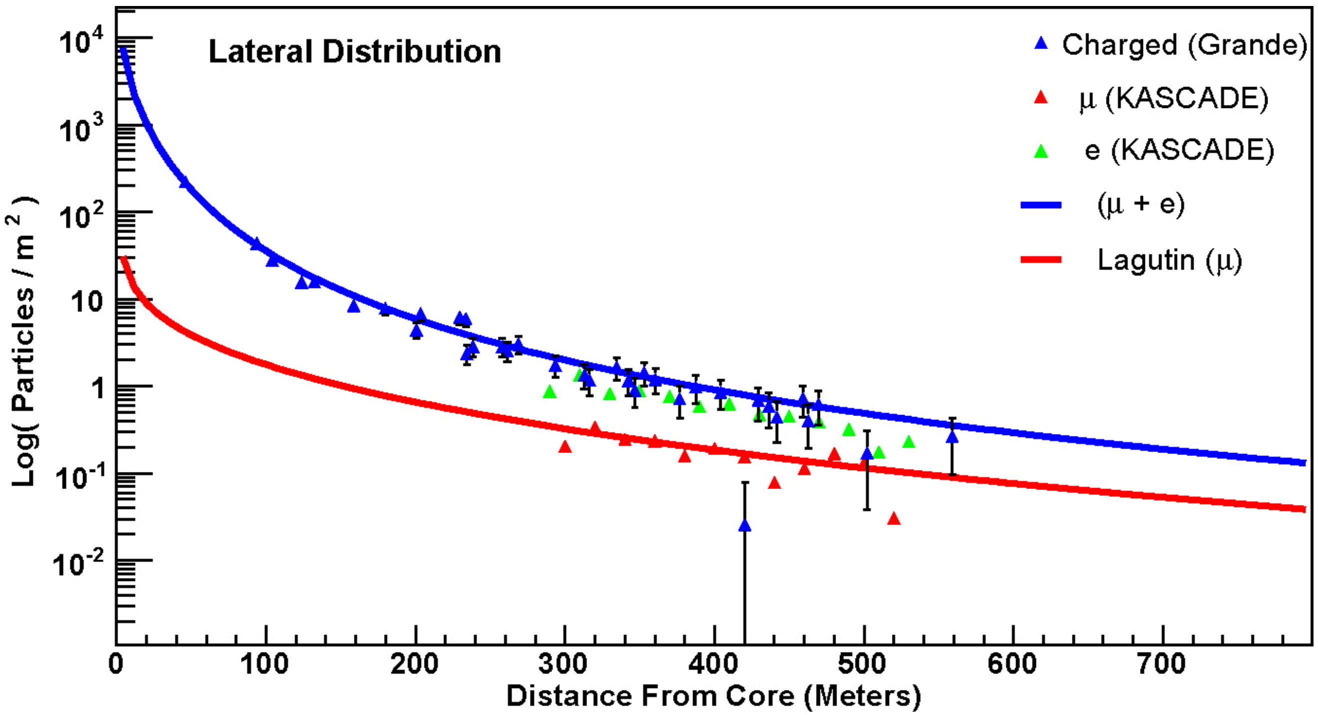
4) two dimensional size spectrum
   for the unfolding analysis





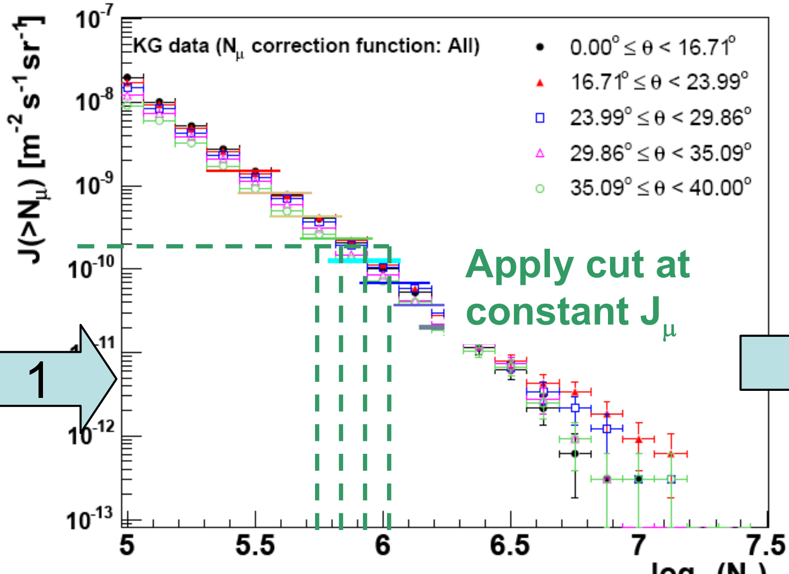
KASCADE-Grande : Single event reconstruction

a single event measured by KASCADE-Grande:
core (-155,- 401) m
log10(Size) : 7.0
log10(Sizm) : 5.7
No saturation
Zenith: 24.2 degrees
Azimuth: 284 degrees
Recorded on 8 July 2005 at 12:11 (UTC)



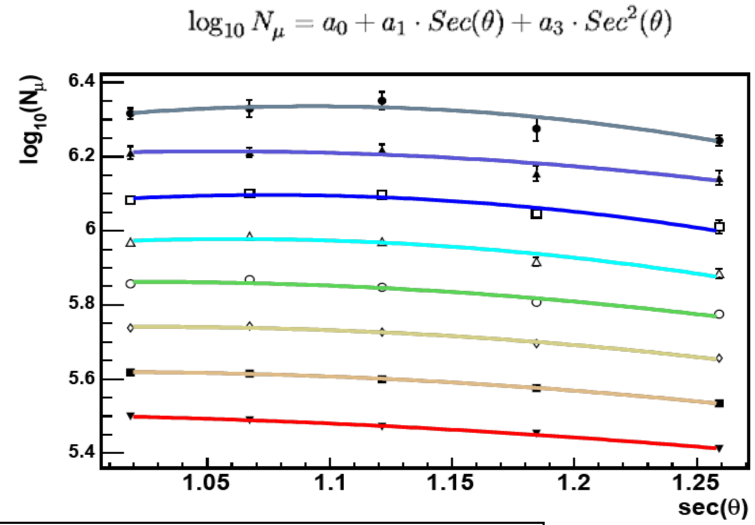
Way to all-particle energy spectrum : constant intensity cut method CIC (N_μ)

1



For a given J_μ, get $N_\mu(\theta)$

2

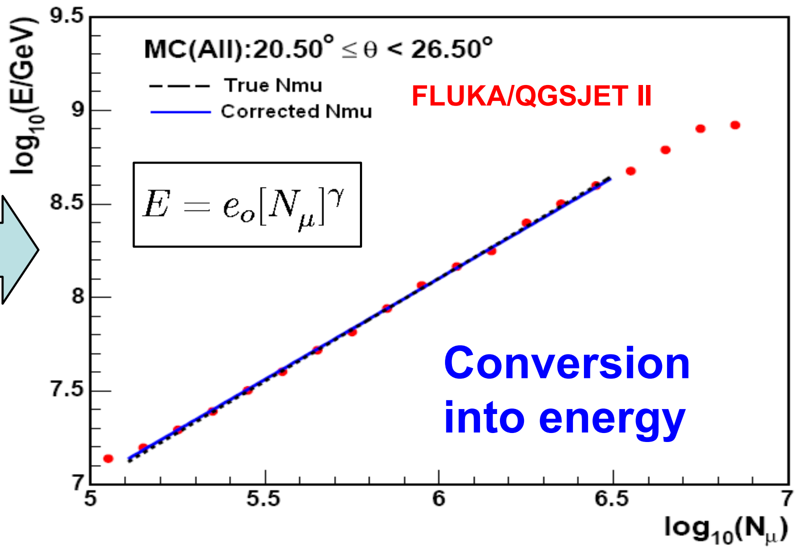


Get attenuation curves

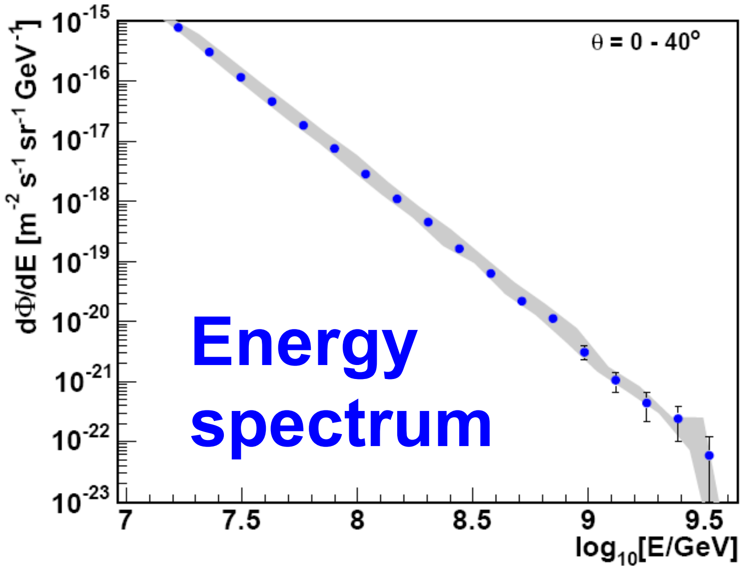
3

$N_\mu(24^\circ)$ of each event

4

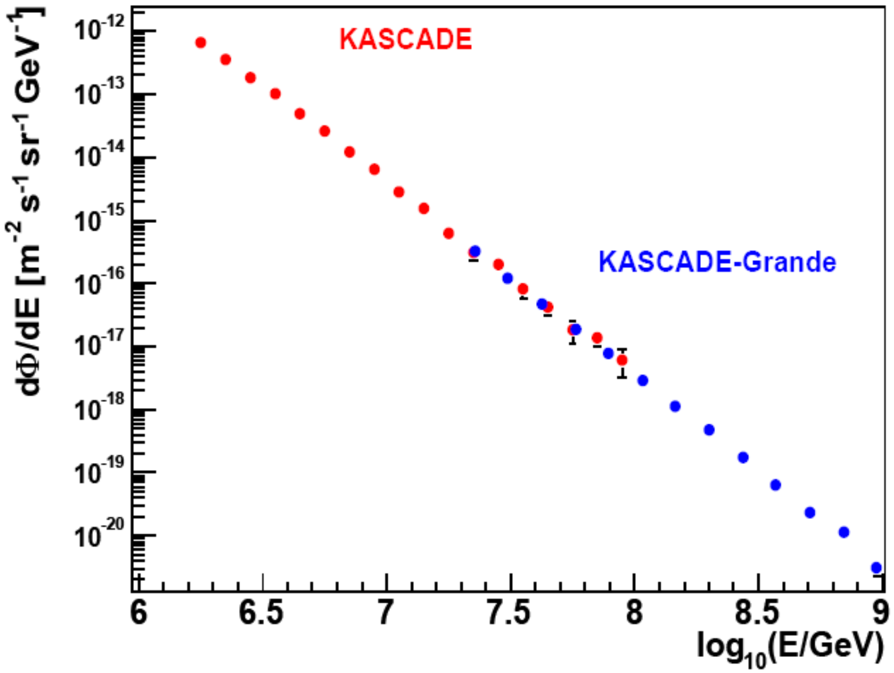


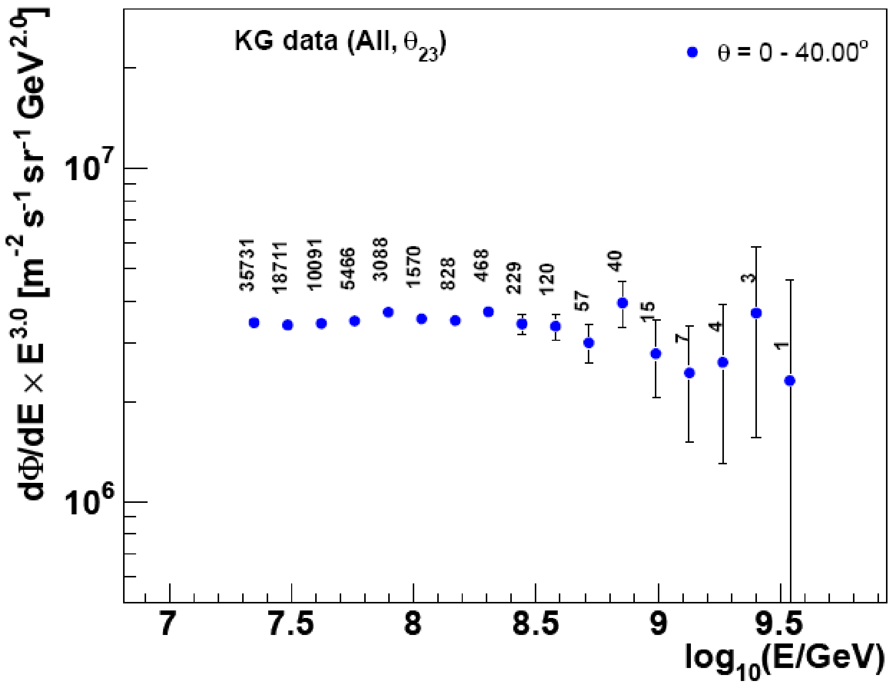
5



Way to all particle energy spectrum : constant intensity cut method CIC (N_μ)

QGSJET II hadronic interaction model

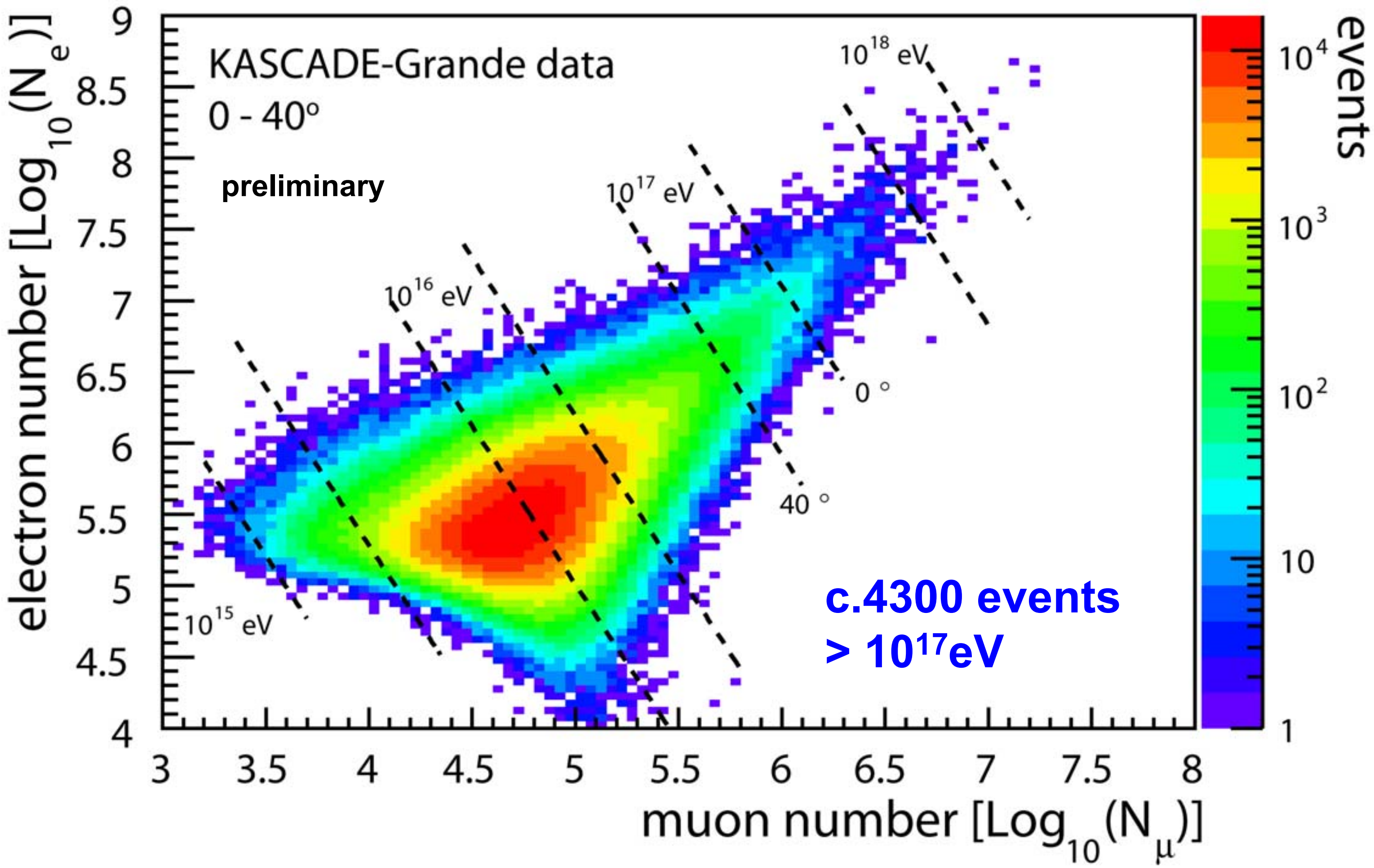




Present work: investigations of systematic uncertainties….

……coming next: ICRC

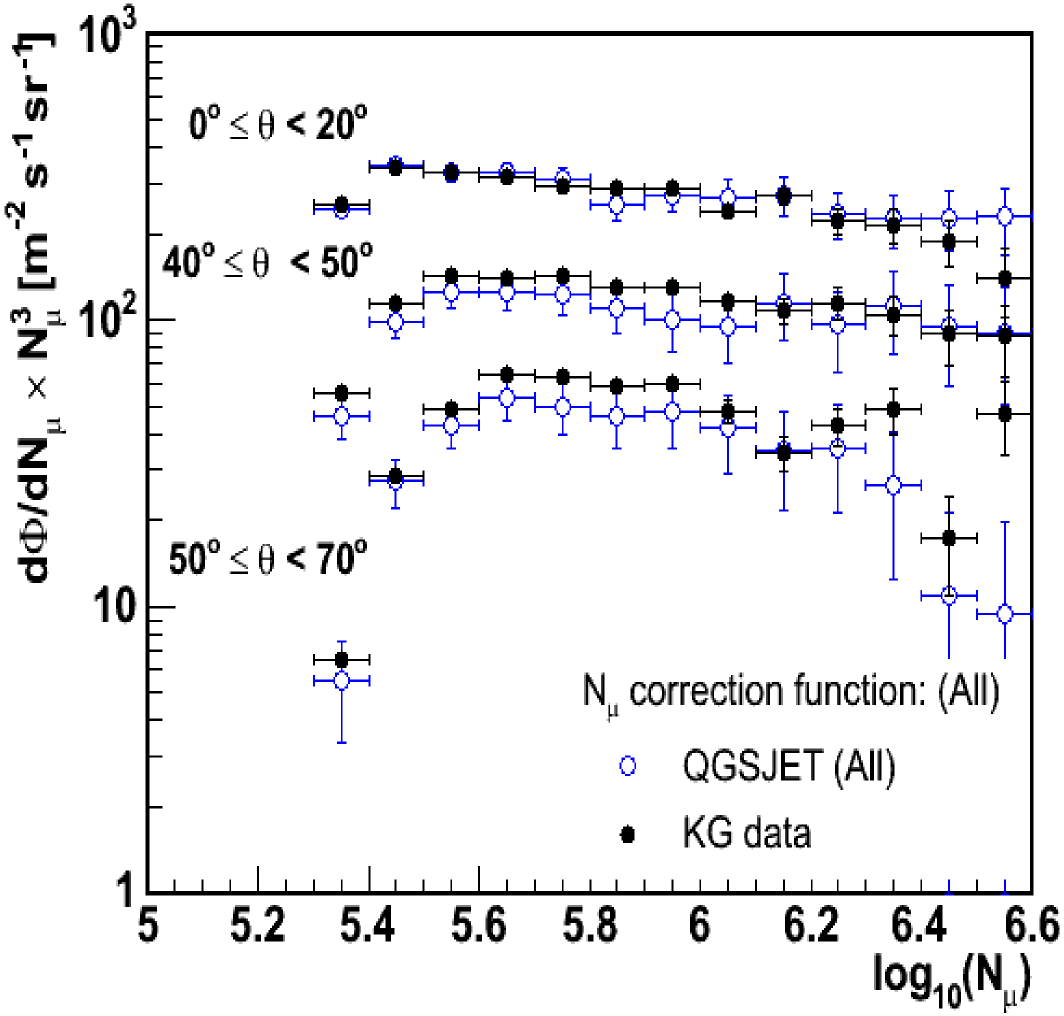
KASCADE-Grande : unfolding analysis



Unfolding of 2-dimensional shower size spectrum possible
- ➔ **energy & composition**
- ➔ **still improvements in systematics needed**
- ➔ **higher statistics**

Muon spectra

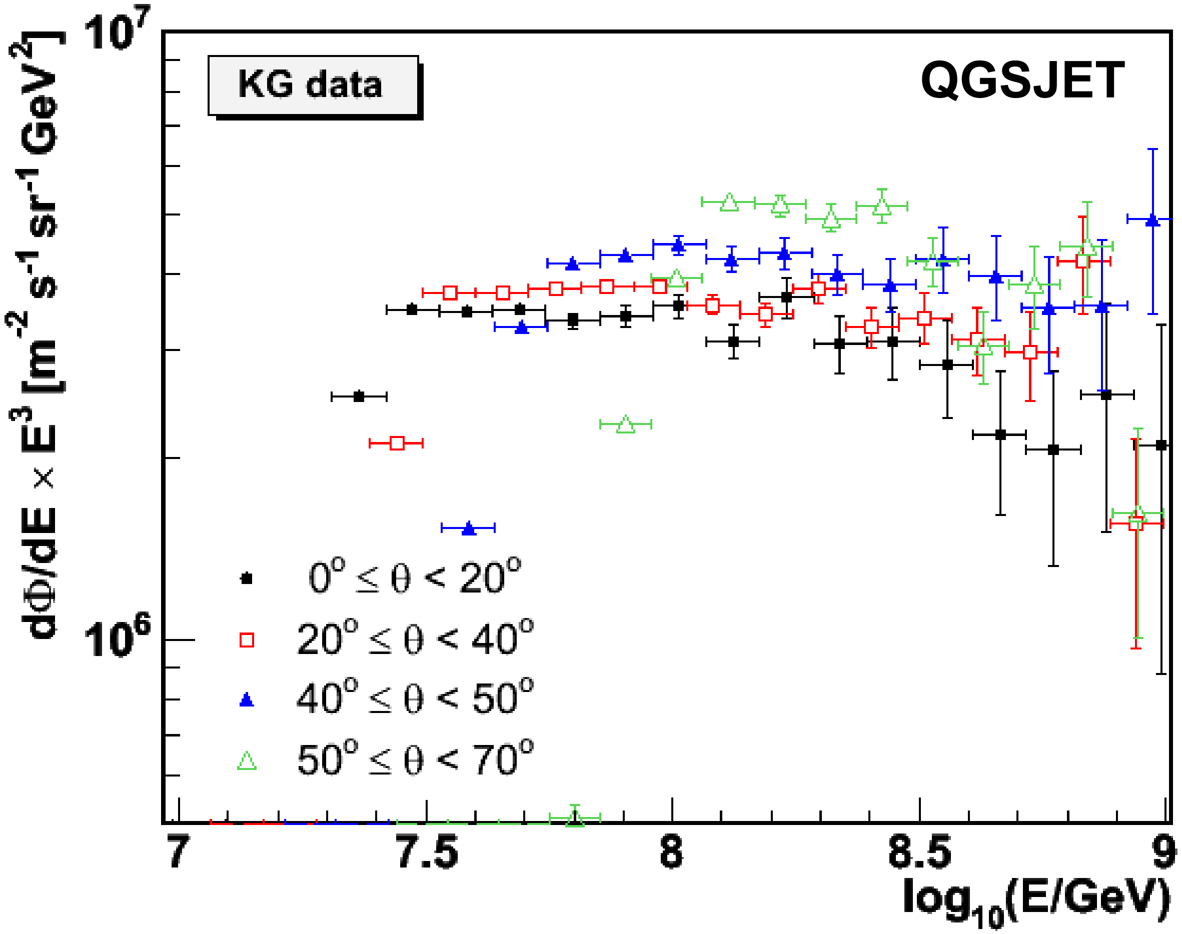
KG data vs MC



Discrepancy between MC (QGSJET II) and KG data increases with zenith angle.

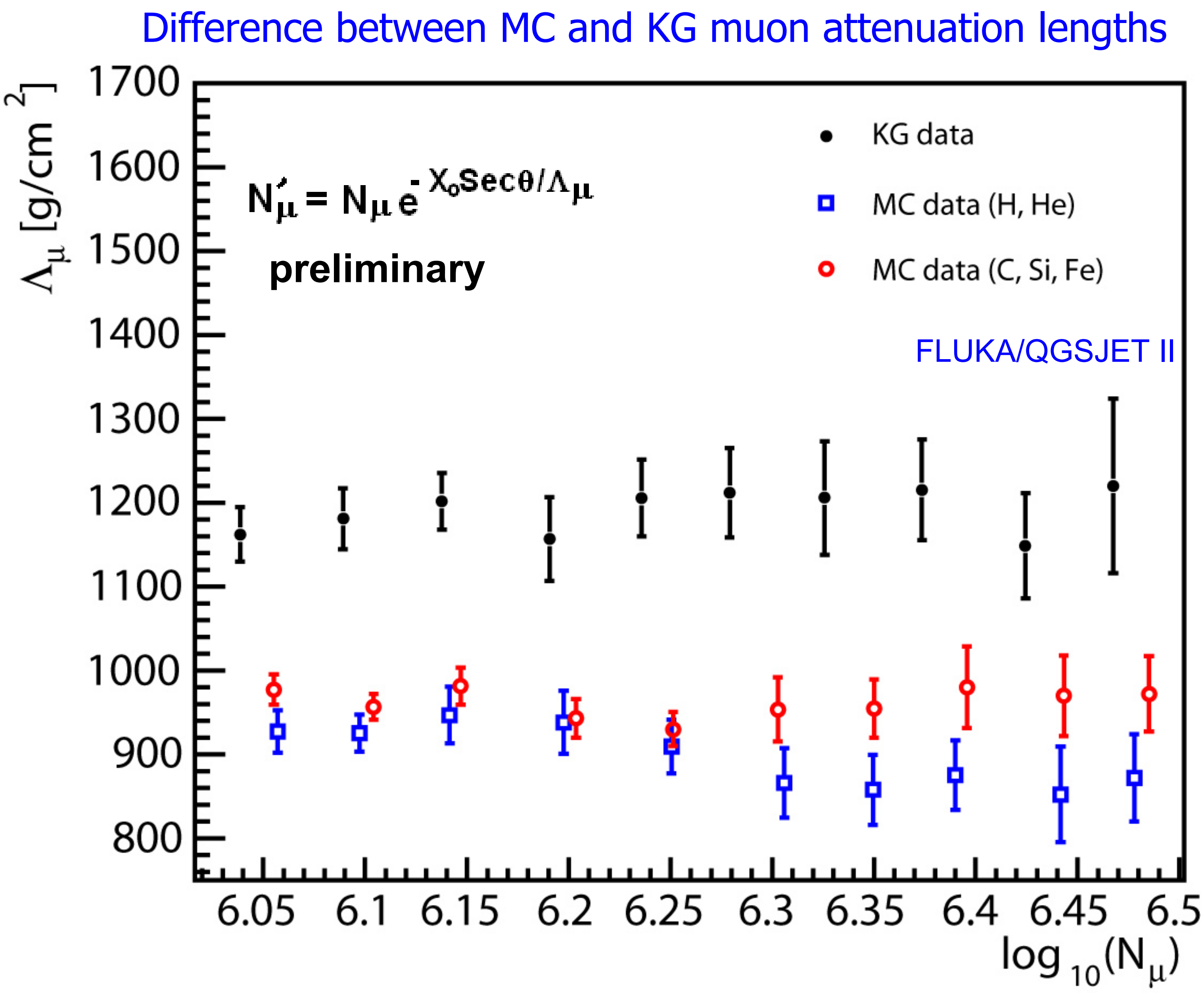
Discrepancy also found when using EPOS

Effect in Energy Spectrum?

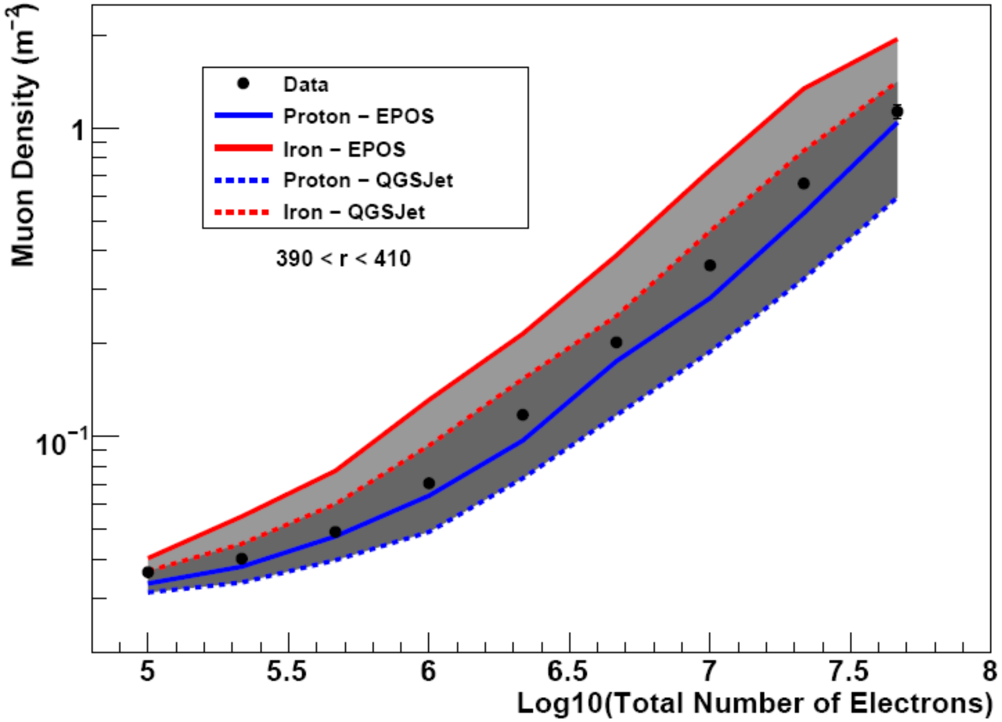


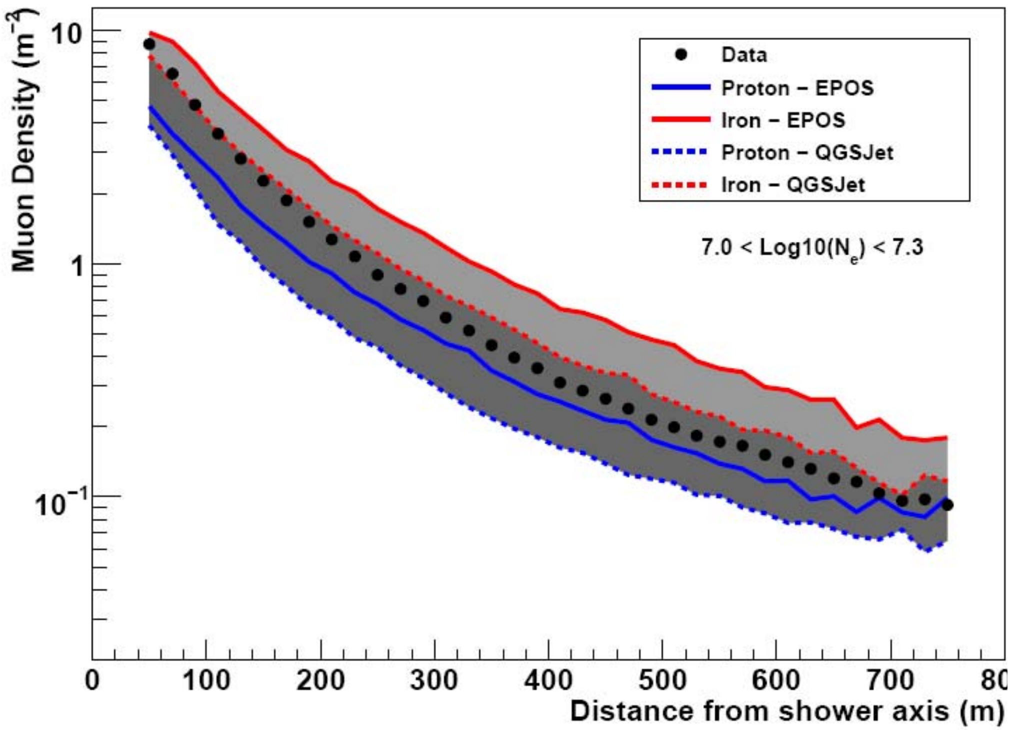
Discrepancy between energy spectra from vertical and inclined showers

Muon attenuation length



muon density investigations



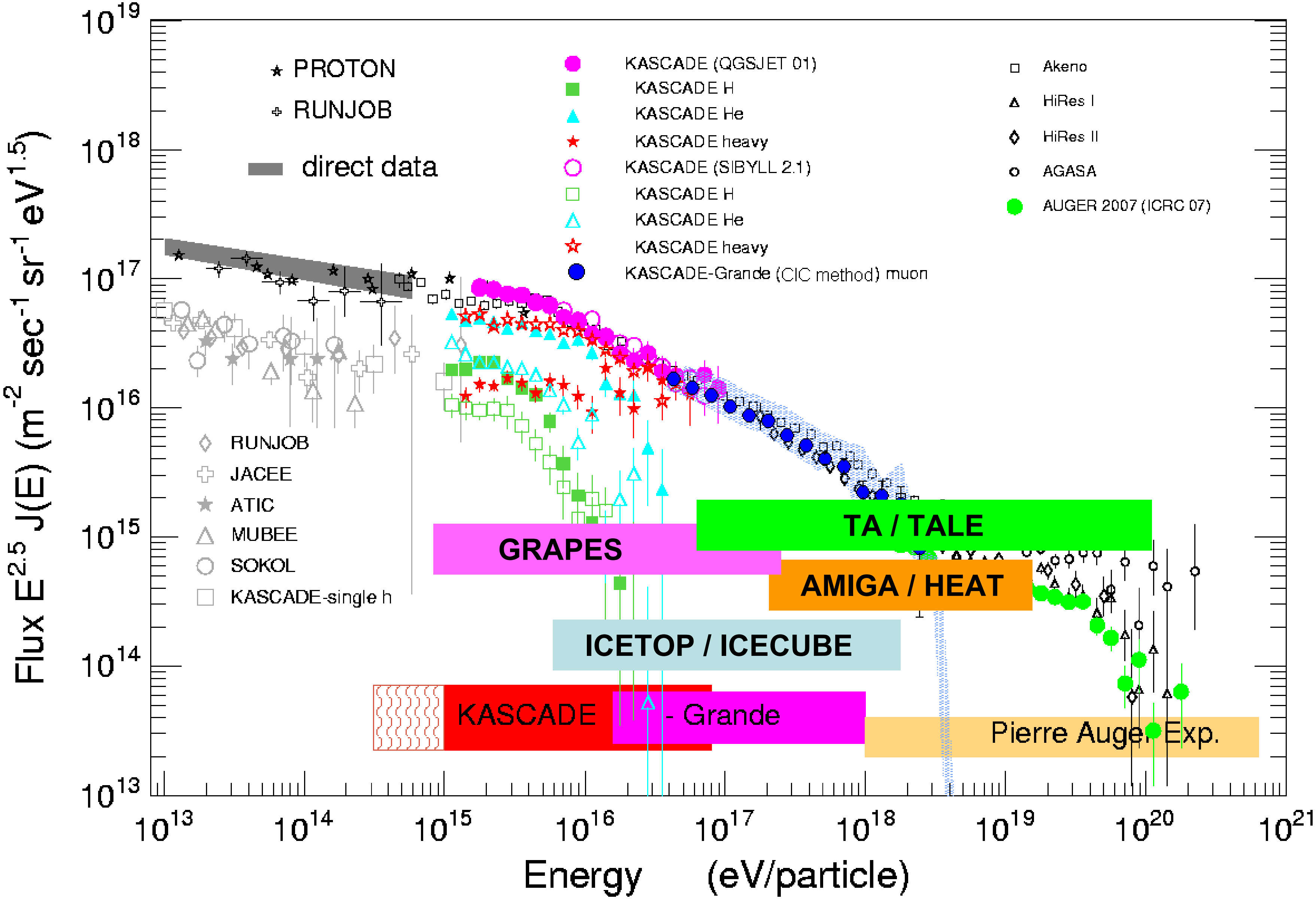


- muon (local) density reconstruction possible for different distances

➔ composition sensitivity

➔ model tests

KASCADE-Grande
+ model tests



KASCADE-Grande Collaboration

Institut für Kernphysik
Forschungszentrum and University of Karlsruhe

W.D. Apel, F. Badea, K. Bekk, J. Blümer, H. Bozdog, F. Cossavella, K. Daumiller, V. de Souza, P. Doll, R. Engel, J. Engler, M. Finger, H.J. Gils, A. Haungs, D. Heck, T. Huege, P.G. Isar, D.Kang, H.O. Klages, H.-J. Mathes, H.J. Mayer, J. Milke, S. Nehls, J. Oehlschläger, S. Ostapchenko, T. Pierog, H. Rebel, M. Roth, H. Schieler, F. Schröder, M. Stümpert, H. Ulrich, A. Weindl, J. Wochele, M. Wommer

Universität Siegen
Experimentelle Teilchenphysik

M. Brüggemann, P. Buchholz, C. Grupen, D.Kickelbick, Y. Kolotaev, S. Over, W. Walkowiak

Universität Wuppertal
Fachbereich Physik

D. Fuhrmann, R. Glasstetter, K-H. Kampert

IFSI, INAF
and University of Torino

M. Bertaina, E. Cantoni, A. Chiavassa, F. Di Pierro, P. Ghia, C. Morello, G. Navarra, G. Trinchero

Universidad Michoacana
Morelia, Mexico

J.C. Arteaga

Radboud University
Nijmegen

J.R.Hörandel

Soltan Institute for
Nuclear Studies, Lodz

P. Luczak, J. Zabierowski

Institute of Physics and Nuclear Engeneering and University Bucharest

I.M. Brancus, C. Manailescu, B. Mitrica, C. Morariu, M. Petcu, O.Sima, G.Toma

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