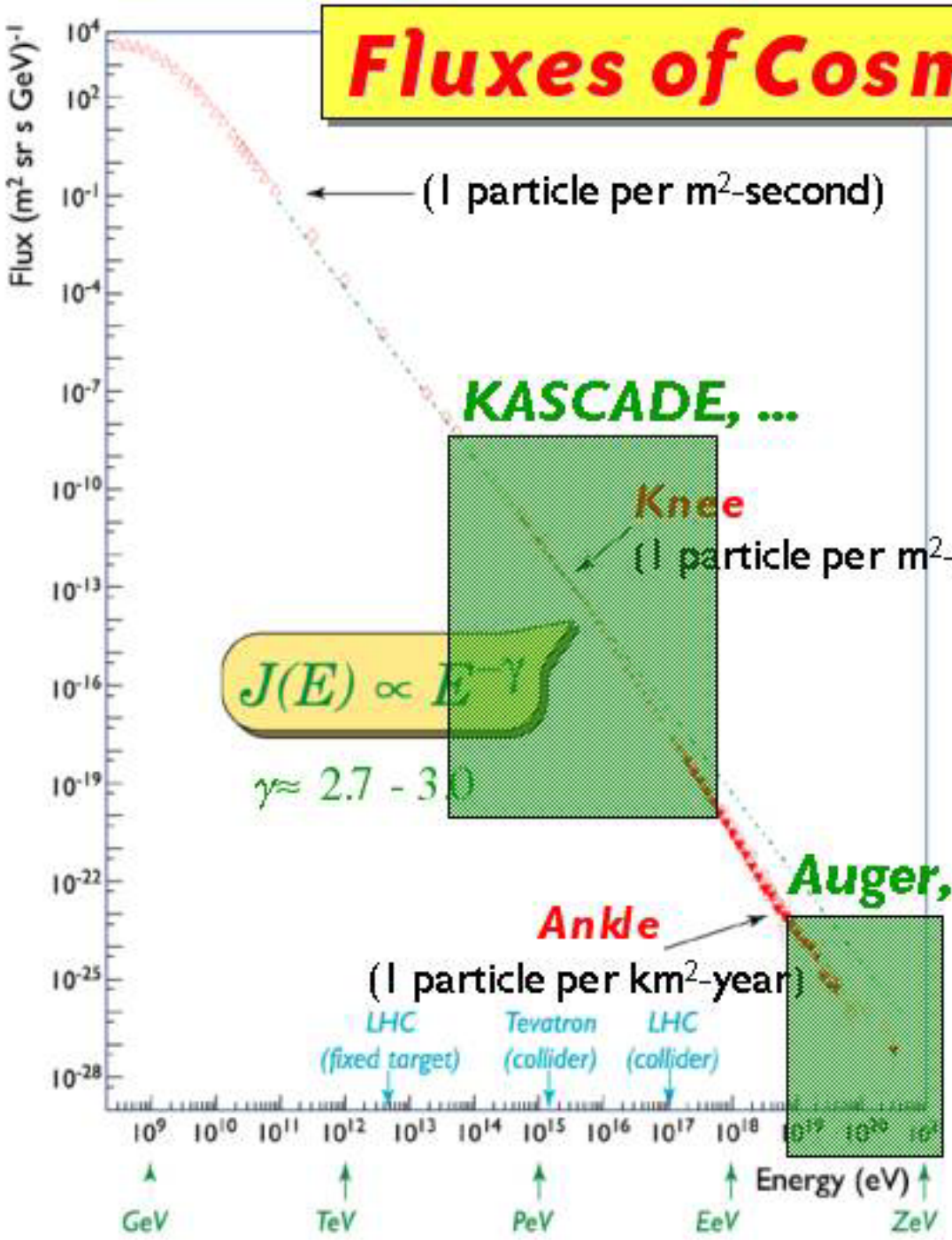
The Physics of the Knee in the Cosmic Ray Spectrum

18th International Workshop on
Weak Interactions and Neutrinos
21-26 January 2002
Christchurch, New Zealand

K.-H. Kampert for the KASCADE Collaboration
University Karlsruhe & Forschungszentrum Karlsruhe

- **The Quest of the Knee**
- **Experimental Set-Up**
- **Verifying Interaction Models by Exp. Data**
- **Energy Spectra of individual Mass Groups**
- **Astrophysical Implications**
- **Outlook**

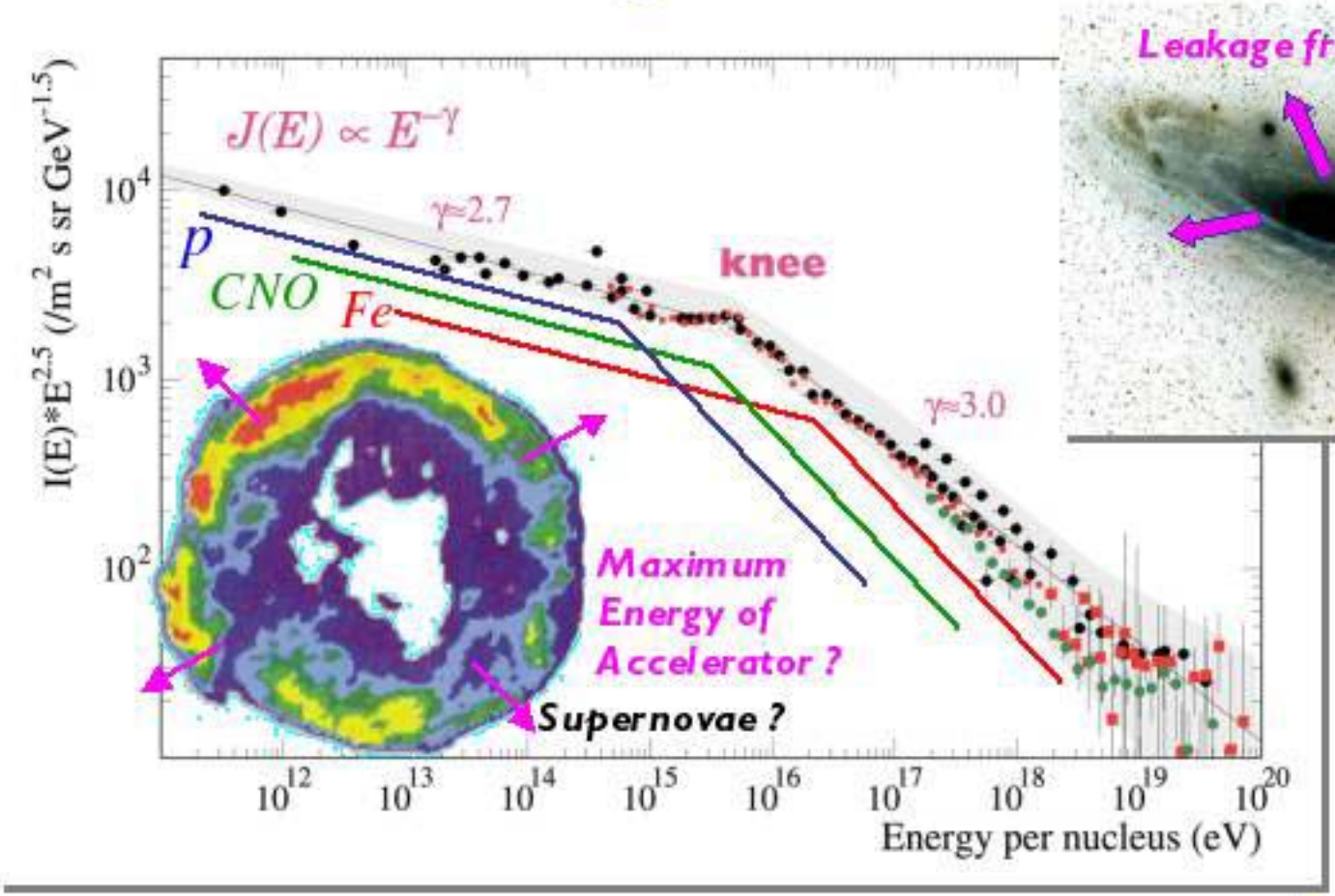
Fluxes of Cosmic Rays



(32 decades in flux; 12 decades in energy)

1 particle per km²-century

What is the origin of the "Knee" ??



Maximum Energy of Accelerator ?
Leakage from Galaxy ?

→ $E_{max} \propto R \cdot B \cdot Z$ (+ isotropies) → *enrichment of heavy elements above the knee*

Some other possible causes of a sharp knee...

- **Single Source Model ?** *(Erlykin & Wolfendale)*
  expect distinct peaks (O+Fe, He+O..?) above smooth background;
  heavier composition above knee

- **CR interaction with Neutrinos ?**
  - ✧ *Wigmans:* $p+\bar{\nu} \rightarrow n+e+$ (E_{th}=3 PeV for m_ν=0.5 eV) @ NS, AGN, ...
    ➥ *p- and α-kink, abrupt change of composition expected*
  - ✧ *Dova et al:* $p+\nu \rightarrow \Delta \rightarrow p+\pi$ (E_{th}=3 PeV for m_ν=100 eV) in gal. halo
    ↥ *magn. or electr. dipole moment required*

- **New type of interaction in atmosphere ?**
  - ✧ *Nikolsky… : new unseen particles produced in EAS*
  - ✧ *Kazanas… : Extra Dimensions (Gravitons)?*
    ⇛ *knee scales with E/nucleon*

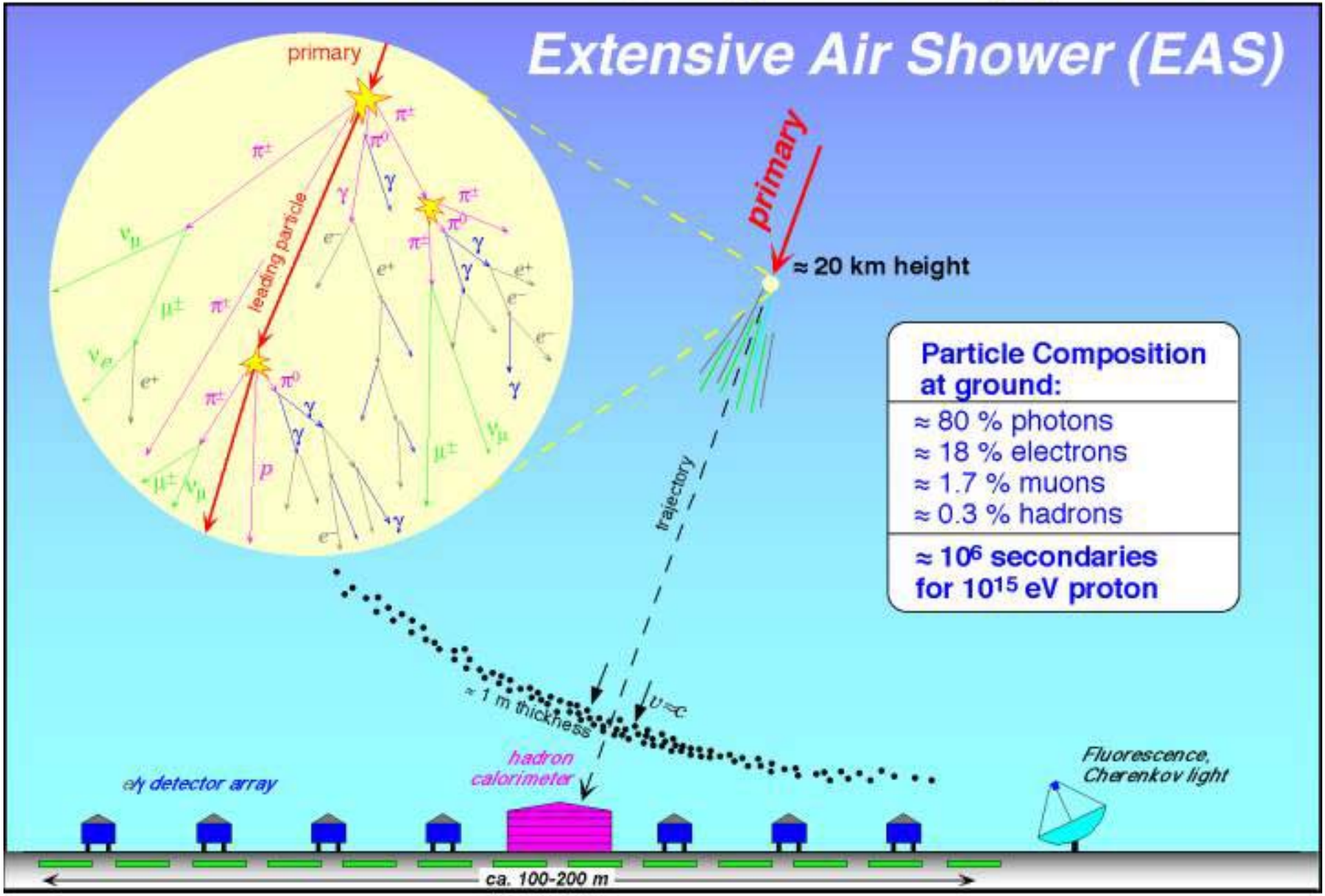
- **...**

If Supernovae: Some specific questions...

- Explosion into ISM or into stellar wind ?
- If ISM: "hot" or "warm" ISM ?
- Local Hot Bubble ?
- Magnetic Field strength in acceleration region ?
- Re-acceleration required ?
- ...

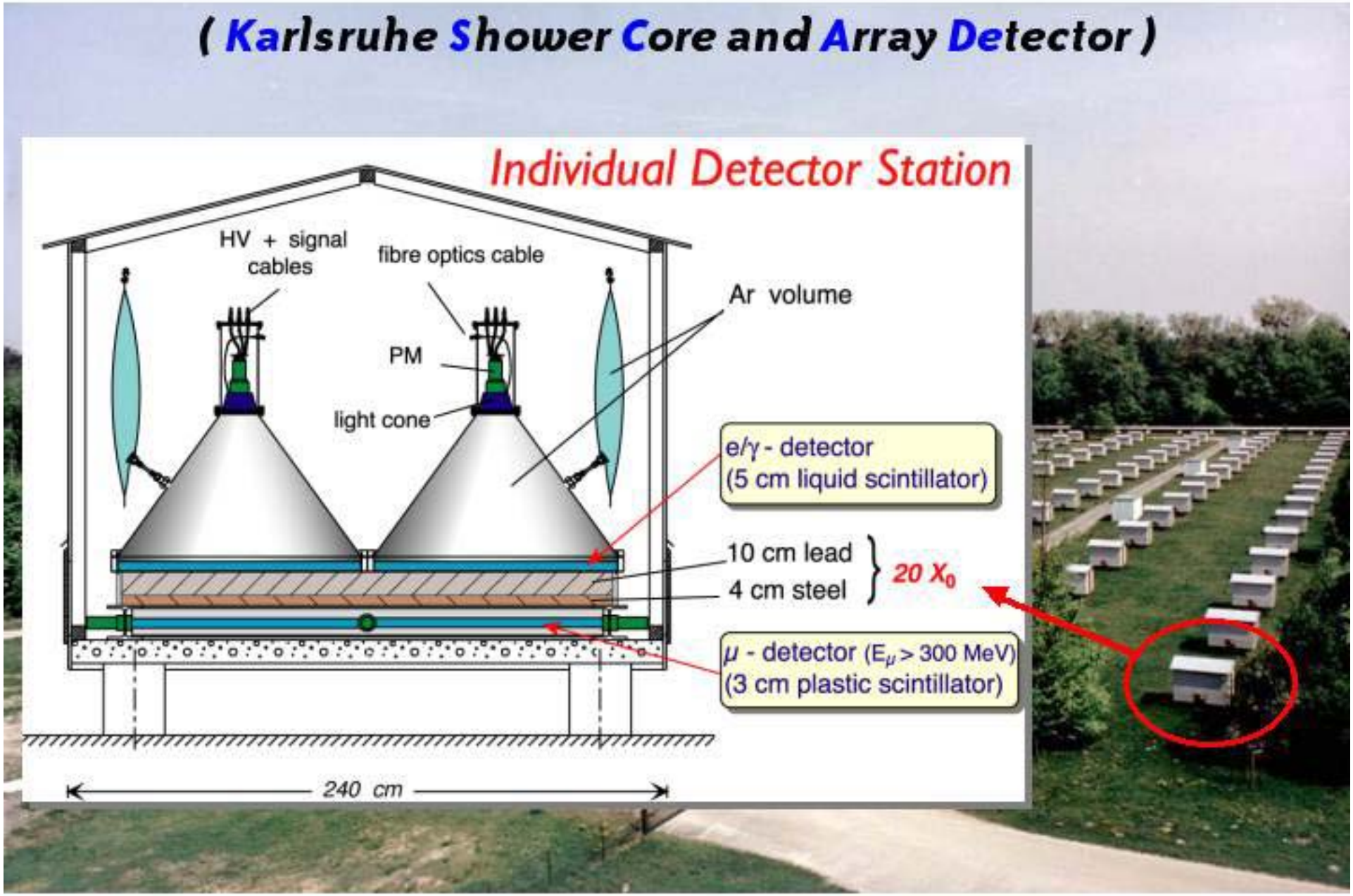
Needed: Energy Spectra
Selected by Mass Groups

Measurement of High-Energy CRs

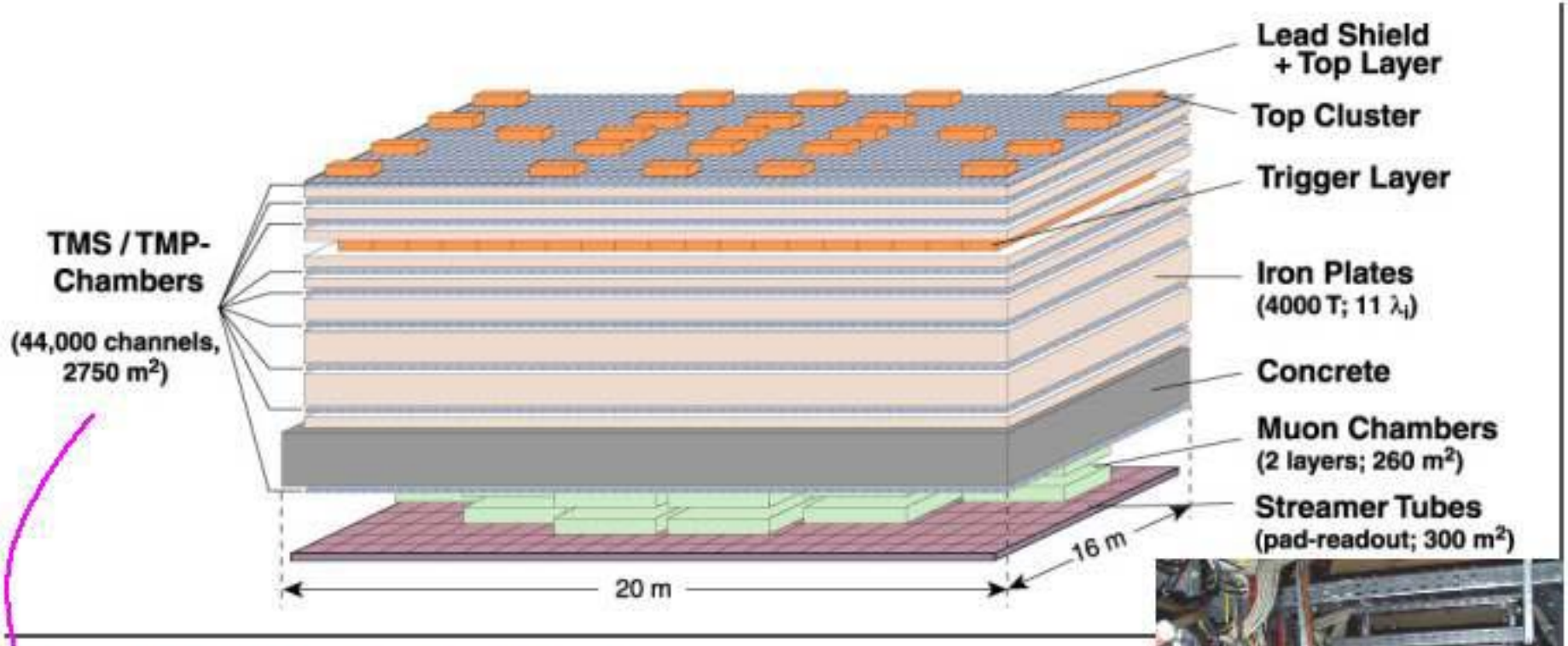


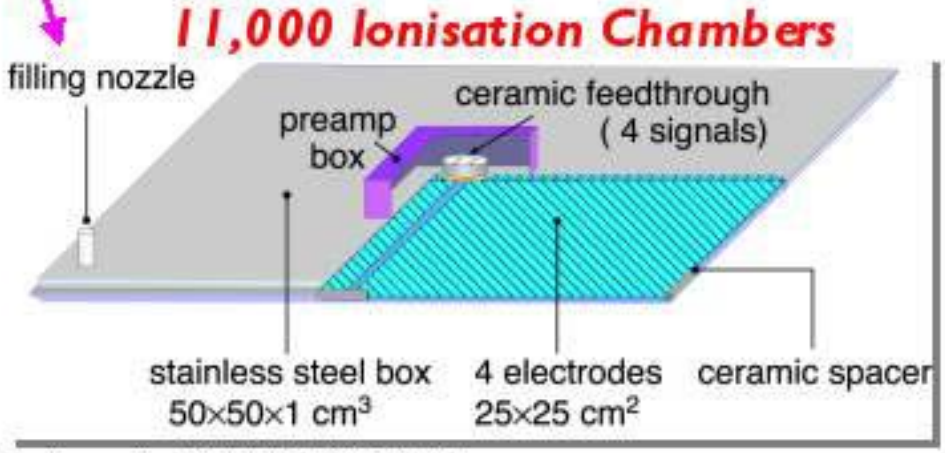
KASCADE

(Karlsruhe Shower Core and Array Detector)



KASCADE Central Detector

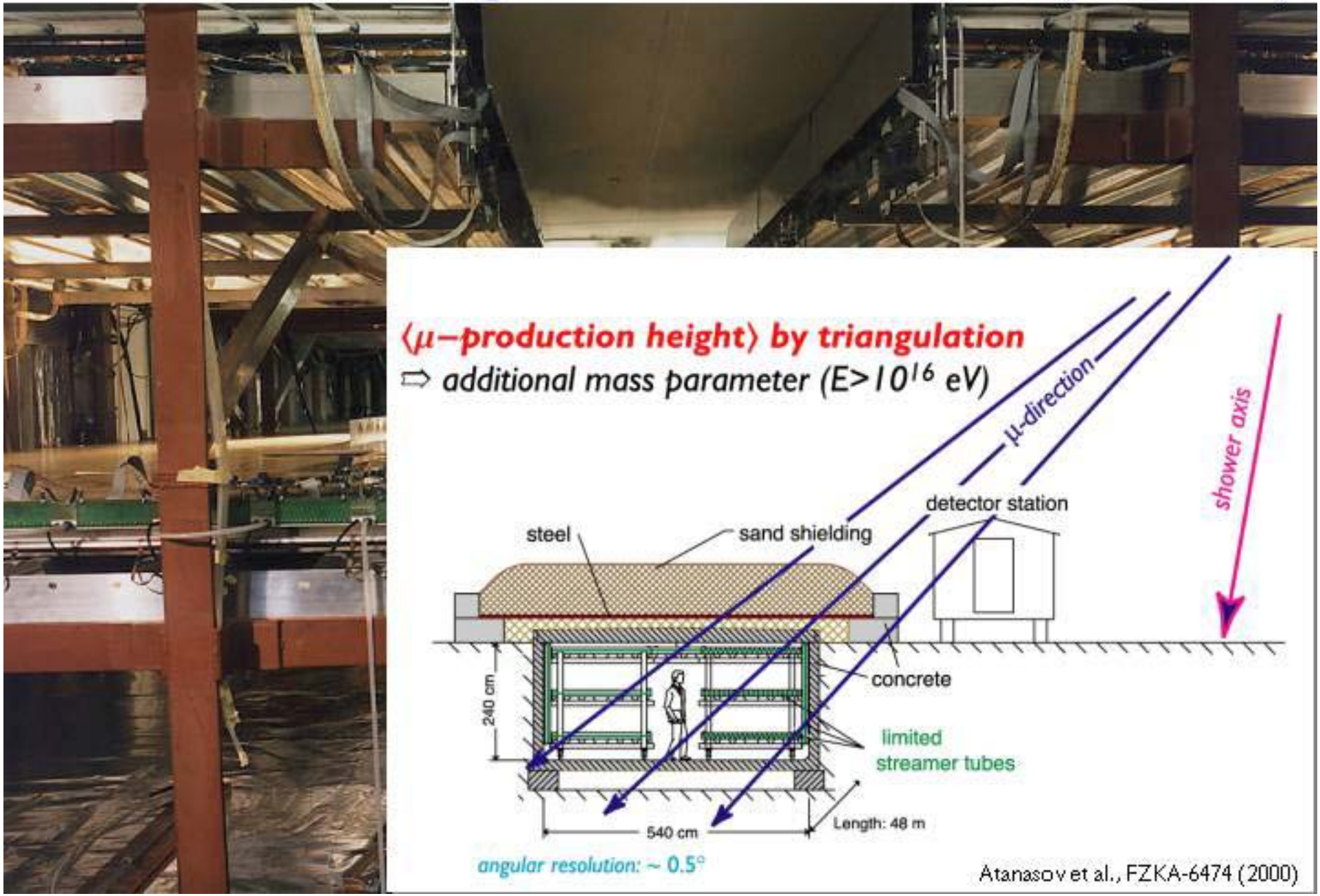




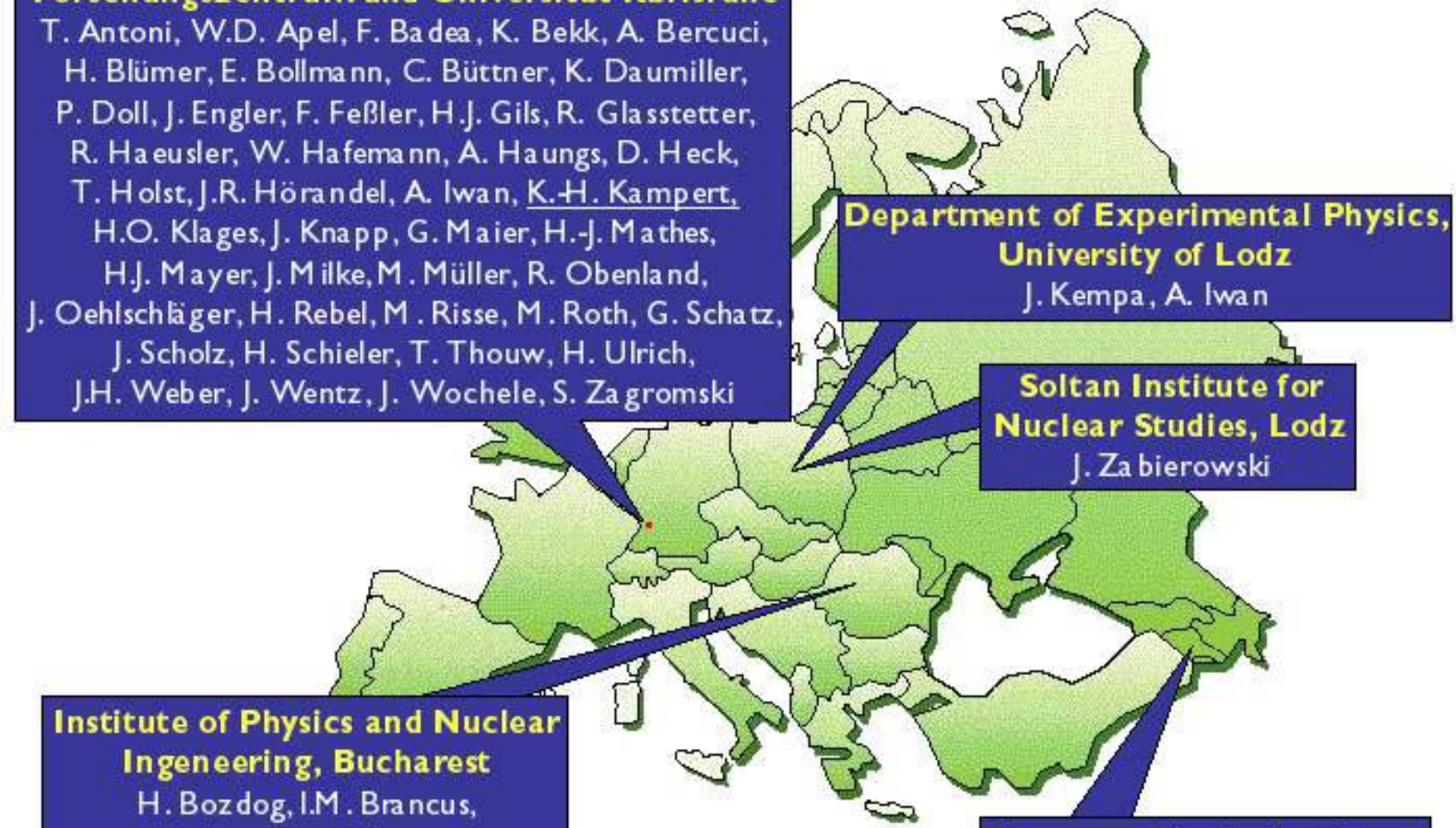
J. Engler at al., NIM A427 (1999) 528

Muon Tracking Tunnel

$(50 \times 5.5\ m^2)$



KASCADE Collaboration



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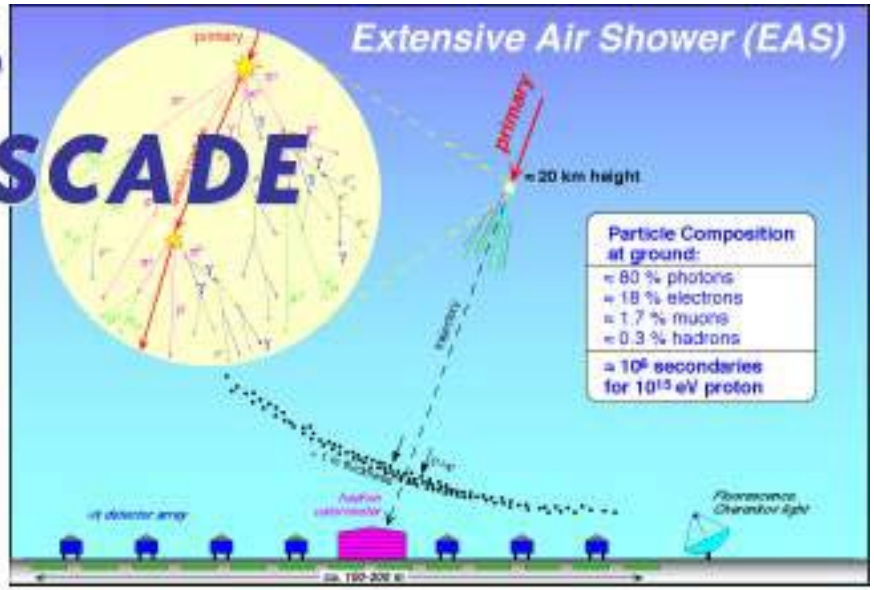
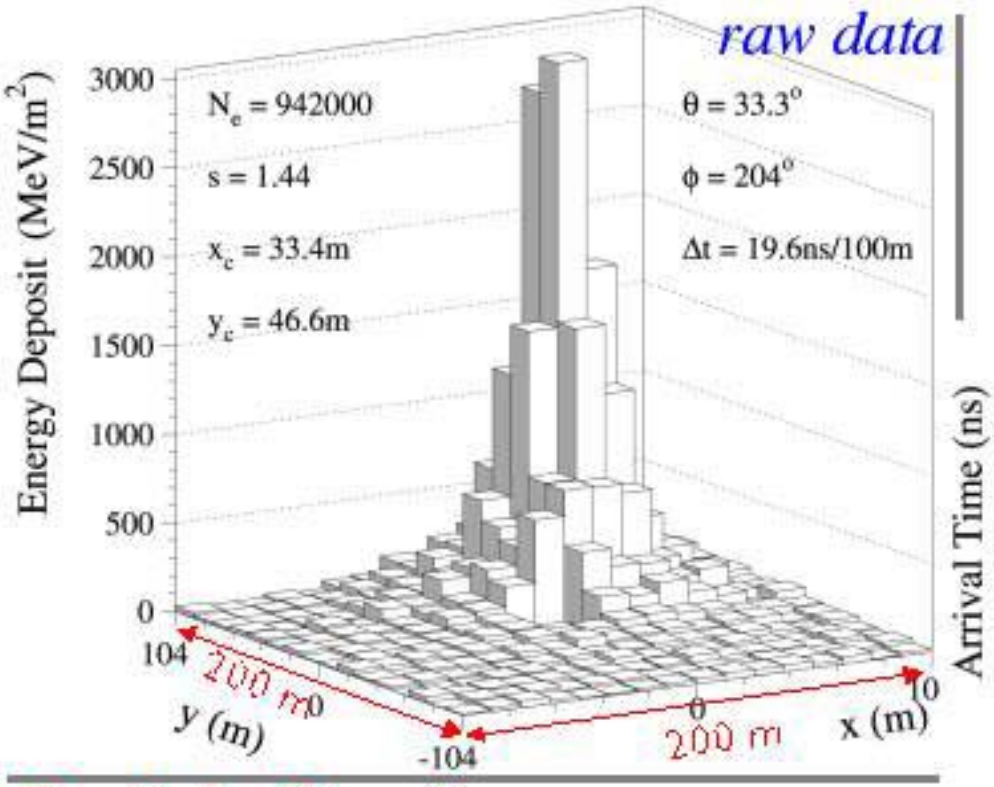
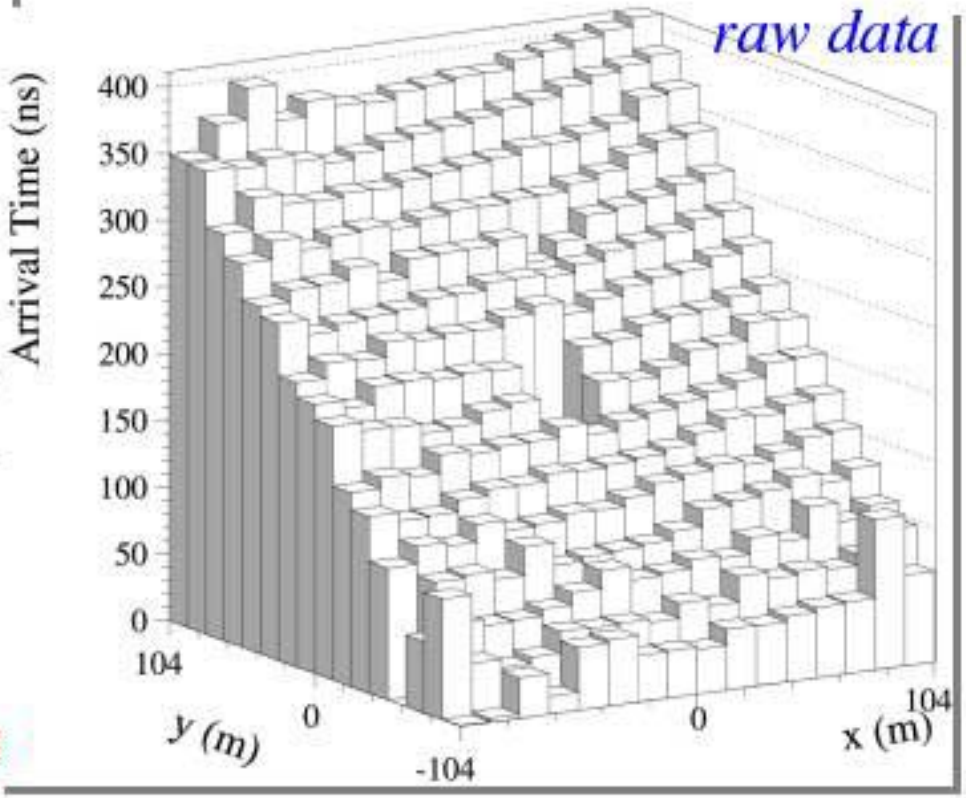
Single EAS as seen by e/γ - Detectors in KASCADE





Particle Density



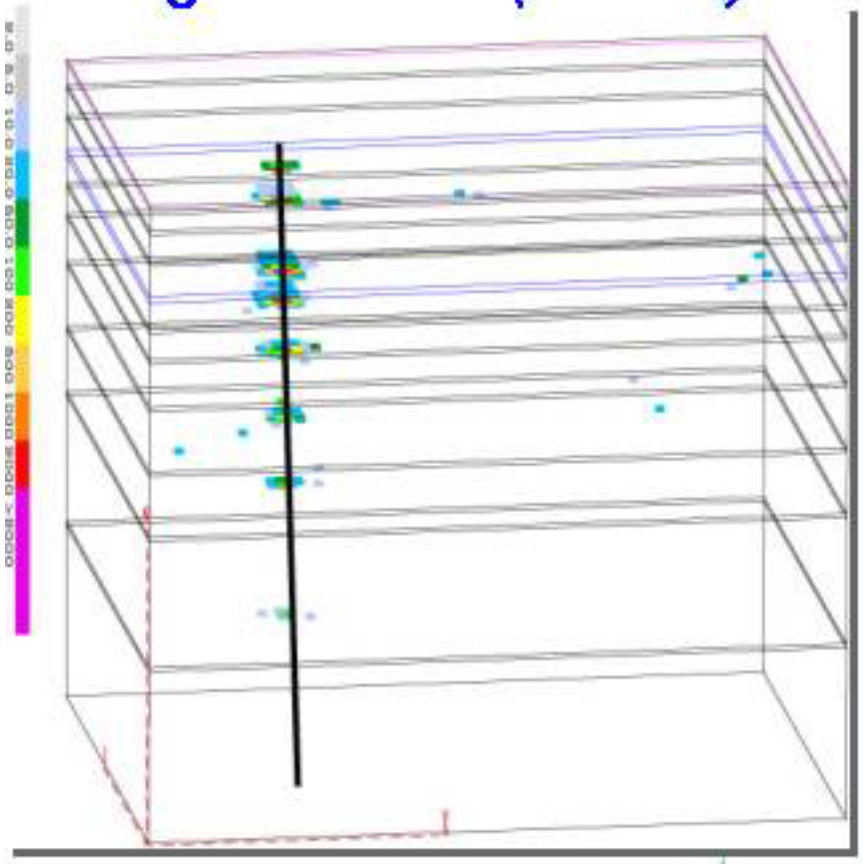
Arrival Times

(200 x 200 m²)

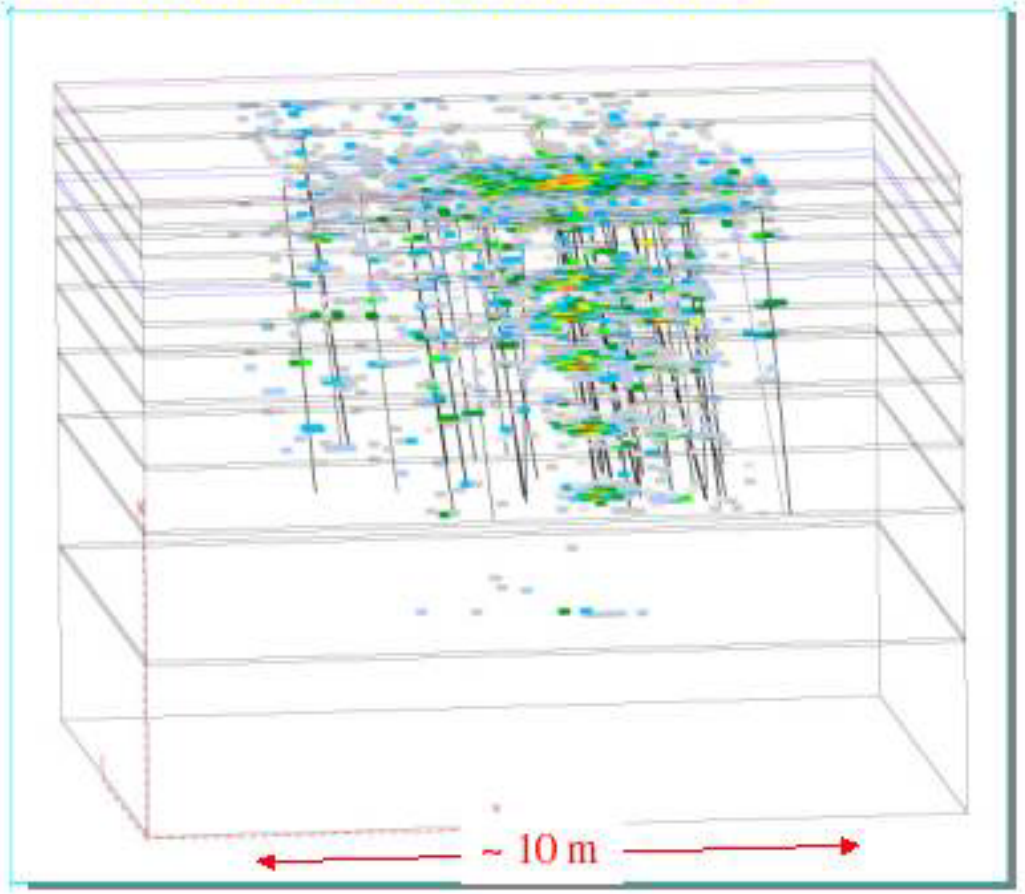
$E_0 \approx 10^{16}$ eV

Single Events in Calorimeter...

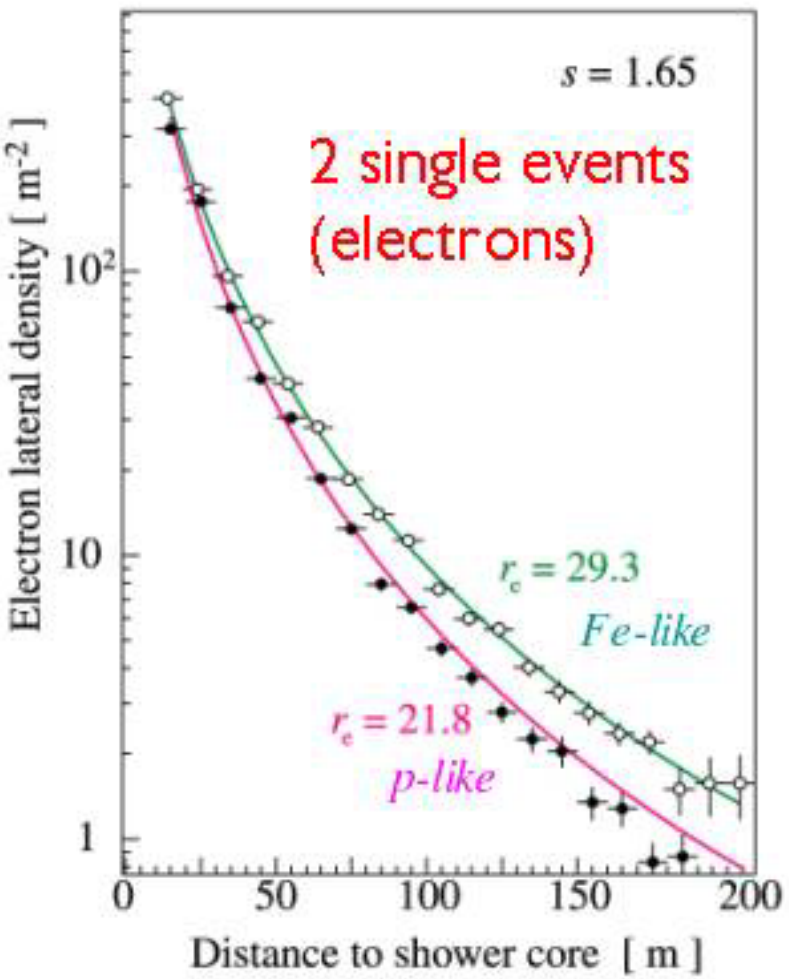
Single Hadron (21 TeV)



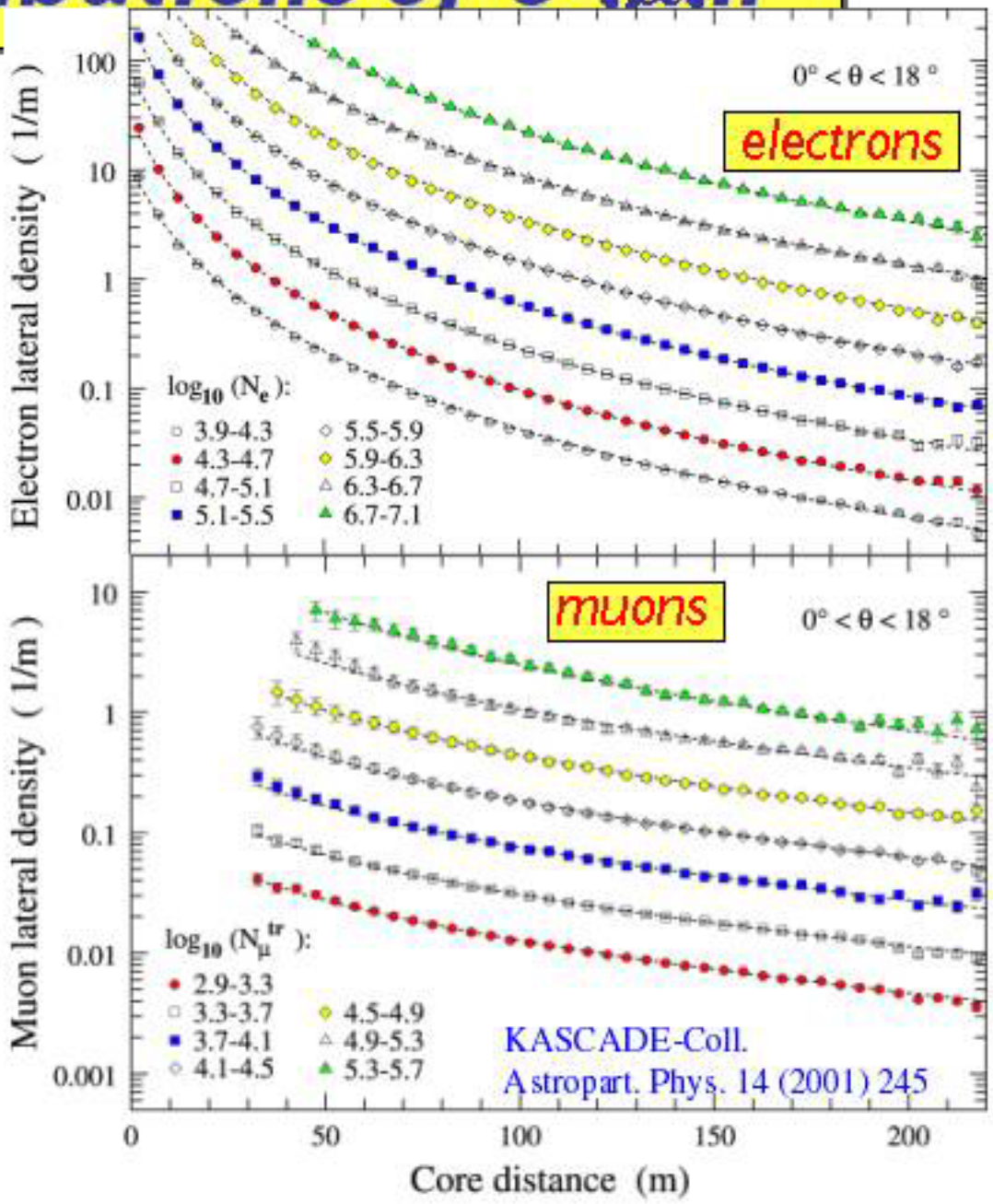
Hadrons in Shower Core



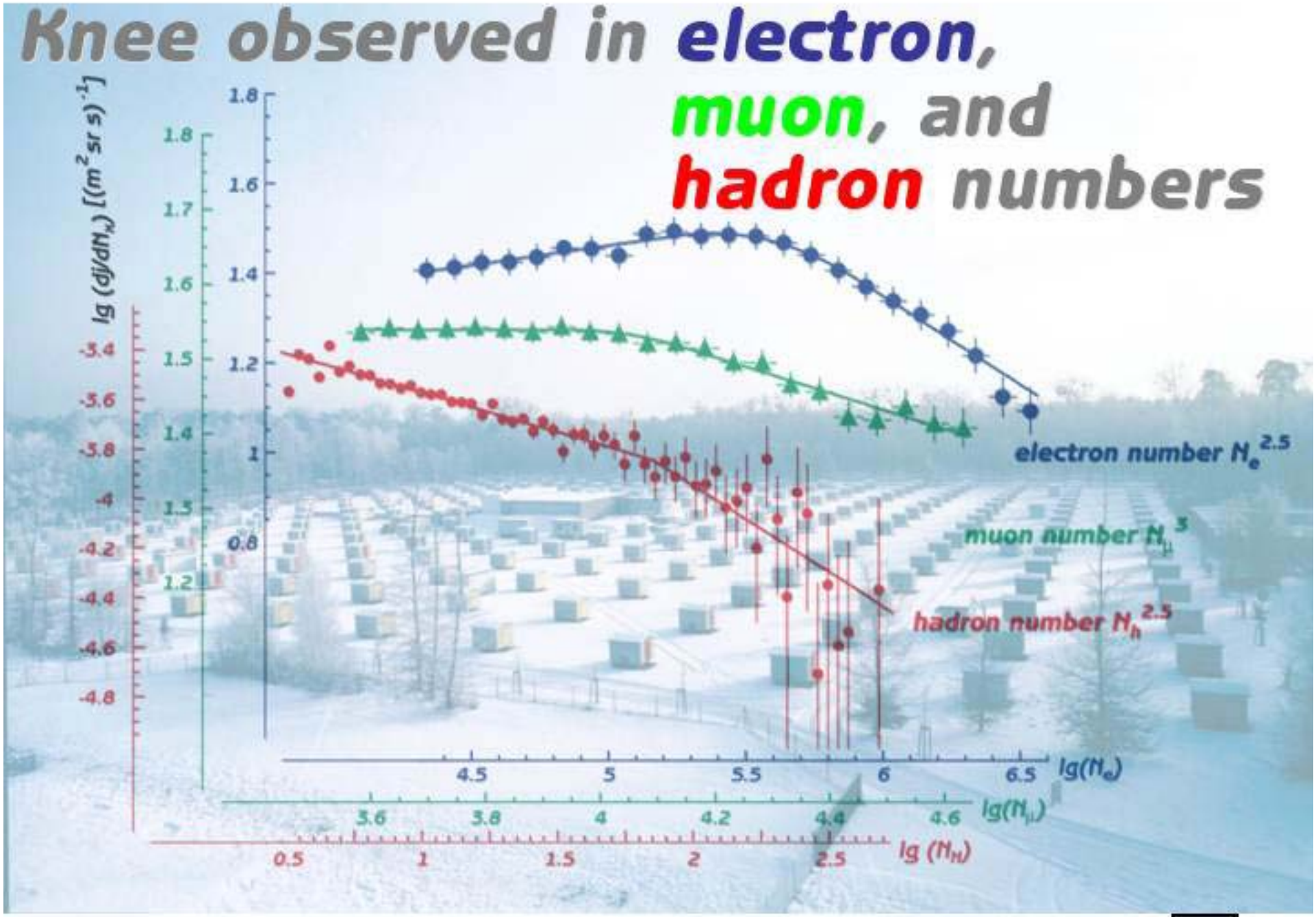
Lateral Distributions of $e^{\pm}, \mu, h$



$$2\pi \cdot \int_0^{\infty} \rho_{e,\mu,h}(r) \cdot dr = N_{e,\mu,h}$$



Knee observed in electron, muon, and hadron numbers



KASCADE X-mas Card '98

Note:

- ***Lateral Distributions***
- ***Shower Size Spectra***
  (Flux + Indices + Knee-Position)
- ***Arrival Time Distributions***
- ....

= direct observables

But:

Energy and Mass assignments of primary particle

= indirect observables

i.e. require comparisons to

EAS Simulations

...thus depend on hadronic interaction model

From Shower-Size to Energy and Mass

Crude Estimate:

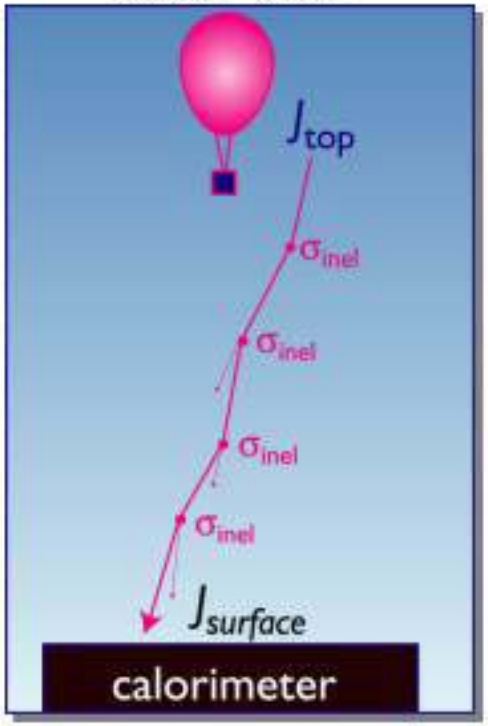
$$\log E \sim a \cdot \log N_\mu + b \cdot \log N_e$$

$$\log M \sim \log N_\mu \,/\, \log N_e$$

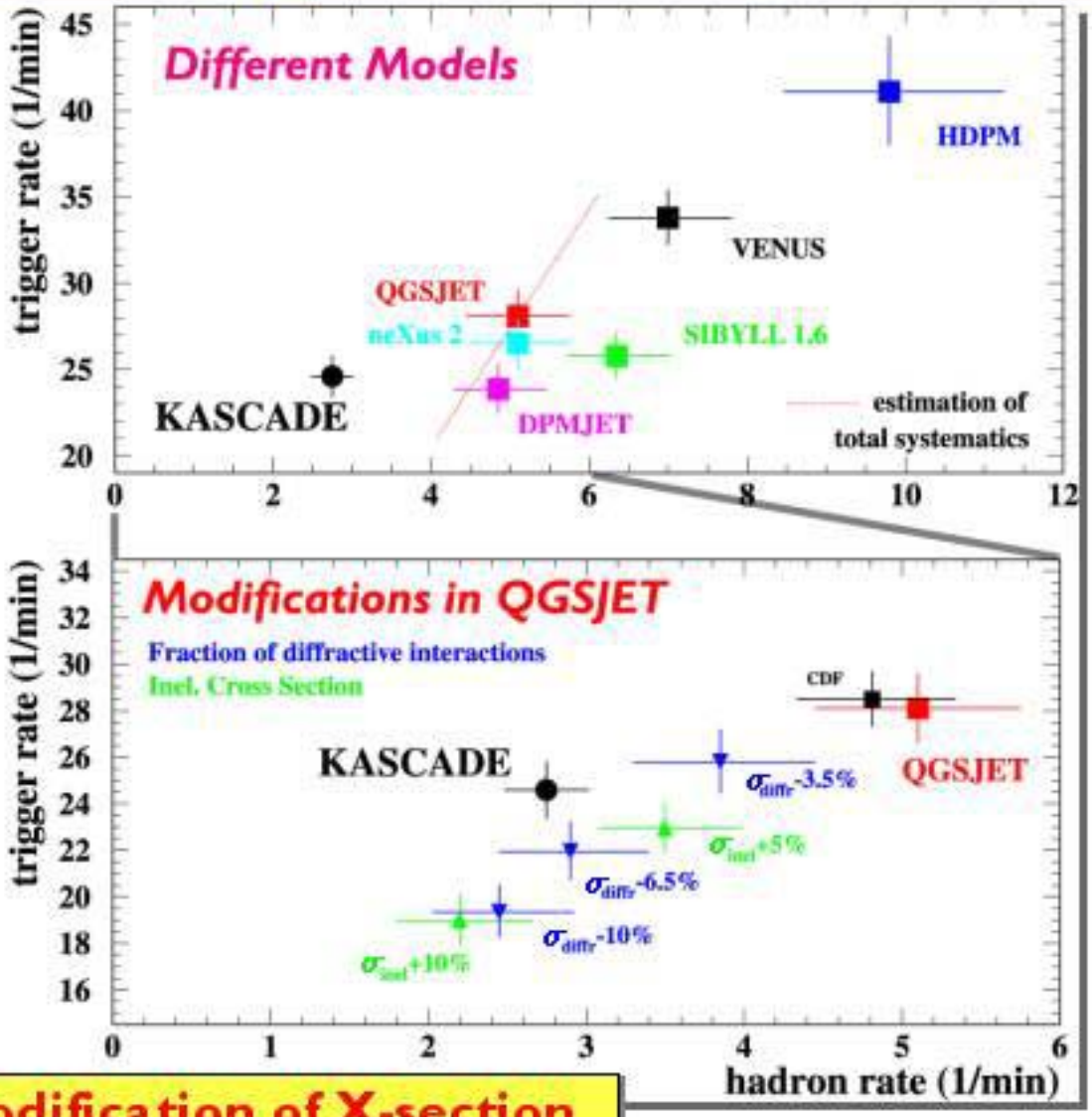
Calibration parameters to be determined from EAS simulations

"Precision" test of Interaction Models by muon & hadron trigger rates in calorimeter

Basic Idea



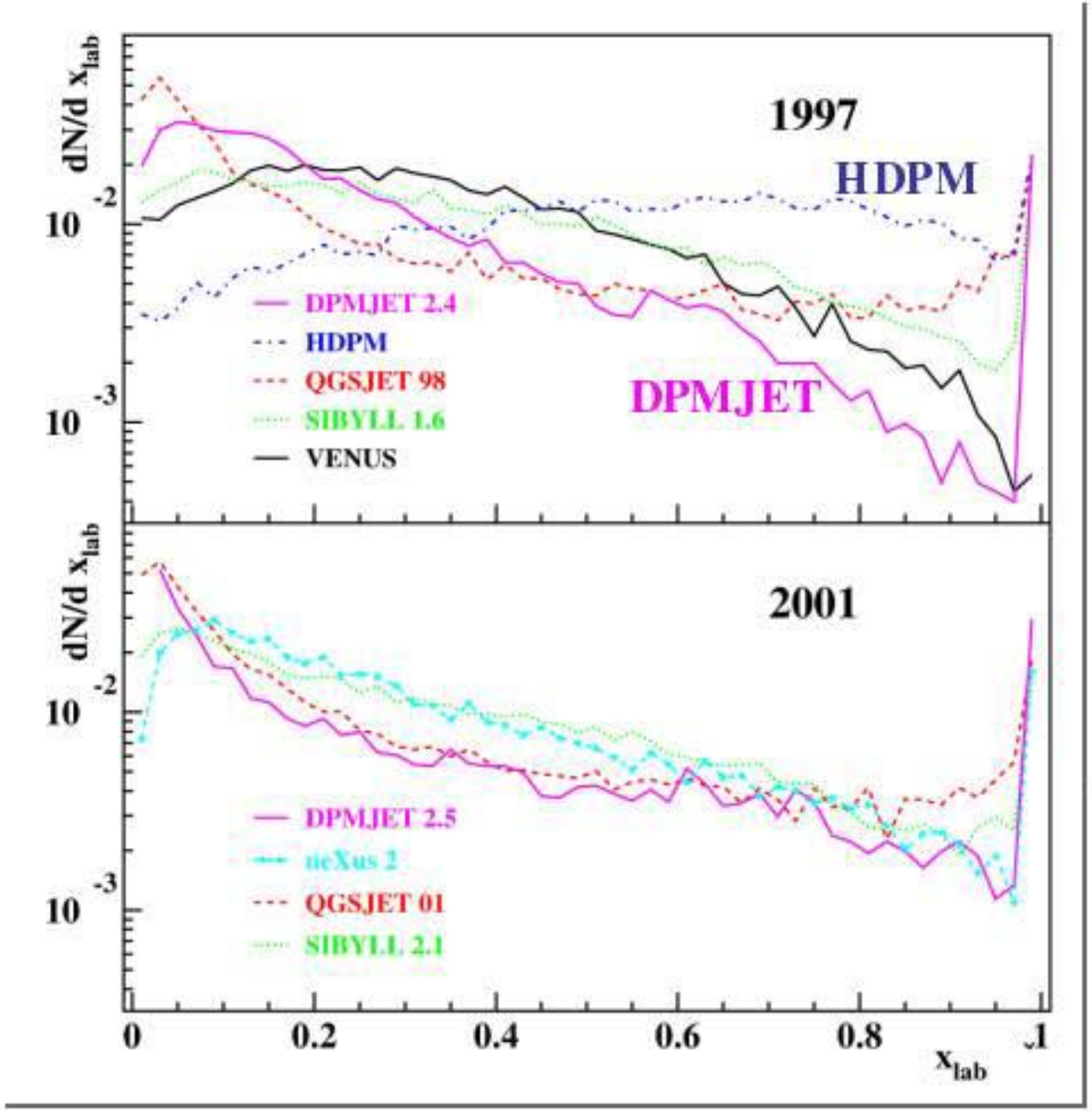
Require ≥ 9 muons;
Determine fraction of events with reconstructed hadrons (E_h > 90 GeV)

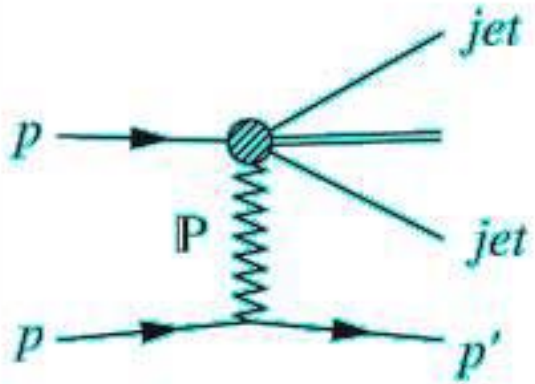


Data sensitive to 1% modification of X-section a/o abundance to diffractive interactions

M.Risse, Doct. Thesis Uni-KA
J. Phys. G27 (2001) 1785

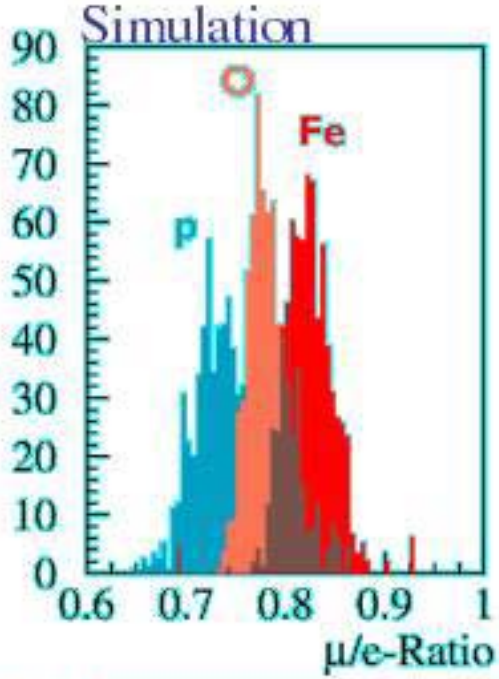
Trigger Rates ↔ Diffractive Interactions





CORSIKA
Simulation
***p+N* (10^{16} eV)**

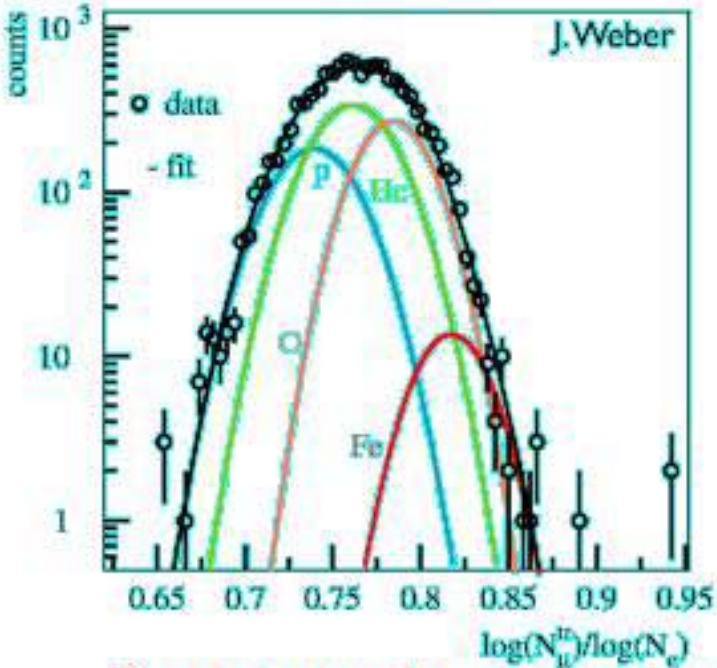
Reconstruction of energy and mass...



Chemical Composition

Large number of EAS-Observables:

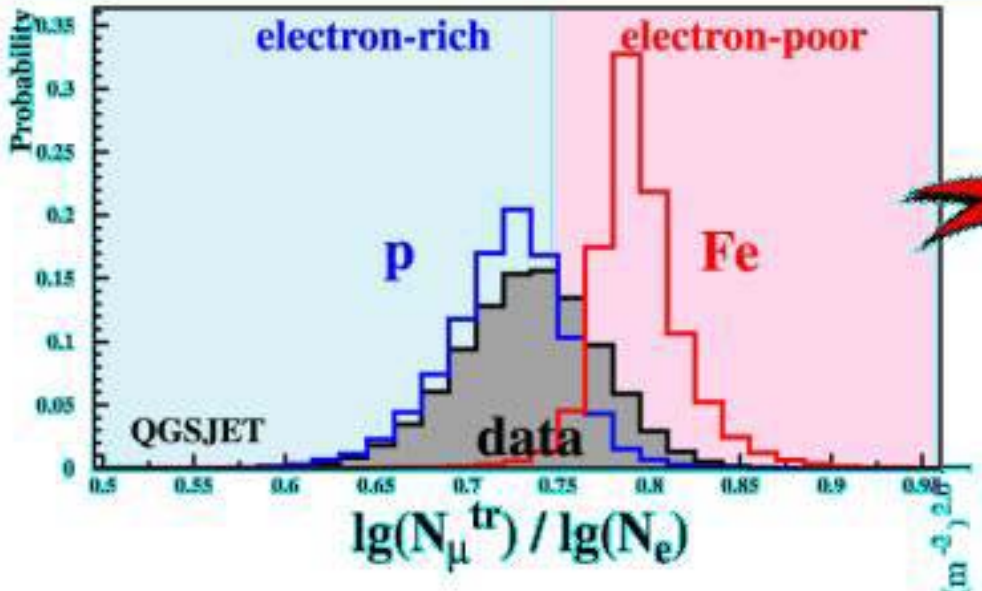
- muon production height (X_{max})
- lateral particle distributions ("age")
- 'features' of hadronic shower core
- muon/electron ratio
- …

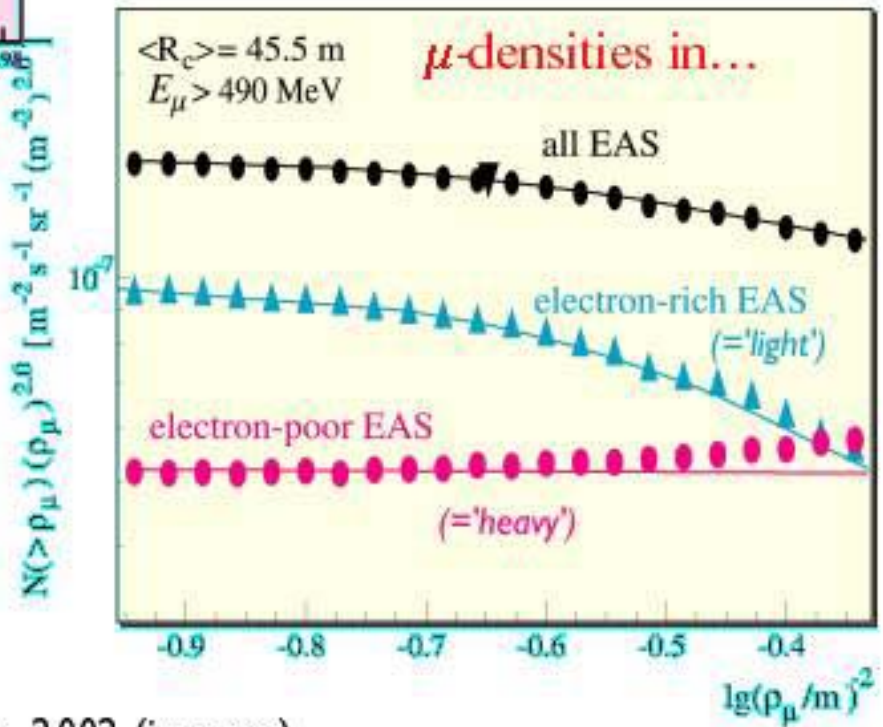


Reconstructed mass-fractions

☞ ***Good agreement between data & MC***
☞ ***more info than just mean mass;***
☞ ***'mixed composition' required***

μ-density for e-rich and e-poor showers





Virtually model independent result:

Knee is a feature of light primaries !

KASCADE, Astropa rt. Phys. 2002 (in p ress)

Advanced Analysis Techniques

Account for

- EAS fluctuations
- Interrelation of Energy & Mass Observables
- Allow for Multi-Parameter Analyses incl. their correlations

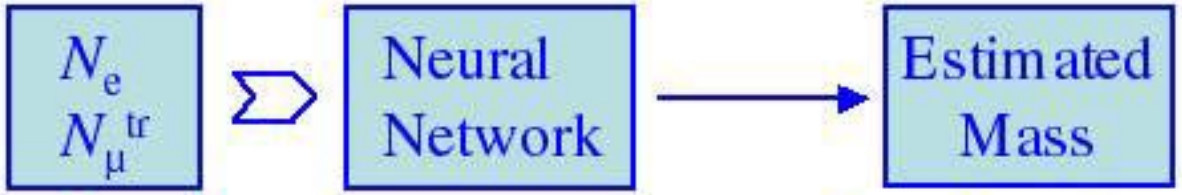
KASCADE:

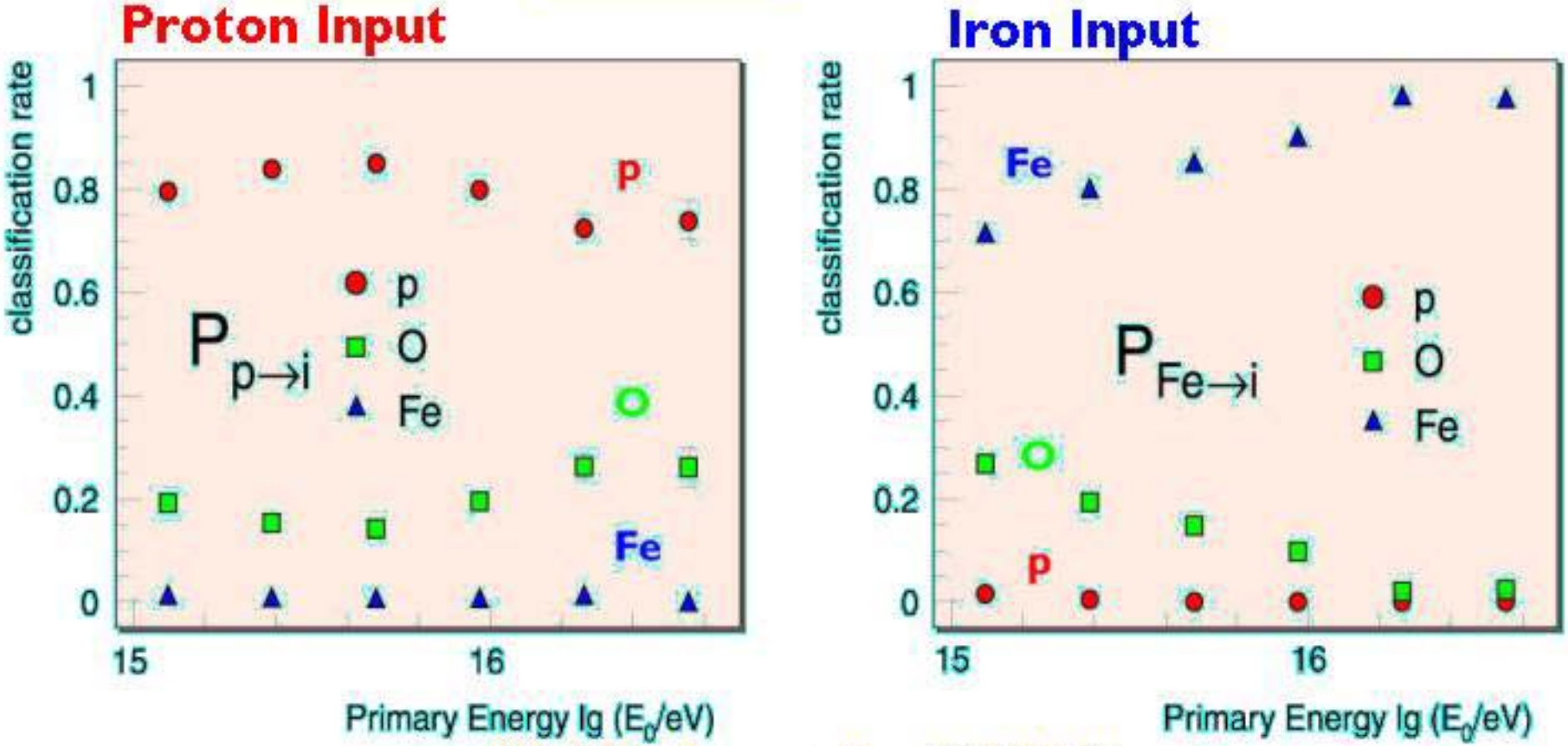
- Non-Parametric Bayesian classifiers } event-by-event
- Neural Networks
- Unfolding techniques } "inclusive"

Note, multi-parameter analyses allow for consistency checks
(→ interaction models)

K.-H. Kampert, J. Phys. G27 (2001) 1663

Neural Net: Quality Check of Mass Reconstruction



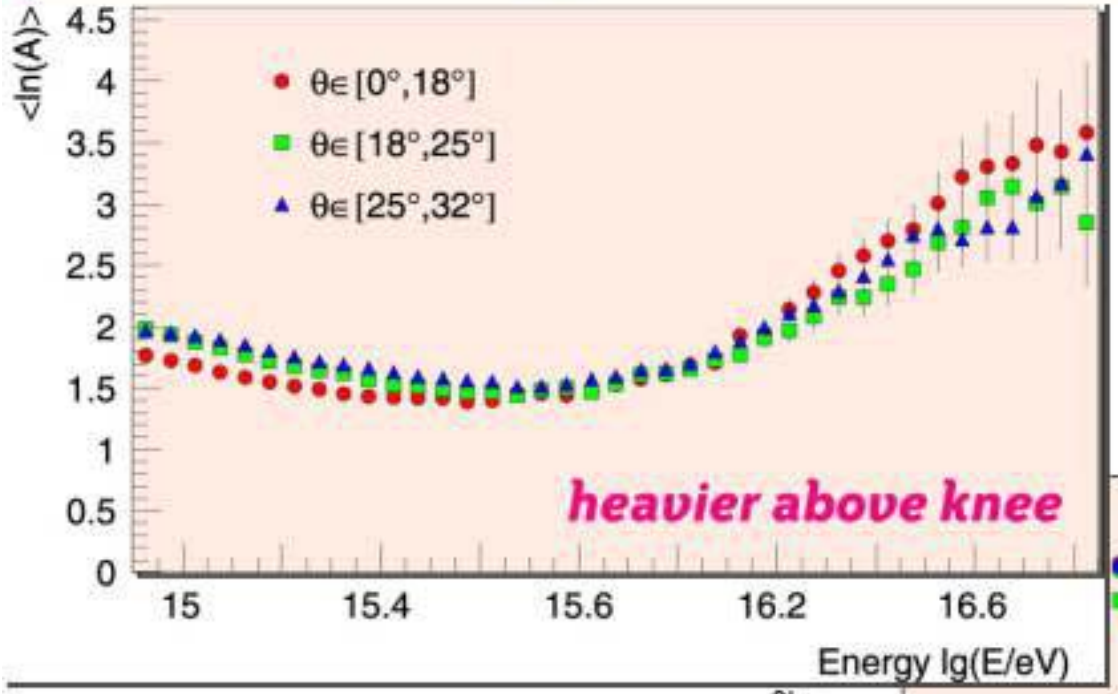


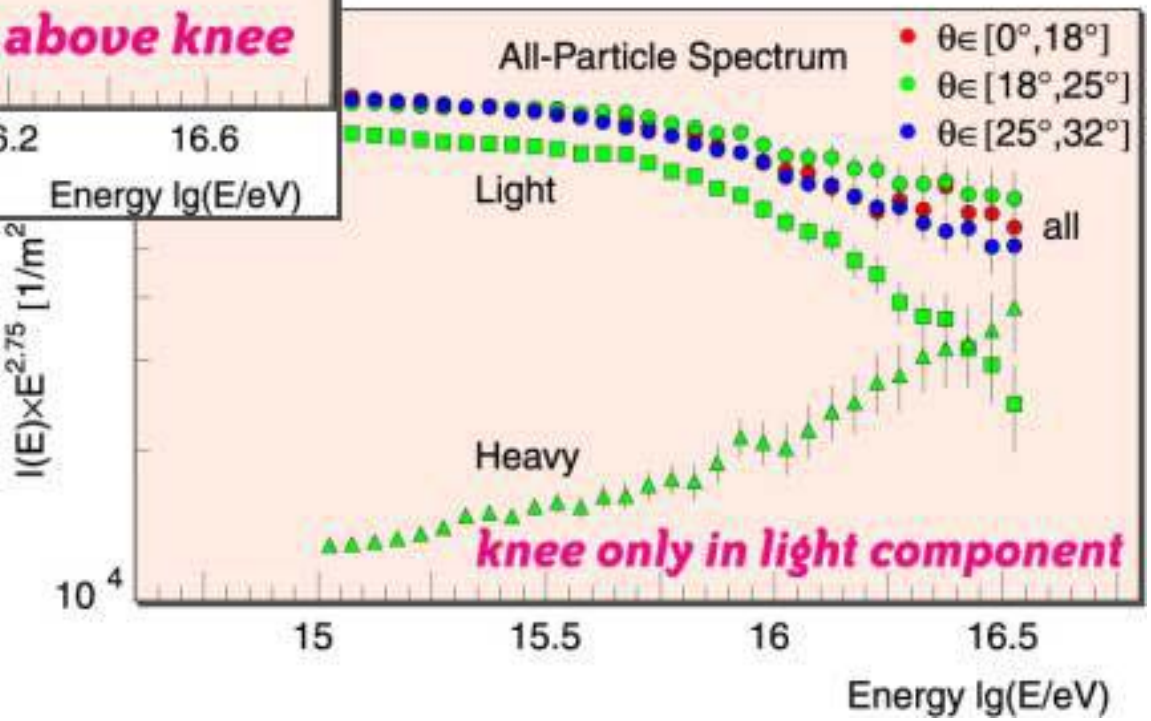
KASCADE, Astropa rt. Phys. 16 (2002) 245

Neural Net: Energy and Mass Estimation

KASCADE, Astropa rt. Phys. 16 (2002) 245

$$\langle \ln A \rangle = \frac{\sum \omega_i \cdot \ln A_i}{\sum \omega_i}$$





Unfolding Technique: $N_e \otimes N_\mu \Rightarrow E_p, E_{Fe}$

$$y_i = \sum_A \int_0^\infty k_A(\lg E \rightarrow \lg N_{e,\mu}) \cdot j_A(\lg E) \cdot d\lg E$$

$N_e N_\mu$ shower distributions

CORSIKA + GEANT simulation

differential E-distr. of primary A

Formulated as Matrix-Equation:

$$y_i = \sum_A K_{ij}^A \cdot x_j^A \quad \text{with } x_j = j_A(\lg E_j)$$

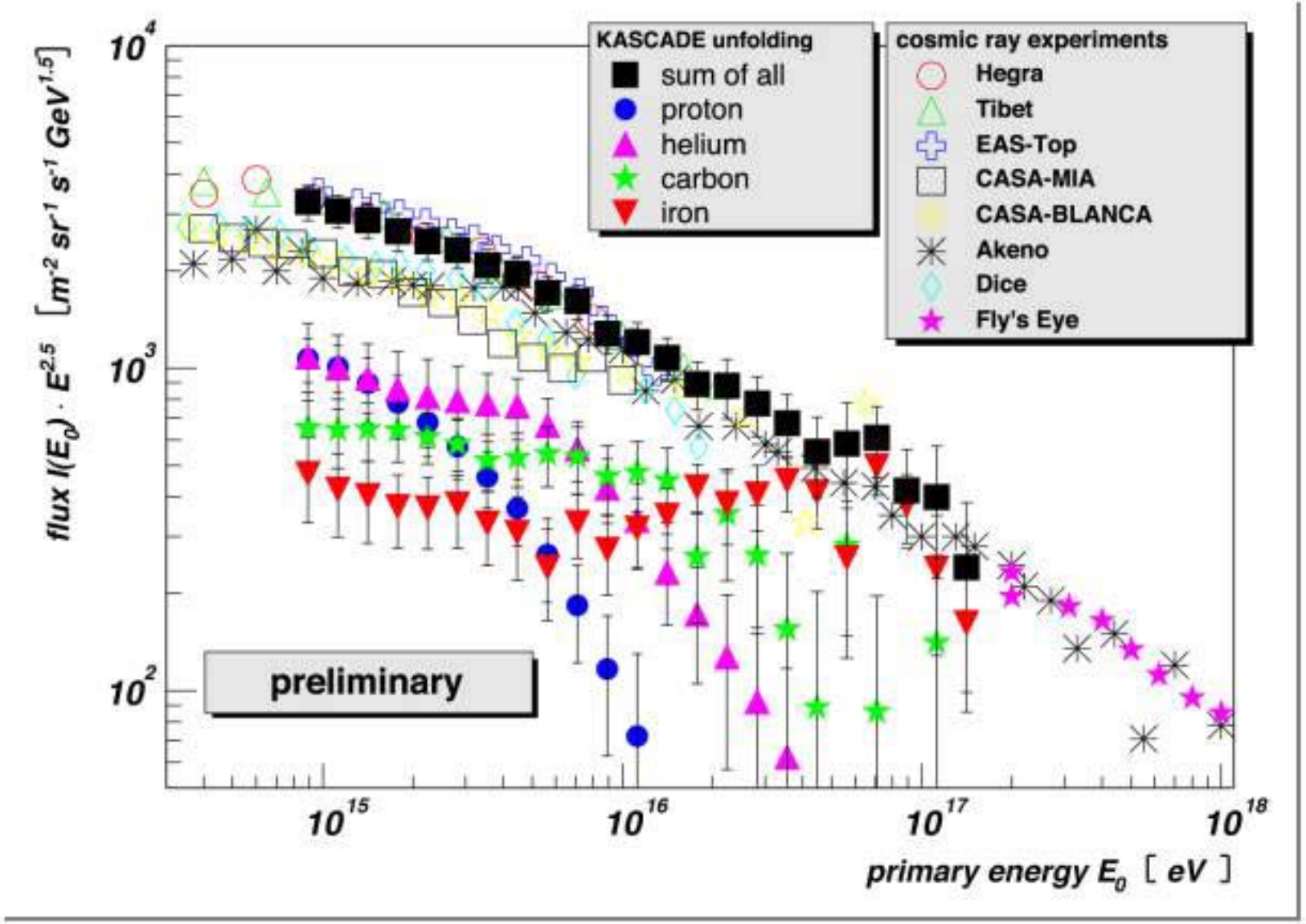
Data Input:

- electron size distributions
- muon size distributions

Unfolding Output:

- Energy distributions of p, He, C, Fe

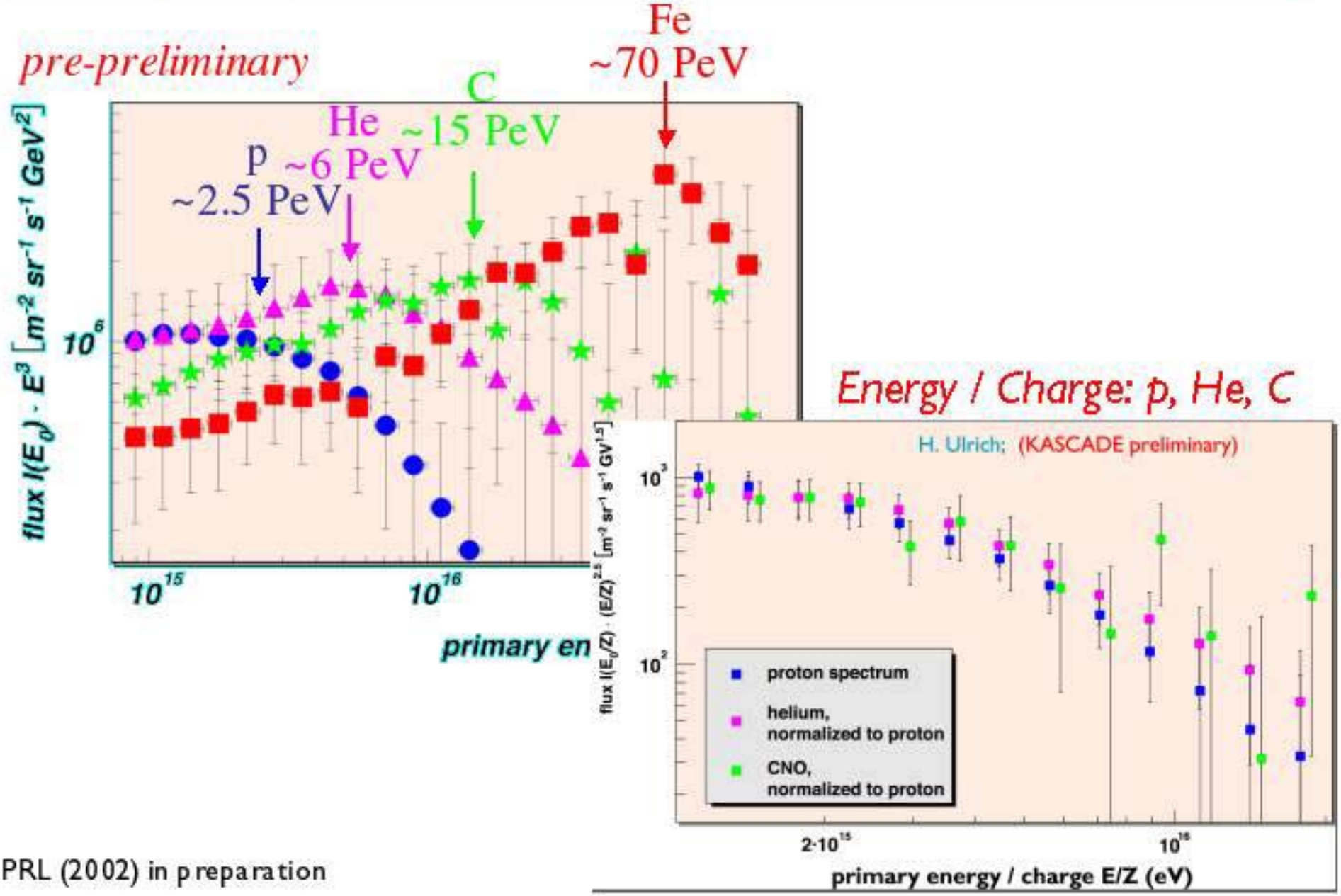
Reconstructed E-Distributions



PRL (2002) in preparation

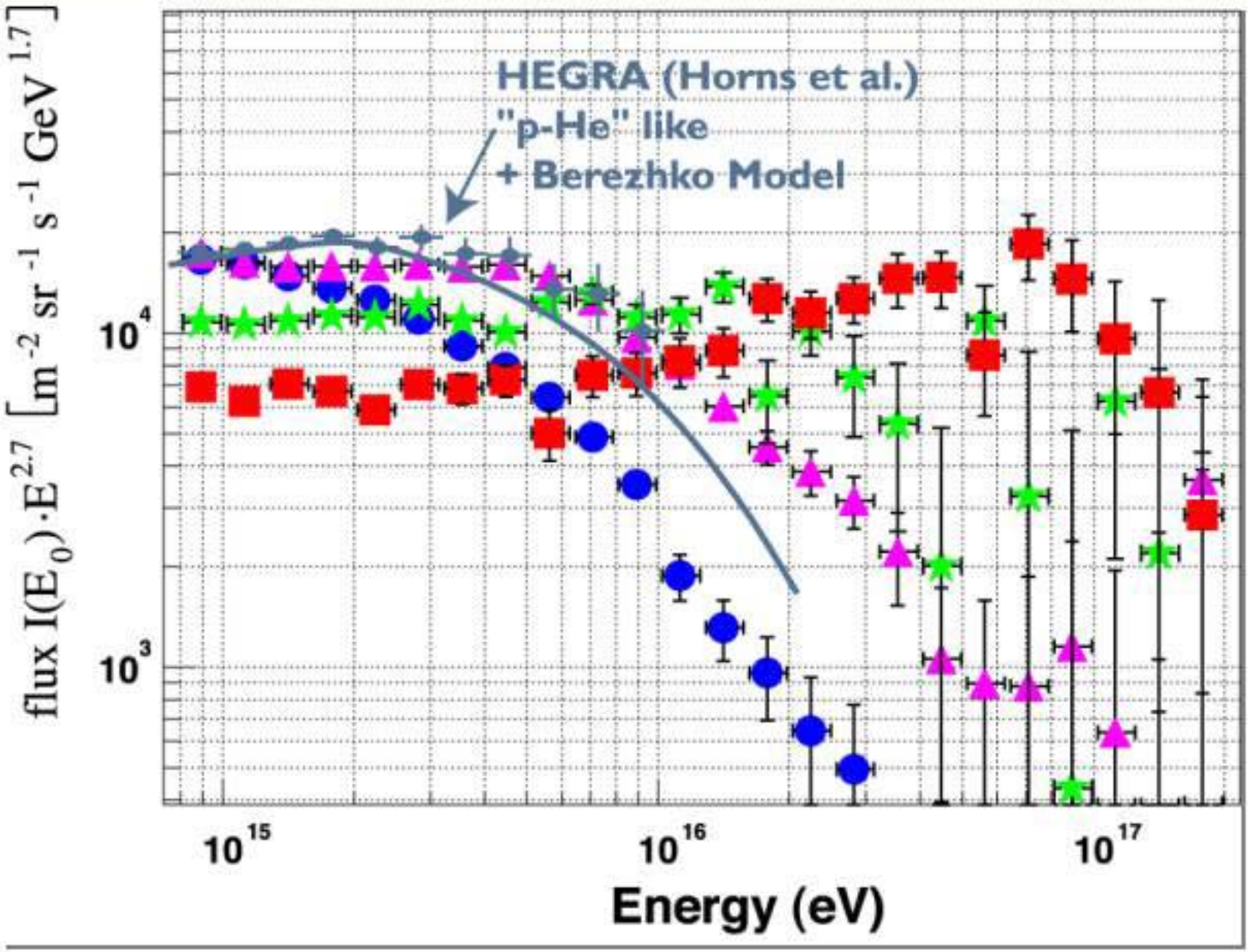
H. Ulrich, KASCADE; ICRC 2001, p97

Rigidity Scaling suggested by data



PRL (2002) in preparation

Comparison to HEGRA and models



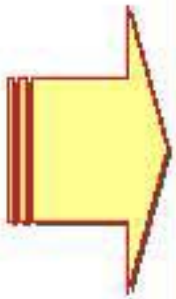
Summary ...

Major Step forward by KASCADE

- Restrictive tests of HE-interaction models

  by high energy hadrons

- Improvements in data analysis techniques



All Particle Energy Spectrum...

reasonable agreement among expts

Composition...

heavier above knee

Rigidity Effect...

observed for the first time

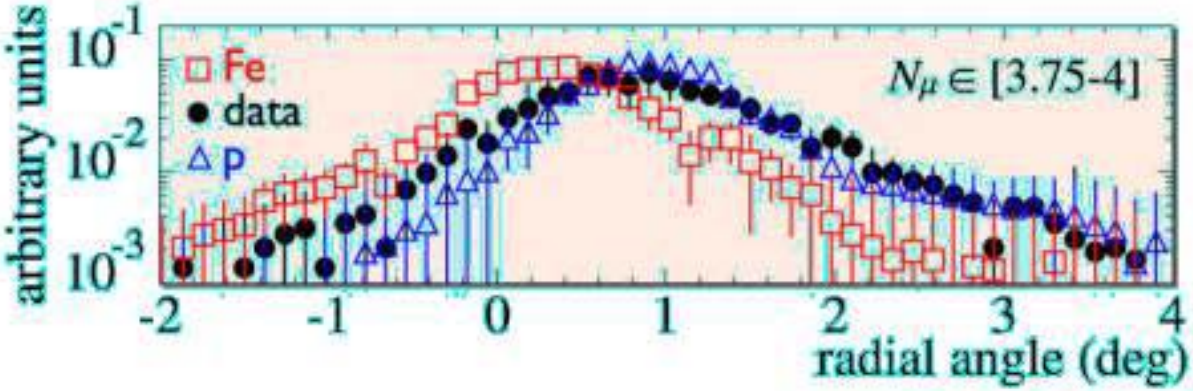
➨ *entering new era for tests of astrophysical models*

... and Outlook

What next ?

- ☞ More systematic studies needed (int. models, analys. techn…)
- ☞ Include & compare other observables

e.g. μ-production height

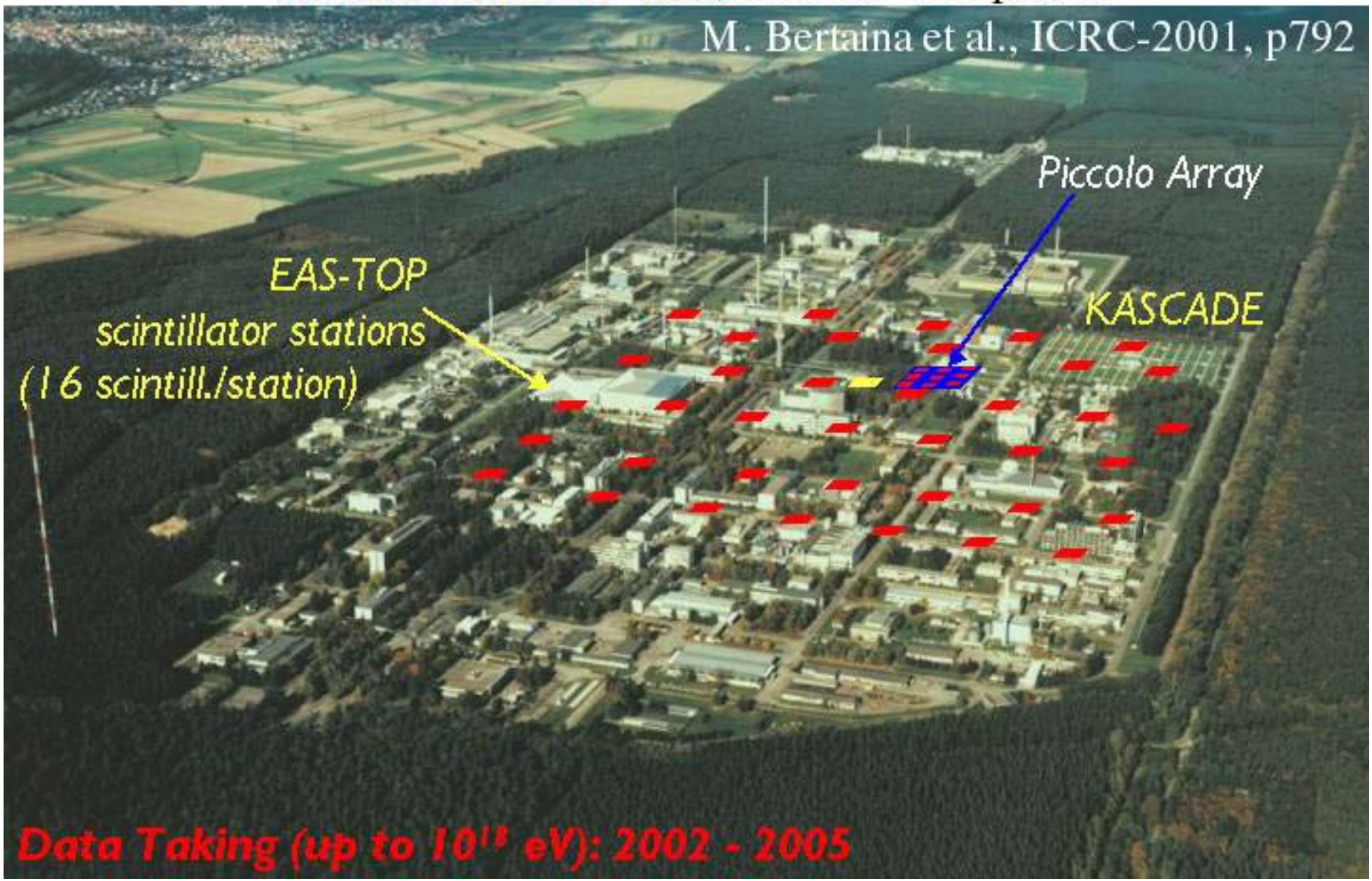


- ☞ Transition galactic → extra-galactic ? Study anisotropies
- ☞ **Verify Iron-Knee @ ~ 10^{17} eV** (i.e. measure up to 10^{18} eV)

KASCADE-Grande

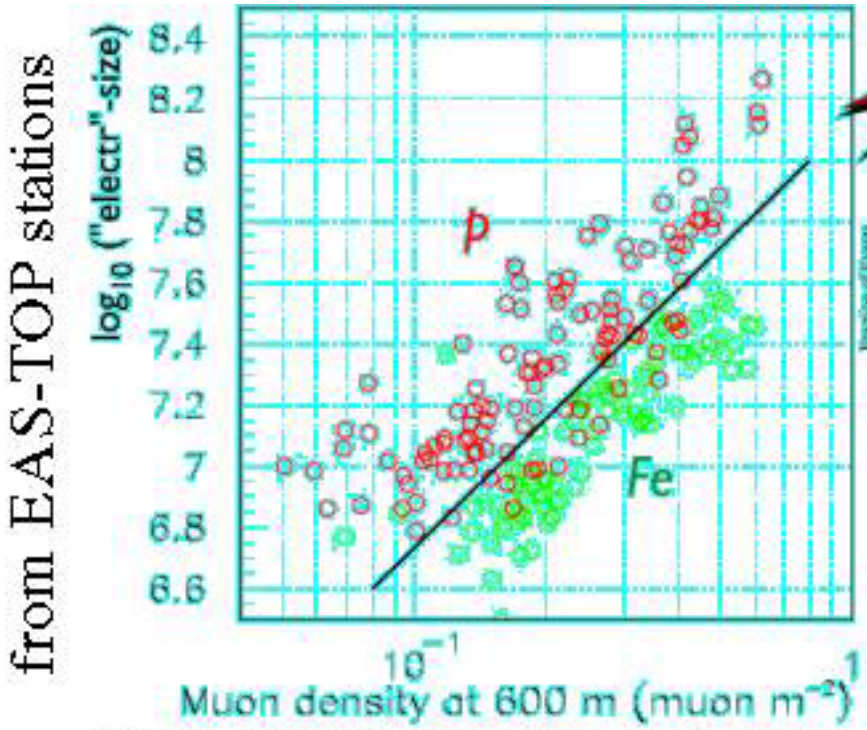
KASCADE-Grande @ FZK

38 Stations á 10 m^2 area; 0.55 km^2 acceptance

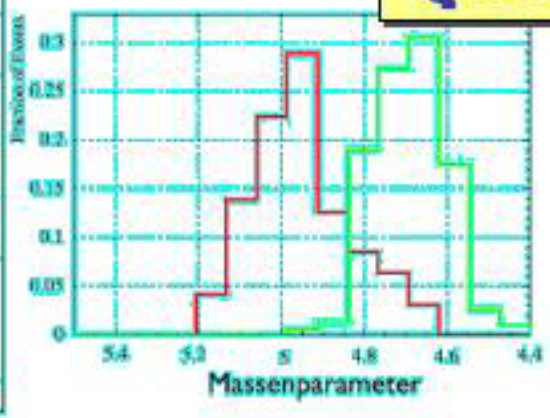


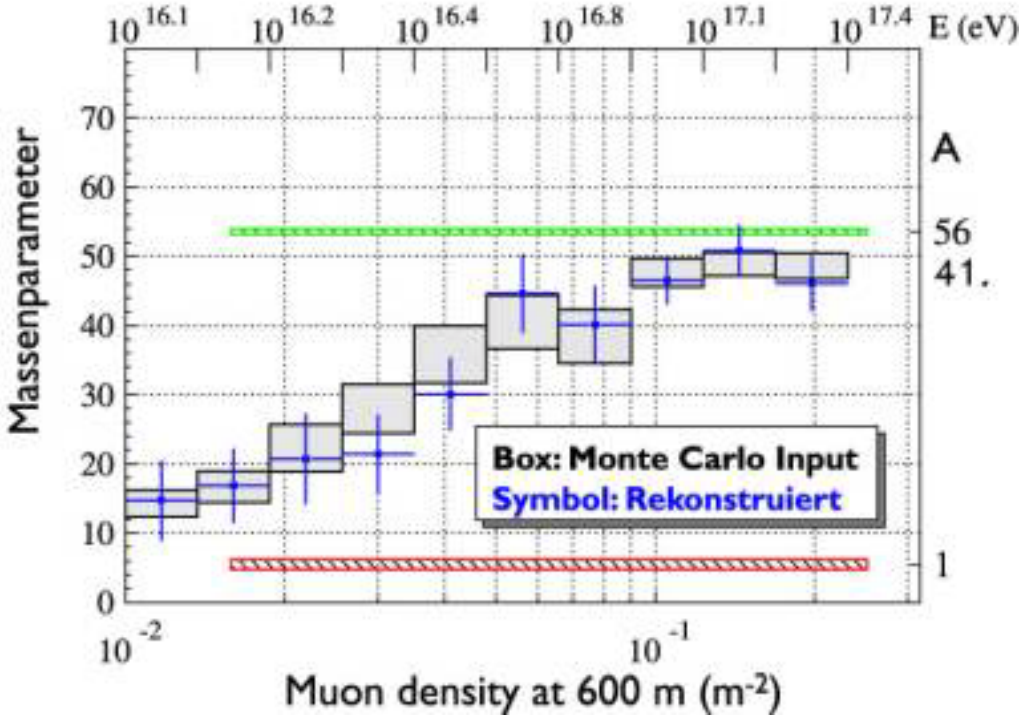
... and deployment @ FZK

Reconstruction Quality



from KASCADE μ-detectors



Bias-free reconstruction
of mass-composition

Additional Parameters:
μ-production height, ...