Measurement of high energy cosmic rays above 10 PeV with KASCADE-Grande

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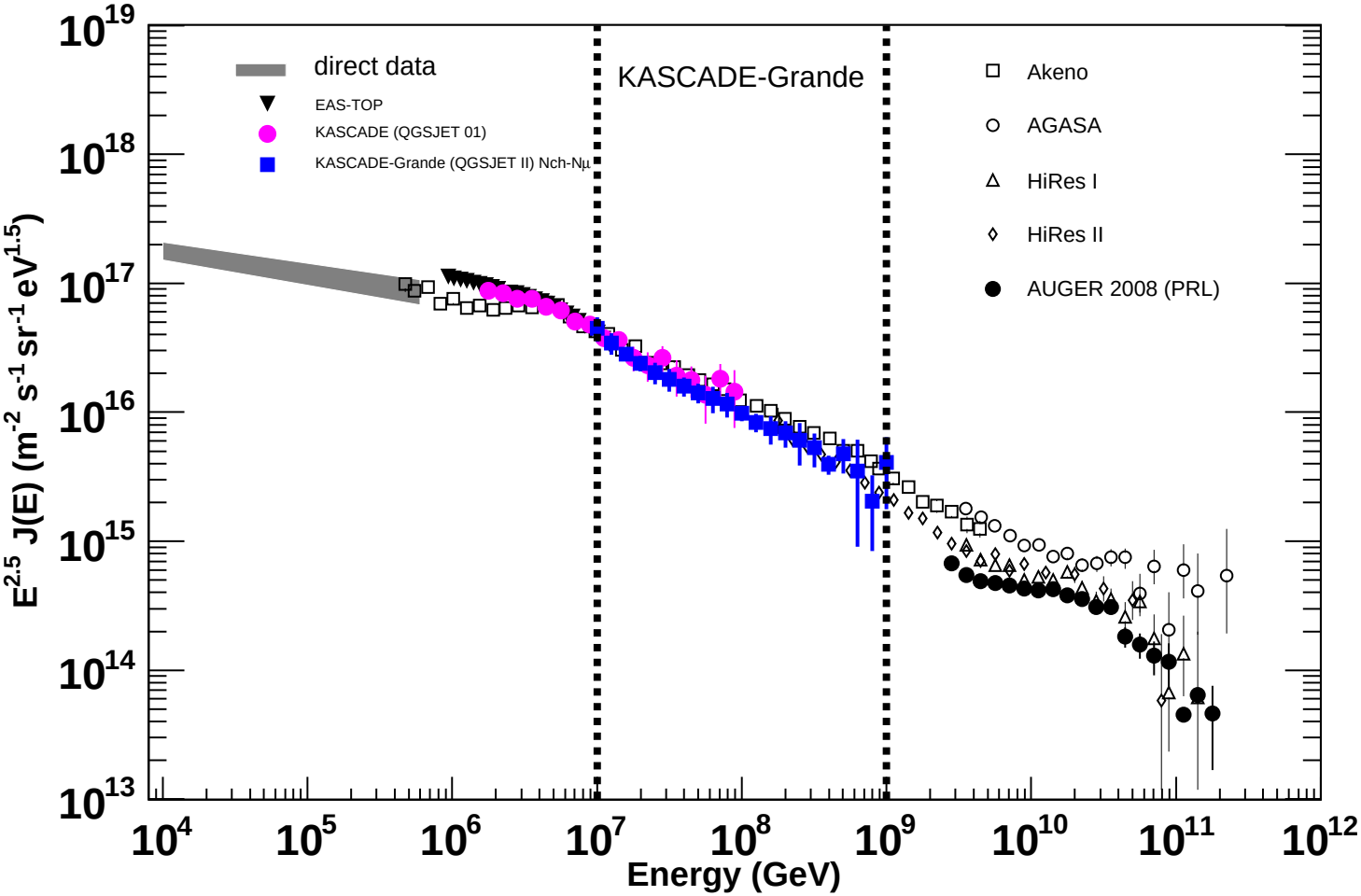
Outline

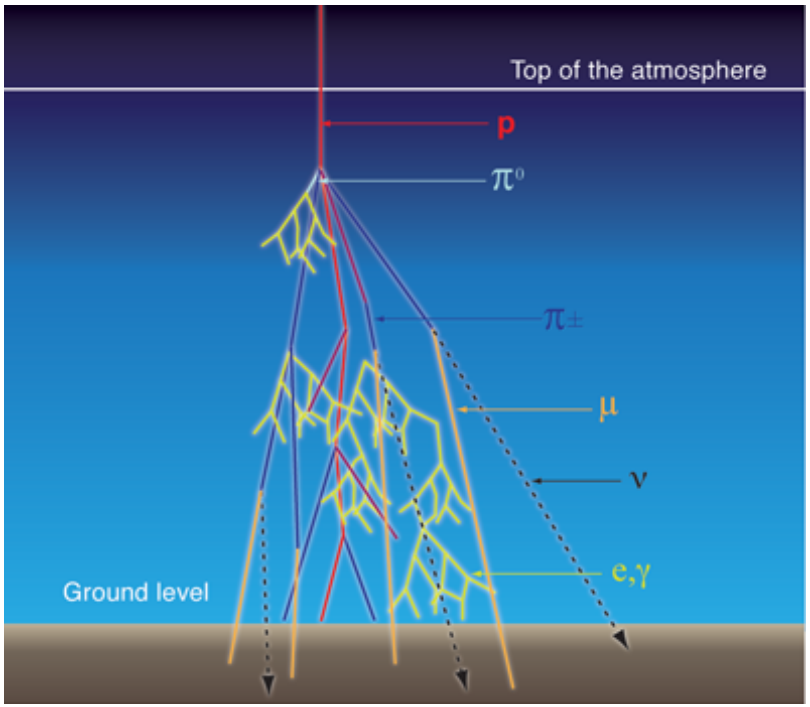
- overview of the KASCADE-Grande experiment
- air shower measurement and reconstruction
- cosmic ray spectrum
- composition study

Cosmic Ray Energy Spectrum



- break in the single elemental spectra at $E \propto Z \cdot E_{knee}$

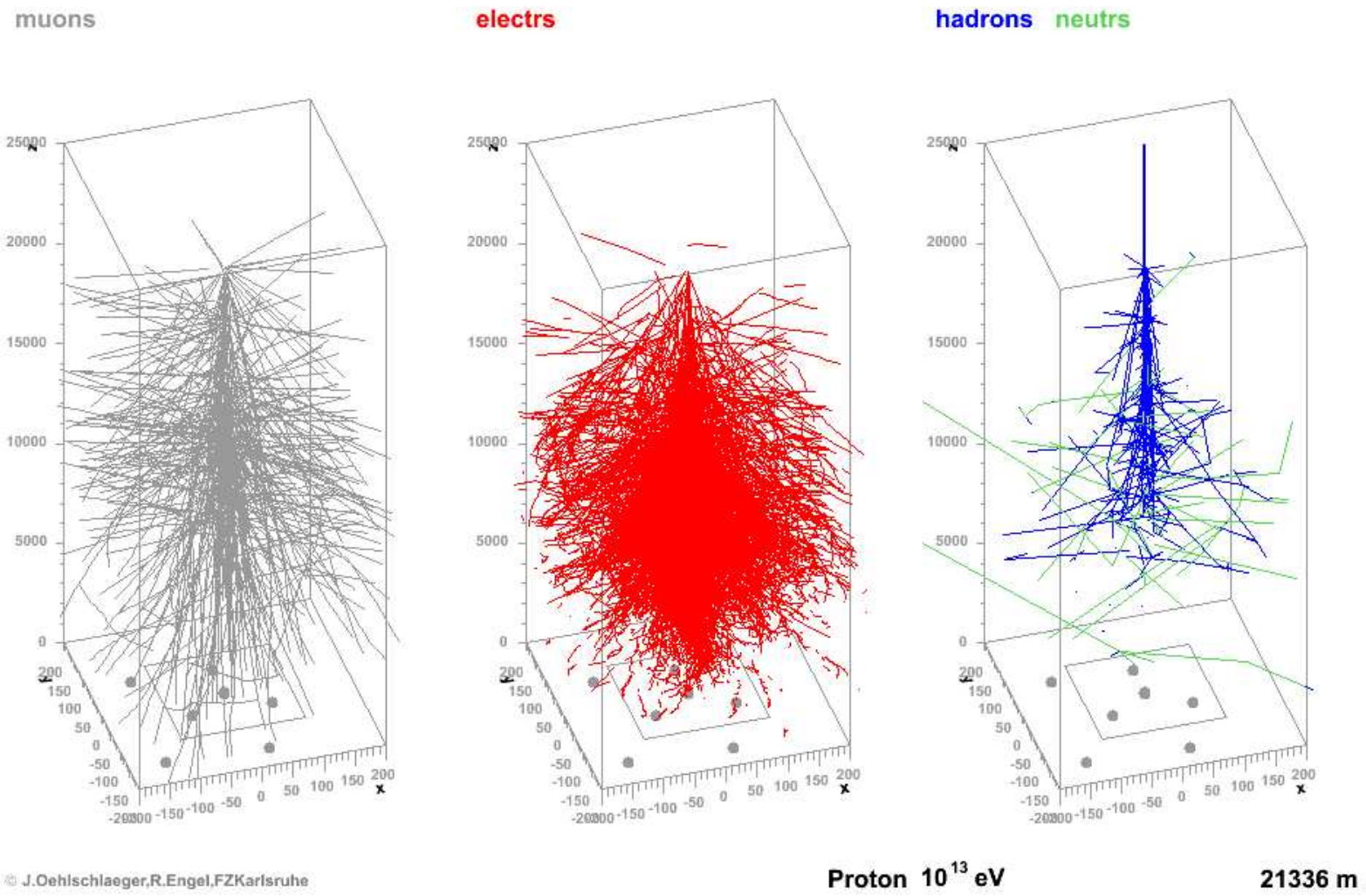
Detection: Extensive Air Showers



- interaction primary-air $\longrightarrow$ mainly π-mesons
- secondary products interact (hadrons) or decay (muons, electrons)
- particles reach ground in a shower disc

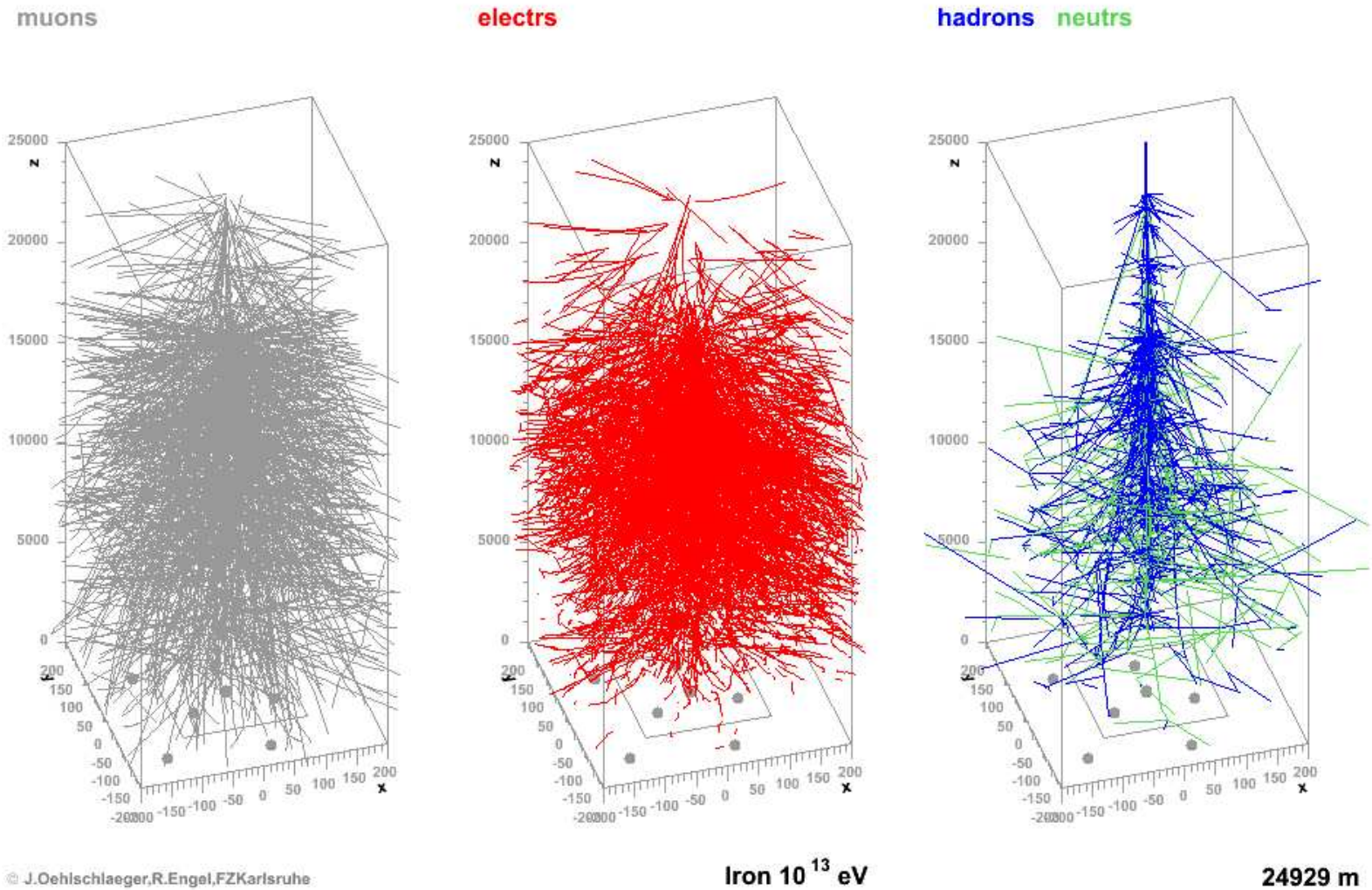
- longitudinal profile $\longrightarrow$ N particles as function of the atmospheric depth
- lateral profile $\longrightarrow$ distribution at ground of the shower particles as a function of the distance from the shower axis

Different primaries



- dominated by electromagnetic component

Different primaries



- N_μ/N_e larger as compared to proton

The KASCADE Experiment

Physics Observables

- electron
- gammas
- muons
- hadrons

The detectors

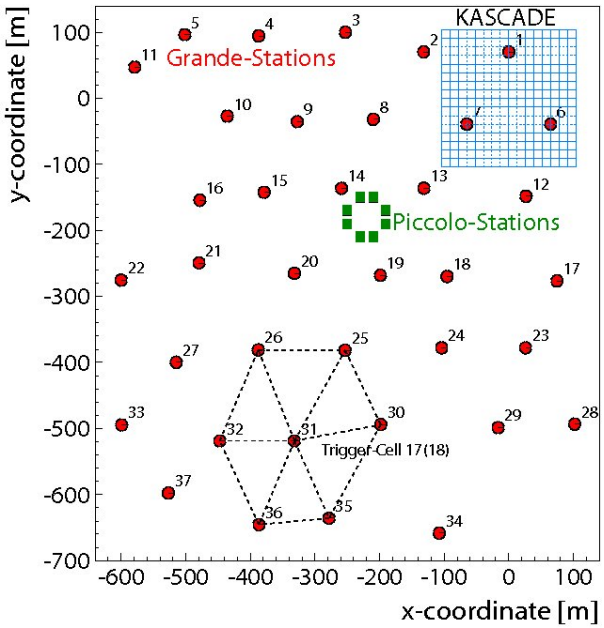
- Array stations: liquid scintillator for e/γ detection and plastic scintillator for μ detection above 230 MeV
- Muon Tracking Detector for $E_\mu \geq 800$ MeV
- MWPC/LSTs for muon detection above 2.4 GeV
- Calorimeter, for hadron detection

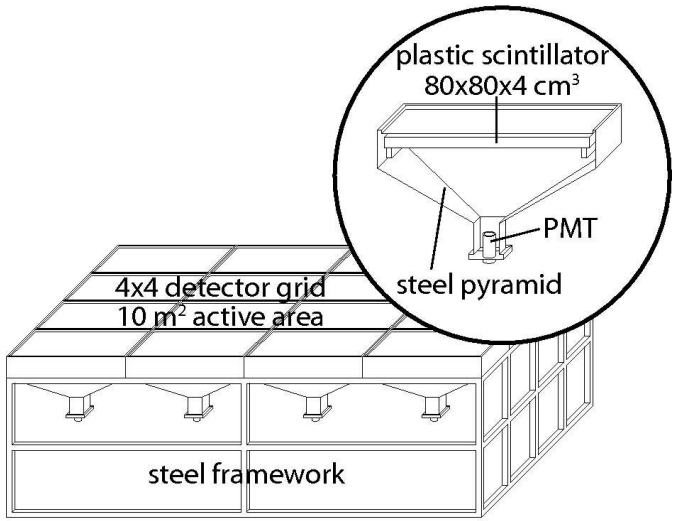
KASCADE-Grande

KASCADE extension to 700×700 m^2

- energy spectrum and composition from 10^{16} eV to 10^{18} eV
- galactic to extragalactic transition?
- Testing hadronic interaction models
- iron knee ?
- origin of the knee ?
- Anisotropies

KASCADE-Grande



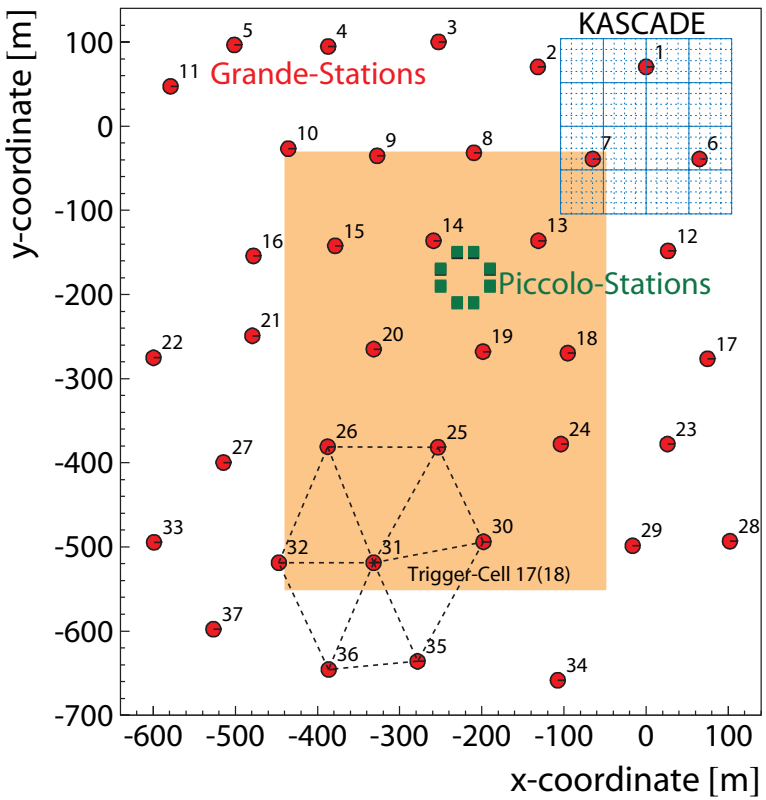


Physics observables

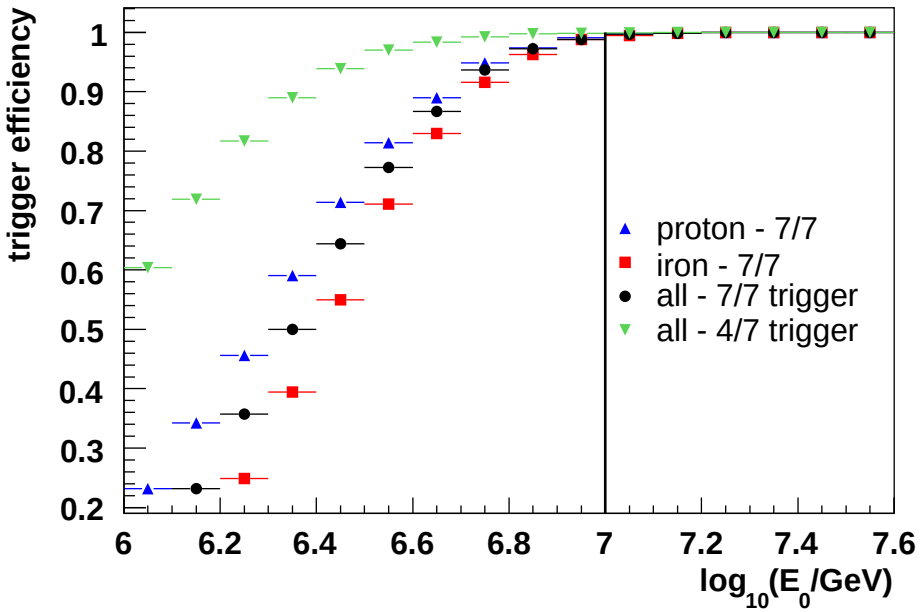
- arrival time and energy deposit by charged particles in each detector $\Rightarrow$ particle densities
- muons from the KASCADE detectors

- $\approx$10 m^2 of plastic scintillator per station
- light detected and coverted into electronic signal by PMTs

Trigger efficiency

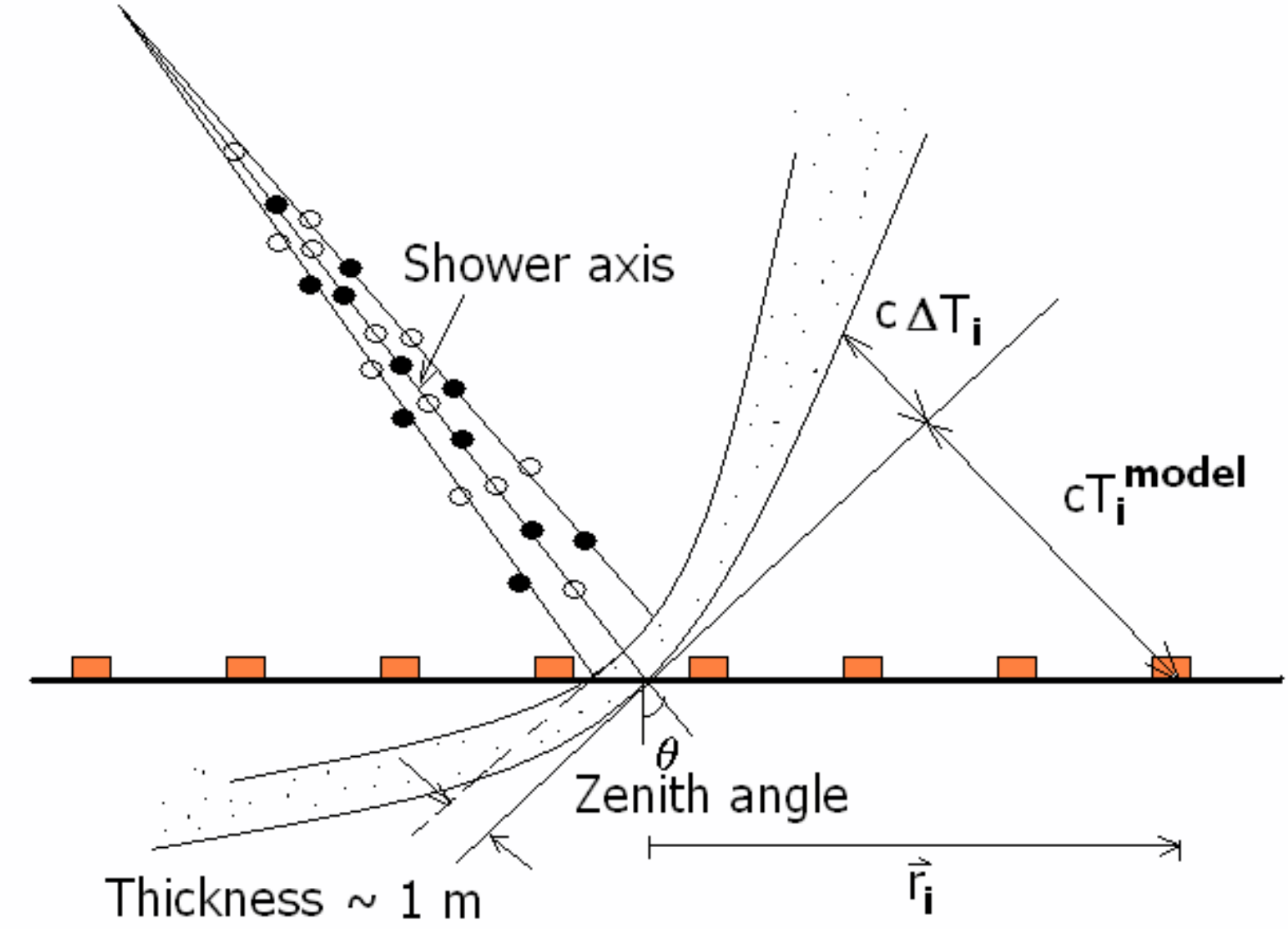


- fiducial area of $\sim$ 192,000 m^2 (orange area),
- trigger by 7/7 coincidence



- based on air shower simulation
- full efficiency at $\mathrm{E} = 10^{16}\,\mathrm{eV}$, for both proton and iron primaries

Shower reconstruction



Shower reconstruction

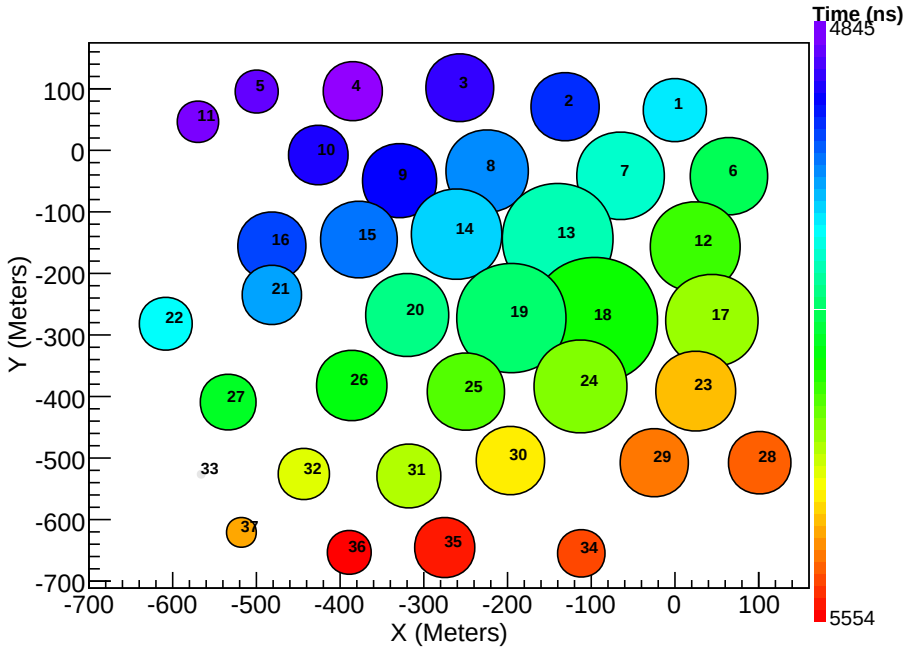
shower core: impact position of the shower axis at ground level
$\Longrightarrow$ Grande measurements

arrival direction $\Longrightarrow$ Grande measurements

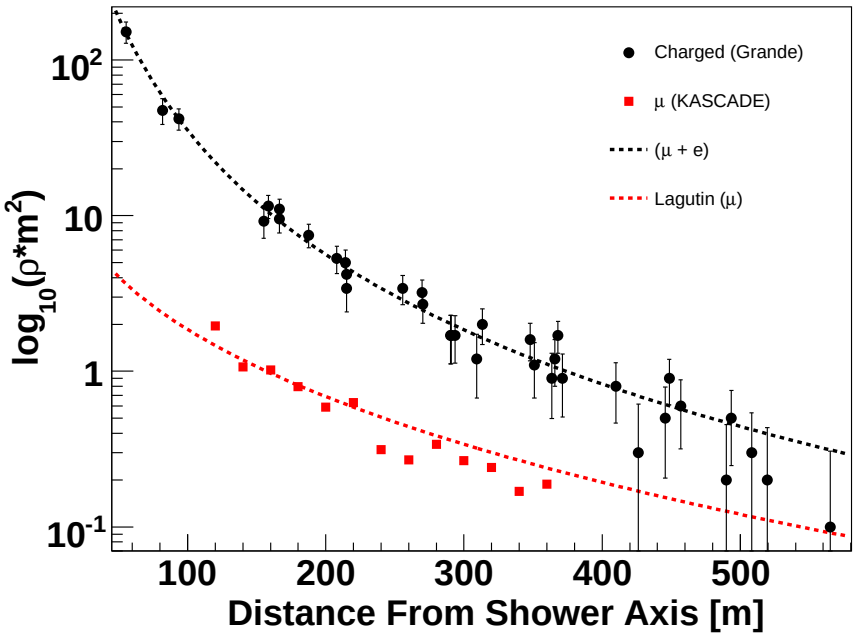
electron shower size N_e: total number of electrons arriving at observation level $\Longrightarrow$ Grande measurements

muon shower size N_μ: total number of muons arriving at observation level $\Longrightarrow$ KASCADE measurements

Reconstruction procedure



(x,y)=(-115 m, -223 m), (θ, ϕ)=(11°, 338°)

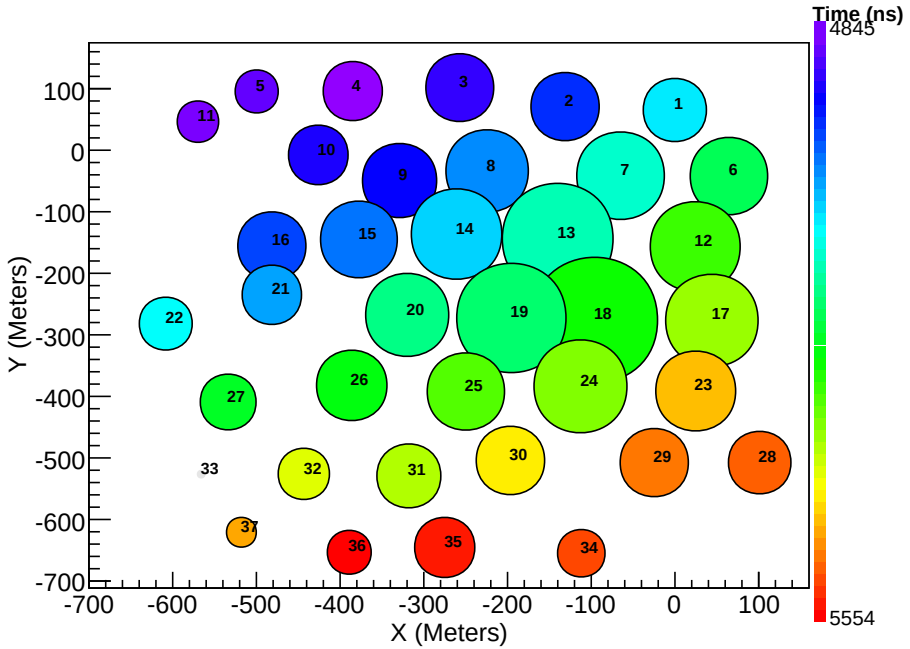


$\log_{10}(N_e) = 7$, $\log_{10} N_\mu = 5.7$

Core position and total number of charged particle (N_{ch}) by fitting the lateral distribution with a modified NKG function:

$$\rho_{ch} = N_{ch} \cdot C(s) \cdot \left(\frac{r}{r_0}\right)^{s-1.6} \cdot \left(1 + \frac{r}{r_0}\right)^{s-3.4} \qquad \mathrm{r_0 = 30m}$$

Reconstruction procedure



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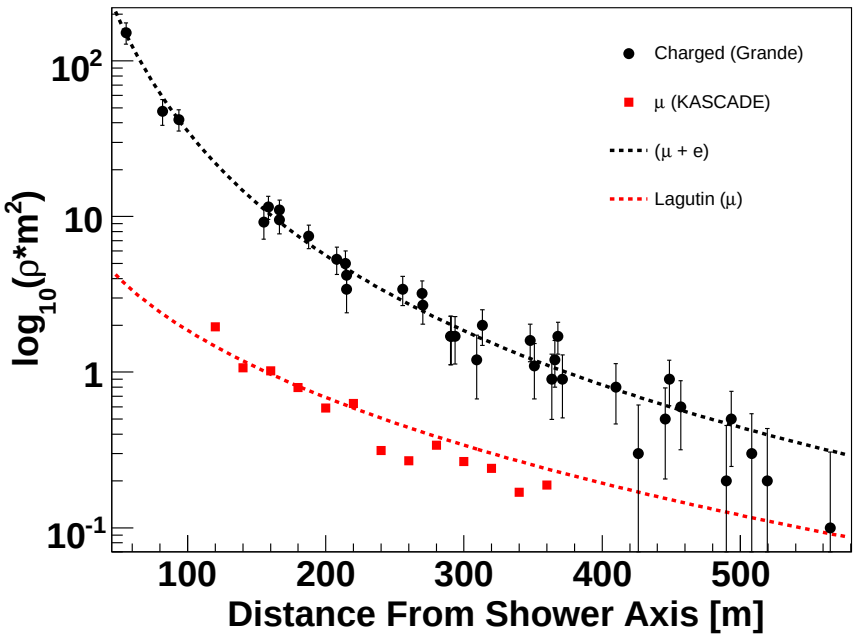
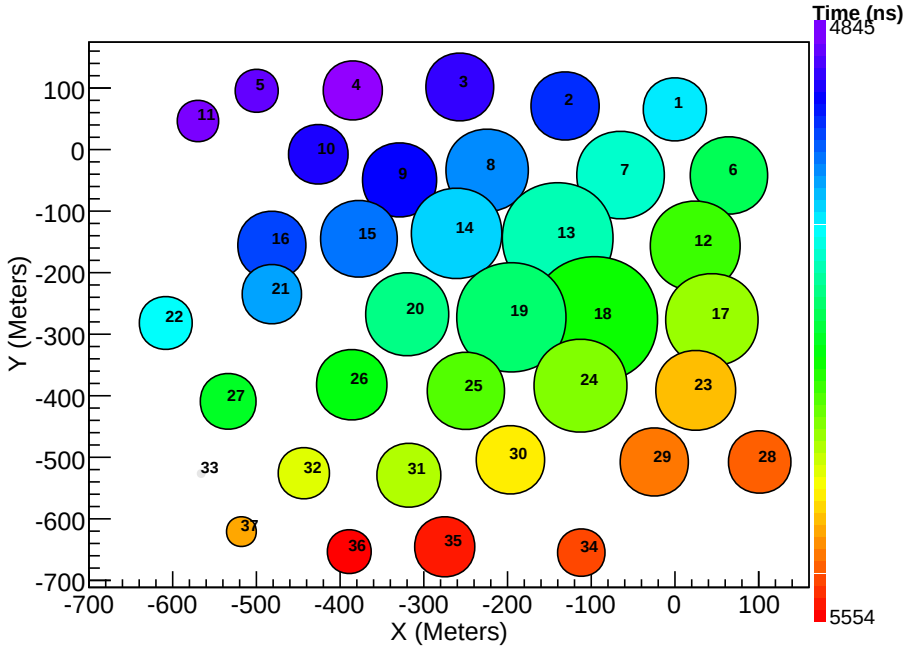


$\log_{10}(N_e) = 7$, $\log_{10} N_\mu = 5.7$

Total number of muons (N_μ) by fitting the muon lateral distribution with a Lagutin function:

$$\rho_\mu = N_\mu \cdot \frac{0.28}{320^2} \cdot \left(\frac{r}{320}\right)^{-0.69} \cdot \left(1 + \frac{r}{320}\right)^{-2.39} \cdot \left(1 + \left(\frac{r}{10 \cdot 320}\right)^2\right)^{-1}$$

Reconstruction procedure



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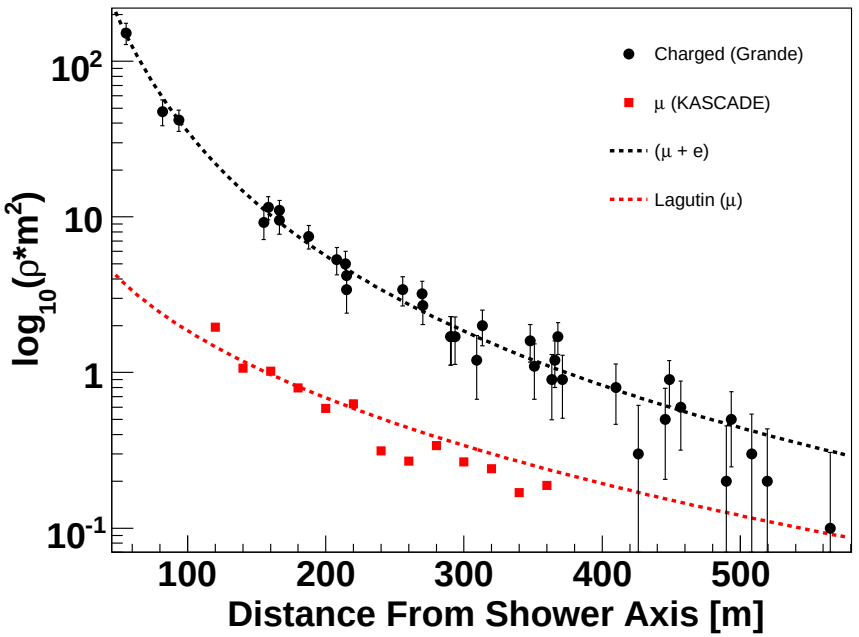
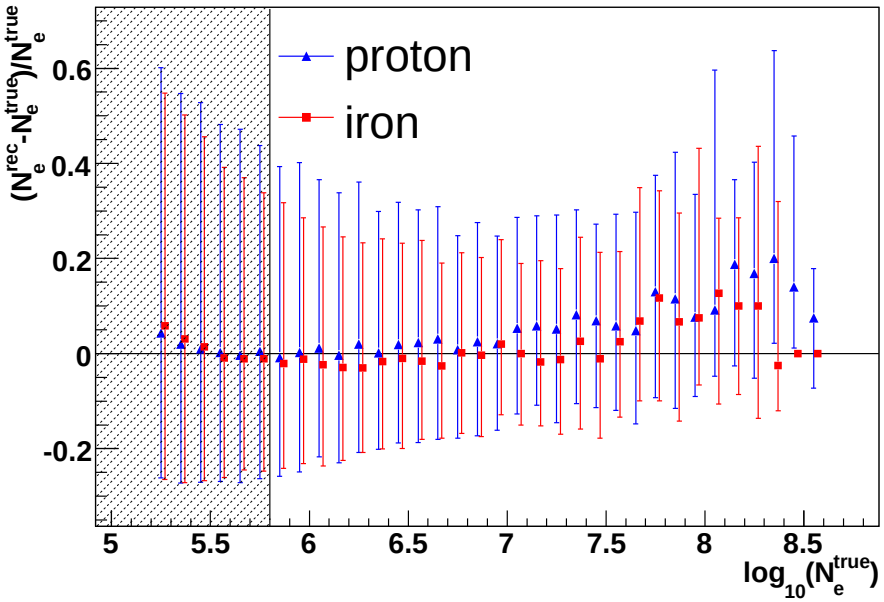
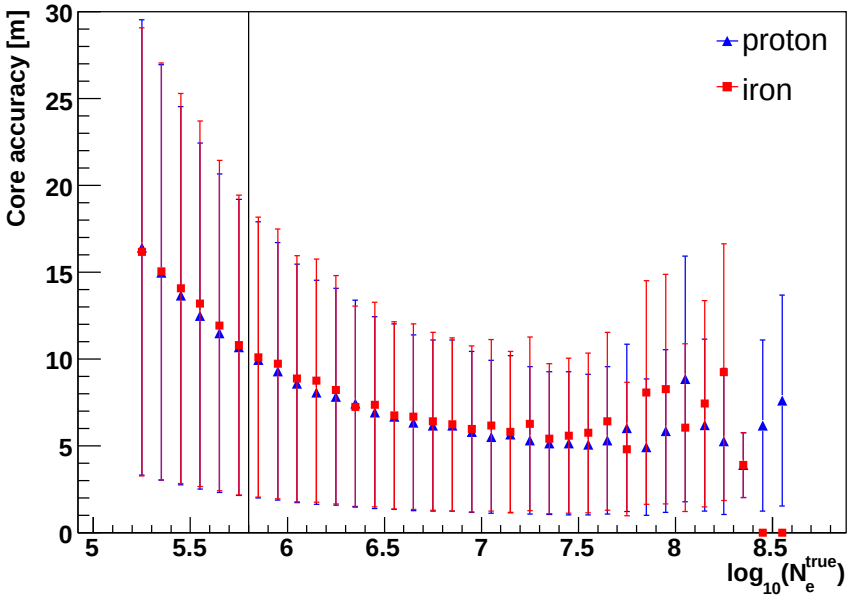


$\log_{10}(N_e) = 7$, $\log_{10} N_\mu = 5.7$

Total number of electrons (N_e) by subtracting the estimated muon content from the estimated charged particles content.

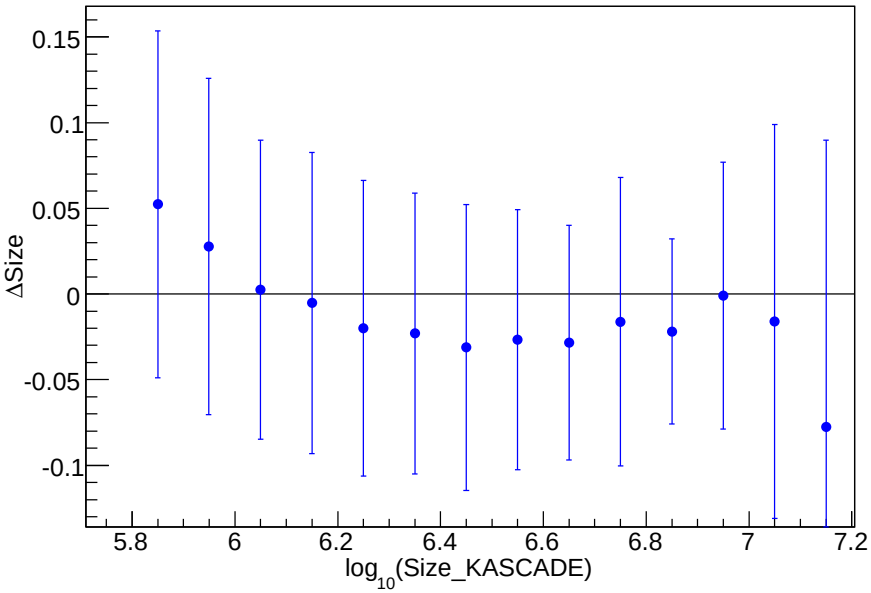
Reconstruction accuracies sim/data

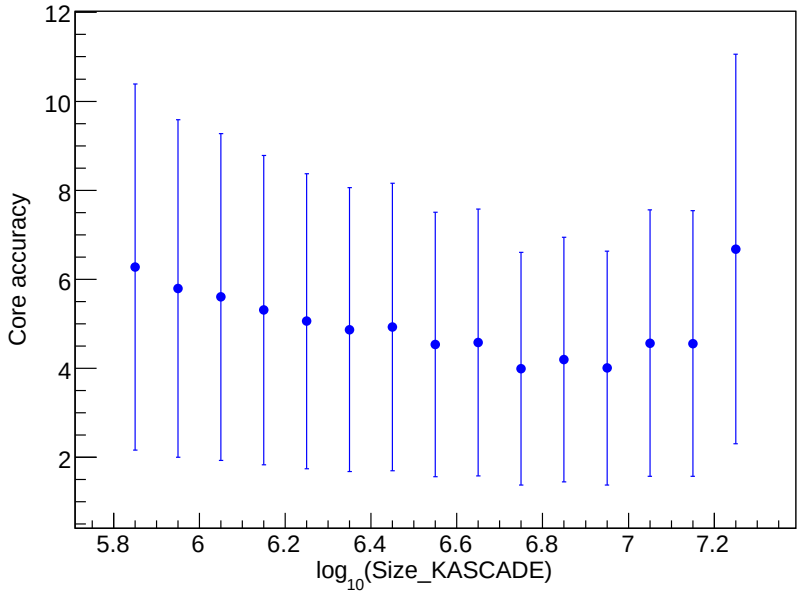




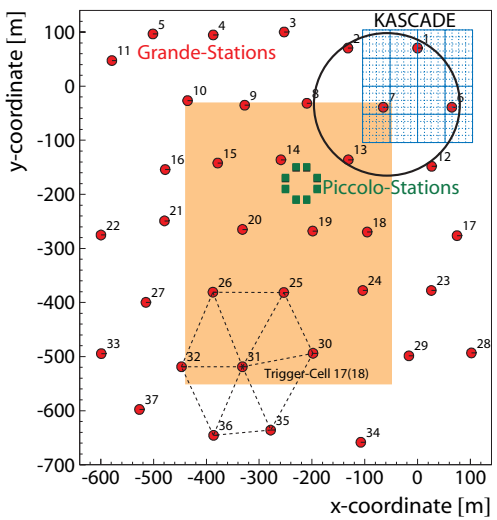
- statistical uncertainty for N_e at full efficiency around 25 %
- systematics change from less than 5% at threshold to 15%
- small dependence on primary particle type
- core accuracy $\approx$ 6 m

Reconstruction accuracies sim/data

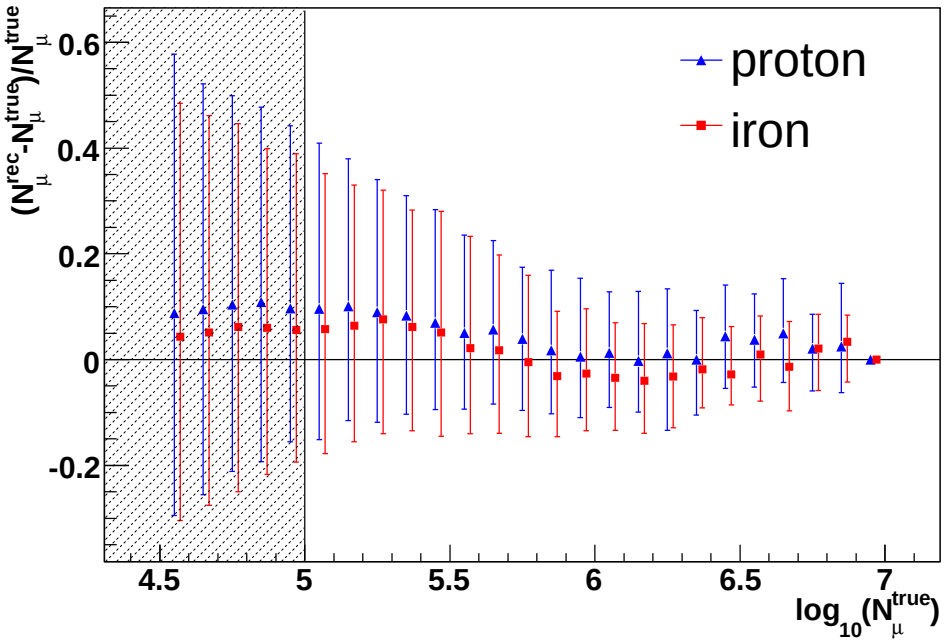


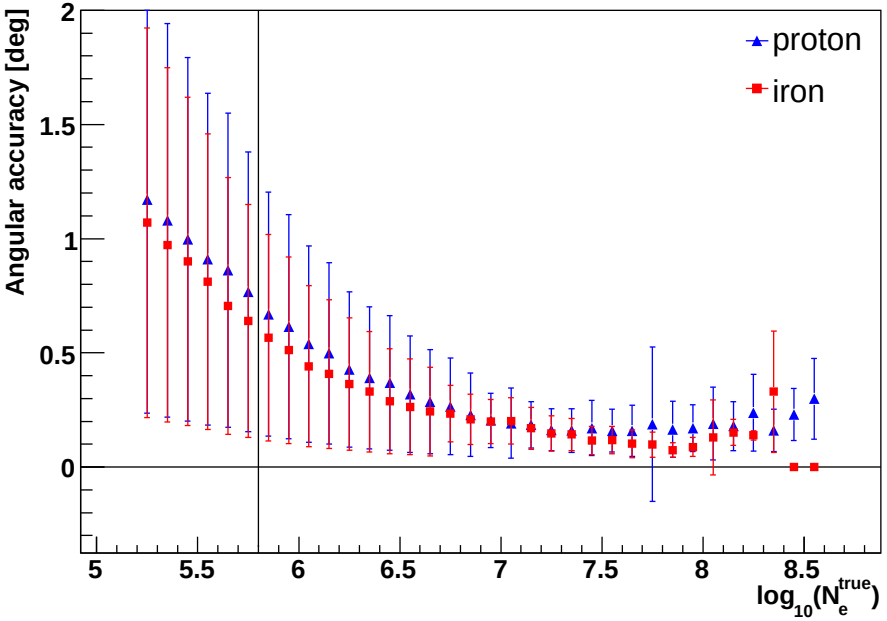


- Trigger from Grande
- Maximum density in the central station of the cluster overlapping with KASCADE
- KASCADE reconstruction used as reference



Reconstruction accuracies sim/data

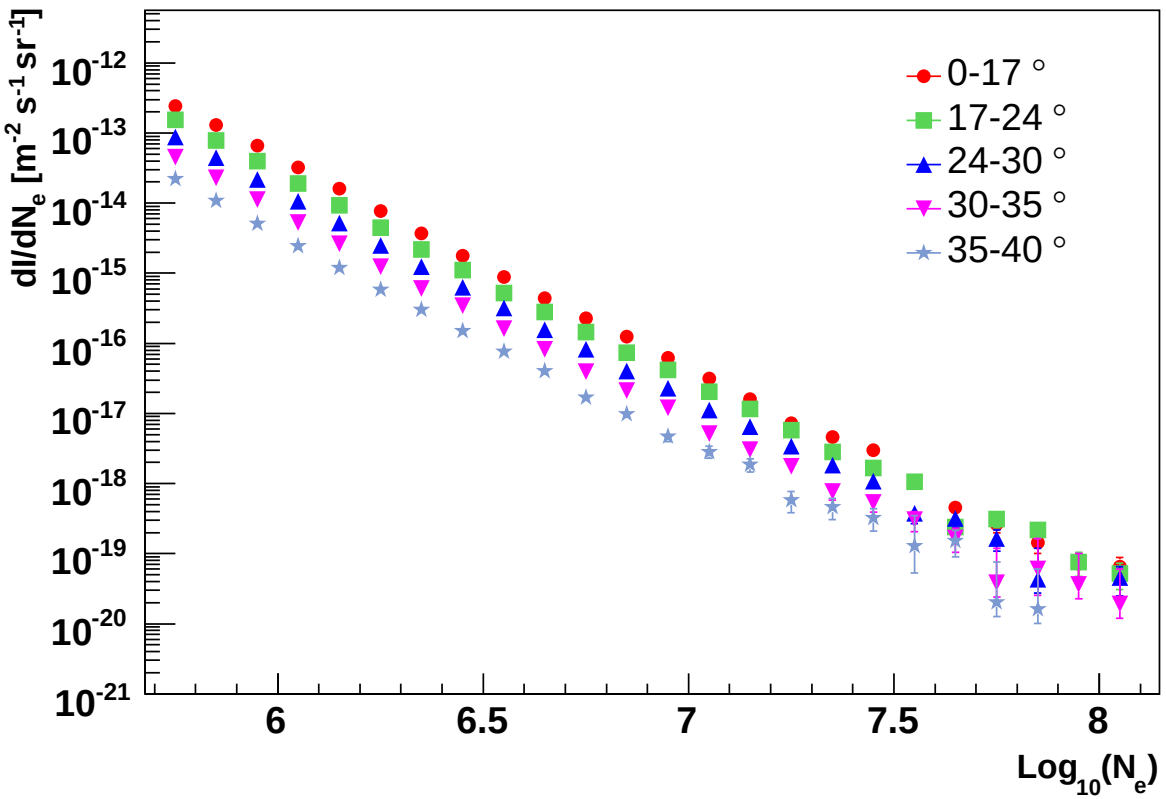




- statistical uncertainty for N_μ at full efficiency around 20 %
- bias of 10% to -5% in energy (muon) dependence
- Angular accuracy $< 0.5^\circ$ up to 40°

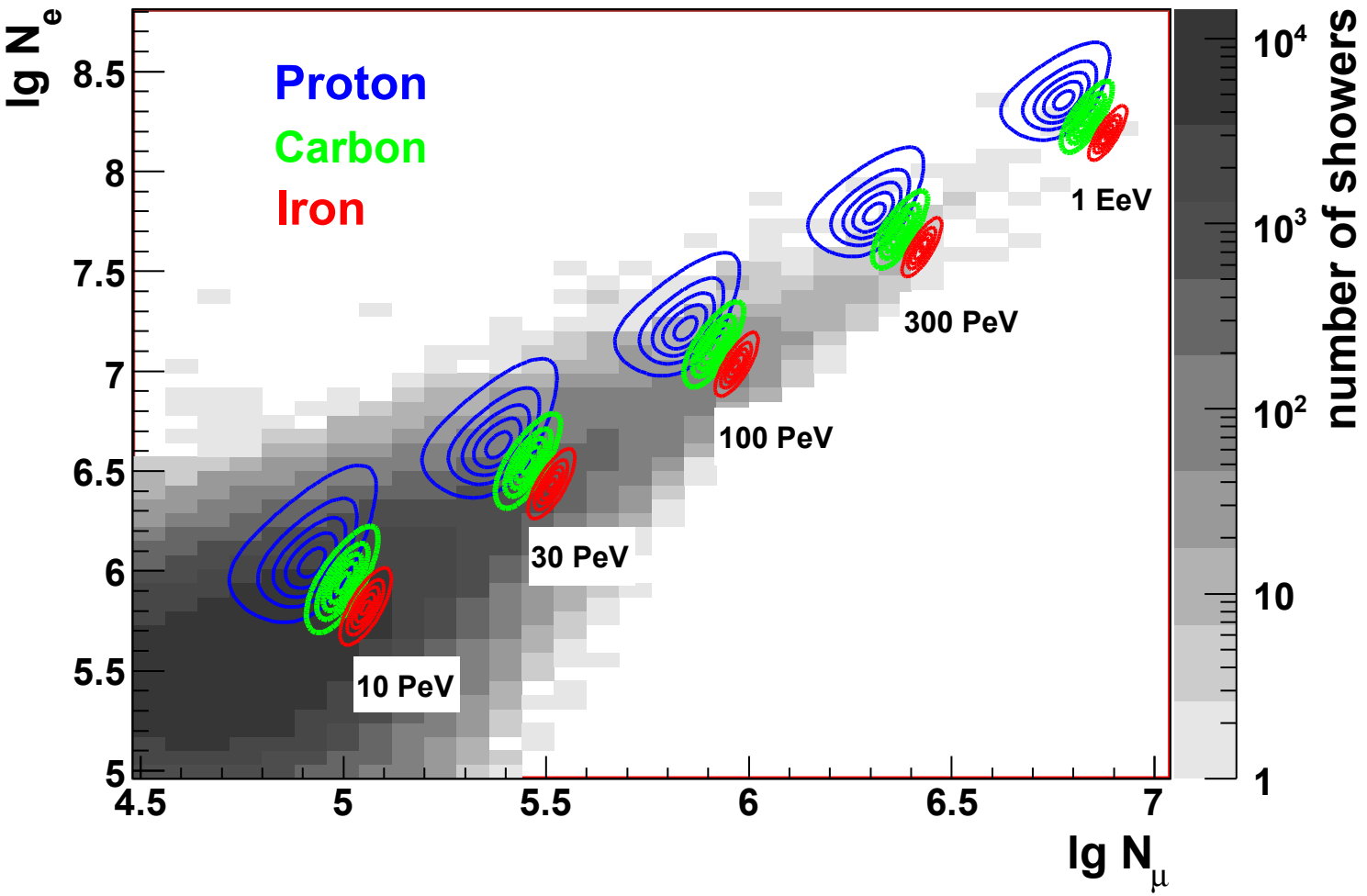
Spectra

SIZE (electron) SPECTRA



- 987 days of data taking
- fiducial area of $\approx 0.2\,\mathrm{km}^2$
- $\approx 880,000$ events

$N_e - N_\mu$ correlation



$$(N_e,\ N_\mu) = f(E, m)$$

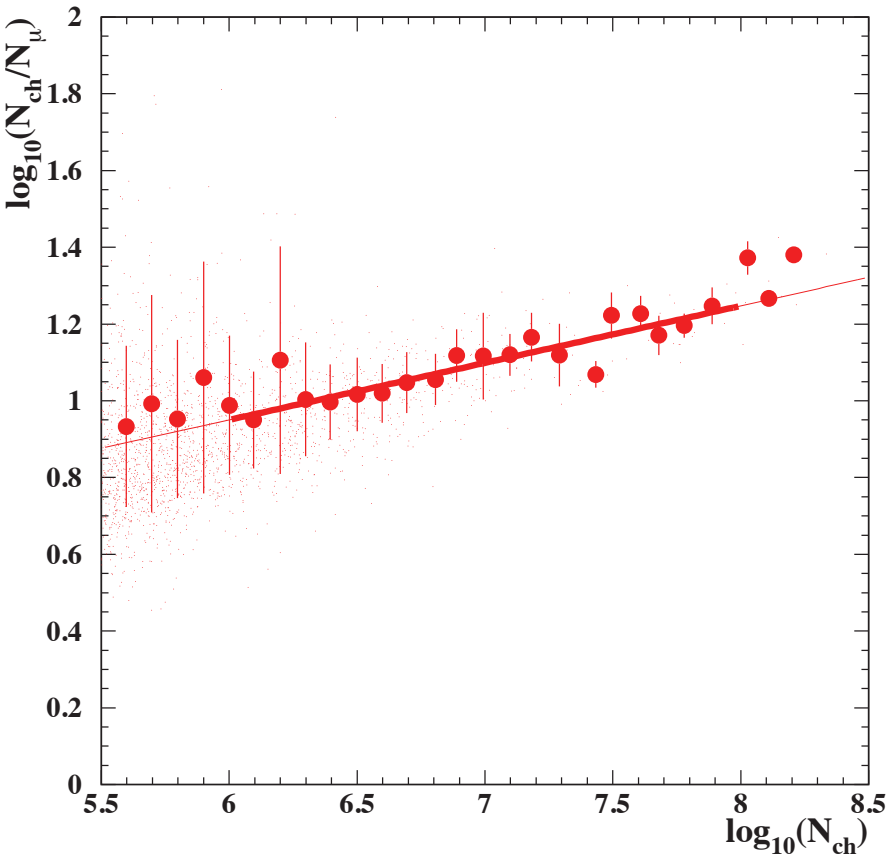
Energy spectrum

- correlation N_{ch} with E_0 from simulation $\rightarrow$ good reconstruction accuracy, BUT very much composition dependent
- correlation N_{μ} with E_0 from simulation $\rightarrow$ problems with reconstruction accuracy, less composition dependent
- estimation of the primary energy as $E_0(N_{ch}, N_{\mu}) \rightarrow$ no composition dependence!

THEY ALL REQUIRE ASSOMPTION ON HIGH ENERGY HADRONIC INTERACTION MODELS

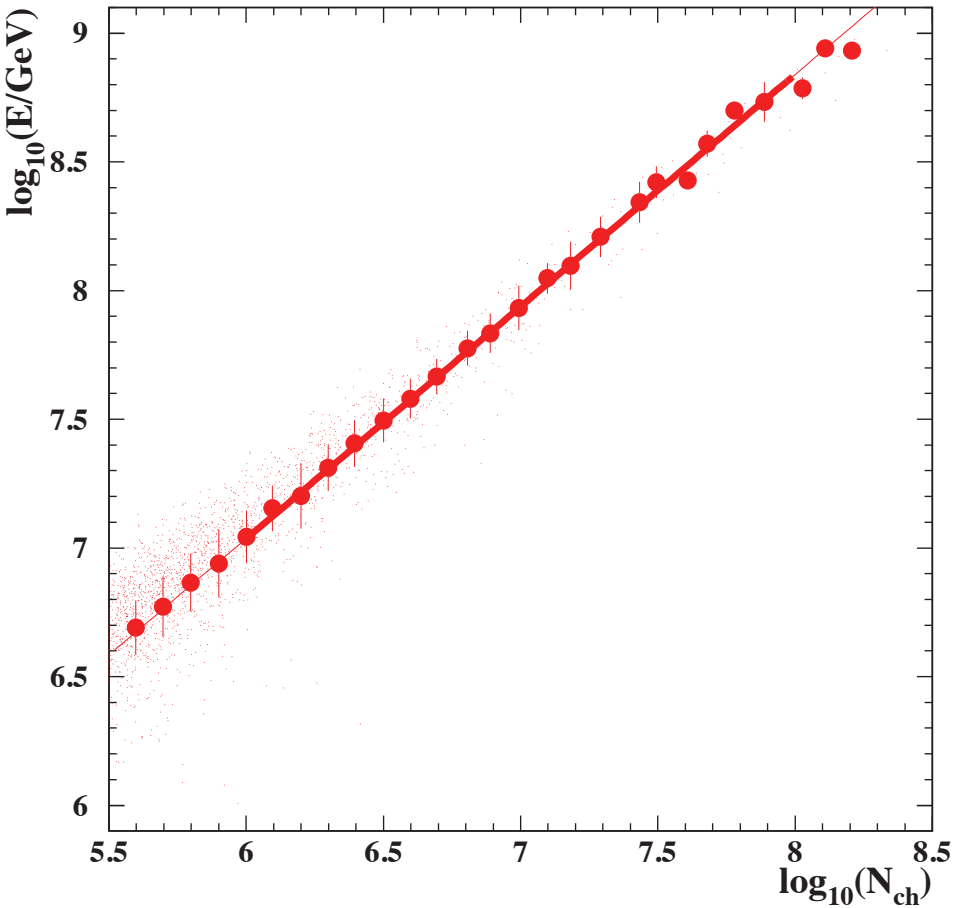
Energy estimation

$$\log_{10}\left(N_{ch}/N_{\mu}\right)_{p,Fe} = c_{p,Fe} \cdot \log_{10}(N_{ch}) + d_{p,Fe}$$



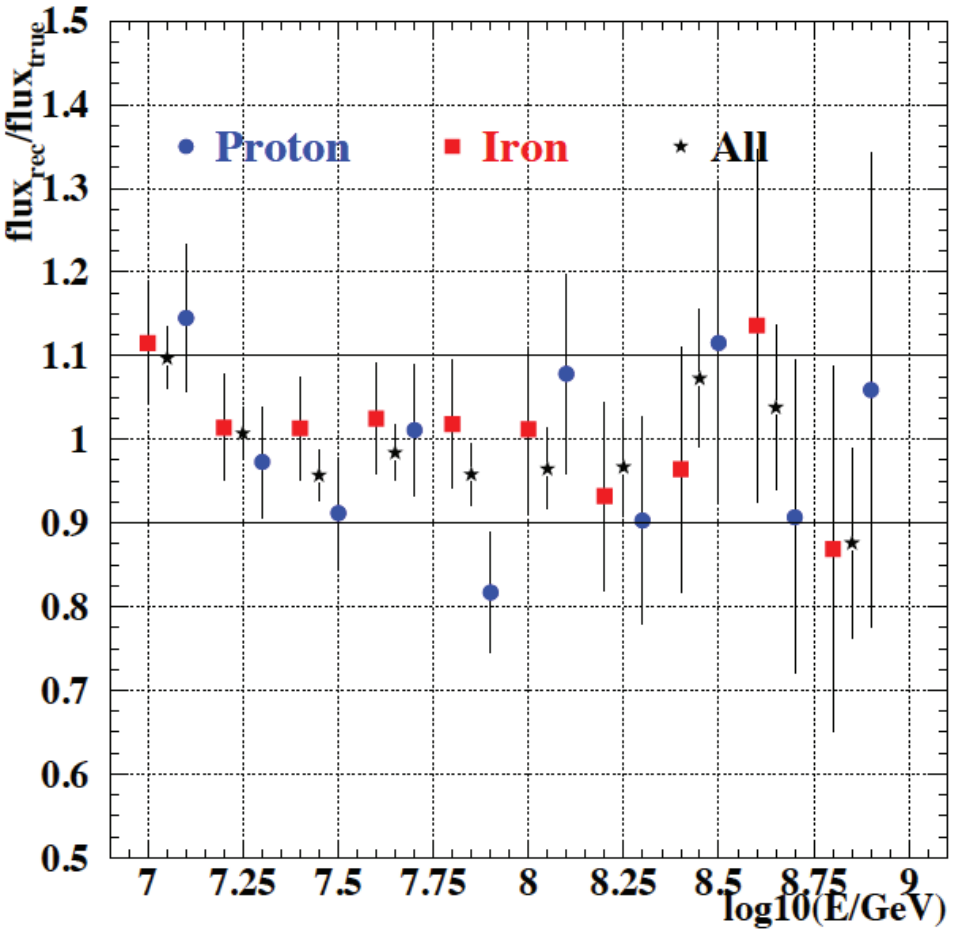
$$r = \frac{\log_{10}(N_{ch}/N_{\mu}) - \log_{10}\left(N_{ch}/N_{\mu}\right)_{p}}{\log_{10}\left(N_{ch}/N_{\mu}\right)_{Fe} - \log_{10}\left(N_{ch}/N_{\mu}\right)_{p}}$$

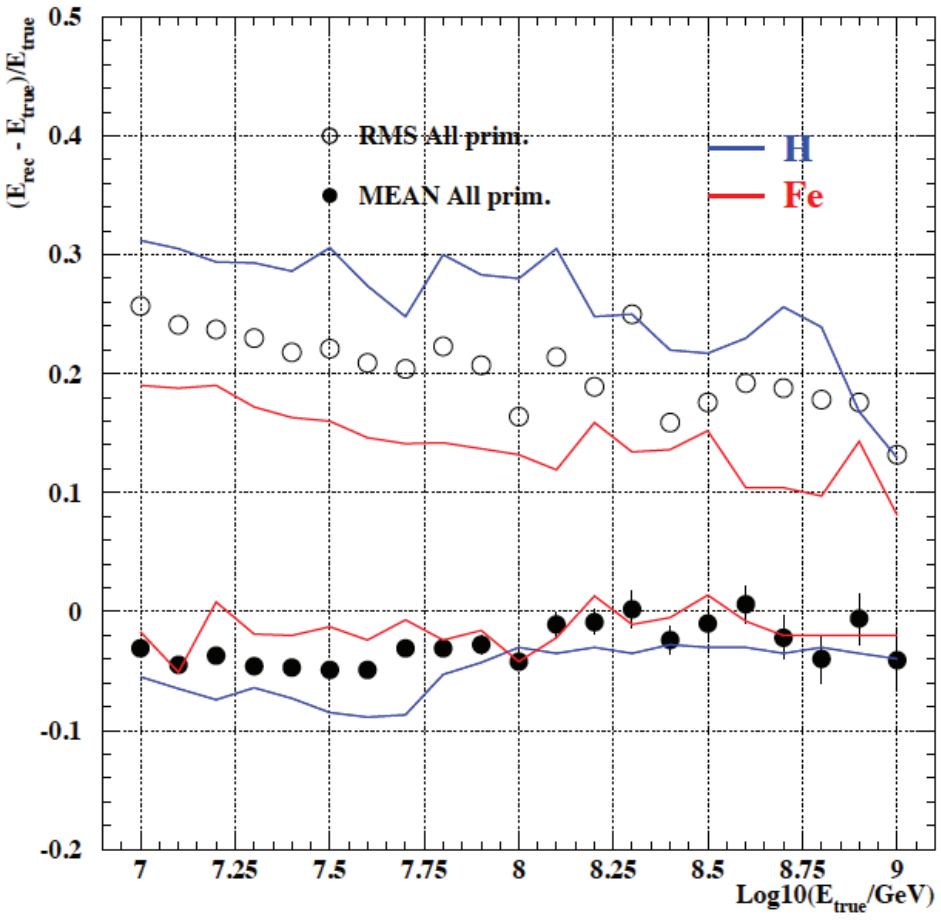
Energy estimation



$$\log_{10}(E_{est}) = (a_p + \Delta a \cdot r) \cdot \log_{10}(N_{ch}(\theta)) + (b_p + \Delta b \cdot r)$$

Energy estimation

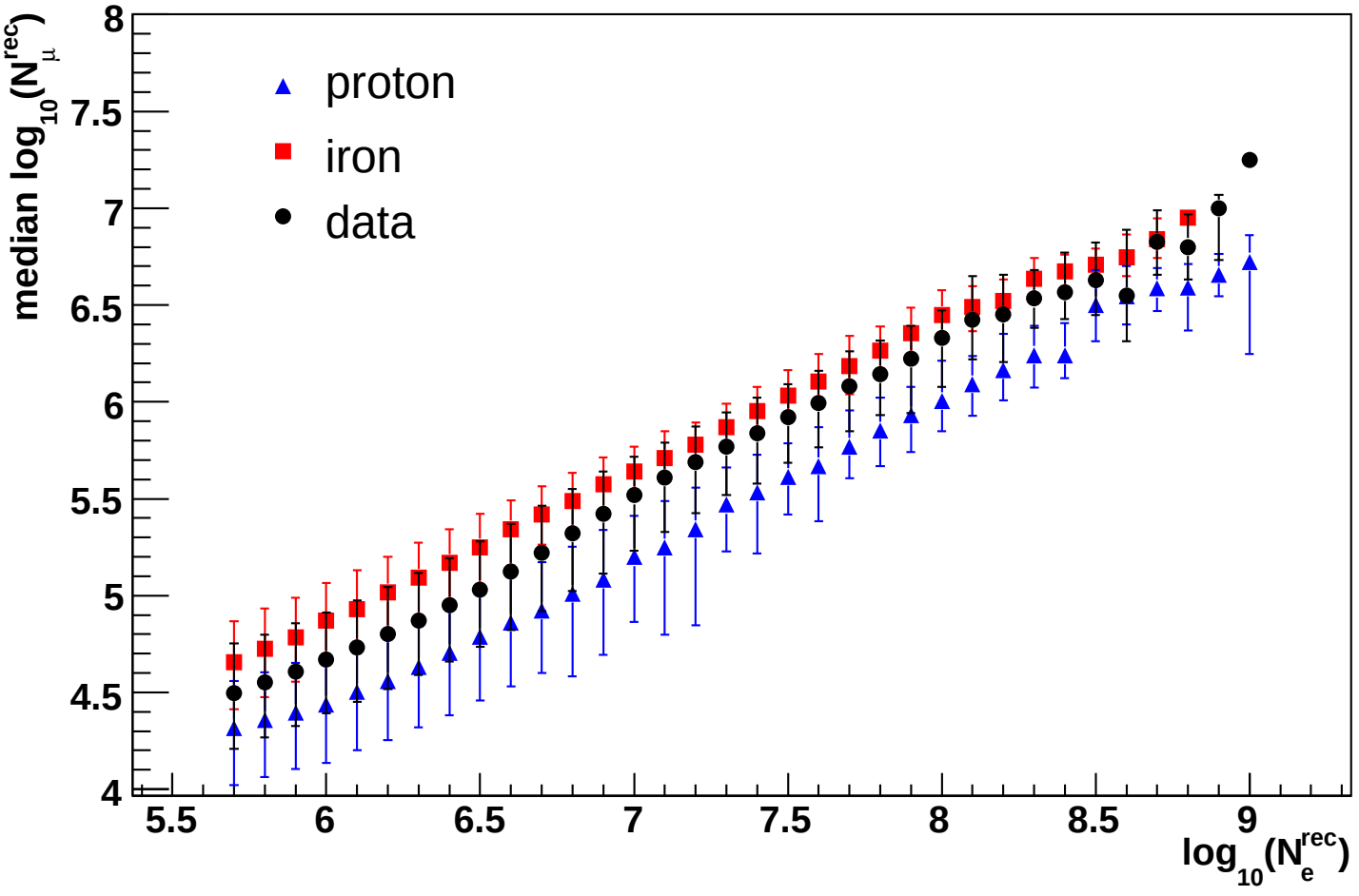




Mass composition analysis method

- statistical methods to infer cosmic rays mass
- search of mass-sensitive observables
- classification of an air shower through kNN method

Parameters relevance

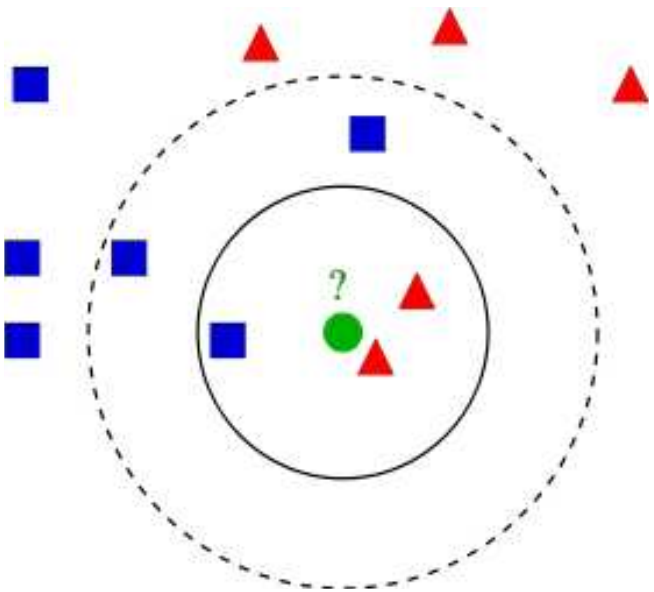


error bars represent the spread of the distribution in each bin

KNN

classification method: comparison of each data point with the "K nearest neighbours" in reference samples

- data point, proton, iron



- characterization of each point through N_{ch} and N_{μ}
- Mahalanobis distance:

$$\sqrt{(\mathbf{x_1}-\mathbf{x_2})^T (S)^{-1} (\mathbf{x_1}-\mathbf{x_2})}$$

with S covariance matrix

- S for each reference sample separately
- K number to be chosen on analysis base
- assignment through majority vote

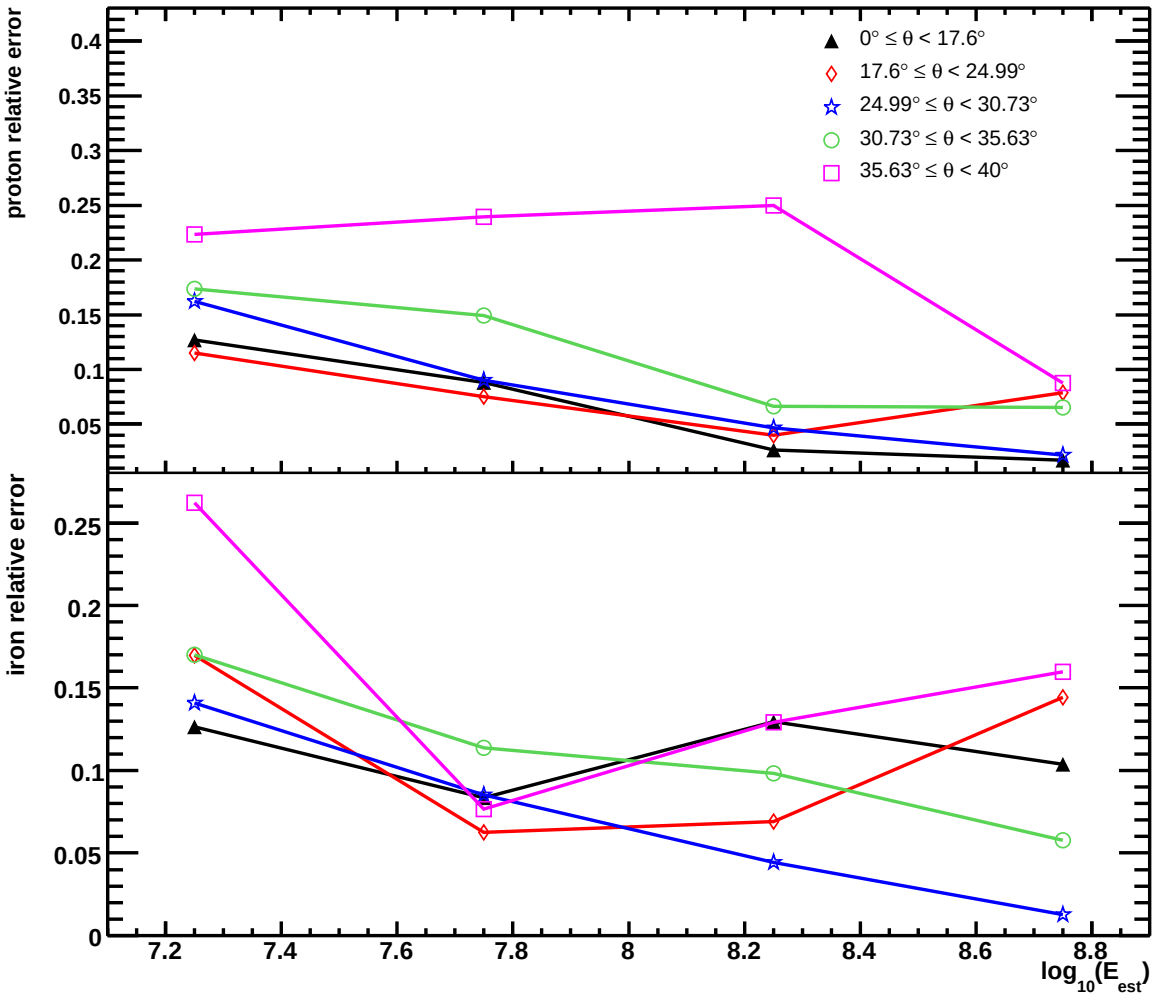
Training

- misclassification rates $P_{\omega_p \to \omega_{Fe}}$
- misclassification matrix

$$\begin{pmatrix} P_{\omega_p \to \omega_p} & P_{\omega_{Fe} \to \omega_p} \\ P_{\omega_p \to \omega_{Fe}} & P_{\omega_{Fe} \to \omega_{Fe}} \end{pmatrix} \begin{pmatrix} n_p^* \\ n_{Fe}^* \end{pmatrix} = \begin{pmatrix} n_p \\ n_{Fe} \end{pmatrix}$$

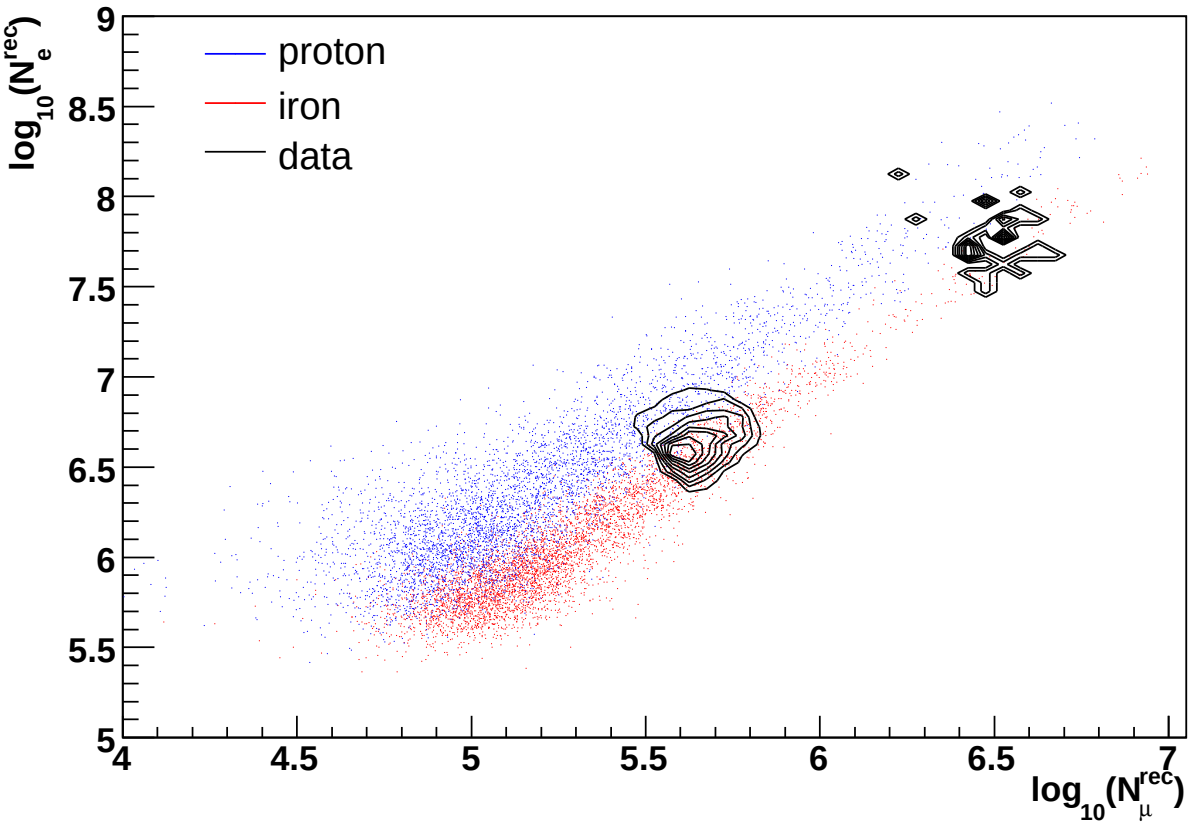
- separability index $G = \sqrt{P_{\omega_p \to \omega_p} \cdot P_{\omega_{Fe} \to \omega_{Fe}}}$
- 5 zenith angle bins: $0^\circ - 40^\circ$
- different energy ranges: $10^{16}\,\mathrm{eV}$ to $10^{18}\,\mathrm{eV}$

Training results

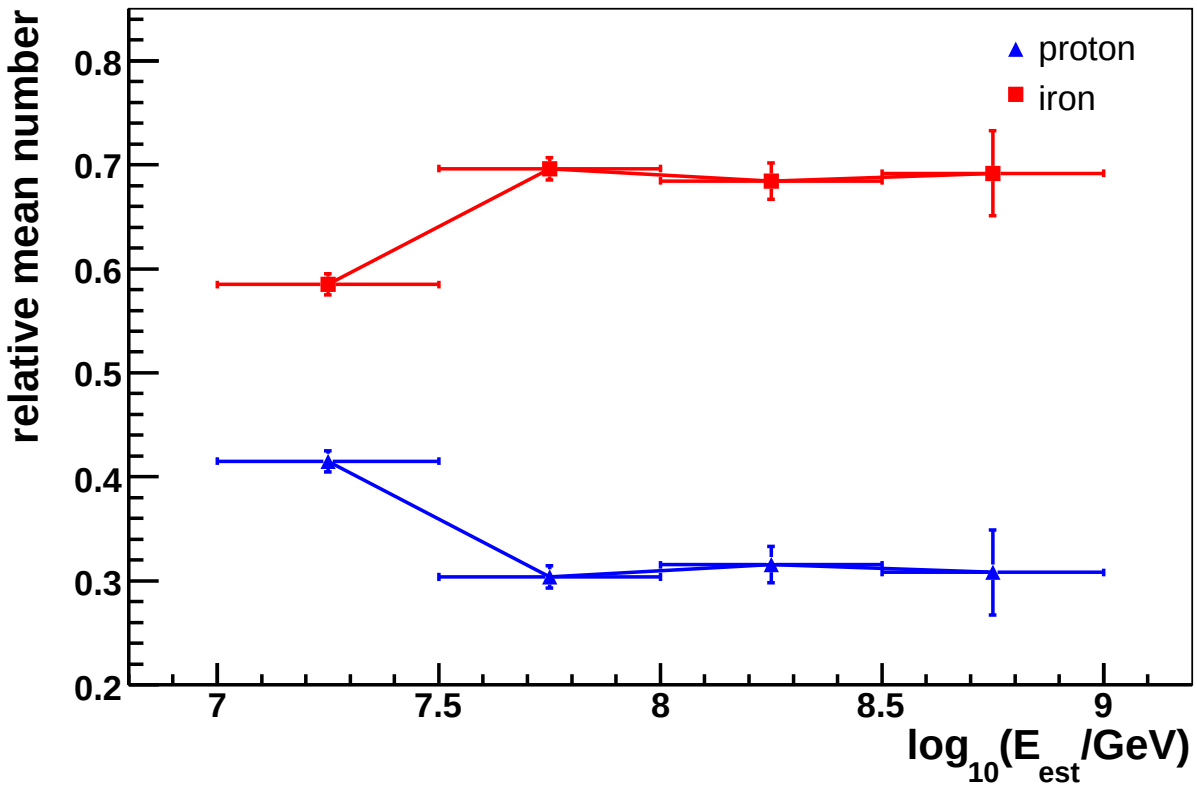


- misclassification better than 25%
- separability better than 80%
- best k=9

kNN on KASCADE-Grande data

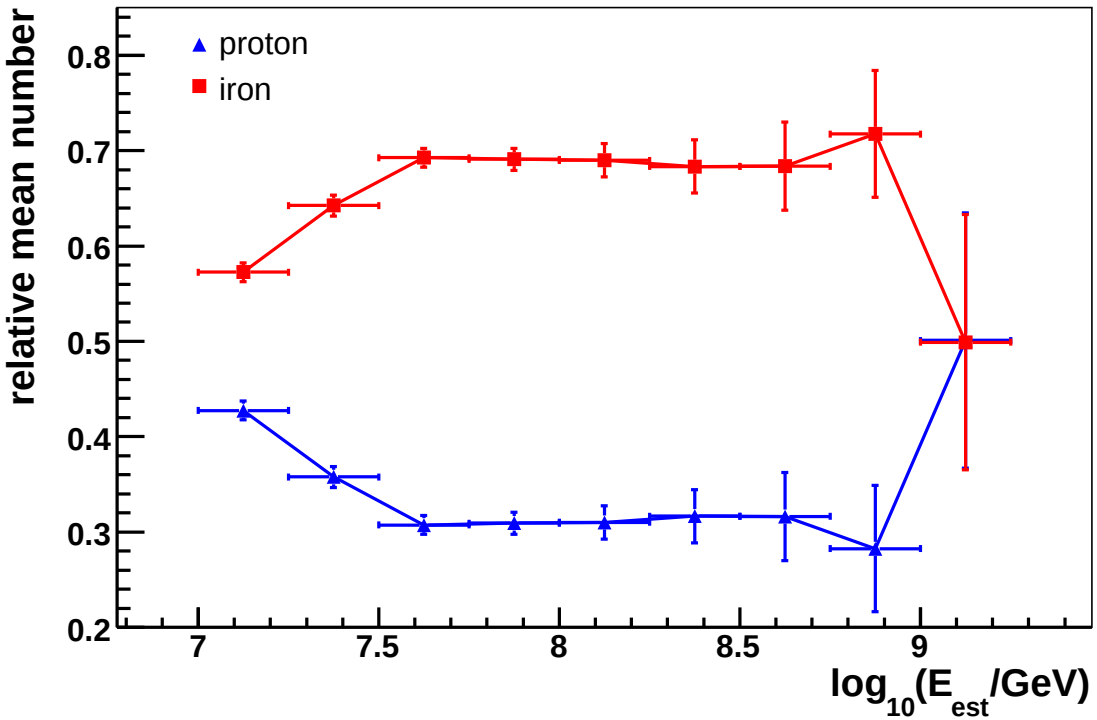


kNN on KASCADE-Grande data



change to heavier composition up to $E = 3 \cdot 10^{16}\,\mathrm{eV}$

kNN on KASCADE-Grande data



- between $3 \cdot 10^{16}\,\mathrm{eV}$ to $10^{18}\,\mathrm{eV}$: $\approx 70\%$ iron-like
- $E > 10^{18}\,\mathrm{eV}$: 6 events per zenith bin, large fluctuation, compatible with constant composition at 1.5 σ level.

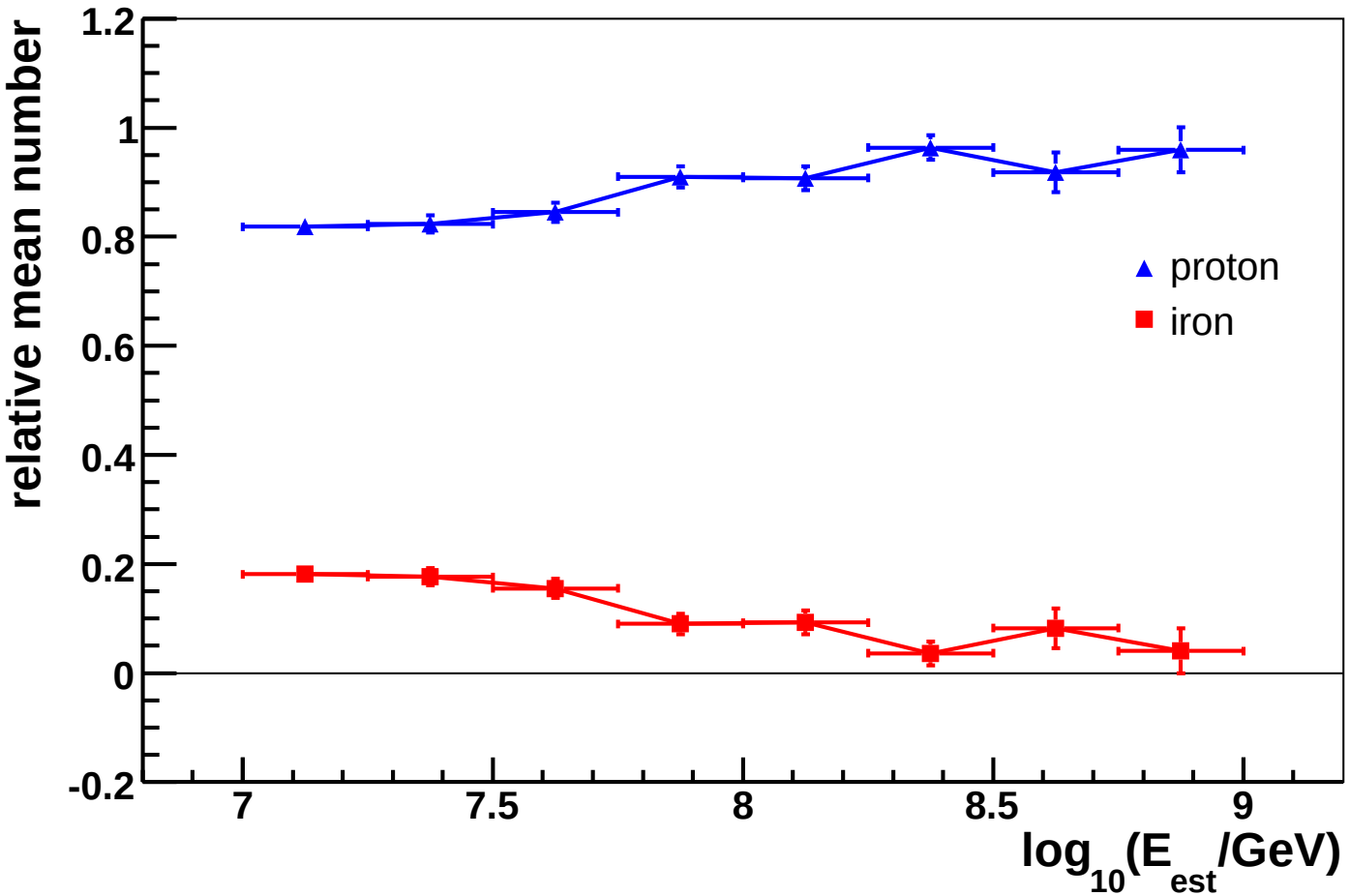
kNN: systematic sources

- method dependent on hadronic interaction model used
- contribution of other primaries to the measured frequencies of proton-like and iron-like air showers:
  - He $\longrightarrow$ 80% proton, 20% iron
  - C $\longrightarrow$ 50% proton, 50% iron
  - Si $\longrightarrow$ 20% proton, 80% iron
- systematic underestimation of energy $\approx -5\%$

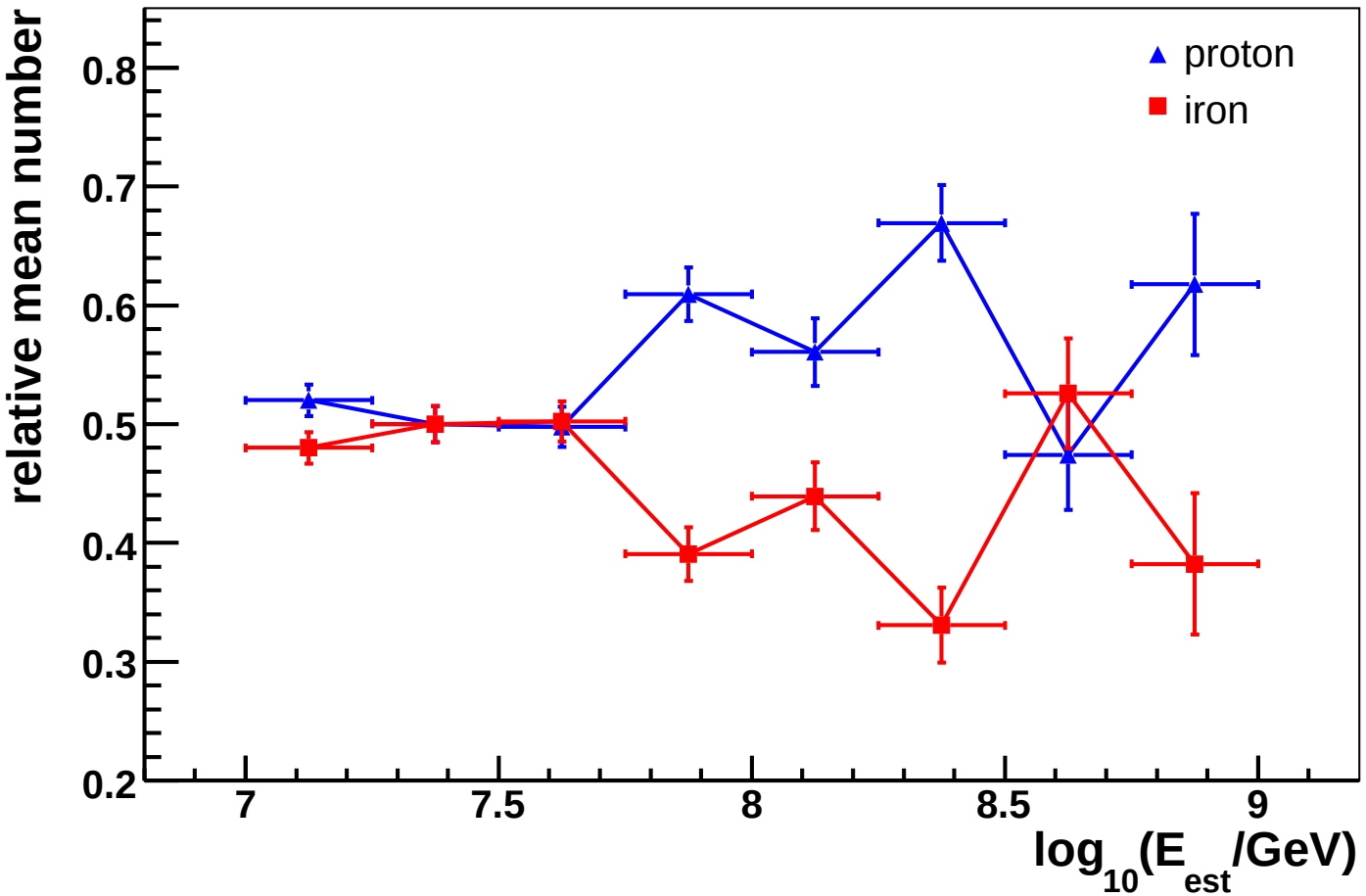
Summary

- Shower reconstruction is accurate enough for analysis
- Methods to reconstruct the energy spectrum available
- Increase of iron fraction up to $E = 3 \cdot 10^{16}\,\mathrm{eV} \rightarrow$ consistent with a decrease of the light primaries
- at $E > 3 \cdot 10^{16}\,\mathrm{eV}$ no evident change of composition observed: $\approx 70\%$ iron-like air showers
- no transition to extragalactic (light) component for $E < 10^{18}\,\mathrm{eV}$

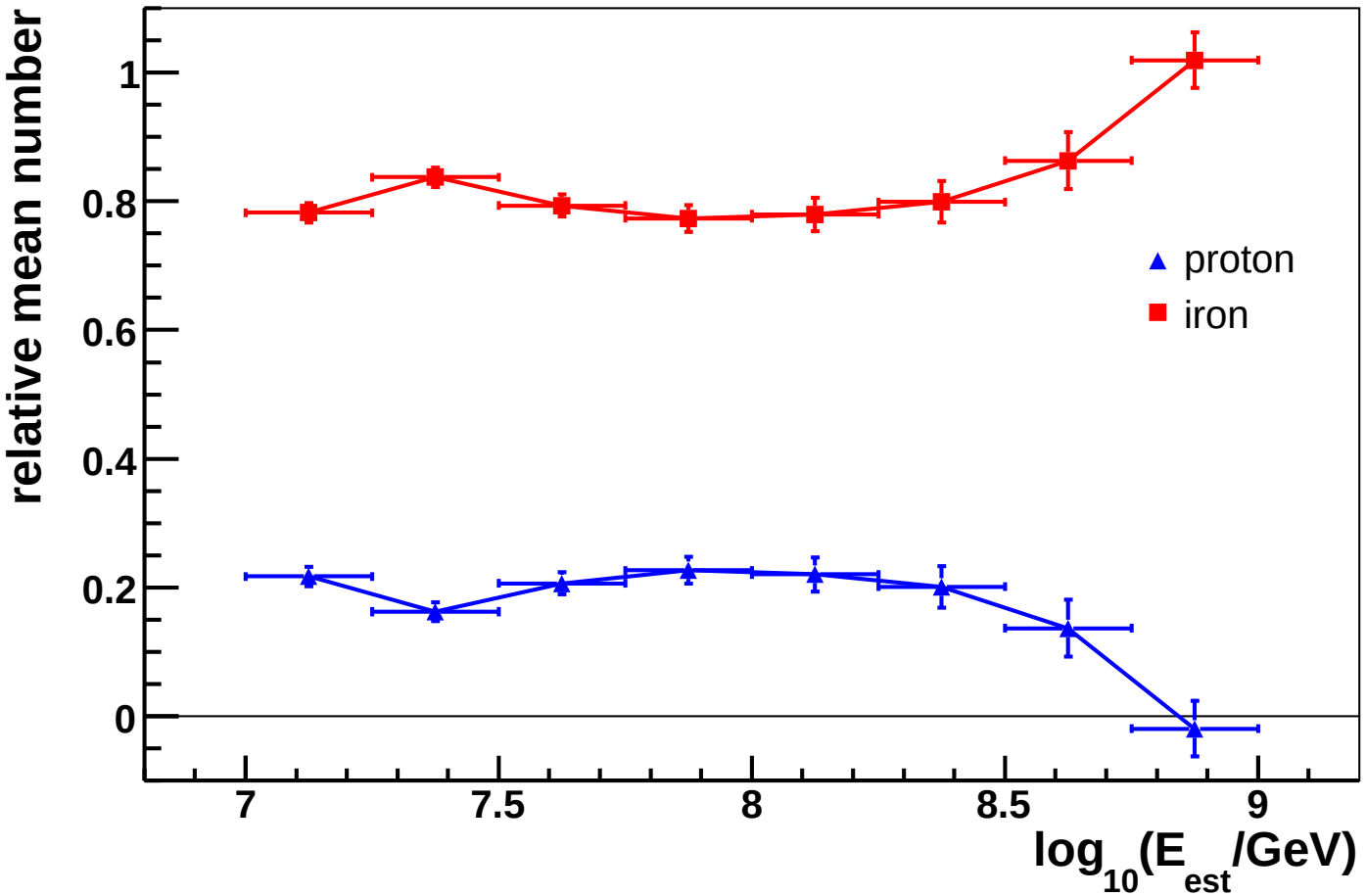
kNN on other primaries



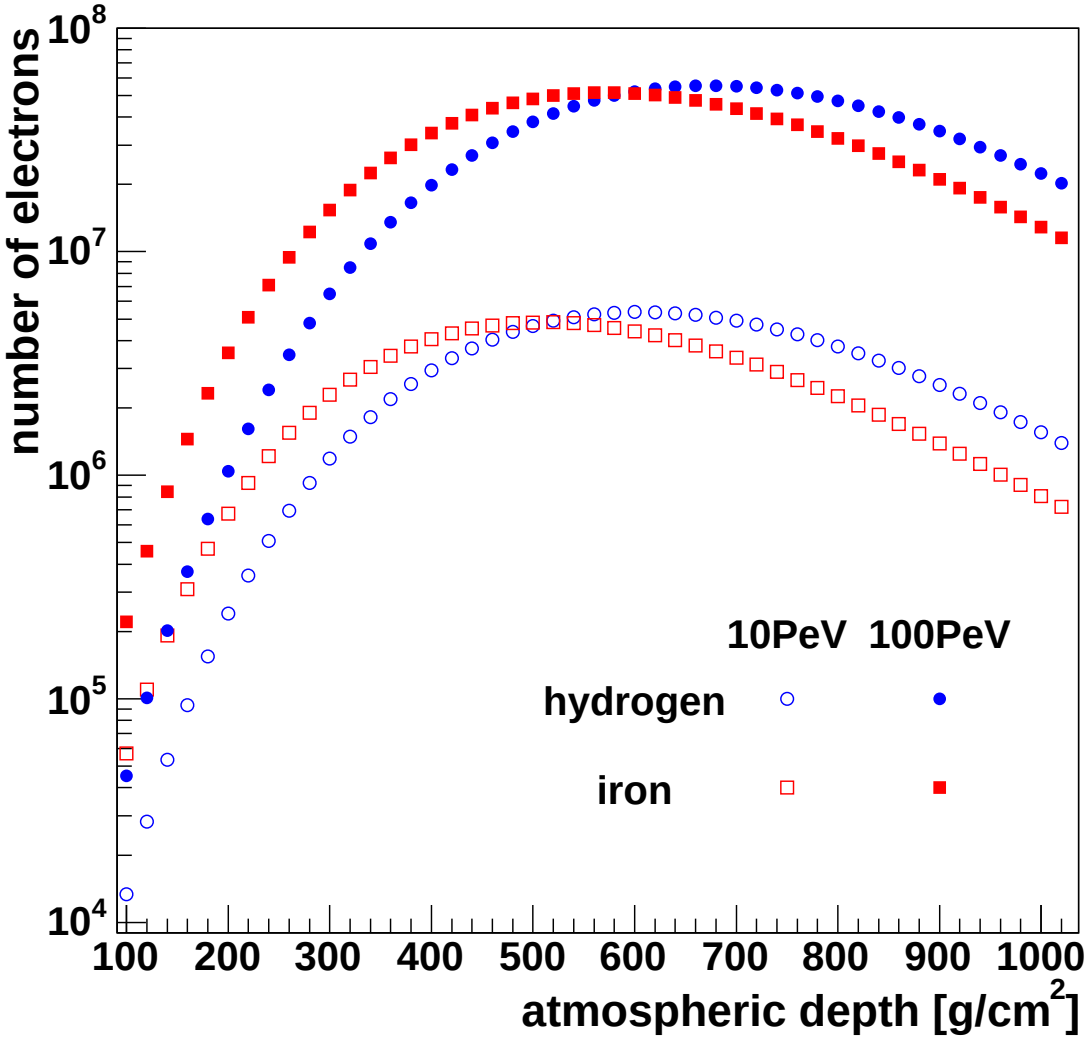
kNN on other primaries



kNN on other primaries



Shower profiles



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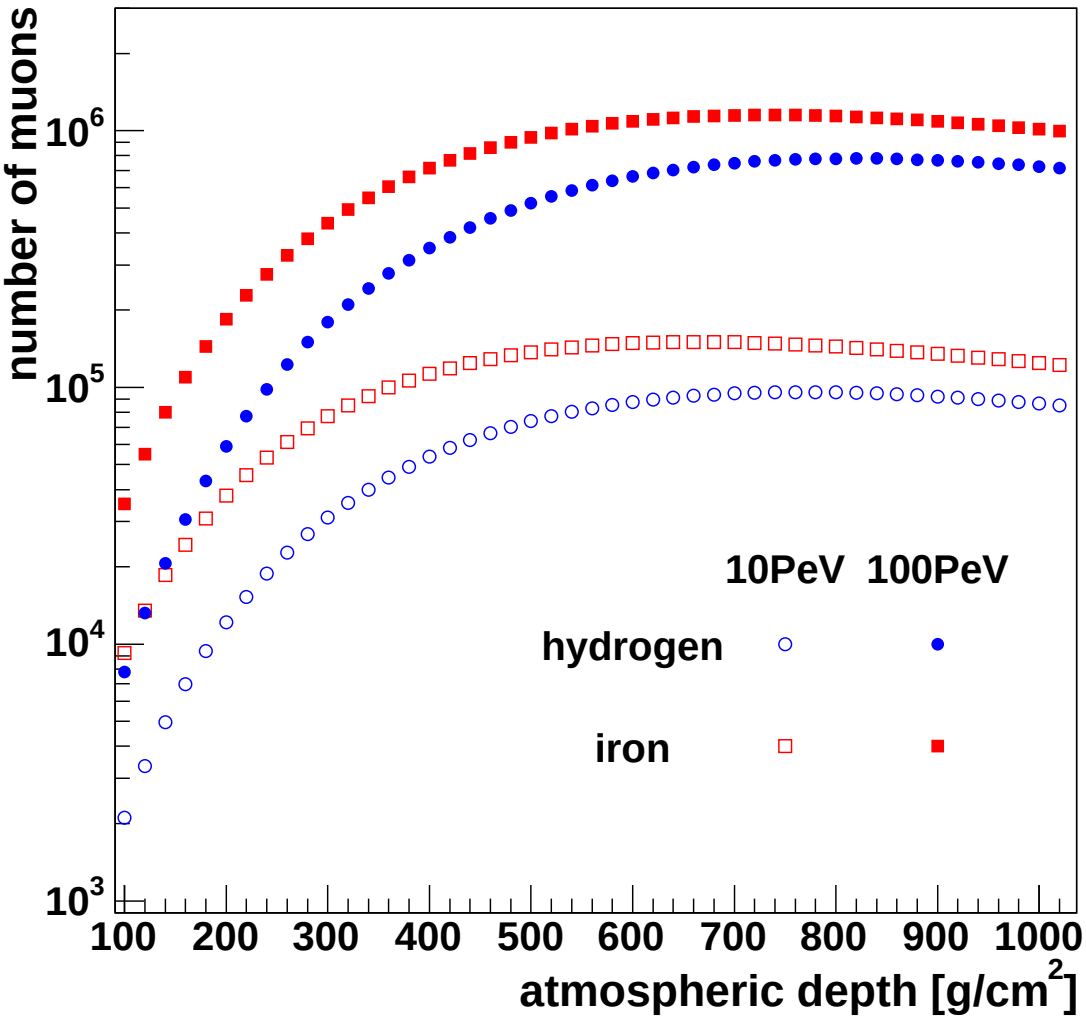
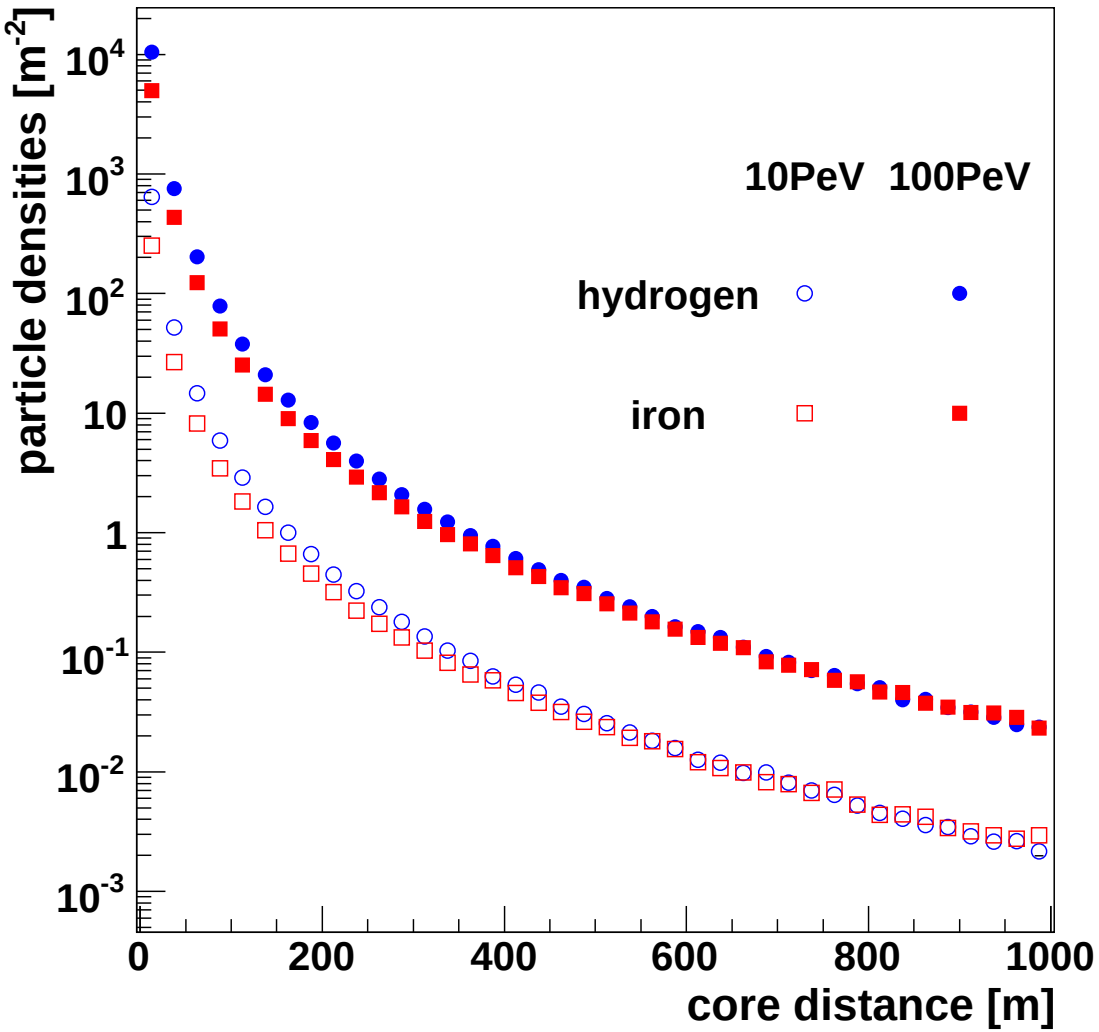


Shower profiles



Shower profiles