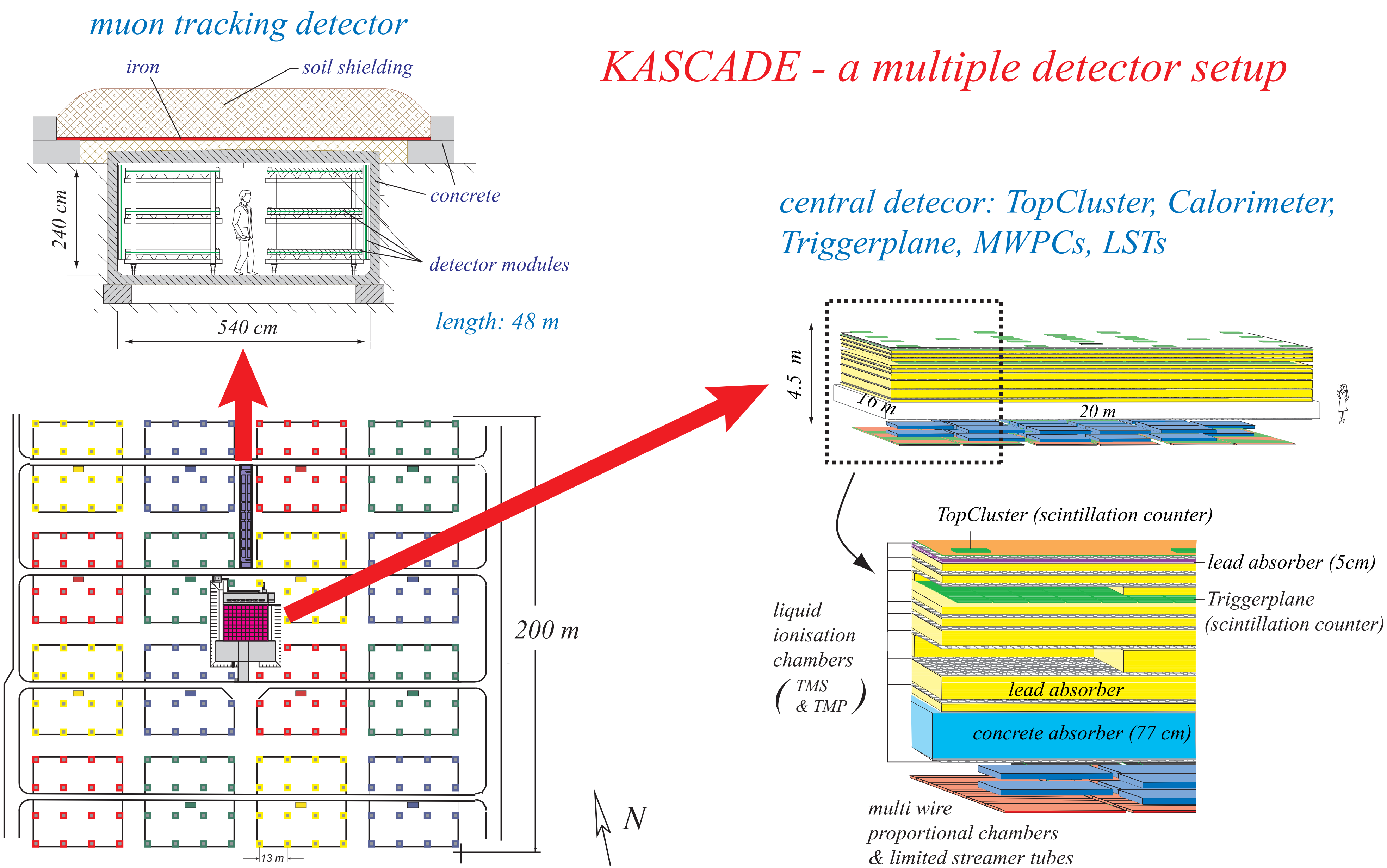
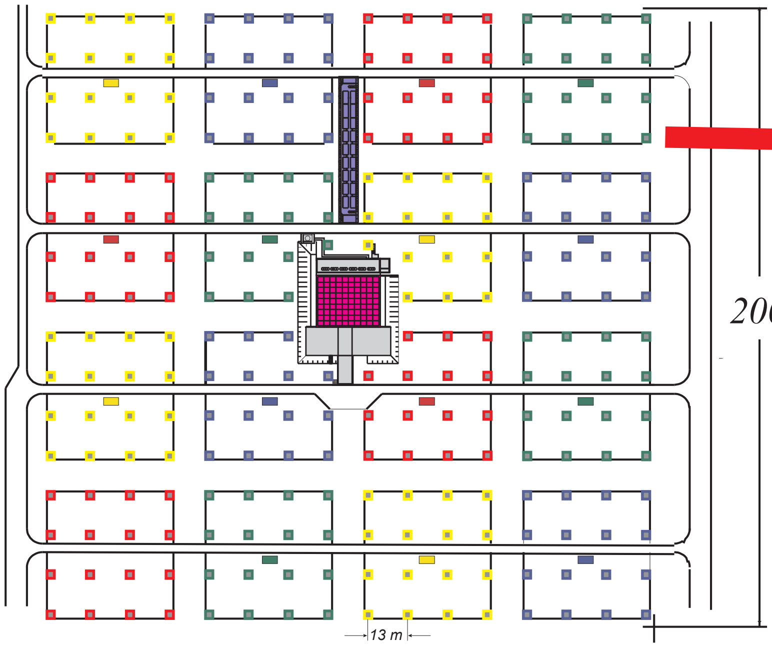
Reconstruction of energy spectra of elemental groups at KASCADE: sensitivity to hadronic interaction models

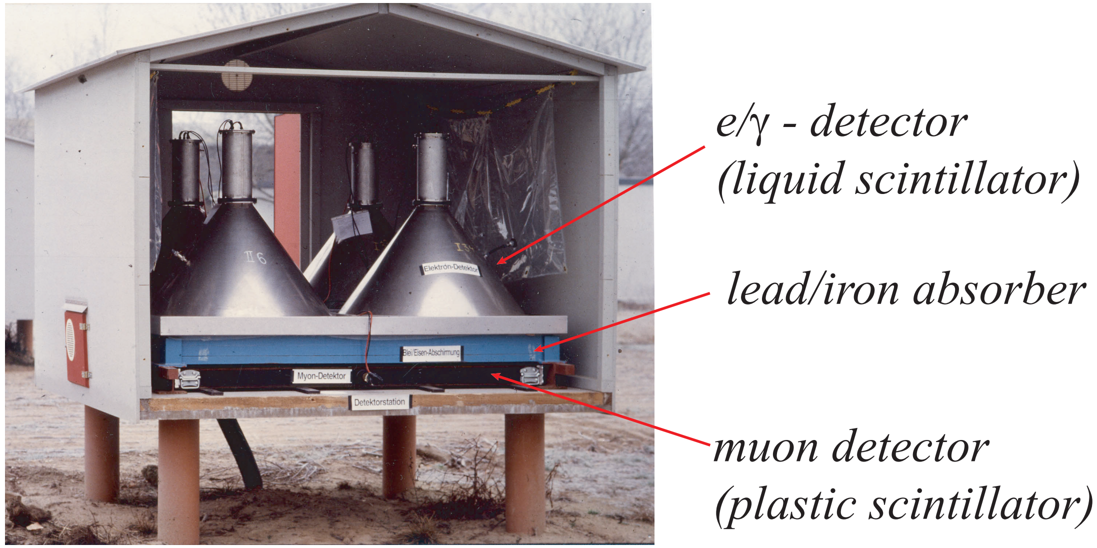
H. Ulrich for the

KASCADE collaboration

KASCADE - a multiple detector setup

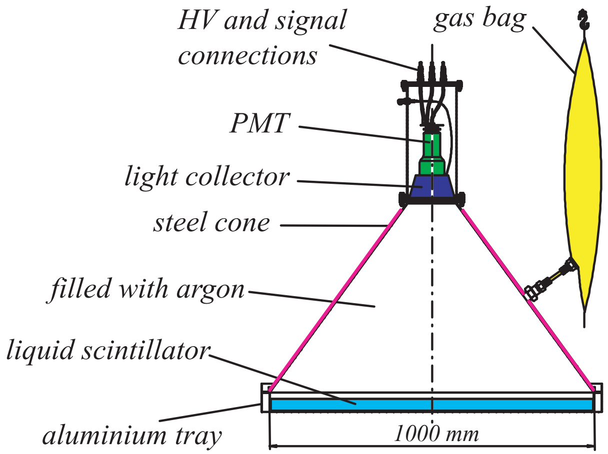




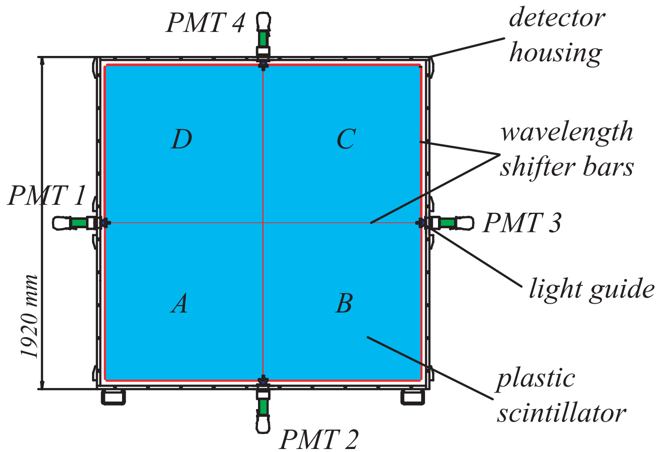


KASCADE array

determination of electron number, muon number, shower core and angle of incidence of air shower



e/γ - detector

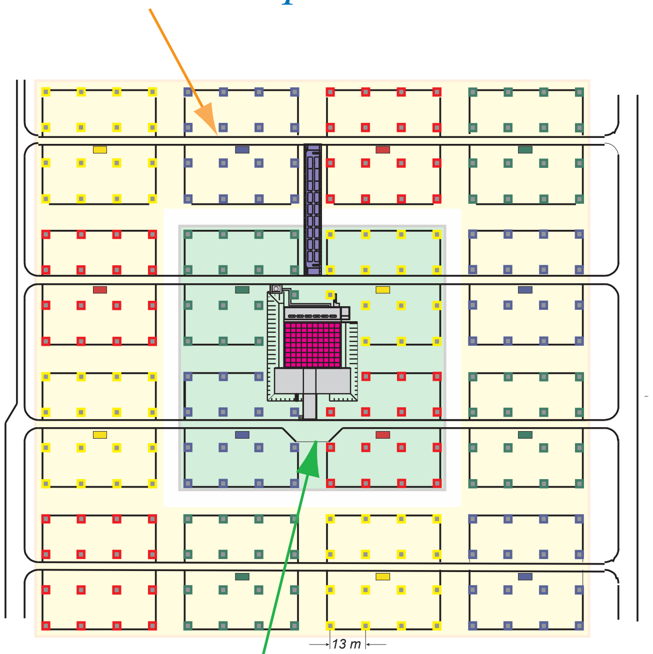


muon detector

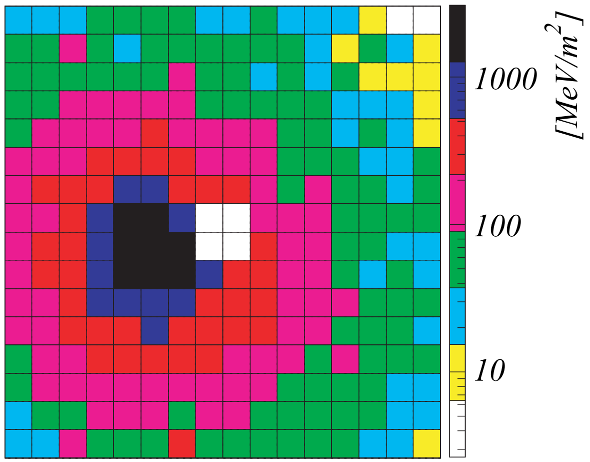
air shower event in the KASCADE array

in reality:

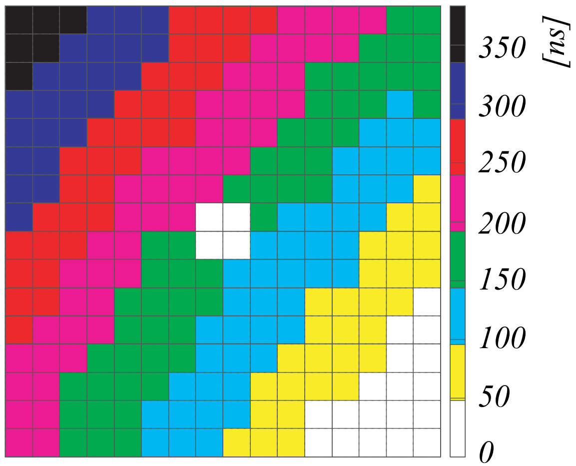
in outer 12 clusters only 2 e/γ-detectors and one muon detector per station



in inner 4 clusters 4 e/γ-detectors per station but no muon detector



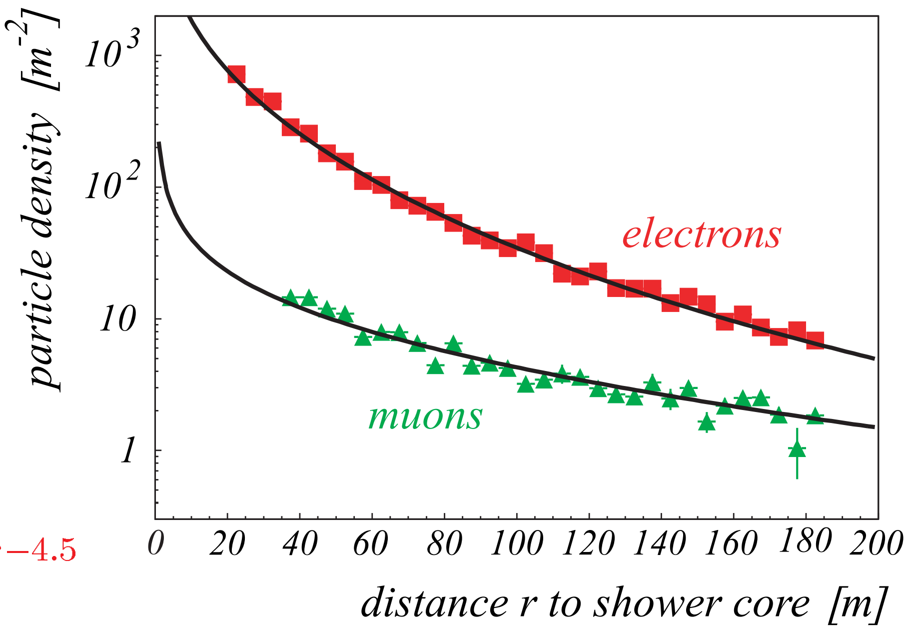
energy deposit



arrival time

determination of particle number (shower size)

→ *fit of lateral particle densities*



fit of lateral particle densities with

NKG function: *(Nishimura, Kamata, Greisen)*

$$\rho_x(r) = \frac{N_x}{2\pi r^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-s)} \left(\frac{r}{r_m}\right)^{s-2} \left(1+\frac{r}{r_m}\right)^{s-4.5}$$

for electrons: $r_m = 89\ m$

for muons: $r_m = 420\ m$

(s not variable, function of N_e*)*

KASCADE speciality:

truncated muon number: $N_\mu^{tr.}$

number of muons within 40 m to 200 m distance from shower core

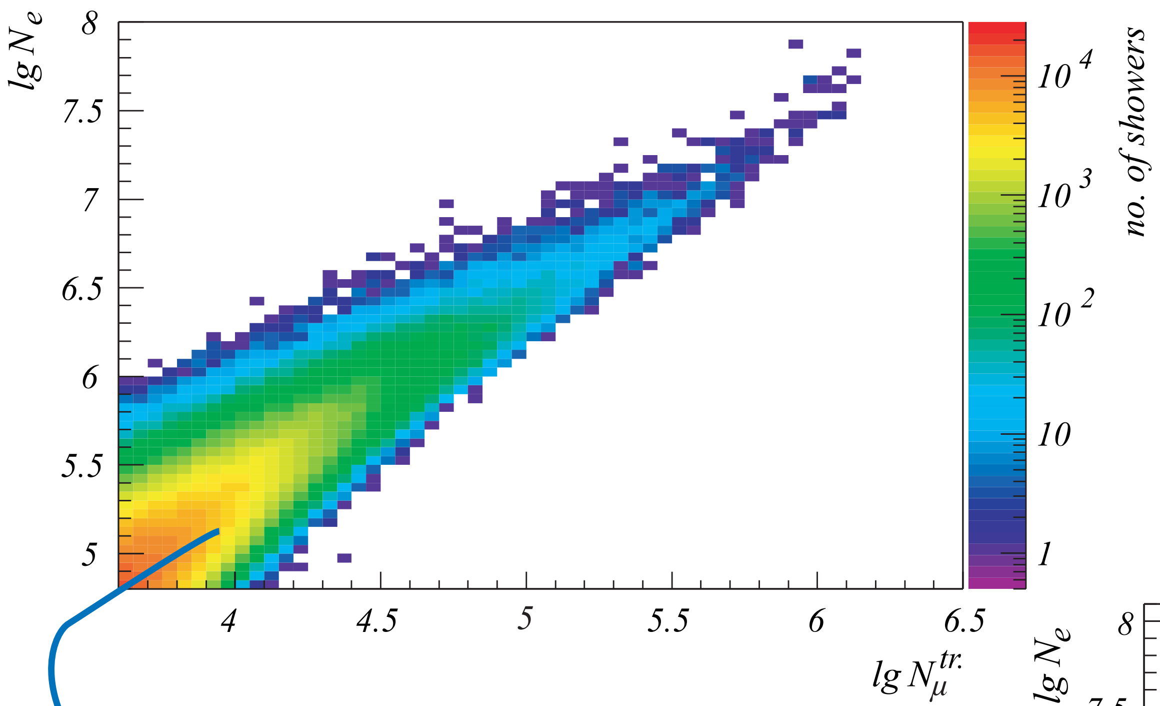
core region: punch through by high energy gammas

theoretical form of muon lateral distribution not known

2-dimensional shower size distribution

frequency of showers dependent on 2 observables

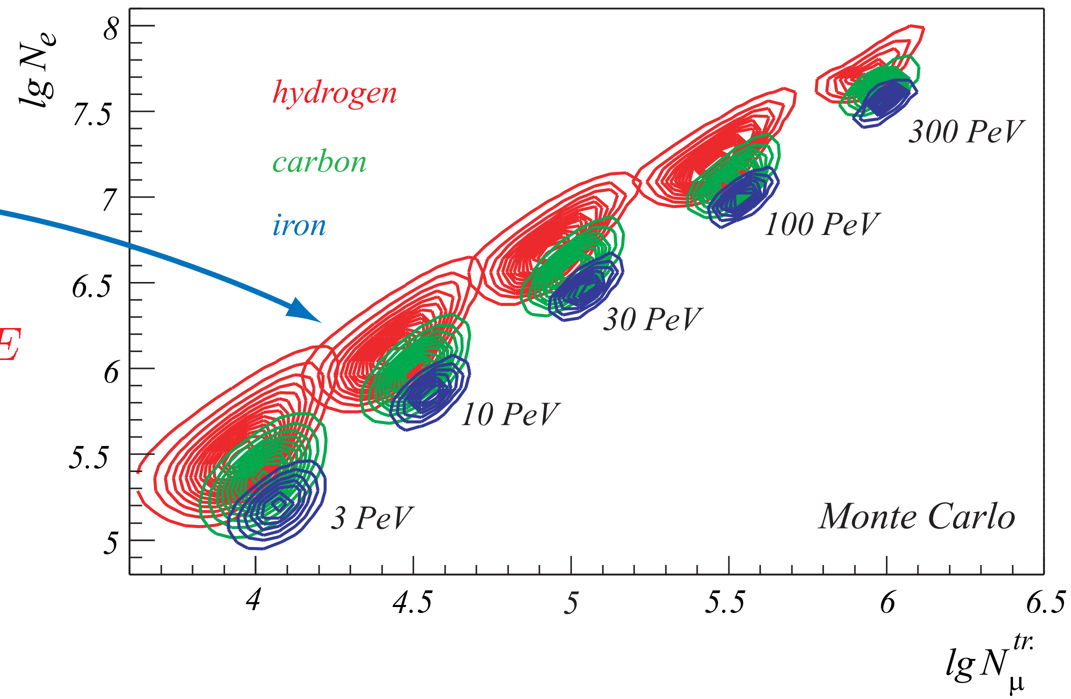
zenith angle < 18°, eff. measurement time: 900 days



$$\frac{dJ}{d\lg N_e\, d\lg N_\mu^{tr}} =$$

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

→ *system of coupled integral equations*



Strategy:

application of unfolding algorithms

(Gold-, Bayes, reduced entropy method)

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

5 primary particle types: H, He, C, Si, Fe

determination by simulations (CORSIKA V6.018 and V6.3)

simulations at fixed energies using thinned showers, parameterization of shower fluctuations and their energy dependence

parameterization of detector response and reconstruction properties using full simulated showers

high energy hadronic interaction models used for the simulations: QGSJet 01, QGSJet II, SIBYLL 2.1

low energy interaction model: GHEISHA (for QGSJet 01 and SIBYLL) and FLUKA (for QGSJet II) *probability p_A itself is an integral*

$$p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) = \int_{-\infty}^{+\infty} r_A \, \epsilon_A \, s_A \, d\lg N_e^t \, d\lg N_\mu^t$$

$s_A(\lg N_e^t, \lg N_\mu^t \mid \lg E)$ — *shower fluctuations, probability to get* $\lg N_e^t, \lg N_\mu^t$ *for primary energy* $\lg E$

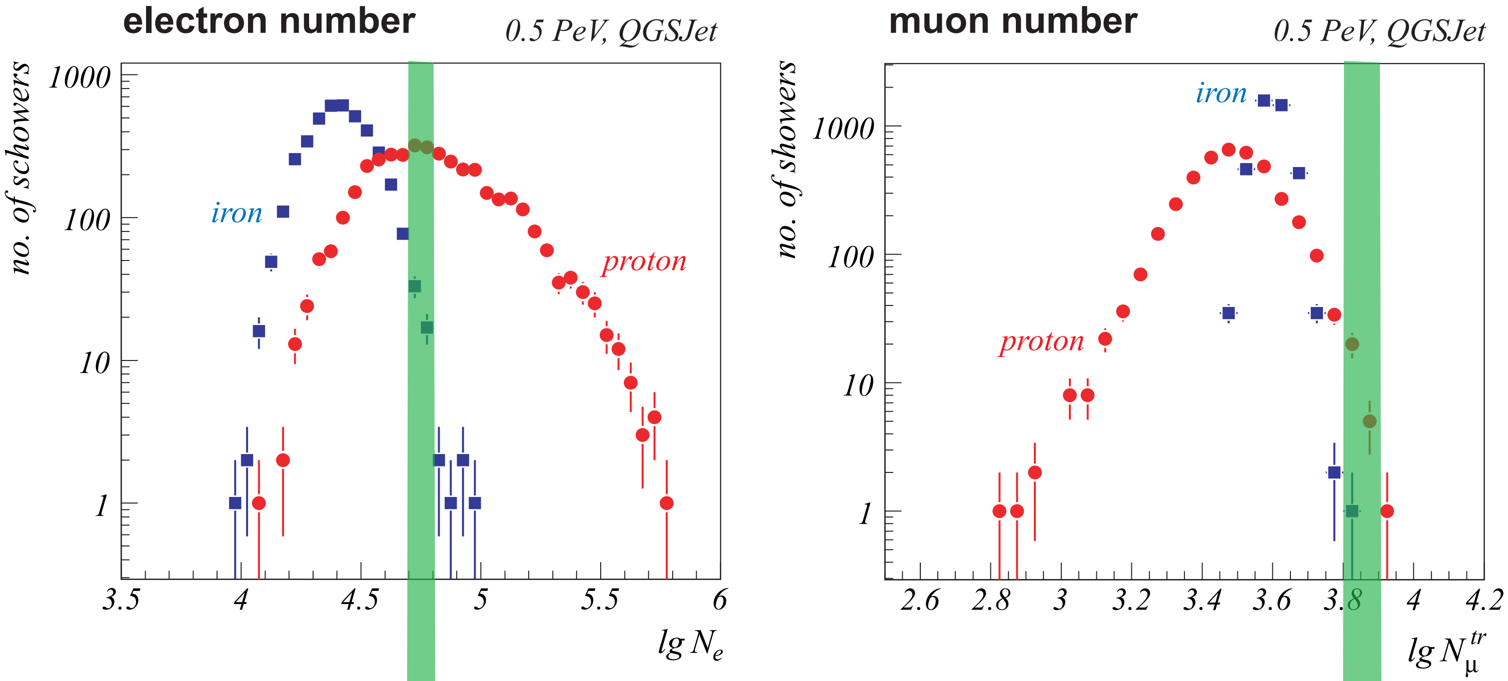
$\epsilon_A(\lg N_e^t, \lg N_\mu^t)$ — *efficiency to trigger experiment*

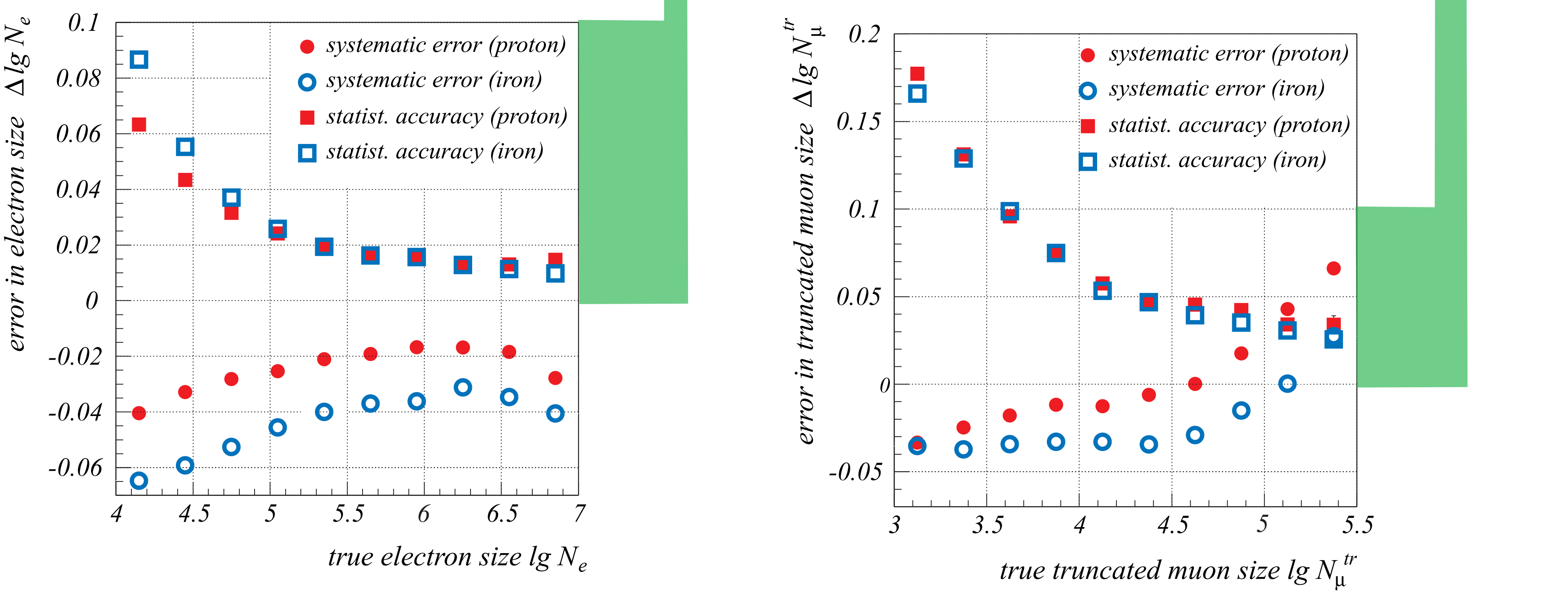
$r_A(\lg N_e, \lg N_\mu^{tr} \mid \lg N_e^t, \lg N_\mu^t)$ — *reconstruction, probability to reconstruct* $\lg N_e, \lg N_\mu^{tr}$ *out of* $\lg N_e^t, \lg N_\mu^t$

Which term is dominating? Sensitive to shower fluctuations?

Scales of shower fluctuations and reconstruction properties

→ shower fluctuations are dominating



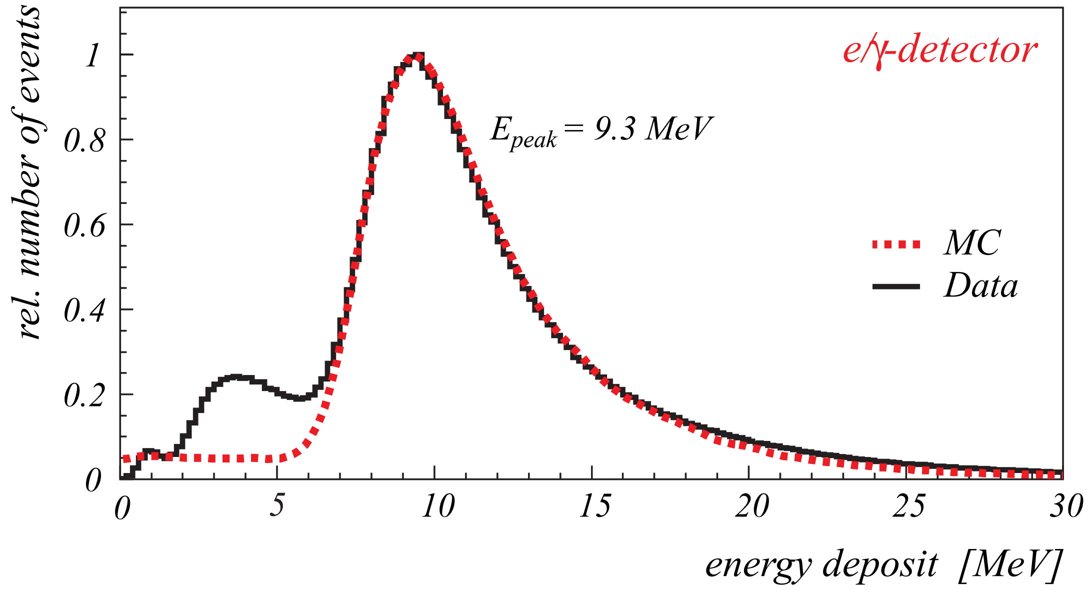


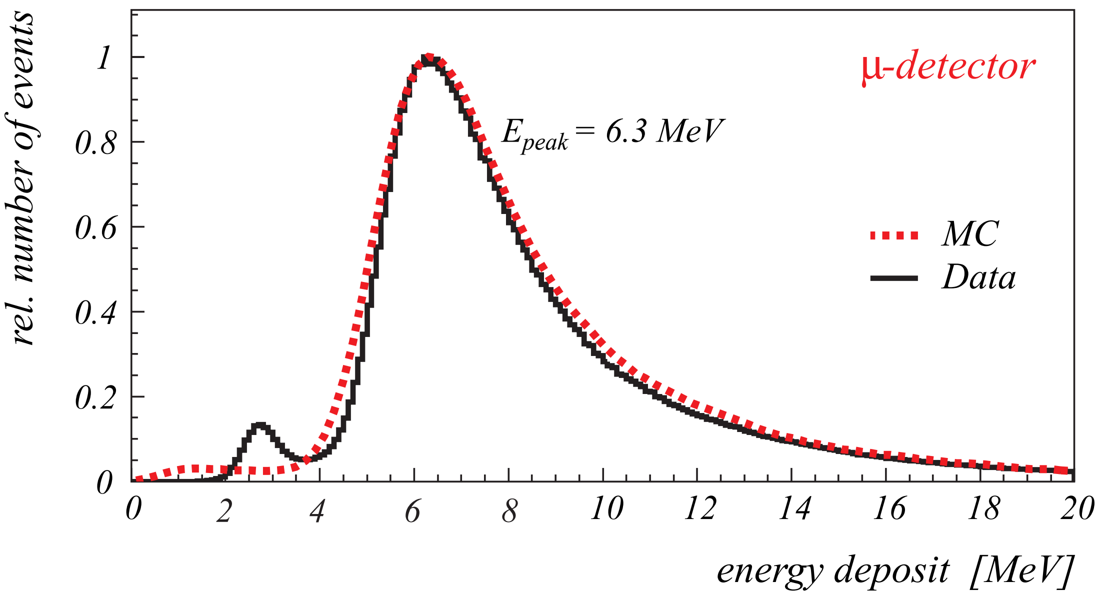
Checks of detector-MC/reconstruction: Description of detectors by Monte Carlo

simulation of signals form uncorrelated (free) muon flux

muon generator from KARMEN collaboration, based on Bugaev et al.

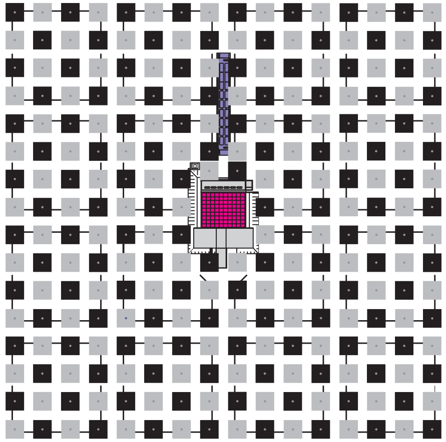
no fine-tuning to measured data





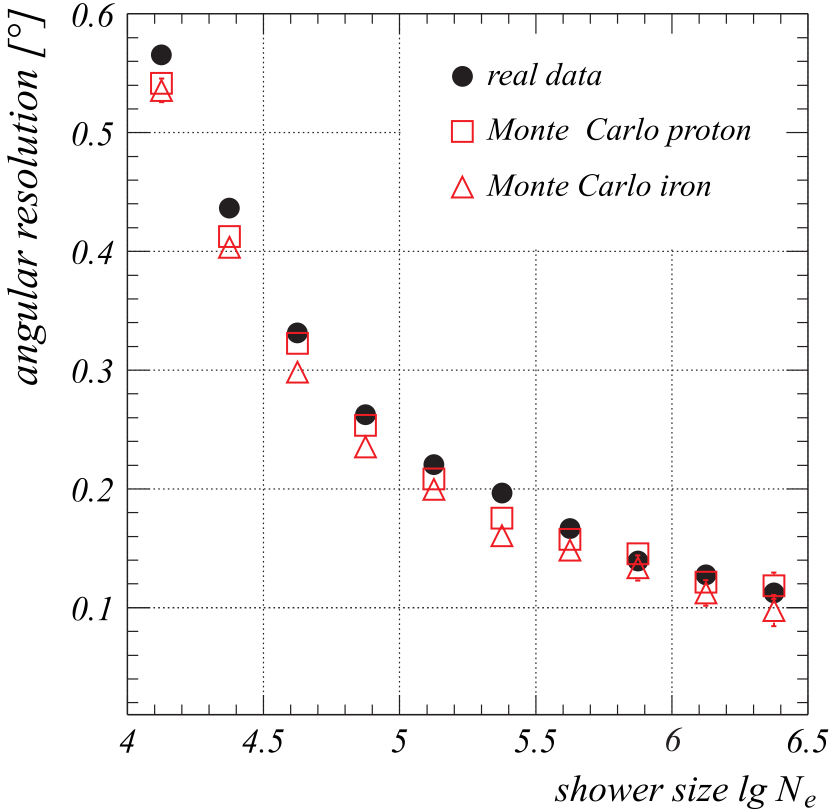
→ very good agreement between Monte Carlo and data

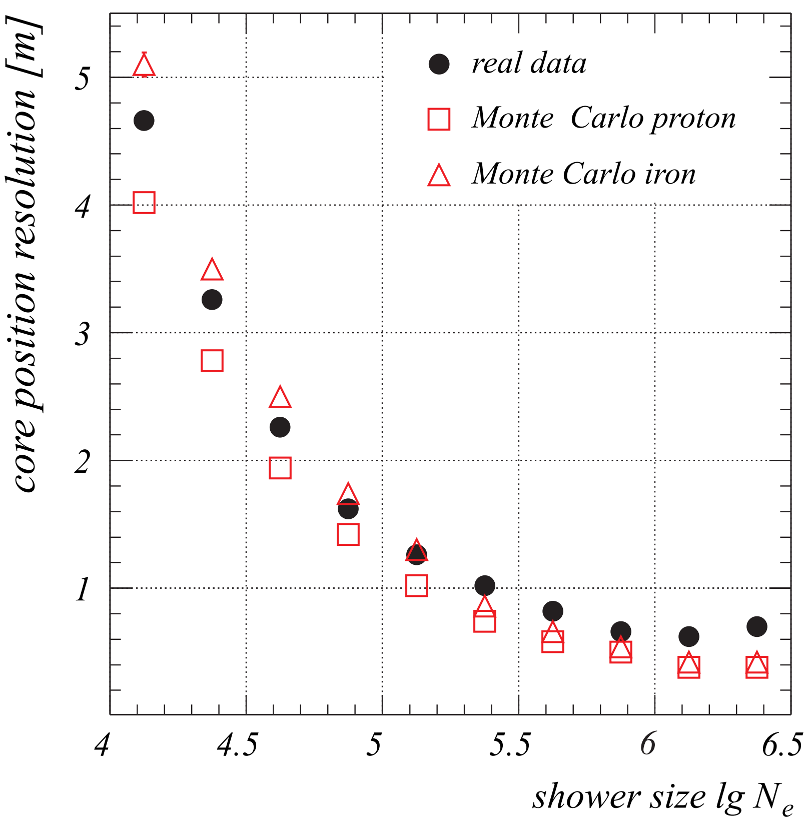
Checks of detector-MC/reconstruction:
checkerboard analysis ...



analyse same showers with black and white detectors
compare results

→ *good agreement between data and Monte Carlo*





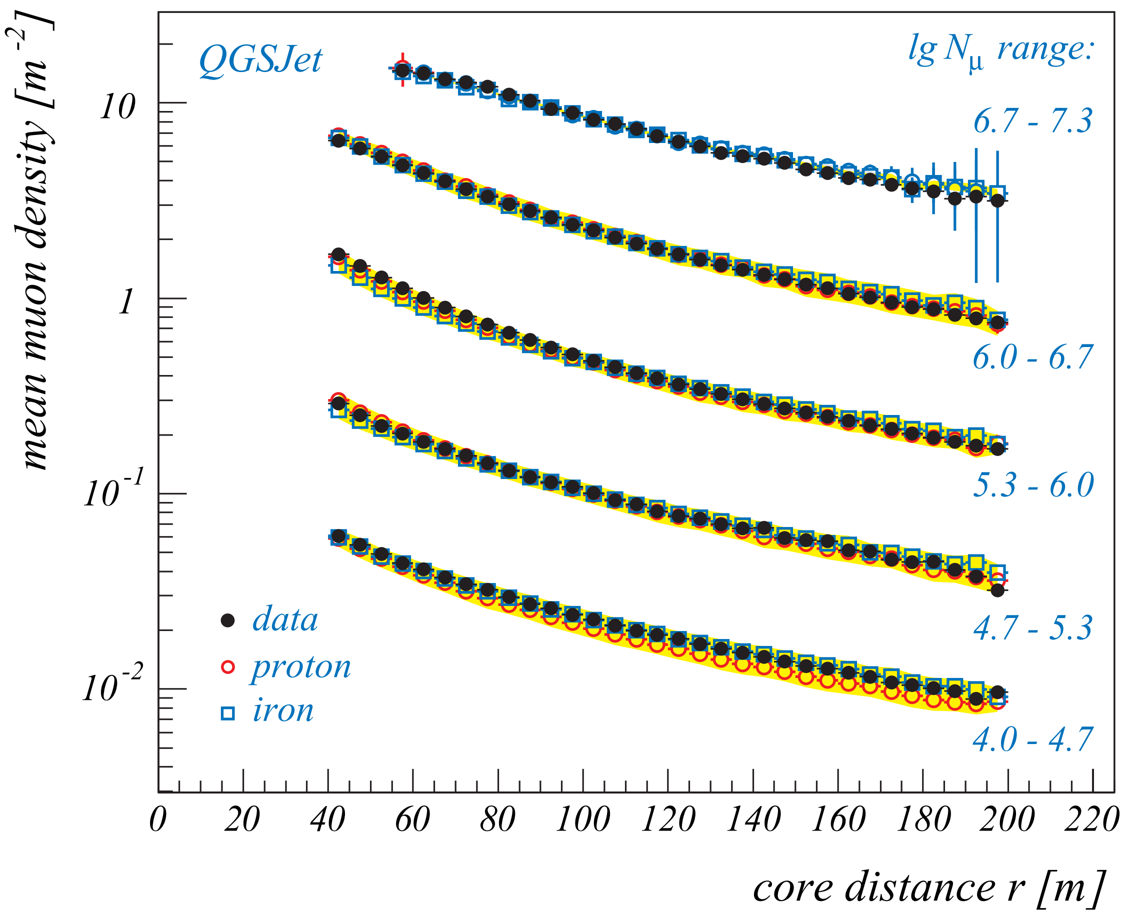
Checks of detector-MC/reconstruction:
Comparison of mean lateral distributions

comparison of mean lateral distribution of muons for different muon numbers

systematic uncertainties (bands) due to primary spectrum and composition

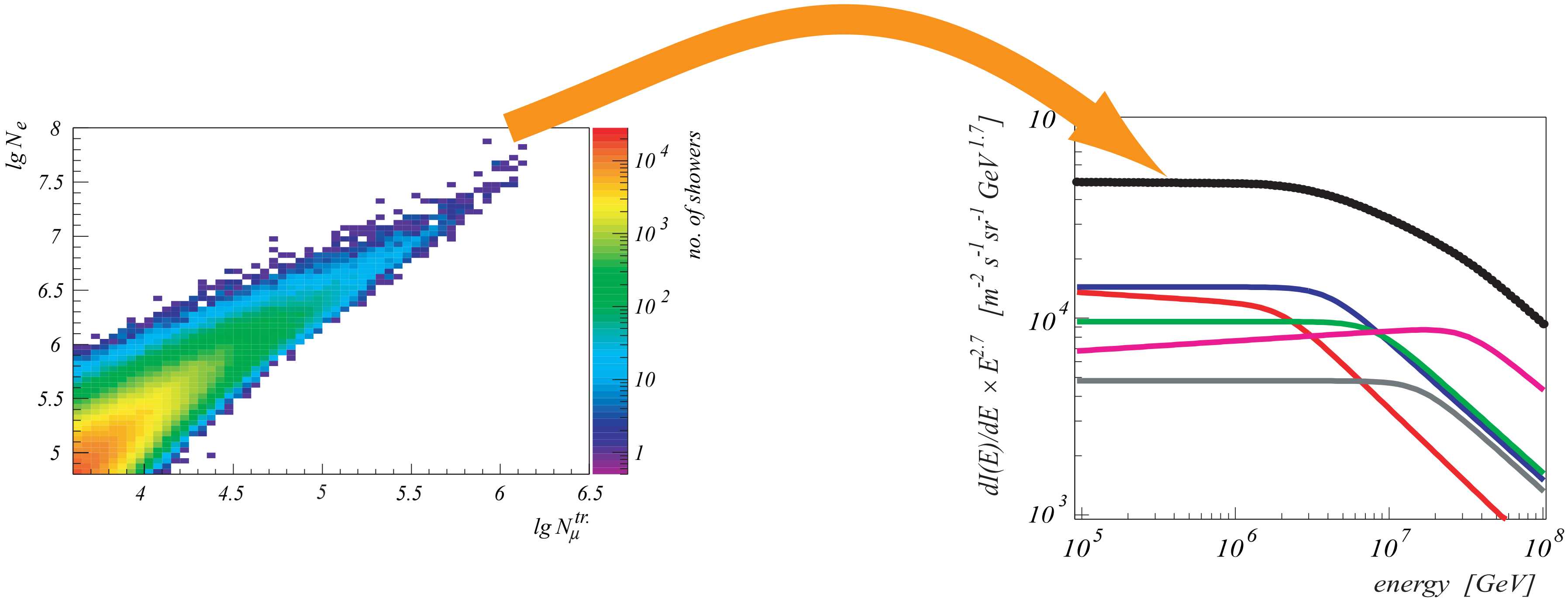
→ good agreement

description of radial dependent effect (punch through, saturation) looks o.k.



back to the analysis ...... results!

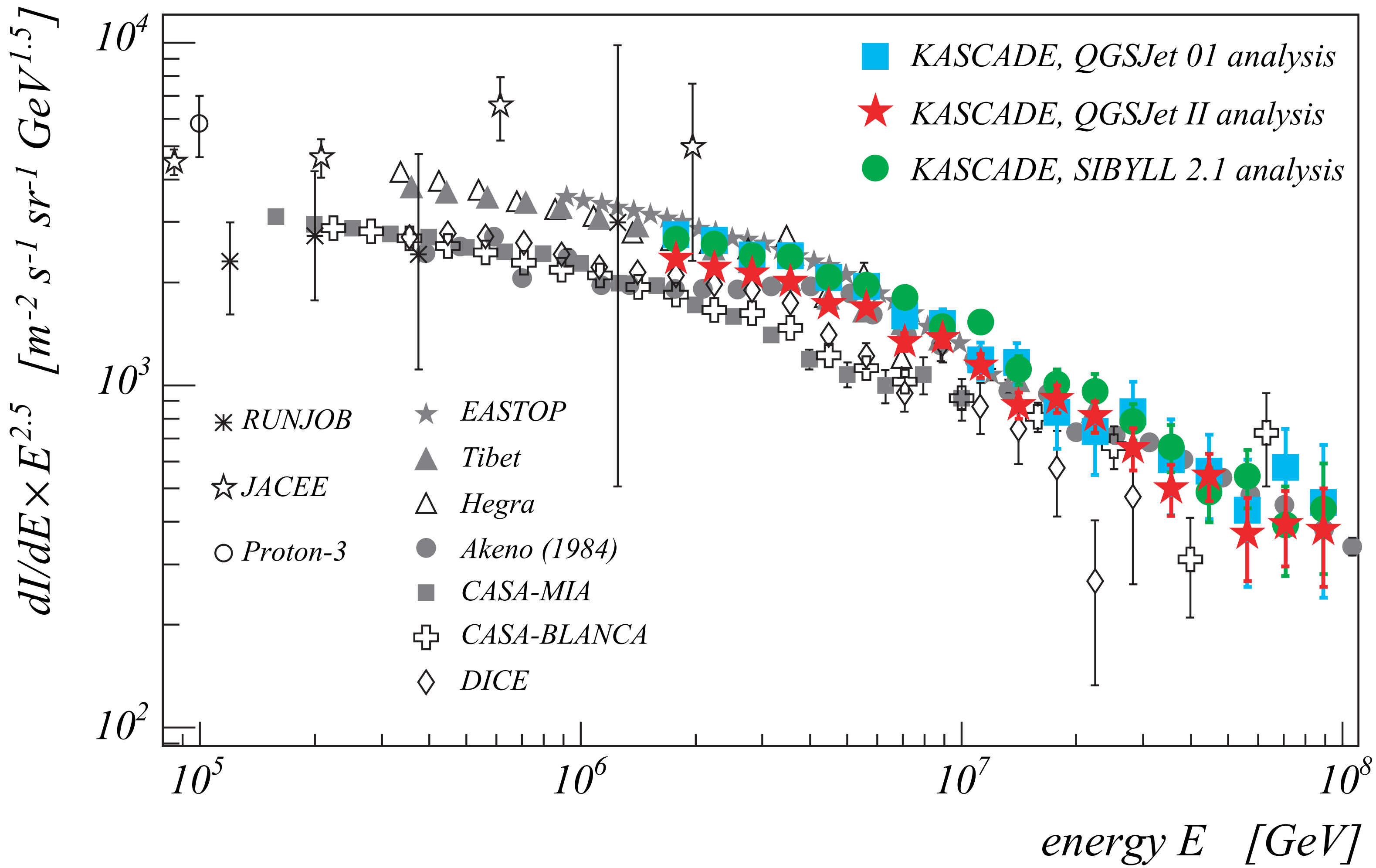
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu | \lg E) \, d\lg E$$



Result of unfolding analysis: all-particle energy spectrum

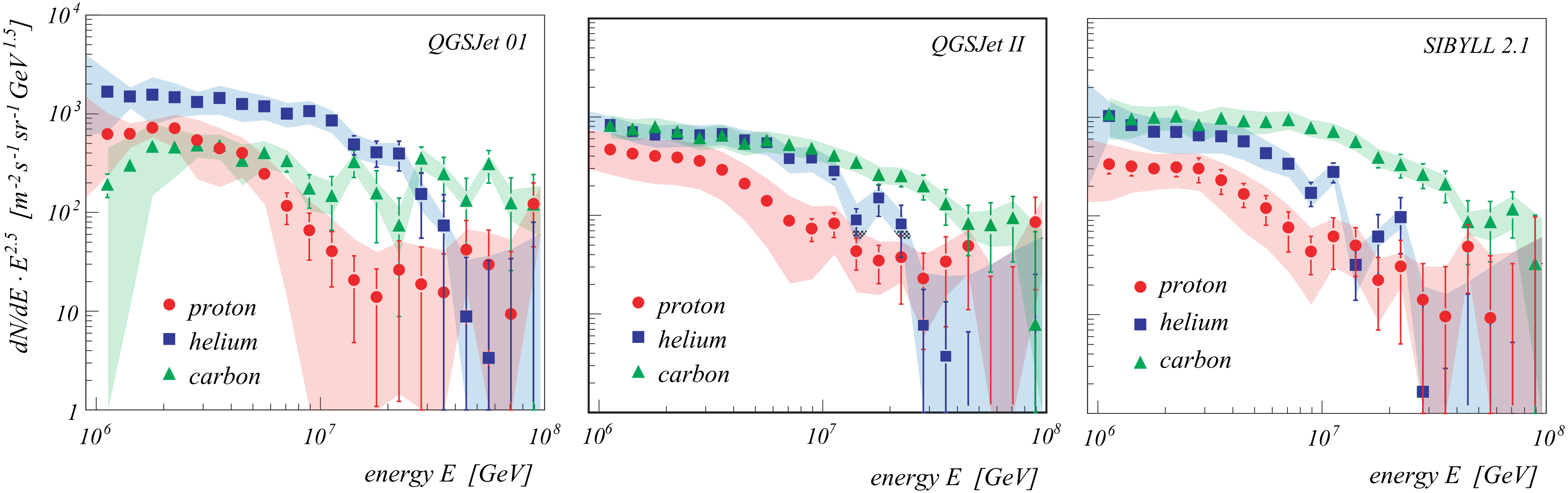
5 assumed primary particle types: H, He, C, Si, Fe

3 different hadronic interaction models (QGSJet 01, QGSJet II, and SIBYLL 2.1)



Comparison of results - individual energy spectra (1)

light elements H, He, C



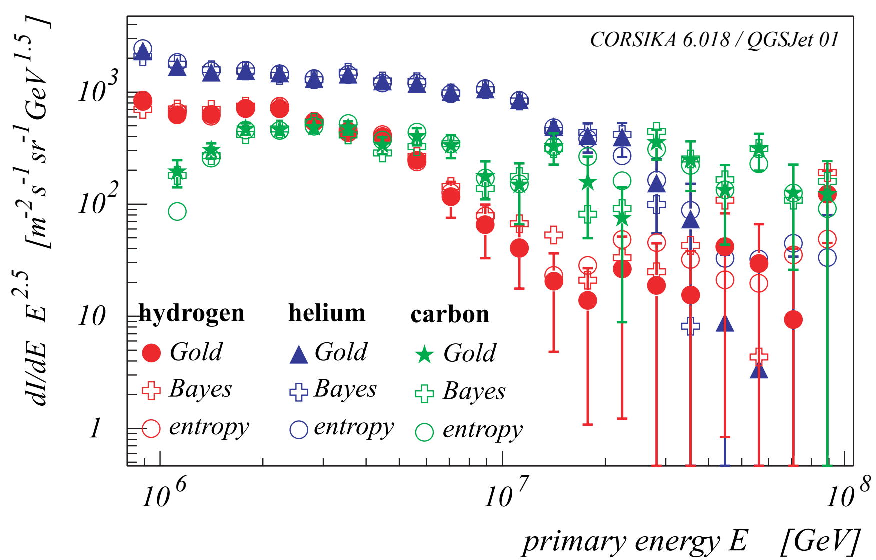
knee visible in all cases, composition below knee dominated by helium statistical uncertainties:

at low energies domiated by Monte Carlo statistics

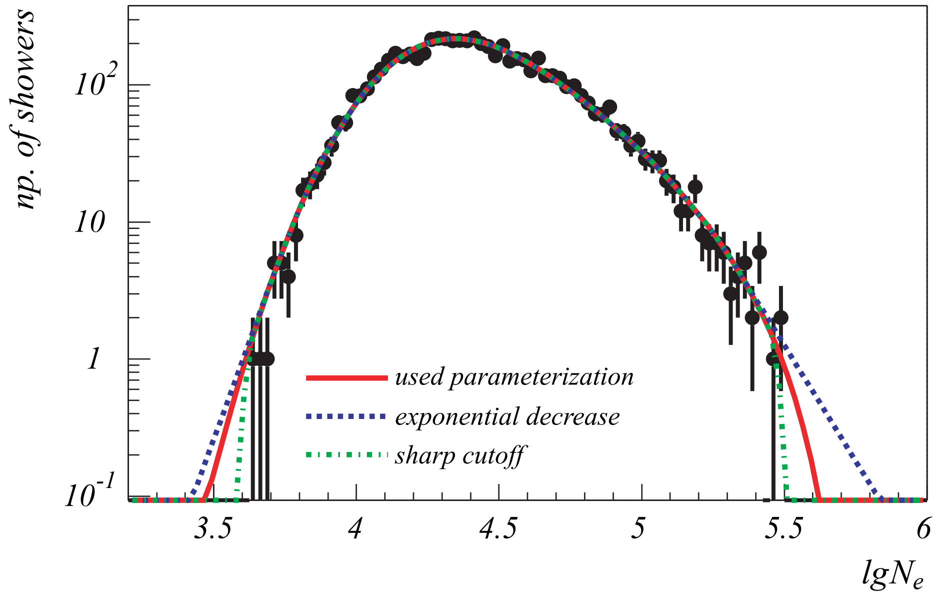
at high energies dominated by no. of measured showers

systematic uncertainties:

dominated by tails of shower fluctuations



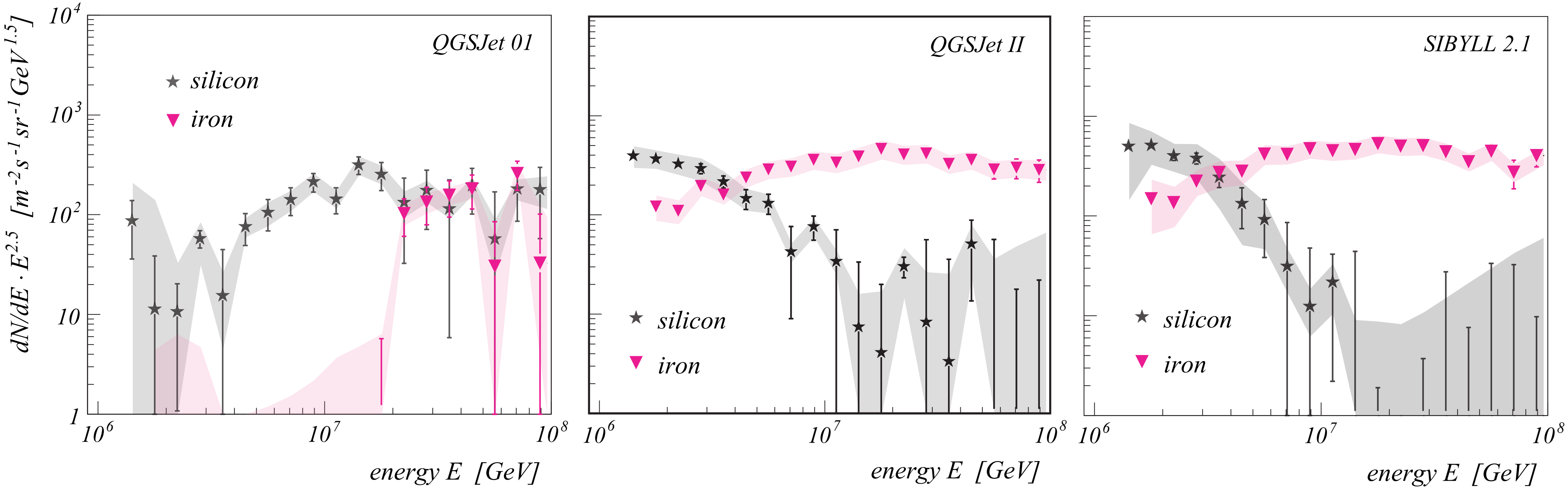
proton, 0.5 PeV, QGSJet 01



applied unfolding algorithm of minor influence

Comparisons of results - individual energy spectra (2)

spectra of heavy elements, Si and Fe



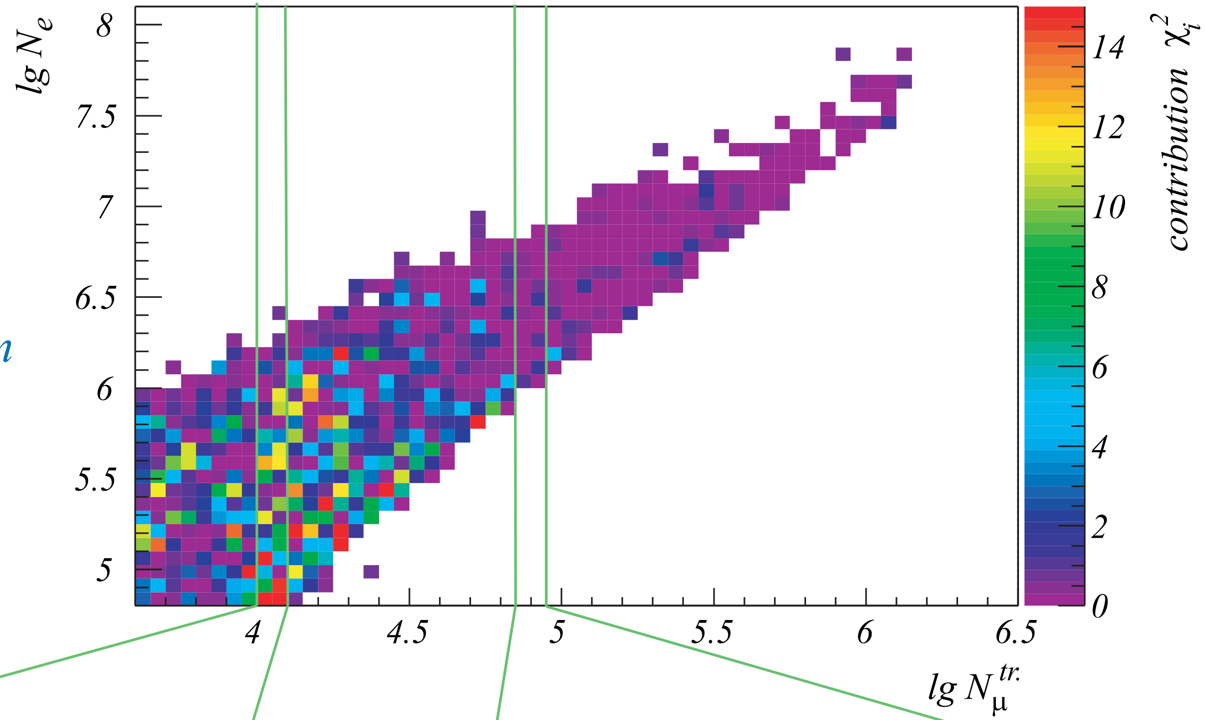
"strange" behaviour ...

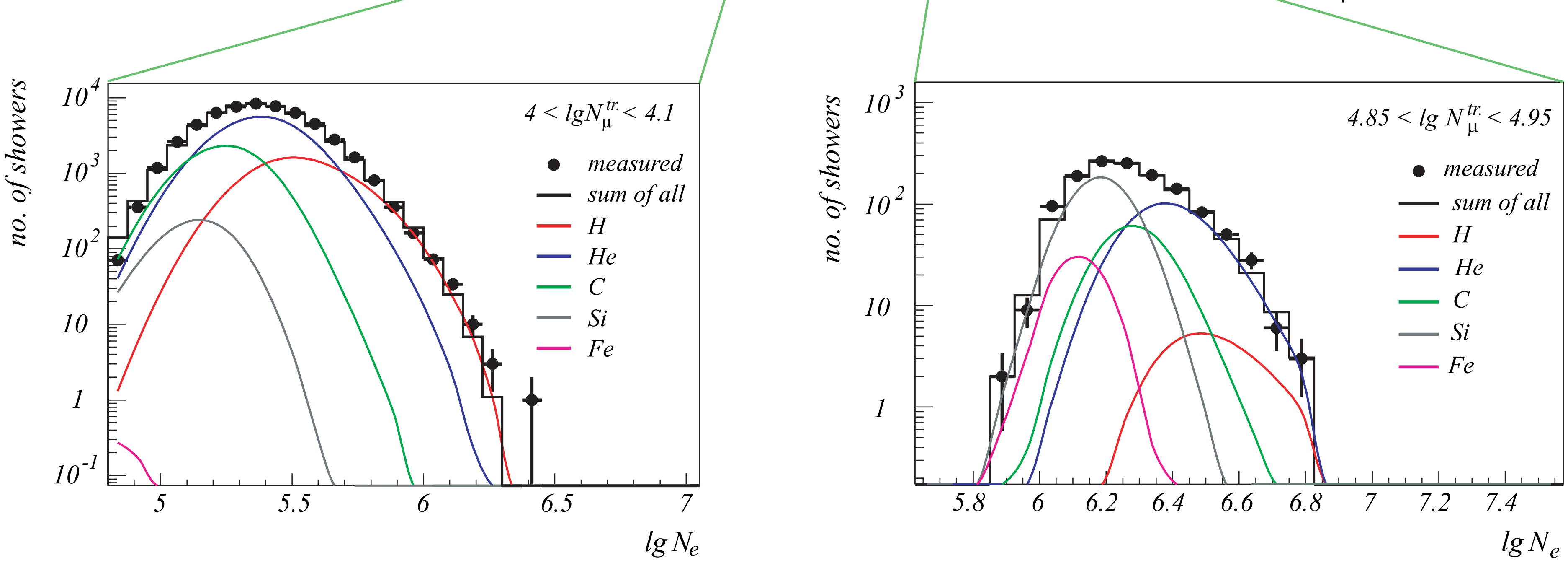
QGSJet 01 - result

Description of data

forward folding of solution with calculated probabilities, calculation of how the data would look like

comparison between calculated and measured data: χ^2



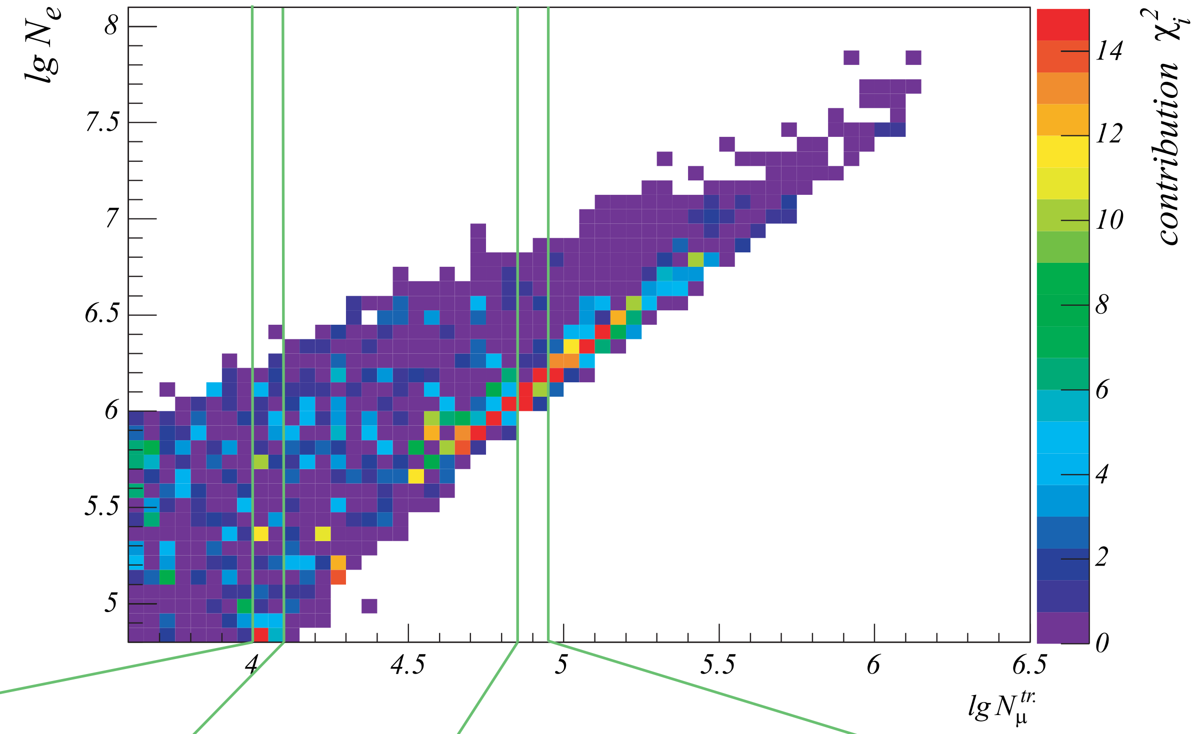


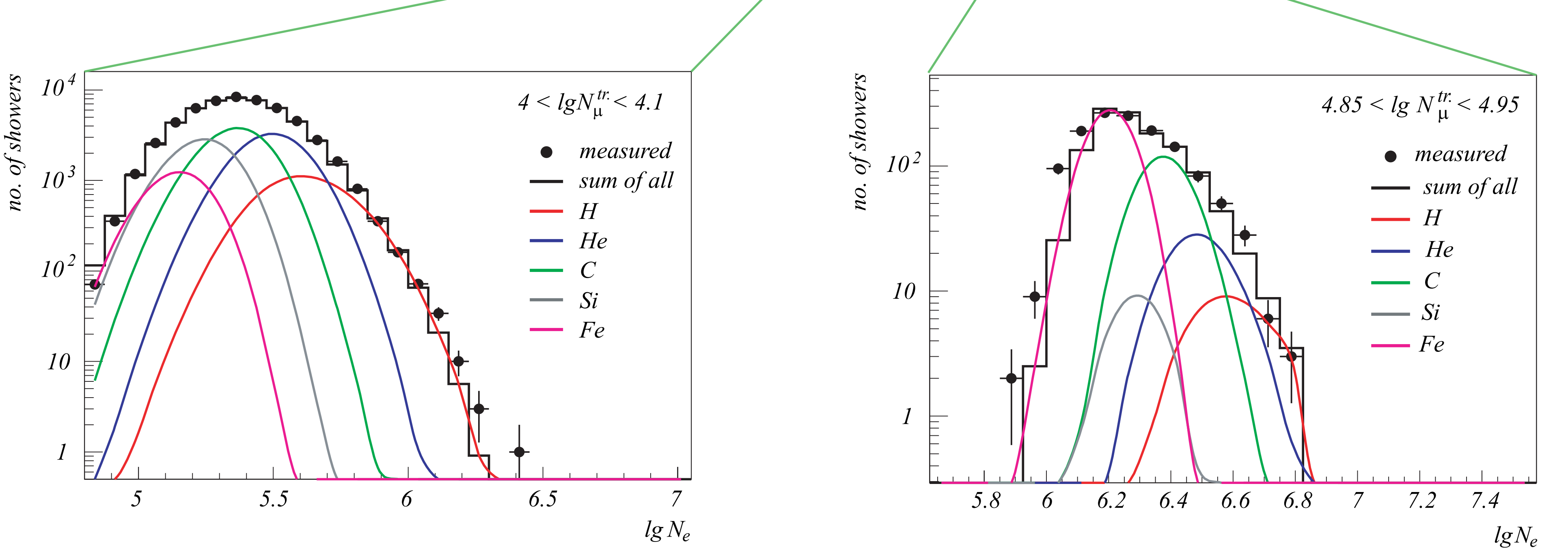
QGSJet II - result

Description of data

forward folding of solution with calculated probabilities, calculation of how the data would look like

comparison between calculated and measured data: χ^2



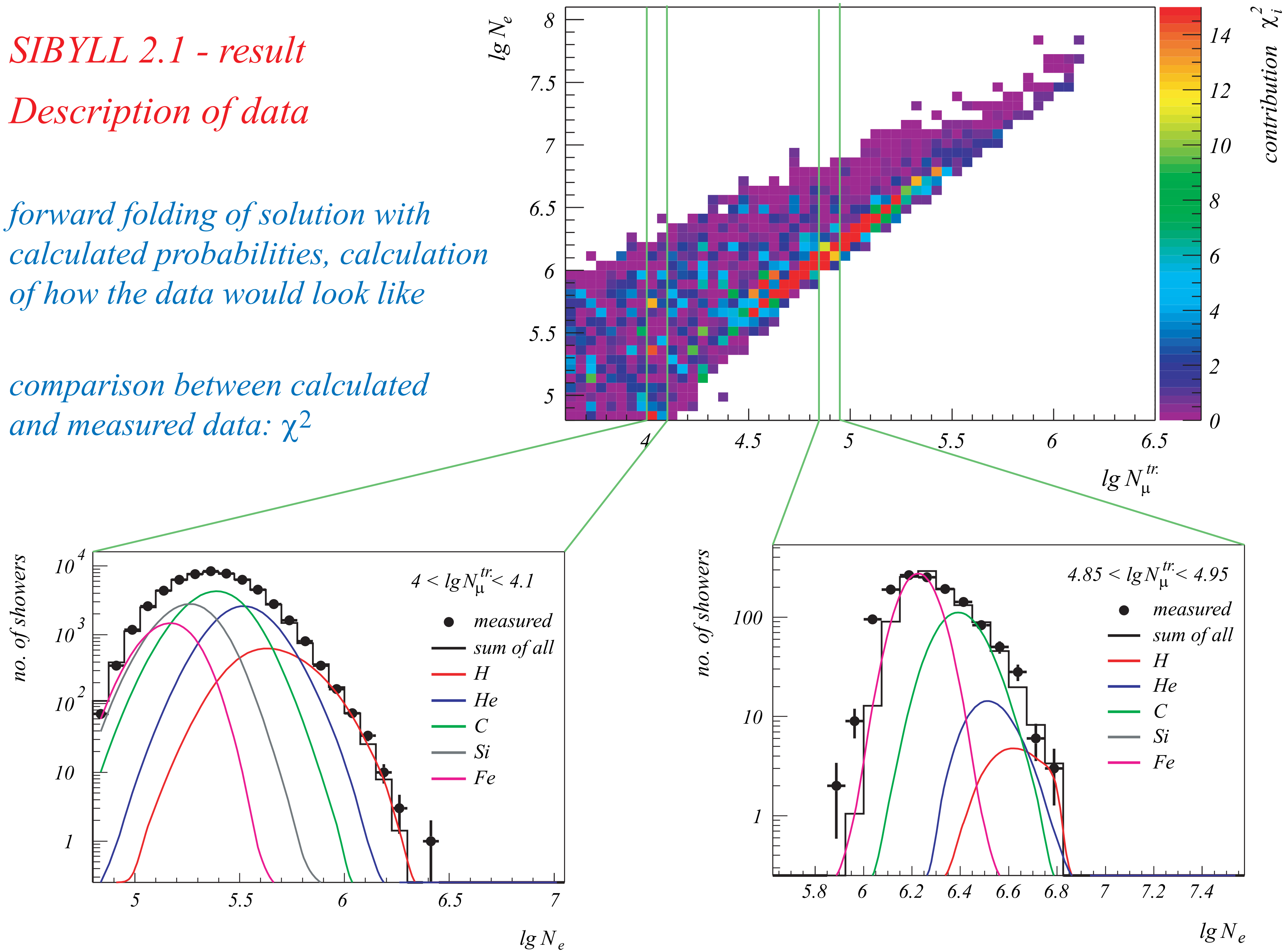


SIBYLL 2.1 - result

Description of data

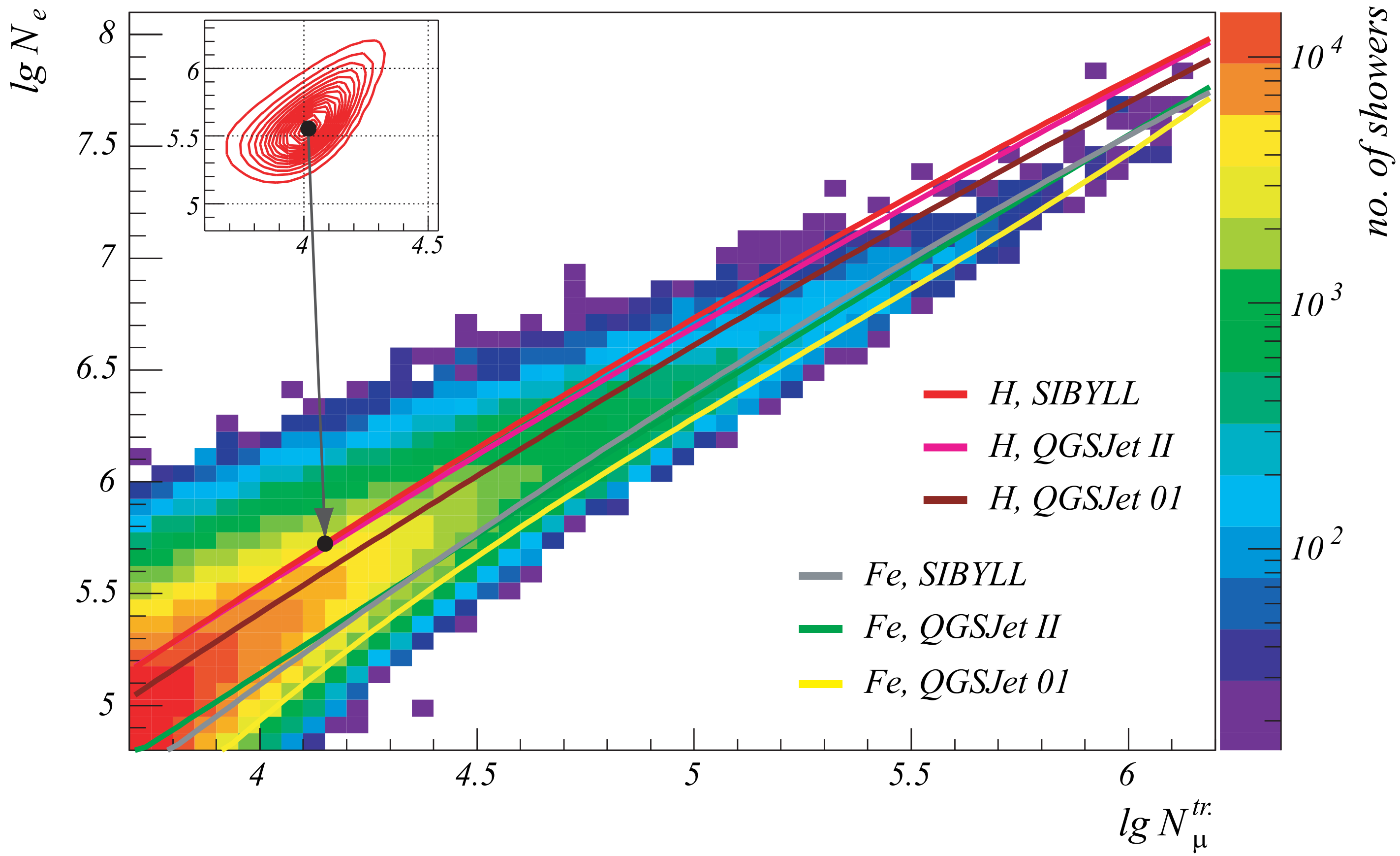
forward folding of solution with calculated probabilities, calculation of how the data would look like

comparison between calculated and measured data: χ^2



Simulation and data ... hints to the problem

lines:
most probable values of
correlated shower sizes
(maximum of distribution)



QGSJet 01

lower energies:

iron too close to heavy edge,
proton too far from light edge

higher energies: o.k.

QGSJet II

looks nearly like SIBYLL ...

SIBYLL

lower energies: o.k.

higher energies: iron too far from heavy edge

could a model start like SIBYLL
and end like QGSJet ?

Conclusions so far ...

possible to determine individual energy spectra by air shower data

knee at approx. 4 PeV in all-particle spectrum

composition gets heavier across knee, individual spectra exhibit knees

result for relative abundances dependent on used interaction model

QGSJet 01, QGSJet II, and SIBYLL 2.1 can't describe whole data range

analysis continues with new interaction models

sensitive to different hadronic interaction models used for the simulations